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**SEARCH FOR NEW PHYSICS PROCESSES WITH SAME CHARGE LEPTONS IN
THE FINAL STATE WITH THE ATLAS DETECTOR USING PROTON-PROTON
COLLISIONS AT $\sqrt{s} = 13$ TeV**

DOCTORAL THESIS

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**ISKANJE PROCESOV NOVE FIZIKE S PARI ENAKO NABITIH LEPTONOV V
KONČNEM STANJU Z DETEKTORJEM ATLAS S TRKI PROTONOV PRI
ENERGIJI $\sqrt{s} = 13 \text{ TeV}$**

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Izveček

V doktorskem delu sem predstavil prednost uporabe parov enako nabitih leptonov v končnem stanju za iskanje procesov nove fizike s trki protonov z detektorjem ATLAS na LHC-ju. Podatki, uporabljeni v analizi, so bili zajeti med letoma 2015 in 2016 pri težiščni energiji 13 TeV in ustrezajo integrirani luminoznosti 36.1 fb^{-1} . Za oceno ozadnja procesov Standardnega modela, ki tvori pare enako nabitih leptonov, sem izpeljal metode, ki temeljijo na podatkih (ang. *data-driven*). Te metode so uporabljene do transversalne gibalne količine leptonov vse do $p_T \sim 1 \text{ TeV}$. Rezultate smo interpretirali v okviru teorije levo-desne simetrije (ang. *Left-Right Symmetry Model*), specifično z iskanjem Higgsovega bozona z nabojem ± 2 ($H^{\pm\pm}$), težkih nevtrinov (N_R) in težkih umeritvenih vektorskih bozonov (W_R). S statistično obdelavo podatkov nismo opazili nobene sledi novih delcev. Posledično smo izpeljali zgornjo mejo za sipalni presek nastanka para bozonov $H^{\pm\pm}$ ($pp \rightarrow H^{++}H^{--}$) in za sipalni presek Keung-Senjanovičevega procesa ($pp \rightarrow \ell N_R \rightarrow \ell \ell W_R \rightarrow \ell \ell j j$). Izpeljane zgornje meje so najstrožje do sedaj, poleg tega pa je predstavljena še nova metoda za karakterizacijo verjetnosti, da je naboj elektrona narobe rekonstruiran, ki je bila prvič uporabljena za analizo ATLAS-ovih podatkov v tem doktorskem delu.

Ključne besede

ATLAS	CERN LHC	13 TeV
istoznačni leptoni	dva pljuska	visoka masa leptonov
gugalnični model	levo-desna simetrija	skalarni triplet
Higgs: naboj 2	Higgs: nastanek v paru	Higgs: razpad na leptone
desno-ročni nevtrino	težki nevtrino	Majoranov nevtrino

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Abstract

The thesis presents the advantage of using same-charge leptons in the final state in searches for new physics processes using proton–proton collisions recorded by the ATLAS detector at the LHC. The used data sample at a centre-of-mass energy of 13 TeV corresponds to 36.1 fb^{-1} of integrated luminosity recorded in 2015 and 2016. Data-driven methods are derived to estimate the Standard Model background in same-charge channels up to transverse momenta of leptons of about $p_T = 1 \text{ TeV}$. The Left-Right Symmetric Model is used as the benchmark beyond the Standard Model framework to optimize the analysis and to search for the production of doubly charged Higgs bosons ($H^{\pm\pm}$), heavy neutrinos (N_R), and right-handed vector gauge bosons (W_R). No significant evidence of a signal is observed and corresponding upper limits on the production cross-section are derived for the pair production of $H^{\pm\pm}$ bosons ($pp \rightarrow H^{++}H^{--}$) and for the Keung-Senjanović process ($pp \rightarrow \ell N_R \rightarrow \ell \ell W_R \rightarrow \ell \ell jj$). The observed limits of the two processes are the strongest to date and a novel method of parametrizing the electron charge misidentification probability is developed and used for the first time in the ATLAS Collaboration.

Keywords

ATLAS	CERN LHC	13 TeV
same-charge leptons	two jets	high di-lepton mass
seesaw model	left-right symmetry	scalar triplet
Higgs: charge 2	Higgs: pair production	Higgs: leptonic decay
neutrino: right-handed	neutrino: heavy	neutrino: Majorana

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Part I

Introduction

1 Theoretical Foundations

In this chapter the Standard Model of particle physics is introduced within the framework of the quantum field theory. As derived in the following, it is a non-abelian gauge theory with the symmetry group $SU(3) \otimes SU(2) \otimes U(1)$. Furthermore, some observed phenomena that can not be explained by the Standard Model are presented and one candidate for an extension, the Left-Right Symmetric Model, is examined in detail.

1.1 The Standard Model

The Standard Model (SM) [1–4] of particle physics classifies all known elementary particles to date, it describes three of the four fundamental interactions (the electromagnetic, weak, and strong interactions), and it introduces the Brout–Englert–Higgs (BEH) mechanism¹ which explains the origin of mass of the elementary particles. The SM is a Yang–Mills theory [5], based on a mathematical framework provided by the quantum field theory (QFT) [6, 7] and out of the four fundamental interactions, the SM does not incorporate gravity. It took its current form in the 1970s and the SM has been scrutinized ever since by numerous high energy physics experiments. It withstood flawlessly all the probes and perhaps even a larger success can be attributed to the predictions of the SM model; it predicted the existence of new particles such as the top quark and the Higgs boson which were observed only decades later. The Higgs boson was the last confirmed elementary particle and with its discovery in 2012 by the CMS [8] and the ATLAS [9] experiments, the SM became widely accepted as a self-sufficient theory.

In the mathematical formalism of the QFT, the most fundamental components of the SM are *quantum fields*. Analogous to *classical fields* (e.g. gravitational field, electric field) they are defined in each point of the space-time, however, they have additional distinct properties to account for observations in nature consistent only with quantum mechanics. Elementary particles are interpreted as discrete excitations of quantum fields and have no independent existence from these excitations. The kinematics of quantum fields and the interactions between them are governed by *Lagrangian densities* $\mathcal{L}$. The equations of motion for a field $\phi(x^\mu)$ are given by the Euler–Lagrange equation

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi)} \right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0, \quad (1.1)$$

which implies the principle of least action, that can also be used to derive the equations of motion of a classical system.

¹ Named after François Englert and Peter Higgs, who received the Nobel Prize in physics in 2013, and the coauthor of Englert–Robert Brout—who could not receive the prize.

The equations of motion obtained with Eq. 1.1 are analogous to the Schrödinger equation which governs the time-evolution of a complex wave-function $\psi(\mathbf{r}, t)$. However, there are several shortcomings to the Schrödinger, classical description of quantum mechanics, which are addressed by the QFT. Unlike the Schrödinger equation, QFT includes the effects of the special relativity which are very apparent at the particle collides. Furthermore, QFT adds a mechanism for particle creation and annihilation, which is a direct representation of the relativistic equation $E = mc^2$, discovered by Albert Einstein in 1905 [10].

1.1.1 Gauge theories

The first and the simplest example of a *gauge theory* is the Maxwell's theory of the electromagnetic interaction, published in the year 1864 [11]. The well known Maxwell equations

$$\nabla \cdot \mathbf{E} = \rho_{\text{em}}, \quad (\text{Gauss's law}) \quad (1.2a)$$

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t, \quad (\text{Faraday-Lenz laws}) \quad (1.2b)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (\text{no magnetic charges}) \quad (1.2c)$$

$$\nabla \times \mathbf{B} = \mathbf{j}_{\text{em}} + \partial \mathbf{E} / \partial t, \quad (\text{Ampère's law}) \quad (1.2d)$$

where $\mathbf{E}$ and $\mathbf{B}$ are the electromagnetic fields, look the same after a certain set of mathematical operations ('transformations') is applied to the fields. It is common and convenient to introduce a 3-vector potential $\mathbf{A}$ and the scalar field V in place of the fields $\mathbf{E}$ and $\mathbf{B}$

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad (1.3a)$$

$$\mathbf{E} = -\nabla V - \partial \mathbf{A} / \partial t. \quad (1.3b)$$

Changing the value of the electrostatic potential V by a constant amount in each point of the three dimensional space simultaneously leaves the physics unchanged. This is an example of a *global* transformation, since the change in the potential is the same everywhere. Invariance under this global transformation leads to the conservation of the electric charge.

The global transformation can be extended into a *local* transformation where the change is different in each point of space-time. Local transformations are by construction much more restrictive than the global transformations. It is apparent that the magnetic field $\mathbf{B}$ remains unchanged under the transformation

$$\mathbf{A} \rightarrow \mathbf{A}' = \mathbf{A} + \nabla \chi, \quad (1.4)$$

where χ is an arbitrary function. However, to preserve $\mathbf{E}$, V must be simultaneously changed by

$$V \rightarrow V' = V - \partial \chi / \partial t. \quad (1.5)$$

Eq. 1.4 and 1.5 can be interpreted in the reversed order; a local change in the electrostatic potential V can be compensated by a corresponding transformation of the magnetic vector potential $\mathbf{A}$ in order to leave the Maxwell equations unchanged. This suggests that the Maxwell equations might be derived just from the requirement that the physics remain unchanged after the global and local (*gauge*) transformations on the electromagnetic potentials. The requirement of the local invariance entails the existence of a ‘compensating’ gauge field, interacting in a special way.

The Maxwell equations can also be written in a manifestly covariant form using the four-vectors. The four-current j_{em}^μ is given by

$$j_{\text{em}}^\mu = (\rho_{\text{em}}, \mathbf{j}_{\text{em}}). \quad (1.6)$$

The continuity equation is then expressed simply as $\partial_\mu j_{\text{em}}^\mu = 0$. Likewise, transformations in Eqs. 1.4 and 1.5 can be combined into a single compact equation by introducing the four-vector potential

$$A^\mu = (V, \mathbf{A}). \quad (1.7)$$

A gauge transformation is specified by²

$$A^\mu \rightarrow A'^\mu = A^\mu - \partial^\mu \chi. \quad (1.8)$$

Moreover, the field strength tensor is defined

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad (1.9)$$

and the Maxwell Eqs. 1.2a and 1.2d then become

$$\partial_\mu F^{\mu\nu} = j_{\text{em}}^\nu, \quad (1.10)$$

while the homogeneous Maxwell Eqs. 1.2b and 1.2c can be expressed as

$$\partial_\alpha (\epsilon^{\alpha\beta\gamma\delta} F_{\gamma\delta}) = 0, \quad (1.11)$$

where $\epsilon^{\alpha\beta\gamma\delta}$ is the Levi–Civita symbol. Laws of classical electromagnetism written in this way are manifestly invariant under Lorentz transformations and pave the way for the quantum theory of electrodynamics introduced in the following.

² The four-vector ∂^μ has differential operators for components $(\partial/\partial t, -\nabla)$.

1.1.2 Gauge invariance in the quantum field theory

All the known fundamental interactions are described by gauge theories [5, 12], very similar to the one briefly presented above. When gauge theories are quantized, *gauge bosons* arise as quanta of the gauge fields.

Group theory plays the central role in classification of the gauge theories. Transformations are described by transformation groups—groups that act on a certain space preserving its inherent structure. One of the examples is the orthogonal group in dimension n , denoted as $O(n)$. Transformations following the rules of this group preserve the distance to a fixed point in the Euclidean space. In two or three dimensions, these transformations are simply described by rotations around a point.

As already indicated in Section 1.1.1 there is an important distinction between global invariance and local invariance. In a global invariance the same transformation is applied to all space-time points. Furthermore, there is a general theorem, the Noether's theorem postulated in 1918 [13], that if a Lagrangian is invariant under a continuous global transformation, then there will be an associated symmetry current and symmetry operator. The above phenomena can be illustrated with a simple example of a particle-antiparticle situation (e.g. π^+ , π^-). In a simplified view, this situation can be described by two free scalar fields ϕ_1 and ϕ_2 of the same mass m with the corresponding Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - \frac{1}{2}m^2\phi_1^2 + \frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - \frac{1}{2}m^2\phi_2^2. \quad (1.12)$$

The Lagrangian in Eq. 1.12 is invariant under the 'O(2) transformation'

$$\begin{aligned} \phi'_1 &= (\cos\alpha)\phi_1 - (\sin\alpha)\phi_2, \\ \phi'_2 &= (\sin\alpha)\phi_1 + (\cos\alpha)\phi_2. \end{aligned} \quad (1.13)$$

It is evident that the Lagrangian is left unchanged after this transformation, $\delta\mathcal{L} = \mathcal{L}(\phi'_1, \phi'_2) - \mathcal{L}(\phi_1, \phi_2) = 0$. For an infinitesimal rotation ϵ for which $\phi'_1 = \phi_1 - \epsilon\phi_2$ and $\phi'_2 = \epsilon\phi_1 + \phi_2$, the change in the Lagrangian, $\delta\mathcal{L}$, can also be explicitly expressed as

$$0 = \delta\mathcal{L} = \epsilon\partial_\mu[\phi_1\partial^\mu\phi_2 - \phi_2\partial^\mu\phi_1]. \quad (1.14)$$

Since ϵ is arbitrary, it follows that the operator $J^\mu = \phi_1\partial^\mu\phi_2 - \phi_2\partial^\mu\phi_1$ is conserved and corresponds to the symmetry current. It implies that the number of particles minus the number of antiparticles is a constant of motion.

Similarly to the above exercise, the quantized theory of electrodynamics, the *quantum electrodynamics*, is classified with the symmetry group U(1). The global U(1) invariance exhibits the symmetric current and symmetry operator identified with the electromagnetic current and charge.

The 'gauge principle' then consists of elevating a global invariance into a local, space-time dependent invariance. In case of quantum electrodynamics, invariance to local U(1) transformations gives rise

to compensating fields being identified as the electromagnetic ones. The quanta of the U(1) gauge field in this case is the photon [14].

The entire Standard Model is constructed in this manner by adding the SU(2) and SU(3) symmetry groups. Therefore, the Standard Model is a non-abelian gauge theory with the symmetry group

$$\text{SU}(3) \otimes \text{SU}(2) \otimes \text{U}(1) \quad (1.15)$$

and has 12 gauge bosons: the photon, three weak bosons, and eight gluons.

1.1.3 Elementary particles

Elementary particles are the indivisible building blocks of the Universe. All matter is composed from elementary particles and in the context of the Standard Model, they also propagate the fundamental forces. In the SM they are divided into fermions, which carry half integer spin, and bosons with a full integer spin. Fermions are further split into three categories: massive leptons interacting with the weak and the electromagnetic force, quarks, interacting also with the strong force, and neutrinos, which SM predicted to be massless leptons interacting only with the weak force.

SM predicts that particles are organized into *families* or *generations* [15], where each one contains a lepton, a neutrino, an up-type quark, and a down-type quark along with their antiparticles. SM does not, however, predict the number of generations. Three generations of quarks were recognized as the minimum in 1973 by Kobayashi and Maskawa [16], however, theoretically, a fourth generation would be possible. On the other hand, Experimental evidence strongly hints that there are exactly three generations of each type of fermions. The most compelling evidence is perhaps the measurement of the Z boson decay width by the LEP experiment [17], which concludes that only three generations of neutrinos exist with a mass smaller than about half the Z boson mass. The lifetime of the Z boson would be significantly shorter if a fourth species of light neutrino existed.

The fermions among the three generations are each others' copies that are identical except for the flavor and the mass of the particle. Furthermore, each particle has its own antiparticle with the same mass but opposite electromagnetic properties. Namely, these are electrons (e), muons (μ), and taus (τ), all carrying unit electric charge ($Q = -1$ ³). They are associated to the three neutrino generations: ν_e , ν_μ , and ν_τ . The quarks are categorized as up-type and down-type quarks. Up-type quarks have a charge of $Q = 2/3$. These particles are up-, charm-, and top-quarks. Similarly, the down-type quarks are the down-, the strange-, and the bottom-quark. They carry a charge of $Q = -1/3$. The first generation quarks, the up-quarks and the down-quarks, form protons and neutrons. Together with the first generation electroweak leptons, electrons, they form atoms and consequently all the matter surrounding us in nature. All other elementary particles are short-lived and are accessible only via accelerator experiments or highly energetic cosmic rays.

Fundamental interactions are mediated by gauge bosons with unit spin. The mediator of the electromagnetic force is the photon (γ) and it couples to the electric charge Q of fermions. The photon

³ Throughout this thesis and very commonly in high energy physics, the electric charge is given in units of the electron charge $q_e = -1.602 \times 10^{-19} \text{ C}$ [18].

is massless and therefore travels with the maximum speed allowed by the theory of special relativity. The consequence is the infinite range of the electromagnetic interaction. The weak force is transmitted via the Z^0 boson and two $W^\pm$ bosons, which are very massive, 91.2 GeV and 80.4 GeV respectively [18]. This is about 2000 times the mass of the electron $m(e) = 0.511$ MeV [18]. The relatively high masses of these gauge bosons leads to a weak coupling at low energies and to a short range of the weak interaction. The weakness of the weak force can be expressed in terms of the muon lifetime, which is inversely proportional to the square of $G_F \sim g^2/m(W)^2$ ⁴. Muon decays via the weak interaction and its lifetime is extremely long ($\sim 10^{-6}$ s) compared to the lifetime of particles decaying via strong ($< 10^{-22}$ s) or electromagnetic (10^{-14} to 10^{-22} s) interactions. Weak gauge bosons couple to the weak isospin I_w . The weak isospin of fermions is $I_w^f = 1/2$ and the weak isospin of gauge bosons is $I_w^b = 1$. Lastly, the strong force is carried by eight gluons (g), which are massless and couple to the color charge. There are three fundamental color charges: red, green, and blue. All quark and gluons have a color charge, which makes it possible for the gluons to interact among themselves and limits the range of the strong interaction.

The SM includes one additional boson, the Higgs boson H . It is a spin zero particle with no electric and no color charge, with a weak isospin of $I_w^H = 1/2$ and a mass of $m(H) = 125$ GeV [19]. The Higgs boson and the BEH mechanism are discussed in more detail in Section 1.1.7 and provide an explanation of the origin of the masses of the elementary particles.

The SM has 19 free parameters [20, 21], which need to be determined experimentally. Among those are the masses of the fermions, the mass of the Higgs boson, the vacuum expectation value of the Higgs field, strength of the three gauge couplings, and the properties of the weak interaction, discussed in more detail in Section 1.1.6. The basic properties of the elementary particles are summarized in Figure 1.1.

Elementary particles and their properties are studied by the collider and accelerator experiments. In the ATLAS experiment, we are accessing them with proton–proton collisions through various production mechanisms. The most probable production mechanisms lead by the proton–proton collisions at the LHC and observed by the ATLAS experiment are summarized in Figure 1.2.

1.1.4 Quantum electrodynamics

The theory of quantum electrodynamics (QED) [6, 24–26] describes all interactions between charged fermions and quanta of the electromagnetic field, the photon. These couplings can be summarized with only one Feynman diagram, presenting the QED coupling vertex, shown in Figure 1.3.

The equation of motion for free fermions with mass m is the Dirac equation,

$$(i\gamma^\mu \partial_\mu - m) \psi = 0, \quad (1.16)$$

⁴ Here g is the coupling constant of the weak interaction, explained in more detail in Section 1.1.6

	1 st	2 nd	3 rd		
QUARKS	2.2 M u $+2/3$ $1/2$ up	1.27 G c $+2/3$ $1/2$ charm	173.21 G t $+2/3$ $1/2$ top	Mass: eV/c^2 Charge Spin Name	strong nuclear force
	4.7 M d $-1/3$ $1/2$ down	96 M s $-1/3$ $1/2$ strange	4.18 G b $-1/3$ $1/2$ bottom		
	0.51 M e -1 $1/2$ electron	105.66 M μ -1 $1/2$ muon	1.78 G τ -1 $1/2$ tau	0 g 0 1 gluon	electromagnetic force
LEPTONS	< 2 ν_e 0 $1/2$ e neutrino	< 0.19 M ν_μ 0 $1/2$ μ neutrino	< 18.2 M ν_τ 0 $1/2$ τ neutrino	0 γ 0 1 photon	
				80.83 G $W^{\pm 1}$ 1 W boson	91.18 G Z^0 0 1 Z boson
	FERMIONS			BOSONS	

Figure 1.1: A summary of the properties of the elementary particles. They are split into fermions, gauge bosons, and the additional Higgs boson. In brackets around each particle the mass, the charge, the spin, and the name of the particle are given. Furthermore, the three fundamental forces along with the involved particles are indicated. Lastly, the three generations of fermions are marked.

where ψ is the Dirac spinor, a complex field, and γ^μ denotes the four-dimensional gamma matrices. The corresponding Lagrangian density, which yields this equation of motion through the Euler–Lagrange Eq. 1.1, is

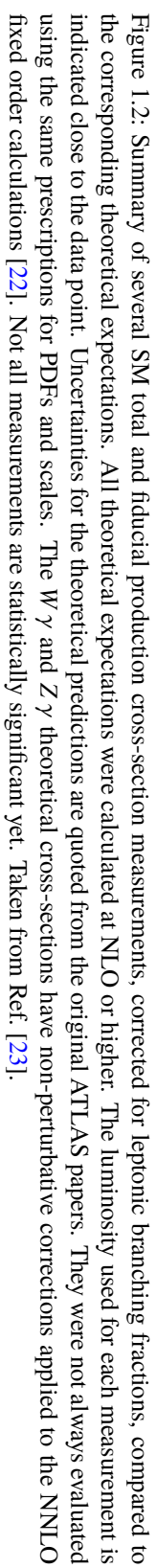
$$\mathcal{L} = \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi, \quad (1.17)$$

where $\bar{\psi}$ is Hermitian adjoint operator of ψ in combination with the matrix γ^0 , $\bar{\psi} = \psi^\dagger \gamma^0$. As we saw in the previous sections, imposing a local gauge invariance is usually a fruitful method, and in this case we can ensure an invariance to a local $U(1)$ transformation,

$$\psi \rightarrow \psi' = \exp(-iq\chi(x))\psi. \quad (1.18)$$

The Lagrangian in Eq. 1.17 will remain unchanged to this transformation only if a compensating field is added and similar transformations are simultaneously imposed on this new gauge field. The invariance can be satisfied by replacing the derivative ∂_μ with a covariant derivative,

$$D_\mu = \partial_\mu + iqA_\mu. \quad (1.19)$$



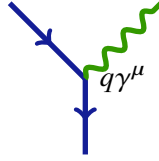


Figure 1.3: The fundamental coupling of the electromagnetic interaction: the interaction between a photon and two charged fermions.

The U(1) gauge invariant Lagrangian density now reads

$$\mathcal{L} = \bar{\psi} (i\gamma^\mu D_\mu - m) \psi, \quad (1.20)$$

where the new vector field A_μ couples to fermions with a coupling strength of q and ensures the invariance of the Lagrangian to the local U(1) transformation in Eq. 1.18. The new field A_μ is analogous to the compensating field defined in Section 1.1.1, $A_\mu = (V, A)$. It can be identified with a photon if another term, formed by the field strength tensor

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad (1.21)$$

is added to the Lagrangian,

$$\mathcal{L}_{\text{QED}} = \bar{\psi} (i\gamma^\mu D_\mu - m) \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}. \quad (1.22)$$

The additional $F^{\mu\nu} F_{\mu\nu}$ term conserves the gauge invariance and yields exactly the Maxwell Eq. 1.10 as equations of motion,

$$\partial_\nu F^{\nu\mu} = -q\bar{\psi}\gamma^\mu\psi = j_{\text{em}}^\mu. \quad (1.23)$$

1.1.5 Quantum chromodynamics

Similarly as the QED describes the interaction between charged fermions and the quanta of the electromagnetic field, the photon, the Quantum Chromodynamics (QCD) [27–31] describe the strong force, i.e. the interactions of quarks and gluons. The strong interaction is mediated by gluons which couple to the color charge, analogous to photons coupling to the electric charge. There are three different color charges, defined as *red*, *green*, and *blue*. Gluons carry a superposition of both the color and the anti-color charge, leading to eight different states. Furthermore, since they carry the color charge, gluons interact with themselves. The fundamental interactions of the strong force are shown with Feynman diagrams in Figure 1.4.

Unlike all other forces (electromagnetic, weak, and gravitational), the strong force does not loose its strength with increased distance between two quarks but rather grows in power. As the separation between the quarks grows, the potential energy becomes large enough to form a new pair of quarks at

each sides. It is therefore impossible for isolated quarks to exist. This phenomenon is called the color confinement and as a result only hadrons, not individual free quarks, can be observed. Furthermore, all observed particles are ‘colorless’, i.e. color singlets. Another intriguing property of the strong force is the asymptotic freedom [32, 33], a counterpart to the confinement. At very short distances (or large energy scales) the running coupling of the strong interaction becomes asymptotically small. As a result, strongly interacting particles are only loosely bound and perturbation theory is valid.

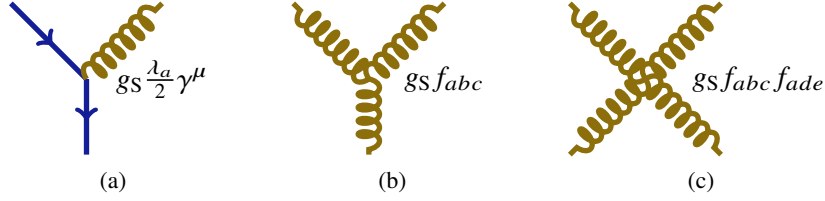


Figure 1.4: The fundamental couplings of the strong interaction: (a) gluon radiation, (b) gluon splitting, and (c) gluon self interaction.

The minimal symmetry group sufficient for the formulation of the QCD that can satisfy all observed phenomena is SU(3). The matrices related to the transformations of this group do not commute and the QCD is therefore a non-Abelian gauge theory. The Lagrangian of the QCD is

$$\mathcal{L}_{\text{QCD}} = \bar{\psi} (i\gamma^\mu D_\mu - m) \psi - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a, \quad (1.24)$$

where $G_{\mu\nu}^a$ is the field strength tensor of the gluon fields G_μ^a ($a = 1, \dots, 8$),

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_S f^{abc} G_\mu^b G_\nu^c. \quad (1.25)$$

In Eq. 1.25 g_S is the coupling parameter, derived from the coupling strength α_S , $g_S = \sqrt{4\pi\alpha_S}$ and f^{abc} are the structure constants of the SU(3) group. The covariant derivative D_μ is in QCD defined as

$$D_\mu = \partial_\mu + ig_S \frac{\lambda_a}{2} G_\mu^a, \quad (1.26)$$

where λ_a denotes the a^{th} Gell-Mann matrix [28].

1.1.6 The electroweak interaction

The electroweak interaction is a unification of the electromagnetic and the weak interactions in a single theory, the Glashow–Salam–Weinberg theory [2, 3, 34], for which the authors received a Nobel Prize in physics in 1979. The underlying symmetry group accompanying this gauge theory is the $\text{SU}(2) \times \text{U}(1)$ symmetry group. The weak interaction is mediated by three gauge bosons and couples to the weak isospin, I_w . The three gauge bosons are: two charged $W^\pm$ bosons and a neutral Z^0 boson.

The exchange of a $W^\pm$ boson modifies both the flavor and the electric charge of the fermions and is called the *charged current*. In contrast, the exchange of a Z^0 boson leaves the flavor intact and is called the *neutral current*.

One peculiar property of the $W^\pm$ bosons is the parity violation; they couple only to left-handed particles and right-handed anti-particles. The laws of nature were long thought to be invariant under the parity transformation, which is described by simultaneously flipping the sign of all spatial coordinates. However, it was first proposed in 1956 by Chen-Ning Yang and Tsung-Dao Lee that the weak interaction might be parity violating, specifically in β decays [35]. One year later, this was indeed experimentally confirmed [36], earning Yang and Lee the 1957 Nobel Prize in Physics. Because of these properties, the SU(2) symmetry group is denoted as SU(2)_L and the hypercharge Y is defined. The connection between the hypercharge, the electric charge Q , and the third component of the weak isospin I_3 is given by the Gell-Mann–Nishijima formula [27, 37]

$$Q = I_3 + \frac{1}{2}Y. \quad (1.27)$$

Left-handed fermions have a weak isospin of $I_w = 1/2$ and have $I_3 = \pm 1/2$. Charged leptons (e^- , μ^- , τ^-) have $I_3 = -1/2$ and neutrinos have $I_3 = +1/2$. Up-type quarks have $I_3 = +1/2$ and via the weak interaction always transform into down-type quarks with $I_3 = -1/2$. In all cases, the corresponding anti-fermions have reversed chirality and sign reversed I_3 . Right-handed fermions and left-handed anti-fermions have a weak isospin of $I_w = 0$ and do not undergo weak interactions. Exchanges of a W boson require a flavor transition: charged leptons are converted to neutrinos and up-type quarks are converted to down-type quarks. However, the weak eigenstates of the down-type quarks that couple to the up-type quarks via the weak interaction, d' , are not the same as the mass eigenstates of these quarks, d . This enables also a transition between generations for quarks interacting with the weak interaction, which is not the case for leptons. The relation between the eigenstates of the weak interaction and the mass eigenstates is given by the Cabibbo–Kobayashi–Maskawa (CKM) matrix [16, 38]

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}, \quad (1.28)$$

where $|V_{ij}|^2$ is the probability that a quark's flavor is changed from i to j undergoing an interaction with the W boson. The CKM matrix is a unitary matrix with diagonal elements being the largest and $|V_{ii}| > 0.97$, reflecting the fact that flavor transition of quarks stay most likely within the same generation. The largest non-diagonal elements are V_{cd} and V_{us} , with the absolute values about 0.23. The matrix is in general a complex matrix and due to the non-vanishing complex phase of the CKM matrix the CP invariance is violated by the weak interaction. The CP violation was experimentally first observed in 1964 [39] and occurred due to the fact that neutral kaons transform into their antiparticles and vice versa, but not with the same probability in both directions.

The SU(2)_L $\times$ U(1)_Y is an *broken* symmetry because the masses of the particles joined by these symmetries are very different. An exact (unbroken) symmetry would involve massless particles and

it is thus obvious that the symmetry must have been broken somehow during the evolution of the universe. The SM predicts the mechanism of spontaneous symmetry breaking, where one starts with three massless vector gauge fields W_μ^a ($a = 1, 2, 3$) to compensate the local alternations imposed by the $SU(2)_L$ transformation and one gauge field B_μ to compensate for the $U(1)_Y$ transformations. The corresponding field strength tensors are defined as $W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a - g\epsilon^{abc}W_\mu^b W_\nu^c$ and $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$. Furthermore, covariant derivatives are defined separately for left-handed and right-handed fermions,

$$D_\mu^L = \partial_\mu + i\frac{g}{2}\tau_a W_\mu^a + i\frac{g'}{2}Y B_\mu, \quad (1.29a)$$

$$D_\mu^R = \partial_\mu + i\frac{g'}{2}Y B_\mu, \quad (1.29b)$$

where two coupling constants, g and g' , are defined, ϵ^{abc} are the structure constants of the $SU(2)$ group, τ_a are the 2×2 Pauli matrices—generators of the $SU(2)$ group, and Y is the generator of the hypercharge. The Lagrangian density for the electroweak interaction than reads

$$\mathcal{L}_{EW} = \bar{\psi}_L i\gamma^\mu D_\mu^L \psi_L + \bar{\psi}_R i\gamma^\mu D_\mu^R \psi_R - \frac{1}{4}W_a^{\mu\nu}W_{\mu\nu}^a - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}. \quad (1.30)$$

The electroweak theory unifies the weak and the electromagnetic interactions, however, the W_μ^a ($a = 1, 2, 3$) and B_μ gauge fields do not directly correspond to the observed gauge bosons, $W^\pm$ bosons, Z^0 boson, and the photon. Furthermore, the already defined photon field A_μ (Eq. 1.19) must emerge from these gauge fields. This can be satisfied by defining the Weinberg angle [2] or weak mixing angle θ_w ,

$$\theta_w = \frac{g}{\sqrt{g^2 + g'^2}}. \quad (1.31)$$

The two neutral fields, A_μ and the Z^0 boson field Z_μ , are now identified as superpositions of the third component of the vector field, W_μ^3 , and the B_μ field,

$$\begin{bmatrix} Z_\mu \\ A_\mu \end{bmatrix} = \begin{bmatrix} \cos(\theta_w) & -\sin(\theta_w) \\ \sin(\theta_w) & \cos(\theta_w) \end{bmatrix} \begin{bmatrix} W_\mu^3 \\ B_\mu \end{bmatrix}. \quad (1.32)$$

Moreover, the coupling constant of the electromagnetic interaction, the electric charge e , can be expressed with the g and g' coupling constants,

$$e = g \sin(\theta_w) - g' \cos(\theta_w). \quad (1.33)$$

The charged vector bosons $W^\pm$ that are the charge eigenstates are constructed with the W_μ^1 and W_μ^2 fields,

$$W_\mu^\pm = \frac{1}{\sqrt{2}} \left(W_\mu^1 \mp i W_\mu^2 \right). \quad (1.34)$$

The electroweak theory introduced in this section assumes that the gauge bosons are massless since any mass terms would break the local gauge invariance of the Lagrangian density in Eq. 1.30. This is contradictory to all observations of various HEP experiments that measured the mass of the Z^0 and $W^\pm$ bosons to be massive to high precision. Notably, Carlo Rubbia and Simon van der Meer received the Nobel Prize in physics in 1984 for their decisive contributions to the discovery of Z and W bosons by the UA1 and UA2 Collaborations [40, 41]. Moreover, the ATLAS Collaboration recently presented a precise measurement of the $W^\pm$ bosons masses [42], summarized in Figure 1.5(a), accompanied with a simultaneous measurement of the Z^0 mass, presented in Figure 1.5(b), using the data recorded in 2011 based on proton–proton collisions at a center-of-mass energy of 7 TeV and corresponding to 4.6 fb^{-1} of integrated luminosity. The ATLAS $W^\pm$ boson mass measurement is compared to other published results, including measurements from the LEP experiments ALEPH, DELPHI, L3 and OPAL [43–46], and from the Tevatron collider experiments CDF and D0 [47, 48]. The simultaneous Z^0 boson mass fit is compared to the most precise measurement of the Z^0 boson mass which comes from the LEP combined value, $m(Z^0) = 91\,187.5 \text{ MeV}$ [17].

This conflict between the theory and the experimental observations is resolved by the BEH mechanism, summarized in Section 1.1.7. The BEH mechanism generates masses of the weak gauge bosons $W^\pm$ and Z^0 through electroweak symmetry breaking and it was proposed by three independent groups in 1964⁵. The BEH mechanism also predicts the existence of a long sought scalar boson, the Higgs boson H . Following its discovery by ATLAS and CMS in 2012, the 2013 Nobel Prize in Physics was awarded to Peter Higgs and François Englert for predicting its existence already in 1964.

1.1.7 The Brout–Englert–Higgs mechanism

The BEH mechanism is an essential component of the SM and explains the generation mechanism for masses of gauge bosons. At some extremely high temperatures (e.g. at the start of the Universe) the electroweak symmetry is unbroken and all elementary particles are massless. However, there exists a critical temperature where the symmetry is spontaneously broken and Z and W bosons acquire masses. Formally, the first step of the BEH mechanism is to introduce a left-handed doublet of complex scalar fields with weak isospin $I_w = 1/2$ (like the lepton-neutrino doublet), which transform under the $SU(2)$ symmetry,

$$\Phi = \begin{bmatrix} \Phi^+ \\ \Phi^0 \end{bmatrix} = \begin{bmatrix} \Phi_1 + i\Phi_2 \\ \Phi_3 + i\Phi_4 \end{bmatrix}, \quad (1.35)$$

⁵ Astonishingly, three different teams published papers about spontaneous symmetry breaking independently in 1964 in PRL: Robert Brout and François Englert [49], Peter Higgs [50], and Gerald Guralnik, Carl Richard Hagen, and Tom Kibble [51].

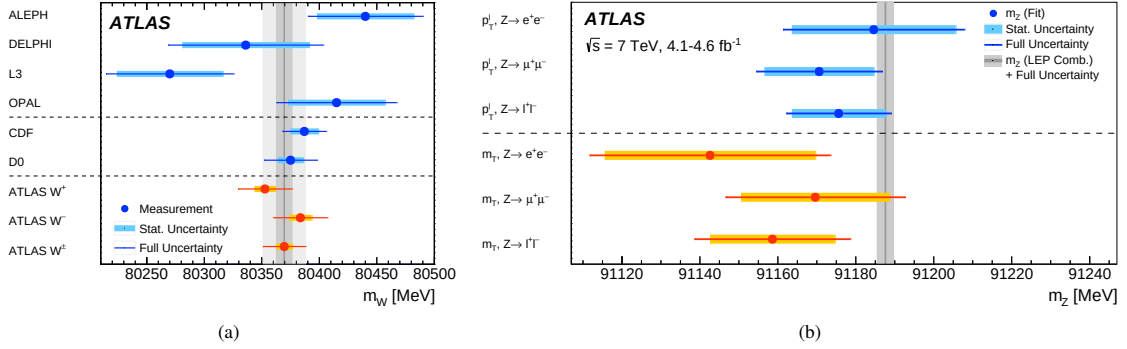


Figure 1.5: A summary of the $W^\pm$ boson mass measurement by the ATLAS Collaboration using the data recorded in 2011 based on proton–proton collisions at a center-of-mass energy of 7 TeV and corresponding to 4.6 fb^{-1} of integrated luminosity. Figure (a) shows a comparison of the mass measurement to other published results, including measurements from the LEP experiments ALEPH, DELPHI, L3 and OPAL [43–46], and from the Tevatron collider experiments CDF and D0 [47, 48]. The vertical bands show the statistical and total uncertainties of the ATLAS measurement, and the horizontal bands and lines show the statistical and total uncertainties of the other published results. Measured values of $m(W)$ for positively and negatively charged W bosons are also shown. Figure (b) shows a simultaneous fit of the Z^0 boson mass in various decay channels and with different variables. It is compared to the most precise Z^0 boson mass measurement, which is the LEP combination [17]. Taken from Ref. [42].

called the *Higgs field*, with a corresponding Lagrangian $\mathcal{L} = (\partial_\mu \Phi)(\partial^\mu \Phi)^\dagger - V(\Phi)$. In order to make it invariant to the $SU(2)_L$ transformation, the derivatives need to be replaced with the covariant ones from Eq. 1.29a,

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) + \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 - \frac{1}{4} W_a^{\mu\nu} W_{\mu\nu}^a - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}, \quad (1.36)$$

where the Higgs potential $V(\Phi)$ is given by

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad \lambda > 0, \mu^2 > 0. \quad (1.37)$$

The Higgs potential is schematically shown in two dimensions in Figure 1.6. The spontaneous symmetry breaking occurs when the Higgs field assumes one specific vacuum state out of the infinite possibilities. For example, we can choose a vacuum which has $\Phi_1 = \Phi_2 = \Phi_4 = 0$ and $\Phi_3 = v$,

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + H \end{bmatrix}, \quad (1.38)$$

where H is the *shifted field* used to describe small perturbations around the minimum v . The invariance to a specific symmetry or ‘rotation’ Z implies schematically that $e^{i\alpha Z} \Phi_0 = \Phi_0$. For infinitesimal rotations this becomes $(1 + i\alpha Z) \Phi_0 = \Phi_0$ and the invariance is satisfied if $iZ \Phi_0 = 0$.

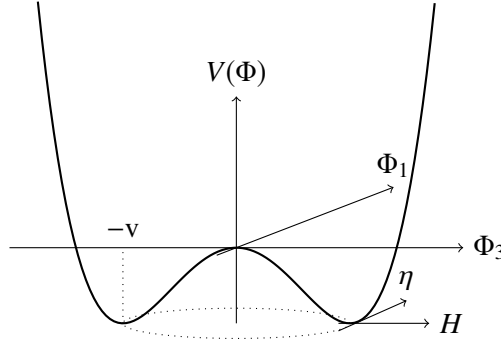


Figure 1.6: The Higgs potential from Eq. 1.37 projected in two dimensions, Φ_3 and Φ_1 . The solid circular line represents the minimum of the potential. After a vacuum value is assumed at any point of the minimum, the Higgs field can be expanded around that value with the new axes, H and η .

This requirement can be verified for the Higgs field expanded around the vacuum state in Eq. 1.38 for the generators of the $SU(2)_L$, $U(1)_Y$, and $U(1)_Q$ groups:

$$SU(2)_L : \quad \tau_3 \Phi_0 = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 0 \\ v + H \end{bmatrix} = -\frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + H \end{bmatrix} \quad (1.39a)$$

$$U(1)_Y : \quad Y \Phi_0 = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ v + H \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + H \end{bmatrix} \quad (1.39b)$$

$$U(1)_Q : \quad Q \Phi_0 = \frac{1}{2}(\tau_3 + Y) \Phi_0 = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ v + H \end{bmatrix} = 0 \quad (1.39c)$$

Indeed, it is evident that the expansion around the vacuum state breaks the $SU(2)_L$ and the $U(1)_Y$ symmetries while preserving the $U(1)_Q$ symmetry ($SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$), therefore one can identify the quantity Z with the EM charge Q . By rewriting the Lagrangian density in Eq. 1.36 with the Higgs field from Eq. 1.38 we obtain a mass term for the Higgs field and the Higgs self-interactions from the $V(\Phi)$ term. Furthermore, the $(D_\mu \Phi)^\dagger (D^\mu \Phi)$ term yields masses for the gauge bosons ($\propto v^2$) and interactions between the gauge bosons and the Higgs boson ($\propto vH$) and ($\propto H^2$). The Lagrangian density expanded around the vacuum and expressed with physical gauge bosons is

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4 \\ & + (v + H)^2 \left(\frac{g^2}{4} W_\mu^+ W_\mu^- + \frac{g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu \right). \end{aligned} \quad (1.40)$$

By expanding the $(v + H)^2$ term in Eq. 1.40 we obtain masses for the $W^\pm$ and Z gauge bosons. Massive vector gauge bosons travel slower than the speed of light and therefore they can now also

acquire longitudinal polarization. Generally, mass term for a field X are of the type $\frac{1}{2}m^2 X_\mu X^\mu$ and in the case of gauge bosons,

$$m(W^\pm) = \frac{1}{2}vg, \quad m(Z^0) = \frac{vg}{2\cos\theta_W} = \frac{m(W^\pm)}{\cos\theta_W}. \quad (1.41)$$

Interestingly, the ratio of the $W^\pm$ masses and Z^0 mass depends only on the Weinberg angle θ_W . Furthermore, the mass of the Higgs boson is given by

$$m(H) = \sqrt{2}\lambda v. \quad (1.42)$$

The Lagrangian density contains interactions between the vector gauge bosons ($V = W^\pm, Z^0$) and the Higgs boson in cubic (HVV) and quartic ($HHVV$) terms. The strength of these interactions is proportional to the gauge boson masses, $m(W^\pm)$ and $m(Z^0)$, and the mass of the Higgs boson $m(H)$. There are also Higgs self-interactions both in cubic (H^3) and quartic (H^4) terms. The vacuum expectation value (VEV) of the Higgs field can be precisely measured by accelerator experiments and the current best estimation is $v \simeq 246 \text{ GeV}$ [18].

1.1.8 Yukawa couplings and masses of charged fermions

In Section 1.1.7 the BEH mechanism was discussed and the mechanism for generating the masses of gauge bosons was presented. However, charged fermions were also observed to be massive and corresponding mass terms need to be added to the SM Lagrangian density. These terms can be introduced with the so called *Yukawa's interaction* or the *Yukawa coupling*, named after Hideki Yukawa. In general, this is an interaction between a scalar field ϕ and a Dirac field ψ of the type $V \sim g\bar{\psi}\phi\psi$. In SM, the only scalar field is the Higgs field and the corresponding Yukawa couplings for leptons (λ_ℓ) are given by

$$\begin{aligned} \mathcal{L}_{\text{Yukawa}}^{\text{leptons}} &= -\frac{\lambda_\ell}{\sqrt{2}} \left([\bar{\nu}_\ell, \bar{\ell}]_L \begin{bmatrix} 0 \\ v + H \end{bmatrix} \ell_R + \bar{\ell}_R [0, v + H] \begin{bmatrix} \nu_\ell \\ \ell \end{bmatrix}_L \right) \\ &= -\frac{\lambda_\ell v}{\sqrt{2}} \bar{\ell}\ell - \frac{\lambda_\ell}{\sqrt{2}} H \bar{\ell}\ell. \end{aligned} \quad (1.43)$$

Eq. 1.43 reflects the fact that the SM does not include right-handed neutrinos and because of the choice of the vacuum in Eq. 1.38 neutrinos remain massless. Furthermore, it holds that $\bar{\ell}_L \ell_R + \bar{\ell}_R \ell_L = \bar{\ell}\ell$. The Lagrangian density in Eq. 1.43 is invariant under $\text{SU}(2)_L \times \text{U}(1)_Y$ transformations and exhibits both the mass terms for charged leptons, $m(\ell) = \frac{\lambda_\ell v}{\sqrt{2}}$, proportional to the Higgs VEV and lepton–Higgs interactions. The strength of these interactions is proportional to the mass of the lepton ($\propto m(\ell)$). In an analogous way mass terms for quarks are introduced and the Yukawa coupling including both leptons and quarks ($f = \ell, q$) is compactly denoted as

$$\mathcal{L}_{\text{Yukawa}} = -m_f \bar{f} f \left(1 + \frac{H}{v} \right). \quad (1.44)$$

It took over 50 years to experimentally measure and verify the EW symmetry breaking and the predicted properties, however, with the stringent measurements performed at LHC by experiments ATLAS and CMS of the Higgs boson properties, most of the scientific community is convinced that the observed scalar particle is indeed the SM Higgs boson. The ATLAS and CMS combined measurement of the Higgs boson mass [19] gives a precise value of $m(H) = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{sys})$ GeV and it was obtained with the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay modes. Furthermore, another ATLAS and CMS combined measurement [52] verified the scaling of the coupling strengths between the Higgs boson and SM particles, depending on the particle mass: linear for the Yukawa couplings to the fermions and quadratic for the gauge couplings of the Higgs boson to the weak vector bosons. The couplings scale as predicted by the SM and a summary of both measurements is presented in Figure 1.7.

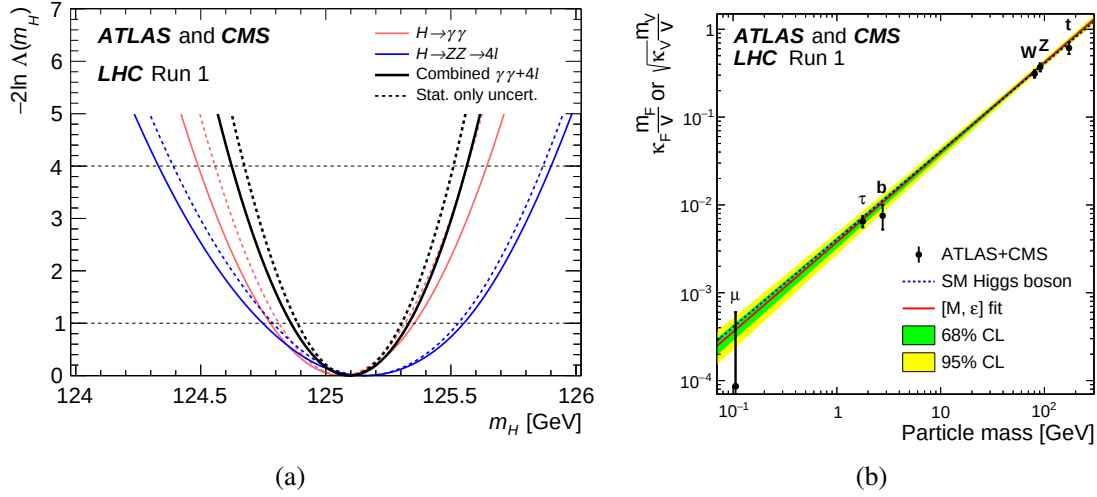


Figure 1.7: A measurement of the Higgs boson properties performed at the LHC by the ATLAS and CMS experiments: (a) Scans of the most probable value of the Higgs boson mass of the $H \rightarrow \gamma\gamma$ (red), $H \rightarrow ZZ \rightarrow 4\ell$ (blue), and combined (black) channels. The dashed curves show results accounting for statistical uncertainties only, with all nuisance parameters associated with systematic uncertainties fixed to their best-fit values. For further information see Ref. [19]. (b) Measurement of the Higgs boson coupling strength to fermions and gauge bosons. The used parametrization exhibits a linear scaling for both fermions and gauge bosons. The measured values are compared to the phenomenological model of Ref. [53] with the corresponding 68 % and 95 % CL bands. Taken from Ref. [52].

The various interactions discussed in previous sections and their corresponding Lagrangian densities form together the SM Lagrangian density,

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{EW}} + \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}. \quad (1.45)$$

1.2 Beyond the Standard Model

The Standard Model describes exceedingly well the observations of accelerator experiments so far, however, the SM needs to be extended in order to find a theory of grand unification of all forces. There are also hints from indirect searches that can not be described with the SM and additional theories or models are needed to address them. Extensions of the SM are called ‘Beyond the Standard Model’ (BSM) theories. The most apparent shortcoming of the SM is that it does not include gravity. The strength of the gravitational force is completely negligible at energies accessible by current accelerators and is expected to become non-negligible only at the Planck scale ($\sim 10^{19}$ GeV).

A very influential argument against the SM, and a reason for new physics to exist at reachable energies, is the ‘hierarchy problem’ of the SM. It is linked to the measured mass of the Higgs boson around 125 GeV which is a free parameter of the SM. As mentioned in the previous paragraph, the SM is only an approximation of a broader theory, which would preferably predict the mass of the Higgs boson to be 125 GeV rather than have it as the input parameter. In such a theory, the mass of the Higgs boson would be subject to very large loop corrections, particularly from the top quark because of its large coupling to the Higgs field. Therefore, any theory predicting the Higgs mass requires some fine-tuning to yield the exact mass, observed by the experiments, and ensure the stability of the SM. It turns out that the SM vacuum is stable on the timescales of our Universe only for small values of the Higgs mass and any perturbations of the Higgs mass (or the top-quark mass) would imply instability [54]. The energy up to which the SM is valid, the cutoff scale Λ , is related to the needed level of fine tuning. If new physics appear only at the Planck scale, extraordinary precision would be required to predict the 125 GeV mass from phenomena occurring at $\sim 10^{19}$ GeV. Various theories were developed that predict new phenomena at the TeVscale and solve the hierarchy problem, most notably the supersymmetry (SUSY), where the superpartner of the top-quark would contribute to the loop corrections with an opposite sign and effectively cancel the very large Higgs mass corrections without any need for precise fine-tuning.

Another, crucial observation—and very relevant for this thesis—is that neutrinos are not massless. Super-Kamiokande [55] and SNO [56] experiments first observed oscillations between electron neutrinos and muon neutrinos coming from the sun and the Earth’s atmosphere. Such oscillations are only possible if there is a difference in mass between the neutrino mass eigenstates and undeniably prove that neutrinos are massive particles, although very light. The then spokespersons of Super-Kamiokande and SNO Collaborations—Takaaki Kajita and Arthur B. McDonald respectively—were awarded the Nobel Prize in Physics 2015 for their discoveries. The origin of the neutrino mass is, however, unknown. One could implement them via the BEH mechanism like for the charged fermions in Eq. 1.45, however, this would require the existence of right-handed neutrinos which were not observed so far and would thus have to be *sterile*, i.e. coupling only to the Higgs field. A neutrino mass term generated this way is called the ‘Dirac’ mass term. A mathematical ‘trick’ to avoid the explicit need for right-handed fermions, first highlighted by Ettore Majorana in 1937 [57], is to define fermions which are their own antiparticles. Such fermions are called ‘Majorana fermions’, opposed to the ‘Dirac fermions’, which have a clear distinction between the particle and the antiparticle. It is possible to define a Majorana neutrino as $\nu = \nu_L + \nu_L^C$, where ν_L^C denotes the charge conjugated pair, $\nu_L^C = C\bar{\nu}_L^T$. Clearly, Majorana fermions can only be valid for neutral fermions to not violate the

conservation of the electric charge. The mass term for Majorana neutrinos can now be constructed as

$$\mathcal{L}_{\text{Majorana}} = \frac{1}{2} m_L (\bar{\nu}_L^C \nu_L + \bar{\nu}_L \nu_L^C), \quad (1.46)$$

however, this term changes weak hypercharge by two units, which is not possible with the SM Higgs interaction, and would require an extension of the Higgs sector. Numerous BSM theories incorporate mass generating mechanisms for SM neutrinos. One of them, the Left-Right Symmetric Model (LRSM), is presented in more detail in the following and used as the benchmark model to test the experimental measurements reported in this thesis.

1.3 Left-Right Symmetric Model

The fact that the weak interaction is not invariant under parity transformations at experimentally achievable energies—because weak gauge bosons couple only to left-handed fermions—inspired theories that restore the left-right symmetry at higher energy scales. The idea was first quantified and published in the seventies by Jogesh C. Pati, Abdus Salam, Rabindra Nath Mohapatra, and Goran Senjanović [58–60] as the Left-Right Symmetric Model (LRSM). The early versions upgraded the SM Higgs doublet to a bi-doublet and added two additional $SU(2)_{L,R}$ doublets to the Higgs sector. However, modern versions—and the one used in this thesis—use $SU(2)_{L,R}$ triplets instead of doublets. A thorough historical overview of the LRSM is given in Ref. [61], modern version left-right symmetric models were first discussed in Refs. [62–65], and more recent papers—also including results from the LHC experiments—are given in Refs. [66–71].

In summary, the Higgs sector in LRSM consists of the bi-doublet Φ and $SU(2)_{L,R}$ triplets $\Delta_{L,R}$

$$\Phi = \begin{bmatrix} \phi_1^0 & \phi_2^+ \\ \Phi_1^- & -\phi_2^{0*} \end{bmatrix} \quad \Delta_{L,R} = \begin{bmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{bmatrix}_{L,R}. \quad (1.47)$$

Furthermore, quarks and leptons are completely left-right symmetric,

$$q_{L,R} = \begin{bmatrix} u \\ d \end{bmatrix}_{L,R} \quad \ell_{L,R} = \begin{bmatrix} \nu \\ e \end{bmatrix}_{L,R}. \quad (1.48)$$

Accordingly to the $SU(2)_L$ gauge fields which couple only to left-handed fermions, a new gauge group $SU(2)_R$ is introduced. Gauge fields corresponding to this symmetry group couple only to right-handed fermions. This extends the electroweak sector symmetry into the $SU(2)_R \times SU(2)_L \times U(1)_Y$ representation. The coupling strengths of the two interactions are assumed equal and the same as the SM weak coupling constants in Eq. 1.31, $g = g_L = g_R$. The formula for the electromagnetic charge, instead of the Gell-Mann–Nishijima Eq. 1.27, becomes

$$Q = I_{3L} + I_{3R} + \frac{B - L}{2}, \quad (1.49)$$

which trades the hypercharge of the SM for $B - L$, where B is the baryon number and L is the lepton number. The left- and right-handed fermions get equal masses from Yukawa couplings to the bi-doublet Φ in Eq. 1.47. However, as right-handed neutrinos were not observed, the Left-Right symmetry must be spontaneously broken.

The LRSM becomes broken once the triplet $\Delta_{L,R}$ in Eq. 1.47 assumes a non-zero vacuum expectation value. Firstly, Δ_L and Δ_R take the form [63]

$$\langle \Delta_L^0 \rangle = 0 \quad \langle \Delta_R^0 \rangle = v_R. \quad (1.50)$$

The v_R yields masses of right-handed gauge bosons W_R and Z_R , right-handed neutrinos and all scalars except the SM Higgs doublet. Furthermore, the neutral components of Φ develop vacuum expectation values,

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \times \text{diag}(\kappa_1, \kappa_2), \quad (1.51)$$

where $v^2 = \kappa_1^2 + \kappa_2^2$. In turn, Δ_L develops a tiny induced vacuum expectation value [61]

$$\langle \Delta_L \rangle \propto v^2/v_R. \quad (1.52)$$

The induced value of v_L modifies the masses of left-handed gauge bosons and enters the SM ρ relation,

$$\rho = \frac{m(W_L)^2}{\cos^2 \theta_W m(Z)^2} \simeq \frac{1 + 2v_L^2/v^2}{1 + 4v_L^2/v^2}. \quad (1.53)$$

Precise measurements of the SM ‘rho-parameter’, $\rho = 1.00037 \pm 0.00023$ [18], indicate that v_L must be small, $v_L \lesssim 1$ GeV, leading to a hierarchy of $v_R > v > v_L$. The spontaneous symmetry breaking process gives masses to all weak gauge bosons in the form [60, 65]

$$m(W_R)^2 \simeq g^2 \left(\frac{v^2}{4} + v_R^2 \right) \quad (1.54a)$$

$$m(W_L)^2 \simeq g^2 \left(\frac{v^2}{4} \right) \quad (1.54b)$$

$$m(Z_R)^2 \simeq \frac{g^2}{c^2} \left(\frac{v^2(c^2 - s^2)}{4} + \frac{c^4 v_R^2}{c^2 - s^2} \right) \quad (1.54c)$$

$$m(Z_L)^2 \simeq \frac{g^2}{c^2} \frac{v^2}{4} \quad (1.54d)$$

where $c = \cos \theta_W$ and $s = \sin \theta_W$. The masses of SM left-handed weak gauge bosons are recovered by the spontaneous symmetry breaking of the LRS gauge theory for low values of v_L .

The LRSM introduces a right-handed neutrino for each lepton flavor, therefore it is possible to now construct Dirac mass terms for SM neutrinos with these new states. The neutrinos couple to the Higgs bi-doublet Φ (Eq. 1.47) and the corresponding Lagrangian for neutrino mass terms is

$$\mathcal{L}_{\text{Yukawa}}^{\text{neutrino}} = - \left(\bar{\nu}_L^i \Gamma_{ij} \nu_R^j + \bar{\nu}_L^i \Theta_{ij} \nu_R^j + h.c. \right), \quad (1.55)$$

where ν_R^i (Eq. 1.48) is the right-handed neutrino from the i -th generation and Γ_{ij} and Θ_{ij} are unknown parameters corresponding to the coupling strength of neutrinos to the Higgs bi-doublet.

Furthermore, neutrinos can gain Majorana mass terms in LRSM, as hinted in Eq. 1.46. The Majorana mass term arises from the coupling of a neutrino and its hermitian conjugate partner to the triplet scalars $\Delta_{L,R}$. By constructing a 6-vector of both left-handed and right-handed neutrinos, one can write down the combined Dirac and Majorana mass term as

$$[\bar{\nu}_L \bar{\nu}_R^C] \begin{bmatrix} M_L & m \\ m^T & M_R \end{bmatrix} \begin{bmatrix} \nu_L^C \\ \nu_R \end{bmatrix}, \quad (1.56)$$

where m is the Dirac mass from Eq. 1.55, mixing left-handed and right-handed states, and $M_{L,R}$ are the Majorana mass terms corresponding to the coupling to the triplet scalars $\Delta_{L,R}$. M_L and M_R are proportional to v_L and v_R respectively [68]. The Dirac neutrino mass, m , must be light, which leads to a hierarchy of $M_R > m > M_L$. Furthermore, the mass matrices satisfy [68]: $M_D = M_D^T$ and $M_L = v_L/v_R M_R$ and the matrix in Eq. 1.56 can be diagonalized to

$$\begin{bmatrix} M_L - m M_R^{-1} m^T & 0 \\ 0 & M_R \end{bmatrix}. \quad (1.57)$$

After the diagonalization, one gets three heavy Majorana neutrinos (M_R) and three light neutrinos ($m_\nu = M_L - m M_R^{-1} m^T$) with small masses as $M_L \propto v_L$ and $M_R = v_R/v_L M_L$. In this regard, the existence of three neutrinos which are much lighter than the other leptons is explained by the existence of three very heavy neutrinos. This process of mass generation via scalar triplet fields is called the type-II seesaw mechanism.

The heavy right-handed neutrinos can be directly probed at the LHC through their coupling to right-handed gauge bosons W_R and charged leptons. A production mechanism at LHC most sensitive to this is the Keung-Senjanović (KS) process [72], shown in Figure 1.8. A search optimized specifically for this production mechanism is presented in Part III.

1.3.1 Doubly-charged scalars $\Delta_{L,R}^{\pm\pm}$

Along with heavy right-handed neutrinos and heavy right-handed gauge bosons, the LRSM, or any theory incorporating the type-II seesaw mechanism, introduces also doubly-charged scalar particles. In case of LRSM, these are $\Delta_{L,R}^{\pm\pm}$, hereinafter referred to as doubly-charged Higgs bosons and denoted as $H_{L,R}^{\pm\pm}$. The difference between $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ is that they couple only to left-handed or right-handed, respectively.

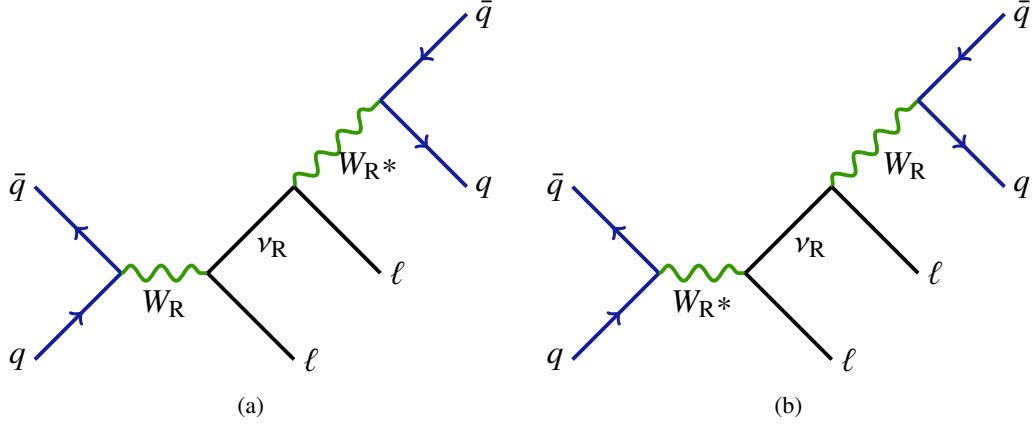


Figure 1.8: The leading Feynman diagram for the Keung–Senjanović process [72], for (a) the $m(W_R) > m(\nu_R)$ case and (b) the $m(W_R) < m(\nu_R)$ case.

The $U(1)_{B-L}$ symmetry prevents quarks from coupling to any of the scalar triplet members. The $H_{L,R}^{\pm\pm}$ can couple to leptons, vector gauge bosons, and scalars from the triplet, as derived in detail in Ref. [73]. The couplings of $H_{L,R}^{\pm\pm}$ to gauge bosons are proportional to $v_{L,R}$ and this coupling is naturally small for $H_L^{\pm\pm}$ due to the SM rho-parameter in Eq. 1.53. Furthermore, the coupling of $H_R^{\pm\pm}$ to W_R is negligible for high W_R masses. The decay width of $H^{\pm\pm}$ to a pair of W_L bosons is given by

$$\Gamma(H^{\pm\pm} \rightarrow W_L^\pm W_L^\pm) = \frac{v_L^2 m(H^{\pm\pm})^3}{4\pi v^4} \left(1 - \frac{4m(W_L)^2}{m(H^{\pm\pm})^2}\right)^{1/2} \left(1 - \frac{2m(W_L)^2}{m(H^{\pm\pm})^2}\right)^2. \quad (1.58)$$

The doubly-charged Higgs search in this thesis is optimized for the case where $H_{L,R}^{\pm\pm}$ couples only to leptons and both electron and muon final states are studied. The partial decay width of $H^{\pm\pm}$ to leptons is given by

$$\Gamma(H^{\pm\pm} \rightarrow \ell^\pm \ell'^\pm) = k \frac{h_{\ell\ell'}^2}{16\pi} m(H^{\pm\pm}), \quad (1.59)$$

with $k = 2$ if both leptons have the same flavor ($\ell = \ell'$) and $k = 1$ for different flavors. The factor $h_{\ell\ell'}$ has an upper bound that depends on the flavor combination, derived from results of non-direct searches [74, 75]. In the analysis presented in this thesis, only prompt decays of the $H^{\pm\pm}$ bosons ($c\tau < 10 \mu\text{m}$) are considered, corresponding to $h_{\ell\ell'} \gtrsim 1.5 \times 10^{-6}$ for $m(H^{\pm\pm}) = 200 \text{ GeV}$. In general, there is no preference for decays into τ leptons, as the coupling is not proportional to the lepton mass like it is for the SM Higgs boson. Additionally, the relative decay branching ratio to a pair of W bosons compared to the branching ratio to a pair of leptons is shown in Figure 1.9.

The main production mechanism of $H^{\pm\pm}$ particles at LHC, in the case where couplings of $H_{L,R}^{\pm\pm}$ to vector gauge bosons are negligible, is the pair production via the Drell–Yan process. The Feynman diagram of this production mechanism is presented in Figure 1.10. The signature corresponding to

this process are four leptons in the final state where the invariant masses of the same-charge pairs reconstruct the mass of the $H^{\pm\pm}$. The search presented in Part III is optimized for this signature.

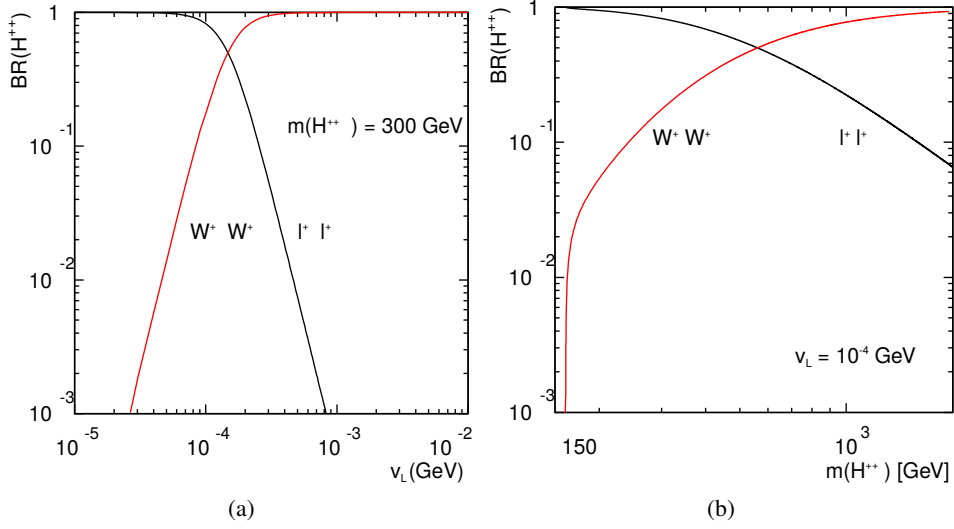


Figure 1.9: Branching fractions of the doubly charged Higgs boson decay versus (a) v_L for $m(H^{\pm\pm}) = 300$ GeV and (b) $m(H^{\pm\pm})$ for $v_L = 10^{-4}$ GeV. Taken from Ref. [73].

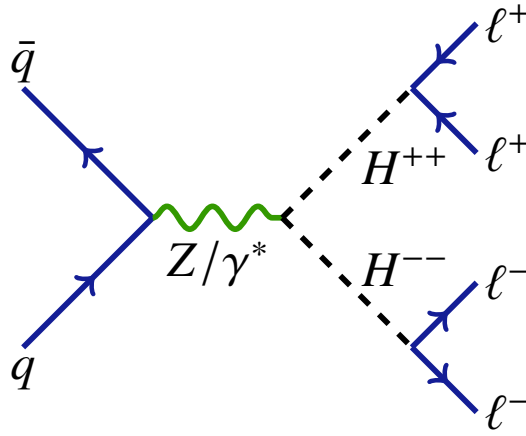


Figure 1.10: Feynman diagram of the pair production process $pp \rightarrow H^{\pm\pm}H^{\mp\mp}$. The doubly-charged Higgs search presented in this thesis studies only the electron and muon channels, where at least one of the lepton pairs is $e^\pm e^\pm$, $e^\pm \mu^\pm$, or $\mu^\pm \mu^\pm$.

Part II

ATLAS experiment at the LHC

2 Experimental Setup

The data analyzed in this thesis originates perhaps from the world's most complex particle physics experimental setup, the Large Hadron Collider. As explained in the following, this is the largest and the most powerful particle accelerator and provides proton–proton collisions up to the energy of $\sqrt{s} = 13$ TeV. Collisions used in this thesis were recorded by the ATLAS experiment, which is described in detail in this chapter. Furthermore, the simulation of proton–proton collisions is briefly summarized in the last section of this chapter.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [76] is the world's largest and the most powerful machine for accelerating protons and heavy ions. LHC is located at CERN, the European Organization for Nuclear Research, (historically *Conseil Européen pour la Recherche Nucléaire*) beneath the France–Switzerland border near Geneva.

The LHC lies in a 27 km long tunnel previously occupied by the Large Electron–Positron (LEP) Collider, which ceased operating in 2000. The LHC was built between 1998 and 2008 and is located approximately 100 m under ground. It has two beam pipes that host accelerated particles traveling in the opposite direction. Strong dipole magnets are used to bend trajectories of protons or heavy ions. Altogether, LHC has 1232 dipole magnets and each of them weights about 35 t and is 15 m long. They produce powerful 8.3 T magnetic fields and use a current of about 11 kA to produce the field, mediated by a superconducting coil. During proton–proton (pp) collisions, both beams can contain up to 2808 bunches which contain about 10^{11} protons each. Typical distance between the bunches is 25 ns. In addition to dipole magnets, 392 quadrupole magnets are used to focus the beams. The beams from the two separate beam lines cross at four ‘interaction points’ (IP), where the four main LHC experiments (ALICE, ATLAS, CMS, and LHCb) are located. The locations of the four experiments and the schematic of the LHC are shown in Figure 2.1. The average number of proton–proton interactions per bunch crossing (pile-up) during the 2015 and 2106 data-taking was around 25. The ATLAS experiment is discussed in more detail in Section 2.2.

