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**Recherche de nouvelles résonances à haute
masse dans l'état final dilepton et calibration
du démonstrateur pour l'upgrade Phase-1 du
calorimètre électromagnétique dans
l'expérience ATLAS**

**Search for new heavy resonances in the
dilepton final state and calibration of the LAr
Phase-1 Upgrade demonstrator at the ATLAS
experiment**

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Abstract

The Standard Model (SM) of particle physics was tested to a high precision at various experiments in the last decades and no significant deviation has been found so far. The LHC is a perfect machine to search for new phenomena, as its energy reach is considerably higher than that of previous accelerators. The so-called Run 2 of the LHC covers the data taking period between 2015 and 2018, during which proton-proton collisions at a centre-of-mass energy of 13 TeV were recorded. The full Run 2 integrated luminosity to be used by the ATLAS analyses is 139 fb^{-1} .

Many theories beyond the Standard Model predict additional resonances that can decay leptonically. A search for dielectron and dimuon resonances in the 250 GeV to 6 TeV mass range, based on the full Run 2 dataset, is presented in this thesis. The background estimation in the analysis is performed by fitting a functional form to the data. A generic signal shape is chosen in order to facilitate reinterpretations of the fiducial cross-section limits. Lower resonance mass limits are set for benchmark models, and reach 4.5 TeV for the E_6 -motivated Z'_ψ boson in the dilepton channel. This search is one of the flagship analyses of the ATLAS experiment.

In addition to the dileptonic decay modes, heavy new resonances can decay into other final states such as pairs of SM W and Z bosons, VH pairs with $V \in \{W, Z\}$ and H as the SM Higgs boson, or pairs of a lepton and a neutrino. Combining searches in various decay channels extends the discovery reach by exploiting their complementarity. The combination of the VV , VH , $\ell\nu$ and dilepton final states with 36.1 fb^{-1} of 2015 – 2016 data is detailed in this document.

The increased instantaneous luminosity of the LHC in the next data-taking period (Run 3) requires an upgrade of the ATLAS liquid argon (LAr) calorimeter trigger electronics. The new electronics increase tenfold the granularity of the LAr information provided to the first level of the trigger system and will enable a more advanced selection at the hardware level of the trigger. To test pre-prototypes of the upgraded electronics, an in-situ demonstrator system was installed at the start of Run 2 to collect data with the new read-out in parallel to the current one. The energy and timing calibration of the demonstrator system is presented in this thesis. Further detailed studies, performed with data collected in 2017, include the comparison of the energy and timing reconstruction between the output of the upgraded system and the standard LAr read-out, event-level shower shape information and pulse shape predictions, among other measurements. A good agreement with the expectation is found, demonstrating the readiness for the Run 3 data-taking period.

Résumé

Le Modèle standard (MS) de la physique des particules a été testé avec une grande précision par diverses expériences au cours des dernières décennies et aucun écart significatif n'a été constaté jusqu'à présent. Le LHC est une machine parfaite pour la recherche de nouveaux phénomènes, car il permet d'atteindre des énergies considérablement plus élevées que celles des accélérateurs précédents. Le Run 2 du LHC couvre la période de collecte des données allant de 2015 à 2018, au cours de laquelle des collisions proton-proton d'une énergie au centre de masse de 13 TeV ont été enregistrées. La luminosité intégrée totale utilisable par les analyses ATLAS pour le Run 2 est de 139 fb^{-1} .

De nombreuses théories au-delà du Modèle standard prédisent des résonances supplémentaires qui peuvent se désintégrer leptoniquement. Cette thèse présente une recherche de résonances dans les états finaux diélectron et dimuon dans la fourchette de masse de 250 GeV à 6 TeV, basée sur l'ensemble de données Run 2. L'estimation du bruit de fond dans l'analyse est effectuée en ajustant une forme fonctionnelle aux données. Une forme de signal générique est choisie afin de faciliter la réinterprétation des limites sur la section efficace dans le volume fiduciel. Des limites inférieures pour la masse de nouvelles résonances sont mesurées pour des modèles de référence. Pour le boson Z'_{ψ} motivé par la symétrie E_6 , la limite mesurée dans le canal dilepton est de 4.5 TeV. Cette recherche est une des analyses les plus importantes de l'expérience ATLAS.

En plus des modes de désintégration dileptoniques, de nouvelles résonances à haute masse peuvent se désintégrer dans d'autres états finaux tels que des paires de bosons W et Z du MS, des paires VH avec $V \in \{W, Z\}$ et le boson de Higgs H du MS, ou des paires lepton-neutrino. La combinaison de recherches dans différents canaux de désintégration permet d'étendre le potentiel de la découverte en exploitant leur complémentarité. La combinaison des états finaux VV , VH , $\ell\nu$ et dilepton avec 36.1 fb^{-1} de données de 2015 – 2016 est détaillée dans ce document.

L'augmentation de la luminosité instantanée du LHC au cours de la prochaine période de prise de données (Run 3) nécessite une mise à niveau de l'électronique de déclenchement du calorimètre à argon liquide (LAr) d'ATLAS. La nouvelle électronique décuple la granularité de l'information LAr fournie au premier niveau du système de déclenchement et permettra une sélection plus fine au niveau hardware du déclenchement. Pour tester les pré-prototypes de l'électronique mise à niveau, un système de démonstration in-situ a été installé au début du Run 2, afin de collecter les données avec la nouvelle lecture en parallèle à l'actuelle. L'étalonnage de l'énergie et de l'information en temps du système démonstrateur sont présentés dans cette thèse. D'autres études détaillées, réalisées à partir de données recueillies en 2017, comprennent la comparaison de la reconstruction de l'énergie et de l'information en temps entre le système démonstrateur et le système LAr standard, l'information sur la forme des gerbes au niveau de l'événement et la prédiction de la forme des impulsions d'ionisation, parmi d'autres mesures. Un bon accord avec les performances attendues est obtenu, démontrant l'état de préparation du système pour la prise de données du Run 3.

Contents

1	Introduction	1
2	Overview of high energy collider physics	5
2.1	Standard Model of particle physics	5
2.1.1	Symmetry group and interaction mediators	5
2.1.2	Quarks and leptons	6
2.1.3	Lagrangian of the Standard Model	7
2.1.4	The Higgs mechanism	7
2.1.5	Further properties of particles	8
2.2	Physics beyond the Standard Model	9
2.2.1	Limitations of the Standard Model	9
2.2.2	Theories beyond the Standard Model	10
2.3	Phenomenology at proton-proton colliders	13
2.3.1	Theoretical predictions and Monte Carlo simulations	15
3	The ATLAS detector at the LHC	17
3.1	The Large Hadron Collider	17
3.2	ATLAS	18
3.2.1	Coordinate system and kinematic quantities	18
3.2.2	Detector setup and subsystems	19
3.3	Reconstruction of physics objects	25
3.3.1	Electrons	25
3.3.2	Muons	25
3.3.3	Jets	25
3.3.4	Missing transverse energy	26
3.4	Data-taking conditions during Run 1 and Run 2 of the LHC	26
3.5	Detector upgrades towards Run 3 and the HL-LHC period	27
4	Read-out of the liquid Argon calorimeters	29
4.1	Detector components and read-out electronics	29
4.2	Signal reconstruction with optimal filtering coefficients	30
4.3	Calibration scheme of the LAr detector	32
4.4	Intermezzo: Properties of electromagnetic and hadronic showers	33
5	Calibration of the LAr Phase-1 demonstrator	37
5.1	Introduction to the LAr Phase-1 upgrade	37
5.2	Demonstrator system for the Phase-1 upgrade	39
5.3	Calibration scheme for demonstrator supercells	41

5.4	Determination of the calibration coefficients	43
5.4.1	Pedestal runs	44
5.4.2	Delay runs	44
5.4.3	Ramp runs	47
5.4.4	Physics pulse prediction	49
5.4.5	Timing alignment	53
5.4.6	Overview of the calibration coefficients	55
5.5	Validation of the calibration with pp collision data	56
5.5.1	Inclusive energy and timing reconstruction	57
5.5.2	Energy dependence of the energy comparison and the timing resolution	62
5.5.3	Physics pulse prediction	66
5.5.4	Event information for full demonstrator coverage	66
5.5.5	Correction of residual energy dependencies	72
5.6	First studies on 2018 data	75
5.7	Conclusion and outlook	77
6	Search for high-mass dilepton resonances	79
6.1	Analysis strategy	79
6.2	Event selection and data/MC samples	80
6.2.1	Object selection	81
6.2.2	Event selection	82
6.2.3	Calibration and corrections	83
6.2.4	Comparison between data and expectation from MC samples	83
6.3	Determination of transfer functions	84
6.3.1	General concept	84
6.3.2	Parametrisation of the detector mass resolution function	86
6.3.3	Validation with 0-width samples	91
6.3.4	Calculation of the acceptance times efficiency	92
6.3.5	Uncertainty of transfer function modelling due to limited MC statistics	92
6.4	Background smoothing with transfer functions	94
6.4.1	Background smoothing for Drell-Yan production	94
6.4.2	Application of the TF approach to $t\bar{t}$ production	94
6.5	Signal modelling with transfer functions	102
6.5.1	Calculation of acceptance times efficiency for wide signals	106
6.6	Systematic uncertainties on the signal modelling	107
6.6.1	Acceptance times efficiency uncertainties	108
6.6.2	Detector response uncertainties	109
6.7	Overview of statistical analysis concepts	110
6.8	Data-driven background estimation with a global fit	114
6.8.1	Motivation	115
6.8.2	Method and general implementation	115
6.8.3	Function choice and its optimisation with the spurious signal test	116
6.8.4	Parametrisation of the spurious signal	118
6.8.5	Treatment of systematic uncertainties	119
6.8.6	Validation of the background modelling function on data	120
6.8.7	Background-only fit results	123
6.8.8	Cross-checks for validation of procedure	124

6.9	Results of the dilepton resonance search	127
6.9.1	Significance and p -value scans	127
6.9.2	Generic cross-section limits	131
6.9.3	Mass limits on benchmark models	134
6.10	Conclusion and outlook	135
7	Combination of the $\ell\ell$ search with the $\ell\nu$, VV and VH channels	137
7.1	Analysis motivation and strategy	137
7.2	Combination of the leptonic channels	139
7.2.1	Signal reweighting	139
7.2.2	Mitigation of interference effects	142
7.2.3	Properties of the signal model	147
7.2.4	Statistical treatment	154
7.2.5	Cross-section and mass limits	154
7.3	Combination of the $\ell\ell$ and $\ell\nu$ channels with diboson searches	156
7.3.1	Overlap studies of signal regions for different searches	157
7.3.2	Cross-section limits	157
7.3.3	Mass limits in the HVT coupling plane	157
7.4	Comparison between the leptonic and bosonic channels	158
7.5	Reinterpretation of results from full Run 2 dilepton search	158
7.6	Conclusion and outlook	160
8	Summary and conclusions	163
A	Résumé français de la thèse	167
A.1	Introduction	167
A.2	La physique des collisionneurs à haute énergie	168
A.3	Le détecteur ATLAS au LHC	169
A.4	Étalonnage du démonstrateur LAr Phase 1	169
A.5	Recherche de résonances dileptoniques à haute masse	171
A.6	Combinaison de la recherche $\ell\ell$ avec les canaux $\ell\nu$, VV et VH	171
B	Further information on the LAr Phase-1 demonstrator calibration	173
B.1	Calibration patterns	173
B.1.1	Structure of calibration patterns	174
B.1.2	Patterns used for calibration runs	174
B.2	Additional calibration pulse shape figures	178
B.3	Summary of calibration coefficients	179
B.4	Dependence of reconstruction properties on shower maximum within supercells	184
B.5	Additional material on the validation of the calibration coefficients	190
B.5.1	Correlation of energy measurements	190
B.5.2	Correction of residual energy dependencies	191
C	Further information on search for high-mass dilepton resonances	193
C.1	Parametrisation of the transfer functions	193
C.2	Parametrisation of the acceptance times efficiency	196
C.3	Parametrisation of the efficiency	197

C.4	Additional figures for global fit cross-checks	198
C.4.1	Injection tests	198
C.4.2	Toy-based limits	201
C.4.3	Ranking plots for systematic uncertainties	201
Bibliography		205
List of Figures		219
List of Tables		237
Acknowledgements		239

Introduction

The Standard Model (SM) of particle physics was tested to a high precision at various experiments in the last decades and no significant deviation has been found so far. The Large Hadron Collider (LHC) is a perfect machine to search for new phenomena, as its energy reach is considerably higher than that of previous accelerators. The so-called Run 2 of the LHC covers the data taking period between 2015 and 2018, during which proton-proton collisions at a centre-of-mass energy of 13 TeV were recorded. The ATLAS collaboration operates one of the four big experiments at the LHC to collect and analyse this data. In addition to the detector operation and data analysis, all experiments at the LHC are preparing detector upgrades to be able to benefit from the LHC improvements in the years to come.

Searches for new phenomena at experiments like ATLAS probe various final states and phase-space regions for deviations from the Standard Model expectation. The coverage of searches by the ATLAS collaboration ranges from analyses that target very specific event topologies to analyses with inclusive selections. The search for new resonances in the dilepton final state is one of the key inclusive searches for phenomena beyond the Standard Model.

This thesis details a search for new dielectron and dimuon resonances in the 250 GeV to 6 TeV mass range based on the full Run 2 dataset of 139 fb^{-1} . The background estimation is performed by fitting a functional form to the data. A generic signal shape is chosen in order to facilitate reinterpretations of the fiducial cross-section limits. Lower resonance mass limits are set for benchmark models, and reach 4.5 TeV for the E_6 -motivated Z'_ψ boson in the dilepton channel.

In addition to the dileptonic decay modes, heavy new resonances can decay into other final states such as pairs of SM W and Z bosons, VH pairs with $V \in \{W, Z\}$ and H as the SM Higgs boson, or pairs of a lepton and a neutrino. Combining searches in various decay channels extends the discovery reach by exploiting their complementarity. The combination of the VV , VH , $\ell\nu$ and dilepton final states with 36.1 fb^{-1} of 2015 – 2016 data is detailed in this thesis, too. It constitutes the first experimental result on the combination of the $\ell\ell$ and $\ell\nu$ final states at the LHC.

The increased instantaneous luminosity of the LHC in the next data-taking period (Run 3) requires an upgrade of the ATLAS liquid argon (LAr) calorimeter trigger electronics. The new electronics increase tenfold the granularity of the LAr information provided to the first level of the trigger system and will enable a more advanced selection at the hardware level of the trigger. To test pre-prototypes of the upgraded electronics, an in-situ demonstrator system was installed at the start of Run 2 to collect data with the new read-out in parallel to the current one.

The energy and timing calibration of the demonstrator system is presented in this thesis. The calibration is important to assess the performance of the system and to validate the reconstruction of quantities that are needed for the online selection in the trigger system. The energy of electromagnetic showers within

the calorimeter needs to be determined as close as possible to the offline value to minimise inefficiencies of the trigger selection. The shower timing is critical to determine which event should be recorded for further data analysis. The validation studies detailed in this thesis, performed with data collected in 2017, include the comparison of the energy and timing reconstruction between the output of the upgraded system and the standard LAr read-out, event-level shower shape information and pulse shape predictions, among other measurements. Additional checks were performed on the 2018 demonstrator system, for which upgraded pre-production hardware was installed.

The thesis is structured as follows: Chapter 2 introduces the main concepts of collider-based particle physics in terms of theory and phenomenology. The Large Hadron Collider, the ATLAS experiment and its subdetectors are explained in Chapter 3. The read-out of the LAr calorimeter is further described in Chapter 4. The calibration of the in-situ LAr Phase-1 demonstrator system is detailed in Chapter 5. Chapter 6 contains information on the search for resonances in the dielectron and dimuon invariant mass spectra using the full Run 2 dataset of 139 fb^{-1} , while the combination of the $\ell\ell$ search with the $\ell\nu$, VV and VH final states at 36.1 fb^{-1} is detailed in Chapter 7. The conclusions are given in Chapter 8.

Personal contributions

The operation of the ATLAS detector and the exploitation of the collected data is only possible due to the continuous effort from a collaboration of several thousand physicists. In addition, a similar number of engineers contribute to the development and the operation of the detector. Within the collaboration, a large number of software frameworks is used to transform raw hits in the detector, via calibrated physics objects to final results of statistical data analyses.

During my doctoral studies, I participated in the operation of the detector, the development of software tools and the data analysis within the ATLAS collaboration. In order to clarify which developments presented in this thesis are my own work, the list below summarises personal contributions. Additionally, the software frameworks used and their origin are described in the main body of this thesis where applicable. In case shown figures and tables do not include substantial contributions from me, their source is given in the respective caption.

Significant contributions were made by myself in the following areas, ordered by the thesis chapter:

- Chapter 5: For the calibration of the in-situ demonstrator system, I worked on modifications in the Athena code framework, the adjustment of the calibration scheme to the Phase-1 read-out architecture and the “low-level” validation of the obtained calibration coefficients. This development builds up on the work presented in Ref. [1]. I extended the available calibration coefficients to the full demonstrator system and by additional steps in the calibration procedure. The validation of the calibration with pp collision data (see Section 5.5) has been performed by myself. Several sets of public plots of this work were made public [2–4].
- Chapter 6: I was an analysis co-coordinator for the full Run 2 dilepton ($\ell\ell$) resonance search between May 2018 and May 2019. This search was the first full Run 2 result of the collaboration to become public [5]. The generation of smooth reconstruction-level background templates by convolving large truth-only MC samples with the parametrised detector mass response was implemented by myself. The detector mass parametrisation is additionally used for the generic signal modelling and for the determination of systematic uncertainties. I provided the nominal data-driven statistical analysis, which is based on a global fit for the background shape description. The above mentioned points are described in Sections 6.3 to 6.8. The main results of the dilepton resonance search were provided by myself, except for the reinterpretation into the HVT model (see Section 7.5), and are given in Section 6.9.
- Chapter 7: I was the main analyser for the $\ell\ell$ channel and worked on the implementation and validation of the signal modelling. The studies to reduce interference effects presented in the thesis were done by myself. The statistical framework based on RooStats has been developed within Ref. [6], while I was responsible for the final calculation of the paper results for the $\ell\ell/\ell\nu$ combination. Within the ongoing preparations for the next combination, which will include the full Run-2 dataset, I serve as an analysis liaison for the $\ell\ell$ channel.

In addition, I participated in the detector operation with ATLAS control room shifts, where I was responsible to monitor the status of the ATLAS calorimeters and forward detectors. I gave a talk on behalf of the ATLAS collaboration at the SUSY2018 conference (see Ref. [7]).

Overview of high energy collider physics

High energy particle physics studies the fundamental constituents of matter and their interactions. The foundations of this field reach back to the discovery of the electron in 1897 by Thomson [8] and first scattering experiments to understand the structure of atoms between 1908 and 1913 by Geiger, Marsden and Rutherford [9, 10]. Advancements in particle acceleration [11] and in detector technology [12] allowed to probe ever increasing centre-of-mass energies and thus smaller length scales since then¹. The Standard Model (SM) of particle physics is the theoretical framework in which quarks and leptons, as well as the bosonic interaction mediators, are currently described. It is introduced in Section 2.1, while Section 2.2 summarises the known limitations of the SM and possible theories beyond it. Section 2.3 gives an overview of the phenomenology at proton-proton colliders. The SM is described more comprehensively in Ref. [13], while Ref. [14] gives an overview of its experimental foundations.

Throughout this thesis, so-called natural units are used. By setting $\hbar = c = 1$, energy, momentum and mass are expressed in units of energy. The typical energy scale of particle physics are electronvolts (eV) with $1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ J}$.

2.1 Standard Model of particle physics

The following description of the SM in this section uses the notation from Ref. [14], which contains more details on the mathematical formulation of the SM and the experimental evidence that lead to its success.

2.1.1 Symmetry group and interaction mediators

The SM of particle physics is a relativistic quantum field theory, based on the principle of local gauge invariance. It describes three fundamental forces: the electromagnetic interaction, the weak interaction and the strong interaction. The symmetry group of the SM is given by

$$SU(2)_L \times U(1)_Y \times SU(3)_C. \quad (2.1)$$

The Lagrangian density $\mathcal{L}$, henceforth called Lagrangian, is locally invariant under all three transformations. The invariance under $SU(2)_L \times U(1)_Y$ describes the unified electromagnetic and weak interactions, i.e. the electroweak interaction, within the Glashow-Salam-Weinberg (GSW) model [15–17]. $SU(2)_L$ acts on the weak isospin I_W , while $U(1)_Y$ acts on the weak hypercharge Y . The symmetries require the

¹ The momentum of a particle, $\vec{p}$, and its wavelength, λ , are related by $\lambda = h/|\vec{p}|$ and thus higher momenta (or energies) lead to smaller probed length scales.

introduction of four gauge fields, W_μ^k ($k \in \{1, 2, 3\}$) for $SU(2)_L$ and B_μ for $U(1)_Y$. The physical states are obtained by a mixing of these fields and give

$$A_\mu = +B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W, \quad (2.2)$$

$$Z_\mu = -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W, \quad (2.3)$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2), \quad (2.4)$$

where A_μ , Z_μ and $W_\mu^\pm$ are the fields of the photon γ , the neutral Z boson and the charged $W^\pm$ bosons, respectively. θ_W is the so-called Weinberg angle. The photon couples to the electric charge Q , which is given by $Q = I_W^3 + \frac{Y}{2}$.

The strong interaction is described by the $SU(3)_C$ group, with C as the “colour” charge. The gauge group requires three colour states, which are named red, green and blue. The strong interaction is mediated by 8 types of gluons, which carry colour and anti-colour. A colour singlet gluon state is not allowed within the gauge group. Unlike the electromagnetic and weak forces, the strong force is observed to become stronger with increasing distance between the interacting particles. This effect gives rise to the so-called confinement, meaning that no particles with free colour charge could be observed in nature.

The strength of the interactions is specified by the gauge coupling constants g , g' and g_s , which are associated to $SU(2)_L$, $U(1)_Y$ and $SU(3)_C$, respectively [18, 19]. The gauge coupling constants are $O(1)$. In renormalisation theory, the gauge coupling constants exhibit a dependence on the energy scale of the considered process, which is the so-called “running” of the coupling constants.

The $SU(2)_L$ and $SU(3)_C$ gauge groups are non-Abelian and thus the interaction mediators of the weak and strong force are self-interacting. The Lagrangian of the SM therefore includes terms which describe gluon-gluon interactions, as well as certain interactions between the $W^\pm$ and Z bosons. The electromagnetic force can be described with an $U(1)_Q$ symmetry, which is Abelian. The photon thus does not interact with itself, but couples to the charged $W^\pm$ bosons. No more direct interactions between the gauge bosons are observed or predicted by the SM. Bosons are defined to have integer spin and the gauge bosons described above are spin-1 particles.

2.1.2 Quarks and leptons

In addition to the gauge bosons described above, the SM contains quarks and leptons, which are spin- $\frac{1}{2}$ fermions. According to the Pauli exclusion principle, fermions are not allowed to have the same state as other fermions.

Experimental measurements on the properties of the weak interaction require that the left-chiral (L) states of the quarks and leptons are grouped in weak isospin doublets with $I_W = \frac{1}{2}$, where $I_W^3 = +\frac{1}{2}$ ($-\frac{1}{2}$) for the upper (lower) doublet entries. Right-chiral (R) particles need to be grouped in weak isospin singlets with $I_W = 0$. The total particle content is then given by

1 st	2 nd	3 rd	generation
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	
u_R, d_R, e_R	c_R, s_R, μ_R	t_R, b_R, τ_R	

The up- (u), charm- (c) and top-quarks (t) are so-called up-type quarks and have $Q = +\frac{2}{3}e$ with e being the elementary charge. Down- (d), strange- (s) and bottom-quarks (b) are the down-type quarks and have $Q = -\frac{1}{3}e$. The SM contains three charged leptons with $Q = -1e$, namely the electron (e), the muon (μ) and the tau (τ). The corresponding neutrinos, ν_i with $i \in \{e, \mu, \tau\}$, are neutral. Quarks are commonly denoted by q , while charged leptons are denoted by ℓ .

The quarks and leptons are grouped into three generations, which are the columns of the above shown particle overview. The masses of the particles increase for each of the generations². Each of the introduced six quark and six lepton species have their own so-called flavour. The flavour is conserved in case of the electromagnetic and strong forces, while the weak interaction allows transitions between different generations and within the weak isospin doublets through the exchange of $W^\pm$ bosons. There are also flavour preserving neutral currents through the exchange of Z bosons.

Quarks carry colour and therefore are affected by the strong interaction. They cannot be observed as free particles in nature due to the previously mentioned confinement. In a process called hadronisation, elementary quarks interact with each other and form color-neutral bound states. These bound states can be grouped into baryons (tri-quark qqq states) and mesons (quark-antiquark $q\bar{q}$ states, where the bar denotes the antiparticle of the quark). Leptons do not carry a colour charge.

2.1.3 Lagrangian of the Standard Model

The Lagrangian of the SM can be summarised by

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (i\bar{\psi}\not{D}\psi + \text{h.c.}). \quad (2.5)$$

The term $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ is the scalar product of the field strength tensor $F_{\mu\nu}$, in which the four introduced gauge fields, W_μ^k and B_μ , as well as the gauge fields of $SU(3)_C$ are encoded. It thus contains the kinetic terms for the gauge bosons and additionally describes the self-interactions between them. In the second term, ψ denotes the fields of quarks and leptons, while $\bar{\psi}$ gives the fields for the corresponding antiquarks and antileptons. The covariant derivative $\not{D}$ describes the interactions between the fermion fields and the gauge fields. A detailed description of the SM Lagrangian can be found in Ref. [20].

2.1.4 The Higgs mechanism

The description of the SM up to this point does not allow the $W^\pm$ and Z bosons to be massive, since the corresponding mass terms in the Lagrangian would not be gauge invariant. This is in contradiction to the observations, where the interaction mediators of the weak force are found to be massive.

The Englert-Brout-Higgs (EBH) mechanism [21, 22] is introduced to solve this problem and, at the same time, gives a natural explanation for the masses of quarks and leptons through the so-called Yukawa couplings. Within the EBH mechanism, a complex $SU(2)_L$ doublet is introduced:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (2.6)$$

The extension of the SM Lagrangian is then given by

$$\mathcal{L}_H = (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi) + (\psi_i y_{ij} \psi_j \Phi + \text{h.c.}), \quad (2.7)$$

² The neutrino mass hierarchy is not yet determined, but the “normal” hierarchy, i.e. more massive neutrinos towards higher generations, is experimentally favoured over the so-called “inverted” hierarchy.

where the scalar EBH potential $V(\Phi)$ is

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2. \quad (2.8)$$

For $\lambda > 0$, the potential has its lowest energy state at $\Phi = 0$ in case $\mu^2 > 0$, while non-zero minima occur for $\mu^2 < 0$. The concrete choice of the minimum for the $\mu^2 < 0$ case then breaks the symmetry of the Lagrangian in a process called “spontaneous symmetry breaking”. The term $(\psi_i y_{ij} \psi_j \Phi + \text{h.c.})$ gives the interaction between the field Φ and the fermion fields. The coupling parameters are given by the Yukawa matrix y_{ij} and can directly be related to the fermion masses.

Through spontaneous symmetry breaking, the EBH mechanism breaks the $SU(2)_L \times U(1)_Y$ symmetry in the SM and allows three of the four introduced degrees of freedom to be manifested as the longitudinal degrees of freedom of the $W^\pm$ and Z bosons. Thus, these particles can be massive in the unitarity gauge. The fourth degree of freedom yields the prediction of an additional neutral spin-0 particle, the Higgs boson H .

A new boson with a mass of about 125 GeV was discovered in 2012 at the LHC experiments ATLAS and CMS [23–25]. Current measurements of production and decay properties (see e.g. Ref. [26]) agree well with the predictions for the SM Higgs boson, such that the particle is widely considered to be the SM Higgs boson. Thus, all particles predicted within the SM have been observed by now.

2.1.5 Further properties of particles

In addition to the described particles, the SM contains corresponding antiparticles. They have the same mass, but the opposite charge. Typically the antiparticles of neutrinos, quarks and neutral mesons are denoted by a bar over their designation³. W^+ and W^- are each others antiparticle; γ , Z and H are their own antiparticles.

The full particle content of the SM, together with the main quantum numbers and mass information, is shown in Figure 2.1. The three fermion generations have distinct mass scales. Ordinary matter is formed out of particles from the first fermion generation, while the second and third generation particles are increasingly difficult to produce and unstable.

The lifetime, τ_{mean} , of unstable particles is the mean time after which they decay into other particles. The total decay width, Γ_{tot} , is connected to the lifetime of the particles by

$$\Gamma_{\text{tot}} = \frac{\hbar}{\tau_{\text{mean}}}. \quad (2.9)$$

The probability for a particle to decay within a unit time is given by Γ_{tot} and for resonances the total decay width corresponds to the width of the line shape in the truth mass spectrum. Particles can typically decay into different final states, each having a partial decay width of Γ_i . The total decay width is then given by the sum over the partial decay widths of all possible final states i , i.e. $\Gamma_{\text{tot}} = \sum_i \Gamma_i$. The relative frequency of decays into a specific final state i is called branching ratio, $\mathcal{B}$ (or BR), and given as

$$\mathcal{B}_i = \frac{\Gamma_i}{\Gamma_{\text{tot}}}. \quad (2.10)$$

³ For charged particles, the corresponding antiparticle can be identified based on the opposite sign of the charge.

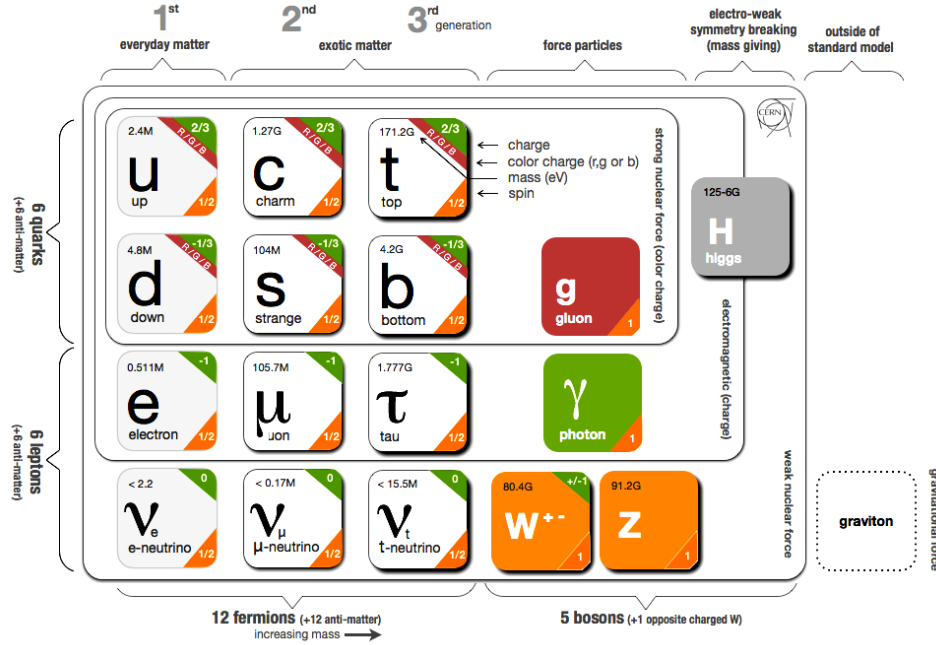


Figure 2.1: Total particle content of the SM together with their main properties. The graviton is the hypothetical force carrier of gravity, but so far not observed nor described within the SM. Figure from Ref. [27].

2.2 Physics beyond the Standard Model

2.2.1 Limitations of the Standard Model

Despite the evident success of the SM, it is found to have limitations in several areas, which point towards the need for theories beyond the SM. The limitations can roughly be grouped into observations in cosmology and high-energy physics, as well as theoretical considerations. A compilation of some of the most noticeable limitations or deviations from the SM predictions is given below.

- Observations in cosmology and high-energy physics
 - Dark matter and dark energy: Originally introduced to explain the rotation curves of galaxies [28], dark matter is assumed to contribute about 25% of the current energy density in our universe [29]. It is assumed to interact gravitationally and to cluster around galaxies, thus having a dominant influence on their formation [30]. The term “dark energy” is introduced to explain the accelerated expansion of our universe [31, 32] and could correspond to the cosmological constant in General Relativity. Both phenomena are yet to be understood, but are not explained within the SM.
 - Neutrino masses: The non-zero mass of neutrinos is a direct implication from the observation of neutrino oscillations [33]. The observed squared mass difference between the first and second mass eigenstate is $\Delta m_{21}^2 = 7.37 \cdot 10^{-5} \text{ eV}^2$, while the first and third mass eigenstates have a squared mass difference of $\Delta m_{31}^2 = 2.56 \cdot 10^{-3} \text{ eV}^2$. Direct measurements and cosmological observations⁴ yield upper limits on the neutrino masses of $m_{\bar{\nu}_e} < 2.05 \text{ eV}$ and $\sum_j m_{\nu_j} < (0.340 - 0.715) \text{ eV}$, respectively. The SM does not contain right-chiral neutrino

⁴ The neutrino mass limits from cosmological observations depend strongly on the underlying model assumptions.

states, such that the neutrinos are required to be massless within the original formulation of the model. While the extension of the SM with right-chiral neutrino states is possible, an extension in the form of Dirac masses does not provide a convincing mechanism to explain the tiny mass scale of neutrinos compared to the other fermions. Different theoretical models exist that provide mechanisms to generate the tiny neutrino mass scale.

- Free parameters of the SM: The SM has in total 25 free parameters⁵, which have to be determined experimentally. The SM does not provide an explanation for the interplay between these, like e.g. the observed mass hierarchy.
- Matter-antimatter asymmetry: The universe appears to be dominated by matter instead of having a symmetric distribution of matter and antimatter [34]. The measured population of anti-particles is explained by secondary interactions with the interstellar medium. The requirements to create a net baryon asymmetry are usually referred to as Sakharov conditions [35] and the SM interactions do not allow to create asymmetries of the observed size.
- Theoretical considerations
 - Hierarchy or naturalness problem: The mass of the Higgs boson is affected by quantum corrections under the presence of heavy particles and thus sensitive to the highest energy scales [36]. The comparably low mass of the Higgs boson thus requires a precise fine-tuning of the SM parameters.
 - Unification with gravity: The SM and the current description of gravity, i.e. the theory of General Relativity, are expected to become incompatible due to significant quantum gravitational effects at the Planck scale, $M_{\text{Pl}} \simeq 10^{19}$ GeV. So far no renormalisable quantum field theory to describe gravity has been found.

The SM nonetheless provides an accurate description of most observations in high-energy physics and beyond. It is always possible that new phenomena only become visible around the Planck scale, which is far beyond the reach of current experiments.

An overview of production cross-section measurements for various processes from the ATLAS experiment is given in Figure 2.2. Further experimental tests of the SM include, but are not limited to, precision measurements of the Higgs boson couplings [37], searches for rare decay modes, e.g. the decay of B_s and B mesons into muon pairs [38], and mass measurements e.g. of the W boson [39].

Specific properties of B -meson decays are measured to deviate from the SM prediction, e.g. the values of $\mathcal{R}_{K^{(*)}} \equiv \mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-) / \mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)$, which are expected to be equal to one in the SM. The observed values typically deviate by $2 - 3\sigma$ from the SM [41, 42] and could hint to additional processes which violate lepton flavour universality.

The measured Higgs and top-quark masses lead to the prediction of a meta-stable SM vacuum [43]. The possible instability of the universe can be interpreted as a sign for the need of SM extensions.

2.2.2 Theories beyond the Standard Model

A variety of models have been created to address one or several of the points given in Subsection 2.2.1. Beyond the Standard Model (BSM) theories predict many potential new particles, for which searches are undertaken to explore their typical experimental signatures. These searches are often designed to be generic and thus allow for reinterpretations into models that predict similar final states. An overview of searches conducted by the ATLAS and CMS collaborations is available in Refs. [44, 45].

⁵ The number of free parameters increases to 26 if the vacuum angle of the strong interaction, θ_{QCD} , is additionally considered.

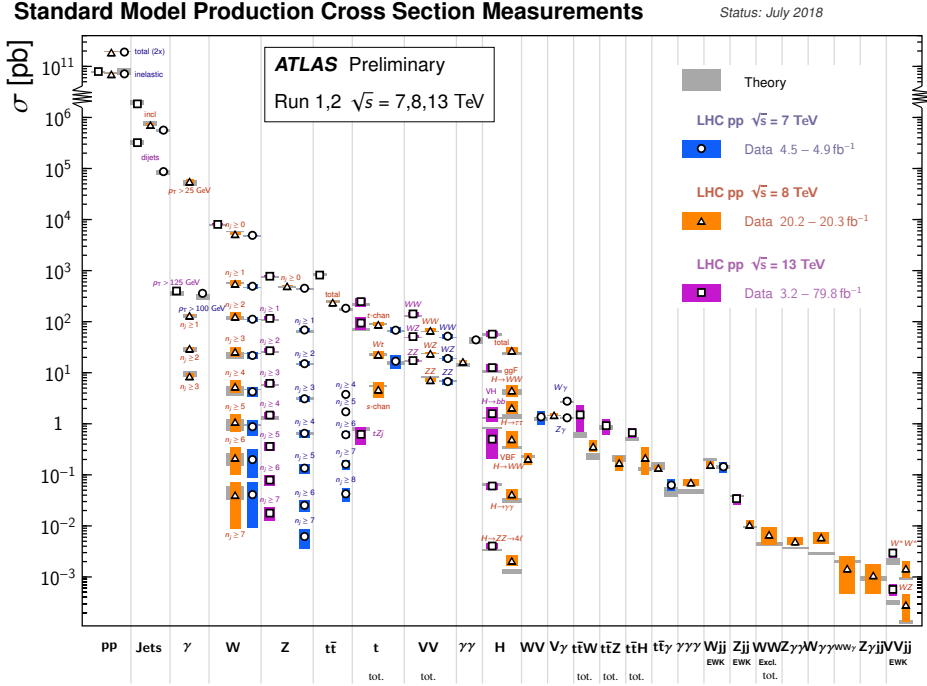


Figure 2.2: Overview of production cross-section measurements from the ATLAS collaboration. No significant deviation from the SM is observed. Figure from Ref. [40].

Several BSM extensions predict new heavy resonances that can decay into dilepton final states [46], which are the subject of this thesis. The models can typically be categorised depending on the spin properties of the predicted particle:

- **Spin-0:** High-mass spin-0 resonances are predicted within an extended scalar sector, e.g. by the Minimal Supersymmetric SM (MSSM) or general two-Higgs doublet models (2HDM) [47]. In case the coupling strength to fermions of such a new boson would be proportional to the mass of the decay products, as is the case for the SM Higgs boson, $\tau\tau$ and $\mu\mu$ final states would be favoured over ee final states.
- **Spin-1:** Models with extended gauge symmetries lead to the prediction of new spin-1 bosons. Singlet Z' bosons emerge from additional U(1) symmetries, while additional SU(2) gauge symmetries with a non-trivial symmetry breaking pattern can give rise to a vector isospin triplet containing a neutral Z' boson and a pair of charged $W'^{\pm}$ bosons. An overview of general SM extensions predicting new vector bosons is given in Ref. [48]. The spin-1 case typically provides the richest experimental phenomenology and a more detailed description for this case is given below.
- **Spin-2:** New spin-2 resonances are e.g. predicted as excited states of the Graviton within the Randall-Sundrum (RS) model [49] with a warped extra dimension.

Benchmark models for spin-1 singlets

Typical benchmark models for singlet Z' resonances are the Sequential Standard Model (SSM) [50], E_6 -motivated Grand Unification models [51] and dark matter mediator models [52, 53]. The Z'_{SSM} is

predicted to have the same coupling parameters as the SM Z boson and exhibits a relative width, Γ/m , of 3.0%. The E_6 symmetry group can be broken down into $SU(5)$ and two additional $U(1)$ groups, where the precise properties of the predicted Z' bosons depend on the parameters of the model. The Z'_χ and Z'_ψ bosons have $\Gamma/m = 1.2\%$ and 0.5% , respectively, and thus represent the widest and narrowest E_6 -motivated Z' bosons. As the production cross-section of the Z'_χ (Z'_ψ) is additionally the highest (lowest) within the E_6 models, these two cases are typically quoted as benchmarks within the E_6 scenario.

Simplified model for spin-1 triplets

The Heavy Vector Triplet (HVT) model [54] is a generic extension of the SM by a triplet of mass-degenerate Z'_{HVT} and $W'^{\pm}_{\text{HVT}}$ bosons. The triplet field $\mathcal{W}$ introduces colorless vector bosons with zero hypercharge. The model is used as the benchmark in ATLAS to combine dibosonic and dileptonic searches [55], as it allows to describe these final states in a common theoretical framework. The interaction Lagrangian of the model is given by

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_q \mathcal{W}_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell \mathcal{W}_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left(\mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right), \quad (2.11)$$

where q_k and ℓ_k denote the left-handed quark and lepton doublets of generation k (with $k \in \{1, 2, 3\}$), respectively, and H denotes the Higgs doublet. The coupling parameters g_q , g_ℓ and g_H give the interaction strength between the triplet field and the quark, lepton and Higgs fields, respectively. The interactions are assumed to be universal between the different fermion generations and the triplet field does not couple to right-handed fermions. In case the coupling to quarks and leptons is the same, $g_f \equiv (g_q = g_\ell)$ is used.

The HVT model is constructed to describe the collider phenomenology of any model containing vector iso-triplets. Triplets of this kind are predicted by composite Higgs and Little Higgs models as well as certain Grand Unified Theories [48, 54]. $W'^{\pm}$ bosons that couple to left-handed fermions, i.e. $W'^{\pm}$ bosons that can be produced at hadron colliders and have a significant branching ratio into a pair of a charged lepton and a neutrino, necessarily belong to this triplet [54]. Special benchmark coupling points [56] are defined within the HVT model with the following parameters:

- HVT model A is defined by $g_H = -0.56$ and $g_f = -0.55$. The phenomenology of models with a significant coupling to fermions is illustrated at this coupling point. The branching ratio of dileptonic final states is about a factor of two higher than the one of dibosonic final states for HVT model A (compare Figure 2.3(a)).
- HVT model B is defined by $g_H = -2.9$ and $g_f = 0.14$. This coupling point illustrates scenarios with a strongly coupled Higgs sector, as e.g. given in composite Higgs models. The branching ratio into dibosonic final states is considerably higher than the one for dileptonic channels for HVT model B (compare Figure 2.3(b)).

The search for any such resonances can be performed in a generic approach, where the selection and the signal modelling are designed to be as independent as possible of underlying model assumptions, e.g. spin properties. In analysis approaches that are tailored to specific parameters of the model, more properties of the predicted final states and its kinematics can be utilised. This second approach can be more sensitive, but the reinterpretability of the results is typically smaller. The first approach is pursued in the dilepton search described in Chapter 6, where generic cross-section limits, that are reinterpretable into spin-0, spin-1 and spin-2 models, are obtained. The second approach is pursued in the combination of dibosonic VV/VH final states and dileptonic $\ell\ell/\ell\nu$ final states within the HVT model, which is detailed in Chapter 7.

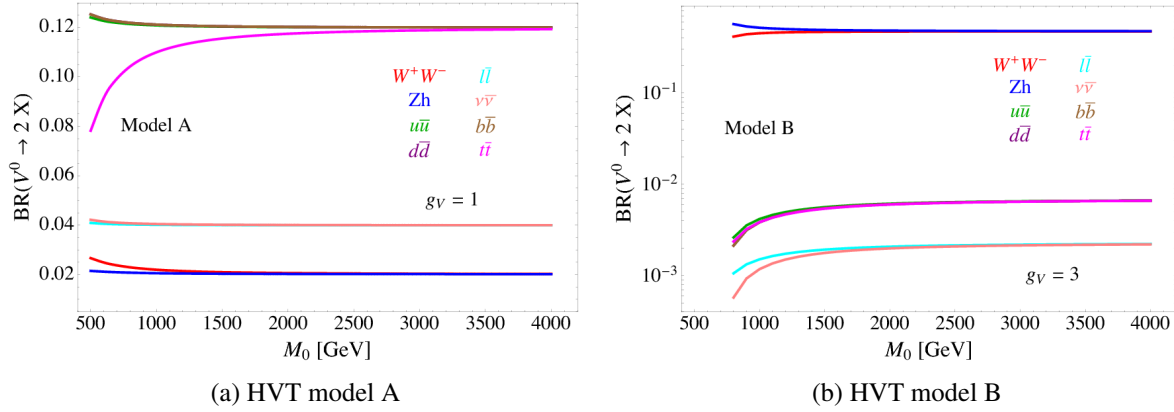


Figure 2.3: Branching ratios into different final states for the Z'_{HVT} at special coupling points. Figures from Ref. [56].

Different production mechanisms are possible for new heavy resonances. The production of spin-1 bosons at pp colliders can, similar to Z boson production, occur through quark-antiquark annihilation in the Drell-Yan mechanism (compare Figure 2.4(a)). In case the spin-1 bosons couple to the SM W and Z bosons, the production can additionally occur through vector-boson fusion (compare Figure 2.4(b)). Spin-0 resonances with similar coupling properties as the SM Higgs boson are produced through gluon-gluon fusion with a heavy particle loop (compare Figure 2.4(c)). For spin-2 Gravitons, the production mechanisms are quark-antiquark annihilation and direct gluon-gluon fusion (compare Figure 2.4(d)). The gluon-gluon fusion dominates due to suppressed couplings to light fermions [55].

Spin-1 Z' models exhibit interference effects with the SM Z/γ^* production. The interference strength varies depending on the coupling parameters, but can have non-negligible effects on the lineshape of the signal. The experimental implications of this effect are further discussed within Subsections 6.5 and 7.2.2.

2.3 Phenomenology at proton-proton colliders

A key element to investigate the predictions of the SM, and to search for physics beyond it, are particle accelerators. The three main types of colliders are hadron colliders, e.g. the LHC and the Tevatron, electron-positron (e^+e^-) colliders, e.g. LEP, and ep colliders, e.g. HERA. While at e^+e^- colliders fundamental particles interact and thus the initial state is fully known, the emission of synchrotron radiation limits the energy reach of such machines. Measurement at ep colliders allow to probe the interior structure of the proton precisely. In the following, the phenomenology of proton-proton (pp) colliders will be further detailed, as the data of the ATLAS experiment, which is used for this thesis, is obtained from pp collisions at the LHC.

The proton is a hadron and thus a composite particle. It consists of so-called partons, which are valence- and sea-quarks as well as gluons. The amount of partons, carrying a given momentum fraction x of the proton momentum, is described by *parton distribution functions* (PDFs), $f_i(x)$, with $i \in \{u, \bar{u}, d, \bar{d}, \dots, g\}$. PDFs have to be measured experimentally and more details on their determination are provided in Ref. [57]. Since in proton-proton collisions the momentum fractions x_1 and x_2 of the colliding partons vary, the longitudinal boost of the interactions is not known *a priori*.

The centre-of-mass (cms) energy, $\sqrt{s}$, is given by the sum of the momenta of the colliding protons at

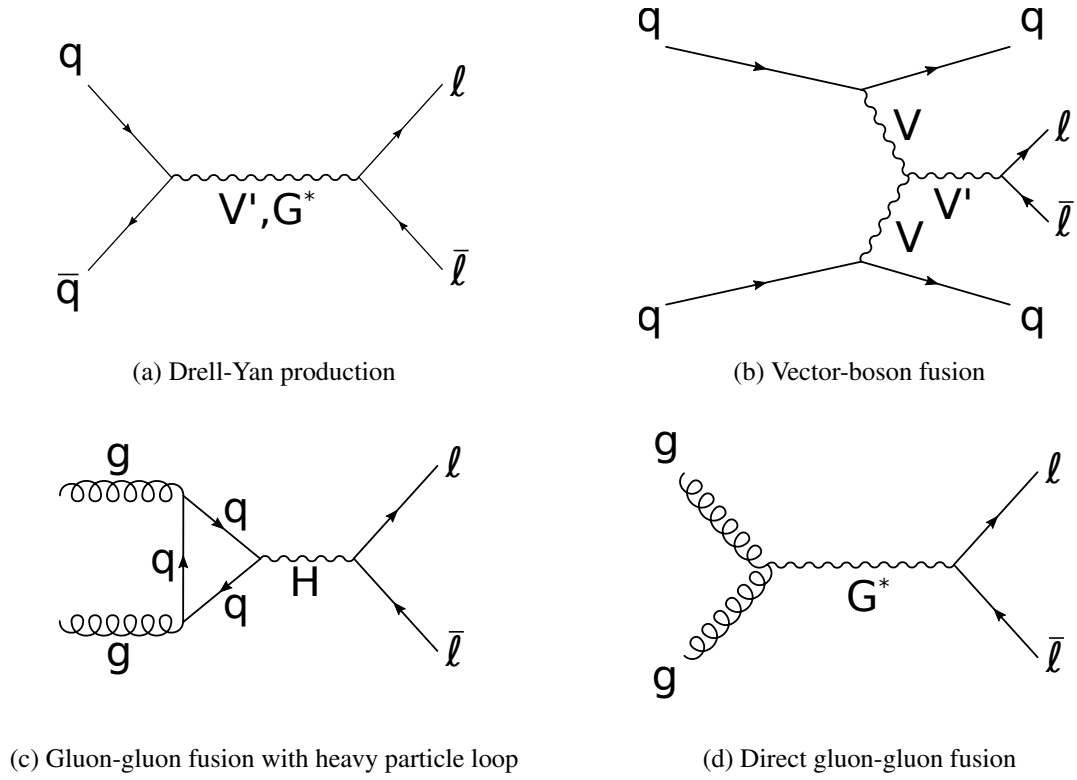


Figure 2.4: Feynman diagrams of typical production mechanisms for new heavy spin-1 (top left and top right), spin-0 (bottom left) and spin-2 (top left and bottom right) resonances.

the LHC and describes the maximal available energy. On parton level, the square of the available energy is given by $\hat{s} = x_1 x_2 s$ and can only reach s in the rare case where both colliding partons carry the full proton momenta.

The amount of interactions per time within the colliding proton-proton beams is usually quoted in terms of the instantaneous luminosity L (see Ref. [11] for more details). It is calculated by

$$L = f_{\text{coll}} \frac{n_1 n_2}{4\pi\sigma_x \sigma_y}, \quad (2.12)$$

where f_{coll} is the collision frequency of the proton bunches, i.e. the packets subdividing the proton beams. n_1 and n_2 are the number of protons in each bunch, while σ_x and σ_y denote the transverse sizes of the bunches. The integrated luminosity, $\int L dt$, is then a measure for the size of a dataset.

The total number of interactions N for a specific process is given as

$$N = \sigma \int L dt, \quad (2.13)$$

where σ denotes the cross-section of the process. The cross-section is a measure for the strength of the interaction process and has the units of an area. It is typically given in the unit barn with $1\text{b} = 10^{-28} \text{m}^2$.

2.3.1 Theoretical predictions and Monte Carlo simulations

Theoretical predictions of production cross-sections for a given process in proton-proton collisions, $\sigma(p_1 p_2 \rightarrow X)$, require the knowledge of the partonic cross-section, $\hat{\sigma}(ij \rightarrow X)$, of the specific process and the proton PDFs. Under the assumption of *factorisation*, i.e. in case the PDF and the partonic cross-section calculations decouple and can be treated separately, the total cross-section is given as

$$\sigma(p_1 p_2 \rightarrow X) = \sum_{i,j} \int dx_1 dx_2 f_{i,p_1}(x_1, \mu_F^2) f_{j,p_2}(x_2, \mu_F^2) \times \hat{\sigma}(ij \rightarrow X, x_1 x_2 s, \mu_F^2), \quad (2.14)$$

with μ_F as the factorisation scale. Emissions with transverse momenta below μ_F are accounted for within the PDFs [19].

The total cross-section is thus given as the sum of the integrated partonic cross-sections for all parton combinations $\{i, j\}$. The partonic cross-sections, which describe the hard scattering process, can be calculated using so-called Feynman rules and are usually displayed with Feynman diagrams. While leading order partonic cross-sections are calculated at the lowest possible order in the coupling constants, higher-order corrections include additional interactions such as (additional) loop contributions. Further details can be found in Ref. [19].

The prediction of specific properties for a given process, e.g. kinematic distributions, is often computationally involved and requires the usage of so-called Monte Carlo (MC) techniques (see also Ref. [58]). For this, the evaluation of complex integrals or probability density functions is performed by relying on random numbers to sample the distributions. For large enough numbers of MC events, a precise knowledge of the full distributions can be obtained.

General-purpose MC generators are available to simulate a variety of processes (see Ref. [59] for a comprehensive review). In order to cover the full event topologies, the hard scattering process, the potential emission of initial and final state radiation, the formation of hadrons from partons and the eventual decay of unstable particles need to be covered. A diagram of the different components is given in Figure 2.5. Examples of general-purpose MC generators are Pythia [60, 61], Powheg [62, 63], Herwig [64–66] and Sherpa [67]. Specialised MC generators like Photos [68] (used to calculate final-state photon radiation), MadSpin [69] (for top-quark spin correlations) and EvtGen [70] (for decays of b - and c -hadrons) are additionally available. After the simulation of the hard scatter process and the immediate decays, the simulation of the particle propagation, the interactions with the detector material and the final reconstructed signals relies on MC techniques, too, and is usually performed with Geant4 [71]. Parametrisations of calorimeter showers and fast track simulation can be used reduce to the overall simulation time [72].

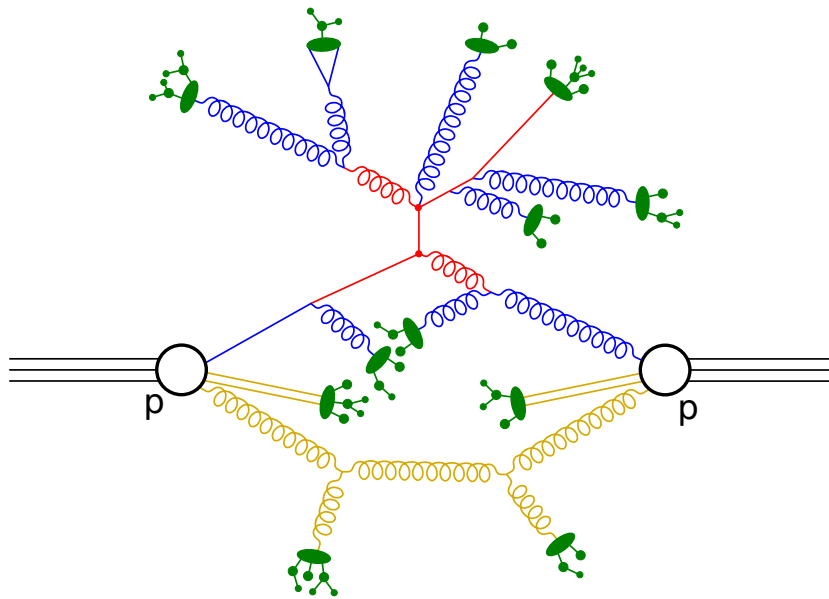


Figure 2.5: Overview of processes to be considered in pp interactions. The red colour denotes the hard parton scattering, in this case an incoming gluon and a quark scattering off each other. The blue part shows initial and final state radiation, which is mainly created due to the strong interaction. Hadronisation processes, generating mesons and baryons out of the coloured quarks and gluons, are shown in green. The created hadrons eventually decay after their production. The incoming protons are shown in black. Yellow depicts the proton remnants after the interaction and secondary interactions. Figure adapted from Ref. [73].

The ATLAS detector at the LHC

3.1 The Large Hadron Collider

In terms of achievable cms energy, the Large Hadron Collider (LHC) is currently the most powerful particle accelerator on Earth. It is situated at the European Organization for Nuclear Research (CERN) at the French-Swiss border close to Geneva. The LHC ring is about 100 m underground and has a circumference of about 27 km. The design energy of the LHC is 7 TeV for both proton beams¹ (summing up to a cms energy of 14 TeV) and the design luminosity is $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The total of 1232 dipole magnets installed in the LHC bend the proton beams on a quasi-circular path. For proton energies of 7 TeV, a magnetic field of 8.3 T is required in these dipoles. Additional quadrupole and higher order magnets, among other use-cases, keep the beams focussed and allow to achieve very small beam sizes at the interaction points of the experiments. The eight straight sections of the LHC ring are needed for the experiments as well as beam collimation, acceleration and dumping. A detailed description of the LHC and the CERN accelerator complex is given in Ref. [74].

The LHC is supported by a chain of pre-accelerators at CERN, which is shown in Figure 3.1. The protons are obtained from hydrogen by stripping off the orbiting electron. After acceleration in Linac2 and the PS Booster (PSB), the protons have an energy of 1.4 GeV. They are then transferred to the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS), reaching an energy of 450 GeV. After the SPS, the protons enter into the LHC ring to be accelerated to their maximum energy, at which collisions under stable conditions are achieved. Several experiments use the beams from the pre-accelerators of the LHC for physics measurements at lower cms energies.

In total 3564 possible bunch positions with a spacing of 25 ns are available at the LHC. The maximal number of filled positions is reduced to 2808 for a spacing of 25 ns due to rise-time constraints of the injector and beam-dump kicker magnets. The concrete filling choice of the LHC ring is the so-called bunch scheme. The bunches are typically clustered in so-called bunch trains, while gaps between the bunch trains again occur due to the injector magnet rise-times.

Four main experiments are installed at the LHC. CMS and ATLAS are general-purpose detectors. They allow to make precision measurements of SM processes, including the properties of the Higgs boson, and to search for physics beyond the SM. LHCb is specialised to study flavour physics, i.e. the properties of *b*- and *c*-hadrons, including rare decays of such particles, and, for example, *CP* violation. The ALICE

¹ The LHC also allows to accelerate heavy ions, where typically lead (Pb) is used, in addition to protons (*p*). It is thus possible to achieve *pp*, *pPb* and *PbPb* collisions. The heavy-ion data taking is not discussed further in this thesis, as only *pp* collision data is used for the presented studies. Dedicated analyses utilise the heavy-ion collision data and the detector settings are adapted for the heavy-ion data taking.

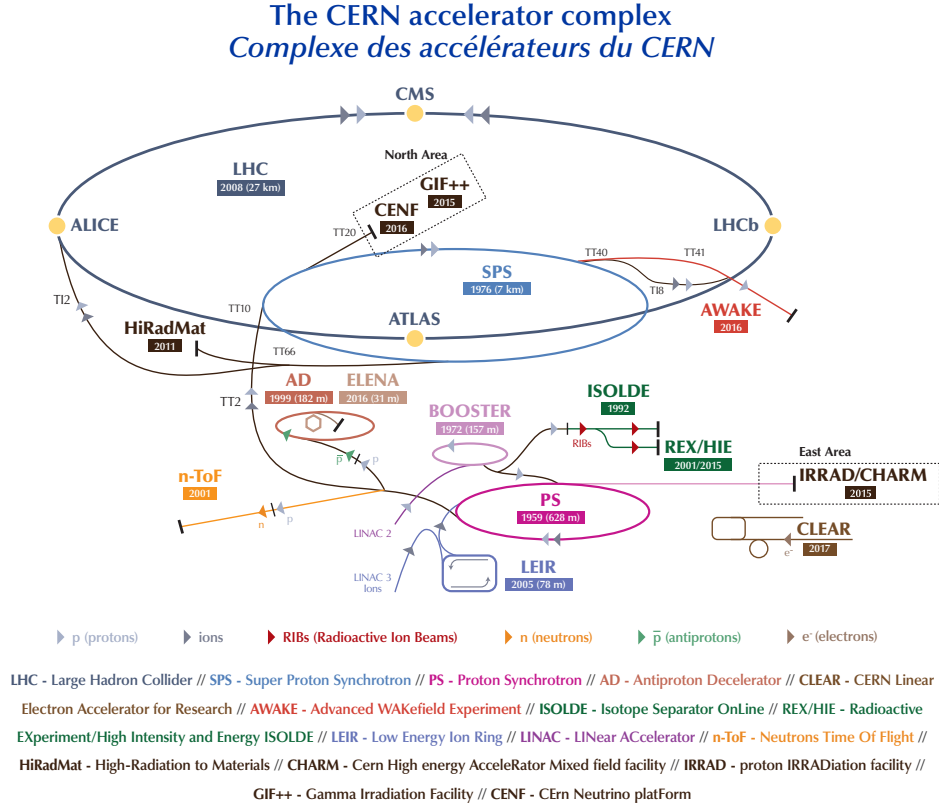


Figure 3.1: Overview of the CERN accelerator complex in 2018, including the LHC and its pre-accelerators. The four main LHC experiments are depicted, too. Figure from Ref. [75].

detector studies heavy-ion collisions and, in particular, the properties of the quark–gluon plasma. LHCf and TOTEM are two additional, smaller experiments installed at the LHC to measure particles with very low scattering angles from the beam (i.e. the so-called forward physics).

3.2 ATLAS

The name ATLAS is an acronym for “A Toroidal LHC ApparatuS”. The detector has been operating since 2008, taking alignment data with cosmic rays before the LHC launch, and its data is exploited by a collaboration of about 3000 scientific authors from 181 institutions in 38 countries. Due to its size of 25 m height, 25 m width and 46 m depth, it is the largest detector at a particle collider ever built. The ATLAS detector weighs 7000 tons.

3.2.1 Coordinate system and kinematic quantities

The right-handed cartesian coordinate system (x, y, z) of the ATLAS detector is chosen such that the z -axis is the beam axis in counter-clockwise direction to the LHC ring. The x -axis is aligned towards the centre of the LHC ring and the y -axis points upwards. The origin is given by the nominal interaction point in the middle of the detector. Spherical coordinates (r, ϕ, θ) in their usual definition are used as well.

The connection of particle momenta $\vec{p}$ and energies E can be described by the four-momenta $\mathbf{p} = (E, \vec{p})$,

with $\mathbf{p}_1 \cdot \mathbf{p}_2 \equiv E_1 E_2 - \vec{p}_1 \vec{p}_2$. The invariant mass, m_{inv} , of a particle is given by $\mathbf{p}^2 = m_{\text{inv}}^2$. The rapidity y is expressed through

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right). \quad (3.1)$$

Rapidity differences are Lorentz invariant under boosts along the z -axis. The rapidity converges for highly relativistic ($\beta = v/c \rightarrow 1$) or massless ($m \rightarrow 0$) particles into the pseudorapidity, η , given by

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]. \quad (3.2)$$

The angular distance ΔR in the η - ϕ plane is a convenient choice as a separation metric and given by

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}. \quad (3.3)$$

Since the longitudinal momentum of particles, p_z , is given by a superposition of the recoil from the hard scattering and the longitudinal boost of the interacting parton system, the total sum of the longitudinal momenta of the particles emerging from the hard scattering, $\sum_i p_{z,i}$, does not contain additional information on the hard scatter processes.

The conservation of transverse momenta in the x - y plane is an important tool at hadron colliders, though. The transverse momentum p_T is given by

$$p_T = \sqrt{p_x^2 + p_y^2}. \quad (3.4)$$

The total transverse momentum is expected to be $p_T \simeq 0$. The transverse energy E_T is defined as $E_T^2 = m^2 + p_T^2$.

3.2.2 Detector setup and subsystems

The ATLAS detector, shown in Figure 3.2, is symmetric in ϕ as well as mirrored on the x - y plane. It captures particles in the full azimuthal space and is designed to reach the highest $|\eta|$ possible. To measure the properties of charged and neutral particles produced in pp collisions, several layers of specialised subdetectors are built around the beam pipe. Their properties are summarised in the following sections and described in detail in Refs. [76, 77].

Inner Detector

The Inner Detector (ID) of ATLAS, illustrated in Figure 3.3, is the subdetector closest to the beam pipe and built to reconstruct tracks of charged particles. The ID is embedded in a 2 T solenoidal magnetic field, that allows the transverse momentum of tracks to be measured from their curvature, and extends up to $|\eta| = 2.5$. High precision tracking, as close as possible to the interaction point, is needed to reconstruct the primary and secondary vertices. The ability to distinguish different primary vertices allows to reject contributions from pile-up interactions and is also a key ingredient to identify jets coming from b -quarks.

The innermost part of the ID is the pixel detector. It consists of the Insertable B -Layer (IBL) [77], which has been added in 2014, and three additional layers in the barrel region. The IBL pixels are situated at a distance of $R = 33.25$ mm from the centre of the beam pipe and have a size of $50 \times 250 \mu\text{m}^2$ in $R\phi \times z$. The sensitive part of the IBL extends until $|z| = 330.15$ mm. The additional layers have a pixel size of $50 \times 400 \mu\text{m}^2$ and extend up to a distance of $R = 122.5$ mm from the centre of the beam pipe as well as up to $|z| = 400.5$ mm. In the forward regions, three end-cap disks on each side of the detector provide

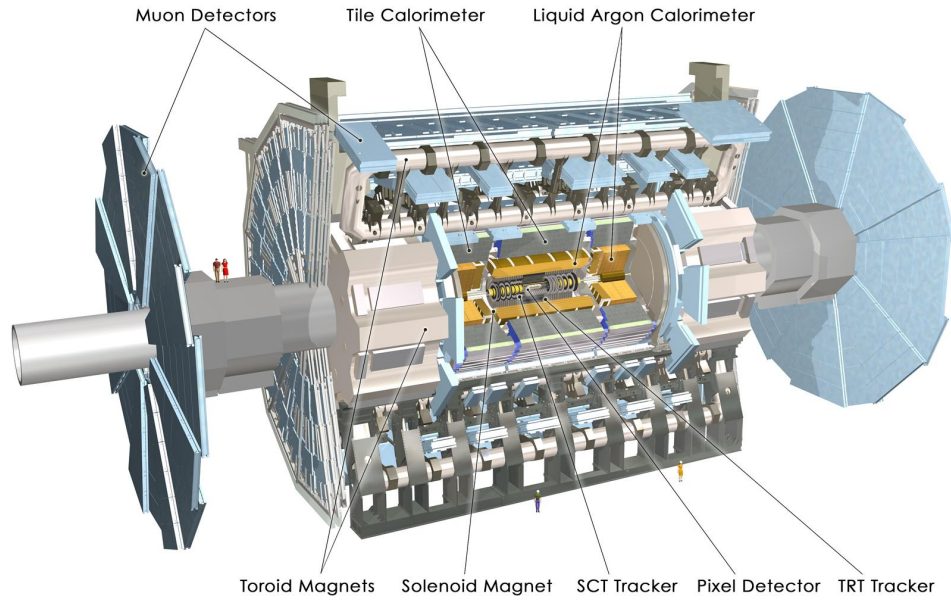


Figure 3.2: Computer generated overview image of the ATLAS detector. Figure from Ref. [78].

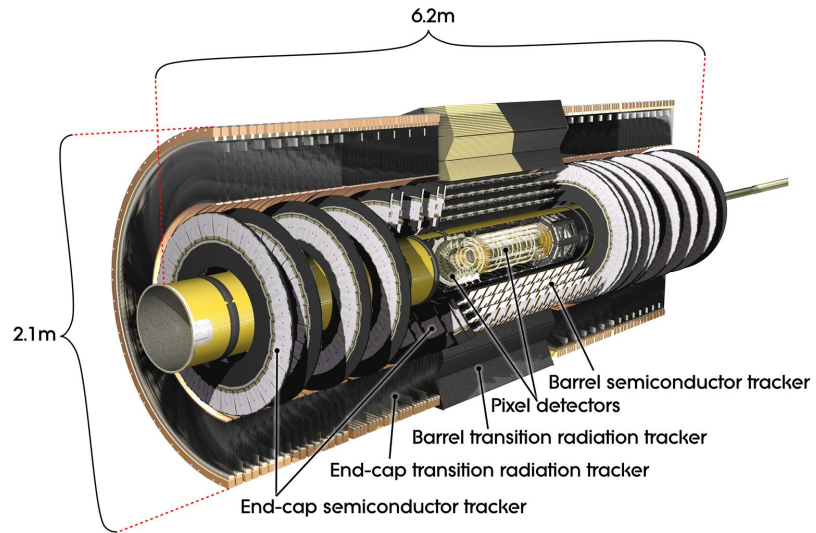


Figure 3.3: Computer generated image of the ATLAS Inner Detector. The image does not contain the Insertable *B*-Layer (IBL), which has been inserted in 2014. Figure from Ref. [79].

additional coverage in the range of $88.8 \text{ mm} < R < 149.6 \text{ mm}$ and $495 \text{ mm} < |z| < 650 \text{ mm}$. The pixel detector has around 86.4 million readout channels. Typically four pixel layers should be crossed by a track. The intrinsic accuracy in the barrel is $10 \mu\text{m}$ in $R\phi$ and $115 \mu\text{m}$ in z .

The Semiconductor Tracker (SCT), that surrounds the pixel detector, is a silicon strip detector with four cylindrical layers in the barrel ($299 \text{ mm} < R < 514 \text{ mm}$ and $|z| < 749 \text{ mm}$) and nine disks in each forward region ($275 \text{ mm} < R < 560 \text{ mm}$ and $853.8 \text{ mm} < |z| < 2720.2 \text{ mm}$). The SCT has about 6.3 million readout channels. For each track, four space points with an intrinsic accuracy of $17 \mu\text{m}$ in $R\phi$ and $580 \mu\text{m}$ in z for the barrel can be obtained.

The Transition Radiation Tracker (TRT) is the outermost part of the ID. By using straw tubes, the TRT is able to add typically 36 measurement points to each track. The TRT has 73 straw planes in the barrel region ($563 \text{ mm} < R < 1066 \text{ mm}$ and $|z| < 712 \text{ mm}$) and 160 straw planes in the end-caps ($848 \text{ mm} < R < 2710 \text{ mm}$ and $644 \text{ mm} < |z| < 1004 \text{ mm}$). It has around 351000 readout channels and covers a pseudorapidity range up to $\eta = 2$. The transition radiation photons produced in the TRT are an important ingredient of electron identification and are used to reject pions and other charged hadrons. The TRT contributes significantly to the momentum measurements of the tracks due to the long lever arm and the large number of measurements. The straw drift tubes are filled with a gas mixture of 70% Xe, 27% CO_2 and 3% O_2 and are interleaved with polypropylene/polyethylene transition radiators. As a mitigation for gas leaks that cannot be repaired without an invasive opening of the ID, some of the TRT modules instead contain a gas mixture of 70% Ar, 28.5% CO_2 and 1.5% O_2 . The presence of this gas mixture is taken into account in the simulation and the corresponding loss in identification power is partially mitigated by a dedicated TRT particle-identification algorithm.

The expected momentum resolution of the inner detector, without the IBL, is given by

$$\sigma\left(\frac{1}{p_T}\right) \cdot p_T \simeq 0.036\% \cdot p_T[\text{GeV}] \oplus 1.3\%. \quad (3.5)$$

The values are calculated according to Ref. [80] and $\oplus$ denotes addition in quadrature. No significant change in the p_T resolution is expected from the IBL due to its short lever arm. It improves the resolution of the impact parameter considerably, though.

Calorimeters

The ATLAS calorimeter system consists of the electromagnetic (EM) and hadronic calorimeters, situated outside of the solenoid. An overview of the full calorimeter system is shown in Figure 3.4. The EM calorimeter has a fine granularity over the pseudorapidity region matched to the ID, which is optimised to measure the properties of electrons and photons. The hadronic calorimeter has a coarser granularity. It measures the energy deposited by jets², which typically lose a large fraction of their energy behind the EM calorimeter. The ATLAS calorimeters are so-called sampling calorimeters, meaning that they have layers of absorber material interleaved by layers of active material.

The EM calorimeter is made of lead absorbers, in which photons and electrons lose energy through pair production and bremsstrahlung (see Section 4.4 for more details), and layers of liquid Argon (LAr). The particles ionize the medium inside the LAr layers and the resulting signal, which is proportional to the deposited energy, is measured by an ionization chamber setup of electrodes. The absorbers are built in an accordion shape to provide full ϕ symmetry. The EM calorimeter is divided into the barrel part, covering $|\eta| < 1.475$, and two end-cap regions ($1.375 < |\eta| < 3.2$). In the central pseudorapidity range ($|\eta| < 2.5$), being important for precision physics, the EM calorimeter has three layers with increasing

² Jets are collimated clusters of hadrons, which emerge out of the hadronisation of partons from the hard scatter process.

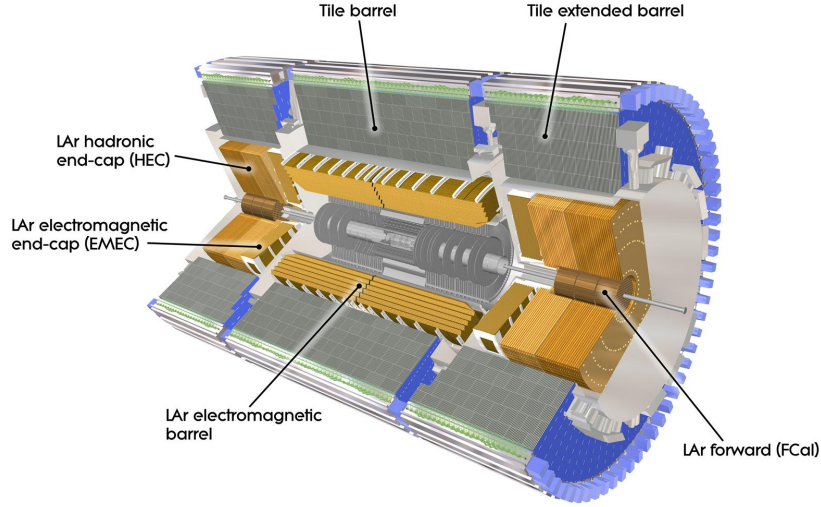


Figure 3.4: Computer generated image of the different ATLAS calorimeters. Figure from Ref. [81].

cell size in $\Delta\eta \times \Delta\phi$ (values given in Table 1.3 of Ref. [76]). The front layer consists of finely segmented “strips”, which have a width of $\Delta\eta = 0.0031$ in the barrel region for $|\eta| < 1.4$, to discriminate between isolated photons and pairs of close by photons from $\pi^0 \rightarrow \gamma\gamma$ decays. Most of the energy for high- E_T electrons and photons is deposited and collected in the middle layer, while the energy deposits of the shower tails are measured in the back layer. Additionally a presampler, covering $|\eta| < 1.8$, is used to correct energy losses of electrons and photons in front of the active EM calorimeter. The layer structure of the LAr EM barrel is shown in Figure 3.5. The total thickness is given by more than 22 radiation lengths (X_0) in the barrel and $> 24X_0$ for the end-caps (see Section 4.4 for the definition of the radiation length). Further details on the LAr calorimeters are given in Chapter 4.

The energy resolution of calorimeters can, according to Ref. [12], be parametrised with the following equation:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}, \quad (3.6)$$

where $\oplus$ denotes addition in quadrature and E is given in GeV. The stochastic term a is due to statistics-related fluctuations, e.g. intrinsic shower fluctuations, dead material in front of the calorimeter or sampling fluctuations. The constant term b is mainly due to detector non-uniformity and calibration uncertainties. The term c finally contains effects due to electronics noise.

The energy resolution of the EM calorimeter, according to Ref. [83], is expected to be

$$\frac{\sigma(E)}{E} \simeq \frac{10\%}{\sqrt{E[\text{GeV}]}} \oplus 0.7\%. \quad (3.7)$$

The parameter c of Equation 3.6 is neglected in Equation 3.7 due to its small impact at the typical energies present in the detector.

The hadronic calorimeter is divided into the Tile calorimeter and the LAr hadronic end-cap calorimeter (HEC). The LAr forward calorimeter (FCal) provides additional EM and hadronic coverage for $3.1 < |\eta| < 4.9$. In total, the EM and hadronic calorimeters thus extend up to $|\eta| = 4.9$. The Tile calorimeter consists of a barrel ($|\eta| < 1.0$) and two extended barrels ($0.8 < |\eta| < 1.7$). The absorber material is steel, scintillating tiles act as the active material. The Tile calorimeter is segmented into three layers. HEC and

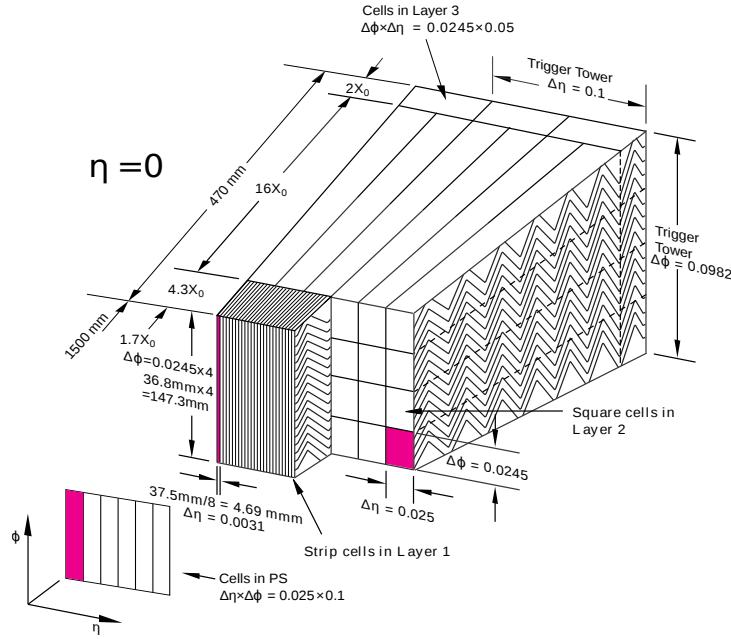


Figure 3.5: Layer structure of the LAr electromagnetic barrel calorimeter. The innermost presampler layer is used to correct for the energy lost in front of the calorimeter. The front (layer 1), middle (layer 2) and back (layer 3) layers are then used to precisely measure the electromagnetic showers. Figure from Ref. [82].

FCal use LAr as the active material and copper or tungsten as the absorber, depending on the radiation environment. The hadronic calorimeter has a depth of approximately 9.7 interaction lengths (λ_I) in the barrel and $10 \lambda_I$ in the end-caps (see Section 4.4 for a description of the interaction length), which is needed to contain the particle showers, and to sufficiently reduce the punch-through of high energy jets into the muon system.

The evolution of hadronic showers includes a variety of processes, increasing the random fluctuations in the calorimeter response. Therefore the resolution of hadronic calorimeters is typically poor in the direct comparison with other detector components. The expected energy resolution of the ATLAS hadronic calorimeter for single charged pions, taken from Ref. [80], is

$$\frac{\sigma(E)}{E} \simeq \frac{50\%}{\sqrt{E[\text{GeV}]}} \oplus 3\%. \quad (3.8)$$

Muon spectrometer

The outermost layers of ATLAS consist of an external muon spectrometer (MS) within $|\eta| < 2.7$, which is depicted in Figure 3.6, incorporating three large toroidal magnetic assemblies with eight coils each [84]. The bending power of the toroidal field varies with η , and is given by 1.5 to 5.5 Tm for $0 < |\eta| < 1.4$ and 1 to 7.5 Tm in the region $1.6 < |\eta| < 2.7$. The transition region ($1.4 < |\eta| < 1.6$) between the barrel and end-cap toroid has a lower bending power. The full magnet system of ATLAS is operated at a temperature of 4.6 K .

Four different kinds of detectors are part of the muon spectrometer. Resistive Place Chambers (RPC) and Thin Gap Chambers (TGC) are used as a trigger for muon signals in the $|\eta| < 2.5$ range. Precision measurements of the positions are performed by Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC), covering a pseudorapidity range up to 2.7 .

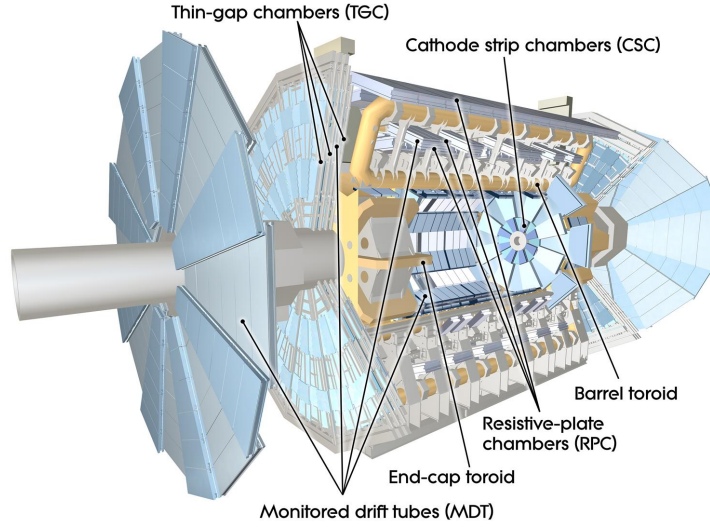


Figure 3.6: Computer generated image of the ATLAS muon subsystem. Figure from Ref. [85].

The muon spectrometer dominates the muon p_T measurement above $p_T \gtrsim 200$ GeV [86] when using the combined ID and MS information due to the low track curvature, which makes a long lever arm necessary. A p_T resolution of about 4.5% can be achieved by the MS at $p_T = 100$ GeV in the $|\eta| < 1.5$ region. For $p_T > 300$ GeV, the single-hit resolution dominates the momentum measurement. The single-hit resolution is limited by detector characteristics, alignment and calibration. The p_T resolution at $p_T = 1$ TeV is about 12% and increases further towards higher momenta.

Trigger and data acquisition (DAQ)

The nominal LHC bunch separation time is 25 ns, which directly converts into a collision frequency of up to 40 MHz. Having raw event sizes of about 1.5 Mbyte, the ATLAS readout and storage system is not able to capture each of these events. Additionally, the cross section of pp interactions is dominated by well understood processes of the strong interaction. A trigger system is needed to retain a reasonable data rate and at the same time store the events most interesting for further studies.

The ATLAS trigger system consists of the hardware Level-1 (L1) and the software-based high-level trigger (HLT). It is described in more detail in Ref. [87]. Each trigger level selects only events passing certain requirements. At the same time, the data acquisition system buffers the event data until a decision is taken whether the event is finally recorded or not.

The L1 trigger utilises reduced granularity signals from the calorimeters and the muon spectrometer to identify Regions-of-Interest (RoI's) with high E_T/p_T objects or high multiplicity at a latency of $2.5 \mu\text{s}$. The events accepted by the L1 trigger are passed on to the HLT with a frequency of at most 100 kHz. At the HLT, a fast analysis of these RoI's followed by an offline-like reconstruction of the events takes place with a processing time of a few seconds. The HLT has an average output of about 1 kHz, creating a data stream of ≈ 1.5 Gbyte/s. The trigger system is configured via the trigger menu, which defines trigger chains that start from a L1 trigger and specify a sequence of reconstruction and selection steps for a specific trigger signature requirement. It is possible to select events with muons, electrons, photons, jets and τ -leptons with a high transverse energy/momentum or multiplicity. Additionally, events with combinations of these particles, b -tagged jets, special rare signatures or high missing transverse energy can be selected.

Each event accepted by the L1 trigger system is assigned an identifier, which is the so-called L1 ID. The trigger type (TType) is an 8-bit word that is used to identify the required read-out configuration.

3.3 Reconstruction of physics objects

The offline reconstruction of the stored events is performed on the LHC Computing Grid in several steps. The main reconstruction is performed on the so-called *Tier 0* sites, while further steps, like e.g. the creation of compressed sets of the data and MC samples, are performed using a worldwide network of computing centres.

The reconstruction of candidates for specific physics objects in the ATLAS detector is described in the following subsections. Additional identification and isolation requirements, that are applied to the candidates in order to reduce the amount of misreconstructed objects, are described in Chapters 6 and 7. The calibration of the objects is done centrally by the so-called combined performance groups in the ATLAS collaboration.

3.3.1 Electrons

Electron candidates are reconstructed by matching localised clusters of energy deposits within the electromagnetic-calorimeter to charged-particle tracks that are constructed from ID measurements [88]. Additional track and cluster information is used to separate electron candidates from photon candidates, or classify the candidates as ambiguous, due to the similar cluster structure of the two objects and the potential random track association or photon conversion inside the ID.

3.3.2 Muons

Muon candidates are formed by combining ID tracks with tracks reconstructed in the MS [89], while the initial reconstruction of tracks in the ID and MS is performed independently. Several algorithms exist to match the ID and MS track information. The combined track is refit using the ID and MS hit information. During the global fit, MS hits may be added to or removed from the track to improve the fit quality [89].

The muon reconstruction quality exhibits a strong η - and ϕ -dependence due to differences in the alignment knowledge, the magnetic field strength and the average number of traversed precision chambers. Only muons passing stringent quality criteria are used at the ATLAS experiment for high- p_T muon reconstruction.

3.3.3 Jets

Jets are reconstructed based on topological cells, which are formed out of calorimeter cells [90]. The topological cells are clustered into “small- R ” jet candidates by using the anti- k_t algorithm [91] with a radius parameter of $R = 0.4$, while additional “large- R ” jet candidates are formed by using a radius parameter of $R = 1.0$. Large- R jets can be associated to decays of boosted objects, like e.g. W bosons or top quarks, using jet tagging techniques [92].

The identification of jets containing b -hadrons, i.e. so-called b -jets, is performed using multivariate b -tagging algorithms in ATLAS [93]. The relatively long lifetime of b -hadrons allows to exploit signatures like secondary or even tertiary vertices.

3.3.4 Missing transverse energy

The vectorial sum of momenta in the transverse plane is expected to be zero for an ideal measurement in events without neutrinos. The missing transverse energy, E_T^{miss} , quantifies the deviation from zero for a measured event. The calculation of the E_T^{miss} is given by

$$\vec{E}_T^{\text{miss}} = - \left(\sum_{i \in \{\text{hard objects}\}} \vec{p}_{T,i} + \sum_{j \in \{\text{soft signals}\}} \vec{p}_{T,j} \right), \quad (3.9)$$

where the hard objects are reconstructed electrons, muons, hadronically decaying τ -leptons, jets and photons [94]. The soft signals are reconstructed charged-particle tracks emerging from the primary vertex, which are not associated with any of the hard objects.

3.4 Data-taking conditions during Run 1 and Run 2 of the LHC

The LHC operation started in 2008. In 2010 and 2011, datasets at $\sqrt{s} = 7$ TeV with a recorded integrated luminosity of 45.0 pb^{-1} and 5.08 fb^{-1} , respectively, were obtained at ATLAS. The dataset of 2012 has been collected at $\sqrt{s} = 8$ TeV, where 21.3 fb^{-1} have been recorded. The period between 2010 and 2012 is the so-called LHC Run 1.

The so-called Run 2 data-taking period of the LHC covers the years 2015 to 2018. During this period, data at a cms energy of $\sqrt{s} = 13$ TeV has been collected. The collected dataset in 2015 and 2016 corresponds to an integrated luminosity of $(36.1 \pm 0.8) \text{ fb}^{-1}$, while the full Run 2 dataset is $(139 \pm 2) \text{ fb}^{-1}$. The uncertainty on the integrated luminosity is derived from the calibration of the luminosity scale using x - y beam-separation scans, following a methodology similar to that detailed in Ref. [95], and using the LUCID-2 detector for the baseline luminosity measurements [96].

The cross-section of typical electroweak processes is small compared to the total proton-proton interaction cross-section, which is dominated by processes involving the strong interaction. Additional interactions within the same bunch crossing³ (BC) of selected events are the so-called in-time pile-up. These additional interactions are considered as a background source for most analyses. The pile-up is typically quantified by the number of additional interactions per bunch crossing, μ . Out-of-time pile-up refers to additional interactions and energy deposits from neighbouring bunch crossings. High pile-up can deteriorate the detector performance at high instantaneous luminosities.

The mean number of interactions per bunch crossing, $\langle \mu \rangle$, during the Run 2 period was 34.2. The pile-up increased for the 2017 and 2018 periods due to the higher achieved instantaneous luminosity. An overview of the Run 2 data-taking period is given in Figure 3.7.

Particle collisions are recorded during so-called runs, which correspond to time periods during which the ATLAS detector is continuously taking data. The instantaneous luminosity as well as the pile-up typically decrease throughout the run, since burn-off losses in the bunches due to the collisions or other interactions occur.

The collected data is thoroughly checked to make sure all detectors have been fully functional during the data-taking and no undesired behaviour is found. An overview of the ATLAS data quality (DQ) efficiencies is given in Ref. [97]. The DQ efficiency during the 2018 data-taking campaign has been 97.5%, while the full Run 2 DQ efficiency is about 95%.

³ A bunch crossing corresponds to the encounter of two proton bunches at the interaction point in the centre of the detector.

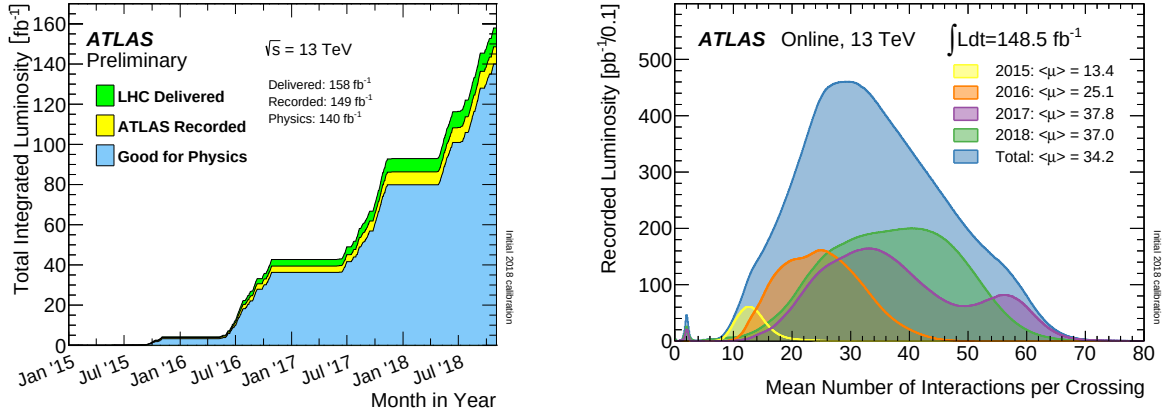


Figure 3.7: Delivered and collected integrated luminosity throughout the full Run 2 data-taking campaign (left) and distribution of pile-up conditions per year (right). Figures from Ref. [98].

At the beginning of single pp runs, mean pile-up values of $\langle \mu \rangle = 60$ and instantaneous luminosities of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ were achieved regularly in 2018. The LHC could thus be operated at about a factor of two higher instantaneous luminosities than its initial design.

3.5 Detector upgrades towards Run 3 and the HL-LHC period

The long-term plan for the instantaneous luminosity delivered by the LHC foresees a step-wise increase due to continuous upgrades to the accelerator [99]. In order to cope with the increased event rate and higher pile-up, the LHC experiments perform upgrades to various detector components, too. The main changes in the detector setup are performed during the long shutdown (LS) phases that are planned for 2019-20 (LS2 with the so-called Phase-1 upgrades) and 2024-26 (LS3 and Phase-2 upgrades). An overview of the LHC operation plan is shown in Figure 3.8, including the high luminosity (HL) phase.



Figure 3.8: Operation plan for the LHC Run 3 and HL-LHC periods. Figure from Ref. [100].

The instantaneous luminosity during Run 3 is expected to be compatible to that at the end of Run 2, while the cms energy is planned to be increased to 14 TeV. For the HL-LHC, about three times higher values compared to the end of Run 2 are expected. The mean pile-up is expected to be up to $\langle \mu \rangle = 200$ during the HL-LHC operation. To cope with the more difficult conditions, the planned upgrades of ATLAS include changes in the TDAQ system [101, 102], a replacement of the small muon wheel [103], an additional high-granularity timing detector [104], a complete replacement of the ID [105, 106] and several further important changes to the detector read-out.

Read-out of the liquid Argon calorimeters

This section details the read-out scheme and the calibration of the ATLAS LAr detector. A comprehensive overview of the detector is given in Ref. [107].

4.1 Detector components and read-out electronics

The interior structure of the LAr EM barrel is shown in Figure 4.1(a). An accordion structure is used for the read-out electrodes of the three main layers. The induced pulse of traversing particles has a triangular shape and is shown in Figure 4.1(b). After the shaping of the signal, the highest amplitude occurs after about 50 ns and is followed by a long downward-fluctuation until about 600 ns after the initial energy deposit. The time constant of the shaper is chosen to minimise the overall noise level from electronics and pile-up noise, which decrease or increase with the shaping time, respectively [76].

The bi-polar pulse shape of the signal after shaping allows to largely cancel pile-up contributions in the LAr detector for long-enough bunch trains. The integral over the full pulse shape is zero. The contributions from in-time and out-of-time pile-up are thus cancelled, as the pile-up is on average constant over many events. This cancellation is only possible when many signals from several events are overlaid, while at the beginning and at the end of bunch trains additional corrections are required.

The signals of triggered events are digitised with sampling steps of 25 ns using commercial 12-bit analogue-to-digital converters (ADCs). In total 4096 separate ADC values are thus available. The ADC counts of 4 samples are stored during the regular Run 2 data-taking for each cell if the deposited energy is above 3σ of the total noise level, while below this threshold only the cell energy is stored¹. In order to capture the positive and negative contributions of the signal shape, a voltage offset corresponding to about 1000 ADCs counts, the so-called pedestal level, is introduced before the digitisation. It is thus ensured that the negative lobe does not extend below the dynamic range of the ADC, at the cost of a small reduction of the precision for the positive lobe.

The current read-out schema of the LAr detector is displayed in Figure 4.2. In the main read-out path, the signals from the detector inside the cryostat are shaped and digitised within the front-end crates on the detector. Only the digitised signals are then transferred to the off-detector system, where the read-out crates are situated. The read-out path for trigger purposes is separated from the main read-out. The trigger signals are based on a coarser granularity, for which the analogue signals of several cells are summed. These analogue signal sums are then transmitted to the external, off-detector trigger system, where the digitisation is performed. Additional calibration boards are situated directly at the detector.

¹ In addition to the 4 samples, the cell timing information and a quality factor are stored if the cell energy is above 3σ of the

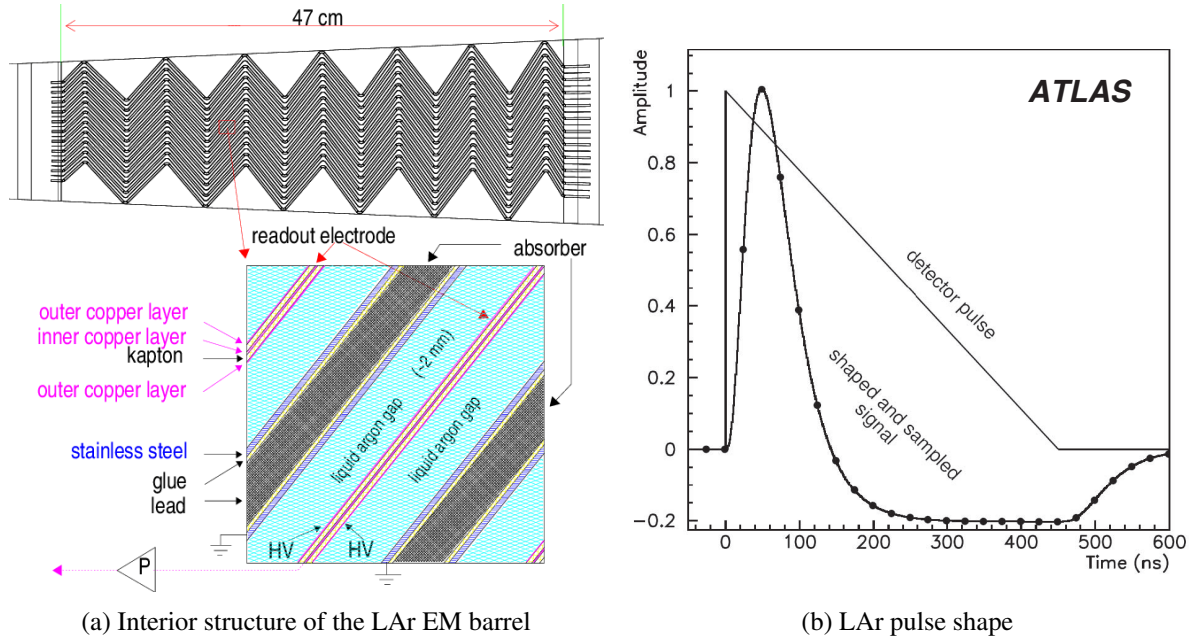


Figure 4.1: Interior structure of the LAr EM barrel with alternating layers of absorber and active material (left) and expected pulse shape in physics data before and after the shaping of the signal (right). Figures from Refs. [108] (left) and [76] (right).

4.2 Signal reconstruction with optimal filtering coefficients

To ensure the best possible energy measurement for physics analyses, the amplitude and the timing of the LAr signals have to be reconstructed with a high precision. In order to minimise the impact of thermal and pile-up noise, optimal filtering coefficients (OFCs) [109] are used to reconstruct the measured signals of the ATLAS LAr detector.

For a normalised known signal shape, $g(t)$, the measurements S_i at time steps t_i are given as

$$S_i = A \cdot g(t_i - \tau), \quad (4.1)$$

with A as the signal amplitude and τ as the pulse start time. The frequency of the measurements is visualised by the black dots in Figure 4.1(b), together with the typical signal shape. The Taylor expansion of the signal shape in Equation 4.1 around $\tau = 0$, together with the consideration of an additional noise component, n_i , leads to

$$S_i = A \cdot (g_i - \tau g'_i) + n_i, \quad (4.2)$$

where $g_i \equiv g(t_i)$ and $g'_i \equiv \frac{dg(t)}{dt}|_{t=t_i}$. For the reconstruction of A and $A\tau$, the following approach based on the linear sums u and v is chosen:

$$u = \sum_i a_i S_i, \quad (4.3)$$

$$v = \sum_i b_i S_i. \quad (4.4)$$

total noise level, too. The total noise level is given by the sum of the electronics noise and the pile-up noise at $\langle \mu \rangle = 50$.