The number of events from a particular process that are expected to be generated per unit of time during the proton–proton collisions is proportional to the instantaneous luminosity $\mathcal{L}$ and the cross-section for this process (e.g. any process from Figure 1.2). Instantaneous luminosity depends on many parameters of the LHC and can be concisely summarized as

$$\mathcal{L} = \frac{n_{bb} N^2 f_{\text{rev}} \gamma}{4\pi \epsilon_n \beta^*} F, \quad (2.1)$$

2 Experimental Setup

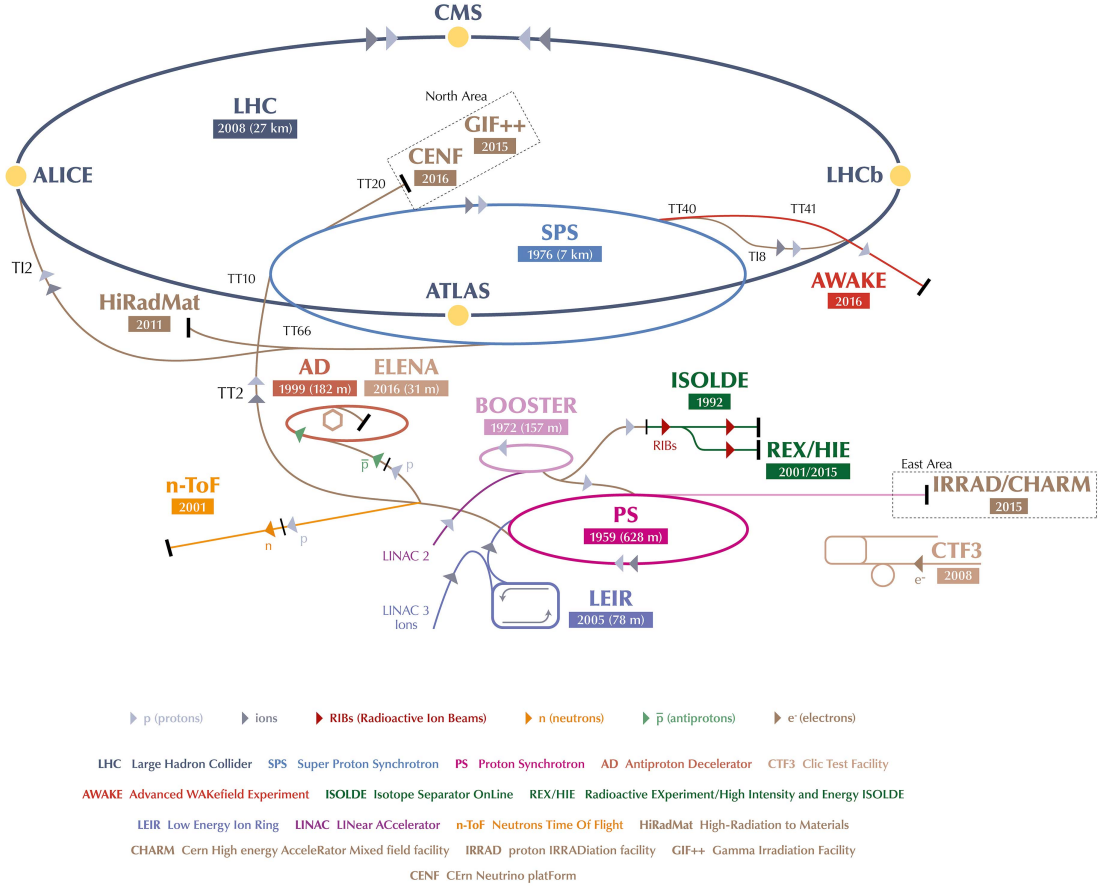


Figure 2.1: The LHC is the last ring (dark blue line) in a complex chain of particle accelerators. The smaller machines are used in a chain to help boost the particles to their final energies and provide beams to a whole set of smaller experiments, which also aim to uncover the mysteries of the Universe. The four main experiments (ALICE, ATLAS, CMS, and LHCb) are indicated with yellow dots. Taken from Ref. [77].

where n_{bb} is the number of colliding bunches, limited by the structure of the LHC orbit (e.g. necessary gaps for kicker magnets), N is the number of protons per bunch, f_{rev} is the revolution frequency, γ is the relativistic factor, ϵ_n is the normalized transverse beam emittance, β^* is related to the size of the beam at the IP (defined by LHC optics), and F is the geometric factor that reflects the reduction of luminosity due to the geometry of bunches and the crossing angle.

The data used in this thesis were collected at centre-of-mass energy of 13 TeV during 2015 and 2016, and correspond to an integrated luminosity ($\int \mathcal{L} dt$) of 3.2 fb^{-1} in 2015 and 32.9 fb^{-1} in 2016. A summary of all data delivered to ATLAS in this period is shown in Figure 2.2.

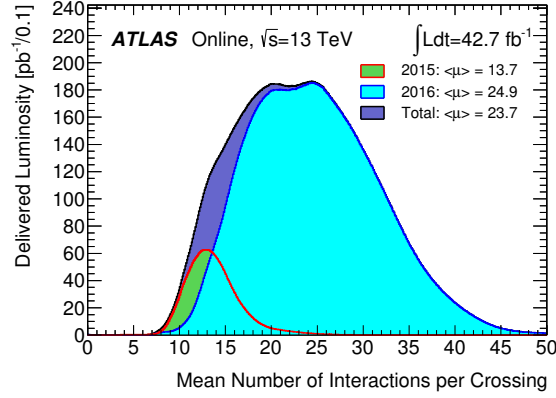


Figure 2.2: The luminosity-weighted distribution of the mean number of interactions per crossing for the 2016 pp collision data at 13 TeV center-of-mass energy. All data delivered to ATLAS during stable beams is shown, and the integrated luminosity and the mean pile-up value are given in the figure. Taken from Ref. [78].

2.2 The ATLAS experiment

Located at LHC ‘point 1’, close to the CERN Meyrin site, the ATLAS (A Toroidal LHC ApparatuS) [79] detector is one of the two general purpose detectors at LHC. It is located about 100 m underground, has a forward-backward cylindrical symmetry around the IP and is spanning 44 m in length with a diameter of 25 m, as shown in Figure 2.3. It is built in layers of sub-detectors with the aim of capturing all detectable particles produced in pp and heavy ion collisions. Starting from the LHC beam pipe, the sub-detectors are: the Inner Detector (ID), the liquid-argon (LAr) calorimeter, the tile calorimeter, and the Muon Spectrometers (MS). ATLAS has its own system of magnets, used to bend the trajectories of charged particles, with a superconducting solenoid magnet producing a 2 T axial magnetic field in the ID, the barrel toroid magnet with 8 separate coils, and the two end-cap toroids. The superconducting toroid magnets produce a 4 T magnetic field, weight over 1000 t, and store over 1 GJ of energy. The general resolution goals and the coverage of the ATLAS detector are given in Table 2.1 and the various sub-systems are summarized in the following sections.

2.2.1 The ATLAS coordinate system

A Cartesian coordinate system originating from the pp interaction point is used in ATLAS. The positive x -axis points to the center of the LHC, the positive y -axis points upwards and the z -axis along the direction of the two beams. Furthermore, the detector uses a cylindrical coordinate system reflecting the rotational symmetry of the experiment. The azimuthal angle ϕ is defined between $(-\pi, \pi]$ with $\phi = 0$ corresponding to the x -axis. The polar angle Θ , defined in $[0, \pi]$, corresponds to the z -axis with $\Theta = 0$ and the y -axis with $\Theta = \pi$. However, instead of the Θ angle, the rapidity $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ is defined to indicate the polar direction of the trajectories. The advantage of rapidity is that differences in this quantity are invariant under Lorentz boosts in direction of the z -axis. More commonly, the pseudorapidity $\eta = -\ln \tan(\Theta/2)$ is used instead of the rapidity and for massless objects the pseudorapidity becomes equal to rapidity. The angular distance between objects is

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measured in terms of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ and the transverse plane to the beam direction, the $x - y$ plane, is used to project the momenta of energetic particles created at the IP, $p_T = p \sin \Theta$.

Table 2.1: Resolution goals and pseudorapidity coverage of the subsystems of the ATLAS detector. Numbers for energy and transverse momentum are in units of GeV. The notation $a \oplus b = \sqrt{a^2 + b^2}$ is used and the coordinate system described in Section 2.2.1 is used. Taken from Ref. [79].

Sub-detector	required resolution	η -coverage	
		measurement	trigger
Inner Detector	$\sigma_{p_T}/p_T = 0.05\% \ p_T \oplus 1\%$	$ \eta < 2.5$	
Electromagnetic LAr calorimeter	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$ \eta < 3.2$	$ \eta < 2.5$
Hadronic calorimeter			
Barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$ \eta < 3.2$	
Forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	
Muon Spectrometer	$\sigma_{p_T}/p_T = 10\% \text{ at } p_T = 1 \text{ TeV}$	$ \eta < 2.7$	$ \eta < 2.4$

2.2.2 The Inner Detector

The purpose of the Inner Detector [80] is to provide track reconstruction of charged particles arising from collisions, allowing for vertex reconstruction and measurement of track momenta. The ID consists of three major sub-detectors, in the order of proximity to the IP: the Pixel detector, the Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT). Pixel and SCT detectors use silicon sensors while the TRT is a drift chamber composed of gas-filled straws. A schematic view of the ID is presented in Figure 2.5.

All sub-systems are separated into a barrel region and an end-cap region. Sensors in the end-cap region are rotated to be orthogonal to the sensors in the barrel region to ensure a better coverage for tracks transversing the detector at high $|\eta|$. During the Long Shutdown after Run 1 in 2013-2014, the ATLAS ID was upgraded. In a delicate procedure, the Pixel detector was extracted from the cavern and several service systems and sensitive modules have been upgraded. Furthermore, the beam pipe was replaced and a new silicon pixel detector, the Insertable B-layer (IBL) [81] was installed. The purpose of the IBL is to more precisely measure the track impact parameters due to a closer positioning from the IP and to have more layers in the Pixel detector and thus a more robust detector overall. The ID along with the upgraded beam pipe and the IBL (at $R = 33.5 \text{ mm}$) is presented in detail in Figure 2.6.

2.2.3 Pixel detector and the IBL

The Pixel detector is the innermost part of the ID and covers the region $|\eta| < 2.5$. It was originally composed of three cylindrical layers in the barrel region and three co-axial discs in the end-cap region. The Pixel detector has 1744 silicon pixel modules, each formed by 16 front-end chips. Each front-end chip has 2880 readout channels bonded to a n-type pixel sensor with $50 \mu\text{m} \times 400 \mu\text{m}$ large pixels

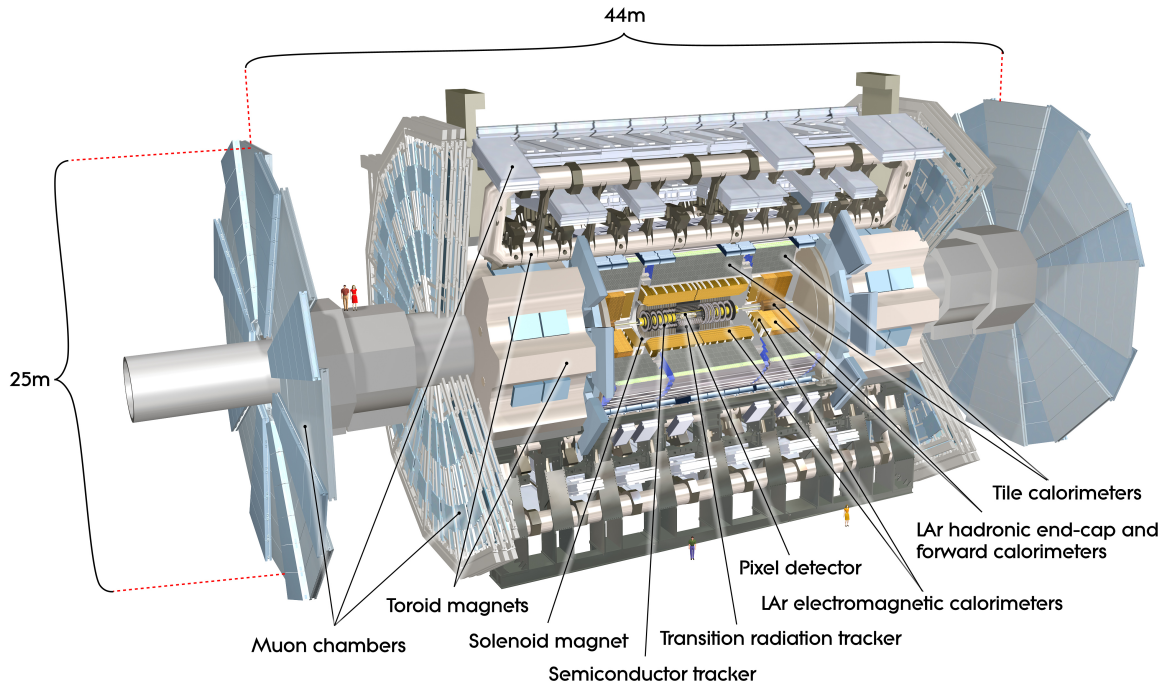


Figure 2.3: Cut-away view of the ATLAS detector. The dimensions of the detector are 25 m in height and 44 m in length. The overall weight of the detector is approximately 7000 t. Taken from Ref. [79].

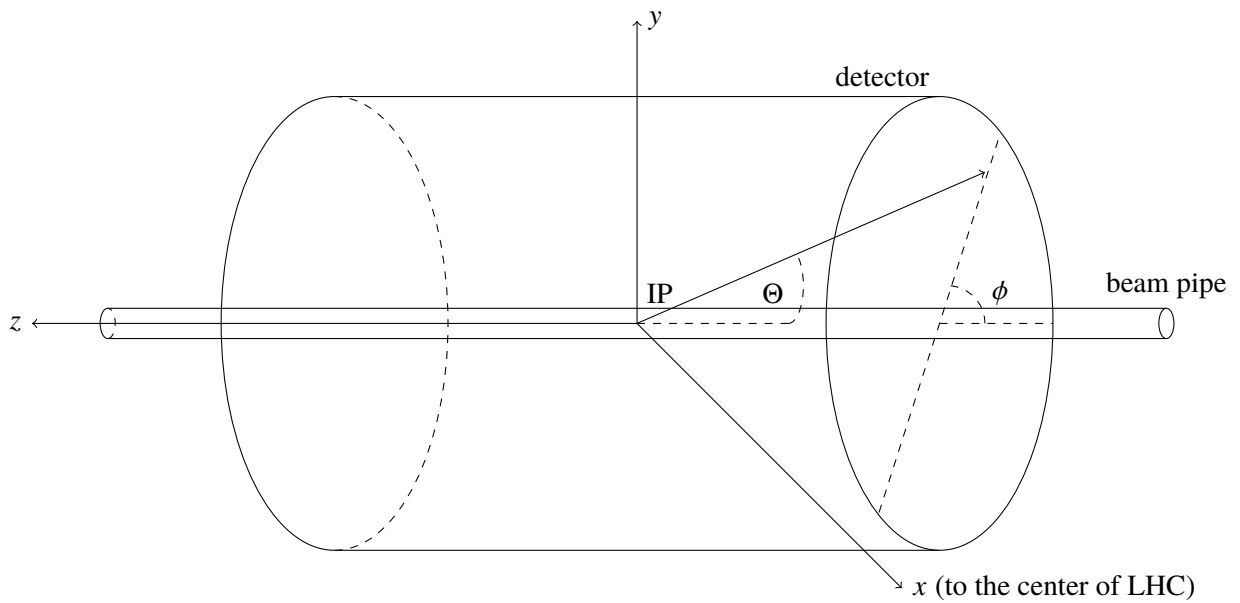


Figure 2.4: ATLAS detector common coordinate system.

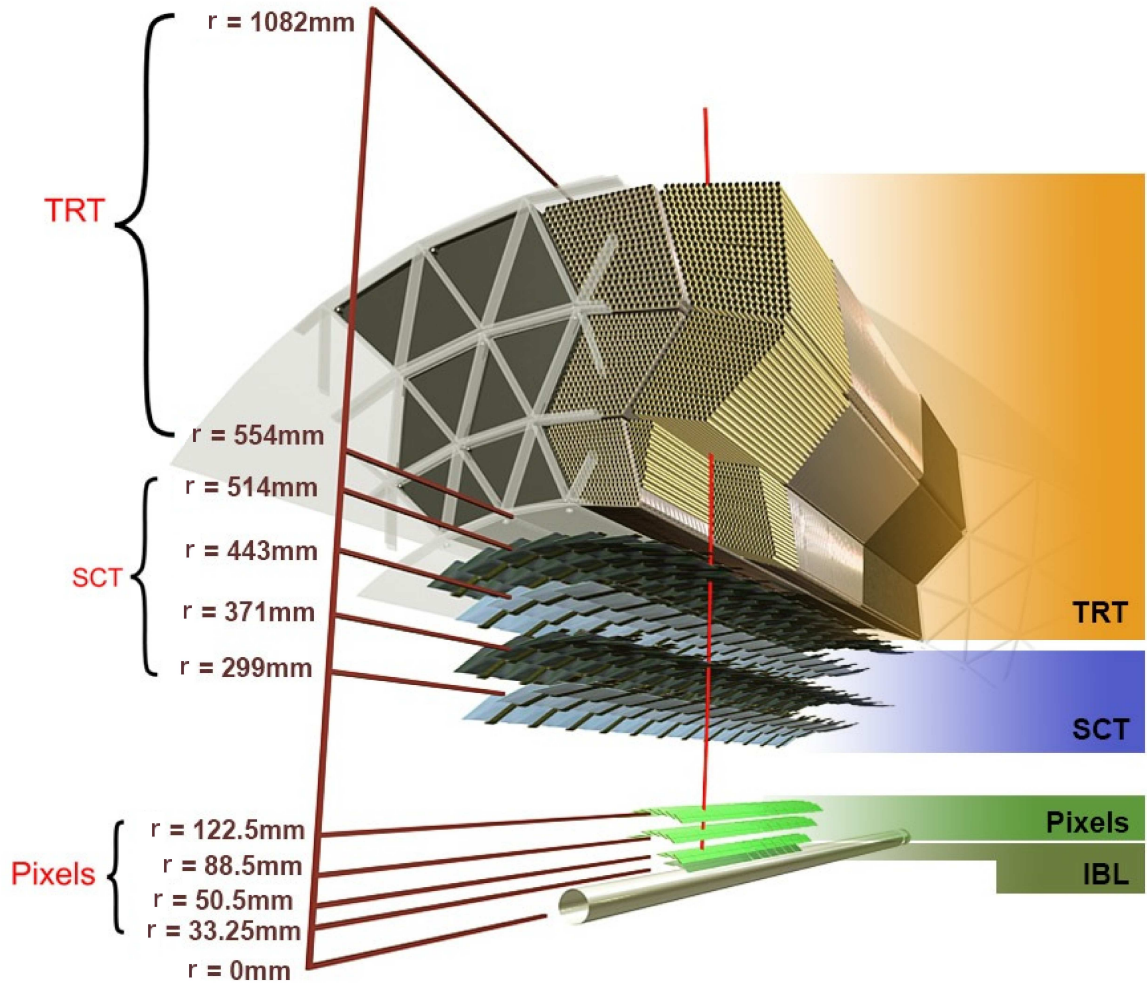


Figure 2.5: Sketch of the barrel region of the ATLAS Inner Detector traversed by a charged track of $p_T = 10\text{ GeV}$. Taken from Ref. [79].

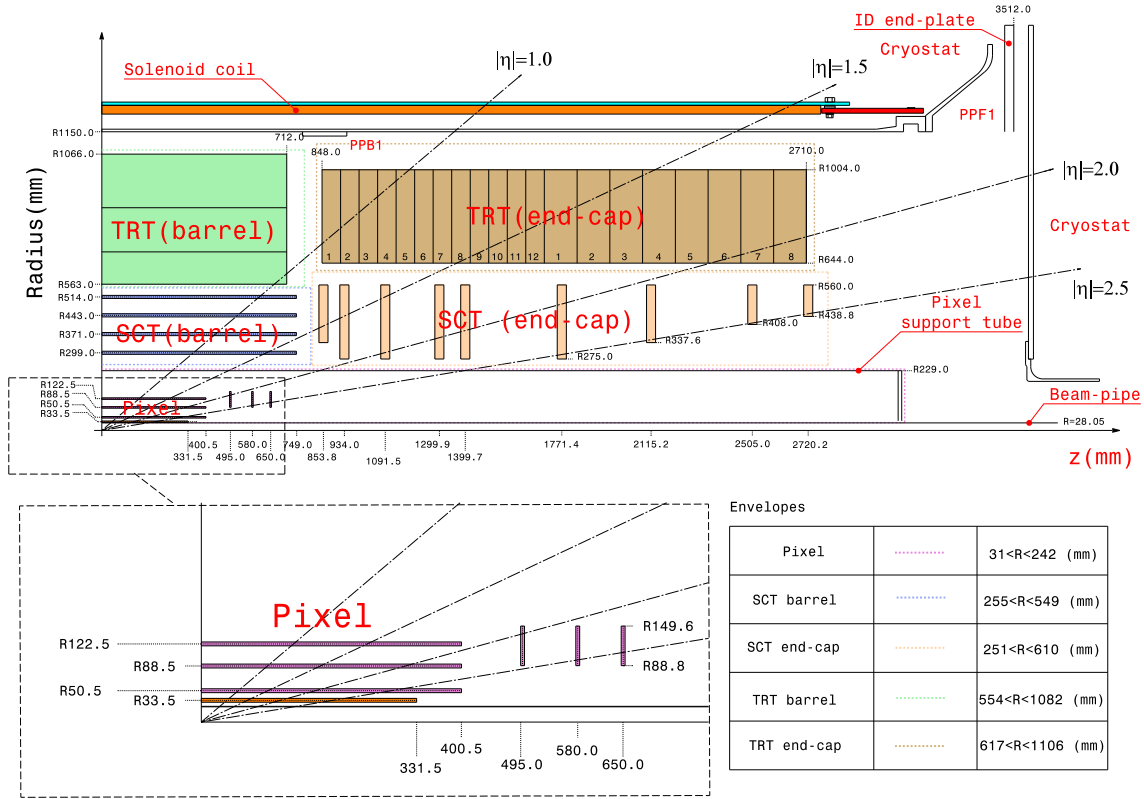


Figure 2.6: The $r - z$ cross-section view of the layout of a quadrant of the ATLAS Inner Detector for Run 2. The top panel shows the whole Inner Detector, whereas the bottom-left panel shows a magnified view of the pixel detector region. In the upgrade for Run 2, the IBL (shown in red in the bottom-left panel) and its services, together with the new beam pipe, were added. Taken from Ref. [82].

and a thickness of $250\mu\text{m}$. In total, the Pixel detector has around 80×10^6 read-out channels. The hit resolution of the Pixel detector is $10\mu\text{m}$ in the barrel region and $115\mu\text{m}$ in the end-cap region.

The fourth pixel layer, the IBL, is formed by 14 staves along the beam pipe with a full coverage in ϕ . It is placed 33.5 mm away from the beam-line, which is a substantial upgrade from the previously closest layer at 50.5 mm from the beam-line, and is 72.4 cm long. A total of 20 modules are mounted on each IBL stave and two different sensor technologies are used: four 3D pixel sensors at both far-end sides and 12 planar silicon sensors in the central part of the IBL. In total, the IBL has about 12×10^6 readout channels. An overview of the ATLAS Pixel detector is shown on Figure 2.7 where the beam pipe and the four Pixel layers are clearly visible.

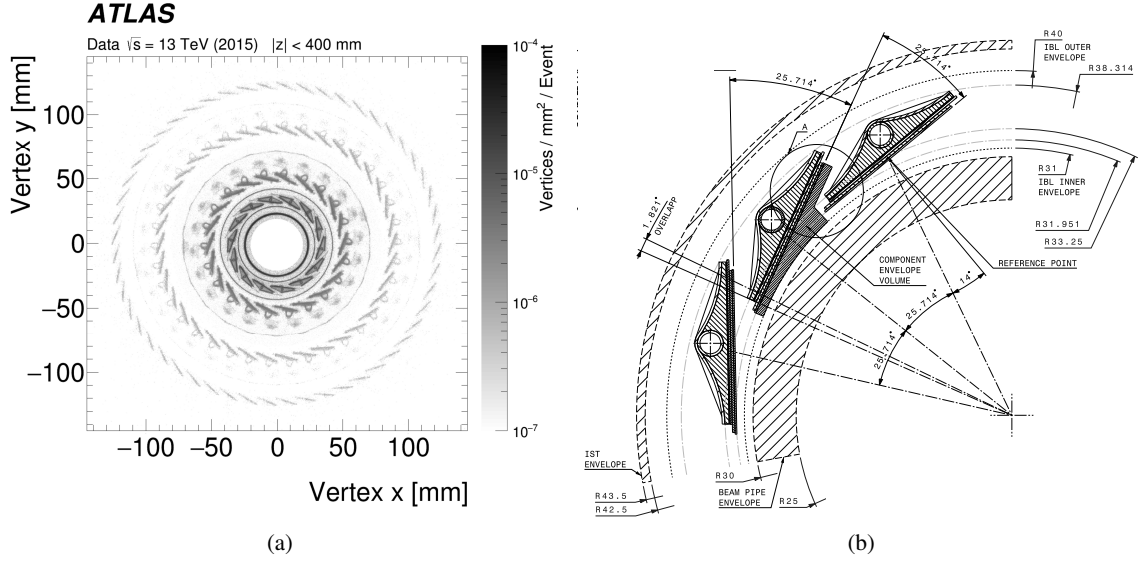


Figure 2.7: Plot (a) shows the distribution of hadronic-interaction vertex candidates within $|\eta| < 2.4$ and $|z| < 400$ mm in 2015 collisions and (b) shows the IBL layout in the $r\phi$ plane for comparison. Traces of the beam pipe, the IBL, and the three Pixel layers are clearly visible. Taken from Refs. [81] and [82].

2.2.4 Semiconductor Tracker

The SCT uses the silicon micro-strip technology and consist of 4088 modules, positioned in four layers in the barrel region and in nine disks in each of the end-caps. Modules in the barrel have an area of $64.0 \text{ mm} \times 63.6 \text{ mm}$ and 768 strips each with a pitch of $80 \mu\text{m}$ whereas the pitch varies in the end-cap modules from about 55 to $95 \mu\text{m}$. All in all, the SCT has 6.3×10^6 readout channels. The micro-strip sensors are mounted back-to-back (glued together) and under an angle of 40 mrad in order to determine the z -coordinate of the hits along the strip length. The hit resolution of the SCT modules is $17 \mu\text{m}$ in the transverse direction and $580 \mu\text{m}$ in the longitudinal direction.

2.2.5 Transition radiation tracker

The TRT is a straw tracker and the outermost part of the ID covering the phase-space up to $|\eta| < 2.0$. It is built of about 3.0×10^5 carbon-fiber reinforced Kapton straws filled with Xe or Ar gas mixtures. The diameter of the tubes is 4 mm and each tube contains a $30 \mu\text{m}$ thick gold-plated tungsten wire, serving as the anode. The potential difference between the straw and the anode is roughly 1.5 kV. The barrel section has the straws aligned with the direction of the beam axis and the two end-cap sections have the straws arranged in planes composing wheels, aligned perpendicular to the beam axis, pointing outwards in the radial direction. For the radiator material polypropylene fibers interwoven between straw layers are used in the barrel section and polypropylene foils in the two end-caps. The signal on each wire is amplified and discriminated against two different thresholds, named low- and high-thresholds. Passage of charged particles through the polypropylene fiber stimulates transition

radiation emission of X-rays, which contribute to high-threshold hits due to absorption in the TRT gas mixture. This phenomenon occurs only for electrons and positrons and not for heavier particles such as pions, therefore the TRT can be used for electron identification. Primarily, Xenon was chosen for the gas mixture due to its high efficiency to absorb TR photons of typical energy 6 to 15 keV. Charged particles transversing the TRT yield large number of hits compared to Pixel and SCT—around 34 on average—however, it only provides a two-dimensional hit information along the $r\phi$ plane with a hit resolution of about 130 μm . In Run 1, it was filled completely with a Xenon gas mixture, while in Run 2 some parts of the detector were also filled with argon.

2.2.6 Calorimeters

The ATLAS calorimeters surround the ID and cover the full ϕ phase-space and the $|\eta|$ space up to 4.9. The calorimeters destructively stop most of the particles from the IP—except neutrinos and muons—and are used to measure their energy. The ATLAS calorimetry consists of the LAr calorimeter and the tile calorimeter. Both are separated in barrel and two end-cap while the LAr calorimeter also has forward structures. The LAr calorimeter [83] has both electromagnetic (EM) and hadronic functionalities, while the tile calorimeter [84] is used exclusively for hadronic measurements. The LAr barrel calorimeter is an EM calorimeter, 6.4 m long and 53 cm thick, while the LAr end-caps have both EM and hadronic functionalities. LAr end-caps have a thickness of about 0.6 m and a radius of about 2 m. Furthermore, the tile barrel is 5.6 m long and the two tile end-caps are 2.6 m long. The EM calorimeter has a fine segmentation for precise measurement of energy of electrons and photons and hadronic calorimeters have coarser structures that allow for a precise measurement of jet kinematics. The ATLAS calorimetry is schematically presented in Figure 2.8.

2.2.7 LAr electromagnetic calorimeter

The electromagnetic calorimeter is a lead-liquid argon sampling detector made of lead absorption plates as passive medium and liquid argon as active material. Lead was chosen as absorption material due to its large electromagnetic interaction cross-section. Energetic electrons and photons transversing the lead medium mainly interact with the detector material via bremsstrahlung and pair production, which causes a cascade of secondary particles and the energy is eventually dispersed. The design resolution of EM calorimeter is $\sigma_E/E = 10\%/\sqrt{E [\text{GeV}]} \oplus 0.7\%$. The EM calorimeter has two parts: the barrel region composed of two identical detectors separated only by a small gap at the center of the ATLAS detector (4 mm) and two end-caps. The barrel regions covers the phase-space up to $|\eta| < 1.5$ and the two end-caps cover the region $1.32 < |\eta| < 3.2$. The transition region between the barrel and end-cap EM calorimeter within $1.37 < |\eta| < 1.52$ is usually excluded from ATLAS analyses due to a worse reconstruction efficiency of electrons. Each end-cap calorimeter consists itself of two co-axial wheels, with a 3 mm boundary between them located at $|\eta| < 2.5$, corresponding to the acceptance of the ATLAS ID.

The EM calorimeter modules exhibit an accordion shape to provide a full coverage in ϕ without any azimuthal cracks. High voltage is applied between the lead absorption plates to collect the ionization electrons from the interaction in the liquid argon as well as to amplify the signal. The readout electrodes are placed in the gaps between the absorbers and consist of three conductive copper layers

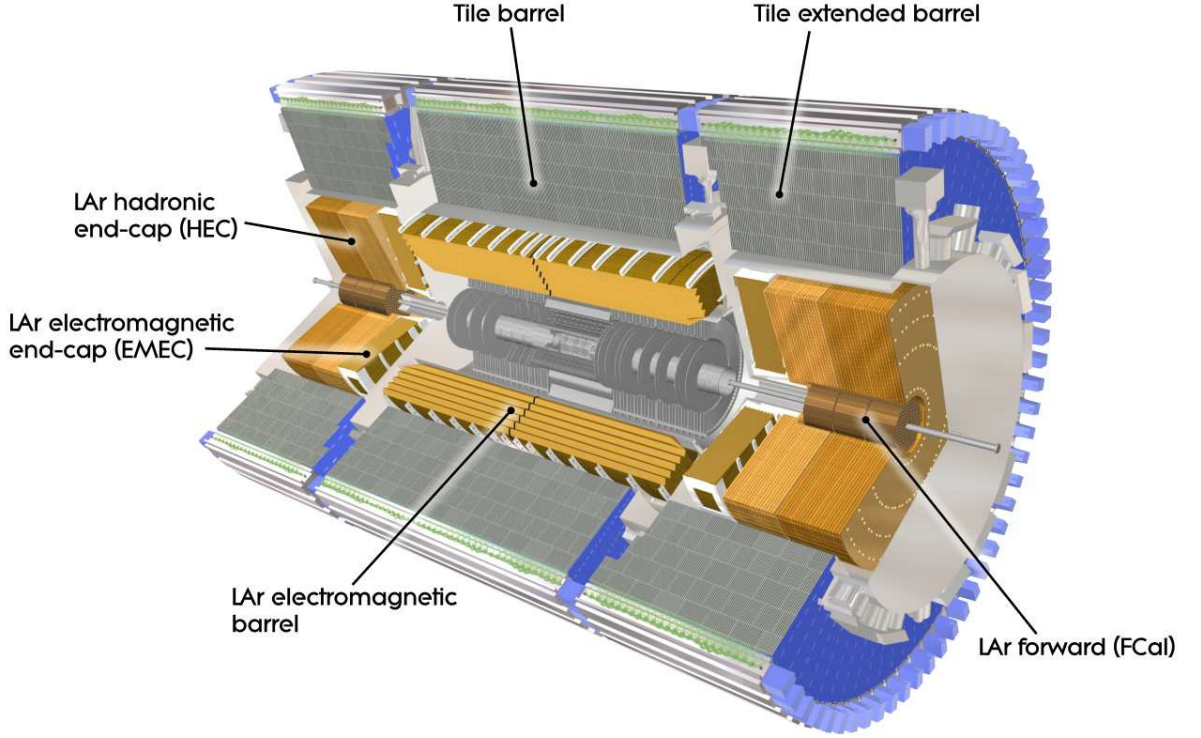


Figure 2.8: Schematic overview of the ATLAS electromagnetic and hadronic calorimeters. Taken from Ref. [79].

separated by insulating polyimide sheets, where the outer two layers are at high-voltage potential and the middle layer is used for readout. The total thickness of the EM calorimeter is larger than $24 X_0$ ¹ in the barrel and larger than $26 X_0$ in the end-caps. The barrel EM calorimeter modules are assembled into three layers, as shown in Figure 2.9(a). The first layer—called the strip layer, or ‘strips’—has a very fine structure to provide precise energy measurement of electrons and photons used as input for their identification. The fragmentation of the first layer is $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$. Furthermore, the second layer absorbs most of the electromagnetic cascades and has a granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. The last layer is designed to collect the tail of the electromagnetic cascades and to determine the amount of energy lost beyond the EM calorimeter. It has broader structures of $\Delta\eta \times \Delta\phi = 0.005 \times 0.025$. Moreover, the end-cap modules have a similar shape and structure: accordion geometry with three longitudinal layers with similar thickness as the barrel modules.

¹ X_0 is the radiation length, representing the average path the particle needs to travel to reduce its initial energy by a factor of $1/e$.

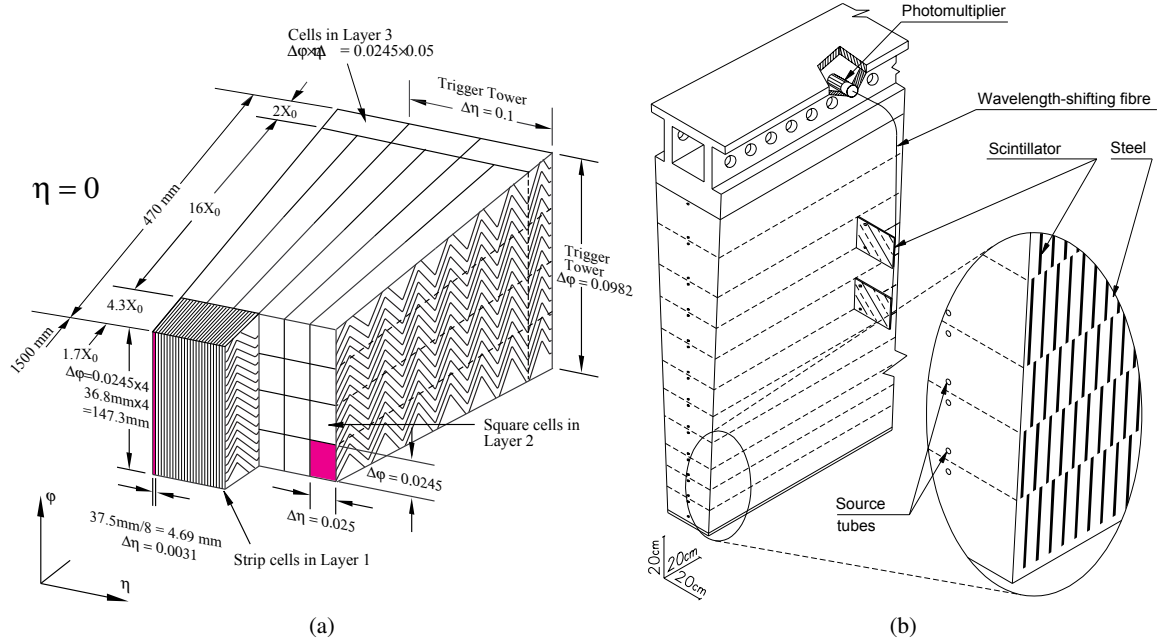


Figure 2.9: Sketch of ATLAS calorimeter modules: (a) a barrel LAr module where the different layers are clearly visible with the ganging of electrodes in ϕ . The granularity in η and ϕ of the cells of each of the three layers and of the trigger towers is also shown. (b) shows how the mechanical assembly and the optical readout of the tile calorimeter are integrated together. The various components of the optical readout, the fibres and the photomultipliers are shown. Taken from Ref. [79].

2.2.8 Hadronic calorimetry

The hadronic calorimeters are positioned around the volume of the EM calorimeter and are separated into several sampling calorimeters using different technologies that target specific physics performance needs in pseudorapidity ranges of interest. Furthermore, the choice of the particular technology and the used materials reflect also the radiation flux as a function of pseudorapidity. The three parts of the hadronic calorimeter are shown in Figure 2.8.

Tile calorimeter

In the central region of the hadronic calorimeter is placed the tile sampling calorimeter, which covers the range $|\eta| < 1.7$. It employs steel tiles as passive absorber material and plastic scintillators as active material. It is further separated into the ‘long barrel’ in the range $|\eta| < 1.0$ and two ‘extended barrels’ in the range $0.8 < |\eta| < 1.7$. A schematic overview of a tile calorimeter module is shown in Figure 2.9(b). The signal from the scintillator is read out through wavelength shifting fibers and directed to photomultipliers. Both central and extended barrels consist of 64 modules positioned in ϕ with a granularity of $\Delta\phi = 0.1$ rad. Similarly to the EM calorimeter structure, the tile calorimeter has three layers as well. In units of the hadronic interaction length, the thickness of the layers from

2 Experimental Setup

the innermost to the outermost is approximately 1.5, 4.1, and 1.8 in the central barrel and 1.5, 2.6, and 3.3 in the two extended barrels.

Hadronic end-cap LAr calorimeters

The hadronic end-cap LAr calorimeter (HEC) is a copper/LAr sampling calorimeter and covers the range $1.5 < |\eta| < 3.2$. The materials were chosen due to their radiation hardness in a region exposed to significant fluxes. Each HEC is built of two wheels and each wheel has four longitudinal layers, with the granularity varying from $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ to $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$. Furthermore, each wheel is built from 32 modules using copper as absorber material interleaved with 8.5 mm LAr gaps as active material.

Forward LAr calorimeters

Lastly, the Forward LAr Calorimeters (FCal) covers the forward region in $3.1 < |\eta| < 4.9$, ensuring almost a full coverage and minimizing energy losses. The FCal is composed of two end-caps that each have three modules. The modules are located approximately 4.7 m from the IP and exposed to very high particle fluxes. The first module in each end-cap uses copper as absorber—for precise electromagnetic energy deposit measurements—and the outer two modules are optimized for a high absorption length. This is achieved by using tungsten instead of copper and all three modules use LAr as active material. A schematic diagram of the three FCal modules is shown in Figure 2.10.

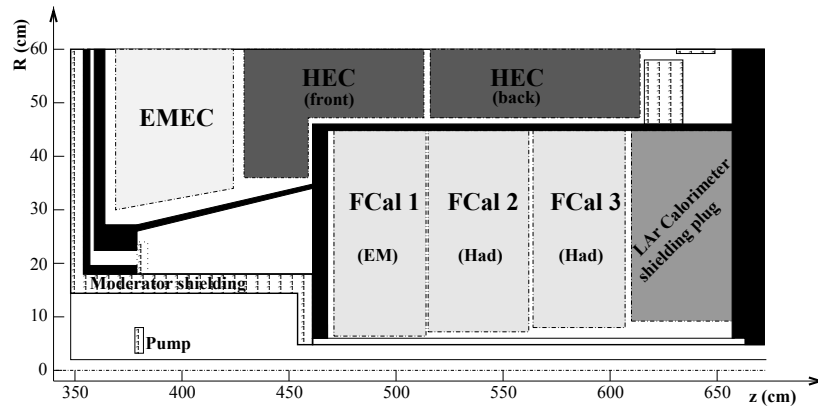


Figure 2.10: Schematic diagram showing the three FCal modules located in the end-cap cryostat. The material in front of the FCal and the shielding plug behind it are also shown. The black regions are structural parts of the cryostat. The EM calorimeter end-cap (EMEC) and the HEC are also clearly visible. Taken from Ref. [79].

The design resolution of the hadronic calorimeters is $\sigma_E/E = 50\%/\sqrt{E [\text{GeV}]} \oplus 3\%$ for the tile and LAr/HEC, while it is $\sigma_E/E = 100\%/\sqrt{E [\text{GeV}]} \oplus 10\%$ for the LAr/FCal.

2.2.9 Muon Spectrometers

The ATLAS Muon Spectrometer (MS) [85] is the outermost system in the detector and consists of a combination of toroidal superconducting magnets and precision chambers covering the range $|\eta| < 2.7$ for the measurement of the muon momenta. Furthermore, it also has a trigger system used for the ‘level-one’ trigger stage (see Section 2.2.10) covering the range $|\eta| < 2.4$. The system is shown schematically in Figure 2.11. The central part is enclosed by a barrel toroidal magnet and two end-cap toroids, that provide an azimuthal magnetic field with a bending power of 1.0 to 7.5 Tm. The muon candidates can be identified from the transverse momentum of $p_T = 3$ GeV onward and the design resolution is targeted at 10% for muons with $p_T = 1$ TeV. The ATLAS Muon Spectrometer is composed out of four sub-detectors: Monitored Drift-Tube (MDT) chambers, Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC), and Thin Gap Chambers (TGC). In the barrel region, the MS has three cylindrical layers around the beam axis and in the end-cap region, the MS has three discs (‘wheels’) perpendicular to the beam axis on each side. Example muon tracks traversing the MS are shown in Figure 2.12.

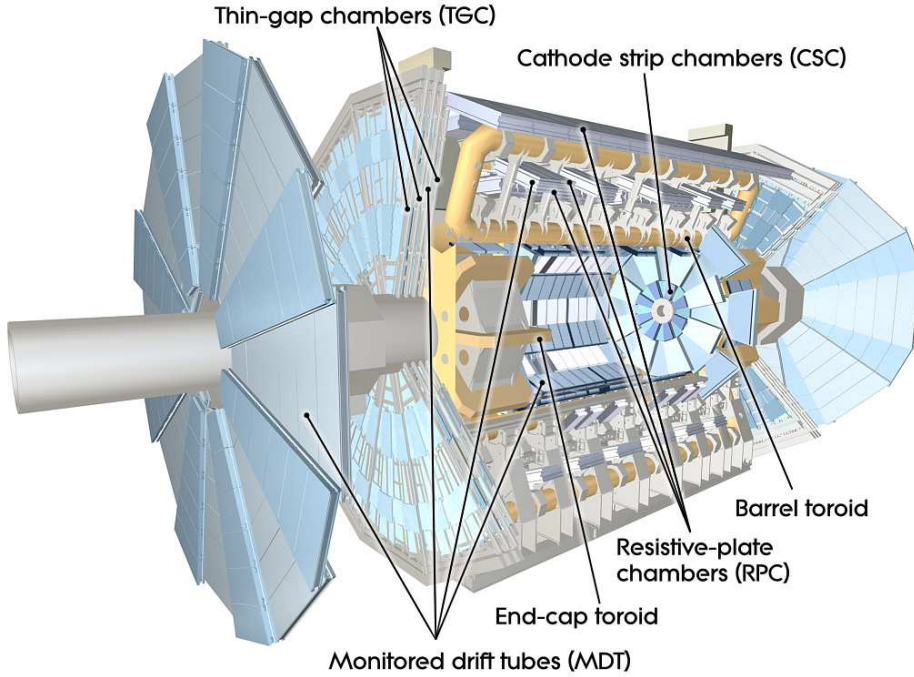


Figure 2.11: Cut away schematic view of the ATLAS Muon Spectrometer. Taken from Ref. [79].

Precision tracking chambers

All regular MDT chambers consist of two groups of tube layers, called multi-layers, separated by a mechanical spacer. In the innermost layer of the muon detector, each multi-layer consists of four tube layers to enhance the pattern-recognition performance; in the middle and outer layer of the muon detector, each multi-layer consists of three tube layers only. Figure 6.10 shows the structure

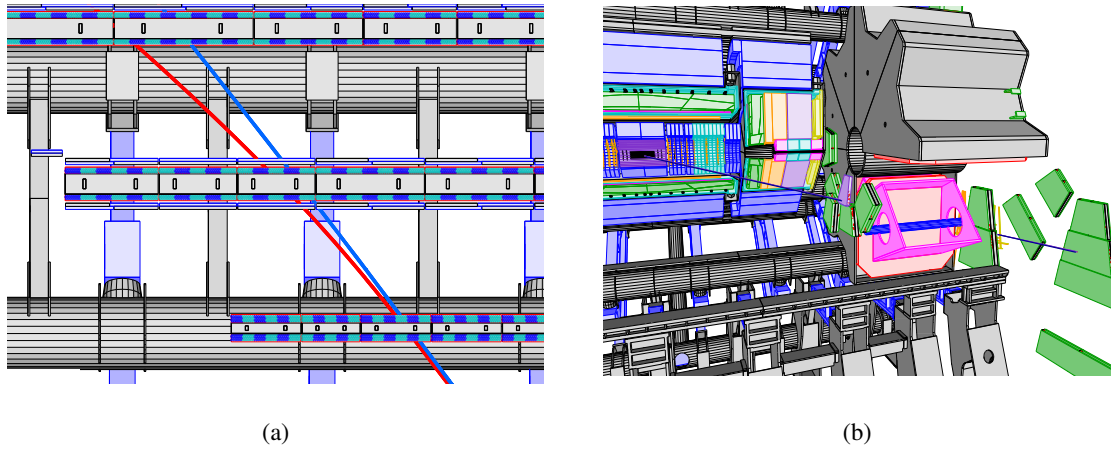


Figure 2.12: Trajectories of muons traversing the Muon Spectrometer: (a) muons with momenta of 4 GeV (red) and 20 GeV (blue) in the bending place of the barrel MS, (b) structure of the barrel and end-cap regions with a muon track at large η , passing through a CSC in the inner wheel and through MDTs in the middle and outer wheels. Taken from Ref. [79].

The majority of precision tracking chambers are MDTs. They cover the range up to $|\eta| < 2.0$ in all layers and up to $|\eta| < 2.7$ only in the innermost layer. MDTs are proportional chambers based on pressurized drift tubes filled with argon and carbon dioxide mixture (93/7) and with a tungsten-rhenium $50\,\mu\text{m}$ anode producing a radial electric field. The tubes are 1 to 6 m long and provide a 2D measurement in the transverse plane with a single hit resolution of $80\,\mu\text{m}$. Each MDT chamber consists of two groups of tube layers, called multi-layers, separated by a mechanical spacer. In the innermost layer of the MS, each multi-layer consists of four tube layers to enhance the pattern-recognition performance. In the middle and outer layer of the MS, each multi-layer consists of three tube layers only. The hit resolution of one chamber is $40\,\mu\text{m}$ and the resolution is improved to $30\,\mu\text{m}$ with three chambers of MDTs. In general, tracks in the barrel cross 2×4 inner, 2×3 middle, and 2×3 outer layers of MDT tubes. Additionally, the MS is equipped with CSCs in the range $2.0 < |\eta| < 2.7$. CSCs have a finer granularity, higher acceptance rate and time resolution compared to MDTs to compensate for a larger number of traversing particles in the forward region. CSCs are multiwire proportional chambers with wires, 2.5 mm apart, oriented in the radial direction. The same gas mixture with a different ratio is used, Ar/CO_2 (80/20). CSCs provide a 3D measurement with a resolution of $40\,\mu\text{m}$ in the bending plane and 5 mm in the non-bending one.

Fast trigger chambers

The main requirement of any trigger unit in ATLAS is the fast response time to accommodate the 25 ns bunch spacing. MDTs have a much slower response time, spanning up to about 500 ns, too slow for triggering. Specialized modules—RPCs and TGCs—are therefore needed for a muon-related triggering system. Furthermore, these specialized detectors provide complementary tracking information to the precision tracking chambers, in particular the ϕ coordinate of the tracks.

RPCs cover the range of $|\eta| < 1.05$, while the TGCs cover the range $1.05 < |\eta| < 2.4$. RPCs have three layers and are formed by two resistive plates separated by two insulating spacers that form a gap filled with a gas mixture of $\text{C}_2\text{H}_2\text{F}_4$ (94.7 %), iso- C_4H_{10} (5 %), and SF_6 (0.3 %). The created charge carriers are collected by two orthogonal copper strips that provide a 2D measurement in η and ϕ directions with a 10 mm resolution and a 1.5 ns time resolution. The TGCs are multi-wire proportional chambers with a reduced cathode-anode distance in order to give a very fast timing information, sufficient for triggering every 25 ns. The end-cap TGCs have four stations and provide a 2D measurement with a timing resolution comparable to the RPCs and the spatial resolution about 2 to 7 mm in both coordinates. TGCs are multi-wire proportional chambers with a smaller anode-to-cathode distance than the anode-to-anode distance for a fast collecting time, assembled in the end-cap wheels.

2.2.10 The ATLAS trigger system

The ATLAS trigger system is an essential component of the experiment because it determines whether a particular pp collision will be saved for offline data analysis or not. When the LHC is operating under nominal conditions, pp collisions occur at a rate of 40 MHz, corresponding to the 25 ns bunch spacing. With conditions relevant for this thesis, one recorded pp collision event is roughly 1.3 MB large [86]. To record all events, a data stream of roughly 52 TB s^{-1} would be needed, which is clearly beyond any reasonable value and not possible with the current technology.

The main goal of the trigger and the data acquisition system (collectively called ‘TDAQ’) is to perform an online event selection of pp collisions that will allow both precision measurements for well known SM processes and enhance sensitivity to new physics processes. The ATLAS trigger system [87] is composed of two layers, a hardware ‘Level-1’ (L1) trigger and a software-based ‘high-level trigger’ (HLT). The L1 trigger reduces the event rate down to about 100 kHz and the HLT further reduces it to about 1.0 kHz and all events passing the HLT are stored for offline processing. A schematic overview of the ATLAS trigger system is shown in Figure 2.13.

The L1 trigger is optimized for fast object identification and selection. It uses information both from the Muon Spectrometer trigger modules and the calorimeter and searches for high energy leptons, photons, and jets. Electrons and photons are triggered from energy deposits in the EM calorimeter, while jets candidates are reconstructed at L1 with the more coarser hadronic calorimeters. Furthermore, muons are triggered based on a coincidence of hits among several layers of trigger chambers in the MS. The L1 trigger selects a Region of Interest (RoI), defined as a $\eta - \phi$ region of the detector where interesting activity was identified, including all the information regarding the selection criteria of the corresponding objects.

Events passing the L1 trigger are further processed by the HLT using finer-granularity calorimeter information, precision measurements from the MS and tracking information from the ID, which are not available at L1. The HLT decision can either be evaluated within RoIs identified at L1 or for the full detector. Most of the HLT triggers use a two-stage approach in order to quickly reject events that do not meet the sufficient selection criteria and to perform a slower precision reconstruction for the remaining events. Furthermore, a ‘prescale’ factor N can be applied to any L1 or HLT trigger to reduce its rate by only storing $1/N$ of the selected events based on a random selection. In conclusion,

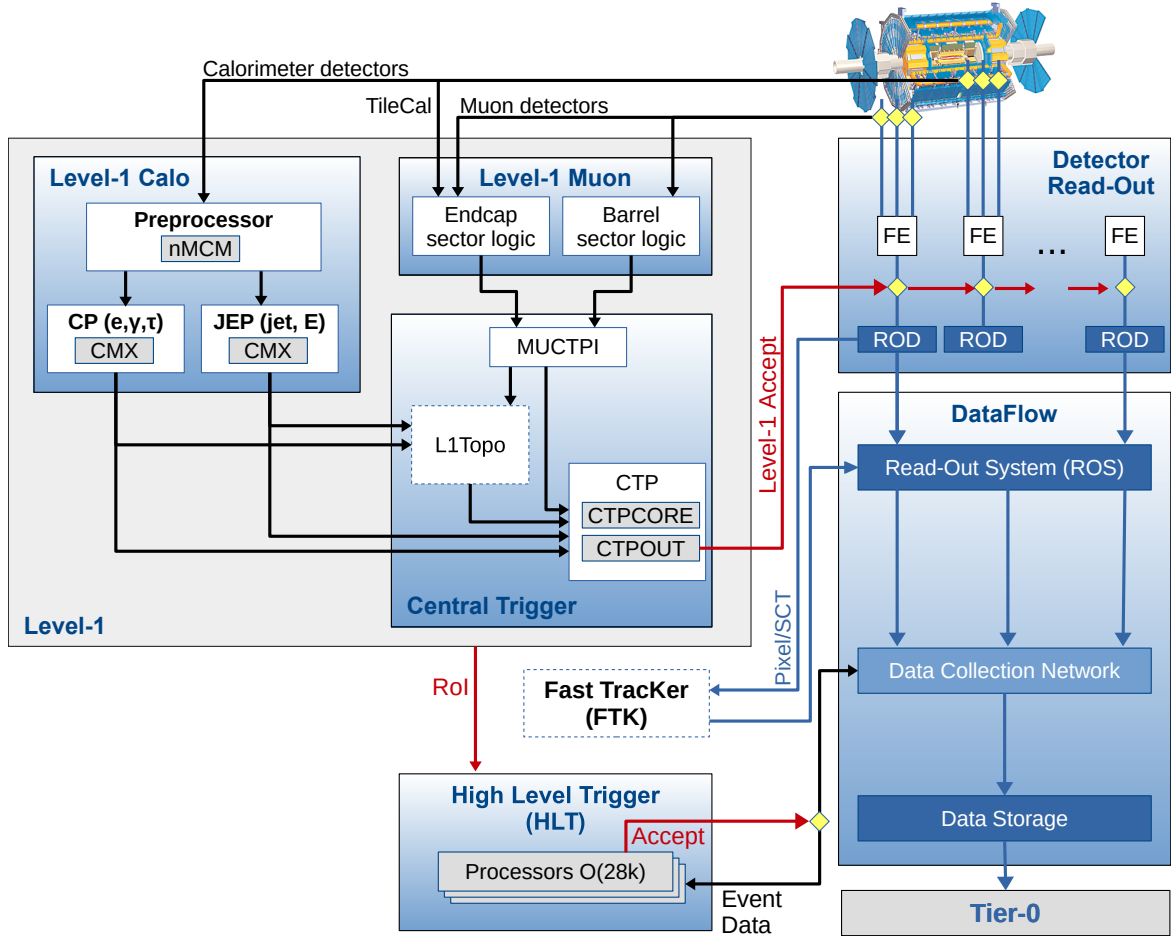


Figure 2.13: The ATLAS TDAQ system in Run 2 with emphasis on the components relevant for triggering. L1Topo and FTK were being commissioned during the entire data-taking period relevant to this thesis. Taken from Ref. [87].

the L1 + HLT system provides a selection of pp collision events targeted both at new physics searches, precise SM measurements, and performance studies, with the maximum possible bandwidth allowed by the ATLAS data acquisition infrastructure.

2.2.11 Luminosity measurement and the Beam Conditions Monitor

A good measurement of luminosity with relatively high precision ($< 5\%$) is of particular importance to perform a reliable measurement of the processes of interest. The luminosity is defined in Eq. 2.1 and measured for each bunch interaction by forward sub-detectors, mainly LUCID [88] and BCM [89]. LUCID was used as the main luminosity measurement source throughout the entire Run 2 data taking period with BCM as the backup luminosity system.

LUCID (LUMinosity measurements using Cherenkov Integrating Detector) is a Cherenkov detector located at a distance of 17 m on each side of the IP, at an $5.5 < |\eta| < 5.9$. It has sixteen mechan-

ically polished aluminum tubes filled with C_4F_{10} gas around the vacuum chamber and coupled to a photomultiplier in the back-end.

BCM (Beam Conditions Monitor) has four readout modules on each side of the IP at a distance of 184 cm and $|\eta| = 4.2$. Each module consists of two diamond sensors, read out in parallel. The stations are equipped with fast electronics with a 2 ns rise time allowing luminosity measurement of each bunch crossing. Furthermore, they measure time-of-flight and pulse height information of transversing particles to distinguish events originating from pp interactions and events occurring due to lost beam particles. In case of unwanted beam conditions the BCM can trigger the LHC beam dump to protect the silicon detectors from damage that might occur due to an uncontrolled beam loss.

The formula for the instantaneous luminosity in Eq. 2.1 can be rewritten as

$$\mathcal{L} = \frac{\mu_{\text{vis}} n_{bb} f_{\text{rev}}}{\sigma_{\text{vis}}}, \quad (2.2)$$

where σ_{vis} is the visible inelastic cross-section (i.e. total inelastic cross-section times the detector acceptance and efficiency), and μ_{vis} is the visible interaction rate per bunch crossing, measured by dedicated detectors such as LUCID or BCM. These detectors are calibrated with *Van Der Meer* scans [90], which are low-intensity LHC runs where the beam separation in the transverse planes is varied to determine the beams' overlap profile and σ_{vis} for each sub-detector.

3 Simulation of physics processes

It is necessary to make an accurate comparison of observed data with theoretical expectations to determine consistency with SM or some of its possible extensions. The simulation of the physics processes and the interactions of particles with the detector material is needed because the response of the detector is non-trivial and non-linear. Therefore, to model the expected contributions from different background or signal sources a complex simulation is required as explained in the following. Computer programs known as Monte Carlo (MC) event generators are used to generate events from specific physics processes. They randomly generate events mimicking those produced in the pp collisions reproducing the predicted distributions. Subsequently, MC techniques are also used to simulate the interaction of generated particles with the detector materials and the read-out of the detector.

The response of the ATLAS detector was simulated using the GEANT 4 toolkit [91]. Both data and simulated events were reconstructed with the default ATLAS software [92] and simulated events were corrected to better match the performance measured in data. This chapter presents an overview of the MC generators used to generate physics processes relevant for the analyses in this thesis (Section 3.1), followed by a description of the ATLAS reconstruction and identification algorithms (Section 4).

3.1 Simulated event samples

All simulated event samples used are summarized in Table 3.1. Detailed descriptions of the configurations used to generate these events are described below.

3.1.1 Signal simulated events

Signal samples for the $pp \rightarrow H^{++}H^{--}$ process were generated at leading-order (LO) using the LRSM package of PYTHIA 8.186 [94] which implements the $H^{\pm\pm}$ scenario described in Ref. [113]. The program was configured to use the NNPDF2.3 [95] parton distribution function (PDF) set. The $h_{\ell\ell'}$ couplings of lepton pairs in Eq. 1.59 were assumed to be the same for $H_R^{\pm\pm}$ and $H_L^{\pm\pm}$ particles. This choice resulted in a good statistical coverage of all possible decay channels. The production of the $H^{\pm\pm}$ was implemented only via the Drell–Yan process. Originally, the cross-section at $\sqrt{s} = 14$ TeV was calculated with NLO accuracy by the authors of Ref. [114]. Subsequently, a rescaling to $\sqrt{s} = 13$ TeV with the CTEQ6 PDF [115, 116] set was provided. The cross-sections and corresponding K -factors are summarized in Table 3.2.

Since the analysis in this thesis exclusively targets the leptonic decays of the $H^{\pm\pm}$ bosons, the vacuum expectation value of the neutral component of the left-handed Higgs triplet (v_L) was set to zero in

3 Simulation of physics processes

Table 3.1: Simulated signal and background event samples: the corresponding event generator, parton shower, cross-section normalization, PDF set used for the matrix element and set of tuned parameters are shown for each sample. The cross-section in the event generator that produces the sample is used where not specifically stated otherwise. Taken from Ref. [93].

Physics process	Event generator	ME PDF set	Cross-section normalisation	Parton shower	Parton shower tune
Signal					
$pp \rightarrow H^{++}H^{--}$	PYTHIA 8.186 [94]	NNPDF2.3NLO [95]	NLO (see Table 3.2)	PYTHIA 8.186	A14 [96]
Keung-Senjanović	MG5_AMC@NLO 2.2.2 [97, 98]	NNPDF2.3NLO	LO	PYTHIA 8.186	A14
Drell–Yan					
$Z/\gamma^* \rightarrow \ell\ell$	POWHEG-Box v2 [99–101]	CT10 [102]	NNLO [103]	PYTHIA 8.186	AZNLO [104]
$Z/\gamma^* \rightarrow \ell\ell$	SHERPA 2.2.1 [105]	SHERPA	NLO [103]	NNPDF3.0NLO	SHERPA default
$W \rightarrow \ell\nu$	SHERPA 2.2.1 [105]	SHERPA	NLO [103]	NNPDF3.0NLO	SHERPA default
Top quark processes					
$t\bar{t}$	POWHEG-Box v2	NNPDF3.0NLO [106]	NNLO [107]	PYTHIA 8.186	A14
Single top	POWHEG-Box v2	CT10	NLO [108]	PYTHIA 6.428 [109]	Perugia 2012 [110]
$t\bar{t}W, t\bar{t}Z/\gamma^*$	MG5_AMC@NLO 2.2.2	NNPDF2.3NLO	NLO [111]	PYTHIA 8.186	A14
$t\bar{t}H$	MG5_AMC@NLO 2.3.2	NNPDF2.3NLO	NLO [111]	PYTHIA 8.186	A14
Diboson					
Fully leptonic	SHERPA 2.2.2	NNPDF3.0NLO	NLO [112]	SHERPA	SHERPA default
Semi leptonic	SHERPA 2.2.1	NNPDF3.0NLO	NLO [112]	SHERPA	SHERPA default
Loop induced	SHERPA 2.1.1	CT10	NLO [112]	SHERPA	SHERPA default

order to exclude $H^{\pm\pm} \rightarrow WW$ decays (see Eq. 1.58 and Figure 1.9). The decay width of the $H^{\pm\pm}$ particle to leptons depends on the $h_{\ell\ell'}$ couplings in Eq. 1.59. These were set to the value $h_{\ell\ell'} = 0.02$ in all PYTHIA 8.186 samples. This setting corresponds to a decay width that is negligible compared to the detector resolution. The $h_{\ell\tau}$ and $h_{\tau\tau}$ couplings were fixed at zero. In total, 23 MC samples with different $H^{\pm\pm}$ particle masses, starting from 200 GeV up to 1300 GeV in steps of 50 GeV were generated. The ATLAS detector is expected to have the best $H^{\pm\pm}$ mass resolution in the electron–electron final states. Resolutions around 30 GeV for masses of 200 to 500 GeV and 50 to 100 GeV for higher masses can be achieved with the event selection defined in Section 4. Furthermore, the $H^{\pm\pm}$ mass resolution in electron–muon final states varies from 50 to 150 GeV and from 50 to 200 GeV in muon–muon final states.

Signal events for the Keung-Senjanović process were generated with MG5_AMC@NLO 2.2.2 [97, 98], using PYTHIA 8.186 with the NNPDF2.3 PDF set and A14 parameter set used for shower tuning. A version of an LRSM model produced with FeynRules [117], was implemented in MG5_AMC@NLO [118] and further modified by the authors of Refs. [69] and [70]. Events were generated containing only Majorana N_R neutrinos, however, Dirac neutrinos can be mimicked by selecting only opposite-charge signal events and scaling the cross-section by a factor of two. Signal samples were generated at different W_R boson and N_R neutrino mass hypotheses, covering a range from 600 to 5800 GeV for $m(W_R)$ and 50 to 8000 GeV for $m(N_R)$. Only samples with $m(N_R) \leq 2m(W_R)$ are used as the cross-section for the KS process drops off rapidly with increasing N_R neutrino mass. We assume the right and left handed weak gauge couplings are the same ($g_L = g_R$). N_R^e , N_R^μ and N_R^τ neutrinos are present in these samples, however there is no mixing between flavors. Only N_R^e and N_R^μ neutrinos are targeted in the analysis strategy.

Table 3.2: NLO cross-sections for the pair production of $H_L^{++}H_L^{--}$ and $H_R^{++}H_R^{--}$ in pp collisions at $\sqrt{s} = 13$ TeV, together with the correction factors ($K = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$) used to obtain those values from the LO prediction. These K -factors are calculated by the authors of Ref. [114] using the CTEQ6 PDF [116]. Taken from Ref. [93].

$m(H^{\pm\pm})$ [GeV]	$\sigma(H_L^{\pm\pm})$ [fb]	$K\text{-factor}(H_L^{\pm\pm})$	$\sigma(H_R^{\pm\pm})$ [fb]	$K\text{-factor}(H_R^{\pm\pm})$
300	13	1.25	5.6	1.25
350	7.0	1.25	3.0	1.25
400	3.9	1.24	1.7	1.24
450	2.3	1.24	0.99	1.24
500	1.4	1.24	0.61	1.24
600	0.58	1.23	0.25	1.24
700	0.26	1.23	0.11	1.23
800	0.12	1.22	0.054	1.23
900	0.062	1.22	0.027	1.23
1000	0.032	1.22	0.014	1.24
1100	0.017	1.23	0.0076	1.24
1200	0.0094	1.23	0.0042	1.25
1300	0.0052	1.24	0.0023	1.26

3.1.2 Standard Model simulated events

The SM Drell–Yan processes with decays $Z \rightarrow ee$, $Z \rightarrow \mu\mu$, and $Z \rightarrow \tau\tau$ are nominally simulated using the SHERPA 2.2.1 event generator. Matrix elements are calculated for up to two partons at next-to-leading-order (NLO) and four partons at LO using Comix [119] and OpenLoops [120] and merged with the SHERPA parton shower [121] according to the ME+PS@NLO prescription [122]. The NNPDF3.0NNLO [106] PDF set is used.

Specifically for higher masses (130 to 13 000 GeV) of the Z boson, the high-mass Drell–Yan process was modelled using POWHEG-Box v2 [99–101] interfaced to PYTHIA 8.186 for parton showering. The CT10 PDF [102] was used to calculate the hard scattering process. A set of tuned parameters called the AZNLO tune [104] was used in combination with the CTEQ6L1 PDF set [115, 116] to model non-perturbative effects. PHOTOS++ version 3.52 [123] was used for photon emissions from electroweak vertices and charged leptons. The generation of the process was divided into 19 samples with subsequent invariant mass intervals to guarantee a good statistical coverage over the entire mass range up to the energy of pp collisions. Higher-order corrections were applied to these Drell–Yan simulated events to scale the mass-dependent cross-section computed at NLO in the strong coupling constant with the CT10 PDF set to next-to-next-to-leading order (NNLO) in the strong coupling constant with the CT14NNLO PDF set [103]. The corrections were calculated with VRAP [124] for QCD effects and MCSANC [125] for electroweak effects. The latter are corrected from LO to NLO.

Diboson processes with four charged leptons (4ℓ), three charged leptons and one neutrino ($3\ell+1\nu$), or two charged leptons and two neutrinos ($2\ell+2\nu$) in the final state were generated using SHERPA 2.2.2 with the NNPDF3.0 PDF set. The considered matrix elements contained all diagrams with four

electroweak vertices. They were calculated for up to three partons at LO accuracy and up to one (4ℓ , $2\ell+2\nu$) or zero partons ($3\ell+1\nu$) at NLO in QCD using the Comix and OpenLoops matrix element generators. Diboson processes with one boson decaying hadronically and the other one decaying leptonically were generated with SHERPA 2.2.1 using the NNPDF3.0 PDF set. They were calculated for up to three additional partons at LO accuracy and up to one (ZZ) or zero (WW, WZ) additional partons at NLO using the Comix and OpenLoops matrix element generators. Loop-induced diboson production and processes with two same-charge W gauge bosons were simulated with SHERPA 2.1.1. The prediction is at LO accuracy in QCD while up to one additional parton is merged with the matrix element. The CT10 PDF set was used in conjunction with a dedicated parton shower tuning. The SHERPA 2.1.1 diboson prediction was scaled by 0.91 to account for differences between the internal electroweak scheme used in this SHERPA version and the default scheme.