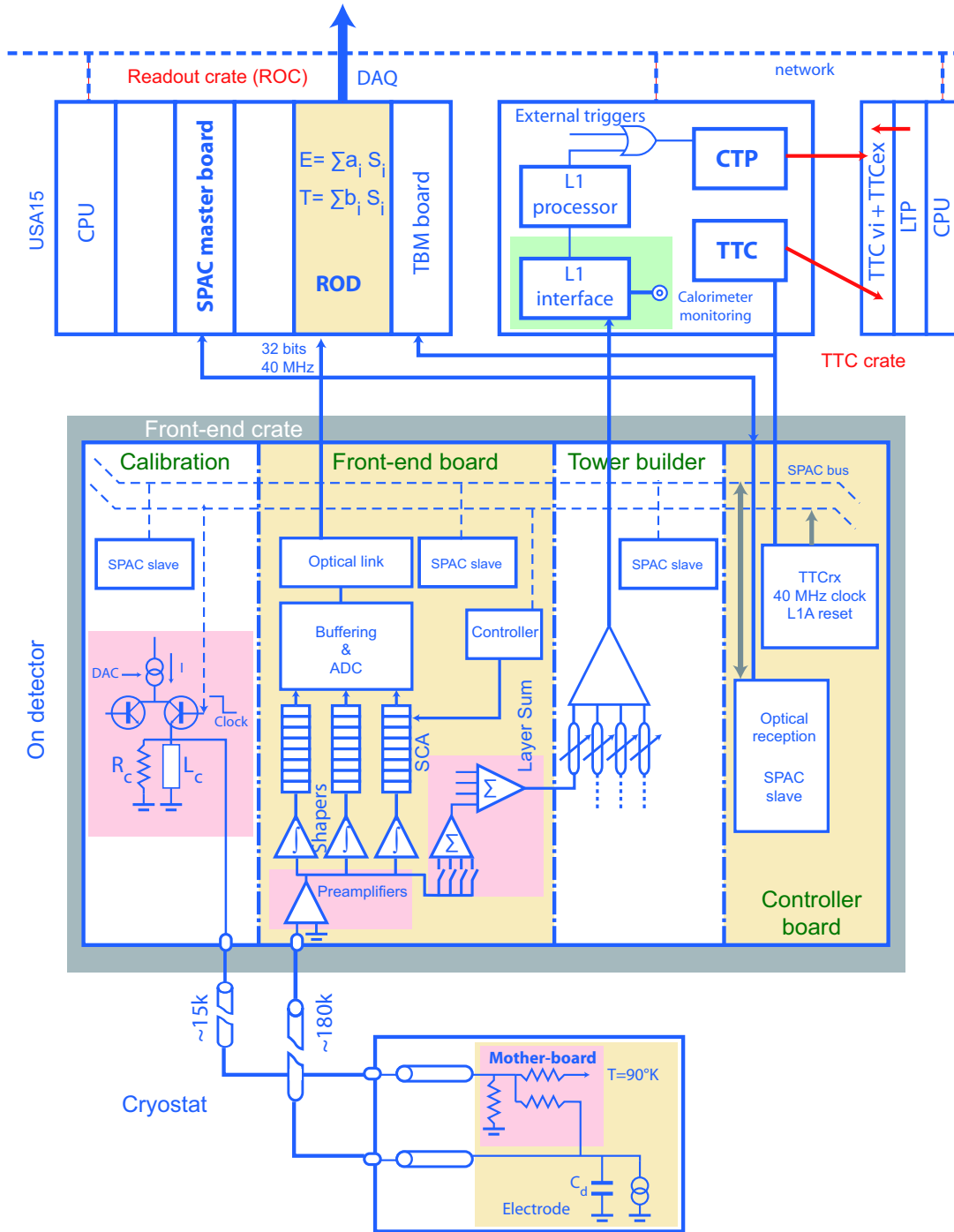


Figure 4.2: Read-out schema of the LAr detector. The pulses are measured on the electrodes within the cryostat and then first analysed within the on-detector front-end electronics. Digitised signals are then transmitted to the off-detector electronics, situated in the counting room USA15. Figure from Ref. [82].

The expectation value of u is required to give A , while the expectation value of v is required to yield $A\tau$. The average noise term, $\langle n_i \rangle$, is assumed to be 0. It is thus

$$A = \langle u \rangle = \sum_i (Aa_i g_i - A\tau a_i g'_i), \quad (4.5)$$

$$A\tau = \langle v \rangle = \sum_i (Ab_i g_i - A\tau b_i g'_i). \quad (4.6)$$

In addition, the variance of u and v is required to be minimal in order to achieve the highest possible precision under the given noise sources. It is

$$\text{Var}(u) = \sum_{ij} a_i a_j \langle n_i n_j \rangle, \quad (4.7)$$

$$\text{Var}(v) = \sum_{ij} b_i b_j \langle n_i n_j \rangle. \quad (4.8)$$

The expectation value $\langle n_i n_j \rangle \equiv R_{ij} = R(t_i - t_j)$ gives the noise autocorrelation function at a time difference of $t_i - t_j$ and has to be measured in data. $R(0)$ is given by σ_S^2 , i.e. the variance of an individual sample S_i .

The minimisation of Equations 4.7 and 4.8, under the constraints imposed by Equations 4.5 and 4.6, is performed using Lagrange multipliers in Ref. [109] and leads to an analytic solution to determine the OFCs $\vec{a}$ and $\vec{b}$. The OFCs thus allow to extract A and $A\tau$ with a minimal expected impact from noise sources according to

$$A = \sum_i a_i S_i, \quad (4.9)$$

$$\tau = \frac{1}{A} \sum_i b_i S_i. \quad (4.10)$$

In addition to the energy and timing determination through OFCs, quality factors can be defined by comparing the observed signals to the expected pulse shape. The quality factors can be used to reject non-nominal pulse shapes. The detection of saturated pulse shapes, i.e. pulses which reach beyond the dynamic range of the electronics, is possible, too, and important as the OFC results are invalid in this case.

4.3 Calibration scheme of the LAr detector

The energy of a calorimeter cell, E_{cell} , is obtained from the pulse samples S_i , given in ADC counts, using the following formula [110]:

$$E_{\text{cell}} = F_{\text{DAC} \rightarrow \mu\text{A}} \cdot F_{\mu\text{A} \rightarrow \text{MeV}} \cdot \left(\frac{M_{\text{phys}}}{M_{\text{cali}}} \right)^{-1} \cdot G_1 \cdot \sum_i^{N_{\text{samples}}} a_i (S_i - p). \quad (4.11)$$

The ADC count baseline is given by the pedestal, p , while the a_i are the OFCs described in Section 4.2. N_{samples} gives the number of pulse samples to be taken into account in the energy calculation. $N_{\text{samples}} = 4$ is chosen for the standard Run 2 data-taking due to read-out constraints. The conversion from ADC counts to current units (DAC) is treated by the conversion factor G_1 , i.e. the so-called gain factor. Since the

underlying pulse shapes in physics runs differ from calibration pulse shapes, dedicated sets of OFCs are needed for both cases and a correction factor, $M_{\text{cali}}/M_{\text{phys}}$, accounts for the difference in the amplitudes. Further conversion factors are given by $F_{\text{DAC} \rightarrow \mu\text{A}}$ and $F_{\mu\text{A} \rightarrow \text{MeV}}$ and are determined by the electronics specifications and test-beam data² for LAr cells, respectively [111].

The calibration coefficients that are obtained based on calibration data, are the pedestal value, OFCs for calibration and physics pulses, the gain factor and the predicted amplitude ratio between calibration and physics pulse shapes. The coefficients are regularly validated.

The procedure to obtain the calibration coefficients for the LAr calorimeter consists of three different kinds of calibration runs:

- In *pedestal runs* no calibration pulses are sent to the cells. These runs are used to measure the pedestal value for each cell and the autocorrelation of the noise, which is used as a part of the OFC computation.
- *Delay runs* are used to measure the pulse shape precisely. The pulse samples are measured at different delay steps, such that the pulses are obtained with a much finer granularity than the usual sampling steps of 25 ns. A typical choice of the sampling step size is $25/24 \text{ ns} \approx 1.04 \text{ ns}$. The delay run information is used to compute the OFCs as well.
- The gain G_1 is obtained using *ramp runs*, in which the calorimeter cells are pulsed using increasing injected currents and for each step the pulse height is determined. A linear slope is fitted to the obtained pulse heights to obtain the relation with the injected current. Since the pulse shape information is measured before this step, the pulse height can be obtained using OFCs already.

From this information, the calibration coefficients for calibration data are first obtained. In order to account for the different pulse shapes in physics and calibration data, as well as differences in the noise autocorrelation, further calibration steps are based on MC predictions and models to describe and predict the difference between the pulse shapes. The different measured pulse shapes emerge from different time-dependencies of the injected current pulses (exponential decay in calibration data, triangular shape for physics data) as well as different spacial injection points within the electronics. The differences in the noise autocorrelation emerge from the additional pile-up noise in physics data, which is not present in the calibration data. The processing of the calibration runs is automatised for the standard LAr calorimeter cells within the Athena framework [112].

The calibration of the timing measurement is required, too, for a precise energy determination and to associate energy deposits to a given bunch crossing. The timing calibration is based on collision data and depends e.g. on the signal processing time within the read-out electronics.

4.4 Intermezzo: Properties of electromagnetic and hadronic showers

Electrons and photons traversing the calorimeters initiate electromagnetic cascades, in which e^+e^- pair production and bremsstrahlung processes occur. The development of hadronic cascades, which are initiated by hadrons and jets, involves a variety of nuclear interactions, as e.g. pion production, nuclear spallation and neutron capture, and additional secondary showers of the produced particles. Muons and neutrinos can traverse through the calorimeters with minimal or no energy losses, respectively.

High-energy electrons predominantly lose energy in matter through bremsstrahlung, i.e. they radiate off photons, while high-energy photons create e^+e^- pairs via the $\gamma \rightarrow e^+e^-$ process [113]. Both processes

² The $F_{\mu\text{A} \rightarrow \text{MeV}}$ values from test-beam data are used. They were cross-checked with MC simulations.

involve the electromagnetic interaction and occur alternatingly within the cascades. The characteristic length scale after which high-energy electrons lose all but $1/e$ of their initial energy is called *radiation length*, X_0 . The radiation length of lead is 5.6 mm [114]. The *critical energy*, E_c , can be defined as the energy for which the energy loss per radiation length due to ionisation of the material is equal to the particle energy. In lead, $E_c = 7.4$ MeV for electrons [114].

The development of electromagnetic cascades can be described using two typical scales [113]:

$$t = x/X_0 \quad y(t) = E/E_c, \quad (4.12)$$

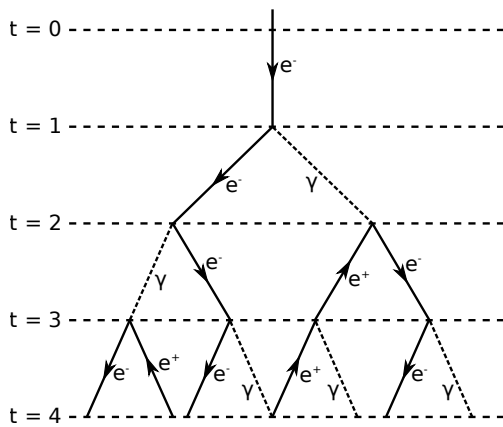
where t is the shower depth and $y(t)$ is the typical energy of the particles within the shower at a given depth. An example of a typical shower development is given in Figure 4.3(a). The shower maximum, i.e. the position where the highest energy deposit per length occurs, is given as

$$t_{\max} = \ln(y_0) + C, \quad (4.13)$$

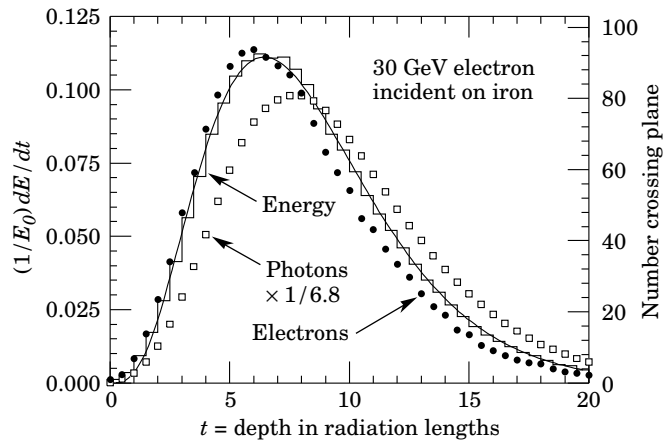
where $C = -0.5 (+0.5)$ for cascades induced by electrons (photons) and $y_0 = E_0/E_c$ is determined from the initial energy E_0 of the particle. The shower length after which 95% of E_0 have been deposited [115] is measured semi-empirically to be

$$t_{95\%} = t_{\max} + 0.08 \cdot Z + 9.6, \quad (4.14)$$

where Z is the atomic number of the detector material. For the example of lead with $Z = 82$, a depth of $16X_0$ behind the shower maximum is needed to contain 95% of the shower energy. For the electromagnetic showers of 100 GeV (2 TeV) electrons, $t_{95\%}$ is thus about $25X_0$ ($28X_0$) in lead. 95% of the shower energy for 100 GeV electrons are thus contained within the central ATLAS LAr barrel calorimeter, when considering the additional material in front of the calorimeter [76], while the leakage into the hadronic calorimeter is higher for 2 TeV electrons. The shower development is depicted in Figure 4.3(b).



(a) Sketch of an electromagnetic cascade



(b) Simulated shower development

Figure 4.3: Sketch of the development of an electromagnetic cascade as a function of t (left) and shower development in terms of the deposited energy per length (right). Figures from Refs. [116] (left) and [113] (right).

The lateral EM shower development is characterised by the *Molière radius*, R_M , which is given by

$$R_M = X_0 \times E_s/E_c, \quad (4.15)$$

with a scale energy E_s of ≈ 21 MeV. Typically only 10% of the shower energy is deposited outside the cylinder with radius R_M [113], while the radius of the cylinder containing about 95% of the energy is given by [115]

$$R_{95\%,\text{EM}} \simeq 2R_M. \quad (4.16)$$

Electromagnetic cascades usually have a narrow cone and broaden for higher t .

The characteristic length scale of hadronic cascades is the *nuclear interaction length*, λ_I , with $\lambda_I = 176 \text{ mm} \gg X_0$ for lead. Hadronic calorimeters thus need to be thicker than EM calorimeters for the same absorber material. For a consecutive sequence of an EM and a hadronic calorimeter, the hadronic shower development can already be initiated within the EM calorimeter, while the shower maximum and most of the energy deposits are given in the hadronic calorimeter.

The lateral radius of hadronic showers, in which 95% of the energy are deposited, can be approximated as [115]

$$R_{95\%,\text{had}} \simeq \lambda_I. \quad (4.17)$$

The comparison of Equations 4.16 and 4.17 shows that hadronic showers are considerably wider than EM cascades in lead. Due to higher intrinsic shower fluctuations, the energy resolution of hadronic calorimeters is typically worse than the one of EM calorimeters.

Calibration of the LAr Phase-1 demonstrator

The LAr detector will undergo significant changes in both upgrade phases described in Section 3.5. The Phase-1 upgrade enables a higher spacial granularity in the LAr trigger read-out hardware [117], while the Phase-2 upgrade is aimed at a replacement of the full LAr read-out electronics [118].

A demonstrator system was installed in the ATLAS detector in 2014 to test pre-prototypes of the newly developed LAr Phase-1 upgrade hardware. The measurements with this in-situ demonstrator allow to collect data under LHC conditions and to validate the energy reconstruction. The 2014 demonstrator system was exchanged in 2018 to pre-production hardware, thus exhibiting all features of the final system. In order to analyse the collected data in terms of “high-level” quantities like energy and timing information, a calibration of the system is necessary. The calibration coefficients derived and validated for the 2014 system are described in this chapter. All shown information and measurements are obtained with the 2014 demonstrator system unless noted otherwise.

Sections 5.1 and 5.2 describe the LAr Phase-1 upgrade and the demonstrator system in more details. In Sections 5.3 and 5.4 the derivation of the demonstrator calibration coefficients is explained. Section 5.5 contains details about the validation of this calibration with proton-proton collision data. Contributions to the commissioning of the 2018 demonstrator system are described in Section 5.6.

5.1 Introduction to the LAr Phase-1 upgrade

The LAr Phase-1 upgrade is targeting the read-out path that provides the LAr read-out information to the trigger system. Measurements of the transverse energy are sent to the Feature Extractor processors of the Level-1 calorimeter trigger system (L1Calo) within a latency of 44.2 BCs, corresponding to $1.105 \mu\text{s}$, for each bunch crossing [101, 117]. The upgrade has a high impact on the abilities of the ATLAS detector to trigger on electron and photon objects, since their energy is determined with the LAr detector, but also improves the trigger performance of other physics objects. The pile-up conditions expected in Run 3, and in particular beyond Run 3 at the HL-LHC, require the utilisation of improved background rejection techniques at the L1 trigger, e.g. in terms of cluster isolation variables, to ensure an efficient data-taking.

Due to the short required latency, the current trigger system is based on so-called trigger towers, for which the analogue signals of 60 LAr cells within $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ are summed in the barrel part of the detector and transmitted to the trigger system. After the upgrade, so-called supercells (SCs) will be read out and already digitised information will be transmitted to the trigger system. The supercells have a finer granularity and additionally allow to separate longitudinal information from the four layers of the calorimeter to allow for a better background rejection. A hardware exchange is required to allow for the increased data rate of the supercell read-out. The layout of the supercells in comparison with the trigger

towers is given in Figure 5.1 for the LAr barrel. For the supercells in the presampler (EM layer 0), as well as the front (EM layer 1), middle (EM layer 2) and back (EM layer 3) layers, 4, 8, 8 and 4 LAr cells are summed, respectively. Their size is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for the presampler and back layer, while the front and middle layer supercells have a size of $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$. The trigger towers are thus split into 10 supercells.

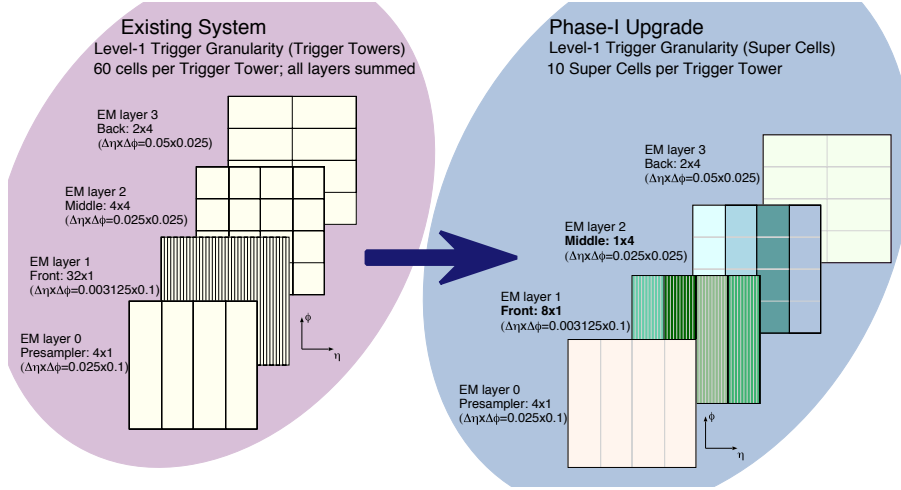


Figure 5.1: Distribution of supercells within the previous trigger towers for the LAr barrel region. After the Phase-1 upgrade, 10 supercells per trigger tower are read out for trigger purposes. The new read-out has a finer granularity and allows to utilise the longitudinal shower development. Figure from Ref. [117].

The impact of the finer trigger read-out granularity on the shower measurement of a simulated 70 GeV electron is shown in Figure 5.2. While the shower is concentrated in a single trigger tower, the read-out after the Phase-1 upgrade allows to extract and distinguish more features of electron showers due to the improved longitudinal and lateral segmentation. It is therefore possible to exploit shower shape variables and to apply more precise isolation requirements on trigger level. The shower shape variables make use of the different longitudinal and lateral properties of electromagnetic and hadronic cascades introduced in Section 4.4. The supercell read-out thus allows to have a higher background rejection at the same reconstruction efficiency.

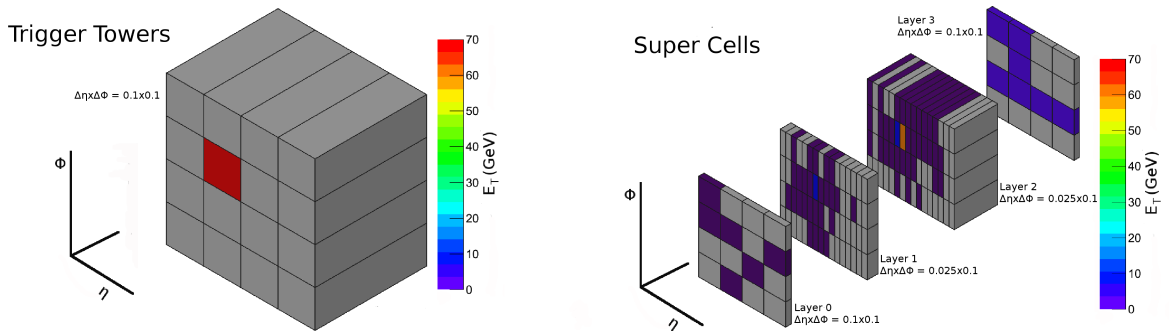


Figure 5.2: Simulated measurements of an electron shower with a transverse energy of 70 GeV based on trigger towers (left) and supercells (right). The supercell read-out exhibits a much higher granularity. Figures from Ref. [117].

An overview of the LAr read-out architecture after the Phase-1 upgrade is given in Figure 5.3. The overall read-out architecture is composed of the Front-End (FE) electronics, which are placed close to the detector, and the off-detector electronics in the counting room. The trigger read-out constitutes of the following new components:

- **New layer sum boards (LSBs):** The analogue signals from the LAr detector are first preamplified on the so-called Front-End boards (FEBs) and then send to the main read-out as well as to the trigger read-out chain. The current LSBs on the FEBs provide summed analogue signals in a window of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for a given layer of the calorimeter¹. The LSBs will be exchanged to provide summed signals in windows corresponding to the supercell sizes.
- **New baseplanes:** The current baseplanes, which transmit signals between the FEBs and other parts of the FE, will be exchanged to allow the transmission of signals to the newly introduced FE elements with a higher bandwidth than before.
- **LAr trigger digitizer boards (LTDBs):** The LTDBs are a new component of the FE in the Phase-1 upgrade. LTDBs receive the analogue supercell signals and digitize them. The digital ADC counts are then transmitted to the off-detector system. In order to keep the current trigger chain unaffected, the LTDBs additionally create analogue trigger tower signals and send them to the legacy trigger system².
- **LAr digital processing system (LDPS):** The off-detector system after the Phase-1 upgrade is required to calculate transverse energy measurements at a rate of 40 MHz for each supercell and transfer this information to the trigger system. The energy is calculated based on the ADC counts from the LTDBs within the LDPS by so-called Advanced Mezzanine Cards (AMCs). The AMCs for the LAr Phase-1 upgrade are called LATOME (LAr Trigger prOcessing MEzzanine) boards.
- **Feature Extractor (FEX):** The level-1 calorimeter trigger system will receive the E_T measurements with the so-called FEX boards. Three specialised systems are planned: eFEX (electron feature extractor), jFEX (jet feature extractor) and gFEX (global feature extractor).

The expected performance improvements in terms of the energy resolution and trigger rates are given in Figure 5.4. For an EM trigger threshold of $E_T = 22$ GeV and an electron efficiency of 95%, a decrease in the trigger rate by a factor of ~ 3 is foreseen under Run-3 conditions. This reduction will subsequently allow to maintain similar EM trigger thresholds for Run 3, after the Phase-1 upgrade, compared to the thresholds in Run 2.

5.2 Demonstrator system for the Phase-1 upgrade

An in-situ demonstrator system for the LAr Phase-1 upgrade was installed in 2014, and subsequently exchanged with newer prototypes in 2018, in order to collect supercell data from proton-proton and heavy ion collisions at the LHC. The demonstrator system is operated without affecting the main data-taking and its information was not used for the trigger decisions. A main purpose of this system is to validate the energy and timing reconstruction algorithms in the high pile-up LHC environment. In addition, it allows to gain experience in terms of the installation, commissioning and operation of the system.

¹ A further summation is done by the Tower Builder Boards (TBBs) to form the final trigger towers.

² The legacy trigger system will thus be available for the commissioning in the early Run 3 period.

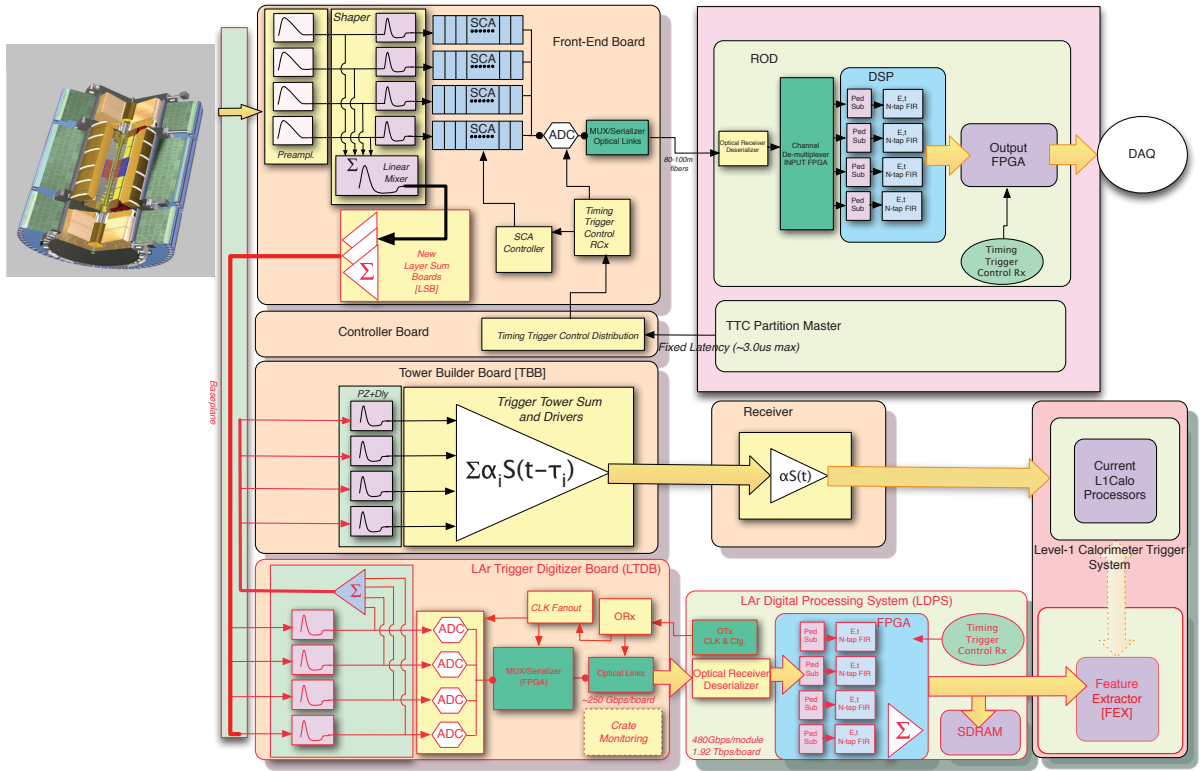


Figure 5.3: Block diagram of the LAr read-out electronics after the LAr Phase-1 upgrade. New components are marked by red outlines, text and arrows. The Front-End boards will be extended by new layer sum boards. The signals are transferred by the new baseplanes to the LAr Trigger Digitizer Boards, which send the signals to the legacy trigger read-out and additionally digitise the analogue pulses. The digitised signals are transferred to the LAr Digital Processing System in the off-detector system and their output further processed in the Feature Extractors. Figure from Ref. [117].

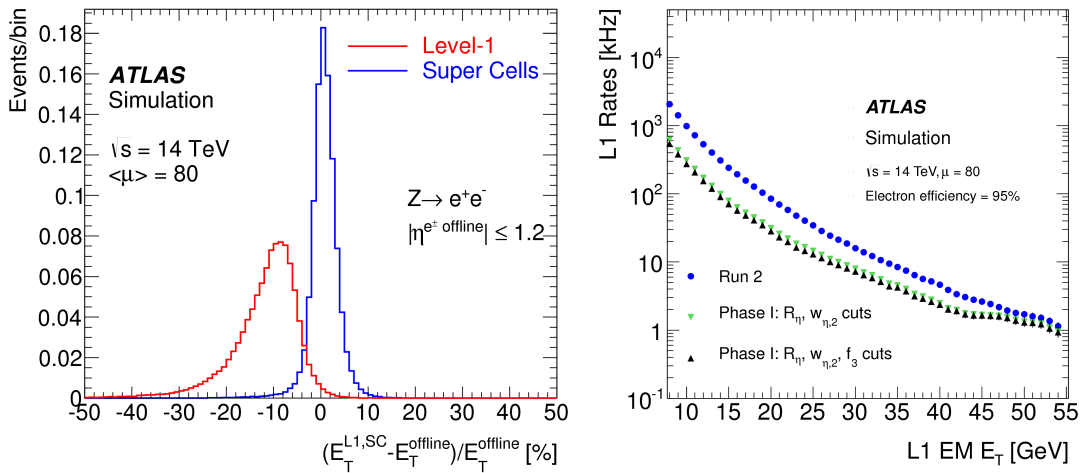


Figure 5.4: Expected performance gains due to the LAr Phase-1 upgrade. The energy resolution at trigger level in comparison with offline reconstruction (left) is expected to improve considerably for electron candidates. The L1 trigger rates (right) can be considerably reduced for a constant trigger threshold due to the usage of shower shape variables (see Equations 5.10 to 5.12 for the definition of R_{η} , $w_{\eta,2}$ and f_3). Figures from Ref. [117].

The demonstrator system is placed in the LAr barrel, covering a region of $0 < \eta < 1.52$ and $9\pi/16 < \phi < 11\pi/16$. The region within $1.4 < \eta < 1.52$ is the so-called Barrel-End part of the calorimeter and only partially shown in the following sections. In total 571 supercells are read out.

The Front-End parts of the demonstrator systems consist of two LTDB prototypes: the 2014 demonstrator system used two different LTDBs, which are called BNL LTDB ($9\pi/16 < \phi < 10\pi/16$) and French LTDB ($10\pi/16 < \phi < 11\pi/16$) in the following. The two LTDBs read out two ϕ -layers of the LAr barrel each, i.e. $\phi = 1.81$ and 1.91 for the BNL LTDB and $\phi = 2.01$ and 2.11 for the French LTDB. For the 2018 demonstrator system both LTDBs are the same. The off-detector electronics for the 2014 demonstrator was made up of three so-called ABBA boards, which are pre-prototypes of the LDPS system. The 2018 demonstrator uses pre-production hardware for the LDPS system, including LATOME boards.

During physics data taking, two special triggers are used to select high-energy deposits that are required to be within the demonstrator system coverage. One of the triggers selects electro-magnetic energy deposits with $E_T > 20$ GeV, while the other selects energy deposits from hadronic showers with $E_T > 100$ GeV. These dedicated triggers are heavily prescaled to run at 1 Hz for the 2017 data-taking.

The demonstrator data is stored for the events accepted by the trigger, in calibration and physics data-taking, in terms of raw ADC counts for each supercell. The data path of the demonstrator system is independent of the standard data path, as e.g. the raw counts cannot be transferred within the standard latency constraints. The ADC counts are measured each 25 ns, i.e. for each bunch crossing. For the 2014 demonstrator, typically 50 ADC counts were stored to allow to capture the full pulse shape (see Section 4.1 for the main read-out information). The position of the pulse peak can be shifted freely within the window. The decoder for the stored data is described in Ref. [1] and integrated in the general ATLAS Athena framework [112]. It has been updated for the studies presented here.

5.3 Calibration scheme for demonstrator supercells

The calibration of supercells is chosen to be performed in the same scheme as presented in Section 4.3 for the LAr cells. While this approach allows to reuse the existing methodology and code implementation, it assumes that the summed signals in the supercell read-out behave as signals from single LAr cells³. Special care is thus needed in the validation of the calibration coefficients.

The measurement of calibration data is based on electric current pulses that are injected by the calibration boards into the detector. The procedure is controlled with pulsing patterns, that describe the pulsed cells, the amount of injected current, as well as the delay time. The amount of injected current controls the calibration pulse height and is given in DAC current units. The delay time between the pulsing and the read-out is given in steps of 25/240 ns. For the calibration all cells within a supercell should be pulsed at the same time and with the same injected current in order to obtain calibration coefficients that average over the full supercell and not a subset of its constituent LAr cells. The calibration boards allow to pulse groups of LAr cells that are connected by the same calibration line. The structure of these lines in the LAr barrel is shown in Figure 5.5. The following criteria are applied for the structure of the pulsing patterns:

- All cells within a supercell are pulsed with the same injected current.
- Pulsing neighbouring supercells is avoided to reduce the impact of cross-talk⁴ effects on the

³ Different supercell pulse shapes can e.g. emerge from a different configuration of the signal shaper circuits.

⁴ The term cross-talk refers to effects that are created between neighbouring channels and the pulsed channel due to a, mostly capacitive, coupling between them. The signal can be spread out to its neighbours and the original pulse shape can be

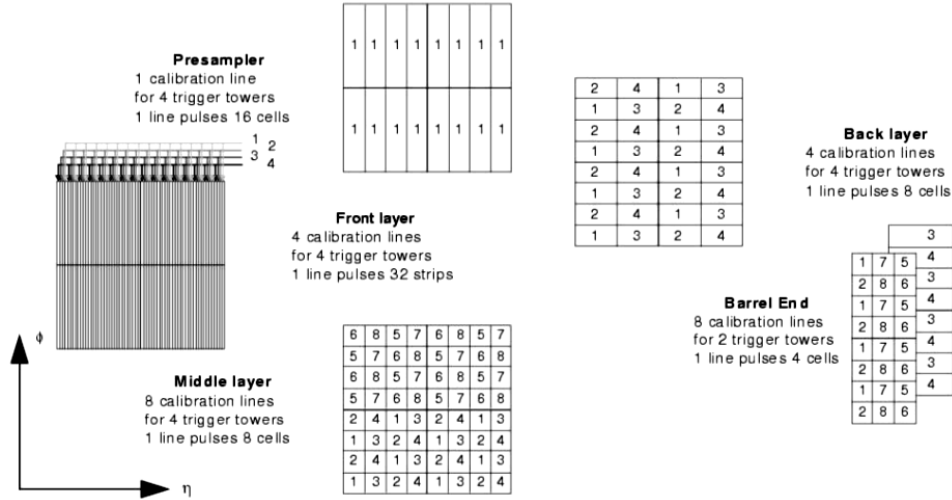


Figure 5.5: Structure of the calibration lines in the LAr barrel region for a window of $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$. Cells of the same layer with the same number are connected to the same calibration line and each layer can be pulsed independently. The pattern is mirrored in the ϕ direction for the full LAr barrel, while in the η direction different calibration lines are available within the same scheme. Figure from Ref. [110].

measured pulse shapes.

- Different calorimeter layers and η -regions are separated if the gain factor is different between them.⁵

As described in Section 4.3, pedestal, delay and ramp runs are needed for a full set of calibration data. For delay runs, pulse shapes at 24 delay time steps are measured for a DAC value that is chosen to yield high pulse amplitudes, while avoiding saturated pulses. In case of ramp runs, different DAC values are chosen to cover a large range of pulse heights that reach into the saturation region. No delay time is applied for ramp runs. Due to the structure of the calibration lines, it is not possible for all layers to avoid pulsing neighbouring supercells. The dedicated calibration patterns for the demonstrator calibration data-taking are described in Appendix B.1, along with the DAC values that are used in the delay and ramp runs. The final pulsing patterns are split into three regions, which allows to separate the detector into areas where the same DAC values can be used. The pulsing patterns are integrated into the online software of the LAr detector.

The $F_{\text{DAC} \rightarrow \mu\text{A}}$ and $F_{\mu\text{A} \rightarrow \text{MeV}}$ conversion factors, which are needed to convert DAC values into energies (compare Equation 4.11) were obtained from the electronics specifications and test-beam data for LAr cells, respectively [110]. Their combination for supercells is performed according to the following equations:

$$F_{\text{DAC} \rightarrow \mu\text{A}, \text{SC}} = \sum_{\text{const}} F_{\text{DAC} \rightarrow \mu\text{A}, \text{cell}}, \quad (5.1)$$

$$F_{\mu\text{A} \rightarrow \text{MeV}, \text{SC}} = \frac{1}{n_{\text{const}}} \cdot \sum_{\text{const}} F_{\mu\text{A} \rightarrow \text{MeV}, \text{cell}}. \quad (5.2)$$

distorted. The biggest cross-talk effects in the LAr calorimeter are observed between neighbouring front layer cells. [110]

⁵ For high gain factor differences it is not possible to avoid saturation effects and too small pulse heights for all supercells simultaneously.

The $F_{\text{DAC} \rightarrow \mu\text{A}}$ factor is summed, since for a given supercell all constituent cells are pulsed in the calibration with the same DAC value for the injected current. $F_{\mu\text{A} \rightarrow \text{MeV}}$ is averaged, since the shower shape within the supercell is a priori not known and thus only the average response for a given supercell can be assumed. The typical spread of these factors for the constituent cells in a supercell is low.

A correction factor due to changes in the high voltage compared to the nominal voltage is additionally applied in the energy calculation⁶. It is provided in a database for the reconstruction within the Athena framework and updated even during a single proton-proton run to keep the calibration factor correct. For supercells, the factor is chosen as the average of their constituent cells.

During the measurement of calibration data and before calculating calibration coefficients from it, rigorous data quality checks are needed. Due to the high radiation environment on the detector, frequent fibre unlocks⁷ and timing shifts occurred for the non-radiation-hard pre-prototype electronics of the 2014 demonstrator. Several delay and ramp runs are thus combined to obtain calibration coefficients for the full demonstrator system, as in single runs a fraction of the supercells might have bad data quality.

5.4 Determination of the calibration coefficients

The following subsections describe the obtained calibration coefficients and their low-level validation for the 2014 demonstrator system. The coefficients are determined for all supercells that could be read out by the system. Examples of the unprocessed raw data for pedestal, delay and ramp runs can be found in Figure 5.6 for a single supercell.

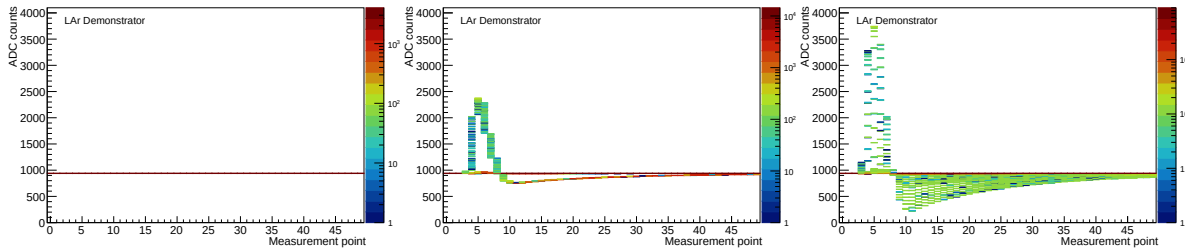


Figure 5.6: Raw data from a pedestal (left), delay (middle) and ramp (right) run for a selected supercell. The numbers of occurrences for a certain ADC count bin is shown by the color scheme.

An overview of the full calibration chain is given in Figure 5.7 and Section 4.3. Optimal filtering coefficients (compare Section 4.2) need to be determined for calibration and physics pulses separately⁸, due to their different pulse shapes. The final calibration coefficients, which are needed to calibrate collision data, are the pedestal value, OFCs for physics pulses and the gain factor. The predicted amplitude ratio between calibration and physics pulse shapes is applied as an additional correction.

The steps presented in this section describe the determination of the complete set of calibration coefficients, while their accuracy cannot be determined from calibration data alone. The validation with pp collision data is described in Section 5.5.

⁶ The high voltage correction is applied as an additional multiplicative factor in Equation 4.11.

⁷ The data from unlocked fibres is not usable, as e.g. the data link between the Front-End and the off-detector system is interrupted and thus no real measurements are retrieved.

⁸ The “calibration” pulse refers to pulse shapes measured in calibration data, where current pulses are injected into the electronics. The “physics” pulse refers to pulse shapes measured in collision data.

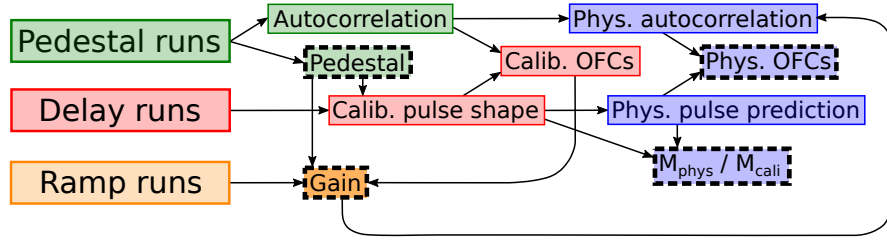


Figure 5.7: Overview of the full calibration chain and dependencies between the different steps. The boxes with a thick black dashed line indicate the final calibration coefficients needed to reconstruct physics data.

5.4.1 Pedestal runs

Pedestal runs allow to extract the baseline ADC counts, i.e. the offset without a pulse being present, and the autocorrelation of electronics noise (compare Section 4.2 for its definition). An overview of the pedestal values can be found in Figure 5.8 for the full demonstrator system. Two main peaks are visible, which correspond to the two different LTDBs. Their spread is defined by the choice of the accuracy for specific resistors in the LTDBs and agrees with the expectation. The root mean square (RMS) value of the pedestal fluctuations within a single pedestal run for each supercell is given in Figure 5.8, too, and shows that the pedestal values typically only fluctuate within less than an ADC count.

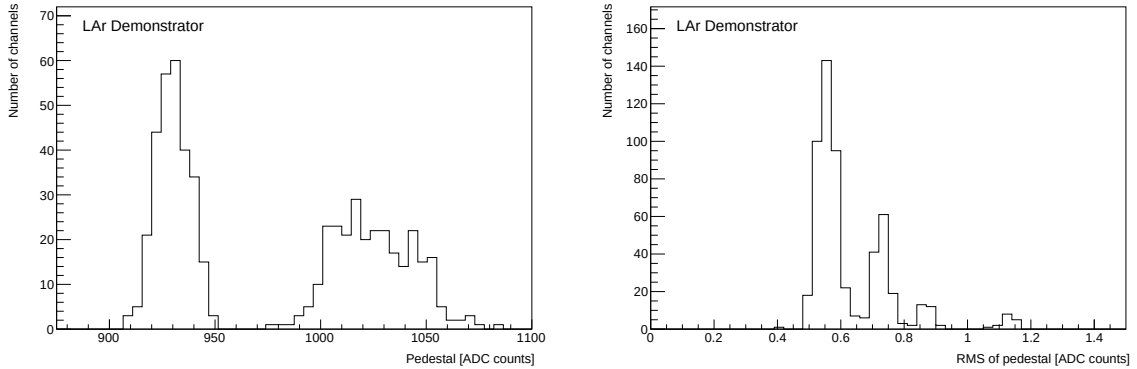


Figure 5.8: Pedestal distribution in ADC counts for the demonstrator system (left) and RMS value of its fluctuations (right). The average pedestal is different for the two LTDBs, resulting in the two separate regions centred around ADC values of 930 for the BNL LTDB and 1025 for the French LTDB. The η -dependence of the pedestal and its RMS is available in Figures B.2 and B.3 of Appendix B, respectively, and explains the multi-peak structure of the distributions.

Figure 5.9 shows typical examples of the measured noise autocorrelation for a supercell in the presampler and the back layer. The autocorrelation of neighbouring measurements is typically positive. For distances of 2 – 3 bunch crossings slightly negative values are present, such that upward fluctuations are typically followed by small downward fluctuations (and vice versa). For longer distances the correlation converges to 0.

5.4.2 Delay runs

The calibration pulse shape measured in delay runs is given in Figure 5.10 for selected supercells from each layer. Their general shapes follow the expectations described in Section 4.1, while specific properties

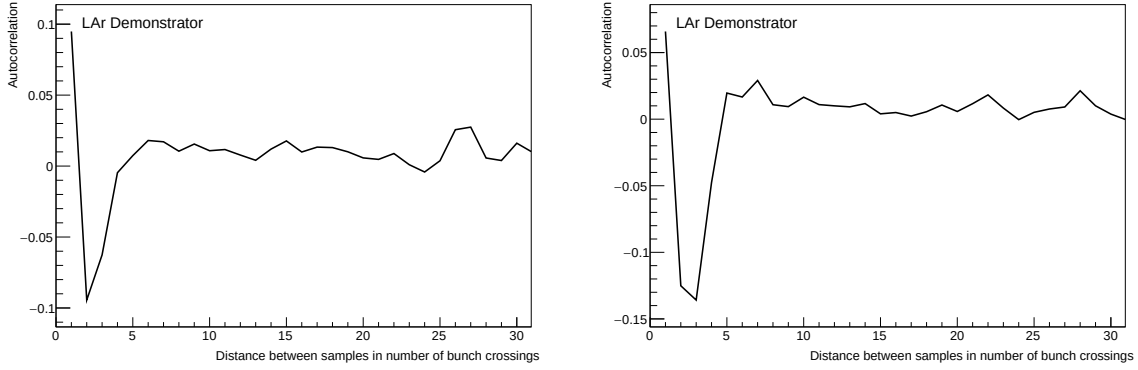


Figure 5.9: Example of the noise autocorrelation for presampler (left) and back layer (right) supercells obtained from calibration data. A positive correlation is observed for neighbouring measurements, while a negative correlation is present for intermediate time differences. No significant correlation is observed for measurements with a distance above 5 BCs. The noise autocorrelation is symmetric in time [109].

like the pulse height or the decay constant of the negative lobe can vary. In addition, some supercells exhibit small sinusoidal fluctuations on top of the regular pulse shapes due to reflections in the electronics (see Figure B.1 in Appendix B.2 for an example).

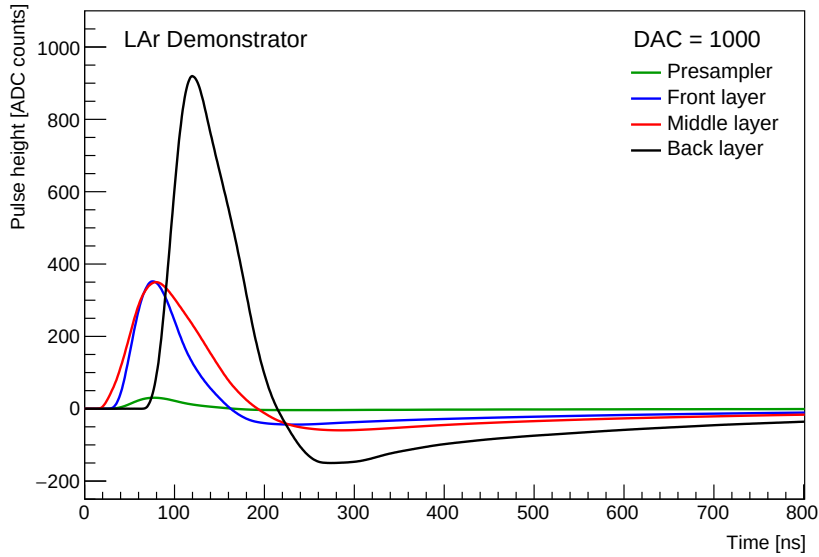


Figure 5.10: Measured pulse shapes for selected supercells from each layer of the LAr calorimeter. The pulse height is different due to the supercell gains, which vary for the different calorimeter layers and within the layers. The pedestal level is subtracted and the alignment of the pulse peak positions is sufficient for calibration purposes.

The amplitude distribution of the pulse shapes is given in Figure 5.11 for the full demonstrator. Typically pulse heights of 1500 – 2000 ADC counts above the pedestal can be reached, while the minimum pulse height is around 800 ADC counts. It is validated that all supercells do not reach the saturation region, i.e. the maximum ADC count is not reached and the pulse shapes are not distorted. The different regions in the pulse height distribution are explained by the choice of the amplification gain

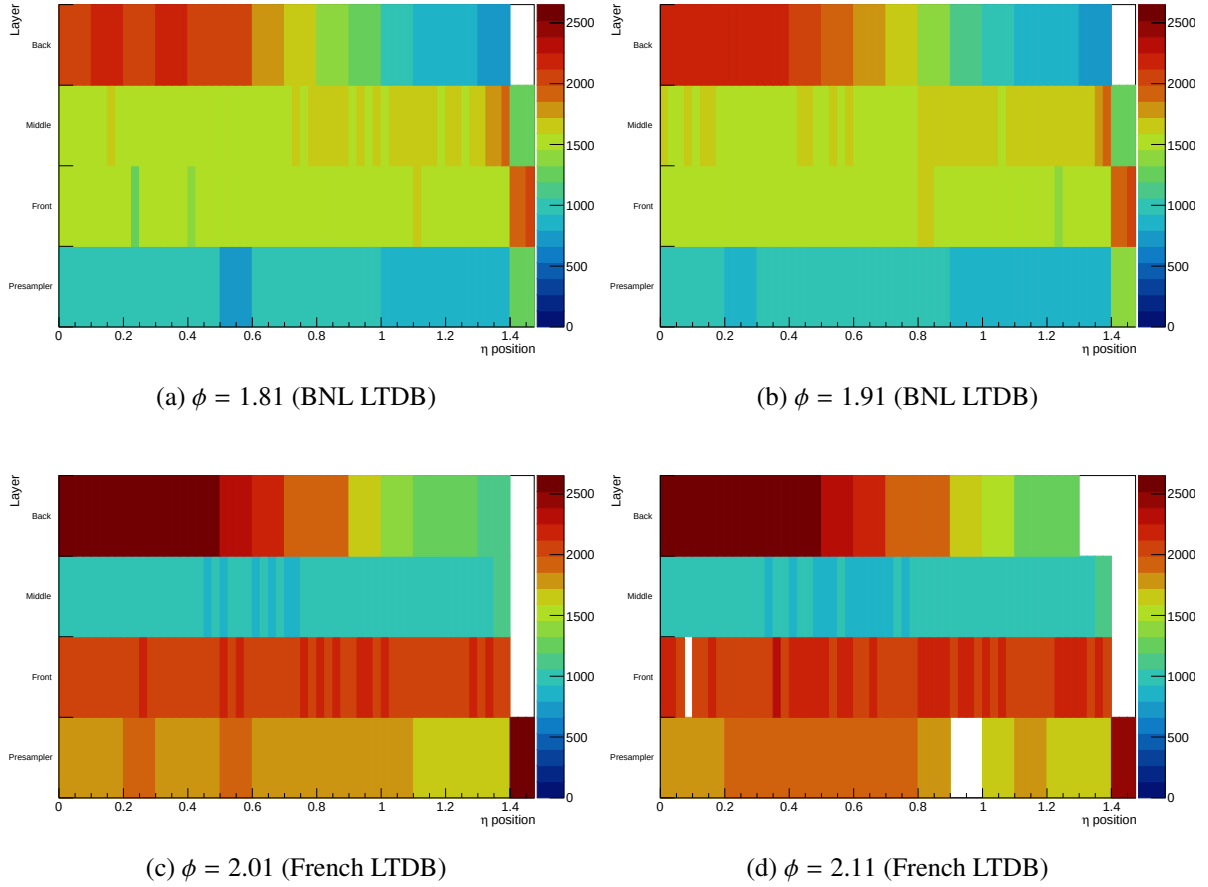


Figure 5.11: Overall pulse height distribution in delay runs, given in ADC counts by the color scheme. Typically pulse heights of 1500 – 2000 ADC counts above the pedestal can be reached, while the minimum pulse height is around 800 ADC counts. The two LTDBs show different distributions due to the different pulsing patterns and different intrinsic gains. It is validated that all supercells do not reach the saturation region.

for each of the LTDBs and for the different calorimeter layers.

Supercell OFCs can be obtained from the calibration pulse shapes (as described in Section 4.2). Examples of OFCs are shown in Figure 5.12. It is selected that the OFCs only use the first 5 measurements, as for the trigger read-out after the Phase-1 upgrade also only 4 or 5 measurements will be used during physics data-taking. 4 (5) measurements per LAr cell are used for the amplitude and timing reconstruction of the main read-out during the Run 2 (Run 1) data-taking. The obtained OFCs are compatible with those from LAr cells.

Two sets of OFCs can be obtained for further usage:

- The *non-iterative* OFC set gives the OFC values at the nominal timing alignment for a given supercell. For timing misalignments, the accuracy of non-iterative OFCs is poor if the offset is above a few ns.
- The *iterative* OFC set contains OFC values for the nominal and misaligned timing values. The proper timing values are determined by an iterative OFC application procedure and the accuracy of iterative OFCs thus remains high even for large deviations in the timing alignment.

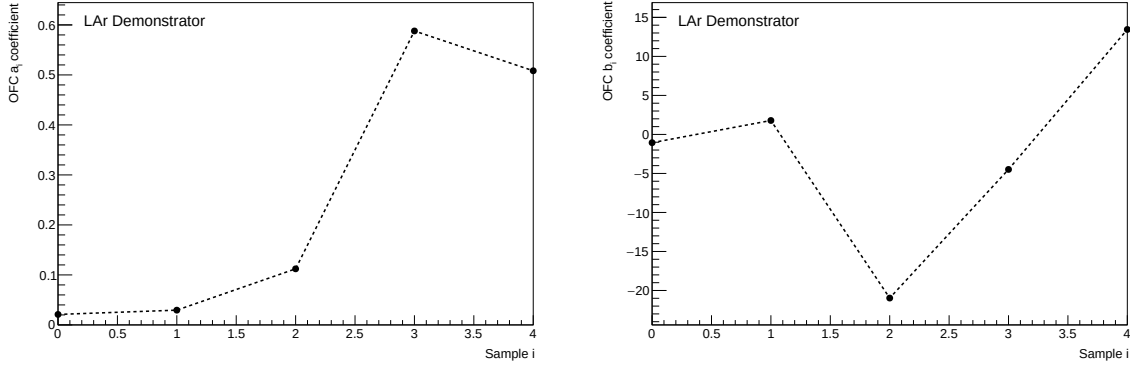


Figure 5.12: Example of optimal filtering coefficients for the amplitude reconstruction (left) and $A\tau$ reconstruction (right) used for the reconstruction of calibration data. The pulse maximum for this set of calibration data is at sample 3, such that for this sample the highest OFC a_i weight is given and the OFC b_i weight is close to 0.

The timing of the LAr cells is pre-determined and thus non-iterative OFCs can be used for the main read-out reconstruction. The timing alignment for the demonstrator supercells is detailed in Subsection 5.4.5. Non-iterative OFCs are used for the demonstrator system studies described in this chapter, too, unless noted otherwise.

The OFCs determined from delay run information are only valid for calibration data, as the pulse shapes in physics data are slightly different and thus different OFC sets are needed as described in Subsection 5.4.4.

5.4.3 Ramp runs

Typical ramp run results are shown in Figure 5.13. For each DAC value, the observed pulse height is determined by using the calibration OFCs. Afterwards, a linear fit is performed to the region of DAC values where no saturation effects are visible. The slope of the fit is used as the gain factor, while the offset at DAC = 0 can be used as an additional correction.

Observed pulse shapes for the different DAC values are given in Figure 5.13, too. While for the presampler even for the highest possible DAC values the saturation region cannot be reached, saturation effects are visible for the other layers. In the saturation region, the pulse height does not increase any more and the negative lobe might exhibit considerable changes in its shape. The determined amplitude for these pulses subsequently does not scale linearly with the injected current any more, such that a precise energy determination is not possible.

The gain distribution⁹ for the full 2014 demonstrator is shown in Figure 5.14, which shows the gain dependence on the detector layer and supercell η position. The two LTDBs behave differently due to the different gain choices during their construction and, generally, a smooth behaviour can be observed. A typical gain value in units of DAC value per ADC count for the presampler is 0.03 (0.06) for the BNL (French) LTDB, while the front layer gain reaches values of 0.35 (0.65). The medium layer gains of the BNL LTDB are about 0.035, while for the French LTDB gains of 0.030 are observed. The back layer exhibits a high η -dependence of the gain with values of 1.05 (2.10) for $\eta < 0.8$ and gains down to 0.17 (0.33) for $\eta > 0.8$ in case of the BNL (French) LTDB. Three pulsing patterns are thus used, one for each distinct gain region: a presampler pattern, a low- η back layer pattern and a combined pattern for the front,

⁹ Three different linear gains are available for each cell in the LAr main read-out to ensure a large dynamic range, while for each supercell one linear gain is available.

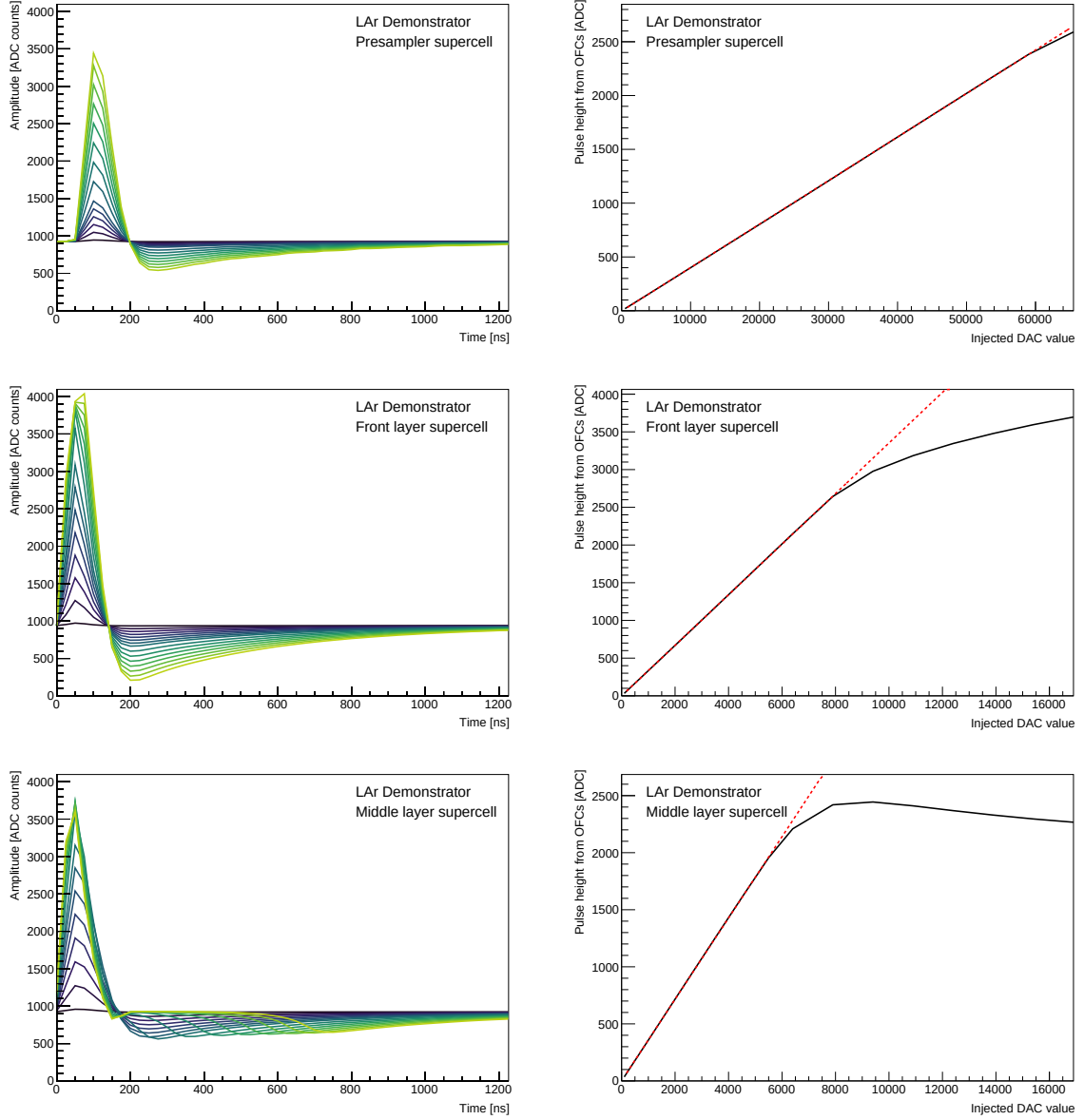


Figure 5.13: Example of ramp run pulse shapes (left column) and the obtained DAC to ADC relation (right column) in the presampler (top) as well as the front (middle) and middle (bottom) layers. A linear fit is performed to the data and the obtained slope used as the gain factor. The presampler does not show significant saturation effects, while the front layer pulse shape reaches the maximum ADC count of 4096 and thus saturates. The middle layer pulse shape exhibits significant saturation effects even before reaching the maximum ADC count and its negative lobe is clearly deformed.

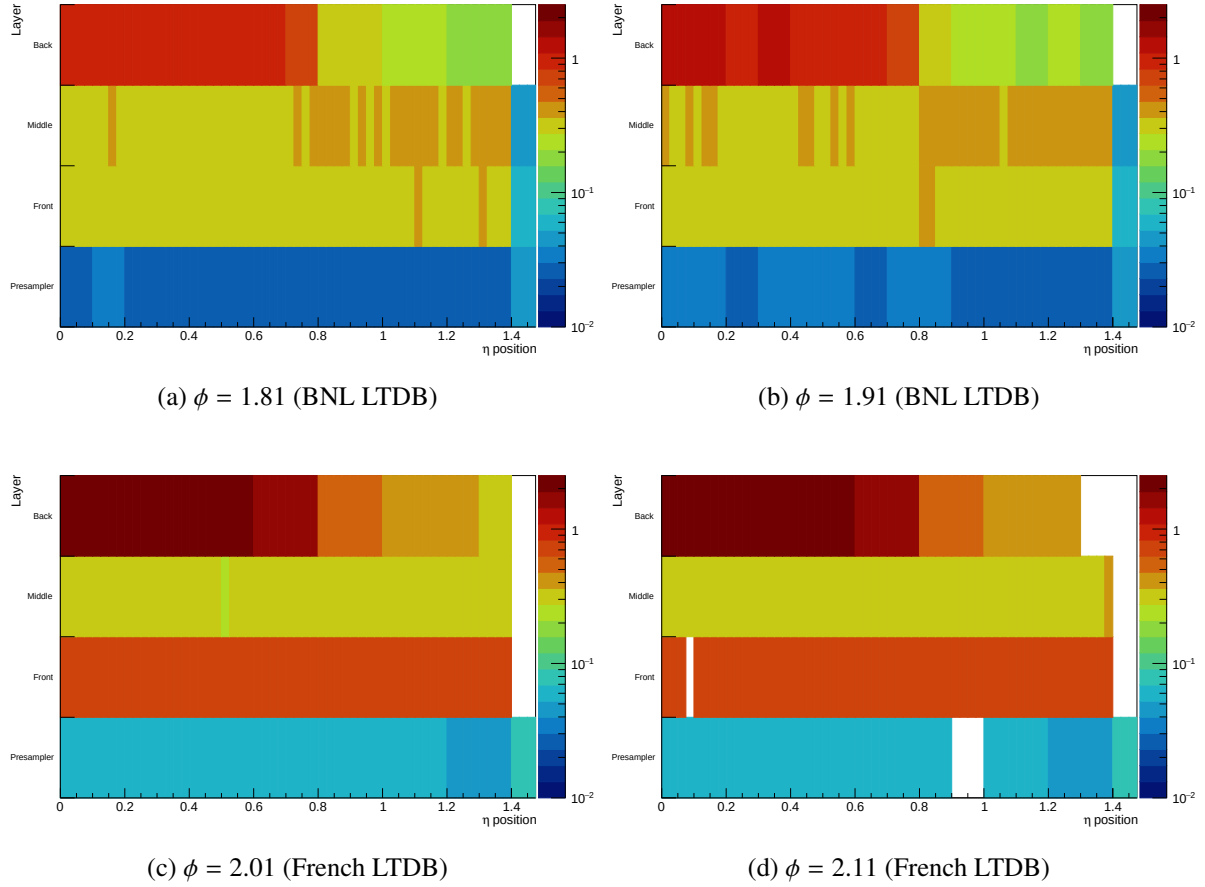


Figure 5.14: Measured gain values for the different ϕ -layers of the demonstrator system, given in units of DAC value per ADC count by the color scheme. The two LTDBs behave differently due to the different gain choices during their construction and a generally smooth behaviour within the layers can be observed. The gain dependencies on the detector layer and η position of the supercells are accounted for by measuring the calibration data with three distinct calibration patterns.

middle and high- η back layers. As the two LTDBs exhibit different gains, two sets of different pulsing patterns are used.

The linearity of the DAC to ADC relation is validated in order to check that a linear fit is sufficient and no higher-order terms need to be included. The relative difference between data and fit is shown in Figure 5.15 for selected supercells. The non-linearities in the non-saturated DAC range are below 1% typically, while slightly higher values for DAC values close to zero are present. DAC values for which saturation effects are visible, are excluded from the linear fit as the region does not allow a precise energy determination. The impact can be observed in Figure 5.13 for DAC values > 8000 (> 5500) in the front (middle) layer.

5.4.4 Physics pulse prediction

In order to calculate the OFCs for physics pulses, a prediction of the noise autocorrelation in physics data is needed. The contribution due to pile-up is non-negligible and is determined from MC predictions. Examples of predicted noise autocorrelation values from pileup can be found in Ref. [109]. The

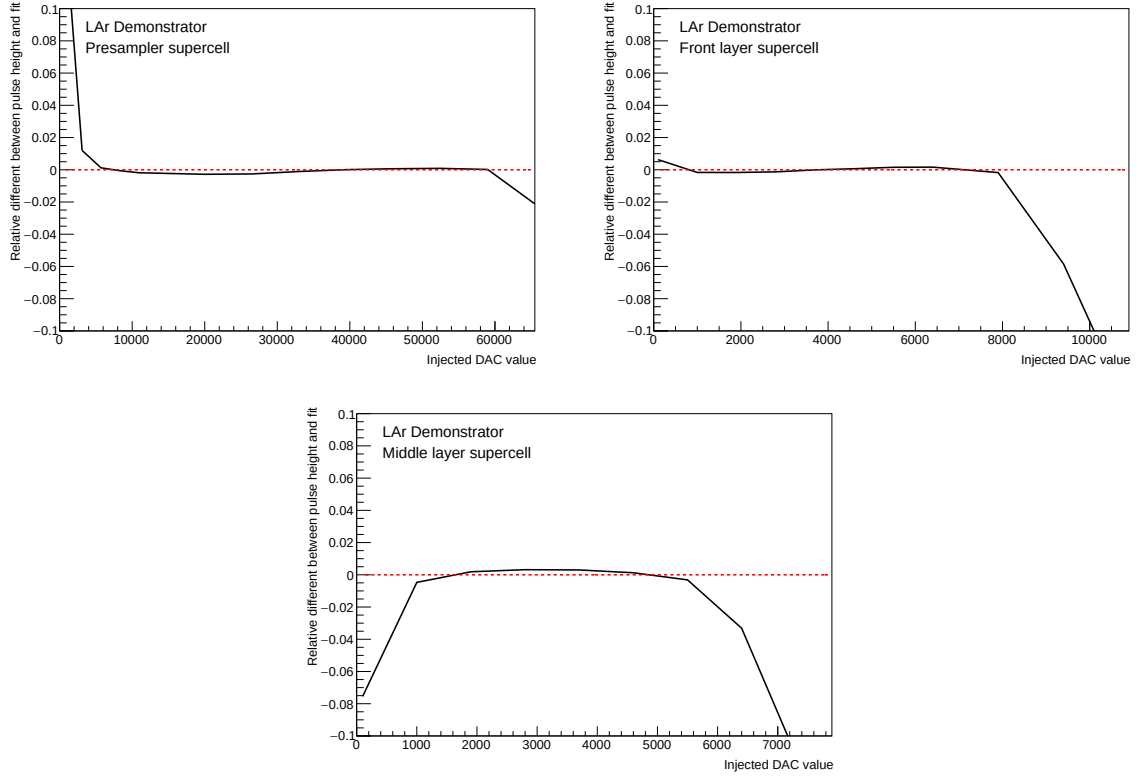


Figure 5.15: Linearity of the measured ADC to DAC relation for selected supercells in the presampler (top left) as well as the front (top right) and middle (bottom) layers.

autocorrelation measured in calibration data is thus corrected for pile-up contributions at $\langle \mu \rangle = 20$. The value of $\langle \mu \rangle = 20$ is chosen in accordance with the choice for the main read-out calibration in Run 2.

The Response Transformation Method (RT method) [119] is used for the prediction of the pulse shape in physics data. Its main principles are described in the following, while more details are available in Ref. [119]. The RT method relies on a description of the LAr read-out electronics by the model given in Figure 5.16. The conversion between the physics and the calibration pulse shape in the Laplace domain is given by

$$g^{\text{phys}}(s) = g^{\text{cali}}(s) \times g^{\text{exp} \rightarrow \text{tri}}(s) \times g^{\text{MB} \rightarrow \text{det}}(s), \quad (5.3)$$

with the following adjustment factors:

$$g^{\text{exp} \rightarrow \text{tri}}(s) = \frac{I_{\text{inj}}^{\text{phys}}(s)}{I_{\text{inj}}^{\text{cali}}(s)}, \quad (5.4)$$

$$g^{\text{MB} \rightarrow \text{det}}(s) = \frac{1}{1 + s\tau_r + s^2\tau_0^2}, \quad (5.5)$$

where $g^{\text{phys}}(s)$ gives the pulse shape in physics data, while $g^{\text{cali}}(s)$ describes the calibration pulse shape. The correction factor $g^{\text{exp} \rightarrow \text{tri}}(s)$ accounts for the different shape of the injected currents, while $g^{\text{MB} \rightarrow \text{det}}(s)$ accounts for the different injection points. The injected current pulses in the Laplace domain for physics and calibration data are described by $I_{\text{inj}}^{\text{phys}}(s)$ and $I_{\text{inj}}^{\text{cali}}(s)$, respectively.

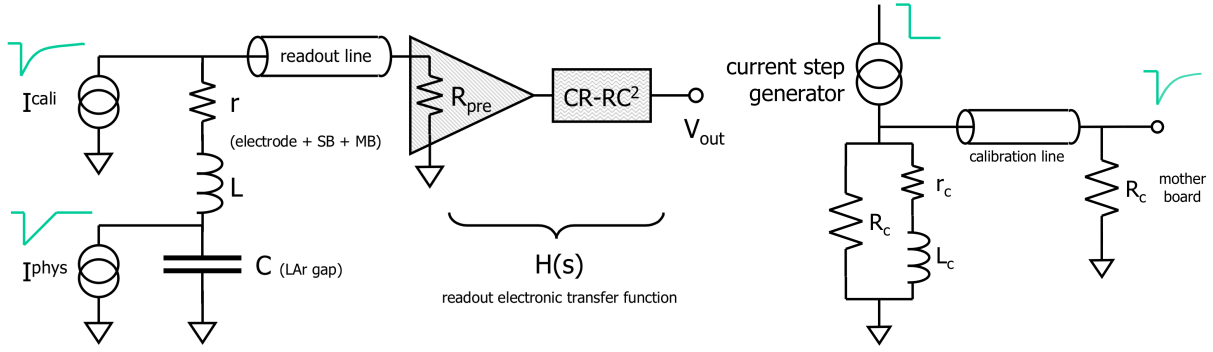


Figure 5.16: Basic equivalent circuit of the LAr detector readout cell (left) and simplified calibration board pulser circuit (right), showing the non-ideal nature of the inductance L_c in its resistive component r_c . Both figures are taken from Ref. [119].

The injected current pulses are given in the time domain by

$$I_{\text{inj}}^{\text{phys}}(t) = I_0^{\text{phys}} \cdot \left(1 - \frac{t}{T_d}\right) \cdot \theta(t)\theta(T_d - t), \quad (5.6)$$

$$I_{\text{inj}}^{\text{cali}}(t) = I_0^{\text{cali}} \cdot \left[\left(1 - f_{\text{step}}\right) e^{-\frac{t}{\tau_{\text{cali}}}} + f_{\text{step}} \right] \cdot \theta(t), \quad (5.7)$$

with t as the time and $\theta(t)$ as the Heaviside step function. It is $\theta(t) = 1$ for $t \geq 0$ and $\theta(t) = 0$ for $t < 0$. The injected current for physics data thus follows a purely triangular shape, while the injected current in calibration data is modelled as an exponential shape that converges to a non-null baseline value. The conversion for each cell is then fully described by the following five free parameters:

- T_d is the maximum drift time within the LAr gap and has a typical value of $\simeq 400$ ns.
- τ_{cali} describes the decay constant of the calibration pulse.
- f_{step} gives the fraction of the calibration pulse amplitude to which the pulse shape converges.
- $\tau_0 = \sqrt{LC}$ and $\tau_r = rC$ are properties of the readout chain as described by the electrical model.

τ_{cali} , f_{step} , τ_0 and τ_r need to be obtained from fits to the calibration pulse shape for each cell separately, which is further detailed in Ref. [119] and performed by using the implementation of the RT method in Athena. T_d is determined from the knowledge of the LAr detector design.

The RT method is *a priori* only valid for single LAr cells. The prediction of supercell physics pulse shapes is possible if their pulse shape is a linear sum of the constituent cell pulse shapes and no strong differences between the pulse shapes of constituent cells in a supercell are present. The validation of this assumption is described in Subsection 5.5.3 and Appendix B.4.

A comparison of the predicted physics and measured calibration pulse shapes is shown in Figure 5.17. The main difference is in the negative lobe, independent of the layer, while the main peak is almost the same due to the properties of the read-out electronics. It is checked for all supercells that the predicted physics pulse shapes look reasonable.

The small differences in the peak amplitudes in Figure 5.17 correspond to the $M_{\text{cali}}/M_{\text{phys}}$ correction factor in Equation 4.11. The effect is mainly due to the presence of the inductance L between the injection points of the two currents [110] (as shown in Figure 5.16). An overview of the amplitude ratios is given in Figure 5.18. The amplitude ratio in the front and back layers as well as the presampler is typically

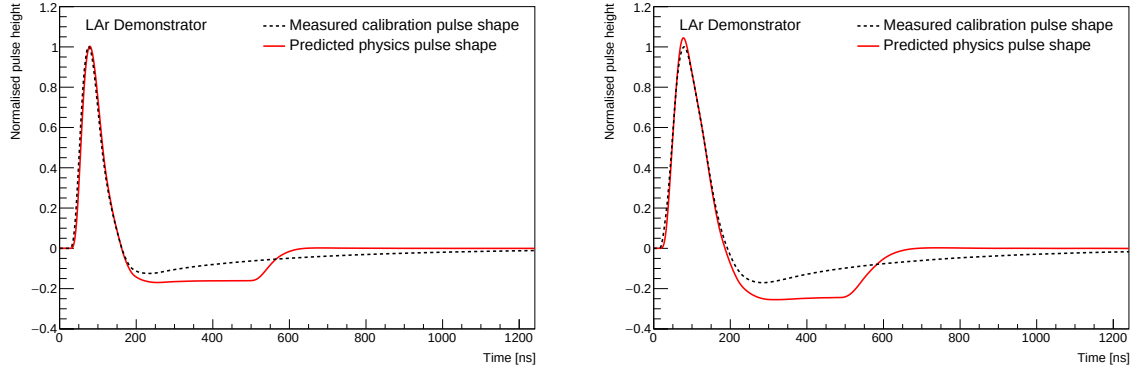


Figure 5.17: Comparison of the calibration pulse shape and the predicted physics pulse shape in the front (left) and middle (right) layers.

about 0 – 2%. The middle layer corrections are higher, with a mean value of about 5% and values ranging up to 8% inside the demonstrator coverage. This is consistent with single cell measurements [110], where the middle layer corrections were found to be higher, too.

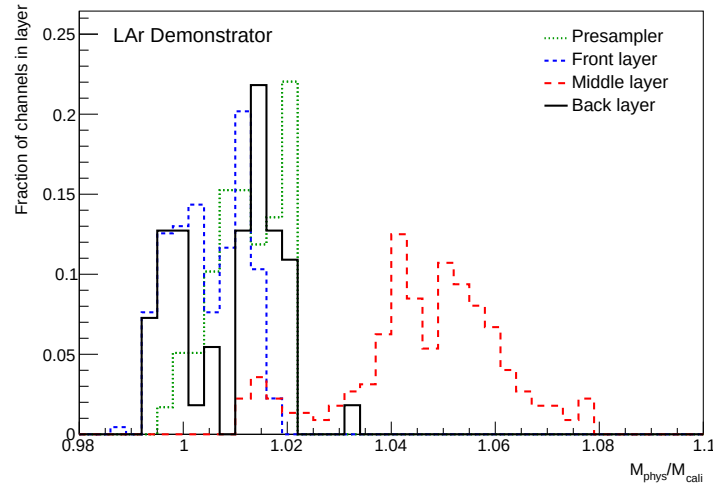


Figure 5.18: Distribution of amplitude ratios separated by the calorimeter layer. The amplitude difference in the front and back layers as well as the presampler is typically about 0 – 2%. The middle layer corrections are higher, with a mean difference of about 5% and values ranging up to 8% inside the demonstrator coverage. The η -dependence of the amplitude ratio is available in Figure B.4 of Appendix B and gives further details on the structure of the distributions.

The OFCs obtained from the predicted physics pulse shapes and the autocorrelation values expected in physics data are shown in Figure 5.19. In contrast to the OFCs obtained for calibration pulse shapes (given in Figure 5.12), the pulse maximum for physics data reconstruction is aligned to be at sample 2, such that for this sample the highest OFC a_i weight is given and the OFC b_i weight is close to 0. The timing alignment of the OFC sets to the bunch crossings with an accuracy below 25 ns is not achieved at this step, though, and described in the following subsection.

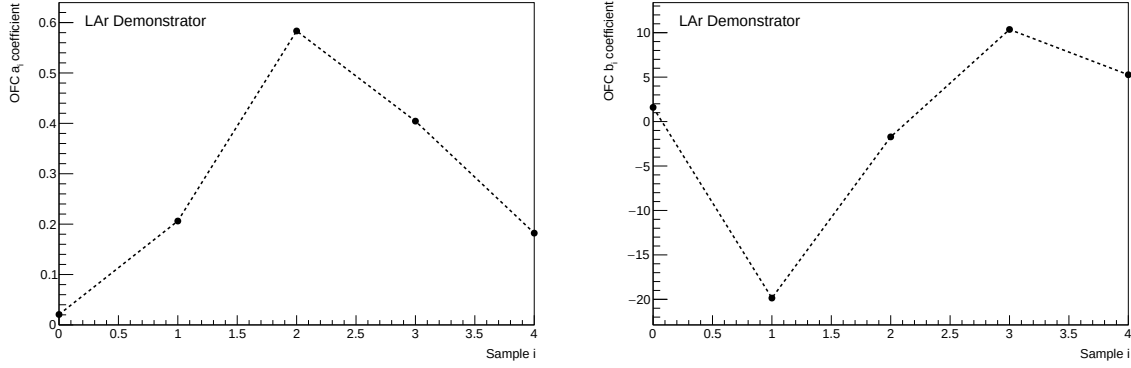


Figure 5.19: Example of optimal filtering coefficients for the amplitude reconstruction (left) and $A\tau$ reconstruction (right) used for the reconstruction of physics data. The pulse maximum for physics data reconstruction has been aligned to be at sample 2 (compare Figure 5.12 for the timing alignment in calibration data), such that for this sample the highest OFC a_i weight is given and the OFC b_i weight is close to 0.

5.4.5 Timing alignment

The timing information obtained from the OFCs needs to be corrected for potential offsets in the read-out chain, for example due to the signal processing time. Considerable offsets between the main read-out and the demonstrator are found, such that the corrections need to be determined separately. Due to run-by-run timing shifts of the 2014 demonstrator system that have a different step size than 25 ns, the correction needs to be determined for each physics run separately¹⁰. In order to obtain the correction factors, physics data needs to be used under the assumption that all pulses for a given supercell emerge from the bunch crossings.

The determination of the timing offset is performed in a step-wise procedure:

- The full physics run is first processed with the nominal timing from the main read-out and, in addition, with a constant offset of 12.5 ns for all supercells. The second processing is needed to cover the cases where the actual timing offset is about ± 12.5 ns, i.e. about half of the bunch crossing distance, from the main read-out value. The bunch crossing association depends on random fluctuations in this case for the nominal timing, where timing offsets with an absolute value of about 12.5 ns are retrieved. Timing distributions are obtained for both cases using pulses with peak heights of ADC > 8, thus rejecting noise contributions. The distributions are determined using iterative OFCs, which allow to determine the correct timing in a wider range of the initial timing offset τ .
- In a second step, the mean value of the timing distribution using the nominal timing offset is determined. In case the distribution for a given supercell exhibits a double-peak structure (i.e. where the actual and tested timing values have a difference of about ± 12.5 ns), the distribution with a constant offset of 12.5 ns is used. If both distributions allow to determine the timing offset, their agreement is checked and the offset determined from the nominal timing of the main read-out is used.

¹⁰ For OFC timing misalignments in steps of 25 ns, a wrong association of the bunch crossing occurs. Due to the large demonstrator read-out window, an energy and timing calculation is still possible in this case, though. For OFC timing misalignments below 25 ns, a precise energy and timing calculation is not possible with non-iterative OFCs any more (compare Subsection 5.4.2). Timing shifts with step sizes below 25 ns can e.g. occur due to the wrong synchronisation of hardware components that have a clock frequency higher than 40 MHz.

- The timing corrections are finally applied to reconstruct the physics data again and the closure of the correction, i.e. an alignment of the timing distributions around an offset of 0 ns, is verified.

The effect of the timing alignment for selected supercells is shown in Figure 5.20. While for the front layer example an original offset of about -9 ns is present, the middle layer example shows an offset close to ± 12.5 ns and thus a double-peak structure. Following the above description, for this supercell the timing is determined from OFCs that are shifted by 12.5 ns and thus avoid the double-peak structure. For both examples, the distribution after the correction is well aligned with a mean offset of 0 ns.

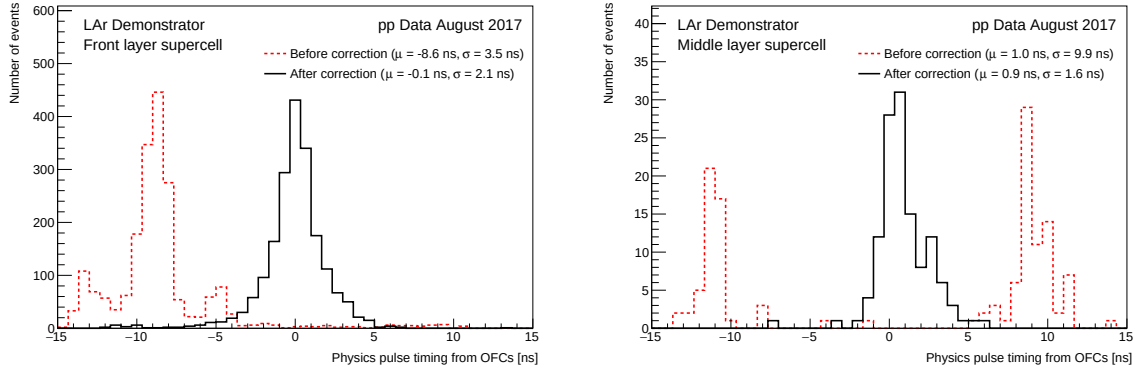


Figure 5.20: Distribution of pulse timing values before and after the correction of the timing offset for selected supercells in the front (left) and middle (right) layers. The distributions after the correction are aligned with a mean offset of 0 ns and overall show a more smooth behaviour due to the proper timing reference.

The overall distribution of the mean timing is shown in Figure 5.21. The distribution of the mean timing before the correction exhibits peaks at around -3 ns and $+6$ ns and is distributed over a broad range, while after the correction an alignment close to 0 ns can be observed and the spread is considerably reduced. The RMS value of the supercell timing distributions is additionally reduced due to the better alignment and does not exhibit long tails any more.

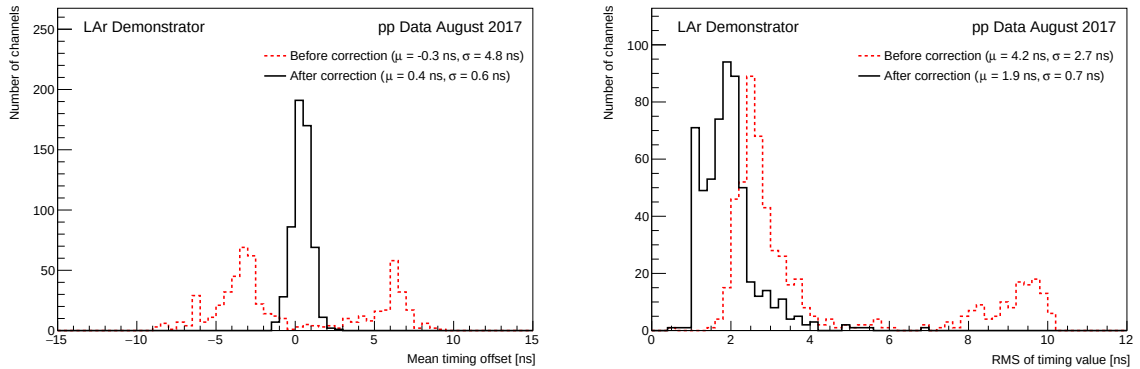


Figure 5.21: Overview of pulse timing properties before and after the correction of the timing offset in terms of the mean (left) and RMS (right) values for the full demonstrator system. RMS values above 7 ns emerge from supercells with initial timing offsets close to ± 12.5 ns (see middle layer example of Figure 5.20) and are considerably reduced by the timing correction.

A misalignment in the timing reference leads to an inaccurate energy determination and a non-linear offset in the determined timing value. An example of the effect for a specific supercell is presented in

Figure 5.22. The error in the amplitude determination, and thus the energy, is below 1% for timing offsets within ± 4 ns. The timing is determined precisely in this region, too. For higher timing offsets, the error in both, the amplitude and timing determination, increases strongly due to the underlying linear approximation of the OFCs.

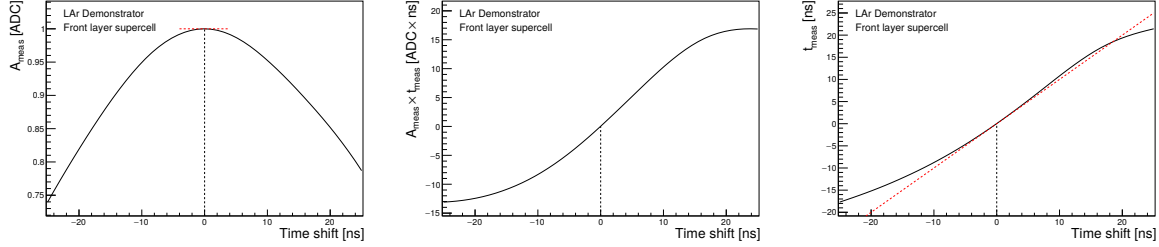


Figure 5.22: Effect of a misalignment of the timing reference on the reconstructed pulse amplitude (left), amplitude $\times$ timing (middle) and timing (right). The pulse amplitude is underestimated by about 4 % for a timing offset of 10 ns, directly corresponding to a wrong energy determination of the same size. The measured timing value starts to deviate from a one-to-one relation (red dashed line) with the misalignment at offsets of about 5 ns, such that outside of this linear region only an imprecise timing determination is possible.

5.4.6 Overview of the calibration coefficients

An overview of the obtained calibration coefficients is given in Figure 5.23, which shows the final conversion factors between the pulse height and supercell energies. Appendix B.3 contains additional figures.

Both LTDBs exhibit similar conversion factors of around 300 – 600 MeV/ADC in the middle layer. For the three other layers, the French LTDB conversion factors are lower than the ones of the BNL LTDB. The η -dependence of the conversion factors is smooth, except for a step at $\eta = 0.8$, where a transition of the lead absorber layer thickness is present [76] and several electronics calibration coefficients change. The two ϕ -layers of a single LTDB show very similar conversion factors, indicating a good closure of the calibration.

The pedestal fluctuations converted to energies give a measure for the electronics noise and are shown in Figure B.5 of Appendix B.3. The noise level is about 100 MeV in the front layer and 200 – 300 MeV for the middle layer as well as the presampler. The back layer exhibits noise levels of up to 500 MeV for $\eta > 0.8$. During physics data-taking, additional noise contributions from pile-up are present.

The saturation energy for the supercells is given in Figure B.6 of Appendix B.3. The front layer supercells saturate for energy deposits above 500 – 600 GeV (200 – 300 GeV) within a single supercell of the BNL (French) LTDB. The middle layer saturation energy is typically within 1 – 2 TeV, while for the back layer high- η region even higher values are found for the BNL LTDB. The saturation of supercells is in general not an issue for the trigger, since it typically just requires the energy of an electromagnetic shower to be above a certain threshold considerably below the saturation energy. Dedicated algorithms are required to ensure the correct identification of the bunch crossing in case of saturated pulse shapes, though [120].

The calibration coefficients agree well with a previous, independent set of calibration values [121], which were calculated outside of the Athena framework and cover a subset of the supercells in the demonstrator system.

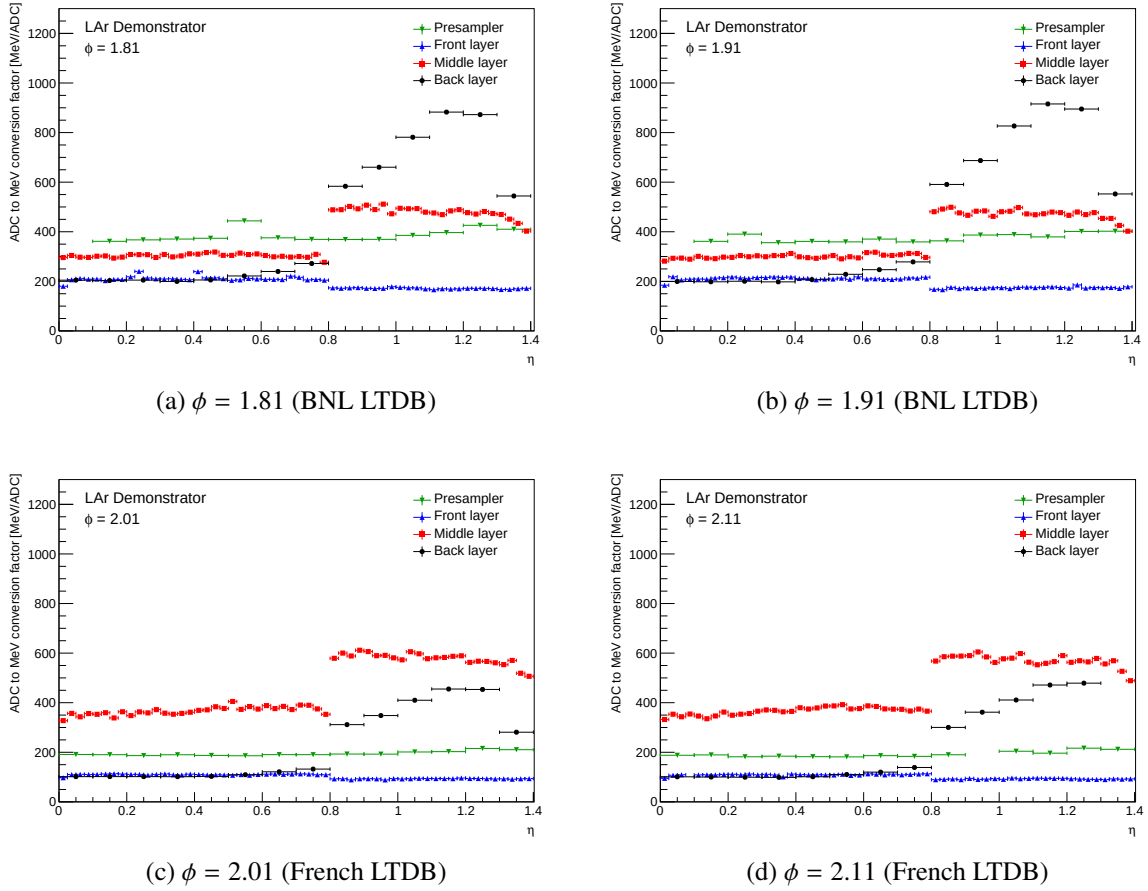


Figure 5.23: Conversion factors between the pulse height and energies for each supercell.

5.5 Validation of the calibration with pp collision data

The demonstrator calibration scheme introduced in Section 5.3 and the methods used to determine the calibration coefficients are *a priori* designed for single LAr cells. Their applicability to supercells needs to be proven. This is particularly important for the prediction of the physics pulse shape, for which the prediction with the RT method explicitly uses the properties of the electronics for single cells.

This section presents several studies using physics data obtained with the demonstrator system in 2017. The reconstruction of the data is performed within the Athena framework and thus all corrections for the main read-out cells, for example the HV correction, can be retrieved directly from the standard databases. The used OFCs are non-iterative and use the reference timing obtained with the procedure described in Subsection 5.4.5.

In order to have a reference value for the energy reconstruction, the events measured with demonstrator system are matched to the main read-out data by requiring events to have the same identifier from the L1 trigger system (i.e. the same L1 ID). A dedicated trigger type is used to select events accepted by the dedicated demonstrator L1 triggers. The single cell energy information is only available in the main read-out. The cell energies from all cells inside a supercell are summed linearly in order to compare main read-out “supercells” with the demonstrator system. The timing reference used to validate the timing reconstruction properties, is given by the “Timing, Trigger and Control” (TTC) system [122, 123]. It is

defined by the points in time where the LAr detector is read out; no separate information from the main read-out is required.

The physics runs used for the validation analyses are required to have a long duration, in order to have sufficient statistics, and to have no unlocked fibres at the end of the run, thus ensuring a stable system throughout the run. The physics runs 328099 (recorded on June 27 – 28, 2017) and 334487 (recorded on August 30, 2017) were finally used. Additional quality cuts are used in the following subsections to ensure good reconstruction properties on the supercell- and event-level. The precise cuts vary and are detailed in each subsection separately.

5.5.1 Inclusive energy and timing reconstruction

The energy reconstruction of the main read-out is used as the reference energy with which the values obtained from demonstrator read-out are compared. Figure 5.24 shows the inclusive energy difference, $E_{\text{demon}} - E_{\text{main}}$, of selected supercells from all four layers of the LAr calorimeter. Only energy deposits with $E_{\text{main}} > 2 \text{ GeV}$ and $(E_{\text{demon}} - E_{\text{main}})/E_{\text{main}} < 0.5$ are considered¹¹ for this figure. It is validated that the distributions show an approximately Gaussian behaviour. The mean value of the distributions varies between 30 MeV in the middle layer and 210 MeV in the back layer. The shift in the mean values is below the pedestal RMS, which gives a measure for the noise level, for each layer except for the back layer, where the pedestal RMS is 175 MeV. A good agreement between the two read-outs is thus observed. The width of the shown distributions is determined by the typical energy distributions and resolutions for the calorimeter layers, such that slight differences are present. It varies between 115 MeV in the front layer and 230 MeV in the presampler.

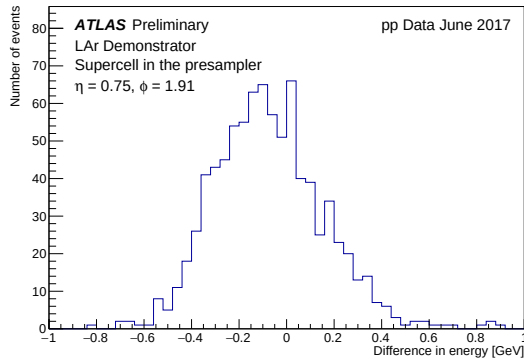
While the outliers in the energy difference are mainly governed by the high-energy tail of the spectrum, the spread of the relative energy deviation increases for low-energy pulses due to the small pulse height and the higher relative impact of fluctuations due to noise. The relative energy deviation, $\mathcal{R} = E_{\text{demon}}/E_{\text{main}}$, in the inclusive case is shown in Figure 5.25 and agrees with the previous findings. For an ideal calibration the mean value of the relative energy deviation should be equal to one, while a low RMS value is desirable and mainly given by the detector properties. The energy scales of the selected supercells match with the requirement on the mean value within 0.5% (middle layer) to 4% (back layer). The approximately Gaussian distribution further confirms the good reconstruction properties of the selected supercells.

An overview of the energy reconstruction performance for the full demonstrator is given in Figures 5.26 and 5.27 as well as Figure 5.28 in terms of the mean and RMS values of the relative energy deviation, respectively. The energy scale for a large fraction of the demonstrator supercells shows deviations below $\pm 10\%$ with respect to the main read-out and thus a good agreement is achieved for the full system. The typical RMS value of $\mathcal{R}$ is (1 – 2)% for the front and middle layers of the BNL LTDB, while the values for the presampler and the back layer are typically within (2 – 6)%. Outliers beyond these ranges are visible for the ϕ layers of the French LTDB, which potentially originate from lower data statistics in this region. The overall agreement of the demonstrator calibration and the main read-out can be considered to be already accurate enough for trigger purposes¹².

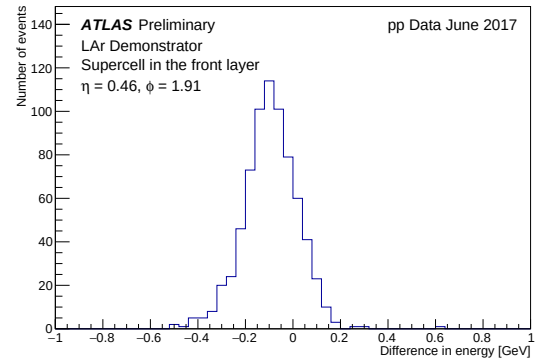
The correlation of the energy measurements between the two read-outs is further presented in Figure B.12 of Appendix B.5.1. All supercells are well aligned with a one-to-one relation in the previously described accuracy and no energy dependence of the energy scale is visible by eye.

¹¹ The quality cuts to remove mismeasurements are found to have a minor impact on the resulting distributions. The cut on the relative energy deviation is well outside the typical width shown in Figure 5.25.

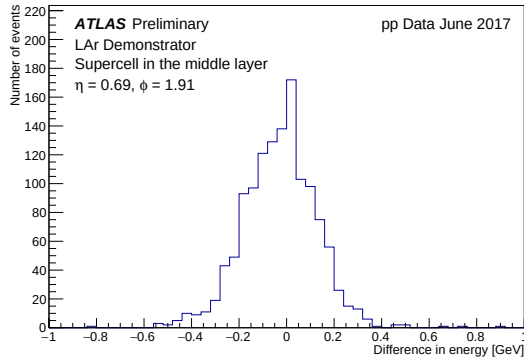
¹² The expected performance for supercell clusters is available in Figure 7 of Ref. [117].



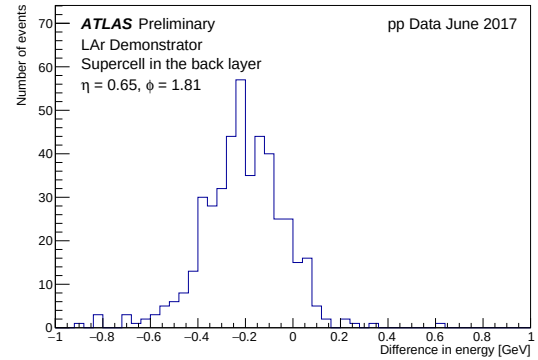
(a) Presampler



(b) Front layer



(c) Middle layer



(d) Back layer

Figure 5.24: Difference of energy measurements, $E_{\text{demon}} - E_{\text{main}}$, between the main and demonstrator read-outs for selected supercells from the four layers of the calorimeter.

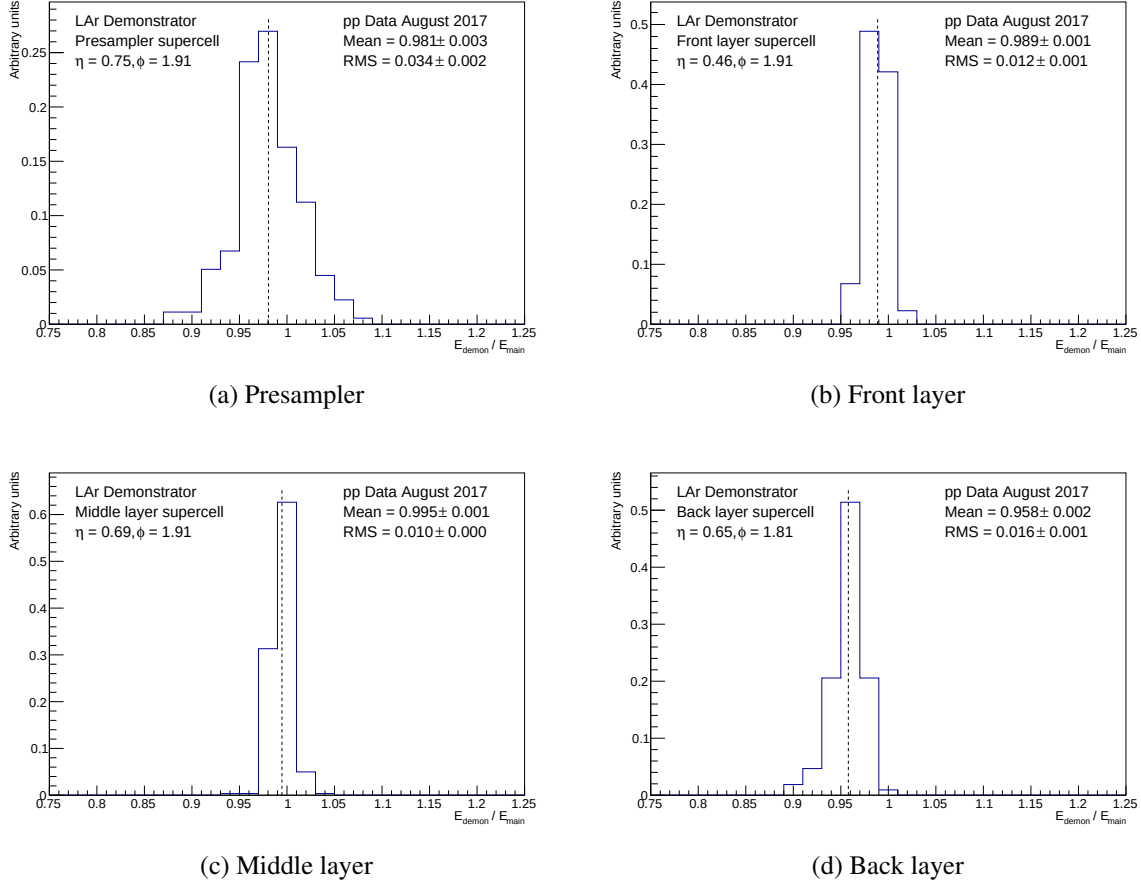


Figure 5.25: Relative energy deviation between the demonstrator and main read-outs for selected supercells from the four layers of the calorimeter. Good agreement is observed between the two read-outs. The mean value is depicted by the black dashed line.

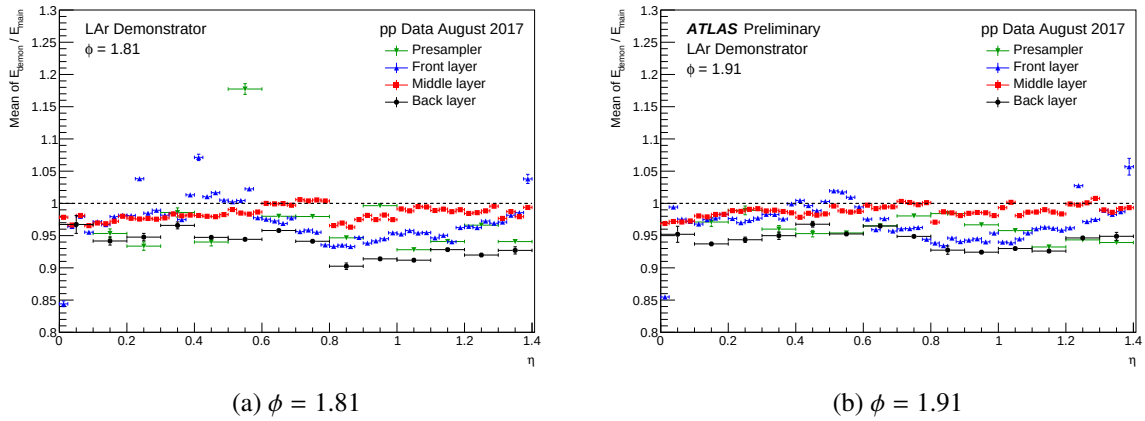


Figure 5.26: Energy scale for the demonstrator supercells of the BNL LTDB, calculated as the mean value of the relative energy deviation, $\mathcal{R} = E_{\text{demon}}/E_{\text{main}}$.

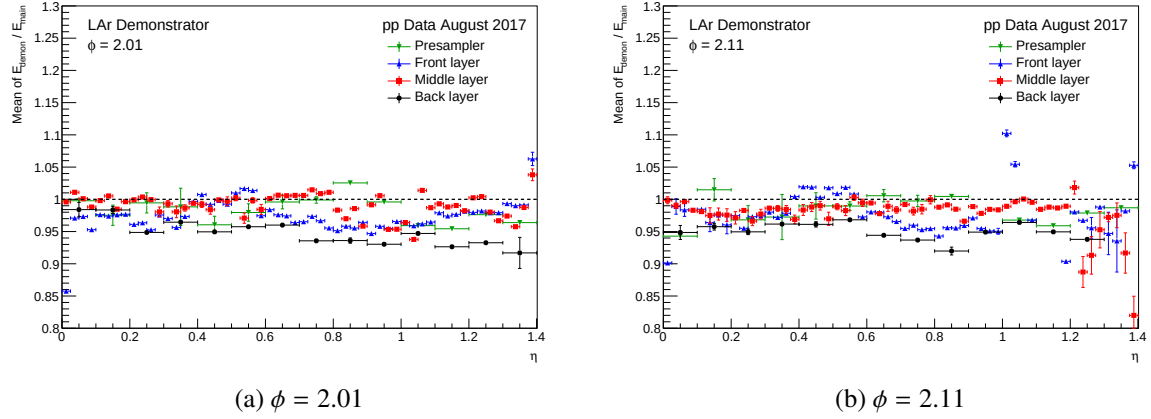


Figure 5.27: Energy scale for the demonstrator supercells of the French LTDB, calculated as the mean value of the relative energy deviation, $\mathcal{R} = E_{\text{demon}}/E_{\text{main}}$.

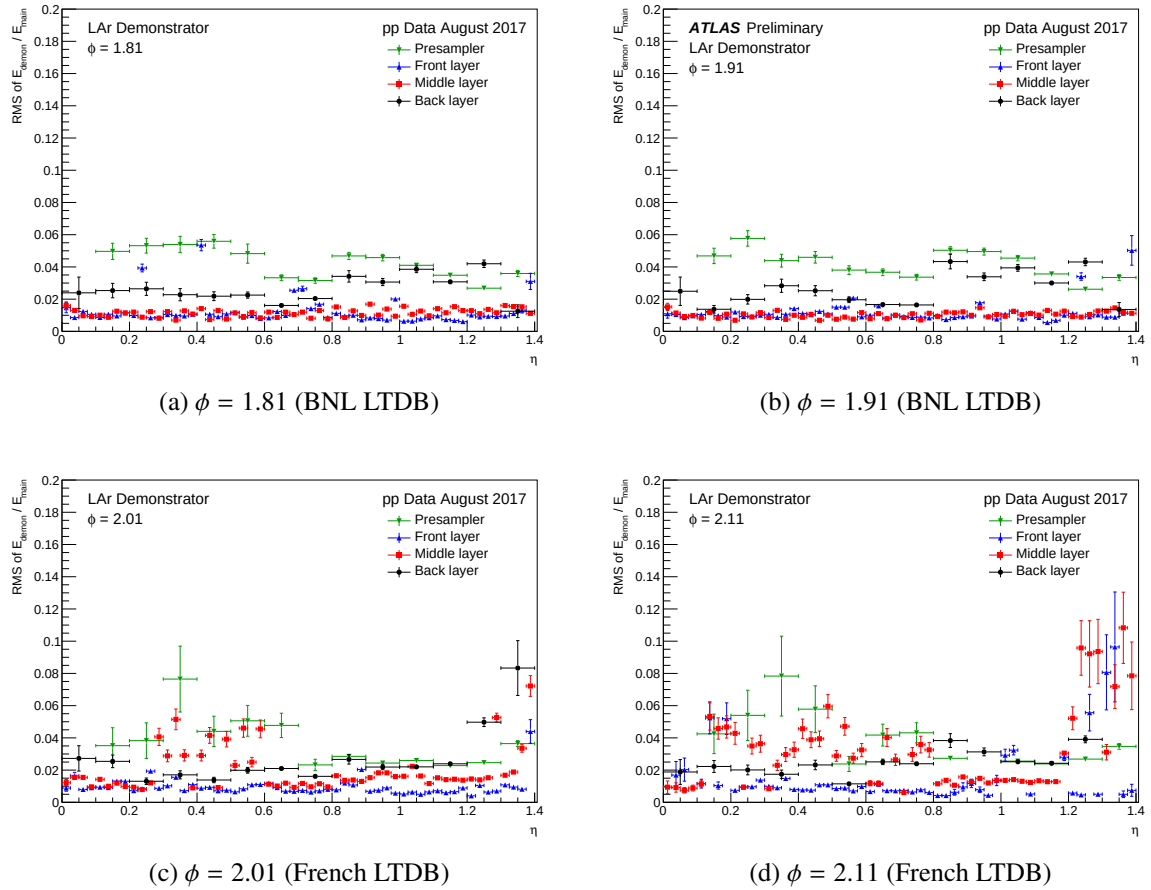


Figure 5.28: RMS value of the relative energy deviation, $\mathcal{R} = E_{\text{demon}}/E_{\text{main}}$, for all demonstrator supercells. The RMS value illustrates the size of the energy measurement fluctuations between the two read-outs.

The offset of the reconstructed timing from the reference value (determined in Subsection 5.4.5) is shown for selected supercells in Figure 5.29. A low RMS value is desirable for a precise determination of the bunch crossings. In addition, a mean offset of 0 ns ensures that the used OFCs are adequate and a precise energy-determination is possible. The mean values in case of the selected supercells have maximum offset of below 1 ns. The RMS value range from 0.6 ns in the middle layer to 1.2 ns in the back layer. It is again validated that the distributions show an approximately Gaussian behaviour. The tails of the distributions mainly emerge from low-energy deposits due to the high relative importance of fluctuations due to noise.

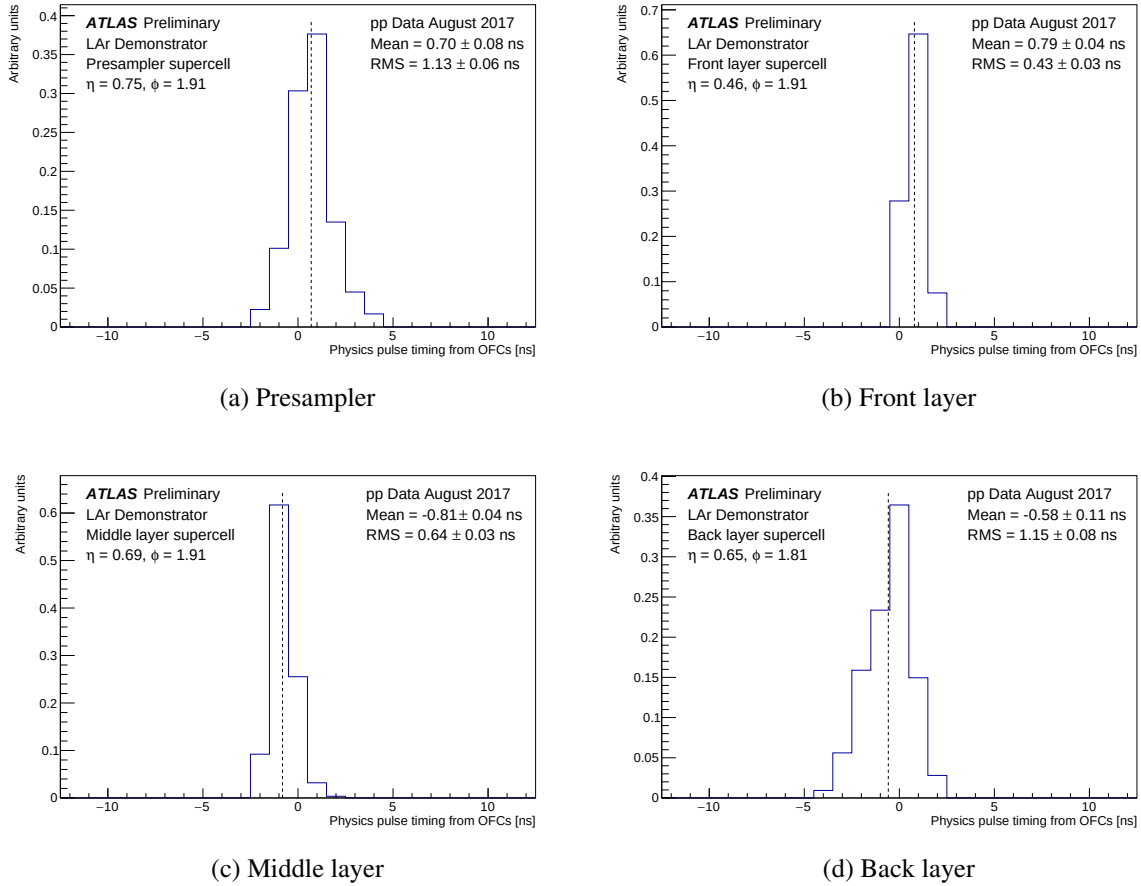


Figure 5.29: Measured supercell timing distribution of the LAr Phase-1 demonstrator compared to the TTC reference for selected supercells. The identification of the bunch-crossing ID is possible due to the low deviation of the mean from 0 ns and an RMS value much smaller than 25 ns. The average supercell energy of the used events is 6.7 GeV in the presampler, 13.3 GeV in the front layer, 24.2 GeV in the middle layer and 8.9 GeV in the back layer. The mean value is depicted by the black dashed line.

The timing reconstruction performance for the full demonstrator system is summarised in Figures 5.30 and 5.31 in terms of the timing mean and RMS, respectively. The mean timing value is aligned to 0 ns within ± 2 ns for most demonstrator supercells. The RMS values of the timing distribution are about 0.4 – 1.2 ns for the front and middle layers of the BNL LTDB, while the presampler and the back layer have timing RMS values of about 1 – 2 ns. Outliers beyond these ranges are visible for the ϕ layers of the French LTDB, e.g. for the middle layer supercells with $\phi = 2.11$ and $\eta > 1.2$. The effect potentially

originates from lower data statistics in this region, and thus a slightly worse timing alignment, and is not expected to persist for the final Phase-1 installation. The determined performance allows the identification of the bunch-crossing ID¹³, for which a low deviation of the mean from 0 ns and an RMS value much smaller than 25 ns are needed. The analysis presented here confirms the timing alignment studies from Subsection 5.4.5, for which less stringent cuts to select the energy deposits are used.

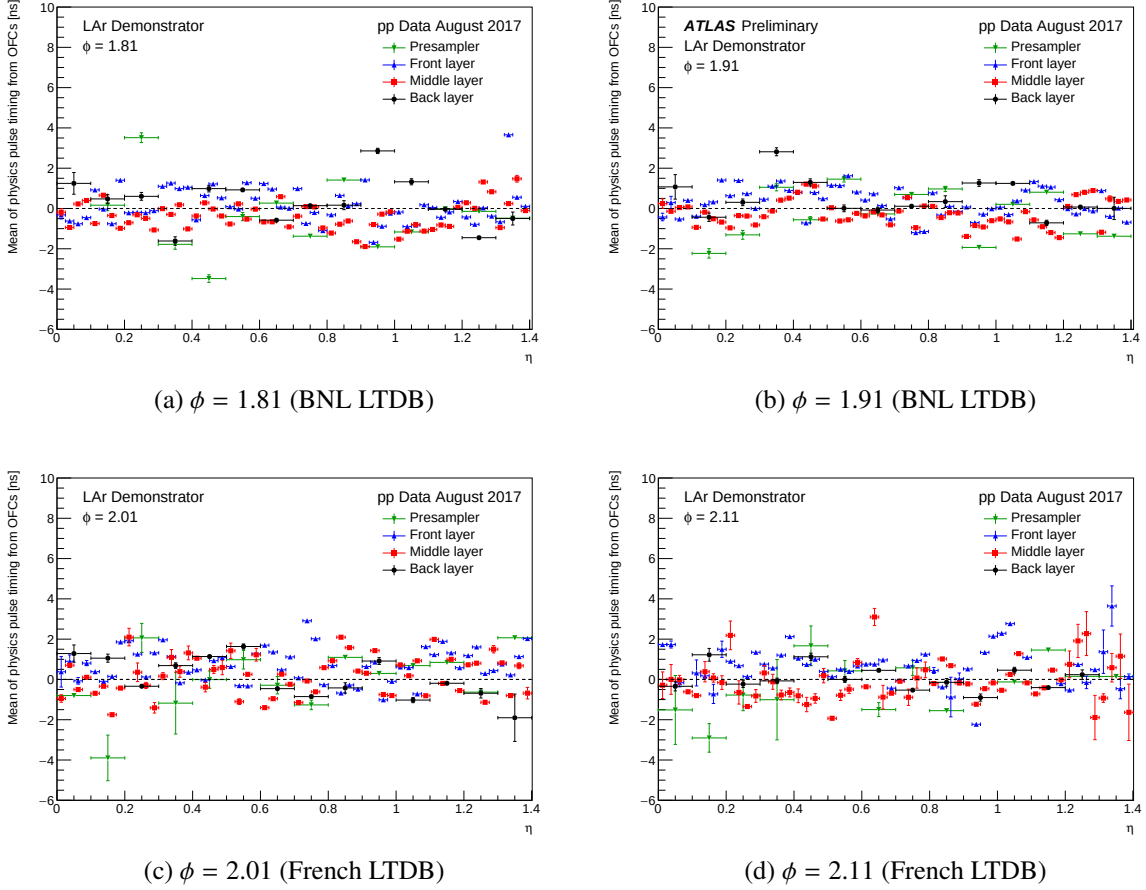


Figure 5.30: Mean timing for all demonstrator supercells. The identification of the bunch-crossing ID is possible due to the low deviation of the mean from 0 ns and an RMS value much smaller than 25 ns.

5.5.2 Energy dependence of the energy comparison and the timing resolution

The precision of the energy and timing measurements depends on the amount of deposited energy. Due to the increased pulse height for high-energy deposits, and thus the relative decrease of noise contributions, the energy and timing resolution improves with the deposited energy. In order to study the effect, the distributions shown in Figures 5.25 and 5.29 of Subsection 5.5.1 are studied as a function of the main read-out energy. The E_{main} -binning is defined individually for each supercell. For this, the inclusive energy spectrum of each supercell is divided into 15 bins of equal statistics. A minimum energy of $E_{\text{main}} > 2 \text{ GeV}$ is required to ensure well-reconstructed pulses, as for lower energies background

¹³ The bunch-crossing identifier (ID) gives a numeric value for each of the 3564 possible bunch positions inside the LHC. The bunch positions have a spacing of 25 ns.

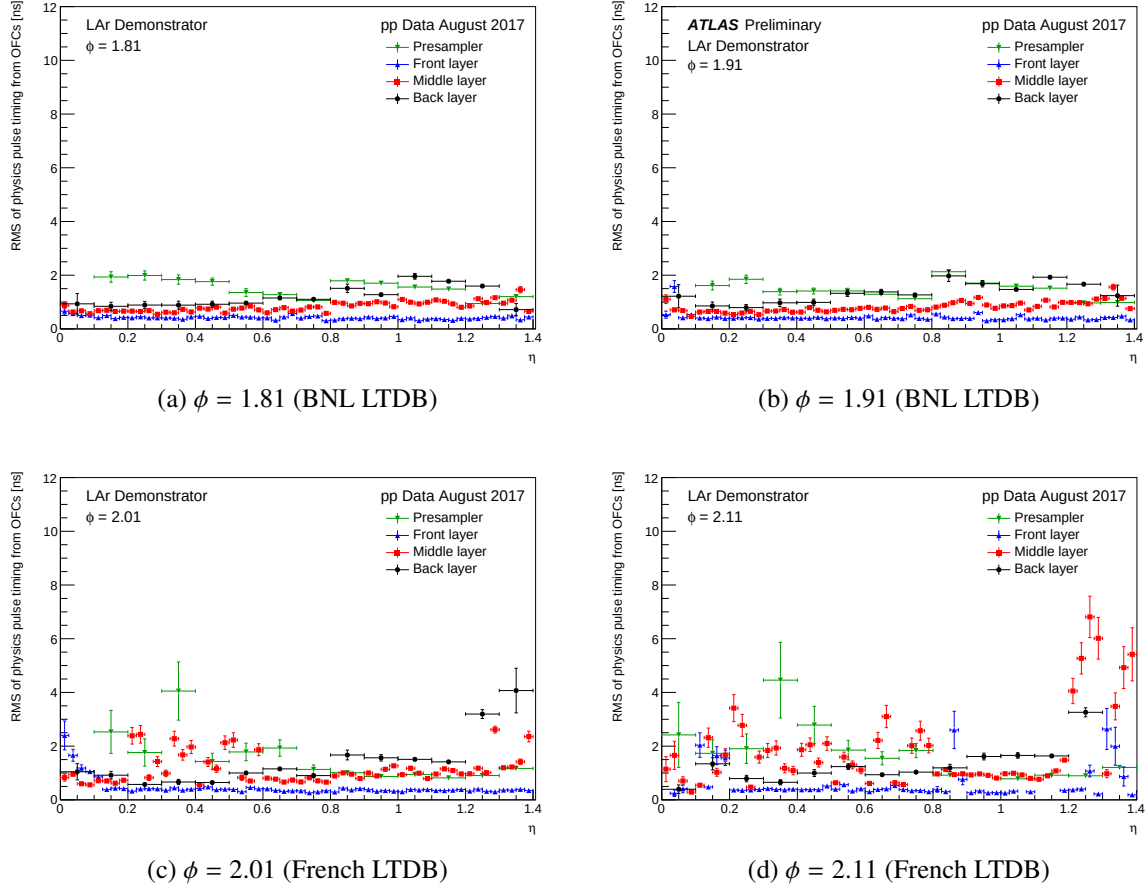


Figure 5.31: Timing resolution for all demonstrator supercells. The identification of the bunch-crossing ID is possible due to the low deviation of the mean from 0 ns and an RMS value much smaller than 25 ns.

contributions increase rapidly. The RMS width of the relative energy deviations as a function of E_{main} is shown in Figure 5.32.

In order to describe the width of the relative energy deviations of the demonstrator system, a functional fit is performed to the distribution with the following parametrisation:

$$\sigma_{\mathcal{R}}(E_{\text{main}}) = \frac{p_0}{E_{\text{main}}} \oplus p_1. \quad (5.8)$$

In comparison with Equation 3.6, the term that describes the resolution impact of the shower evolution ($\propto 1/\sqrt{E}$) is neglected in this parametrisation. Since the relative energy deviation used here, $\mathcal{R} = E_{\text{demon}}/E_{\text{main}}$, makes use of the main read-out energy determination, potential shower fluctuations affect both measurements at the same time in the same direction and thus their effect is cancelled out. The relative energy deviation and its parametrisation thus describe the intrinsic difference between the two read-outs due to the different energy reconstruction and the different noise in the electronics chain. E_{main} is used as the best available approximation for the true energy deposit in Equation 5.8.

The width of the relative energy deviations is lower for high energies and typically converges to values below 1% in the case of $E_{\text{main}} \rightarrow \infty$, which is given by the p_1 parameter. A slightly higher width might be present for the presampler, for which higher extrapolation uncertainties are present. At low energies

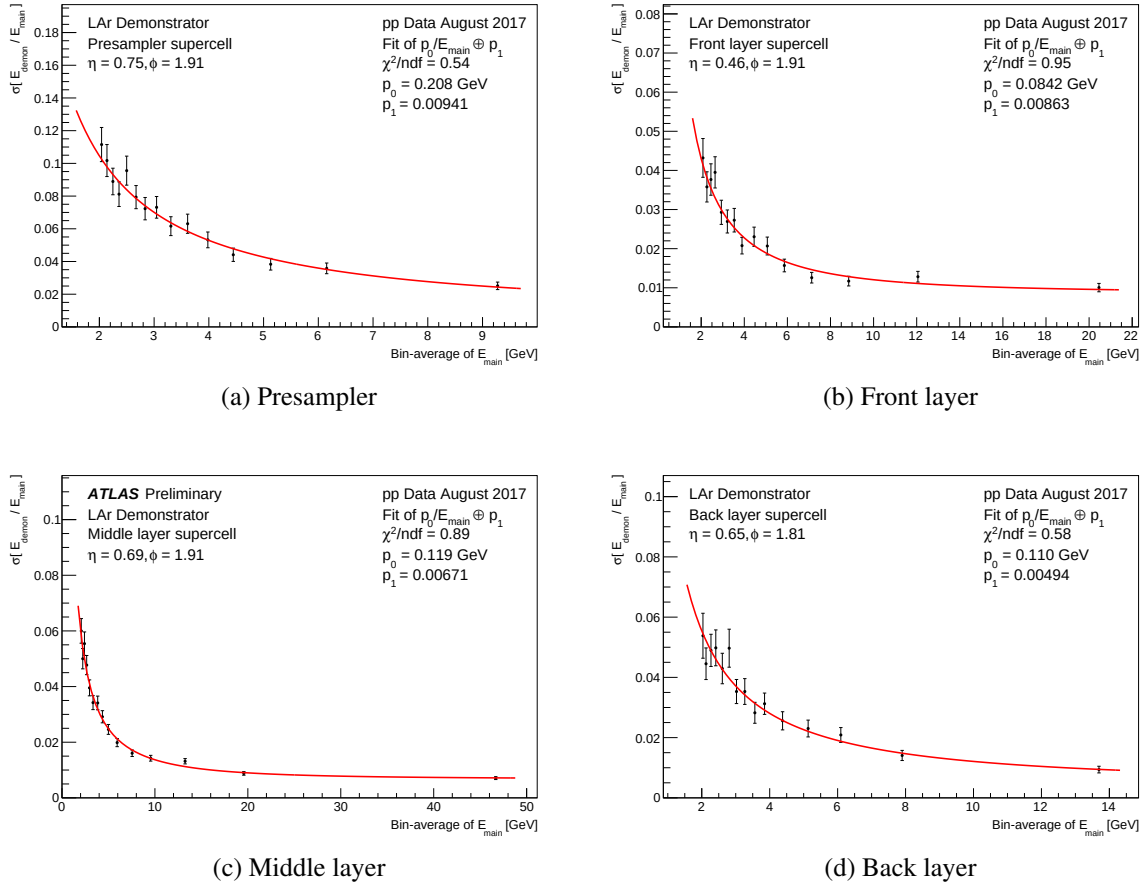


Figure 5.32: Measured energy comparison for selected supercells from the four calorimeter layers. The available events are subdivided into 15 energy-bins and the width of the relative energy deviations shown for each bin.

of $E_{\text{main}} \approx 2 \text{ GeV}$, the energy measurements between the two read-outs agree within $(5 - 6)\%$ for the front, middle and back layers. For the presampler, an agreement within about 10% is found.

The energy dependence of the timing resolution is given in Figure 5.33. A functional fit is again performed to describe the timing resolution using the following parametrisation¹⁴:

$$\sigma_{\tau}(E_{\text{main}}) = \frac{p_0}{E_{\text{main}}} \oplus p_1. \quad (5.9)$$

The timing resolution of the system typically converges to values below 0.5 ns for the front and middle layers. The back layer exhibits a higher timing resolution of about 1 ns, which is also observed for the presampler in the high-energy tail. The obtained values again show a timing resolution well below 25 ns for high-energy deposits, which allows to determine the bunch crossing with a low error rate. The timing resolution in the low-energy range is below 2 ns for the front layer and below 4 ns for the other layers, which is thus still sufficient to identify the correct bunch crossing. The LHC beam-spread of about 0.2 ns contributes to the constant term of the timing resolution measurement [124]. The timing resolution for $E_{\text{main}} \rightarrow \infty$ is not directly given by p_1 , since the functional fit is only valid in the range where data points

¹⁴ The chosen functional form is also used in studies of the timing resolution for the main read-out [124].

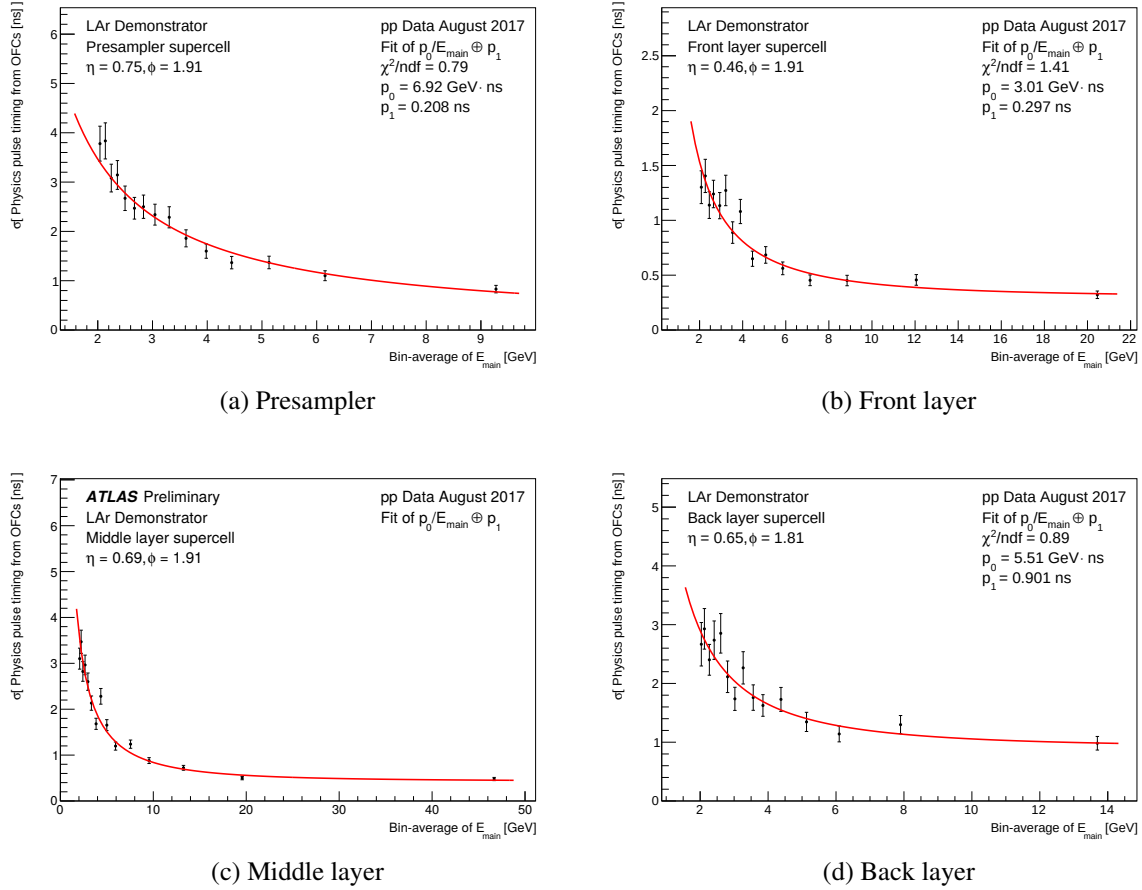


Figure 5.33: Measured timing resolution for selected supercells from the four layers of the calorimeter. The available events are subdivided into 15 energy-bins and the width of the timing distribution shown for each bin. The timing resolution is around 0.5 ns in the high-energy tail, such that the identification of the bunch-crossing ID is possible due to the resolution being much smaller than 25 ns. The LHC beam-spread of about 0.2 ns contributes to the constant term, p_1 , of the timing resolution measurement [124]. The fit result for the middle layer is $p_0 = 7.24 \text{ GeV} \cdot \text{ns}$ and $p_1 = 0.425 \text{ ns}$ with $\chi^2/\text{ndf} = 2.50$.

are still available and thus high extrapolation uncertainties are present beyond this range.

5.5.3 Physics pulse prediction

The agreement of the predicted pulse shape in physics data with the actual pulse shape is essential for a precise calibration. A study is thus performed to extract the pulse shapes from raw physics data and compare it with the predicted pulse according to the RT method (described in Subsection 5.4.4). The two estimations of the physics pulse shape, i.e. the measurement and the prediction, need to be determined independently in terms of their normalisation and shape.

In order to select pulse shapes with a high amplitude, the main read-out energy information is used to select events from the raw demonstrator data. Out of the pulses that satisfy the quality criteria defined in Subsection 5.5.1, only the subset of events with the 20% highest E_{main} values is used per supercell (i.e. with energies above the fourth quintile of the total E_{main} distribution). The calibration pedestal value is then subtracted from the raw ADC counts, which are measured in a read-out window of 1250 ns. The obtained pulse shapes are further normalised according to the main read-out energy measurement to obtain pulse shapes in units of ADC counts per energy. The resulting pulse shapes are averaged¹⁵ by calculating the mean and RMS of the pulse heights at each bunch crossing separately. A slightly enhanced pulse height RMS value is expected for regions with a high derivative of the pulse shape, as for these the influence of jitter effects in the read-out is higher.

The physics pulse shape, i.e. the one present in collision data, is predicted based on calibration data as described in Subsection 5.4.4 and normalised according to the determined calibration coefficients. The shape is thus completely independent from the measured physics pulse shape, which is obtained directly from collision data. In the normalisation of the two estimates, only the calibration coefficients that are obtained from the electronics specifications and test-beam data are common.

The extracted pulse shapes for selected supercells are shown in Figure 5.34 and a good agreement can be observed. The small offset in the OFC-based normalisation, $A_{\text{meas}}/A_{\text{pred}}$, matches with the observations from Figure 5.25. The pulse shape agrees well for the peak region, which is solely used for the energy and timing reconstruction. The small residual deviations in the peak region potentially emerge from remaining normalisation offsets, while fluctuations of a few percent are observed similarly for the main read-out [125]. The difference of the pulse shapes for $t \approx 1000$ ns is expected to originate from a small mismodelling of the electrode position inside the LAr ionisation gap. In case the electrode is not exactly centred, similar deviations are reported for the main read-out [126], too. The difference in the OFC-based timing values of the measured and predicted pulse shapes, $t_{\text{meas}} - t_{\text{pred}}$, is below 1 ns and thus well modelled.

The RT method thus overall allows to predict physics pulse shapes for supercells with a sufficient precision¹⁶. The underlying requirement for this is a linear behaviour of the system in terms of summing the constituent LAr cells into supercells, as well as similar constituent cell pulse shapes for a given supercell. These conditions appear to be fulfilled. For a better matching of the observed pulse shape at $t \approx 1000$ ns, it might be possible to tune the T_{drift} parameter or to extend the model according to Ref. [126].

5.5.4 Event information for full demonstrator coverage

The trigger read-out after the LAr Phase-1 upgrade will allow to utilise more complex shower variables for the background rejection, e.g. improved isolation information of electromagnetic clusters, in addition

¹⁵ The obtained pulse shape does not vary if the average is calculated energy-weighted or not.

¹⁶ The agreement of the prediction from the RT method with physics pulse shapes for LAr cells is available in Ref. [127].

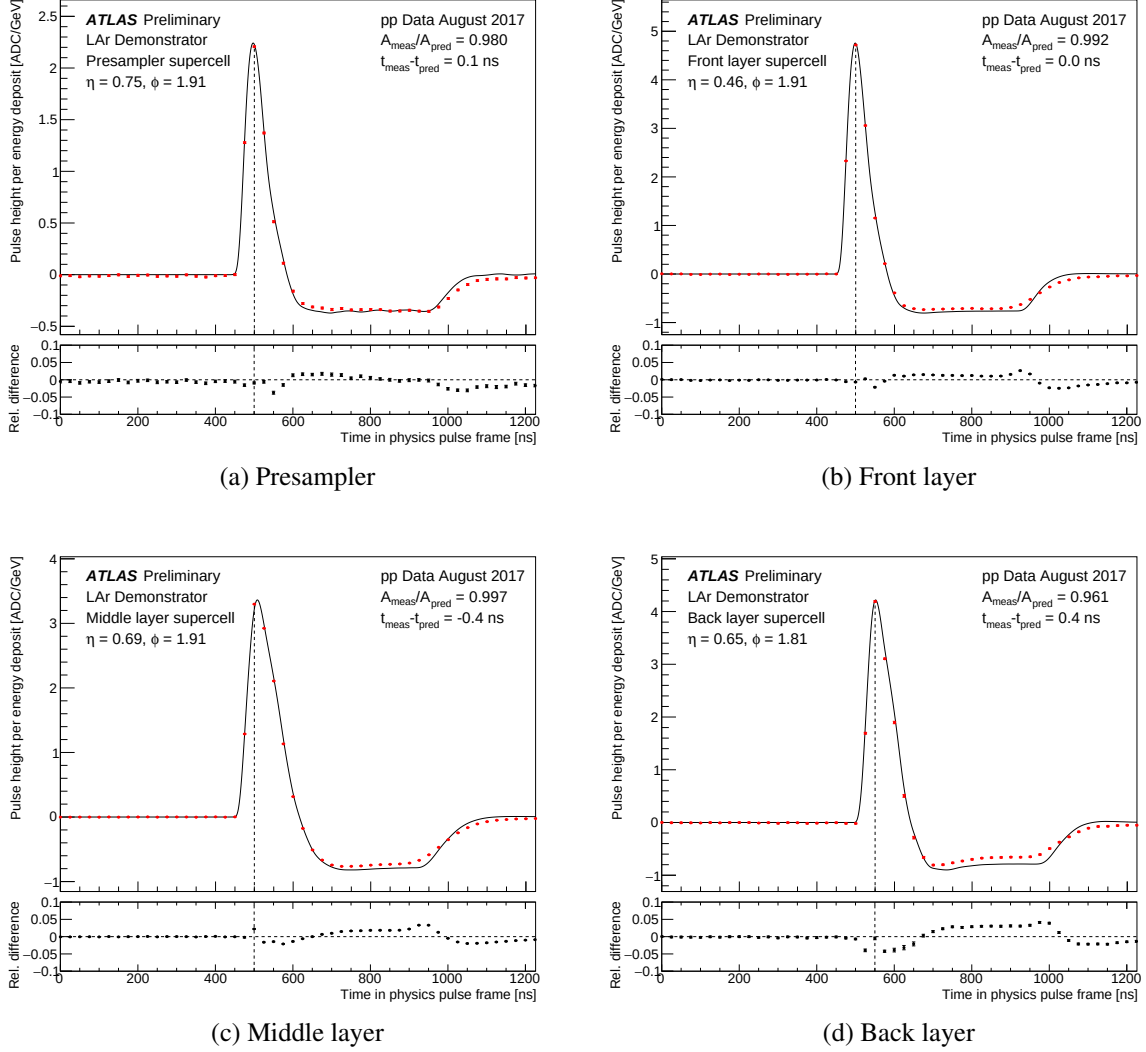


Figure 5.34: Measured pulse shapes (red) of supercells in the LAr Phase-1 demonstrator are compared to the, independently obtained, predicted pulse shapes (black). Good agreement is observed between measurement and prediction, while remaining small normalisation offsets are due to the preliminary calibration of the supercells. Only the five measurements around the peak (dashed line) are used for the energy and timing reconstruction. The shape difference at $t \approx 1000 \text{ ns}$ is expected to originate from the modelling of the electrode position in the LAr gap.

to the more precise energy measurement. It is thus essential that the complete calorimeter showers are well measured by the LAr trigger read-out and agree with the information retrieved from the main read-out, too. In order to study this, the information of full physics events in the demonstrator coverage is analysed.

Event displays of measured showers are shown in Figure 5.35 for different shower energies and positions. The total energy in the selected events, E_{total} , agrees within 8.5% between the two read-outs, while the maximum supercell energy, $E_{\text{max}}^{\text{SC}}$, agrees within 2.5%. Differences between the two read-outs can be observed for low-energy deposits. Supercells with a measured energy below 1% of $E_{\text{max}}^{\text{SC}}$ are not considered in the figure to reject noise.

Figure 5.36 compares several basic quantities of the measured showers between the demonstrator and the main read-out. A good agreement is observed with shower energies reaching up to the TeV-scale. The shower cone is defined as the region within $|\eta^{\text{SC}} - \eta_{\text{max}}^{\text{SC}}| < 0.05$ and $|\phi^{\text{SC}} - \phi_{\text{max}}^{\text{SC}}| < 0.15$, relative to the position of the supercell with the highest energy deposit. In this definition, the shower cone typically encompasses a fraction of about 85% of the total energy deposit (see Figure 5.36(b)). The larger window size in the ϕ direction is chosen due the direction of the solenoidal magnetic field. Only energy deposits with a maximum relative deviation of 80% between the two read-outs and above 1% of $E_{\text{max}}^{\text{SC}}$ are used to reject misreadings¹⁷. The energy measurement of the supercell with the highest energy deposit is required to match within 10% for the two read-outs.

The energy and timing reconstruction is shown in Figure 5.37. The RMS width of the $E_{\text{demon}}/E_{\text{main}}$ distribution for the shower cone is 1.7%, while a small energy scale misalignment of the same order is present. The measured energy deposits in the full event agree with the main read-out information within an RMS width of 2.4%. The timing resolution is about 0.6 ns for the showers as well as the full event information, for which a good alignment of the scale to 0 ns is observed. The supercells with the maximum energy deposit in the events show a slightly higher timing resolution of 0.9 ns. An offset of -0.65 ns in the timing scale for these supercells is observed, which originates from residual energy dependencies of the timing scale (see Subsection 5.5.5).

The modelling of shower shape variables, that could be used to discriminate electromagnetic clusters from electrons and photons against jets on trigger level, is shown in Figure 5.38. The three shower shape variables considered in Ref. [117] are defined as follows:

$$R_{\eta} = \frac{E_{\text{T}, \Delta\eta \times \Delta\phi = 0.075 \times 0.2}^{(2)}}{E_{\text{T}, \Delta\eta \times \Delta\phi = 0.175 \times 0.2}^{(2)}}, \quad (5.10)$$

$$w_{\eta,2} = \sqrt{\frac{\sum (E_{\text{T}}^{(2)} \times \eta^2)_{\Delta\eta \times \Delta\phi = 0.075 \times 0.2}}{E_{\text{T}, \Delta\eta \times \Delta\phi = 0.075 \times 0.2}^{(2)}} - \left(\frac{\sum (E_{\text{T}}^{(2)} \times \eta)_{\Delta\eta \times \Delta\phi = 0.075 \times 0.2}}{E_{\text{T}, \Delta\eta \times \Delta\phi = 0.075 \times 0.2}^{(2)}} \right)^2}, \quad (5.11)$$

$$f_3 = \frac{E_{\text{T}, \Delta\eta \times \Delta\phi = 0.2 \times 0.2}^{(3)}}{E_{\text{T}, \Delta\eta \times \Delta\phi = 0.075 \times 0.2}^{(1)} + E_{\text{T}, \Delta\eta \times \Delta\phi = 0.075 \times 0.2}^{(2)} + E_{\text{T}, \Delta\eta \times \Delta\phi = 0.2 \times 0.2}^{(3)}}. \quad (5.12)$$

The sums for $w_{\eta,2}$ run over the supercells in the specified $\Delta\eta \times \Delta\phi$ region. $E_{\text{T}}^{(i)}$ is defined as the transverse energy in the i -th calorimeter layer with $i = 1$ for the front layer, $i = 2$ for the middle layer and $i = 3$ for the back layer. The $E_{\text{T}}^{(i)}$ values are obtained by summing over the supercells in the denoted $\Delta\eta \times \Delta\phi$ regions, too. The $\Delta\eta \times \Delta\phi$ regions are centred around the supercell with the highest energy. R_{η}

¹⁷ The maximum relative deviation of 80% is chosen to ensure that the acceptance of the quality cuts remains high even for low-energy deposits. No strong dependence on the precise cut value is expected.

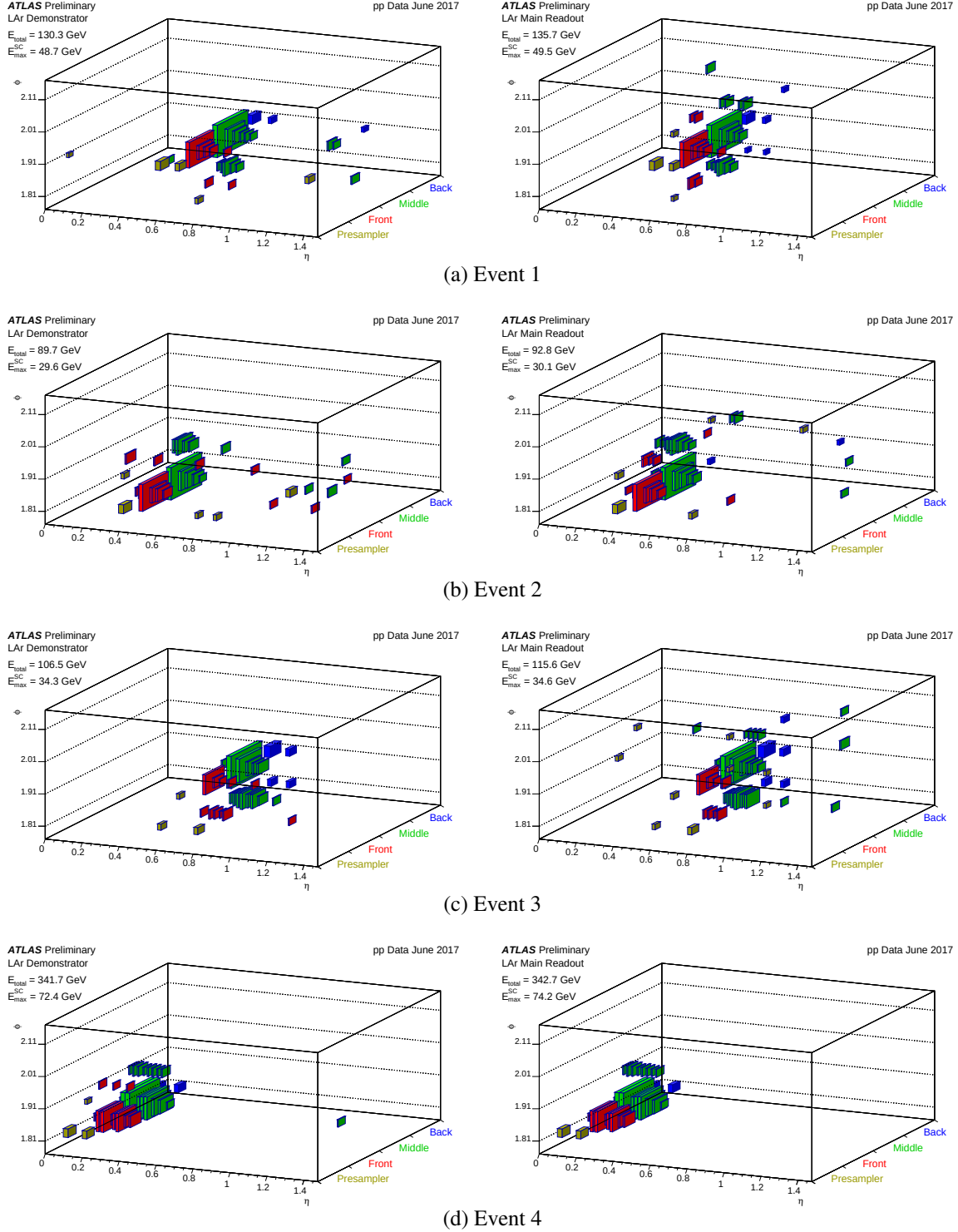


Figure 5.35: Event displays of the demonstrator region with information from the demonstrator read-out (left row) and main read-out (right row). The particles enter the shower volume on the bottom left and traverse to the top right. The different colors depict the four calorimeter layers and the full geometrical coverage of the demonstrator system is shown. The volume of the depicted boxes is proportional to the deposited energy. Only energy deposits above 1% of $E_{\text{max}}^{\text{SC}}$ are plotted.

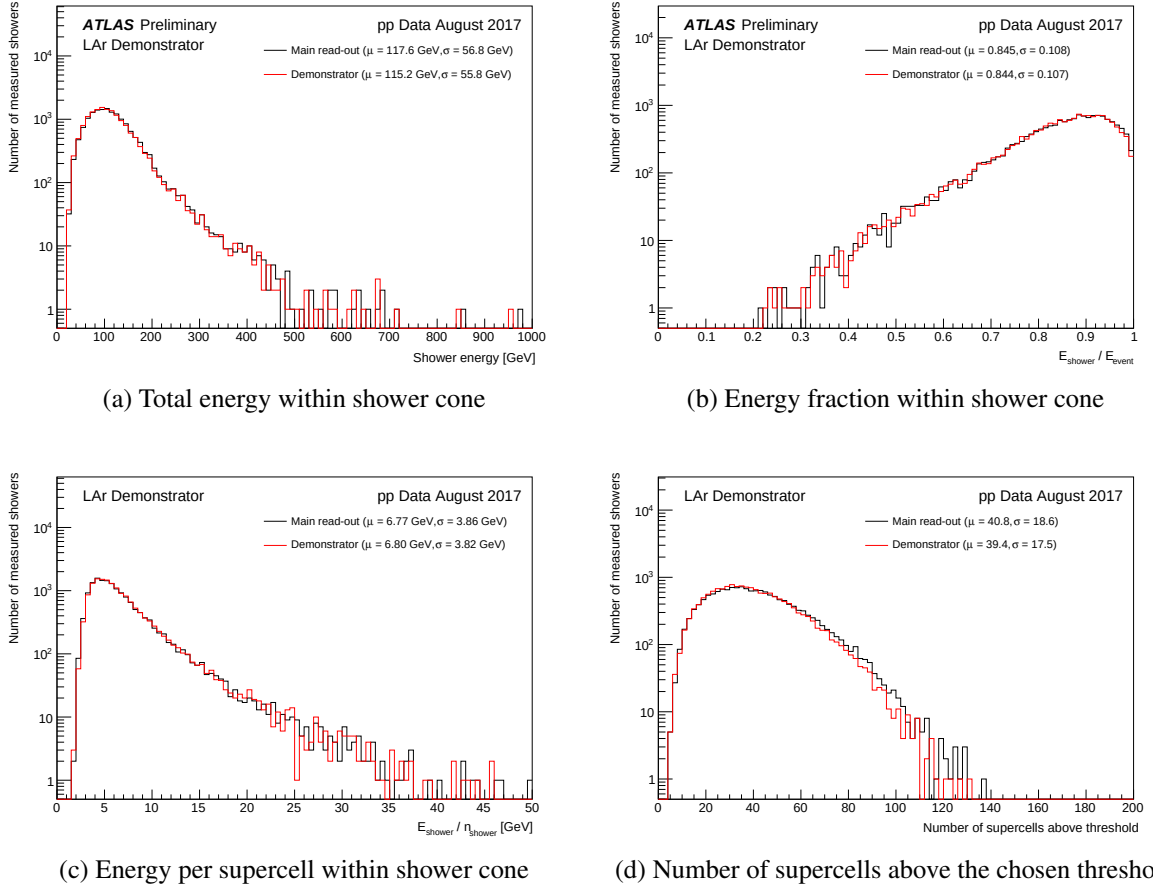


Figure 5.36: Comparison of variables that describe general event and shower properties in the main and demonstrator read-outs.

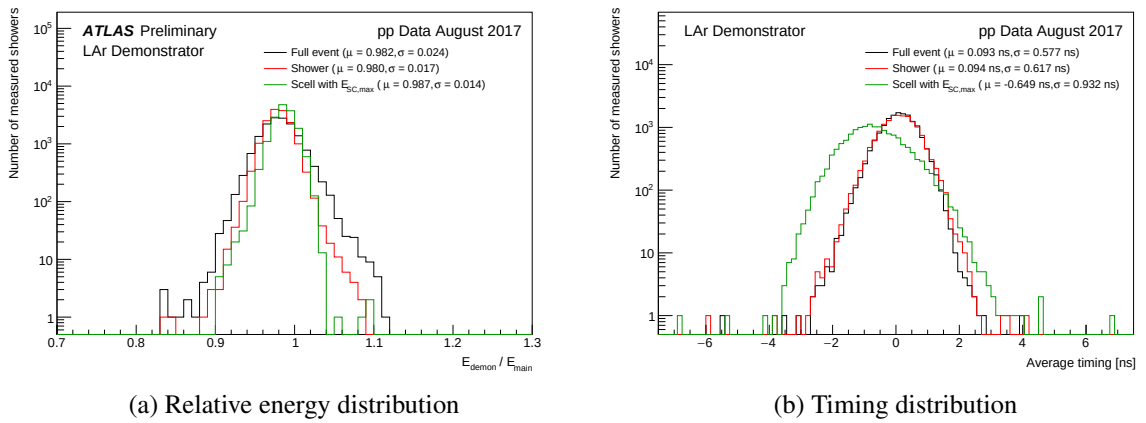


Figure 5.37: Energy comparison and timing distribution of showers in the demonstrator region. A good agreement for the energy measurement can be observed. The timing resolution for the full shower improves compared to single supercells. The small misalignment of the timing scale for single supercells is due to residual energy dependencies (compare Subsection 5.5.5).

gives an estimate of the energy fraction of the shower cone in the middle layer, which is typically lower for jets compared to electrons due to the higher width of hadronic showers. f_3 is the energy fraction of the shower in the back layer. It is typically higher for hadronic showers as they propagate through the LAr calorimeter and further into the Tile calorimeter. The width of the showers is further parametrised by $w_{\eta,2}$ and typically lower for electromagnetic showers. Figures of the expected distributions for electrons and jets are given in Ref. [117], while the different properties of electromagnetic and hadronic cascades are discussed in Section 4.4.

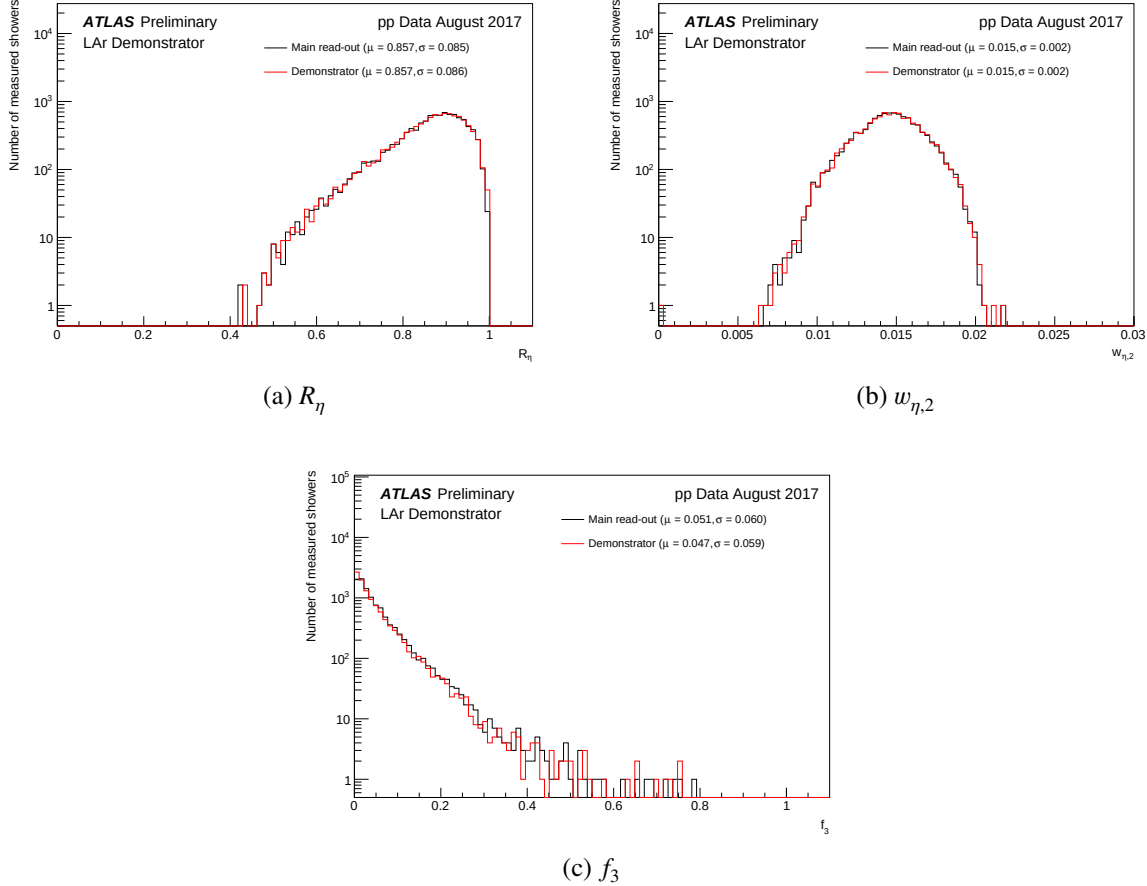


Figure 5.38: Comparison of the modelling for shower shape variables in the demonstrator and the main read-out. The shown variables are defined according to Equations 5.10 to 5.12. A good agreement between the two read-outs is observed. The variables could be used to discriminate electromagnetic clusters from electrons and photons against jets on trigger level, such that a good modelling is required for them.

While the shower shape variables are by construction reducing the impact of a mis-calibration by using energy ratios, differences between the trigger and offline reconstruction could still emerge from the different read-out granularity or other effects. The demonstrator measurements are found to agree closely with the main read-out information. The reconstruction quality of shower shape variables with the system thus has a high accuracy and seems well suited for the usage in the trigger read-out chain.

The presented shower shape distributions are dominated by the jet contribution, as the trigger items used for the 2017 data-taking had a low efficiency to select real electrons¹⁸. A new trigger requiring

¹⁸ No identification or isolation requirements are placed on the electromagnetic clusters in the 2017 trigger selection, such that

isolated electromagnetic clusters, with an invariant mass close to the Z boson mass, was introduced for the 2018 data-taking period (see Section 5.6). It might thus be good to revisit the presented study using data from the 2018 demonstrator system in the future.

5.5.5 Correction of residual energy dependencies

The overall energy and timing calibration as presented in Subsections 5.5.1 and 5.5.2 exhibits small residual differences in comparison to the main read-out and the TTC signal, respectively. Their origin could be properties of the used pre-prototypes for the demonstrator system or differences in the supercell calibration characteristics compared to LAr cells. While the agreement is expected to be good enough for the final trigger read-out chain, it is useful to assess the potential gains from a better closure in the calibration.

Figure 5.39 shows the energy dependence of the residual energy deviations between the demonstrator system and the main read-out for selected supercells. The observed offset is parametrised with the following linear function:

$$\Delta E(E_{\text{main}}) = p_0 + p_1 \cdot E_{\text{main}}. \quad (5.13)$$

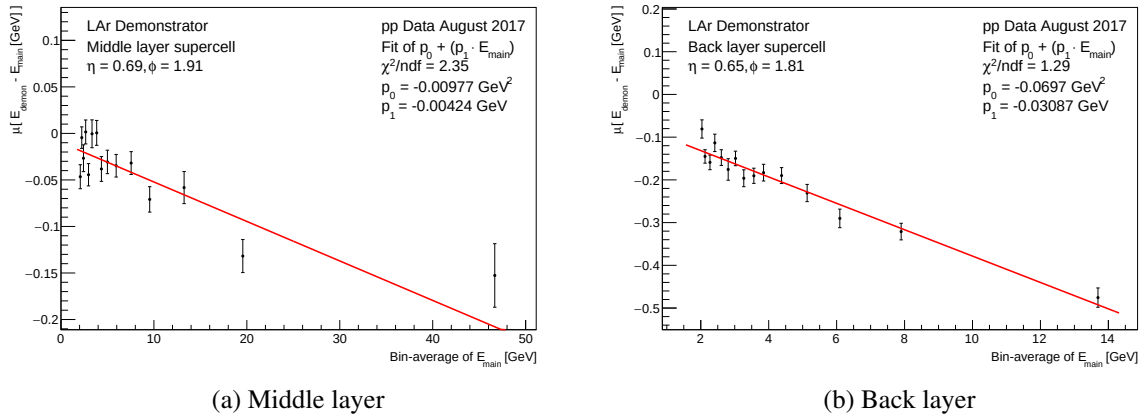


Figure 5.39: Energy dependence of the residual mean energy deviations between the demonstrator system and the main read-out for selected supercells. The fitted function corresponds to Equation 5.13 and is an ad-hoc parametrisation of the difference. Figures for the presampler and the front layer are given in Figure B.13 of Appendix B.5.1.

The parameter p_0 can be understood as a small offset in the pedestal, which yields a constant offset in the determined energy. The parameter p_1 corresponds to a deviation in the gain, manifesting in a linearly increasing ΔE . The function choice is chosen *ad hoc* and fits well, although further parameters could improve the description of $\Delta E(E_{\text{main}})$. A correction to the supercell energy in the demonstrator read-out can be performed according to

$$E_{\text{demon}} \rightarrow E'_{\text{demon}} = (1 - p_1) \cdot E_{\text{demon}} - p_0. \quad (5.14)$$

The correction is chosen to not use the main read-out energy information in order to keep the two read-outs independent. The application of Equation 5.14 allows to obtain a better closure in the energy

are large fraction of them is due to jet backgrounds.

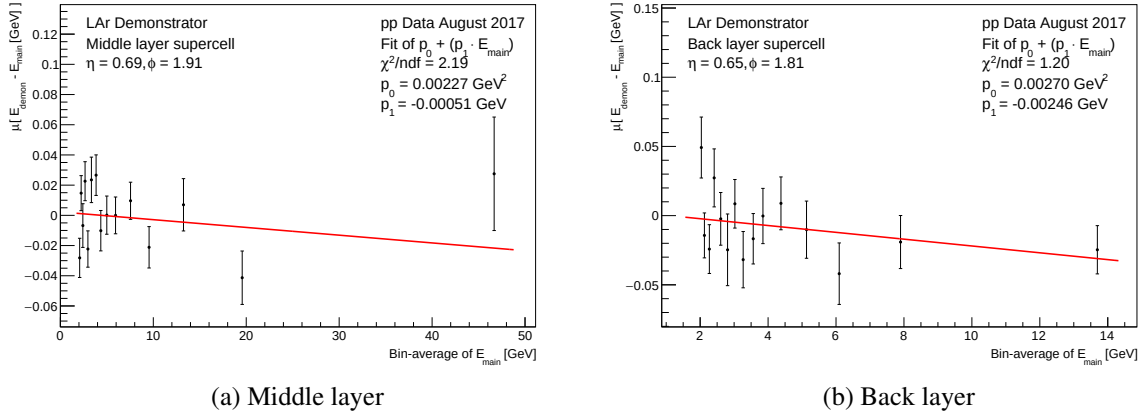


Figure 5.40: Corrected residual energy dependence of the mean energy deviation between the demonstrator system and the main read-out for selected supercells. The correction is performed according to Equation 5.14 and the parameters given in Figure 5.39. Figures for the presampler and the front layer are given in Figure B.14 of Appendix B.5.1.

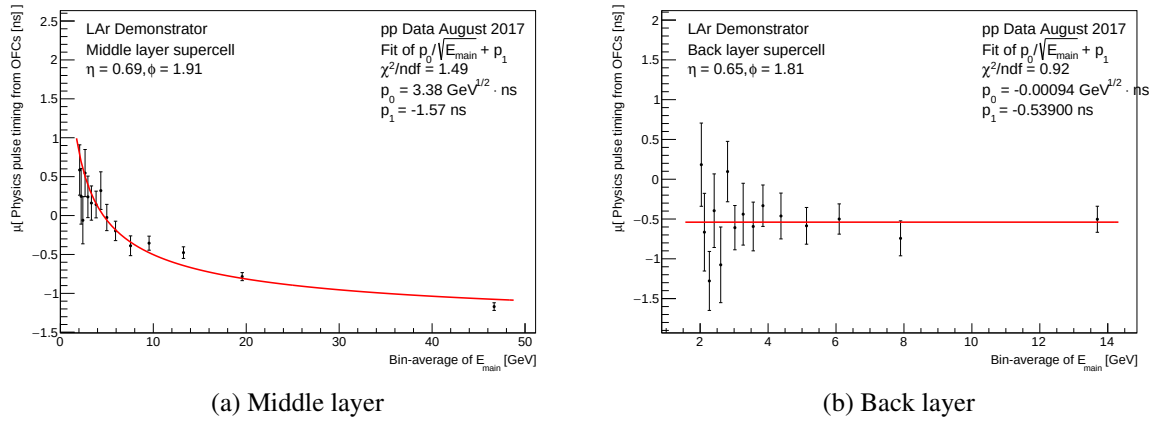


Figure 5.41: Residual energy dependence of the mean timing information for selected supercells. The fitted function corresponds to Equation 5.15 and is an ad-hoc parametrisation of the difference. Figures for the presampler and the front layer are given in Figure B.15 of Appendix B.5.1.

dependence as shown in Figure 5.40. The remaining energy dependence is about a factor of 10 smaller than the original effects.

Residual energy dependencies are observed for the mean timing value, too. Figure 5.41 contains the observed distribution for the selected supercells. For the middle layer, the mean timing scale shows a shift of about 2 ns between the low- and high-energy regions. In the back layer, an overall misalignment of about 0.5 ns is visible. The effect is parametrised as follows:

$$\Delta\tau(E_{\text{main}}) = \frac{p_0}{\sqrt{E_{\text{main}}}} + p_1. \quad (5.15)$$

The function in Equation 5.15 is chosen to describe the observed values well and is not motivated from

basic principles. The correction of the supercell timing is then performed according to

$$\tau_{\text{demon}} \rightarrow \tau'_{\text{demon}} = \tau_{\text{demon}} - \left(\frac{p_0}{\sqrt{E_{\text{demon}}}} + p_1 \right). \quad (5.16)$$

The correction is again chosen to not use the main read-out energy information in order to keep the two read-outs independent. The energy dependence after the correction is shown in Figure 5.42. For the given figure, the energy scale correction is performed prior to the timing correction. Due to this order, a more precise timing correction is possible, since the demonstrator energy scale after correction is closer to the main read-out energy scale used for the parametrisation. The back layer timing scale is aligned with 0 ns after the correction. For the middle layer, residual offsets are present in the low-energy region and could potentially be removed by a different choice of the parametrisation in Equation 5.15.

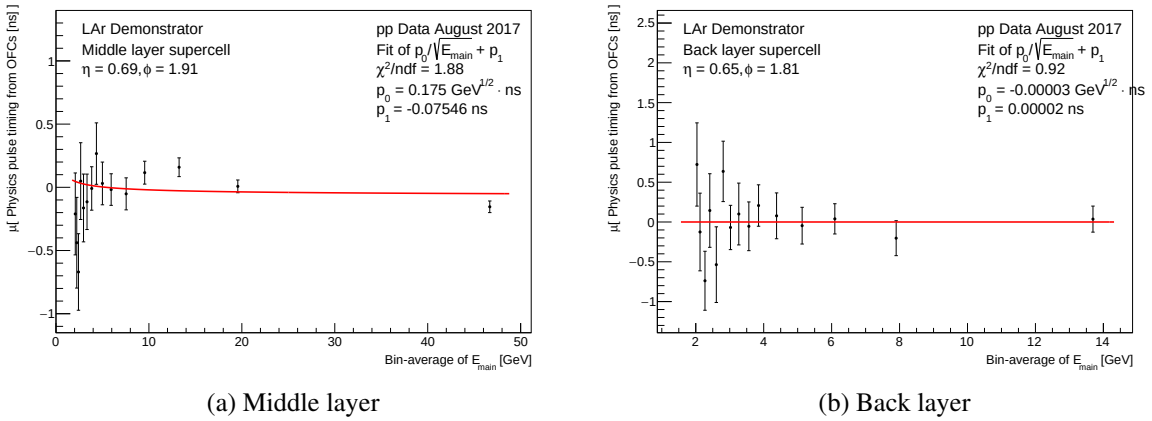


Figure 5.42: Corrected residual energy dependence of the mean timing information for selected supercells. The correction is performed according to Equation 5.16 and the parameters given in Figure 5.41. Figures for the presampler and the front layer are given in Figure B.16 of Appendix B.5.1.

The relative energy deviation with respect to the main read-out and the timing scale of observed showers in the demonstrator after the application of the corrections is given in Figure 5.43. In comparison with Figure 5.37, the reconstruction shows a better agreement. The energy comparison between the two read-outs exhibits a better alignment with one after the correction and the width of the distributions decreases by 4%, 18% and 36% for the full event, the selected shower and the supercell with the highest energy deposit, respectively. The timing alignment with 0 ns improves, too, especially for the supercell with $E_{\text{SC,max}}$. The width of the timing distributions improves by 25%, 29% and 49% for the full event, the selected shower and the supercell with the highest energy deposit, respectively. The calibration coefficients that are used for the demonstrator calibration are not corrected according to the shown study to avoid a bias in the energy reconstruction due to the usage of the main read-out information and to allow to judge the performance of the standard calibration scheme.

While the presented corrections allow for a better agreement between the demonstrator and the main read-out, the physical reason for the differences has not been studied in full detail. Potential reasons for the differences in the reconstructed energy are small shifts of the pedestal over time (for the p_0 parameter of Equation 5.13) and a small mismodelling of the amplitude ratio from the physics pulse prediction (for the p_1 parameter of Equation 5.13).

The energy dependence of the timing is observed in the main read-out calibration with a similar

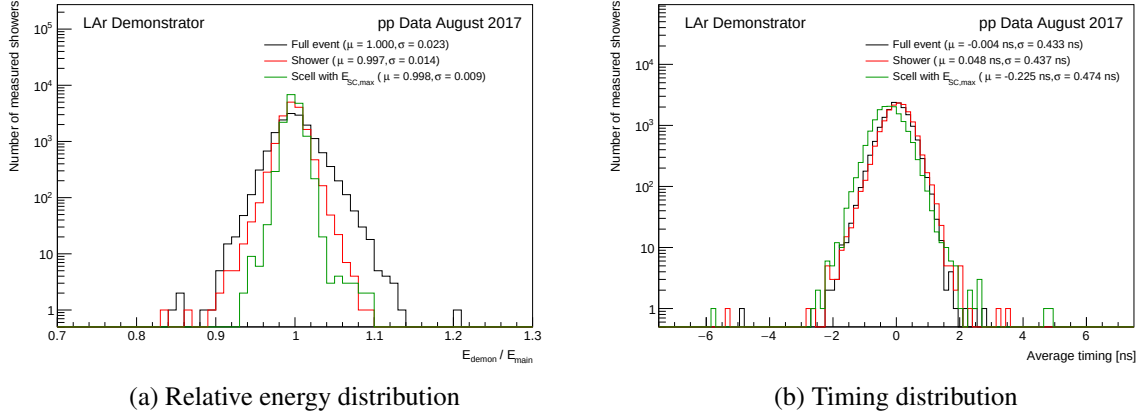


Figure 5.43: Energy and timing distribution of showers in the demonstrator region after the application of the correction described in Subsection 5.5.5. An improved agreement for the energy and timing measurements can be observed.

structure [128–130] and might originate from changes in the electronics response (i.e. the preamplifier and shaper). A dedicated correction of the timing measurement is performed for the main read-out, similar to the scheme presented here.

5.6 First studies on 2018 data

The dedicated triggers for the demonstrator system were updated prior to the 2018 data-taking period. A new trigger was introduced, which requires two isolated electromagnetic L1 trigger clusters with an invariant mass close to the Z boson mass. The events which are selected by the new trigger, in coincidence with the trigger selecting electromagnetic energy deposits within the demonstrator system coverage (compare Section 5.2), have a higher fraction of real electrons and photons in the data than the triggers used previously. For the 2018 data-taking period, the dedicated demonstrator triggers are operated at a rate of 3 Hz.

The spacial distribution of electron and jet candidates from offline reconstruction is shown in Figure 5.44 for the case without further identification requirements. The figure gives the overall distribution from all demonstrator triggers. A clearly higher density of candidates is visible in the region that is covered by the demonstrator system, such that the trigger items properly select clusters within the demonstrator coverage. A homogeneous background is visible and originates from secondary objects in the event. The higher electron and jet density at $\phi \simeq -1.2$ is expected to originate from back-to-back dielectron (e.g. from $Z \rightarrow ee$ events) or dijet production, where one electron or jet is inside the demonstrator region.

The number of electron candidates passing additional loose identification criteria [88] in events selected by the 2017 demonstrator trigger for electromagnetic clusters, as well as in events selected by the dedicated trigger to select Z -boson-like signatures from the 2018 setup, is shown in Figure 5.45. Two electron candidates are found with a much higher fraction for the 2018 trigger, which points towards a proper selection of $Z \rightarrow ee$ events. Figure 5.46 shows the distribution of the loose electron candidates in events with exactly two loose electrons and the invariant mass distribution of them. A clear peak around the Z boson mass is visible.

The data collected with the 2018 demonstrator system allows to repeat, and potentially extend, the

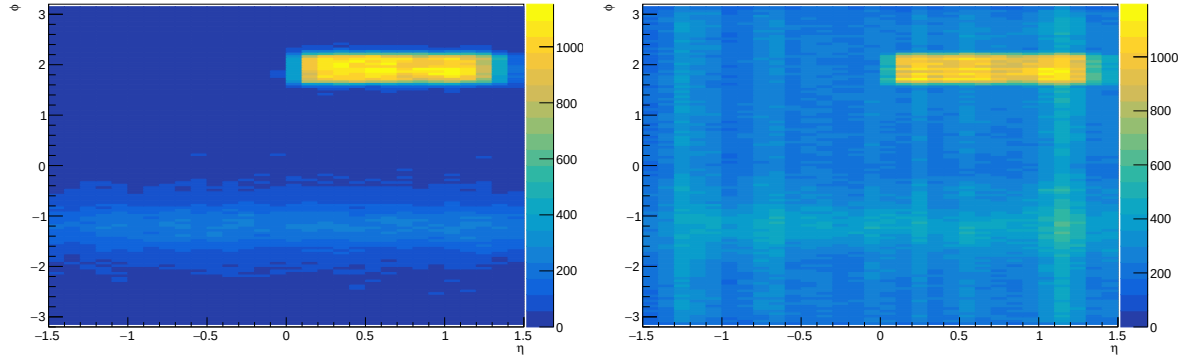


Figure 5.44: Distribution of electron (left) and jet (right) candidates from offline reconstruction with $p_T > 10$ GeV inside the LAr barrel for events that were selected by the demonstrator trigger type. A clear enhancement of the density inside the demonstrator region is visible.

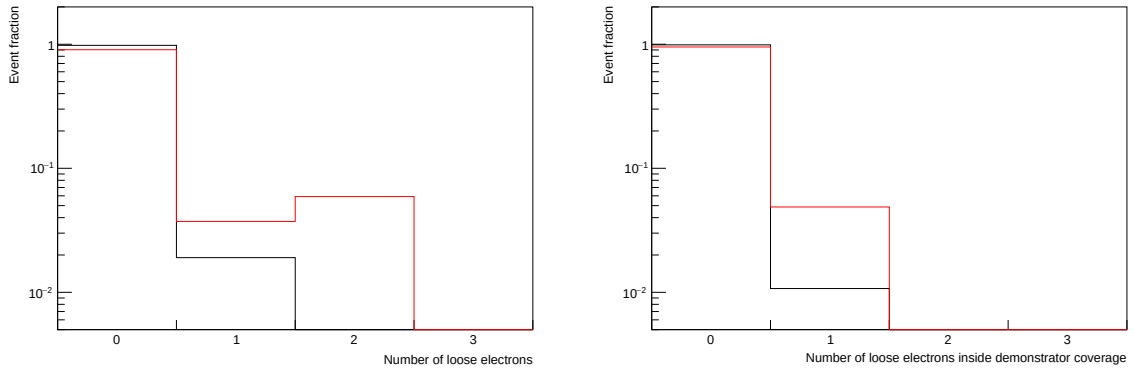


Figure 5.45: Number of electron candidates from offline reconstruction with $p_T > 10$ GeV passing loose identification criteria for the triggers used to select electro-magnetic showers in 2017 (black) and 2018 (red). The left figure shows the full LAr barrel, while the right figure depicts the number of candidates inside the demonstrator coverage. An increase of the event fraction with a loose electron inside the demonstrator region by a factor of 5 can be observed.

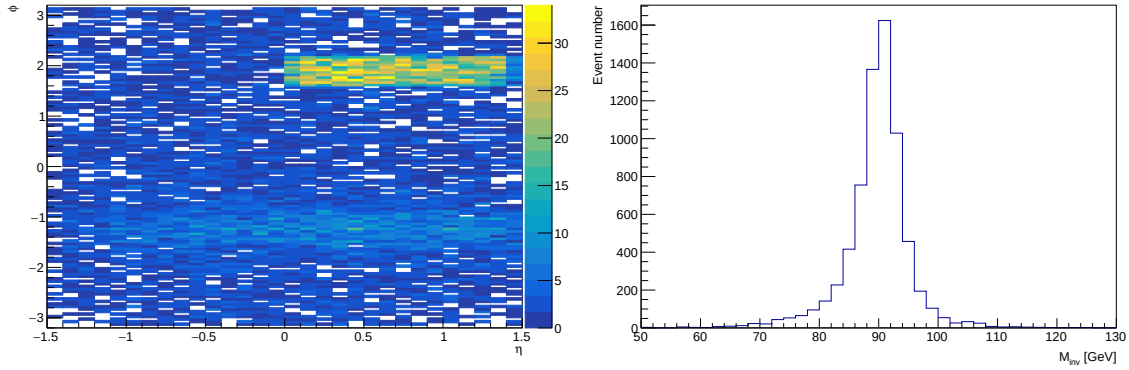


Figure 5.46: Distribution of loose electrons from offline reconstruction for events with exactly two loose electrons with $p_T > 10$ GeV (left) and invariant mass distribution of these electrons (right). A peak in the mass distribution at the Z boson mass is visible. The higher electron density at $\phi \simeq -1.2$ is expected to originate from back-to-back production with the electrons inside the demonstrator region, e.g. due to $Z \rightarrow ee$ production. The figure gives the overall distribution from all demonstrator triggers, but is dominated by the 2018 trigger.

studies presented in this chapter. The data analysis for this system is ongoing and provides valuable input for the remaining development towards Run 3.

5.7 Conclusion and outlook

The presented calibration coefficients for the 2014 LAr Phase-1 demonstrator system allow to convert the collected ADC measurements into energy and timing information. In order to obtain these coefficients, a calibration procedure was developed. The procedure is based on the LAr cells calibration scheme, with several modifications for the supercells. The full procedure includes the development of pulsing patterns, data-taking of pedestal, delay and ramp runs as well as the analysis of the calibration data.

The validation of the calibration coefficients with pp physics data is also presented. The calibration scheme for the supercells was developed under the assumption that the summation of the constituent cell pulse shapes in the upgraded LAr trigger read-out electronics is linear enough to treat supercells as cells. The validation showed good agreement between the demonstrator and the main read-out. The available calibration scheme is expected to be already precise enough for the L1 calorimeter trigger after the LAr Phase-1 upgrade.

Small residual energy dependencies of the energy and timing scale are found and corrected for an improved shower reconstruction. The resolution of the shower timing values could be improved by 29%, while the energy resolution could be improved by 18%. The correction is not applied by default in the current calibration, mainly to keep the calibration scheme for the demonstrator system simple. The calibration scheme for the final Phase-1 upgrade installation could be improved to account for the observed residual differences, though.

With the installation of the 2018 demonstrator system, the LAr Phase-1 upgrade made a step closer to the installation and commissioning phase in 2019-2020. The new trigger items were validated and a considerably higher fraction of real electrons in the data was achieved, which will allow an improved understanding of the final system.

The work presented here could be used as a baseline approach for the calibration of the final system, too, as main parts of the code are already integrated in the Athena reconstruction software. This code

framework is expected to be easily adaptable to the final Run 3 configuration.

Search for high-mass dilepton resonances

6.1 Analysis strategy

The dilepton ($\ell\ell$ with $\ell \in \{e, \mu\}$) final state offers an experimentally clean signature to search for new high-mass phenomena in the dilepton invariant mass ($m_{\ell\ell}$) spectrum. The search presented in this chapter is published in Ref. [84], using the full Run 2 dataset of 139 fb^{-1} . The analysis is based on a background estimate using a functional fit to the data, i.e. a so-called “data-driven” search strategy. It is thus considerably less affected by the size of the available MC samples or a potential MC mismodelling. Rather than a specific model, a generic signal model is used to facilitate an easy reinterpretation of the results. An overview of the theoretical motivation for dilepton searches is given in Subsection 2.2.2. A typical reinterpretation of the search are e.g. constraints on mediator-based dark matter models [131].

The full Run 2 dilepton search is performed with an inclusive selection, i.e. it does not target a specific model, spin assumption or further properties of the potential new resonance. The main background is the irreducible Z/γ^* (Drell-Yan, DY) process. Contributions from top-quark pair ($t\bar{t}$) production and diboson production are also present. Misreconstructed multi-jet and W +jets events contribute in the dielectron channel, while this contribution is negligible in the dimuon channel. The relative contribution of these background is shown in Figure 6.2.

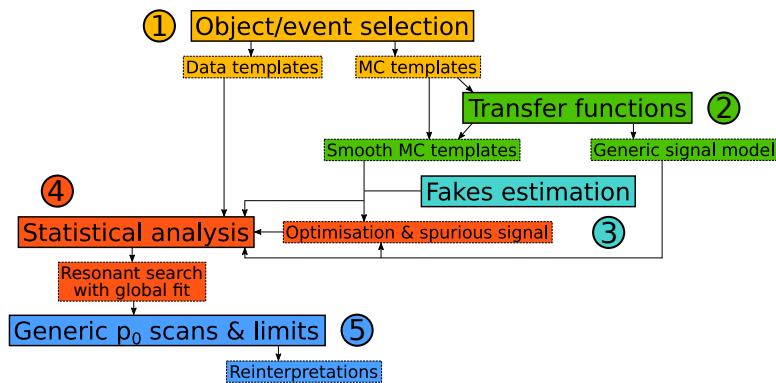


Figure 6.1: Analysis model of the full Run 2 dilepton search.

The analysis model of the search is given in Figure 6.1 and consists of the following steps:

1. The object and event selection is described in Section 6.2. The validation of the selection is done in terms of data/MC comparisons and event-by-event checks.

2. The “transfer functions” are a parametrisation of the detector mass resolution function and are introduced in the analysis to overcome limitations of low statistics in the MC samples and to obtain a generic signal model. The transfer function approach is introduced in Section 6.3, while its application to the background and signal modelling are given in Sections 6.4 and 6.5, respectively.
3. The background contribution of events with misreconstructed, so-called “fake” electrons is taken from the previous analysis round at 36.1 fb^{-1} . The estimation is based on the so-called matrix method. It is further described in Ref. [132].
4. The statistical analysis with a global fit, i.e. a background estimate using a functional form to model the background shape in the full invariant mass region, is detailed in Section 6.8. An overview of the main statistical analysis concepts is given in Section 6.7.
5. In Section 6.9, the final analysis results are presented. The deviations from the expectation of a smoothly falling background are first analysed. No significant deviation from the SM expectation is found, such that limits on the cross-section of potential new resonances are set and reinterpreted into different models.

The systematic uncertainties in the search can be split into uncertainties on the signal model and the uncertainty from the data-driven background modelling. An overview of the systematic uncertainties, and in particular a description of the signal-related uncertainties, is given in Section 6.6. The minimisation of the background modelling uncertainty, i.e. the so-called spurious signal, is used as the guiding principle for the function choice of the background model in Section 6.8.

6.2 Event selection and data/MC samples

The event selection for the dilepton search is performed using the SUSYTools package [133] within the Athena framework. Common analysis ntuples are produced based on so-called derivations, which are compressed sets of the data and MC samples. An overview of the used MC event generators for the hard-scatter process, the showering and the used PDF sets is given in Table 6.1, while further information is available in Ref. [84].

Table 6.1: The event generators used for simulation of the signal and background processes. The acronyms ME and PS stand for matrix element and parton shower. The top-quark mass is set to 172.5 GeV . The $G^* \rightarrow \ell\ell$ and $H \rightarrow \ell\ell$ samples are generated with fast simulation techniques, while full simulation samples are available for a few pole masses. The “0-width” $Z' \rightarrow \ell\ell$ samples are generated with full simulation, and additionally available for fast simulation at a few pole masses. Table adapted from Ref. [84].

Background Process	ME Generator and ME PDFs	PS and non-perturbative effect with PDFs
NLO Drell–Yan	POWHEG-Box [62, 63], CT10 [134], PHOTOS	PYTHIA v8.186 [135], CTEQ6L1 [136, 137], EvtGEN1.2.0
$t\bar{t}$	POWHEG-Box, NNPDF3.0NLO [138]	PYTHIA v8.230, NNPDF23LO [139], EvtGEN1.6.0
Single top s -channel, Wt	POWHEG-Box, NNPDF3.0NLO	PYTHIA v8.230, NNPDF23LO, EvtGEN1.6.0
Single top t -channel	POWHEG-Box, NNPDF3.04fNLO, MADSPIN	PYTHIA v8.230, NNPDF23LO, EvtGEN1.6.0
Diboson (WW , WZ and ZZ)	SHERPA 2.1.1 [67], CT10	SHERPA 2.1.1, CT10
Signal Process		
LO Drell–Yan	PYTHIA v8.186, NNPDF23LO	PYTHIA v8.186, NNPDF23LO, EvtGEN1.2.0
“0-width” $Z' \rightarrow \ell\ell$	PYTHIA v8.212, NNPDF23LO	PYTHIA v8.212, NNPDF23LO, EvtGEN1.6.0
Randall–Sundrum $G^* \rightarrow \ell\ell$	PYTHIA v8.210, NNPDF23LO	PYTHIA v8.210, NNPDF23LO, EvtGEN1.2.0
MSSM $gg \rightarrow H \rightarrow \ell\ell$	POWHEG-Box, CT10	PYTHIA v8.212, CTEQ6L1, EvtGEN1.2.0

The effective integrated luminosity of the background MC samples is at least a factor of two higher than the integrated luminosity of the available dataset. For these samples the full detector simulation

[140] based on Geant4 [71] is used, i.e. the samples are so-called “fullsim” MC samples. The generated truth-only NLO DY samples, used to obtain very smooth DY background distributions in Subsection 6.4.1, correspond to at least 8000 fb^{-1} of effective integrated luminosity. In these samples the detector simulation and reconstruction steps are skipped, resulting in a significant reduction of the required CPU resources. The LO and NLO DY MC samples are so-called “mass-sliced” samples, i.e. they are generated in specific $m_{\ell\ell}^{\text{truth}}$ intervals to enhance the MC statistics in the high-mass region. It is thus possible to produce MC samples with significantly higher effective integrated luminosities for high $m_{\ell\ell}^{\text{truth}}$ than for low $m_{\ell\ell}^{\text{truth}}$. Spin-1 signal samples with a resonance width of 20 MeV, used to validate the detector mass resolution parametrisation in Subsection 6.3.3, are additionally available. These samples are referred to as 0-width samples in the following, since their intrinsic resonance width is much smaller than the experimental mass resolution. Further MC samples for signal processes are solely used to evaluate the selection efficiency for different spin configurations as a function of the resonance mass.

6.2.1 Object selection

The main physics objects of the search are electrons and muons. The reconstruction of electron and muon candidates is described in Section 3.3. The event selection is detailed in Subsection 6.2.2.

Primary vertex

The primary vertex is selected as the vertex with the largest $\sum p_T^2$, corresponding to the sum over all tracks with $p_T > 0.5 \text{ GeV}$ that are associated with the vertex.

Electrons

Electron candidates are required to have $E_T > 30 \text{ GeV}$ and a pseudorapidity of $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ ¹. The electron identification is performed according to the “Medium” likelihood working point [88], while the electron isolation is required to pass the “Gradient” working point [88]. The track associated to the candidate needs to emerge from the primary vertex and thus fulfil $|d_0| < 5\sigma$ for the transverse impact parameter and $|z_0 \sin \theta| < 0.5 \text{ mm}$ for the longitudinal impact parameter.

Muons

Muon candidates need to have $p_T > 30 \text{ GeV}$ and $|\eta| < 2.5$. The muons are required to pass the high- p_T identification working point, which ensures a good momentum resolution of the muons at high p_T [89]. The working point requires at least three hits in each of the three layers of precision tracking chambers in the MS, while additional vetoes are placed on specific regions of the MS where the alignment knowledge is suboptimal. An additional “good muon” requirement is placed on the relative uncertainty of the q/p measurement (i.e. the charge-to-momentum ratio) with a p_T -dependent cut to further ensure good reconstruction properties. The muons are required to be isolated using the “FCTightTrackOnly” working point [84]. The track associated to the candidate needs to emerge from the primary vertex and thus fulfil $|d_0| < 3\sigma$ for the transverse impact parameter and $|z_0 \sin \theta| < 0.5 \text{ mm}$ for the longitudinal impact parameter.

¹ The overlap region between the barrel and end-cap LAr calorimeters is excluded. The region exhibits a lower rejection of fake electron candidates, and a worse energy resolution due to significant additional inactive material and a lower cell granularity.

Overlap removal

An overlap removal between electrons and muons is applied to ensure that the particles are reconstructed from orthogonal information. The following requirements are applied:

1. Electrons are rejected against other electrons in case they share the associated track and have a lower E_T .
2. Muons are rejected against electrons in case the muon is a calorimeter muon² and the ID track is shared.
3. Electrons are rejected against muons in case the ID track is shared and case 2 does not apply.

A further event-level overlap removal between the two considered channels, i.e. dielectron and dimuon, is defined below.

6.2.2 Event selection

The events are required to pass the following general criteria:

- Event cleaning: The event needs to be measured in a time period where the detector is fully operational. Additional event-level vetoes are applied to reject bad or corrupted events, e.g. due to noise bursts, based on data-quality flags of certain detector subsystems.
- Primary vertex: Events are required to have a primary vertex with at least two associated tracks.
- Trigger: Events in the dielectron channel are recorded using dielectron trigger items with E_T thresholds between 12 and 24 GeV for both electrons, depending on the data-taking period. “Loose” or “very loose” identification criteria are applied on trigger level to reduce the trigger rate. For the dimuon channel, single muon trigger items with p_T thresholds of 50 and 26 GeV are used. The trigger item with a threshold of 26 GeV additionally requires the muon candidate to be isolated [87].

The event reconstruction in the dielectron and dimuon channels is then performed according to the following steps:

- The event has to contain at least two same-flavour leptons (electrons or muons).
- From the available same-flavour leptons, the leading and subleading leptons in terms of their E_T (p_T) are selected in the electron (muon) channel.
- The selected pair needs to be oppositely charged in the dimuon channel³. No cut on the charge is applied in the dielectron channel, as the efficiency loss in the high- E_T regime is high and only a small reduction of the background processes is expected. Events with more than two muons, where the leading and subleading muons have the same charge and a further muon is oppositely charged, are not selected.
- A dilepton invariant mass of $m_{\ell\ell} > 130$ GeV is finally required⁴.

² The reconstruction of calorimeter muons is based on ID tracks and energy cluster information in the calorimeters, but does not depend on the MS information.

³ The opposite-charge requirement in the dimuon channel helps to ensure a proper p_T reconstruction, as muons with a misidentified charge will have strongly distorted p_T measurements.

⁴ Further restrictions on the invariant mass range are placed in the statistical analysis.

In case events are selected in the ee and $\mu\mu$ channels, the dielectron channel is preferred over the dimuon channel due to the better invariant mass resolution in this channel. The overlapping events are thus rejected in the dimuon channel, but only constitute a tiny fraction of the observed events⁵. The cut is done to avoid overlapping events in the combination of the ee and $\mu\mu$ channels into the $\ell\ell$ channel.

Data and MC templates are retrieved in a range of $m_{\ell\ell}^{\text{reco}} \in [130 \text{ GeV}, 6 \text{ TeV}]$ at most. It is checked that no events beyond $m_{\ell\ell}^{\text{reco}} = 6 \text{ TeV}$ are found in data. Different binning choices are used depending on the use case.

6.2.3 Calibration and corrections

The electron and muon objects are calibrated according to the recommendations of the corresponding ATLAS performance groups. Corrections are applied to electron (muon) candidates to match the energy (momentum) scale and resolution between simulation and data [84].

Scale factors (SFs) are used to correct for residual differences between the data and MC samples and are obtained from data/MC comparisons in reference final states. The SFs are retrieved according to the recommendations of the ATLAS performance groups. The following SFs are applied to the MC samples:

- Pile-up reweighting: The pile-up reweighting allows to match the pile-up profile from data and the specific MC samples. The pile-up profile for the MC samples often needs to be estimated before the full dataset is measured, such that small differences can be present.
- SFs for electrons: Reconstruction, trigger, isolation and identification scales factors are applied.
- SFs for muons: Reconstruction, trigger, isolation and track-to-vertex-association (TTVA) scale factors are applied.

The MC samples are additionally rescaled with k -factors according to Section 4 of Ref. [132] by using the so-called “LPXKFactorTool”. These SFs account for differences in the total cross-section if higher order calculations are available for a given process compared to the order available in the MC samples. In case of the LO and NLO DY samples, the SFs provide corrections for higher-order QCD, EW and photon-induced (PI) effects [132]. The corrections can change the cross-section by up to 30% in the high-mass region.

Theoretical uncertainties on the DY background prediction are evaluated with the LPXKFactorTool, too. The uncertainties are given by a set of seven eigenvector variations of the nominal PDF set, differences between PDF sets, as well as variations of PDF scales, the strong coupling $\alpha_s(m_Z)$, EW corrections, and photon-induced corrections (see Section 7 of Ref. [132]). The theoretical uncertainty on the top-quark pair production cross-section is additionally considered in the search.

6.2.4 Comparison between data and expectation from MC samples

The observed data distribution is compared to the expectation from MC and shown in Figure 6.2. The expected distribution is obtained from different MC samples for processes that produce real two leptons, and in addition a data-driven estimate of fake lepton contributions in the ee channel [132]. The comparison is mainly given for illustrative purposes, as the MC prediction is only used for the choice of the background function.

A good agreement between the data and the MC background estimation is nonetheless needed for the optimisation of the data-driven fit strategy and to determine associated uncertainty. The functional

⁵ Only six events with $m_{\ell\ell}^{\text{reco}} > 130 \text{ GeV}$ in either of the channels are found in the 2015/16 dataset of 36.1 fb^{-1} .