The $t\bar{t}$ process was generated with the NLO QCD event generator PowHEG-Box v2 which was interfaced to PYTHIA 8.186 for parton showering. The A14 parameter set was used together with the NNPDF2.3 PDF set for tuning the shower. Furthermore, the PDF set used for generation was NNPDF3.0. Additionally, top-quark spin correlations were preserved through the use of MADSPIN [126]. The predicted $t\bar{t}$ production cross-section is 832^{+20}_{-30} (scale) ± 35 (PDF + α_s) pb as calculated with TOP++2.0 [107] to NNLO in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading-log order. The top-quark mass was assumed to be 172.5 GeV. The scale uncertainty results from independent variations of the factorisation and renormalisation scales, while the second uncertainty is associated with variations of the PDF set and α_s , following the PDF4LHC [127] prescription using the MSTW2008 68% CL NNLO [128], CT10 NNLO [129], and NNPDF2.3 PDF sets.

Single-top-quark events produced in Wt final states were generated by PowHEG-Box v2 with the CT10 PDF set used in the matrix element calculations. Single-top-quark events in other final states were generated by PowHEG-Box v1. This event generator uses the four-flavour scheme for the NLO QCD matrix element calculations together with the fixed four-flavour PDF set CT10f4. The parton shower, hadronisation, and underlying event were simulated with PYTHIA 6.428 [109] using the CTEQ6L1 PDF set and the corresponding Perugia 2012 tune (P2012) [110]. The top-quark mass was set to 172.5 GeV. The NLO cross-sections used to normalise these MC samples are summarised in Ref. [108].

The $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$ processes were generated at LO with MG5_AMC@NLO v2.2.2 [97] and MG5_AMC@NLO v2.3.2 using the NNPDF2.3 PDF set. PYTHIA 8.186 was applied for shower modelling configured with the A14, as explained in more detail in Ref. [130]. They were normalized using theoretical cross-sections summarized in Ref. [111].

Additional rare backgrounds such as the production of four or three top quarks, as well as the $t\bar{t}WW$, $t\bar{t}WZ$, tZ , and tWZ production were found to be negligible in both analyses covered by this thesis.

The effect of the pile-up was included by overlaying minimum-bias collisions, simulated with PYTHIA 8.186 with a set of tuned parameters referred to as the A2 tune [131] and the MSTW2008LO PDF [132], on each generated signal and background event. Simulated samples are weighted to reproduce the distribution of the average number of interactions per pp bunch crossing observed in data (see Figure 2.2).

3.1.3 Truth classification in MC samples

Precise truth classification is crucial for analyses that combine data-driven and MC background estimation techniques in order to avoid overlap between the two, as described further in Sections 7.1 and 7.2. Furthermore, truth classification is important for MC performance studies. Particles in simulated events are separated into two categories: *truth* particles and *reconstructed* particles. Truth particles are the ones created in MC generators and reconstructed particles are objects identified by ATLAS reconstruction algorithms from the detector response created by simulated truth particles. Furthermore, truth leptons in MC samples can be divided into several categories:

- **prompt:** leptons originating from Z , W , and H boson decays, or leptons from τ decays if the τ originates from a prompt decay (e.g. $Z \rightarrow \tau^+ \tau^-$),
- **non-prompt:** decays of light-flavour or heavy-flavour hadrons into light leptons or photons that consequently convert,
- **fake:** jets which satisfy the lepton identification criteria or leptons incorrectly identified as wrong-flavor leptons.

Non-prompt and fake leptons are collectively called ‘fakes’. Simulated events with fakes are removed because background processes with reconstructed fake leptons are modelled using data-driven techniques instead, as described in Section 7.2. Using fake leptons from Monte Carlo would thus result in double counting.

Another crucial aspect is that true electric charge of electrons in simulated events must also be obtained to correct the charge reconstruction in MC with the charge-flip scale factors derived from the data, as described in Section 7.1.

Truth classification of reconstructed leptons is performed in several steps. Firstly, each reconstructed lepton is assigned a truth lepton that most likely caused the detector response leading to reconstructing this particular object. This process is called *truth matching*. For electrons, the major component of truth matching to charged truth particles is the *truth match probability*, constructed as the ratio of ID hits caused by the truth electron to the number of all ID hits of the electron’s track. Furthermore, hits are weighted depending on the position in the detector; pixel hits are weighted with a factor of 10, SCT hits with a factor of 5, and TRT hits with a factor of 1. The truth electron with the largest truth match probability is then matched to the reconstructed electron.

For muons it is sufficient to check the truth origin of the matched truth muon to determine whether the muon is prompt or not. However, for electrons this classification alone is not sufficient because electrons can originate from photon conversions, whereas this process is negligible for muons. Photons that subsequently convert and yield a reconstructed electron can originate either from prompt electrons (bremsstrahlung radiation), light-flavor hadrons (Dalitz π_0 decay), or final state radiation (FSR). Among the three, only electrons originating from bremsstrahlung photons are considered as prompt electrons (estimated with simulation) and the rest are considered fakes (estimated with data-driven methods). The difference between bremsstrahlung and FSR is that in case of bremsstrahlung, the photon is created due to interactions with the material detector (in the GEANT 4 simulation), while in the case of FSR, the real photon is already created in the generator and is usually very collimated with the electron that emitted it. Electrons originating from bremsstrahlung are in most

cases successfully recovered by the electron-specific track reconstruction described in Section 4.4.2, while fake electrons are typically displaced and do not correspond to the primary vertex as well. To distinguish between these sources, additional classification is needed for electrons. In cases where the truth matched electron originates from a photon, it is needed to trace back the decay chain until the first generator truth particle is reached (bremsstrahlung is caused by interactions of charged particles with the detector material and therefore occurs in the GEANT 4 simulation). If this generator particle originates from a prompt source (e.g. Z boson), the reconstructed electron is classified as prompt and the reconstructed electron is classified as fake if the corresponding generator particle originates from a photon (FSR or light-flavor decays). The truth matching scheme for electrons is illustratively presented in Figure 3.1.

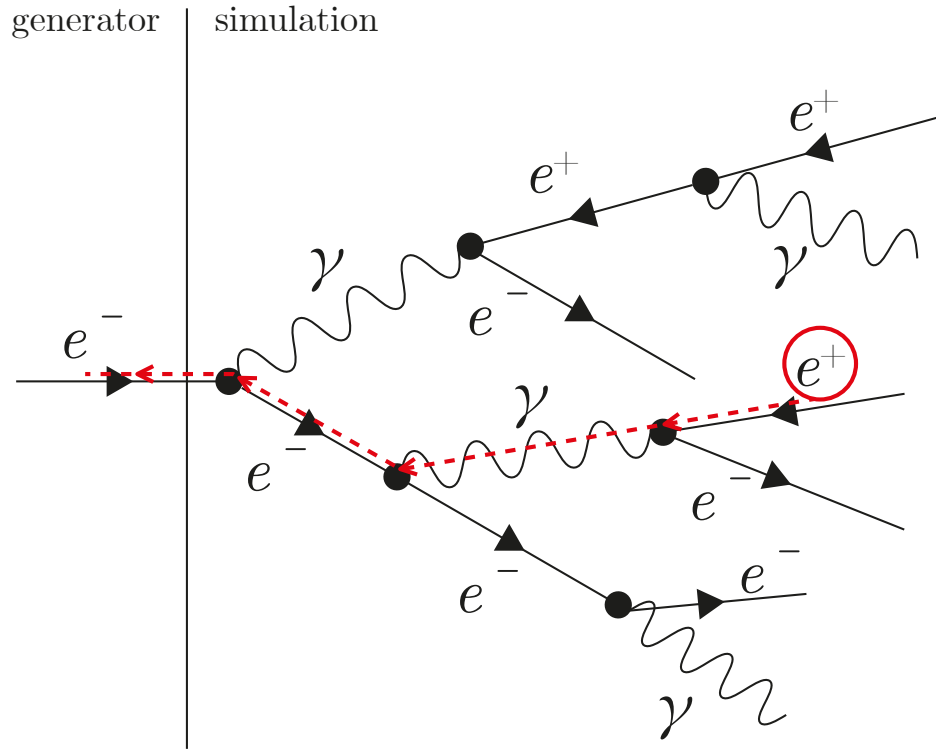


Figure 3.1: Schematic view of the electron truth classification. Reconstructed electron is matched to one of the truth electrons in the decay chain (encircled). The true charge is found by looping back through the decay chain until a first vertex from the generator is found.

4 Event reconstruction

Particles produced by pp collisions traversing the ATLAS detector leave signatures in various sub-systems in the form of energy deposits (or charge deposits) caused by the electromagnetic interaction. The raw information from various sub-detectors—the detector response—is combined and used to reconstruct the corresponding particle candidates and their physical properties. This process of forming high-level objects from the detector response is called the *event reconstruction*. The reconstruction of electrons, muons, jets, b-jets and missing transverse energy is discussed in detail in this Section along with the calibration and identification of these objects.

4.1 Track reconstruction

Due to the solenoidal magnetic field of the ID, a charged particle moves along a helicoidal trajectory with a curvature inversely proportional to its momentum. These trajectories can be fully parametrized by five parameters and the representation used in the ATLAS reconstruction is

$$(d_0, z_0, \phi_0, \theta, q/p), \quad (4.1)$$

where d_0 is the transverse impact parameter, z_0 is the longitudinal impact parameter. Furthermore, ϕ_0 and θ are defined as the azimuthal and the polar angle of the track at its perigee¹, and q/p defines the orientation and the curvature of the helicoidal trajectory with q corresponding to the electric charge of the charged particle and p corresponding to the momentum of the particle. A graphical presentation of the five track defining parameters is presented in Figure 4.1.

The charged particles trajectories are identified in the ID using a set of local and global pattern recognition algorithms, referred to as New Tracking [134], and is performed in several steps and described in detail in Ref. [135]. The first step is to form *track seeds* from sets of three space-points corresponding to *clusters* in the ID sub-detectors. The pixel detectors measure the charge collected in each individual pixel using the time over threshold (ToT) [136]. ToT is the time the pulse exceeds a given threshold and is proportional to the deposited energy. Clusters are constructed by a connected component analysis (CCA) [137] that groups pixels and strips in a given sensor with a common edge or corner where the deposited energy yields a charge above threshold. The basic units of detectors (pixels or strips) where the signal is above threshold are called *hits*.

To maximize the purity of seeds that result in good-quality tracks, seed types are considered starting with SCT-only, then PIX-only, and finally mixed-detector seeds. Furthermore, a combinatorial

¹ The perigee is the point of closest approach of a reference point. In ATLAS this point is usually chosen as the position of the beam-line.

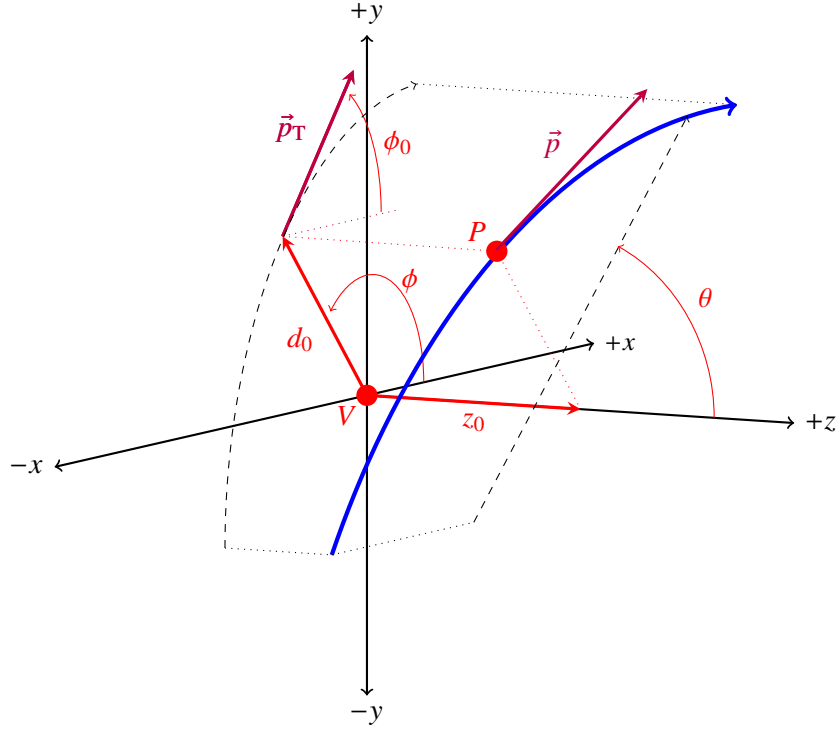


Figure 4.1: Graphical view of the defining track parameters at the perigee. Taken from Ref. [133].

Kalman filter [138] is used to build track candidates from the chosen seeds by incorporating additional space-points from the remaining layers of the PIX and SCT sub-detectors which are compatible with the preliminary trajectory. The Kalman filter creates multiple track candidates for each seed if more than one compatible space-point extension exists on the same sub-detector layer. Moreover, pixel clusters compatible with multiple track candidates are frequent in dense environments such as pp collisions at the LHC. This ambiguity is solved by a dedicated scoring algorithm [135] which assigns a score to each track candidate according to its properties (e.g. χ^2 of the track fit) as well as the number of *holes* and *shared hits* associated to it. Holes are defined as the sensor elements where a hit is expected by the track fit but none was registered and shared measurements are defined as hits that are assigned to multiple track candidates. Shared hits are those which are used in multiple reconstructed tracks but are not sufficiently compatible with the properties of a merged cluster to be identified as merged by the reconstruction. Finally, track candidates are automatically rejected by the scoring algorithm if they fail to meet any of the following basic quality criteria:

- $p_T > 400 \text{ MeV}$,
- $|\eta| < 2.5$,
- Minimum of seven PIX and SCT clusters,
- Maximum of either one shared PIX cluster or two shared SCT clusters on the same layer,
- Not more than two holes in the combined PIX and SCT detectors,

- Not more than one hole in the PIX detector,
- $|d_0^{\text{BL}}| < 2.0 \text{ mm}$,
- $|z_0^{\text{BL}} \sin \theta| < 3.0 \text{ mm}$,

where d_0^{BL} and z_0^{BL} are the impact parameters calculated with respect to the measured beam-line position. Furthermore, to aid the scoring algorithm and to minimize the loss of efficiency due to limitations on the number of shared clusters per track, an artificial neural network (NN) trained to identify merged clusters is used [139]. Lastly, the track candidates fulfilling all the requirements listed above are refitted with a high-resolution fit using the positions of the hit clusters determined with NNs [139]. Delaying the high-resolution track fit until this stage is advantageous as it is a relatively CPU-intensive process. An example track reconstruction efficiency performance is presented in Figure 4.2, which shows the efficiency to reconstruct charged primary particles close to jets as a function of the distance between the charged particle and the jet.

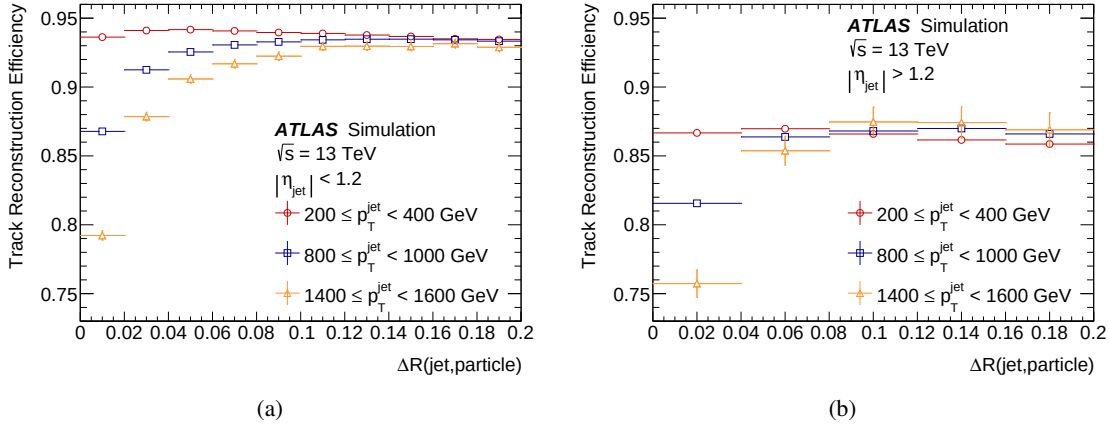


Figure 4.2: The efficiency to reconstruct charged primary particles in jets with (a) $|\eta| < 1.2$ and (b) $|\eta| > 1.2$ is shown as a function of the angular distance of the particle from the jet axis for various jet p_T for simulated dijet MC events. Taken from Ref. [135].

4.2 Primary vertices

Multiple interaction vertices are usually reconstructed in each event due to a large number of pp collisions per bunch crossing. Using the reconstructed tracks, primary vertices are reconstructed with an adaptive vertex fitting algorithm [140]. In order to improve the resolution on the vertex spatial position, only vertices that have at least five tracks with $p_T > 500 \text{ MeV}$ associated with them are considered. The number of reconstructed primary vertices is used as a measure of the in-time pile-up and several calibration parameters depend on it. The vertex with the highest sum of the squared track p_T is assumed to be the main vertex of the event corresponding to the hardest pp interaction. The rest of the primary vertices are considered pile-up interactions. Vertices incompatible with the beam collision region are considered as secondary vertices, also referred to as displaced vertices.

4.3 Muon reconstruction

Muons are reconstructed separately in the ID and MS and the information is later combined to form muon tracks used in physics analyses. In the ID, muon tracks are reconstructed as described in Section 4.1, and in the MS muon reconstruction starts with a search for hit patterns within each muon chamber to form segments. In MDT chambers and nearby trigger chambers (RPC, TGC), a Hough transform [141] is used to search for aligned hits on a trajectory in the bending plane. The orthogonal coordinate to the bending plane is determined with RPC and TGC hits and segments in the CSC detectors are built using a combinatorial search in the $\eta\phi$ detector planes. A detailed description of the muon reconstruction and identification is given in Ref. [142].

Four muon types are defined from the combined ID-MS muon reconstruction coupled with the calorimeter information, depending on which sub-detectors are used in the reconstruction:

- Combined (CB) muon: track reconstruction is performed independently in the ID and MS, and a combined track is formed with hits from both the ID and MS sub-detectors. During the global fit procedure, MS hits may be added to or removed from the track to improve the fit quality. Most CB muons are reconstructed following an outside-in pattern recognition, in which the muons are first reconstructed in the MS and then extrapolated inward and matched to an ID track. To complement the measurement, the opposite procedure starting from the ID and proceeding outward to the MS is also performed. These muon candidates have the highest purity and can be reconstructed in the $|\eta| < 2.5$ region.
- Segment-tagged (ST) muons: a track in the ID is classified as a muon if it is associated with at least one local track segment in the MDT or CSC chambers once extrapolated to the MS. ST muons are used when muons cross only one layer of MS chambers, either because of their low p_T or because they fall in regions with reduced MS acceptance.
- Calorimeter-tagged (CT) muon: reconstructed by matching an ID track to an energy deposit in the calorimeter compatible with a minimum-ionizing particle. Despite the low purity provided by this type of muons, they recover the acceptance in the region where the MS is only partially adapted ($|\eta| < 0.1$) and in the p_T range of 15 to 100 GeV.
- Extrapolated (ME) muon: reconstruction is performed using just the information provided by the MS track with an additional requirement on compatibility with originating from the IP. Muon track parameters are defined at the IP, considering also the energy loss in the calorimeters. The muon is required to traverse at least two layers of the MS and three layers in the forward region. Standalone muons are generally used to recover ATLAS acceptance in the region $2.5 < |\eta| < 2.7$ not covered by the ID, where the CB muon reconstruction is not possible.

Overlaps between different muon types are resolved by giving the preference to CB muons over ST, and finally CT muons, when two muon types share the same ID track.

4.3.1 Muon identification

Additional selection criteria are applied to muon candidates to suppress fakes, mainly originating from pion and kaon decays, while selecting prompt muons with high efficiency and ensuring a robust momentum measurement. This set of additional selection criteria is called the *identification criteria*.

Three inclusive categories are defined to address the specific needs of different physics analyses in ATLAS: **LOOSE**, **MEDIUM**, **TIGHT**. They are defined in a way that muons identified with tighter requirements are also included in the looser categories.

- **MEDIUM**: the default working point for muons in ATLAS, minimizing the systematic uncertainties associated to muon reconstruction and calibration and using only CB or ME muons. CB muons are required to have at least three hits in at least two MDT layers, except for tracks in the $|\eta| < 0.1$ region, where tracks with at least one MDT layer but no more than one MDT hole layer are allowed. ME muons are required to have at least three MDT/CSC layers and are used only in the region $2.5 < |\eta| < 2.7$ to extend the acceptance outside the ID geometrical coverage. The q/p of the track is required to be less than seven to suppress the contamination due to fake hadrons. In the $|\eta| < 2.5$ region, only about 0.5 % of **MEDIUM** muons originate from the inside-out CB reconstruction strategy, while the rest originate from the nominal outside-in algorithm.
- **LOOSE**: all muon types are used for this identification criteria and all CB and ME muons satisfying the **MEDIUM** requirement are included in the **LOOSE** selection. CT and ST muons are restricted to the $|\eta| < 0.1$ region. The composition of **LOOSE** muons in the $|\eta| < 2.5$ region is roughly 97.5 % CB muons, 1.5 % CT, and 1 % ST muons.
- **TIGHT**: this identification working point maximizes muon purity at the cost of identification efficiency. **TIGHT** muons need to satisfy the **MEDIUM** identification criteria and only CB muons with hits in at least two stations of the MS are considered. The normalized χ^2 of the combined track fit is required to be below eight and a two-dimensional cut in the ρ'^2 and q/p variables is performed as a function of the track p_T to increase the purity in the region below $p_T = 20$ GeV, which is most affected by fakes.

The reconstruction efficiency as a function of η measured in $Z \rightarrow \mu\mu$ events for muons with $p_T > 10$ GeV is shown in Figure 4.3 for the three identification criteria.

² ρ' is defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the p_T of the combined track.

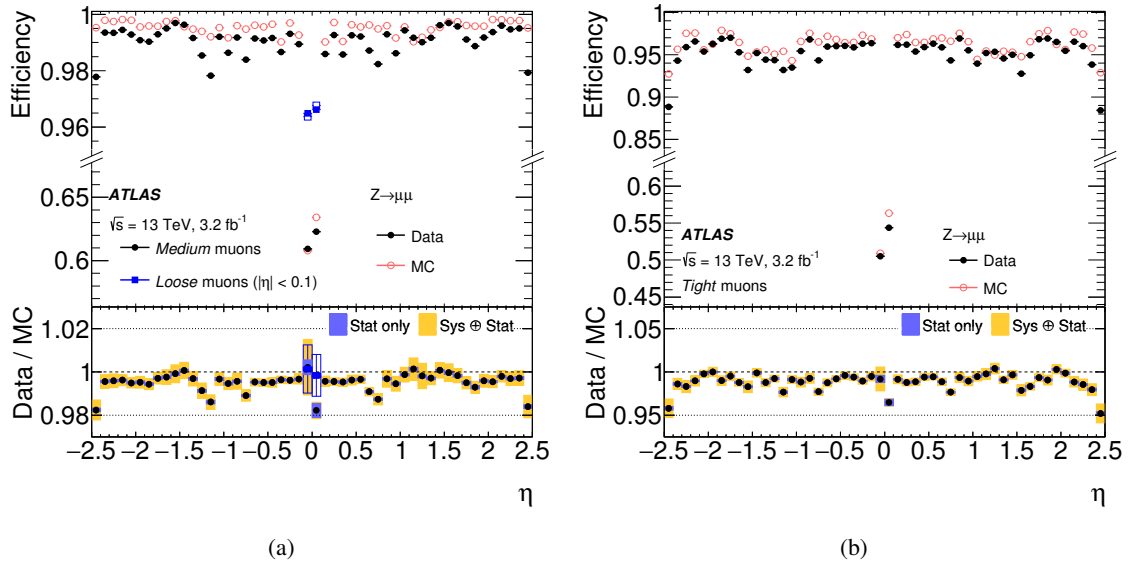


Figure 4.3: Muon reconstruction efficiency as a function of η measured in $Z \rightarrow \mu\mu$ events for muons with $p_T > 10 \text{ GeV}$ shown for (a) the MEDIUM muon identification and (b) the TIGHT muon identification criteria. The error bars on the efficiencies indicate the statistical uncertainty. Panels at the bottom show the ratio of the measured to predicted efficiencies, with statistical and systematic uncertainties. In addition, the plot also shows the efficiency of the Loose identification (squares) in the region $|\eta| < 0.1$ where the LOOSE and MEDIUM identification criteria differ significantly. Taken from Ref. [142].

4.4 Electron reconstruction

The electron reconstruction algorithm uses information from the ID and the EM calorimeter and is optimized to recover energy losses that occur due to bremsstrahlung when the electron traverses the detector material. The radiated photon may convert into an electron–positron pair due to further interactions with the detector material and a chain of such interactions can follow. The emitted particles are usually collimated and reconstructed as part of the same electromagnetic cluster. However, it is possible to produce and match multiple tracks to the same electromagnetic cluster, all caused by the same primary electron. The electron reconstruction is performed in the $|\eta| < 2.47$ region in several steps, described below. Electron reconstruction and identification is discussed in more detail in Refs. [143] and [144] and schematically summarized in Figure 4.4.

4.4.1 Seed-cluster reconstruction

The energy deposits collected in the first, second, and third EM calorimeter layers as well as in the presampler (only in the $|\eta| < 1.8$ range, corresponding to the acceptance) are summed in localized elements (towers) within a grid of 200×256 towers of size $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$, corresponding to the granularity of the second layer of the EM calorimeter. Cluster candidates are then formed from these localized energy deposits whose summed transverse energy, E_T , exceeds 2.5 GeV using a

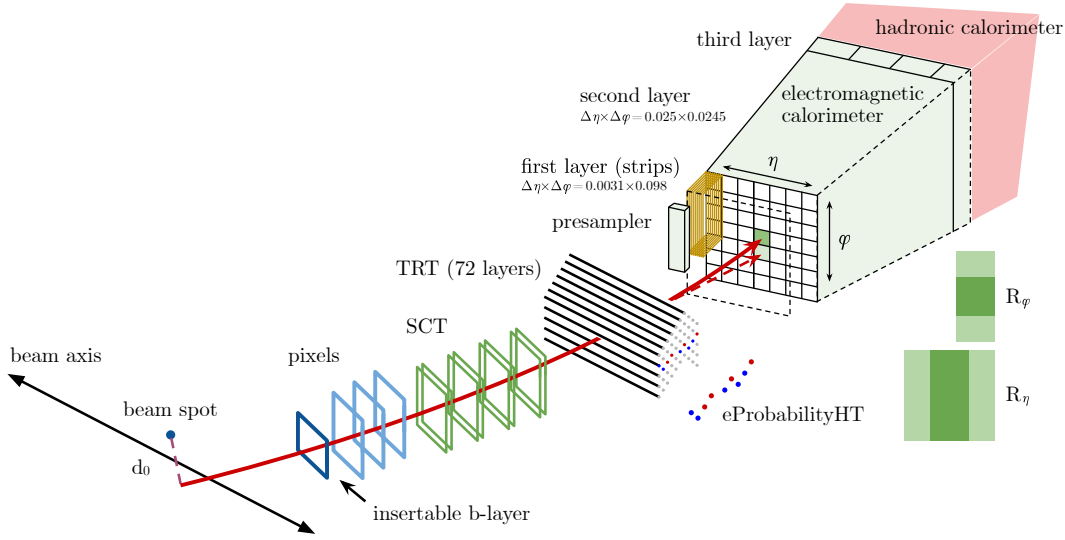


Figure 4.4: A schematic illustration of the various inputs used to form the electron reconstruction and identification quantities. The red trajectory shows the hypothetical path of an electron, which first traverses the tracking system (PIXT detectors, then SCT detectors and lastly the TRT) and then enters the EM calorimeter. The dashed red trajectory indicates the path of a photon produced by the interaction of the electron with the material in the tracking system. See Table 4.1 for the definitions of the portrayed variables. Taken from Ref. [144].

$\Delta\eta \times \Delta\phi = 3 \times 5$ sliding-window algorithm. The seed-cluster search is performed for every element in the calorimeter by shifting the center of the 3×5 cluster in 0.025 steps in either the η or ϕ direction. If two candidate clusters overlap within an area of $\Delta\eta \times \Delta\phi = 5 \times 9$ units, the candidate with the highest transverse energy is retained if the relative difference between E_T is more than 10 %, otherwise, the candidate with the highest E_T of the central tower is kept. The reconstruction efficiency of the seed-cluster varies from 65 to 96 % for electrons with E_T from 4.5 to 7 GeV and is more than 99 % for electrons with E_T above 15 GeV.

4.4.2 Electron-track reconstruction

A region-of-interest (ROI) with a cone-size of $\Delta R = 0.3$ around the seed cluster barycenter is defined for each seed EM calorimeter cluster passing a requirement of $R_\eta > 0.65$ and $R_{\text{had}} < 0.1$ ³. The selected ROIs are further used for electron track reconstruction.

Track reconstruction is performed in two steps: pattern recognition and track fit, as described in Section 4.1. The standard pattern recognition uses the pion hypothesis to describe energy loss at material surfaces. However, if a track seed (consisting of three hits in different layers of the PIX or SCT) cannot be extended to a full track with at least seven silicon hits with the pion hypothesis, an electron-specific algorithm is tried instead. This modified pattern recognition algorithm is based on a Kalman filter-smoother formalism [138] which allows up to 30 % energy loss at each material

³ See Table 4.1 for the definitions of R_η and R_{had} .

surface. This refitting procedure improves the performance of electron reconstruction with minimal interference. Tracks are fitted with either hypotheses using the ATLAS Global χ^2 Track Fitter [145].

After the Global χ^2 fit, tracks are considered as loosely matched to an EM calorimeter cluster if they pass one of the following two requirements:

1. Track candidates with at least four silicon hits (PIX or SCT), extrapolated from the point of closest approach with respect to the primary vertex to the second layer of the EM calorimeter, have to be within $\Delta\phi = 0.2$ of the EM cluster on the side the track is bending towards or within 0.05 on the other side. Furthermore, they have to be within $\Delta\eta = 0.05$ of the EM cluster. TRT-only tracks⁴ are extrapolated from the last measurement point instead and have to pass the same $\Delta\phi$ requirement. They are not required to pass any $\Delta\eta$ requirement.
2. The momentum of the track is rescaled to the measured cluster energy and the extrapolated track has to be within $\Delta\phi = 0.1$ of the EM cluster on the side the track is bending towards or within 0.05 on the other side. Furthermore, tracks with at least four silicon hits must be within $\Delta\eta = 0.05$ of the EM cluster. The extrapolation is made from same points as in point 1..

The requirement in point 2. targets tracks with large curvature that have potentially lost a significant amount of energy before reaching the calorimeter. Furthermore, the measured momentum in the ID does not necessarily match the energy deposit reconstructed in the EM calorimeter due to bremsstrahlung. Rescaling the momentum of the track to that of the reconstructed EM cluster retains tracks which underwent bremsstrahlung before the calorimeter, for example in the beam-pipe or the first layers of the ID. Tracks passing either of the two requirements are considered as electron-track candidates and for all tracks, except the TRT-only tracks, an optimized electron track fit is performed with the Gaussian Sum Filter (GSF) [146] algorithm, which is a non-linear generalization of the Kalman filter algorithm. TRT-only tracks and tracks that fail the GSF fit (about 0.01 %) keep the defining track parameters from the Global χ^2 fit. The GSF fit better takes the bremsstrahlung into account and improves the original determination of the defining track parameters. One of the most affected variables is the transverse impact parameter, d_0 , which plays a major role in the charge misidentification studies presented in Section 5.

4.4.3 Electron-candidate reconstruction

An electron object is reconstructed if at least one post-GSF fit track is matched to the seed cluster. The track–cluster matching criteria are the same as in points (1. and 2.) in Section 4.4.2, but with a tighter requirement of $\Delta\phi = 0.1$ for tracks with at least four silicon hits. Furthermore, TRT-only tracks must also satisfy tighter $\Delta\phi$ and $\Delta\eta$ requirements [143].

More than one track can be assigned to a seed cluster. The best-matched track is chosen as the primary track and used to define kinematic properties of the electron and its charge. Furthermore, all tracks match to the seed cluster are kept for each electron and used for further studies, e.g. charge misidentification studies in Section 5. The selection of the primary track is a crucial step with large consequences in the electron reconstruction chain. Firstly, tracks with at least one PIX

⁴ TRT-only tracks are defined as tracks with less than four silicon (PIX or SCT) hits.

hit are preferred. If more than one track assigned to the seed cluster has PIX hits, further scoring criteria are considered. Two angular distance variables are defined in the $\eta\phi$ plane: ΔR , the distance between the cluster barycenter and the extrapolated track in the second layer of the EM calorimeter, and $\Delta R_{\text{rescaled}}$, the distance between the cluster barycenter and the extrapolated track with the track momentum rescaled to the energy deposit in the EM cluster. Among two tracks, defined as track i and track j , if $|\Delta R_{\text{rescaled}}^i - \Delta R_{\text{rescaled}}^j| > 0.01$, the track with smaller $\Delta R_{\text{rescaled}}$ is preferred. Otherwise, if $|\Delta R^i - \Delta R^j| > 0.01$, the track with smaller ΔR is taken. For all other cases, the track with more PIX hits plus the number of PIX holes is used, where a hit in the first PIX layer counts twice. If, after all scoring criteria, two best tracks have the same number of hits plus holes, the track with smaller ΔR is taken.

A candidate cluster with an associated track with at least four hits in the silicon layers and no association to a vertex from a photon conversion is considered as an electron candidate. Electron candidates without any associated PIX hits are removed and considered to be photons. Finally, EM calorimeter clusters associated with any electron candidate are rebuilt around the seed cluster using an extended window size of 3×7 in the barrel region ($|\eta| < 1.37$) and 5×5 in the end-cap region ($1.52 < |\eta| < 2.47$).

After selecting all electron candidates, the energy of the rebuilt clusters is calibrated to correspond to the original electron energy. The calibration is based on multivariate techniques and detailed in Ref. [147].

4.4.4 Electron identification

To further improve the purity of reconstructed electrons, identification criteria are applied to suppress backgrounds from light-flavor, heavy-flavor, and photon conversion induced fakes. Prompt electrons are selected with a likelihood (LH) based identification. The inputs to the LH include measurements from the tracking system, the calorimetry system, and quantities that combine both tracks and calorimeter information. All input variables are summarized in Table 4.1.

The LH identification is a multivariate method that simultaneously evaluates several properties of the electron candidates when making a selection decision. The advantage of this method over the more conventional cut-based identification is that an electron can still pass the selection criteria if it does not meet the requirement in one or more specific variables and portrays good agreement with the electron hypothesis on other variables. The efficiency for selecting prompt electrons of the LH-based selection is therefore larger compared to the cut-based selection with very little impact on the background rejection level. The LH method uses the input signal and background probability density functions (PDFs) of the chosen discriminating variables and based on this PDFs, an overall probability is calculated for the object to pass the electron hypothesis or not. The likelihood is based on LHs for signal, L_S , and for background, L_B , which are products of the input PDFs. For each electron candidate, a discriminant dL is then formed,

$$dL = \frac{L_S}{L_S + L_B}, \quad L_{S(B)}(\vec{x}) = \prod_{i=1}^n P_{s(b),i}(x_i), \quad (4.2)$$

where $\vec{x}$ is the vector of discriminating variable values and $P_{s(b),i}(x_i)$ is the value of the PDF of the i -th variable evaluated at x_i . The discriminant dL has a sharp peak at unity for signal and zero for background. In addition to the variables used as input to the LH discriminant, additional simple selection criteria are used as summarized in the following and indicated in Table 4.1.

The input PDFs are derived from the simulated events and they are determined separately in η and E_T bins. To cover the needs of many ATLAS searches, several working points are defined by choosing fixed values of the likelihood discriminant targeting specific efficiencies and background rejection factors. The working points are denoted **Loose**, **MEDIUM**, and **TIGHT** with an efficiency to identify a prompt electron of $E_T = 40$ GeV 93 %, 88 %, and 80 %. The working points are inclusive; electrons passing the **MEDIUM** and the **TIGHT** working point also pass the **Loose** requirement and electrons passing the **TIGHT** requirement also pass the **MEDIUM** working point. All working points have fixed requirements on tracking parameters; electrons are required to have at least two hits in the PIX detector and seven hits in the SCT detector to pass any of the working points. Furthermore, to pass **MEDIUM** and **TIGHT** criteria, track associated with the electron must also have a hit on the innermost PIX layer (IBL) or on the next-to-innermost layer if the innermost layer is non-operational. An additional working point is defined, **LooseAndBLayer**, which uses the same LH discriminant as the **Loose** working point and adds the requirement of the innermost PIX layer hit.

The reconstruction efficiency as a function of E_T measured in $Z \rightarrow ee$ events for electrons along with the efficiency to (mis)identify hadrons as electrons estimated using di-jet simulated events is presented in Figure 4.5 for various identification working points.

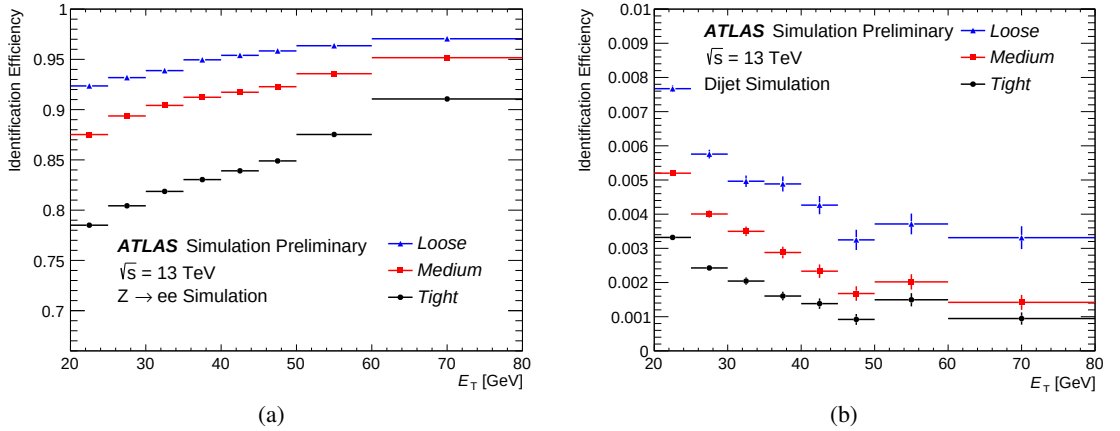


Figure 4.5: The efficiency to identify electrons from $Z \rightarrow ee$ decays (a) and the efficiency to identify hadrons as electrons (b) estimated using simulated di-jet samples. The efficiencies are obtained using MC simulations, and are measured with respect to reconstructed electrons. The candidates are matched to true electron candidates for $Z \rightarrow ee$ events. Taken from Ref. [144].

Table 4.1: Definitions of electron discriminating variables and the types of backgrounds the variables help to discriminate against (indicated with a check-mark ✓). ‘LF’ indicates fakes originating from light quarks (u or d) or gluons, ‘ γ ’ indicates photon conversions, and ‘HF’ indicates non-prompt electrons originating from decays of hadrons containing heavy quarks (b , c , or s). Furthermore, it is marked whether a variable is used as a likelihood PDF (L) or used as a rectangular cut (C). The * refers to the fact that the E/p and w_{stot} variables are only used for electrons with $p_T > 150$ GeV for the TIGHT identification operating point, and are not used for the looser operating points.

Type	Description	Name	Rejects			Usage
			LF	γ	HF	
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster. (used over the range $ \eta < 0.8$ or $ \eta > 1.37$)	R_{had1}	✓		✓	L
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster. (used over the range $0.8 < \eta < 1.37$)	R_{had}	✓		✓	L
Back layer of EM calorimeter	Ratio of the energy in the back layer to the total energy in the EM accordion calorimeter. This variable is only used for $p_T < 80$ GeV due to known inefficiencies at high p_T , and is also removed from the LH for $ \eta > 2.37$, where it is poorly modeled by the MC.	f_3	✓			L
Middle layer of EM calorimeter	Lateral shower width, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, where E_i is the energy and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	$w_{\eta 2}$	✓	✓		L
	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centered at the electron cluster position	R_ϕ	✓	✓	✓	L
	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position	R_η	✓	✓	✓	L
Strip layer of EM calorimeter	Shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all strips in a window of $\Delta\eta \times \Delta\phi \approx 0.0625 \times 0.2$, corresponding typically to 20 strips in η , and i_{max} is the index of the highest-energy strip	w_{stot}	✓	✓	✓	C*
	Ratio of the energy difference between the maximum energy deposit and the energy deposit in a secondary maximum in the cluster to the sum of these energies	E_{ratio}	✓	✓		L
	Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter	f_1	✓			L
Track conditions	Number of hits in the innermost pixel layer; discriminates against photon conversions	n_{Blayer}		✓		C
	Number of hits in the pixel detector	n_{Pixel}		✓		C
	Number of total hits in the pixel and SCT detectors	n_{Si}		✓		C
	Transverse impact parameter with respect to the beam-line	d_0		✓	✓	L
	Significance of transverse impact parameter defined as the ratio of d_0 and its uncertainty	$ d_0/\sigma_{d_0} $		✓	✓	L
	Momentum lost by the track between the perigee and the last measurement point divided by the original momentum	$\Delta p/p$	✓			L
TRT	Likelihood probability based on transition radiation in the TRT	eProbabilityHT	✓			L
Track-cluster matching	$\Delta\eta$ between the cluster position in the strip layer and the extrapolated track	$\Delta\eta_1$	✓	✓		L
	$\Delta\phi$ between the cluster position in the middle layer of the calorimeter and the momentum rescaled track extrapolated from the perigee	$\Delta\phi_{\text{res}}$	✓	✓		L
	Ratio of the cluster energy to the track momentum	E/p	✓	✓		C*

4.5 Electron and muon isolation

At dense environments such as pp collisions at the LHC it is challenging to differentiate prompt electrons and muons from background processes such as semi-leptonic decays of heavy quarks, hadrons misidentified as leptons, and photons converting into electron–positron pairs in the detector material. For these purposes lepton identification criteria are introduced (see Sections 4.3.1 and 4.4.4), however, even further separation can be achieved by exploiting the fact that prompt leptons usually exhibit an absence of activity (both in the calorimeter and in the inner detector) in an area of ΔR space surrounding the candidate object. Some prompt decays such as the top quark pair production ($t\bar{t}$) distort this picture because in these cases prompt leptons are produced together with jets originating from the same primary vertex. Variables describing this activity around the candidate object, the *isolation*, are carefully chosen and tuned to target specific efficiency of selecting prompt leptons with as large as possible background rejection. Refs. [144] and [142] discuss these optimization studies in great detail and a short summary is given below.

Two variables are used as input for the isolation criteria, constructed separately from the calorimeter and the ID information. The calorimeter-based isolation variable is constructed by building a cone of size ΔR around the lepton. In case of electron, the cone is build around the candidate electron’s cluster position. Initially, the calorimeter-based isolation was simply the sum of the transverse energy of the calorimeter cells (EM and hadronic calorimeters) within this cone, excluding the candidate object’s own contribution to this energy. However, this type of isolation exhibited large dependence on pile-up effects. A significant improvement was achieved by using topological clusters [148] instead of individual cells and thus effectively applying a noise-filter to mitigate the pile-up activity.

The topological clusters are built starting from cells with a deposited EM-scale energy of more than four times the expected noise threshold of that cell. The noise threshold is determined both from the electronic noise and the effects of pile-up. Furthermore, the cluster is then expanded in all spatial directions across all EM and hadronic calorimeter layers by adding only cells that exhibit a deposited energy of more than two times the noise threshold. The expansion stops when no further neighboring cells satisfy the noise criteria and the final shell of cells surrounding the cluster is added. The raw activity surrounding the target object (electron or muon), $E_{T,raw}^{isol}$, is then defined as the sum of energies of all positive-energy topological clusters whose barycentres fall within the ΔR cone of a specific radius. Furthermore, this raw isolation criteria still contains the energy deposited by the candidate object, $E_{T,core}$. This core is subtracted by simply removing the cells included in area $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$ around the candidate. However, this rectangular core may not always properly reflect the candidate object’s energy deposit and further studies are performed with simulated single-particle events to determine the leakage correction outside this core, $E_{T,leakage}$. Moreover, the contribution of pile-up to the calorimeter-based isolation cone, $E_{T,pile-up}$, is estimated with the ambient energy-density technique [149] and corrected on an event-by-event basis. The final fully corrected calorimeter-based isolation variable, $E_{T,\Delta R}^{isol}$, calculated within the cone ΔR around the candidate object is

$$E_{T,\Delta R}^{isol} = E_{T,raw}^{isol} - E_{T,core} - E_{T,leakage} - E_{T,pile-up}. \quad (4.3)$$

The track-based isolation, using the ID information, is constructed from tracks with $p_T > 1$ GeV, and further requirements on the minimum number of hits in the silicon detectors and the longitudinal impact parameter z_0 to minimize the impact of pile-up effects. Track-based isolation variables are then constructed by summing the p_T of these tracks within a cone of radius ΔR around the candidate object's track, excluding its own contribution. Electrons undergo bremsstrahlung which makes it harder to precisely subtract their own contribution due to secondary tracks arising from converted photons. For this reason, tracks considered for the isolation variables are extrapolated to the second layer of the EM calorimeter and all tracks within area of $\Delta\eta \times \Delta\phi = 0.05 \times 0.1$ around the electron's cluster position are considered to be part of the original electron and are subtracted from the ΔR . The size of the ΔR cone is not limited by the finite granularity of the calorimeter for the track-based isolation variables and therefore much narrower cones can be used. For isolation variables in ATLAS, variable-cone-size track-based isolation, $p_{T,\text{var}}^{\text{isol}}$, is used. The size of the ΔR cone progressively reduces in size as a function of the candidate's p_T ,

$$\Delta R = \min \left(\frac{10 \text{ GeV}}{p_T[\text{GeV}]}, R_{\text{max}} \right), \quad (4.4)$$

where R_{max} is the maximum allowed cone size, 0.2 for electrons and 0.3 for muons. A variety of isolation working points are defined to target different needs of ATLAS analyses, separated into two categories, as summarized below:

- fixed efficiency isolation: requirements on $E_{T,\Delta R}^{\text{isol}}$ and $p_{T,\text{var}}^{\text{isol}}$ are imposed as a function of object's energy and η to achieve the same efficiency of this requirement across all phase-space. The targeted efficiency is for example 95 % or 99 %,
- fixed cut isolation: in this case the upper thresholds on the isolation variables $E_{T,\Delta R}^{\text{isol}}$ and $p_{T,\text{var}}^{\text{isol}}$ divided by the object's energy (E_T for electrons and p_T for muons) are constant with varying efficiency across the phase-space.

All working points are presented in Table 4.2. Some of the working points use both the $E_{T,\Delta R}^{\text{isol}}$ and $p_{T,\text{var}}^{\text{isol}}$ variables and others use only the track-based isolation variable, $p_{T,\text{var}}^{\text{isol}}$. An example isolation efficiency as a function of muon p_T for two isolation working points is presented in Figure 4.6.

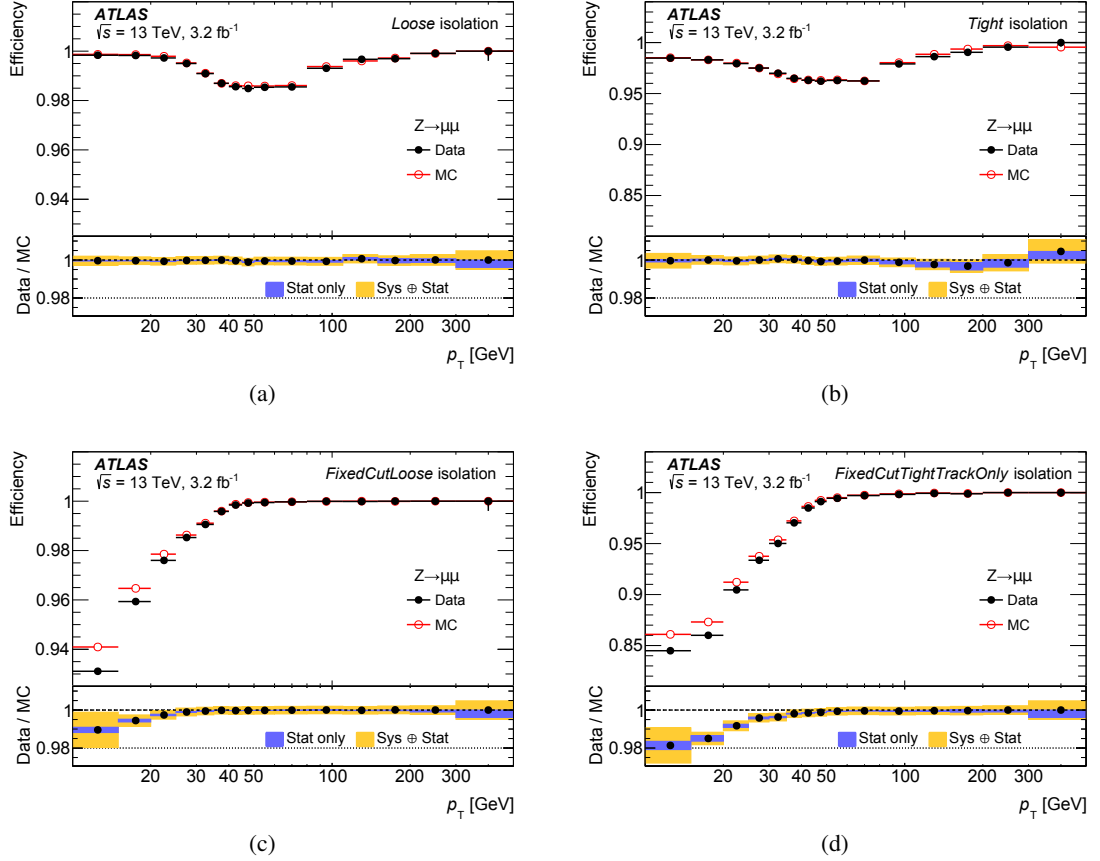


Figure 4.6: Muon isolation efficiency as a function of p_T measured in $Z \rightarrow \mu\mu$ events shown for (a) the LOOSE muon isolation, (b) the TIGHT muon isolation, (c) the FIXEDCUTLOOSE muon isolation, and (d) the FIXEDCUTTIGHTTRACKONLY muon isolation criteria. The error bars on the efficiencies indicate the statistical uncertainty. Panels at the bottom show the ratio of the measured to predicted efficiencies, with statistical and systematic uncertainties. Taken from Ref. [142].

Table 4.2: Isolation working points for electrons and muons. The upper part of the table shows the ‘fixed efficiency isolation’ working points. In this case the values in the table correspond to the partial targeted calorimeter- and track-based isolation efficiency values and the last column gives the total isolation efficiency. The bottom part of the table portrays the ‘fixed cut isolation’ working points where the value in the table gives the upper threshold on the corresponding variable instead. In case of electrons, E_T is used instead of p_T .

Working point	$E_{T,\Delta R}^{isol}$ $\Delta R = 0.2$	$R_{\max} = 0.2(0.3)$ for $e(\mu)$	$p_{T,var}^{isol}$	tot. eff.
LOOSETRACKONLY	–		99 %	99 %
LOOSE	99 %		99 %	98 %
TIGHT	96 %		99 %	95 %
FIXEDCUTLOOSE	$E_{T,\Delta R}^{isol}/p_T = 0.2(0.3)$ for $e(\mu)$		$p_{T,var}^{isol}/p_T = 0.15$	–
FIXEDCUTTIGHTTRACKONLY	–		$p_{T,var}^{isol}/p_T = 0.06$	–
FIXEDCUTTIGHT	$E_{T,\Delta R}^{isol}/p_T = 0.06$		$p_{T,var}^{isol}/p_T = 0.06$	–

4.6 Jets and the missing transverse momentum

Quarks and gluons carry a color charge and can not exist on their own due to QCD confinement (see Section 1.1.5) which only allows colorless states. When an object containing color charge fragments, each fragment carries away some amount of color charge and in order to satisfy the confinement, other colored objects form around the fragments to create colorless objects. This ensemble of particles is usually formed in a narrow cone around the initial quark or gluon and is commonly referred to as a *jet*. The majority of pp collisions in the LHC produce final state quarks and gluons that may form jets. Jets may also originate from final state radiation accompanying SM processes of interest such as $Z \rightarrow \ell\ell$ and it is therefore of key importance to correctly identify and reconstruct these objects. Jets leave large energy deposits in the calorimeters together with collimated tracks in the ID.

4.6.1 Jet reconstruction

Jets are reconstructed with the anti- k_t algorithm [150] using a radius parameter $R = 0.4$ with the FASTJET 2.4.3 software package [151]. Three-dimensional, massless topological clusters [148] with positive-energy are used as input to the anti- k_t algorithm. The calorimeter cell energies are measured at the electromagnetic scale (EM scale), corresponding to the raw deposited energy by electromagnetically interacting particles.

The calibration of EM scale jets is performed in several steps and aims to restore the jet energy scale to that of truth jets reconstructed at the particle-level energy scale using simulated events. A schematic overview of the jet calibration is presented in Figure 4.7. Each calibration step changes the full jet four-momentum, scaling the jet p_T , energy, and mass. The details of the jet calibration are discussed in Ref. [152]. Firstly, the four-momentum of jets is corrected to point to the hard-scatter

primary vertex instead of the center of the detector, while keeping the energy constant. This step is called the origin correction and is identical to the one used in the 2011 calibration [153]. Next steps removes the excess energy due to pile-up with the area-based p_T density subtraction technique [149] and a residual correction derived from the MC simulation. Furthermore, the absolute jet energy scale (JES) calibration corrects the jet four-momentum to the particle-level energy scale. This procedure is derived using truth jets in di-jet simulated MC events. Further corrections include improvements to the reconstructed energy with calorimeter, MS, and track-based variables and, finally, *in situ* calibration is applied to correct jets in data using well-known and calibrated objects such as Z bosons, photons, and calibrated jets (without the *in situ* calibration).

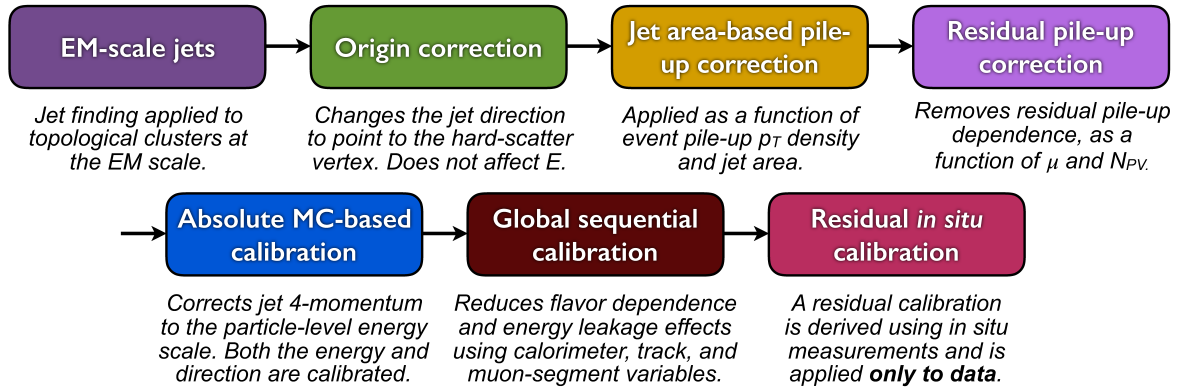


Figure 4.7: Calibration stages for EM-scale jets. Other than the origin correction, each stage of the calibration is applied to the four-momentum of the jet. Taken from Ref. [152].

The average jet energy response is shown in Figure 4.8 and defined as the mean of a Gaussian fit to the core of the $E^{\text{reco}}/E^{\text{truth}}$ distribution for jets, where E^{reco} is the reconstructed jet energy and E^{truth} is the energy of the truth particle jet. The response is derived as a function of the detector pseudorapidity, η_{det} , defined as the jet η pointing from the geometric center of the detector. The response is shown for jets after the origin and pile-up corrections and serves as input to the JES calibration.

4.6.2 b -jet identification

Jets containing b hadrons can be identified exploiting the relatively long b -hadron lifetime with variables such as a likelihood-based combination of the transverse and longitudinal impact parameter significances, the presence of a secondary vertex, and the reconstruction of the b -hadron decay chain using a Kalman filter. Various algorithms used for b -jet identification in ATLAS are discussed in Ref. [154]. The nominal multivariate b -tagging algorithm used in Run 2, referred to as MV2c10, is presented in detail in Ref. [155]. For the analyses presented in this thesis b -tagging is important to reduce the SM background originating from $t\bar{t}$ events by imposing a b -jet veto, i.e. requiring exactly zero b -jets to be reconstructed in the event. The MV2c10 algorithm utilises a boosted decision tree (BDT). Compared to Run 1 b -tagging algorithms it identifies b -jets with a greater efficiency by exploiting the installation of the IBL and the improved tracking software [156, 157]. The BDT

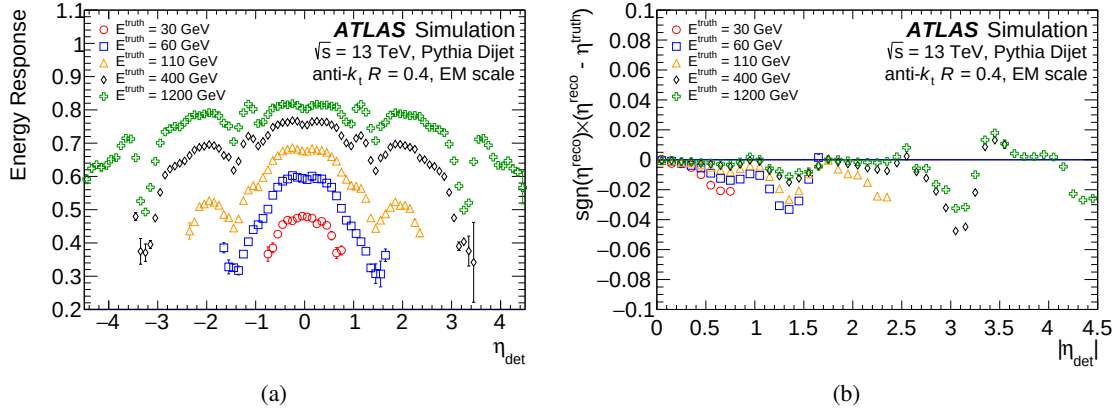


Figure 4.8: (a) the average energy response as a function of the detector pseudorapidity, η_{det} , for jets of a truth energy of 30, 60, 110, 400, and 1200 GeV. The energy response is shown after the origin and pile-up corrections. (b) the signed difference between the truth jet pseudorapidity and the reconstructed jet pseudorapidity. Taken from Ref. [152].

is trained using simulated $t\bar{t}$ events by assigning b -jets as signal and c -jets and light-flavor jets as background. The fraction of c -jets in the training background sample was set to 7 % (with 93 % light-flavor jets) in order to enhance the c -jet rejection. The performance of the MV2c10 b -jet tagging algorithm is presented in Figure 4.9; it shows the BDT outputs for b -jets, c -jets, and light-flavor jets as well as the rejection factors for c -jets and light-flavor jets as a function of the b -jet tagging efficiency.

4.6.3 Missing transverse momentum

Neutrinos and some hypothetical BSM particles produced in the pp collisions of LHC do not interact with the ATLAS detector material and transverse the detector without leaving any direct signal. However, indirect information on the presence of such particles can still be determined by momentum conservation in the xy plane since the transverse momentum of the initial state is zero. An imbalance in the total measured momentum in the transverse plane is defined as the *missing transverse momentum* $E_{\text{T}}^{\text{miss}}$. Generally, the $E_{\text{T}}^{\text{miss}}$ is calculated using both the ID information and the calorimeter information as discussed in Refs. [158] and [159]. In searches presented in this thesis, the $E_{\text{T}}^{\text{miss}}$ is calculated with a vector sum of momenta of calibrated electrons, muons, and jets together with a low-momentum hadronic activity,

$$E_{\text{T}}^{\text{miss}} = E_{\text{T},e}^{\text{miss}} + E_{\text{T},\mu}^{\text{miss}} + E_{\text{T},\text{jet}}^{\text{miss}} + E_{\text{T},\text{SoftTerms}}^{\text{miss}}. \quad (4.5)$$

where the notation $E_{\text{T,obj}}^{\text{miss}}$ indicates a vector sum of momenta of a certain type of objects, $E_{\text{T,obj}}^{\text{miss}} = -\sum \vec{p}_{\text{T}}^{\text{obj}}$. The soft term $E_{\text{T},\text{SoftTerms}}^{\text{miss}}$ is reconstructed from all ID tracks originating from the hard-scatter vertex passing reconstruction quality and kinematic selections and an internal ‘overlap re-

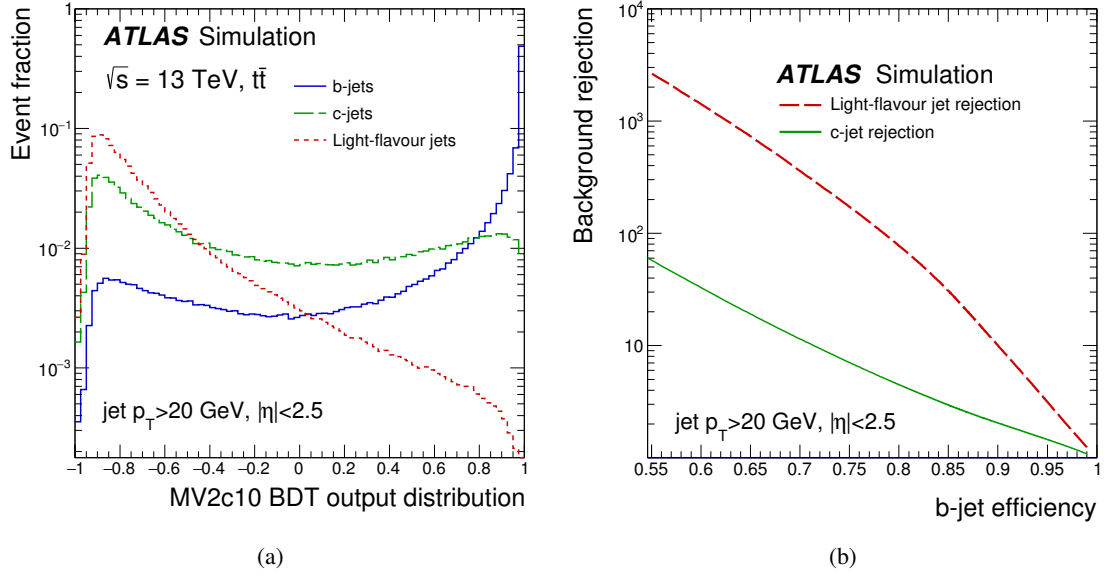


Figure 4.9: (a) the MV2c10 output for b -jets (solid line), c -jets (dashed line), and light-flavor jets (dotted line) in simulated $t\bar{t}$ events. (b) the light-flavor jet (dashed line) and c -jet (solid line) rejection factors as a function of the b -jet tagging efficiency of the MV2c10 algorithm. Taken from Ref. [144].

moval' procedure is used during the E_T^{miss} calculation to avoid double counting any objects that are reconstructed as two separate high-level objects (e.g. both as an electron and a jet) [158].

5 Electron charge misidentification studies

Electron charge misidentification is one of the leading sources of background in the presented analyses due to a very low production cross-section of SM processes with two prompt same-charge electrons. Even though the probability to misidentify electron's charge is relatively low, the $Z \rightarrow ee$ process is a significant source of background events in any selection with two same-charge electrons and it is therefore important to understand the charge misidentification process and its modeling in the simulation in detail. Electron charge misidentification at pp collisions is best studied with $Z \rightarrow ee$ events because they dominate all other backgrounds by orders of magnitude, as shown in Figure 5.1. By selecting events with two isolated electrons with invariant mass around the Z boson mass, a very pure selection of $Z \rightarrow ee$ events is achieved. The disagreement between the simulation and data in Figure 5.1(b) indicates mismodeling of the charge misidentification process in the simulation.

Author of the thesis also performed electron charge misidentification studies for the ATLAS Phase-II upgrade, comparing the misidentification probability between the current ATLAS geometry and the planned Phase-II geometry. These studies are summarized in Appendix A and published in the Technical Design Report for the ATLAS ITk Pixel detector [160].

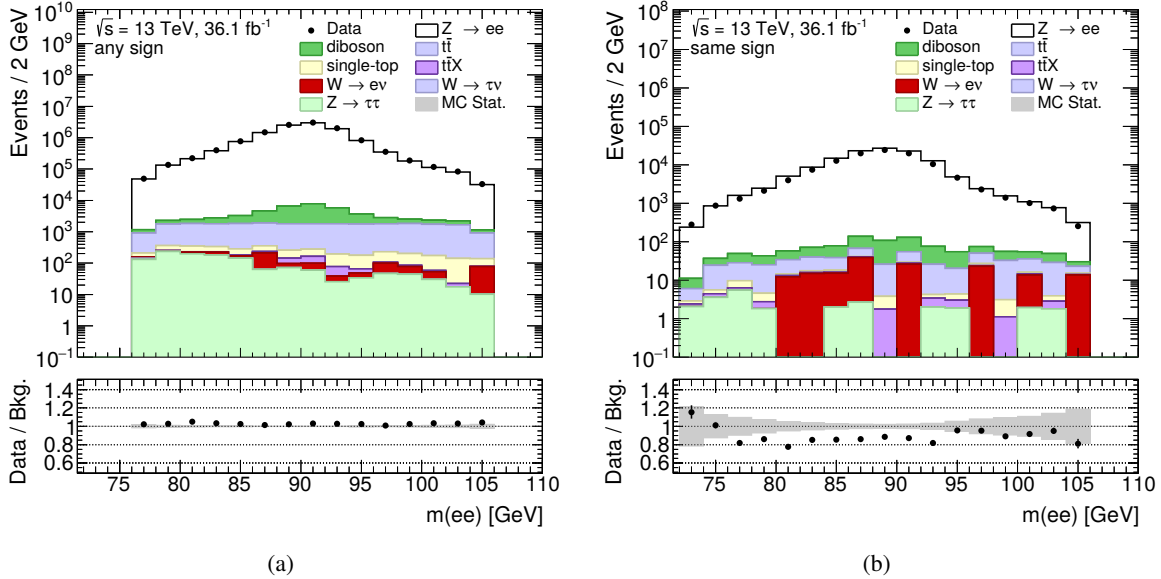


Figure 5.1: The composition of signal and background events in the $Z \rightarrow ee$ peak: (a) events without any requirement on the electron pair charge and (b) events with same-charge electron pairs.

5.1 The origin of electron charge misidentification

The electric charge of an electron is reconstructed from the curvature of the associated ‘best matching’ track, reconstructed in the inner detector, to the EM calorimeter cluster, as discussed in Section 4.4.2. The misidentification of electron charge can result from the association of the incorrect track to the electron candidate or from a mismeasurement of the curvature of the primary electron track. At typical energies of ATLAS analyses it is caused predominantly by bremsstrahlung. The emitted photon can either convert to an electron–positron pair or pass through the ID without directly creating any measurable tracks. Electrons with incorrect charge and wrong matched track are called *trident events* (due to the topology of three collinear electrons) and electrons with incorrect charge and correctly matched track are called the *stiff tracks*.

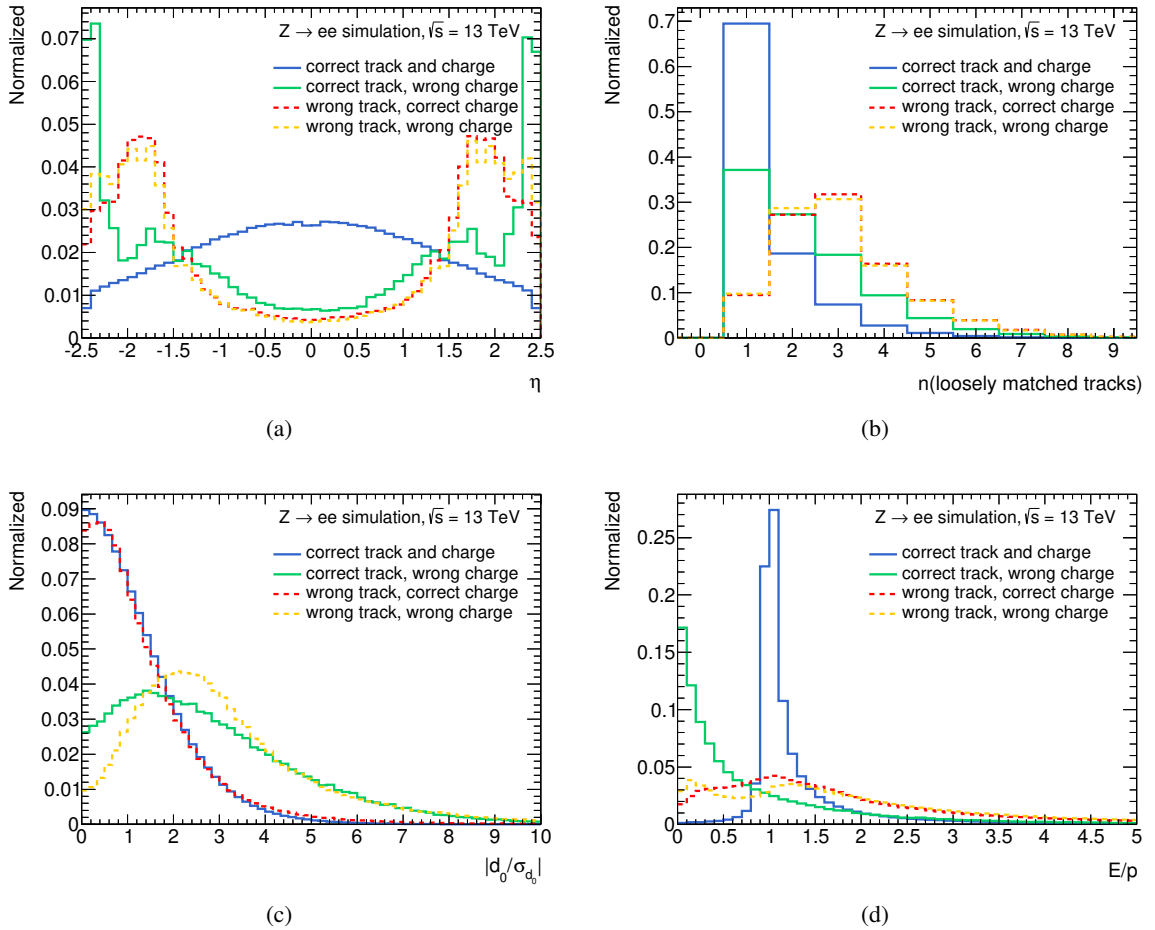


Figure 5.2: Kinematic and tracking properties of electrons with correctly and incorrectly reconstructed charge determined with simulated $Z \rightarrow ee$ events: (a) electron-track pseudorapidity, (b) multiplicity of loosely matched tracks to the cluster, (c) magnitude of the transverse impact parameter significance, and (d) energy-to-momentum ratio. The distributions are normalized to same area.