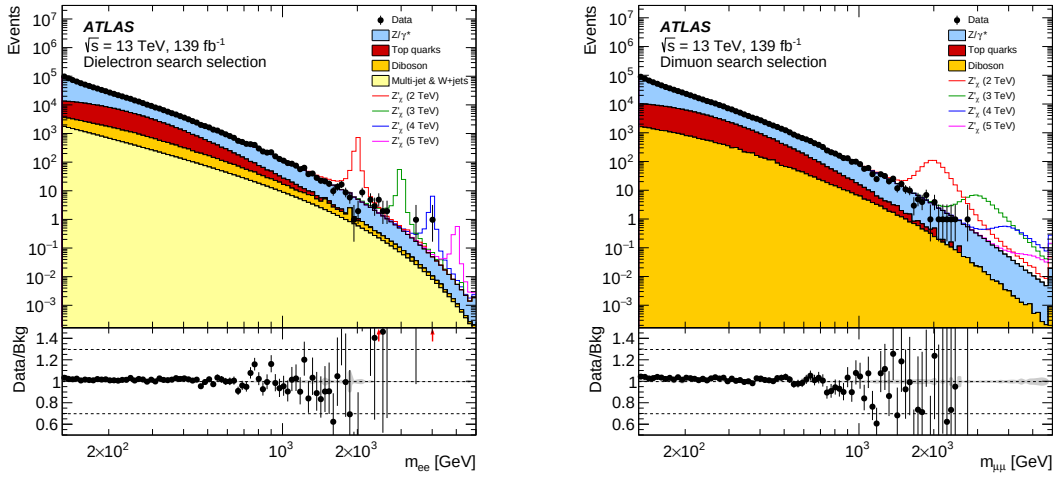


Figure 6.2: Distributions of reconstructed dielectron (left) and dimuon (right) invariant mass after selection, for data and the SM background estimates as well as their ratio. The data points are shown together with their statistical uncertainty. Selected Z'_χ signals with a pole mass of 2, 3, 4 and 5 TeV are overlaid. In the lower panel, the shaded band corresponds to the MC statistical uncertainty, dashed lines correspond to $\pm 30\%$ and red arrows indicate data points that are outside the displayed range.

form in the data-driven fit is expected to be able to absorb long-range MC mismodelling⁶. The shown uncertainty band in Figure 6.2 corresponds to the statistical uncertainty of the MC samples.

6.3 Determination of transfer functions

The transfer function (TF) method is based on an analytic parametrisation of the detector mass resolution. It is used in the analysis to produce smoothed DY and $t\bar{t}$ background templates. This approach was developed to overcome limitations due to insufficient MC statistics for invariant masses below about 1 TeV. The TF parametrisation is additionally used to provide a generic signal model description and to determine its systematic uncertainties. The framework to determine the transfer functions is implemented in ROOT [141] and RooFit [142].

6.3.1 General concept

For the analysis of the 2015/16 dataset, the available DY MC samples exhibited statistical uncertainties in the low- $m_{\ell\ell}$ region that were compatible with the statistical uncertainty of the data. In order to not suffer from this in terms of a reduced search sensitivity, background smoothing with a functional fit had been performed [132].

The transfer function approach offers an alternative method for the background smoothing, while allowing to determine a generic signal model in parallel. Within this method, the transformation between the truth- and reconstruction-level spectra, due to the detector reconstruction, is analytically parametrised to obtain a smooth transition. The mass spectra themselves are not smoothed using a fit, though, and thus no functional form is imposed on them.

⁶ Long-range mismodelling refers to effects that create deviations in the data/MC ratio that are considerably wider than the invariant mass resolution of the respective channel.

The transition between a known truth spectrum, $S_{\text{truth}}(m_{\ell\ell}^{\text{truth}})$, and an unknown reconstructed spectrum, $S_{\text{reco}}(m_{\ell\ell}^{\text{reco}})$, can be parametrised by a transfer function, $P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}})$. It describes the probability to reconstruct an event at the invariant mass of $m_{\ell\ell}^{\text{reco}}$ for events with a truth mass of $m_{\ell\ell}^{\text{truth}}$ that pass the selection. The transfer functions are determined from MC samples with a full detector simulation and can additionally be smoothed by fitting the $P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}})$ distributions over the full $m_{\ell\ell}^{\text{truth}}$ range. The fit procedure is further described in Subsection 6.3.2 and its validation using 0-width samples is detailed in Subsection 6.3.3. The truth spectra can be obtained from very large truth-only MC samples with a size of more than 55 times the dataset, which, due to the smaller CPU time and disk space requirements for these samples, allow to determine $S_{\text{truth}}(m_{\ell\ell}^{\text{truth}})$ very precisely. The size of the truth-only MC samples is a factor of 7 (6) higher than for the available fullsim MC samples within the $m_{\ell\ell}^{\text{truth}} \in [180 \text{ GeV}, 250 \text{ GeV}]$ mass-slice in the ee ($\mu\mu$) channel, such that a considerably more smooth spectrum is obtained. The reconstruction level spectrum can then be obtained by using the following convolution:

$$S_{\text{reco}}(m_{\ell\ell}^{\text{reco}}) = P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}}) \otimes [S_{\text{truth}}(m_{\ell\ell}^{\text{truth}}) \cdot A\epsilon(m_{\ell\ell}^{\text{truth}})]. \quad (6.1)$$

The acceptance times efficiency, $A\epsilon(m_{\ell\ell}^{\text{truth}})$, describes the probability that an event with a truth invariant mass of $m_{\ell\ell}^{\text{truth}}$ passes the selection. It is defined by the fraction of accepted events compared to the total number of events inside a $m_{\ell\ell}^{\text{truth}}$ bin and further described in Subsection 6.3.4. A sketch of the TF application procedure is given in Figure 6.3.

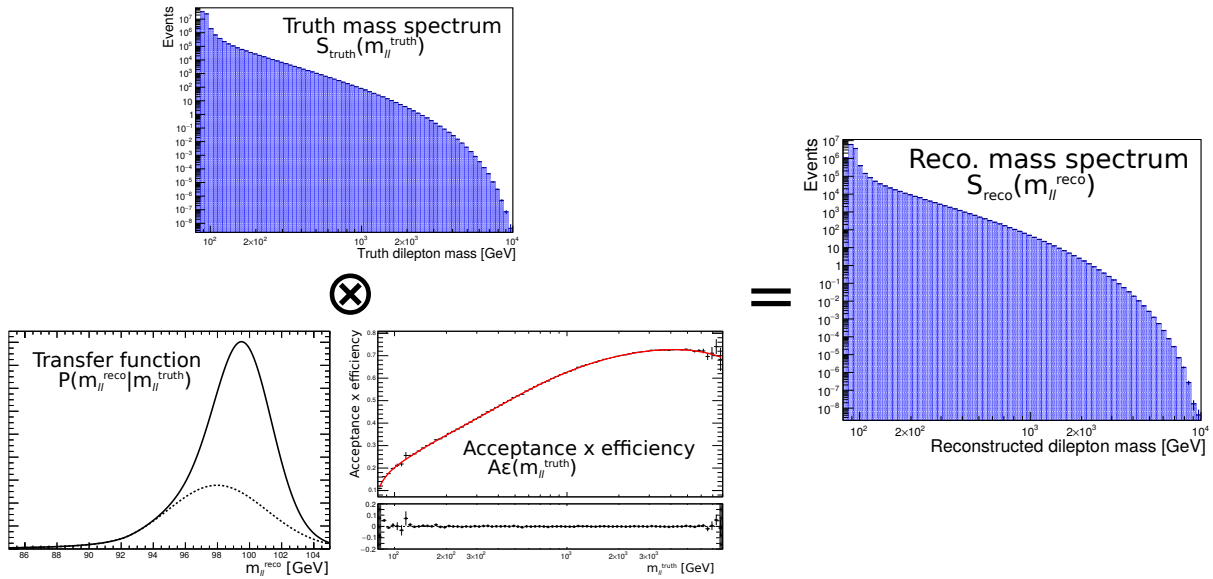


Figure 6.3: Sketch of the basic principle behind the transfer function (TF) method and its application. The procedure is based on fullsim MC to derive the transfer functions and the acceptance times efficiency curve, while large-scale truth-only MC samples are used to have a smooth underlying distribution. No information from data is used.

The parametrisation of the TFs can be used as a generic signal model, too, as $P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}})$ describes the detector mass resolution for a given $m_{\ell\ell}^{\text{truth}}$ value and thus corresponds to a 0-width signal (i.e. a signal with a delta function as its truth-level shape). A further description of the generic signal model is given in Subsection 6.5, while the validation of the 0-width signal assumption is available in Subsection 6.3.3. Applying systematic variations to the TF inputs allows to determine a smooth description of systematic uncertainties on $A\epsilon(m_{\ell\ell}^{\text{truth}})$ or $P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}})$, and is described in Section 6.6. Variations of $S_{\text{truth}}(m_{\ell\ell}^{\text{truth}})$ due to uncertainties on the parton luminosity functions and other background uncertainties are migrated

into the determination of the spurious signal uncertainty as detailed in Subsection 6.8.3.

6.3.2 Parametrisation of the detector mass resolution function

The transfer functions, $P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}})$, are obtained by fitting the detector mass resolution function, $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$, with a simultaneous fit in 200 $m_{\ell\ell}^{\text{truth}}$ regions or “bins”. The regions have an equal size in the $\log(m_{\ell\ell}^{\text{truth}})$ space to ensure sufficient statistics in each of the regions and reach from $m_{\ell\ell}^{\text{truth}} = 130$ GeV to 6 TeV. The relative deviation between the reconstructed and truth invariant mass is defined as $\mathcal{R} = (m_{\ell\ell}^{\text{reco}} - m_{\ell\ell}^{\text{truth}})/m_{\ell\ell}^{\text{truth}}$ for a given event. The distribution of $\mathcal{R}$ is the detector mass resolution function, and also called (detector) mass response in the following. Examples of the $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$ distribution are e.g. given in Figure 6.7. The mass response is used as the main variable for the fit since the mean value of $\mathcal{R}$ for each $m_{\ell\ell}^{\text{truth}}$ region is expected to be equal to zero, while the width of the distribution directly yields the relative mass resolution. The interval size in the $\log(m_{\ell\ell}^{\text{truth}})$ space is chosen small enough such that $\mathcal{R}$ is not expected to vary strongly within a $m_{\ell\ell}^{\text{truth}}$ region. Additionally, a more stable distribution of $\mathcal{R}$ as a function of $m_{\ell\ell}^{\text{truth}}$ is given due to the subtraction of and division by $m_{\ell\ell}^{\text{truth}}$. The usage of $\mathcal{R}$, instead of $m_{\ell\ell}^{\text{reco}}$, thus already accounts for a linear increase of the detector mass resolution with $m_{\ell\ell}^{\text{truth}}$.

A range of $\mathcal{R} \in [-0.2, 0.1]$ ($\mathcal{R} \in [-0.75, 0.75]$) is fitted for the ee ($\mu\mu$) channel and chosen the capture the response even in the tail regions. The range is adapted to cover the different detector resolutions in the high (i.e. several TeV) and low (i.e. ≈ 200 GeV) mass regions for both channels. No significant change in the TF parametrisation is observed for wider response ranges. The response histograms are binned in 200 (750) bins of equal size in the ee ($\mu\mu$) channels. The response distribution over the full mass range is shown in Figure 6.4 in a two-dimensional plot to depict the response variations for different truth masses.

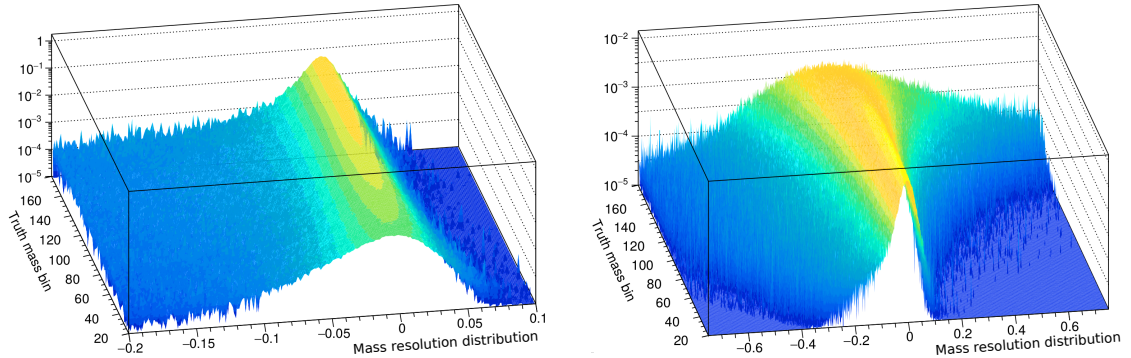


Figure 6.4: Example of a two-dimensional representation of $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$ in the full considered truth mass range for the ee (left) and $\mu\mu$ (right) channels. The $\mu\mu$ channel shows a considerably stronger mass dependence due to the worse muon p_T resolution in the high- p_T region.

$m_{\ell\ell}^{\text{reco}}$ is obtained using the nominal selection of the analysis, while $m_{\ell\ell}^{\text{truth}}$ is defined as the truth invariant mass of the Z/γ^* particle in NLO DY MC samples. The truth mass is obtained at Born level, i.e. before the emission of final state radiation (FSR). The effects of FSR on the reconstruction of electrons and muons are expected to be different, as collimated FSR photons will be part of the electron reconstruction, while they are lost in case of muons.

Several function choices have been tested to obtain a good description of $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$ throughout the full $m_{\ell\ell}^{\text{truth}}$ spectrum. Finally, the sum of a Gaussian function and a Crystal-Ball function is used. The summed function is given in Equation 6.2 and has in total 7 parameters:

$$P(\mathcal{R}) = \kappa \cdot \text{CB}(\mathcal{R}|\mu_{\text{CB}}, \sigma_{\text{CB}}, \alpha_{\text{CB}}, n_{\text{CB}}) + (1 - \kappa) \cdot G(\mathcal{R}|\mu_G, \sigma_G). \quad (6.2)$$

The Gaussian (G) part of the function describes the main peak of the response distribution. The Crystal-Ball (CB) component has longer tails on one side of the distribution and thus describes the tails of the response. For the dielectron channel the tail is mainly given due to electromagnetic radiation (e.g. Bremsstrahlung). In the dimuon channel, the tails are due to badly reconstructed muons. The parameters inside Equation 6.2 have the following properties:

- μ_{CB} and μ_{G} describe the mean value of the CB and Gaussian components, respectively. As $\mathcal{R}$ is given by $(m_{\ell\ell}^{\text{reco}} - m_{\ell\ell}^{\text{truth}})/m_{\ell\ell}^{\text{truth}}$, and typically $m_{\ell\ell}^{\text{reco}} \approx m_{\ell\ell}^{\text{truth}}$, the typical values of μ_i should be close to 0. Due to the dimensionless definition of $\mathcal{R}$, the μ_i parameters are dimensionless, too.
- σ_{CB} and σ_{G} are the width parameters of the CB and Gaussian components, respectively. Their value corresponds to the relative uncertainty of the response, such that they are dimensionless in this parametrisation. A decreasing behaviour is expected for the ee channel, limited by the constant term of the calorimeter resolution. The $\mu\mu$ channel is expected to have an increasing mass resolution, as for high- p_{T} muons the track curvature is low and thus the relative error on the Sagitta measurement high.
- α_{CB} defines the cut-off in the Crystal-Ball function after which the Gaussian behaviour is replaced by a power-law. α_{CB} is given in units of σ_{CB} . No strong $m_{\ell\ell}^{\text{truth}}$ -dependence is expected.
- n_{CB} is the exponent in the power-law region of the Crystal-Ball function. No strong dependence on $m_{\ell\ell}^{\text{truth}}$ is expected, too.
- κ defines the fraction of the Crystal-Ball function in the total pdf. The $m_{\ell\ell}^{\text{truth}}$ -dependence of this parameter should reflect the relative importance of the tails.

Each of the parameters needs a dedicated description as a function of $m_{\ell\ell}^{\text{truth}}$ to allow for the simultaneous fit in all $m_{\ell\ell}^{\text{truth}}$ regions. The parameter dependencies with $m_{\ell\ell}^{\text{truth}}$ are shown in Figures 6.5 and 6.6 for the ee and $\mu\mu$ channels, respectively. The functional form of these parametrisations is given in Tables C.1 and C.2 of Appendix C.1 for the ee and $\mu\mu$ channels, respectively. The initial values for the parameters in the simultaneous fit were obtained by fitting the parametrisation of Equation 6.2 in single $m_{\ell\ell}^{\text{truth}}$ regions and then determining a functional shape for the $m_{\ell\ell}^{\text{truth}}$ dependence of each of the 7 parameters. Due to the high complexity, the initial values for the evolution of the width parameters, σ_{G} and σ_{CB} , are set to the parametrisation used in the previous analysis round [132] and are motivated by the detector properties in the respective channels.

Examples of the response description after the simultaneous fit can be found in Figure 6.7 for the ee and $\mu\mu$ in the low, medium and high truth mass regions. The χ^2/ndf distributions for all $m_{\ell\ell}^{\text{truth}}$ bins of the simultaneous fit are given in Figure 6.8⁷. The agreement in the reconstructed spectrum after the smoothing process using the TFs is mainly dominated by the agreement in the peak region, while the tail modelling mainly affects the χ^2/ndf distribution.

The detector response, $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$, is finally reparametrised to obtain the TFs, $P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}})$:

$$\begin{aligned}\mu_i(m_{\ell\ell}^{\text{truth}}) &\rightarrow \mu'_i(m_{\ell\ell}^{\text{truth}}) = (\mu_i(m_{\ell\ell}^{\text{truth}}) \cdot m_{\ell\ell}^{\text{truth}}) + m_{\ell\ell}^{\text{truth}}, \\ \sigma_i(m_{\ell\ell}^{\text{truth}}) &\rightarrow \sigma'_i(m_{\ell\ell}^{\text{truth}}) = \sigma_i(m_{\ell\ell}^{\text{truth}}) \cdot m_{\ell\ell}^{\text{truth}}.\end{aligned}\tag{6.3}$$

μ'_i and σ'_i are thus given in units of mass, while μ_i and σ_i are dimensionless. κ , α_{CB} , n_{CB} are invariant under the reparametrisation.

⁷ The χ^2/ndf values are calculated in the response region where a Gaussian behaviour of the MC template uncertainty is given, i.e. in the validity region of the χ^2/ndf distribution.

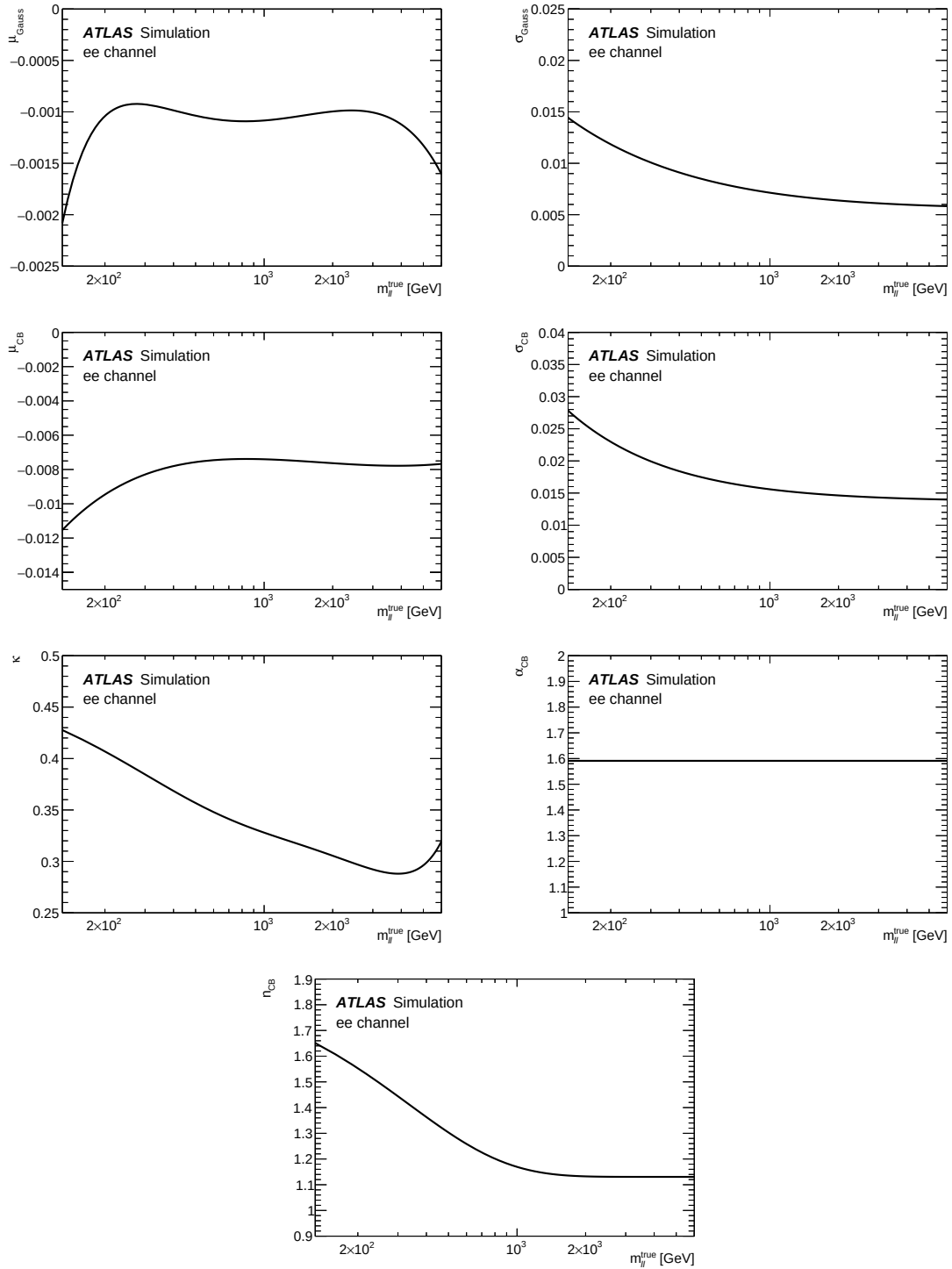


Figure 6.5: $m_{\ell\ell}^{\text{truth}}$ -dependence of the TF parameters after the simultaneous fit in the ee channel. The behaviour of κ reflects the relative importance of the tails inside the parametrisation, as κ gives the fraction of the Crystal-Ball component inside the total pdf. At low $m_{\ell\ell}^{\text{truth}}$, FSR effects are expected to have a higher relative importance, as more FSR photons might not be reconstructed as part of the electrons. Due to the higher E_T , and thus a higher collimation, this effect is reduced at high $m_{\ell\ell}^{\text{truth}}$. The increase above $m_{\ell\ell}^{\text{truth}}$ values of 4 TeV might be related with detector properties like punch through effects.

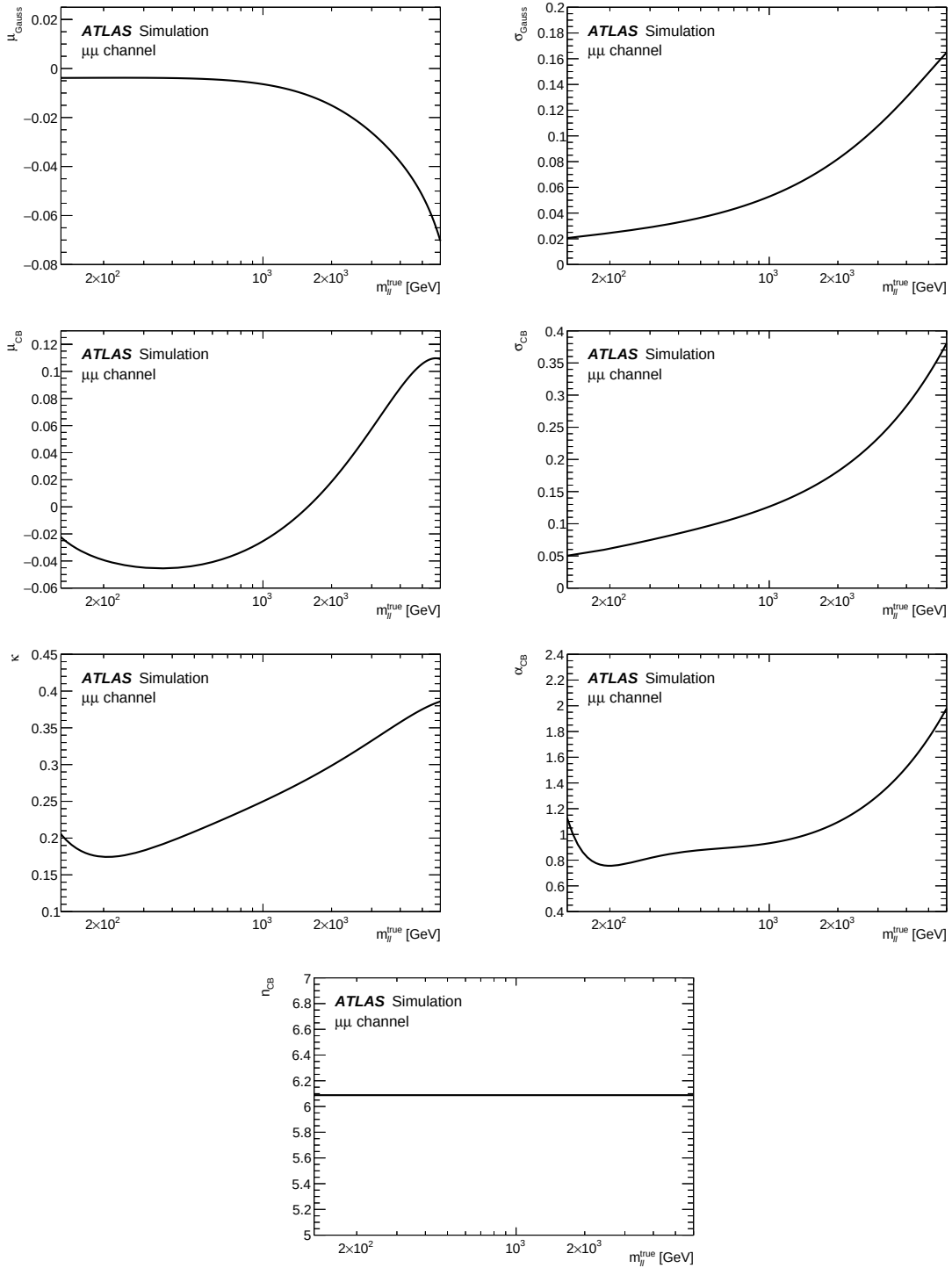


Figure 6.6: $m_{\ell\ell}^{\text{truth}}$ -dependence of the TF parameters after the simultaneous fit in the $\mu\mu$ channel. The interplay between μ_{CB} and μ_{G} is expected to be related with the tail behaviour. While at low $m_{\ell\ell}^{\text{truth}}$ the response tails are more pronounced in the negative region (potentially due to energy losses before the MS), at high $m_{\ell\ell}^{\text{truth}}$ stronger tails are visible for positive response values (potentially due to the approximately Gaussian behaviour in the q/p measurements, which creates longer tails towards high p_{T} values). μ_{CB} and μ_{G} balance each other to describe these changes.

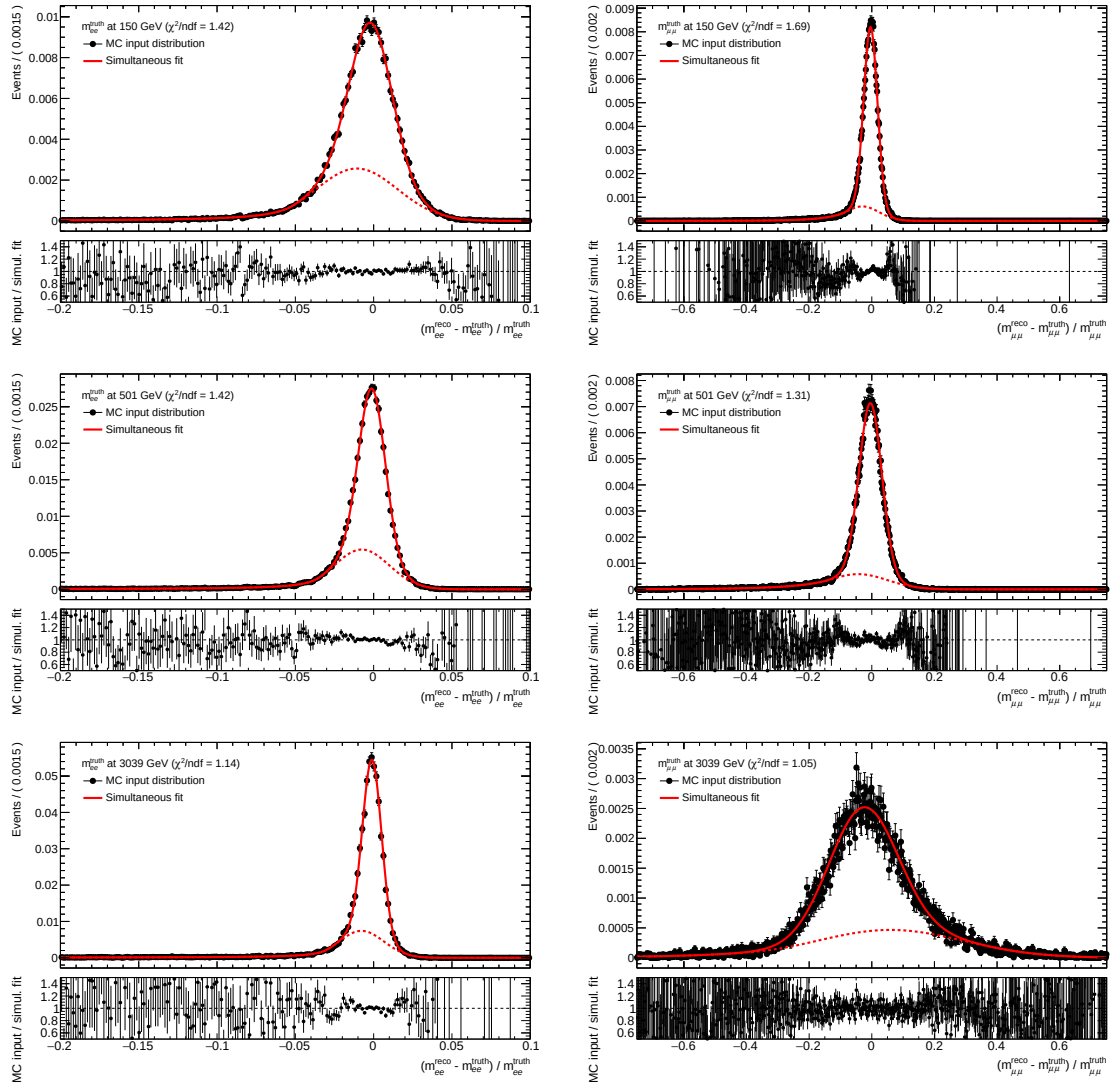


Figure 6.7: Examples of the response description after the simultaneous fit for the ee (left) and $\mu\mu$ (right) channels. Three different truth mass regions are shown and the mean truth mass is given in the legend of the figures. The red line corresponds to the functional description by the sum of a Crystal-Ball (red dashed line) and a Gaussian.

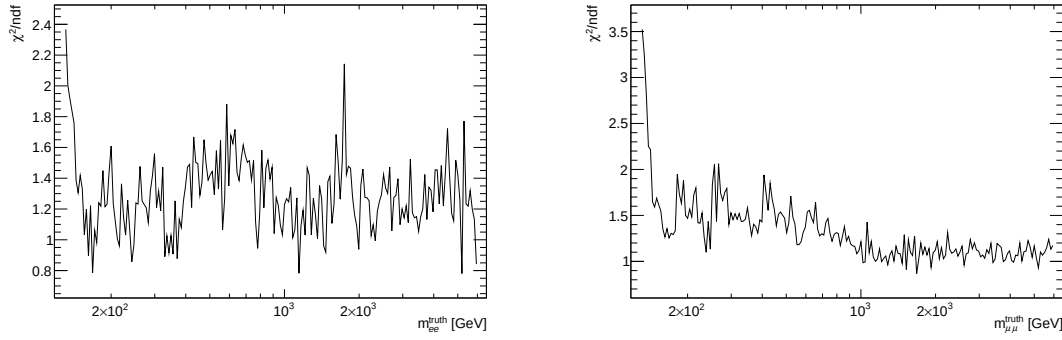


Figure 6.8: χ^2/ndf distributions of the response description after the simultaneous fit for the ee (left) and $\mu\mu$ (right) channels. Only the region with $m_{\ell\ell}^{\text{truth}} \geq 250$ GeV is later used for the signal modelling.

The relative mass resolution is extracted by combining the width parameters according to their relative weight:

$$\sigma_{\text{combined}}(m_{\ell\ell}^{\text{truth}}) = \sqrt{\kappa(m_{\ell\ell}^{\text{truth}}) \cdot \sigma_{\text{CB}}^2(m_{\ell\ell}^{\text{truth}}) + (1 - \kappa(m_{\ell\ell}^{\text{truth}})) \cdot \sigma_G^2(m_{\ell\ell}^{\text{truth}})}. \quad (6.4)$$

The resulting values are given in Figure 6.9 and compare well with detector mass resolution values of the previous analysis round [132], although the extraction method is considerably extended and tail effects are incorporated more precisely.

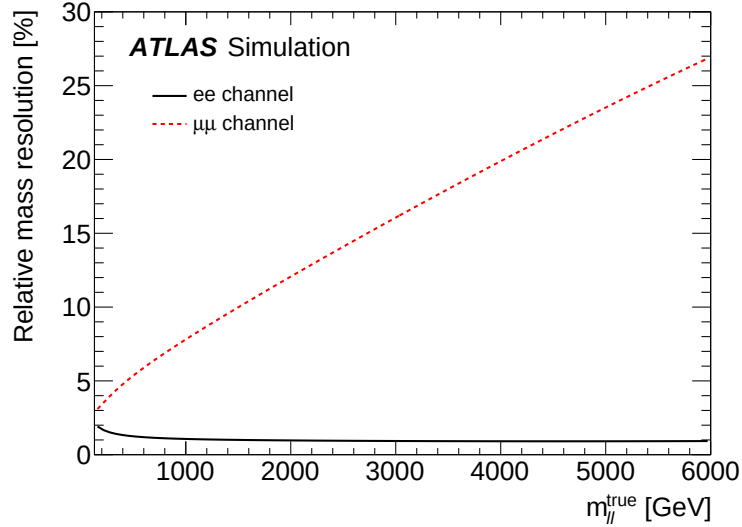


Figure 6.9: Relative dilepton invariant mass resolution for the ee and $\mu\mu$ channels as a function of $m_{\ell\ell}^{\text{truth}}$. The ee mass resolution is given by the LAr detector properties and its sampling term for high m_{ee} . The $\mu\mu$ mass resolution degrades for high $m_{\mu\mu}$ due to the low muon track curvature and thus the increasing relative error on the Sagitta measurement.

6.3.3 Validation with 0-width samples

Fullsim MC samples with a 0-width truth lineshape at 11 pole masses between 90 GeV and 5 TeV allow to validate the description of the transfer functions. For the 0-width samples, the $m_{\ell\ell}^{\text{truth}}$ value is treated

to be equal to the pole mass, as the intrinsic resonance width of 20 MeV is negligible. The 0-width samples thus have a fixed $m_{\ell\ell}^{\text{truth}}$ and allow to probe $P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}})$ without averaging over a truth mass range, like performed for the TF derivation from the DY samples. The results of this comparison are given in Figure 6.10. A good closure between the predicted shape, obtained using transfer functions from the NLO DY samples that are evaluated at a given $m_{\ell\ell}^{\text{truth}}$, and the fullsim MC shape from the 0-width samples is observed. This confirms that the $m_{\ell\ell}^{\text{truth}}$ binning chosen is fine enough for the mass resolution parametrisation.

6.3.4 Calculation of the acceptance times efficiency

The probability to reconstruct and select an event with $m_{\ell\ell}^{\text{truth}}$, i.e. the acceptance times efficiency, $A\epsilon(m_{\ell\ell}^{\text{truth}})$, is determined from the fullsim NLO DY MC samples according to

$$A\epsilon(m_{\ell\ell}^{\text{truth}}) = \frac{\text{events passing selection cuts}}{\text{truth events in MC sample}} \bigg|_{m_{\ell\ell}^{\text{truth}} \text{ within bin}}. \quad (6.5)$$

The obtained $A\epsilon$ distributions for the ee and $\mu\mu$ channels are shown in Figure 6.11. The same $m_{\ell\ell}^{\text{truth}}$ binning and range as in Subsection 6.3.2 is used. A functional description of $A\epsilon_{ee}(m_{\ell\ell}^{\text{truth}})$ and $A\epsilon_{\mu\mu}(m_{\ell\ell}^{\text{truth}})$ is given by Equations C.1 and C.2 of Appendix C.2, respectively.

6.3.5 Uncertainty of transfer function modelling due to limited MC statistics

The uncertainty of the TF fits, i.e. the simultaneous fit to the response and the acceptance times efficiency parametrisation, is determined using a bootstrapping technique for the available NLO DY MC samples.

In order to obtain statistically different samples, each of the MC events is weighted according to a Poisson distribution with a mean of one. 10000 of such bootstrap MC samples are generated with different seeds and the TF fits are performed on each of them. Based on this fit ensemble, it is possible to extract the distribution of each TF parameter, the correlation between the parameters as well as the uncertainty on the final TF variables. Figures 6.12 and 6.13 depict the uncertainties on the TF variables. It can be observed that the μ_G and μ_{CB} parameters are well determined, as small changes of these parameters directly impact the quality of the description significantly. σ_G and σ_{CB} exhibit slightly higher uncertainties, which are about 1% throughout the $m_{\ell\ell}^{\text{truth}}$ range. The parameters related to the tail behaviour of the TFs, κ , α_{CB} and n_{CB} , show larger uncertainties in the order of several percent. The TF variables exhibit correlations between them, such that the impact of these uncertainties does not directly transfer to the full TF shape.

The fluctuations for the full TF shapes are given in Figure 6.14 for several mass points. It can be observed that the variations are small in the peak region and only have a significant size in the tails of the distribution. The uncertainty on the TF shape is thus neglected in the statistical analysis due to the very low number of events in these regions and since the TF shape uncertainty is additionally considerably smaller than the experimental uncertainties described in Section 6.6.

The uncertainties on the acceptance times efficiency parametrisation are shown in Figure 6.15. Higher uncertainties can be observed at the edges of the distribution, where the functional fit is less constrained. The relative uncertainty is below 0.5% for the full mass range and typically at a level of 0.1% for both channels. The uncertainty is therefore also neglected.

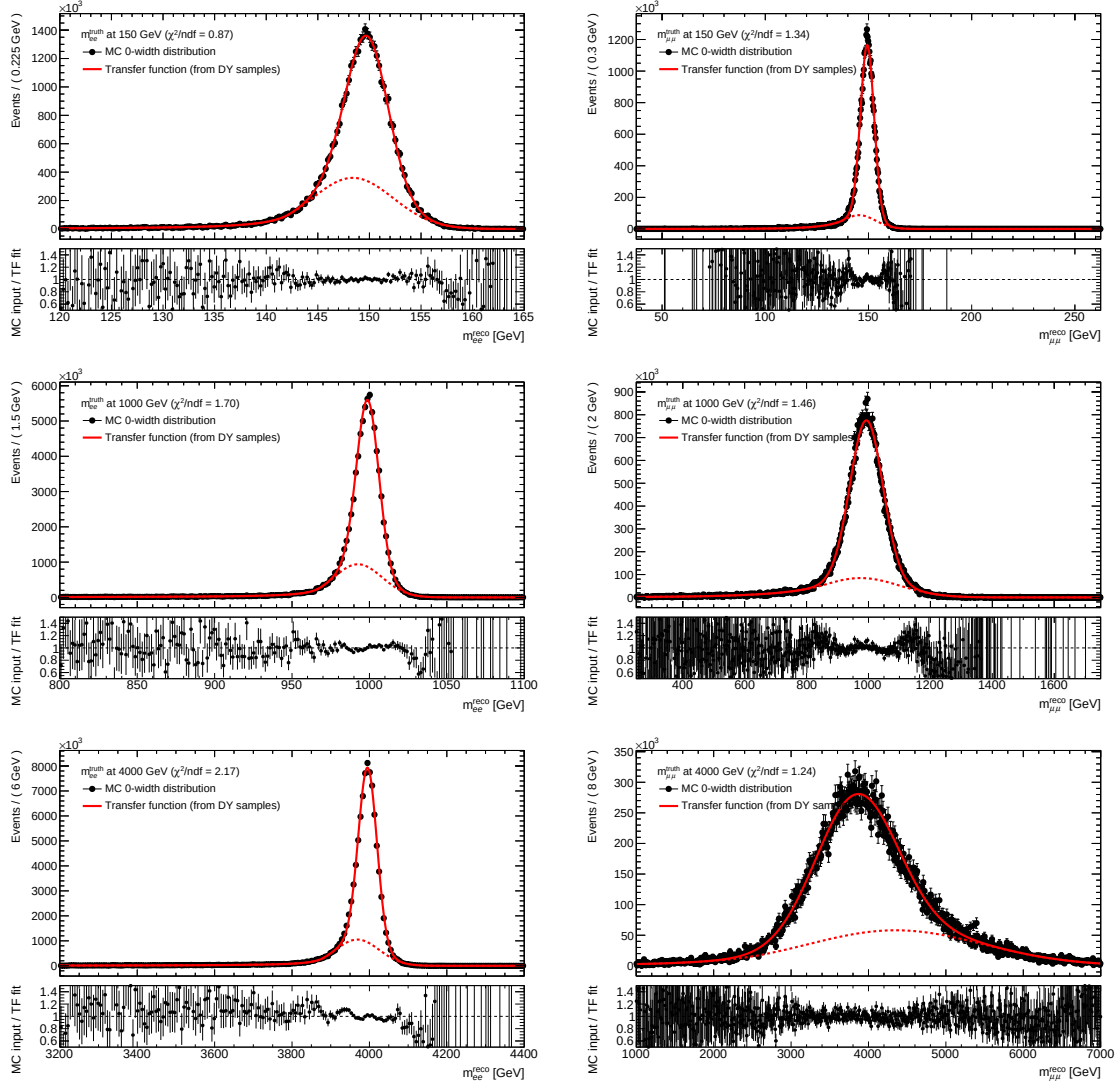


Figure 6.10: Validation of the TF parametrisation using MC samples with a 0-width truth lineshape for the ee (left) and $\mu\mu$ (right) channels. Three different pole masses are depicted. The functional description of the transfer functions (given by the red line and its Crystal-Ball component by the red dashed line) is completely independent of the fullsim MC samples (black data points) and agrees well for the full invariant mass region.

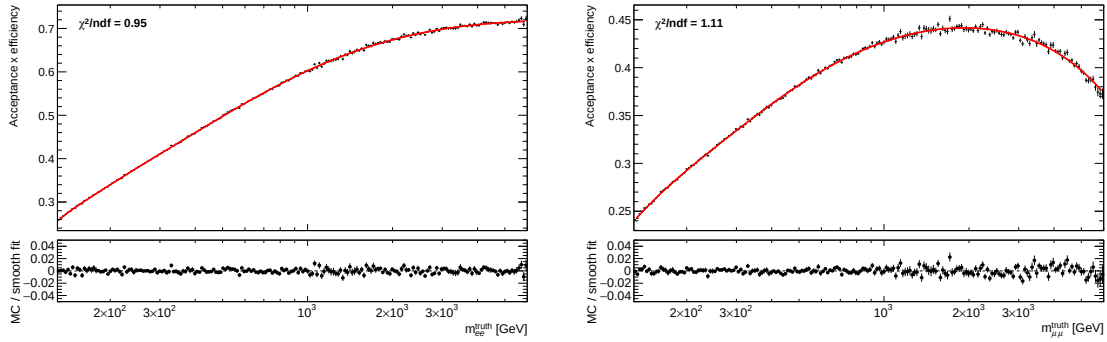


Figure 6.11: Acceptance times efficiency in the ee (left) and $\mu\mu$ (right) channels. A polynomial fit (red line) is performed to the values obtained from fullsim MC (black points). The error bands are due to MC statistics and have a non-linear behaviour due to the mass-sliced DY MC samples.

6.4 Background smoothing with transfer functions

6.4.1 Background smoothing for Drell-Yan production

The general procedure to combine truth-only MC samples and the transfer functions is described in Subsection 6.3.1. The generation of the reconstruction-level spectrum is implemented according to Equation 6.6 with a step size of 0.1 GeV, i.e. considerably below the detector resolution for both channels, to avoid any small-scale effects due to mass shifts.

$$S_{\text{reco}}(m_{\ell\ell}^{\text{reco}}) = \sum_{m_{\ell\ell}^{\text{truth}} \text{ bins with 0.1 GeV step size}} P(m_{\ell\ell}^{\text{reco}} | m_{\ell\ell}^{\text{truth}}) \cdot A\varepsilon(m_{\ell\ell}^{\text{truth}}) \cdot S_{\text{truth}}(m_{\ell\ell}^{\text{truth}}). \quad (6.6)$$

The resulting $S_{\text{reco}}(m_{\ell\ell}^{\text{reco}})$ histogram is thus, due to the analytic description of the transfer functions, smooth and can be determined with an arbitrary bin width. The precision limit in the TF method is mainly given by the fluctuations in the $S_{\text{truth}}(m_{\ell\ell}^{\text{truth}})$ spectrum, which can be obtained very precisely with truth-only MC, and the parametrisation accuracy of $P(m_{\ell\ell}^{\text{reco}} | m_{\ell\ell}^{\text{truth}})$ and $A\varepsilon(m_{\ell\ell}^{\text{truth}})$. In contrast, spectra based on fullsim MC show large fluctuations at a fine granularity (e.g. a bin width of 0.1 GeV) due to the underlying MC statistics. The resulting histogram is afterwards re-binned according to the needs of the statistical analysis code.

The validation of the procedure is performed on statistically independent samples by using 50% of the fullsim MC to determine the transfer functions, the truth-level spectrum and the acceptance times efficiency, while the other 50% are used to obtain a fullsim reconstruction-level shape. A comparison between these two options is given in Figure 6.16 and shows good agreement.

The final smooth background spectra are given in Figure 6.17 and again show a good agreement with the superimposed fullsim MC shape. The TF smoothed templates are used for the determination of the spurious signal in Subsection 6.8.3. The impact of the template uncertainties due to the available truth-only MC statistics on the spurious signal estimate is expected to be small.

6.4.2 Application of the TF approach to $t\bar{t}$ production

The production of top-quark pairs is another important background in the dilepton search and thus any large fluctuations in its MC shape might also affect the spurious signal determination. The application of the transfer function method is possible if exactly two prompt leptons are produced in the $t\bar{t}$ decay,

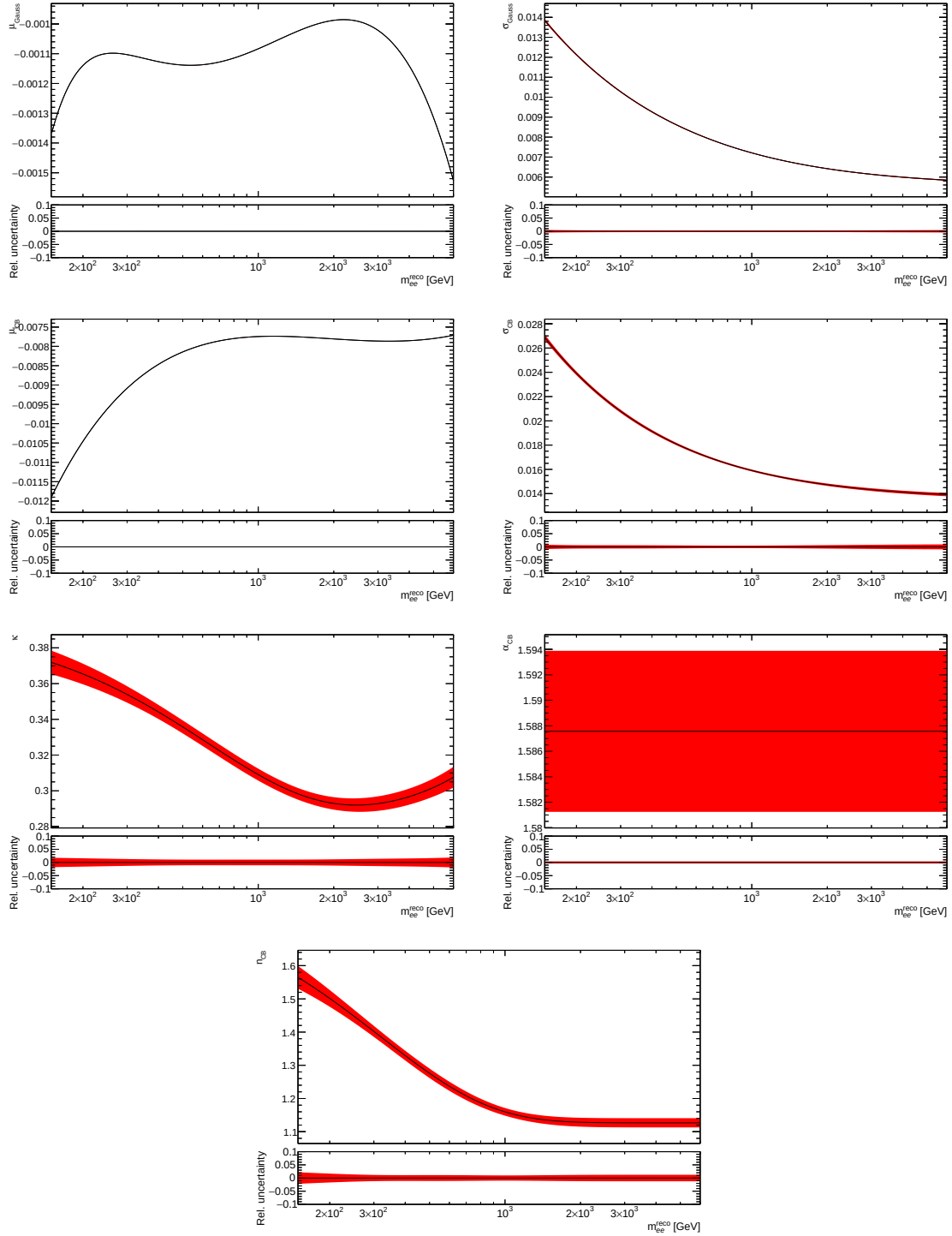


Figure 6.12: $m_{\ell\ell}^{\text{truth}}$ -dependence and uncertainty bands of the TF parameters after the simultaneous fit in the ee channel. The shown variables are, from top left to bottom right, μ_G , σ_G , μ_{CB} , σ_{CB} , κ , α_{CB} and n_{CB} . The given uncertainty band is due to the available fullsim MC statistics and evaluated by using a bootstrapping technique.

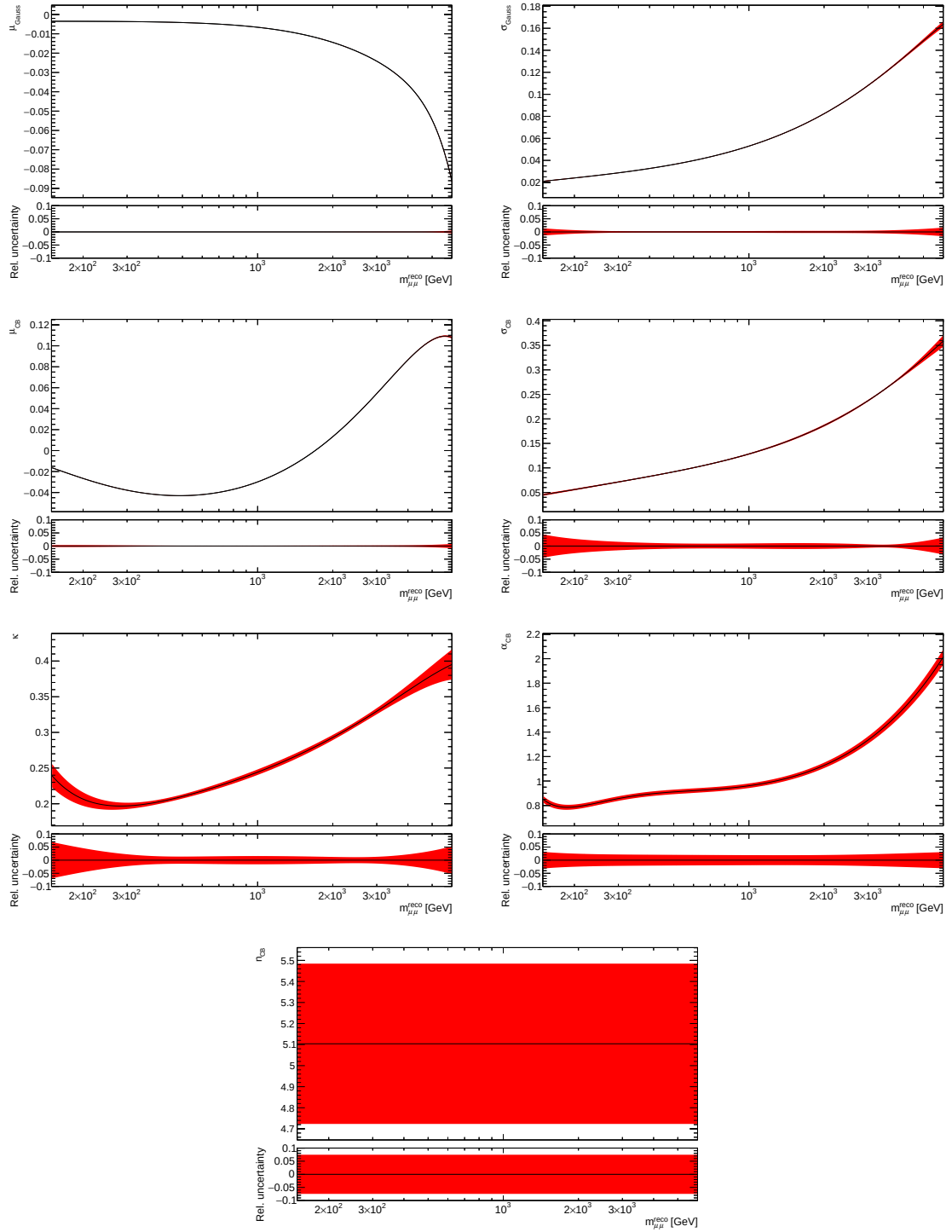


Figure 6.13: $m_{\ell\ell}^{\text{truth}}$ -dependence and uncertainty bands of the TF parameters after the simultaneous fit in the $\mu\mu$ channel. The shown variables are, from top left to bottom right, μ_{G} , σ_{G} , μ_{CB} , σ_{CB} , κ , α_{CB} and n_{CB} . The given uncertainty band is due to the available fullsim MC statistics and evaluated by using a bootstrapping technique.

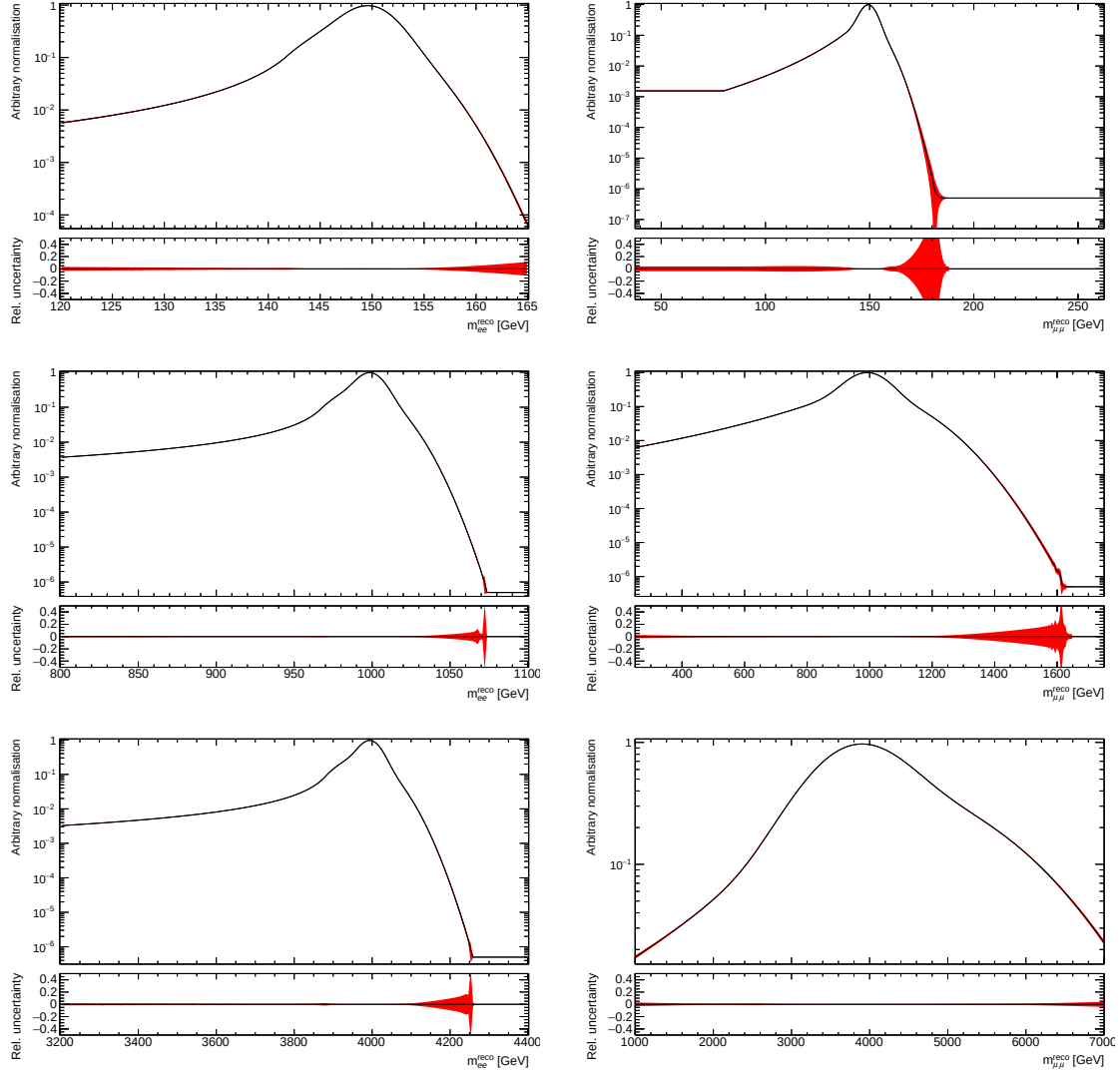


Figure 6.14: Uncertainties on the TF shape, $P(m_{\ell\ell}^{\text{reco}}|m_{\ell\ell}^{\text{truth}})$, for the ee (left) and $\mu\mu$ (right) channels at $m_{\ell\ell}^{\text{truth}} = 150$ GeV (top row), 1 TeV (middle row) and 4 TeV (bottom row). The given uncertainty band is due to the available fullsim MC statistics and evaluated by using a bootstrapping technique. Higher uncertainties can be observed in the tails of the distribution, which have an overall low impact on the final results. The uncertainties increase towards higher pole masses due to the lower available MC statistics.

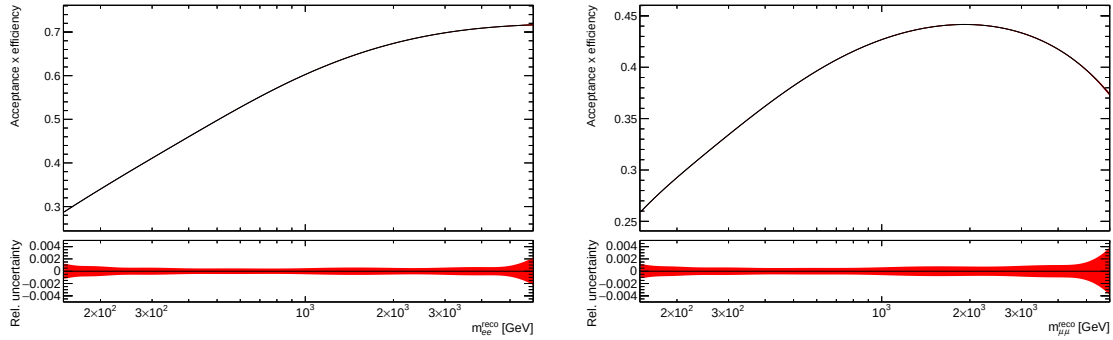


Figure 6.15: Uncertainties on the acceptance times efficiency parametrisation for the ee (left) and $\mu\mu$ (right) channels. The given uncertainty band is due to the available fullsim MC statistics and evaluated by using a bootstrapping technique. Higher uncertainties can be observed at the edges of the distribution, where the functional fit is less constrained.

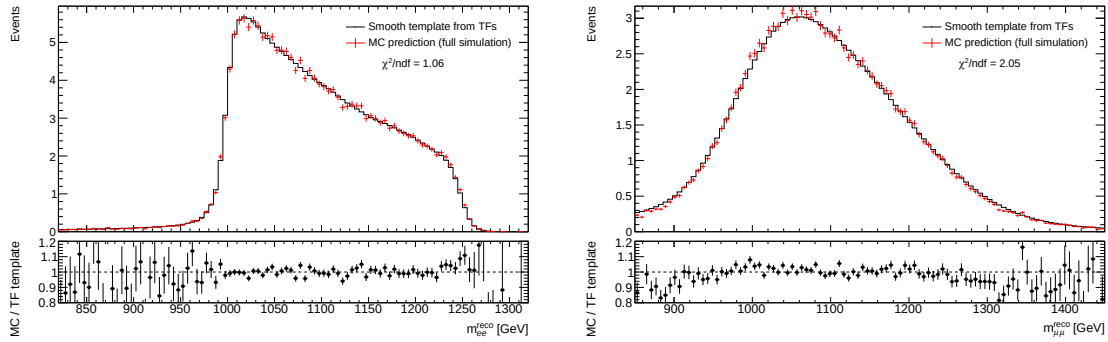


Figure 6.16: Example of independently obtained spectra using TFs (black line) compared with the fullsim MC prediction (red points) in the ee (left) and $\mu\mu$ (right) channels. The $m_{\ell\ell}^{\text{truth}} \in [1.0 \text{ TeV}, 1.25 \text{ TeV}]$ mass-slice of the DY MC is split into one half, which is used for the TF determination, and a second half, which is used as the test sample. The $m_{\ell\ell}^{\text{truth}}$ distribution thus only covers the 1 – 1.25 TeV region and is smeared into a broader $m_{\ell\ell}^{\text{reco}}$ distribution due to the detector reconstruction. Good agreement between the two options is found, while the TF shape is considerably more smooth. The small deviations in the tails of the $\mu\mu$ distribution are not expected to deteriorate the agreement when smoothing the full mass distribution.

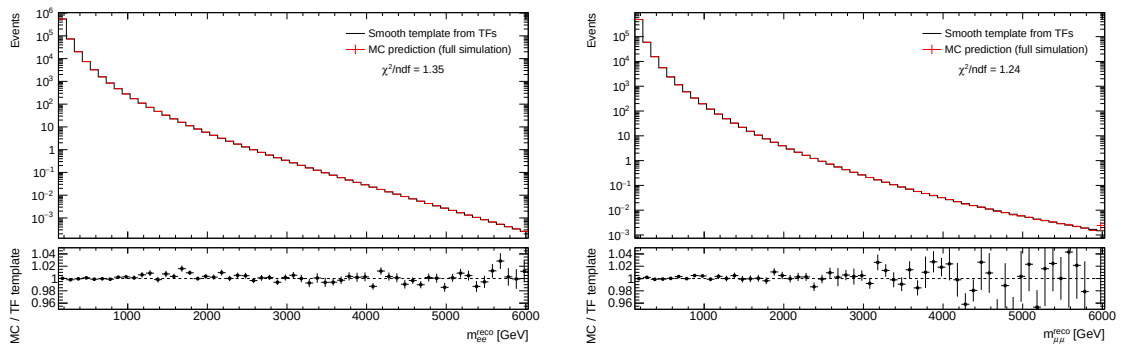


Figure 6.17: Final TF-smoothed templates in the Drell-Yan channel for the dielectron (left) and dimuon (right) channels, normalised to the integrated luminosity of the full Run 2 dataset. The shown uncertainties are predominantly due to the MC statistics in the fullsim samples.

which is true for $t\bar{t} \rightarrow ee, e\tau, \mu\mu$ and $\mu\tau$ decays. Their fraction within the selected events is 99.2% and 99.4% for the ee and $\mu\mu$ channels, respectively, and thus a significant improvement in the spurious signal determination is expected from their smoothing. The decay mode of the $t\bar{t}$ pair can be determined from truth information inside the MC samples by selecting particles that emerge from the W boson decays associated to the top-quark decays.

The value for $m_{\ell\ell}^{\text{reco}}$ is again obtained using the nominal selection of the analysis. The truth mass definition for $t\bar{t}$ production is adjusted for the two considered types of decay modes:

1. $\ell\ell$ ($\ell \in [e, \mu]$): The four-momenta of the selected decay products of the W bosons are summed.
2. $\ell\tau$ ($\ell \in [e, \mu]$): The four-momenta of the electron/muon from the W boson decay and the electron/muon from the τ lepton decay are summed.

In both cases the truth mass is again obtained before FSR.

A precise determination of $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$ from a dedicated fit is found to be difficult to achieve due to the limited statistics in the $t\bar{t}$ fullsim MC samples at high invariant masses. For the full $m_{\ell\ell}^{\text{truth}}$ spectrum, the response is thus compared between $t\bar{t}$ and DY production and found to be similar, as shown in Figure 6.18, although small remaining offsets are visible. The differences are expected to emerge from the different kinematics of the underlying processes or potential small differences in the MC generator tuning. The dominating $\ell\ell$ decay modes exhibit smaller differences towards the DY response distribution than the $\ell\tau$ decay modes.

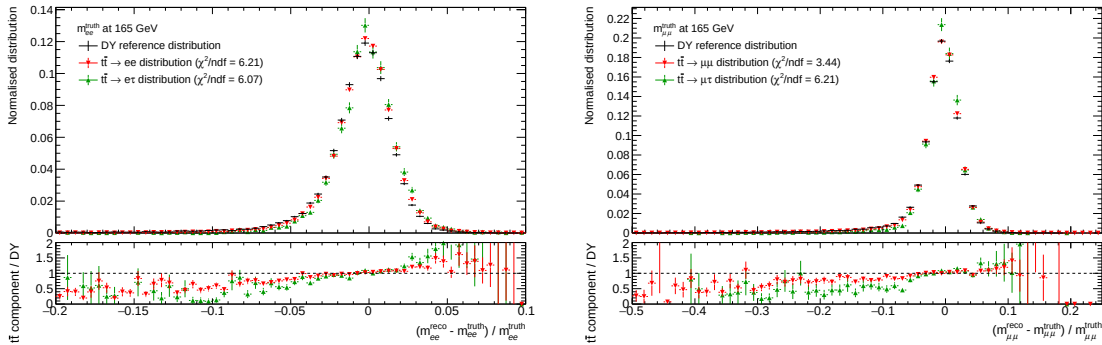


Figure 6.18: Comparison of the response distributions in $t\bar{t} \rightarrow ee (\rightarrow \mu\mu)$ and $t\bar{t} \rightarrow e\tau (\rightarrow \mu\tau)$ events with the response of $Z/\gamma^* \rightarrow ee (\rightarrow \mu\mu)$ production used to derive the nominal TFs in the left (right) figure.

A correction for the remaining offset in the response description is obtained from the inclusive, i.e. not binned in $m_{\ell\ell}^{\text{truth}}$, distributions for the $\ell\ell$ and $\ell\tau$ channels separately. The correction is extracted from the ratio between the DY and the $t\bar{t}$ response and subsequently used to modify the $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$ parametrisation from the DY TFs in the smoothing process. The inclusive response distributions before the correction are shown in Figures 6.19 and 6.20, together with the functional fit to the ratio histogram. The chosen correction function is given by the following equation:

$$\delta(\mathcal{R}) = \tanh[\delta_1 \cdot (\mathcal{R} - \delta_2)] \cdot \delta_3 + \delta_4. \quad (6.7)$$

The parameters of $\delta(\mathcal{R})$ are extracted for the $ee, e\tau, \mu\mu$ and $\mu\tau$ decay channels separately. The correction

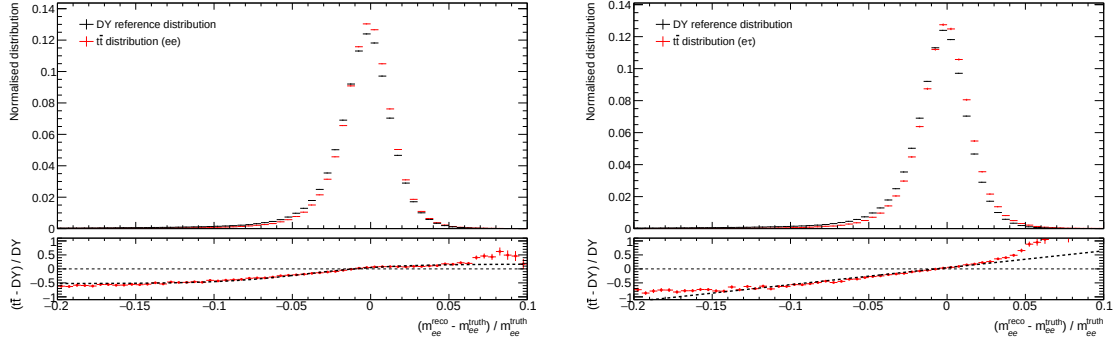


Figure 6.19: Inclusive response distributions in the $t\bar{t} \rightarrow ee$ (left) and $t\bar{t} \rightarrow e\tau$ (right) channels, compared to the reference distribution from DY MC samples. The relative difference between the distributions is shown in the lower part of the figures, together with a functional fit according to Equation 6.7. The small deviation in the $\mathcal{R}$ tails is not expected to deteriorate the correction.

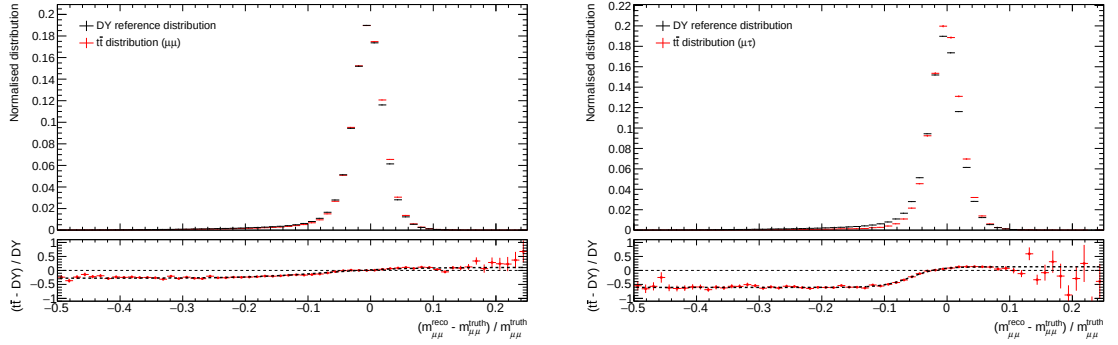


Figure 6.20: Inclusive response distributions in the $t\bar{t} \rightarrow \mu\mu$ (left) and $t\bar{t} \rightarrow \mu\tau$ (right) channels, compared to the reference distribution from DY MC samples. The relative difference between the distributions is shown in the lower part of the figures, together with a functional fit according to Equation 6.7.

factor is subsequently applied in the smoothing process according to

$$S_{\text{reco}}(m_{\ell\ell}^{\text{reco}}) = \sum_{0.1 \text{ GeV } m_{\ell\ell}^{\text{truth}} \text{ bins}} \left[P_{\text{DY}}(m_{\ell\ell}^{\text{reco}} | m_{\ell\ell}^{\text{truth}}) \cdot \left(1 + \delta \left(\frac{m_{\ell\ell}^{\text{reco}} - m_{\ell\ell}^{\text{truth}}}{m_{\ell\ell}^{\text{truth}}} \right) \right) \right] \cdot A\mathcal{E}(m_{\ell\ell}^{\text{truth}}) \cdot S_{\text{truth}}(m_{\ell\ell}^{\text{truth}}). \quad (6.8)$$

Compared to Equation 6.6, which describes the smoothing for the DY spectra, the correction factor is applied in addition. Due to the correction, it is possible to use the TF parametrisation in the full mass range based on the DY MC, while a proper agreement with the $t\bar{t}$ response is ensured due to the correction factor. The agreement of the DY and $t\bar{t}$ response distributions after the correction is shown in Figures 6.21 and 6.22.

The acceptance times efficiency needs to be determined and fitted in each decay channel of the $t\bar{t}$ production separately due to the different reconstruction efficiencies, as for example the τ lepton decay products have typically a lower energy than their directly-produced counterparts. The resulting distributions are given in Figures 6.23 and 6.24. Due to the low statistics for the acceptance times efficiency determination above $m_{\ell\ell}^{\text{truth}} \gtrsim 1.5 \text{ TeV}$, a functional parametrisation is chosen that exhibits a stable behaviour in the high $m_{\ell\ell}^{\text{truth}}$ region.

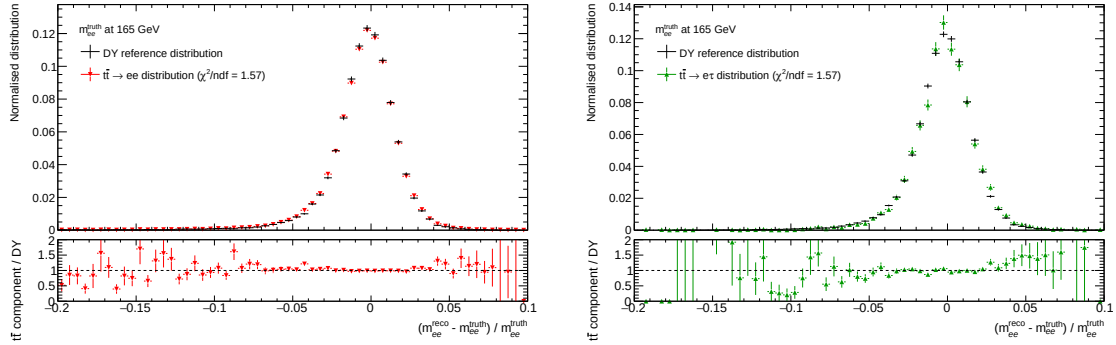


Figure 6.21: Comparison of the response distributions in $t\bar{t} \rightarrow ee$ (left) and $t\bar{t} \rightarrow e\tau$ (right) events with the response of $Z/\gamma^* \rightarrow ee$ production used to derive the nominal TFs after the correction factor is applied. Compared to Figure 6.18, a considerably improved agreement can be observed.

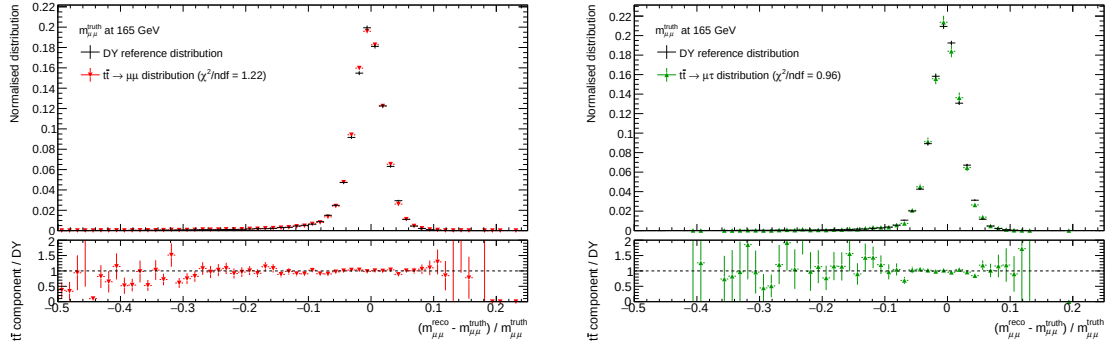


Figure 6.22: Comparison of the response distributions in $t\bar{t} \rightarrow \mu\mu$ (left) and $t\bar{t} \rightarrow \mu\tau$ (right) events with the response of $Z/\gamma^* \rightarrow \mu\mu$ production used to derive the nominal TFs after the correction factor is applied. Compared to Figure 6.18, a considerably improved agreement can be observed.

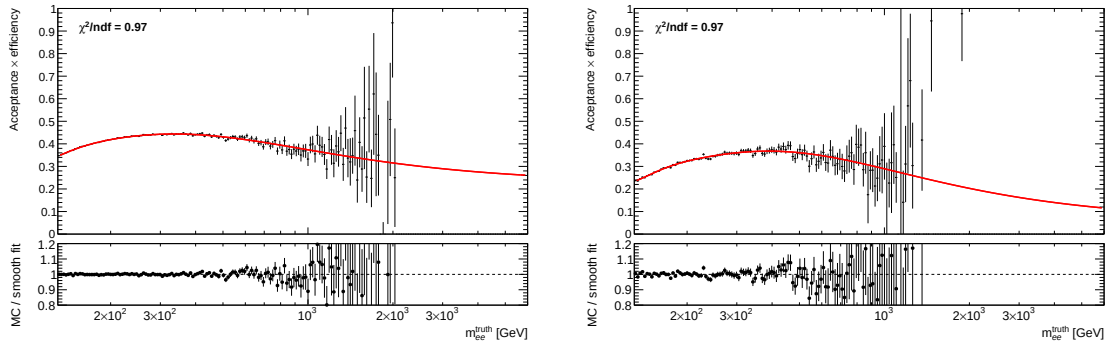


Figure 6.23: Acceptance times efficiency distribution in $t\bar{t} \rightarrow ee$ (left) and $t\bar{t} \rightarrow e\tau$ (right) events. The functional parametrisation is chosen to have a stable behaviour in the low statistics region for $m_{\ell\ell}^{\text{truth}} \gtrsim 1.5$ TeV. While only few events are available to constrain the parametrisation in this mass region, the number of $t\bar{t}$ events is similarly reduced and thus not expected to affect the statistical analysis.

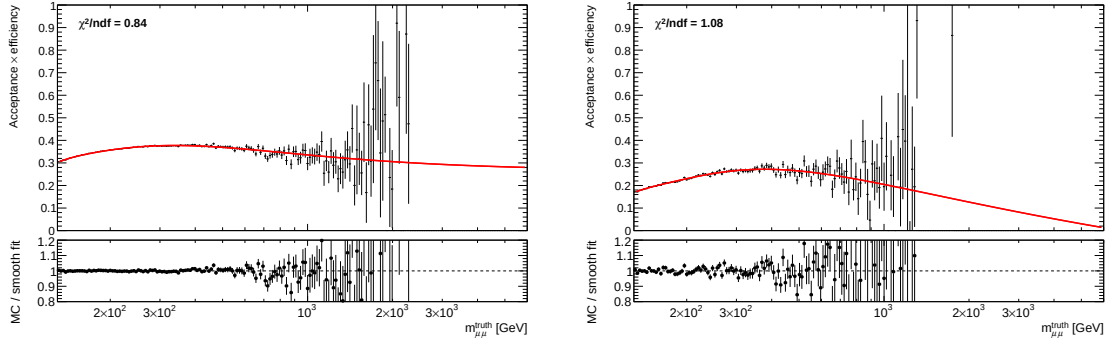


Figure 6.24: Acceptance times efficiency distribution in $t\bar{t} \rightarrow \mu\mu$ (left) and $t\bar{t} \rightarrow \mu\tau$ (right) events. The functional parametrisation is chosen to have a stable behaviour in the low statistics region for $m_{\ell\ell}^{\text{truth}} \gtrsim 1.5$ TeV. While only few events are available to constrain the parametrisation in this mass region, the number of $t\bar{t}$ events is similarly reduced and thus not expected to affect the statistical analysis.

The $t\bar{t}$ decay modes other than ee ($\mu\mu$) and $e\tau$ ($\mu\tau$) in the dielectron (dimuon) channel only have a contribution of less than 1% to the final spectrum. Their contributions are shown in Figures 6.25 and 6.26 in comparison with the total $t\bar{t}$ spectrum. The additional decay modes either do not show considerable differences in the $m_{\ell\ell}^{\text{reco}}$ shape or only have higher relative contribution in the high-mass end of the $t\bar{t}$ spectrum, where the impact on the final analysis is negligible⁸. While their overall contribution is small, the impact of statistical fluctuations from these components in the final smoothed spectrum is non-negligible. They are thus neglected and the overall normalisation of the smoothed $\ell\ell$ and $\ell\tau$ ($\ell \in [e, \mu]$) components adjusted to match the total amount of $t\bar{t}$ events.

The final smoothed spectra for $t\bar{t}$ production are shown in Figure 6.27 and show a good agreement with the fullsim MC samples. Smooth templates can be obtained until $m_{\ell\ell} \simeq 2$ TeV. For higher invariant masses, the templates exhibit non-smooth features due to the available MC statistics on truth- and reconstruction-level, which is not sufficient to obtain fully smooth templates even with the described smoothing procedure⁹. As the fraction of $t\bar{t}$ events compared to the total event yield is $< 5\%$ in the high-mass region, no significant impact is expected from the non-smooth behaviour.

6.5 Signal modelling with transfer functions

The transfer functions directly model the signal shape for 0-width resonances, as is described in Subsection 6.3.1 and also used for the method validation in Subsection 6.3.3. The modelling of generic signal shapes can be obtained by a convolution of the transfer functions with a truth line-shape according to Equation 6.1. $S_{\text{truth}}(m_{\ell\ell}^{\text{truth}})$ in this case describes the truth line-shape of the chosen model.

The generic signal with non-zero width for this resonant dilepton search is chosen to be modelled by a non-relativistic Breit-Wigner truth line-shape [143], which is selected to facilitate an easy reinterpretation of the results. The relative width of the resonance, Γ/m , is chosen to be constant as a function of the pole mass. Examples of reinterpretations from the generic limits of the previous analysis round can e.g. be found in Refs. [144] and [131]. The convolution of the truth lineshape with the TFs is implemented using a RooFit RooFFTConvPdf object [145]. An example of the convolution can be found in Figure 6.28 for

⁸ The $t\bar{t}$ spectrum falls considerably faster with $m_{\ell\ell}^{\text{reco}}$ than the dominating DY background component, such that the impact is reduced towards high $m_{\ell\ell}^{\text{reco}}$.

⁹ The $t\bar{t}$ MC samples are not available as samples that are sliced in $m_{\ell\ell}^{\text{truth}}$.

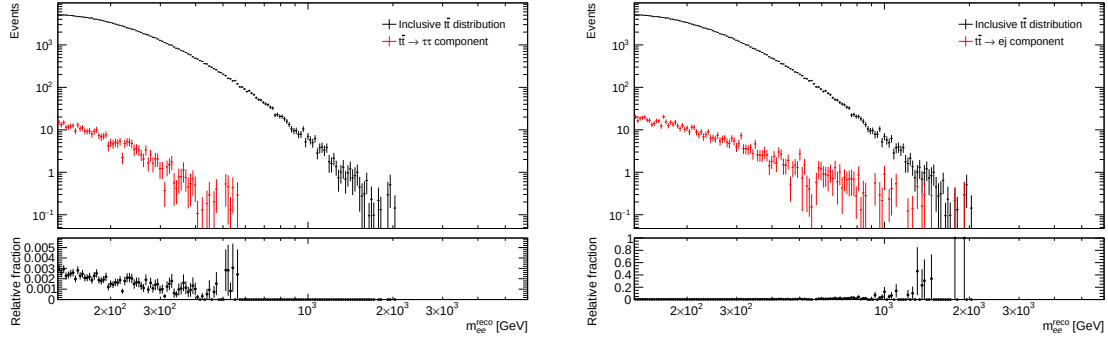


Figure 6.25: Reconstructed invariant mass distribution for the two $t\bar{t}$ decay modes with the highest contributions after ee and $e\tau$ in the dielectron channel, $\tau\tau$ (left) and $e + \text{jet}$ (right).

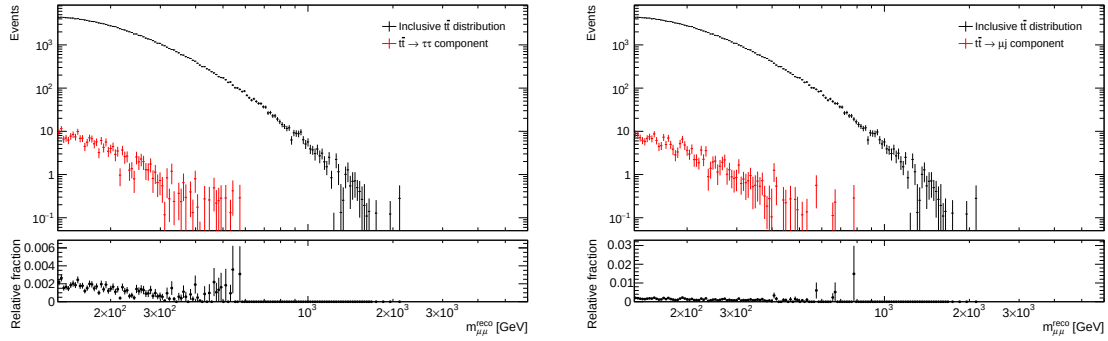


Figure 6.26: Reconstructed invariant mass distribution for the two $t\bar{t}$ decay modes with the highest contributions after $\mu\mu$ and $\mu\tau$ in the dimuon channel, $\tau\tau$ (left) and $\mu + \text{jet}$ (right).

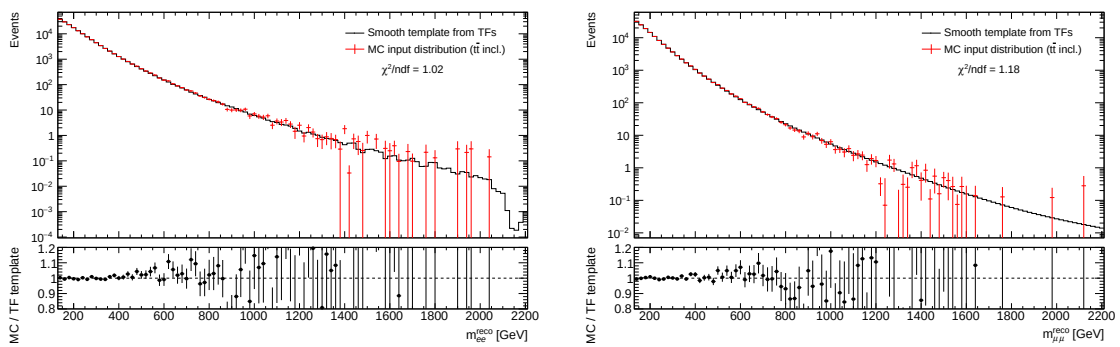


Figure 6.27: Comparison of the invariant mass distribution after TF smoothing and neglecting minor $t\bar{t}$ decay channels (black line) and the complete fullsim MC template (red points) for the ee (left) and $\mu\mu$ (right) channels. Smooth templates can be obtained until $m_{\ell\ell} \approx 2 \text{ TeV}$. For higher invariant masses, the templates exhibit non-smooth features (especially in the ee channel) due to the available MC statistics on truth- and reconstruction-level, which is not sufficient to obtain fully smooth templates even with the described smoothing procedure.

both channels.

In order to allow reinterpretations of the results, the fiducial volume for the signal processes is defined as follows:

- $p_{T,\ell}^{\text{truth}} > 30 \text{ GeV}$, applied to the leading and subleading lepton on truth-level.
- $|\eta_\ell^{\text{truth}}| < 2.5$, applied to the leading and subleading lepton on truth-level.
- $m_{\ell\ell}^{\text{truth}} - m_X > -2\Gamma_X$, with m_X as the pole mass of the resonance and Γ_X as the resonance width.

The cuts for the fiducial volume are applied to the leptons and the dilepton object before FSR. The fiducial volume cuts need to be applied for the signal cross-section and efficiency calculations. The definition mainly follows the procedure from the previous analysis round [132].

The restriction on the truth invariant mass is needed due to the model-dependence of the tails in the $m_{\ell\ell}^{\text{truth}}$ spectrum of potential new resonances, which might dominate the total cross-section while not having a significant impact on the statistical analysis. The model-dependence of the tails has been studied and is found to be large for the low-mass tail, while the high-mass tail exhibits considerably smaller variations for different models. A one-sided cut is thus chosen instead of a two-sided implementation, which avoids additional acceptance losses. The mass cut is additionally expected to reduce the impact of interference effect on the analysis [146].

While the cuts to define fiducial volume affect the truth-level lineshape, the cuts on p_T and η do not alter the response distribution as given in Subsection 6.3.2 and thus the same transfer function parametrisation can be used¹⁰.

In addition to the acceptance times efficiency values described in Subsection 6.3.4, the definition of the fiducial volume allows to obtain separate acceptance and efficiency curves for 0-width resonances. The definition of both quantities is given in Equations 6.9 and 6.10:

$$A(m_{\ell\ell}^{\text{truth}}) = \frac{\text{truth events passing acceptance cuts}}{\text{truth events in MC sample}} \bigg|_{m_{\ell\ell}^{\text{truth}} \text{ within bin}}, \quad (6.9)$$

$$\varepsilon(m_{\ell\ell}^{\text{truth}}) = \frac{\text{events passing selection cuts}}{\text{truth events passing acceptance cuts}} \bigg|_{m_{\ell\ell}^{\text{truth}} \text{ within bin}}. \quad (6.10)$$

The results are given in Figures 6.29 and 6.30 for the acceptance and efficiency, respectively, and are derived from NLO DY MC samples. The acceptance in both channels agrees well, as expected, and increases for high $m_{\ell\ell}^{\text{truth}}$ due to the more central event topologies. The efficiency differs for the ee and $\mu\mu$ channels. While in the ee channel an increasing efficiency can be observed towards higher masses, the dimuon channel efficiency decreases due to the more stringent muon identification requirements at high $m_{\ell\ell}^{\text{truth}}$. A functional description of $\varepsilon_{ee}(m_{\ell\ell}^{\text{truth}})$ and $\varepsilon_{\mu\mu}(m_{\ell\ell}^{\text{truth}})$ is given by Equations C.3 and C.4 of Appendix C.3, respectively.

The derivation of the TFs is based on NLO DY MC samples¹¹ and thus inherently assumes the kinematics of a spin-1 particle for the potential new resonance. In order to ensure that the analysis is interpretable into the spin-0 and spin-2 cases, a good agreement of the reconstruction efficiencies between the three spin cases is essential. It was validated in the previous analysis round that the difference in the kinematic properties between the generic limits (which are based on the kinematics of spin-1

¹⁰ The cut on $p_{T,\ell}^{\text{truth}}$ is well below the typical p_T values of the leptons from the considered high-mass resonances and the η_ℓ^{truth} cut does not affect the response distribution as both electrons and muons have a good angular resolution.

¹¹ It is checked that the results from LO and NLO DY MC samples agree well.

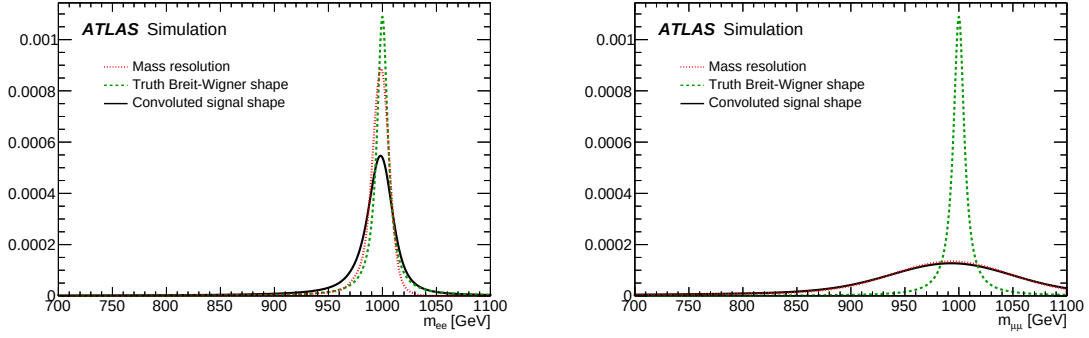


Figure 6.28: Example for the convolution of the TF detector response with a truth-level Breit-Wigner signal shape for the ee (left) and $\mu\mu$ (right) channels at a pole mass of 1 TeV and $\Gamma/m = 1.2\%$. The dimuon TF is considerably broader due to the worse detector resolution compared to the dielectron channel.

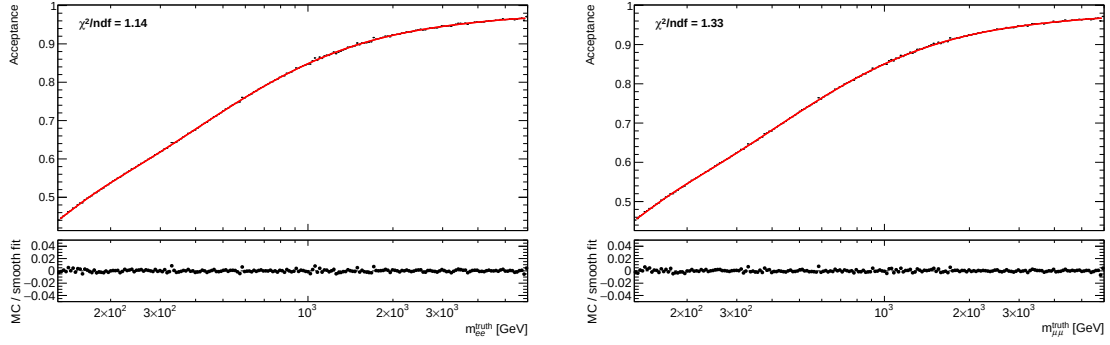


Figure 6.29: Acceptance distribution for the ee (left) and $\mu\mu$ (right) channels. A polynomial fit (red line) is performed to the values obtained from fullsim MC (black points). The error bands are due to MC statistics and have a non-linear behaviour due to the mass-sliced NLO DY samples.

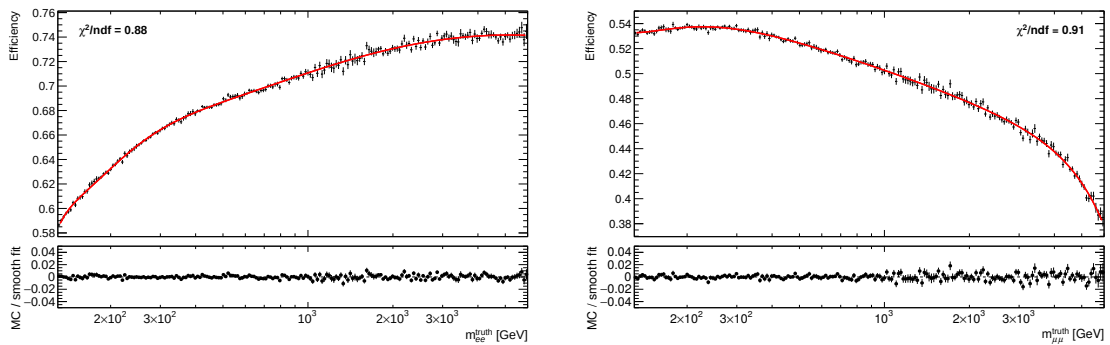


Figure 6.30: Efficiency distribution for the ee (left) and $\mu\mu$ (right) channels. A polynomial fit (red line) is performed to the values obtained from fullsim MC (black points). The error bands are due to MC statistics and have a non-linear behaviour due to the mass-sliced NLO DY samples.

resonances) and spin-2 Gravitons does not have an impact above 5% on the fiducial cross-section limits for $m_{\ell\ell}^{\text{truth}} \geq 1$ TeV.

A comparison of the selection efficiencies for different spin configurations is shown in Figure 6.31. The values are based on dedicated spin-0 (MSSM Higgs) and spin-2 (RS1 Graviton excitations) samples, and shown together with the nominal efficiency values from Figure 6.30. In the ee channel, the spin-0 and spin-2 efficiencies are higher than the corresponding spin-1 values by at most 4%¹². For the $\mu\mu$ channel, the efficiencies for spin-0 and spin-2 signals are at most 1% lower than the corresponding spin-1 values. The differences are found to originate mainly from variations in the η distributions of the reconstructed leptons, which are more central in the spin-0 and spin-2 cases than in the spin-1 case¹³.

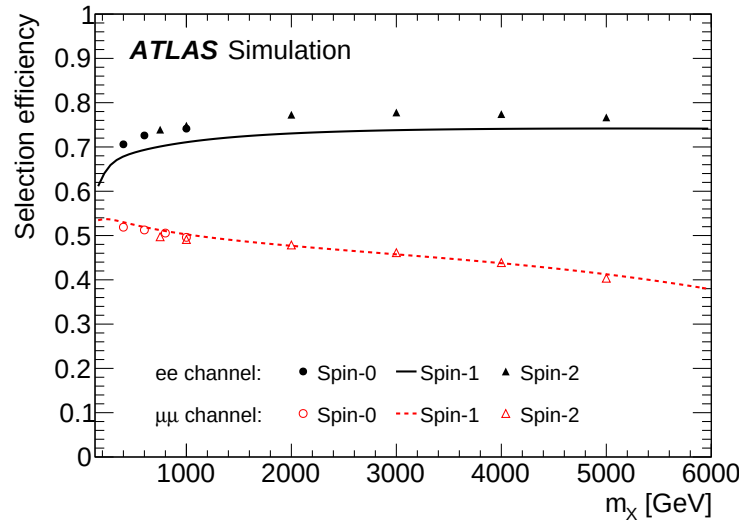


Figure 6.31: Dielectron and dimuon selection efficiency as a function of the pole mass m_X for spin-0, spin-1 and spin-2 resonances. Drell-Yan MC samples are used for the spin-1 efficiencies and correspond to the zero-width signal hypothesis. Spin-0 (spin-2) efficiencies are obtained from dedicated MC samples with relative widths in the range of 0 – 20% (1 – 13%) and are averaged over all available width assumptions. Figure from Ref. [84].