Simulated electrons are classified into four categories, depending on whether the charge was correctly

reconstructed and whether the main associated track to the cluster is truth matched to a prompt electron (see Section 3.1.3 for details about truth matching). Properties of these four electron categories are presented in Figure 5.2. Electrons with correct charge and correct track are the purest prompt electrons where the hits of the best matched tracks nicely correspond to the truth prompt electron. Electrons with wrong charge and correct track indicate difficulties in the measurement of the track's curvature, likely due to insufficient SCT hits and consequently a short lever arm. Furthermore, electrons with wrong track underwent bremsstrahlung and the best matched track to the EM calorimeter cluster in this case corresponds to a truth electron originating from the photon conversion of the emitted photon. Since the photon converts into a pair of electron–positron, the charge of the electron is more-or-less random in these cases (correctly reconstructed in about 50 % of the time).

The probability of a bremsstrahlung emission and subsequent photon conversion to an electron–positron pair depends significantly on the amount of detector material traversed. As shown in Figure 5.2(a) for simulated $Z \rightarrow ee$ events, most electrons that have undergone bremsstrahlung with subsequent pair production are found in the pseudorapidity region $1.5 < |\eta| < 2.2$, corresponding to a region in the detector with a relatively large amount of inactive material. Moreover, electrons with correct track and wrong charge are populated mostly at the edge of the acceptance, $2.2 < |\eta| < 2.5$, where the curvature of the track is most difficult to measure.

The number of loosely matched tracks to the seed cluster is shown in Figure 5.2(b) and it is evident that electrons with wrongly assigned track tend to have higher multiplicities of track candidates. The most likely number of track candidates is three, corresponding to the bremsstrahlung process and subsequent photon conversion ($e^- \rightarrow \gamma e^- \rightarrow e^+ e^- e^-$), regardless of whether the charge was correctly determined or not, illustrating further the probabilistic nature of the process.

Figures 5.2(c) and 5.2(d) show the magnitude of the transverse impact parameter significance, d_0/σ_{d_0} , and E/p respectively. Electrons with incorrectly reconstructed charge tend to have larger values of d_0/σ_{d_0} due to the wrong curvature of the matched track. Furthermore, the d_0/σ_{d_0} distribution of electrons with correct charge and wrong track is very similar to the one of electrons with correctly matched track, showing the power of the GSF track fit. Moreover, electrons with correct track and charge exhibit a peak in E/p around one, indicating that the deposited energy in the EM calorimeter corresponds well to the measured momentum of the primary track. Other three electron categories have a broader E/p distribution, either due to the wrong track being associated to the EM calorimeter cluster or due to the wrong curvature measurement of the correct track. In the latter case, the momentum of the track is greatly mismeasured, without much correlation to the original electron energy, and yields an E/p distribution that diverges for $E/p \rightarrow 0$.

Since electrons with incorrectly reconstructed charge quite often exhibit more than one loosely matched track candidate, these additional track candidates are studied. They are particularly interesting in case of electrons with incorrectly matched track since they could contain the correct track. The number of additional track candidates that are matched to a prompt truth electron, called ‘alternative tracks’, is presented in Figure 5.3.

In about 60 % of cases where the wrong track is matched to the cluster there is one alternative track candidate, matched to a truth prompt electron. Furthermore, in about 20 % of the time, electrons with correct track and wrong charge have one alternative track and electrons with correct track and charge almost never have an alternative track among the track candidates. The charge of this

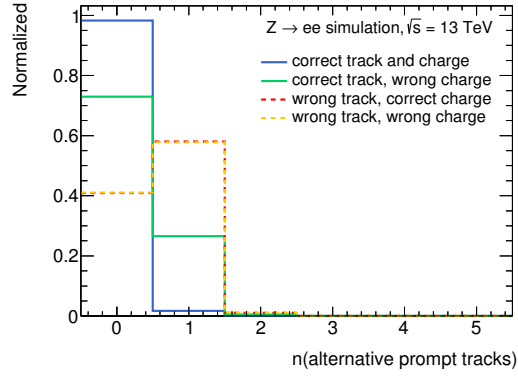


Figure 5.3: The number of alternative track candidates matched to a prompt truth electron. See text for details.

additional prompt track is found to be correct in about 98 % of the cases for electrons with incorrectly reconstructed charge (both for electrons with correct and incorrect primary track).

The number of IBL hits both on the primary track and the alternative track is presented in Figures 5.4(a) and 5.4(b) respectively. The track-cluster matching algorithm prefers tracks with a hit in the innermost layer of the PIX layer (IBL) and it is evident that alternative tracks very often have zero IBL hits which is likely the reason why they were not selected as the primary track. Furthermore, the number of SCT hits on the primary and alternative tracks is shown in Figures 5.4(c) and 5.4(d). In case of electrons with incorrectly reconstructed charge and correct primary track, the number of SCT hits is low, corresponding to the far end-cap region and in about 20 % of the cases there exists one alternative track among the loosely matched track candidates that has more SCT hits than the primary track on average.

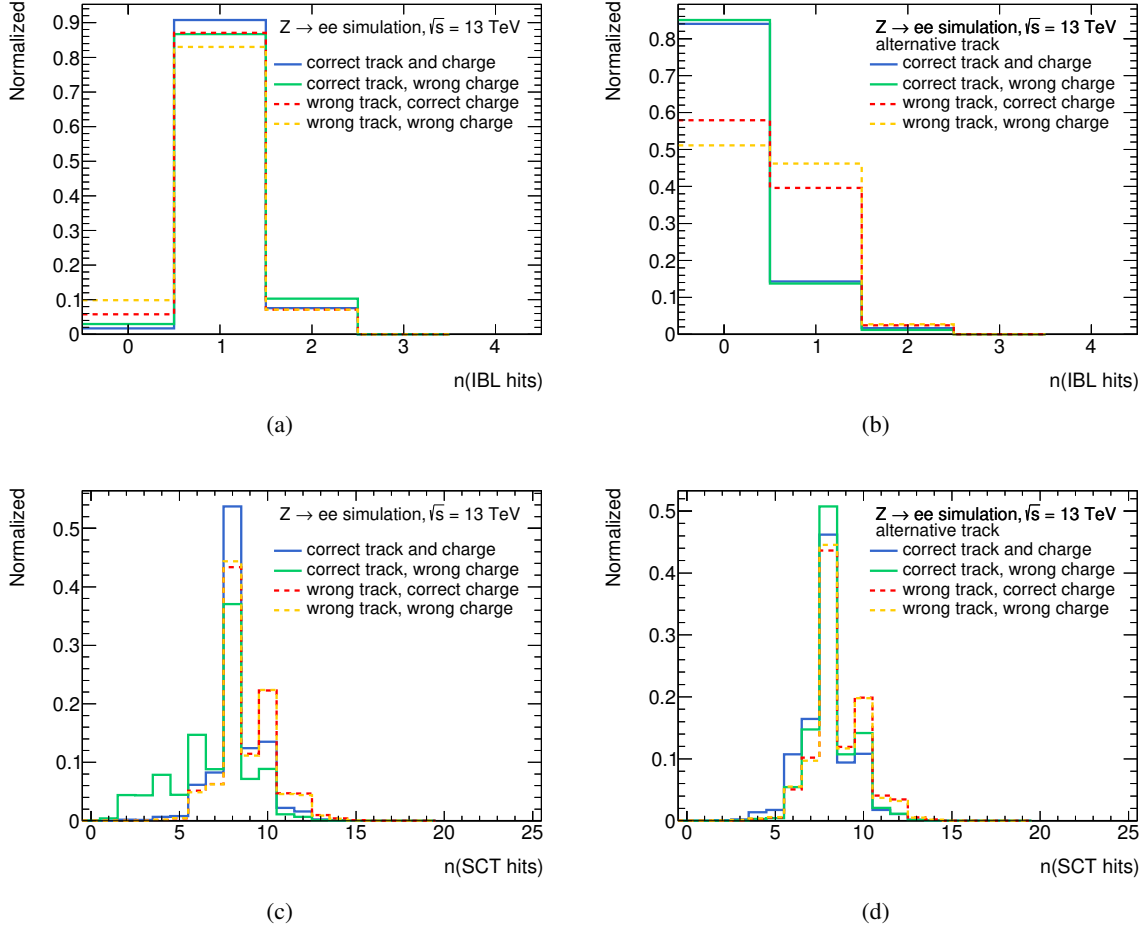


Figure 5.4: Tracking properties of electrons with correctly and incorrectly reconstructed charge determined with simulated $Z \rightarrow ee$ events. Both the properties of the primary track (left) and the alternative track (right) are presented: (a) number of IBL hits on the primary track, (b) number of IBL hits on the alternative track, (c) number of SCT hits on the primary track, and (d) number of SCT hits on the alternative track. The distributions are normalized to same area.

5.2 Truth electron decay-chain displays

Event-by-event studies are performed in addition to extend the understanding of the charge misidentification process. The entire truth record of electrons classified with incorrectly reconstructed charge is graphically represented with the following rules:

- dots represent the decay vertices of truth particles,
- straight lines connect the production and decay vertex of each truth particle,
- the color of the dots and lines indicates the type of the particles (electron, positron, photon),
- the width of lines is proportional to the p_T of the truth particle,
- the direction of the momentum of the reconstructed track is displayed with an arrow labeled ‘primary track’
- up to two other track candidates are shown in addition to the main track, labeled ‘track candidate 1’ and ‘track candidate 2’. These two additional tracks are the two best track candidates, according to the track-cluster matching algorithm described in Section 4.4.2, without taking the main track into the account,
- the "×" symbol indicates the truth particle matched to the primary electron-track,
- the last generator-level electron in the decay chain (see Figure 3.1) is represented with a square over the line corresponding to the truth particle,
- the figures show the xy projection and are rotated in the p_x direction of the main track momenta,
- kinematic and tracking properties of the last generator-level electron, reconstructed electron, and the primary track are shown in the bottom panel.

Two typical examples of an electron with incorrectly reconstructed charge and a wrong primary track are presented in Figures 5.5 and 5.6. Furthermore, an electron with incorrectly reconstructed charge and the correct primary track is shown in Figure 5.7. Together with the truth decay chain, the displays also show the ATLAS detector geometry. The decay and production vertices are most commonly position close to a layer of a sub-detector due to interactions of electrons and photons with the detector material. In case of electrons with the wrong primary track, hard bremsstrahlung occurs before the SCT sub-detector and the primary track is matched to a truth electron (marked with the "×" symbol) with a production vertex well beyond the PIX detector. Likewise, in case of electrons with correctly matched track and wrong charge, hard bremsstrahlung followed by no photon conversion is typical. In this case the primary track is matched to the last generator-level truth electron (likely the only candidate), however, this electron contributed only a few PIX hits while other hits are from unknown sources and distort the track momentum measurement.

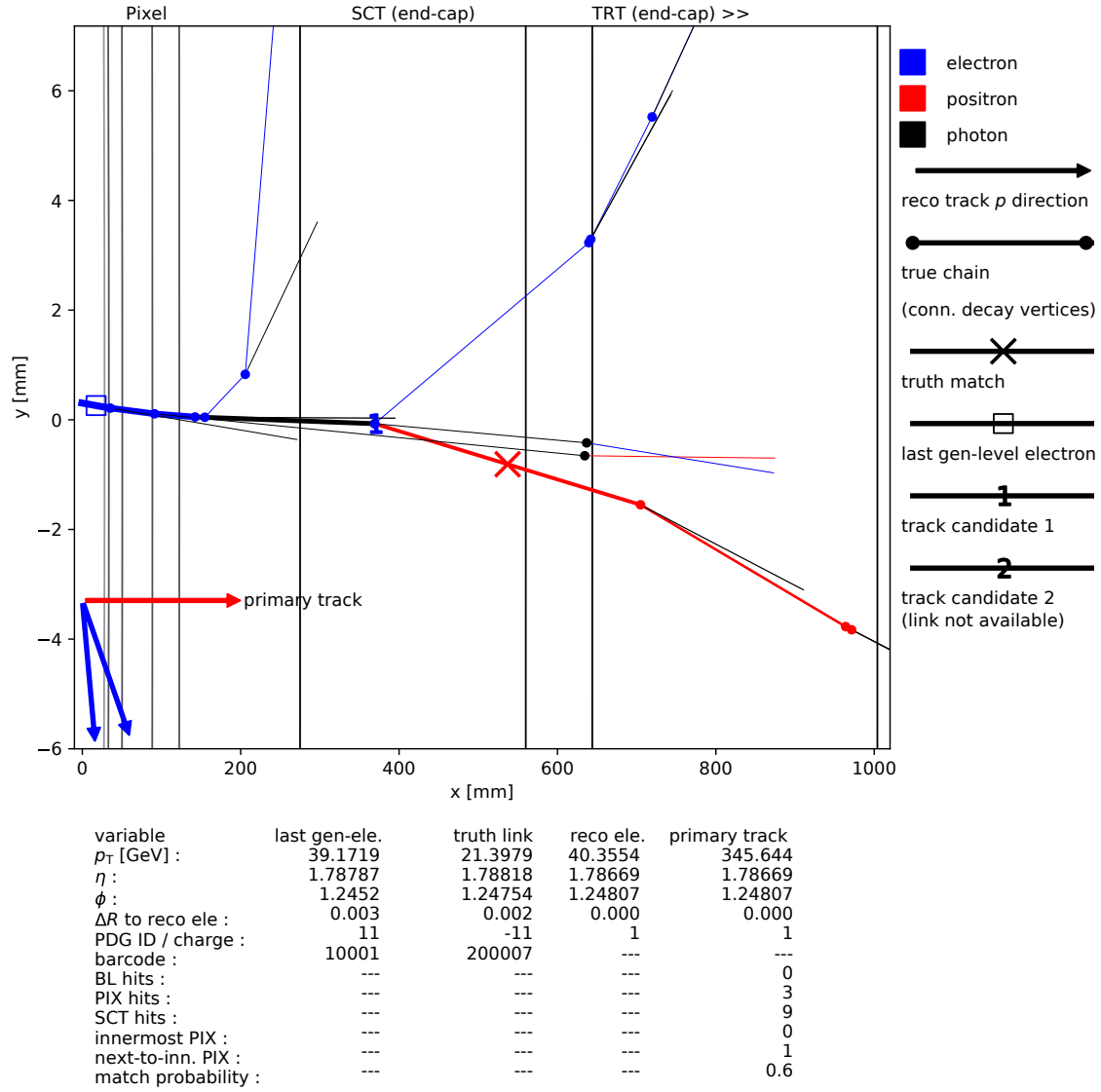


Figure 5.5: Graphical presentation of the entire truth decay-chain of an electron with incorrectly reconstructed charge and wrong primary track.

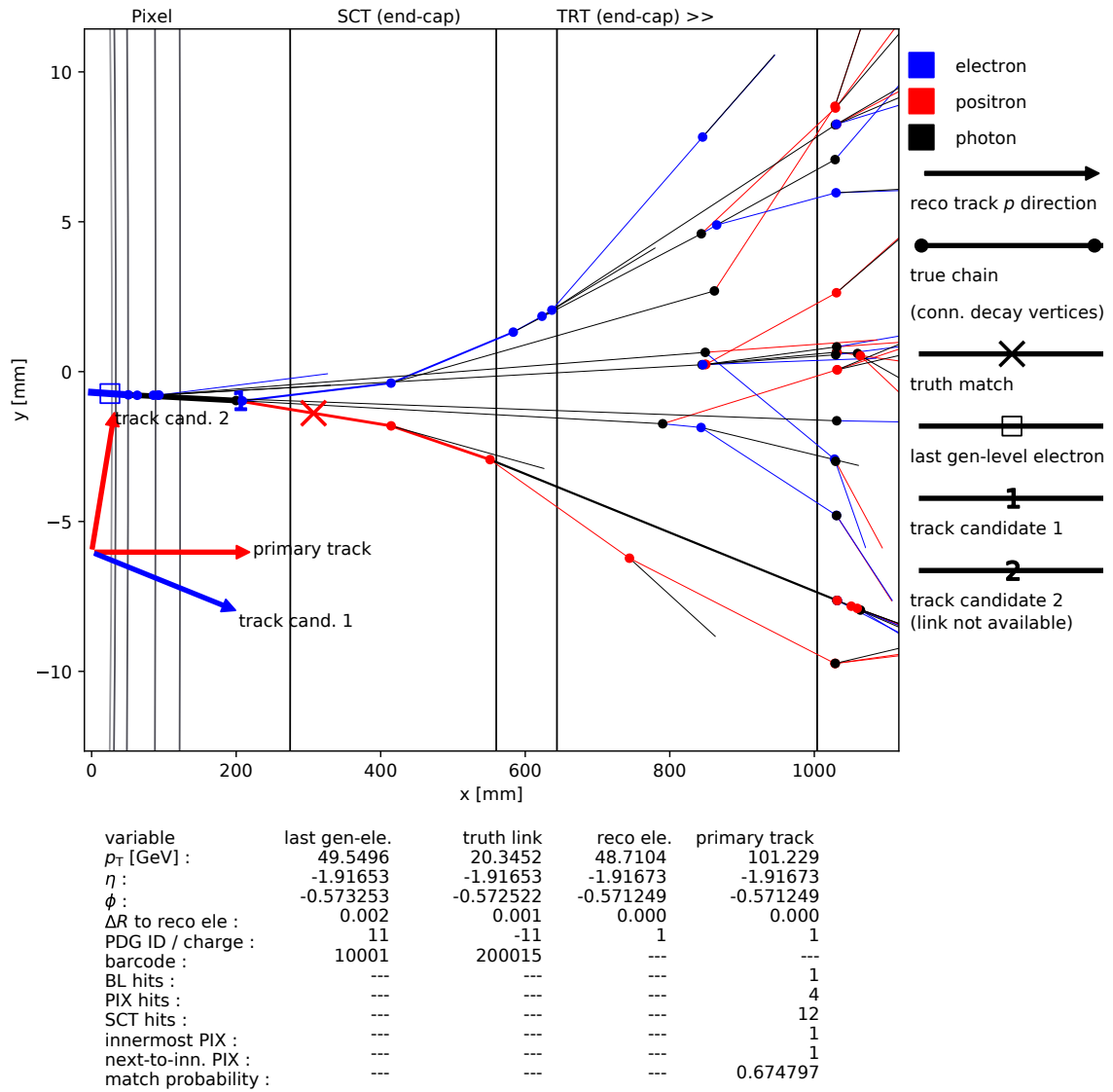


Figure 5.6: Graphical presentation of the entire truth decay-chain of an electron with incorrectly reconstructed charge and wrong primary track.

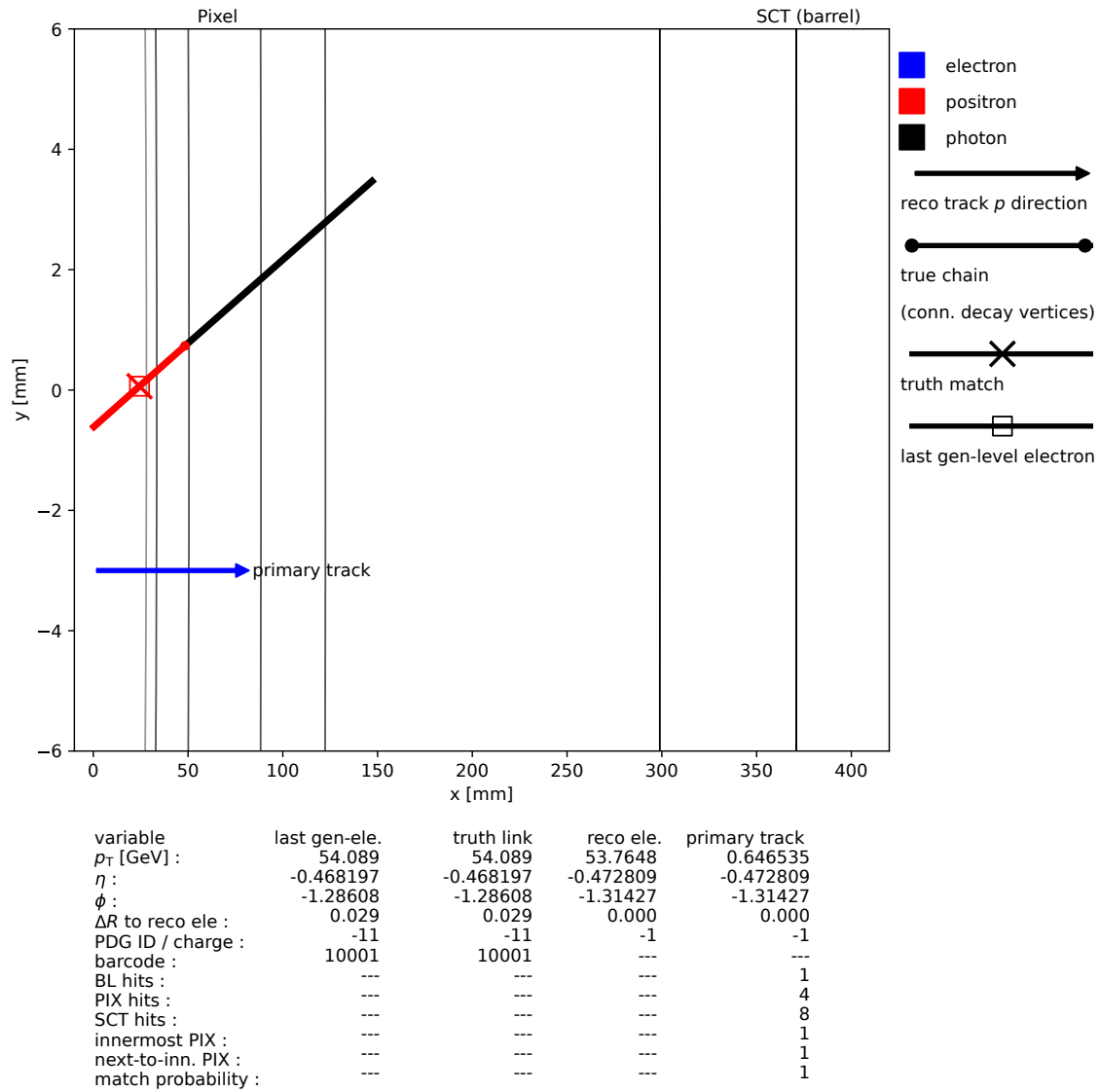


Figure 5.7: Graphical presentation of the entire truth decay-chain of an electron with incorrectly reconstructed charge and correctly matched primary track.

Part III

**Search for doubly-charged Higgs bosons, heavy neutrinos,
and heavy right-handed gauge bosons**

6 Analysis strategy and event selection

This chapter presents a search for new BSM phenomena in same-charge final states. Standard Model processes rarely produce two leptons with significant transverse momenta and the same electric charge, however, there are many BSM predictions that yield such signatures with large rates. Among them are the LRSM [58–60, 161–163] type-II see-saw models [114, 164–167], Higgs triplet models [168, 169], the little Higgs model [170], the Georgi–Machacek model [171], scalar singlet dark matter [172], and the Zee–Babu neutrino mass model [173–175].

As discussed in Section 1.3, BSM same-charge signature can occur either due to doubly-charged resonances (e.g. $H^{\pm\pm}$) or indirectly through production processes such as the Keung–Senjanović process (see Figure 1.8). The thesis presents two distinct searches: a search for doubly charged Higgs boson production in multi-lepton final states and a search for heavy neutrinos and right-handed W gauge bosons in final states with two same-charge leptons and two energetic jets. For both searches, the LRSM is used as the benchmark model for signal region selection optimization and the details of the corresponding simulated signal events are presented in Section 3.1.1.

All event selection criteria involve properties of high-level reconstructed objects such as electrons, muons, and jets. Objects in pp collision events are reconstructed with the algorithms described in Section 4 and specific identification criteria are chosen for the presented analyses. Objects selected in this manner are called *analysis objects*. Their exact definition along with the analysis regions for both searches is presented in Section 6.3.

In addition to data quality criteria which ensure that the detector was functioning properly, events are rejected if they contain reconstructed jets not associated to real energy deposits that can arise from hardware problems, beam conditions or cosmic ray showers using the methods from Ref. [176]. To further increase the purity and quality of the data sample by rejecting non-collision events originating from cosmic rays and beam-halo events, at least one reconstructed primary vertex is required with at least two associated tracks. The primary vertex is chosen as the pp vertex candidate with the highest sum of the squared transverse momenta of all associated tracks.

6.1 The doubly charged Higgs boson production search

The assumption in this thesis is that the $H^{\pm\pm}$ boson decays into two same-charge leptons and is a narrow resonance. Only electron and muon final states are considered, i.e. $H^{\pm\pm} \rightarrow e^\pm e^\pm / e^\pm \mu^\pm / \mu^\pm \mu^\pm$ or also denoted as $H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$. Other final states X that are not directly selected in this analysis are taken into account by reducing the lepton multiplicity of the final state. These states X would include, for instance, τ leptons or W bosons, as well as particles that escape direct detection. The

total assumed branching ratio of $H^{\pm\pm}$ is therefore $B(H^{\pm\pm} \rightarrow e^\pm e^\pm) + B(H^{\pm\pm} \rightarrow e^\pm \mu^\pm) + B(H^{\pm\pm} \rightarrow \mu^\pm \mu^\pm) + B(H^{\pm\pm} \rightarrow X) = B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) + B(H^{\pm\pm} \rightarrow X) = 100\%$.

The reconstructed invariant mass of same-charge electron pairs in simulated $pp \rightarrow H^{++}H^{--}$ events is presented in Figure 6.1 and the multiplicity of reconstructed leptons is presented in Table 6.1. For a branching ratio of $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ the number of reconstructed signal leptons varies from one to four, with three and four being the most probable values. However, for lower values of $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$ the distribution shifts towards lower lepton multiplicities. Two-, three-, and four-lepton signal regions are defined to select the majority of such events. These regions are further divided into unique flavor categories (e or μ) to increase the sensitivity.

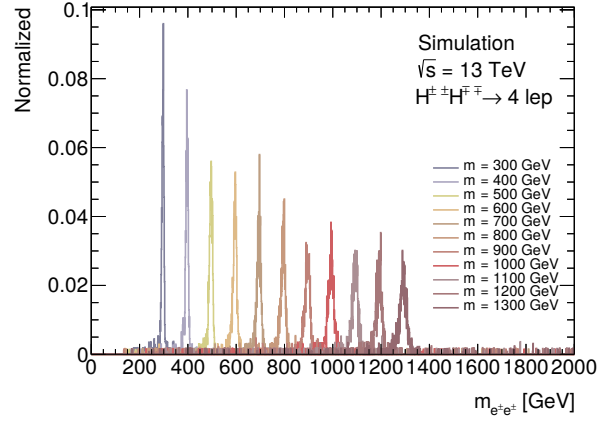


Figure 6.1: Reconstructed invariant mass of same-charge electrons in simulated $pp \rightarrow H^{++}H^{--}$ events for $B(H^{\pm\pm} \rightarrow e^\pm e^\pm) = 100\%$.

Table 6.1: Distribution of the number of reconstructed leptons in simulated $pp \rightarrow H^{++}H^{--}$ events for three different masses of the $H^{\pm\pm}$ boson: 200 GeV, 500 GeV, and 1000 GeV. The branching ratio assumption is $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$.

$m(H^{\pm\pm})$ [GeV]	Lepton multiplicity					
	0	1	2	3	4	5
200	0.2 %	2.8 %	17 %	40 %	40 %	0.2 %
500	0.04 %	0.9 %	8.1 %	34 %	57 %	0.5 %
1000	0.03 %	0.7 %	6.6 %	32 %	61 %	0.2 %

Additional motivation to study cases with $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) < 100\%$ is given by type-II see-saw models with specific neutrino mass hypotheses resulting in a fixed branching ratio combination [73, 167, 177] which does not necessarily correspond to $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$.

Both ATLAS and CMS previously analyzed same-charge dilepton final states in search of the doubly charged Higgs boson. The ATLAS Collaboration performed searches at $\sqrt{s} = 7$ TeV [178, 179] and $\sqrt{s} = 8$ TeV [180] with the Run 1 dataset. Furthermore, the CMS Collaboration performed a

doubly charged Higgs search at $\sqrt{s} = 7$ TeV [181]. No evidence for a signal was found in any of the searches and the most stringent limits are imposed by ATLAS analyzed data corresponding to 20.3 fb^{-1} of integrated luminosity which, recorded in 2012 at a center-of-mass energy of 8 TeV [180]. Depending on the flavor of the final-state leptons, the observed limits vary between 465 GeV and 550 GeV assuming $B(H_L^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$. The analysis presented in this thesis extends the one described in Ref. [180] and is based on 36.1 fb^{-1} of integrated luminosity collected in 2015 and 2016 at a center-of-mass energy of 13 TeV. The author of the thesis played a significant role in this analysis which was published as Ref. [93].

6.2 Search for heavy right-handed neutrinos and W_R bosons

The search for heavy neutrinos and right-handed W gauge bosons was performed separately for opposite-charge and same-charge final states in ATLAS and combined in the statistical interpretation of the results. As the author of this thesis worked only on the same-charge channel and the statistical combination of both channels, the opposite-charge channel is presented in less detail. The results of the same-charge only channel are presented in Section 9.3.2 and the results of the combined analysis are presented in Section 9.3.3.

The studied process of interest is the Keung-Senjanović process (see Figure 1.8 for the Feynman diagram), which predicts production of heavy right-handed neutrinos N_R (Majorana or Dirac) and right-handed gauge bosons W_R at the LHC pp collisions. The Majorana or Dirac nature of the right-handed neutrinos can be tested by observing the charge of final state leptons. If the N_R are Dirac particles, the two leptons produced in the Keung-Senjanović process will always have charges with opposite signs. However, if they are Majorana particles, the right-handed neutrinos are their own anti-particles, and leptons arising from their decay will have both opposite and same charges with equal probability. In this thesis, the search for W_R bosons and N_R neutrinos is performed in a final state containing two charged leptons and two jets ($\ell\ell jj$, $\ell = e, \mu$) and the equivalence of right- and left-handed weak gauge couplings ($g_L = g_R$) is assumed. If the W_R boson is heavier than the N_R neutrino ($m(W_R) > m(N_R)$), the on-shell W_R mass can be reconstructed from the invariant mass of the $\ell\ell jj$ system. In case of $m(N_R) > m(W_R)$, the on-shell W_R mass can be reconstructed from the invariant mass of the jj system. Expected mass-related distributions for typical $m(W_R)$ and $m(N_R)$ values are presented in Figure 6.2.

The Keung-Senjanović process resulting in a $\ell\ell jj$ final state in the electron and muon channels has been studied by both ATLAS and CMS collaborations using $\sqrt{s} = 7$ TeV [182, 183], $\sqrt{s} = 8$ TeV [184, 185] and $\sqrt{s} = 13$ TeV [186] collision data. CMS also has results for the hadronic $\tau\tau jj$ final state at $\sqrt{s} = 13$ TeV [187, 188]. No evidence for a W_R boson or a N_R neutrino has emerged from these studies. The previous most stringent exclusion limits on W_R boson and Majorana N_R neutrino masses were derived by the CMS experiment [186] at $\sqrt{s} = 13$ TeV. In both electron and muon channels, the CMS collaboration excluded regions extending to $m(W_R) \sim 4.4$ TeV (for a range of $m(N_R)$ values), whilst the $m(N_R)$ limits reach ~ 2.9 TeV in the electron channel (for $m(W_R) \sim 3.8$ TeV) and ~ 3 TeV in the muon channel (for $m(W_R) \sim 3.6$ TeV). This search extends the previous ATLAS searches to 36.1 fb^{-1} of data at $\sqrt{s} = 13$ TeV and improves the previously most stringent limits.

6 Analysis strategy and event selection

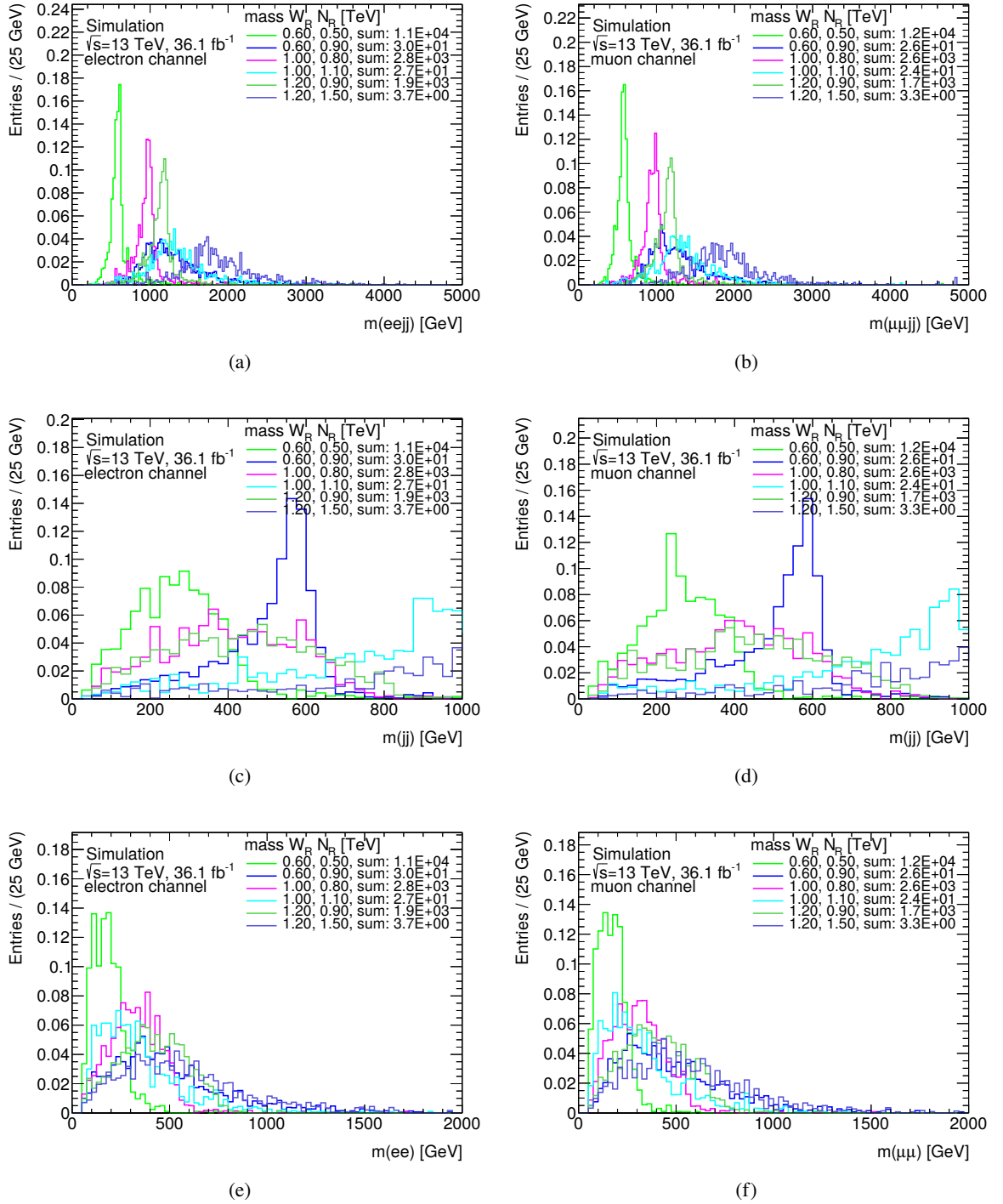


Figure 6.2: Various distributions related to masses of heavy neutrinos and right-handed gauge W bosons in simulated Keung-Senjanović process events: (a) the four-body invariant mass of two electrons and two jets, (b) the four-body invariant mass of two muons and two jets, (c) the invariant mass of two jets in the electron channel, (d) the invariant mass of two jets in the muon channel, (e) the invariant mass of electrons, and (f) the invariant mass of two muons. The sum given in the legend is normalized to 36.1 fb^{-1} and the predicted signal cross-section.

6.3 Analysis event selection

Events are classified in independent categories, called *analysis regions*, which serve different purposes. The so-called *control regions* (CRs) are used to constrain free background parameters in the statistical analysis detailed in Section 9. The background model is validated against data in *validation regions* (VRs). Both the control and validation regions are designed to reject signal events. A dedicated selection targeting signal events is utilized to define the *signal regions* (SRs). The selection criteria of analysis regions for the presented searches are given in Sections 6.3.2 and 6.3.3.

Both the $H^{\pm\pm}$ search and the N_R and W_R search utilize same-charge lepton final states to increase the signal sensitivity. Furthermore, lepton working points with high efficiency of selecting signal lepton candidates that still allow a robust background estimation are chosen. Both analyses use the same definition of analysis objects.

An irreducible background originates from SM processes resulting in same-charge leptons, hereafter referred to as prompt background. Prompt background events mainly originate from diboson ($W^\pm W^\pm$, ZZ , WZ) and $t\bar{t} X$ processes ($t\bar{t} W$, $t\bar{t} Z$, and $t\bar{t} H$). They also provide a source of reducible background due to charge misidentification in channels that contain electrons.¹ As described in Section 7, the modeling of charge misidentification in simulation deviates from data and consequently charge reconstruction scale factors are derived in a data-driven way and applied to the simulated events to compensate for the differences. The highest-yield process which enters the analysis through charge misidentification is Drell–Yan ($q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$) followed by $t\bar{t}$ production.

Another source of reducible background arises from events with fake electrons or muons. For both this contribution originates within jets, from decays of light-flavor or heavy-flavor hadrons into light leptons. For electrons, a significant component of fakes arises from jets which satisfy the electron reconstruction criteria and from photon conversions. MC samples are not used to estimate this background because the simulation of jets and hadronization has large uncertainties. Furthermore, the probability to incorrectly reconstruct a lepton is relatively low and a prohibitively large set of simulated events would be needed to reliably estimate the fake background with the corresponding theory uncertainties. Instead, a data-driven approach is used to assess this contribution from production of W +jets, $t\bar{t}$ and multi-jet events (described in Section 7). The method is validated in specialized validation regions.

6.3.1 Analysis object definition

The presented analyses classify leptons in two exclusive categories called *tight* and *loose*, defined specifically for each lepton flavor as described below. Leptons selected in the tight category feature a predominant component of prompt leptons, while loose leptons are mostly fakes, which are used for the fake-background estimation. All tracks associated with lepton candidates must have a longitudinal impact parameter with respect to the primary vertex satisfy $|z_0 \sin \theta| < 0.5$ mm. Requirements of analysis electrons and muons are summarized in Tables 6.2 and 6.3 respectively. Electron transverse

¹ The probability of muon charge misidentification is negligible because muon tracks are measured both in the inner detector and in the muon spectrometer which provides a much larger lever arm for the curvature measurement.

momenta are measured and calibrated with the EM calorimeter energy deposits, E_T , however, it is denoted p_T in the following to have a uniform definition with muons.

Electron candidates are reconstructed using information from the EM calorimeter and ID by matching an isolated calorimeter energy deposit to an ID track. They are required to have $|\eta| < 2.47$, $p_T > 30$ GeV, and to pass at least the LOOSE identification level based on a multivariate likelihood discriminant, introduced in Section 4.4.4. The likelihood discriminant is based on track and calorimeter cluster information. Electron candidates within the transition region between the barrel and end-cap electromagnetic calorimeters ($1.37 < |\eta| < 1.52$) are vetoed due to limitations in their reconstruction quality. The track associated with the electron candidate must have an impact parameter evaluated at the point of closest approach between the track and the beam axis in the transverse plane (d_0) that satisfies $|d_0/\sigma_{d_0}| < 5$, where σ_{d_0} is the uncertainty on d_0 . In addition to this, electron candidates are classified as tight if they satisfy the MEDIUM working point of the likelihood discriminant and the LOOSE fixed efficiency isolation criteria described in Section 4.5. It is based on calorimeter cluster and track isolation, which vary to obtain a fixed efficiency for selecting prompt electrons of 99% across p_T and η . Electrons are classified as loose if they fail to satisfy either of the identification or the isolation criteria.

Table 6.2: A summary of the baseline electron definitions in the analysis.

Requirement	tight electrons	loose electrons
Identification	MEDIUM	LOOSE and fail MEDIUM OR
Isolation	LOOSE	fail LOOSE
p_T cut	$p_T > 30$ GeV	$p_T > 30$ GeV
η cut	$ \eta < 2.47$ and veto $1.37 < \eta < 1.52$	$ \eta < 2.47$ and veto $1.37 < \eta < 1.52$
$ d_0/\sigma_{d_0} $ cut	$ d_0/\sigma_{d_0} < 5.0$	$ d_0/\sigma_{d_0} < 5.0$
$ z_0 \sin \theta $ cut	$ z_0 \sin \theta < 0.5$ mm	$ z_0 \sin \theta < 0.5$ mm

Muon candidates are selected by combining information from the muon spectrometer and the ID. They are required to satisfy the MEDIUM identification criteria described in Section 4.3.1 and to have $p_T > 30$ GeV, $|\eta| < 2.5$ and $|d_0/\sigma_{d_0}| < 10$. Muon candidates are classified as tight if their impact parameter satisfies $|d_0/\sigma_{d_0}| < 3.0$ and if they satisfy the most stringent isolation working point of the fixed cut track isolation, FIXEDCUTTIGHTTRACKONLY. Muons are classified as loose if they fail the isolation requirement FIXEDCUTTIGHTTRACKONLY and are not required to have $|d_0/\sigma_{d_0}| < 3.0$. Isolated muons with $3.0 < |d_0/\sigma_{d_0}| < 10$ are not within the analysis acceptance.

Jets or particles originating from the hadronization of partons are reconstructed by clustering energy deposits in the calorimeter calibrated at the EM scale. The anti- k_t algorithm is used with a radius parameter of 0.4, which is implemented with the FASTJET package, as described in more detail in Section 4.6.1. The majority of pile-up jets are rejected using the *jet-vertex-tagger* [189], which is a combination of track-based variables providing discrimination against pile-up jets. For all jets the expected average transverse energy contribution from pile-up is subtracted using an area-based p_T density subtraction method and a residual correction derived from the MC simulation, both detailed

Table 6.3: Summary of the baseline muon definitions in the analysis.

Requirement	tight muons	loose muons
Identification	MEDIUM	MEDIUM
Isolation	FIXEDCUTTIGHTTRACKONLY	fail FIXEDCUTTIGHTTRACKONLY
p_T cut	$p_T > 30 \text{ GeV}$	$p_T > 30 \text{ GeV}$
η cut	$ \eta < 2.5$	$ \eta < 2.5$
$ d_0/\sigma_{d_0} $ cut	$ d_0/\sigma_{d_0} < 3.0$	$ d_0/\sigma_{d_0} < 10$
$ z_0 \sin \theta $ cut	$ z_0 \sin \theta < 0.5 \text{ mm}$	$ z_0 \sin \theta < 0.5 \text{ mm}$

further in Section 4.6.1. In this analysis, events containing jets identified as originating from b -quarks are vetoed. They are identified with a multivariate discriminant (see Section 4.6.2) that has a b -jet efficiency of 77 % in simulated $t\bar{t}$ events and a rejection factor of ≈ 40 (≈ 20) for jets originating from gluons and light quarks (c -quarks). Kinematic requirements imposed on all jets in the analysis are $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$, however, some analysis regions require presence of jets with larger p_T thresholds.

After electron and muon identification, jet calibration, and pile-up jet removal, overlaps between reconstructed particles or jets are resolved. First, electrons are removed if they share a track with a muon. Secondly, ambiguities between electrons and jets are resolved. If a jet is closer than $\sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 0.2$ the jet is rejected. If $0.2 < \sqrt{(\Delta y)^2 + (\Delta \phi)^2} < 0.4$ the electron is removed. Finally, if a muon and a jet are closer than $\sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 0.4$, and the jet features less than three tracks, the jet is removed. Otherwise the muon is discarded. Both tight and loose leptons are used in this overlap removal procedure and rapidity is defined as $y \equiv 0.5 \ln [(E + p_z)/(E - p_z)]$ where E denotes the energy and p_z is the momentum component along the beam direction.

Simulated events are corrected on an event-by-event basis to account for the differences in identification criteria in simulation and data. For each criteria (e.g. lepton identification, lepton isolation, b -jet tagging) selection efficiency is measured both in data (ϵ_d) and MC (ϵ_{MC}). The ratio of the two is called the *scale factor*, $SF = \epsilon_d/\epsilon_{MC}$, and is applied for each object in the event. Generally, these corrections are small (less than 1 %), reflecting the precision of the ATLAS simulation. Examples of scale factors are given in bottom panels in Figures 4.3 and 4.6 for muon reconstruction efficiency and isolation efficiency respectively.

6.3.2 Analysis regions for the doubly charged Higgs search

The lepton multiplicity in the event is used to define the analysis regions for the $H^{\pm\pm}$ search. Signal region candidate events with two or three leptons are required to contain exactly one same-charge lepton pair, while four-lepton events are required to feature two same-charge pairs where the sum of all lepton charges has to be zero. In all regions, events with at least one b -tagged jet are vetoed, in order to suppress background events arising from top-quark decays. In signal regions with two or three leptons, events are rejected if any opposite-charge same-flavor lepton pair is within 10 GeV

6 Analysis strategy and event selection

Table 6.4: Summary of all regions used in the $pp \rightarrow H^{++}H^{--}$ search. The table is split into three blocks: the upper block indicates the final states for each region, the middle block indicates the mass range of the corresponding final state, and the lower block indicates the event selection criteria for the region. The application of a selection requirement is indicated by a check-mark (✓). The 2P4L regions include all lepton flavor combinations. In the three lepton regions, $\ell^\pm \ell^\pm \ell'^\mp$ indicates that same-charge leptons have the same flavor, while the opposite-sign lepton has a different flavor. Taken from Ref. [93].

	Control Regions			Validation Regions			Signal Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
Electron channel	$e^\pm e^\mp$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$	
Mixed channel	-	$e^\pm \mu^\pm \ell^\mp$	$\ell^\pm \ell^\pm \ell'^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm \ell'^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm \ell'^\mp$
Muon channel	-	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$	
$m(e^\pm e^\pm)$ [GeV]	[130, 2000]	[90, 200)		[130, 200)	[90, 200)		[200, ∞)	[200, ∞)	
$m(\ell^\pm \ell^\pm)$ [GeV]	-	[90, 200)	[60, 150)	[130, 200)	[90, 200)	[150, 200)	[200, ∞)	[200, ∞)	[200, ∞)
$m(\mu^\pm \mu^\pm)$ [GeV]	-	[60, 200)		[60, 200)	[60, 200)		[200, ∞)	[200, ∞)	
b -jet veto	✓	✓	✓	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-	-	✓	✓
$\Delta R(\ell^\pm, \ell^\pm) < 3.5$	-	-	-	-	-	-	✓	✓	-
$p_T(\ell^\pm \ell^\pm) > 100$ GeV	-	-	-	-	-	-	✓	✓	-
$\sum p_T(\ell) > 300$ GeV	-	-	-	-	-	-	✓	✓	-
$\Delta M/\bar{M}$ requirement	-	-	-	-	-	-	-	-	✓

of the Z boson mass ($81.2 \text{ GeV} < m(\ell^+ \ell^-) < 101.2 \text{ GeV}$). The selection criteria utilized for each analysis region are summarized in Table 6.4. The invariant mass distribution of the same-charge lepton pair is used in the final fit of the analysis for the two- and three-lepton regions. A lower bound of 60 GeV on the invariant mass is imposed in all regions to discard low-mass events which would potentially bias the background estimation of the analysis while maximizing the available number of events. Furthermore, invariant masses of same-charge lepton pairs are required to be above 200 GeV in signal regions and below 200 GeV in most CRs and VRs.

Control regions assist the background modeling in SRs and are defined to target specific processes that dominate the backgrounds in the SRs. The main variable that defines the type of the region is the invariant mass of same-charge lepton pairs. An exception to this rule is the *opposite-charge control region* (OCCR) which features two opposite-charge electrons with an invariant mass of $130 \text{ GeV} < m(e^+ e^-) < 2000 \text{ GeV}$. This CR is enriched in high-mass Drell–Yan events which also enter the two-electron SR. Furthermore, control regions for the diboson production are defined by inverting the Z boson veto in three-lepton regions. They are denoted as DBCR (*diboson control region*) and are split depending on the flavor combination of the same-charge lepton pair. Lastly, a control region for the four lepton final state is defined with a requirement on the same-charge lepton pair invariant masses of $60 \text{ GeV} < m(\ell^\pm \ell^\pm) < 150 \text{ GeV}$.

The modeling of the SM background is verified in designated validation regions which are optimized to be as close as possible to SRs. Generally, they employ the same event selection as the signal regions,

however, the invariant mass of the same-charge lepton pair in the event is required to be below 200 GeV to ensure the orthogonality with SRs. The *same-charge validation region* (SCVR) is used to validate the data-driven fake-background estimation and the charge misidentification effect in the electron channel. The *three-lepton validation region* (3LVR) is used to validate the SM diboson background and fake events with three reconstructed leptons with different proportions across channels. The *four-lepton validation region* (4LVR) is used to validate the diboson modeling in four-lepton region. Furthermore, the *diboson control region* (DBCR) is used to constrain the diboson background yield in each channel while the opposite-charge control region is used to constrain the Drell–Yan contribution in the electron channel only. The *four-lepton control region* (4LCR) is used to constrain the yield of the diboson background in four-lepton regions.

In the electron and mixed channels the lower bound on the same-charge pair invariant mass of 60 GeV is increased to 90 GeV in the three-lepton regions and to 130 GeV in the two-lepton regions. The motivation for increasing the lower mass bound in regions containing electrons is the data-driven charge misidentification background correction, where the $Z \rightarrow ee$ peak is used to measure the charge misidentification rates (described in Section 7). Differences between data and MC simulation in the di-electron same-charge $Z \rightarrow ee$ peak were minimized by construction and the $Z \rightarrow ee$ peak was therefore not used in the fit. In the two-lepton regions, this bound is set to 130 GeV to completely remove the Z peak region. In the three-lepton regions, where this effect is not as strong, the bound is relaxed to 90 GeV to reduce the statistical uncertainty of the sample. As the charge misidentification background is not present in the muon channel, there is no need to increase the lower mass bound there.

In order to maximize the sensitivity in two-lepton and three-lepton signal regions (SR1P2L and SR1P3L), additional requirements are imposed on same-charge lepton pairs, regardless of the lepton flavor. These exploit both the boosted decay topology of the $H^{\pm\pm}$ resonance and the high energy of the decay products. The same-charge lepton separation is required to be $\Delta R(\ell^\pm, \ell^\pm) < 3.5$. Their combined transverse momentum has to be $p_T(\ell^\pm \ell^\pm) > 100$ GeV.² Finally, the scalar sum of the leptons' transverse momenta is required to be above 300 GeV in the signal regions. In SR1P2L and SR1P3L, the signal selection efficiency combined with the detector acceptance varies greatly with the assumed branching ratio into light leptons. It is the highest for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \approx 60\%$ where about 40 % of signal events are selected either in SR1P2L or SR1P3L. For $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$, about 25 % of signal events are selected in either of the regions.

In the four-lepton signal region (SR2P4L), the fit variable is the average invariant mass of the two same-charge lepton pairs $\bar{M} \equiv (m^{++} + m^{--})/2$. A selection on the variable $\Delta M/\bar{M} \equiv |m^{++} - m^{--}|/\bar{M}$ is applied to reject background where the two same-charge pairs have inconsistent invariant masses. The $\Delta M/\bar{M}$ requirement is optimized for different flavor combinations which generally feature different mass resolutions. This selection corresponds to ΔM values which are required to be below 15 to 50 GeV for $\bar{M} = 200$ GeV, 30 to 160 GeV for $\bar{M} = 500$ GeV, and 50 to 500 GeV for $\bar{M} = 1000$ GeV. In the 2P4L signal region, the fraction of signal events that are selected is approximately 50 % for the $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ case and lower for branching ratios into light leptons below 100 %. The combined selection efficiency times acceptance for the $pp \rightarrow H^{++}H^{--}$ process to be reconstructed in any of the SRs is shown in Figure 6.3 for all three lepton flavor categories.

² The variable $p_T(\ell^\pm \ell^\pm)$ is the vector sum of the leptons' transverse momenta.

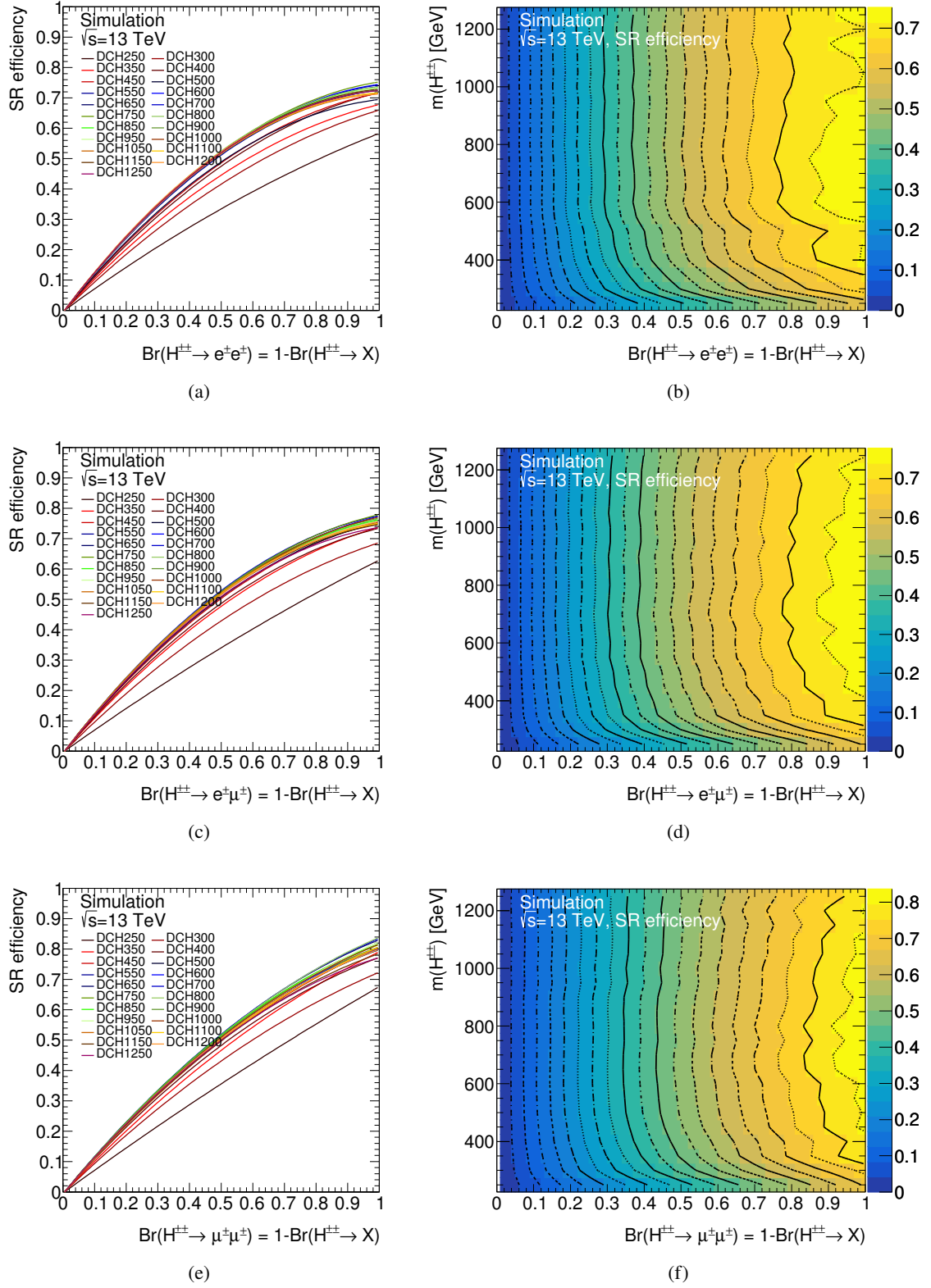


Figure 6.3: Combined SR efficiency times acceptance as a function of the $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$ branching ratio and the $H^{\pm\pm}$ boson mass: (a), (b) e^+e^- channel, (c), (d) $e^\pm\mu^\pm$ channel, and (e), (f) $\mu^\pm\mu^\pm$ channel.

6.3.3 Analysis regions for the heavy neutrino and W_R search

All analysis regions devoted to the heavy N_R and W_R search contain two same-flavor leptons (ee or $\mu\mu$) and at least two high- p_T jets to target the topology of the Keung-Senjanović process. A b -jet veto is applied on a collection of all jets with $p_T > 20$ GeV and $|\eta| < 2.5$ to reject SM backgrounds involving top quarks. Furthermore, at least two of the jets in the event are required to satisfy $p_T > 50$ GeV and the two jets with the highest p_T are used in jet-related variables such as $m(jj)$. A summary of the analysis regions is given in Table 6.5.

Table 6.5: Summary of all regions defined in the analysis. Jets considered for the b -jet veto are not subject to the ‘jet p_T ’ cut defined in the table, but are rather a collection of all jets with $p_T > 20$ GeV and $|\eta| < 2.5$.

	$Z \rightarrow ee$ peak VR	Control Regions	Validation Regions	Signal Regions
$m(e^\pm e^\pm)$ [GeV]	[60, 110]	[110, 300]	[300, 400]	[400, ∞)
$m(\mu^\pm \mu^\pm)$ [GeV]	-	[60, 300]	[300, 400]	[400, ∞)
H_T [GeV]	-	-	-	[400, ∞)
$m(jj)$ [GeV]	-	-	-	[110, ∞)
jet p_T [GeV]	50 GeV	50 GeV	50 GeV	100 GeV
$N(\text{jet})$	≥ 2	≥ 2	≥ 2	≥ 2
$N(b\text{-jet})$	0	0	0	0

Analysis control, validation, and signal regions are defined with the invariant mass of the two same-charge leptons. The control region requires $110 \text{ GeV} < m(e^\pm e^\pm) < 300 \text{ GeV}$ in the electron–electron channel and $60 \text{ GeV} < m(\mu^\pm \mu^\pm) < 300 \text{ GeV}$ in the muon–muon channel. The validation region requires $300 \text{ GeV} < m(e^\pm e^\pm) < 400 \text{ GeV}$ in the electron–electron channel and $300 \text{ GeV} < m(\mu^\pm \mu^\pm) < 400 \text{ GeV}$ in the muon–muon channel. The motivation for increasing the lower mass bound in control regions containing electrons is the data-driven charge misidentification background correction, where the $Z \rightarrow ee$ peak is used to measure the charge misidentification rates (described in Section 7), to avoid any interference. Nevertheless, the $60 \text{ GeV} < m(e^\pm e^\pm) < 110 \text{ GeV}$ region is used as an additional validation region to verify the estimation of the charge misidentification background in events with two high- p_T jets.

Additional requirements are imposed in signal regions to reduce the contribution from the main backgrounds such as $Z \rightarrow \ell^+ \ell^- jj$, $WZ \rightarrow \ell^\pm \ell^\pm jj$ and $ZZ \rightarrow \ell^\pm \ell^\pm jj$. The invariant mass of the two leading jets is required to be $m(jj) > 110 \text{ GeV}$ and the scalar sum of lepton and the two leading jets p_T must satisfy $H_T > 400 \text{ GeV}$. These cuts are not used in control and validation regions to increase the available statistics. The selection efficiency of the simulated Keung-Senjanović process in the defined SRs is presented in Figure 6.4.

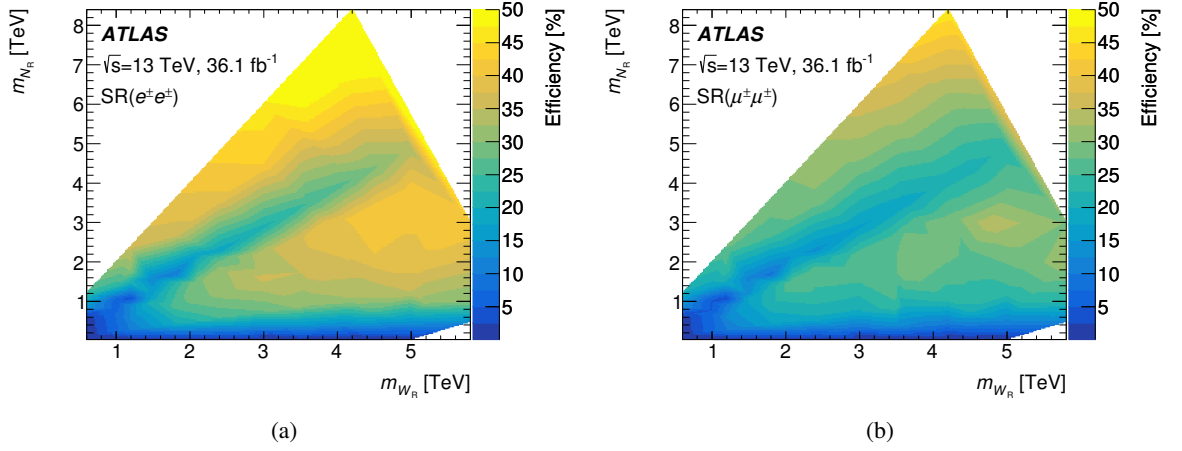


Figure 6.4: Efficiencies for signal region selection as a function of the different W_R and N_R masses for: (a) the electron and (b) muon channel. Taken from Ref. [190].

6.4 Triggers

Triggers are crucial for efficient data-taking as explained in Section 2.2.10. The trigger decision is simulated in MC and the same set of triggers are used in data and MC. The selection of the HLT triggers is dictated by the analysis object definition; electron and muon analysis identification and isolation requirements are ideally tighter than the trigger requirements to avoid any trigger bias. In presented analyses, loose electrons and muons are both defined without any isolation criteria therefore triggers imposing isolation criteria were avoided if possible. Furthermore, since loose electrons employ the LOOSE identification criteria, electron triggers that require tighter identification levels were not used.

It is important to note that triggers impose identification and isolation requirements which are derived in the same way as the ones described in Section 4, however, the identification criteria used in the analysis are re-tuned after data-taking to improve efficiency and reduce the corresponding systematic uncertainty. These are called the ‘online’ (trigger) and ‘offline’ (analysis) criteria and the inclusiveness of working points no longer holds across the two. For example, online MEDIUM electron identification is not entirely included in the offline LOOSE electron identification criteria. Furthermore, triggers change during data-taking to keep the write-out rate constant despite the changes in the instantaneous luminosity. The triggers used in presented analyses depending on the data-taking period and the lepton channel are summarized in Table 6.6. The trigger menu is detailed in Refs. [87] and [191].

Events in the electron channel are required to pass the HLT_2e12_1hloose_L12EM10VH trigger for the 2015 data-taking period and HLT_2e17_1hvloose_nod0 for 2016. They require two electrons with $E_T > 12$ GeV for 2015 data and $E_T > 17$ GeV for 2016. Furthermore, the 2015 trigger imposes the online LOOSE identification criteria on the two electrons while the 2016 trigger requires two electrons passing the online VERYLOOSE identification criteria, tuned without the d_0 variable.

Candidate events in the muon channel are selected using a combination of two single-muon triggers

Table 6.6: A summary of the used triggers in the presented analyses.

Channel	2015	2016
ee	HLT_2e12_lhloose_L12EM10VH	HLT_2e17_lhvloose_nod0
$e\mu$	HLT_e17_lhloose_nod0_mu14	HLT_e17_lhloose_nod0_mu14
$\mu\mu$	HLT_mu26_imediu OR HLT_mu50	HLT_mu26_ivarmediu OR HLT_mu50

with p_T thresholds of 26 GeV and 50 GeV. The single-muon trigger with the lower p_T threshold also requires track-based isolation of the muon according to the isolation criteria described in Refs. [87] and [191], depending on the data-taking period.

Events containing both electrons and muons (mixed channel) are required to pass either the combined electron–muon trigger or any of the triggers used for the muon channel or the electron channel. The combined trigger has an E_T threshold of 17 GeV and requires the online LOOSE identification criteria for the electron and a p_T threshold of 14 GeV for the muon. Events with four leptons are selected using a combination of dilepton triggers.

Similarly as object identification criteria efficiencies, trigger efficiencies are corrected in simulation as well on an event-by-event basis. Efficiencies of triggers are calculated both in data and MC and scale factors are derived as their ratio. However, the scale factors are not simply multiplied for each object in the event since not all leptons need to satisfy the trigger requirement; as long as one of the chosen triggers fire, the event will be recorded. In general, the corresponding event weight depends on the chosen triggers and the lepton multiplicity.

7 Background estimation

Prompt SM backgrounds in all regions are estimated using the simulated samples listed in Section 3.1.2. MC events containing at least one fake selected tight or loose lepton are discarded to avoid an overlap with the data-driven fake-background estimation. Prompt electrons in the remaining simulated events are corrected to account for different charge misidentification probabilities in data and simulation. The derivation of the electron charge reconstruction corrections is detailed in Section 7.1 and the methods used to estimate the fake background are presented in Section 7.2.

7.1 Electron charge misidentification background estimation

The misidentification of charge of prompt electrons (*charge-flip*) is responsible for the largest background in the electron channel. This background consists of events with a pair of opposite-charge electrons among which one has its charge misidentified. By far the most probable mechanism of electron charge misidentification is bremsstrahlung, as discussed in Section 5.1. Electrons in MC are classified into four categories, depending on whether the charge was correctly reconstructed and whether the main associated track to the cluster is truth matched to a prompt electron. Electrons with incorrect charge and wrong matched track are called *trident events* (due to the topology of three collinear electrons) and electrons with incorrect charge and correctly matched track are called the *stiff tracks*.

Charge misidentification is simulated by GEANT in Monte Carlo samples but it is not reliable to use it immediately. Misidentification due to trident events is caused by interactions of particles with the detector material and such processes are hard to simulate precisely. Furthermore, a very accurate description of the detector material would be needed to reliably predict these events. A data-driven approach was used to tackle this problem; the probability of an electron undergoing charge misidentification was measured in the data and compared to the Monte Carlo prediction.

Trident events arise when an electron undergoes bremsstrahlung and the radiated photon converts into a pair of electron-positron due to interactions with the detector material. It can happen that the calorimeter is matched to a track with the opposite charge compared to the original electron or that the photon transfers all of the energy to the opposite charge electron and the original charge is lost. Stiff tracks are a special case of bremsstrahlung where the radiated photon does not convert into a pair of electron-positron. The energy of the electron is correctly reconstructed from the calorimeter information, however, the matched track has very few hits corresponding to the original electron and its curvature is not well defined. These tracks can have very high momenta and are therefore called stiff tracks. The probability for these two effects is dependent on the energy scale of the studied region. Appendix B shows that even though the composition of these two processes is different in

the region used to measure the charge-flip probability and other analysis regions no significant bias is introduced.

In presented analyses, scale factor are derived for the electron charge-flip probability which is applied to all electrons simulated events. Scale factors are defined as the ratio of the charge-flip probability in data and MC, $SF = P_d/P_{MC}$. Electrons with incorrectly reconstructed charge are corrected by multiplying the event weight with the scale factor and electrons with correctly reconstructed charge yield a weight of $(1 - P_d)/(1 - P_{MC})$. The measurement of the charge-flip rate is presented in the following.

7.1.1 Measurement of the charge misidentification probability

Charge-flip probability is measured by performing a selection of $Z \rightarrow ee$ data events by requiring the pairs of electrons to be inside the Z mass window. The initial Monte Carlo agreement with the data in the $Z \rightarrow ee$ region is presented in Appendix C. Most of the background (non $Z \rightarrow ee$ events) is composed of top physics, diboson events, and fake electrons from W +jets events and it is larger in the same-charge region. The mismodeling in the same-charge $Z \rightarrow ee$ region is immediately evident for example in p_T and η distributions (Figures C.3(c) and C.4(a)). The most affected variables are electron p_T and η distributions. This mismodeling can be attributed to the poor description of charge-flip probability in the simulation.