6.5.1 Calculation of acceptance times efficiency for wide signals

The description of the acceptance times efficiency from Subsection 6.3.4 is only valid for 0-width signals. In order to calculate it for generic signals, as described in Subsection 6.5, the following formula is used:

$$A\mathcal{E}(m_X|\{p_i\}) = \frac{\int S_{\text{truth}}(m_{\ell\ell}^{\text{truth}}|m_X, \{p_i\}) \cdot A\mathcal{E}(m_{\ell\ell}^{\text{truth}}) dm_{\ell\ell}^{\text{truth}}}{\int S_{\text{truth}}(m_{\ell\ell}^{\text{truth}}|m_X, \{p_i\}) dm_{\ell\ell}^{\text{truth}}}. \quad (6.11)$$

$S_{\text{truth}}(m_{\ell\ell}^{\text{truth}}|M_{\text{pole}}, \{p_i\})$ describes the truth invariant mass spectrum of the given model for a pole mass of m_X and a set of model parameters, $\{p_i\}$. $A\mathcal{E}(m_{\ell\ell}^{\text{truth}})$ is the parametrisation determined in Subsection 6.3.4. The integration is performed over $m_{\ell\ell}^{\text{truth}}$ as only the truth-level shape of the resonances is considered

¹² The spin-0 and spin-2 signal samples are generated using fast simulation, which causes an offset of 1 – 1.5% in the determined efficiency compared to full simulation.

¹³ The production via gluon-gluon fusion dominates for the spin-0 and spin-2 cases, while in the spin-1 case the production of the new heavy resonances occurs via the DY mechanism.

in the calculation. The transformation to reconstruction-level shapes is performed as described above. Equation 6.11 holds similarly for the standalone efficiency values obtained in Subsection 6.5. The values of $A\varepsilon(m_X|\{p_i\})$ need to be determined separately for each point of $\{p_i\}$ in case a significant change of the acceptance times efficiency is present.

For the considered generic signal model inside the fiducial volume, the efficiency difference is found to be less than 0.5% for a signal with 10% relative width compared to a signal with zero width for both channels over most of the considered m_X range. Only for $m_X \geq 5$ TeV, the variations can become as large as 2% in absolute efficiency for the dimuon channel. The efficiency differences for varying Γ_X are thus neglected in the statistical analysis, as their size is small compared to the systematic uncertainties.

6.6 Systematic uncertainties on the signal modelling

An overview of the experimental systematic uncertainties that are considered in the dilepton search is given in Table 6.2. The background-related uncertainties are covered in Subsections 6.8.3 and 6.8.4, while this section contains information on uncertainties related to the signal. The implementation in terms of the statistical analysis is described in Subsection 6.8.5. Theoretical uncertainties on the Z'_{SSM} production cross-section are depicted in the figures of Subsection 6.9.2, but not included in the statistical analysis.

Table 6.2: Systematic variations of signal efficiency and mass resolution parameters, as well as spurious signal and luminosity uncertainties. The systematic uncertainties are probed for masses from 250 GeV to 6 TeV resulting in ranges of values given in the table. More detailed descriptions of the considered systematic uncertainties are available in Subsections 6.8.3 (spurious signal), 6.6.1 (signal efficiency) and 6.6.2 (mass resolution parameters). The uncertainties are given according to their pre-fit size and affect the signal shape and normalisation. The spurious signal is taken into account as an additional signal-like component (compare Equations 6.24 and 6.25).

Uncertainty source per channel	dielectron	dimuon
Spurious signal for zero-width [events]	46 – 0.001	44 – 0.03
Spurious signal for 10% relative width [events]	146 – 0.006	122 – 0.04
Identification [% of ε]	1 – 6	1 – 31
Isolation [% of ε]	0.3 – 1.1	0.5
<i>Good muon</i> requirement [% of ε]	-	1 – 52
Luminosity [%]	1.7	1.7
Energy scale [% of μ_G]	0.4 – 0.7	-
Energy scale [% of μ_{CB}]	$^{+0.5}_{-0.6}$ – 1.2	-
Electron energy resolution [% of σ_G]	$^{+17}_{-14}$ – $^{+68}_{-38}$	-
Electron energy resolution [% of σ_{CB}]	8 – $^{+17}_{-27}$	-
Muon ID (MS) resolution [% of σ_G]	-	$^{+1}_{-3}$ – 1 ($^{+4}_{-5}$ – 6)
Muon ID (MS) resolution [% of σ_{CB}]	-	$^{+0}_{-4}$ – $^{+3}_{-1}$ (2 – $^{+8}_{-9}$)

Experimental systematic uncertainties on the trigger, isolation, identification and reconstruction efficiencies are provided centrally in terms of official recommendations in ATLAS. The uncertainties are applied in terms of SF variations. For the uncertainties on the electron energy calibration, a reduced, fully correlated scheme is used which provides one systematic uncertainty for the energy scale and one for the energy resolution. In case of the muon momentum uncertainties, the systematic variations

are provided for the momentum scale and separate uncertainties for the impact of inner detector (ID) and MS uncertainties on the momentum resolution. The TF framework is used to determine the size of these signal-related uncertainties in the dilepton search. For each systematic uncertainty up- and down-variations, i.e. shifts by $\pm 1\sigma$, of the respective calibration constants or scale factors are propagated.

The signal modelling uncertainties either have an impact on the acceptance times efficiency, while not having a significant impact on the detector response, or to affect the detector response, while no large impact on the acceptance times efficiency is present. These two categories are further described in Subsections 6.6.1 and 6.6.2, respectively. It is checked that all uncertainties fulfil this categorisation and do not have a significant impact on the detector response and the acceptance times efficiency simultaneously.

Further systematic uncertainties on the signal, other than the ones presented in this chapter, are investigated and found to be negligible. Only systematic uncertainties which have an impact above 0.5% relative change in the signal yield, at any pole mass or width assumption, are kept.

6.6.1 Acceptance times efficiency uncertainties

The uncertainties on the acceptance times efficiency considered in this search are given in Figures 6.32 and 6.33. In addition to the shown uncertainties, the luminosity uncertainty of 1.7% (see Section 3.4 for its calculation) directly affects the conversion of the number of signal events into the signal cross-section. For each systematic uncertainty the up- and down-variations are checked for the 0-width signal assumption, as well as truth Breit-Wigner shapes with Γ_X/m_X values from 0 to 10% in steps of 0.5%. It is found that the large-width signal assumptions do not exhibit significantly different uncertainties on the acceptance times efficiency and thus only the parametrisation for 0-width signals is used in the statistical analysis.

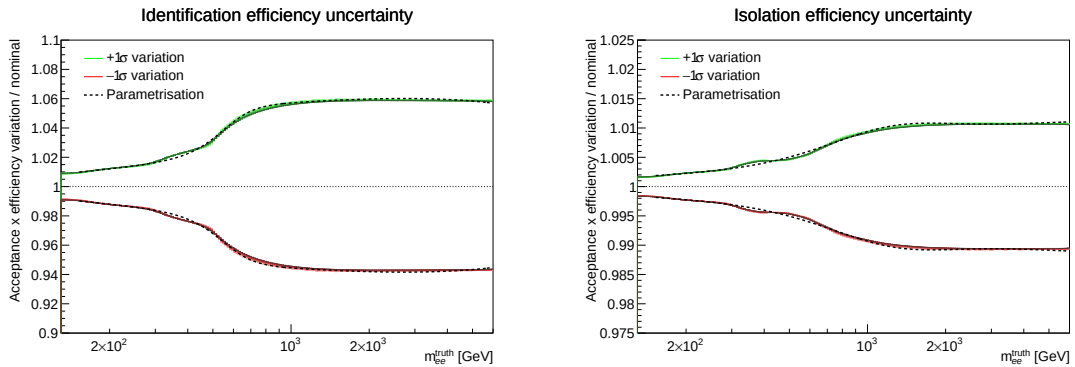


Figure 6.32: Electron identification (left) and isolation (right) uncertainties on the signal acceptance times efficiency, i.e. its normalisation. Both uncertainties are considered for the ee channel. The different solid lines represent the changes in the acceptance times efficiency due to up- (green) and down-variations (red) from the nominal for $\Gamma_X/m_X \in [0\%, 10\%]$. The black dashed lines represent the functional description. The steps in the obtained distributions emerge from the binning of the corresponding SFs.

A functional fit is performed for each systematic uncertainty to obtain a smooth parametrisation. It is checked that no large deviations between the functional fit and the obtained histograms are present. The systematic uncertainties are symmetrised and the parameters from the up- and down-fluctuations averaged to reduce fluctuations.

All signal normalisation uncertainties are treated as fully uncorrelated between the ee and $\mu\mu$ channels, except for the luminosity uncertainty, which is treated as fully correlated between the channels.

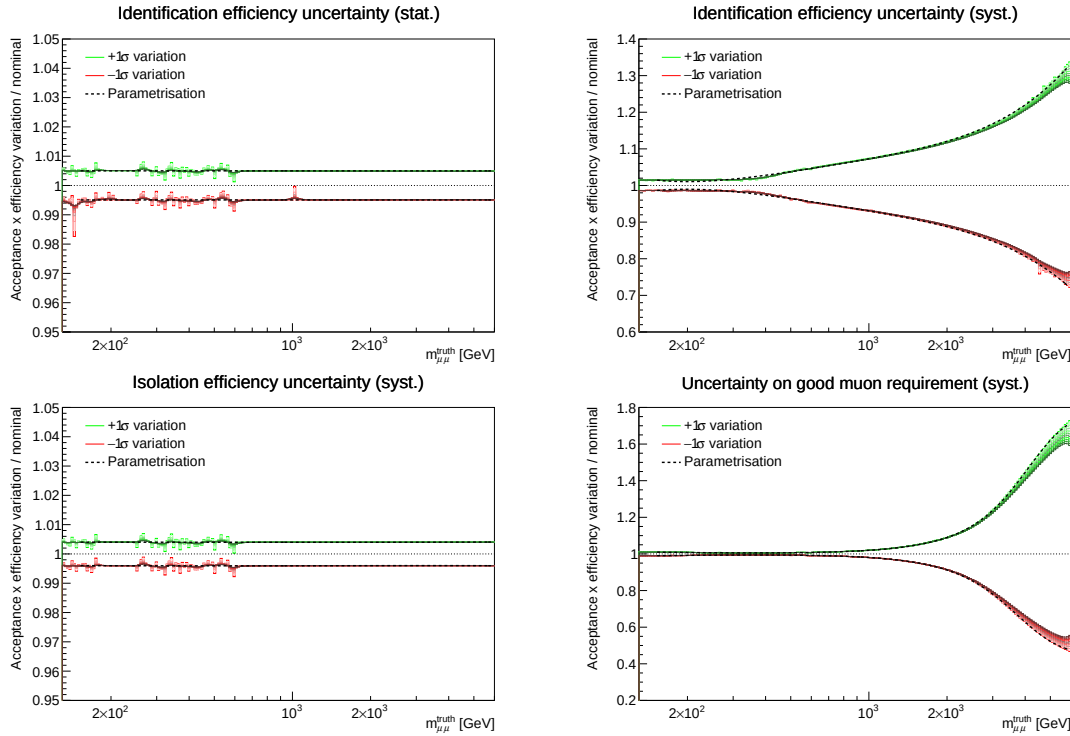


Figure 6.33: Muon identification (top left: statistical part, top right: systematic part), isolation (bottom left: systematic part) and good muon requirement (bottom right: systematic part) uncertainties on the signal acceptance times efficiency, i.e. its normalisation. All four uncertainties are considered for the $\mu\mu$ channel. The different solid lines represent the changes in the acceptance times efficiency due to up- (green) and down-variations (red) from the nominal for $\Gamma_X/m_X \in [0\%, 10\%]$. The black dashed lines represent the functional description. The statistical component of the muon isolation efficiency uncertainty is neglected, as the impact of this uncertainty is smaller than 0.2% throughout the whole mass spectrum.

6.6.2 Detector response uncertainties

The detector response uncertainties require a dedicated fit of the $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$ distribution as described in Subsection 6.3.2 for each up- and down-variation. The only uncertainties that change the detector response significantly are the energy/momentum scale and resolution uncertainties. Energy/momentum scale uncertainties mainly affect the mean value of the response distribution (i.e. for a given $m_{\ell\ell}^{\text{truth}}$ the $m_{\ell\ell}^{\text{reco}}$ scale is shifted), which is parametrised by the μ_i ($i \in [\text{CB}, \text{G}]$) parameters. The impact of the scale uncertainties on the invariant mass resolution is negligible compared to the dedicated uncertainties. Resolution uncertainties mainly affect the width of the response distribution (i.e. for a given $m_{\ell\ell}^{\text{truth}}$ the $m_{\ell\ell}^{\text{reco}}$ spread is modified), which is parametrised by the σ_i parameters. Due to their respective effects, all parameters except for μ_i and σ_i are kept at their nominal values for scale and resolution uncertainties, respectively. It is checked that in a free fit the description of the response distribution does not improve significantly.

For each of the $p_{\mu_{\text{CB},i}}$ and $p_{\mu_{\text{G},i}}$ ($p_{\sigma_{\text{CB},i}}$ and $p_{\sigma_{\text{G},i}}$) parameters a nominal value and values at systematic shifts if -1σ and $+1\sigma$ are thus obtained for scale (resolution) uncertainties. In order to obtain a smooth description of the final parametrisation, the $p_{i,j}$ are smoothly interpolated. Figures 6.34 to 6.35 show the obtained behaviour for the considered systematic uncertainties.

In case of the muon ID resolution uncertainty, both systematic variations (i.e. $\pm 1\sigma$) of the σ_{CB}

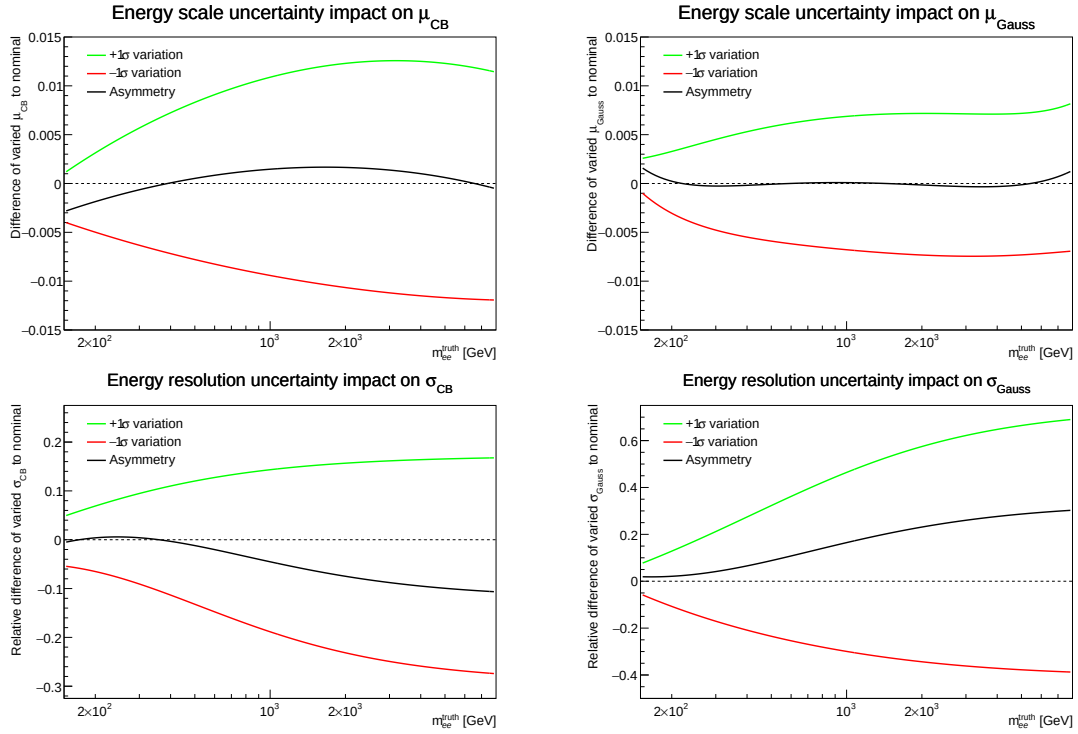


Figure 6.34: Effect of the systematic uncertainty on the electron energy scale (upper plots) and resolution (lower plots) in terms of the variation of the μ_{CB}/σ_{CB} (left) and μ_G/σ_G (right) TF parameters. The green line corresponds to the upward-variation, the red line to the downward-variation and the black line is the sum of the two (i.e. the asymmetry).

parameter result in changes with the same sign (i.e. towards a more narrow distribution) in a small part of the $m_{\ell\ell}^{\text{truth}}$ spectrum below about 250 GeV. As the Gaussian component of the signal model is dominant in both cases, the overall signal shape still gets wider/narrower for the up-/down-variations and no undesired behaviour is present.

For each of the considered uncertainties a comparison of the response distributions and their respective functional description for the variations is given in Figures 6.36 and 6.37 to illustrate their respective effect. It can be observed that the dedicated TF fits capture the variations of the $P(\mathcal{R}|m_{\ell\ell}^{\text{truth}})$ distribution due to the systematic uncertainties well and no increased mismodelling is visible. The determined parameter variations thus encompass the $\pm 1\sigma$ variations of the systematic uncertainties.

The impact of the muon p_T scale uncertainty yields a shift in the TF μ_i parameters below 0.1% for almost the full $m_{\ell\ell}^{\text{truth}}$ range. The variations for $m_{\ell\ell}^{\text{truth}} \gtrsim 5$ TeV remain considerably lower than the dimuon invariant mass resolution for these pole masses with best-fit variations of the μ_i parameters below 1%. The uncertainty on the muon p_T scale is thus neglected, as it is considerably smaller than the dimuon mass resolution for the full considered $m_{\ell\ell}^{\text{truth}}$ range.

6.7 Overview of statistical analysis concepts

The following section summarises the most important concepts of statistical analysis, while a comprehensive overview of statistical methods can be found in Ref. [147]. The frequentist interpretation of statistics is used for the data analysis in this thesis, where probability is interpreted as the frequency of a

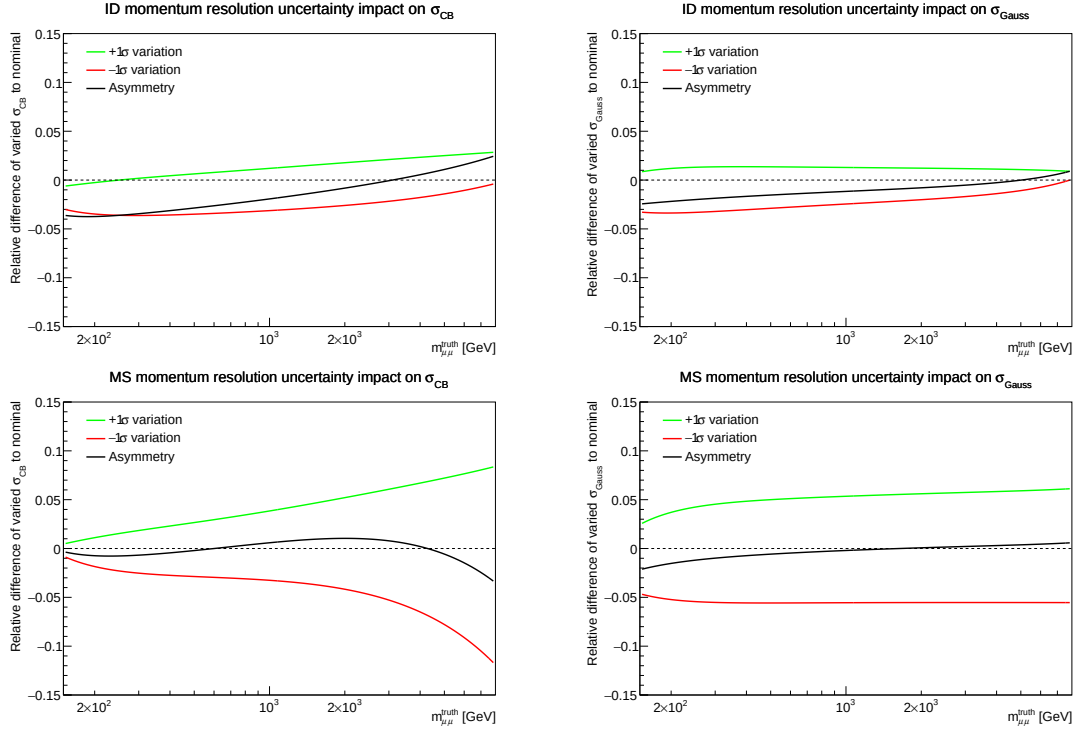


Figure 6.35: Effect of the systematic uncertainty on the muon resolution from the ID (upper plots) and MS (lower plots) components in terms of the variation of the σ_{CB} (left) and σ_G (right) TF parameters. The green line corresponds to the upward-variation, the red line to the downward-variation and the black line is the sum of the two (i.e. the asymmetry).

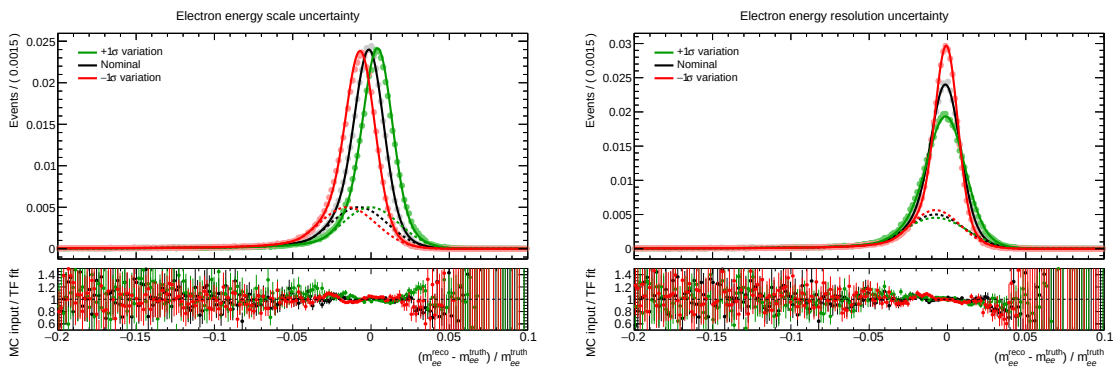


Figure 6.36: Visualisation of the effect of systematic uncertainties on the response distribution (points) and the TF parametrisation (smooth line) for the ee channel. The electron energy scale (left) and resolution (right) uncertainties are shown.

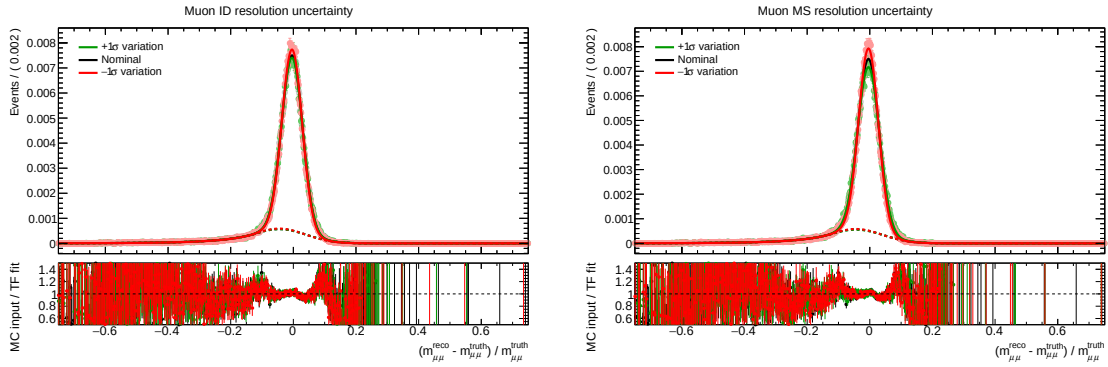


Figure 6.37: Visualisation of the effect of systematic uncertainties on the response distribution (points) and the TF parametrisation (smooth line) for the $\mu\mu$ channel. The muon resolution uncertainties due to the ID (left) and MS (right) components are shown.

specific outcome in a series of infinite iterations of a repeatable experiment.

The *likelihood* function, $L(\mu, \{\theta\} | \{n\})$, is equal to the probability, $P(\{n\} | \mu, \{\theta\})$, to observe a certain set of measurements $\{n\}$ for a given parameter of interest, μ , and a set of further nuisance parameters of the model, $\{\theta\}$ ¹⁴. The model in the dilepton search is given by the signal component (as described in Section 6.5) and the background function (described in Subsection 6.8.3). The free parameters of this specific model are given by the cross-section of the signal process inside the fiducial volume, σ_{fid} , and the free parameters of the background function, b and p_i (compare Equations 6.20 and 6.21), as well as the background normalisation. Therefore $\mu = \sigma_{\text{fid}}$ and $\{\theta\} = \{b, p_i, N_{\text{bkg}}\}$ is chosen. The likelihood function in the case of a binned shape analysis is given by

$$L(\mu, \{\theta\} | \{n\}) = \prod_{j=1}^{N_{\text{bins}}} \text{Pois} \left[n_j; \mu \cdot S_j(\{\theta\}) + B_j(\{\theta\}) \right]. \quad (6.12)$$

$\text{Pois}[n; \mu_{\text{Pois}}]$ describes the Poisson distribution with mean value μ_{Pois} and n as the number of observed events. S_j and B_j give the signal and background height in bin j , respectively. The signal shape S_j needs to be normalised according to the chosen definition of μ . The maximum value of the likelihood for a given signal mass and width assumption gives the *best-fit values* $\hat{\mu}$ and $\{\hat{\theta}\}$.

The statistical model of Equation 6.12 is extended with systematic uncertainties by introducing additional nuisance parameters into the likelihood function, which are constrained by external knowledge. The nuisance parameters in the dilepton search allow to alter the statistical model to consider the uncertainties described in Section 6.6 and can thus change the signal efficiency and the detector response parametrisation. The external knowledge about the systematic uncertainties is incorporated by multiplicative *constraints* in the likelihood function. Auxiliary measurements provide the external knowledge, like e.g. the integrated luminosity and its uncertainty.

The data analysis in searches is typically first performed in the “discovery step”, where deviations from the expectation are quantified. In case no significant deviations are found, in the subsequent step limits on the signal strength are set.

To quantify the significance of a signal-like background deviation, the background-only hypothesis

¹⁴ The distinction between the parameter(s) of interest (POIs) and additional (nuisance) parameters is a convention and used here to distinguish between parameters that are interpreted further, i.e. the POIs, and parameters that are constrained by the data in the fit, but not part of the further interpretation.

(H_0) with $\sigma_{\text{fid}} = 0$ has to be tested against the hypothesis to have a signal contribution (H_1), i.e. $\sigma_{\text{fid}} \neq 0$. The discovery test statistic is given by the following likelihood ratio:

$$t_0 = -2 \log \left[\frac{L(\sigma_{\text{fid}} = 0)}{L(\hat{\sigma}_{\text{fid}})} \right]. \quad (6.13)$$

For large values of t_0 , the background-only hypothesis is disfavoured against the $\sigma_{\text{fid}} \neq 0$ hypothesis. The above definition of t_0 allows to have the $\sigma_{\text{fid}} < 0$ case in H_1 , which is typically referred to as two-sided test statistic. For the one-sided test statistic, $\sigma_{\text{fid}} < 0$ is part of H_0 . The p -value allows to quantify the probability for a given observed t_0 value, t_0^{obs} , and gives the fraction of outcomes that are at least as signal-like as the data, given that the background-only hypothesis is true. The p -value is given as

$$p_0 = \int_{t_0^{\text{obs}}}^{\infty} f(t_0|H_0) dt_0. \quad (6.14)$$

The function $f(t_0|H_0)$ gives the distribution of t_0 values under H_0 . The p -value can additionally be expressed in terms of Gaussian quantiles as a *discovery significance*, Z . The distribution of $f(t_0|H_0)$ can be approximated by a χ^2 distribution with one degree of freedom in the Gaussian regime [148], i.e. for large total event numbers.

In case of searches for new resonances, the mass and width of these resonances are typically not predicted or known. The possible parameters are therefore scanned and fluctuations in the data might create signal-like shapes at various points in the parameters space. In order to avoid a bias, the *look-elsewhere effect* needs to be taken into account, i.e. in which fraction of background-only experiments fluctuations with a given significance occur by chance for any value of the scanned parameter space. The calculation of the *global significance* takes the look-elsewhere effect into account and provides the significance of a fluctuation with respect to the expected fluctuations in the full parameter space. It is smaller than the *local significance*, which is calculated at a specific point in the parameter space. The look-elsewhere effect can be estimated by generating a large number of randomly thrown background-only distributions, so-called “toys”, and determining the frequency of fluctuations with a certain local significance. The frequency can subsequently be converted into the global significance.

The look-elsewhere effect in the one-dimensional case can be approximated for local significances above 2σ with an asymptotic approximation [149]. The relation between the global p -value, p_{global} , and the local p -value of the most significant observed excess, p_{local} , is in this approximation given by

$$p_{\text{global}} = p_{\text{local}} + N_{\text{down}} \cdot \exp\left(-\frac{1}{2}(Z_{\text{local}}^2 - Z_{\text{ref}}^2)\right). \quad (6.15)$$

In this equation, Z_{ref} denotes a reference significance value, which can be chosen. In the following, it is chosen to be 0 and thus corresponds to a reference p -value of $p_{\text{ref}} = 0.5$. N_{down} is the number of down-crossings of the p -value distribution at the value of p_{ref} , i.e. the crossings after which the p -value corresponds to a more significant fluctuation than p_{ref} . The value of Z_{local} is given by the significance corresponding to p_{local} .

The uncertainty on p_{global} is determined by varying the value of N_{down} within its statistical uncertainty, i.e. to $N_{\text{down}} \pm N_{\text{down}}^{1/2}$. In case N_{down} is high enough to yield a low uncertainty, it is possible to extract N_{down} from data. If the statistical uncertainty is too large (e.g. if only few crossings are available in a mass scan due to a wide mass resolution), the method can instead be applied to a set of toy experiments generated in the background-only hypothesis, allowing to reduce the uncertainty on N_{down} .

In order to set limits on the signal strength, the hypothesis to have a signal strength of $\sigma_{\text{fid},0}$ (H_0) needs

to be rejected against the hypothesis to have $\sigma_{\text{fid}} < \sigma_{\text{fid},0}$ (H_1). The test statistic is thus given by the following likelihood ratio [148]:

$$\tilde{q}_{\sigma_{\text{fid},0}} = \begin{cases} 0 & \text{for } \sigma_{\text{fid},0} < \hat{\sigma}_{\text{fid}} \\ -2 \log \left[\frac{L(\sigma_{\text{fid},0})}{L(\hat{\sigma}_{\text{fid}})} \right] & \text{for } 0 \leq \hat{\sigma}_{\text{fid}} \leq \sigma_{\text{fid},0} \\ -2 \log \left[\frac{L(\sigma_{\text{fid},0})}{L(\sigma_{\text{fid}}=0)} \right] & \text{for } \hat{\sigma}_{\text{fid}} < 0 \end{cases} \quad (6.16)$$

The value of $\sigma_{\text{fid},0}$ is adjusted in the limit setting process to have a predefined p_{s+b} -value. The definition of p_{s+b} follows Equation 6.14, but is based on the test statistic of Equation 6.16:

$$p_{s+b} = \int_{\tilde{q}_{\sigma_{\text{fid},0}}^{\text{obs}}}^{\infty} f(\tilde{q}_{\sigma_{\text{fid},0}} | H_0) d\tilde{q}_{\sigma_{\text{fid},0}}. \quad (6.17)$$

The *confidence level*, CL, is given as $\text{CL} = 1 - p$. The CL value of the limit is commonly chosen as 95% for ATLAS and CMS results. For the choice of 95% CL, the experimentally measured cross-section thus only occurs in 5% of the toy experiments in case H_0 is true.

The limit setting under $\tilde{q}_{\sigma_{\text{fid},0}}$ (i.e. CL_{s+b}) can yield negative limits for $\hat{\sigma}_{\text{fid}} < 0$. The quoted limit values are thus commonly given in the definition of the CL_s method [150], for which the following p -value ratio is used [147]:

$$\text{CL}_s = \frac{p_{s+b}}{p_b}, \quad (6.18)$$

$$\text{with } p_b = \int_{\tilde{q}_{\sigma_{\text{fid},0}}^{\text{obs}}}^{\infty} f(\tilde{q}_{\sigma_{\text{fid},0}} | H_{\sigma_{\text{fid},0}=0}) d\tilde{q}_{\sigma_{\text{fid},0}}. \quad (6.19)$$

The limits in the CL_s approach cannot become negative and converge towards $\sigma_{\text{fid},0} = 0$ for very low $\hat{\sigma}_{\text{fid}}$. The limit setting can again be performed based on toy experiments or asymptotic formulae [148].

6.8 Data-driven background estimation with a global fit

In the “global fit” approach, the data-driven background estimation of the $m_{\ell\ell}^{\text{reco}}$ distribution is performed with a single function. It is used to describe the full invariant mass spectrum simultaneously. The alternative “sliding window fit” technique is briefly discussed in Subsection 6.8.1. In order to identify a set functional forms that model the background spectrum well, background-only fits to MC templates are performed. For the fit on the data, the signal normalisation and the parameters of the background function are kept free.

The potential signal bias from background mismodelling of the functional form compared to the real spectrum in data is estimated using the “spurious signal” test, which is widely used in ATLAS Higgs boson analyses (see e.g. Ref. [151]). The spurious signal is derived by performing signal+background fits on the background-only MC templates. The resulting signal-like contribution corresponds to the bias and is considered as a systematic uncertainty on the signal yield in the statistical analysis.

The statistical analysis of the dilepton search is based on the Hfitter [152, 153] and HGGfitter [154] frameworks, which are developed within ATLAS and are based on RooFit [142]. The chosen global fit approach is closely aligned to the method used in the search for high-mass diphoton resonances [155, 156], for which an implementation in Hfitter was extensively tested during the study of the potential $m_{\gamma\gamma}$ excess at 750 GeV and afterwards.

6.8.1 Motivation

The global fit approach models the full invariant mass spectrum with a single background-function within the full accessible mass range, independent of the considered pole mass. In case the background shape can be modelled well with a suitable function, as shown e.g. by the diphoton search [155, 156], the global fit option provides a very rigid background description as the full data statistics is used to constrain the background shape. The approach is thus well suited to analyse signal shapes with a comparably broad distribution on truth level, due to the large “side bands” around the resonance. The global fit naturally provides an extrapolation into the high mass region, that is well constrained by the low mass region. The extrapolation into the high mass region is validated by the spurious signal test (see Subsection 6.8.3), too.

The main challenge of this approach is to find a “suitable” function that models well the full invariant mass spectrum. While these functions typically have more parameters than functions used in the sliding window fit technique (compare e.g. Ref. [157]), the full background is modelled with considerably less free parameters since only a single mass range (i.e. the full spectrum) is fitted instead of many overlapping fit windows.

6.8.2 Method and general implementation

The general method to optimise the global fit and perform fits to data is given by the following steps:

1. Function choice optimisation:

For the optimisation of the global fit, suitable functional forms need to be determined. In order to achieve this, background-only fits are performed on a variety of functions to determine a set of “realistic” functions that model well the invariant mass spectra in the ee and $\mu\mu$ channels. For each channel, the suitable functions are then further investigated using the spurious signal test, described in Subsection 6.8.3.

2. Parametrisation of the spurious signal:

The determined spurious signal, N_{spur} , is parametrised as a function of the resonance pole mass using a functional fit to obtain a smooth description for the full m_X range. A conservative estimate is chosen by only using the main maxima of $|N_{\text{spur}}|$ for the parametrisation, i.e. the envelope of the distribution. The concrete results are described in Subsection 6.8.4.

3. Implementation in Hfitter and calculation of statistical results:

The chosen function and the spurious signal parametrisation are integrated into the Hfitter framework together with the signal model and its additional uncertainties. The treatment of systematic uncertainties is described in Subsection 6.8.5, while the validation of the functional form on data is detailed in Subsection 6.8.6. Background-only fits are shown in Subsection 6.8.7, while the final results are given in Section 6.9. Additional cross-checks are described in Subsection 6.8.8.

The data inputs are retrieved as histograms in a range of $m_{\ell\ell}^{\text{reco}} \in [150 \text{ GeV}, 6 \text{ TeV}]$ with a linear binning of 1 GeV. The final statistical analysis uses the invariant mass range of $m_{\ell\ell}^{\text{reco}} \in [225 \text{ GeV}, 6 \text{ TeV}]$, as for lower $m_{\ell\ell}^{\text{reco}}$ the influence of the Z boson peak becomes significant. The background-only templates from MC are given in the same mass range and binning. The MC information is smoothed with the TF approach (see Section 6.3) in case of the DY and $t\bar{t}$ processes, while the shapes of the diboson and single-top production templates are directly retrieved from MC. In the ee channel, the contribution from W +jets and multijet processes with fake electrons is additionally included.

6.8.3 Function choice and its optimisation with the spurious signal test

The function choice for the global fit is largely based on the minimisation of the spurious signal yield, which is a measure for the potential signal bias due to background mismodelling. For the spurious signal test, at each pole mass m_X and signal width Γ_X hypothesis, a signal+background fit is performed on the full MC background-only template. The significance of the spurious signal is given by the ratio of N_{spur} and the uncertainty on this signal yield, σ_{bkg} , which is mainly driven by the uncertainty on the number of background events. The spurious signal significance thus gives a measure of the functional mismodelling in comparison to the expected statistical background fluctuations. If this ratio is significantly smaller than one, no impact on the statistical analysis is expected and the chosen function models the background “well enough”.

The function choice is finally performed on the following criteria:

1. The function needs to have a small spurious signal significance. Typical values to accept a function based on this criterion are $N_{\text{spur}}/\sigma_{\text{bkg}} \lesssim (30 - 50)\%$ [156] in searches.
2. If several functions have spurious signal contributions that are small enough, the option with the most rigid background estimation is chosen, i.e. functions which are not able to bend in a signal-like way. These functions often correspond to the option with the least parameters, as their flexibility to adapt to signal-like deviations is smaller. More flexible functions might absorb signal-like deviations, which consequently results in a reduced sensitivity.

The functions that are found to give the smallest spurious signal contributions are given in Equations 6.20 and 6.21¹⁵. The functions are based on the functional form that is used in the diphoton search, while an additional multiplicative non-relativistic Breit-Wigner term, that models the tails of the Z boson peak, is added:

$$f_{ee}(m_{\ell\ell}^{\text{reco}}) = f_{\text{BW},Z}(m_{\ell\ell}^{\text{reco}}) \cdot (1-x)^b \cdot x^{p_0+p_1 \cdot \ln(x)+p_2 \cdot \ln(x)^2+p_3 \cdot \ln(x)^3}, \quad (6.20)$$

$$f_{\mu\mu}(m_{\ell\ell}^{\text{reco}}) = f_{\text{BW},Z}(m_{\ell\ell}^{\text{reco}}) \cdot (1-x^{1/3})^b \cdot x^{p_0+p_1 \cdot \ln(x)+p_2 \cdot \ln(x)^2+p_3 \cdot \ln(x)^3}, \quad (6.21)$$

$$\text{with } f_{\text{BW},Z}(m_{\ell\ell}^{\text{reco}}) = \frac{\Gamma_Z}{(m_Z - m_{\ell\ell}^{\text{reco}})^2 + \Gamma_Z^2}. \quad (6.22)$$

$x = m_{\ell\ell}^{\text{reco}}/\sqrt{s}$ with $\sqrt{s} = 13 \text{ TeV}$, $m_Z = 91.1876 \text{ GeV}$ and $\Gamma_Z = 2.4952 \text{ GeV}$ [158] are used in the above equations. b and p_i are free parameters in the fit and independently given for both channels.

A background-only fit example is shown in Figure 6.38 for the MC background template at an integrated luminosity of 140.5 fb^{-1} . No large deviations from peaking signal-like contributions or an overall mismodelling of the chosen functions are visible by eye. The remaining differences between the chosen function and the template are parametrised in terms of spurious signal values.

The spurious signal values for the $\Gamma_X/m_X = 0\%$ case are given in Figures 6.39 and 6.40. For the ee channel a maximal value of $N_{\text{spur}}/\sigma_{\text{bkg}} \simeq 30\%$ is obtained, which is most likely an effect of statistical fluctuations in the background template. A reduction of the spurious signal below the statistical fluctuations is not possible. In the $\mu\mu$ channel a maximal value of $N_{\text{spur}}/\sigma_{\text{bkg}} \simeq 30\%$ is obtained, too. Compared to the ee channel, slightly higher spurious signal values are present in the high m_X region for the $\mu\mu$ channel, but are still well below $N_{\text{spur}}/\sigma_{\text{bkg}} \simeq 30\%$. The spurious signal is thus at a reasonable level in both channels and low enough for the further statistical analysis.

¹⁵ Additional function families that were tested include the function from the diphoton search without the Breit-Wigner term for the Z peak and polynomials in the log-log-space. The $(1-x^*)^b$ term is found to result in more stable fits for the high-mass region.

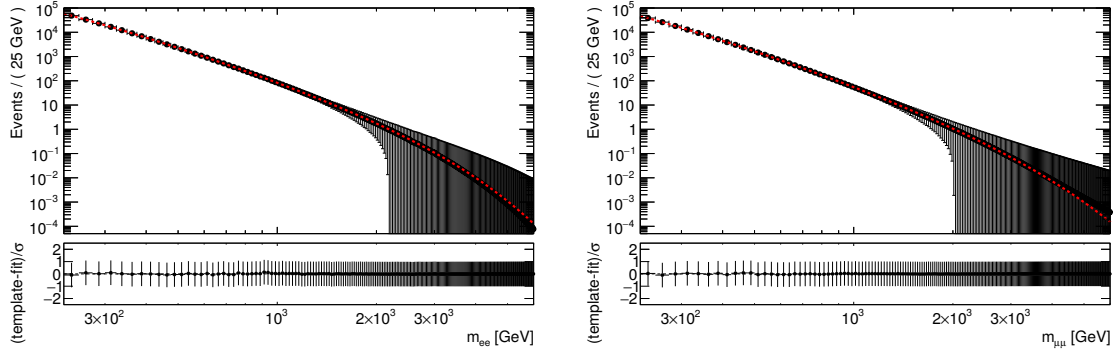


Figure 6.38: Background-only fit results in the ee (left) and $\mu\mu$ (right) channels using the functions given in Equations 6.20 and 6.21. The shown MC templates (black) correspond to an integrated luminosity of 140.5 fb^{-1} and are used in the optimisation procedure. No large deviations from peaking signal-like contributions or an overall mismodelling of the chosen functions are visible by eye. The uncertainty bands correspond to the expected uncertainty in data.

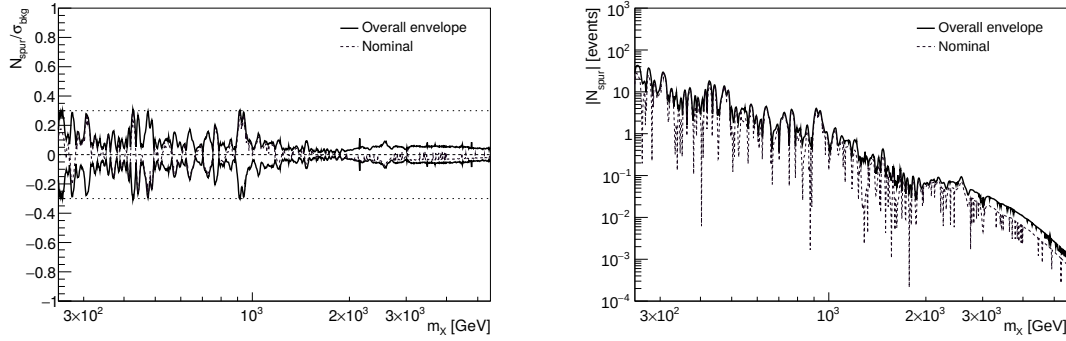


Figure 6.39: Spurious signal estimation at $\Gamma_X/m_X = 0\%$ in the ee channel. The left plot shows $N_{\text{spur}}/\sigma_{\text{bkg}}$ for a range of $m_X \in [250 \text{ GeV}, 6000 \text{ GeV}]$, while the plot on the right shows $|N_{\text{spur}}|$. The dashed line corresponds to the nominal background template, while the thick solid line corresponds to the envelope of the determined spurious signal values from systematic background variations.

The chosen fit range of $m_{\ell\ell}^{\text{reco}} \in [225 \text{ GeV}, 6 \text{ TeV}]$ is mainly affected by the Z boson peak region, which starts to modify the spectrum towards lower $m_{\ell\ell}^{\text{reco}}$. Studies with modified fit ranges show that a lower starting point of the fit range yields higher spurious signal values.

The spurious signal values that are given in Figures 6.39 and 6.40 show the obtained values for the nominal background templates as well as the envelope of the $N_{\text{spur}}/\sigma_{\text{bkg}}(m_X)$ and $|N_{\text{spur}}|(m_X)$ values from systematic variations of the background templates. The main uncertainties that change the shape of the background distribution in the high-mass tail are variations of the PDFs (i.e. PDF eigenvector variations, the PDF choice and related uncertainties) as well as the uncertainty on the fake electron background in the ee channel. More information on these background uncertainties is given in Ref. [132]. The uncertainty on the normalisation of the $t\bar{t}$ background component is evaluated by taking into account the theoretical uncertainties on the $t\bar{t}$ production cross-section (i.e. variations of -5.5% and $+4.8\%$ from the nominal value according to Ref. [159]) and mainly has an impact on the spurious signal in the low mass region. The functional form used for the data-driven background model needs to be able to accommodate for these shape changes and spurious signal estimates are performed for each variation.

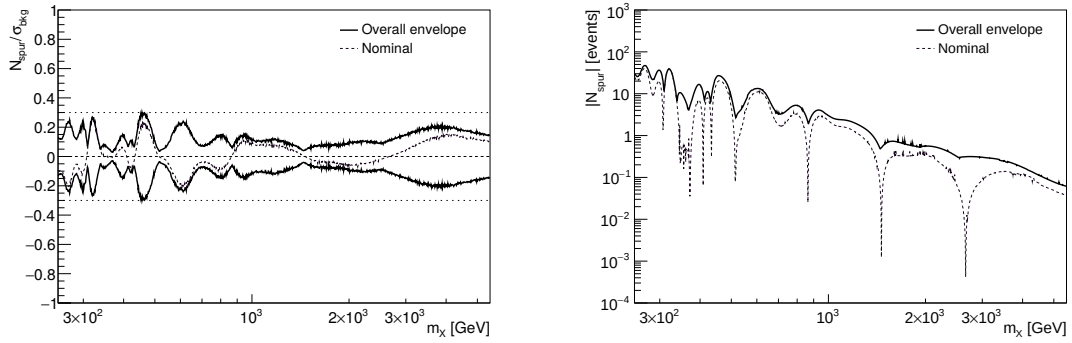


Figure 6.40: Spurious signal estimation at $\Gamma_X/m_X = 0\%$ in the $\mu\mu$ channel. The left plot shows $N_{\text{spur}}/\sigma_{\text{bkg}}$ for a range of $m_X \in [250 \text{ GeV}, 6000 \text{ GeV}]$, while the plot on the right shows $|N_{\text{spur}}|$. The dashed line corresponds to the nominal background template, while the thick solid line corresponds to the envelope of the determined spurious signal values from systematic background variations.

While a small increase of the spurious signal due to the background variations can be observed in both channels, the chosen function captures the variations well and the final estimate is within $N_{\text{spur}}/\sigma_{\text{bkg}} \simeq 30\%$. For the following parametrisation of the spurious signal, the envelope of the obtained spurious signal values from all background variations is used to obtain a conservative estimate. The uncertainties related to the background modelling are thus propagated into the determination of the spurious signal. The precision of the background estimate for MC-based analyses is parametrised in terms of the described background variations, e.g. PDF variations in the high-mass tail, while the statistical uncertainty on the functional form parameters and the spurious signal uncertainty constitute the precision measures for the background shape knowledge of data-driven analyses.

The spurious signal test is repeated for signal assumptions from $\Gamma_X/m_X = 0\%$ to 10% in steps of 0.5% . An overview of the $|N_{\text{spur}}|/\sigma_{\text{bkg}}$ values from all width assumptions is shown in Figure 6.41, depicting the envelope from all systematic variations. It can be observed that the spurious signal stays below $N_{\text{spur}}/\sigma_{\text{bkg}} = 50\%$ for the full $m_{\ell\ell}^{\text{reco}}$ range in case of all width assumptions. The size of the spurious signal is thus still reasonable for the wider resonances. The ee channel shows a strong dependence on the signal width, especially in the high-mass tail. The highest spurious signal value is given for large width assumptions at $m_X \simeq 950 \text{ GeV}$ with $N_{\text{spur}}/\sigma_{\text{bkg}} \simeq 40-45\%$. The width-dependence is considerably lower in the $\mu\mu$ channel due to the worse mass resolution and values of $N_{\text{spur}}/\sigma_{\text{bkg}} \lesssim 30\%$ can be achieved throughout the full m_X range.

6.8.4 Parametrisation of the spurious signal

The parametrisation of $|N_{\text{spur}}|$ is performed by first selecting the main maxima of the spurious signal distribution. The main maxima are then connected by a fit with the following functional description:

$$N_{\text{spur}}(m_X) = \left(1 - x^{1/3}\right)^{p_{\text{spur},1}} \cdot x^{p_{\text{spur},2} \cdot \ln(x) + p_{\text{spur},3} \cdot \ln(x)^2 + p_{\text{spur},4} \cdot \ln(x)^3 + p_{\text{spur},5} \cdot \ln(x)^4}, \quad (6.23)$$

with $x = m_X/\sqrt{s}$. The functional form is chosen to model $N_{\text{spur}}(m_X)$ well, but does not have a further physical explanation. The fit results for the $\Gamma_X/m_X = 0\%$ case are shown in Figures 6.42 and 6.43, which additionally depict the raw spurious signal values and the selection of the main maxima. The distribution of $|N_{\text{spur}}|$ is evaluated for an integrated luminosity of 139 fb^{-1} , i.e. the full Run 2 dataset.

The spurious signal parametrisation is repeated for all width assumptions from $\Gamma_X/m_X = 0\%$ to 10% in

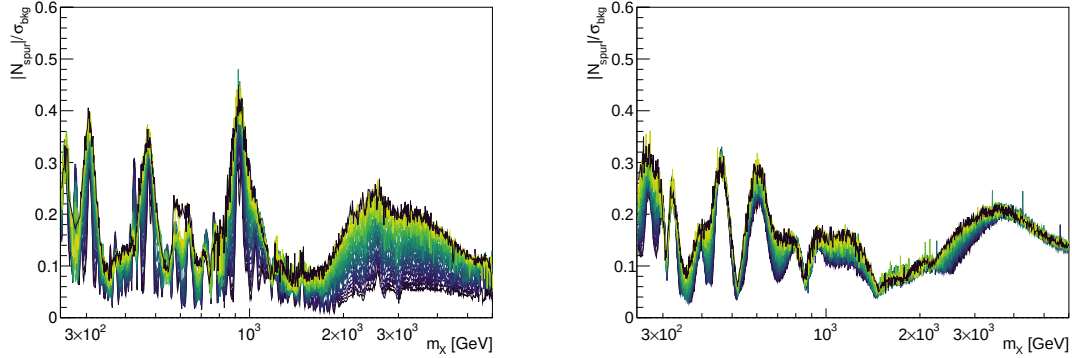


Figure 6.41: Spurious signal estimations in the ee (left) and $\mu\mu$ (right) channels with the nominal function choice. Both plots show $|N_{\text{spur}}|/\sigma_{\text{bkg}}$ for a range of $m_X \in [250 \text{ GeV}, 6000 \text{ GeV}]$. The different lines and colors represent different width assumptions, ranging from $\Gamma_X/m_X = 0\%$ to 10% in steps of 0.5% . $\Gamma_X/m_X = 0\%$ is shown in dark blue, which then shades off into yellow for higher width values. $\Gamma_X/m_X = 10\%$ is drawn in black.

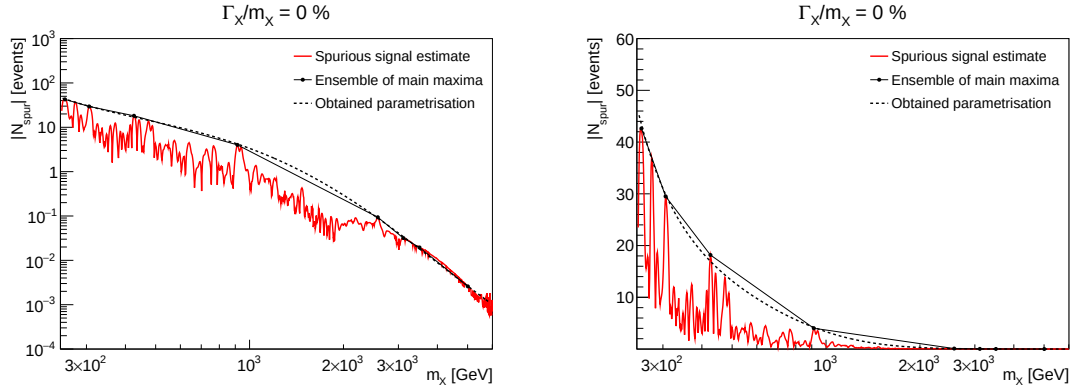


Figure 6.42: Spurious signal parametrisation for the $\Gamma_X/m_X = 0\%$ case in the ee channel with a logarithmically- (left) and linearly-scaled (right) y -axis. The spurious signal values are given by the red line and correspond to the envelope of $|N_{\text{spur}}|$ given in Figure 6.39, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.

steps of 0.5% . Figures 6.44 and 6.45 show the spurious signal values for some of these width assumptions in the ee and $\mu\mu$ channels, respectively, while a smooth transition can be observed between all width values. The same functional form is used for the parametrisation in all width cases.

6.8.5 Treatment of systematic uncertainties

The only considered systematic uncertainty related to the background modelling is the spurious signal uncertainty as described in Subsection 6.8.4. The signal normalisation uncertainties, described in Subsection 6.6.1, and the spurious signal uncertainty are considered in the signal shape normalisation as follows:

$$N_{\text{sig},ee} = \left(\int L dt \right) \cdot \sigma_{\text{fid},Z' \rightarrow \ell\ell} \cdot \varepsilon_{ee} \cdot \kappa_{\text{Lumi}} \cdot \kappa_{\text{Iso},\mu\mu} \cdot \kappa_{\text{Ident},\mu\mu} + N_{\text{spur},ee} \cdot \theta_{\text{spur},ee}, \quad (6.24)$$

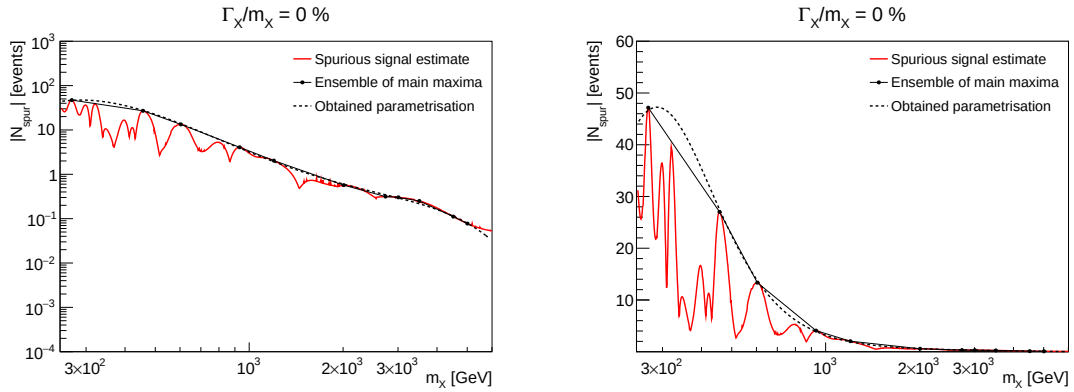


Figure 6.43: Spurious signal parametrisation for the $\Gamma_X/m_X = 0\%$ case in the $\mu\mu$ channel with a logarithmically- (left) and linearly-scaled (right) y -axis. The spurious signal values are given by the red line and correspond to the envelope of $|N_{\text{spur}}|$ given in Figure 6.40, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.

$$N_{\text{sig},\mu\mu} = \left(\int L dt \right) \cdot \sigma_{\text{fid},Z' \rightarrow \ell\ell} \cdot \varepsilon_{\mu\mu} \cdot K_{\text{Lumi}} \cdot K_{\text{Iso,syst},\mu\mu} \cdot K_{\text{Ident,stat},\mu\mu} \cdot K_{\text{Ident,syst},\mu\mu} \cdot K_{\text{GoodMuonReq,syst},\mu\mu} + N_{\text{spur},\mu\mu} \cdot \theta_{\text{spur},\mu\mu} \quad (6.25)$$

ε_i gives the efficiency at the tested pole mass and the κ_i factors contain the nuisance parameter for the respective uncertainty and the amplitude of the uncertainty at the tested pole mass. The signal normalisation uncertainties, as well as the luminosity uncertainty, each have a log-normal constraint that is included into the overall likelihood. $\sigma_{\text{fid},Z' \rightarrow \ell\ell}$ is the fitted signal cross-section times branching ratio for a single fermion generation inside the fiducial volume. The signal model and the predicted cross-section values from theoretical models need to incorporate the same definition of the fiducial volume. $N_{\text{spur},i}$ is defined as the spurious signal at the given pole mass, and the corresponding nuisance parameters, $\theta_{\text{spur},i}$, have a Gaussian constraint in the likelihood. Second order effects on the systematic uncertainties, like e.g. the impact of the luminosity uncertainty on $N_{\text{spur},i}$, are neglected.

The signal shape uncertainties (see Subsection 6.6.2) are added with a log-normal constraint in the likelihood for uncertainties on the energy and momentum resolution, while a Gaussian constraint is chosen for the energy scale uncertainty.

6.8.6 Validation of the background modelling function on data

While the spurious signal test, described in Subsection 6.8.3, allows to validate the function choice based on MC templates, unexpected properties of the data spectrum could still be present. It is important to prepare for this possibility before looking into the data in order to avoid a bias in the final result. The procedure to validate the function choice, that is given below, was defined prior to the ATLAS-internal unblinding approval and thus before looking into the full Run 2 dataset.

Shape differences might require to have more degrees of freedom in the functional form to account for the mismodelling, or to reject a given function choice. The validation method is based on the possibility to extend the expansion in $\sum_{i=0}^k p_i \cdot \ln(x)^i$ for the $x^{p_i \cdot \ln(x)^i}$ term given in Equations 6.20 and 6.21. The nominal functional form is chosen as $k = 3$ and becomes more flexible for $k > 3$.

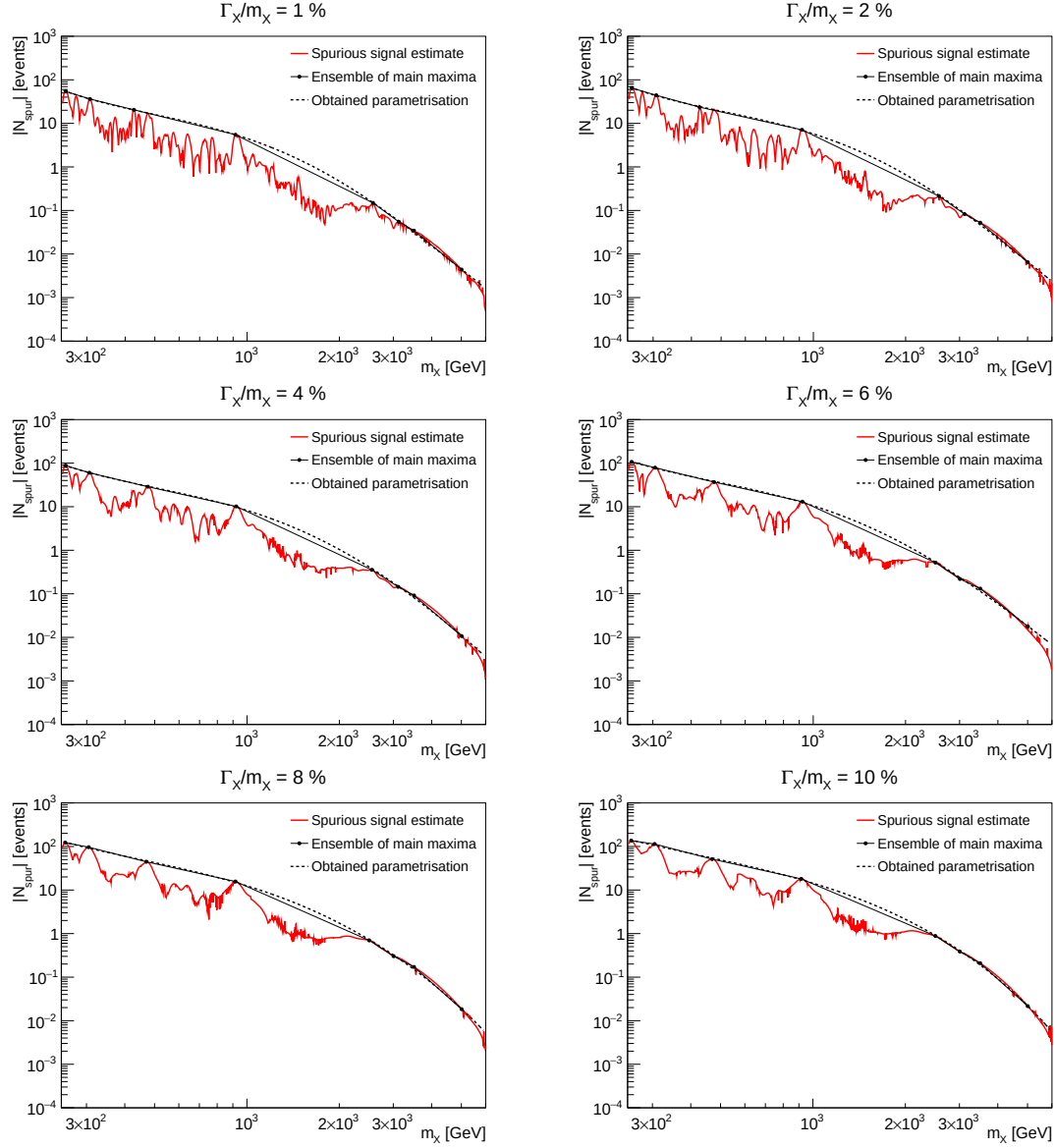


Figure 6.44: Spurious signal parametrisation for different width assumptions in the ee channel with a logarithmically-scaled y -axis. The spurious signal values are given by the red line, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.

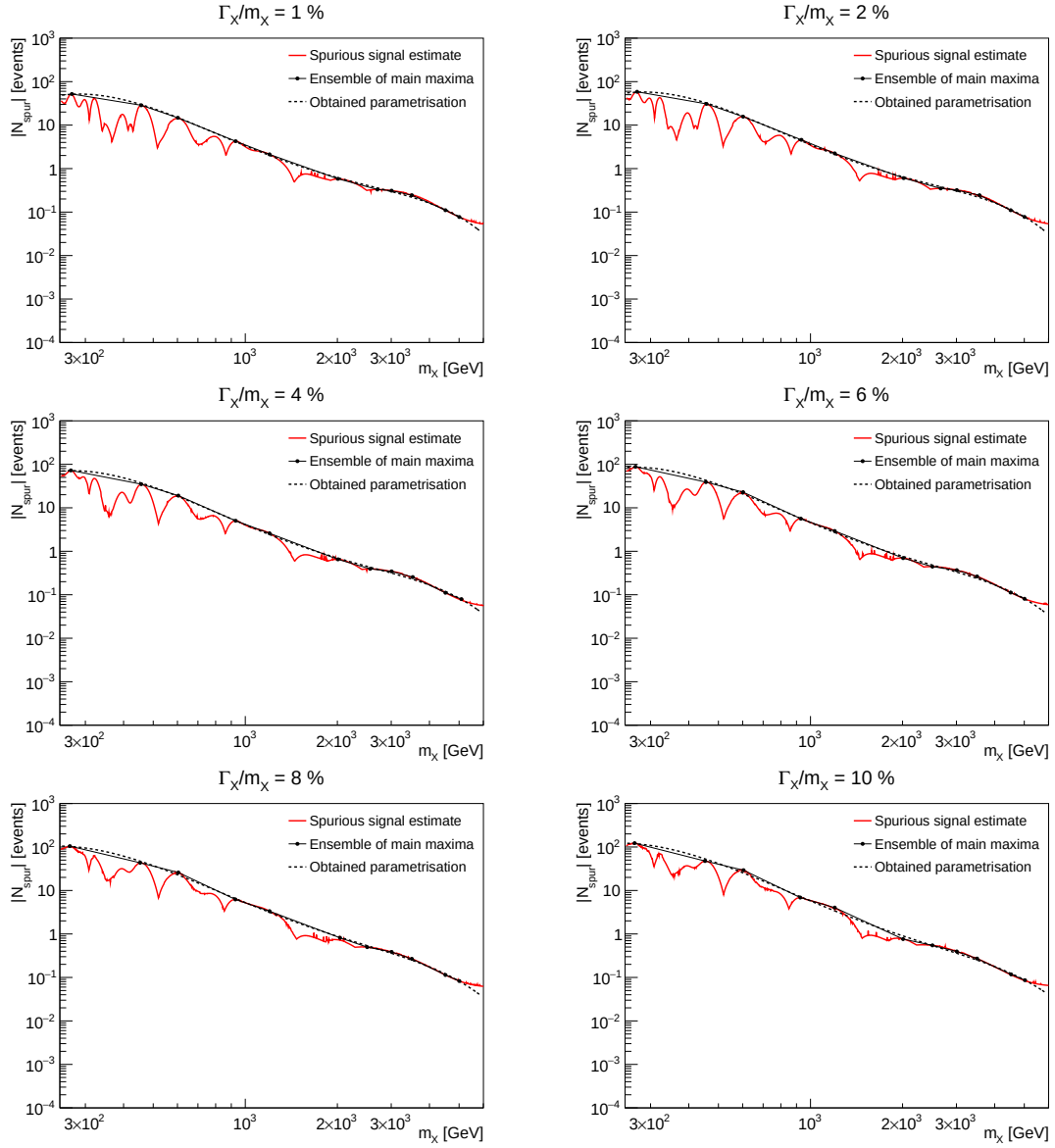


Figure 6.45: Spurious signal parametrisation for different width assumptions in the $\mu\mu$ channel with a logarithmically-scaled y -axis. The spurious signal values are given by the red line, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.

The test is performed on the complete dataset and defined as follows:

- A double-sided p_0 value test is performed to check the hypothesis of a cut-off of $k' + 1$ against k' , such that an additional parameter is present in the function.
- An additional degree of freedom is added to the functional form if it gives a 2σ improvement in the p_0 value for the background-only fit.

The functional form to describe the non-resonant background is thus validated by increasing the cut-off in the expansion, k . The test is repeated until no further improvements above 2σ are given by increasing k .

The validation of the functional form is performed on the full Run 2 dataset, starting from the nominal choice of $k = 3$. The following results are obtained:

- ee channel: $t_0 = -2 \ln(L_{k=4}/L_{k=3}) = 0.35$
- $\mu\mu$ channel: $t_0 = -2 \ln(L_{k=4}/L_{k=3}) = 0.11$

In both channels the extension of the functional form thus does not yield an improved description by 2σ (or $t_0 \simeq 4$) and the nominal function choice thus successfully validated.

6.8.7 Background-only fit results

After the validation of the function choice, the statistical analysis of the data can be performed. Background-only fit results are given in Figure 6.46. No large deviations from peaking signal-like contributions or an overall mismodelling of the chosen functions are visible by eye. The best-fit background parameters for the observed data distribution are given in Table 6.3.

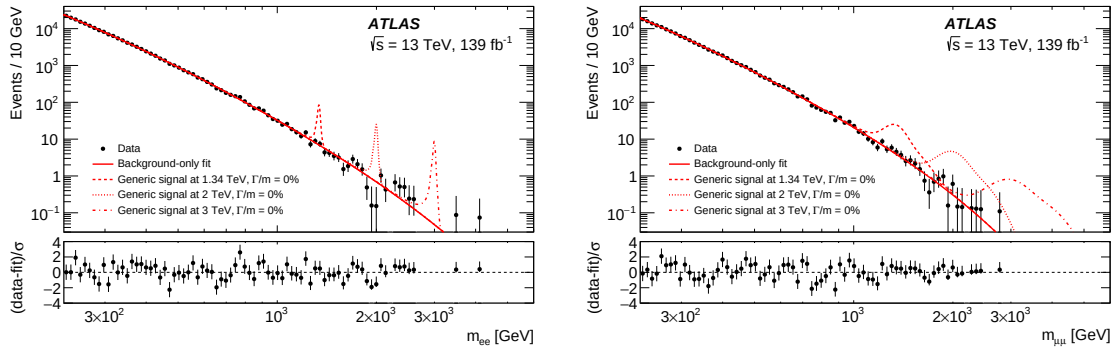


Figure 6.46: Background-only fit results in the ee (left) and $\mu\mu$ (right) channels. The shown data corresponds to the full Run 2 dataset of 139 fb^{-1} . No large deviations from peaking signal-like contributions or an overall mismodelling of the chosen functions are visible by eye. Generic 0-width signal shapes, scaled to 20 times the value of the corresponding expected upper limit at 95% CL, are overlaid to depict the detector mass resolution in the high-mass region.

Table 6.3: Parameters of the fit to data using the function of Equations 6.20 and 6.21. The normalisation of the background function is such that the integral, N_{bkg} , corresponds to the total number of background events.

Parameter	ee channel	$\mu\mu$ channel
N_{bkg}	178000 ± 400	138700 ± 400
b	1.5 ± 1.0	11.8 ± 0.5
p_0	-12.38 ± 0.09	-7.38 ± 0.12
p_1	-4.295 ± 0.014	-4.132 ± 0.017
p_2	-0.9191 ± 0.0027	-1.0637 ± 0.0029
p_3	-0.0845 ± 0.0005	-0.1022 ± 0.0005

6.8.8 Cross-checks for validation of procedure

Several cross-checks are performed to validate the global fit procedure and are given in this subsection.

Injection tests

The validation of the signal extraction in the statistical model is performed with signal injection tests. The tests are performed on Asimov data, i.e. datasets without statistical fluctuations that are obtained at the expectation values of the background model parameters. Signal contributions, with a given normalisation and pole mass, are injected and fits are performed in order to validate that the same signal normalisation and pole mass is retrieved back. The results are given in Figures 6.47 to 6.49 and additional figures are available in Appendix C.4.1. The figures show that the global fit allows to extract the injected signals in terms of their mass and normalisation.

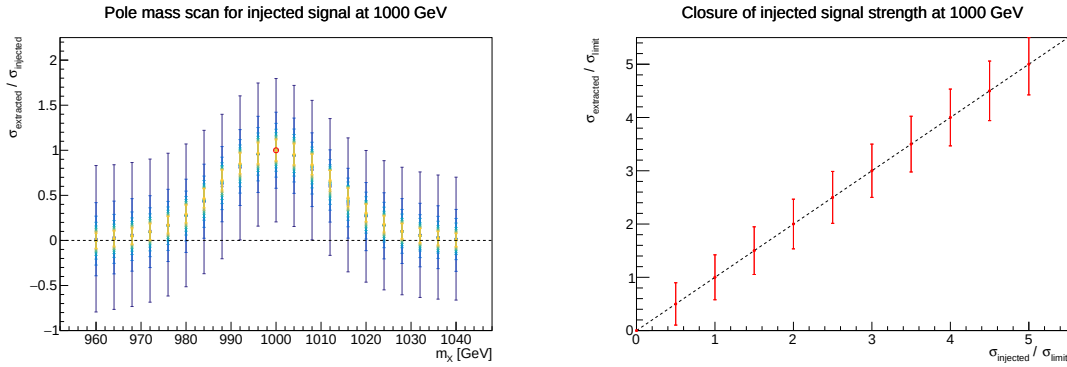


Figure 6.47: Example for injection tests at a pole mass of 1000 GeV in the ee channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_X = 1000$ GeV, while for other masses only a smaller response should be present. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets if the signal is fully retrieved back, as no statistical fluctuations are considered. The expectations are matched well in both cases.

Toy-based limits

Toy-based limits in the $\ell\ell$ channel are calculated in the high-mass region to evaluate the offset with respect to the asymptotic approximation, which is used for the nominal analysis results in Ref. [84]. The

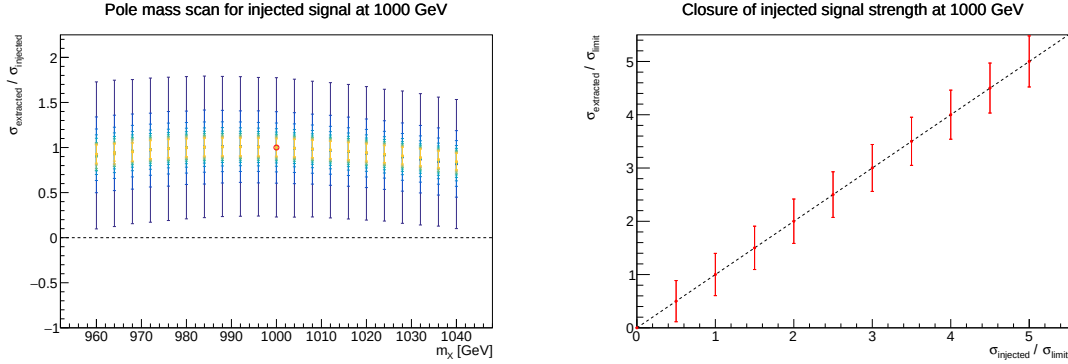


Figure 6.48: Example for injection tests at a pole mass of 1000 GeV in the $\mu\mu$ channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_\chi = 1000$ GeV, while for other masses only a smaller response should be present. A wider response is visible in the $\mu\mu$ channel compared to the ee channel due to the worse mass resolution. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets if the signal is fully retrieved back, as no statistical fluctuations are considered. The expectations are matched well in both cases.

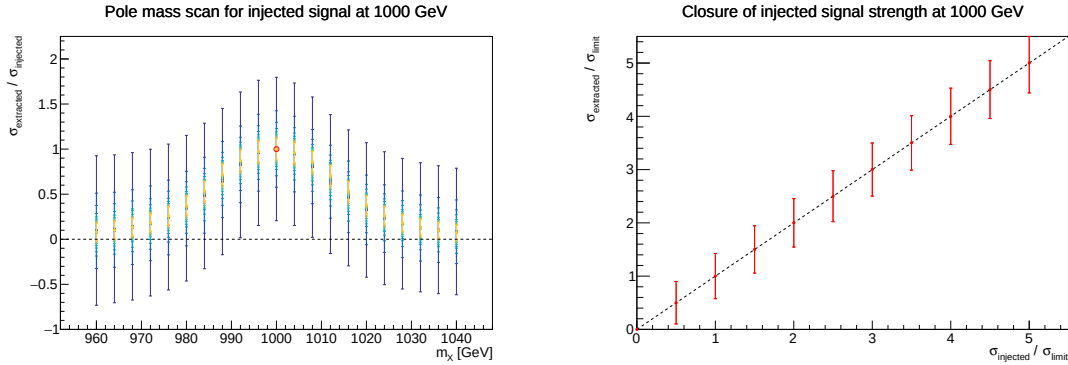


Figure 6.49: Example for injection tests at a pole mass of 1000 GeV in the $\ell\ell$ channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_\chi = 1000$ GeV, while for other masses only a smaller response should be present. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets if the signal is fully retrieved back, as no statistical fluctuations are considered. The expectations are matched well in both cases.

results are calculated based on about 1500 toys for pole masses of $m_X = 3, 4, 5$ and 6 TeV, while 500 toys are used at $m_X = 1$ TeV. The distributions of the calculated upper limits are shown in Figure 6.50 for two examples, while additional figures are available in Appendix C.4.2.

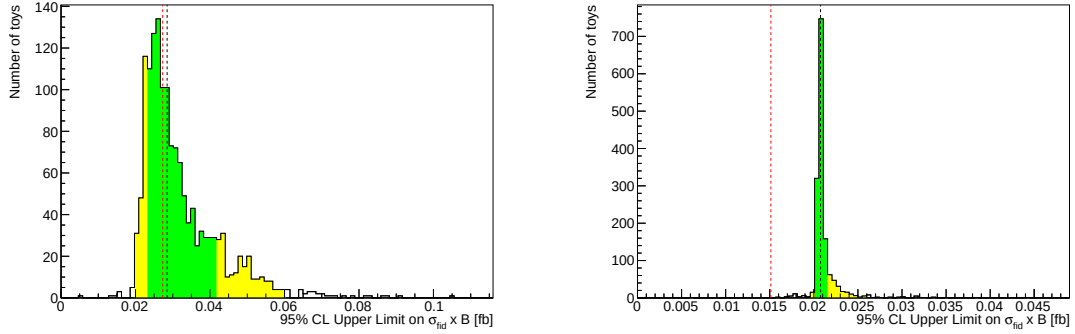


Figure 6.50: Expected limit distribution for about 1500 toy experiments in the $\ell\ell$ channel for $m_X = 3$ TeV (left) and 6 TeV (right). The dashed red line shows the result based on the asymptotic approximation, while the dashed black line gives the results based on toys (i.e. the median value of the obtained distribution). The non-Gaussian distributions lead to the observed offset in the expected upper limit and its uncertainty with respect to the asymptotic approximation.

The offset of the expected upper limit in both cases is given in Table 6.4 as a function of m_X . The results agree with the expectation that the limits based on the asymptotic approximation yield too aggressive limits at high pole masses where almost zero background events are expected, while the toy-based cross-section limits converge to $N_{\text{sig,lim}} \simeq 3$ for $N_{\text{bkg}} \rightarrow 0$.

Table 6.4: Offset of the toy-based upper limit values compared to the asymptotic approximation for the $\ell\ell$ channel.

m_X [TeV]	$\sigma_{\text{lim,toys}}/\sigma_{\text{lim,asymptotics}} - 1$
1	-1%
3	+4%
4	+13%
5	+27%
6	+36%

The computational needs in order to calculate toy-based expected and observed cross-section limit curves with a fine enough granularity outweigh the gain in precision. The impact of the calculated offset on the mass limits for specific models is low, such that the results in Ref. [84] are based on the asymptotic approximation.

Ranking plots for systematic uncertainties

The impact of the studied systematic uncertainties on the signal yield is evaluated for the full Run 2 luminosity of 139 fb^{-1} in the ee , $\mu\mu$ and $\ell\ell$ channels. Ranking plots are given in Figures 6.51 and 6.52 for $m_X = 300 \text{ GeV}$ and 5 TeV at $\Gamma_X/m_X = 0\%$ and 10%, respectively. Additional figures are available in Appendix C.4.3. The ranking plots are calculated based on Asimov datasets with an injected signal corresponding to the cross-section at the expected upper limit. The spurious signal uncertainty is dominating at low m_X for the ee and $\mu\mu$ channels, while at high pole masses detector-related systematic

uncertainties show a higher impact. The impact of the electron energy scale uncertainty is one-sided for $\Gamma_X = 0$, as the signal model for both variations has less overlap with the generated Asimov dataset (i.e. the variation moves the expected signal peak to higher or lower $m_{\ell\ell}^{\text{reco}}$ values than the injected signal peak; compare also Figure 6.47).

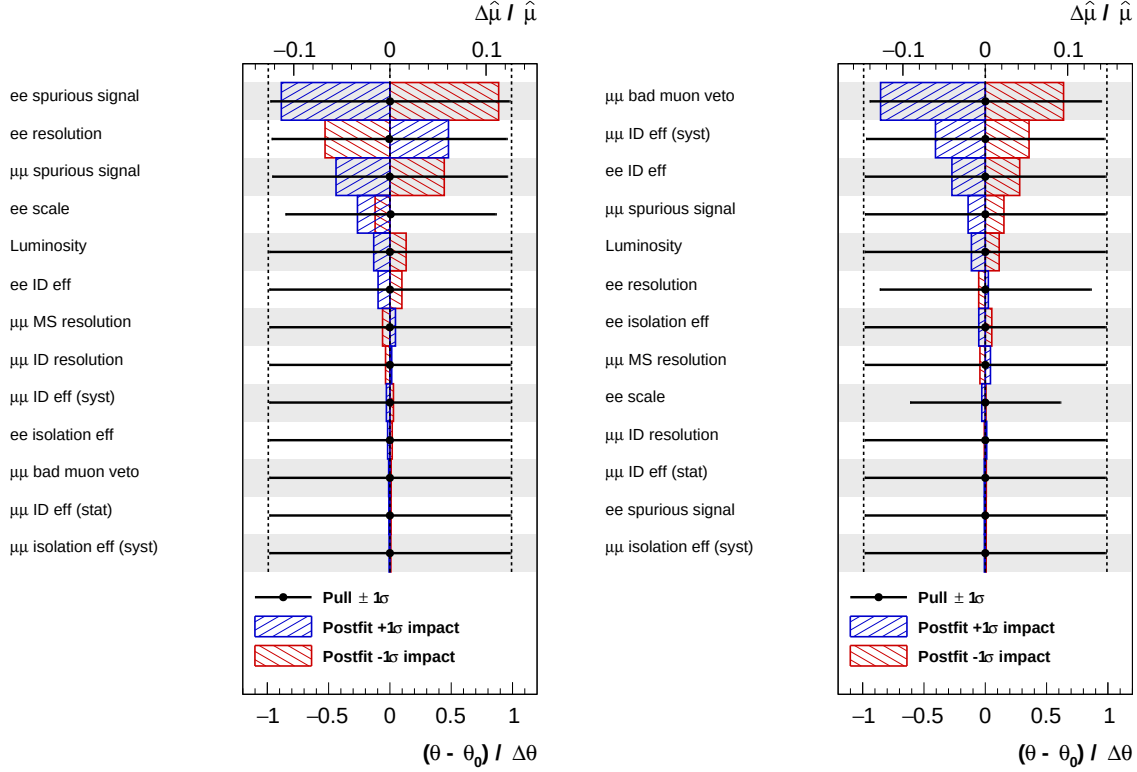


Figure 6.51: Ranking plot for the considered systematic uncertainties in the $\ell\ell$ channel at $\Gamma_X/m_X = 0\%$. The impact is shown for $m_X = 300$ GeV (left) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.

The relative impact of systematic variations, retrieved from the ee and $\mu\mu$ channel ranking plots, is additionally given in Table 6.5 for different pole masses and width assumptions.

6.9 Results of the dilepton resonance search

The analysis results of the full Run 2 dilepton search are presented in this section. Significance and p -value scans are given in Subsection 6.9.1. As no significant deviation from the SM is found, cross-section limits in the fiducial volume are calculated and presented in Subsection 6.9.2. Further reinterpretations of these limits are given in Subsection 6.9.3 and Section 7.5.

6.9.1 Significance and p -value scans

Significance scans for width assumptions of $\Gamma_X/m_X = 0\%$ and 10% are shown in Figure 6.53, while the corresponding p -value scans are given in Figure 6.54. The ee channel exhibits more fluctuations than the $\mu\mu$ channel due to the better mass resolution, which allows to probe a narrower mass range in

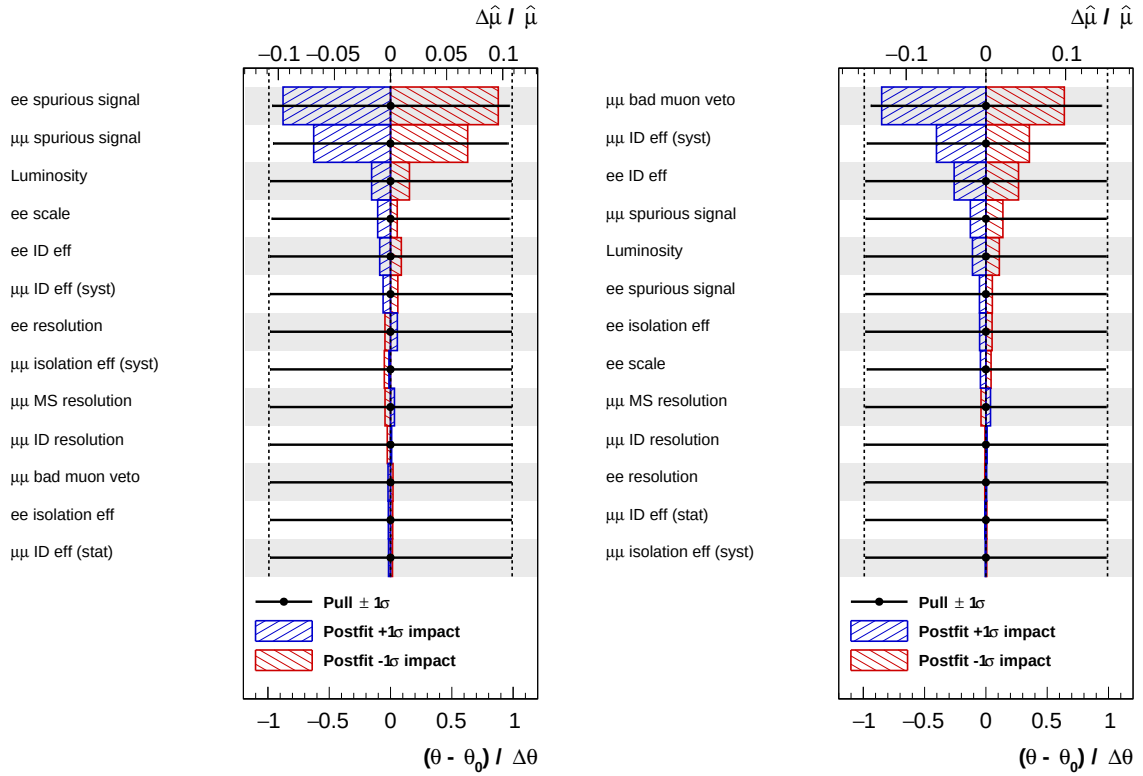


Figure 6.52: Ranking plot for the considered systematic uncertainties in the $\ell\ell$ channel at $\Gamma_X/m_X = 10\%$. The impact is shown for $m_X = 300$ GeV (left) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.

Table 6.5: The relative impact of $\pm 1\sigma$ variations of systematic uncertainties on the signal yield in percent for zero (10%) relative width signals at the pole masses of 300 GeV and 5 TeV for dielectron and dimuon channels. A signal is injected at the cross-section limit. Table from Ref. [84].

Uncertainty source for m_X [GeV]	Dielectron		Dimuon	
	300	5000	300	5000
Spurious signal	± 12.5 (12.0)	± 0.1 (1.0)	± 11.7 (11.0)	± 2.1 (2.2)
Lepton identification	± 1.6 (1.6)	± 5.6 (5.6)	± 1.8 (1.8)	$^{+25}_{-20}$ ($^{+25}_{-20}$)
Isolation	± 0.3 (0.3)	± 1.1 (1.1)	± 0.4 (0.4)	± 0.4 (0.5)
Luminosity	± 1.7 (1.7)	± 1.7 (1.7)	± 1.7 (1.7)	± 1.7 (1.7)
Electron energy scale	$^{-1.7}_{-4.0}$ ($^{+1.0}_{-1.8}$)	$^{+0.1}_{-0.4}$ (± 0.8)	-	-
Electron energy resolution	$^{+7.9}_{-8.3}$ ($^{+1.1}_{-0.9}$)	$^{+0.4}_{-0.9}$ (± 0.1)	-	-
Muon ID resolution	-	-	$^{+0.8}_{-2.3}$ ($^{+0.3}_{-0.8}$)	$^{+0.6}_{-0.4}$ ($^{+0.5}_{-0.3}$)
Muon MS resolution	-	-	$^{+2.8}_{-3.8}$ ($^{+1.0}_{-1.3}$)	± 2.4 (2.1)
‘Good muon’ requirement	-	-	± 0.6 (0.6)	$^{+55}_{-35}$ ($^{+55}_{-35}$)

the $m_{\ell\ell}^{\text{reco}}$ spectrum. The scans are obtained with a spacing of 1 GeV in m_X , which is below the mass resolution in all three channels. Global significance values are given in Tables 6.6 and 6.7 for the scans at $\Gamma_X/m_X = 0\%$ and 10% , respectively. Only the one-dimensional look-elsewhere effect is taken into account for the calculated global significances.

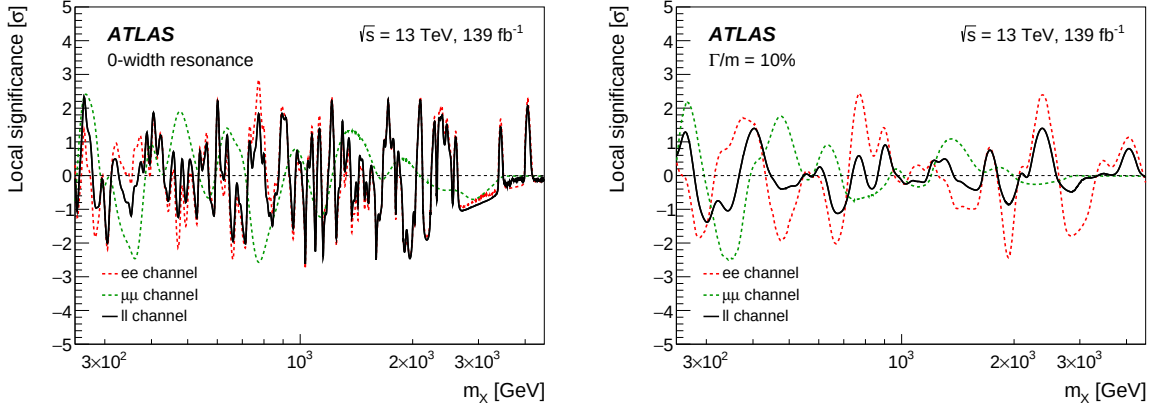


Figure 6.53: Observed 1-dimensional significance scans of deviations from the background-only hypothesis, as a function of the assumed pole mass, m_X , for signal width assumptions of $\Gamma_X/m_X = 0\%$ (left) and $\Gamma_X/m_X = 10\%$ (right) on truth-level in the ee , $\mu\mu$ and $\ell\ell$ channels.

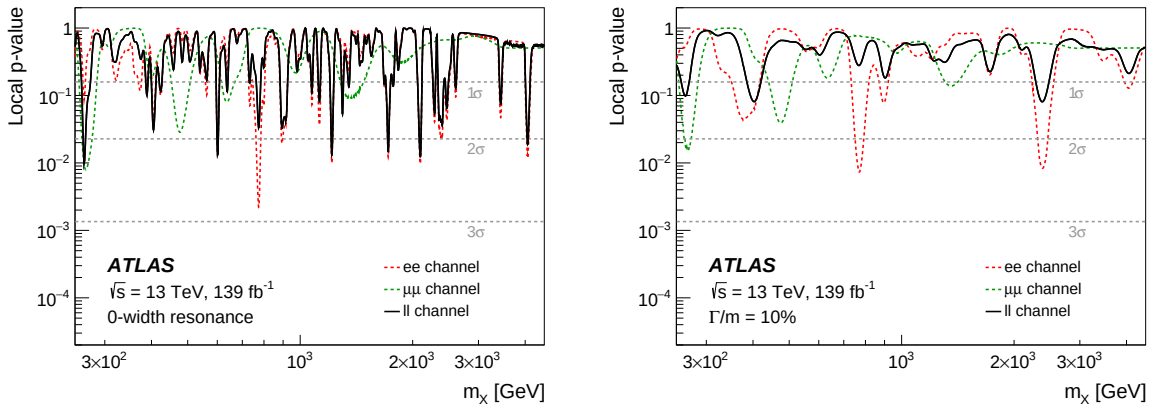


Figure 6.54: Observed 1-dimensional p -value scans of deviations from the background-only hypothesis, as a function of the assumed pole mass, m_X , for signal width assumptions of $\Gamma_X/m_X = 0\%$ (left) and $\Gamma_X/m_X = 10\%$ (right) on truth-level in the ee , $\mu\mu$ and $\ell\ell$ channels.

Further two-dimensional significance scans as a function of m_X and Γ_X/m_X are shown in Figure 6.55. The scans are obtained with a spacing of 1 GeV in m_X and 0.5% in Γ_X/m_X .

The highest local excesses and deficits are given in Table 6.8. The most significant excess occurs for $m_X = 773$ GeV and $\Gamma_X/m_X = 2.5\%$ in the ee channel with a local significance of 3.0σ and a global significance of 0.9σ (only considering the look-elsewhere effect in m_X).

Table 6.6: Highest local and the corresponding global significance values for the 1-dimensional significance scans at a signal width assumption of $\Gamma_X/m_X = 0\%$ on truth-level. The uncertainties on the global significance are calculated according to Section 6.7.

Channel	Mass [GeV]	Local sig. [σ]	N_{down}	Global sig. [σ]
ee	774	2.85	26 ± 5	0.1 ± 0.2
$\mu\mu$	267	2.41	7 ± 3	0.3 ± 0.4
$\ell\ell$	264	2.33	26 ± 5	$\lesssim 0$

Table 6.7: Highest local and the corresponding global significance values for the 1-dimensional significance scans at a signal width assumption of $\Gamma_X/m_X = 10\%$ on truth-level. The uncertainties on the global significance are calculated according to Section 6.7.

Channel	Mass [GeV]	Local sig. [σ]	N_{down}	Global sig. [σ]
ee	771	2.51	7 ± 3	0.5 ± 0.3
$\mu\mu$	267	2.17	5 ± 2	0.0 ± 0.6
$\ell\ell$	2390	1.42	10 ± 3	$\lesssim 0$

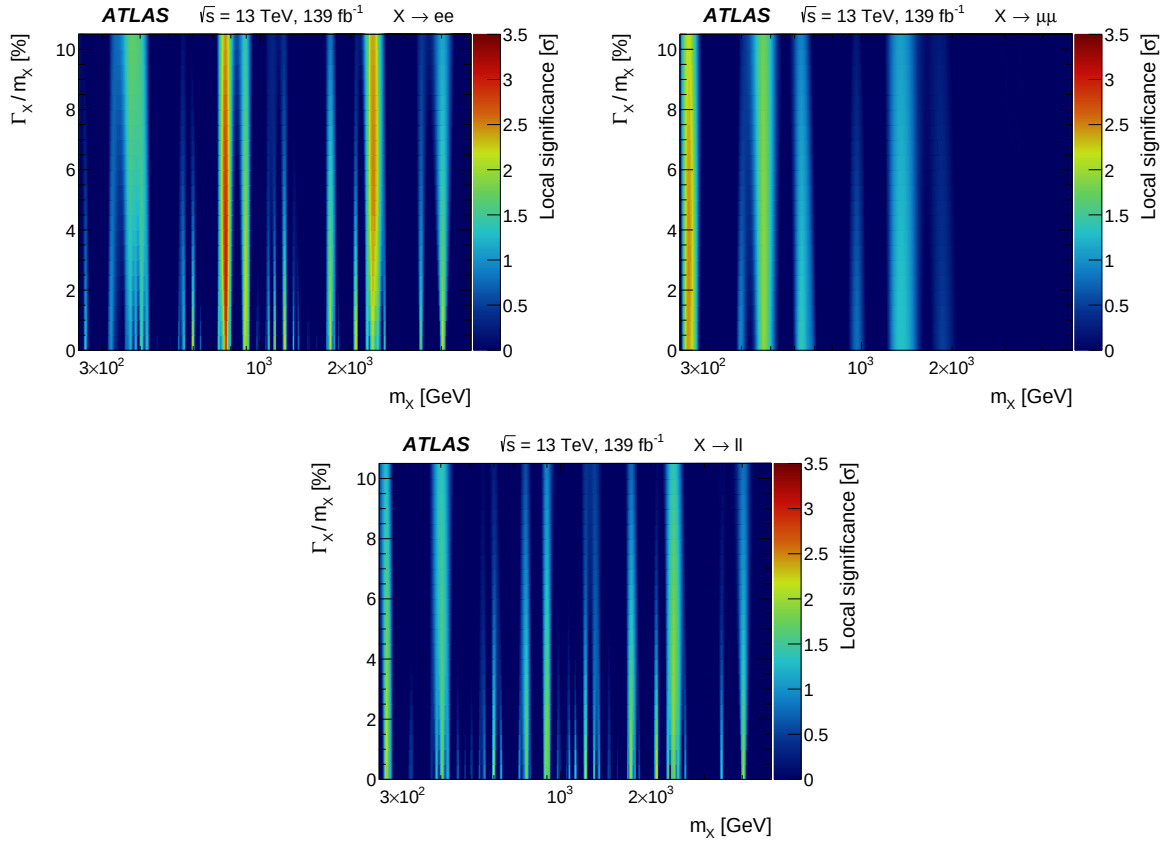


Figure 6.55: Observed 2-dimensional significance scans of positive deviations from the background-only hypothesis, as a function of the assumed pole mass, m_X , and the signal width on truth-level, Γ_X/m_X , in the ee (upper left), $\mu\mu$ (upper right) and $\ell\ell$ (bottom) channels.

Table 6.8: Largest positive and negative deviations (excess and deficit), in terms of the local p_0 -value converted into units of standard deviations σ , from the background-only hypothesis for the ee , $\mu\mu$, and $\ell\ell$ channels. The relative width Γ_X/m_X scan is performed in units of 0.5%. The values are retrieved from the scans shown in Figure 6.55.

Channel	Excess			Deficit		
	p_0 [σ]	m_X [GeV]	Γ_X/m_X [%]	p_0 [σ]	m_X [GeV]	Γ_X/m_X [%]
ee	3.0	773	2.5	-3.2	1957	4.0
$\mu\mu$	2.5	268	2.5	-2.8	349	8.5
$\ell\ell$	2.3	264	0	-2.9	1958	3.0

6.9.2 Generic cross-section limits

The fiducial cross-section limits for the generic signal model are given in Figures 6.56 to 6.58. The strongest limits are set in the combined $\ell\ell$ channel, while the ee channel typically yields stronger limits than the $\mu\mu$ channel. Examples of theoretical cross-sections in the fiducial volume from benchmark models are overlaid. The impact of the difference in the upper cross-section limits from toy-based limits compared to the asymptotic approximation on the lower mass limits is expected to be below 100 GeV for the considered range of models.