The $Z \rightarrow ee$ region is divided into three regions: the main region and two side-bands orthogonal to the main region. The purpose of the side-bands is to estimate the non- Z background and subtract it from the main region. This data-driven method of background subtraction is called the *sideband* method. We assume that other backgrounds have flat distributions in this invariant mass range. Two types of $Z \rightarrow ee$ events are used for the charge-flip measurement: opposite-sign (OS) and same-sign (SS) events. The width and the position of the Z peak in each region is studied to correctly determine the three regions. The OS and SS Z peaks are presented in Figure 7.1. The SS peak is shifted by approximately 2.0 GeV to lower energies and that the width is slightly broader compared to the OS peak. Two times the FWHM values are used for the charge-flip estimation. The sidebands are made large enough to ensure sufficient statistics. The final definition of the three regions is presented below in Table 7.1.

Table 7.1: Definitions of main regions and sideband regions for opposite-sign and same-sign type Z peak events. The position of the Z peak as measured in the two regions is indicated by $m_{OS}(Z)$ and $m_{SS}(Z)$.

Event type	main region		side-bands
opposite-sign	$ m(ee) - m_{OS}(Z) < 14 \text{ GeV}$	$14 \text{ GeV} < m(ee) - m_{OS}(Z) < 28 \text{ GeV}$	
same-sign	$ m(ee) - m_{SS}(Z) < 15.8 \text{ GeV}$	$15.8 \text{ GeV} < m(ee) - m_{SS}(Z) < 31.6 \text{ GeV}$	

The width of the bands has to be the same as the central region or scaled to the same size. Some of the signal ($Z \rightarrow ee$) is subtracted along the fakes as well, however, that does not affect the charge-flip rate as all the signal electrons are the same (for a small enough $[p_T, \eta]$ region of the first electron, the

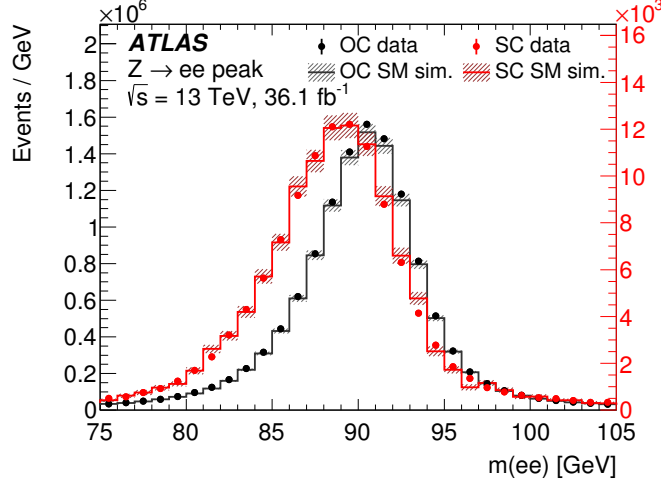


Figure 7.1: Di-electron mass distributions for opposite-charge (black) and same-charge (red) pairs for data (filled circles) and MC simulation (continuous line). The latter includes a correction for charge misidentification. The hatched band indicates the statistical error and the luminosity uncertainty summed in quadrature applied to MC simulated events. Taken from Ref. [93].

invariant mass formed with the second electron will not affect the charge-flip rate). Effectively, some statistics are lost due to the side-band subtraction method because some signal electrons are removed, but the effect is very small overall (i.e. $< 1\%$).

To measure the flip probability, standard event selection (Section 6.3) is applied and same-sign electrons pairs are selected. It is assumed that one of the electrons in the pair has incorrectly measured charge, because they originate from the $Z \rightarrow ee$ events. The total number of electron pairs is denoted by N^{ij} , where i stands for the leading electrons bin and j for the sub-leading electrons bin. Charge-flip probability is measured as a function of p_T and η , therefore i and j are both two dimensional bins $((p_{Ti}, \eta_i))$. The total number of electron pairs can be divided into same-sign and opposite-sign pairs: $N^{ij} = N_{SS}^{ij} + N_{OS}^{ij}$ and the probability of observing N_{SS}^{ij} same-sign events is a Poissonian probability:

$$f(N_{SS}^{ij}; \lambda) = \frac{\lambda^{N_{SS}^{ij}} e^{-\lambda}}{N_{SS}^{ij}!}, \quad (7.1)$$

where $\lambda = (\epsilon_i(1 - \epsilon_j) + \epsilon_j(1 - \epsilon_i))N^{ij}$ is the expected number of same-sign events in bin (i, j) given the charge misidentification probabilities ϵ_i and ϵ_j and N_{SS}^{ij} is the measured number of same-sign events.

The charge-flip rates are extracted with a *likelihood fit* by summing all of the Poissonian probabilities in Eq. 7.1 and maximizing the likelihood by varying the charge-flip probabilities. A standard procedure

to do this is to construct a negative logarithm of the summed likelihood:

$$-\log L(\vec{\epsilon}|\vec{N}_{\text{SS}}, \vec{N}) \approx \sum_{i,j} \log \left(N^{ij} (\epsilon_i(1 - \epsilon_j) + \epsilon_j(1 - \epsilon_i)) \right) N_{\text{SS}}^{ij} - N^{ij} (\epsilon_i(1 - \epsilon_j) + \epsilon_j(1 - \epsilon_i)). \quad (7.2)$$

The constant terms in the denominator of Eq. 7.1 were not included into the likelihood function because they do not have any effect on the minimization. The likelihood function is minimized using the ROOT minimization interface with the MINUIT2 package and MIGRAD algorithm.

7.1.2 Electron charge reconstruction scale factors

Charge misidentification probability is usually expressed in two-dimensional p_T and η bins. However, the parametrization can be improved by using the fact that the shape of the η dependence is very similar for all p_T bins and thus the parametrization can be expressed as a product of two one-dimensional functions:

$$\epsilon(p_T, \eta) = f(\eta) \times \sigma(p_T). \quad (7.3)$$

Furthermore, one of the functions must be normalized ($\int f(\eta) d\eta = 1$) to avoid infinite minimums of the likelihood function in Eq. 7.2. This requirement further decreases the number of free parameters to $N_\eta + N_{p_T} - 1$ compared to the number of parameters $N_\eta \times N_{p_T}$ in the two-dimensional parametrization. This parametrization effectively extracts the η dependence of the bremsstrahlung probability and scales it with a combined p_T scale. This reflects well the fact that bremsstrahlung probability mostly depends on the amount of transversed material. The requirement of unit area of the $f(\eta)$ function is realized in the likelihood fit by adding a constraint to the likelihood function

$$\alpha \left(\sum_{n=1}^{N_\eta} [f(i) \times \Delta\eta_i] - 1 \right)^2, \quad (7.4)$$

where $f(i)$ is the value of the i -th bin of the $f(\eta)$ function, $\Delta\eta_i$ is the width of the i -th bin and the sum which goes over all bins of the $f(\eta)$ function yields the area under the function. Parameter α is an arbitrary scale which is set in a way to minimize the correlations between the free parameters in the likelihood fit.

The one-dimensional fit has a much smaller statistical uncertainty and allows to measure charge-flip probability of highly energetic electrons ($p_T > 200$ GeV), which would otherwise not be possible. The result of the one-dimensional likelihood fit in the data is shown in Figure 7.2 with black dots. Charge-flip probability is increasing with both p_T and η .

The correlation matrix of the fits are presented on Figure 7.3. Most of the correlations are lower than 10 %, however, a significant correlation between the last η parameter and other η parameters is observed. This is explained with the enforced normalization of the η function: the last η bin

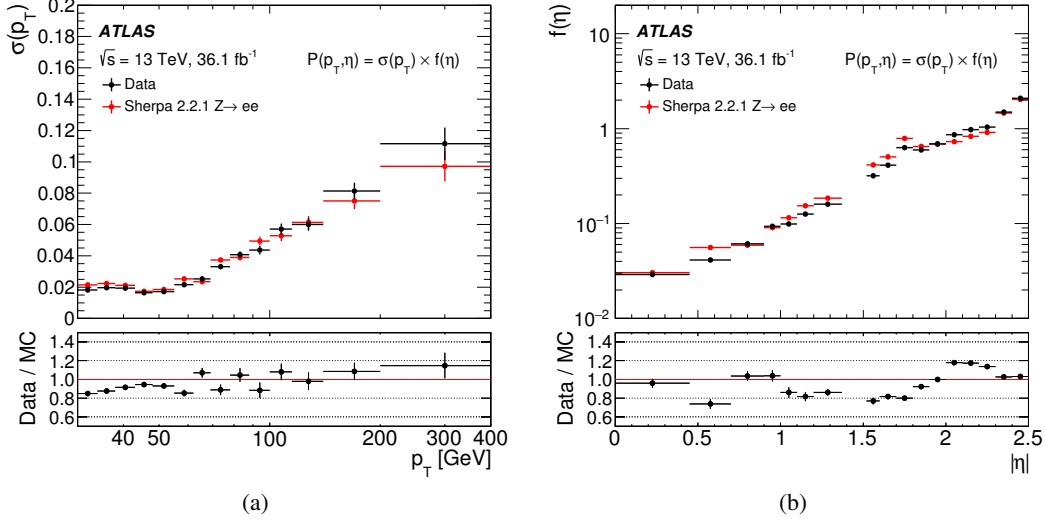


Figure 7.2: Comparison of the factors composing the charge misidentification probability $P(p_T, \eta) = \sigma(p_T) \times f(\eta)$ measured in data and in simulation using the likelihood fit in the $Z/\gamma^* \rightarrow ee$ region. The area of the distribution describing $f(\eta)$ was set to unity (see text for details). Error bars correspond to the statistical uncertainties estimated with the likelihood fit. Plot (a) shows the charge misidentification probability component as a function of p_T and plot (b) shows the component as a function of $|\eta|$. Taken from Ref. [93].

has the largest value and all the other η bins have to balance out its potential growth to maintain the normalization. This correlation indicates that there is one less free parameter than the sum of $N_\eta + N_{p_T}$. Furthermore, we observe that the eighth η parameter does not have any correlation at all. This parameter is limited to the transition region ($1.37 < |\eta| < 1.52$), which is excluded from the analysis acceptance.

The charge reconstruction scale factors are applied to MC as the product of two one dimensional functions shown in bottom panels in Figures 7.2(b) and 7.2(a). A clear tendency of mis-modeling near the transition region is observed in the η distribution and the p_T ratio is relatively flat at higher energies and has a distinct shape at lower energies. The bins were chosen in a way to have the largest possible granularity in ranges with the largest mismodeling while balancing the bin width with the available statistics. The ranges with the largest mis-modeling are the low p_T range (Figures C.3(c) and C.3(d)) and the η ranges near the transition region (Figures C.4(a) and C.4(b)).

Electron charge reconstruction correction closure

A closure test is performed to verify the likelihood fit. Same-charge pairs with invariant mass around the Z peak are selected from the data and compared to the MC prediction corrected with charge-flip scale factors (Figure 7.2). Resulting distributions are shown in Figure 7.4. They exhibit a much better agreement compared to the initial distributions of the same-sign $Z \rightarrow ee$ region (Figures C.3 and C.4). It is evident that the mismodeling in the low- p_T spectrum as well as the η mismodeling are recovered.

7 Background estimation

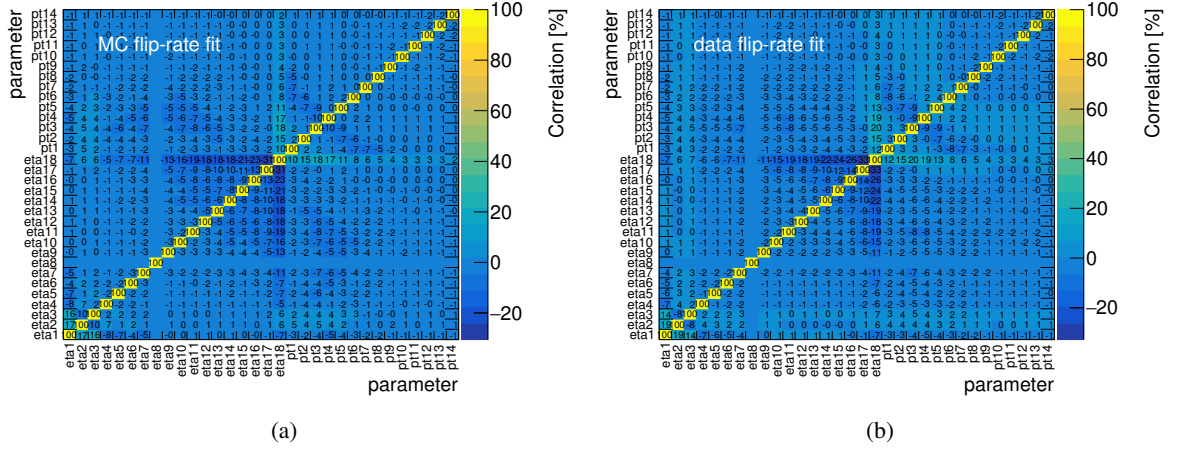


Figure 7.3: Correlation matrices for the charge-flip likelihood fits. Each bin represents a charge-flip parameter, used for the computation of charge-flip scale factors. (a) the correlation matrix for the $Z \rightarrow ee$ MC fit and (b) the correlation matrix for the data fit.

Further validation of the charge-flip background estimation is performed in the Z peak VR, defined in Table 6.5. In this test, at least two high- p_T jets are required to test the validity of charge-flip background estimation in an environment similar to the one in control and signal regions of the heavy N_R and W_R search. Distributions presented in Figures 7.5 and 7.6 showcase a good agreement between the prediction and the data, which gives us further confidence in the data-driven charge-flip background estimation also in topologies with two energetic jets in the event.

7.1 Electron charge misidentification background estimation

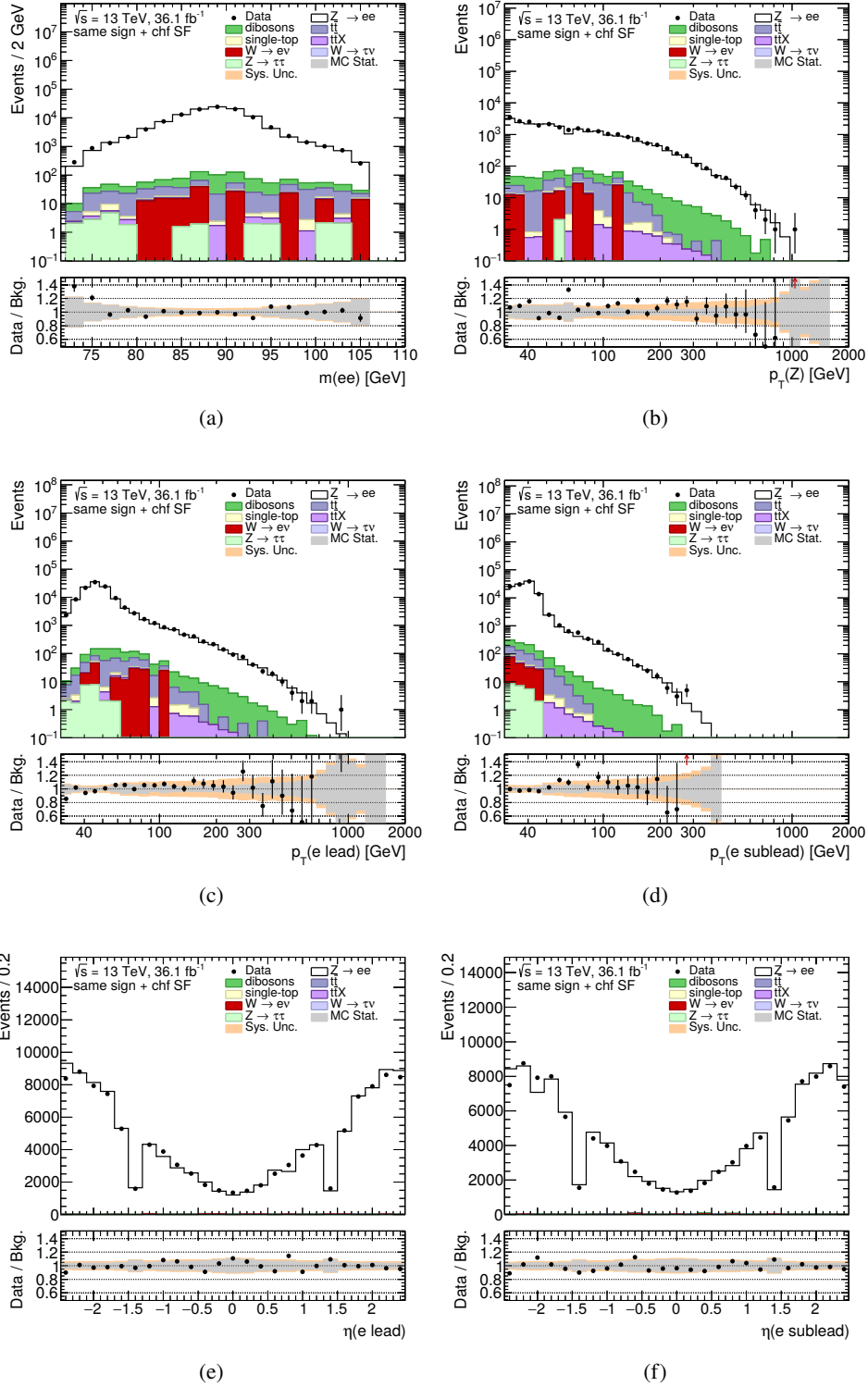


Figure 7.4: Charge reconstruction correction closure test. Same-charge pairs with invariant mass around the Z peak are selected from the data and compared to the MC prediction corrected with charge-flip scale factors: (a) invariant mass distribution of the same-sign electron pair, (b) di-electron p_T distribution, (c) and (d) p_T distribution of electrons, (e) and (f) η distribution of electrons.

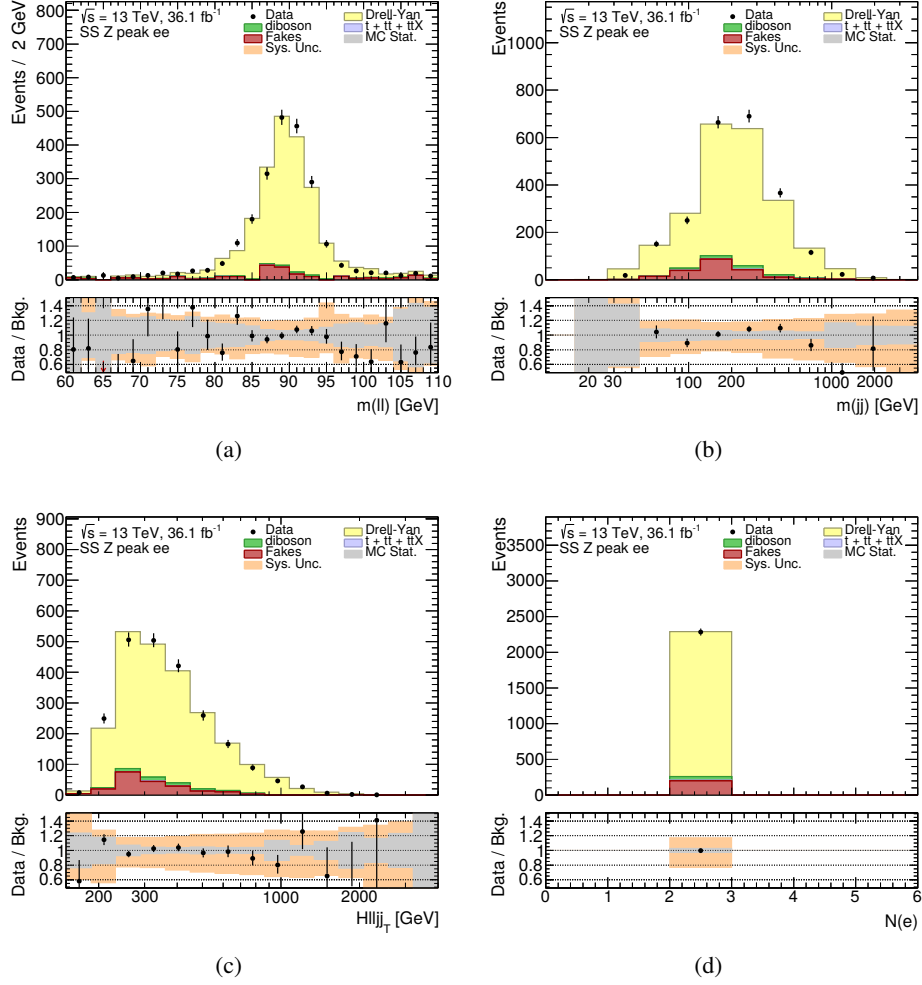


Figure 7.5: Distributions for data and SM background predictions corrected with charge-flip scale factors in the electron Z peak validation region (see Table 6.5): (a) invariant mass of the two electrons, (b) invariant mass of the two leading jets, (c) scalar sum of the p_T of leptons and two leading jets, and (d) total number of events in the region.

7.1 Electron charge misidentification background estimation

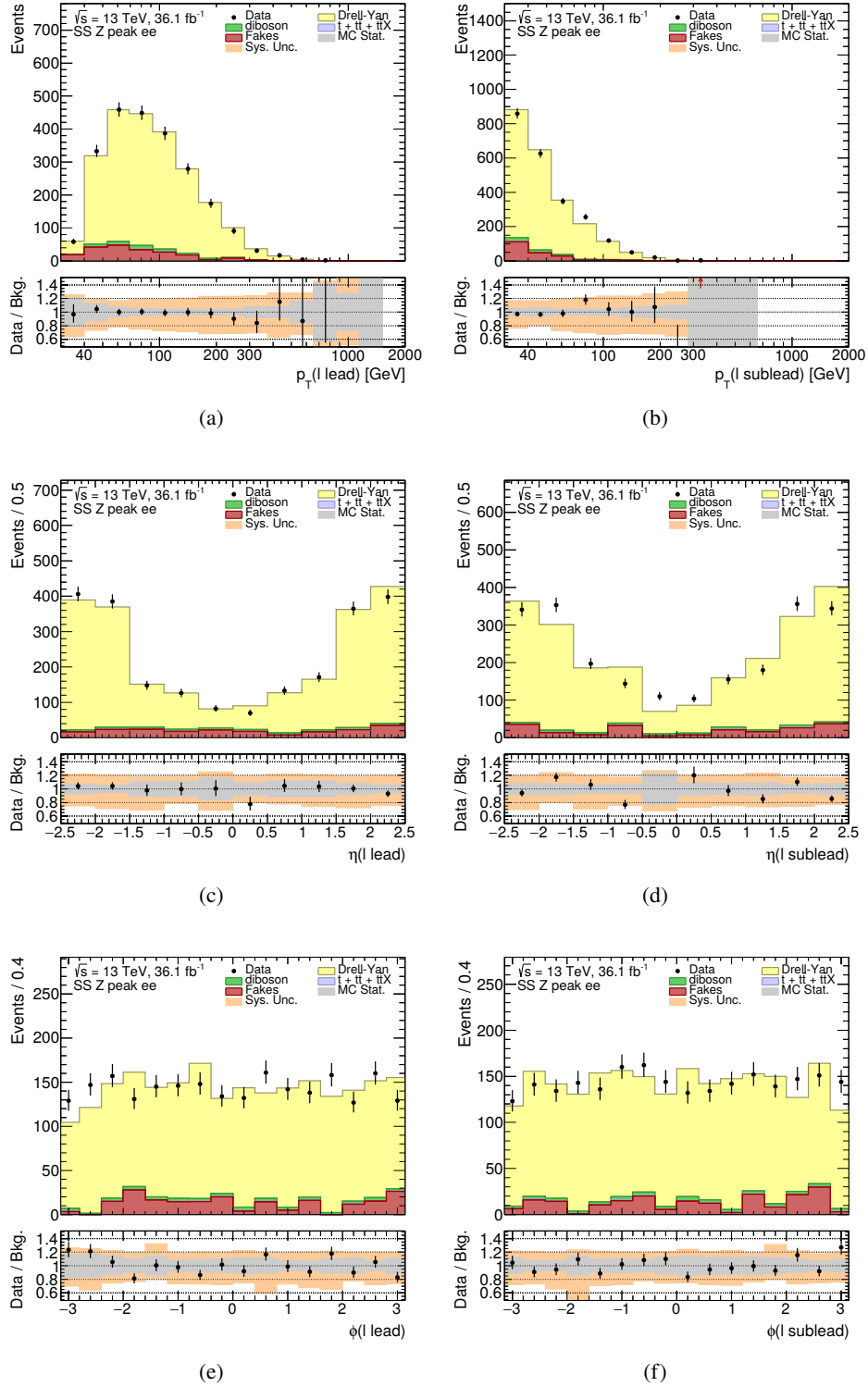


Figure 7.6: Distributions for data and SM background predictions in the electron Z peak validation region (see Table 6.5): (a) leading electron p_T , (b) subleading electron p_T , (c) leading electron η , (d) subleading electron η , (e) leading electron ϕ , and (f) subleading electron ϕ .

7.1.3 Systematic uncertainties in electron charge reconstruction

Several sources of systematic uncertainty are attributed to the 1D×1D electron charge reconstruction corrections:

- Statistical uncertainty due to finite statistics of the $Z \rightarrow ee$ samples used to measure the charge-flip rates.
- Impact of changing the definitions of the main and side-band regions (Table 7.1).
- Validity of the likelihood fit. MC charge-flip rates obtained with the likelihood fit are compared to the true charge-flip rates in MC.
- Validity of the 1D×1D parametrization.

The statistical uncertainty related to the finite statistics of the $Z \rightarrow ee$ samples is evaluated with the likelihood fit using the MINOS algorithm. These uncertainties are presented in Figure 7.2 with horizontal bars. This uncertainty varies from 5 to 20 %, depending on the electron p_T and η .

The uncertainty due to the used definition of side-band and central regions is evaluated by increasing all regions by 0.5 FWHM. Charge-flip scale factors are recalculated with the new regions and compared to the nominal results. The effect is negligible compared to the statistical uncertainty and not considered as an additional source of uncertainty.

The validity of the likelihood fit is evaluated by comparing the MC charge-flip rates estimated with the likelihood fit to the true MC charge-flip rates. The true rates are calculated simply by dividing the number of electrons with incorrect charge in MC with the number of all electrons. The true charge-flip rate can not be expressed in the same 1D×1D parametrization. To achieve a fair comparison, true charge-flip rates are derived inclusively in p_T , only as a function of the electron η , and normalized to unit area. The η shape of the true charge-flip rate is then compared to the η shape obtained with the likelihood fit. Furthermore, this procedure is repeated for several p_T slices and the results are presented in Figure 7.7. A good agreement between the true charge-flip rates and the likelihood-based flip-rates is observed and no additional uncertainty is considered from this test.

The closure of the 1D×1D parametrization is evaluated by selecting opposite-sign $Z \rightarrow ee$ events, re-weighting them with the charge-flip rates, and comparing them to the corresponding same-sign $Z \rightarrow ee$ events. The event weight used to re-weight the CS events is presented in Eq. 7.5.

$$w = \frac{\epsilon_1(1 - \epsilon_2) + \epsilon_2(1 - \epsilon_1)}{1 - (\epsilon_1(1 - \epsilon_2) + \epsilon_2(1 - \epsilon_1))}, \quad (7.5)$$

where ϵ_1 and ϵ_2 are charge-flip rates for the two electrons in the OS event. The test is performed separately for both data and MC with the corresponding charge-flip rates. It is expected that the yield of re-weighted OS events would match perfectly with the yield of SS events since this is what was minimized in the likelihood fit. However, the 1D×1D parametrization could hold some intrinsic non-closure which would be evident in this test. The resulting yields of OS and SS events are within 0.5% for both data and MC. Furthermore, p_T and η distributions are tested and the results in data are presented in Figure 7.8. Systematic uncertainty of the charge-flip background is derived by

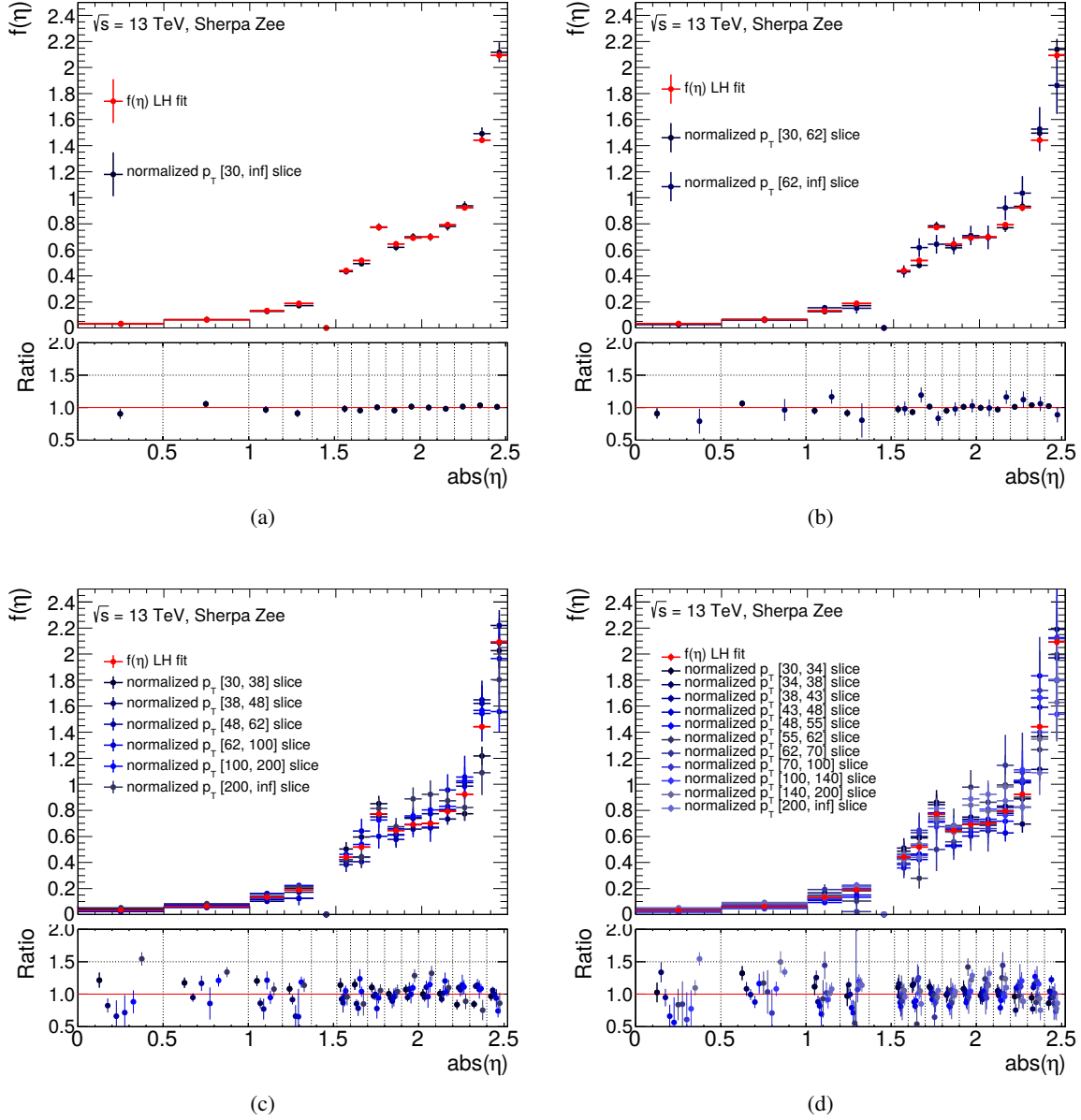


Figure 7.7: A comparison of the true charge-flip rate with the charge-flip rates extracted with the likelihood fit. The true charge-flip rate is expressed in 2D p_T and η bins. Different p_T slices are then normalized to unit area and compared to the $f(\eta)$ function: (a) one inclusive p_T slice, (b) two large p_T slices, (c) five smaller p_T slices, and (d) 10 p_T slices.

propagating the uncertainty of charge-flip rates, given by the likelihood fit, to OS events, taken as fully correlated. The p_T distribution matches perfectly, however, η distributions exhibits some non-closure at low values which is not completely covered by the systematic and statistical uncertainties.

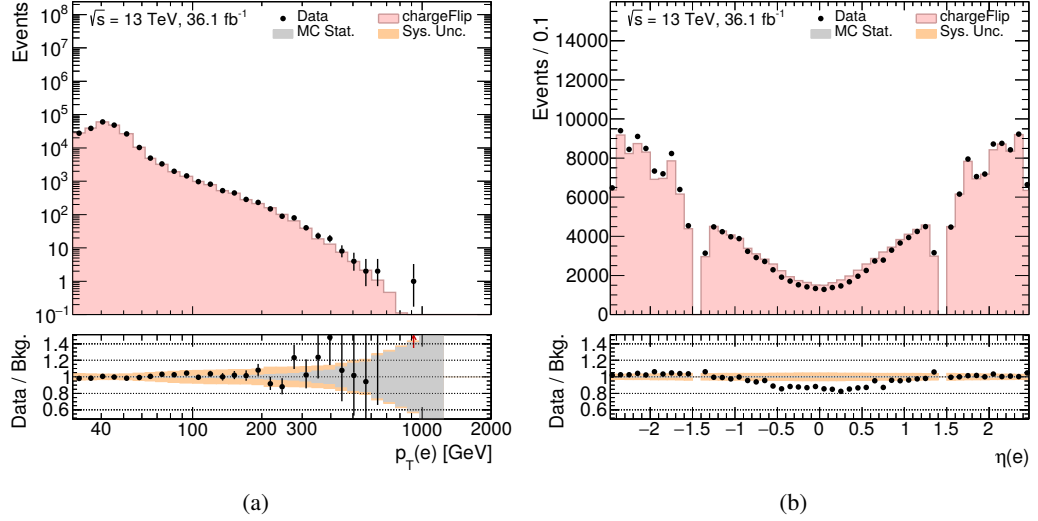


Figure 7.8: Closure test for the 1Dx1D charge-flip rate parametrization in the data. Re-weighted opposite-sign $Z \rightarrow ee$ events are compared to the same-sign $Z \rightarrow ee$ events: (a) p_T distribution of all electrons and (b) η distribution of all electrons.

Further tests are performed to better understand the η discrepancy. Events are separated into 14 p_T slices corresponding to the p_T bins used in the charge-flip rate measurement. η distributions of SS events are compared to re-weighted OS events in each p_T slice both for data and MC. The resulting distributions are presented in Figures D.1–D.5. Some non-closure is observed up to 20 %, however, the effect is correlated in data and MC as the same parametrization is used in both cases. Correlated effects cancel out in the scale-factors which are a ratio of data to MC charge-flip rates. Since the analyses in this thesis use charge-flip scale-factors and not directly the charge-flip rates, no additional uncertainty is considered due to the observed non-closure of the 1Dx1D charge-flip rate parametrization.

7.2 Fake background estimation

Fakes for electrons and muons are estimated with the so-called *fake-factor method*. This is thoroughly discussed and motivated in Appendix E as a special case scenario of a more general technique called the *matrix method*. While the reader is invited to read Appendix E for more details, here a brief overview of the method is given in Section 7.2.1.

7.2.1 Fake-factor method

For each analysis region a corresponding *side-band* region is defined. It requires exactly the same selection and lepton multiplicity except that at least one lepton must fail to satisfy the tight identification criteria. The ratio of tight to loose leptons is measured in dedicated ‘fake-enriched regions’. It is determined as a function of lepton flavor, p_T , and η , and referred to as the ‘fake factor’ ($F(p_T, \eta, \text{flavour})$). It describes the probability for a fake lepton to be identified as a tight lepton. The measurement of the fake factors is presented in Sections 7.2.2 and 7.2.4 for electrons and muons respectively.

The number of events in the analysis regions containing at least one fake lepton, N^{fake} , is estimated from the side-bands. Data are weighted with fake factors according to the loose lepton multiplicity of the region:

$$N^{\text{fakes}} = \sum_{i=1}^{N_{\text{SB}}^{\text{data}}} (-1)^{N_{L,i}+1} \prod_{l=1}^{N_{L,i}} F_l - \sum_{i=1}^{N_{\text{SB}}^{\text{MC}}} (-1)^{N_{L,i}+1} \prod_{l=1}^{N_{L,i}} F_l, \quad (7.6)$$

with $N_{\text{SB}}^{\text{data}}$ denoting the number of data events in the side-band, $N_{L,i}$ is the loose lepton multiplicity in the i -th event of the side-band region and l indicates the loose lepton. The contamination of prompt leptons in the side-band region is subtracted using simulated events, denoted by $N_{\text{SB}}^{\text{MC}}$. This subtraction ensures the compatibility with the more general Matrix Method, as motivated in Appendix E.2. For example, in case of two leptons in the event, the formula in Eq. 7.6 simplifies to

$$N_{TT}^{\text{fakes}} = \left[\sum_{N_{TL}} F_2 + \sum_{N_{LT}} F_1 - \sum_{N_{LL}} F_1 F_2 \right]_{\text{data}} - \left[\sum_{N_{TL}} F_2 + \sum_{N_{LT}} F_1 - \sum_{N_{LL}} F_1 F_2 \right]_{N_{RR} \text{ from MC}}, \quad (7.7)$$

where indexes T and L indicate whether the first or second leptons in the event are tight or loose, N_{TL} , N_{LT} , N_{LL} indicate the corresponding side-band regions and R indicates that only prompt (Real) leptons are selected (to subtract the prompt contamination).

7.2.2 Electron fake-factor measurement

Electron fake-factors are measured by selecting a region in data that is significantly enriched in fake electrons while still kinematically close enough to the signal regions. This is not easily achieved because fake electrons can very closely mimic the attributes of prompt electrons, and the contribution of prompt leptons cannot be completely suppressed. To fully deplete the region of prompt electrons, one needs to explicitly subtract the expected prompt electron contamination using MC predictions.

To select a region with a significant content of fake electrons, a special single electron region is defined. Several event requirements are imposed to discard events with prompt electrons:

- require exactly one electron and zero muons,
- select only events with $E_T^{\text{miss}} < 25$ GeV to reject prompt electrons from W + jets production,

- the b -jet veto is applied.

All object definitions are the same as in defined in Section 6.3.1. This region corresponds to a di-jet selection and is called the *fake-enriched region*. Two sub-regions are defined out of the fake-enriched region, *tight* and *loose*, which are filled with electrons satisfying the corresponding analysis requirement.

Selecting events with only one electron is a large technical obstacle as the electron trigger object must not have any tighter requirements than the loose selection from Table 6.2. The nominal di-electron trigger cannot be used and two prescaled single electron triggers with sufficiently loose identification criteria are used instead. Because the triggers are prescaled, they can not be simply joined with a logical OR. Each electron in the event is assigned its own trigger corresponding to its p_T . The minimum p_T for each trigger is defined in Table 7.2. If a trigger with lower prescale and higher p_T threshold is available, it is used instead. If the electron is matched to the corresponding trigger and the trigger fired the electron is included in the histogram.

Table 7.2: A summary of the electron fake-factor estimation trigger requirements.

Trigger	p_T range [GeV]	average prescale
HLT_e26_lhvloose_nod0_L1EM20VH	30 – 65	112.4
HLT_e60_lhvloose_nod0	65 –	25.6

The fake-enriched regions are shown in Figure 7.9. Selected events still contain prompt electrons after all selection requirements are applied. These residual prompt electrons are subtracted from data before the calculation of fake-factors using the Monte Carlo simulation. The MC samples used are W +jets, Drell-Yan, $t\bar{t}$, dibosons, and single top. The MC subtraction is much larger in the tight region compared to the loose region. The amount of subtracted prompt leptons in that region amounts for up to 50 % of all electrons.

The p_T dependence of the fake-factor is shown in Figure 7.10. The fake factor was measured in three η slices (two slices for the forward region and one slices for the barrel region) and several p_T bins. The last p_T bin includes the overflow and is extended to infinity. These fake factors are used for the background estimation of the $H^{\pm\pm}$ boson search.

Systematic Uncertainties on Electron Fake-factors

The main sources of the systematic uncertainties of the fake-factor arise from Monte Carlo modeling of the subtracted leptons, from different composition of fake electrons in the fake enriched region compared to the signal region, and from the normalization of Monte Carlo samples in the fakes-enriched region.

The fake-factor was measured independently for each of systematic variations presented in Table 7.3. The nominal E_T^{miss} cut for the fake enriched region is loosened to 60.0 GeV in order to probe the modeling of the W +jets MC and to vary the fake composition. Furthermore, all used MC

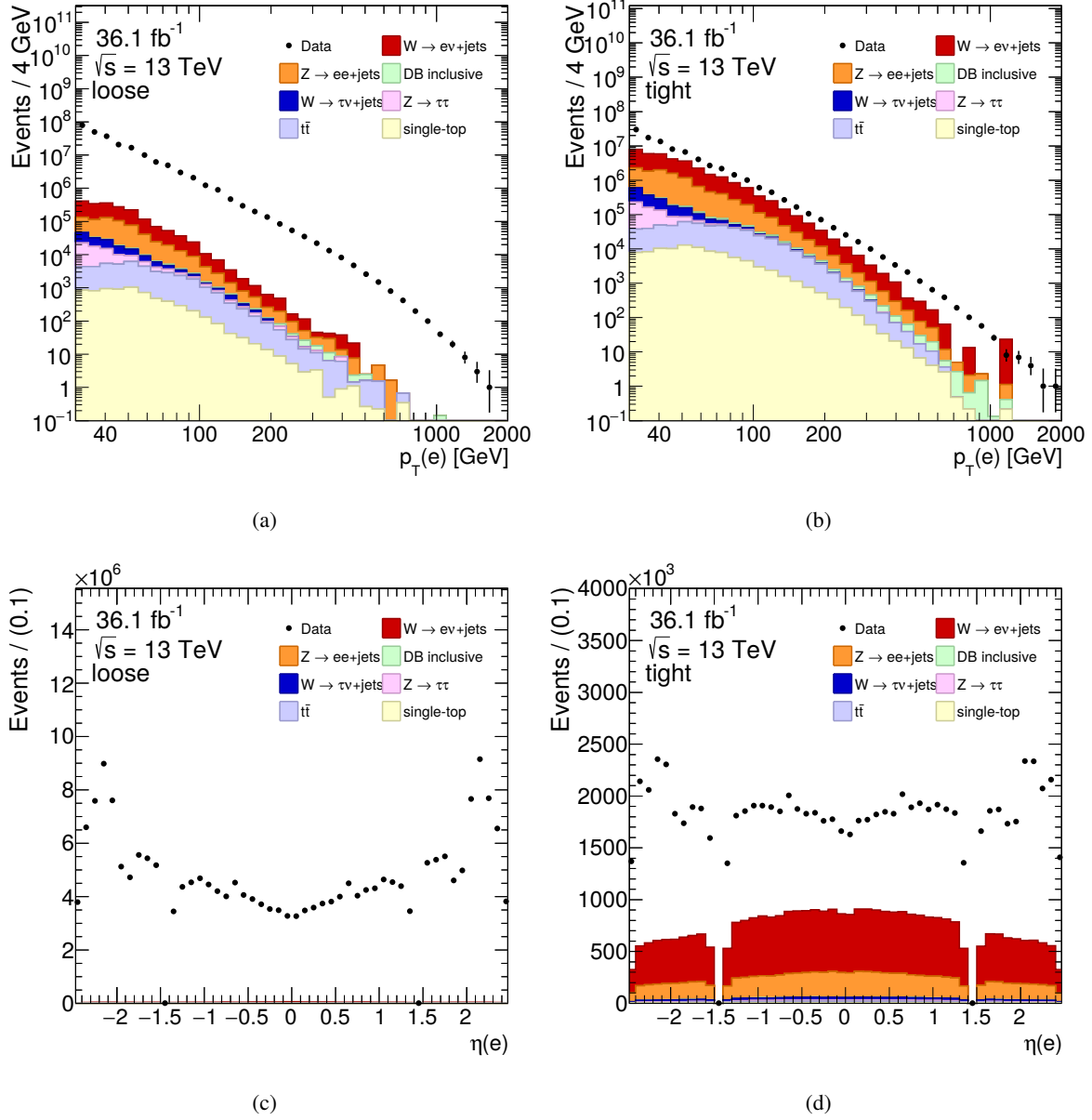


Figure 7.9: Fake enriched regions in the nominal selection for the electron channel: (a) p_T distribution of loose electrons in the fake enriched region, (b) p_T distribution of tight electrons in the fake enriched region, (c) η distribution of loose electrons in the fake enriched region, (d) η distribution of tight electrons in the fake enriched region. All the distributions show data events and the prompt MC component subtracted from data, to ensure a fake dominated region.

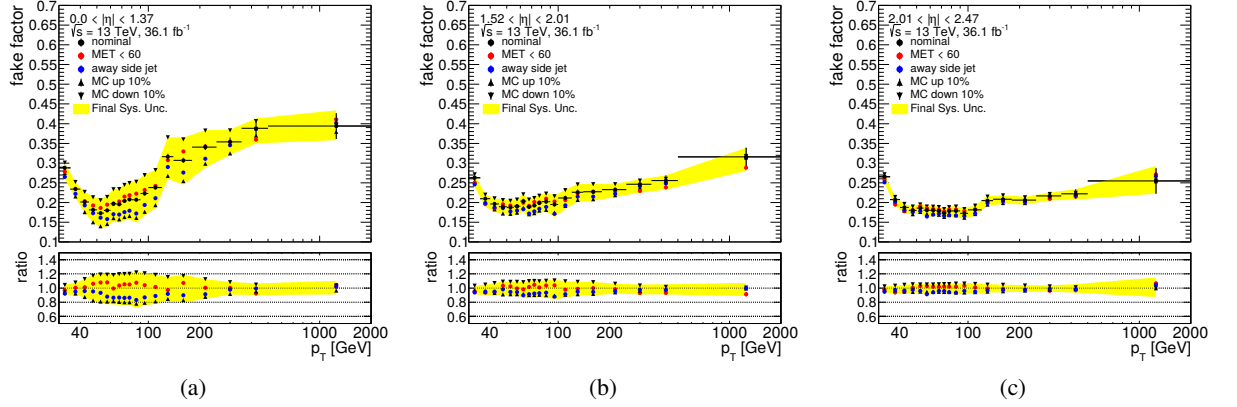


Figure 7.10: The measured nominal electron fake-factors for each variation summarized in Table 7.3. (a) fake-factor variations for the first η bin, (b) fake-factor variations for the second η bin, (c) and fake-factor variations for the last η bin.

samples are varied by 10% to account for cross-section and luminosity uncertainties. Lastly, an additional requirement is imposed along the nominal selection to measure the fake-factor for a different composition of fake leptons. The additional requirement is the *away side jet* cut, where an away side jet¹ with $p_T > 30$ GeV for each electron in the event is required in order to select a different topology of events, with more non-prompt electrons compared to the nominal selection.

Table 7.3: Summary of the variations used for the determination of the systematic uncertainty of the fake-factors.

Variation	Purpose
$E_T^{\text{miss}} < 60.0$ GeV	MC modeling, fake composition
MC scaled up by 10 %	cross-section and luminosity
MC scaled down by 10 %	cross-section and luminosity
away side jet requirement	fake composition

Combined systematic uncertainty on the fake-factors is derived by adding all variations and the statistical uncertainty in quadrature. The largest contribution to the uncertainty are the $E_T^{\text{miss}} < 60.0$ GeV requirement and the 10 % MC variation in the first η slice. The measurement is relatively stable overall up to very high electron p_T and the maximum uncertainty is only 20 %.

Electron fake-factors in topologies with two high- p_T jets

At least two jets with $p_T > 50$ GeV are required in the fake enriched region along with the nominal requirements to reproduce the environment in which electrons appear in analysis control, validation,

¹ Away side jet of an electron is a jet with $\Delta\phi(\text{jet}, \text{electron}) > 2.4$.

and signal regions for the heavy N_R and W_R search. The requirement of two additional jets in the event significantly impacts the fake factors because the denser requirement affects the isolation level of electrons.

The systematic uncertainty of electron fake factors with the two high- p_T jet requirement is evaluated in an analogous way as for the nominal fake factors, however, the 10 % MC variation is increased to 30 % to account for a larger uncertainty in the cross-section in topologies with two jets. Electron fake factors used for the heavy N_R and W_R search are presented in Figure 7.11.

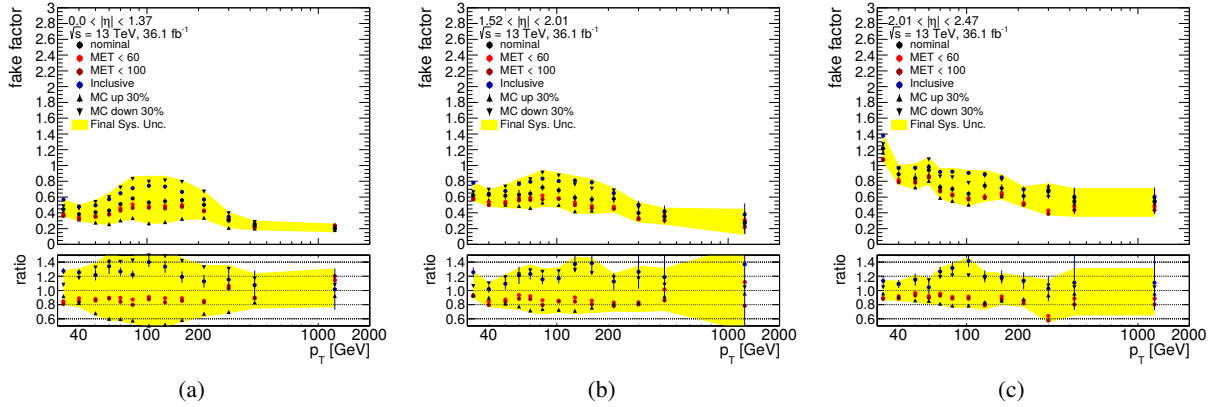


Figure 7.11: The measured electron fake-factors for two high- p_T jets in the event. (a) fake-factor variations for the first η bin, (b) fake-factor variations for the second η bin, (c) and fake-factor variations for the last η bin.

7.2.3 Electron fake-factor validation

The measured fake factors are validated in a dedicated W +jets selection, orthogonal to the fake-enriched region, but with a similar composition of fake electrons. The selection of this W +jets validation region is the same as the nominal event selection with some additional cuts designed to select the W +jets topology:

- $25 \text{ GeV} < E_T^{\text{miss}} < 60 \text{ GeV}$,
- $50 \text{ GeV} < m_T < 120 \text{ GeV}$,
- require exactly one tight electron and zero muons,
- single electron trigger chain from Table 7.2 instead of the di-electron trigger.

Prompt MC processes that were used in this region are $W \rightarrow e\nu$, $W \rightarrow \tau\nu$, $Z \rightarrow ee$, $Z \rightarrow \tau\tau$, $t\bar{t}$, diboson and single top. The remaining events are described well by the fake factor method as seen in Figure 7.12. The only considered systematic uncertainty in this region is the systematic uncertainty in the fake factors.

A dedicated validation is performed for electron fake factors measured with two high- p_T jets and presented in Figure 7.13. The corresponding W +jets validation region for those employs the same

event selection and further requires at least two jets with $p_T > 50 \text{ GeV}$ to mimic the analysis regions of the heavy N_R and W_R search.

Both inclusive and the high- p_T jet validation regions showcase a good agreement between the prediction and the data up to very high transverse momenta of electrons within the derived systematic uncertainties. The fraction of the data-driven fake background is about 20 % in the inclusive case and 50 % in the case with two high- p_T jets. This gives confidence to the electron fake factors used for the BSM searches in this thesis. On top of that, fake electron background estimation is also validated in dedicated analysis validation regions, summarized in Tables [6.4](#) and [6.5](#).

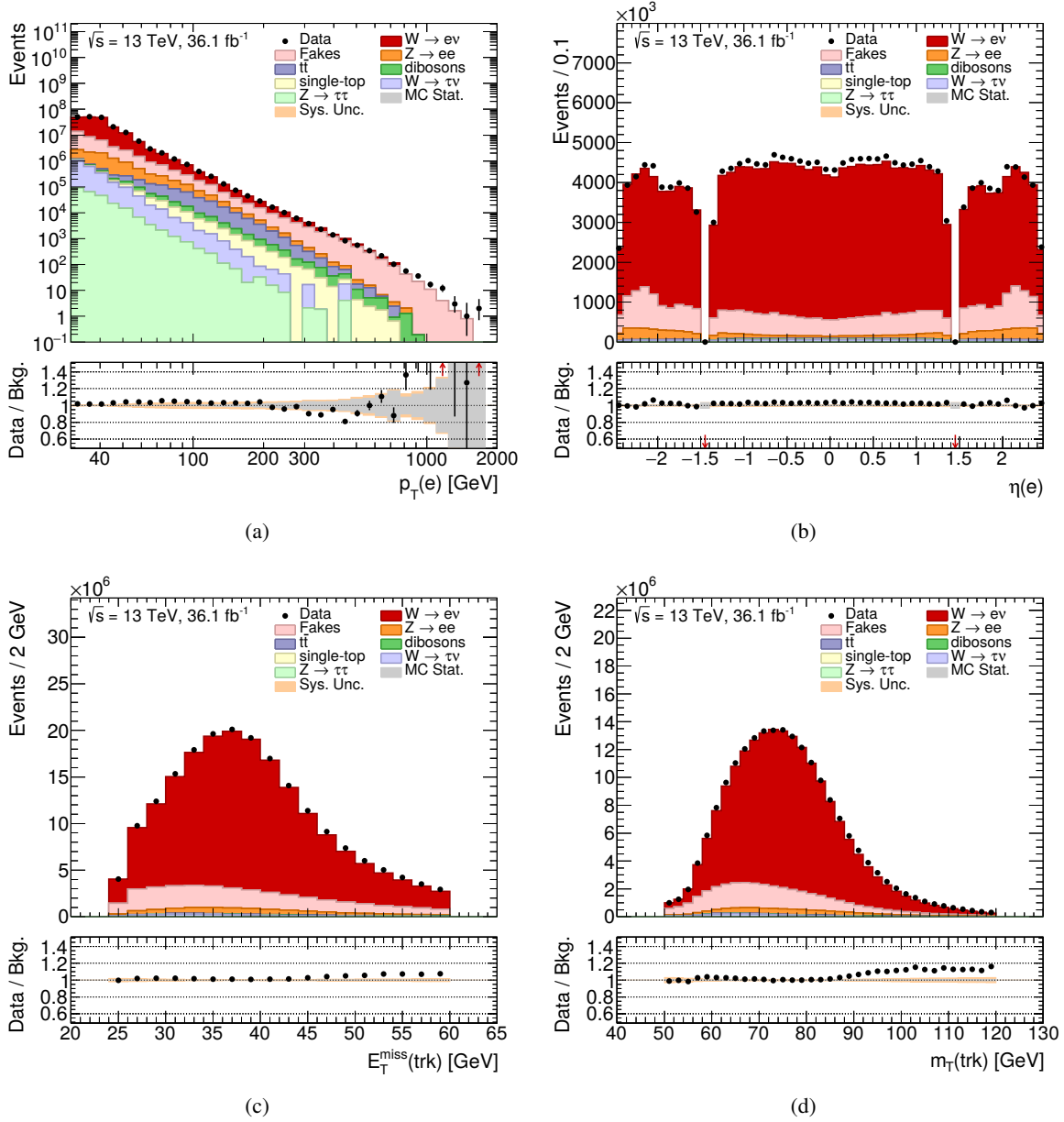


Figure 7.12: The W +jets validation region for the nominal electron fake factors: (a) electron p_T distribution, (b) electron η distribution, (c) E_T^{miss} distribution, (d) and the m_T distribution. The orange band shows the systematic uncertainty associated to the fake factor measurement. Fake factors displayed in Figure 7.10 are used for these distributions.

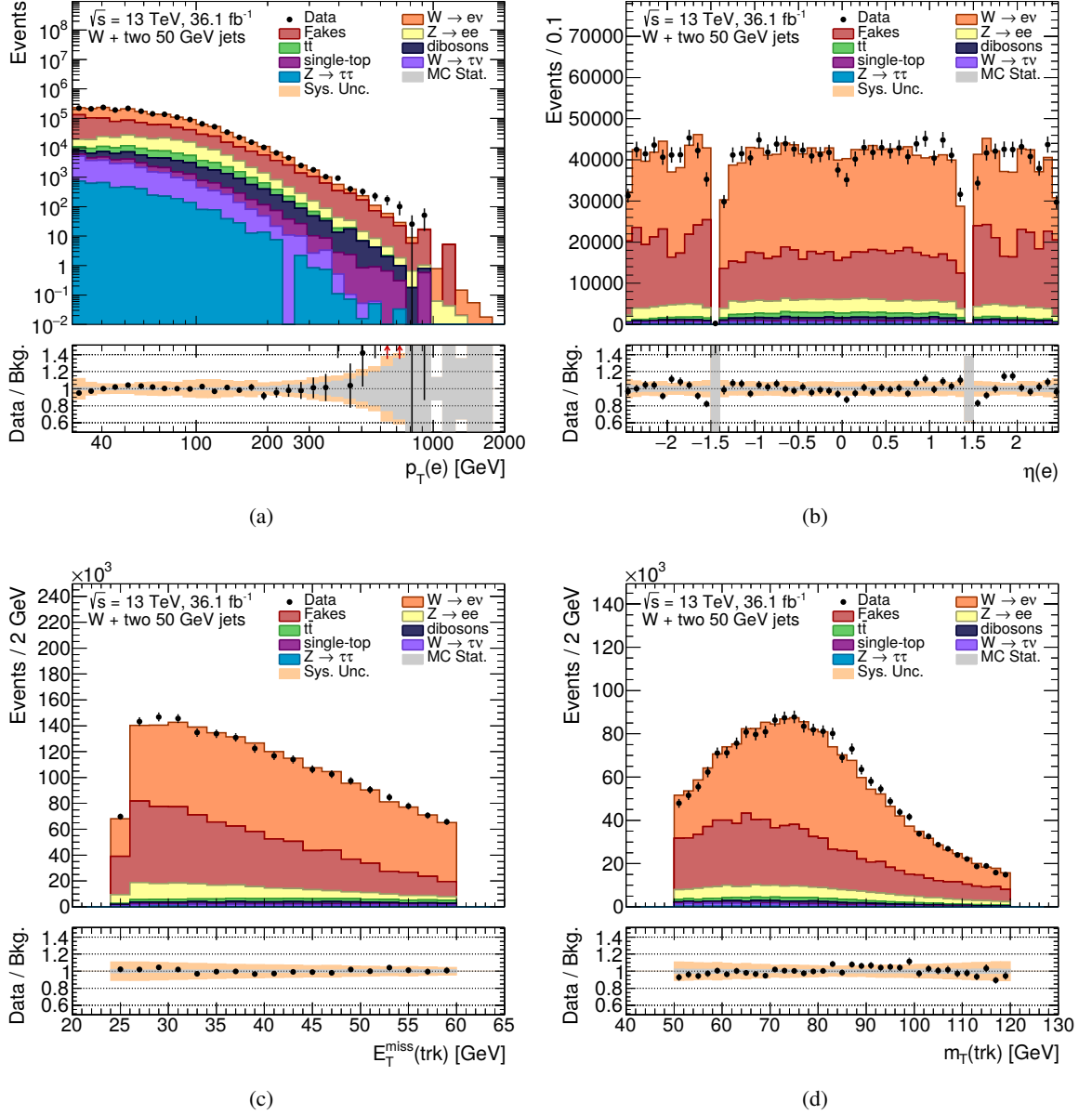


Figure 7.13: The W +jets validation region for the nominal electron fake factors: (a) electron p_T distribution, (b) electron η distribution, (c) E_T^{miss} distribution, (d) and the m_T distribution. The orange band shows the systematic uncertainty associated to the fake factor measurement. Fake factors displayed in Figure 7.11 are used for these distributions.

7.2.4 Muon fake-factor measurement

The composition of fakes in the muon channel is much more uniform compared to the electron channel. Essentially, the only source of fake muons are decays of heavy flavor hadrons resulting in non-prompt muons. Consequently, in the muon channel, fake-factors are measured using a tag-and-probe technique, aiming to target di-jet events where one jet resulted in production of a non-prompt muon. Events are selected by requiring exactly one jet in the event, the *tag*, and a reconstructed muon, the *probe*. The azimuthal angular distance between the two objects in the event has to be greater than $\Delta\phi > 2.7$.

The selection of di-jet events allows to achieve high statistics for measuring fake-factors, while also allowing to address systematic uncertainties using the properties of the recoiling tag jet. However, similarly as for the electron fake factor measurement, one prescaled single muon trigger needs to be used to avoid bias from isolation requirement of unprescaled low- p_T single muon triggers. Used triggers for the muon fake-factor measurement are presented in Table 7.4. The same p_T -range technique is used to combine prescaled triggers as in the electron channel; each muon is assigned a trigger depending on its p_T and other triggers are ignored.

Table 7.4: A summary of the muon fake-factor estimation trigger requirements.

Trigger	p_T range [GeV]	average prescale
HLT_mu24	30 – 50	45
HLT_mu50	50 –	unprescaled

The tag and the probe in the event have to be back-to-back in the transverse plane, i.e. $\Delta\phi(\mu, \text{jet}) > 2.7$ and have p_T thresholds of $p_T(\mu) > 25\text{GeV}$ and $p_T(\text{jet}) > 35\text{GeV}$. In addition to this, prompt muons from W +jets production are rejected by requiring $E_T^{\text{miss}} < 40\text{GeV}$. Finally, events featuring a b-jet are rejected to mimic the analysis regions. After the tag and probe selection is applied in the data, remaining prompt leptons are subtracted using simulated events to achieve a pure selection of muon fakes, i.e. the fake-enriched region. The resulting muon fake-factors are shown in Figure 7.14. Due to the low statistics of the muon fake enriched region, the muon fake-factors are binned only in p_T . The statistics are lower compared to the electron fake enriched region due to the tighter isolation requirement in the muon channel and due to the fact that fake muons are less likely than electron fakes.

Systematic uncertainties on the measurement on muon fake-factors are estimated by altering the selection of di-jet events. The nominal requirement on the missing transverse energy E_T^{miss} is varied by 10 GeV upward and downward in turn, for tight and loose muons simultaneously. This effect varies the fraction of W +jets events contaminating the selection, hence the largest fraction of prompt muons which have to be subtracted from data using simulation.

The definition of the tight muons is also altered by varying up and down the selection on d_0/σ_{d_0} by one unit. As muon fakes originate from in-flight decays of mesons with different flavor composition and

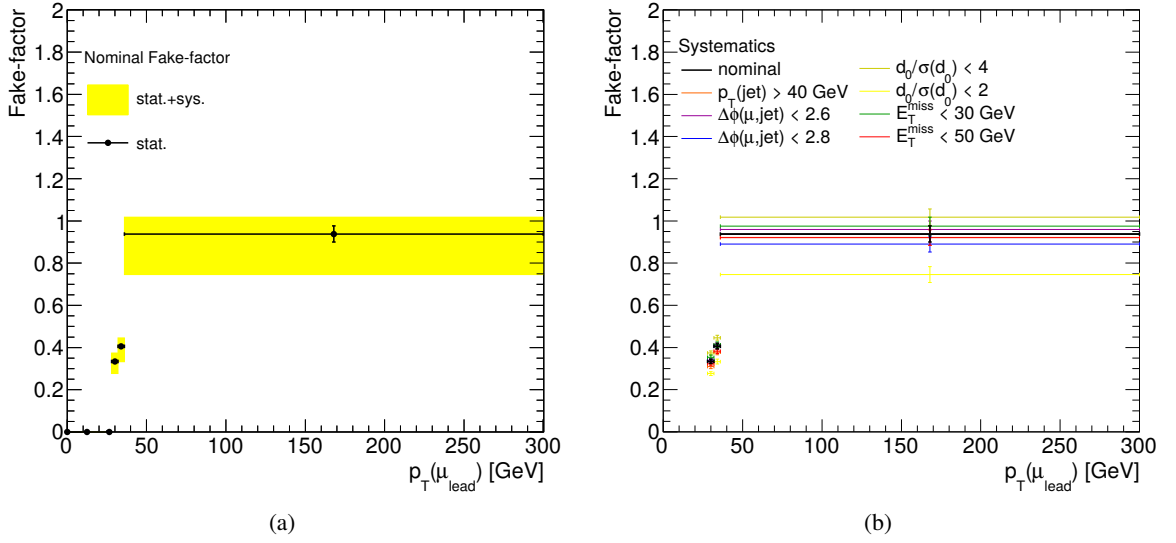


Figure 7.14: Muon fake-factors as a function of muon p_T . The nominal measured value is shown with black dots (a) while each systematic effect is shown separately. The total uncertainty is illustrated in (b) together with the nominal measurement.

lifetimes this variation is intended to get a handle on their relative fraction which might be different on the nominal sidebands used in the fake-factor method.

For the same reason, the isolation distribution of the fake muon might differ between the di-jet selection and the sidebands. We can address this effect by varying the transverse momentum of the recoiling jet in the event up to $p_T(\text{jet}) > 40$ GeV hence altering the collimation of the fake jet.

The kinematic balance of the muon and the recoiling jet, which affects the isolation, might also be altered varying the back-to-back requirement $\Delta\phi(\mu, \text{jet})$. An upward and downward variation of 0.1 is chosen.

The effect of each systematic alteration on the nominal measurement can be seen in Figure 7.14(b). The total systematic uncertainty is determined by added in quadrature the statistical uncertainty and all variations of the fake factor measurement. The uncertainty ranges between 10 to 25 % across the p_T bins. Due to the low statistics of muon fakes in the fake enriched region and the more uniform composition of muon fakes, the measurement was not performed with two high- p_T jets like in the electron channel. The fake factors summarized in Figure 7.14 are used both in the $H^{\pm\pm}$ search and the heavy N_R and W_R search.

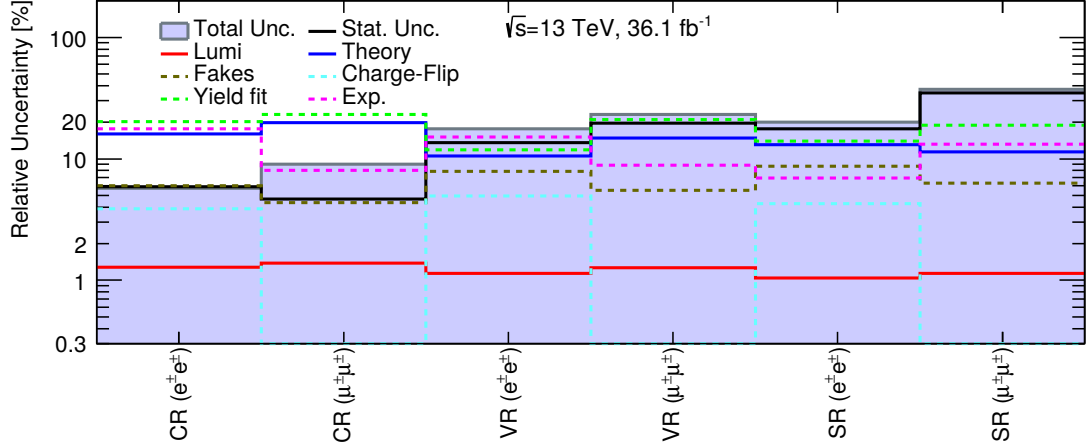


Figure 8.2: Relative uncertainties in the total background yield estimation after the fit for the heavy N_R and W_R search. ‘Stat. Unc.’ corresponds to reducible and irreducible background statistical uncertainties. ‘Yield fit’ corresponds to the uncertainty arising from fitting the yield of diboson, Drell–Yan, and top backgrounds. ‘Lumi’ corresponds to the uncertainty in the luminosity. ‘Theory’ indicates the theory uncertainty in the physics model used for simulation (e.g. QCD scale). ‘Exp.’ indicates the uncertainty in the simulation of electron, muon, and jet efficiencies and calibration. ‘Fakes’ is the uncertainty associated with the model of the fake background. Individual uncertainties can be correlated, and do not necessarily add in quadrature to the total background uncertainty, which is indicated by ‘Total Unc.’. The total uncertainty can be less than individual contributions, taking the correlations properly into account.

8.1 Experimental uncertainties

The uncertainty on the 2015 and 2016 integrated luminosity is 2.1 % derived with the methodology described in Ref. [192], from a calibration of the luminosity scale using x – y beam-separation scans.

An additional set of experimental systematic uncertainties arises from the calibrations of the lepton and jet energy and momentum, the lepton detection efficiencies and isolation, and the trigger efficiency. In the heavy N_R and W_R search, the largest such uncertainty on the total SM yield arises from the energy calibration and smearing of jets and is between 5 to 10 % depending on the invariant mass of the $\ell\ell jj$ system. In the $H^{\pm\pm}$ search, where there are no explicit requirements on jet multiplicity, experimental systematic uncertainties associated to lepton reconstruction, identification, isolation and trigger efficiencies, as well as energy or momentum calibration and b -jet veto, vary between 0.5 to 4.0 % and are negligible compared to other systematic uncertainties and the statistical uncertainty.

The experimental uncertainty related to the charge misidentification probability of electrons arises from the statistical uncertainty of both the data and the simulated sample of $Z/\gamma^* \rightarrow ee$ events used to measure this probability. Furthermore, additional considered sources, closure tests, and validations are presented in Section 7.1 The uncertainty ranges between 10 to 20 % as a function of the electron p_T and η .