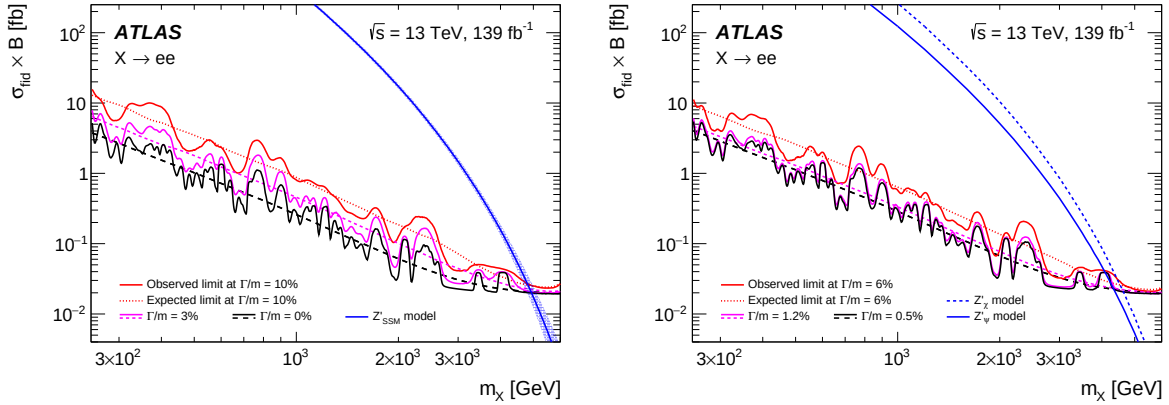


Figure 6.56: Expected and observed limits at 95% confidence level on the fiducial production cross-section times branching ratio into one fermion generation, $\sigma_{\text{fid}} \times \mathcal{B}$, as a function of the assumed pole mass, m_X , in the ee channel. Signal width assumptions of $\Gamma_X/m_X = 0\%$, 3% and 10% (left) as well as $\Gamma_X/m_X = 0.5\%$, 1.2% and 6% (right) are shown. Theoretical predictions from the Z'_ψ ($\Gamma_X/m_X = 0.5\%$), Z'_χ ($\Gamma_X/m_X = 1.2\%$) and Z'_{SSM} ($\Gamma_X/m_X = 3\%$) are overlaid where applicable.

Uncertainties on the Z'_{SSM} production cross-section due to PDF eigenvector variations and the PDF choice [132] are shown as a band on the corresponding theory curve for illustration purposes only.

Figure 6.59 additionally depicts the cross-section limits for $m_X \leq 2$ TeV including the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands on the expected limit. The uncertainty bands within the asymptotic approximation are considerably wider than the ones retrieved with toy-based results above this pole mass, such that the figures are restricted to the mass region below 2 TeV. The difference in the uncertainty bands is shown in Figure C.9 of Appendix C.4.2 for the high-mass region.

The impact of systematic uncertainties on the fiducial cross-section limits is small across all mass and width assumptions. The expected limits in the $\ell\ell$ channel are (4 – 7)% weaker when considering systematic uncertainties.

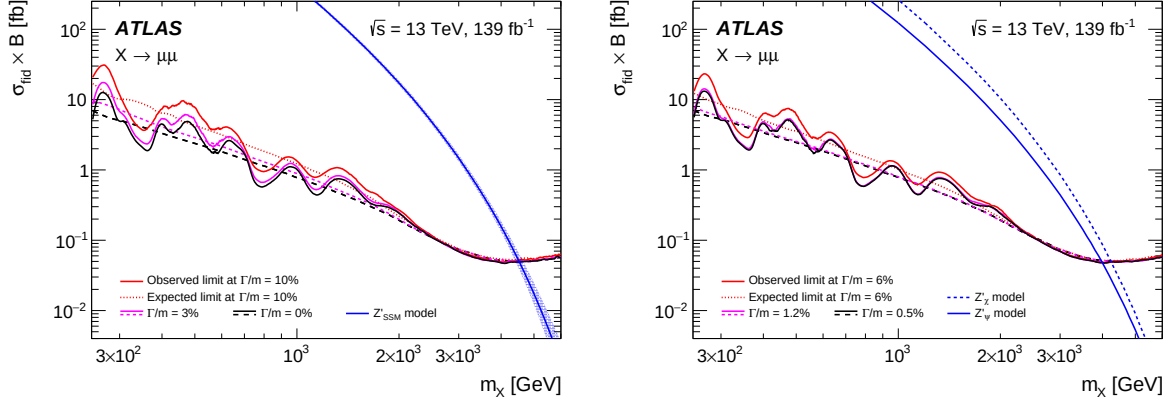


Figure 6.57: Expected and observed limits at 95% confidence level on the fiducial production cross-section times branching ratio into one fermion generation, $\sigma_{\text{fid}} \times \mathcal{B}$, as a function of the assumed pole mass, m_X , in the $\mu\mu$ channel. Signal width assumptions of $\Gamma_X/m_X = 0\%$, 3% and 10% (left) as well as $\Gamma_X/m_X = 0.5\%$, 1.2% and 6% (right) are shown. Theoretical predictions from the Z'_ψ ($\Gamma_X/m_X = 0.5\%$), Z'_χ ($\Gamma_X/m_X = 1.2\%$) and Z'_{SSM} ($\Gamma_X/m_X = 3\%$) are overlaid where applicable.

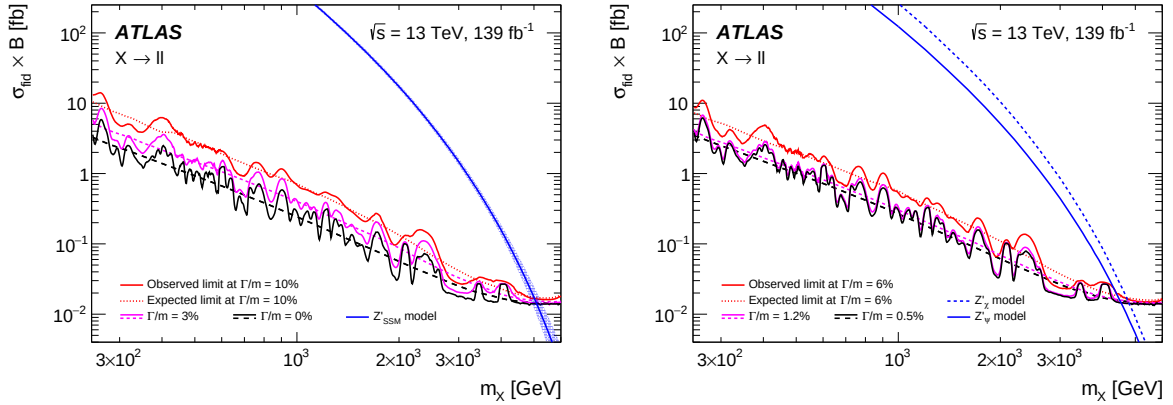


Figure 6.58: Expected and observed limits at 95% confidence level on the fiducial production cross-section times branching ratio into one fermion generation, $\sigma_{\text{fid}} \times \mathcal{B}$, as a function of the assumed pole mass, m_X , in the $\ell\ell$ channel. Signal width assumptions of $\Gamma_X/m_X = 0\%$, 3% and 10% (left) as well as $\Gamma_X/m_X = 0.5\%$, 1.2% and 6% (right) are shown. Theoretical predictions from the Z'_ψ ($\Gamma_X/m_X = 0.5\%$), Z'_χ ($\Gamma_X/m_X = 1.2\%$) and Z'_{SSM} ($\Gamma_X/m_X = 3\%$) are overlaid where applicable.

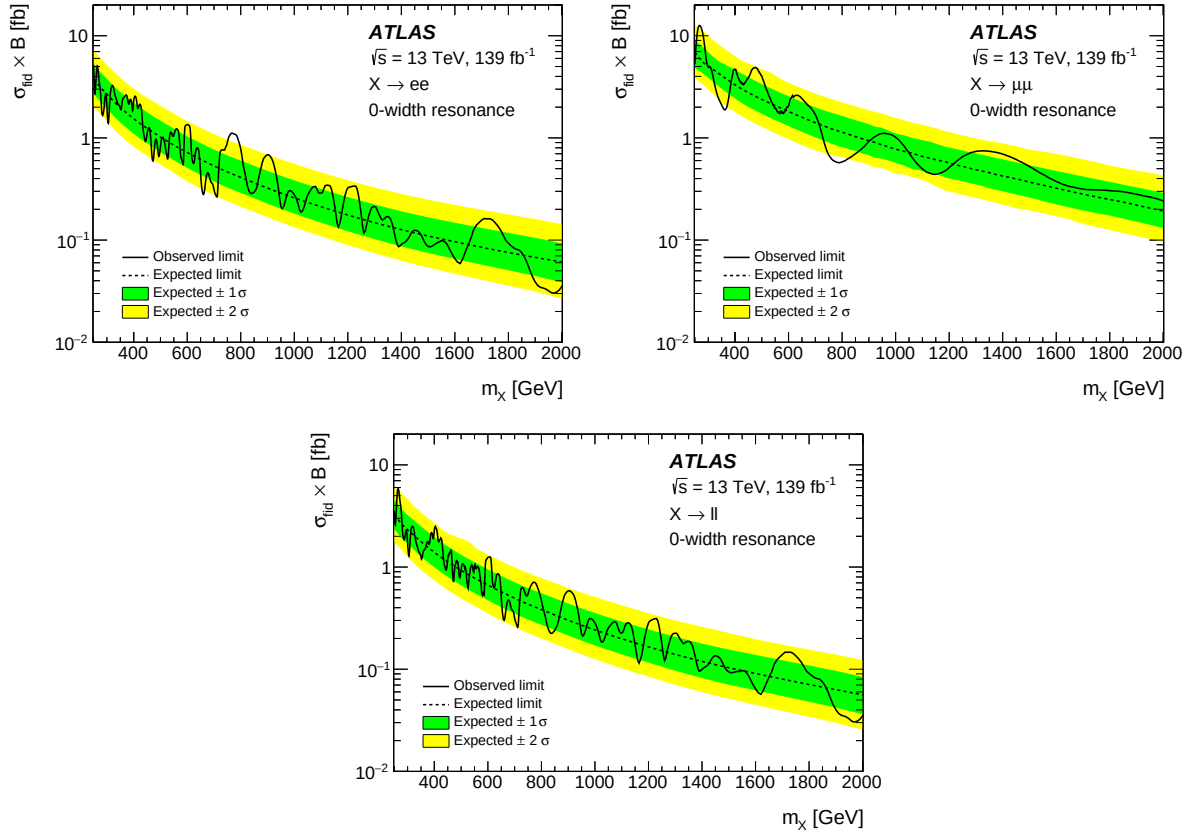


Figure 6.59: Expected and observed limits at 95% confidence level on the fiducial production cross-section times branching ratio into one fermion generation, $\sigma_{\text{fid}} \times \mathcal{B}$, as a function of the assumed pole mass, m_X , in the ee (upper left), $\mu\mu$ (upper right) and $\ell\ell$ (bottom) channels. A signal width assumption of $\Gamma_X/m_X = 0\%$ is shown. The limit curves and their uncertainty bands are calculated using the asymptotic approximation.

6.9.3 Mass limits on benchmark models

The cross-section limits of Subsection 6.9.2 can be reinterpreted into mass limits on specific models by calculating the cross-section prediction of a given theoretical model inside the fiducial volume. The predictions for the Z'_ψ , Z'_χ and Z'_{SSM} models (see Subsection 2.2.2) are already given in Figures 6.56 to 6.58 and yield the mass limits given in Table 6.9. The mass limits are stronger by 500 – 800 GeV than the results from the previous ATLAS dilepton search publication [132].

Table 6.9: Observed and expected 95% CL lower limits on $m_{Z'}$ for three Z' gauge boson models, quoted to the nearest 100 GeV in the ee and $\mu\mu$ channels as well as their combination ($\ell\ell$).

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

The obtained limits on the signal strength, $\mu_{\text{SSM}} = \sigma_{\text{limit}}/\sigma_{\text{SSM}}$, for the Z'_{SSM} model are additionally compared to the signal strength limits from previous ATLAS dilepton searches in Figure 6.60. The cross-section limits show an improvement over time due to the increasing dataset size and gains in the cms energy. In comparison with the final Run 1 result at $\sqrt{s} = 8$ TeV, the observed cross-section limits are lower by roughly a factor of 3 – 5 for $m_{Z'_{\text{SSM}}} < 1.5$ TeV. The mass limit on $Z'_{\text{SSM}} \rightarrow \ell\ell$ production increased from 2.9 TeV at the end of Run 1 to 5.1 TeV at the end of Run 2.

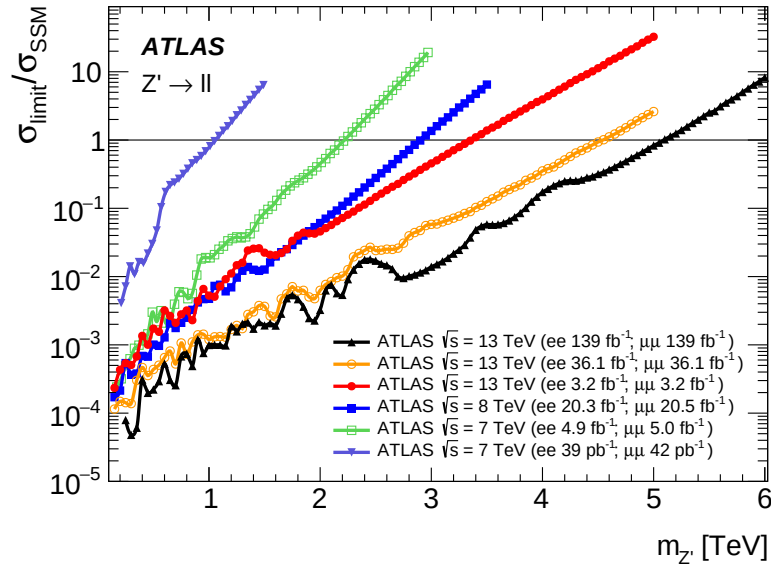


Figure 6.60: Observed cross-section limits in the dilepton channel, normalised to the prediction of the Z'_{SSM} model. Various dilepton search results at $\sqrt{s} = 7, 8$ and 13 TeV are presented together with the result of the full Run 2 search. Figure from Ref. [84].

6.10 Conclusion and outlook

The analysis strategy of the dilepton search was updated for the full Run 2 analysis round. The background model is based on a functional fit to the invariant mass spectrum observed in data. The presented global fit approach is used as the baseline strategy for the published result. The signal model is chosen to be a generic non-relativistic Breit-Wigner shape, convoluted with the parametrised detector mass resolution, and thus does not target a specific theoretical model for an easy reinterpretation of the analysis results.

The analysis of the full Run 2 dataset allowed to increase the mass limits on typical benchmark models by 500 – 800 GeV compared to the previous ATLAS dilepton search results at 36.1 fb^{-1} [132]. An additional reinterpretation into the HVT model serves as a benchmark for a potential future full Run 2 heavy resonance combination (see Section 7.4).

The chosen “data-driven” search strategy produces compatible results when compared with the previous MC-based approach. The new strategy is expected to be more scalable towards the Run 3 and HL-LHC data-taking periods.

The inclusive selection used in this analysis allows to search for resonances without specific assumptions on their properties. In the future, extensions of the search towards more exclusive final states might allow to probe additional phase-space regions, for which the presented search is not sensitive due to the inclusive selection and thus higher backgrounds for these specific channels.

Combination of the $\ell\ell$ search with the $\ell\nu$, VV and VH channels

Many theories beyond the SM predict new resonances which can decay into various final states, similarly to, for example, the SM model W and Z bosons. While experimentally the different final states need to be targeted with dedicated selections, the theoretical interpretation gains considerably from the combination of the available final states.

The combination of searches in the VV ($V \in \{W, Z\}$), VH , $\ell\nu$ and $\ell\ell$ channels (see Ref. [55]) presented in this chapter is performed on the 2015/16 dataset with an integrated luminosity of 36.1 fb^{-1} . The results of the 2015/16 dilepton search [132] are thus used. The results of the full Run 2 dilepton search, presented in Chapter 6, are planned to be used in the next iteration of the combination.

7.1 Analysis motivation and strategy

The combination of the mentioned dibosonic and dileptonic searches is motivated by theoretical models that predict new heavy resonances which can directly decay into the bosonic VV and VH or the leptonic $\ell\ell$ and $\ell\nu$ final states. A combination allows to extend the mass limit reach for coupling points where decays into various final states are predicted with a similar branching ratio, and thus to better constrain the available models. The complementarity of the search sensitivity for different coupling parameters in addition allows to extend the discovery reach into different phase space corners. It could therefore be possible to identify hints for new physics considerably earlier than would be possible when only considering single channels.

The interpretation of the data is performed in terms of spin-1, mass-degenerate $W'^{\pm}$ and Z' bosons within the HVT model [54, 56]. An overview of the HVT model and its properties is given in Subsection 2.2.2. This combination in total includes 12 baseline searches, which each target different final states and decay modes. An overview of the searches is given in Table 7.1, together with their respective selections and references to the publications. The searches are combined depending on the targeted resonance decay modes.

An overview of the combination procedure is given in Figure 7.1. Only the decay modes that are predicted by a certain model are used in the specific interpretation. In the following, the combination in the HVT model and particularly the characteristics of the leptonic $\ell\ell/\ell\nu$ channels are described.

Table 7.1: Summary of analysis channels, diboson states they are sensitive to, and their experimental signatures. The selection reflects requirements specific to each channel. Additional jets (not included in the “Jets” column) are required to define VBF categories. The notation “j” represents small- R jets and “J” represents large- R jets. Leptons are either electrons or muons. The notation “ $1e, 1\mu$ ” means that the signature is either $1e$ or 1μ , whereas “ $1e+1\mu$ ” means $1e$ and 1μ . A veto is imposed on E_T^{miss} in some channels to guarantee orthogonality between final-state channels. The symbol “–” signifies that no requirement is imposed on a given signature. Table adapted from Ref. [55].

Channel	Diboson state	Selection		VBF cat.			Reference
		Leptons	E_T^{miss}	Jets	b -tags		
$qqqq$	WW/WZ	0	veto	2J	–	–	[160]
$\nu\nu qq$	WZ	0	yes	1J	–	yes	[161]
$\ell\nu qq$	WW/WZ	$1e, 1\mu$	yes	2j, 1J	–	yes	[162]
$\ell\ell qq$	WZ	$2e, 2\mu$	–	2j, 1J	–	yes	[161]
$\ell\nu\ell\nu$	WW	$1e+1\mu$	yes	–	0	yes	[163]
$\ell\nu\ell\ell$	WZ	$3e, 2e+1\mu, 1e+2\mu, 3\mu$	yes	–	0	yes	[164]
$qqbb$	WH/ZH	0	veto	2J	1, 2	–	[165]
$\nu\nu bb$	ZH	0	yes	2j, 1J	1, 2	–	[166]
$\ell\nu bb$	WH	$1e, 1\mu$	yes	2j, 1J	1, 2	–	[166]
$\ell\ell bb$	ZH	$2e, 2\mu$	veto	2j, 1J	1, 2	–	[166]
$\ell\nu$	–	$1e, 1\mu$	yes	–	–	–	[167]
$\ell\ell$	–	$2e, 2\mu$	–	–	–	–	[132]

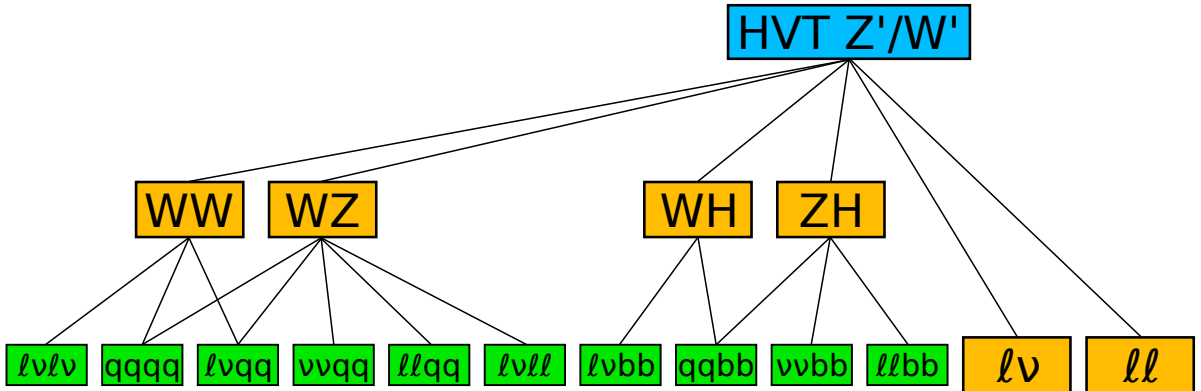


Figure 7.1: Combination procedure of the 12 baseline final states (green boxes and $\ell\ell/\ell\nu$ channels) into the heavy resonance decay modes (orange boxes). The interpretation is performed in the HVT model (blue box) predicting new heavy resonances with spin-1.

It is important to ensure the orthogonality between the selections of the different searches, such that no signal region events are used twice, and to allow to statistically combine the searches by using similar frameworks. The baseline analyses thus need to consider the combination needs early in the analysis development in order to facilitate the later combination.

7.2 Combination of the leptonic channels

The combination of the leptonic decay modes, $\ell\ell$ and $\ell\nu$, has not been performed in ATLAS prior to the publication presented here, nor a combination of the VV and VH searches. The combination of the bosonic VV final states has been published previously with 3.2 fb^{-1} [168]. Step-wise combination results for the VV/VH and $\ell\ell/\ell\nu$ decay modes are presented in Ref. [55], as well as the full combination.

The $\ell\nu$ search at 36 fb^{-1} , with details on the concrete selection, is described in Ref. [167]. In contrast to the $\ell\ell$ search, the $\ell\nu$ search is performed in the transverse mass, m_T , spectrum due to the presence of the neutrino in the final state. The transverse mass is defined as

$$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi(\ell, E_T^{\text{miss}}))}, \quad (7.1)$$

with $\ell \in \{e, \mu\}$. E_T^{miss} is the missing transverse energy, which is associated fully to the final state neutrino. The baseline selection of physics objects between the $\ell\ell$ and $\ell\nu$ channels is kept aligned to ensure an easy overlap removal between the two searches. In particular, a veto on additional same-flavour leptons is applied in the baseline $\ell\nu$ search.

7.2.1 Signal reweighting

The generation of signal templates in the $\ell\ell$ and $\ell\nu$ searches is based on so-called signal reweighting¹. In this procedure, leading order DY MC samples are used and for each event a weight is assigned according to the difference in the matrix elements for SM DY production and the considered BSM model. The procedure is detailed for the $\ell\ell$ channel in the following, but applicable similarly to the $\ell\nu$ channel. The event weight is calculated as

$$w_{\text{rew}}(\mathbf{q}_a, \bar{\mathbf{q}}_b, \mathbf{f}_c, \bar{\mathbf{f}}_d | m_{Z'}, \vec{g}) = \frac{\sum_{i,j \in \{L,R\}} |A_{ij}(q_a \bar{q}_b \rightarrow X \rightarrow f_c \bar{f}_d)|^2}{\sum_{i,j \in \{L,R\}} |A_{ij}(q_a \bar{q}_b \rightarrow Z, \gamma^* \rightarrow f_c \bar{f}_d)|^2}. \quad (7.2)$$

A_{ij} is the matrix element for the LO s -channel production of a fermion pair, $f_c \bar{f}_d$, from a specific quark-antiquark initial state, $q_a \bar{q}_b$. A sum over all possible chirality configurations is used, as this quantity cannot be measured in the experiment. The initial and final state information, given by the four-momenta of the particles (i.e. $\mathbf{q}_a, \bar{\mathbf{q}}_b, \mathbf{f}_c$ and $\bar{\mathbf{f}}_d$), for a specific MC event is extracted from the truth record. $\vec{g}$ denotes the predicted BSM coupling values for a given model, which describe the coupling strength between the Z' boson and a given fermion. The assumed Z' boson mass is given by $m_{Z'}$. The intermediate state X can be chosen as a pure Z' contribution or combined Z, γ^*, Z' production with and without considering interference effects by calculating the appropriate propagator terms. Different choices for X are used in the following depending on the specific study.

The weight w_{rew} finally describes the probability ratio for an event to occur in a given BSM model (numerator of Eq. 7.2) compared to the SM prediction (denominator of Eq. 7.2) in case of the specific

¹ The signal reweighting procedure is described for spin-1 resonances here, while a similar implementation for spin-2 resonances in the “RS1” model [49] exists.

kinematics of the event. While the procedure only uses truth-level information, the reconstruction-level information is additionally available in the used DY MC samples. Therefore, signal templates on reconstruction-level can be generated. The total cross-section of a BSM signal process can be obtained by reweighting all events in the DY MC samples, weighted to the DY production cross-section, on truth level. The integral of the template after the application of the event weights then gives the cross-section of the signal process, since the DY production cross-section is factored out within Equation 7.2.

The advantage of signal reweighting is given by the flexibility to obtain signal templates at arbitrary pole masses, at arbitrary coupling points and for various theoretical models based on the same baseline DY MC samples. It thus allows to avoid the generation of many signal MC samples, which would otherwise be needed and which are computationally not feasible. The calculation of the matrix element A_{ij} is required to only contribute a small fraction of the computational needs for the MC event generation, though. The signal reweighting exploits the factorisation of the partonic cross-section and the proton PDFs (compare Equation 2.14), as the complex treatment of the PDFs is done within the production of the LO DY samples and no further treatment is required within the signal reweighting. The signal reweighting tool used in the $\ell\ell$ and $\ell\nu$ searches has been validated extensively for the SSM and E_6 models and is documented in Ref. [169].

An implementation of the signal reweighting for the HVT model is done in order to generate signal templates within the model used in the combination. The Lagrangian of the HVT model is given in Equation 2.11. The matrix element A_{ij} is given as [169]

$$|A_{ij}(\hat{s})|^2 = 4|G_{ij}(\hat{s})|^2(1 + \lambda_{ij} \cos \theta)^2, \quad (7.3)$$

with $\lambda_{ij} = +1$ for $i = j$, $\lambda_{ij} = -1$ for $i \neq j$ and θ as the angle between the incoming anti-quark and the outgoing lepton in the dilepton rest frame. The term G_{ij} contains the specific coupling structure of the model and the Z' propagator term according to

$$G_{ij}(\hat{s}) = g_{Z'}^2 \frac{z_i^f z_j^q}{\hat{s} - m_{Z'}^2 + i\hat{s}\Gamma_{Z'}/m_{Z'}}, \quad (7.4)$$

with the gauge coupling constant $g_{Z'}$. The chiral charges z_i^f and z_j^q are given as defined below. Additional terms are required to model Z/γ^* contributions. The gauge coupling constant in the HVT model is given as

$$g_{Z'} = 1. \quad (7.5)$$

The chiral charges for the HVT model depend on the coupling parameters g_q and g_ℓ (see Equation 2.11), and are defined as follows:

$$\begin{aligned} z_L^u &= -0.5 g_q & z_L^{v_\ell} &= -0.5 g_\ell \\ z_R^u &= 0 & z_R^{v_\ell} &= 0 \\ z_L^d &= +0.5 g_q & z_L^\ell &= +0.5 g_\ell \\ z_R^d &= 0 & z_R^\ell &= 0, \end{aligned} \quad (7.6)$$

where $\ell \in \{e, \mu, \tau\}$, $\nu_\ell \in \{\nu_e, \nu_\mu, \nu_\tau\}$, d are the down-type quarks and u are the up-type quarks. The HVT bosons thus do not couple to right-chiral states.

The width of the HVT Z' boson can subsequently be calculated as

$$\Gamma_{\text{tot}} = \sum_f \Gamma(Z' \rightarrow f\bar{f}) + \Gamma(Z' \rightarrow t\bar{t}), \quad (7.7)$$

where f contains the above ℓ , ν_ℓ , u and d sets except for the top-quark. $\Gamma(Z' \rightarrow t\bar{t})$ only contributes for $m_{Z'} > 2m_t$ and needs a dedicated treatment close to the production threshold [170]. For the limit of massless fermions (i.e. $m_{Z'} \gg m_f$), the following expression is used:

$$\Gamma(Z' \rightarrow f\bar{f}) = C_F \left(1 + \frac{\alpha_S(m_{Z'})}{\pi} \right) \frac{g_{Z'}^2 m_{Z'}}{24\pi} \left((z_L^f)^2 + (z_R^f)^2 \right), \quad (7.8)$$

where $\alpha_S(m_{Z'})$ denotes the strong coupling constant and the colour factor C_F , which is 1 (3) for leptons (quarks). The decay width due to dibosonic final states gives an additional contribution to Γ_{tot} . It is given as [56]

$$\Gamma(Z' \rightarrow WW + ZH) = \frac{g_H^2 m_{Z'}}{96\pi}. \quad (7.9)$$

The width thus depends on the chosen coupling parameters of the HVT model and, as also diboson decay modes are allowed, needs a correction depending on the coupling parameter g_H . Width values at $m_{Z'} = 5 \text{ TeV}$ for varying coupling parameters are shown in Figure 7.2.

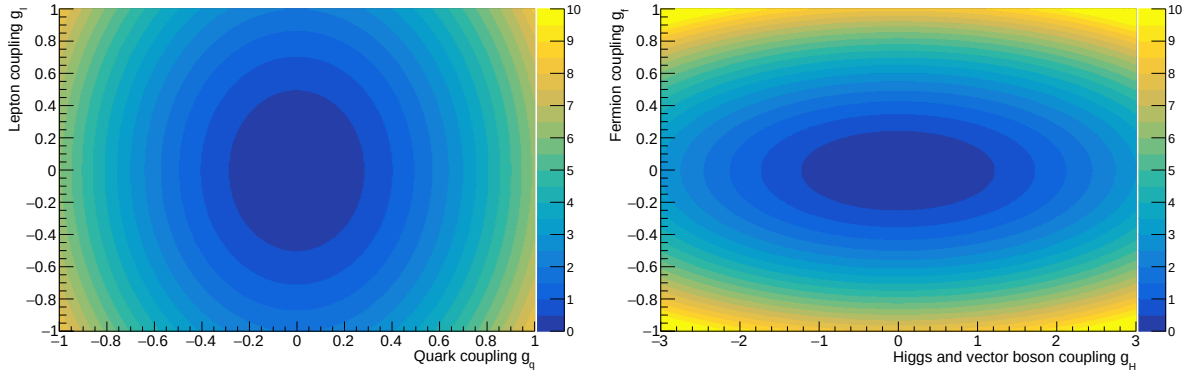


Figure 7.2: Predicted relative width, $\Gamma_{Z'}/m_{Z'}$, in percent (on the z -axis) for the HVT model at $m_{Z'} = 5 \text{ TeV}$. The g_q/g_ℓ (left) and g_H/g_f (right) planes are depicted within the considered coupling regions.

The cross-section for Z' production can finally be calculated by reweighting LO DY samples according to Equation 7.2. The cross-section for LO DY production is known from the dedicated MC samples and the integral of the signal model templates then corresponds to the total production cross-section of Z' production.

The signal reweighting tool allows to modify the interference effects that are present between the Z' boson and the SM Z boson. The structure of the propagators is adjusted in this case and allows to neglect the interference term. Further studies on this are given in Subsection 7.2.2.

The implementation for the $W' \rightarrow \ell\nu$ signal templates follows the same scheme and is done within the same tool. The $\ell\nu$ search uses slightly modified input MC samples, though, which have an additional cross-section modification to obtain a flat spectrum in the transverse mass to ensure low uncertainties of the signal template shape in the tails.

Validation using Pythia and MadGraph MC samples

Figure 7.3 shows truth-level signal templates that are obtained using the signal reweighting method for $Z' \rightarrow \ell\ell$ decays in comparison with HVT MC samples that are generated with Pythia. The coupling parameters are $g_q = g_\ell = 0.1$ and $g_H = 0$ for Figure 7.3, while further coupling parameters are additionally tested. The shape and the normalisation are independent between the two templates. The signal templates do not exhibit strong differences and the resonance width agrees within 5%, such that a good agreement between the two methods can be observed.

An additional validation with MadGraph [171] is shown in Figures 7.4 to 7.6 for the HVT A coupling point. The distributions in Figure 7.4 depict the truth-level distributions, while Figures 7.5 and 7.6 show the reconstruction-level agreement for the ee and $\mu\mu$ channels, respectively. MadGraph allows to simulate decays into diboson final states, and thus a validation in the $g_H \neq 0$ case is possible in contrast to Pythia. A good agreement between the two approaches can again be observed. The differences between the two shapes on truth-level are due to a cut of $|m_{\ell\ell}^{\text{truth}} - m_{Z'}| < 15 \times \Gamma_{Z'}$ that is applied by default within MadGraph. The effect of this truth-level cut is also visible in the reconstruction-level comparisons.

7.2.2 Mitigation of interference effects

The interference between the hypothetical Z' boson and the SM Z boson has non-negligible effects on the shape of the invariant mass spectrum and depends on the sign of the coupling parameters. An example for this effect is shown in Figure 7.7(a), where the differential cross-section deviates by up to 60 – 80% for the expected signal-plus-background shape in the $g_q = +g_\ell$ and $g_q = -g_\ell$ cases in comparison with the neglect of interference effects. The main deviations in the cross-section are given in regions where the event yield is low, though, such that the impact of interference effects on the cross-section limit is considerably lower than the maximal cross-section deviation. Nevertheless, considerable offsets in the integrated cross-section close to the Z' pole can occur depending on the coupling parameters.

A reduction of the interference effect is possible by introducing a mass window cut, as described in Ref. [146]. Interference effects are usually highly model-dependent and thus a proper treatment within an analysis can only be performed for a specific model. The mass window cut allows to obtain analysis results that depend less on the underlying model assumptions by ensuring a low impact of the interference effects. The definition of the mass windows is chosen to be as follows:

$$|m_{\ell\ell}^{\text{truth}} - m_{Z'}| \leq \Delta m, \quad (7.10)$$

where Δm defines the width of the mass window². It has to be chosen such that only a low dependency of the cross-section on the interference assumption is present for a broad range of coupling parameters and pole masses. The mass window cut is only applied on truth level.

The optimisation of Δm is based on the cross-section difference between the case where interference is neglected and the case where interference effects are fully considered. The difference is calculated by generating signal templates through the signal reweighting procedure, which allows to perform the reweighting with and without considering the interference terms for the matrix element calculation.

The observed cross-section difference is shown in Figure 7.8 for different pole mass dependencies of Δm . It can be observed that a cut of the form $\Delta m \propto \kappa \cdot m_{Z'}$, where κ is a constant that can be chosen freely, yields considerably higher $\Delta\sigma$ values for high $m_{Z'}$ than for lower pole masses. A cut of this type would scale similarly as the resonance width, $\Gamma_{Z'}$. The opposite behaviour is visible for a cut of the form $\Delta m = \kappa$, which yields lower $\Delta\sigma$ values for high $m_{Z'}$. In addition, a constant Δm might remove a

² In case of the $\ell\nu$ search, m_T is used to define the mass window cut instead of $m_{\ell\ell}$.

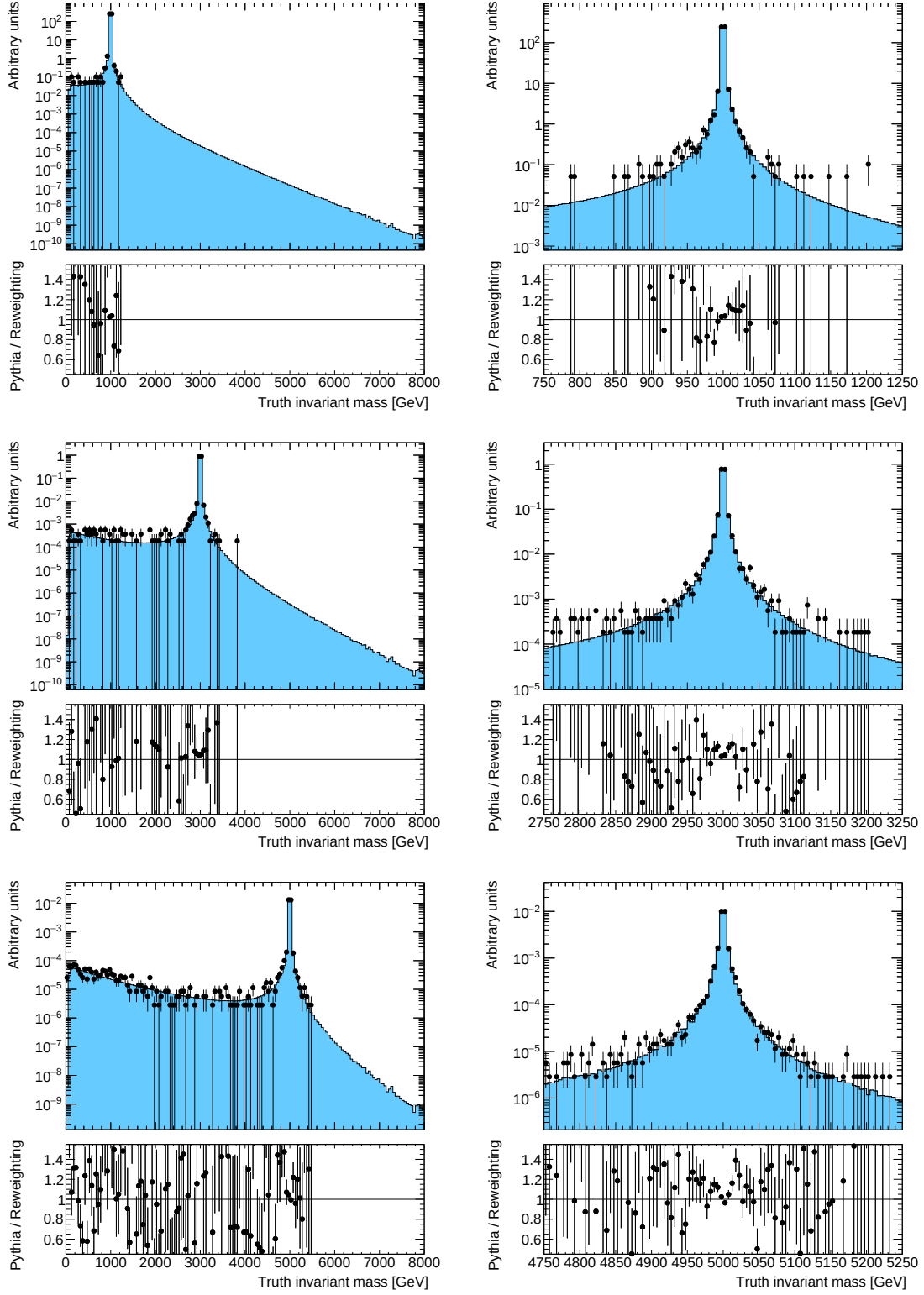


Figure 7.3: Validation of the signal templates from reweighting (blue area) with dedicated Pythia samples (data points) on truth level. The full signal shape (left row) and the peak region (right row) is shown for assumed pole masses of 1, 3 and 5 TeV. The coupling parameters are $g_q = g_\ell = 0.1$ and $g_H = 0$.

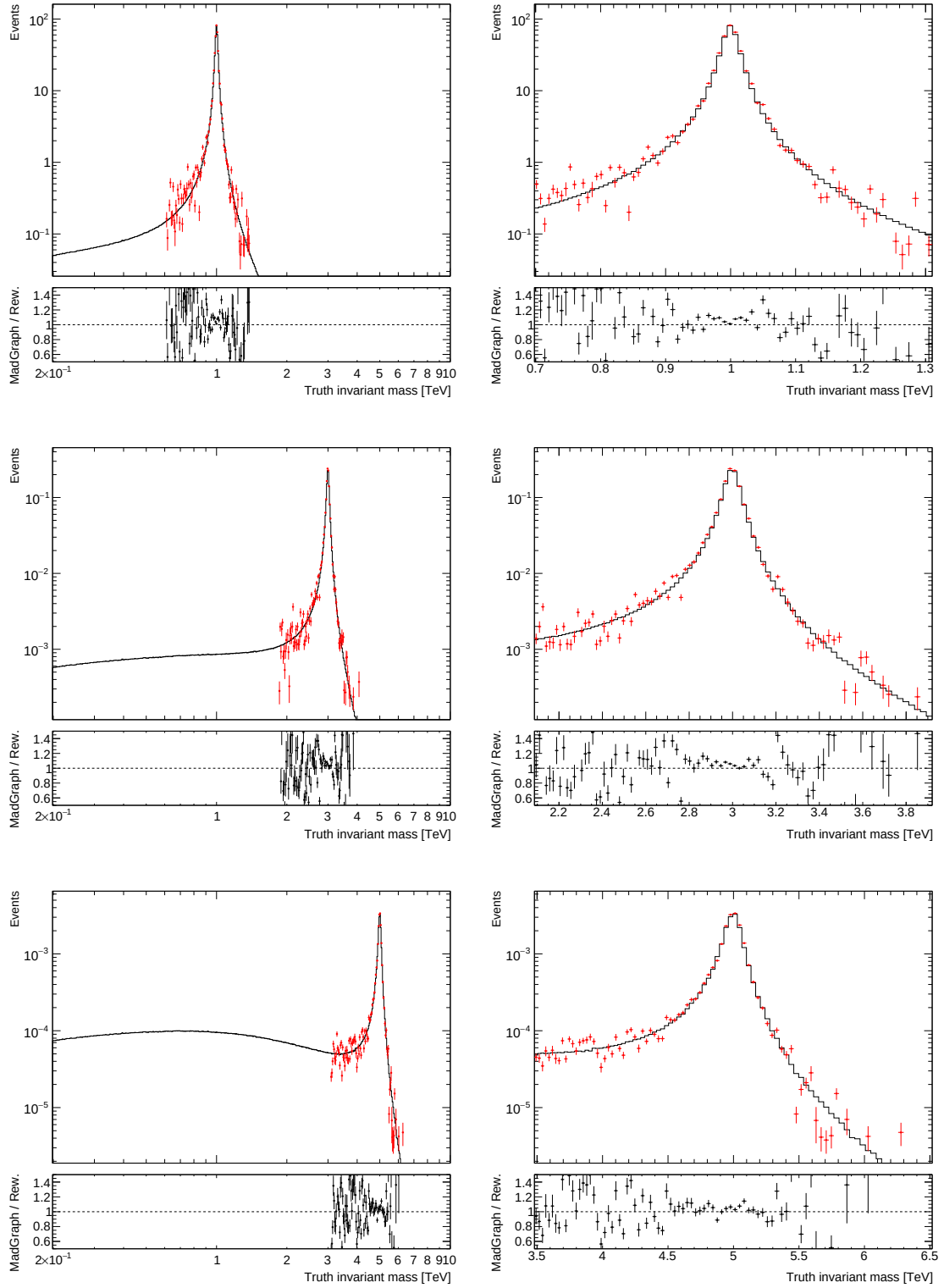


Figure 7.4: Validation of the signal templates from reweighting (black solid line) with dedicated MadGraph samples (red data points) on truth level at the HVT A coupling point. A truth-level cut of $|m_{\ell\ell}^{\text{truth}} - m_{Z'}| < 15 \times \Gamma_{Z'}$ is applied within MadGraph, leading to the observed differences in the low- and high-mass tails. The binning is chosen according to the ee resolution binning. The full signal shape (left row) and the peak region (right row) is shown for assumed pole masses of 1, 3 and 5 TeV.

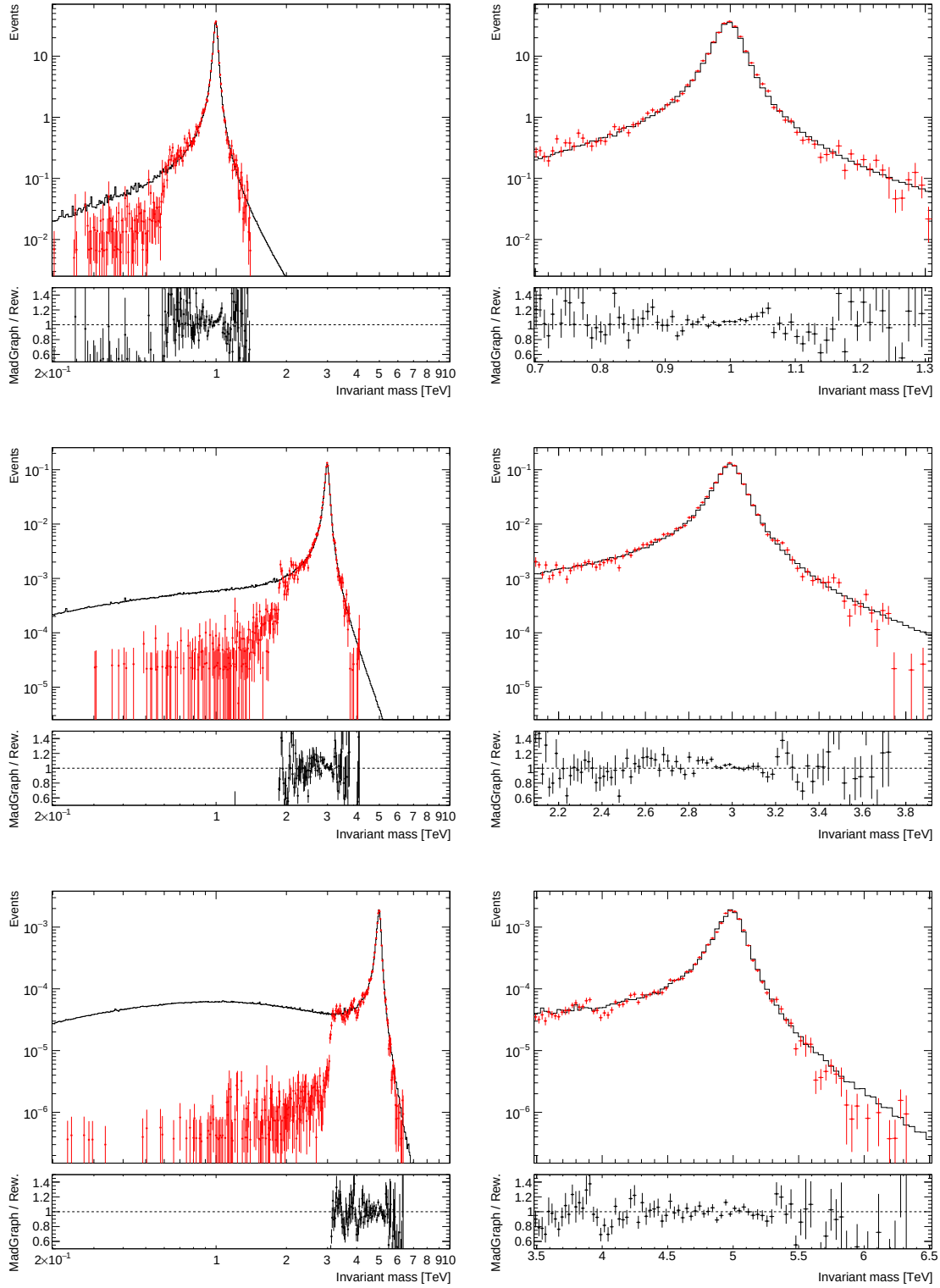


Figure 7.5: Validation of the ee signal templates from reweighting (black solid line) with dedicated MadGraph samples (red data points) on reconstruction level at the HVT A coupling point. A truth-level cut of $|m_{\ell\ell}^{\text{truth}} - m_{Z'}| < 15 \times \Gamma_{Z'}$ is applied within MadGraph, leading to the observed differences in the low- and high-mass tails. The full signal shape (left row) and the peak region (right row) is shown for assumed pole masses of 1, 3 and 5 TeV.

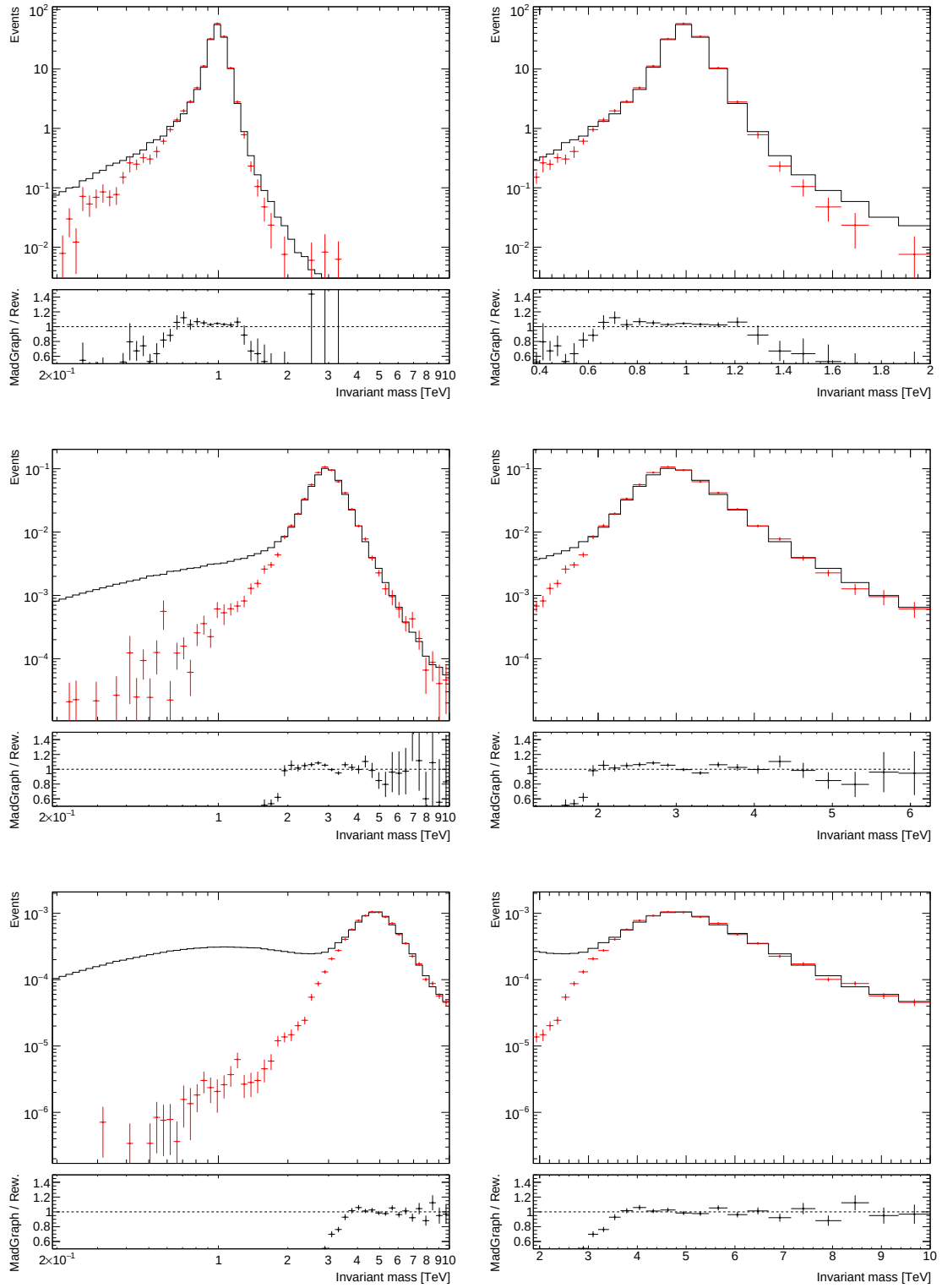


Figure 7.6: Validation of the $\mu\mu$ signal templates from reweighting (black solid line) with dedicated MadGraph samples (red data points) on reconstruction level at the HVT A coupling point. A truth-level cut of $|m_{\ell\ell}^{\text{truth}} - m_Z| < 15 \times \Gamma_Z$ is applied within MadGraph, leading to the observed differences in the low- and high-mass tails. The full signal shape (left row) and the peak region (right row) is shown for assumed pole masses of 1, 3 and 5 TeV.

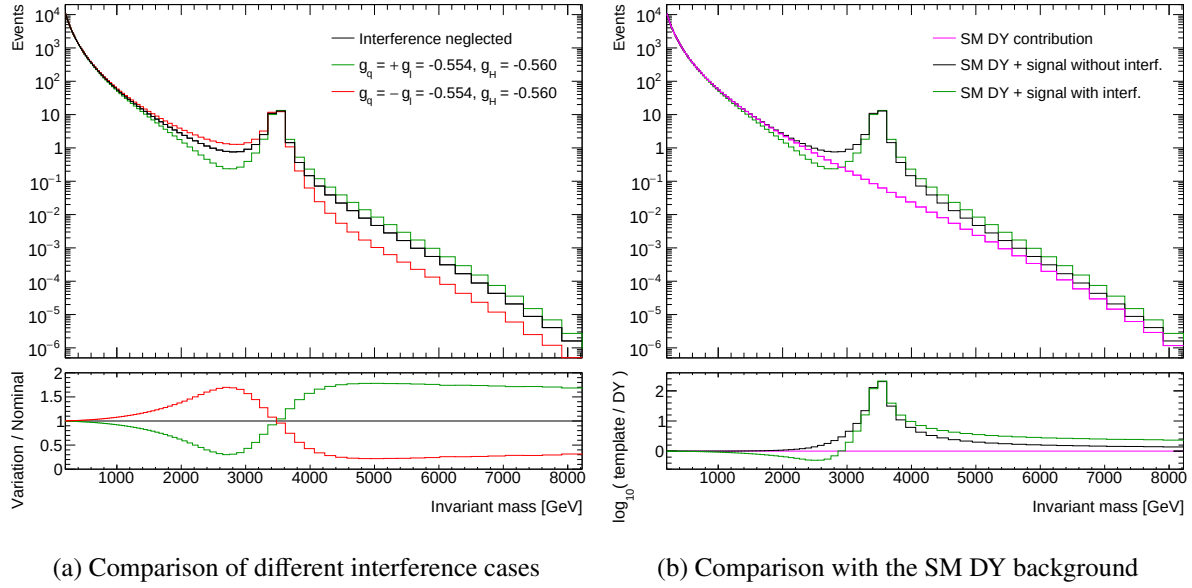


Figure 7.7: Impact of interference effects on the reconstructed line-shape in the ee channel at the HVT A coupling point and $m_{V'} = 3.5$ TeV. Figure 7.7(a) gives the difference of the signal-plus-background line-shapes for $g_q = +g_\ell$, for $g_q = -g_\ell$ and in case the interference is neglected. The relative difference can reach up to 80% in the high-mass tails of the distribution, while the signal normalisation in this region is small. The impact compared to the SM DY background is given in Figure 7.7(b). The neglect of interference effects yields purely positive signal contributions, while in case interference effects are taken into account a dip is given for invariant masses below $m_{V'}$.

considerable fraction of the resonance peak for high pole masses if it is chosen too narrow, as the absolute resonance width increases for higher pole masses.

A stable behaviour of $\Delta\sigma$ with $m_{Z'}$ is found empirically for $\Delta m \propto \kappa \sqrt{m_{Z'}}$, which is an intermediate step between the cases described before. Figure 7.8(c) shows the behaviour of $\Delta\sigma$ for different pole masses and values of κ . In order to obtain a maximal $\Delta\sigma$ of 15% (30%), a κ value of 5 $\sqrt{\text{GeV}}$ (10 $\sqrt{\text{GeV}}$) is chosen. These two points, hereafter called narrow and wide mass window, are analysed further in order to check the impact on the cross-section limits.

The cross-section offset is calculated in the $m_{Z'}/g_f$ plane to check that the desired maximal $\Delta\sigma$ is not reached within a broad region of coupling values. Figure 7.9 shows the behaviour for both mass window definitions. A higher $\Delta\sigma$ is visible for low g_f values, where higher interference effects are visible for the especially narrow resonances, and the lowest and highest $m_{Z'}$ values considered in the search. No deviations above the described $\Delta\sigma_{\text{max}}$ are present. In Ref. [6] further studies on the impact of the mass window on the sensitivity are presented. The narrow mass window of $\Delta m = \sqrt{m_{Z'}} \times 25 \text{ GeV}$ has been finally chosen for the combination analysis due to the more conservative choice of the maximal $\Delta\sigma$.

7.2.3 Properties of the signal model

For the further statistical analysis, information about the signal model in terms of the acceptance times efficiency, the production cross-section depending on the model parameters and systematic uncertainties is required and described in the following.

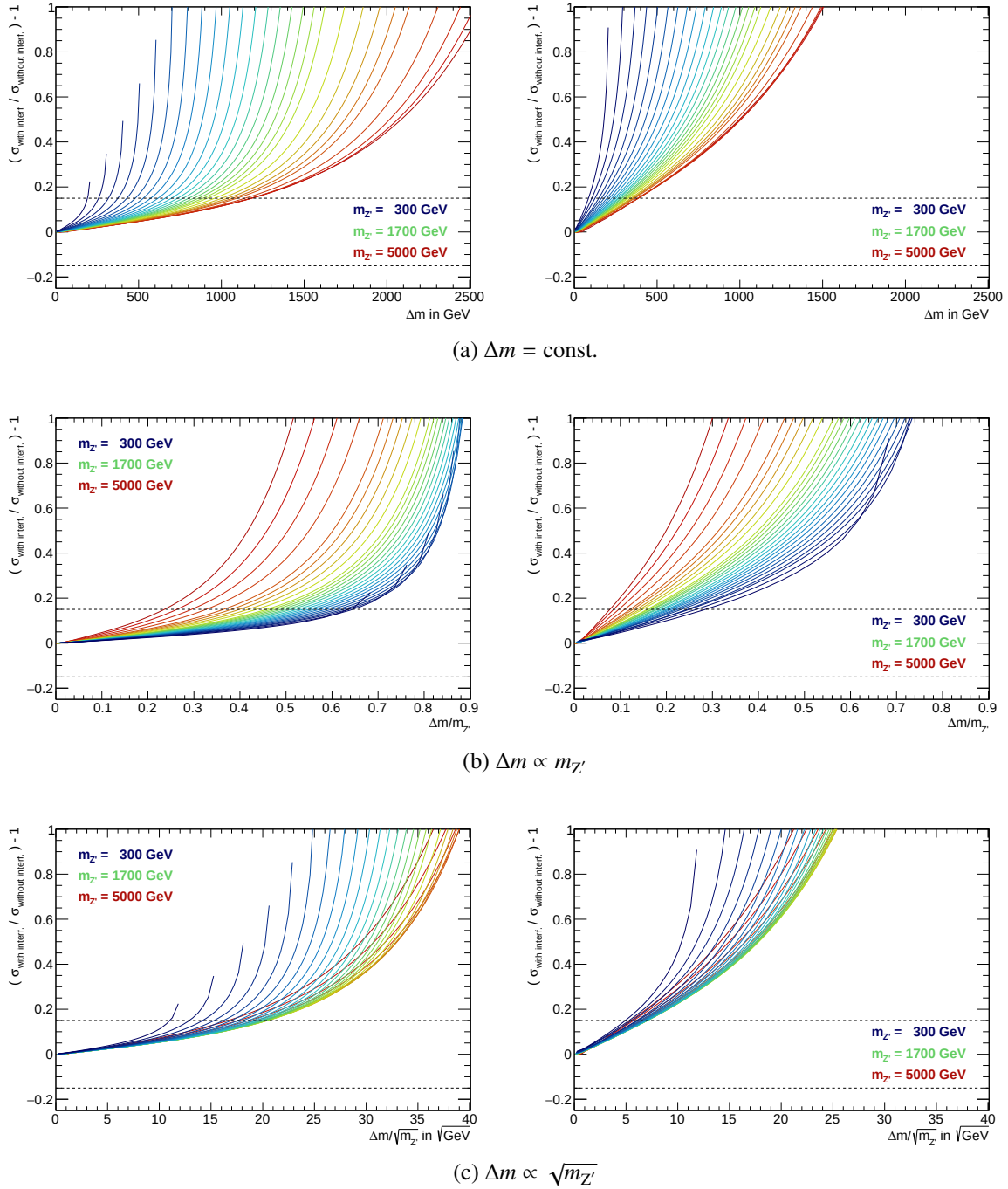


Figure 7.8: Relative difference of the signal template cross-section with and without considering interference effects within mass windows as defined in Equation 7.10. The mass windows are chosen to be constant (see Figure 7.8(a)), proportional to the pole mass (see Figure 7.8(b)) or proportional to $\sqrt{m_{Z'}}$ (see Figure 7.8(c)). The different coloured line represent pole mass from 300 GeV to 5 TeV. A stable behaviour is found for mass windows with a window size that is proportional to $\sqrt{m_{Z'}}$. The coupling parameters are $g_q = -g_\ell = -0.55$ and $g_H = 0$ for the left column, while for the right column $g_q = -0.55$, $g_\ell = 0.1$ and $g_H = 0$ is used.

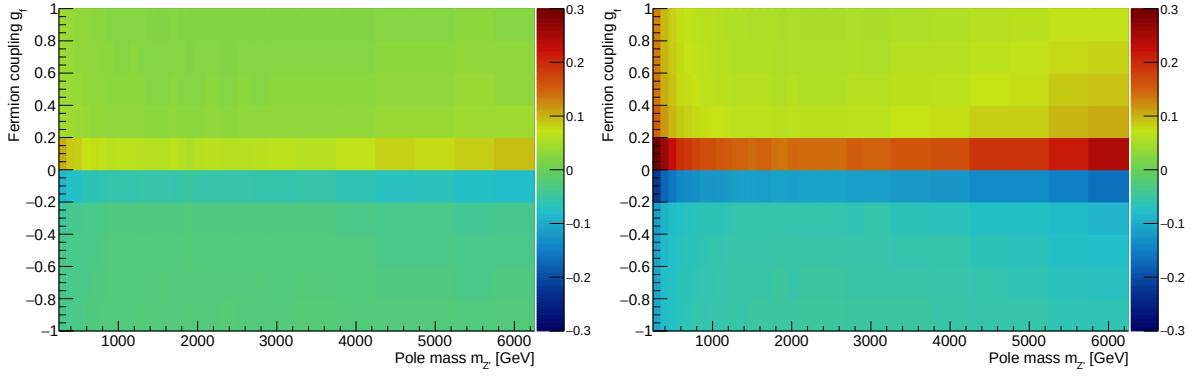


Figure 7.9: Relative difference of the signal template cross-section with and without considering interference effects within the narrow (left) and wide (right) mass window definitions, given in percent (on the z -axis). The maximal cross-section difference is below 15% (30%) for the narrow (wide) windows.

Calculation of the acceptance times efficiency

The acceptance times efficiency, $A\epsilon$, for the signal templates is defined as follows:

$$A\epsilon(m_{Z'}) = \frac{\text{events passing selection cuts}}{\text{truth events in MC sample}} \bigg|_{m_{\ell\ell}^{\text{truth}} \text{ within mass window}}. \quad (7.11)$$

The value describes the fraction of events that pass the detector acceptance and are subsequently reconstructed, but only considers events within the truth mass windows. Figure 7.10 shows the obtained values as a function of the Z' pole mass, together with the independently obtained $A\epsilon$ of the $\ell\nu$ search. A similar behaviour as in Subsection 6.3.4 can be observed, although the different definition of the acceptance times efficiency in both cases has to be noted.

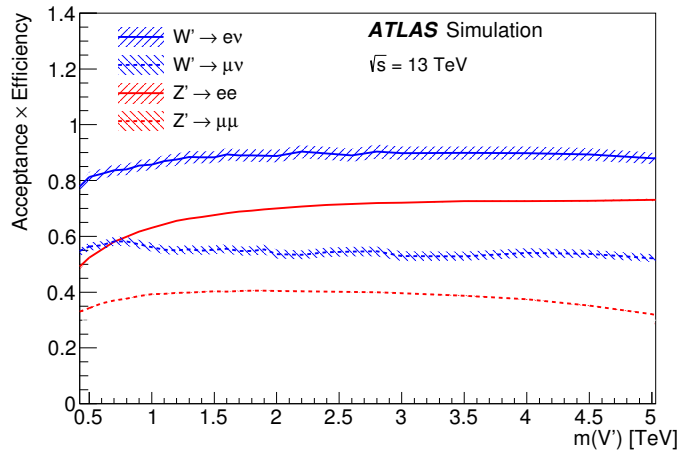


Figure 7.10: Acceptance times efficiency of the W' and Z' searches for the electron and muon decay modes as a function of the pole mass $m_{V'}$. Higher values are given in the W' search as the $\ell\nu$ selection only depends on the proper reconstruction of a single lepton. The bands show the statistical uncertainty of the underlying MC samples.

The obtained acceptance times efficiency values depend on the chosen mass window and have to be calculated accordingly. No strong dependence with the coupling parameters is observed, as it mainly affects the resonance width on truth-level and the $A\epsilon$ is stable enough throughout the mass window.

Cross-section maps for HVT coupling parameters

In order to interpret the cross-section limits in terms of limits on the Z' pole mass, fine binned cross-section maps are needed in the g_q/g_ℓ and g_H/g_f planes. The maps are calculated using the signal reweighting procedure and given in Figure 7.11 for selected pole masses. It can be observed that the signal cross-section varies by several orders of magnitude within the considered coupling space. For $g_q \rightarrow 0$ and $g_f \rightarrow 0$, the production cross-section at the LHC vanishes for the quark-antiquark annihilation process. Oppositely, a strong increase in the cross-section for higher g_q values can be observed. Higher values of g_ℓ result in higher cross-section values, as the branching fraction of the decay mode becomes higher. Only a low dependency of the cross-section on g_H is visible, as it does not contribute to the production or decay modes in the $\ell\ell$ decay channel.

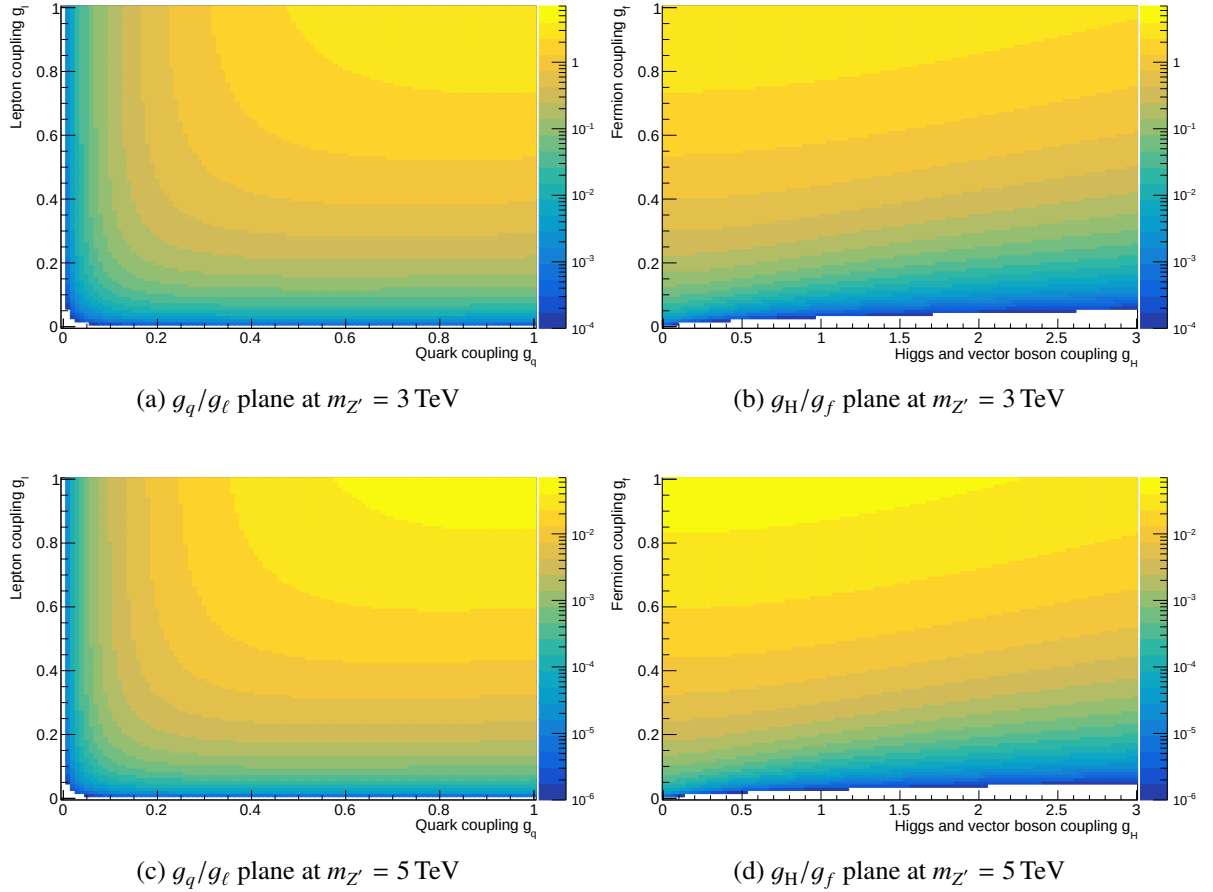


Figure 7.11: Cross-section (given in fb on the z -axis) of $Z'_{\text{HVT}} \rightarrow \ell\ell$ production for a single fermion generation in the g_q/g_ℓ (left) and g_H/g_f (right) planes. Pole masses of $m_{Z'} = 3$ TeV (top row) and 5 TeV (bottom row) are selected for these values.

Similar cross-section maps are produced for the $W' \rightarrow \ell\nu$ decay channel, too. In order to understand a potential difference in the scaling behaviour of the two channels, ratios of the cross-section maps are calculated for selected pole masses. Typically the cross-section for W' production is about 1.4 (at $m_{W'} = 6 \text{ TeV}$) to 2 (at $m_{W'} = 2 \text{ TeV}$) times higher due to the interplay between the higher total W' production cross-section and the mass window definitions. A stable cross-section ratio as a function of the coupling parameters is observed.

In addition to the validation of the cross-section ratio maps, the ratio maps themselves are again compared between different pole masses by dividing the ratio maps with each other, i.e. by calculating double-ratios. A stable behaviour as a function of the coupling parameters is again observed, which provides a further validation of the cross-section calculation due to the stable behaviour as a function of the pole mass $m_{W'}$.

Contrary to the leptonic channels, the diboson analyses use cross-section values that are calculated within the narrow width assumption (NWA) [172]. In order to ensure a stable agreement between the two calculations, $pp \rightarrow Z' \rightarrow \ell\ell$ cross-section values are compared at different pole masses and given in Table 7.2. The agreement between the calculations is more stable in case a mass window requirement is applied, which is given within the table, too. The mass window rejects the so called “parton luminosity tails” in the low invariant mass region³ for the signal reweighting case, while these tails are neglected in the NWA. An extended description of the mass window definition is given in Subsection 7.2.2, which is additionally introduced to reduce the impact of interference effects on the analysis results.

Table 7.2: Comparison of $pp \rightarrow Z' \rightarrow \ell\ell$ cross-section predictions from the narrow width assumption (NWA), signal reweighting in the full mass range as well as signal reweighting within the two mass window definitions. An overall stable behaviour is only found if the mass window cuts are applied. The remaining offset is considered within the combination by using signal cross-section predictions from signal reweighting for the leptonic channels.

$m_{Z'} [\text{TeV}]$	$\sigma_{\text{NWA}} [\text{fb}]$	$\sigma_{\text{full}} [\text{fb}]$	$\sigma_{\text{wide}} [\text{fb}]$	$\sigma_{\text{narrow}} [\text{fb}]$	$\sigma_{\text{wide}}/\sigma_{\text{NWA}}$	$\sigma_{\text{narrow}}/\sigma_{\text{NWA}}$
1	451.8	418.5	404.2	392.2	0.89	0.87
2	18.06	16.99	15.59	14.93	0.86	0.83
3	1.584	1.671	1.382	1.313	0.87	0.83
4	0.1746	0.2496	0.1642	0.1533	0.94	0.88
5	0.02015	0.05321	0.02063	0.01913	1.02	0.95

For the cross-section calculation in case of the leptonic channels, no higher order corrections, so called k -factors, are applied. These factors are not available for the diboson decay modes and thus, for consistency, are neglected in case of the leptonic channels⁴. A comparison between these two assumptions yields cross-section differences of 30 – 45% for the signal templates without mass cut.

Systematic uncertainties on signal shape

The signal templates are produced for different systematic variations, too. Comparisons between the nominal templates and the ± 1 sigma variations are given in Figures 7.12 and 7.13 for the main systematic uncertainties in the ee and $\mu\mu$ channels, respectively. The overall behaviour is similar to the dilepton channel results described in Section 6.6, although the electron and muon reconstruction slightly changed for the full Run 2 result.

³ The parton luminosity tails refer to the increase of the signal cross-section towards low invariant masses, i.e. outside the resonance peak region, which is driven by the strong increase of the parton distribution functions for low proton momentum fractions.

⁴ The k -factors were applied in case of the baseline $Z' \rightarrow \ell\ell$ and $W' \rightarrow \ell\nu$ analyses, though.

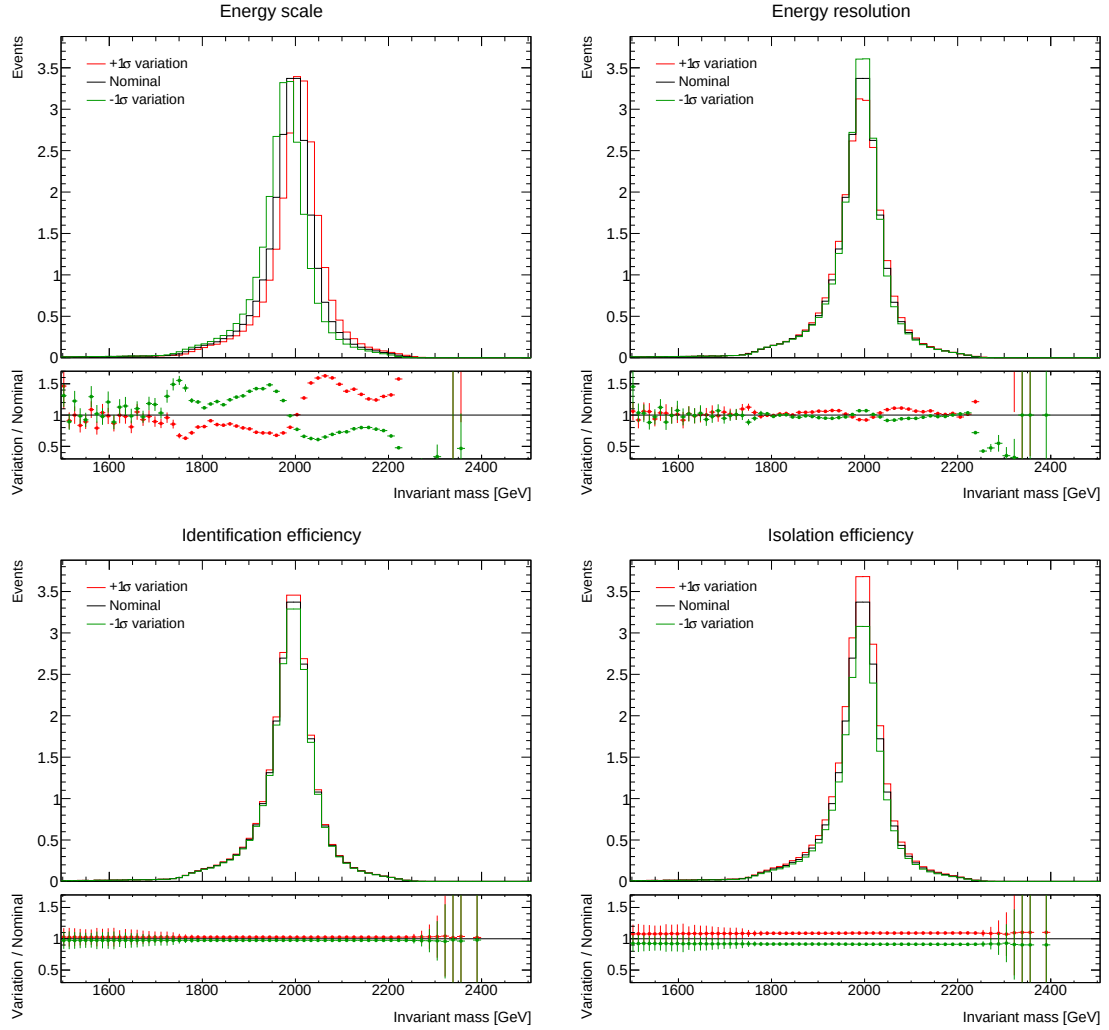


Figure 7.12: Variations of the signal templates due to systematic uncertainties in the ee channel. The signal is evaluated at the HVT A coupling point with $m_{Z'} = 2$ TeV.

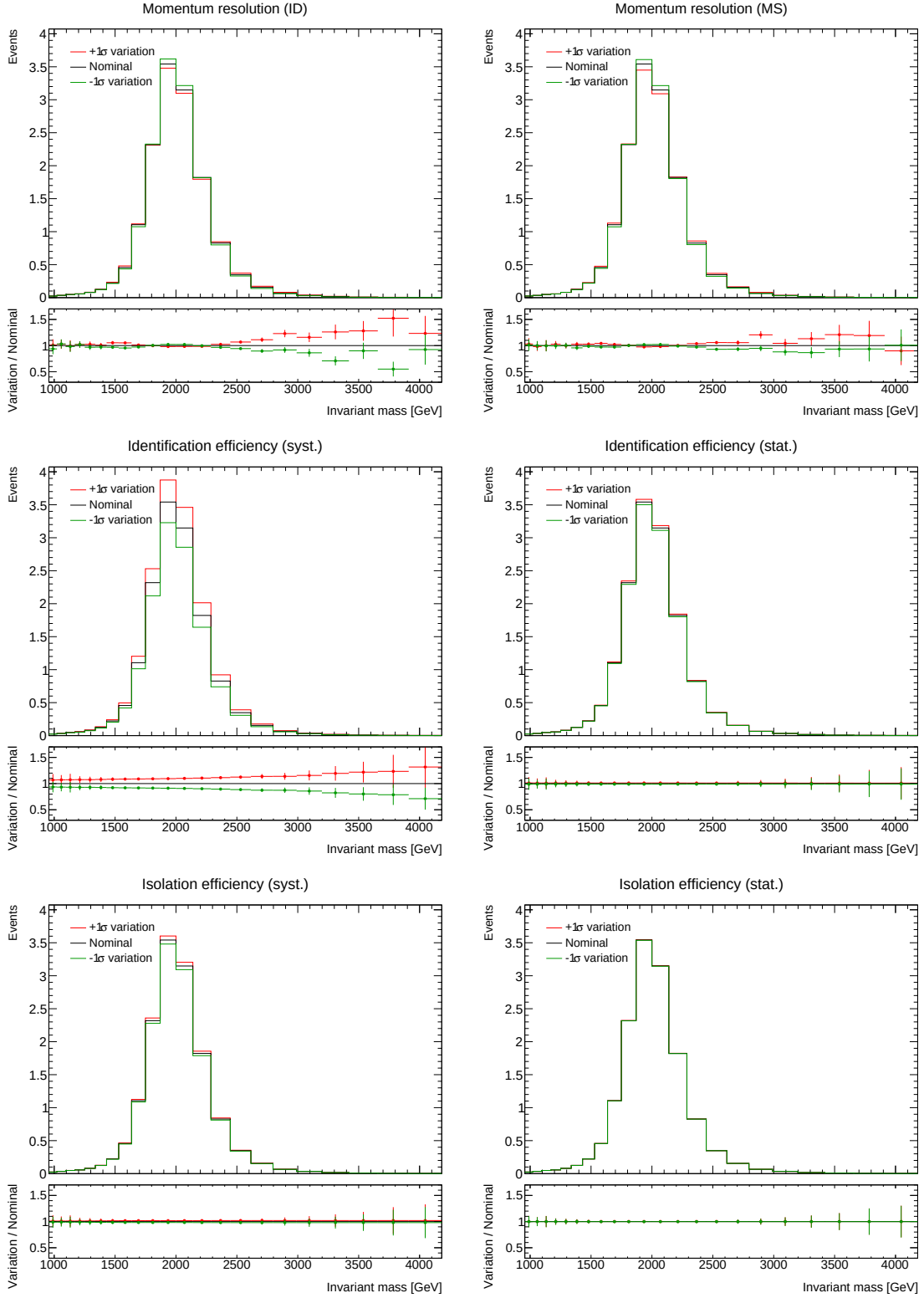


Figure 7.13: Variations of the signal templates due to systematic uncertainties in the $\mu\mu$ channel. The signal is evaluated at the HVT A coupling point with $m_{Z'} = 2$ TeV.

7.2.4 Statistical treatment

The 2015/16 $\ell\ell$ and $\ell\nu$ analyses [132, 167] used the Bayesian Analysis Toolkit (BAT) [173] for the statistical interpretation. Previous diboson combinations were carried out using RooStats [174] and frameworks based on this toolkit, like the RooFit framework [142]. In order to allow for a combination, a statistical framework based on RooStats was developed for the $\ell\ell$ and $\ell\nu$ channels. It was validated using the published BAT results and a good agreement is found [6]. The considered systematic uncertainties and their correlation scheme are detailed in Ref. [6], too.

The statistical analysis for the $\ell\ell/\ell\nu$ combination and the full combination (compare Sections 7.3 and 7.4) is performed in terms of one-dimensional upper limits on the cross-section times branching ratio, $\sigma \times \mathcal{B}$, and two-dimensional limits on coupling strengths. These two different signal parametrization paradigms and their statistical treatment are further described in Ref. [55].

7.2.5 Cross-section and mass limits

The cross-section limits that are obtained with the final choice of the mass window are given in Figure 7.14 for the $\ell\ell/\ell\nu$ channel⁵. Table 7.3 additionally gives the mass limit values at the HVT A coupling point. The expected mass reach of the $\ell\nu$ channel is 180 GeV higher than the $\ell\ell$ channel, while the combination additionally allows to extend the reach by 350 GeV (530 GeV) compared to the separate $\ell\nu$ ($\ell\ell$) channels. A further comparison is shown in Figure 7.15, where the cross-section limits are normalised by the predicted cross-section for V' production for the HVT A coupling point.

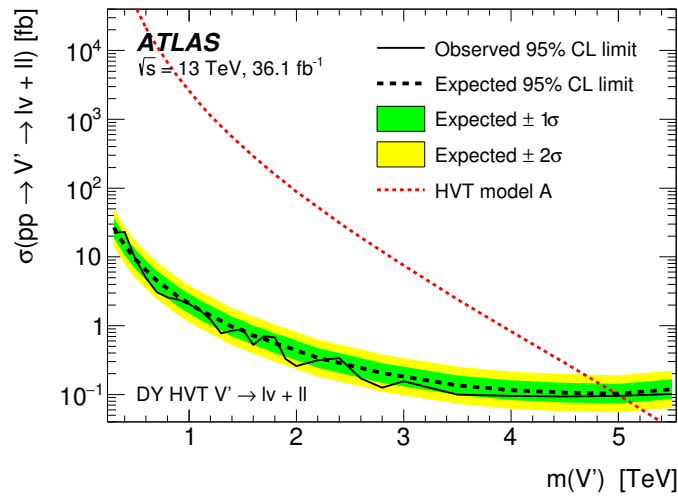


Figure 7.14: Cross-section limit on the $V' \rightarrow \ell\ell + \ell\nu$ production. The theory prediction for the HVT A coupling point is overlaid.

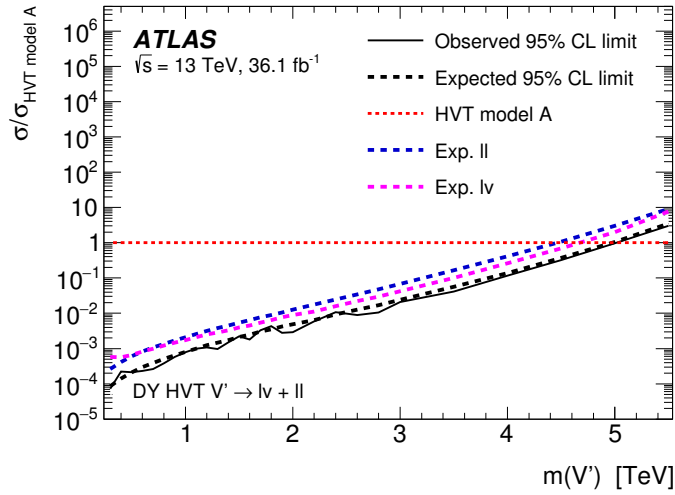
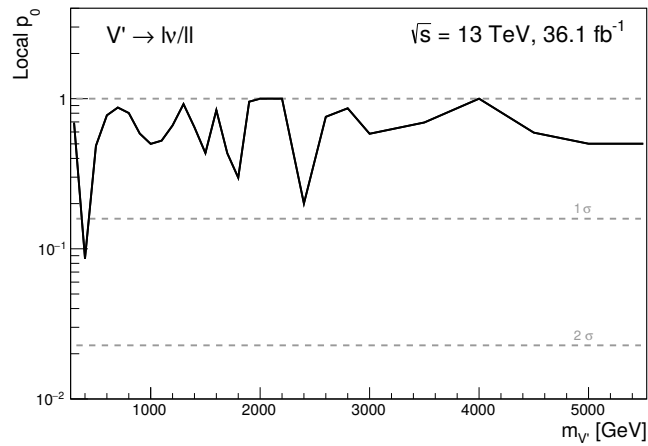
The p_0 value scan of the combined channel is given in Figure 7.16 in addition and shows no significant deviation from the SM expectation.

The standalone mass limits from the $\ell\ell/\ell\nu$ combination in the g_q/g_ℓ and g_H/g_f coupling planes are given in Figure 7.17. A strong dependence on the coupling parameters g_ℓ and g_q can be observed, as these dominate the branching ratio into leptonic final states and the production cross-section, respectively. A vanishing exclusion for $g_q \rightarrow 0$ and $g_f \rightarrow 0$ can be observed, as the production cross-section goes

⁵ The cross-section values are summed for the underlying decay channels (i.e. ee , $\mu\mu$, $e\nu$ and $\mu\nu$) here, while in Chapter 6 the cross-section in the combined $\ell\ell$ channel is calculated with respect to the branching ratio into one fermion generation.

Table 7.3: Limits on $m_{V'}$ in the $Z' \rightarrow \ell\ell$, $W' \rightarrow \ell\nu$ and $V' \rightarrow \ell\ell + \ell\nu$ channels at the HVT A coupling point.

	$\ell\ell$	$\ell\nu$	Combination
Expected	4.44 TeV	4.62 TeV	4.97 TeV
Observed	4.51 TeV	4.62 TeV	5.01 TeV


 Figure 7.15: Cross-section limit on the $Z' \rightarrow \ell\ell$ and $W' \rightarrow \ell\nu$ production, normalised to the prediction of the HVT model at the HVT A coupling point. The $\ell\nu$ channel provides a stronger exclusion for almost the full $m_{V'}$ space. A significant improvement due to the combination of the $\ell\ell$ and $\ell\nu$ final states is visible.

 Figure 7.16: Local p_0 value scan in the $V' \rightarrow \ell\ell/\ell\nu$ channel as a function of the pole mass $m_{V'}$. The p_0 values are calculated every 100 GeV for $m_{V'} \in [300 \text{ GeV}, 2 \text{ TeV}]$ and are interpolated between the points. A larger step size is chosen for $m_{V'} > 2 \text{ TeV}$.

to zero for a vanishing coupling to quarks in case of a proton-proton collider. The dependence on g_H is small. While the mass limits can go beyond 5 TeV, for example beyond the HVT A coupling point, considerably weaker exclusion limits are present for phase space regions with small g_f , as can be seen in case of the HVT B coupling point.

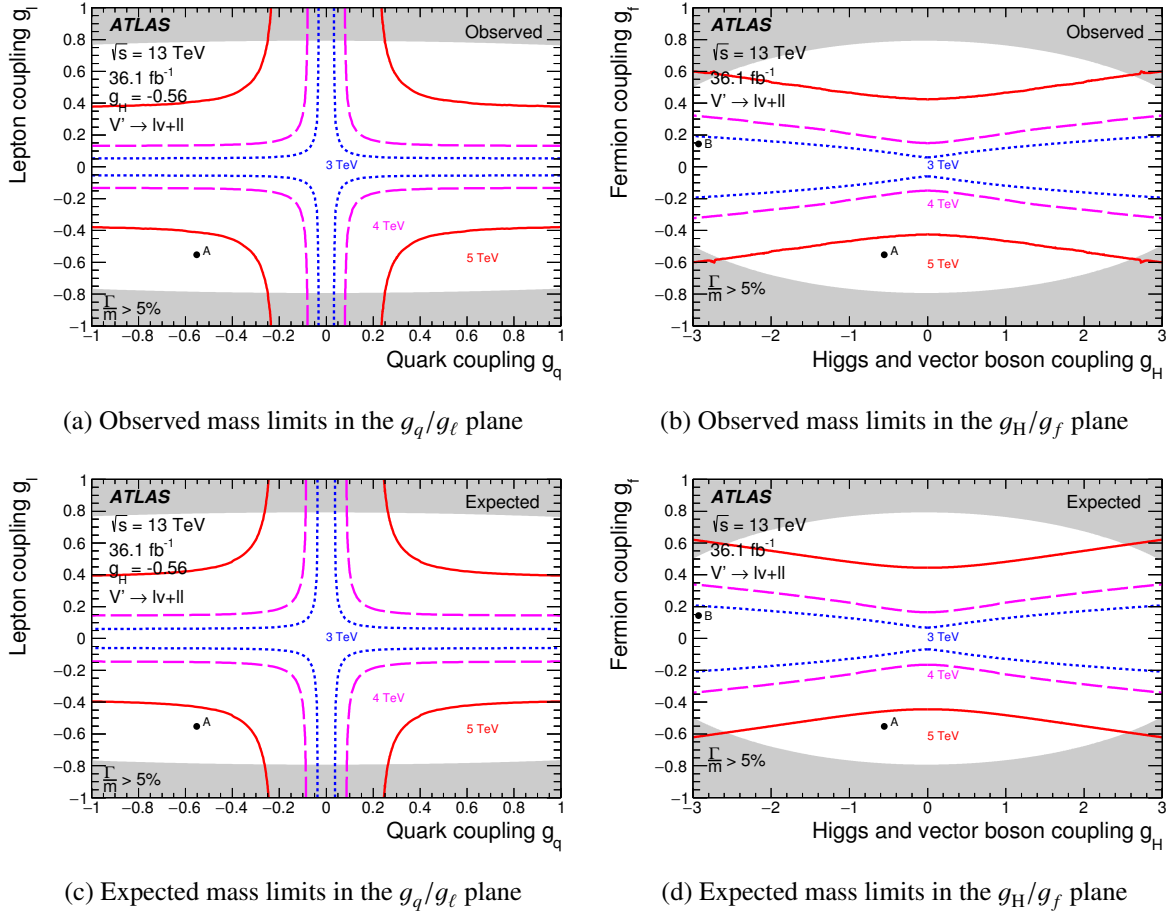


Figure 7.17: Mass limits in the g_q/g_ℓ (left column) and g_H/g_f (right column) coupling planes at $m_{V'} = 3, 4$ and 5 TeV for the $\ell\ell/\ell\nu$ combination. The observed (top row) and expected (bottom row) limits are shown. The gray area depicts the validity limit of the combination, which is not given for $\Gamma/m > 5\%$.

7.3 Combination of the $\ell\ell$ and $\ell\nu$ channels with diboson searches

The diboson final states allow to improve the search sensitivity in the phase space region with $g_H \neq 0$ and provide orthogonal information to the dilepton final states. The various searches are grouped into VV and VH production with $V \in \{W, Z\}$ and H as the SM Higgs boson. Leptonic and hadronic decay modes of the V bosons are considered, while for the Higgs boson only the $H \rightarrow b\bar{b}$ decay is considered due to its high branching ratio (compare Table 7.1).

7.3.1 Overlap studies of signal regions for different searches

In order to allow for a combination of the channels, the selection overlap between the channels needs to be small in order to avoid correlations between the channels. The overlap between the W' and Z' searches is removed by construction in the analysis selections.

Dedicated checks in MC signal samples and data are performed to ensure a low overlap between the Z' selection and the VV/VH channels. The overlap is found to be small, with the highest overlap being present between the $Z' \rightarrow \ell\ell$ and the $W' \rightarrow WZ \rightarrow \ell\nu\ell\ell$ selections. For this case, the $Z' \rightarrow \ell\ell$ search is missing a lepton and the neutrino for the invariant mass calculation, such that the reconstructed signal shape additionally does not peak at the true $m_{V'}$. No significant overlap between the data events is found and especially none of the highest mass candidates overlap.

7.3.2 Cross-section limits

The cross-section limits of the separate VV/VH and $\ell\ell/\ell\nu$ combinations are available in Figures 7.18 and 7.14, respectively. Figure 7.19(a) shows the cross-section limit from the full combination at the HVT A coupling point, while Figure 7.19(b) provides a comparison of the separate combinations with the full combination. The $\ell\ell/\ell\nu$ channels dominate the combination at this specific coupling point, and in general for high g_ℓ , while the dibosonic final states provide stronger limits for the phase-space regions with high g_H .

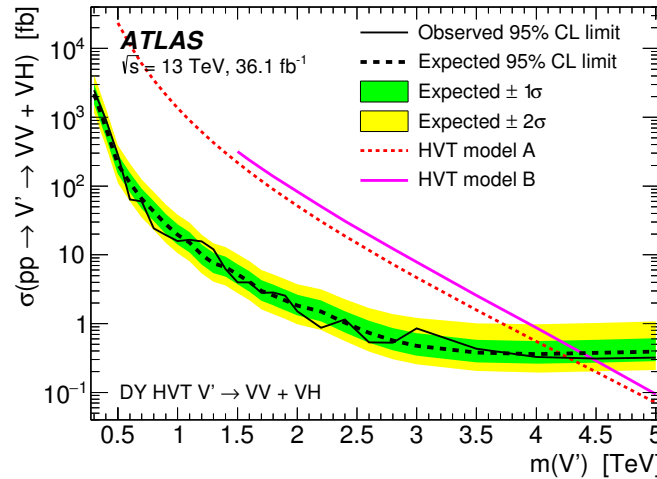


Figure 7.18: Cross-section limit on the $V' \rightarrow VV + VH$ production. The theory predictions for the HVT A and HVT B coupling points are overlaid.

7.3.3 Mass limits in the HVT coupling plane

The limits in the g_q/g_ℓ and g_H/g_f coupling planes for the full combination are given in Figure 7.20. The results are overlaid with EW fits (compare Ref. [48, 175]), which are obtained from electroweak precision observables, e.g. derived from LEP 2 data. The results from the ATLAS $VV/VH/\ell\ell/\ell\nu$ combination are stronger than the EW fits in the entire g_H/g_f plane (see Figures 7.20(b) and 7.20(d)). In the g_q/g_ℓ plane (see Figures 7.20(a) and 7.20(c)), the EW results are stronger for the $g_q \rightarrow 0$ case due to the vanishing cross-section at the LHC.

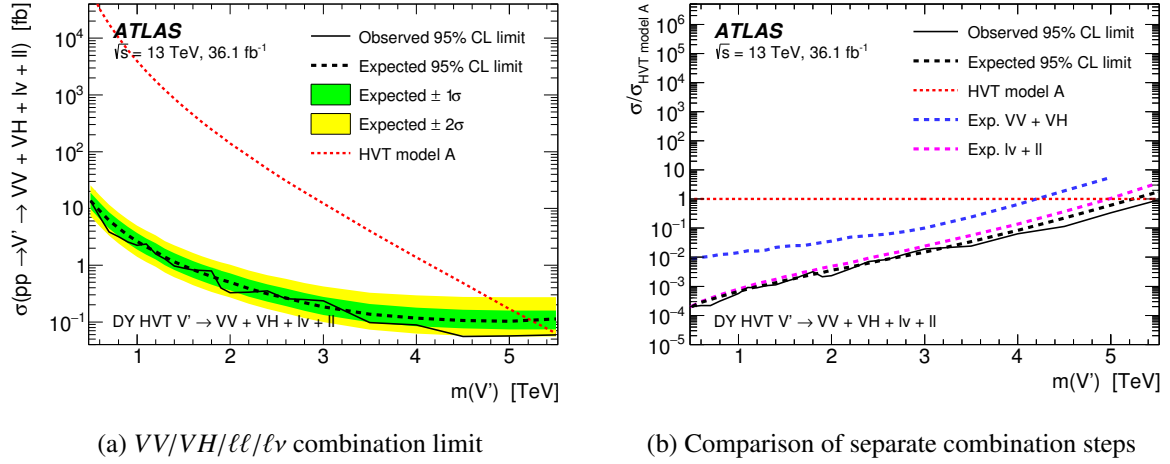


Figure 7.19: Cross-section limit on the $V' \rightarrow VV/VH/\ell\ell/\ell\nu$ production (left) at the HVT A coupling point. The cross-section limits normalised to the prediction of the HVT model at the HVT A coupling point are given in the right figure. The $\ell\ell/\ell\nu$ channels dominate the combination as this specific coupling point.

The EW fits show an asymmetric behaviour for the different quadrants of the coupling planes, which is due to interference effects. The interference effects are mitigated by the described mass cut in the $\ell\ell/\ell\nu$ channels for the ATLAS search combination, and negligible for the diboson final states. The limit curves are thus mirrored along the axes of the plots for the ATLAS result.

7.4 Comparison between the leptonic and bosonic channels

The comparison of the standalone $\ell\ell/\ell\nu$ combination (see Figure 7.17), the VV/VH combination and the full combination (see Figure 7.20) is shown in Figure 7.21 for the observed limits at $m_{V'} = 4 \text{ TeV}$.

The $\ell\ell/\ell\nu$ combination is dominating for high g_ℓ , where the branching ratios into leptonic final states are high. The VV/VH combination on the other hand dominates for high g_H coupling values due to high branching ratios into bosonic final states. Both channels show a vanishing exclusion power for $g_q \rightarrow 0$ and $g_f \rightarrow 0$ due to the vanishing production cross-section.