The experimental systematic uncertainty in the data-driven estimate of the fake-lepton background is evaluated by varying the nominal fake-factor to account for different effects, as described in detail in

Section 7.2. Furthermore, the normalization of the subtracted simulated samples in the fake enriched region (used to remove residual prompt leptons), is altered within its uncertainties. This accounts for uncertainties related to the luminosity, the cross-section, and the corrections applied to simulated predictions. The variation in the MC normalization is 10 % for the inclusive fake factors, used in the $H^{\pm\pm}$ search, and 30 % for the fake factors used in the heavy N_R and W_R search. The variation is larger due to the additional requirement of two high- p_T jets during the measurement of the fake-factors and arises from the uncertainty in the QCD scale. The final uncertainty on the fake-factors ranges between 10 to 40 % across all p_T and η bins.

8.2 Theory uncertainties

Cross-sections used to normalize the simulated samples are varied to account for the scale and PDF uncertainties in the cross-section calculation. A 10 % normalization uncertainty is applied on Keung-Senjanović signal samples as well as on $t\bar{t} X$ production, with X denoting an associated vector boson. For diboson and Drell–Yan production, theory uncertainty is estimated in a more thorough way by considering four separate sources: QCD scale, PDF uncertainty, α_S uncertainty, and the choice of the PDF. The uncertainty related to the α_S parameter is estimated by comparing the MC event weights of the nominal choice $\alpha_S = 0.118$ to weights obtained by changing the α_S parameter to 0.117 and 0.119.

The theory uncertainty estimation for SHERPA Drell–Yan and diboson samples (see Table 3.1) is described in Section 8.2.1. These samples are used in the heavy N_R and W_R search, while in the $H^{\pm\pm}$ search a high-mass POWHEG Drell–Yan sample is used instead of the SHERPA sample. The theory uncertainty related to the high-mass POWHEG sample is presented in Section 8.2.2.

Theory uncertainty is a leading source of systematic uncertainty in the heavy N_R and W_R search due to the requirement of two high- p_T jets in the event. Because of this requirement the QCD scale uncertainty is as high as 20 to 40 % for SHERPA Drell–Yan and diboson samples. However, the theory uncertainty is relatively small in the $H^{\pm\pm}$ search due to the more inclusive event selection, without any requirement on the jet multiplicity.

The theory uncertainty in the NLO K -factors (Table 3.2) for $pp \rightarrow H^{++}H^{--}$ is reported to be about 15 % [114]. It includes the QCD renormalization and factorization scales dependence, μ_R and μ_F respectively, and the uncertainty in the parton densities. Furthermore, the theory uncertainty in the simulated $pp \rightarrow H^{++}H^{--}$ events is assessed by varying the A14 parameter set in PYTHIA 8.186 and choosing alternative PDFs CTEQ6L1 [115, 116] and CT09MC1 [193]. The impact on the signal acceptance is found to be negligible.

The theory uncertainty on the signal efficiency times acceptance for N_R/W_R signal MC samples amounts to 10 %. It is evaluated by varying μ_R and μ_F scales as described below and by using alternative PDF sets, CTEQ6 [115, 116] and MSTW [132]. The α_S emission scale factor was also varied to half and twice the nominal value. The uncertainty is dominated by the variation in renormalization scale. The variations were performed using the SysCALC [194] software.

8.2.1 Theory uncertainty estimation for SHERPA MC samples

QCD scale uncertainty

The uncertainty due to the choice of the QCD μ_R and μ_F is evaluated by taking the minimum and the maximum value of the observable calculated with the standard seven-point variation. In other words, the QCD scale uncertainty is estimated as the asymmetric envelope of the seven variations obtained by varying the μ_R and μ_F parameters up and down by a factor of two, but excluding the extremal variations where one is varied up and the other varied down:

- 1 μ_R and 1 μ_F (nominal)
- 2 μ_R and 1 μ_F
- 1 μ_R and 2 μ_F
- 0.5 μ_R and 1 μ_F
- 1 μ_R and 0.5 μ_F
- 0.5 μ_R and 0.5 μ_F
- 2 μ_R and 2 μ_F

PDF and α_S uncertainty

The nominal PDF used for the largest background processes is the NNPDF3.0 set. The corresponding uncertainty is estimated using 100 NNPDF3.0 variations, constructed in pairs of up (+) and down (−) variations, as recommended by the PDF4LHC procedure [127]. Every variation results in different event weights and thus affects the predicted distribution and total yield of an observable O . The resulting uncertainty of O is estimated as

$$\Delta O^\pm = \sqrt{\sum_{N_{\text{variations}}}^i [\max(\pm(O^{+,i} - O), \pm(O^{-,i} - O), 0)]^2},$$

where ΔO^+ (ΔO^-) is the upper (lower) PDF uncertainty of O . Furthermore, these values are divided by 1.645 to account the fact that the PDF variations cover a 90% confidence interval, whereas the O uncertainty is expected to represent the 68% confidence interval in the likelihood fit.

In addition, uncertainty due to the choice of the NNPDF3.0 PDF set is estimated by comparing MC event weights to the weights obtained using the MMHT2014 [195] PDF set and the CT14NNLO [103] PDF set.

8.2.2 Theory uncertainty for high-mass POWHEG Drell–Yan MC samples

The theory systematic uncertainty due to the PDF choice for the Drell–Yan background is assessed by comparing the nominal PDF (CT14NNLO [103]) to more up-to-date PDFs. Among those PDFs are CT10NNLO [129], MMHT14 [196], NNPDF3.0 [106], ABM12 [197], HERAPDF2.0 [198], and JR14 [199]. The ratios of the NNLO corrections of the listed PDFs to the CT14NNLO high-order correction are shown on Figure 8.3. NNPDF3.0 shows the highest disagreement at high invariant masses and HERPDF2.0 at low invariant masses.

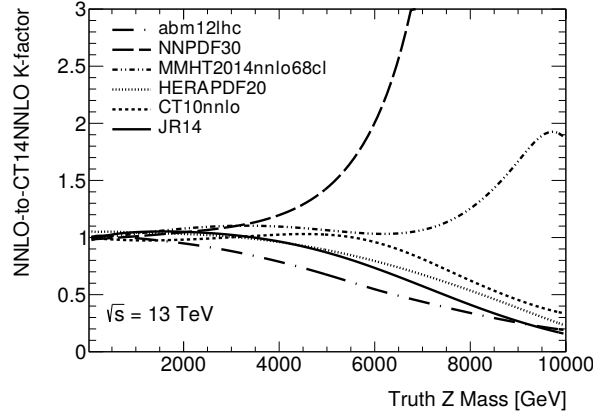


Figure 8.3: The comparison of different high-order NNLO corrections for the high-mass Drell–Yan process, corresponding to different parton distribution functions. All ratios are calculated w.r.t CT14NNLO PDF, which is used for the nominal high-order correction.

Furthermore, the nominal PDF choice (CT14NNLO) with a set of 7 eigen-vectors, provided by the CT14 authors [103], is used to estimate the PDF uncertainty, as described further in Ref. [200]. The 90 % CL of the CT14NNLO PDF is presented with a solid line in Figure 8.4(a). It turns out that the systematic uncertainty of the nominal PDF surpasses the systematic uncertainty due to the PDF choice in almost all of the mass bins. The two sources of uncertainty are correlated and a special procedure is performed to avoid double counting.

The eigen-vector variation of the nominal PDF was taken as a full systematic uncertainty and the uncertainty due to the PDF choice was used only as a residual of the PDF variation uncertainty. Effectively, this means that one takes the full PDF choice uncertainty, and quadratically subtracts the PDF variation uncertainty, with what remains being considered as an additional nuisance parameter due to the PDF choice. The comparison of both theory uncertainties is shown on Figure 8.4. The total theory uncertainty due to the choice of the PDF and variation of the nominal PDF is lower than 10 % up to masses of 2000 GeV.

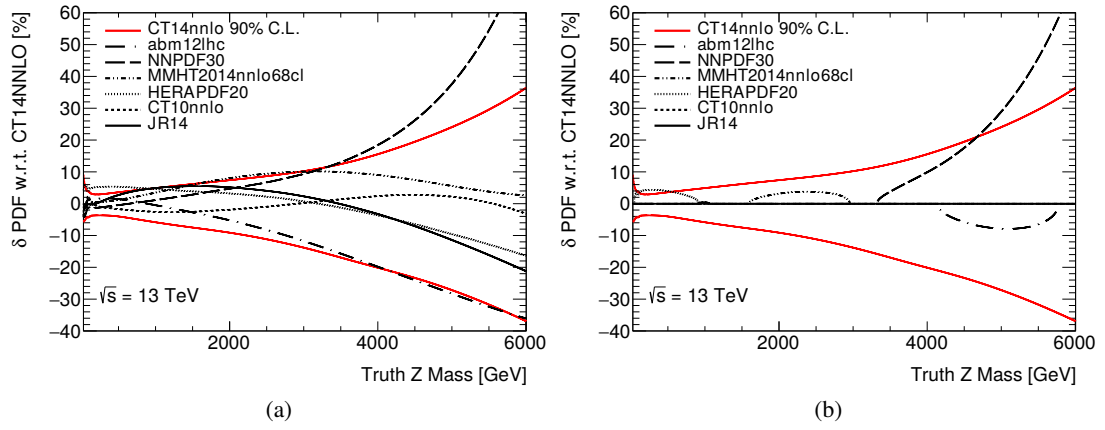


Figure 8.4: Comparison of different high-order NNLO corrections for the high-mass PowHEG Drell–Yan process, corresponding to different PDF, along with the eigen-vector variation of the nominal PDF (CT14NNLO). (a) All PDF choices and CT14NNLO 90 % CL, (b) CT14NNLO90 % CL and additional nuisance parameters from the PDF choice only where larger than the variation.

9 Statistical analysis and results

Final results are presented in this chapter through a rigorous statistical analysis based on frequentist statistics. First, the statistical treatment is described in detail followed by the results of the $H^{\pm\pm}$ search. Lastly, the results of the search for heavy right-handed neutrinos N_R and gauge bosons W_R is presented. The latter is split into the analysis of the same-charge channel, to which the author of the thesis contributed significantly, and the statistical combination of the same-charge channel with the opposite-charge channel.

9.1 Statistical treatment

The statistical framework `HISTFITTER` [201] is used in the analysis to perform a maximum-likelihood fit to determine an upper bound on the signal production cross-section as a function of the mass hypothesis or branching ratios. In the fit, systematic uncertainties are implemented as parametrization of both the signal hypothesis and expected background, and can alter their shape and normalization. In addition, the normalization of some of the backgrounds obtained by simulation is determined in control regions, simultaneously fitted together with the signal region. As a cross-check of this procedure, fitted parameters are applied in the validation regions where the compatibility between the data and the prediction is tested. In absence of an observed signal, 95 % CL upper limits are derived on the signal production cross-section, using the CL_s method [202].

9.1.1 The Likelihood Function

A likelihood function is defined featuring a Poissonian term, describing the statistical fluctuations of the data, and a Gaussian term modeling the effect of auxiliary measurement to constrain the systematic uncertainties:

$$\mathcal{L}(\mu, \sigma) = \prod_i^{\text{bins}} \mathcal{L}_{\text{poiss}}(N_{\text{data}}^i | \mu s^i(\theta) + b^i(\theta)) \times \mathcal{L}_{\text{gauss}}(\theta), \quad (9.1)$$

where μ is the signal strength parameterizing the yield of expected signal events for each signal hypothesis between zero and one. In Eq. 9.1 θ parametrises the effect of systematic uncertainties and represents the so-called *nuisance parameters*. N_{data}^i is the number of data events in the i -th bin, $s^i(\theta)$ is the expected signal yield in the i -th bin, and $b^i(\theta)$ is the expected background yield in the i -th bin. Expected yields are a function of the systematic uncertainty parameters θ .

The nuisance parameter θ is usually given in units of the uncertainty standard deviation. This can be expressed as

$$\theta = (\xi - \xi_{\text{CP}})/\sigma_{\xi}, \quad (9.2)$$

where ξ is the nominal value and ξ_{CP} is the measured value for one standard deviation variation (σ_{ξ}) of the systematic uncertainty. The inputs for the HISTFITTER software for a given systematic uncertainty are the nominal yield and the yields corresponding to one standard deviation variations for this systematic source (e.g. electron energy scale) for each bin and each MC sample. However, to perform the fit one must obtain the yield for any possible values of θ parameters. This is performed by interpolating the three input points as described in the HISTFACTORY manual [203]. The default interpolation scheme in ATLAS is *Polynomial Interpolation and Exponential Extrapolation*. It uses exponential extrapolation to avoid negative yields and interpolation using a 5D polynomial within the one standard deviation interval to allow a smooth transition with the exponential extrapolation. An example of this interpolation scheme is presented in Figure 9.1.

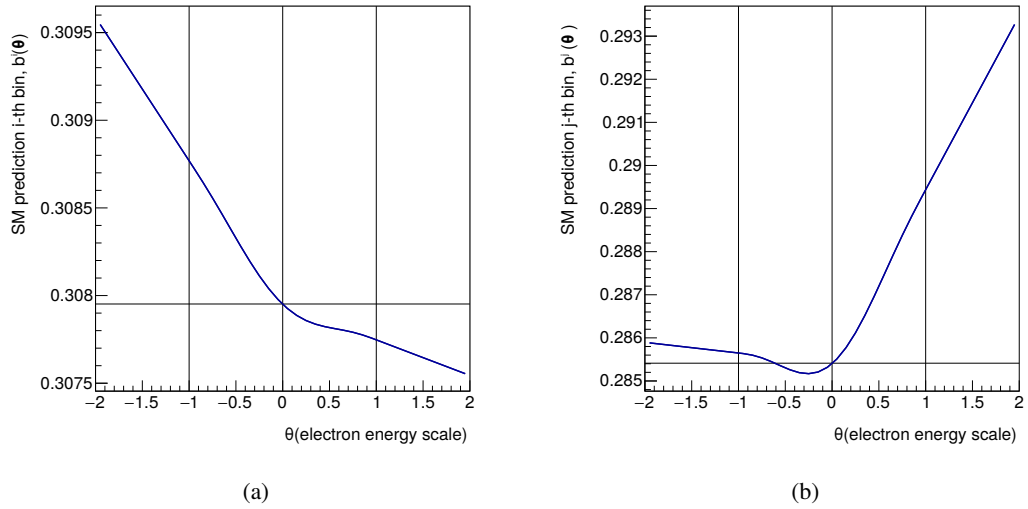


Figure 9.1: Example interpolation of the expected yield, $b^i(\theta)$, as a function of one nuisance parameter θ . Input values are the yields ($b^i(\theta)$) corresponding to the nominal value ($\theta = 0$) and the one standard deviation variations ($\theta = \pm 1\sigma$).

9.1.2 Hypothesis Test for Expected 95 % CL Limits

A discriminating variable is defined in order to obtain the expected 95 % CL limits on the production cross-section of the signal. The variable provides separation power between the background

hypothesis (B) and the signal plus background hypothesis (S+B). The test-statistic q_μ is defined as:

$$q_\mu = -2 \ln \left(\frac{\mathcal{L}(\mu, \hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \right), \quad (9.3)$$

where $\mathcal{L}(\hat{\mu}, \hat{\theta})$ is the unconditional maximum likelihood with floating μ and θ parameters, while $\mathcal{L}(\mu, \hat{\theta}_\mu)$ is the conditional maximum likelihood for a given signal strength μ . In the latter case, the values of θ depend on the value of μ . The test-statistic is positive-defined. Signal-like data distributions will more likely exhibit a low test-statistic (q_μ close to 0) and background-like data will have a larger q_μ .

The probability density function (PDF) of the test-statistic ($f(q_\mu | \text{hyp})$) has to be determined in order to derive the 95 % CL limits. They are estimated using asymptotic formulae [204] to speed up the very time consuming—but more precise—process of determining them with toy experiments. Once the PDFs are known, the probability p_{S+B} can be defined that a S+B hypothesis gives a test-statistic above a reference value q_μ^{ref} . Likewise, the probability p_B is defined that a background only hypothesis exhibits a test-statistic lower than the reference value:

$$p_B = P(q_\mu < q_\mu^{\text{ref}} | B) = \int_{-\infty}^{q_\mu^{\text{ref}}} f(q_\mu | B) dq_\mu \quad (9.4)$$

$$p_{S+B} = P(q_\mu > q_\mu^{\text{ref}} | S + B) = \int_{q_\mu^{\text{ref}}}^{\infty} f(q_\mu | S + B) dq_\mu \quad (9.5)$$

For a given set of signal mass or branching ratios, the signal hypothesis is tested for several values of μ . For each value, the PDF of the test-statistic is obtained for the S+B hypothesis and compared to the one for the B hypothesis. For expected limits, the p_{S+B} value is then computed using the median of the B hypothesis test-statistic distribution as a reference value. For the observed limits, the reference value is determined from the fit to observed data. To obtain the median of the B hypothesis, *Asimov data set* [204] is used. This is a mock data set that matches perfectly the predicted SM background and follows Poissonian distribution in each bin. The excluded μ at 95 % CL is defined to fulfil the following requirement:

$$\text{CL}_s \equiv \frac{p_{S+B}}{1 - p_B} < 5 \% \quad (9.6)$$

The fraction in Eq. 9.6 accounts for the probability that the S+B hypothesis gives a background-like fluctuation given that the B only hypothesis gave a background-like test-statistic.

Table 9.1: The number of predicted background events in $H^{\pm\pm}$ control regions after the fit, compared to the data. Uncertainties correspond to the total uncertainties in the predicted event yields, and are smaller for the total than the sum of the components in quadrature due to correlations between these components. Due to rounding the totals can differ from the sums of components. Background processes with a negligible yield are marked with the en dash (–). Taken from Ref. [93].

	OCCR $e^\pm e^\mp$	DBCR $e^\pm e^\pm e^\mp$	DBCR $e^\pm \mu^\pm \ell^\mp$	DBCR $\mu^\pm \mu^\pm \mu^\mp$	4LCR $\ell^\pm \ell^\pm \ell^\mp \ell^\mp$
Observed events	184 569	576	1025	797	140
Total background	$184\,570 \pm 430$	574 ± 24	1025 ± 32	797 ± 28	140 ± 12
Drell–Yan	$169\,980 \pm 990$	–	–	–	–
Diboson	5060 ± 900	449 ± 28	909 ± 35	775 ± 29	138 ± 12
Fakes	2340 ± 300	123 ± 15	113 ± 14	19.9 ± 6.5	1.31 ± 0.16
Top	7200 ± 250	1.58 ± 0.06	2.90 ± 0.11	2.04 ± 0.08	0.37 ± 0.01

Table 9.2: The number of predicted background events in two-lepton and four-lepton $H^{\pm\pm}$ validation regions (top) and three-lepton $H^{\pm\pm}$ validation regions (bottom) after the fit, compared to the data. Uncertainties correspond to the total uncertainties in the predicted event yields, and are smaller for the total than the sum of the components in quadrature due to correlations between these components. Due to rounding the totals can differ from the sums of components. Background processes with a negligible yield are marked with the en dash (–). Taken from Ref. [93].

	SCVR $e^\pm e^\pm$	SCVR $e^\pm \mu^\pm$	SCVR $\mu^\pm \mu^\pm$	4LVR $\ell^\pm \ell^\pm \ell^\mp \ell^\mp$
Observed events	3237	1162	1006	3
Total background	3330 ± 210	1119 ± 51	975 ± 50	4.62 ± 0.40
Drell–Yan	2300 ± 190	–	–	–
Diboson	319 ± 25	547 ± 23	719 ± 30	4.59 ± 0.4
Fakes	640 ± 65	502 ± 54	249 ± 47	–
Top	71.5 ± 6.8	70.5 ± 2.6	6.93 ± 0.27	0.033 ± 0.001

	3LVR $e^\pm e^\pm e^\mp$	3LVR $e^\pm \mu^\pm \ell^\mp$	3LVR $\mu^\pm \mu^\pm \mu^\mp$	3LVR $\mu^\pm \mu^\pm e^\mp, e^\pm e^\pm \mu^\mp$
Observed events	108	180	126	16
Total background	88.1 ± 5.8	192.9 ± 9.9	107.0 ± 5.1	27.0 ± 3.9
Diboson	64.4 ± 5.8	147.3 ± 9.0	100.9 ± 5.0	4.72 ± 0.79
Fakes	23.3 ± 3.0	43.9 ± 4.9	5.3 ± 1.2	21.3 ± 3.4
Top	0.50 ± 0.03	1.73 ± 0.09	0.82 ± 0.05	1.01 ± 0.15

Table 9.3: The number of predicted background events in two-lepton and four-lepton $H^{\pm\pm}$ signal regions (top) and three-lepton $H^{\pm\pm}$ signal regions (bottom) after the fit, compared to the data. Uncertainties correspond to the total uncertainties in the predicted event yields, and are smaller for the total than the sum of the components in quadrature due to correlations between these components. Due to rounding the totals can differ from the sums of components. Background processes with a negligible yield are marked with the en dash (–). Taken from Ref. [93].

	SR1P2L $e^{\pm}e^{\pm}$	SR1P2L $e^{\pm}\mu^{\pm}$	SR1P2L $\mu^{\pm}\mu^{\pm}$	SR2P4L $\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$
Observed events	132	106	26	1
Total background	160 $\pm$ 14	97.1 $\pm$ 7.7	22.6 $\pm$ 2.0	0.33 $\pm$ 0.23
Drell–Yan	70 $\pm$ 10	–	–	–
Diboson	30.5 $\pm$ 3.0	40.4 $\pm$ 4.5	20.3 $\pm$ 1.8	0.11 $\pm$ 0.06
Fakes	52.2 $\pm$ 5.0	53.1 $\pm$ 5.8	1.94 $\pm$ 0.47	0.22 $\pm$ 0.19
Top	7.20 $\pm$ 0.97	3.62 $\pm$ 0.53	0.42 $\pm$ 0.03	0.007 $\pm$ 0.002

	SR1P3L $e^{\pm}e^{\pm}e^{\mp}$	SR1P3L $e^{\pm}\mu^{\pm}\ell^{\mp}$	SR1P3L $\mu^{\pm}\mu^{\pm}\mu^{\mp}$	SR1P3L $\mu^{\pm}\mu^{\pm}e^{\mp}, e^{\pm}e^{\pm}\mu^{\mp}$
Observed events	11	23	13	2
Total background	13.0 $\pm$ 1.6	34.2 $\pm$ 3.6	13.2 $\pm$ 1.3	3.1 $\pm$ 1.4
Diboson	9.5 $\pm$ 1.3	23.1 $\pm$ 2.9	13.1 $\pm$ 1.3	0.27 $\pm$ 0.14
Fakes	3.3 $\pm$ 0.67	10.7 $\pm$ 1.7	–	2.6 $\pm$ 1.2
Top	0.14 $\pm$ 0.02	0.45 $\pm$ 0.04	0.12 $\pm$ 0.01	0.19 $\pm$ 0.08

9.2.1 Fitted distributions in the $H_R^{\pm\pm}$ search

Best-fit values of nuisance parameters (θ), corresponding to $\mathcal{L}(\hat{\mu}, \hat{\theta})$, are presented in Figure 9.3. All nuisance parameters stay within the one standard deviation interval after the likelihood fit. Moreover, all fitted yields of SM backgrounds are compatible with unity within the uncertainty. In this section, ‘post-fit’ distributions are shown; corresponding to expected background yields evaluated at the best-fit values of θ parameters and using the fitted yields of the largest SM backgrounds.

A non-equidistant binning was introduced to adequately bin the data distribution and the number of bins was optimized to be as low as possible to maximize the per-bin statistics without incurring a loss on sensitivity. The bin edge is given using a power formula $A \cdot \delta^n$, with n being the bin number and A and δ optimized constant terms, which gives the desired result of all bins looking equally wide in the log scale.

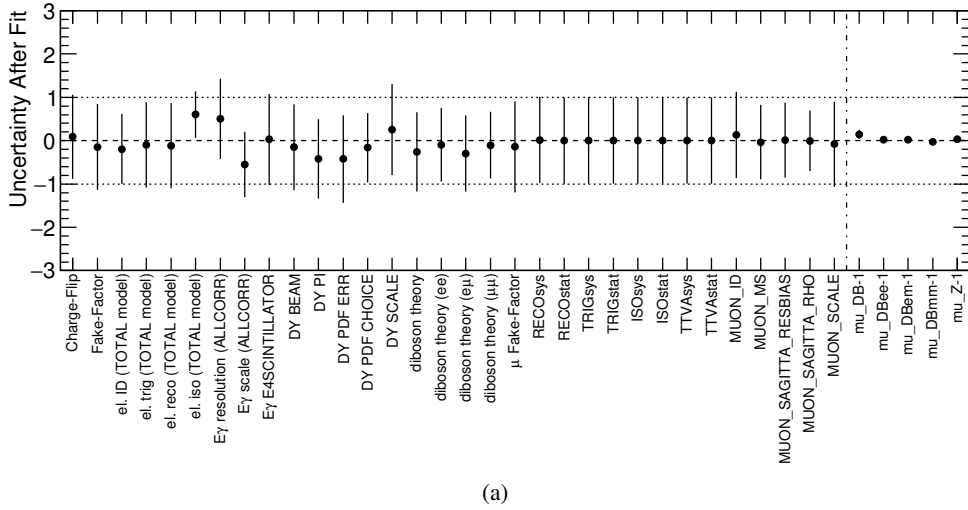


Figure 9.3: Best-fit values of nuisance parameters in the $H^{\pm\pm}$ likelihood fit. The right side of the plot shows the fitted yields of the largest SM contributions. The fitted yields are shown as the relative difference compared to the nominal prediction along with the related uncertainty in units of %.

Signal regions and control regions

Signal region distributions used in the likelihood fit for two- and four-lepton signal regions are presented in Figure 9.4, and three-lepton signal regions are presented in Figure 9.5. Along with the expected SM yields, $H^{\pm\pm}$ signal distributions for various mass and branching ratio hypotheses are shown. The presented signal samples are normalized to the predicted NLO cross-section (Table 3.2). Control region distributions used in the likelihood are shown in Figure 9.6.

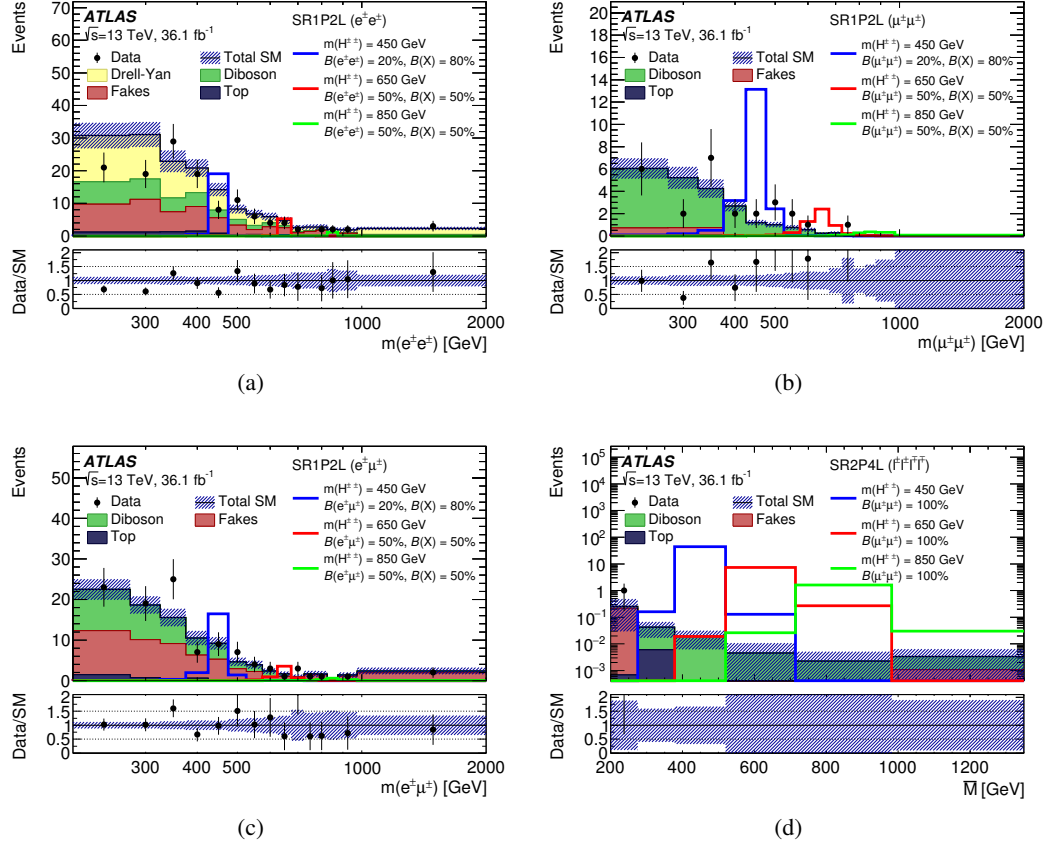


Figure 9.4: Distributions of $m(\ell^\pm \ell^\pm)$ in $H^{\pm\pm}$ two- and four-lepton $H^{\pm\pm}$ signal regions, namely (a) the electron–electron two-lepton signal region (SR1P2L), (b) the muon–muon two-lepton signal region (SR1P2L), (c) the electron–muon two-lepton signal region (SR1P2L), and (d) the four-lepton signal region (SR2P4L). The hatched bands include all systematic uncertainties post-fit with the correlations between the various sources taken into account. The solid colored lines correspond to signal samples, normalized using the theory cross-section, with the $H^{\pm\pm}$ mass and decay modes marked in the legend. Taken from Ref. [93].

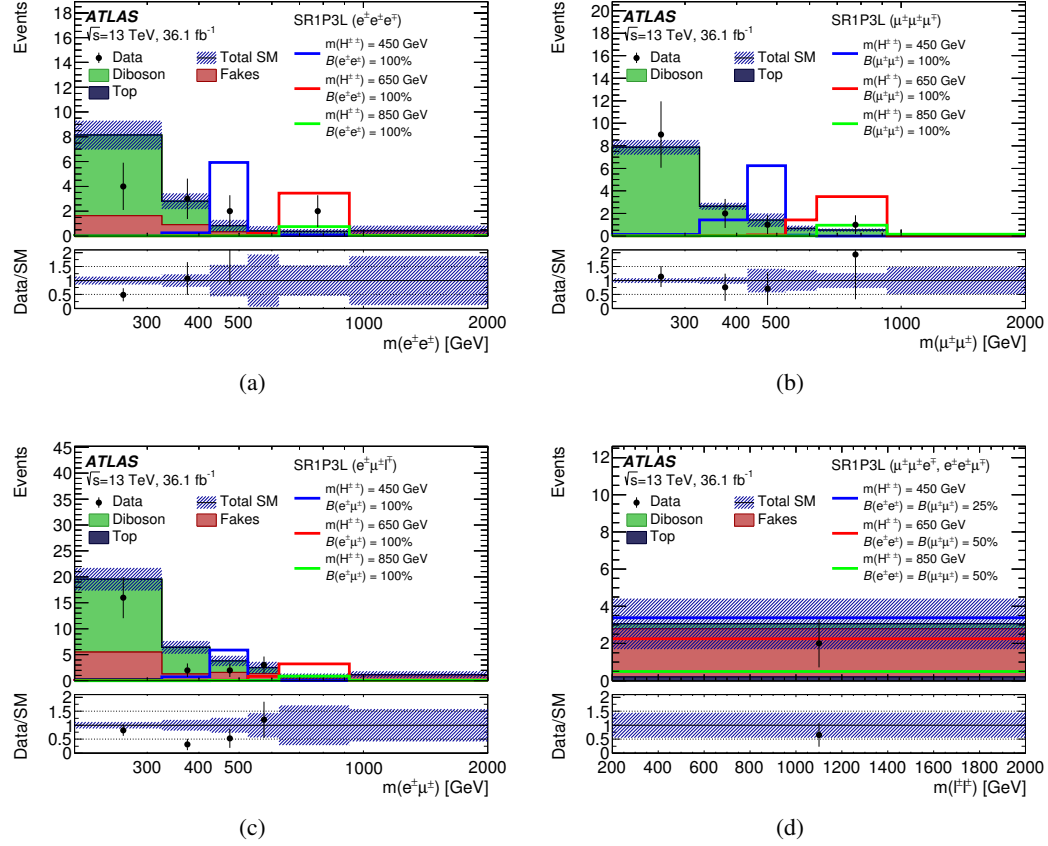


Figure 9.5: Distributions of $m(\ell^\pm\ell^\pm)$ in three-lepton $H^{\pm\pm}$ signal regions, namely (a) the three-electron SR (SR1P3L), (b) the three-muon SR (SR1P3L), (c) the SR1P3L with an electron–muon same-charge pair ($e^\pm\mu^\pm\ell^\mp$), and (d) the SR1P3L with a same-flavor same-charge pair ($e^\pm e^\pm\mu^\mp$ or $\mu^\pm\mu^\pm e^\mp$). The hatched bands include all systematic uncertainties post-fit with the correlations between various sources taken into account. The solid colored lines correspond to signal samples, normalized using the theory cross-section, with the $H^{\pm\pm}$ mass and decay modes marked in the legend. Taken from Ref. [93].

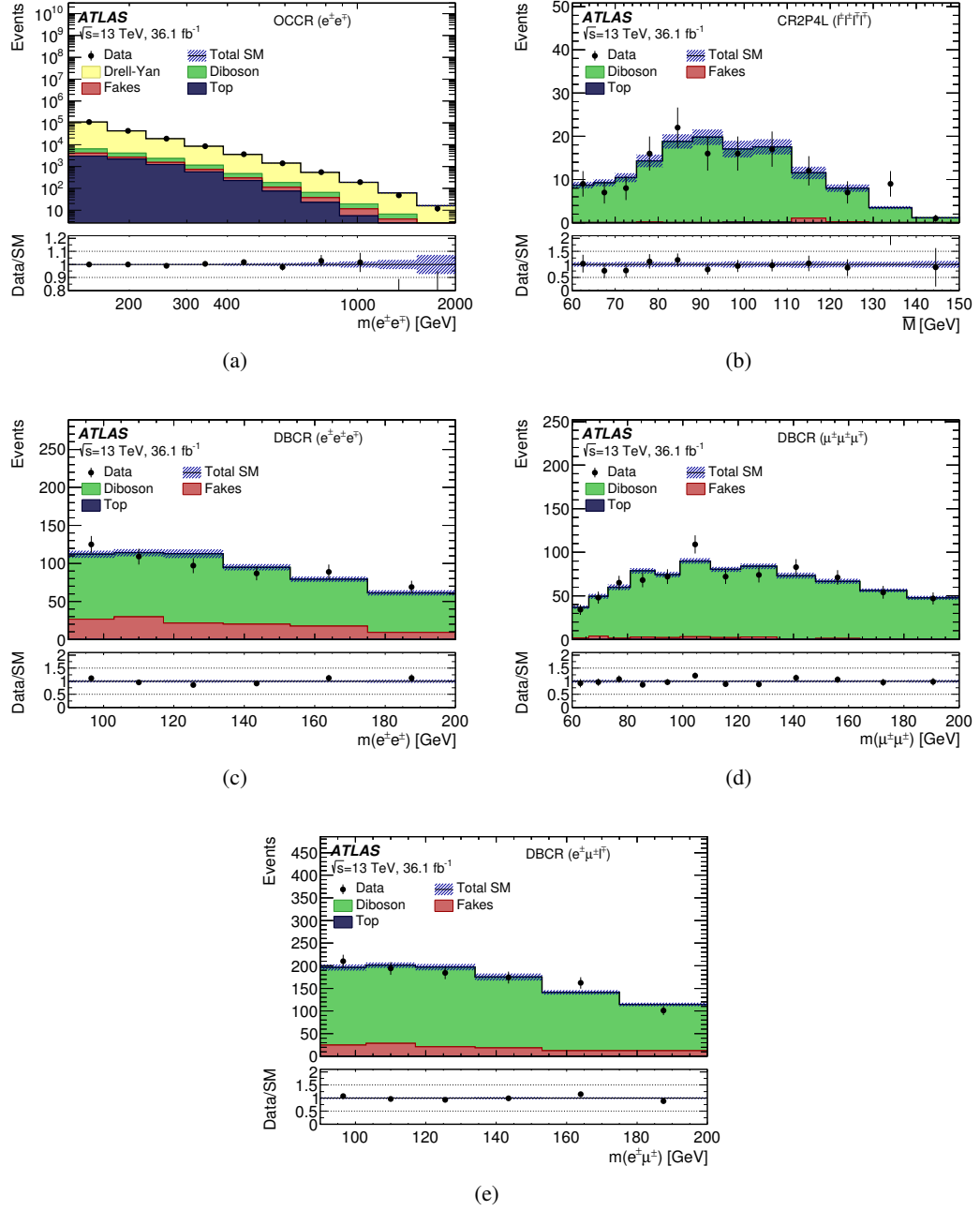


Figure 9.6: Distributions of $m(\ell^\pm\ell^\pm)$ and $\bar{M}$ in $H^{\pm\pm}$ control regions, namely (a) the opposite-charge electron–electron control region (OCCR), (b) the four-lepton control region (4LCR), (c) the electron channel diboson control region ($e^+e^+e^-$), (d) the electron channel diboson control region ($\mu^\pm\mu^\pm\mu^\mp$), and (e) the mixed-flavor diboson control region ($e^\pm\mu^\pm\ell^\mp$). The hatched bands include all systematic uncertainties post-fit with the correlations between various sources taken into account. Taken from Ref. [93].

Validation regions

Post-fit values of nuisance parameters and the fitted yields of SM backgrounds are used to extrapolate the SM expectation to validation regions. Figures 9.7 and 9.8 present all validation regions sensitive to different background sources: same-charge two-lepton validation regions (SCVR) for testing the charge misidentification background modeling and fake-background predictions, and three-lepton and four-lepton validation regions (3LVR and 4LVR) for testing the diboson modeling. Good background modeling is observed in all these regions.

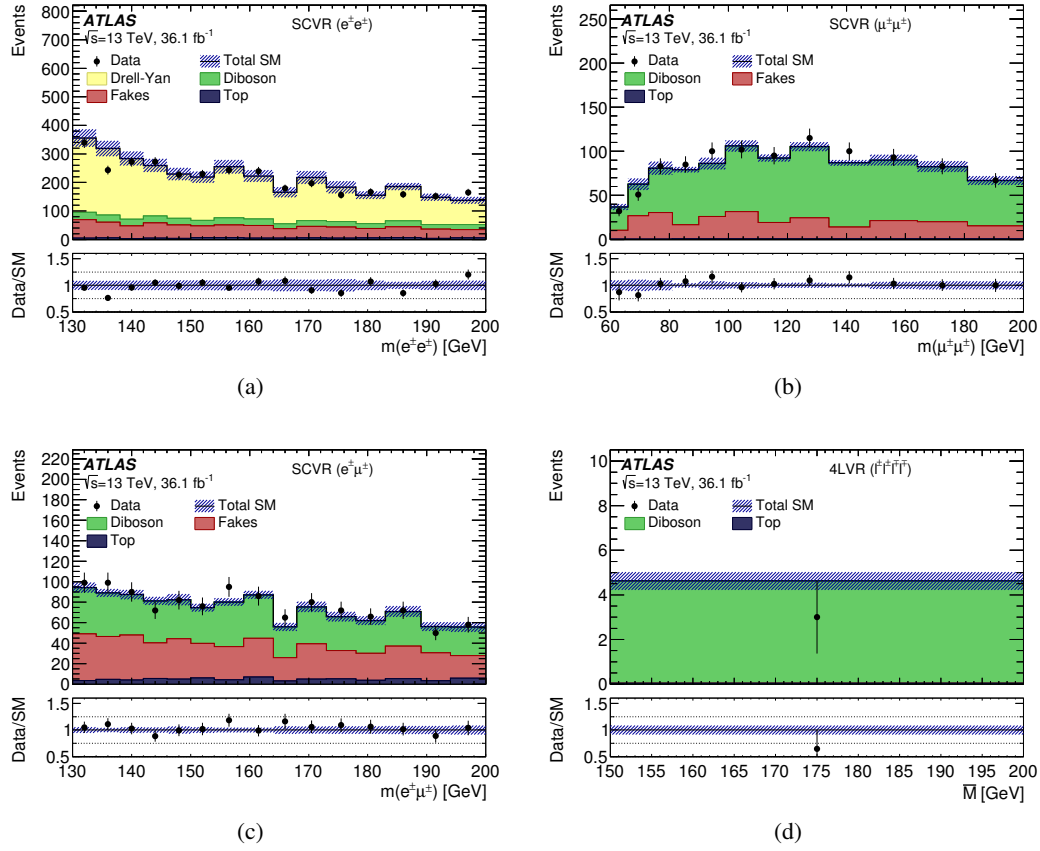


Figure 9.7: Distributions of dilepton mass for data and SM background predictions in two- and four-lepton $H^{\pm\pm}$ validation regions: (a) the electron–electron, (b) the muon–muon, and (c) the electron–muon two-lepton validation regions, as well as (d) the four-lepton validation region. The hatched bands include all systematic uncertainties post-fit, with the correlations between various sources taken into account. Taken from Ref. [93].

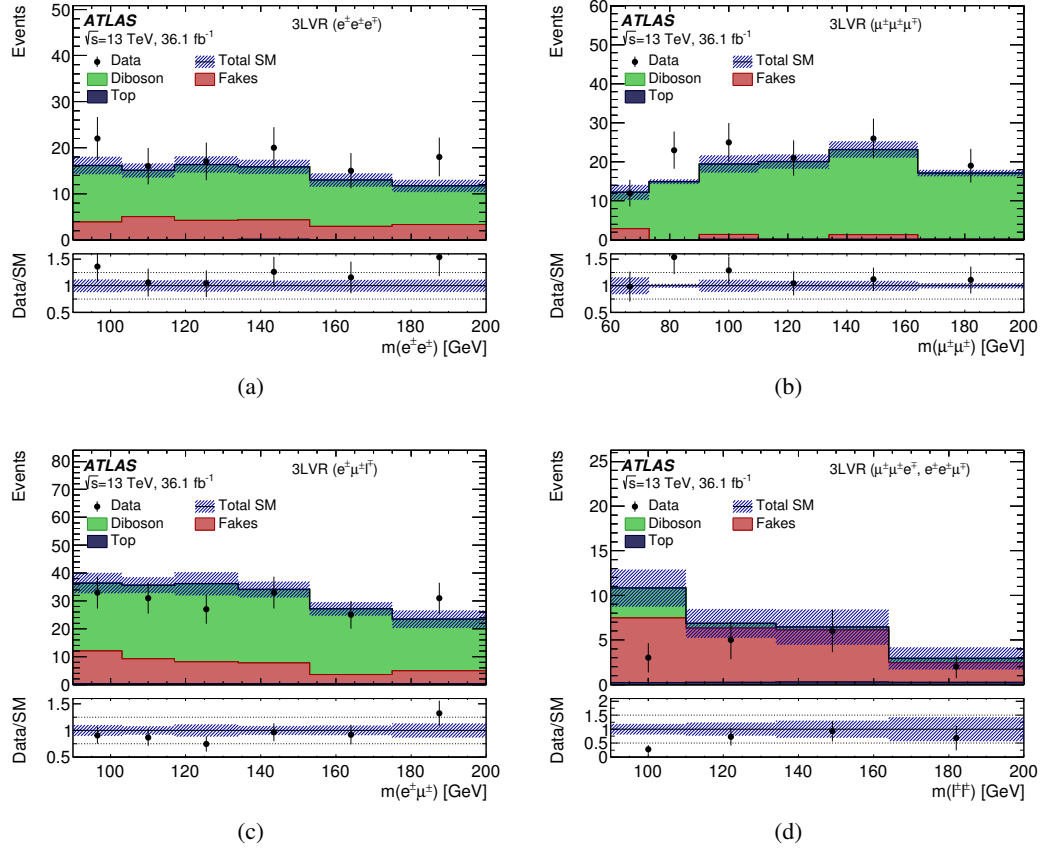


Figure 9.8: Distribution of dilepton mass for data and SM background predictions in three-lepton H^{++} validation regions: (a) the three-electron validation region, (b) the three-muon validation region, (c) the 3LVR with an electron–muon same-charge pair ($e^\pm\mu^\pm\ell^\mp$), and (d) the 3LVR with a same-flavour same-charge pair ($e^\pm e^\pm\mu^\mp$ or $\mu^\pm\mu^\pm e^\mp$). The hatched bands include all systematic uncertainties post-fit, with the correlations between various sources taken into account. Taken from Ref. [93].

9.2.2 Upper limits on $pp \rightarrow H^{++}H^{--}$ production cross-section

The likelihood fit to the two-, three-, and four-lepton control and signal regions was designed to fully exploit the pair production of the $H^{\pm\pm}$ boson with its boosted topology and lepton multiplicity. For $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ the production cross-section is excluded down to 0.1 fb, corresponding to 3 to 4 signal events, which is the theoretical limit of a 95% CL exclusion ($\mathcal{L}_{\text{poiss}}(0|3) \simeq 0.05$). Some representative cross-section upper limits as a function of the $H^{\pm\pm}$ boson mass are presented in Figure 9.9, for different combinations of the branching ratios for decay into light-lepton pairs. Limits for high electron branching ratio scenarios have a wide one standard deviation discrepancy between 600 to 900 GeV mass due to the two observed events in the corresponding range in the electron channel SR1P3L (see Figure 9.5(a)).

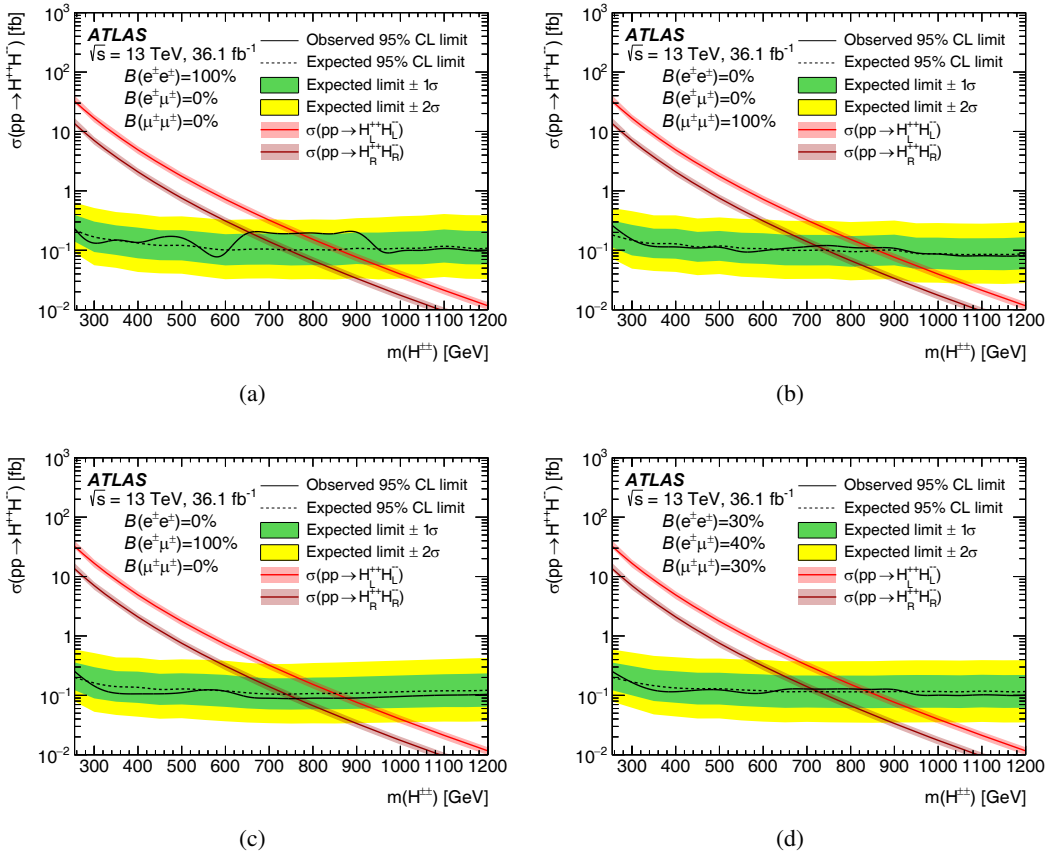


Figure 9.9: Upper limit on the cross-section for $pp \rightarrow H^{++}H^{--}$ for several branching ratio values, presented in the form $B(ee)/B(e\mu)/B(\mu\mu)$: (a) 100%/0%/0%, (b) 0%/0%/100%, (c) 0%/100%/0%, and (d) 30%/40%/30%. The theoretical uncertainty in the cross-section for $pp \rightarrow H^{++}H^{--}$ is presented with the shaded band around the central value. Taken from Ref. [93].

The final result of the fit is a lower limit on the two-dimensional grid of the $H^{\pm\pm}$ boson mass for any combination of light lepton branching ratios that sum to a certain value. The fit was performed for values of $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$ from 1% to 5% in 1% intervals, and from 10% to 100% in 10% intervals.

Expected limits for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ are presented in Figure 9.10 for $H_L^{\pm\pm}$ and in Figure 9.11 for $H_R^{\pm\pm}$. For brevity, the results for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) < 100\%$ are presented in Appendix H.

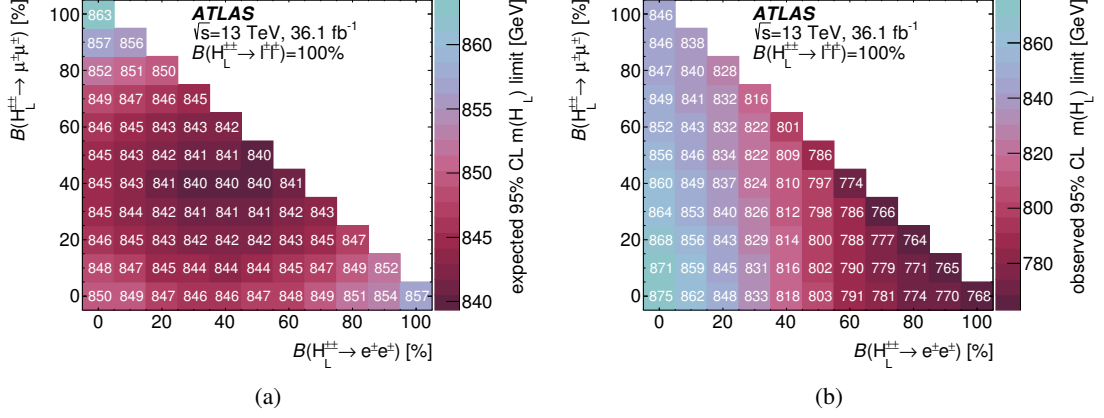


Figure 9.10: Expected (a) and observed (b) lower limit on the $H_L^{\pm\pm}$ mass for all branching ratio combinations that sum to 100%. Taken from Ref. [93].

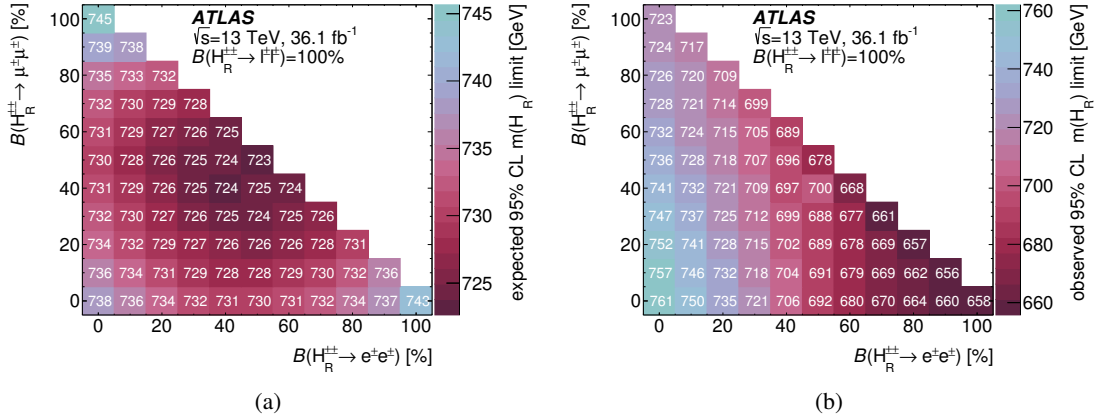


Figure 9.11: Expected (a) and observed (b) lower limit on the $H_R^{\pm\pm}$ mass for all branching ratio combinations that sum to 100%. Taken from Ref. [93].

Since both the expected and observed limits are relatively flavor-blind—resulting from uniform signal efficiencies across all channels (see Figure 6.3)—the results can be presented in a more compact manner in Figures 9.12 and 9.13 for $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$, respectively. Here, three specific decay scenarios to only $e^\pm e^\pm$, $\mu^\pm \mu^\pm$, and $e^\pm \mu^\pm$ are considered and the minimum limit for each value of $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$ is given. The minimum limit is obtained by taking, for each value of $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$, the least stringent limit for any combination of branching ratios that sum to $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$. The lower mass limits for these four cases are similar, which indicates further that the analysis is almost equally sensitive to each decay channel.

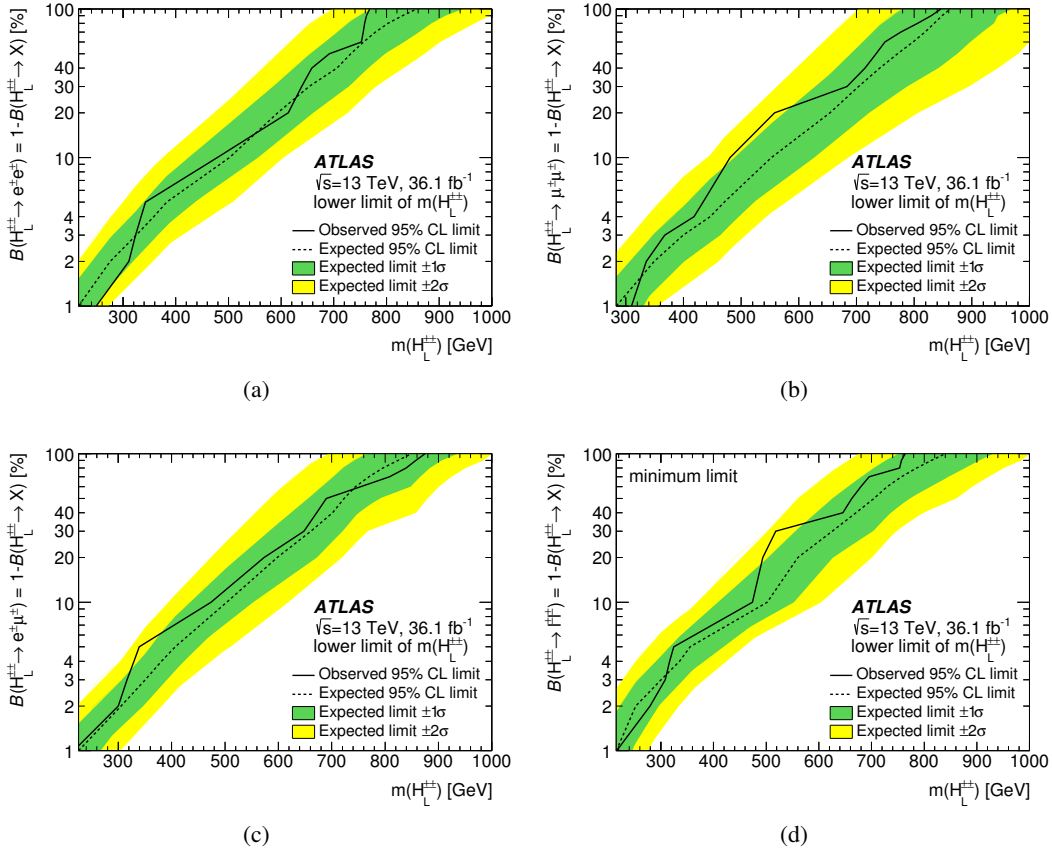


Figure 9.12: Lower limit on the $H_L^{\pm\pm}$ boson mass as a function of the branching ratio $B(H_L^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$. Several cases are presented: (a) $H_L^{\pm\pm}$ decays only into electrons and "X", (b) $H_L^{\pm\pm}$ decays only into muons and "X", and (c) $H_L^{\pm\pm}$ decays only into electron-muon pairs and "X", with "X" not entering any of the signal regions. Plot (d) shows the minimum observed and expected limit as a function of $B(H_L^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$. Taken from Ref. [93].

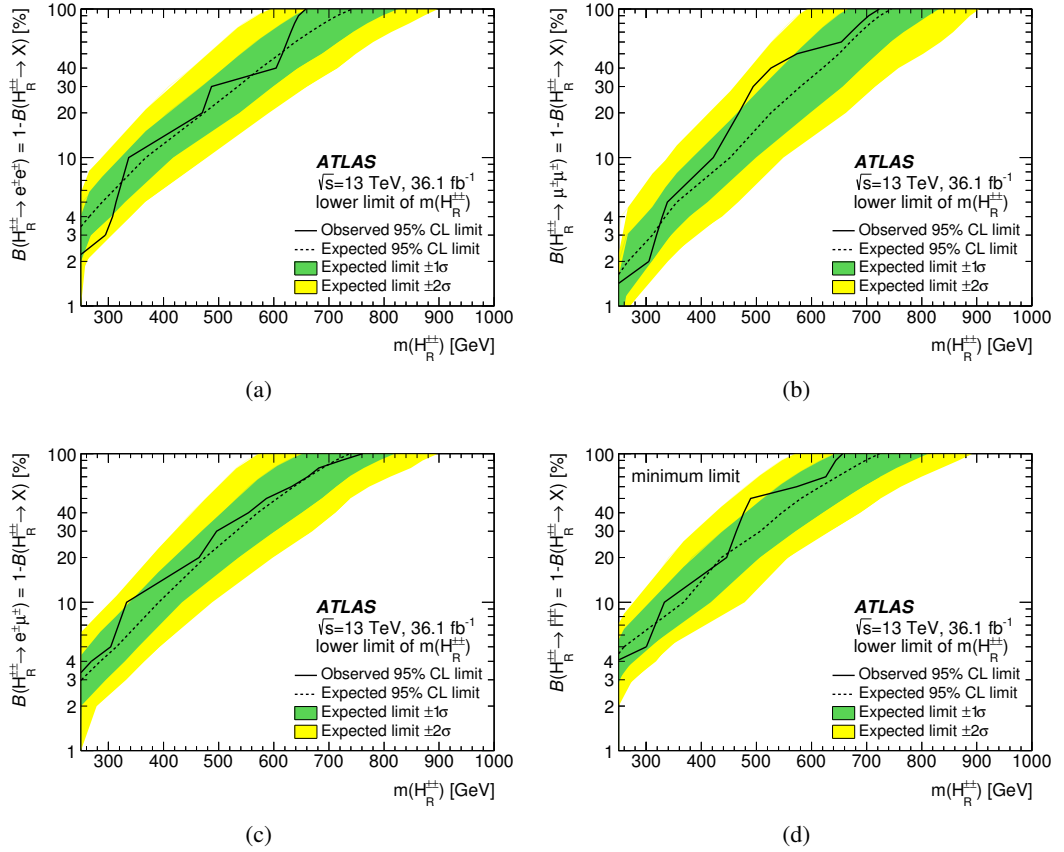


Figure 9.13: Lower limit on the $H_R^{\pm\pm}$ boson mass as a function of the branching ratio $B(H_R^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$. Several cases are presented: (a) $H_R^{\pm\pm}$ decays only into electrons and "X", (b) $H_R^{\pm\pm}$ decays only into muons and "X", and (c) $H_R^{\pm\pm}$ decays only into electron–muon pairs and "X", with "X" not entering any of the signal regions. Plot (d) shows the minimum observed and expected limit as a function of $B(H_R^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$. Taken from Ref. [93].

The observed lower mass limits vary from 770 GeV to 870 GeV for $H_L^{\pm\pm}$ with $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ and are above 450 GeV for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \geq 10\%$. For $H_R^{\pm\pm}$ the lower mass limits vary from 660 GeV to 760 GeV for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ and are above 320 GeV for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \geq 10\%$.

9.3 Fit results of the heavy N_R and W_R search

The variable chosen to perform the fit on is H_T , i.e. the scalar sum of the transverse momenta of two leptons and the two leading jets, in signal regions and $m(jj)$ in control regions. H_T variable has a good discriminating power also for low W_R mass signals. At the contrary m_{lljj} poorly discriminates low W_R mass points. Finally m_{jj} poorly discriminates both low and high W_R mass points. Pre-fit distributions, shown in detail in Appendix C, have shown that the H_T variable is particularly sensitive to discriminating between signal and the SM background.

Two additional free parameters are constrained in the fit: the Z + jets and the diboson yields. Z + jets yield is extracted from the electron channel control region and applied to validation and signal regions. Diboson yield is extracted both from the muon control region and the electron control region and applied to both electron/muon validation and signal regions. For the electron control region, Z + jets and fakes are the dominant backgrounds.

The likelihood fit is split into two channels (ee and $\mu\mu$) where only one signal region is used in each while both control regions are still used at all times. The motivation for this is to keep results independent from the $m(N_R) = m(N_R^e) = m(N_R^\mu)$ assumption used in the generated signal events.

Expected post-fit yields in all control, validation and signal regions used in the analysis are summarized in Figure 9.14 and shown in Table 9.4. No significant excess is observed in any of the signal regions and good agreement between the expected SM yield and the data is observed in validation regions.

Table 9.4: Numbers of expected background events in analysis regions after the background-only fit in the same-charge channel, compared to the data. The quoted uncertainties correspond to the total uncertainty in the predicted event yield including correlations between the various sources of systematic uncertainties. Due to rounding the total background can differ from the sums of components. Diboson and Z + jets yields are floating in the fit. Background processes with a negligible yield are marked with the dash (–).

	CR ($e^\pm e^\pm$)	CR ($\mu^\pm \mu^\pm$)	VR ($e^\pm e^\pm$)	VR ($\mu^\pm \mu^\pm$)	SR ($e^\pm e^\pm$)	SR ($\mu^\pm \mu^\pm$)
Observed events	304	119	33	11	11	5
Total background	306 ± 17	119 ± 11	31.1 ± 5.5	10.3 ± 2.4	11.2 ± 2.0	5.5 ± 1.7
Z + jets	100 ± 31	–	4.3 ± 2.0	–	2.0 ± 0.9	–
Fakes	119 ± 23	40.4 ± 9.6	14.1 ± 4.6	4.1 ± 2.0	5.9 ± 1.9	3.3 ± 1.7
Diboson	61 ± 13	74 ± 14	7.3 ± 1.6	5.8 ± 1.4	2.6 ± 0.6	2.0 ± 0.5
$t\bar{t}$, single- t , $t\bar{t}V$	25.8 ± 5.9	4.3 ± 0.8	5.4 ± 1.7	0.35 ± 0.08	0.8 ± 0.3	0.14 ± 0.05

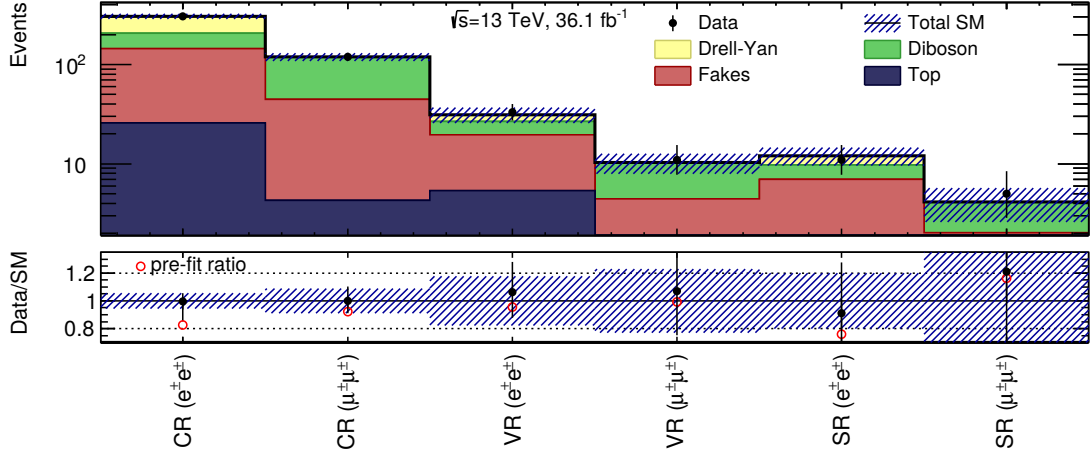


Figure 9.14: Number of observed and expected events in the control, validation, and signal regions for all channels considered in the heavy N_R and W_R search. The background expectation is the result of the fit described in the text using both control regions. The hatched bands include all post-fit systematic uncertainties with the correlations between various sources taken into account. The pre-fit SM yield is indicated with red bars in the ratio plot.

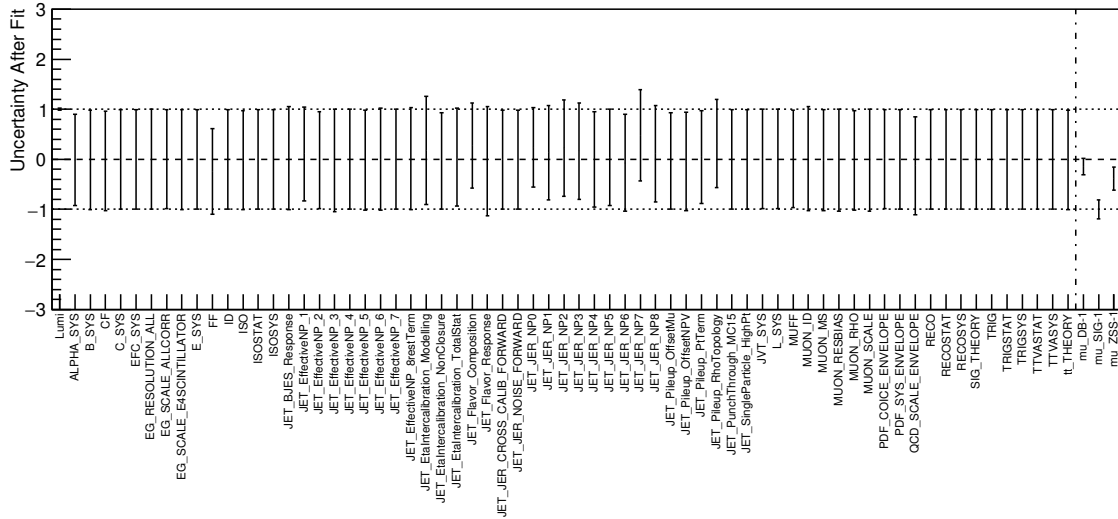
9.3.1 Fitted distributions in the heavy N_R and W_R search

Best-fit values of nuisance parameters (θ) are presented in Figure 9.15. All nuisance parameters stay within the one standard deviation interval after the likelihood fit. Pre-fit and Post-fit distributions, using the non-equidistant binning introduced in Section 9.2.1 are shown in Figures 9.16 and 9.17. It is evident that the agreement between the prediction and the data is better post-fit and the uncertainty is smaller. Typical N_R/W_R signal distributions are overlaid on the SM prediction in signal regions.

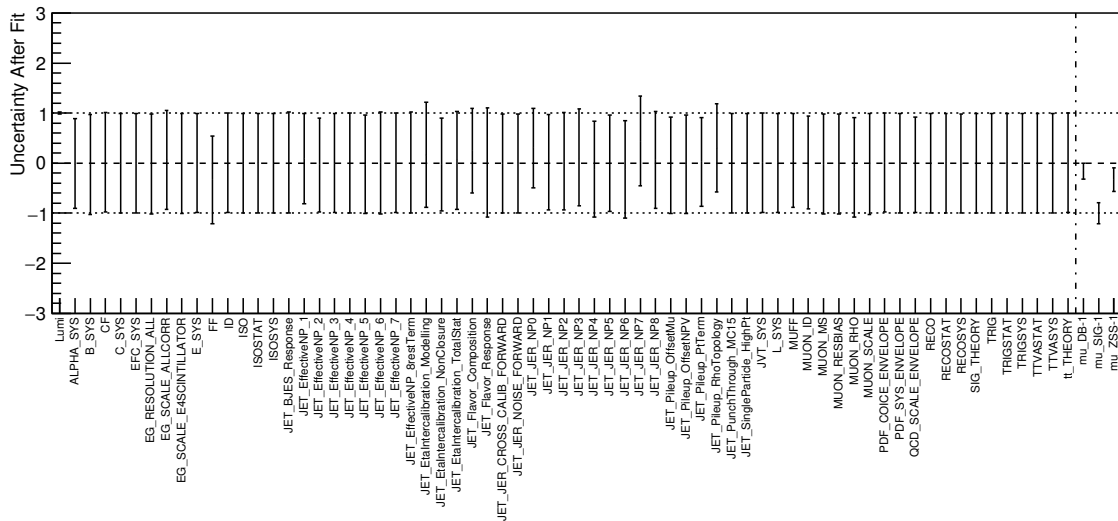
The fitted yields of the Z + jets and diboson background are summarized in Table 9.5. In signal regions, the dominant uncertainty is the statistical uncertainty, followed by the uncertainty on the fitted yields and the uncertainty on the data-driven fake background estimation techniques. The correlations between the nuisance parameters are presented in Figure 9.18. For presentational purposes, only correlations greater than 5 % are shown. As expected, the uncertainties on the fitted yields showcase large negative correlations with various nuisance parameters, which reduces the total uncertainty on the SM prediction. In the process of fitting the yields of the largest SM backgrounds, the additional free parameters effectively absorb all uncertainties in the total yield of these backgrounds and only the shape uncertainties remain.

Table 9.5: Summary of the fitted yields in the N_R/W_R likelihood fit. First column presents the background process, the second column indicated in which regions the yield was fitted, and the last column gives the fitted value.

Background process	fitted in	fitted yield
Z + jets	$CR(e^\pm e^\pm)$	0.66 ± 0.23
Diboson	$CR(e^\pm e^\pm)$ and $CR(\mu^\pm \mu^\pm)$	0.86 ± 0.16



(a)



(b)

Figure 9.15: Best-fit values of nuisance parameters in the N_R/W_R likelihood fit. The right side of the plot shows the fitted yields of the largest SM contributions. The fitted yields are shown as the relative difference compared to the nominal prediction along with the related uncertainty in units of %. (a) shows the electron channel fit and (b) shows the muon channel fit.

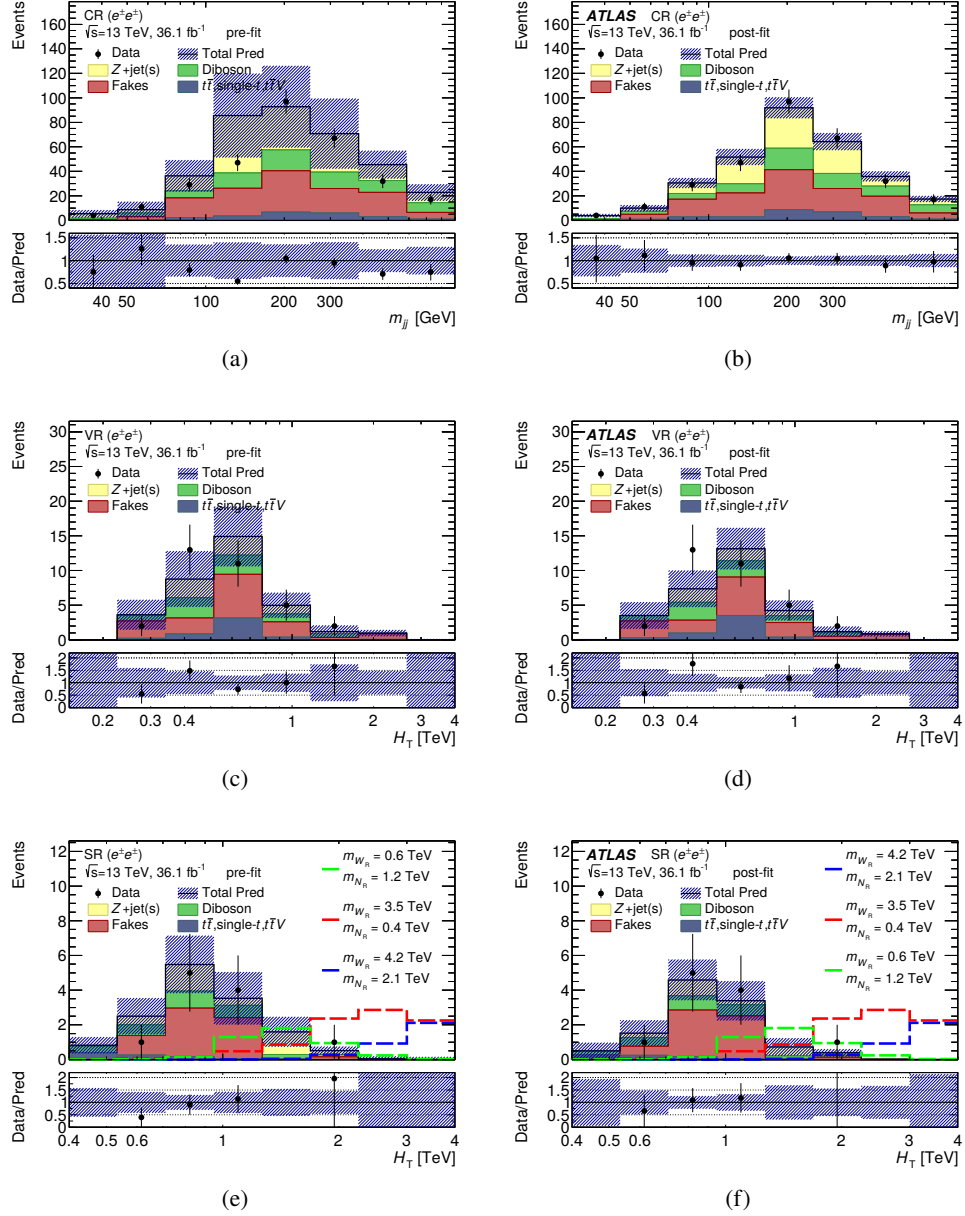


Figure 9.16: Pre- (left column) and post-fit (right column) distributions for the N_R/W_R electron channel: control region (a), (b), validation region (c), (d), and signal region (e), (f). The hatched bands include all systematic uncertainties with the correlations between various sources taken into account. The dashed colored lines correspond to signal samples, normalized using the theory cross-section, with the N_R and W_R masses marked in the legend. Post-fit plots are taken from Ref. [190].

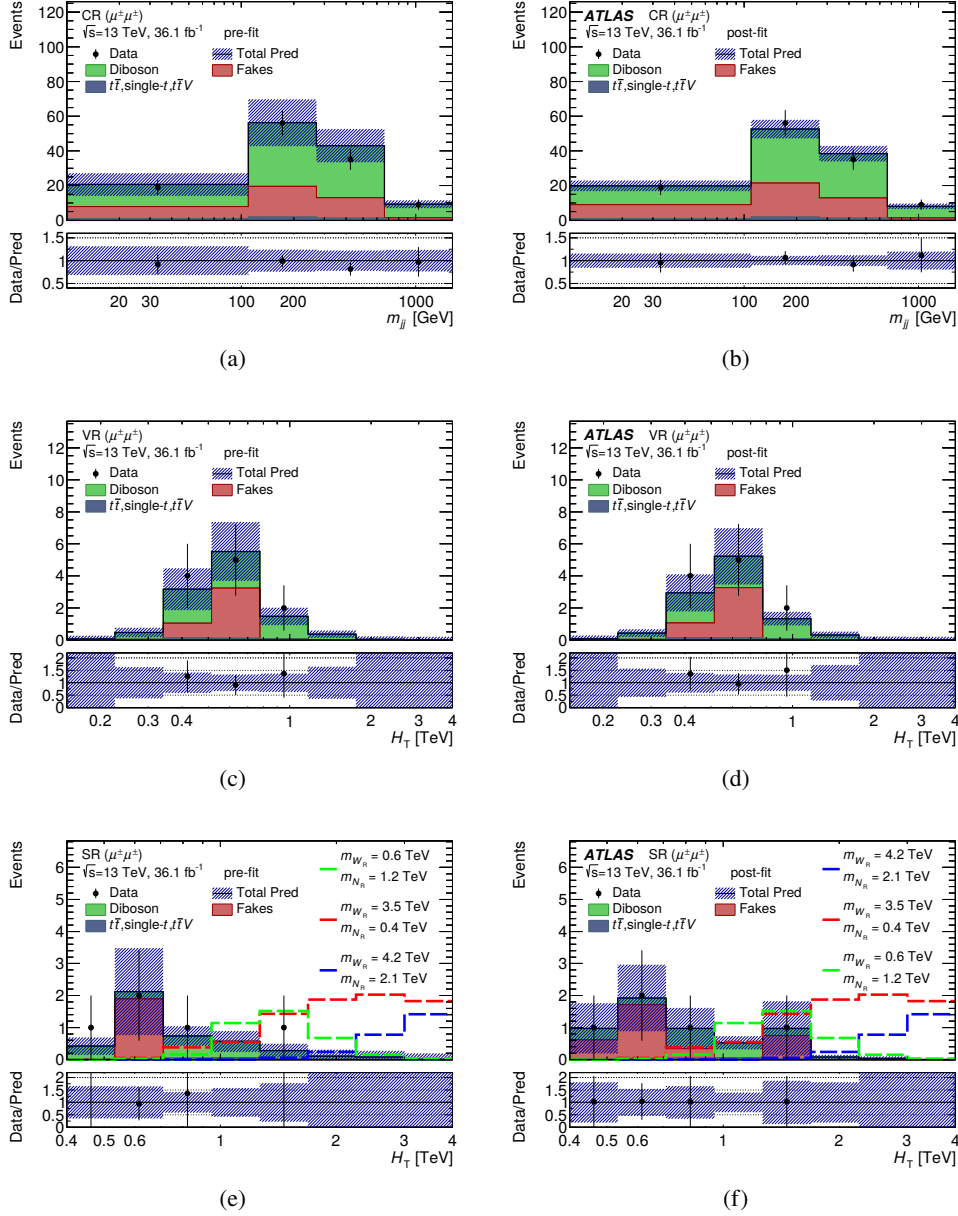


Figure 9.17: Pre- (left column) and post-fit (right column) distributions for the N_R/W_R muon channel: control region (a), (b), validation region (c), (d), and signal region (e), (f). The hatched bands include all systematic uncertainties with the correlations between various sources taken into account. The dashed colored lines correspond to signal samples, normalized using the theory cross-section, with the N_R and W_R masses marked in the legend. Post-fit plots are taken from Ref. [190].

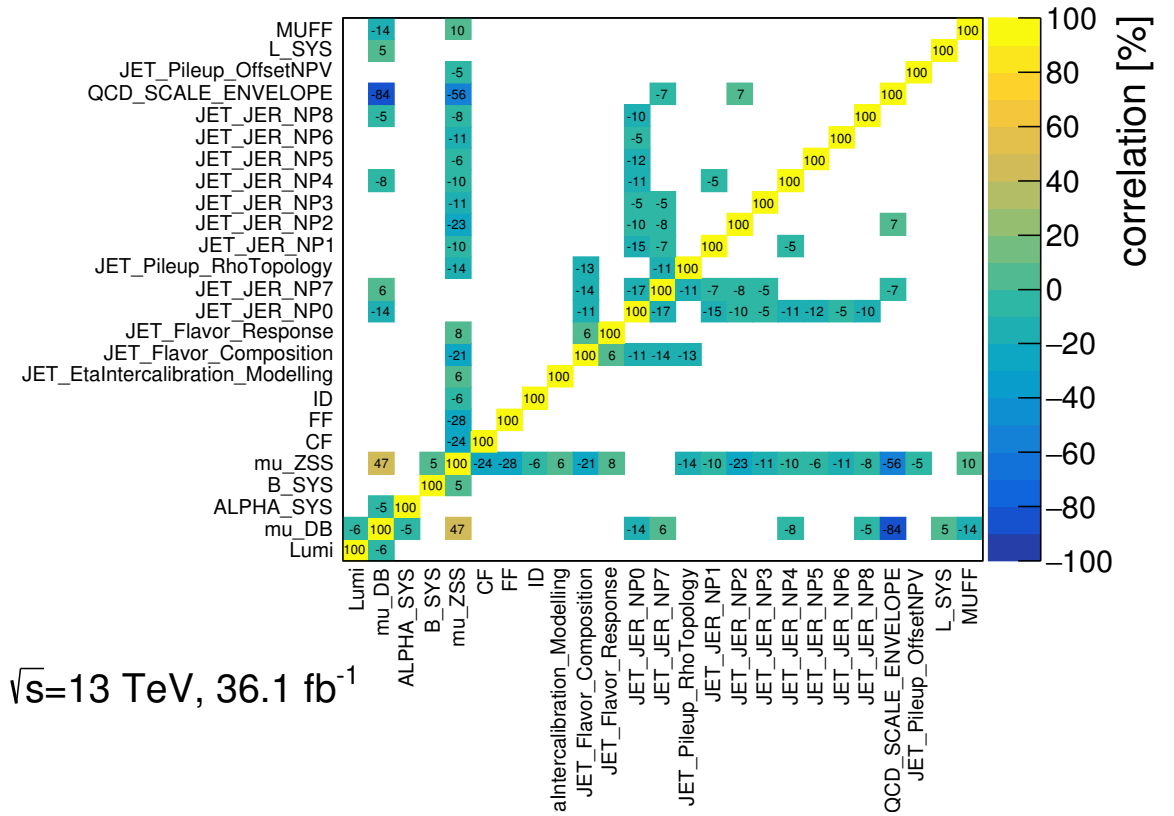


Figure 9.18: Reduced correlation matrix of all nuisance parameters used in the N_R/W_R likelihood fit. Only correlations greater than 5% are shown.

9.3.2 Upper limits on the Keung-Senjanović process cross-section

In the absence of evidence for a signal, upper limits on the production cross-section of the Keung-Senjanović process are derived for different masses hypotheses both in the $m(W_R) > m(N_R)$ and $m(N_R) > m(W_R)$ hierarchies for ee and $\mu\mu$ channel separately. Consequently, the expected and observed 95 % CL lower mass limits in the N_R/W_R plane are shown in Figures 9.19(a) and 9.19(b). The contours shows similar behavior for the ee and $\mu\mu$ channel, therefore heavy Majorana neutrino masses from 50 to 3000 GeV can be excluded for heavy right-handed gauge boson masses above 500 GeV.

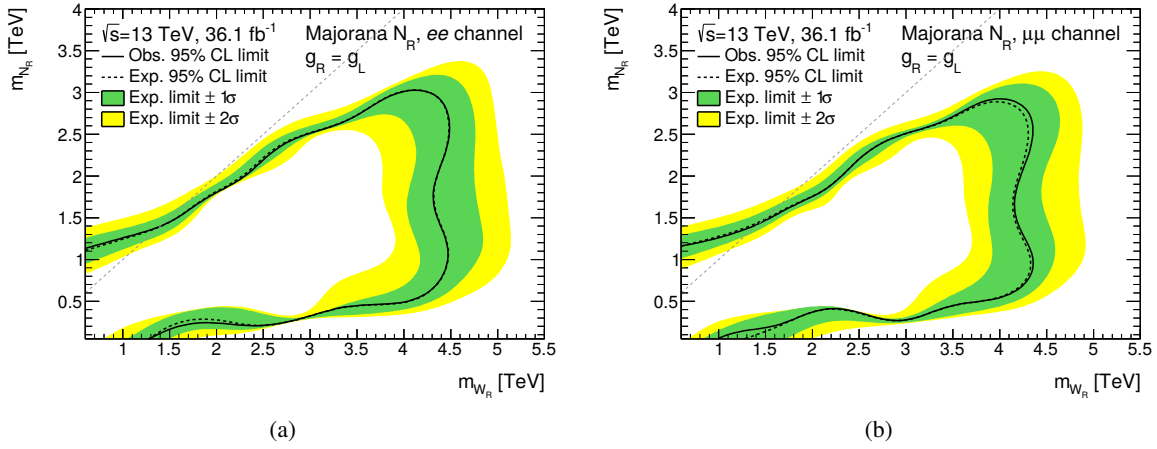


Figure 9.19: Expected and observed 95 % CL exclusion contour for the same-charge channel with the corresponding one and two standard deviation bands: (a) electron channel and (b) muon channel.

Furthermore, one dimensional projections of the exclusion contour are presented to broaden the understanding of the experiment sensitivity. These are made for four mass relations: $m(W_R) = [2/3, 3/4, 2, 4] \times m(N_R)$, and presented in Figure 9.20 for the electron channel and in Figure 9.21 for the muon channel.

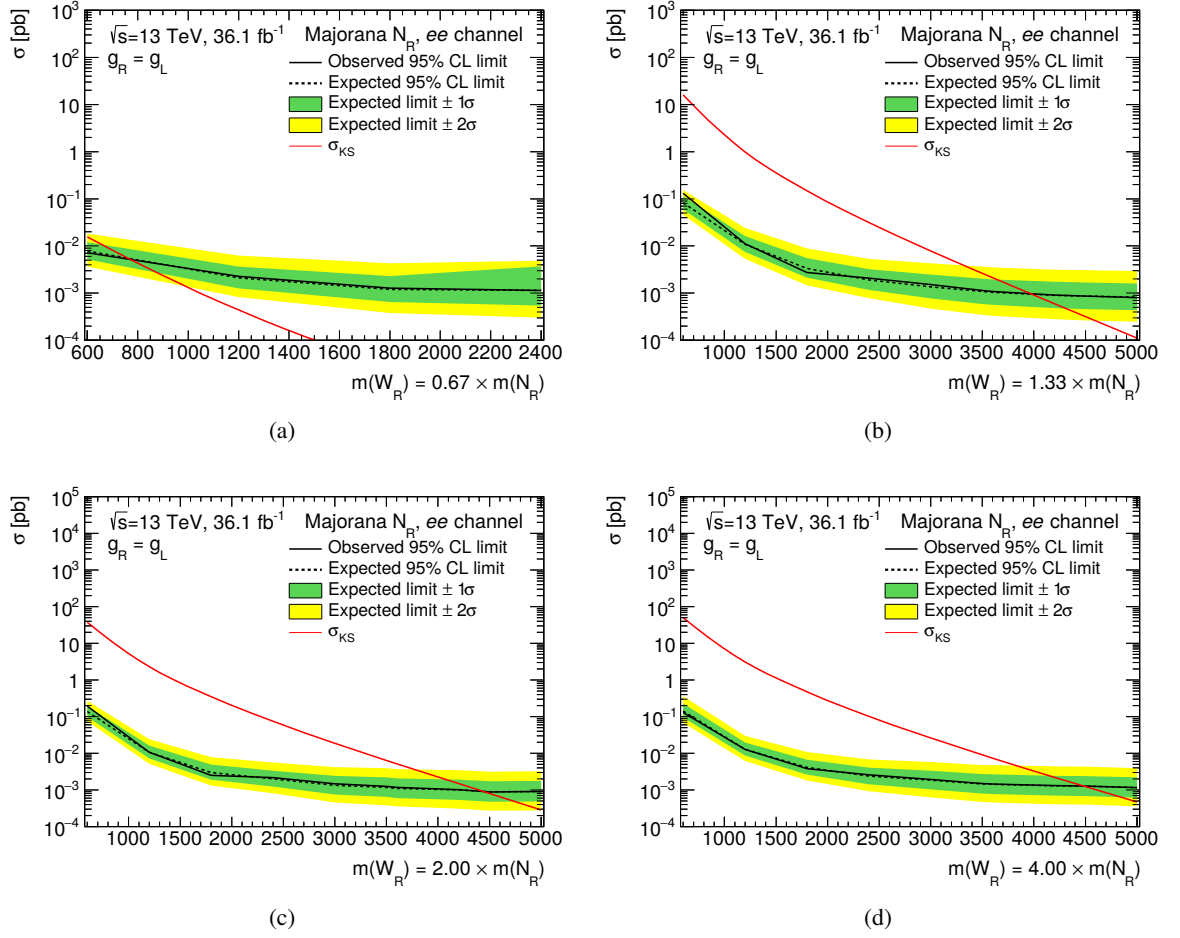


Figure 9.20: Expected and observed upper limit for the electron channel on the Keung-Senjanović process production cross-section at 95% CL as a function of $m(W_R) = k \times m(N_R)$, where: (a) $k = 2/3$, (b) $k = 4/3$, (c) $k = 2$, and (d) $k = 4$.

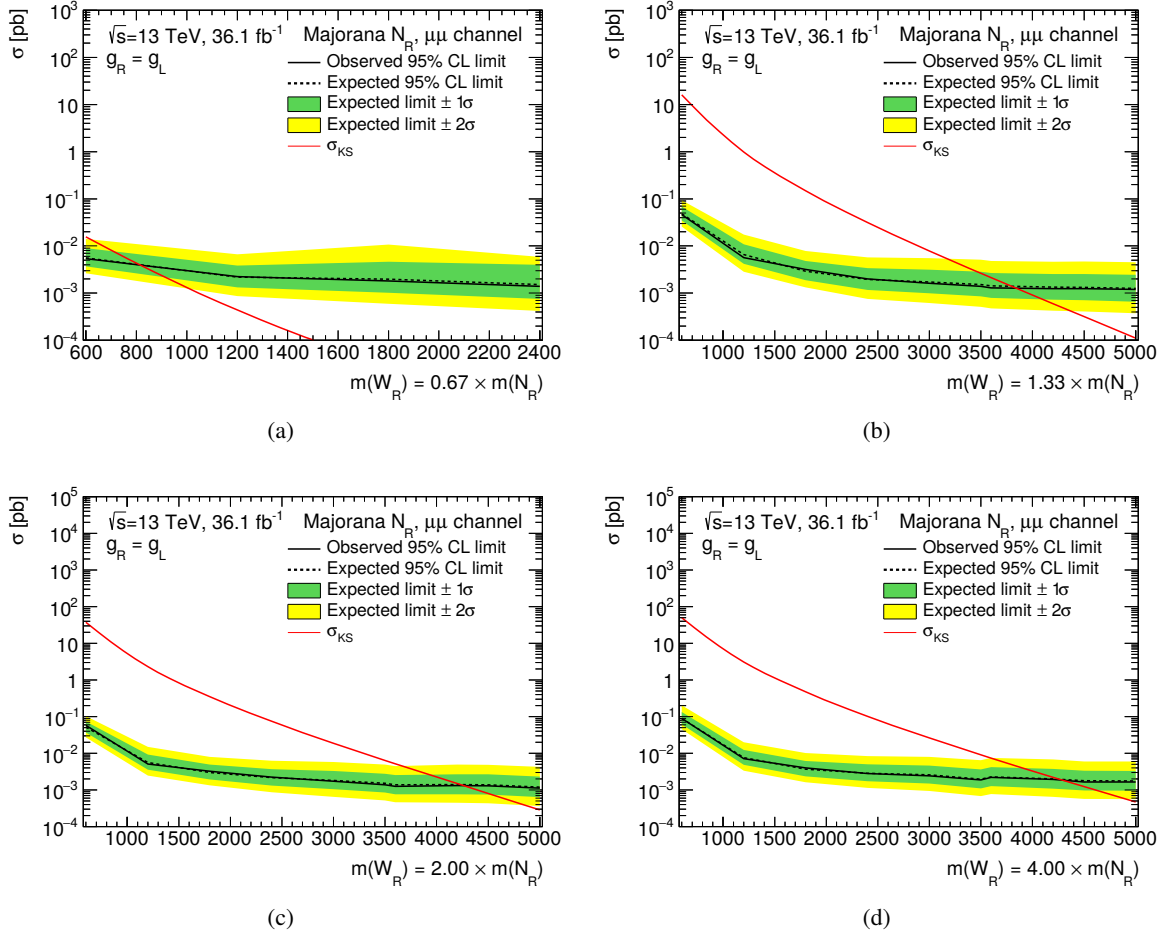


Figure 9.21: Expected and observed upper limit for the muon channel on the Keung-Senjanović process production cross-section at 95% CL as a function of $m(W_R) = k \times m(N_R)$, where: (a) $k = 2/3$, (b) $k = 4/3$, (c) $k = 2$, and (d) $k = 4$.

9.3.3 Statistical combination with the opposite-charge channel

The same-charge and opposite-charge heavy N_R and W_R searches are two separate analyses in ATLAS and a statistical combination is performed to increase the sensitivity to the Keung-Senjanović process and to gain additional information on the nature of the heavy neutrino particle (Majorana or Dirac). The combination is described in more detail in Ref. [190]. The additional opposite-charge analysis regions together with the same-charge regions, already defined in Table 6.5, are presented in Table 9.6. The expected and observed yields in all analysis regions are presented in Figure 9.22 and yields in the opposite-charge signal regions are presented in Table 9.7.

Table 9.6: Summary of all regions defined in the N_R/W_R analysis divided into the opposite-charge and same-charge channels. The table is split into two blocks: the top half indicates the mass range of the dilepton final state, whereas the bottom half indicates the event selection criteria used for a given region. The flavour combinations are summarised as follows: $\ell^\pm \ell^\mp = \{e^\pm e^\mp, \mu^\pm \mu^\mp\}$, $\ell^\pm \ell^\pm = \{e^\pm e^\pm, \mu^\pm \mu^\pm\}$, $\ell^\pm \ell'^\mp = \{e^\pm \mu^\mp\}$. Pairs of values $[X, Y]$ indicate the minimum and maximum values the quantity in question may take in the analysis region in question. Taken from Ref. [190].

Region	Control region			Validation region		Signal region	
Channel	CR($\ell^\pm \ell^\mp$)	CR($\ell^\pm \ell'^\mp$)	CR($\ell^\pm \ell^\pm$)	VR($\ell^\pm \ell^\mp$)	VR($\ell^\pm \ell^\pm$)	SR($\ell^\pm \ell^\mp$)	SR($\ell^\pm \ell^\pm$)
m_{ee} [GeV]	[60, 110]	—	[110, 300]	[110, 400]	[300, 400]	> 400	> 400
$m_{\mu\mu}$ [GeV]	[60, 110]	—	[60, 300]	[110, 400]	[300, 400]	> 400	> 400
$m_{e\mu}$ [GeV]	—	> 400	—	—	—	—	—
H_T [GeV]	> 400	> 400	—	> 400	—	> 400	> 400
$m(jj)$ [GeV]	> 110	> 110	—	> 110	—	> 110	> 110
jet p_T [GeV]	> 100	> 100	> 50	> 100	> 50	> 100	> 100

Due to the different object definitions and background components in the opposite-charge and same-charge channels, separate nuisance parameters are used for all sources of uncertainties and fitted

Table 9.7: Numbers of expected background events in signal regions after the background-only fit in the opposite-charge channel, compared to the data. The quoted uncertainties correspond to the total uncertainty in the predicted event yield including correlations between the various sources of systematic uncertainties. Due to rounding the total background can differ from the sums of components. Top-quark and Z + jets yields are floating in the fit.

	SR ($e^\pm e^\mp$)	SR ($\mu^\pm \mu^\mp$)
Observed events	156	169
Total background	152.2 ± 8.4	165.9 ± 8.9
Z + jets	53.9 ± 5.1	61.8 ± 4.8
$t\bar{t}$, single- t , $t\bar{t}V$	74.0 ± 7.6	89.6 ± 8.3
Diboson and W + jets	24.5 ± 1.6	12.8 ± 0.7

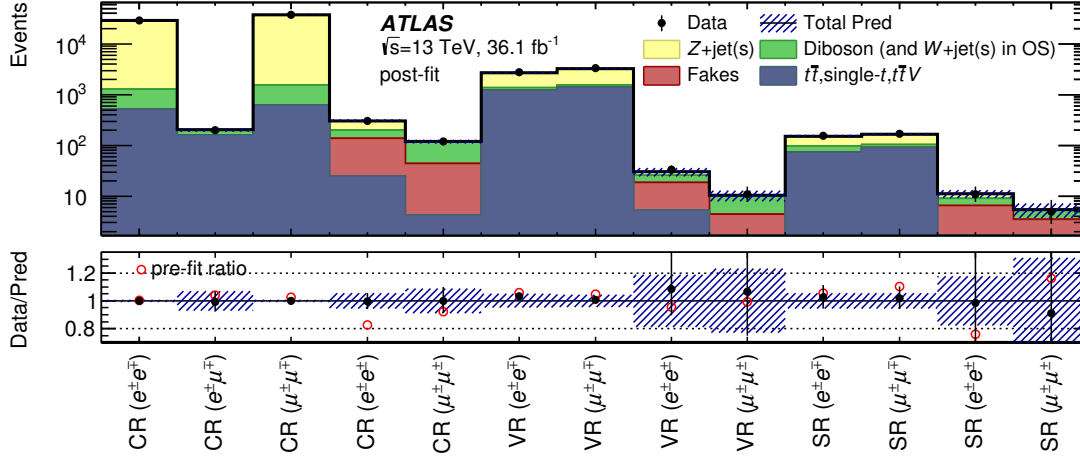


Figure 9.22: Number of observed and expected events in the control (CR), validation (VR), and signal (SR) regions for all channels considered in the heavy N_R and W_R search. The background expectation is the result of the fit described in the text using both opposite-charge and same-charge control regions. The hatched bands include all post-fit systematic uncertainties with the correlations between various sources taken into account. The pre-fit ratio is indicated with the red hollow markers in the ratio plot. Taken from Ref. [190].

yields for the largest backgrounds. The $CR(e^\pm e^\mp)$ and $CR(\mu^\pm \mu^\mp)$ are used to extract the yield of Z + jets background, as the proportion of Z + jets events is above 95 % in both these regions. The $CR(e^\pm \mu^\mp)$ is mostly populated by top-quark background events (~ 80 % contribution) and used to extract their normalization.

In the opposite-charge channel, different discriminating distributions are used in the likelihood fit depending on the mass hierarchy of the signal sample used in that fit. The $m_{\ell\ell jj}$ distribution is used as the discriminant for the $m(W_R) > m(N_R)$ hypothesis, and the m_{jj} spectrum is used as the discriminant for the $m(W_R) < m(N_R)$ hypothesis. Additional mass hypotheses were added by interpolating the discriminating distributions obtained for existing signal simulation samples using a moment morphing technique [205]. The opposite-charge signal regions are shown in Figure 9.23 along with a few simulated signal distributions, normalized to the predicted cross-section.

No significant deviation with respect to the SM predictions is observed in any of the signal regions and upper limits are derived on the production cross-section of the Keung-Senjanović process. The results are split into two neutrino hypotheses: Majorana and Dirac. In the Majorana case, both opposite-charge and same-charge regions are used in the likelihood fit and in the Dirac case only opposite-charge regions are used. The cross-section in the Dirac case is scaled by a factor of 2 to match the cross-section in the Majorana case because the used signal samples were generated with both opposite-charge and same-charge events. 95 % CL upper limits on the production cross-section of the Keung-Senjanović process in the N_R/W_R plane are shown in Figure 9.24.

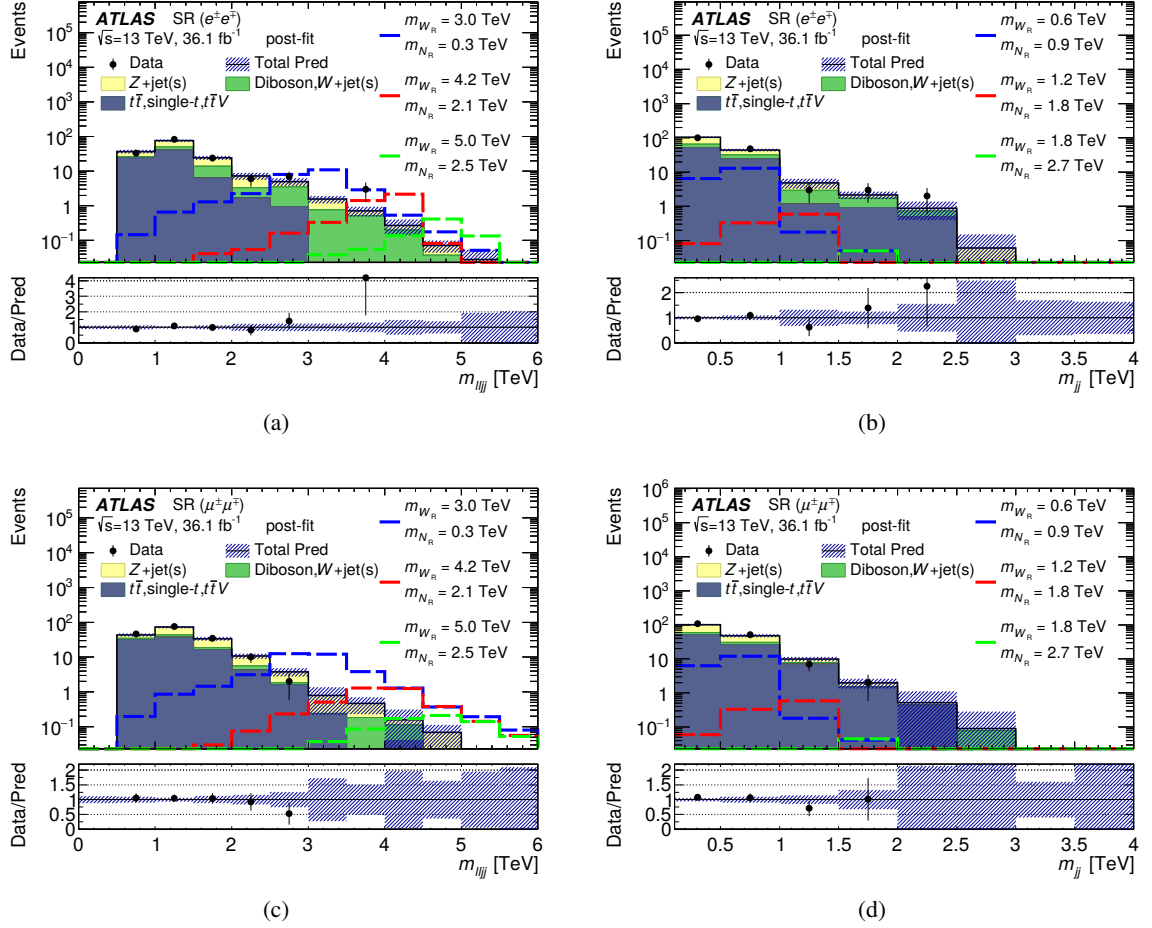


Figure 9.23: Distributions for data and background predictions for discriminants in opposite-charge N_R/W_R signal regions: (a) $m_{\ell\ell jj}$ in $SR(e^\pm e^\mp)$, (b) m_{jj} in $SR(e^\pm e^\mp)$, (c) $m_{\ell\ell jj}$ in $SR(\mu^\pm \mu^\mp)$, (d) m_{jj} in $SR(\mu^\pm \mu^\mp)$. The hatched bands include all post-fit systematic uncertainties, with the correlations between various sources taken into account. A few simulated signal distributions, normalized to the predicted cross-section, are overlaid on top of the background prediction in the plots. The last bin in each histogram also contains the overflow. Taken from Ref. [190].

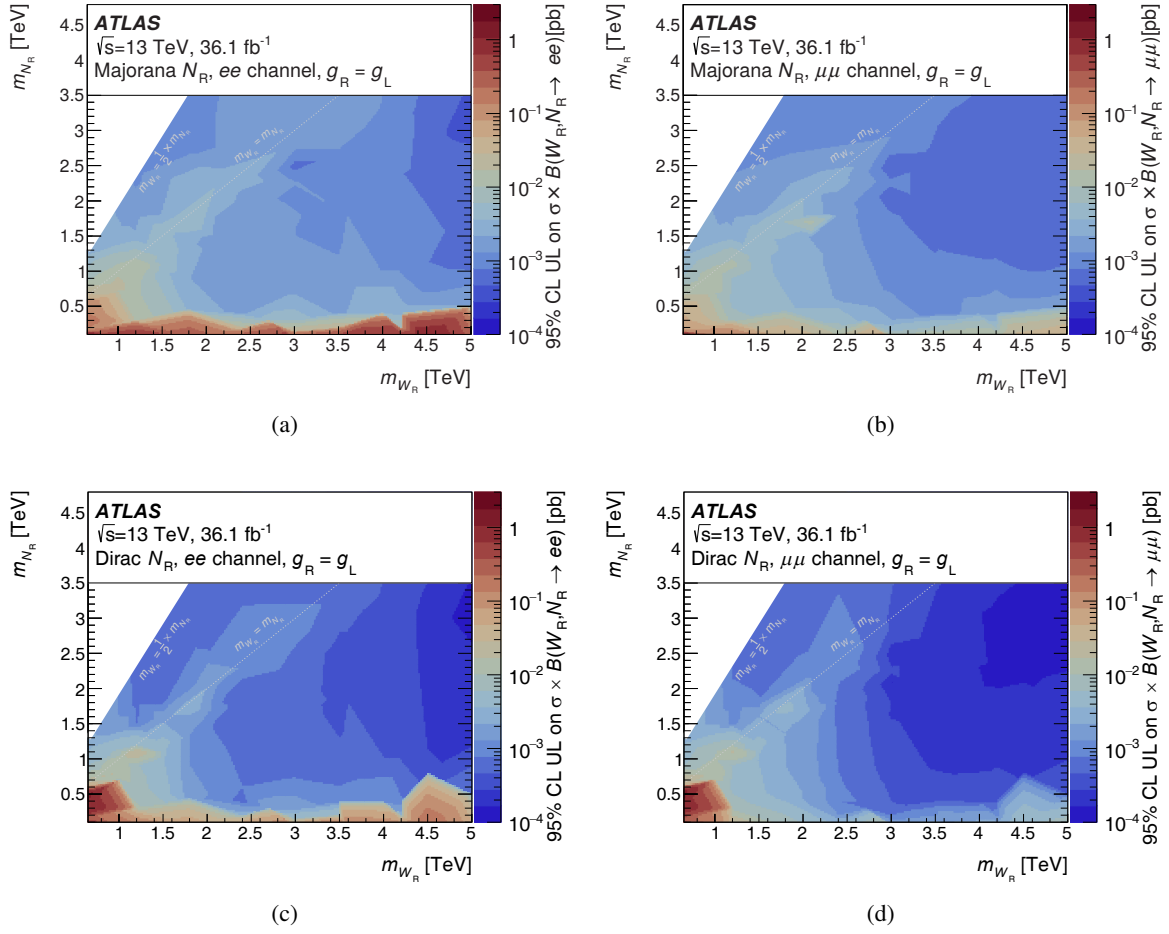


Figure 9.24: Observed 95 % CL upper limit on the production cross-section for the Keung-Senjanović process in the $m(W_R)/m(N_R)$ plane: (a) Majorana N_R neutrino electron channel, (b) Majorana N_R neutrino muon channel, (c) Dirac N_R neutrino electron channel, and (d) Dirac N_R neutrino muon channel. The right- and left-handed weak gauge couplings are assumed to be the same, as indicated by $g_L = g_R$. Taken from Ref. [190].

Exclusion contours are shown in Figure 9.25 for both the Majorana and Dirac cases of N_R neutrino. In both cases, W_R bosons with masses up to 4.7 TeV are excluded at 95 % CL for $m(N_R)$ of about 1 TeV. A comparison between the opposite-charge and same-charge channels is presented in Figures 9.25(e) and 9.25(f). The power of same-charge final states is visible in the electron channel where the same-charge sensitivity dominates the opposite-charge sensitivity due to less background. In the muon channel, limits are still greater in the same-charge channel for low $m(N_R)$, while they are lower for low $m(W_R)$ due to a tighter isolation requirement for muons in the same-charge channel. In this comparison opposite-charge cross-sections are the same as the same-charge cross-sections (not rescaled by 2).

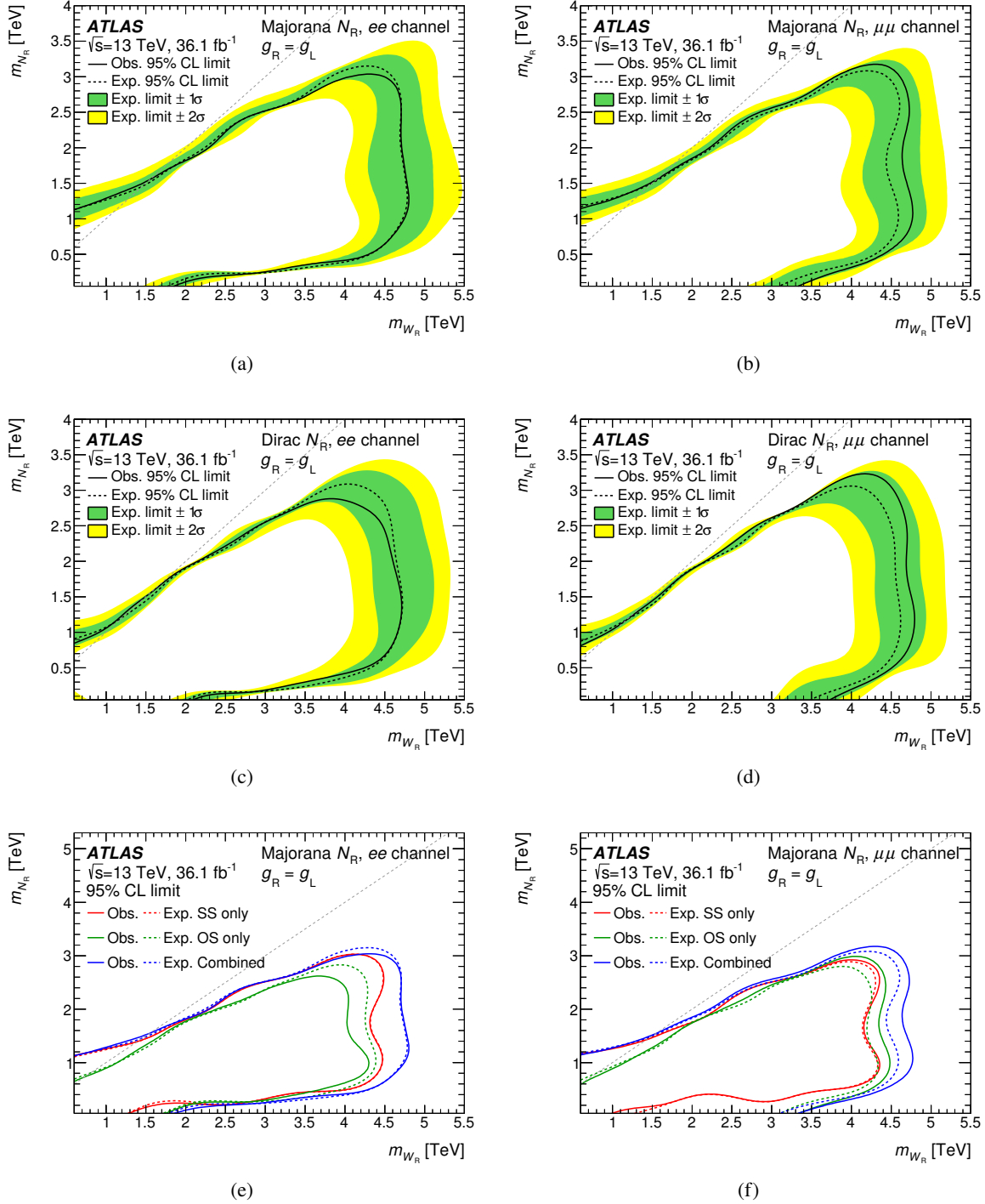


Figure 9.25: Observed (continuous line) and expected (dashed line) 95 % CL exclusion contours in the $m(W_R)/m(N_R)$ plane, along with the one and two standard deviation bands in the (a) electron and (b) muon channels for Majorana N_R neutrinos, (c) electron, (d) muon channels for Dirac N_R neutrinos. The dashed gray lines indicate $m(W_R) = m(N_R)$. Figures (e) and (f) show a comparison of the separate same-charge and opposite-charge limits along with the combination. In this comparison, opposite-charge cross-sections are not scaled by a factor of 2 as for the Dirac limits. Taken from Ref. [190].

Summary and outlook

10 Summary and outlook

The Standard Model can very precisely predict observable quantities such as cross-sections for a variety of different processes, it can explain the masses of composite particles such as protons or neutrons, and it even predicted the existence of new elementary particles. The Higgs boson was the last particle predicted by the Standard Model to be experimentally measured and with its discovery in 2012 the Standard Model became a complete and a closed theory. However, it does not explain all of the observed phenomena in the world of particle physics and it has many free parameters. Some notable problems of the Standard Model are the unexplained origin of the neutrino masses, the lack of the dark matter description, the hierarchy problem, and the complete asymmetry between left and right chirality in the weak sector.

"God may be left-handed, but not an invalid."

—Goran Senjanović

The fact that the weak interaction itself is not invariant under parity transformations at experimentally achievable energies inspired theories that restore the left-right symmetry at higher energy scales. The left-right symmetric models have been one of the principal candidates for the description of beyond the Standard Model phenomena during the last decades. The left-right symmetric model cures in a very elegant way the chiral asymmetry of the standard model. The W boson of the SM obtains its mirror-like twin and, furthermore, the Higgs sector is extended with a scalar bi-doublet and two scalar triplets. This simple idea of restoring the left-right weak symmetry leads naturally to the seesaw mechanism offering an explanation for the tiny Standard Model neutrino masses. The principal interest of this thesis is to determine the lower limit on the left-right symmetric scale by experimentally imposing the lower mass limit on the additional heavy right-handed gauge boson, W_R , additional heavy neutrinos, N_R , and the doubly-charged components of the two scalar triplets, $H_{L,R}^{\pm\pm}$, called the doubly charged Higgs bosons.

The ATLAS detector at the Large Hadron Collider was used to search for new phenomena with same-charge dilepton final states, using $e^\pm e^\pm$, $e^\pm \mu^\pm$ and $\mu^\pm \mu^\pm$ final states as well as final states with three or four leptons (electrons and/or muons). The search was performed with 36.1 fb^{-1} of data from proton–proton collisions at $\sqrt{s} = 13 \text{ TeV}$, recorded during the 2015 and 2016 data-taking periods. No significant excess above the Standard Model prediction was found. As a result of the search, lower limits are set on the mass of additional elementary particles predicted by the left-right symmetry models. The lower limit on the $H_{L,R}^{\pm\pm}$ mass varies between 770 to 870 GeV for the left-handed component and for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ and is still above 450 GeV for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \geq 10\%$ for any combination of partial branching ratios. The observed lower limits on the $H_R^{\pm\pm}$ mass vary from

660 to 760 GeV for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ and are above 320 GeV for $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \geq 10\%$. The observed limits are consistent with the expected limits. The lower limits on the $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ masses obtained in this thesis, under the assumption $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$, are 300 GeV higher than those from the previous ATLAS analysis [180] and 450 GeV higher than those from the CMS analysis [181]. Furthermore, a search for right-handed W bosons and heavy right-handed Majorana or Dirac neutrinos is presented using a final state containing a pair of charged leptons, electrons or muons, and two jets ($\ell\ell jj$), with $\ell = e, \mu$. No evidence of W_R bosons or Majorana or Dirac heavy neutrinos, N_R , is found assuming the Keung-Senjanović production and lower limits are set on the $m(W_R)$ and $m(N_R)$ masses, assuming equality of left- and right-handed weak gauge couplings ($g_L = g_R$). The excluded region for the Majorana N_R neutrinos extends to about $m(W_R) = 4.7$ TeV, for $m(N_R) = 1.2$ TeV in the electron channel and for $m(N_R) = 1$ TeV in the muon channel. The $m(N_R)$ limits reach about 2.9 TeV in the electron channel and 3.1 TeV in the muon channel (for $m(W_R) = 4.3$ TeV). For Dirac N_R neutrinos, limits reach about $m(W_R) = 4.7$ TeV, for $m(N_R) = 1$ TeV in the electron channel and for $m(N_R) = 1.2$ TeV in the muon channel. Limits on $m(N_R)$ up to about 2.8 TeV (for $m(W_R) = 3.7$ TeV) in the electron channel and up to 3.2 TeV (for $m(W_R) = 4.1$ TeV) in the muon channel are set. In the low-mass regime ($m(W_R) < 1.5$ TeV), under the hierarchy hypothesis $m(N_R) > m(W_R)$, N_R masses up to 1.5 TeV are excluded at 95 % CL. These results improve upon previous ATLAS searches [184] and extend the exclusion limits on $m(W_R)$ by 1 to 2 TeV. Additionally, the scenario in which the N_R neutrino is heavier than the W_R boson is explored for the first time.

The thesis illustrates the power of same-charge lepton final states at pp colliders. Standard Model processes rarely produce two leptons with significant transverse momenta and the same electric charge, but there are many beyond the Standard Model theories of various elegance and plausibility that predict such signatures. The searches presented in this thesis exploit this fact by—in addition to the same-charge of the leptons—requiring very large sum of transverse momenta of identified high-level objects (leptons and jets) in the event. With these requirements the SM background is reduced to just a few background events among all recorded during 2015 and 2016 data-taking periods while the efficiency to reconstruct the predicted signals remains high. This is nicely reflected in the most-stringent limits on $m(H_{L,R}^{\pm\pm})$ to date, with very little room for improvement with the used dataset, and in the strongest limits to date on $m(N_R)$ in the $m(N_R) > m(W_R)$ case. The latter would not be possible using only opposite-charge final states as is evident in Figures 9.25(e) and 9.25(f).

Same-charge lepton searches, however, come with an increased difficulty due to backgrounds caused by unwanted interactions between particles and the detector material and due to uncertainties in the reconstruction of leptons. Same-charge final states frequently occur due to misreconstructed leptons since their charge is arbitrary. These can be either non-prompt electrons and muons originating from meson decays or photon conversions or non-lepton objects incorrectly identified as leptons. An example of such background is W +jets production where the prompt lepton from the W boson is accompanied by a fake lepton caused by the additionally produced jets in the pp collision. Furthermore, same-charge di-electron final states suffer from electron charge misidentification. The electron charge reconstruction is studied in great detail in this thesis to pinpoint the exact mechanism of charge misidentification and offer ways of discriminating against such cases or improving the electron charge reconstruction. The leading SM process entering the signal regions due to charge misidentification is Drell–Yan $Z \rightarrow ee$ production simply due to its large cross-section. These background are very sizable in the presented analysis regions and robust methods are derived to tackle them.

It was observed that the simulation of fakes and electron charge misidentification does not describe the data with sufficient accuracy. A prohibitively large sample of simulated events would be needed to reliably estimate the corresponding uncertainties. Data-driven methods are introduced both for the estimation of the fake background and the electron charge misidentification process. The thesis offers unique solutions to use these data-driven background for leptons with very high transverse momenta. A novel parametrization of the charge misidentification probability is presented, exploiting the fact that p_T and η effects are decorrelated. η describes the amount of transversed material by the electron and p_T accounts for the electron scattering cross-section. This allows a ‘1D×1D’ parametrization instead of the more frequently used 2D parametrization, as presented in Section 7.1. The decreased number of parameters describing this parametrization effectively increase the available statistics and make measurement of the charge misidentification probability at high electron transverse momenta more precise and robust ($p_T > 200$ GeV).

The future of same-charge di-lepton searches at pp colliders is very bright. A study of the electron charge misidentification for the Phase-II upgrade of the ATLAS detector is presented in this thesis in Appendix A. Because of the large reduction in material budget of the ITk, the probability to misidentify the electron charge is reduced by at least a factor of three compared to the current detector. Furthermore, methods to identify electrons with incorrectly reconstructed charge are being developed in ATLAS, which will further decrease the SM background of same-charge di-electron final states. In addition, more challenging final states such as hadronic taus, that were not yet considered in many ATLAS searches, could potentially lead to discoveries. Many predicted BSM resonances could have enhanced couplings to tau leptons, however, due to complex background modeling of tau final states these searches were not yet performed. The benchmark tau analysis in ATLAS, the SM $H \rightarrow \tau\tau$ measurement [206], sets a great example on how to deal with tau related backgrounds (e.g. the distinction between quark-jet and gluon-jet initiated fakes). These methods could be used to extend the presented search for new phenomena also to tau final states, where the hypothesized particles in left-right symmetric models ($H_{L,R}^{\pm\pm}$ and N_R) could finally reveal themselves.

Appendix

A Electron charge misidentification studies for the ATLAS Phase-II upgrade

The High-Luminosity LHC (HL-LHC) project was recently approved by the CERN Council in June 2016. The HL-LHC project aims to greatly extend the initial discovery reach of the LHC and by 2026 considerably improve the performance of the LHC by increasing the luminosity by a factor between five and seven, up to $\mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, and allowing to accumulate integrated luminosity of up to 4000 fb^{-1} between 2026 and 2036. The number of proton–proton per bunch crossing will increase up to 200.

Due to the high instantaneous luminosity, the HL-LHC presents a unique challenge for a charged particle tracking detector close to the operating beam-line and all ATLAS sub-systems need to be upgraded. The central tracking system for the ATLAS experiment is planned to be upgraded with the Inner Tracker (ITk) detector [160, 207]. A schematic overview of the ITk detector is presented in Figure A.1.

Electron charge misidentification process in Run 2 is discussed in detail in Section 5 and Figure A.2(a) shows a comparison between the charge misidentification probabilities in Run 2 and Phase-II conditions. The charge misidentification probability is determined in both cases with simulated $Z \rightarrow ee$ events and defined as the ratio of the number of electrons with incorrectly reconstructed charge to the number of all electrons, $P = N(\text{wrong})/N(\text{all})$. Electrons are required to have a minimal transverse energy of $E_T > 25 \text{ GeV}$ and no further identification requirements are imposed in order to keep the results comparable between Run 2 and Phase-II. Because of the large reduction in material budget of the ITk, the probability to misidentify the electron charge is reduced by at least a factor of three compared to the current detector. The magnitude of improvement depends on η of the electron in the detector and the comparison of the amount of material in the two corresponding detectors is presented terms of radiation lengths in Figure A.2(b). Furthermore, no significant effects due to the increased levels of pile-up are observed.

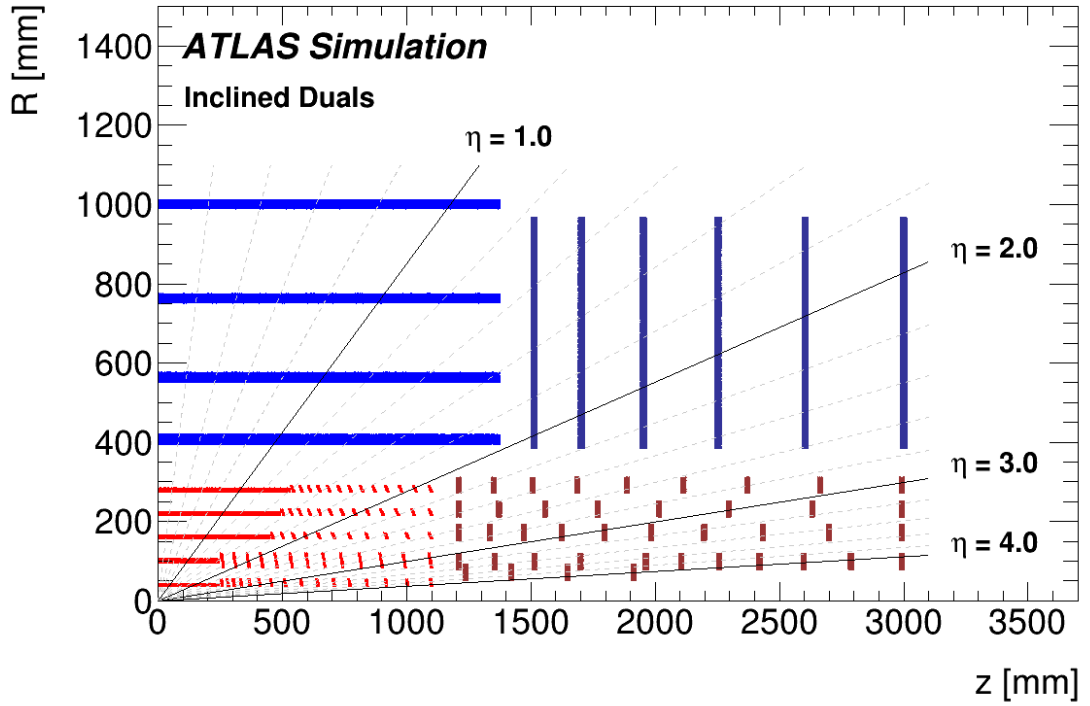


Figure A.1: A schematic layout of the ITk detector for the HL-LHC Phase-II upgrade of the ATLAS detector. The active elements of the barrel and end-cap Strip Detector are shown in blue, for the Pixel Detector the sensors are shown in red for the barrel layers and in dark red for the end-cap rings. The horizontal axis is along the beam-line with zero being the interaction point. The vertical axis is the radius measured from the interaction region. Taken from Ref. [160].

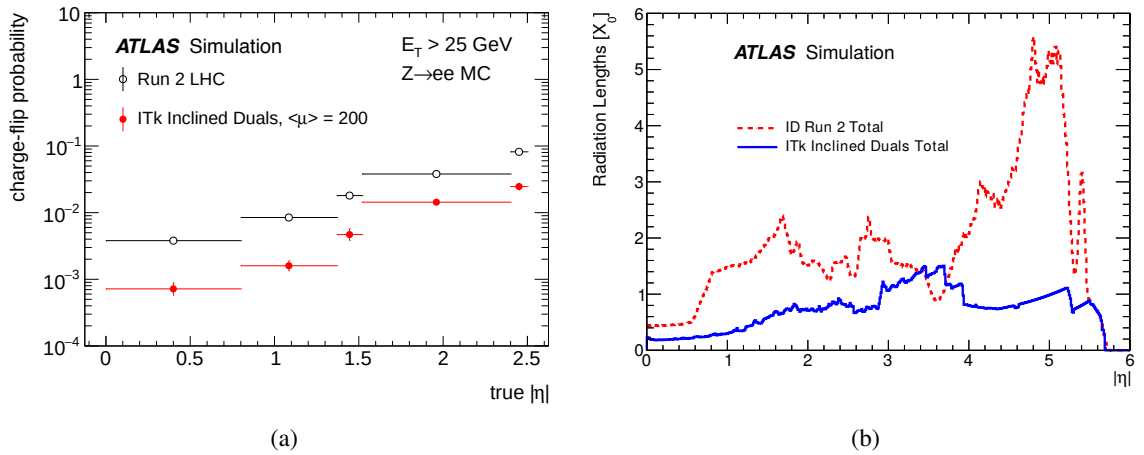


Figure A.2: Electron charge misidentification probability (a) as a function of the truth electron η for the Run 2 geometry (black empty circles) and the Phase-II geometry (red full circles). (b) the comparison of detector material budget of the inner detector in ITk compared to the current detector. Taken from Ref. [160].

B Composition of the electron charge misidentification processes

Charge misidentification of electrons is studied with MC to predict the amount of trident events and stiff tracks in the signal region and in the $Z \rightarrow ee$ region. The origin of charge misidentification is presented in Section 5.1. Electrons with incorrect charge are classified into two distinct categories, stiff tracks and tridents, and their kinematic distributions are presented in Figure 5.2.

A potential bias could arise from measuring the charge-flip probability inclusively in the $Z \rightarrow ee$ peak. It is therefore important to verify the composition of these two processes is either the same in the SR and the $Z \rightarrow ee$ peak or that the different composition does not introduce a bias. Figure B.2 presents the ratio of these processes both at the $Z \rightarrow ee$ peak and in the signal region. The ratio of stiff tracks to tridents varies in the SR compared to the $Z \rightarrow ee$ peak. However, the ratio in the mass spectrum is highly correlated to p_T and η distributions of these processes. A further test comparing the probabilities of these two processes in the $Z \rightarrow ee$ peak compared to the signal region is presented in Figure B.1. With the given statistics we can conclude that the ratios are compatible with one. This implies that the separate charge-flip probabilities of the two processes do not change explicitly with the invariant mass.

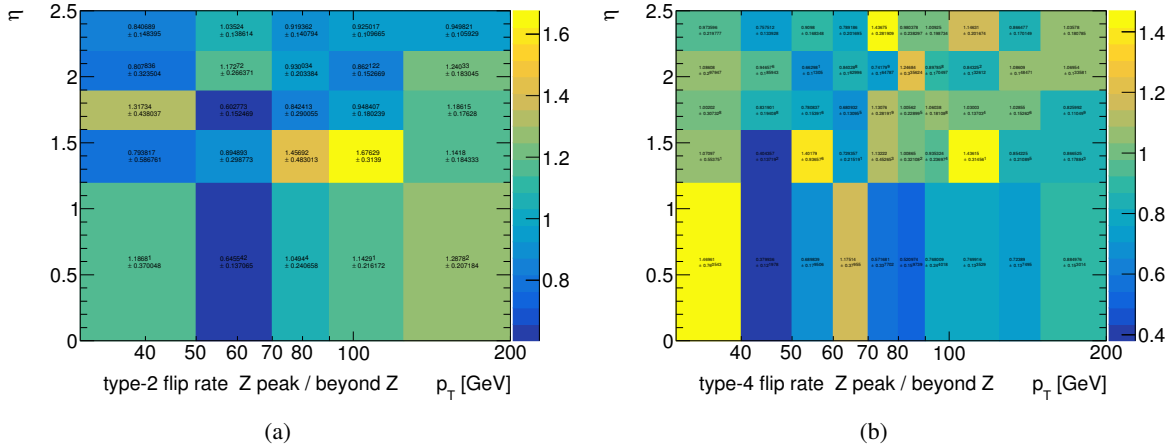


Figure B.1: Composition of the charge-flip probability of tridents and stiff tracks in the $Z \rightarrow ee$ peak and the high-mass signal region: (a) $Z \rightarrow ee$ peak and (b) high-mass $Z \rightarrow ee$ region.

B Composition of the electron charge misidentification processes

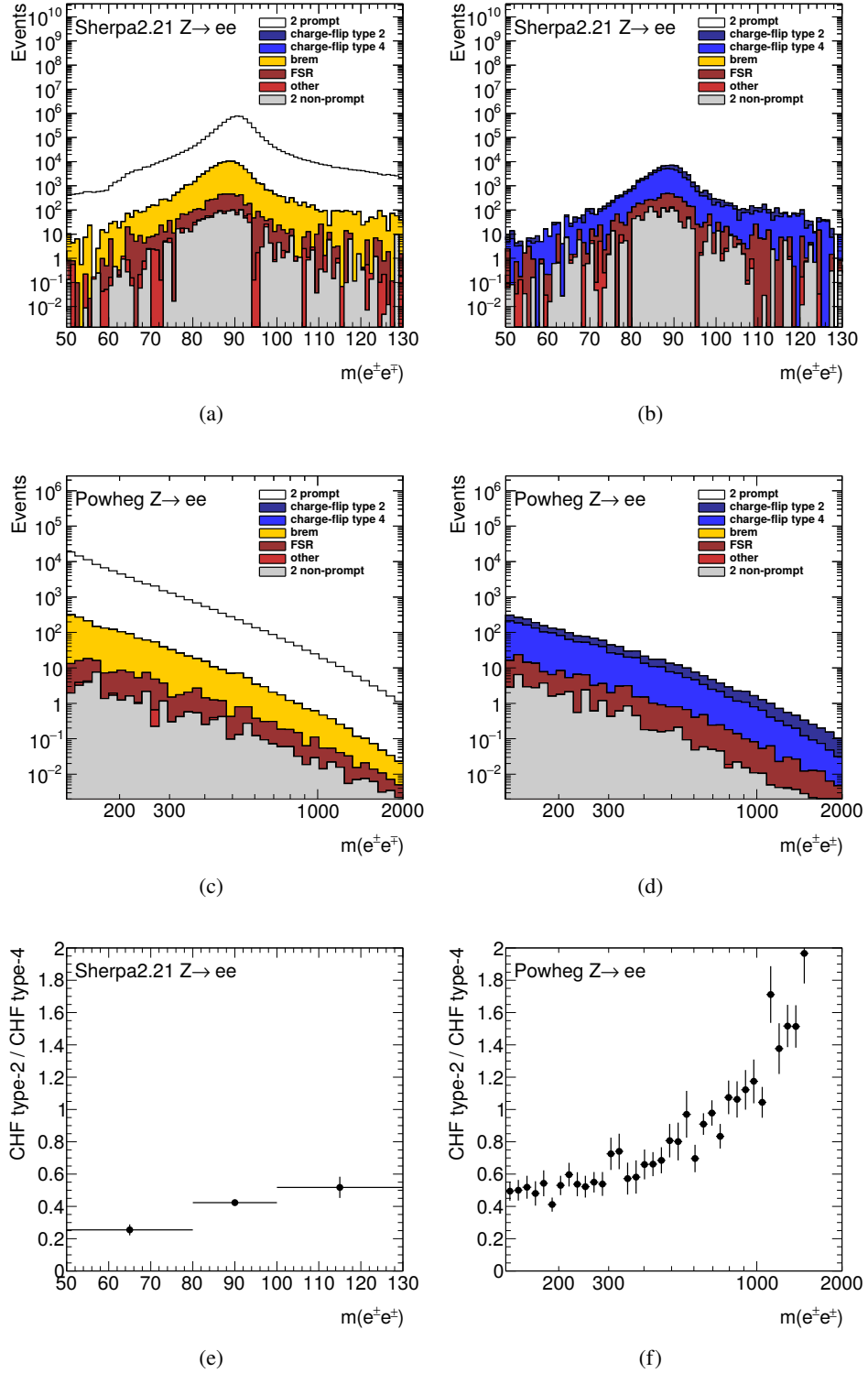


Figure B.2: All the processes in $Z \rightarrow ee$ MC in four regions as a function of the invariant mass in units of GeV: (a) opposite-sign $Z \rightarrow ee$ peak, (b) same-sign $Z \rightarrow ee$ peak, (c) high-mass opposite-sign $Z \rightarrow ee$, and (d) high-mass same-sign $Z \rightarrow ee$. The ratio of the compositions of the two charge-flip processes are shown in (e) and (f).

C The $Z \rightarrow ee$ peak region

The $Z \rightarrow ee$ region is an important region in this analysis as it is used to measure the charge-flip probability. The nominal event selection is applied and events with exactly two tight electrons are selected. Furthermore, the invariant mass of the two electrons is required to be within 15 GeV of the Z mass.

The $Z \rightarrow ee$ region is divided into two categories:

- any-sign (AS): no charge requirement on the two electrons
- same-sign (SS): the two selected electrons have the same electric charge

These two regions are used to measure the charge-flip probability. The kinematic distribution of the AS $Z \rightarrow ee$ region are shown in Figure C.1 and the angular distributions are shown in Figure C.2. The data/MC agreement is very good in this region even up to very high electron p_T . The same distributions of the SS region are presented in Figure C.3 and Figure C.4. Mismodeling in the same-sign region is immediately evident. There is an overall scale error along with mis-modeling at low electron p_T (Figure C.3(c) and Figure C.3(d)).

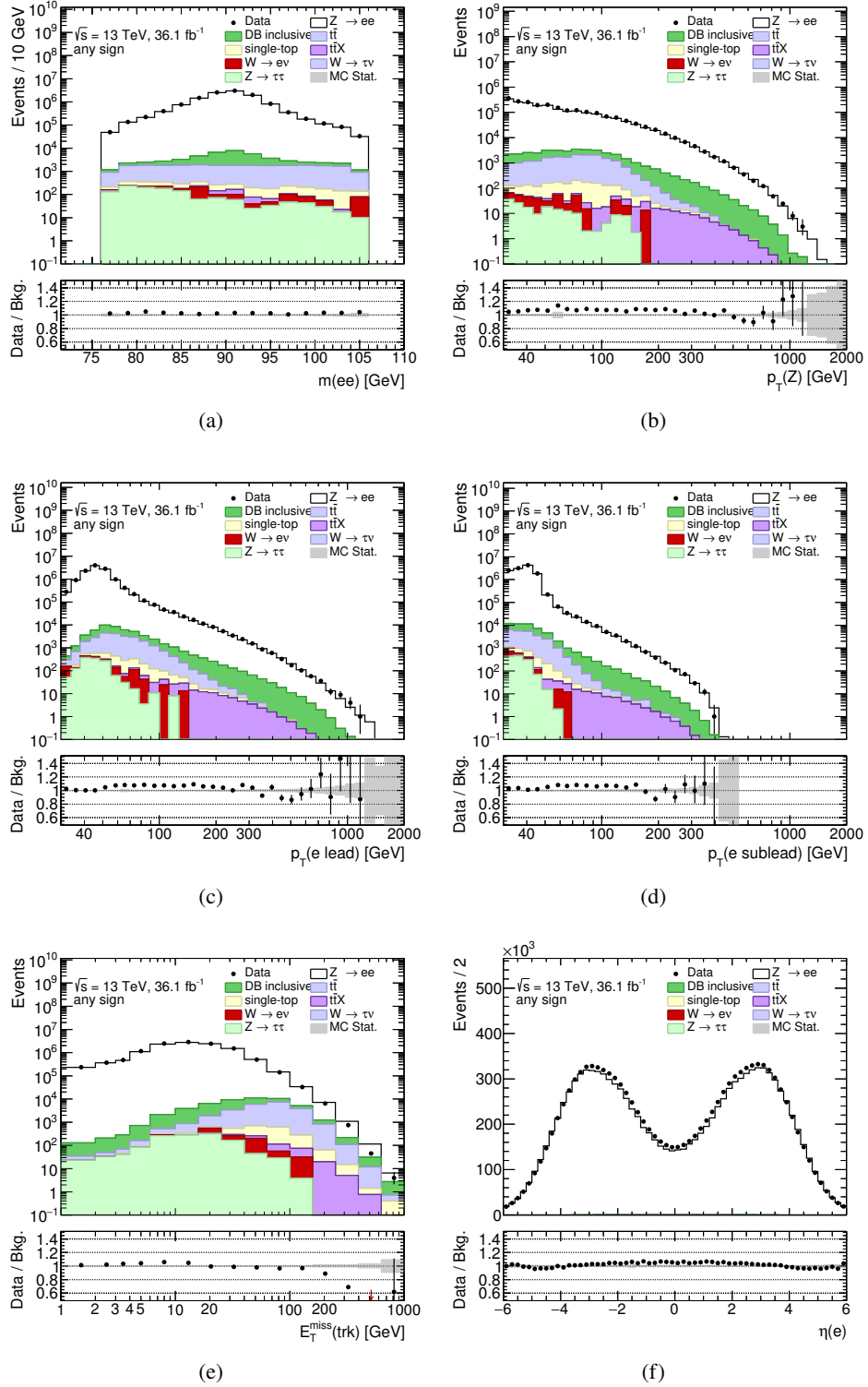
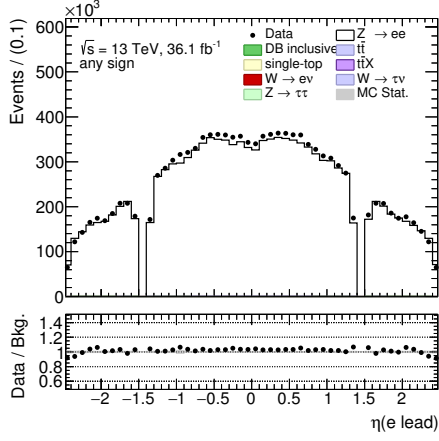
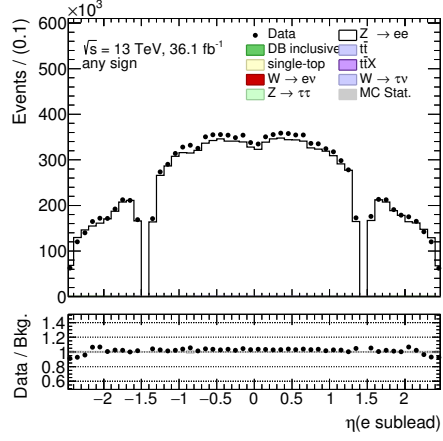


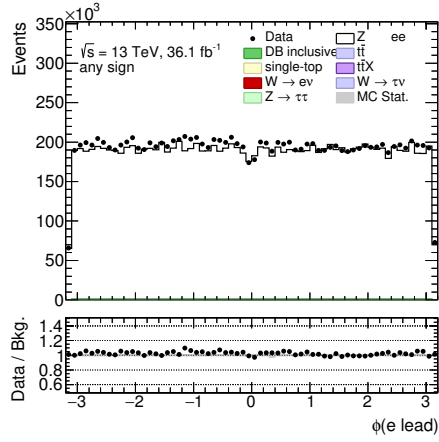
Figure C.1: Distributions of the any-sign $Z \rightarrow ee$ region. (a) invariant mass distribution of the same-sign electron pair, (b) di-electron p_T distribution, (c) and (d) p_T distribution of electrons, (e) the E_T^{miss} distribution and, (f) the di-electron η distribution.