A statistical combination of searches is only improving the exclusion power in case a similar sensitivity is given for the various components. The comparison between the $\ell\ell/\ell\nu$ and VV/VH exclusion contours shows a significant improvement of the mass limits within the g_H/g_f plane for almost the full $g_H \neq 0$ phase-space. At $|g_H| = 3$, the exclusion in $|g_f|$ still improves by about 0.05 units. The exclusion in the g_q/g_ℓ plane shows an improvement for $0.05 < |g_\ell| < 0.4$, where e.g. at $|g_\ell| = 0.2$ the single combinations provide limits of $|g_q| \simeq 0.15$ and the full combination allows to exclude $|g_q|$ until about 0.09.

The statistical combination of the $\ell\ell/\ell\nu$ and VV/VH searches thus allows to improve the constraints on the HVT model. The separate combinations provide additional insight and do not rely on assumptions of the relative branching ratio between $\ell\ell/\ell\nu$ and VV/VH production.

7.5 Reinterpretation of results from full Run 2 dilepton search

The fiducial cross-section limits of the full Run 2 dilepton search (see Chapter 6) are additionally interpreted in the coupling planes of the HVT model [84]. The results are given in Figure 7.22. Compared to the approach pursued in the $VV/VH/\ell\ell/\ell\nu$ combination at 36.1 fb^{-1} , the generic results are reinterpreted

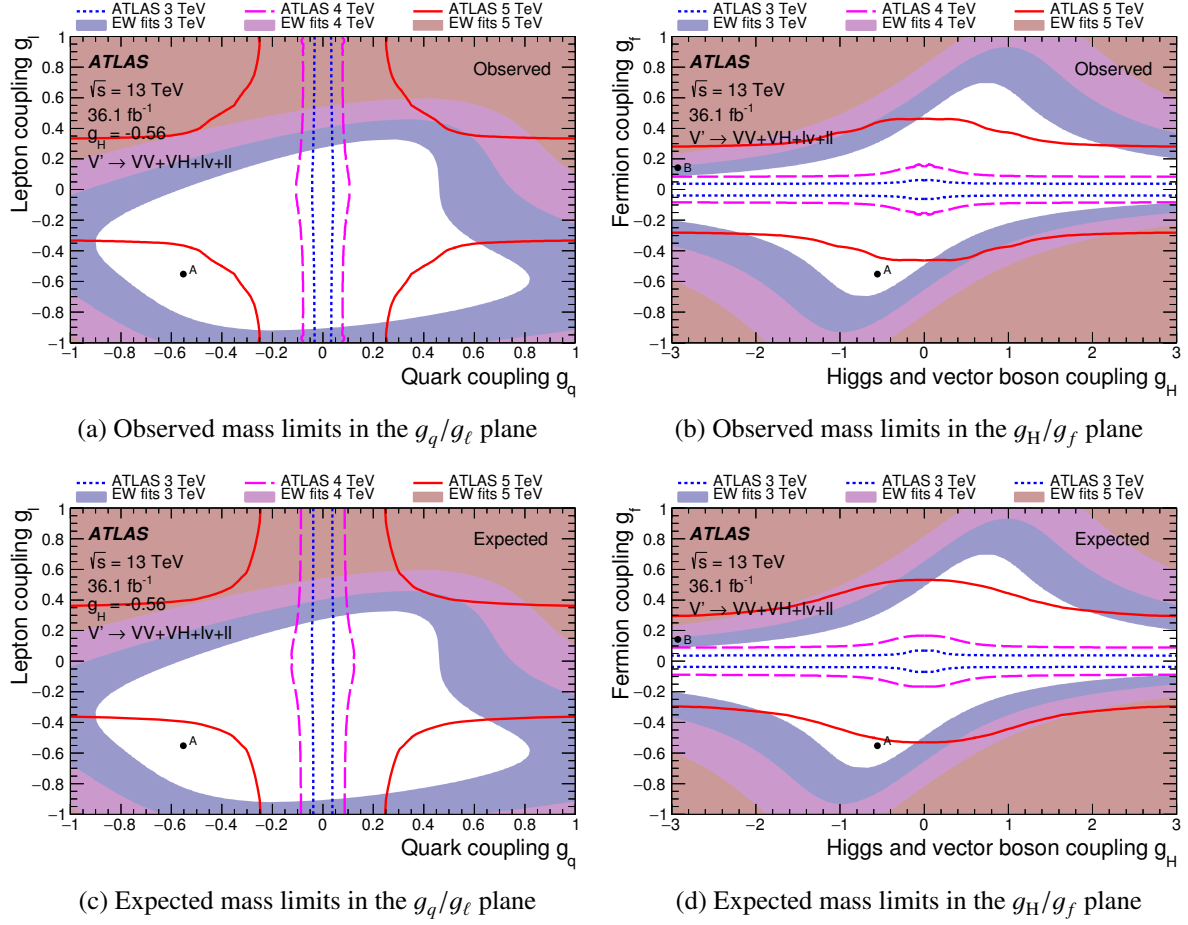


Figure 7.20: Mass limits in the g_q/g_ℓ (left column) and g_H/g_f (right column) coupling planes at $m_{V'} = 3, 4$ and 5 TeV. The observed (top row) and expected (bottom row) limits are shown. The results from EW fits and the corresponding exclusion contours are given as the filled areas.

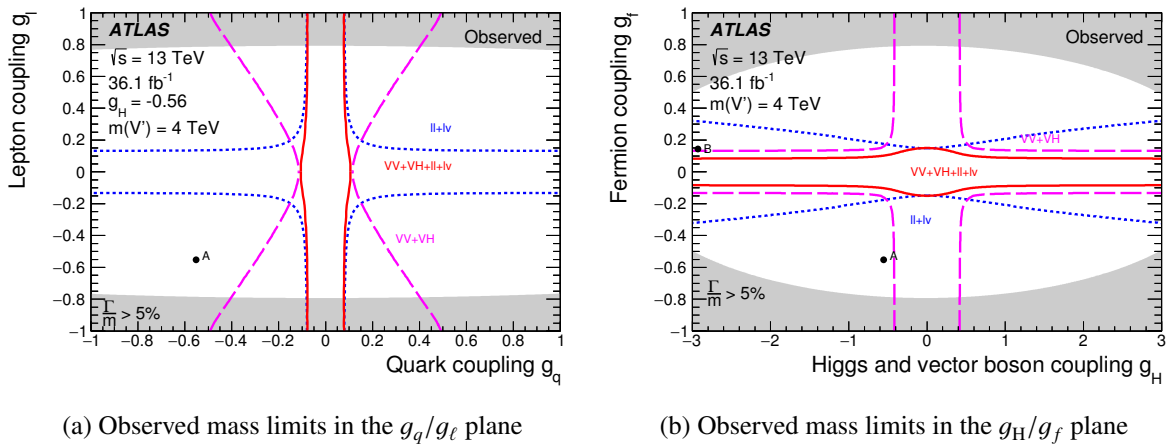


Figure 7.21: Comparison of the exclusion curves from the separate $\ell\ell/\ell\nu$ and VV/VH combinations and the full combination. The differences in the exclusion regions are given by the different branching ratios, which depend on the coupling values.

considering the width-dependence of the limits. The observed limits can be compared with the limits obtained for the $\ell\ell/\ell\nu$ combination given in Subsection 7.2.5 (provided in brackets): for $g_h = 0$ and $m_{Z'_{\text{HVT}}} = 3 \text{ TeV}$, 4 TeV and 5 TeV the $|g_f|$ values above 0.07 (0.06), 0.23 (0.15) and 0.49 (0.42) are excluded at 95% CL, respectively [84]. The resulting dilepton-only limits at 139 fb^{-1} are thus slightly weaker than those for the $\ell\ell/\ell\nu$ combination at 36.1 fb^{-1} , even with a four times larger dataset, because of the higher $W'_{\text{HVT}} \rightarrow \ell\nu$ cross-section in the HVT model [84]. The HVT coupling parameter g_H is denoted by g_h in the results presented here to avoid confusion with the spin-0 MSSM Higgs boson used to validate the efficiency values in Chapter 6.

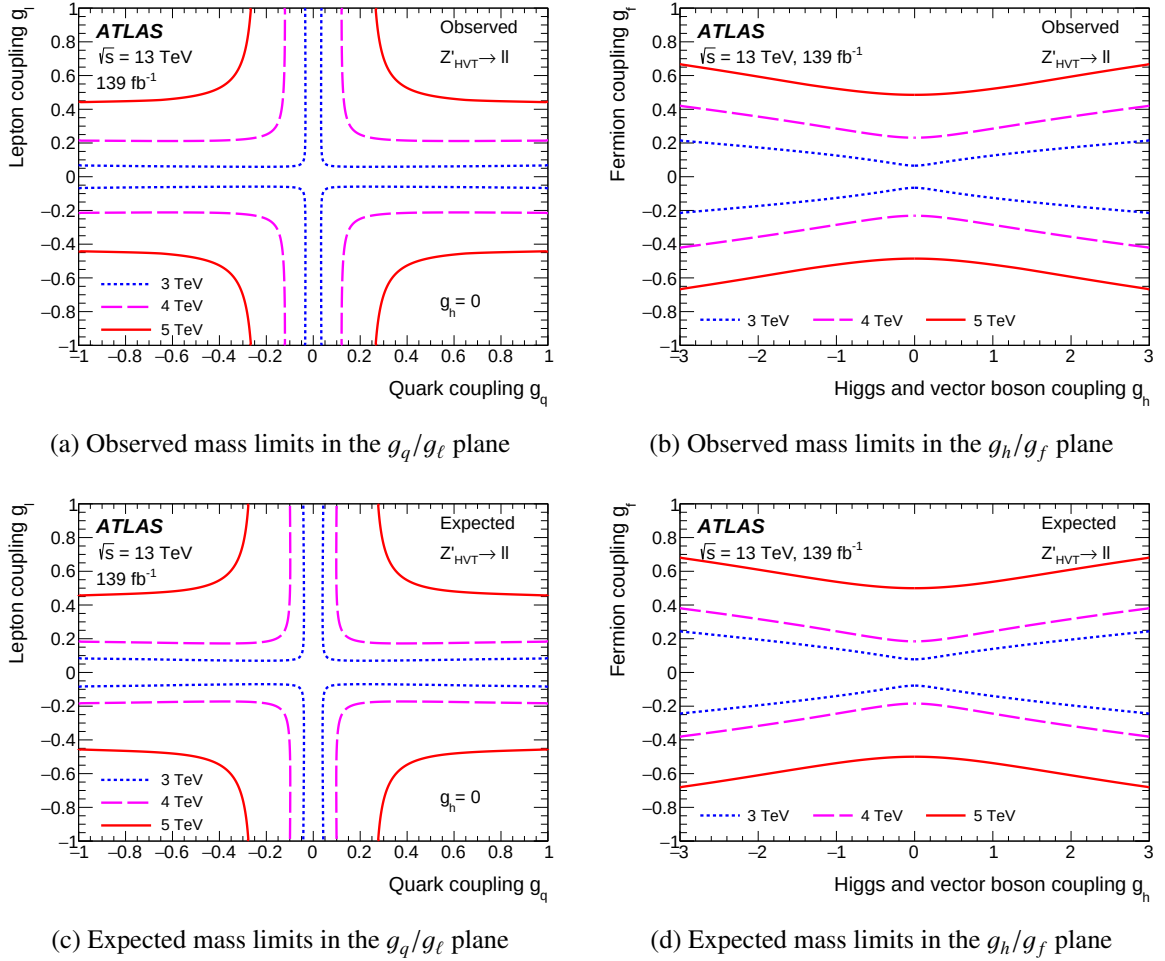


Figure 7.22: Mass limits in the g_q/g_ℓ (left column) and g_h/g_f (right column) coupling planes at $m_{Z'} = 3, 4$ and 5 TeV for the full Run 2 dilepton search. The observed (top row) and expected (bottom row) limits are shown. The HVT coupling parameter g_H is denoted by g_h in the results presented here to avoid confusion with the spin-0 MSSM Higgs boson used to validate the efficiency values in Chapter 6. Figures from Ref. [84].

7.6 Conclusion and outlook

The combination of the VV/VH and $\ell\ell/\ell\nu$ final states allows to set stronger exclusion limits on the production of new heavy vector bosons in the context of the HVT model. While the VV/VH and $\ell\ell/\ell\nu$

combinations provided exclusion limits of 4.3 (4.3) TeV and 5.0 (5.0) TeV for the observed (expected) case, respectively, the full combination allows to exclude the HVT model at the HVT A coupling point up to 5.5 (5.3) TeV. The exclusion limits from the single analyses do not reach into this mass region. Due to the three free coupling parameters, an investigation of the coupling phase-space is beneficial in the HVT model. Exclusion limits are thus additionally provided in the g_q/g_ℓ and g_H/g_f coupling planes.

The combination of the $\ell\ell$ and $\ell\nu$ final states at 36.1 fb^{-1} required the development of a dedicated implementation of the statistical analysis in RooStats in order to allow for a combination between themselves and with the VV/VH searches. In addition, a special treatment of interference effects in the signal modelling is developed to comply better with the NWA cross-section values that are used in the VV/VH searches. Both points are addressed in the full Run 2 dilepton search on analysis level due to the development of the data-driven search within a RooStats-based statistical analysis framework and due to the baseline choice of a generic signal modelling (compare Section 6.5). NWA cross-section values can thus be used by construction in potential future full Run 2 combinations. The full Run 2 dilepton search additionally provided standalone limits in the HVT coupling planes, as given in Subsection 7.5.

Further extensions of the presented search combination are possible e.g. by including searches for diquark production [176]. As the g_q coupling parameter is so far not constrained, searches in the dijet and di- b -jet final states, as well as for resonances decaying into top-quark pairs, allow to provide insight into this phase-space region. Limits on V' production could in this case even be set for $g_\ell = g_H = 0$. Many lepton non-universal models additionally predict new heavy resonances that couple predominantly to heavy quarks and leptons. A further possibility are thus dedicated constraints on the coupling to third generation quarks and leptons, i.e. top quarks and τ leptons, under the assumption of lepton non-universality.

Summary and conclusions

The full Run 2 data taking period of the ATLAS experiment and the LHC allowed to collect 139 fb^{-1} of proton-proton collision data at a centre-of-mass energy of 13 TeV. The dataset has an unprecedented potential in terms of the discovery reach for high-mass resonances, as the cms energy and the integrated luminosity exceed the dataset collected in the Run 1 period.

The analysis strategy of the ATLAS dilepton search has been updated towards the full Run 2 analysis round by focussing the search on a generic signal model that allows for an easy reinterpretation of the analysis results. The background model is based on a functional fit to the invariant mass spectrum observed in data. The analysis allowed to increase the mass limits on typical benchmark models by 500–800 GeV compared to the previous ATLAS dilepton search results at 36.1 fb^{-1} [132]. In comparison with the final Run 1 result at $\sqrt{s} = 8 \text{ TeV}$, the observed cross-section limits improved by roughly a factor of 3–5 for $m_{Z'_{\text{SSM}}} < 1.5 \text{ TeV}$. The mass limit on $Z'_{\text{SSM}} \rightarrow \ell\ell$ production improved from 2.9 TeV at the end of Run 1 to 5.1 TeV at the end of Run 2.

The inclusive selection used in this analysis allows to search for new heavy resonances without specific assumptions on their properties, like e.g. the spin. In the future, extensions of the search by targeting specific production modes or final states with additional associated particles might allow to probe additional phase-space regions. The present search might not be sensitive to these phase-space corners due to the inclusive selection choice and thus higher overall background levels.

The combination of the VV/VH and $\ell\ell/\ell\nu$ final states allows to set stronger exclusion limits on the production of new heavy vector bosons than searches in single final states. The search combination in the context of the HVT model presented in this thesis uses a dataset of 36.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$. While the VV/VH and $\ell\ell/\ell\nu$ combinations provided exclusion limits of 4.3 (4.3) TeV and 5.0 (5.0) TeV for the observed (expected) case, respectively, the full combination allows to exclude the HVT model at the HVT A coupling point up to 5.5 (5.3) TeV. Exclusion limits are additionally provided in the g_q/g_ℓ and g_H/g_f coupling planes.

Further extensions of the presented search combination are possible e.g. by including searches for diquark production [176]. As the g_q coupling parameter is so far not constrained, searches in the dijet and di- b -jet final states, as well as for resonances decaying into top-quark pairs, allow to provide insight into this phase-space region. An additional possibility are dedicated constraints on the coupling to third generation quarks and leptons, i.e. top quarks and τ leptons, under the assumption of lepton non-universality.

The preparation for the Run 3 data taking period is ongoing. The Phase-1 upgrade of the LAr detector provides an increased granularity of the trigger read-out and will allow to exploit more precise measurements of shower shapes at the trigger level. The presented calibration scheme for the 2014 LAr

Phase-1 demonstrator system allows to convert the collected ADC measurements into energy and timing information. The procedure is based on the LAr cells calibration scheme, while several adoptions were needed for the supercells. The full procedure includes the development of pulsing patterns, data-taking of pedestal, delay and ramp runs as well as the analysis of the calibration data. In the validation of the calibration coefficients, which uses proton-proton collision data, a good agreement of the demonstrator system measurements and the main read-out is found. The available calibration is expected to reach the precision required for the trigger selection in the Phase-1 system during Run 3.

So far no deviations from the Standard Model expectations have been found. The data taking in Run 3 and the HL-LHC phase will allow to extend the discovery reach for new heavy resonances to even higher masses and lower cross-sections. The development of new analysis techniques, improvements in the detector and advancements in the theoretical understanding might provide an additional insight into the properties of nature.

Appendix

Résumé français de la thèse

A.1 Introduction

Le Modèle standard (MS) de la physique des particules a été testé avec une grande précision lors de diverses expériences au cours des dernières décennies et aucun écart significatif n'a été constaté jusqu'à présent. Le LHC offre une occasion unique de rechercher de nouvelles particules, car il permet d'atteindre des énergies considérablement plus élevées que celles des accélérateurs précédents. Le Run 2 du LHC couvre la période de collecte des données allant de 2015 à 2018, au cours de laquelle des collisions proton-proton d'une énergie au centre de la masse de 13 TeV ont été enregistrées. La collaboration ATLAS est en charge d'une des quatre grandes expériences du LHC pour mesurer et analyser ces données. En plus du fonctionnement actuel des détecteurs et de l'analyse des données, toutes les expériences menées au LHC préparent la mise à niveau des détecteurs afin qu'elles puissent bénéficier des améliorations apportées au LHC dans les années à venir.

La recherche de nouveaux phénomènes auprès d'expériences comme ATLAS permet de sonder divers états finaux et régions de l'espace de phase à la recherche d'écarts par rapport aux attentes du Modèle standard. La couverture des recherches par la collaboration ATLAS s'étend des analyses qui ciblent des topologies d'événements très spécifiques aux analyses avec des sélections inclusives. La recherche de nouvelles résonances dans l'état final du dilepton est l'une des principales recherches inclusives et pourrait conduire à l'observation de phénomènes au-delà du modèle standard.

L'état final du dilepton a joué un rôle central dans la découverte du méson J/ψ en 1974 [177, 178], le méson Υ en 1977 [179] et le boson Z en 1983 [180, 181]. Dans cette thèse, une recherche de nouvelles résonances dans les états finaux dielectron et dimuon dans la fourchette de masse de 250 GeV à 6 TeV, basée sur l'ensemble de données Run 2, est détaillée. L'estimation du bruit de fond dans l'analyse est effectuée en ajustant une forme fonctionnelle aux données. Une forme de signal générique est choisie afin de faciliter la réinterprétation des limites sur la section efficace fiducielle.

La combinaison de l'état final dilepton avec des recherches supplémentaires permet d'étendre le potentiel de découverte de nouvelles résonances à haute masse qui peuvent se désintégrer dans divers états finaux, comme les bosons W et Z dans le MS. Une combinaison des états finaux $\ell\ell$, $\ell\nu$, VV et VH basée sur 36.1 fb^{-1} de données de collision proton-proton est également présentée dans cette thèse. La combinaison est réalisée dans un cadre théorique commun et permet de sonder l'espace de phase de couplage du modèle.

L'augmentation de la luminosité instantanée du LHC au cours de la prochaine période de prise de données (Run 3) nécessite une mise à niveau de l'électronique de déclenchement du calorimètre à argon liquide (LAr) d'ATLAS. La nouvelle électronique décuple la granularité de l'information LAr

fournie au premier niveau du système de déclenchement et permettra une sélection plus fine au niveau hardware du déclenchement. Pour tester les pré-prototypes de l'électronique mise à niveau, un système de démonstration in-situ a été installé au début du Run 2, afin de collecter les données avec la nouvelle lecture en parallèle à l'actuelle.

L'étalonnage de l'énergie et de l'information en temps du système démonstrateur est présenté dans cette thèse. L'étalonnage est important pour évaluer les performances du système et pour valider la reconstruction des quantités nécessaires à la sélection en ligne dans le système de déclenchement. L'énergie des cascades électromagnétiques dans le calorimètre doit être déterminée aussi proche que possible de la valeur hors ligne pour minimiser les inefficacités au seuil de déclenchement. L'information en temps de la cascade est essentielle pour déterminer quels événements doivent être enregistrés. Les études de validation détaillées dans cette thèse, réalisées avec des données recueillies en 2017, comprennent la comparaison de la reconstruction de l'énergie et de l'information en temps entre le système démonstrateur et le système LAr standard, l'information sur la forme des cascades au niveau de l'événement et la prédiction de la forme des impulsions d'ionisation, parmi d'autres mesures. Un bon accord avec les performances attendues est obtenu, démontrant l'état de préparation du système pour la prise de données du Run 3. Des vérifications supplémentaires ont été effectuées sur le système du démonstrateur 2018, pour lequel hardware de pré-production a été installé.

A.2 La physique des collisionneurs à haute énergie

En physique des particules de haute énergie, les constituants fondamentaux de la matière et leurs interactions sont étudiés. Les fondements de ce domaine remontent à la découverte de l'électron en 1897 par Thomson [8] et aux premières expériences de diffusion pour comprendre la structure des atomes entre 1908 et 1913 par Geiger, Marsden et Rutherford [9, 10]. Les progrès de l'accélération des particules [11] et de la technologie des détecteurs [12] ont permis de sonder des énergies au centre de masse en constante augmentation et donc des échelles de longueur de plus en plus petites. Le Modèle standard de la physique des particules est le cadre théorique dans lequel les quarks et les leptons, ainsi que les médiateurs d'interaction bosonique, sont actuellement décrits. Le MS est décrit en détail dans [13], tandis que [14] donne un aperçu de ses bases expérimentales.

Jusqu'à présent, les expériences du LHC n'ont révélé aucun écart significatif par rapport aux attentes du MS. La figure 2.2 donne un aperçu des mesures de section efficace de production pour divers processus de l'expérience ATLAS. D'autres tests expérimentaux de la MS comprennent, entre autres, des mesures de précision des couplages de boson de Higgs [37], la recherche de modes de désintégration rares, par exemple la désintégration de mésons B_s et B en paires de muons [38], et des mesures de masse, par exemple celle du boson W [39]. Il est néanmoins important de chercher des indications de physique au-delà du Modèle standard, car de nouveaux phénomènes peuvent apparaître à des énergies plus élevées.

Au-delà du Modèle standard, les théories prédisent de nombreuses nouvelles particules potentielles, pour lesquelles des recherches dans le cadre de la collaboration ATLAS sont entreprises pour explorer leurs signatures expérimentales. Ces recherches sont souvent conçues pour être génériques et faciliter donc la réinterprétation dans le cadre des modèles prédisant des états finaux similaires. Aucune nouvelle physique n'ayant été trouvée jusqu'à présent.

Les modèles de référence typiques pour les résonances singlet Z' sont le Modèle standard séquentiel (SSM) [50] et du modèles de grande unification inspirés du E_6 [51]. Le Z'_{SSM} devrait avoir les mêmes paramètres de couplage que le boson Z du MS et présente une largeur relative, Γ/m , de 3.0%. Le groupe de symétrie E_6 peut être décomposé en $SU(5)$ et deux groupes $U(1)$ supplémentaires. Les propriétés précises des bosons Z' prédits dépendant des paramètres du modèle. Les bosons Z'_χ et Z'_ψ ont $\Gamma/m = 1.2\%$

et 0.5%, respectivement.

Le modèle Heavy Vector Triplet (HVT) [54] est une extension générique du MS par un triplet de bosons Z'_{HVT} et $W'_{\text{HVT}}^{\pm}$ dégénérés en masse. Le triplet de champs $\mathcal{W}$ introduit des bosons incolores vecteurs et sans hypercharge. Le modèle est utilisé comme référence dans ATLAS pour combiner les recherches diboson et dilepton [55], car il permet de décrire ces états finaux dans un cadre commun. Les paramètres de couplage g_q , g_ℓ et g_H donnent la force de l'interaction entre le champ triplet et les champs de quark, lepton et Higgs, respectivement. Les interactions sont universelles entre les différentes générations de fermions et le champ triplet ne se couple pas aux fermions droitiers. Dans le cas où le couplage aux quarks et aux leptons est le même, $g_f \equiv (g_q = g_\ell)$ sera utilisé.

A.3 Le détecteur ATLAS au LHC

En termes d'énergie au centre de la masse, l'accélérateur de particules le plus puissant actuellement sur Terre est le Large Hadron Collider (LHC). Il est situé à l'Organisation européenne pour la recherche nucléaire (CERN), à la frontière franco-suisse, près de Genève. L'anneau du LHC est situé à 100 m sous terre et a une circonférence d'environ 27 km. L'énergie nominale du LHC est de 7 TeV pour les deux faisceaux de protons (totalisant jusqu'à 14 TeV) et la luminosité nominale est de $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

Quatre expériences principales sont installées au LHC. CMS et ATLAS sont des détecteurs universels. Ils permettent d'effectuer des mesures de précision des processus SM, y compris les propriétés du boson de Higgs, et de rechercher la physique au-delà du MS. LHCb est spécialisé dans l'étude des propriétés des b -hadrons, y compris les désintégrations rares de ces particules, et la violation de CP . Le détecteur ALICE a été conçu pour étudier les collisions d'ions lourds, qui peuvent également être produites au LHC et permettre l'étude des propriétés du plasma quark-gluon. LHCf et TOTEM sont deux autres expériences de plus petite envergure installées au LHC.

Le nom ATLAS est l'acronyme de «A Toroidal LHC Apparatus». Le détecteur fonctionne depuis 2008, prenant des données d'alignement avec des rayons cosmiques avant le lancement du LHC, et ses données sont exploitées par une collaboration d'environ 3000 auteurs scientifiques de 181 institutions dans 38 pays. Du fait de ses dimensions de 25 m hauteur, 25 m largeur et 46 m profondeur, c'est le plus grand détecteur à un collisionneur de particules jamais construit. Le détecteur ATLAS pèse 7000 tonnes.

ATLAS est symétrique en ϕ ainsi qu'en miroir par rapport au plan $z = 0$, capturant ainsi les particules dans tout l'espace azimutal et conçu pour atteindre le plus haut $|\eta|$ possible. Il est illustré dans la figure 3.2. Pour mesurer les propriétés des particules chargées et neutres, plusieurs couches de sous-détecteurs spécialisés sont construites autour du tube de faisceau. Leurs propriétés sont résumées dans la thèse et décrites en détail dans [76, 77].

L'objectif à long terme pour la luminosité instantanée délivrée par le LHC prévoit une augmentation progressive grâce à des améliorations continues de l'accélérateur [99]. Afin de faire face à l'augmentation du taux d'événements et de l'empilement, les expériences du LHC effectuent également des mises à niveau de divers composants du détecteur. Les principaux changements dans la configuration du détecteur sont effectués au cours des phases d'arrêt prolongé (LS) qui sont prévues pour 2019-20 (LS2 avec les mises à niveau de la phase 1) et 2024-26 (LS3 et phase 2). La figure 3.8 donne un aperçu du plan d'exploitation du LHC, y compris la phase haute luminosité (HL).

A.4 Étalonnage du démonstrateur LAr Phase 1

Le calorimètre électromagnétique d'ATLAS est un calorimètre à échantillonnage constitué d'absorbeurs en plomb, dans lesquels les particules initiales créent des gerbes électromagnétiques dues à la production

de paires de particules et au Bremsstrahlung, et de couches d'argon liquide, où les particules ionisent le milieu et un signal est mesuré par une chambre d'ionisation constituée d'électrodes. Les absorbeurs sont construits en forme d'accordéon pour fournir une couverture complète en ϕ . Le calorimètre est divisé en deux parties: la partie tonneau, couvrant $|\eta| < 1.475$, et deux bouchons ($1.375 < |\eta| < 3.2$). Dans la plage centrale de pseudo-rapacité ($|\eta| < 2.5$), importante pour la physique de précision, le calorimètre électromagnétique a trois couches avec une taille de cellule croissante en $\Delta\eta \times \Delta\phi$ (valeurs données dans le tableau 1.3 de [76]). De plus, un pré-échantillonneur, couvrant $|\eta| < 1.8$, est utilisé pour corriger les pertes d'énergie des électrons et photons avant le calorimètre. L'épaisseur totale est de plus de 22 longueurs de radiation (X_0) dans le tonneau et $> 24X_0$ pour les bouchons. L'électronique de lecture subira des changements importants dans les deux phases de mise à niveau. La mise à niveau de phase 1 consiste en une amélioration du hardware de lecture des déclencheurs [117], tandis que la mise à niveau de phase 2 vise une amélioration plus générale du hardware [118].

Un système de démonstration a été installé sur le détecteur ATLAS en 2014 pour tester les prototypes du nouveau hardware développé pour la mise à niveau de la phase 1 de LAr. La nouvelle électronique décuple la granularité de l'information LAr fournie au premier niveau du système de déclenchement et permettra une sélection plus fine au niveau hardware du déclenchement. Les mesures avec un démonstrateur in situ permettent de recueillir des données dans les conditions du LHC et de valider la reconstruction énergétique des nouvelles «supercellules». Le système de démonstration 2014 a été remplacé en 2018 par le hardware de pré-production, présentant ainsi toutes les caractéristiques du système final. Afin d'analyser les données recueillies en termes de quantités de haut niveau comme l'énergie et l'information en temps, un étalonnage de ces systèmes est nécessaire. Les coefficients d'étalonnage ont été déterminés et validés pour le système de 2014 dans le cadre de ce travail. Les informations et mesures présentées dans cette thèse proviennent principalement du système de démonstration 2014.

L'énergie d'une cellule calorimétrique, E_{cell} , est obtenue à partir des échantillons d'impulsions S_i , donnés en nombre de coup d'ADC, en utilisant la formule suivante [110]:

$$E_{\text{cell}} = F_{\text{DAC} \rightarrow \mu\text{A}} \cdot F_{\mu\text{A} \rightarrow \text{MeV}} \cdot \left(\frac{M_{\text{phys}}}{M_{\text{cali}}} \right)^{-1} \cdot G_1 \cdot \sum_i^{N_{\text{samples}}} a_i (S_i - p). \quad (\text{A.1})$$

Le niveau de référence du comptage ADC est donnée par le piédestal, p , tandis que les a_i sont les coefficients de filtrage dits optimaux (OFCs). N_{samples} donne le nombre d'échantillons d'impulsions à prendre en compte. $N_{\text{samples}} = 4$ est choisi pour les cellules calorimétriques standard en raison des contraintes de lecture. La conversion des ADC en unités de courant (DAC) est traitée par le facteur de conversion G_1 , le facteur de gain. Comme la forme des impulsions de physique est différente de celle des impulsions d'étalonnage, des jeux spécifiques d'OFCs sont nécessaires dans chaque cas et un facteur de correction, $M_{\text{cali}}/M_{\text{phys}}$, explique la différence d'amplitude. D'autres facteurs de conversion sont donnés par $F_{\text{DAC} \rightarrow \mu\text{A}}$ et $F_{\mu\text{A} \rightarrow \text{MeV}}$ et sont déterminés par les spécifications électroniques et les données des faisceaux de test des cellules LAr respectivement.

Les coefficients d'étalonnage du système démonstrateur LAr Phase 1 permettent de convertir les mesures ADC collectées en informations d'énergie et en temps. Afin d'obtenir ces coefficients, une procédure d'étalonnage a été mise au point. La procédure est basée sur le schéma d'étalonnage des cellules LAr, tandis que plusieurs modifications ont été nécessaires pour les supercellules. La procédure complète comprend le développement de modèles d'impulsions, la prise de données ainsi que l'analyse des données d'étalonnage.

L'accent est mis sur la validation des coefficients d'étalonnage avec les données de physiques proton-proton. Le schéma d'étalonnage des supercellules a été développé en supposant que le système démon-

strateur est suffisamment linéaire pour traiter des supercellules très similaires aux cellules. La validation a montré un bon accord entre le démonstrateur et la lecture principale. On s'attend à ce que le plan d'étalonnage disponible soit déjà assez précis pour le déclenchement du calorimètre après la mise à niveau de la phase 1 de LAr.

A.5 Recherche de résonances dileptoniques à haute masse

L'état final dilepton offre une signature expérimentalement propre pour reconstruire les résonances à haute masse dans le spectre de masse invariante du dilepton ($m_{\ell\ell}$). La recherche présentée dans cette thèse a été publiée dans la référence [84], en utilisant l'ensemble de données complet Run 2 de 139 fb^{-1} . L'estimation du bruit de fond dans l'analyse est effectuée en ajustant une forme fonctionnelle aux données, c'est-à-dire une stratégie de recherche «axée sur les données». Une motivation expérimentale pour les recherches de dileptons à haute masse est, en plus des résultats physiques, de sonder la reconstruction de leptons dans le régime à p_T élevé.

L'objectif de la recherche complète de dileptons au Run 2 est d'obtenir un résultat facilement réinterprétable. La recherche est effectuée avec une sélection inclusive, c'est-à-dire qu'elle n'est pas ciblée sur un mode de production spécifique, une hypothèse de spin ou d'autres propriétés de la nouvelle résonance potentielle. Le bruit de fond principal de l'état final est le processus irréductible Z/γ^* (DY), tandis que d'autres contributions de la production des paires de quarks top ($t\bar{t}$) et de la production de dibosons sont présentes. Les événements multi-jets et W +jets mal reconstruits contribuent dans le canal électronique, alors que cette contribution est négligeable dans le canal dimuon. Le modèle d'analyse de la recherche est donné en figure 6.1.

Un nouveau concept important est la méthode de la «fonction de transfert» (TF), qui est basée sur une paramétrisation de la réponse en masse du détecteur. Elle est utilisée dans l'analyse pour lisser les estimations de fond DY et $t\bar{t}$ et est donc développée pour surmonter les limitations dues aux faibles statistiques MC. Les résultats de la TF sont également utilisés pour fournir une description générique du modèle de signal et pour déterminer les incertitudes systématiques du signal pour la recherche.

Un aperçu des incertitudes systématiques qui sont prises en compte dans la recherche est donné dans le tableau 6.2. Les incertitudes systématiques expérimentales sur l'efficacité du déclenchement, de l'isolement, de l'identification et de la reconstruction sont incluses, ainsi que les incertitudes sur l'échelle et la résolution de l'énergie/impulsion. Pour prendre en compte l'éventuelle erreur de modélisation du spectre de données avec la forme fonctionnelle, la méthode des «signaux parasites» est utilisée.

Les principaux résultats d'analyse sont la mesure de la signification statistiques des excès d'événements observés et les limites sur la section efficace dans le volume fiduciel. L'analyse de l'ensemble de données Run 2 a permis d'augmenter les limites en masse des modèles de référence typiques de 500 à 800 GeV par rapport aux résultats de recherche ATLAS précédents utilisant à 36.1 fb^{-1} pour le canal dilepton. Une réinterprétation supplémentaire dans le modèle HVT vise à fournir des résultats en vue d'une éventuelle combinaison future des recherches de résonances à haute masse avec les données complet Run 2.

A.6 Combinaison de la recherche $\ell\ell$ avec les canaux $\ell\nu$, VV et VH

La combinaison de recherche des canaux VV , VH , $\ell\nu$ et $\ell\ell$ (voir réf. [55]) présentée dans cette thèse est effectuée sur les données 2015/16 avec une luminosité intégrée de 36.1 fb^{-1} . La recherche du canal dilepton de 2015/16 [132] est donc utilisée, tandis que les nouveaux résultats de la recherche dans ce canal présentés dans cette thèse seront utilisés dans la prochaine itération de la combinaison. Au total, la combinaison porte sur 12 analyses qui ciblent des états finaux et des modes de désintégration différents.

Une vue d'ensemble des recherches est donnée dans le tableau 7.1, avec leurs sélections respectives et les références aux publications correspondantes.

La combinaison des recherches VV/VH et $\ell\ell/\ell\nu$ est motivée par des modèles théoriques qui prédisent de nouvelles résonances à haute masse qui peuvent se désintégrer en états finaux diboson et dilepton. Une combinaison permet d'étendre le potentiel de découverte sur la masse de la résonance pour les valeurs des couplages où l'on prévoit des décroissances dans plusieurs états finaux avec des rapports de branchement similaire. Il pourrait donc être possible d'identifier des signes de physique au-delà du Modèle standard plus tôt que si l'on ne considérait qu'un seul canal.

La combinaison des états finaux VV/VH et $\ell\ell/\ell\nu$ a permis de fixer des limites d'exclusion plus strictes pour la production de nouveaux bosons vecteurs à haute masse dans le contexte du modèle HVT. Alors que les combinaisons VV/VH et $\ell\ell/\ell\nu$ prévoyaient des limites d'exclusion de 4.3 (4.3) TeV et 5.0 (5.0) TeV, respectivement pour la limite observée (attendue), la combinaison complète permet d'exclure le modèle HVT au point de couplage HVT A, jusqu'à une masse de 5.5 (5.3) TeV. Les limites d'exclusion des analyses en entrée de la combinaison ne s'appliquent pas à cette région de masse. Du fait de la présence de trois paramètres de couplage libre, une étude de l'espace des couplages est bénéfique dans le modèle HVT. Des limites d'exclusion sont donc également rapportées dans les plans des couplages g_q/g_ℓ et g_H/g_f .

D'autres extensions de la combinaison présentée sont possibles, par exemple en incluant des recherches pour la production dans l'état final $q\bar{q}$ [176]. Comme le paramètre de couplage g_q n'est pas encore contraint, les recherches dans les états finaux dijet et di- b -jet, ainsi que la recherche de résonances se décomposant en paires de quarks top, permettent de donner un aperçu de cette région de l'espace des paramètres. Une autre possibilité est celle de contraintes dédiées sur le couplage aux quarks et leptons de troisième génération, c'est-à-dire le quark top et le lepton τ , dans l'hypothèse de la non-universalité des leptons.

Further information on the LAr Phase-1 demonstrator calibration

In this appendix, additional information is presented for the studies detailed in Section 5.

B.1 Calibration patterns

The calibration of the LAr calorimeter is performed by injecting current pulses into certain LAr cells by so-called calibration boards. In order to calibrate the demonstrator, all cells within a given supercell are pulsed using the same injected current. The pulsing scheme is defined in so-called pulsing patterns. Dedicated patterns are developed for the demonstrator system trying to minimize the impact of cross-talk between the supercells. The patterns include information about the pulsed calibration lines, the injected current (given in DAC current units) and delay values between the injection and the read-out time.

The association between calibration board lines and cells in the LAr calorimeter is shown in Figure 5.5 in Section 5.3 of the main body for a region of 0.2×0.2 in $\Delta\eta \times \Delta\phi$, describing a group of four trigger towers. In addition, the barrel end is treated in a special way. The scheme is repeated in terms of these groups in the η direction using different calibration lines according to Table B.1. All layers in the ϕ direction use the same calibration lines. [110]

Table B.1: Association of the calibration lines to different trigger tower groups. [110]

Region in $ \eta $	PS	Front	Middle	Back	Barrel end
0.0 – 0.2	120	0 – 3	4 – 11	12 – 15	/
0.2 – 0.4	121	16 – 19	20 – 27	28 – 31	/
0.4 – 0.6	122	32 – 35	36 – 43	44 – 47	/
0.6 – 0.8	123	48 – 51	52 – 59	60 – 63	/
0.8 – 1.0	124	64 – 67	68 – 75	76 – 79	/
1.0 – 1.2	125	80 – 83	84 – 91	92 – 95	/
1.2 – 1.4	126	96 – 99	100 – 107	108 – 111	112 – 119

B.1.1 Structure of calibration patterns

The calibration patterns include three different parts to specify the DAC values, the delay values and the pulsed calibration lines. Each part begins with the number of settings to be used. The DAC values and delay values are then given in a single line, separated by space characters. The delay is given in units of 25/240 ns, while the injected currents are related to the DAC values according to

$$I_{\text{inj}} = \frac{5 \text{ V}}{(2^{16} - 1) R_{\text{inj}}} \cdot \text{DAC}. \quad (\text{B.1})$$

R_{inj} describes the injection resistor and varies for different regions in the calorimeter.

The pulsed calibration lines are given in rows of four words, in which each word is composed out of eight hexadecimal values. A hexadecimal value decodes four binary values, each indicating if a certain calibration line shall be pulsed or not. The order of calibration lines in the words is given as bits 31 – 0, 63 – 32, 95 – 64 and 127 – 96. Examples are shown in Table B.2. Python scripts were used to decode and to create the pulsing schemes in this format.

Table B.2: Examples of the encoding scheme for the pulsed calibration lines in the pulsing patterns.

Pulsed calibration lines	Word 1	Word 2	Word 3	Word 4
0	0x00000001	0x00000000	0x00000000	0x00000000
32	0x00000000	0x00000001	0x00000000	0x00000000
5 & 87	0x00000020	0x00000000	0x00800000	0x00000000

B.1.2 Patterns used for calibration runs

Tables B.3 to B.14 give the calibration patterns used to obtain the demonstrator calibration runs that are used within this thesis. No pattern is needed for pedestal runs, since in this case no pulses are sent into the calorimeter cells.

Table B.3: Delay run pulsing pattern for the front, middle and high- η back layers of the BNL LTDB.

```

1
4400
24
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
220 230
6
0x0000000f 0x0000000f 0xf000000f 0x0000000f
0x00300030 0x00300030 0x00300030 0x00000030
0x00c000c0 0x00c000c0 0x00c000c0 0x000000c0
0x03000300 0x03000300 0x03000300 0x00000300
0xc000c000 0xc000c000 0xc000c000 0x00000c00
0x000f0000 0x000f0000 0x000ff000 0x0000f000

```

Table B.4: Delay run pulsing pattern for the low- η back layer of the BNL LTDB.

```

1
2000
24
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
220 230
2
0x0000f000 0x0000f000 0x00000000 0x00000000
0xf0000000 0xf0000000 0x00000000 0x00000000

```

Table B.5: Delay run pulsing pattern for the presampler and barrel end of the BNL LTDB.

```

1
32000
24
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
220 230
3
0x00000000 0x00000000 0x00000000 0x55c00000
0x00000000 0x00000000 0x00000000 0xaa0c0000
0x00000000 0x00000000 0x00000000 0x00330000

```

Table B.6: Delay run pulsing pattern for the front, middle and high- η back layers of the French LTDB.

```

1
3200
24
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
220 230
6
0x0000000f 0x0000000f 0xf000000f 0x0000000f
0x00300030 0x00300030 0x00300030 0x00000030
0x00c000c0 0x00c000c0 0x00c000c0 0x000000c0
0x03000300 0x03000300 0x03000300 0x00000300
0x0c000c00 0x0c000c00 0x0c000c00 0x00000c00
0x000f0000 0x000f0000 0x000ff000 0x0000f000

```

Table B.7: Delay run pulsing pattern for the low- η back layer of the French LTDB.

```

1
1200
24
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
220 230
2
0x0000f000 0x0000f000 0x00000000 0x00000000
0xf0000000 0xf0000000 0x00000000 0x00000000

```

Table B.8: Delay run pulsing pattern for the presampler and barrel end of the French LTDB.

```

1
32000
24
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
220 230
3
0x00000000 0x00000000 0x00000000 0x55c00000
0x00000000 0x00000000 0x00000000 0xaa0c0000
0x00000000 0x00000000 0x00000000 0x00330000

```

Table B.9: Ramp run pulsing pattern for the front, middle and high- η back layers of the BNL LTDB.

```

15
100 1000 1900 2800 3700 4600 5500 6400 7900 9400 10900 12400 13900 15400 16900
1
0
6
0x0000000f 0x0000000f 0xf000000f 0x0000000f
0x00300030 0x00300030 0x00300030 0x00000030
0x00c000c0 0x00c000c0 0x00c000c0 0x000000c0
0x03000300 0x03000300 0x03000300 0x00000300
0x0c000c00 0x0c000c00 0x0c000c00 0x00000c00
0x000f0000 0x000f0000 0x000ff000 0x000f0000

```

Table B.10: Ramp run pulsing pattern for the low- η back layer of the BNL LTDB.

```

15
100 390 680 970 1260 1550 1840 2130 2420 2710 3000 3500 4000 4500 5000
1
0
2
0x0000f000 0x0000f000 0x00000000 0x00000000
0xf0000000 0xf0000000 0x00000000 0x00000000

```

Table B.11: Ramp run pulsing pattern for the presampler and barrel end of the BNL LTDB.

```

14 500 3100 5700 8300 10900 13500 20000 26500 33000 39500 46000 52500 59000
65500
1
0
3
0x00000000 0x00000000 0x00000000 0x55c00000
0x00000000 0x00000000 0x00000000 0xaa0c0000
0x00000000 0x00000000 0x00000000 0x00330000

```

Table B.12: Ramp run pulsing pattern for the front, middle and high- η back layers of the French LTDB.

```

15
100 775 1450 2125 2800 3475 4150 4825 5950 7075 8200 9325 10450 11575 12700
1
0
6
0x0000000f 0x0000000f 0xf000000f 0x0000000f
0x00300030 0x00300030 0x00300030 0x00000030
0x00c000c0 0x00c000c0 0x00c000c0 0x000000c0
0x03000300 0x03000300 0x03000300 0x00000300
0x0c000c00 0x0c000c00 0x0c000c00 0x00000c00
0x000f0000 0x000f0000 0x000ff000 0x0000f000

```

Table B.13: Ramp run pulsing pattern for the low- η back layer of the French LTDB.

```

15
100 280 460 640 820 1000 1180 1360 1540 1720 1900 2150 2400 2650 2900
1
0
2
0x0000f000 0x0000f000 0x00000000 0x00000000
0xf0000000 0xf0000000 0x00000000 0x00000000

```

Table B.14: Ramp run pulsing pattern for the presampler and barrel end of the French LTDB.

```

14
500 3100 5700 8300 10900 13500 20000 26500 33000 39500 46000 52500 59000 65500
1
0
3
0x00000000 0x00000000 0x00000000 0x55c00000
0x00000000 0x00000000 0x00000000 0xaa0c0000
0x00000000 0x00000000 0x00000000 0x00330000

```

B.2 Additional calibration pulse shape figures

An additional pulse shape example is shown in Figure B.1. More information is given in Subsection 5.4.2 of the main body.

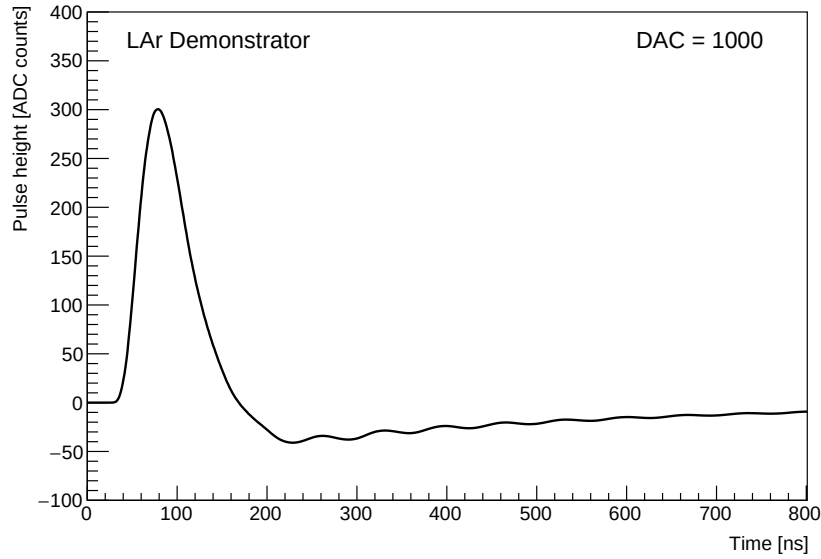


Figure B.1: Measured calibration pulse shape for a front layer supercell, which exhibits sinusoidal fluctuations in the negative lobe. The pedestal level is subtracted.

B.3 Summary of calibration coefficients

Information on the calibration coefficients is available in Figures B.2 to B.6, in addition to the main body description in Section 5.4. The pedestal values for the full demonstrator system are shown in Figure B.2, while the fluctuations of the pedestal level in terms of the RMS value are given in Figure B.3. The η -dependence of the $M_{\text{cali}}/M_{\text{phys}}$ correction factor is shown in Figure B.4.

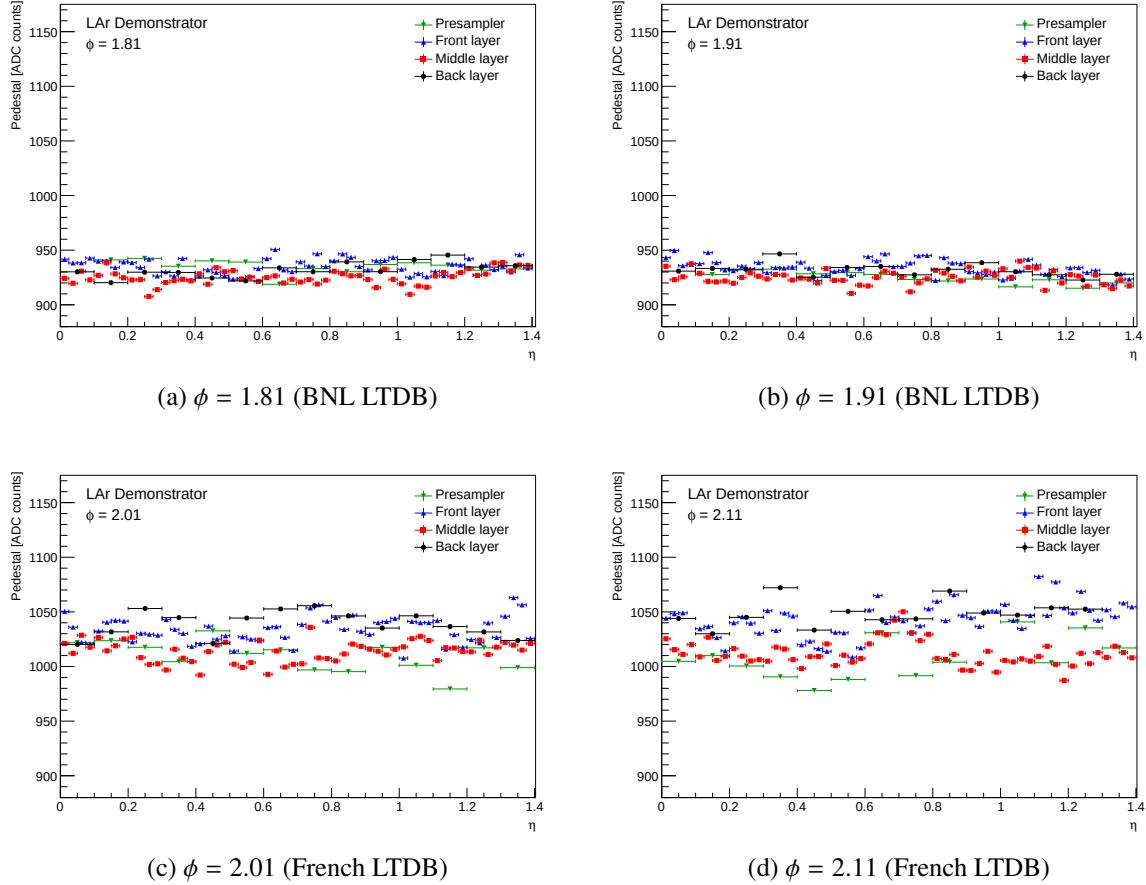
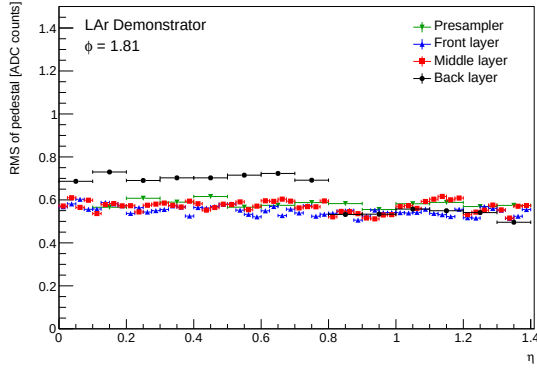
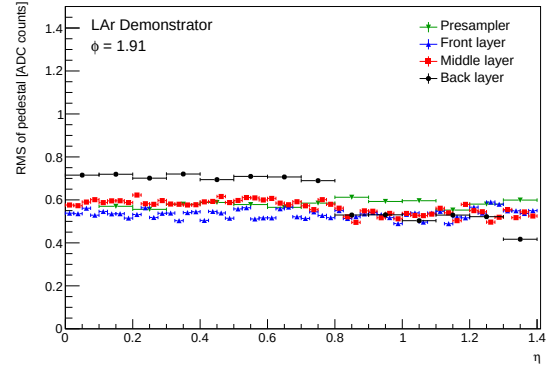


Figure B.2: Pedestal level in ADC counts for the different ϕ regions of the demonstrator system as a function of η .

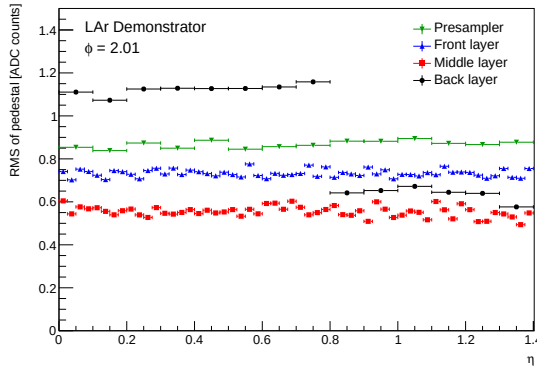
Figure B.5 gives an overview of the pedestal fluctuations in units of energies. The pedestal fluctuations reflect the baseline noise level, which is also present in physics data-taking. The saturation energy of the demonstrator supercells is given in Figure B.6.



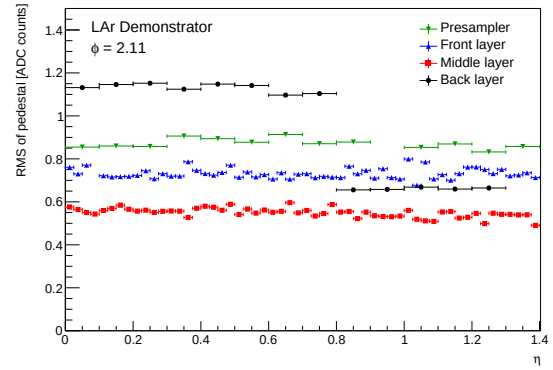
(a) $\phi = 1.81$ (BNL LTDB)



(b) $\phi = 1.91$ (BNL LTDB)



(c) $\phi = 2.01$ (French LTDB)



(d) $\phi = 2.11$ (French LTDB)

Figure B.3: RMS value of pedestal fluctuations in ADC counts for the different ϕ regions of the demonstrator system as a function of η .

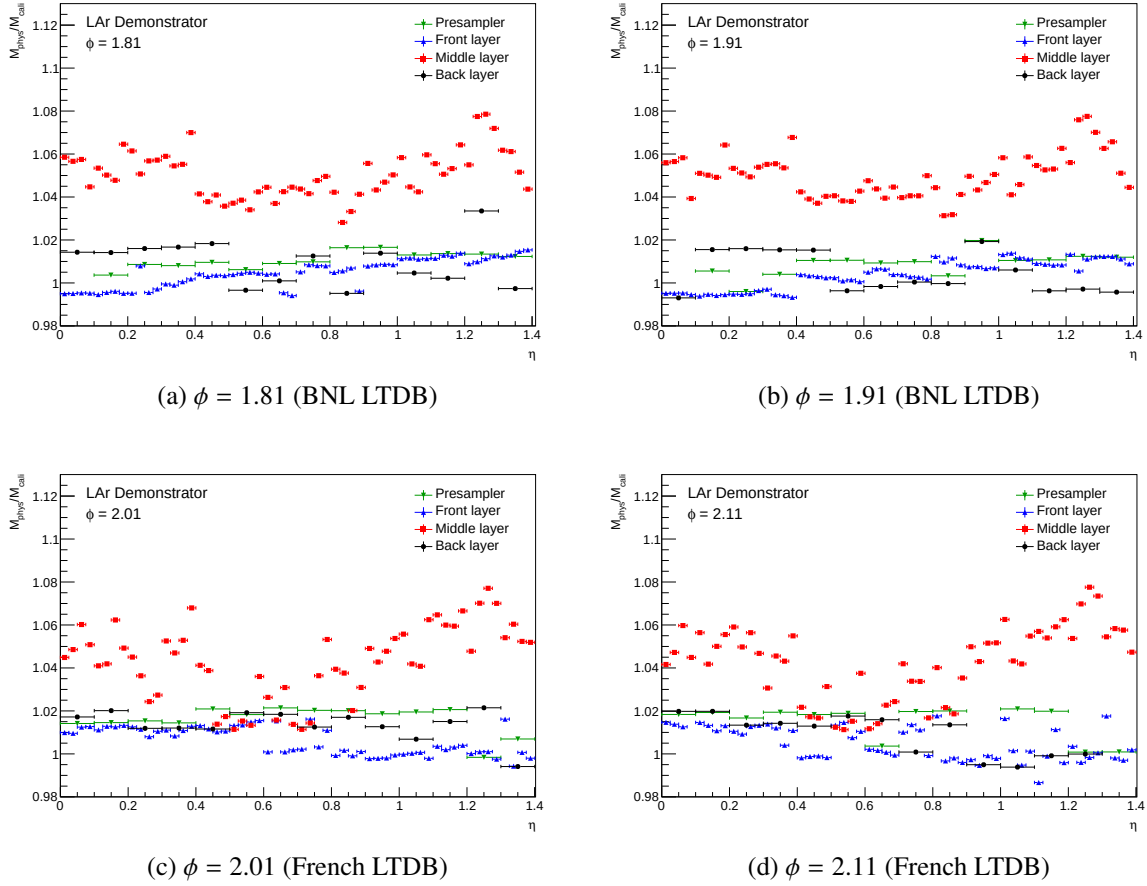
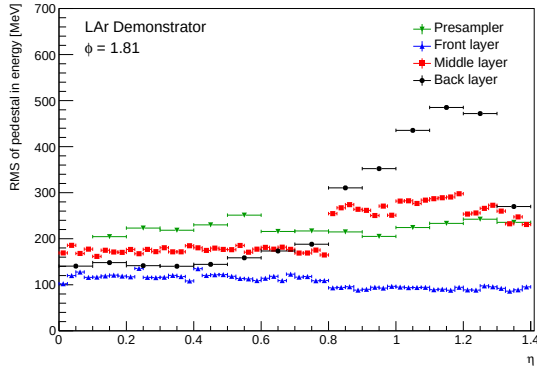
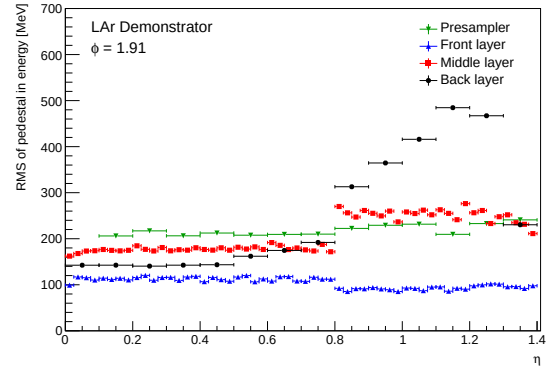


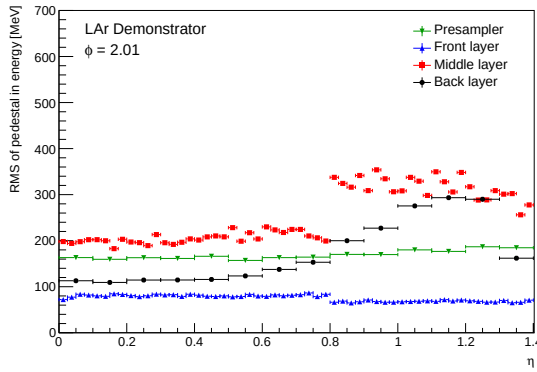
Figure B.4: Distribution of amplitude ratios from the physics pulse prediction for the different ϕ regions of the demonstrator system as a function of η . The amplitude ratio in the front and back layers as well as the presampler is typically about 0 – 2%. The middle layer corrections are higher, with a mean value of about 5% and values ranging up to 8%.



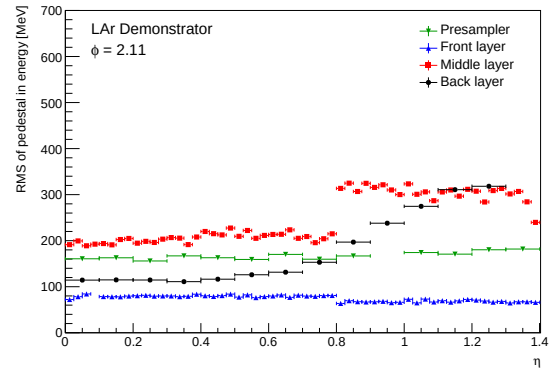
(a) $\phi = 1.81$ (BNL LTDB)



(b) $\phi = 1.91$ (BNL LTDB)



(c) $\phi = 2.01$ (French LTDB)



(d) $\phi = 2.11$ (French LTDB)

Figure B.5: RMS value of pedestal fluctuations in units of energies for the different ϕ regions of the demonstrator system as a function of η .

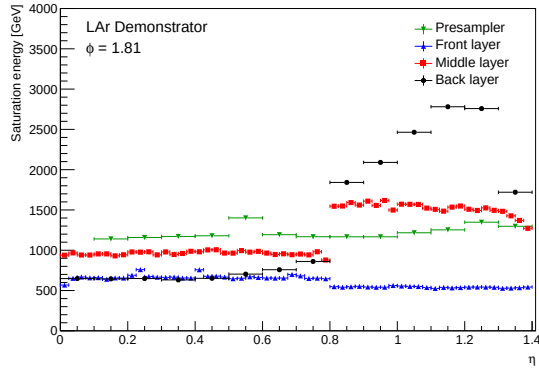
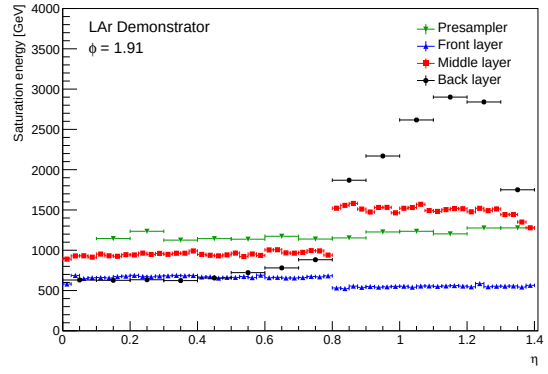
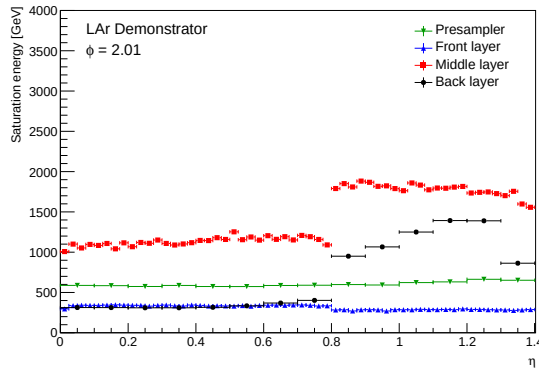
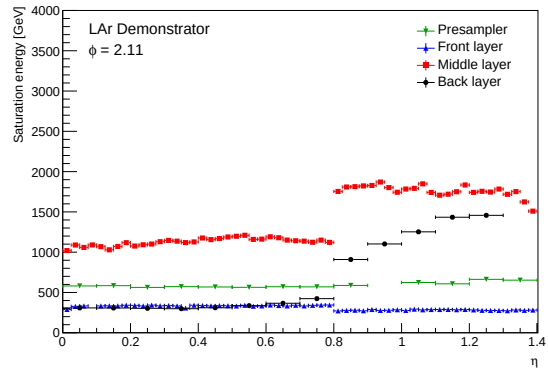

 (a) $\phi = 1.81$ (BNL LTDB)

 (b) $\phi = 1.91$ (BNL LTDB)

 (c) $\phi = 2.01$ (French LTDB)

 (d) $\phi = 2.11$ (French LTDB)

 Figure B.6: Saturation energy of the demonstrator supercells for the different ϕ regions of the demonstrator system as a function of η .

B.4 Dependence of reconstruction properties on shower maximum within supercells

The energy and timing reconstruction is “only” performed for full supercells in the final trigger read-out, i.e. no further information from the constituent cells is available. It is therefore necessary that the constituent cells of a supercell behave similarly and no significant variation of the reconstruction properties depending on the shower position within the supercell can be observed. The study presented in this section estimates the impact of constituent cell differences by making use of the main read-out information, for which the full cell granularity is accessible from the offline reconstruction.

The association of an energy deposit in the demonstrator read-out to a certain constituent cell, and thus the determination of the position of the shower maximum within the supercell, is done according to the following criteria:

- The event or energy deposit is associated to the constituent cell with the highest E_{cell} within a given supercell.
- From the available associated events, only the subset of events with the 20% highest energy deposits is used per associated constituent cell (i.e. with energies above the fourth quintile of the energy distribution). This criterion reduces contributions from events where the shower maximum is between two constituent cells. An additional rejection is present for showers that point to a position outside of the given supercell, as for those the average deposited energy should also be smaller than for showers which point to a position inside the supercell.

The energy fraction of given constituent cells compared to the total supercell is given in Figure B.7. It can be observed that in the front layer not more than about 50 % of the supercell energy is deposited within one constituent cell due to their very narrow size in η . For the three other layers, there are events where almost the full energy is deposited in a single constituent cell of the supercell. The distributions are due to an interplay between the LAr cell and supercell sizes (compare Figure 5.1) and the shower development (compare Section 4.4).

The overall correlation matrix between the constituent cell energy distribution and the associated cell, i.e. the one with the highest energy deposit, is depicted in Figure B.8. It can be observed that typically 60% of the energy is deposited in the associated constituent cell for the presampler and the middle layer. About 50% could be achieved in the back layer, while the front layer shows a broader distribution for which about 30% of the energy is deposited in the associated cell. The position of the shower maximum thus corresponds well to that of the constituent cell that has the maximum energy deposit and a high purity of the energy deposits for a given constituent cell association could be achieved using the chosen association method. In addition, the requirement that the energy deposit is within the highest 20% ensures to select predominantly the supercell energy deposits for which the shower maximum is actually inside the studied supercell.

For each of the associated constituent cells, the pulse shape is extracted according to the procedure described in Subsection 5.5.3. A comparison of the constituent pulse shapes for the selected supercells is given in Figure B.9. The amplitude variations of the pulses have an RMS of up to 0.9% for different associated constituent cells. The variations of the pulse timing have an RMS of up to 0.9 ns. No pulse shape changes apart from timing shifts or normalisation differences are visible.

The impact of different constituent cell properties on the energy and timing reconstruction is shown in Figures B.10 and B.11 for selected supercells. For the full system, it can be observed that for most supercells the fluctuations from the constituent cells are smaller than the intrinsic resolution, while for about 20% (10%) of the supercells the constituent cell differences dominate the energy comparison

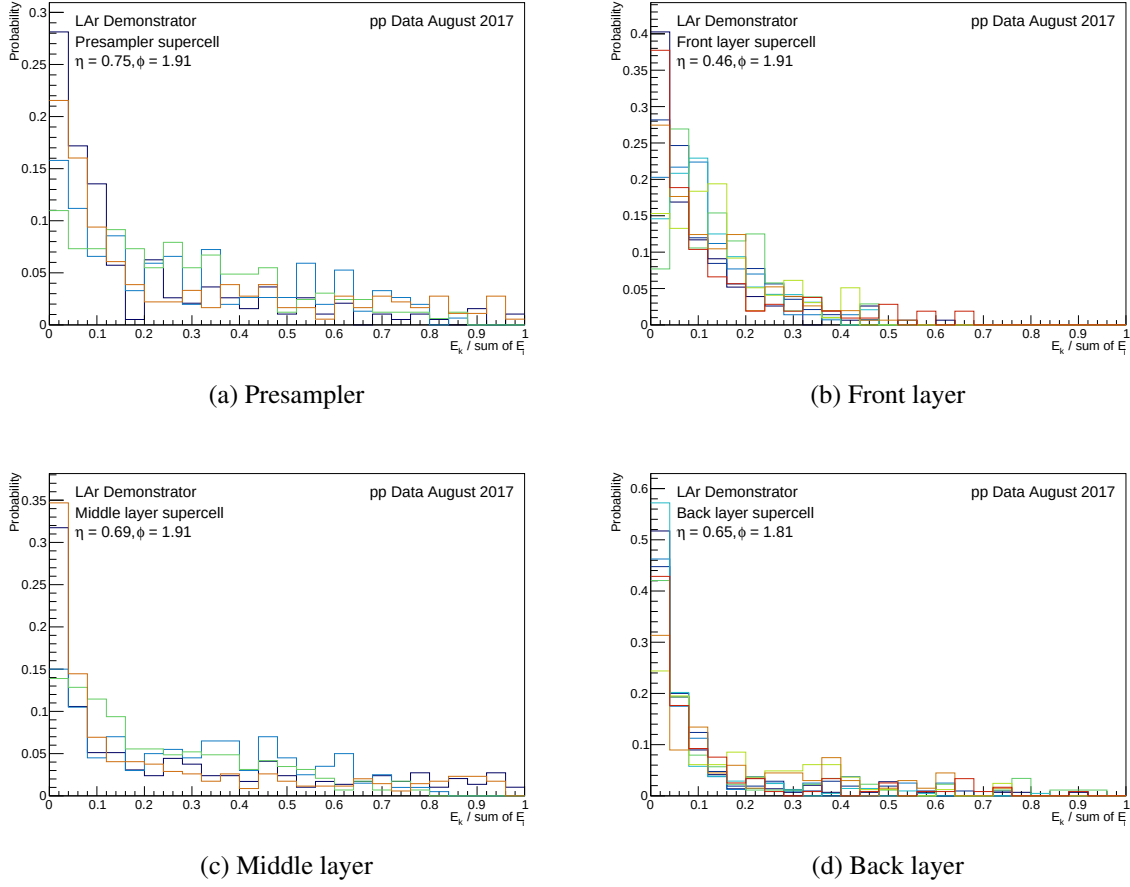


Figure B.7: Energy fraction of specific constituent cells compared to the total energy deposit in the supercell. The different colors represent different constituent cells. A fraction of up to almost the complete deposited energy can be present for constituent cells in the presampler and the middle layer. In the front and back layers, the energy is typically distributed over several constituent cells.

(timing resolution). The mean of the energy and timing distributions from different associated constituent cells has a spread of up to 1.5 – 2 times the RMS value in these cases.

Differences of the constituent cell properties are thus negligible for a large part of the supercells in the demonstrator system. This conclusion agrees with the expectations, as the LAr cells do not exhibit considerable differences over short distances in pseudorapidity and thus over the supercell width. A small part of the supercells shows enlarged energy fluctuations or timing resolutions due to averaging over the constituent cells, though. It is worth to emphasise that only the high-energy tail is studied here, though, and at lower energies the intrinsic fluctuations/resolutions are typically considerably larger than the variations of the mean values due to the constituent cell properties.

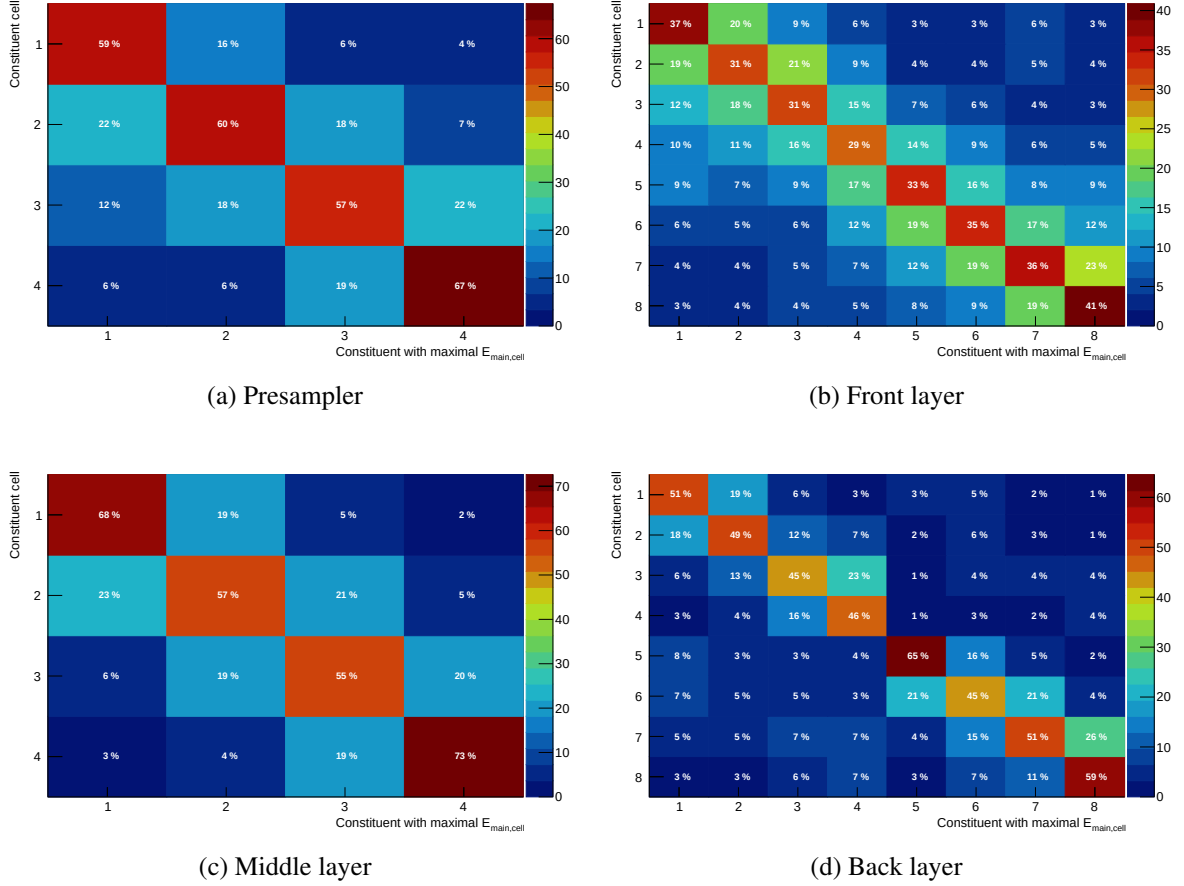


Figure B.8: Correlation matrix between the constituent cell with the maximum energy deposit on the x -axis and the distribution of constituent cell energies inside the supercell on the y -axis. The columns of the matrix give the composition of constituent cell energy contributions for a given constituent cell association on the x -axis. The columns are normalised to 100%.

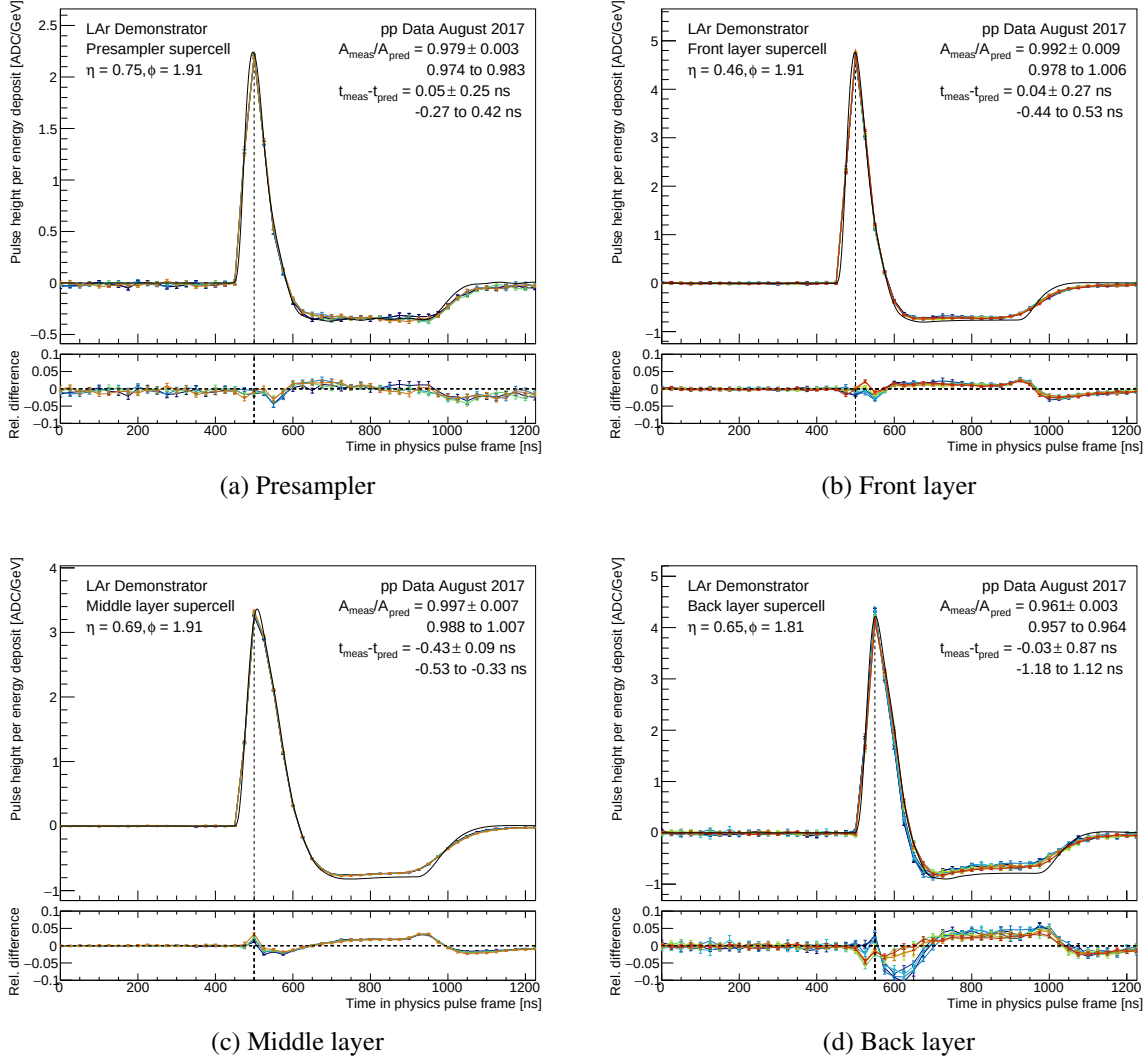


Figure B.9: Measured pulse shapes of supercells in the LAr Phase-1 demonstrator compared to the, independently obtained, predicted pulse shapes (black). The different colors represent the different associated constituent cells. Significant differences between the pulse shapes depending on the associated constituent cell are visible in the front and back layers. The values for $A_{\text{meas}}/A_{\text{pred}}$ and $t_{\text{meas}} - t_{\text{pred}}$ are given in terms of the mean value of the different constituents, the RMS value and in addition the total range for all constituent cells of a given supercell. The same procedure as for Figure 5.34 is used to obtain the pulse shapes.

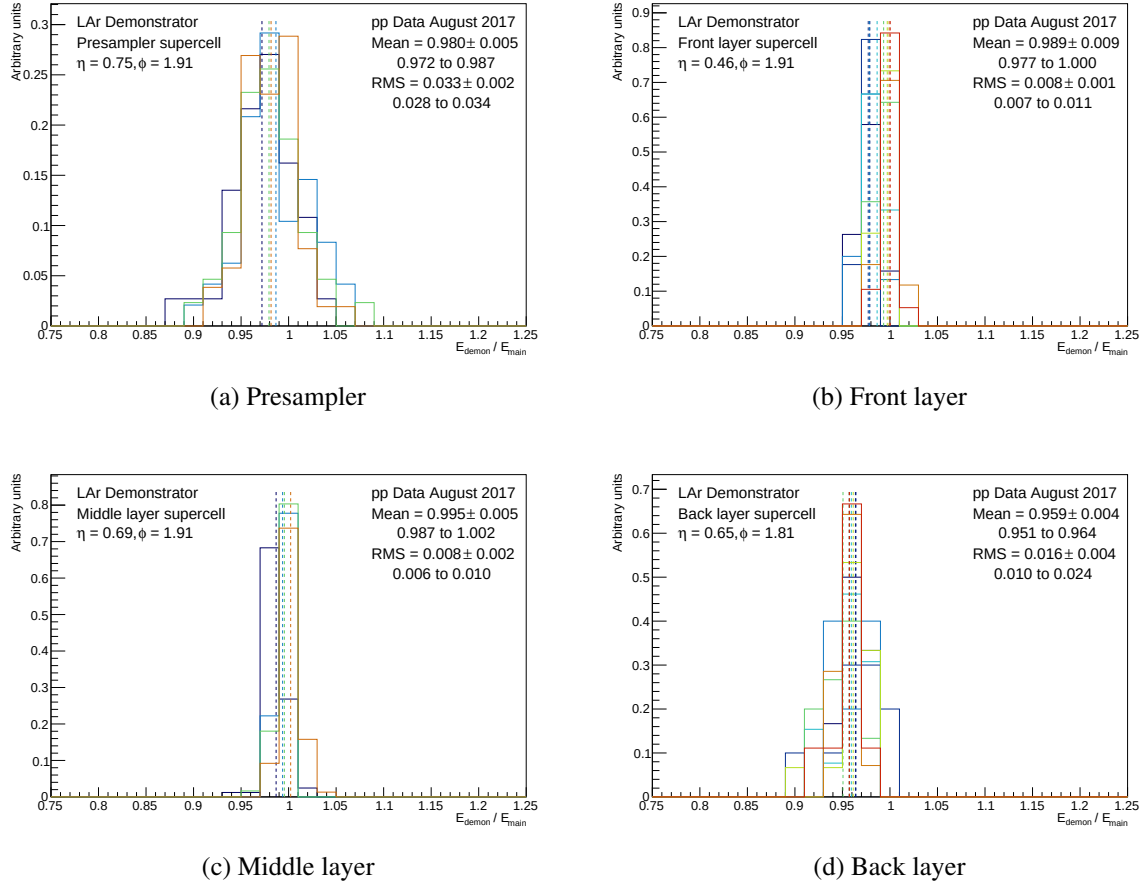


Figure B.10: Variation of the relative energy deviation for different associated constituent cells, which are represented by different colors. The mean values are depicted by the dashed lines. The range of mean and RMS values, as well as their spread, is given. The front layer supercell shows variations of the mean relative energy deviation, due to different associated constituent cells, in the order of the RMS value. The total accuracy of the supercell energy measurement, without constituent association, is thus slightly worsened by these variations.

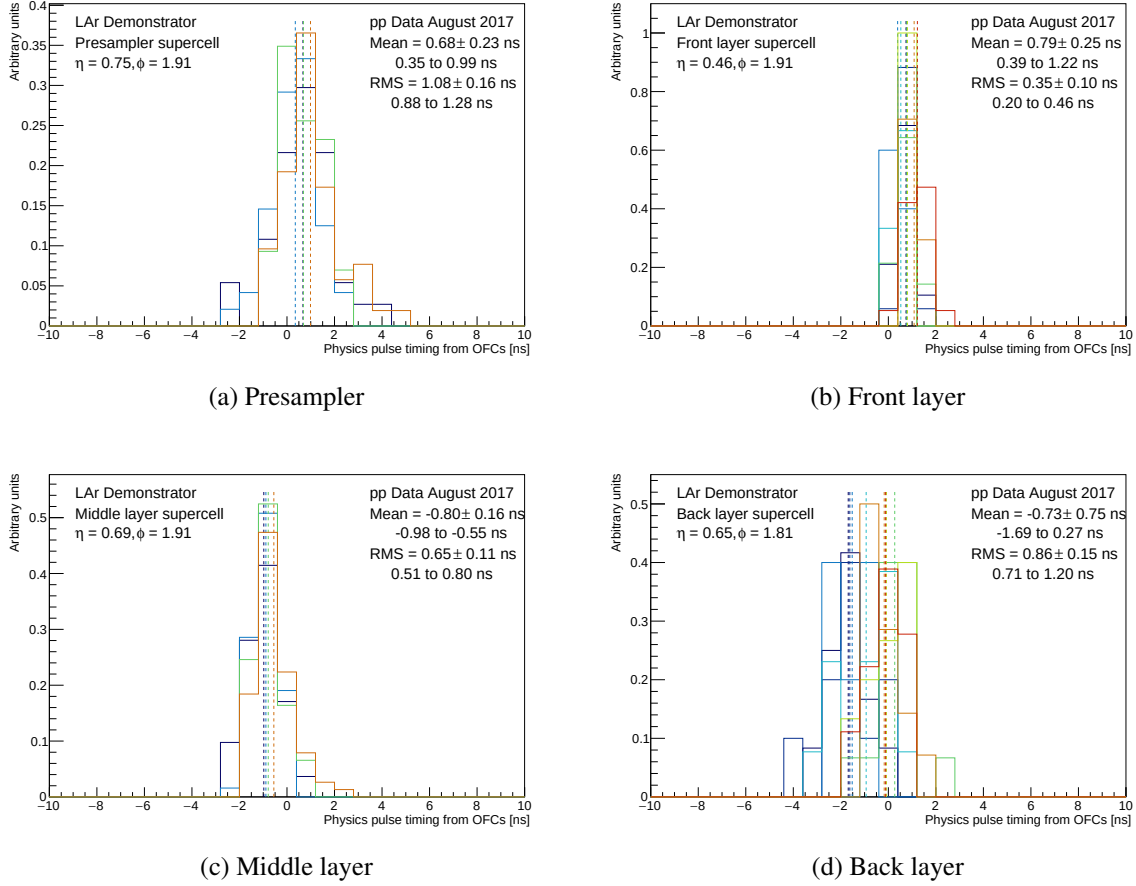


Figure B.11: Variation of the timing measurement distribution for different associated constituent cells, which are represented by different colors. The mean values are depicted by the dashed lines. The range of mean and RMS values, as well as their spread, is given. The back layer supercell shows variations of the mean timing offset, due to different associated constituent cells, in the order of the RMS value. The total accuracy of the supercell timing measurement, without constituent association, is thus slightly worsened by these variations.

B.5 Additional material on the validation of the calibration coefficients

B.5.1 Correlation of energy measurements

The correlation between the energy measurements of the main read-out and the demonstrator system is shown in Figure B.12.

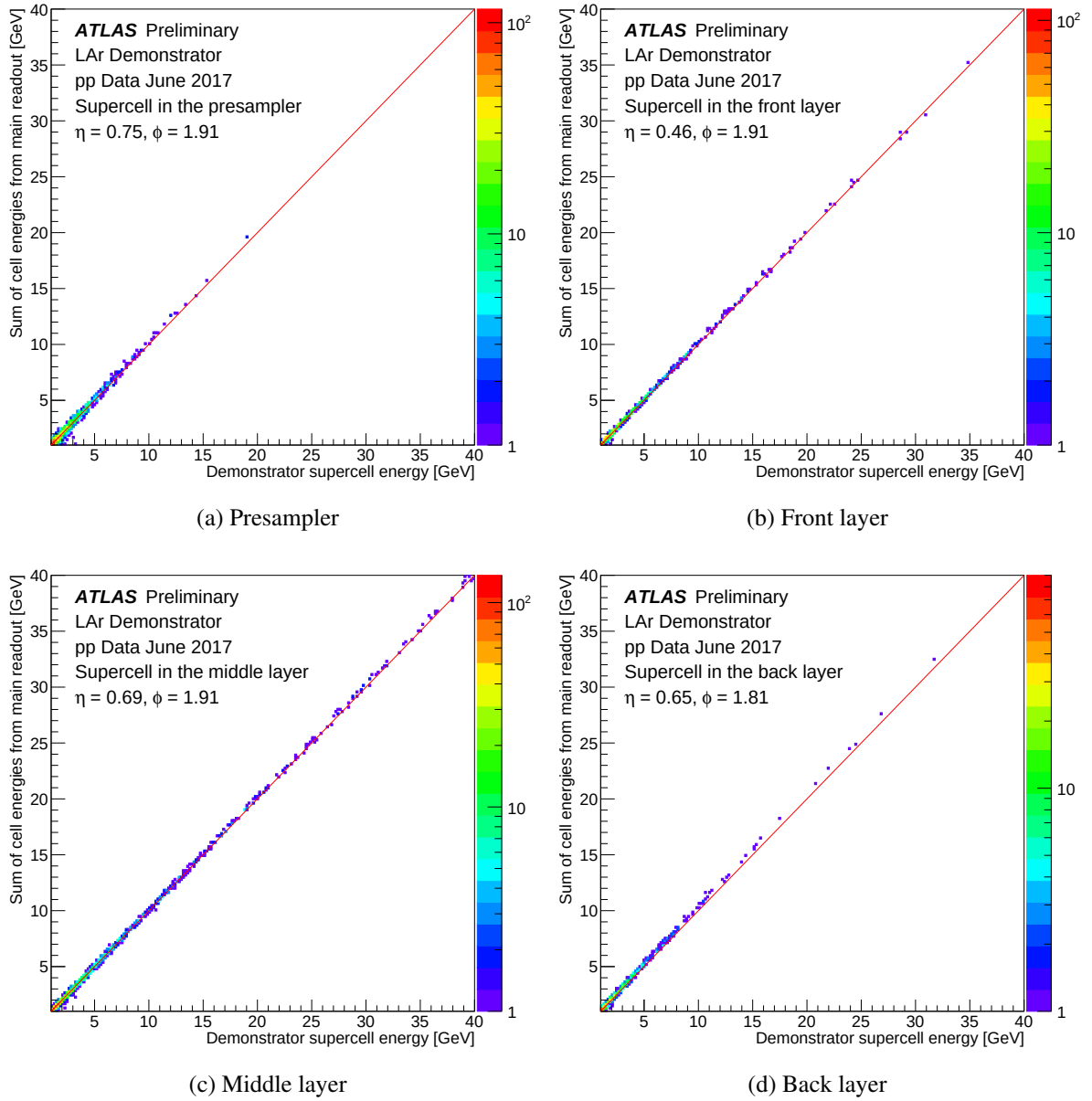


Figure B.12: Correlation of the energy measurements in the main read-out and the demonstrator system for selected supercells from the four layers of the calorimeter.

B.5.2 Correction of residual energy dependencies

This subsection contains additional figures for the studies detailed in Subsection 5.5.5, where the residual energy dependencies of the energy and timing scale are discussed.

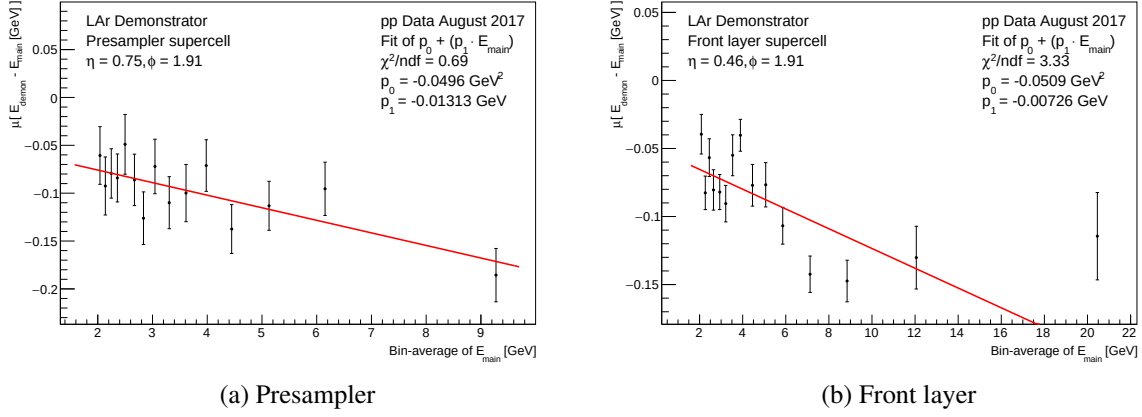


Figure B.13: Residual energy dependence of the mean energy deviation between the demonstrator system and the main read-out for selected supercells. The fitted function corresponds to Equation 5.13 and is an ad-hoc parametrisation of the difference.

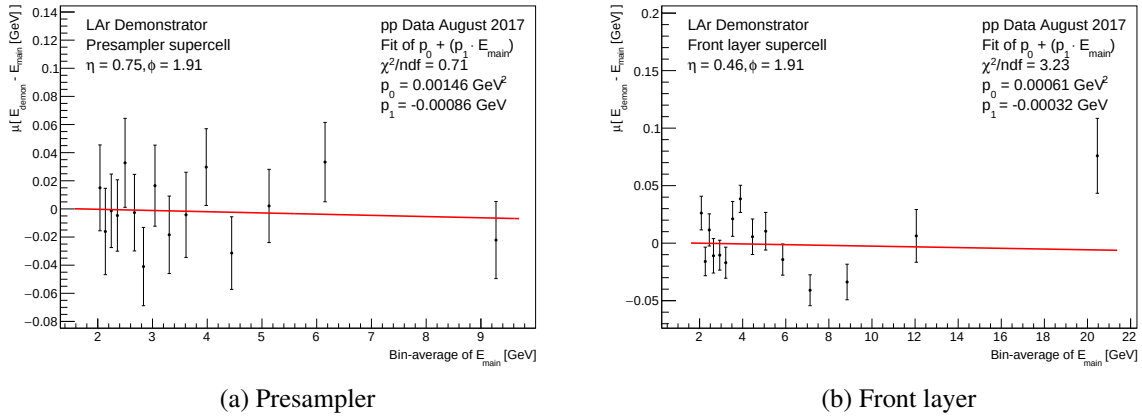


Figure B.14: Corrected residual energy dependence of the mean energy deviation between the demonstrator system and the main read-out for selected supercells. The correction is performed according to Equation 5.14 and the parameters given in Figure B.13.

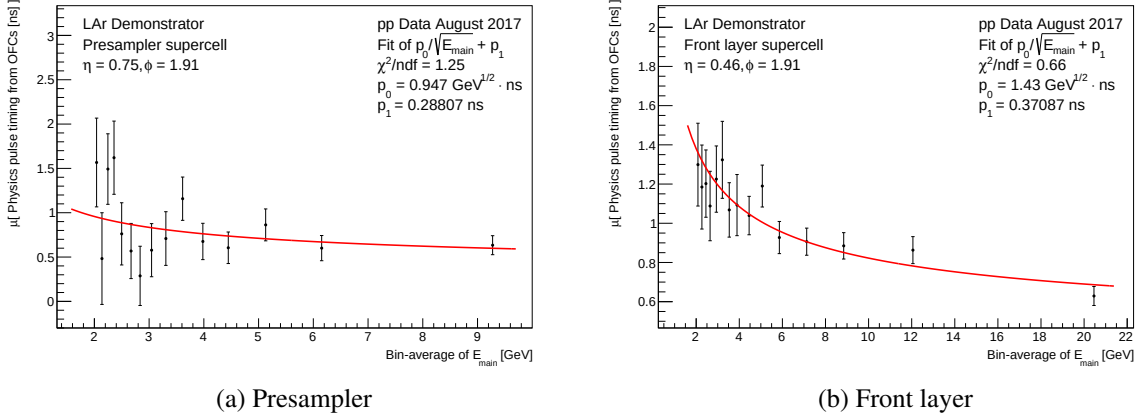


Figure B.15: Residual energy dependence of the mean timing information for selected supercells. The fitted function corresponds to Equation 5.15 and is an ad-hoc parametrisation of the difference.

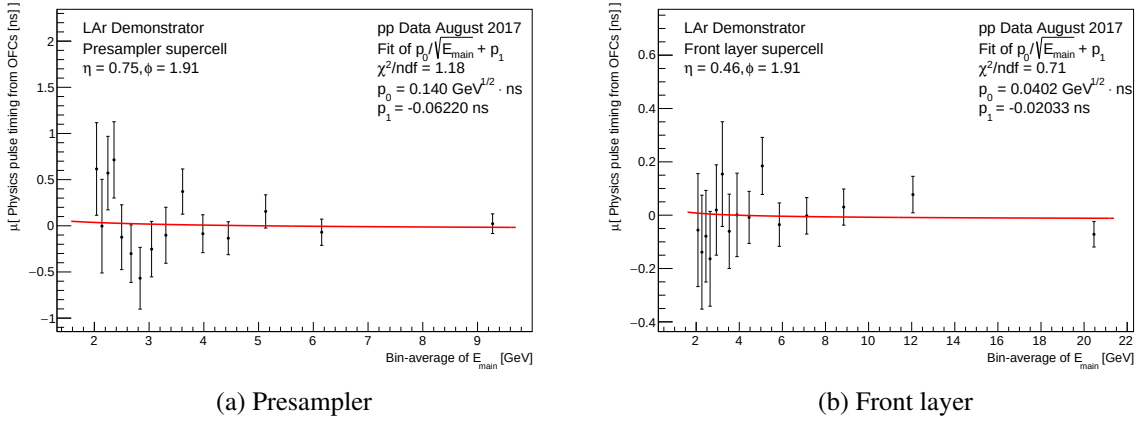


Figure B.16: Corrected residual energy dependence of the mean timing information for selected supercells. The correction is performed according to Equation 5.16 and the parameters given in Figure B.15.

Further information on search for high-mass dilepton resonances

In this appendix, additional information is presented for the studies detailed in Chapter [6](#).

C.1 Parametrisation of the transfer functions

Tables [C.1](#) and [C.2](#) contain the functional form of the $m_{\ell\ell}^{\text{truth}}$ dependence for the 7 TF parameters in the ee and $\mu\mu$ channels, respectively.

Table C.1: Description of the $m_{\ell\ell}^{\text{truth}}$ -dependence for the seven mass resolution parameters in the dielectron channel.

Parameter $m_{\ell\ell}^{\text{truth}}$ -dependence	Fit result
$\mu_{\text{CB}}(m_{\ell\ell}^{\text{truth}}) = p_{\mu_{\text{CB}},1} + p_{\mu_{\text{CB}},2}/\ln(m_{\ell\ell}^{\text{truth}}) + p_{\mu_{\text{CB}},3} \cdot \ln(m_{\ell\ell}^{\text{truth}}) + p_{\mu_{\text{CB}},4} \cdot \ln(m_{\ell\ell}^{\text{truth}})^4$	$p_{\mu_{\text{CB}},1} = 0.13287$ $p_{\mu_{\text{CB}},2} = -0.410663$ $p_{\mu_{\text{CB}},3} = -0.0126743$ $p_{\mu_{\text{CB}},4} = 2.9547 \cdot 10^{-6}$
$\sigma_{\text{CB}}(m_{\ell\ell}^{\text{truth}}) = \sqrt{p_{\sigma_{\text{CB}},1}^2 + (p_{\sigma_{\text{CB}},2}/\sqrt{m_{\ell\ell}^{\text{truth}}})^2 + (p_{\sigma_{\text{CB}},3}/m_{\ell\ell}^{\text{truth}})^2}$	$p_{\sigma_{\text{CB}},1} = 0.0136624$ $p_{\sigma_{\text{CB}},2} = 0.230678$ $p_{\sigma_{\text{CB}},3} = 1.73254$
$\alpha_{\text{CB}}(m_{\ell\ell}^{\text{truth}}) = p_{\alpha_{\text{CB}},1}$	$p_{\alpha_{\text{CB}},1} = 1.59112$
$n_{\text{CB}}(m_{\ell\ell}^{\text{truth}}) = p_{n_{\text{CB}},1} + p_{n_{\text{CB}},2} \cdot \exp(-p_{n_{\text{CB}},3} \cdot m_{\ell\ell}^{\text{truth}})$	$p_{n_{\text{CB}},1} = 1.13055$ $p_{n_{\text{CB}},2} = 0.76705$ $p_{n_{\text{CB}},3} = 0.00298312$
$\mu_{\text{G}}(m_{\ell\ell}^{\text{truth}}) = p_{\mu_{\text{G}},1} + p_{\mu_{\text{G}},2}/m_{\ell\ell}^{\text{truth}} + p_{\mu_{\text{G}},3} \cdot m_{\ell\ell}^{\text{truth}} + p_{\mu_{\text{G}},4} \cdot \ln(m_{\ell\ell}^{\text{truth}})^3 + p_{\mu_{\text{G}},5}/(m_{\ell\ell}^{\text{truth}})^2 + p_{\mu_{\text{G}},6} \cdot (m_{\ell\ell}^{\text{truth}})^2$	$p_{\mu_{\text{G}},1} = -0.00402708$ $p_{\mu_{\text{G}},2} = 0.814172$ $p_{\mu_{\text{G}},3} = -3.94281 \cdot 10^{-7}$ $p_{\mu_{\text{G}},4} = 7.97076 \cdot 10^{-6}$ $p_{\mu_{\text{G}},5} = -87.6397$ $p_{\mu_{\text{G}},6} = -1.64806 \cdot 10^{-11}$
$\sigma_{\text{G}}(m_{\ell\ell}^{\text{truth}}) = \sqrt{p_{\sigma_{\text{G}},1}^2 + (p_{\sigma_{\text{G}},2}/\sqrt{m_{\ell\ell}^{\text{truth}}})^2 + (p_{\sigma_{\text{G}},3}/m_{\ell\ell}^{\text{truth}})^2}$	$p_{\sigma_{\text{G}},1} = 0.00553858$ $p_{\sigma_{\text{G}},2} = 0.140909$ $p_{\sigma_{\text{G}},3} = 0.644418$
$\kappa(m_{\ell\ell}^{\text{truth}}) = p_{\kappa,1} + p_{\kappa,2} \cdot \exp(-p_{\kappa,3} \cdot m_{\ell\ell}^{\text{truth}}) + p_{\kappa,4} \cdot m_{\ell\ell}^{\text{truth}} + p_{\kappa,5} \cdot (m_{\ell\ell}^{\text{truth}})^3$	$p_{\kappa,1} = 0.347003$ $p_{\kappa,2} = 0.135768$ $p_{\kappa,3} = 0.00372497$ $p_{\kappa,4} = -2.2822 \cdot 10^{-5}$ $p_{\kappa,5} = 5.06351 \cdot 10^{-13}$

Table C.2: Description of the $m_{\ell\ell}^{\text{truth}}$ -dependence for the seven mass resolution parameters in the dimuon channel.

Parameter $m_{\ell\ell}^{\text{truth}}$ -dependence	Fit result
$\mu_{\text{CB}}(m_{\ell\ell}^{\text{truth}}) = p_{\mu_{\text{CB}},1} + p_{\mu_{\text{CB}},2}/m_{\ell\ell}^{\text{truth}} + p_{\mu_{\text{CB}},3}/(m_{\ell\ell}^{\text{truth}})^2 + p_{\mu_{\text{CB}},4}/(m_{\ell\ell}^{\text{truth}})^3$ $+ p_{\mu_{\text{CB}},5} \cdot m_{\ell\ell}^{\text{truth}} + p_{\mu_{\text{CB}},6} \cdot (m_{\ell\ell}^{\text{truth}})^2 + p_{\mu_{\text{CB}},7} \cdot (m_{\ell\ell}^{\text{truth}})^3$	$p_{\mu_{\text{CB}},1} = -0.0891397$ $p_{\mu_{\text{CB}},2} = 10.6169$ $p_{\mu_{\text{CB}},3} = -951.712$ $p_{\mu_{\text{CB}},4} = 74775.3$ $p_{\mu_{\text{CB}},5} = 5.60192 \cdot 10^{-5}$ $p_{\mu_{\text{CB}},6} = -1.58827 \cdot 10^{-9}$ $p_{\mu_{\text{CB}},7} = -3.81706 \cdot 10^{-13}$
$\sigma_{\text{CB}}(m_{\ell\ell}^{\text{truth}}) = p_{\sigma_{\text{CB}},1} + p_{\sigma_{\text{CB}},2}/m_{\ell\ell}^{\text{truth}} + p_{\sigma_{\text{CB}},3}/(m_{\ell\ell}^{\text{truth}})^2$ $+ p_{\sigma_{\text{CB}},4} \cdot m_{\ell\ell}^{\text{truth}} + p_{\sigma_{\text{CB}},5} \cdot (m_{\ell\ell}^{\text{truth}})^2$	$p_{\sigma_{\text{CB}},1} = 0.0836349$ $p_{\sigma_{\text{CB}},2} = -8.98476$ $p_{\sigma_{\text{CB}},3} = 491.19$ $p_{\sigma_{\text{CB}},4} = 5.18068 \cdot 10^{-5}$ $p_{\sigma_{\text{CB}},5} = -3.45042 \cdot 10^{-10}$
$\alpha_{\text{CB}}(m_{\ell\ell}^{\text{truth}}) = p_{\alpha_{\text{CB}},1} + p_{\alpha_{\text{CB}},2}/m_{\ell\ell}^{\text{truth}} + p_{\alpha_{\text{CB}},3}/(m_{\ell\ell}^{\text{truth}})^2$ $+ p_{\alpha_{\text{CB}},4}/(m_{\ell\ell}^{\text{truth}})^3 + p_{\alpha_{\text{CB}},5} \cdot m_{\ell\ell}^{\text{truth}}$	$p_{\alpha_{\text{CB}},1} = 0.512577$ $p_{\alpha_{\text{CB}},2} = 252.922$ $p_{\alpha_{\text{CB}},3} = -79337.4$ $p_{\alpha_{\text{CB}},4} = 7.31863 \cdot 10^6$ $p_{\alpha_{\text{CB}},5} = 0.000237883$
$n_{\text{CB}}(m_{\ell\ell}^{\text{truth}}) = p_{n_{\text{CB}},1}$	$p_{n_{\text{CB}},1} = 6.08818$
$\mu_{\text{G}}(m_{\ell\ell}^{\text{truth}}) = p_{\mu_{\text{G}},1} + p_{\mu_{\text{G}},2} \cdot m_{\ell\ell}^{\text{truth}} + p_{\mu_{\text{G}},3} \cdot (m_{\ell\ell}^{\text{truth}})^2$ $+ p_{\mu_{\text{G}},4} \cdot (m_{\ell\ell}^{\text{truth}})^3 + p_{\mu_{\text{G}},5} \cdot (m_{\ell\ell}^{\text{truth}})^4$	$p_{\mu_{\text{G}},1} = -0.00410659$ $p_{\mu_{\text{G}},2} = 2.82352 \cdot 10^{-6}$ $p_{\mu_{\text{G}},3} = -6.264 \cdot 10^{-9}$ $p_{\mu_{\text{G}},4} = 1.25547 \cdot 10^{-12}$ $p_{\mu_{\text{G}},5} = -9.94431 \cdot 10^{-17}$
$\sigma_{\text{G}}(m_{\ell\ell}^{\text{truth}}) = p_{\sigma_{\text{G}},1} + p_{\sigma_{\text{G}},2}/m_{\ell\ell}^{\text{truth}} + p_{\sigma_{\text{G}},3}/(m_{\ell\ell}^{\text{truth}})^2$ $+ p_{\sigma_{\text{G}},4} \cdot m_{\ell\ell}^{\text{truth}} + p_{\sigma_{\text{G}},5} \cdot (m_{\ell\ell}^{\text{truth}})^2$	$p_{\sigma_{\text{G}},1} = 0.0214264$ $p_{\sigma_{\text{G}},2} = -0.795058$ $p_{\sigma_{\text{G}},3} = 15.4726$ $p_{\sigma_{\text{G}},4} = 3.38205 \cdot 10^{-5}$ $p_{\sigma_{\text{G}},5} = -1.64984 \cdot 10^{-9}$
$\kappa(m_{\ell\ell}^{\text{truth}}) = p_{\kappa,1} + p_{\kappa,2}/m_{\ell\ell}^{\text{truth}} + p_{\kappa,3}/(m_{\ell\ell}^{\text{truth}})^2$ $+ p_{\kappa,4} \cdot m_{\ell\ell}^{\text{truth}} + p_{\kappa,5} \cdot (m_{\ell\ell}^{\text{truth}})^2$	$p_{\kappa,1} = 0.235477$ $p_{\kappa,2} = -31.2227$ $p_{\kappa,3} = 3447.34$ $p_{\kappa,4} = 4.54408 \cdot 10^{-5}$ $p_{\kappa,5} = -3.25374 \cdot 10^{-9}$

C.2 Parametrisation of the acceptance times efficiency

The parametrisation of the acceptance times efficiency curves is given in Equations C.1 and C.2 for the ee and $\mu\mu$ channels, respectively:

$$\begin{aligned}
 A\epsilon_{ee}(m_{\ell\ell}^{\text{truth}}) &= p_{A\epsilon,1} + p_{A\epsilon,2}/m_{\ell\ell}^{\text{truth}} + p_{A\epsilon,3}/(m_{\ell\ell}^{\text{truth}})^2 + p_{A\epsilon,4}/(m_{\ell\ell}^{\text{truth}})^3 + p_{A\epsilon,5}/(m_{\ell\ell}^{\text{truth}})^4 \\
 &\quad + p_{A\epsilon,6}/(m_{\ell\ell}^{\text{truth}})^5 + p_{A\epsilon,7} \cdot m_{\ell\ell}^{\text{truth}} + p_{A\epsilon,8} \cdot (m_{\ell\ell}^{\text{truth}})^2 \\
 p_{A\epsilon,1} &= 0.79336 \\
 p_{A\epsilon,2} &= -234.118 \\
 p_{A\epsilon,3} &= 61575.1 \\
 p_{A\epsilon,4} &= -1.046 \cdot 10^7 \\
 p_{A\epsilon,5} &= 9.63491 \cdot 10^8 \\
 p_{A\epsilon,6} &= -3.67989 \cdot 10^{10} \\
 p_{A\epsilon,7} &= -9.10565 \cdot 10^{-6} \\
 p_{A\epsilon,8} &= 4.221 \cdot 10^{-10},
 \end{aligned} \tag{C.1}$$

$$\begin{aligned}
 A\epsilon_{\mu\mu}(m_{\ell\ell}^{\text{truth}}) &= p_{A\epsilon,1} + p_{A\epsilon,2}/m_{\ell\ell}^{\text{truth}} + p_{A\epsilon,3}/(m_{\ell\ell}^{\text{truth}})^2 + p_{A\epsilon,4}/(m_{\ell\ell}^{\text{truth}})^3 + p_{A\epsilon,5}/(m_{\ell\ell}^{\text{truth}})^4 \\
 &\quad + p_{A\epsilon,6}/(m_{\ell\ell}^{\text{truth}})^5 + p_{A\epsilon,7} \cdot m_{\ell\ell}^{\text{truth}} + p_{A\epsilon,8} \cdot (m_{\ell\ell}^{\text{truth}})^2 \\
 p_{A\epsilon,1} &= 0.511039 \\
 p_{A\epsilon,2} &= -76.9574 \\
 p_{A\epsilon,3} &= 8309.76 \\
 p_{A\epsilon,4} &= 63073.7 \\
 p_{A\epsilon,5} &= -1.06868 \cdot 10^8 \\
 p_{A\epsilon,6} &= 6.55554 \cdot 10^9 \\
 p_{A\epsilon,7} &= -1.44231 \cdot 10^{-5} \\
 p_{A\epsilon,8} &= -1.0696 \cdot 10^{-9}.
 \end{aligned} \tag{C.2}$$

C.3 Parametrisation of the efficiency

The parametrisation of the efficiency curves is given in Equations C.3 and C.4 for the ee and $\mu\mu$ channels, respectively:

$$\begin{aligned}
 \varepsilon_{ee}(m_{\ell\ell}^{\text{truth}}) &= p_{\varepsilon,1} + p_{\varepsilon,2}/m_{\ell\ell}^{\text{truth}} + p_{\varepsilon,3}/(m_{\ell\ell}^{\text{truth}})^2 + p_{\varepsilon,4}/(m_{\ell\ell}^{\text{truth}})^3 + p_{\varepsilon,5}/(m_{\ell\ell}^{\text{truth}})^4 \\
 &\quad + p_{\varepsilon,6}/(m_{\ell\ell}^{\text{truth}})^5 + p_{\varepsilon,7} \cdot m_{\ell\ell}^{\text{truth}} \\
 p_{\varepsilon,1} &= 0.771977 \\
 p_{\varepsilon,2} &= -89.1917 \\
 p_{\varepsilon,3} &= 39964.9 \\
 p_{\varepsilon,4} &= -1.04391 \cdot 10^7 \\
 p_{\varepsilon,5} &= 1.27128 \cdot 10^9 \\
 p_{\varepsilon,6} &= -5.81548 \cdot 10^{10} \\
 p_{\varepsilon,7} &= -2.79691 \cdot 10^{-6},
 \end{aligned} \tag{C.3}$$

$$\begin{aligned}
 \varepsilon_{\mu\mu}(m_{\ell\ell}^{\text{truth}}) &= p_{\varepsilon,1} + p_{\varepsilon,2} \cdot m_{\ell\ell}^{\text{truth}} + p_{\varepsilon,3} \cdot (m_{\ell\ell}^{\text{truth}})^2 + p_{\varepsilon,4} \cdot (m_{\ell\ell}^{\text{truth}})^3 + p_{\varepsilon,5}/m_{\ell\ell}^{\text{truth}} \\
 &\quad + p_{\varepsilon,6}/(m_{\ell\ell}^{\text{truth}})^2 + p_{\varepsilon,7}/(m_{\ell\ell}^{\text{truth}})^3 \\
 p_{\varepsilon,1} &= 0.507108 \\
 p_{\varepsilon,2} &= -2.65444 \cdot 10^{-5} \\
 p_{\varepsilon,3} &= 4.36865 \cdot 10^{-9} \\
 p_{\varepsilon,4} &= -6.03179 \cdot 10^{-13} \\
 p_{\varepsilon,5} &= 22.3689 \\
 p_{\varepsilon,6} &= -4284.12 \\
 p_{\varepsilon,7} &= 242608.
 \end{aligned} \tag{C.4}$$

C.4 Additional figures for global fit cross-checks

C.4.1 Injection tests

Figures C.1 to C.6 show additional injection tests at different values of m_X . The main description is given in Subsection 6.8.8.

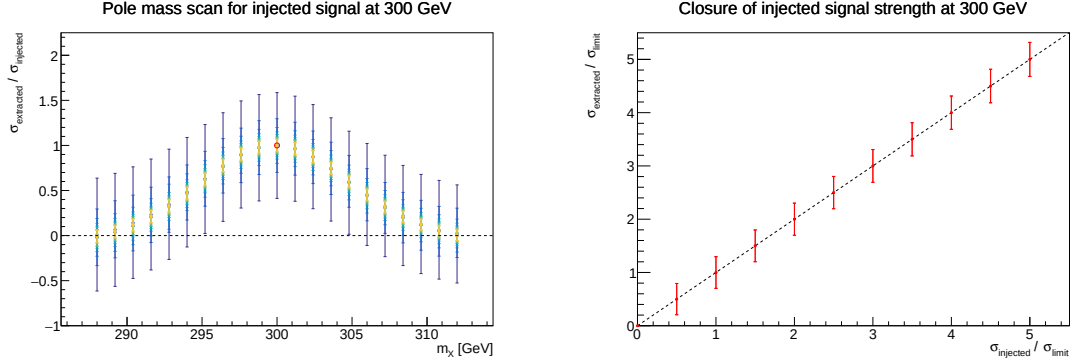


Figure C.1: Example for injection tests at a pole mass of 300 GeV in the ee channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_X = 300$ GeV, while for other masses only a smaller response should be present. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectations are matched well in both cases.

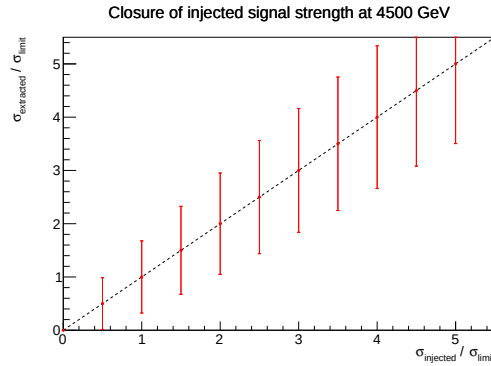


Figure C.2: Example for injection tests at a pole mass of 4500 GeV in the ee channel. The figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectation is matched well.

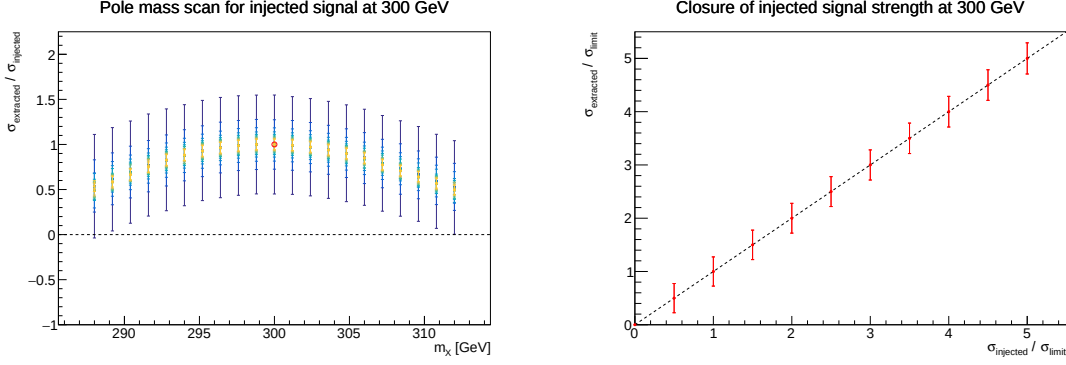


Figure C.3: Example for injection tests at a pole mass of 300 GeV in the $\mu\mu$ channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_\chi = 300$ GeV, while for other masses only a smaller response should be present. A wider response is visible in the $\mu\mu$ channel compared to the ee channel due to the worse mass resolution. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectations are matched well in both cases.

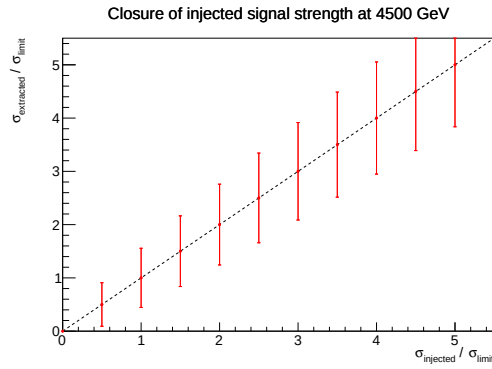


Figure C.4: Example for injection tests at a pole mass of 4500 GeV in the $\mu\mu$ channel. The figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectation is matched well.

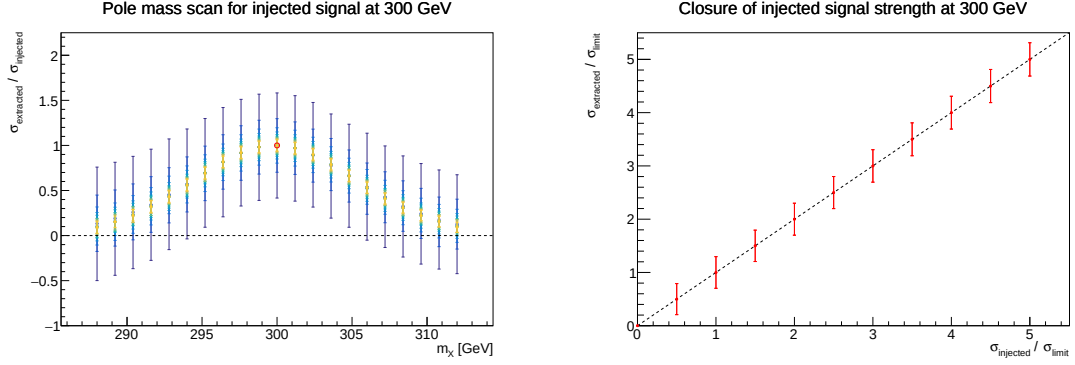


Figure C.5: Example for injection tests at a pole mass of 300 GeV in the $\ell\ell$ channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_\chi = 300$ GeV, while for other masses only a smaller response should be present. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectations are matched well in both cases.

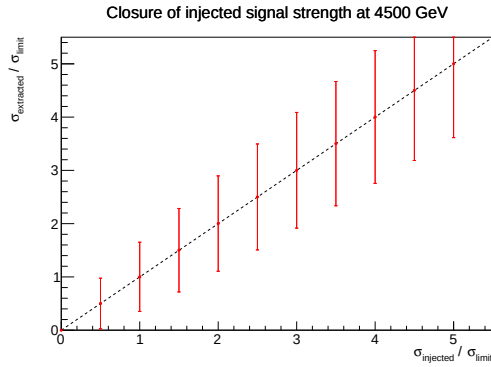


Figure C.6: Example for injection tests at a pole mass of 4500 GeV in the $\ell\ell$ channel. The figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectation is matched well.

C.4.2 Toy-based limits

In addition to the distributions of the calculated upper limits shown in Figure 6.50 of Subsection 6.8.8, Figures C.7 and C.8 give the distributions for the remaining pole masses. A summary of the results is given in Table 6.4.

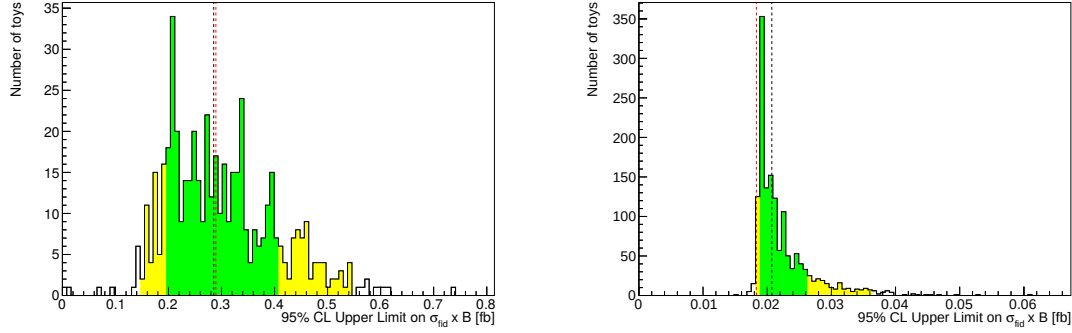


Figure C.7: Expected limit distribution for about 500 and 1500 toy experiments in the $\ell\ell$ channel for $m_X = 1$ TeV (left) and 4 TeV (right), respectively. The dashed red line shows the result based on the asymptotic assumption, while the dashed black line gives the results based on toys (i.e. the median value of the obtained distribution).

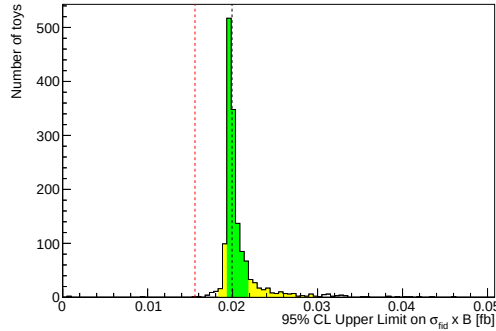


Figure C.8: Expected limit distribution for about 1500 toy experiments in the $\ell\ell$ channel for $m_X = 5$ TeV. The dashed red line shows the result based on the asymptotic assumption, while the dashed black line gives the results based on toys (i.e. the median value of the obtained distribution).

A comparison of the expected limit uncertainty bands is given in Figure C.9 for results based on the asymptotic assumption and for toy-based results. The uncertainty bands based on the asymptotic assumption above around $m_X \simeq 2$ TeV are considerably wider than the ones retrieved with toy-based results and thus considered to be invalid.

C.4.3 Ranking plots for systematic uncertainties

The ranking of systematic uncertainties is given in Subsection 6.8.8 for the $\ell\ell$ channel with $m_X = 300$ GeV and 5 TeV at $\Gamma_X/m_X = 0\%$ and 10%. Figures C.10 to C.14 give the ranking of systematic uncertainties for additional pole masses and in the ee and $\mu\mu$ channels separately.

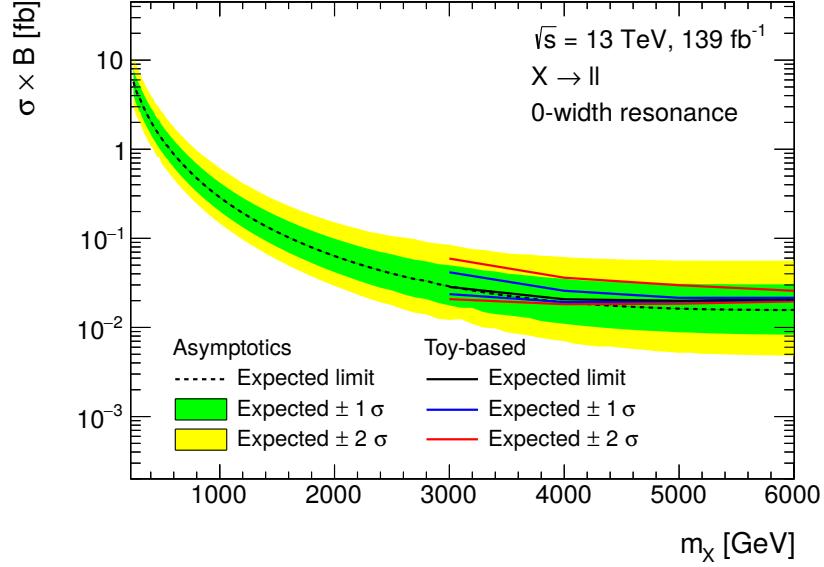


Figure C.9: Comparison of the expected limit uncertainty bands for results based on the asymptotic assumption and for toy-based results. The uncertainty bands based on the asymptotic assumption above around $m_X \simeq 2$ TeV are considerably wider than the ones retrieved with toy-based results and thus considered to be invalid. The shown expected limit curves are not calculated inside the fiducial volume.

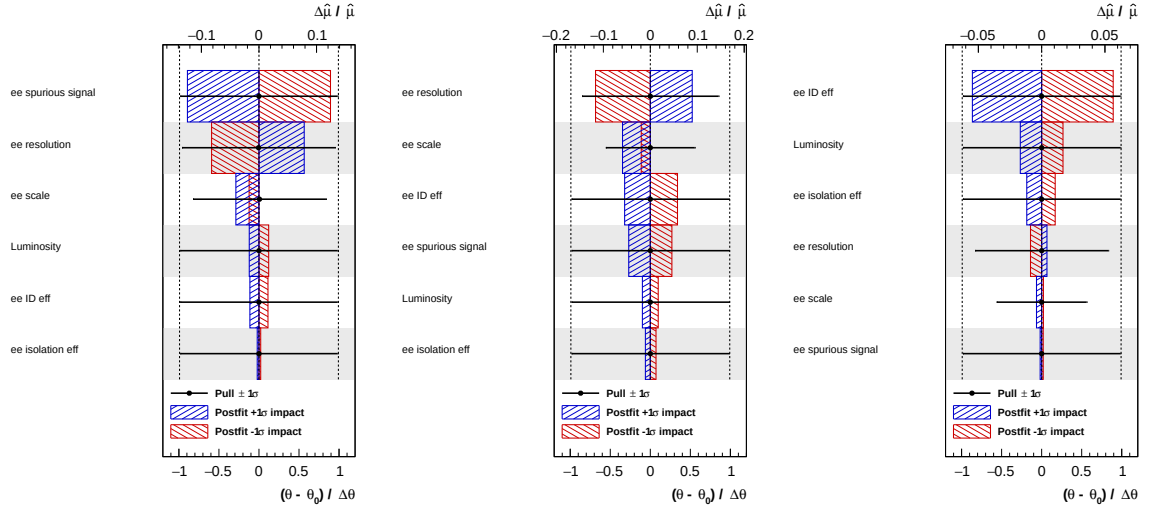


Figure C.10: Ranking plot for the considered systematic uncertainties in the ee channel at $\Gamma/m = 0\%$. The impact is shown for $m_X = 300$ GeV (left), 2 TeV (middle) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.

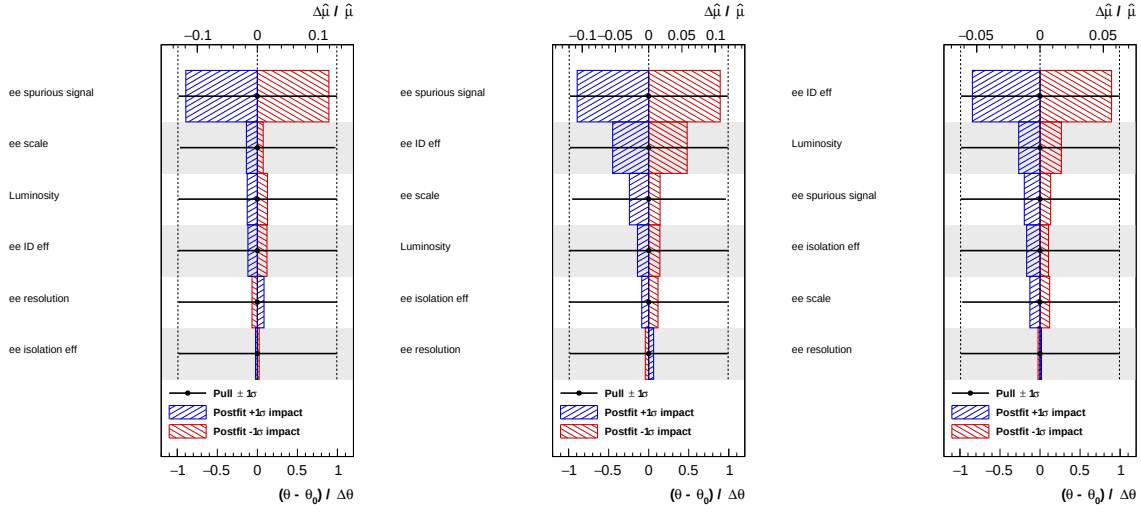


Figure C.11: Ranking plot for the considered systematic uncertainties in the ee channel at $\Gamma/m = 10\%$. The impact is shown for $m_\chi = 300$ GeV (left), 2 TeV (middle) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.

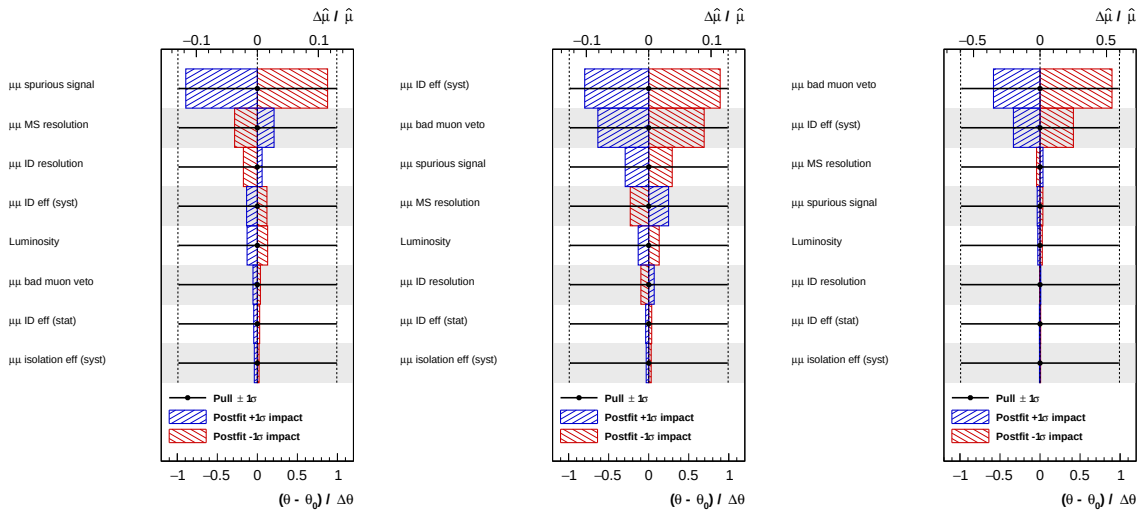


Figure C.12: Ranking plot for the considered systematic uncertainties in the $\mu\mu$ channel at $\Gamma/m = 0\%$. The impact is shown for $m_\chi = 300$ GeV (left), 2 TeV (middle) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.

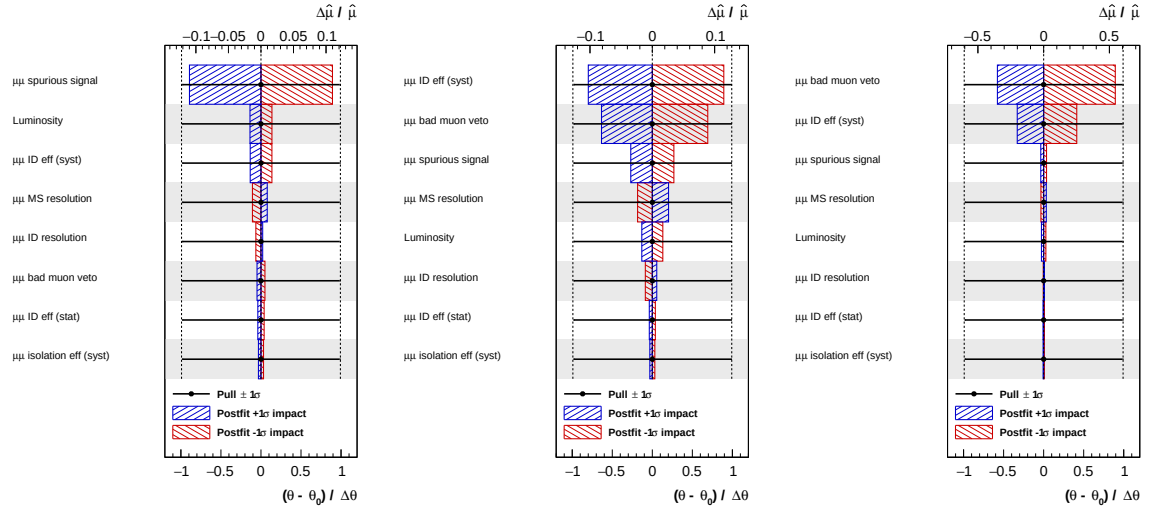


Figure C.13: Ranking plot for the considered systematic uncertainties in the $\mu\mu$ channel at $\Gamma/m = 10\%$. The impact is shown for $m_X = 300$ GeV (left), 2 TeV (middle) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.

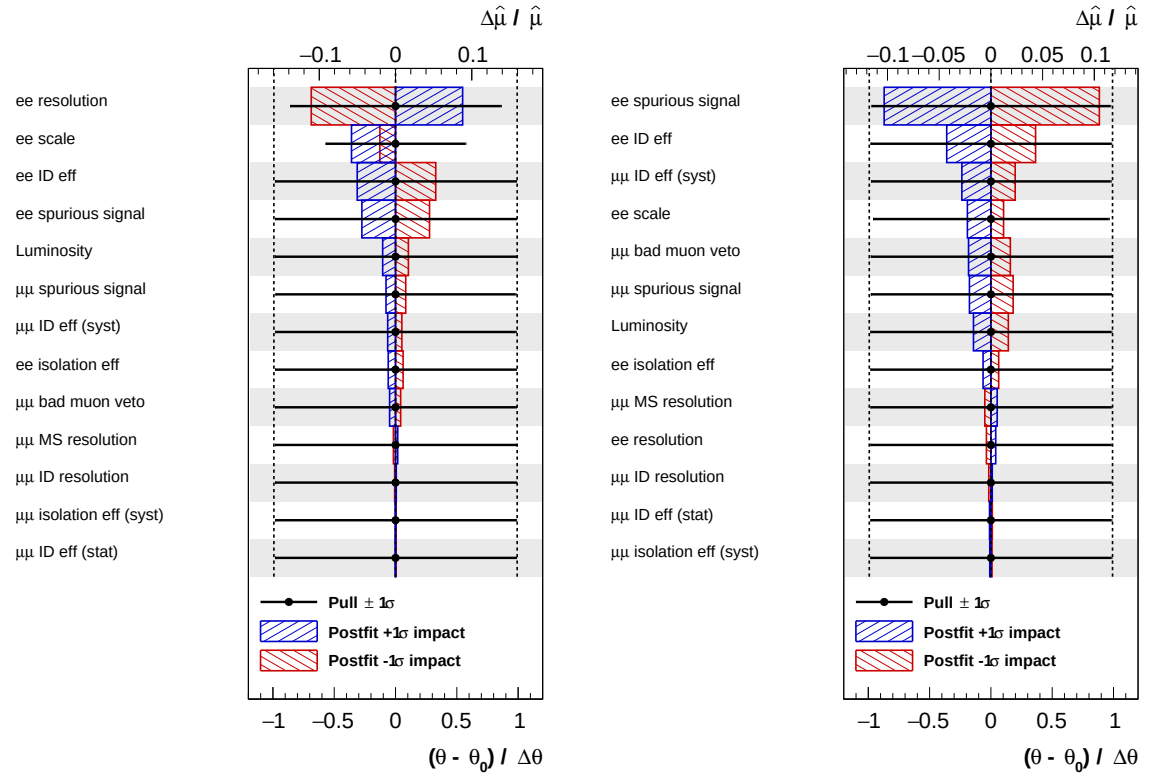


Figure C.14: Ranking plot for the considered systematic uncertainties in the $\ell\ell$ channel at $\Gamma/m = 0\%$ (left) and $\Gamma/m = 10\%$ (right). The impact is shown for $m_X = 2$ TeV in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.

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List of Figures

2.1	Total particle content of the SM together with their main properties. The graviton is the hypothetical force carrier of gravity, but so far not observed nor described within the SM. Figure from Ref. [27].	9
2.2	Overview of production cross-section measurements from the ATLAS collaboration. No significant deviation from the SM is observed. Figure from Ref. [40].	11
2.3	Branching ratios into different final states for the Z'_{HVT} at special coupling points. Figures from Ref. [56].	13
2.4	Feynman diagrams of typical production mechanisms for new heavy spin-1 (top left and top right), spin-0 (bottom left) and spin-2 (top left and bottom right) resonances.	14
2.5	Overview of processes to be considered in pp interactions. The red colour denotes the hard parton scattering, in this case an incoming gluon and a quark scattering off each other. The blue part shows initial and final state radiation, which is mainly created due to the strong interaction. Hadronisation processes, generating mesons and baryons out of the coloured quarks and gluons, are shown in green. The created hadrons eventually decay after their production. The incoming protons are shown in black. Yellow depicts the proton remnants after the interaction and secondary interactions. Figure adapted from Ref. [73].	16
3.1	Overview of the CERN accelerator complex in 2018, including the LHC and its pre-accelerators. The four main LHC experiments are depicted, too. Figure from Ref. [75].	18
3.2	Computer generated overview image of the ATLAS detector. Figure from Ref. [78]. . .	20
3.3	Computer generated image of the ATLAS Inner Detector. The image does not contain the Insertable B -Layer (IBL), which has been inserted in 2014. Figure from Ref. [79]. .	20
3.4	Computer generated image of the different ATLAS calorimeters. Figure from Ref. [81].	22
3.5	Layer structure of the LAr electromagnetic barrel calorimeter. The innermost presampler layer is used to correct for the energy lost in front of the calorimeter. The front (layer 1), middle (layer 2) and back (layer 3) layers are then used to precisely measure the electromagnetic showers. Figure from Ref. [82].	23
3.6	Computer generated image of the ATLAS muon subsystem. Figure from Ref. [85]. . .	24
3.7	Delivered and collected integrated luminosity throughout the full Run 2 data-taking campaign (left) and distribution of pile-up conditions per year (right). Figures from Ref. [98].	27
3.8	Operation plan for the LHC Run 3 and HL-LHC periods. Figure from Ref. [100]. . . .	27
4.1	Interior structure of the LAr EM barrel with alternating layers of absorber and active material (left) and expected pulse shape in physics data before and after the shaping of the signal (right). Figures from Refs. [108] (left) and [76] (right).	30

4.2	Read-out schema of the LAr detector. The pulses are measured on the electrodes within the cryostat and then first analysed within the on-detector front-end electronics. Digitised signals are then transmitted to the off-detector electronics, situated in the counting room USA15. Figure from Ref. [82].	31
4.3	Sketch of the development of an electromagnetic cascade as a function of t (left) and shower development in terms of the deposited energy per length (right). Figures from Refs. [116] (left) and [113] (right).	34
5.1	Distribution of supercells within the previous trigger towers for the LAr barrel region. After the Phase-1 upgrade, 10 supercells per trigger tower are read out for trigger purposes. The new read-out has a finer granularity and allows to utilise the longitudinal shower development. Figure from Ref. [117].	38
5.2	Simulated measurements of an electron shower with a transverse energy of 70 GeV based on trigger towers (left) and supercells (right). The supercell read-out exhibits a much higher granularity. Figures from Ref. [117].	38
5.3	Block diagram of the LAr read-out electronics after the LAr Phase-1 upgrade. New components are marked by red outlines, text and arrows. The Front-End boards will be extended by new layer sum boards. The signals are transferred by the new baseplanes to the LAr Trigger Digitizer Boards, which send the signals to the legacy trigger read-out and additionally digitise the analogue pulses. The digitised signals are transferred to the LAr Digital Processing System in the off-detector system and their output further processed in the Feature Extractors. Figure from Ref. [117].	40
5.4	Expected performance gains due to the LAr Phase-1 upgrade. The energy resolution at trigger level in comparison with offline reconstruction (left) is expected to improve considerably for electron candidates. The L1 trigger rates (right) can be considerably reduced for a constant trigger threshold due to the usage of shower shape variables (see Equations 5.10 to 5.12 for the definition of R_η , $w_{\eta,2}$ and f_3). Figures from Ref. [117].	40
5.5	Structure of the calibration lines in the LAr barrel region for a window of $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$. Cells of the same layer with the same number are connected to the same calibration line and each layer can be pulsed independently. The pattern is mirrored in the ϕ direction for the full LAr barrel, while in the η direction different calibration lines are available within the same scheme. Figure from Ref. [110].	42
5.6	Raw data from a pedestal (left), delay (middle) and ramp (right) run for a selected supercell. The numbers of occurrences for a certain ADC count bin is shown by the color scheme.	43
5.7	Overview of the full calibration chain and dependencies between the different steps. The boxes with a thick black dashed line indicate the final calibration coefficients needed to reconstruct physics data.	44
5.8	Pedestal distribution in ADC counts for the demonstrator system (left) and RMS value of its fluctuations (right). The average pedestal is different for the two LTDBs, resulting in the two separate regions centred around ADC values of 930 for the BNL LTDB and 1025 for the French LTDB. The η -dependence of the pedestal and its RMS is available in Figures B.2 and B.3 of Appendix B, respectively, and explains the multi-peak structure of the distributions.	44

5.9	Example of the noise autocorrelation for presampler (left) and back layer (right) supercells obtained from calibration data. A positive correlation is observed for neighbouring measurements, while a negative correlation is present for intermediate time differences. No significant correlation is observed for measurements with a distance above 5 BCs. The noise autocorrelation is symmetric in time [109].	45
5.10	Measured pulse shapes for selected supercells from each layer of the LAr calorimeter. The pulse height is different due to the supercell gains, which vary for the different calorimeter layers and within the layers. The pedestal level is subtracted and the alignment of the pulse peak positions is sufficient for calibration purposes.	45
5.11	Overall pulse height distribution in delay runs, given in ADC counts by the color scheme. Typically pulse heights of 1500 – 2000 ADC counts above the pedestal can be reached, while the minimum pulse height is around 800 ADC counts. The two LTDBs show different distributions due to the different pulsing patterns and different intrinsic gains. It is validated that all supercells do not reach the saturation region.	46
5.12	Example of optimal filtering coefficients for the amplitude reconstruction (left) and A_T reconstruction (right) used for the reconstruction of calibration data. The pulse maximum for this set of calibration data is at sample 3, such that for this sample the highest OFC a_i weight is given and the OFC b_i weight is close to 0.	47
5.13	Example of ramp run pulse shapes (left column) and the obtained DAC to ADC relation (right column) in the presampler (top) as well as the front (middle) and middle (bottom) layers. A linear fit is performed to the data and the obtained slope used as the gain factor. The presampler does not show significant saturation effects, while the front layer pulse shape reaches the maximum ADC count of 4096 and thus saturates. The middle layer pulse shape exhibits significant saturation effects even before reaching the maximum ADC count and its negative lobe is clearly deformed.	48
5.14	Measured gain values for the different ϕ -layers of the demonstrator system, given in units of DAC value per ADC count by the color scheme. The two LTDBs behave differently due to the different gain choices during their construction and a generally smooth behaviour within the layers can be observed. The gain dependencies on the detector layer and η position of the supercells are accounted for by measuring the calibration data with three distinct calibration patterns.	49
5.15	Linearity of the measured ADC to DAC relation for selected supercells in the presampler (top left) as well as the front (top right) and middle (bottom) layers.	50
5.16	Basic equivalent circuit of the LAr detector readout cell (left) and simplified calibration board pulser circuit (right), showing the non-ideal nature of the inductance L_c in its resistive component r_c . Both figures are taken from Ref. [119].	51
5.17	Comparison of the calibration pulse shape and the predicted physics pulse shape in the front (left) and middle (right) layers.	52
5.18	Distribution of amplitude ratios separated by the calorimeter layer. The amplitude difference in the front and back layers as well as the presampler is typically about 0 – 2%. The middle layer corrections are higher, with a mean difference of about 5% and values ranging up to 8% inside the demonstrator coverage. The η -dependence of the amplitude ratio is available in Figure B.4 of Appendix B and gives further details on the structure of the distributions.	52

5.19	Example of optimal filtering coefficients for the amplitude reconstruction (left) and A_T reconstruction (right) used for the reconstruction of physics data. The pulse maximum for physics data reconstruction has been aligned to be at sample 2 (compare Figure 5.12 for the timing alignment in calibration data), such that for this sample the highest OFC a_i weight is given and the OFC b_i weight is close to 0.	53
5.20	Distribution of pulse timing values before and after the correction of the timing offset for selected supercells in the front (left) and middle (right) layers. The distributions after the correction are aligned with a mean offset of 0 ns and overall show a more smooth behaviour due to the proper timing reference.	54
5.21	Overview of pulse timing properties before and after the correction of the timing offset in terms of the mean (left) and RMS (right) values for the full demonstrator system. RMS values above 7 ns emerge from supercells with initial timing offsets close to ± 12.5 ns (see middle layer example of Figure 5.20) and are considerably reduced by the timing correction.	54
5.22	Effect of a misalignment of the timing reference on the reconstructed pulse amplitude (left), amplitude $\times$ timing (middle) and timing (right). The pulse amplitude is underestimated by about 4 % for a timing offset of 10 ns, directly corresponding to a wrong energy determination of the same size. The measured timing value starts to deviate from a one-to-one relation (red dashed line) with the misalignment at offsets of about 5 ns, such that outside of this linear region only an imprecise timing determination is possible.	55
5.23	Conversion factors between the pulse height and energies for each supercell.	56
5.24	Difference of energy measurements, $E_{\text{demon}} - E_{\text{main}}$, between the main and demonstrator read-outs for selected supercells from the four layers of the calorimeter.	58
5.25	Relative energy deviation between the demonstrator and main read-outs for selected supercells from the four layers of the calorimeter. Good agreement is observed between the two read-outs. The mean value is depicted by the black dashed line.	59
5.26	Energy scale for the demonstrator supercells of the BNL LTDB, calculated as the mean value of the relative energy deviation, $\mathcal{R} = E_{\text{demon}}/E_{\text{main}}$	59
5.27	Energy scale for the demonstrator supercells of the French LTDB, calculated as the mean value of the relative energy deviation, $\mathcal{R} = E_{\text{demon}}/E_{\text{main}}$	60
5.28	RMS value of the relative energy deviation, $\mathcal{R} = E_{\text{demon}}/E_{\text{main}}$, for all demonstrator supercells. The RMS value illustrates the size of the energy measurement fluctuations between the two read-outs.	60
5.29	Measured supercell timing distribution of the LAr Phase-1 demonstrator compared to the TTC reference for selected supercells. The identification of the bunch-crossing ID is possible due to the low deviation of the mean from 0 ns and an RMS value much smaller than 25 ns. The average supercell energy of the used events is 6.7 GeV in the presampler, 13.3 GeV in the front layer, 24.2 GeV in the middle layer and 8.9 GeV in the back layer. The mean value is depicted by the black dashed line.	61
5.30	Mean timing for all demonstrator supercells. The identification of the bunch-crossing ID is possible due to the low deviation of the mean from 0 ns and an RMS value much smaller than 25 ns.	62
5.31	Timing resolution for all demonstrator supercells. The identification of the bunch-crossing ID is possible due to the low deviation of the mean from 0 ns and an RMS value much smaller than 25 ns.	63

5.32	Measured energy comparison for selected supercells from the four calorimeter layers. The available events are subdivided into 15 energy-bins and the width of the relative energy deviations shown for each bin.	64
5.33	Measured timing resolution for selected supercells from the four layers of the calorimeter. The available events are subdivided into 15 energy-bins and the width of the timing distribution shown for each bin. The timing resolution is around 0.5 ns in the high-energy tail, such that the identification of the bunch-crossing ID is possible due to the resolution being much smaller than 25 ns. The LHC beam-spread of about 0.2 ns contributes to the constant term, p_1 , of the timing resolution measurement [124]. The fit result for the middle layer is $p_0 = 7.24 \text{ GeV} \cdot \text{ns}$ and $p_1 = 0.425 \text{ ns}$ with $\chi^2/\text{ndf} = 2.50$	65
5.34	Measured pulse shapes (red) of supercells in the LAr Phase-1 demonstrator are compared to the, independently obtained, predicted pulse shapes (black). Good agreement is observed between measurement and prediction, while remaining small normalisation offsets are due to the preliminary calibration of the supercells. Only the five measurements around the peak (dashed line) are used for the energy and timing reconstruction. The shape difference at $t \approx 1000 \text{ ns}$ is expected to originate from the modelling of the electrode position in the LAr gap.	67
5.35	Event displays of the demonstrator region with information from the demonstrator read-out (left row) and main read-out (right row). The particles enter the shower volume on the bottom left and traverse to the top right. The different colors depict the four calorimeter layers and the full geometrical coverage of the demonstrator system is shown. The volume of the depicted boxes is proportional to the deposited energy. Only energy deposits above 1% of $E_{\text{max}}^{\text{SC}}$ are plotted.	69
5.36	Comparison of variables that describe general event and shower properties in the main and demonstrator read-outs.	70
5.37	Energy comparison and timing distribution of showers in the demonstrator region. A good agreement for the energy measurement can be observed. The timing resolution for the full shower improves compared to single supercells. The small misalignment of the timing scale for single supercells is due to residual energy dependencies (compare Subsection 5.5.5).	70
5.38	Comparison of the modelling for shower shape variables in the demonstrator and the main read-out. The shown variables are defined according to Equations 5.10 to 5.12. A good agreement between the two read-outs is observed. The variables could be used to discriminate electromagnetic clusters from electrons and photons against jets on trigger level, such that a good modelling is required for them.	71
5.39	Energy dependence of the residual mean energy deviations between the demonstrator system and the main read-out for selected supercells. The fitted function corresponds to Equation 5.13 and is an ad-hoc parametrisation of the difference. Figures for the presampler and the front layer are given in Figure B.13 of Appendix B.5.1.	72
5.40	Corrected residual energy dependence of the mean energy deviation between the demonstrator system and the main read-out for selected supercells. The correction is performed according to Equation 5.14 and the parameters given in Figure 5.39. Figures for the presampler and the front layer are given in Figure B.14 of Appendix B.5.1.	73
5.41	Residual energy dependence of the mean timing information for selected supercells. The fitted function corresponds to Equation 5.15 and is an ad-hoc parametrisation of the difference. Figures for the presampler and the front layer are given in Figure B.15 of Appendix B.5.1.	73

5.42	Corrected residual energy dependence of the mean timing information for selected supercells. The correction is performed according to Equation 5.16 and the parameters given in Figure 5.41. Figures for the presampler and the front layer are given in Figure B.16 of Appendix B.5.1.	74
5.43	Energy and timing distribution of showers in the demonstrator region after the application of the correction described in Subsection 5.5.5. An improved agreement for the energy and timing measurements can be observed.	75
5.44	Distribution of electron (left) and jet (right) candidates from offline reconstruction with $p_T > 10$ GeV inside the LAr barrel for events that were selected by the demonstrator trigger type. A clear enhancement of the density inside the demonstrator region is visible.	76
5.45	Number of electron candidates from offline reconstruction with $p_T > 10$ GeV passing loose identification criteria for the triggers used to select electro-magnetic showers in 2017 (black) and 2018 (red). The left figure shows the full LAr barrel, while the right figure depicts the number of candidates inside the demonstrator coverage. An increase of the event fraction with a loose electron inside the demonstrator region by a factor of 5 can be observed.	76
5.46	Distribution of loose electrons from offline reconstruction for events with exactly two loose electrons with $p_T > 10$ GeV (left) and invariant mass distribution of these electrons (right). A peak in the mass distribution at the Z boson mass is visible. The higher electron density at $\phi \simeq -1.2$ is expected to originate from back-to-back production with the electrons inside the demonstrator region, e.g. due to $Z \rightarrow ee$ production. The figure gives the overall distribution from all demonstrator triggers, but is dominated by the 2018 trigger.	77
6.1	Analysis model of the full Run 2 dilepton search.	79
6.2	Distributions of reconstructed dielectron (left) and dimuon (right) invariant mass after selection, for data and the SM background estimates as well as their ratio. The data points are shown together with their statistical uncertainty. Selected Z'_χ signals with a pole mass of 2, 3, 4 and 5 TeV are overlaid. In the lower panel, the shaded band corresponds to the MC statistical uncertainty, dashed lines correspond to $\pm 30\%$ and red arrows indicate data points that are outside the displayed range.	84
6.3	Sketch of the basic principle behind the transfer function (TF) method and its application. The procedure is based on fullsim MC to derive the transfer functions and the acceptance times efficiency curve, while large-scale truth-only MC samples are used to have a smooth underlying distribution. No information from data is used.	85
6.4	Example of a two-dimensional representation of $P(\mathcal{R} m_{\ell\ell}^{\text{truth}})$ in the full considered truth mass range for the ee (left) and $\mu\mu$ (right) channels. The $\mu\mu$ channel shows a considerably stronger mass dependence due to the worse muon p_T resolution in the high- p_T region.	86
6.5	$m_{\ell\ell}^{\text{truth}}$ -dependence of the TF parameters after the simultaneous fit in the ee channel. The behaviour of κ reflects the relative importance of the tails inside the parametrisation, as κ gives the fraction of the Crystal-Ball component inside the total pdf. At low $m_{\ell\ell}^{\text{truth}}$, FSR effects are expected to have a higher relative importance, as more FSR photons might not be reconstructed as part of the electrons. Due to the higher E_T , and thus a higher collimation, this effect is reduced at high $m_{\ell\ell}^{\text{truth}}$. The increase above $m_{\ell\ell}^{\text{truth}}$ values of 4 TeV might be related with detector properties like punch through effects.	88

6.6	$m_{\ell\ell}^{\text{truth}}$ -dependence of the TF parameters after the simultaneous fit in the $\mu\mu$ channel. The interplay between μ_{CB} and μ_{G} is expected to be related with the tail behaviour. While at low $m_{\ell\ell}^{\text{truth}}$ the response tails are more pronounced in the negative region (potentially due to energy losses before the MS), at high $m_{\ell\ell}^{\text{truth}}$ stronger tails are visible for positive response values (potentially due to the approximately Gaussian behaviour in the q/p measurements, which creates longer tails towards high p_{T} values). μ_{CB} and μ_{G} balance each other to describe these changes.	89
6.7	Examples of the response description after the simultaneous fit for the ee (left) and $\mu\mu$ (right) channels. Three different truth mass regions are shown and the mean truth mass is given in the legend of the figures. The red line corresponds to the functional description by the sum of a Crystal-Ball (red dashed line) and a Gaussian.	90
6.8	χ^2/ndf distributions of the response description after the simultaneous fit for the ee (left) and $\mu\mu$ (right) channels. Only the region with $m_{\ell\ell}^{\text{truth}} \geq 250 \text{ GeV}$ is later used for the signal modelling.	91
6.9	Relative dilepton invariant mass resolution for the ee and $\mu\mu$ channels as a function of $m_{\ell\ell}^{\text{truth}}$. The ee mass resolution is given by the LAr detector properties and its sampling term for high m_{ee} . The $\mu\mu$ mass resolution degrades for high $m_{\mu\mu}$ due to the low muon track curvature and thus the increasing relative error on the Sagitta measurement. . . .	91
6.10	Validation of the TF parametrisation using MC samples with a 0-width truth lineshape for the ee (left) and $\mu\mu$ (right) channels. Three different pole masses are depicted. The functional description of the transfer functions (given by the red line and its Crystal-Ball component by the red dashed line) is completely independent of the fullsim MC samples (black data points) and agrees well for the full invariant mass region.	93
6.11	Acceptance times efficiency in the ee (left) and $\mu\mu$ (right) channels. A polynomial fit (red line) is performed to the values obtained from fullsim MC (black points). The error bands are due to MC statistics and have a non-linear behaviour due to the mass-sliced DY MC samples.	94
6.12	$m_{\ell\ell}^{\text{truth}}$ -dependence and uncertainty bands of the TF parameters after the simultaneous fit in the ee channel. The shown variables are, from top left to bottom right, μ_{G} , σ_{G} , μ_{CB} , σ_{CB} , κ , α_{CB} and n_{CB} . The given uncertainty band is due to the available fullsim MC statistics and evaluated by using a bootstrapping technique.	95
6.13	$m_{\ell\ell}^{\text{truth}}$ -dependence and uncertainty bands of the TF parameters after the simultaneous fit in the $\mu\mu$ channel. The shown variables are, from top left to bottom right, μ_{G} , σ_{G} , μ_{CB} , σ_{CB} , κ , α_{CB} and n_{CB} . The given uncertainty band is due to the available fullsim MC statistics and evaluated by using a bootstrapping technique.	96
6.14	Uncertainties on the TF shape, $P(m_{\ell\ell}^{\text{reco}} m_{\ell\ell}^{\text{truth}})$, for the ee (left) and $\mu\mu$ (right) channels at $m_{\ell\ell}^{\text{truth}} = 150 \text{ GeV}$ (top row), 1 TeV (middle row) and 4 TeV (bottom row). The given uncertainty band is due to the available fullsim MC statistics and evaluated by using a bootstrapping technique. Higher uncertainties can be observed in the tails of the distribution, which have an overall low impact on the final results. The uncertainties increase towards higher pole masses due to the lower available MC statistics.	97
6.15	Uncertainties on the acceptance times efficiency parametrisation for the ee (left) and $\mu\mu$ (right) channels. The given uncertainty band is due to the available fullsim MC statistics and evaluated by using a bootstrapping technique. Higher uncertainties can be observed at the edges of the distribution, where the functional fit is less constrained.	98

6.16	Example of independently obtained spectra using TFs (black line) compared with the fullsim MC prediction (red points) in the ee (left) and $\mu\mu$ (right) channels. The $m_{\ell\ell}^{\text{truth}} \in [1.0 \text{ TeV}, 1.25 \text{ TeV}]$ mass-slice of the DY MC is split into one half, which is used for the TF determination, and a second half, which is used as the test sample. The $m_{\ell\ell}^{\text{truth}}$ distribution thus only covers the 1 – 1.25 TeV region and is smeared into a broader $m_{\ell\ell}^{\text{reco}}$ distribution due to the detector reconstruction. Good agreement between the two options is found, while the TF shape is considerably more smooth. The small deviations in the tails of the $\mu\mu$ distribution are not expected to deteriorate the agreement when smoothing the full mass distribution.	98
6.17	Final TF-smoothed templates in the Drell-Yan channel for the dielectron (left) and dimuon (right) channels, normalised to the integrated luminosity of the full Run 2 dataset. The shown uncertainties are predominantly due to the MC statistics in the fullsim samples.	98
6.18	Comparison of the response distributions in $t\bar{t} \rightarrow ee (\rightarrow \mu\mu)$ and $t\bar{t} \rightarrow e\tau (\rightarrow \mu\tau)$ events with the response of $Z/\gamma^* \rightarrow ee (\rightarrow \mu\mu)$ production used to derive the nominal TFs in the left (right) figure.	99
6.19	Inclusive response distributions in the $t\bar{t} \rightarrow ee$ (left) and $t\bar{t} \rightarrow e\tau$ (right) channels, compared to the reference distribution from DY MC samples. The relative difference between the distributions is shown in the lower part of the figures, together with a functional fit according to Equation 6.7. The small deviation in the $\mathcal{R}$ tails is not expected to deteriorate the correction.	100
6.20	Inclusive response distributions in the $t\bar{t} \rightarrow \mu\mu$ (left) and $t\bar{t} \rightarrow \mu\tau$ (right) channels, compared to the reference distribution from DY MC samples. The relative difference between the distributions is shown in the lower part of the figures, together with a functional fit according to Equation 6.7.	100
6.21	Comparison of the response distributions in $t\bar{t} \rightarrow ee$ (left) and $t\bar{t} \rightarrow e\tau$ (right) events with the response of $Z/\gamma^* \rightarrow ee$ production used to derive the nominal TFs after the correction factor is applied. Compared to Figure 6.18, a considerably improved agreement can be observed.	101
6.22	Comparison of the response distributions in $t\bar{t} \rightarrow \mu\mu$ (left) and $t\bar{t} \rightarrow \mu\tau$ (right) events with the response of $Z/\gamma^* \rightarrow \mu\mu$ production used to derive the nominal TFs after the correction factor is applied. Compared to Figure 6.18, a considerably improved agreement can be observed.	101
6.23	Acceptance times efficiency distribution in $t\bar{t} \rightarrow ee$ (left) and $t\bar{t} \rightarrow e\tau$ (right) events. The functional parametrisation is chosen to have a stable behaviour in the low statistics region for $m_{\ell\ell}^{\text{truth}} \gtrsim 1.5 \text{ TeV}$. While only few events are available to constrain the parametrisation in this mass region, the number of $t\bar{t}$ events is similarly reduced and thus not expected to affect the statistical analysis.	101
6.24	Acceptance times efficiency distribution in $t\bar{t} \rightarrow \mu\mu$ (left) and $t\bar{t} \rightarrow \mu\tau$ (right) events. The functional parametrisation is chosen to have a stable behaviour in the low statistics region for $m_{\ell\ell}^{\text{truth}} \gtrsim 1.5 \text{ TeV}$. While only few events are available to constrain the parametrisation in this mass region, the number of $t\bar{t}$ events is similarly reduced and thus not expected to affect the statistical analysis.	102
6.25	Reconstructed invariant mass distribution for the two $t\bar{t}$ decay modes with the highest contributions after ee and $e\tau$ in the dielectron channel, $\tau\tau$ (left) and $e + \text{jet}$ (right).	103
6.26	Reconstructed invariant mass distribution for the two $t\bar{t}$ decay modes with the highest contributions after $\mu\mu$ and $\mu\tau$ in the dimuon channel, $\tau\tau$ (left) and $\mu + \text{jet}$ (right).	103

6.27	Comparison of the invariant mass distribution after TF smoothing and neglecting minor $t\bar{t}$ decay channels (black line) and the complete fullsim MC template (red points) for the ee (left) and $\mu\mu$ (right) channels. Smooth templates can be obtained until $m_{\ell\ell} \simeq 2$ TeV. For higher invariant masses, the templates exhibit non-smooth features (especially in the ee channel) due to the available MC statistics on truth- and reconstruction-level, which is not sufficient to obtain fully smooth templates even with the described smoothing procedure.	103
6.28	Example for the convolution of the TF detector response with a truth-level Breit-Wigner signal shape for the ee (left) and $\mu\mu$ (right) channels at a pole mass of 1 TeV and $\Gamma/m = 1.2\%$. The dimuon TF is considerably broader due to the worse detector resolution compared to the dielectron channel.	105
6.29	Acceptance distribution for the ee (left) and $\mu\mu$ (right) channels. A polynomial fit (red line) is performed to the values obtained from fullsim MC (black points). The error bands are due to MC statistics and have a non-linear behaviour due to the mass-sliced NLO DY samples.	105
6.30	Efficiency distribution for the ee (left) and $\mu\mu$ (right) channels. A polynomial fit (red line) is performed to the values obtained from fullsim MC (black points). The error bands are due to MC statistics and have a non-linear behaviour due to the mass-sliced NLO DY samples.	105
6.31	Dielectron and dimuon selection efficiency as a function of the pole mass m_X for spin-0, spin-1 and spin-2 resonances. Drell-Yan MC samples are used for the spin-1 efficiencies and correspond to the zero-width signal hypothesis. Spin-0 (spin-2) efficiencies are obtained from dedicated MC samples with relative widths in the range of 0 – 20% (1 – 13%) and are averaged over all available width assumptions. Figure from Ref. [84].	106
6.32	Electron identification (left) and isolation (right) uncertainties on the signal acceptance times efficiency, i.e. its normalisation. Both uncertainties are considered for the ee channel. The different solid lines represent the changes in the acceptance times efficiency due to up- (green) and down-variations (red) from the nominal for $\Gamma_X/m_X \in [0\%, 10\%]$. The black dashed lines represent the functional description. The steps in the obtained distributions emerge from the binning of the corresponding SFs.	108
6.33	Muon identification (top left: statistical part, top right: systematic part), isolation (bottom left: systematic part) and good muon requirement (bottom right: systematic part) uncertainties on the signal acceptance times efficiency, i.e. its normalisation. All four uncertainties are considered for the $\mu\mu$ channel. The different solid lines represent the changes in the acceptance times efficiency due to up- (green) and down-variations (red) from the nominal for $\Gamma_X/m_X \in [0\%, 10\%]$. The black dashed lines represent the functional description. The statistical component of the muon isolation efficiency uncertainty is neglected, as the impact of this uncertainty is smaller than 0.2% throughout the whole mass spectrum.	109
6.34	Effect of the systematic uncertainty on the electron energy scale (upper plots) and resolution (lower plots) in terms of the variation of the μ_{CB}/σ_{CB} (left) and μ_G/σ_G (right) TF parameters. The green line corresponds to the upward-variation, the red line to the downward-variation and the black line is the sum of the two (i.e. the asymmetry).	110
6.35	Effect of the systematic uncertainty on the muon resolution from the ID (upper plots) and MS (lower plots) components in terms of the variation of the σ_{CB} (left) and σ_G (right) TF parameters. The green line corresponds to the upward-variation, the red line to the downward-variation and the black line is the sum of the two (i.e. the asymmetry).	111

6.36	Visualisation of the effect of systematic uncertainties on the response distribution (points) and the TF parametrisation (smooth line) for the ee channel. The electron energy scale (left) and resolution (right) uncertainties are shown.	111
6.37	Visualisation of the effect of systematic uncertainties on the response distribution (points) and the TF parametrisation (smooth line) for the $\mu\mu$ channel. The muon resolution uncertainties due to the ID (left) and MS (right) components are shown.	112
6.38	Background-only fit results in the ee (left) and $\mu\mu$ (right) channels using the functions given in Equations 6.20 and 6.21. The shown MC templates (black) correspond to an integrated luminosity of 140.5 fb^{-1} and are used in the optimisation procedure. No large deviations from peaking signal-like contributions or an overall mismodelling of the chosen functions are visible by eye. The uncertainty bands correspond to the expected uncertainty in data.	117
6.39	Spurious signal estimation at $\Gamma_X/m_X = 0\%$ in the ee channel. The left plot shows $N_{\text{spur}}/\sigma_{\text{bkg}}$ for a range of $m_X \in [250 \text{ GeV}, 6000 \text{ GeV}]$, while the plot on the right shows $ N_{\text{spur}} $. The dashed line corresponds to the nominal background template, while the thick solid line corresponds to the envelope of the determined spurious signal values from systematic background variations.	117
6.40	Spurious signal estimation at $\Gamma_X/m_X = 0\%$ in the $\mu\mu$ channel. The left plot shows $N_{\text{spur}}/\sigma_{\text{bkg}}$ for a range of $m_X \in [250 \text{ GeV}, 6000 \text{ GeV}]$, while the plot on the right shows $ N_{\text{spur}} $. The dashed line corresponds to the nominal background template, while the thick solid line corresponds to the envelope of the determined spurious signal values from systematic background variations.	118
6.41	Spurious signal estimations in the ee (left) and $\mu\mu$ (right) channels with the nominal function choice. Both plots show $ N_{\text{spur}} /\sigma_{\text{bkg}}$ for a range of $m_X \in [250 \text{ GeV}, 6000 \text{ GeV}]$. The different lines and colors represent different width assumptions, ranging from $\Gamma_X/m_X = 0\%$ to 10% in steps of 0.5% . $\Gamma_X/m_X = 0\%$ is shown in dark blue, which then shades off into yellow for higher width values. $\Gamma_X/m_X = 10\%$ is drawn in black.	119
6.42	Spurious signal parametrisation for the $\Gamma_X/m_X = 0\%$ case in the ee channel with a logarithmically- (left) and linearly-scaled (right) y -axis. The spurious signal values are given by the red line and correspond to the envelope of $ N_{\text{spur}} $ given in Figure 6.39, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.	119
6.43	Spurious signal parametrisation for the $\Gamma_X/m_X = 0\%$ case in the $\mu\mu$ channel with a logarithmically- (left) and linearly-scaled (right) y -axis. The spurious signal values are given by the red line and correspond to the envelope of $ N_{\text{spur}} $ given in Figure 6.40, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.	120
6.44	Spurious signal parametrisation for different width assumptions in the ee channel with a logarithmically-scaled y -axis. The spurious signal values are given by the red line, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.	121
6.45	Spurious signal parametrisation for different width assumptions in the $\mu\mu$ channel with a logarithmically-scaled y -axis. The spurious signal values are given by the red line, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.	122

- 6.46 Background-only fit results in the ee (left) and $\mu\mu$ (right) channels. The shown data corresponds to the full Run 2 dataset of 139 fb^{-1} . No large deviations from peaking signal-like contributions or an overall mismodelling of the chosen functions are visible by eye. Generic 0-width signal shapes, scaled to 20 times the value of the corresponding expected upper limit at 95% CL, are overlaid to depict the detector mass resolution in the high-mass region. 123
- 6.47 Example for injection tests at a pole mass of 1000 GeV in the ee channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_X = 1000\text{ GeV}$, while for other masses only a smaller response should be present. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets if the signal is fully retrieved back, as no statistical fluctuations are considered. The expectations are matched well in both cases. 124
- 6.48 Example for injection tests at a pole mass of 1000 GeV in the $\mu\mu$ channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_X = 1000\text{ GeV}$, while for other masses only a smaller response should be present. A wider response is visible in the $\mu\mu$ channel compared to the ee channel due to the worse mass resolution. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets if the signal is fully retrieved back, as no statistical fluctuations are considered. The expectations are matched well in both cases. 125
- 6.49 Example for injection tests at a pole mass of 1000 GeV in the $\ell\ell$ channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_X = 1000\text{ GeV}$, while for other masses only a smaller response should be present. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets if the signal is fully retrieved back, as no statistical fluctuations are considered. The expectations are matched well in both cases. 125
- 6.50 Expected limit distribution for about 1500 toy experiments in the $\ell\ell$ channel for $m_X = 3\text{ TeV}$ (left) and 6 TeV (right). The dashed red line shows the result based on the asymptotic approximation, while the dashed black line gives the results based on toys (i.e. the median value of the obtained distribution). The non-Gaussian distributions lead to the observed offset in the expected upper limit and its uncertainty with respect to the asymptotic approximation. 126
- 6.51 Ranking plot for the considered systematic uncertainties in the $\ell\ell$ channel at $\Gamma_X/m_X = 0\%$. The impact is shown for $m_X = 300\text{ GeV}$ (left) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact. 127
- 6.52 Ranking plot for the considered systematic uncertainties in the $\ell\ell$ channel at $\Gamma_X/m_X = 10\%$. The impact is shown for $m_X = 300\text{ GeV}$ (left) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact. 128

6.53	Observed 1-dimensional significance scans of deviations from the background-only hypothesis, as a function of the assumed pole mass, m_X , for signal width assumptions of $\Gamma_X/m_X = 0\%$ (left) and $\Gamma_X/m_X = 10\%$ (right) on truth-level in the ee , $\mu\mu$ and $\ell\ell$ channels.	129
6.54	Observed 1-dimensional p -value scans of deviations from the background-only hypothesis, as a function of the assumed pole mass, m_X , for signal width assumptions of $\Gamma_X/m_X = 0\%$ (left) and $\Gamma_X/m_X = 10\%$ (right) on truth-level in the ee , $\mu\mu$ and $\ell\ell$ channels.	129
6.55	Observed 2-dimensional significance scans of positive deviations from the background-only hypothesis, as a function of the assumed pole mass, m_X , and the signal width on truth-level, Γ_X/m_X , in the ee (upper left), $\mu\mu$ (upper right) and $\ell\ell$ (bottom) channels.	130
6.56	Expected and observed limits at 95% confidence level on the fiducial production cross-section times branching ratio into one fermion generation, $\sigma_{\text{fid}} \times \mathcal{B}$, as a function of the assumed pole mass, m_X , in the ee channel. Signal width assumptions of $\Gamma_X/m_X = 0\%$, 3% and 10% (left) as well as $\Gamma_X/m_X = 0.5\%$, 1.2% and 6% (right) are shown. Theoretical predictions from the Z'_ψ ($\Gamma_X/m_X = 0.5\%$), Z'_χ ($\Gamma_X/m_X = 1.2\%$) and Z'_{SSM} ($\Gamma_X/m_X = 3\%$) are overlaid where applicable.	131
6.57	Expected and observed limits at 95% confidence level on the fiducial production cross-section times branching ratio into one fermion generation, $\sigma_{\text{fid}} \times \mathcal{B}$, as a function of the assumed pole mass, m_X , in the $\mu\mu$ channel. Signal width assumptions of $\Gamma_X/m_X = 0\%$, 3% and 10% (left) as well as $\Gamma_X/m_X = 0.5\%$, 1.2% and 6% (right) are shown. Theoretical predictions from the Z'_ψ ($\Gamma_X/m_X = 0.5\%$), Z'_χ ($\Gamma_X/m_X = 1.2\%$) and Z'_{SSM} ($\Gamma_X/m_X = 3\%$) are overlaid where applicable.	132
6.58	Expected and observed limits at 95% confidence level on the fiducial production cross-section times branching ratio into one fermion generation, $\sigma_{\text{fid}} \times \mathcal{B}$, as a function of the assumed pole mass, m_X , in the $\ell\ell$ channel. Signal width assumptions of $\Gamma_X/m_X = 0\%$, 3% and 10% (left) as well as $\Gamma_X/m_X = 0.5\%$, 1.2% and 6% (right) are shown. Theoretical predictions from the Z'_ψ ($\Gamma_X/m_X = 0.5\%$), Z'_χ ($\Gamma_X/m_X = 1.2\%$) and Z'_{SSM} ($\Gamma_X/m_X = 3\%$) are overlaid where applicable.	132
6.59	Expected and observed limits at 95% confidence level on the fiducial production cross-section times branching ratio into one fermion generation, $\sigma_{\text{fid}} \times \mathcal{B}$, as a function of the assumed pole mass, m_X , in the ee (upper left), $\mu\mu$ (upper right) and $\ell\ell$ (bottom) channels. A signal width assumption of $\Gamma_X/m_X = 0\%$ is shown. The limit curves and their uncertainty bands are calculated using the asymptotic approximation.	133
6.60	Observed cross-section limits in the dilepton channel, normalised to the prediction of the Z'_{SSM} model. Various dilepton search results at $\sqrt{s} = 7, 8$ and 13 TeV are presented together with the result of the full Run 2 search. Figure from Ref. [84].	134
7.1	Combination procedure of the 12 baseline final states (green boxes and $\ell\ell/\ell\nu$ channels) into the heavy resonance decay modes (orange boxes). The interpretation is performed in the HVT model (blue box) predicting new heavy resonances with spin-1.	138
7.2	Predicted relative width, $\Gamma_{Z'}/m_{Z'}$, in percent (on the z -axis) for the HVT model at $m_{Z'} = 5$ TeV. The g_q/g_ℓ (left) and g_H/g_f (right) planes are depicted within the considered coupling regions.	141
7.3	Validation of the signal templates from reweighting (blue area) with dedicated Pythia samples (data points) on truth level. The full signal shape (left row) and the peak region (right row) is shown for assumed pole masses of 1, 3 and 5 TeV. The coupling parameters are $g_q = g_\ell = 0.1$ and $g_H = 0$.	143

7.4	Validation of the signal templates from reweighting (black solid line) with dedicated MadGraph samples (red data points) on truth level at the HVT A coupling point. A truth-level cut of $ m_{\ell\ell}^{\text{truth}} - m_{Z'} < 15 \times \Gamma_{Z'}$ is applied within MadGraph, leading to the observed differences in the low- and high-mass tails. The binning is chosen according to the ee resolution binning. The full signal shape (left row) and the peak region (right row) is shown for assumed pole masses of 1, 3 and 5 TeV.	144
7.5	Validation of the ee signal templates from reweighting (black solid line) with dedicated MadGraph samples (red data points) on reconstruction level at the HVT A coupling point. A truth-level cut of $ m_{\ell\ell}^{\text{truth}} - m_{Z'} < 15 \times \Gamma_{Z'}$ is applied within MadGraph, leading to the observed differences in the low- and high-mass tails. The full signal shape (left row) and the peak region (right row) is shown for assumed pole masses of 1, 3 and 5 TeV.	145
7.6	Validation of the $\mu\mu$ signal templates from reweighting (black solid line) with dedicated MadGraph samples (red data points) on reconstruction level at the HVT A coupling point. A truth-level cut of $ m_{\ell\ell}^{\text{truth}} - m_{Z'} < 15 \times \Gamma_{Z'}$ is applied within MadGraph, leading to the observed differences in the low- and high-mass tails. The full signal shape (left row) and the peak region (right row) is shown for assumed pole masses of 1, 3 and 5 TeV.	146
7.7	Impact of interference effects on the reconstructed line-shape in the ee channel at the HVT A coupling point and $m_{V'} = 3.5$ TeV. Figure 7.7(a) gives the difference of the signal-plus-background line-shapes for $g_q = +g_\ell$, for $g_q = -g_\ell$ and in case the interference is neglected. The relative difference can reach up to 80% in the high-mass tails of the distribution, while the signal normalisation in this region is small. The impact compared to the SM DY background is given in Figure 7.7(b). The neglect of interference effects yields purely positive signal contributions, while in case interference effects are taken into account a dip is given for invariant masses below $m_{V'}$	147
7.8	Relative difference of the signal template cross-section with and without considering interference effects within mass windows as defined in Equation 7.10. The mass windows are chosen to be constant (see Figure 7.8(a)), proportional to the pole mass (see Figure 7.8(b)) or proportional to $\sqrt{m_{Z'}}$ (see Figure 7.8(c)). The different coloured line represent pole mass from 300 GeV to 5 TeV. A stable behaviour is found for mass windows with a window size that is proportional to $\sqrt{m_{Z'}}$. The coupling parameters are $g_q = -g_\ell = -0.55$ and $g_H = 0$ for the left column, while for the right column $g_q = -0.55$, $g_\ell = 0.1$ and $g_H = 0$ is used.	148
7.9	Relative difference of the signal template cross-section with and without considering interference effects within the narrow (left) and wide (right) mass window definitions, given in percent (on the z -axis). The maximal cross-section difference is below 15% (30%) for the narrow (wide) windows.	149
7.10	Acceptance times efficiency of the W' and Z' searches for the electron and muon decay modes as a function of the pole mass $m_{V'}$. Higher values are given in the W' search as the $\ell\nu$ selection only depends on the proper reconstruction of a single lepton. The bands show the statistical uncertainty of the underlying MC samples.	149
7.11	Cross-section (given in fb on the z -axis) of $Z'_{\text{HVT}} \rightarrow \ell\ell$ production for a single fermion generation in the g_q/g_ℓ (left) and g_H/g_f (right) planes. Pole masses of $m_{Z'} = 3$ TeV (top row) and 5 TeV (bottom row) are selected for these values.	150
7.12	Variations of the signal templates due to systematic uncertainties in the ee channel. The signal is evaluated at the HVT A coupling point with $m_{Z'} = 2$ TeV.	152
7.13	Variations of the signal templates due to systematic uncertainties in the $\mu\mu$ channel. The signal is evaluated at the HVT A coupling point with $m_{Z'} = 2$ TeV.	153

7.14	Cross-section limit on the $V' \rightarrow \ell\ell + \ell\nu$ production. The theory prediction for the HVT A coupling point is overlaid.	154
7.15	Cross-section limit on the $Z' \rightarrow \ell\ell$ and $W' \rightarrow \ell\nu$ production, normalised to the prediction of the HVT model at the HVT A coupling point. The $\ell\nu$ channel provides a stronger exclusion for almost the full $m_{V'}$ space. A significant improvement due to the combination of the $\ell\ell$ and $\ell\nu$ final states is visible.	155
7.16	Local p_0 value scan in the $V' \rightarrow \ell\ell/\ell\nu$ channel as a function of the pole mass $m_{V'}$. The p_0 values are calculated every 100 GeV for $m_{V'} \in [300 \text{ GeV}, 2 \text{ TeV}]$ and are interpolated between the points. A larger step size is chosen for $m_{V'} > 2 \text{ TeV}$	155
7.17	Mass limits in the g_q/g_ℓ (left column) and g_H/g_f (right column) coupling planes at $m_{V'} = 3, 4$ and 5 TeV for the $\ell\ell/\ell\nu$ combination. The observed (top row) and expected (bottom row) limits are shown. The gray area depicts the validity limit of the combination, which is not given for $\Gamma/m > 5\%$	156
7.18	Cross-section limit on the $V' \rightarrow VV + VH$ production. The theory predictions for the HVT A and HVT B coupling points are overlaid.	157
7.19	Cross-section limit on the $V' \rightarrow VV/VH/\ell\ell/\ell\nu$ production (left) at the HVT A coupling point. The cross-section limits normalised to the prediction of the HVT model at the HVT A coupling point are given in the right figure. The $\ell\ell/\ell\nu$ channels dominate the combination as this specific coupling point.	158
7.20	Mass limits in the g_q/g_ℓ (left column) and g_H/g_f (right column) coupling planes at $m_{V'} = 3, 4$ and 5 TeV . The observed (top row) and expected (bottom row) limits are shown. The results from EW fits and the corresponding exclusion contours are given as the filled areas.	159
7.21	Comparison of the exclusion curves from the separate $\ell\ell/\ell\nu$ and VV/VH combinations and the full combination. The differences in the exclusion regions are given by the different branching ratios, which depend on the coupling values.	159
7.22	Mass limits in the g_q/g_ℓ (left column) and g_h/g_f (right column) coupling planes at $m_{Z'} = 3, 4$ and 5 TeV for the full Run 2 dilepton search. The observed (top row) and expected (bottom row) limits are shown. The HVT coupling parameter g_H is denoted by g_h in the results presented here to avoid confusion with the spin-0 MSSM Higgs boson used to validate the efficiency values in Chapter 6. Figures from Ref. [84].	160
B.1	Measured calibration pulse shape for a front layer supercell, which exhibits sinusoidal fluctuations in the negative lobe. The pedestal level is subtracted.	178
B.2	Pedestal level in ADC counts for the different ϕ regions of the demonstrator system as a function of η	179
B.3	RMS value of pedestal fluctuations in ADC counts for the different ϕ regions of the demonstrator system as a function of η	180
B.4	Distribution of amplitude ratios from the physics pulse prediction for the different ϕ regions of the demonstrator system as a function of η . The amplitude ratio in the front and back layers as well as the presampler is typically about 0 – 2%. The middle layer corrections are higher, with a mean value of about 5% and values ranging up to 8%. . .	181
B.5	RMS value of pedestal fluctuations in units of energies for the different ϕ regions of the demonstrator system as a function of η	182
B.6	Saturation energy of the demonstrator supercells for the different ϕ regions of the demonstrator system as a function of η	183

B.7	Energy fraction of specific constituent cells compared to the total energy deposit in the supercell. The different colors represent different constituent cells. A fraction of up to almost the complete deposited energy can be present for constituent cells in the presampler and the middle layer. In the front and back layers, the energy is typically distributed over several constituent cells.	185
B.8	Correlation matrix between the constituent cell with the maximum energy deposit on the x -axis and the distribution of constituent cell energies inside the supercell on the y -axis. The columns of the matrix give the composition of constituent cell energy contributions for a given constituent cell association on the x -axis. The columns are normalised to 100%.	186
B.9	Measured pulse shapes of supercells in the LAr Phase-1 demonstrator compared to the, independently obtained, predicted pulse shapes (black). The different colors represent the different associated constituent cells. Significant differences between the pulse shapes depending on the associated constituent cell are visible in the front and back layers. The values for $A_{\text{meas}}/A_{\text{pred}}$ and $t_{\text{meas}} - t_{\text{pred}}$ are given in terms of the mean value of the different constituents, the RMS value and in addition the total range for all constituent cells of a given supercell. The same procedure as for Figure 5.34 is used to obtain the pulse shapes.	187
B.10	Variation of the relative energy deviation for different associated constituent cells, which are represented by different colors. The mean values are depicted by the dashed lines. The range of mean and RMS values, as well as their spread, is given. The front layer supercell shows variations of the mean relative energy deviation, due to different associated constituent cells, in the order of the RMS value. The total accuracy of the supercell energy measurement, without constituent association, is thus slightly worsened by these variations.	188
B.11	Variation of the timing measurement distribution for different associated constituent cells, which are represented by different colors. The mean values are depicted by the dashed lines. The range of mean and RMS values, as well as their spread, is given. The back layer supercell shows variations of the mean timing offset, due to different associated constituent cells, in the order of the RMS value. The total accuracy of the supercell timing measurement, without constituent association, is thus slightly worsened by these variations.	189
B.12	Correlation of the energy measurements in the main read-out and the demonstrator system for selected supercells from the four layers of the calorimeter.	190
B.13	Residual energy dependence of the mean energy deviation between the demonstrator system and the main read-out for selected supercells. The fitted function corresponds to Equation 5.13 and is an ad-hoc parametrisation of the difference.	191
B.14	Corrected residual energy dependence of the mean energy deviation between the demonstrator system and the main read-out for selected supercells. The correction is performed according to Equation 5.14 and the parameters given in Figure B.13.	191
B.15	Residual energy dependence of the mean timing information for selected supercells. The fitted function corresponds to Equation 5.15 and is an ad-hoc parametrisation of the difference.	192
B.16	Corrected residual energy dependence of the mean timing information for selected supercells. The correction is performed according to Equation 5.16 and the parameters given in Figure B.15.	192

C.1	Example for injection tests at a pole mass of 300 GeV in the ee channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_X = 300$ GeV, while for other masses only a smaller response should be present. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectations are matched well in both cases.	198
C.2	Example for injection tests at a pole mass of 4500 GeV in the ee channel. The figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectation is matched well.	198
C.3	Example for injection tests at a pole mass of 300 GeV in the $\mu\mu$ channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_X = 300$ GeV, while for other masses only a smaller response should be present. A wider response is visible in the $\mu\mu$ channel compared to the ee channel due to the worse mass resolution. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectations are matched well in both cases.	199
C.4	Example for injection tests at a pole mass of 4500 GeV in the $\mu\mu$ channel. The figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectation is matched well.	199
C.5	Example for injection tests at a pole mass of 300 GeV in the $\ell\ell$ channel. The left figure shows the normalised extracted signal strength depending on the pole mass for several injected signal strengths (different colours). The value should be equal to one at $m_X = 300$ GeV, while for other masses only a smaller response should be present. The right figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectations are matched well in both cases.	200
C.6	Example for injection tests at a pole mass of 4500 GeV in the $\ell\ell$ channel. The figure shows the extracted signal strength depending on the injection strength close to the expected limit. A one-to-one relation should be present for Asimov datasets. The expectation is matched well.	200
C.7	Expected limit distribution for about 500 and 1500 toy experiments in the $\ell\ell$ channel for $m_X = 1$ TeV (left) and 4 TeV (right), respectively. The dashed red line shows the result based on the asymptotic assumption, while the dashed black line gives the results based on toys (i.e. the median value of the obtained distribution).	201
C.8	Expected limit distribution for about 1500 toy experiments in the $\ell\ell$ channel for $m_X = 5$ TeV. The dashed red line shows the result based on the asymptotic assumption, while the dashed black line gives the results based on toys (i.e. the median value of the obtained distribution).	201
C.9	Comparison of the expected limit uncertainty bands for results based on the asymptotic assumption and for toy-based results. The uncertainty bands based on the asymptotic assumption above around $m_X \simeq 2$ TeV are considerably wider than the ones retrieved with toy-based results and thus considered to be invalid. The shown expected limit curves are not calculated inside the fiducial volume.	202

C.10	Ranking plot for the considered systematic uncertainties in the ee channel at $\Gamma/m = 0\%$. The impact is shown for $m_\chi = 300$ GeV (left), 2 TeV (middle) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.	202
C.11	Ranking plot for the considered systematic uncertainties in the ee channel at $\Gamma/m = 10\%$. The impact is shown for $m_\chi = 300$ GeV (left), 2 TeV (middle) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.	203
C.12	Ranking plot for the considered systematic uncertainties in the $\mu\mu$ channel at $\Gamma/m = 0\%$. The impact is shown for $m_\chi = 300$ GeV (left), 2 TeV (middle) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.	203
C.13	Ranking plot for the considered systematic uncertainties in the $\mu\mu$ channel at $\Gamma/m = 10\%$. The impact is shown for $m_\chi = 300$ GeV (left), 2 TeV (middle) and 5 TeV (right) in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.	204
C.14	Ranking plot for the considered systematic uncertainties in the $\ell\ell$ channel at $\Gamma/m = 0\%$ (left) and $\Gamma/m = 10\%$ (right). The impact is shown for $m_\chi = 2$ TeV in case of an Asimov dataset where a signal injection is done with the cross-section at the expected limit. The ordering is done according to the postfit downward impact.	204

List of Tables

6.1	The event generators used for simulation of the signal and background processes. The acronyms ME and PS stand for matrix element and parton shower. The top-quark mass is set to 172.5 GeV. The $G^* \rightarrow \ell\ell$ and $H \rightarrow \ell\ell$ samples are generated with fast simulation techniques, while full simulation samples are available for a few pole masses. The “0-width” $Z' \rightarrow \ell\ell$ samples are generated with full simulation, and additionally available for fast simulation at a few pole masses. Table adapted from Ref. [84].	80
6.2	Systematic variations of signal efficiency and mass resolution parameters, as well as spurious signal and luminosity uncertainties. The systematic uncertainties are probed for masses from 250 GeV to 6 TeV resulting in ranges of values given in the table. More detailed descriptions of the considered systematic uncertainties are available in Subsections 6.8.3 (spurious signal), 6.6.1 (signal efficiency) and 6.6.2 (mass resolution parameters). The uncertainties are given according to their pre-fit size and affect the signal shape and normalisation. The spurious signal is taken into account as an additional signal-like component (compare Equations 6.24 and 6.25).	107
6.3	Parameters of the fit to data using the function of Equations 6.20 and 6.21. The normalisation of the background function is such that the integral, N_{bkg} , corresponds to the total number of background events.	124
6.4	Offset of the toy-based upper limit values compared to the asymptotic approximation for the $\ell\ell$ channel.	126
6.5	The relative impact of $\pm 1\sigma$ variations of systematic uncertainties on the signal yield in percent for zero (10%) relative width signals at the pole masses of 300 GeV and 5 TeV for dielectron and dimuon channels. A signal is injected at the cross-section limit. Table from Ref. [84].	128
6.6	Highest local and the corresponding global significance values for the 1-dimensional significance scans at a signal width assumption of $\Gamma_X/m_X = 0\%$ on truth-level. The uncertainties on the global significance are calculated according to Section 6.7.	130
6.7	Highest local and the corresponding global significance values for the 1-dimensional significance scans at a signal width assumption of $\Gamma_X/m_X = 10\%$ on truth-level. The uncertainties on the global significance are calculated according to Section 6.7.	130
6.8	Largest positive and negative deviations (excess and deficit), in terms of the local p_0 -value converted into units of standard deviations σ , from the background-only hypothesis for the ee , $\mu\mu$, and $\ell\ell$ channels. The relative width Γ_X/m_X scan is performed in units of 0.5%. The values are retrieved from the scans shown in Figure 6.55.	131
6.9	Observed and expected 95% CL lower limits on $m_{Z'}$ for three Z' gauge boson models, quoted to the nearest 100 GeV in the ee and $\mu\mu$ channels as well as their combination ($\ell\ell$).	134

7.1	Summary of analysis channels, diboson states they are sensitive to, and their experimental signatures. The selection reflects requirements specific to each channel. Additional jets (not included in the “Jets” column) are required to define VBF categories. The notation “j” represents small- R jets and “J” represents large- R jets. Leptons are either electrons or muons. The notation “ $1e, 1\mu$ ” means that the signature is either $1e$ or 1μ , whereas “ $1e+1\mu$ ” means $1e$ and 1μ . A veto is imposed on E_T^{miss} in some channels to guarantee orthogonality between final-state channels. The symbol “–” signifies that no requirement is imposed on a given signature. Table adapted from Ref. [55].	138
7.2	Comparison of $pp \rightarrow Z' \rightarrow \ell\ell$ cross-section predictions from the narrow width assumption (NWA), signal reweighting in the full mass range as well as signal reweighting within the two mass window definitions. An overall stable behaviour is only found if the mass window cuts are applied. The remaining offset is considered within the combination by using signal cross-section predictions from signal reweighting for the leptonic channels.	151
7.3	Limits on $m_{V'}$ in the $Z' \rightarrow \ell\ell$, $W' \rightarrow \ell\nu$ and $V' \rightarrow \ell\ell + \ell\nu$ channels at the HVT A coupling point.	155
B.1	Association of the calibration lines to different trigger tower groups. [110]	173
B.2	Examples of the encoding scheme for the pulsed calibration lines in the pulsing patterns.	174
B.3	Delay run pulsing pattern for the front, middle and high- η back layers of the BNL LTDB.	174
B.4	Delay run pulsing pattern for the low- η back layer of the BNL LTDB.	175
B.5	Delay run pulsing pattern for the presampler and barrel end of the BNL LTDB.	175
B.6	Delay run pulsing pattern for the front, middle and high- η back layers of the French LTDB.	175
B.7	Delay run pulsing pattern for the low- η back layer of the French LTDB.	176
B.8	Delay run pulsing pattern for the presampler and barrel end of the French LTDB.	176
B.9	Ramp run pulsing pattern for the front, middle and high- η back layers of the BNL LTDB.	176
B.10	Ramp run pulsing pattern for the low- η back layer of the BNL LTDB.	176
B.11	Ramp run pulsing pattern for the presampler and barrel end of the BNL LTDB.	177
B.12	Ramp run pulsing pattern for the front, middle and high- η back layers of the French LTDB.	177
B.13	Ramp run pulsing pattern for the low- η back layer of the French LTDB.	177
B.14	Ramp run pulsing pattern for the presampler and barrel end of the French LTDB.	177
C.1	Description of the $m_{\ell\ell}^{\text{truth}}$ -dependence for the seven mass resolution parameters in the dielectron channel.	194
C.2	Description of the $m_{\ell\ell}^{\text{truth}}$ -dependence for the seven mass resolution parameters in the dimuon channel.	195

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