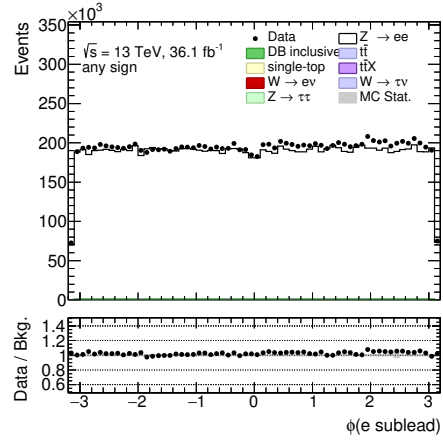
(a)



(b)



(c)



(d)

Figure C.2: Distributions of the any-sign $Z \rightarrow ee$ region. (a) and (b) η distributions, (c) and (d) ϕ distributions.

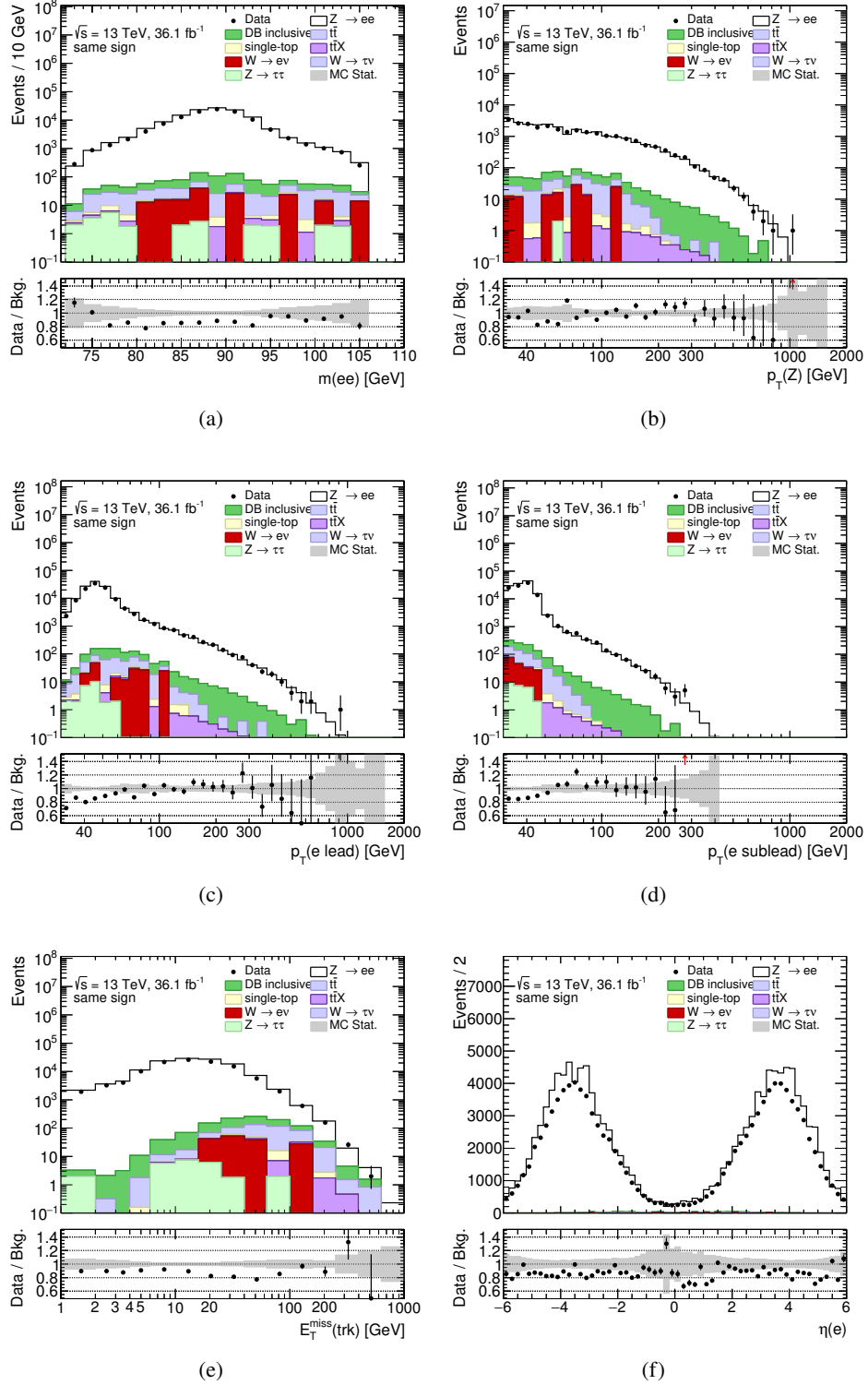
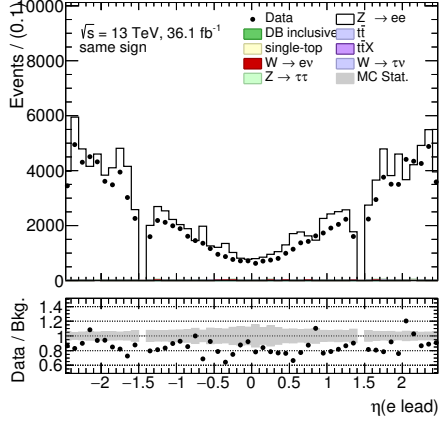
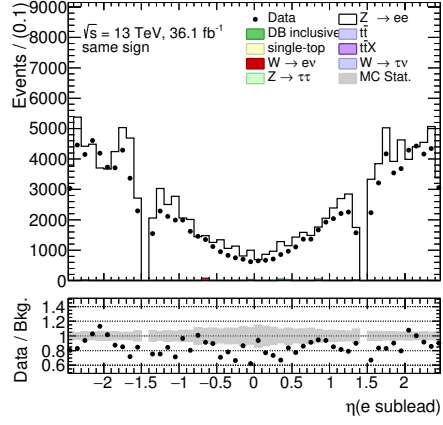


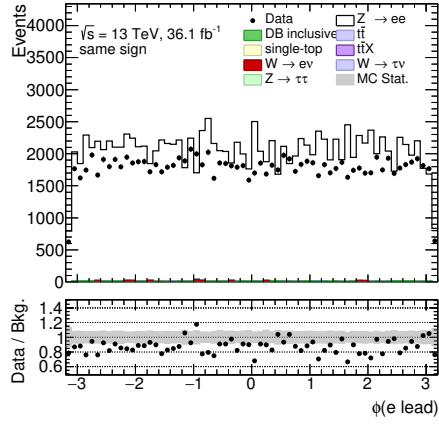
Figure C.3: Distributions of the same-sign $Z \rightarrow ee$ region. (a) invariant mass distribution of the same-sign electron pair, (b) di-electron p_T distribution, (c) and (d) p_T distribution of electrons, (e) the E_T^{miss} distribution and, (f) the di-electron η distribution.



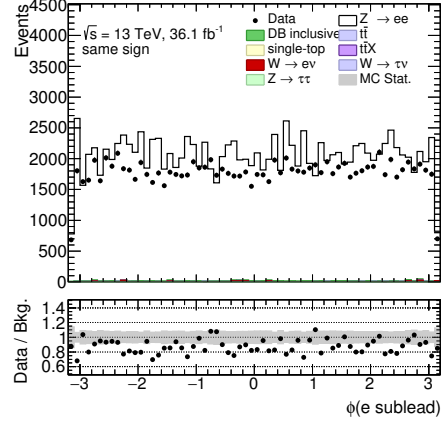
(a)



(b)



(c)



(d)

Figure C.4: Distributions of the same-sign $Z \rightarrow ee$ region. (a) and (b) η distributions, (c) and (d) ϕ distributions.

D Closure test for the 1D×1D charge-flip rate parametrization

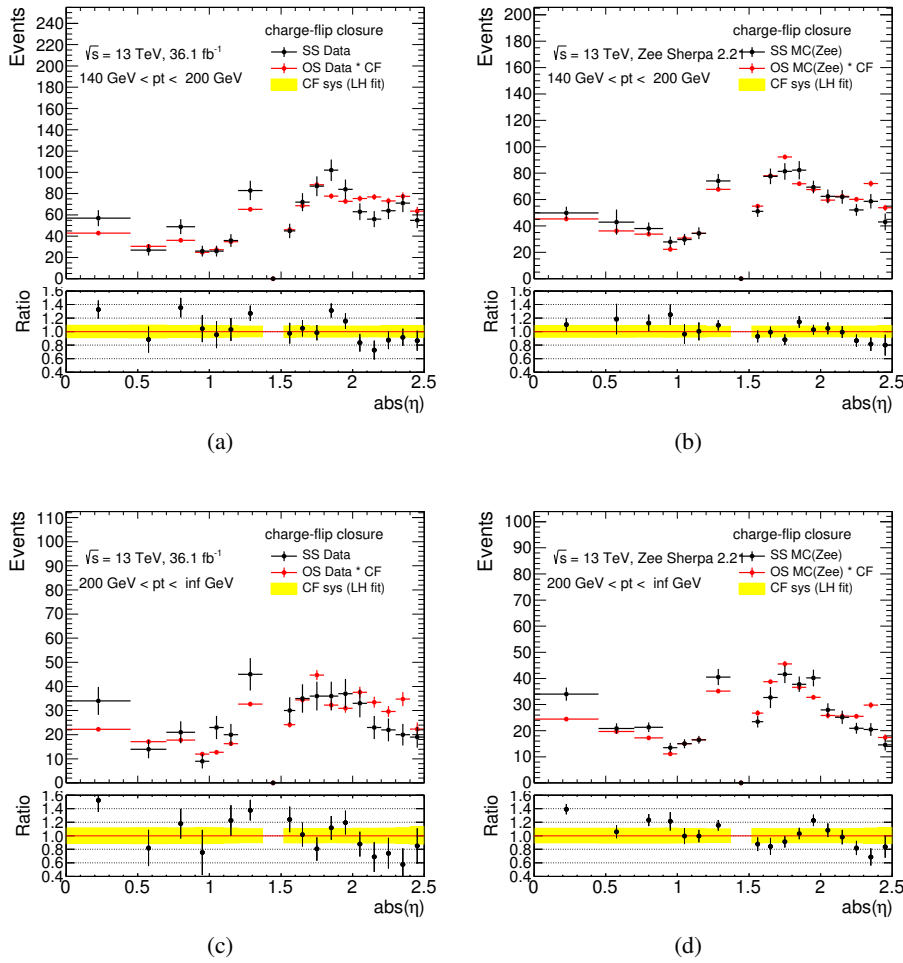


Figure D.1: Closure test for the 1D×1D charge-flip rate parametrization in data and MC, split into p_T slices. Data events are in the left column and MC events are in the right column. η distributions for SC events are compared to η distributions of re-weighted OC events in p_T slices used in the charge-flip rate measurement.

D Closure test for the 1D×1D charge-flip rate parametrization

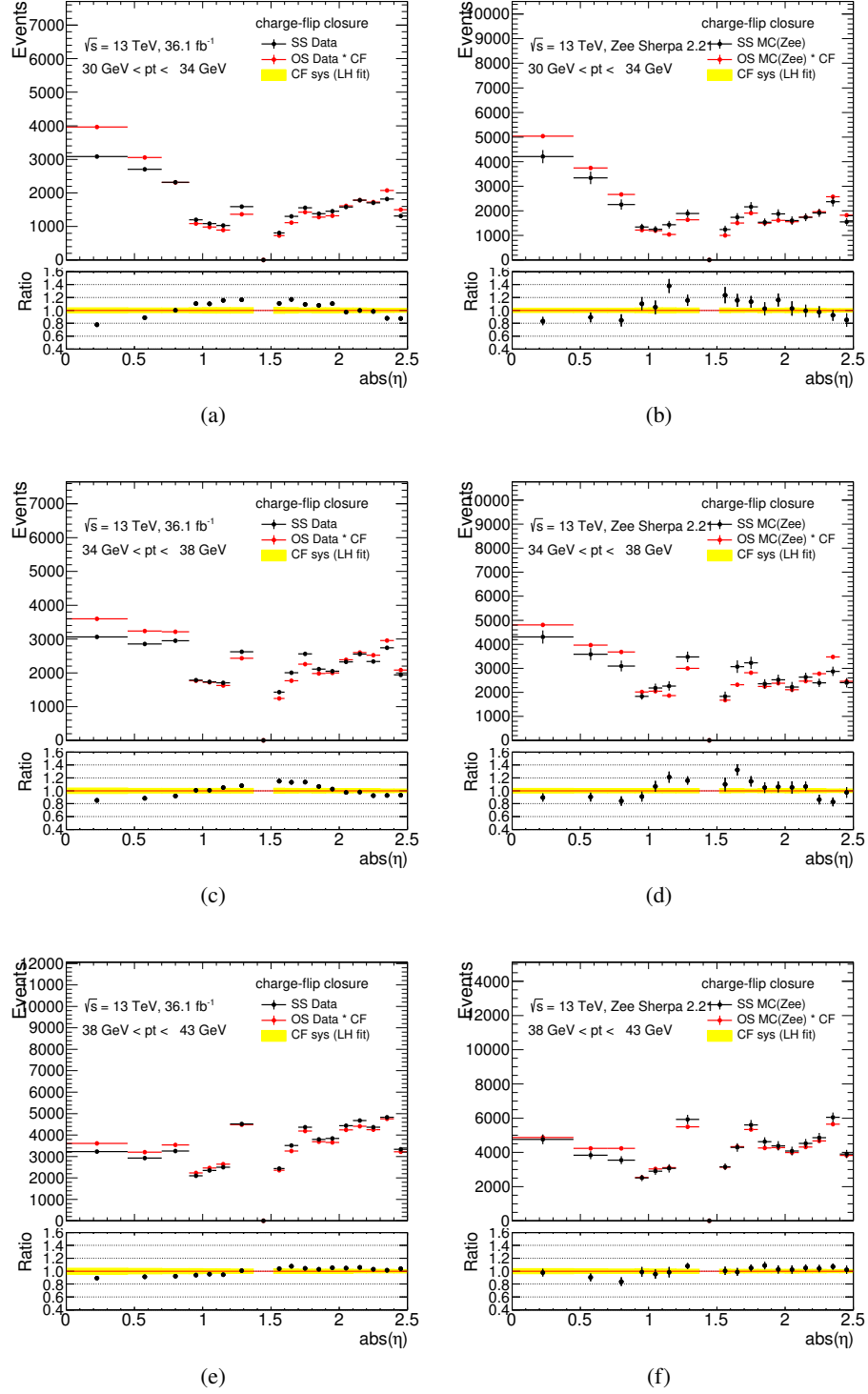


Figure D.2: Closure test for the 1D×1D charge-flip rate parametrization in data and MC, split into p_T slices. Data events are in the left column and MC events are in the right column. η distributions for SC events are compared to η distributions of re-weighted OC events in p_T slices used in the charge-flip rate measurement.

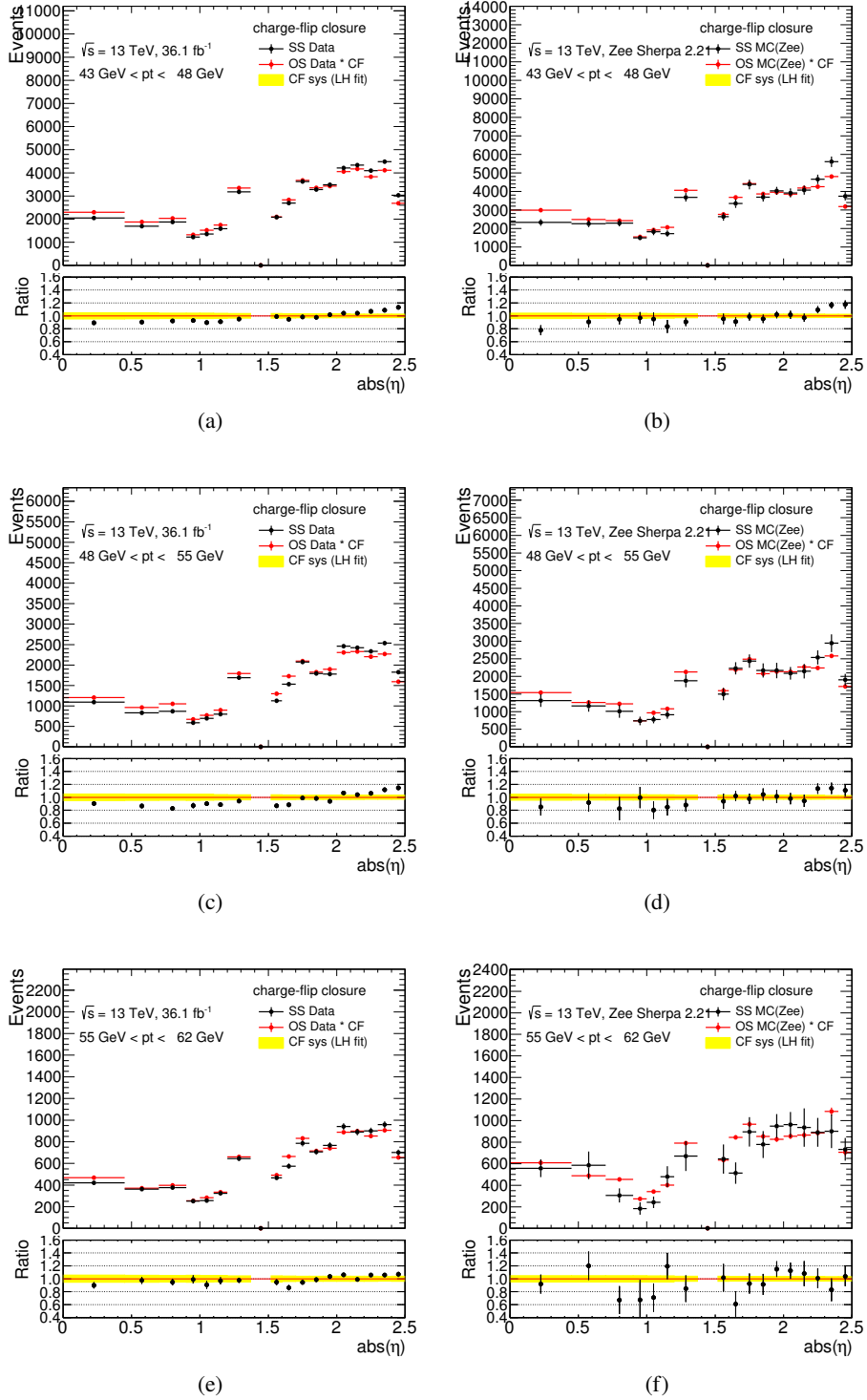


Figure D.3: Closure test for the 1D×1D charge-flip rate parametrization in data and MC, split into p_T slices. Data events are in the left column and MC events are in the right column. η distributions for SC events are compared to η distributions of re-weighted OC events in p_T slices used in the charge-flip rate measurement.

D Closure test for the 1D×1D charge-flip rate parametrization

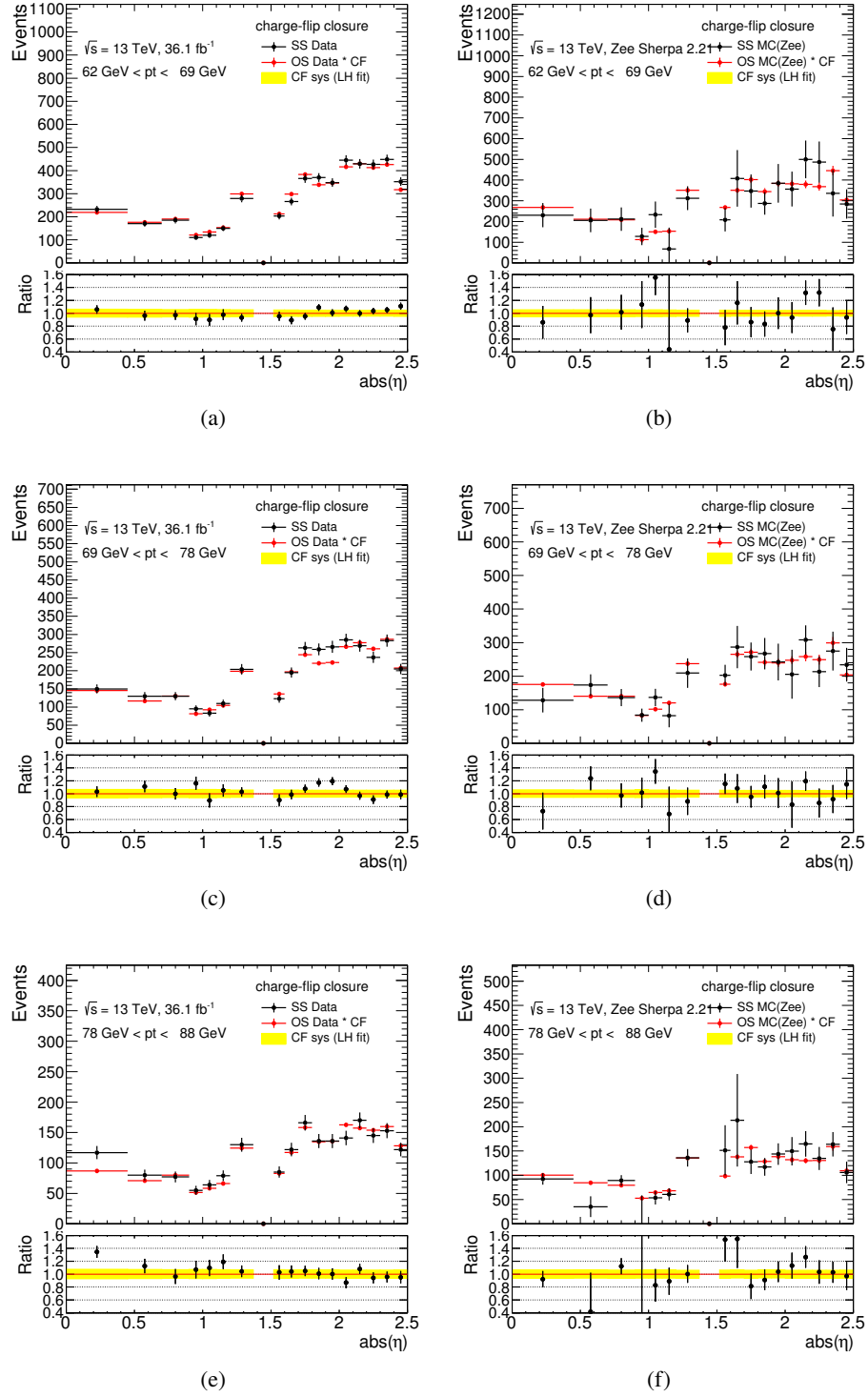


Figure D.4: Closure test for the 1D×1D charge-flip rate parametrization in data and MC, split into p_T slices. Data events are in the left column and MC events are in the right column. η distributions for SC events are compared to η distributions of re-weighted OC events in p_T slices used in the charge-flip rate measurement.

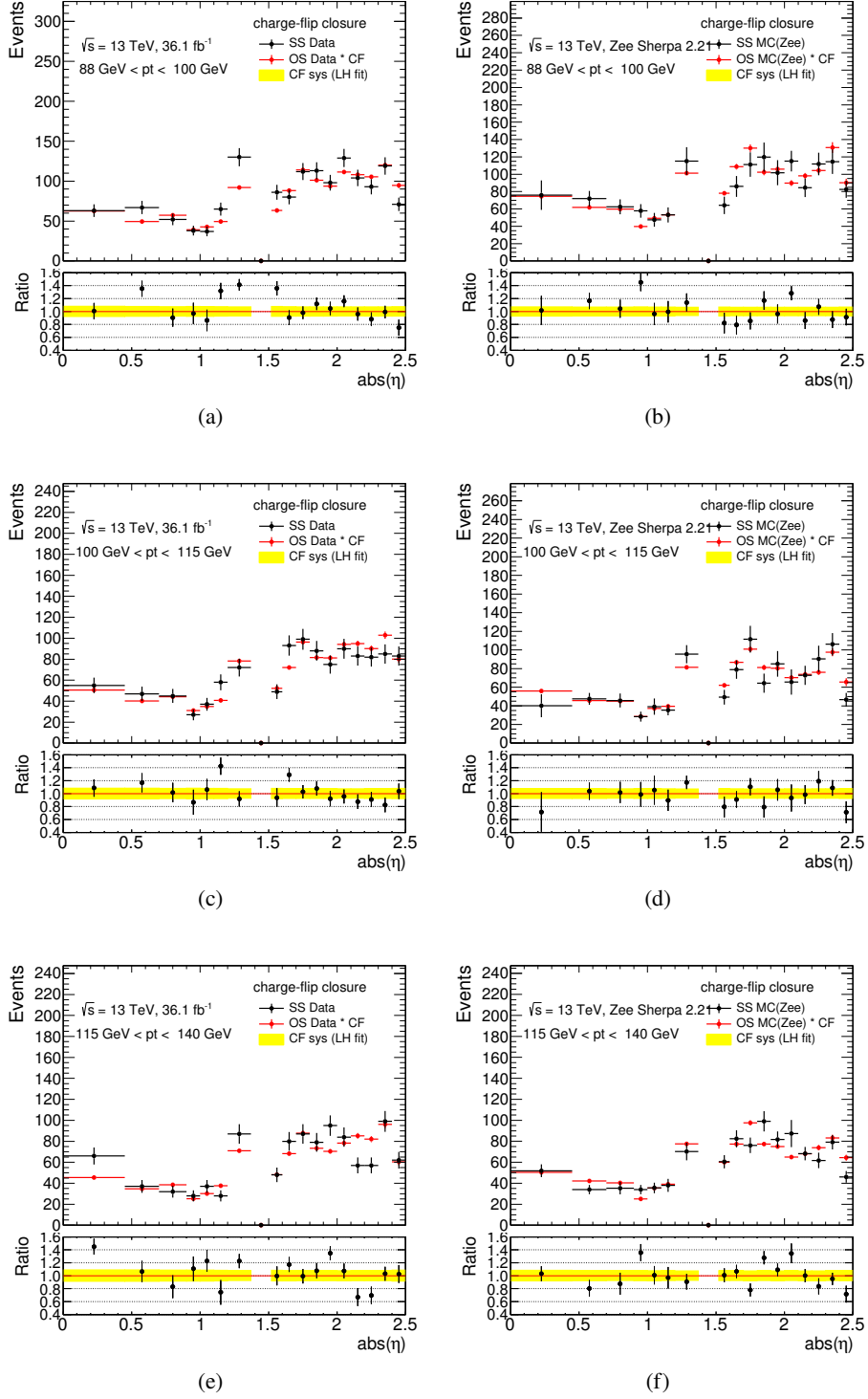


Figure D.5: Closure test for the 1D×1D charge-flip rate parametrization in data and MC, split into p_T slices. Data events are in the left column and MC events are in the right column. η distributions for SC events are compared to η distributions of re-weighted OC events in p_T slices used in the charge-flip rate measurement.

E Matrix Method and the Fake Factor method

The Matrix Method is presented in this section for the case of two leptons in the event. Furthermore, the Fake Factor method is derived from the Matrix Method and the equivalence between the two methods is shown. It is trivial to extend the Fake Factor method to any number of leptons in the event.

E.1 The Matrix Method

The matrix method is based upon loosening certain identification criteria applied in the nominal selection to assess the probability of looser objects passing the nominal selection. This allows us to probe the transfer rate of looser fake leptons into the nominal selection. Two different selection criteria are defined in the matrix method:

- The tight selection (same as the nominal selection)
- The loose selection

The tight selection should be the same as the nominal analysis selection. By definition, the set of objects passing the tight selection N_{tight} must be a subset of those passing the loose selection N_{loose} , as schematically portrayed on Fig. E.1. Practically, this can be achieved by loosening some of the tight selection requirements (e.g. the lepton identification level or the lepton isolation level).

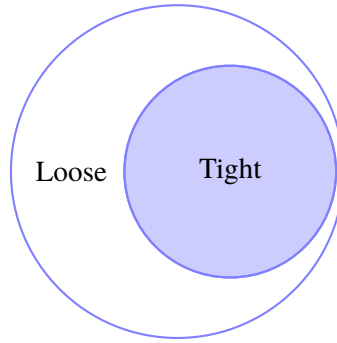


Figure E.1: The loose and the tight regions in the matrix method. The tight region must be a subset of the loose region (i.e. tight leptons should also pass all of the loose requirements).

The matrix method links the number of real and fake objects to the number of tight and loose objects. In a two lepton analysis, all of the possible combinations of lepton candidates are denoted by N_{xy} with $x, y \in R, F$. The index R refers to real leptons and the index F stands for fake leptons. The

first index represents the first object and the second index the second object (without a particular p_T ordering). Both real and fake objects are required to at least pass the loose selection criteria to be considered by the matrix method. They can then yield four kinds of pairs: pairs with two tight objects, pairs with two strictly loose objects, and pairs with one tight and one strictly loose object. Strictly loose objects are objects that pass the loose criteria and fail the tight criteria. To avoid the confusion with the previously defined loose objects, let's symbolize them by L' . The numbers of each of those events are then denoted by N_{xy} with $x, y \in T, L'$. The transfer matrix between the number of real and fake leptons and the number of tight and strictly loose objects is shown in Equation E.1:

$$\begin{pmatrix} N_{TT} \\ N_{TL'} \\ N_{L'T} \\ N_{L'L'} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}, \quad (\text{E.1})$$

where r_1 and r_2 are respectively the real rates for the first and the second real leptons and f_1 and f_2 are the fake rates for the first and the second fake leptons. The real (fake) rate is defined as the probability that a real (fake) lepton, that passes the loose selection criteria, also passes the tight selection criteria. They can be obtained by measuring the number of loose and the number of tight objects, as shown in Equation E.2:

$$r = \frac{N_{\text{tight}}^{\text{real}}}{N_{\text{loose}}^{\text{real}}}, \quad f = \frac{N_{\text{tight}}^{\text{fake}}}{N_{\text{loose}}^{\text{fake}}}. \quad (\text{E.2})$$

The rates are the crucial part of the matrix method. The whole idea of the matrix method is that given the rates, we can invert the matrix shown in Equation E.1 and deduce the number of events that pass the nominal selection of the analysis (N_{TT}) caused by pairs of lepton candidates with at least one of them being a fake lepton. The rates are usually determined in a data-driven approach by measuring them in a region, dominated by real (fake) leptons, and then extrapolating them into the signal region. The contribution of pairs with at least one fake lepton to the nominal selection, expressed in the notation of the matrix method is shown in Equation E.3.

$$N_{TT}^{\text{fakes}} = r f (N_{RF} + N_{FR}) + f^2 N_{FF} \quad (\text{E.3})$$

The Equation E.3 covers all of the possible sources of fake leptons to the nominal di-lepton selection. However, it depends on inaccessible truth quantities which can not be measured. By inverting the matrix in Equation E.1 those quantities can be expressed by measurable numbers of different kinds of pairs ($N_{TT}, N_{TL'}, \dots$). The inverted matrix is shown in Equation E.4.

$$\begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix} = \frac{1}{(r-f)^2} \begin{pmatrix} (1-f)^2 & (f-1)f & f(f-1) & f^2 \\ (f-1)(1-r) & (1-f)r & f(1-r) & -rf \\ (r-1)(1-f) & (1-r)f & r(1-f) & -rf \\ (1-r)^2 & (r-1)r & r(r-1) & r^2 \end{pmatrix} \begin{pmatrix} N_{TT} \\ N_{TL'} \\ N_{L'T} \\ N_{L'L'} \end{pmatrix} \quad (\text{E.4})$$

The combined contribution of fake leptons to the nominal di-lepton selection is then given by

$$N_{TT}^{\text{fakes}} = \alpha[2rf(f-1)(1-r) + f^2(1-r)^2]N_{TT} + \alpha(1-f)fr^2(N_{TL'} + N_{L'T}) - \alpha r^2 f^2 N_{L'L'}, \quad (\text{E.5})$$

where $\alpha = 1/(r-f)^2$.

E.2 The Fake Factor Method

The fake factor method is derived from the matrix method by making an approximation that the real rate equals to 1 ($r = 1$). To demonstrate this, lets rewrite the Equation E.5 with operators A , B , and C :

$$N_{TT}^{\text{fakes}} = AN_{TT} + B(N_{TL'} + N_{L'T}) + CN_{L'L'}, \quad (\text{E.6})$$

where $A = \alpha[2rf(f-1)(1-r) + f^2(1-r)^2]$, $B = \alpha(1-f)fr^2$, and $C = -\alpha r^2 f^2$. By assuming the real rate equals to 1, the operator A becomes equal to 0. With definition of the *fake factor*

$$F = \frac{f}{1-f} \quad (\text{E.7})$$

the total contribution of fake leptons to the nominal selection can be expressed as seen in Equation E.8.

$$N_{TT}^{\text{fakes (FF)}} = F(N_{TL'} + N_{L'T}) - F^2 N_{L'L'} \quad (\text{E.8})$$

However, the fake factor formula is just an approximation, which doesn't hold for realistic values of r . We can precisely calculate the error of the fake factor formula by comparing Equation E.8 to the exact fake background in Equation E.3. On the contrary, the matrix method formula in Equation E.6 reproduces the fake background in Equation E.3 by construct. Starting with the fake factor formula and replacing $N_{TL'}$, $N_{L'T}$, and $N_{L'L'}$ with the exact expressions from Equation E.1 we get:

$$N_{TT}^{\text{fakes (FF)}} = \frac{f}{1-f}r(1-r)N_{RR} + \frac{f}{1-f}r(1-f)N_{RF} + \frac{f}{1-f}f(1-r)N_{FR} + \frac{f}{1-f}f(1-f)N_{FF} + \frac{f}{1-f}(1-r)rN_{RR} + \frac{f}{1-f}(1-r)fN_{RF} + \frac{f}{1-f}(1-f)rN_{FR} + \frac{f}{1-f}(1-f)fN_{FF} - \frac{f^2}{(1-f)^2}(1-r)^2N_{RR} - \frac{f^2}{(1-f)^2}(1-r)(1-f)N_{RF} - \frac{f^2}{(1-f)^2}(1-f)(1-r)N_{FR} - \frac{f^2}{(1-f)^2}(1-f)^2N_{FF} \quad (\text{E.9})$$

Simplifying Equation E.9 yields to:

$$N_{TT}^{\text{fakes (FF)}} = \frac{f(1-r)}{(1-f)} \frac{2r-fr-f}{1-f} N_{RR} + rf(N_{RF} + N_{FR}) + f^2 N_{FF} \quad (\text{E.10})$$

Astonishingly, we can see that the last three terms in Equation E.10 correspond exactly to the true fake background contribution in Equation E.3. The only difference is the contribution from sources with two real leptons, which is clearly wrong as lepton pairs with two real leptons shouldn't contribute to the fake background. This can be easily fixed using Monte Carlo to estimate the number of real leptons (N_{RR}) in all the strictly loose regions ($N_{TL'}$, $N_{L'T}$, and $N_{L'L'}$) and subtracting them, as shown in Equation E.11. This is also the final fake factor formula which is used in the analysis.

$$N_{TT}^{\text{fakes}} = (F(N_{TL'} + N_{L'T}) - F^2 N_{L'L'})_{\text{data}} - (F(N_{TL'} + N_{L'T}) - F^2 N_{L'L'})_{N_{RR} \text{ from MC}} \quad (\text{E.11})$$

The equation can be generalized by separating the fake factor into two different fake factors F_1 and F_2 , respectively for the first and the second lepton candidate. Furthermore, we can acknowledge that the fake factor is not a constant and should be evaluated for each lepton candidate separately and rewrite the Equation E.11 with a sum over all the lepton pairs. Equation E.12 is more representative for the fake factor method and is used in several other searches as well (e.g. [208], [180]).

$$N_{TT}^{\text{fakes}} = \left[\sum_{N_{TL'}} F_2 + \sum_{N_{L'T}} F_1 - \sum_{N_{L'L'}} F_1 F_2 \right]_{\text{data}} - \left[\sum_{N_{TL'}} F_2 + \sum_{N_{L'T}} F_1 - \sum_{N_{L'L'}} F_1 F_2 \right]_{N_{RR} \text{ from MC}} \quad (\text{E.12})$$

To conclude, the fake factor method is convenient because the real rate does not have to be obtained from the data, but is effectively evaluated using prompt only Monte Carlo. Furthermore, the loose selection criteria from the matrix method does not have to be defined in the fake factor method. Instead, the "strictly loose" region is defined directly. The strictly loose and the tight regions are usually named the denominator and the numerator region in the fake factor method. It is important to note that the denominator and numerator regions must be mutually exclusive by construction.

- Denominator $\Leftrightarrow$ strictly loose (pass loose criteria and fail tight criteria)
- Numerator $\Leftrightarrow$ tight

The fake factor can then be measured by observing the ratio of Numerator to Denominator objects in a fake enriched sample, similarly to the fake rate in Equation E.2.

$$F = \frac{f}{1-f} = \frac{N_{\text{tight}}^{\text{fake}}}{N_{\text{loose-tight}}^{\text{fake}}} = \frac{N_{\text{num}}^{\text{fake}}}{N_{\text{den}}^{\text{fake}}} \quad (\text{E.13})$$

F Detailed distributions of the $H^{\pm\pm}$ search analysis regions

F.1 Diboson Control Region (DBCR)

The diboson control regions are used in the $H^{\pm\pm}$ search to constrain the diboson background model in the fit used in the final hypothesis test. Plots for the electron channel are illustrated in Figures [F.1](#) and [F.2](#). Distributions for the mixed channel are shown in Figures [F.3](#) and [F.4](#) and muon DBCR distributions are shown in Figures [F.5](#) and [F.6](#). Furthermore, a four lepton diboson control region (4LCR) is used to constrain the diboson normalization for the four lepton signal region (2P4L) and the corresponding distributions are presented in Figures [F.7](#) and [F.8](#).

F.1.1 Electron Channel DBCR plots

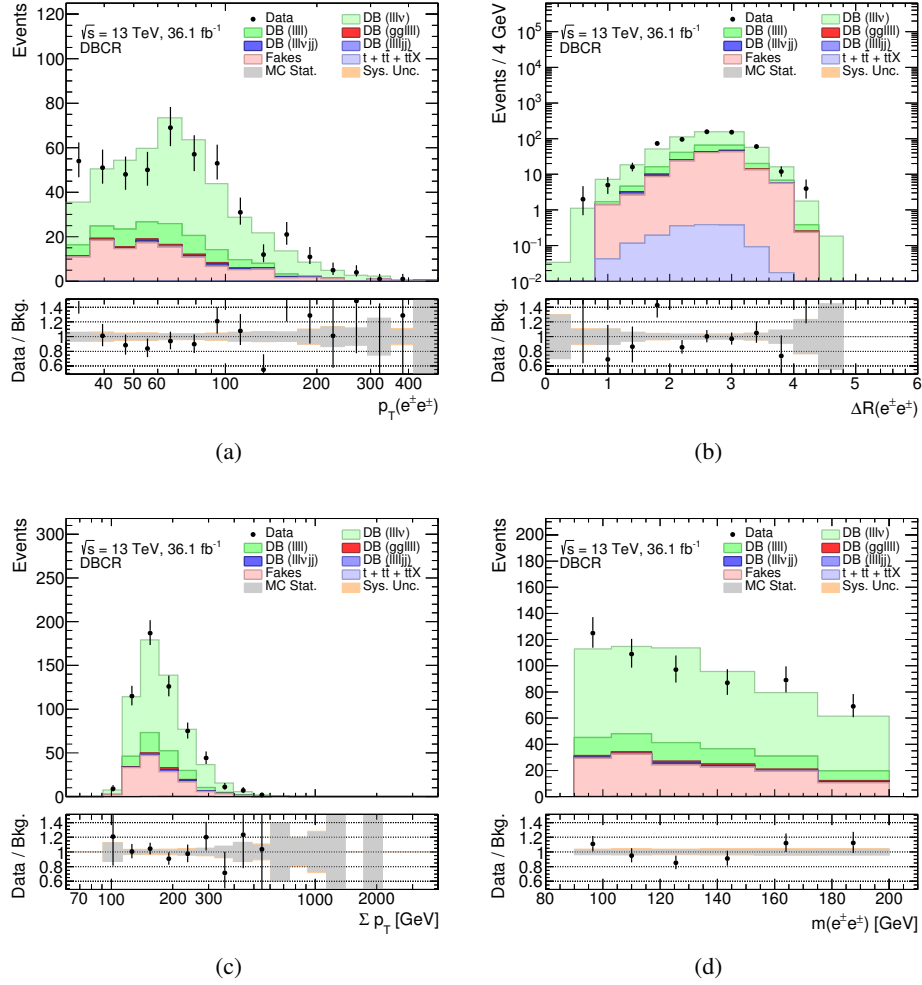


Figure F.1: Pre-fit event distributions in the diboson control region of the electron channel: (a) $p_T(e^{\pm}, e^{\pm})$ of the same-sign electrons, (b) $\Delta R(e^{\pm}, e^{\pm})$ separation of the same-sign electrons, (c) $\Sigma |p_T|$ distribution of all electrons in the event (d) and invariant mass $m(e^{\pm}, e^{\pm})$ of the same-sign electron pair.

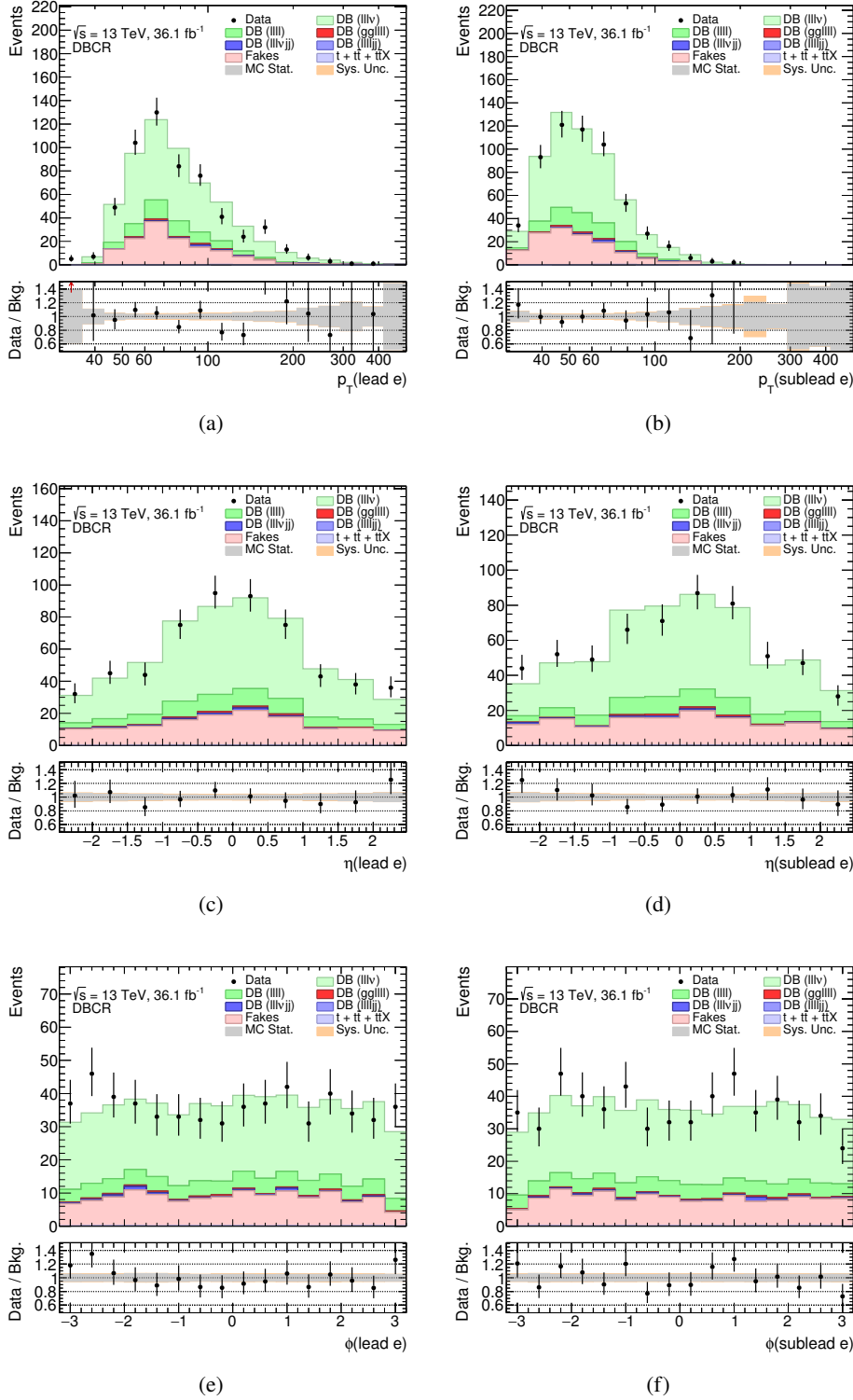


Figure F.2: Pre-fit kinematic distributions in the diboson control region of the electron channel referred to the electrons in the same-sign pair: (a) p_T distribution of the leading electron, (b) p_T distribution of the sub-leading electron, (c) η distribution of the leading electron, (d) η distribution of the sub-leading electron, (e) ϕ distribution of the leading electron (f) and ϕ distribution of the sub-leading electron.

F.1.2 Mixed Channel DBCR plots

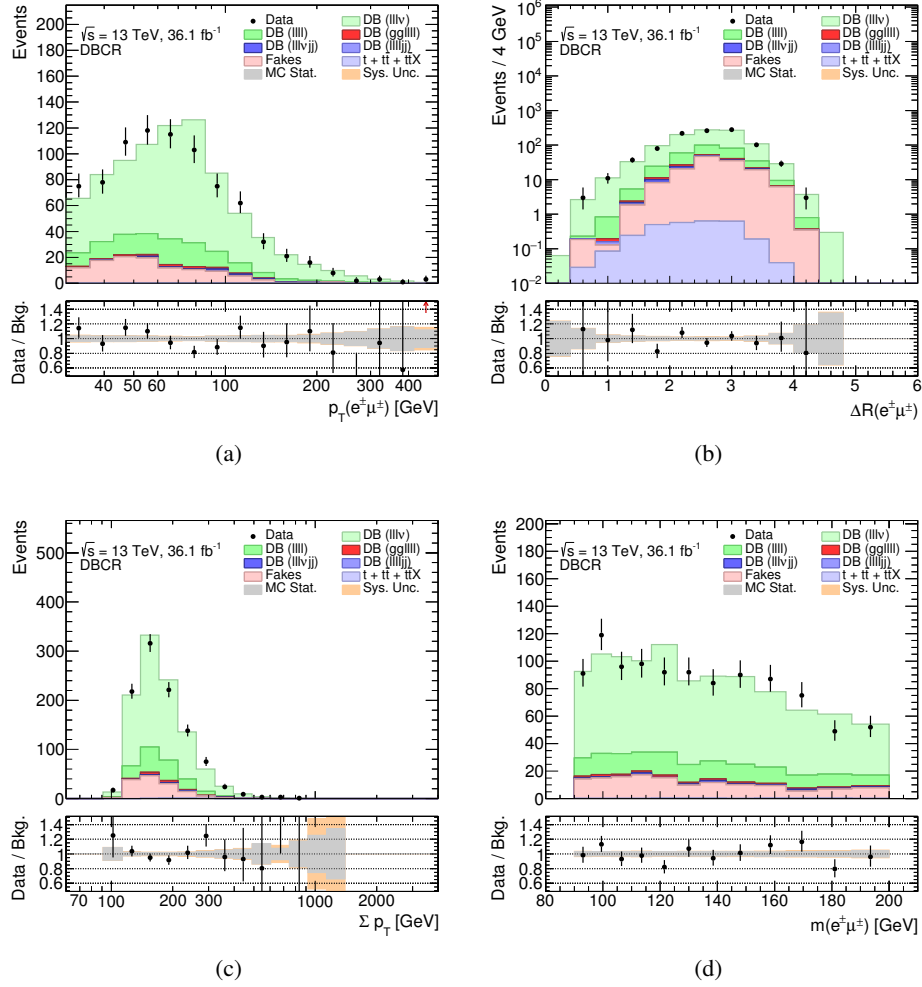


Figure F.3: Pre-fit event distributions in the diboson control region of the mixed channel: (a) $p_T(e^+, \mu^+)$ of the same-sign leptons, (b) $\Delta R(e^+, \mu^+)$ separation of the same-sign leptons, (c) $\sum |p_T|$ distribution of all leptons in the event (d) and invariant mass $m(e^+, \mu^+)$ of the same-sign lepton pair.

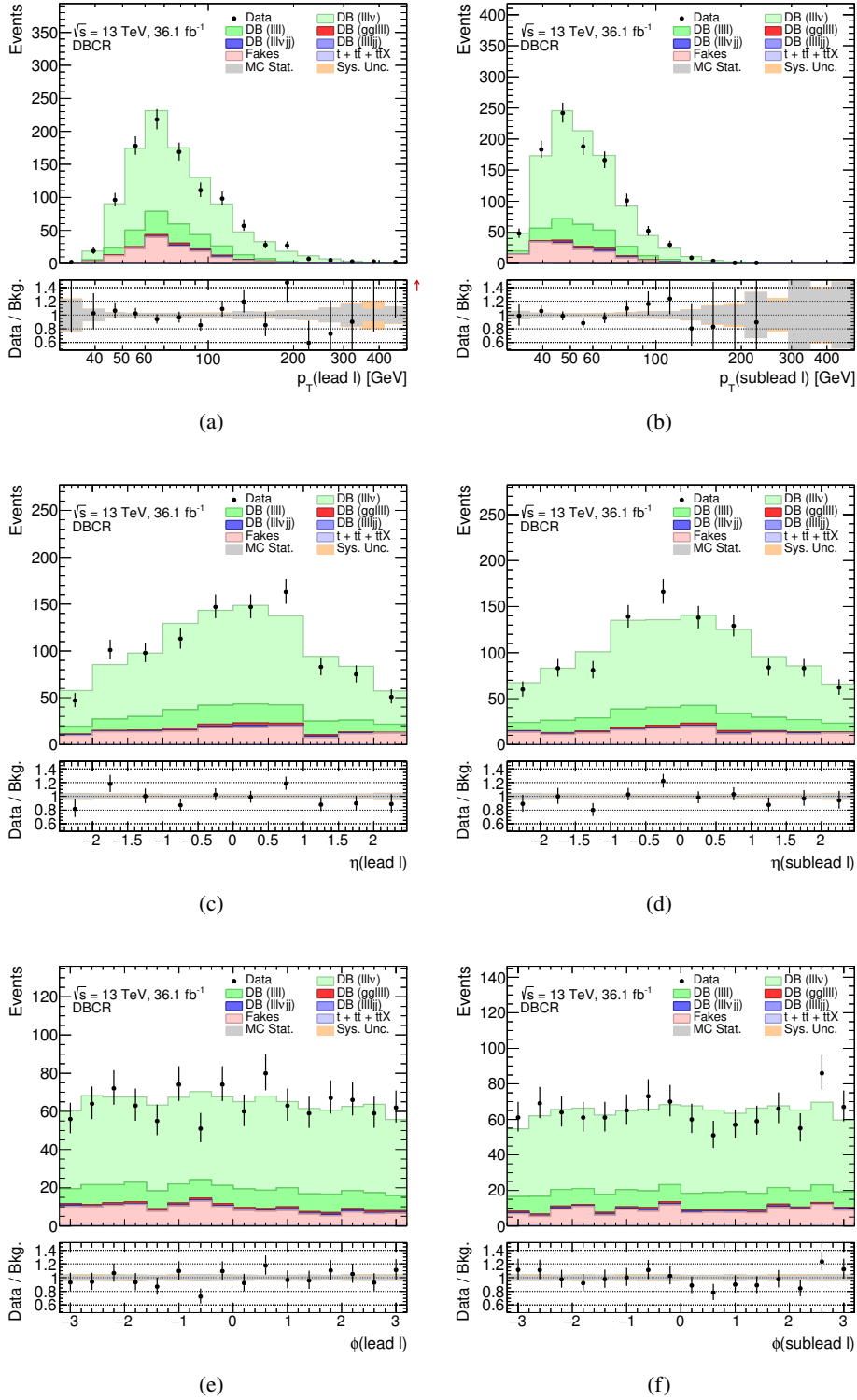


Figure F.4: Pre-fit kinematic distributions in the diboson control region of the mixed channel referred to the leptons in the same-sign pair: (a) p_T distribution of the leading lepton, (b) p_T distribution of the sub-leading lepton, (c) η distribution of the leading lepton, (d) η distribution of the sub-leading lepton, (e) ϕ distribution of the leading lepton (f) and ϕ distribution of the sub-leading lepton.

F.1.3 Muon Channel DBCR plots

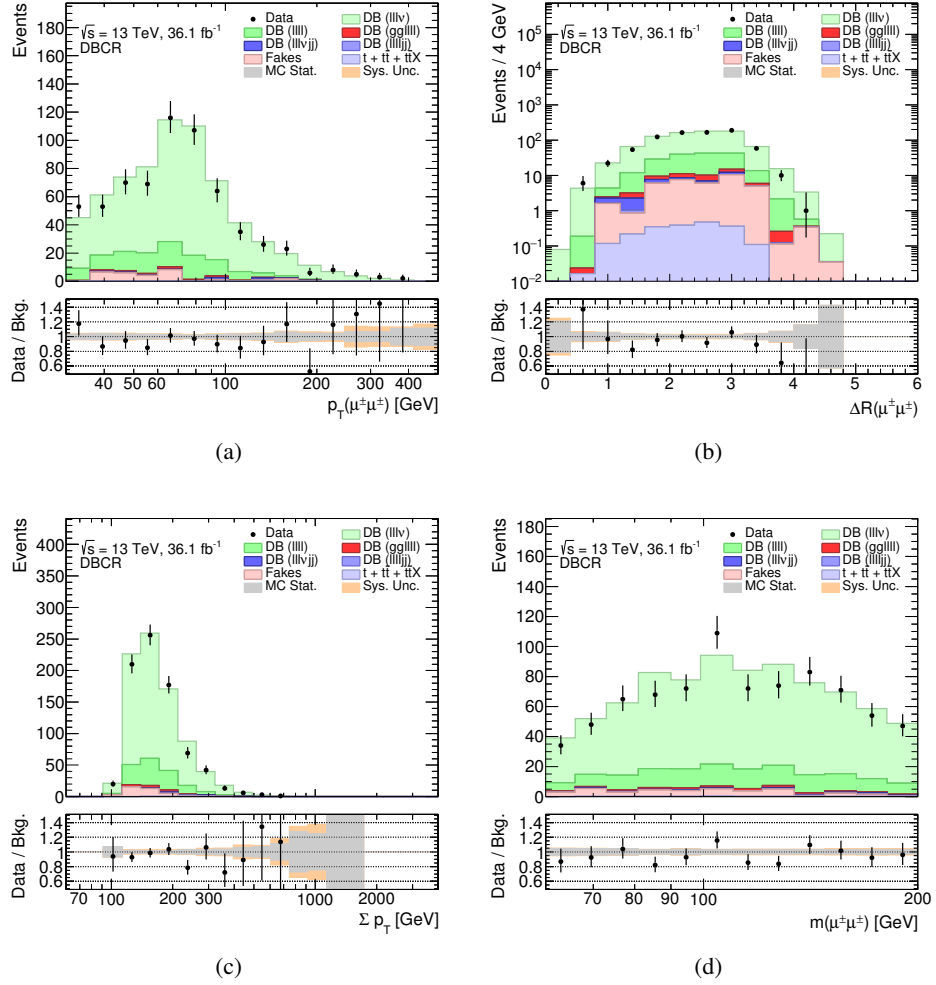


Figure F.5: Pre-fit event distributions in the diboson control region of the muon channel: (a) $p_T(\mu^{\pm}, \mu^{\pm})$ of the same-sign muons, (b) $\Delta R(\mu^{\pm}, \mu^{\pm})$ separation of the same-sign muons, (c) $\sum |p_T|$ distribution of all muons in the event (d) and invariant mass $m(\mu^{\pm}, \mu^{\pm})$ of the same-sign muon pair.

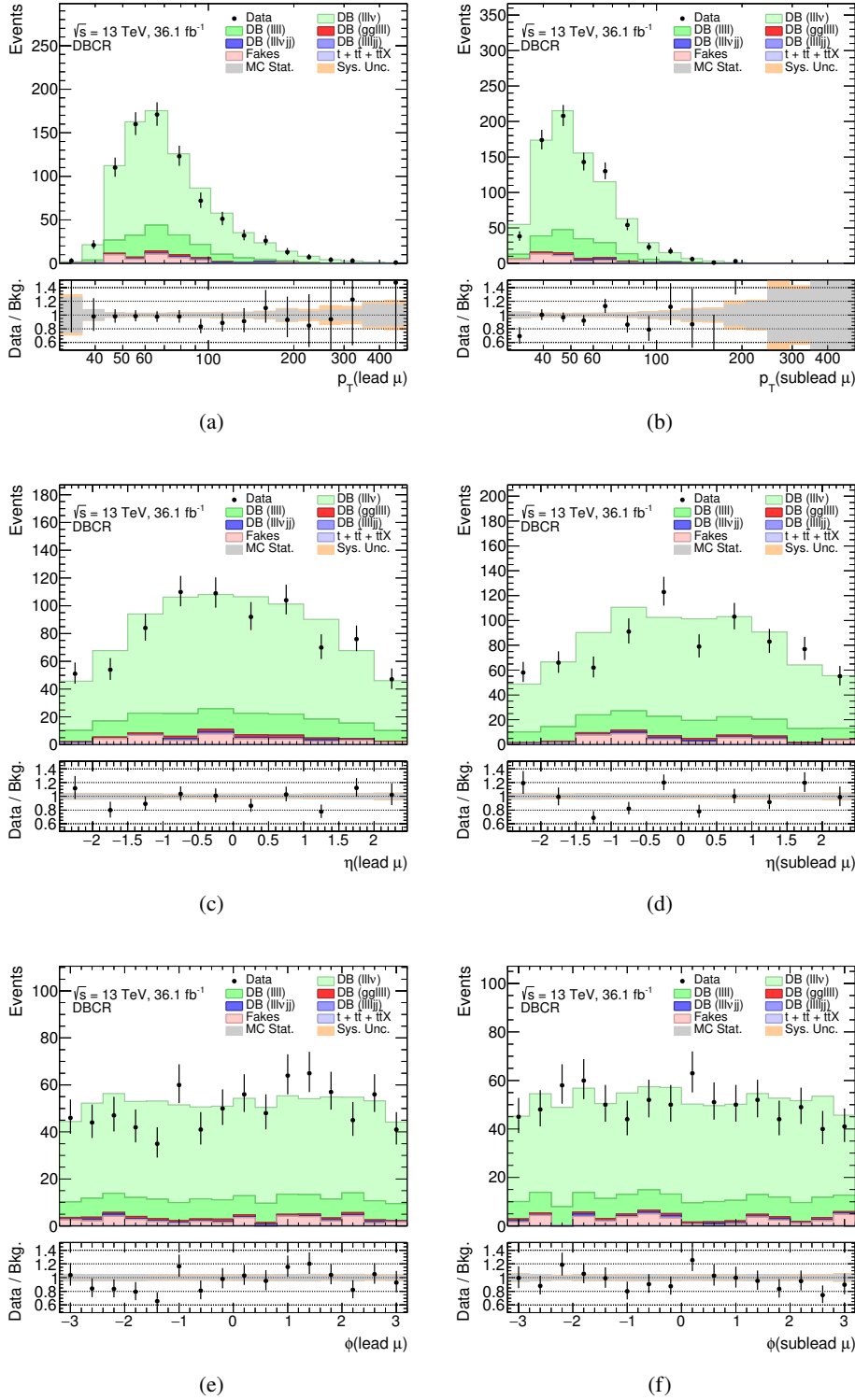


Figure F.6: Pre-fit kinematic distributions in the diboson control region of the muon channel referred to the muons in the same-sign pair: (a) p_T distribution of the leading muon, (b) p_T distribution of the sub-leading muon, (c) η distribution of the leading muon, (d) η distribution of the sub-leading muon, (e) ϕ distribution of the leading muon (f) and ϕ distribution of the sub-leading muon.

F.1.4 Four Lepton Channel DBCR plots

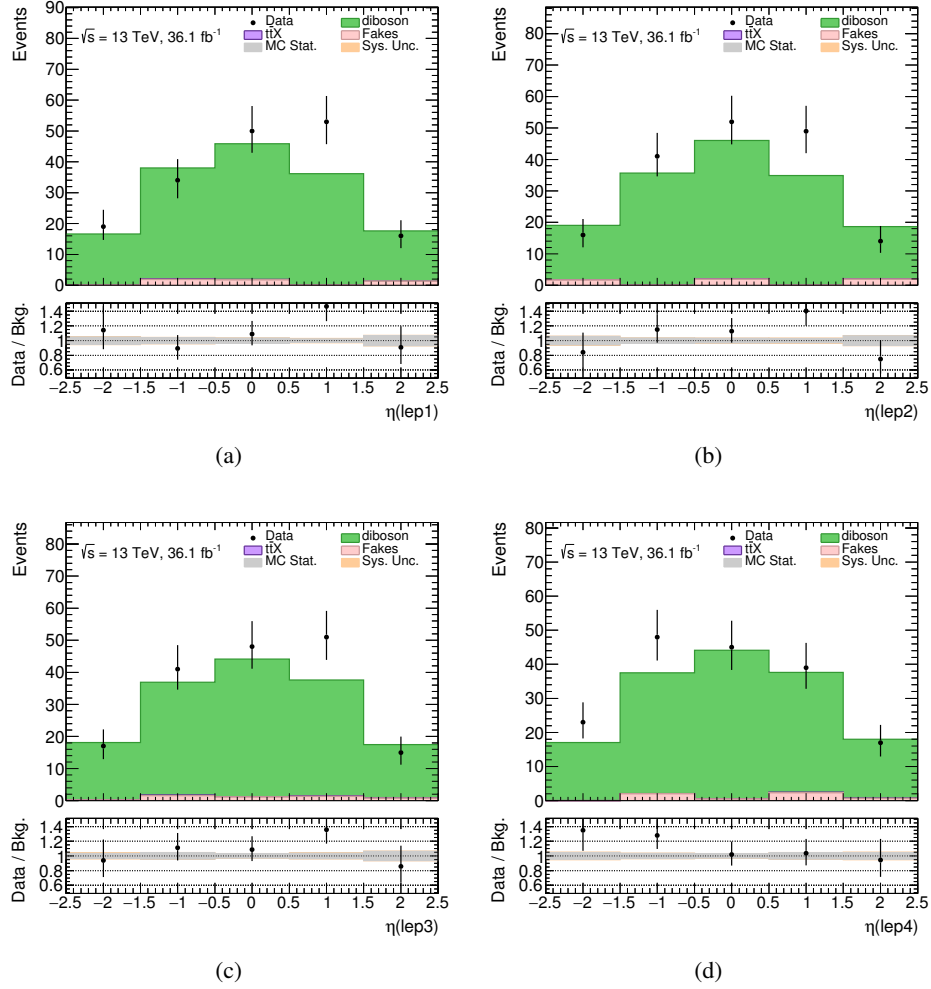


Figure F.7: Pre-fit η distributions in the four lepton diboson control region.

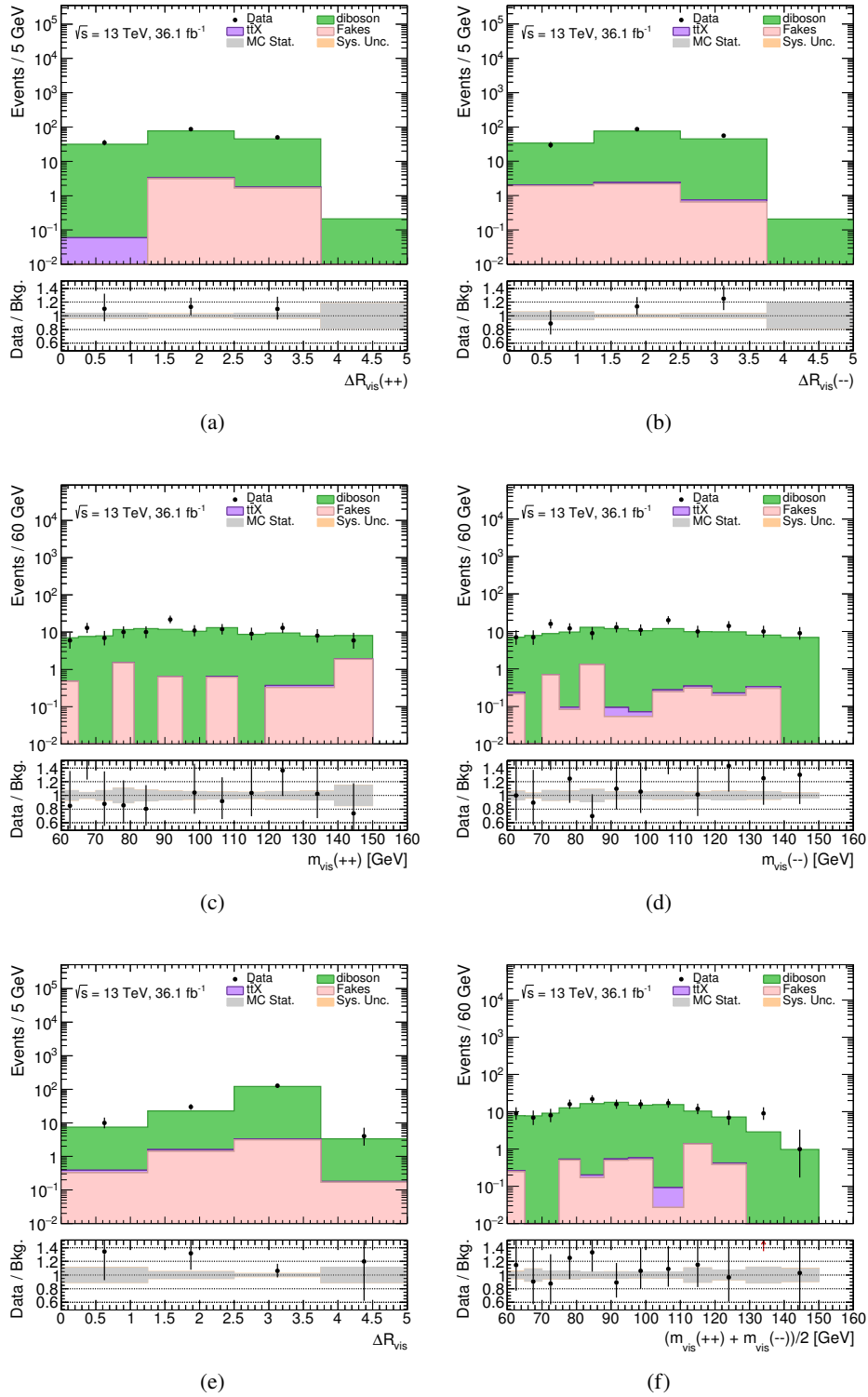


Figure F.8: Pre-fit event distributions in the four lepton diboson control region: (a) ΔR for the positive couple, (b) ΔR for the negative couple, (c) invariant mass of the positive couple, (d) invariant mass of the negative couple, (e) ΔR between the two couples and (f) mean mass of the two same-sign couples.

F.2 Opposite-charge Control Region (OCCR)

The opposite-charge control region (OCCR) is used to constrain the $Z \rightarrow ee$ background which is contaminating the signal region of the electrons channel due to the charge-flip process. Distributions are shown in the electron channel in Figures F.9 and F.10.

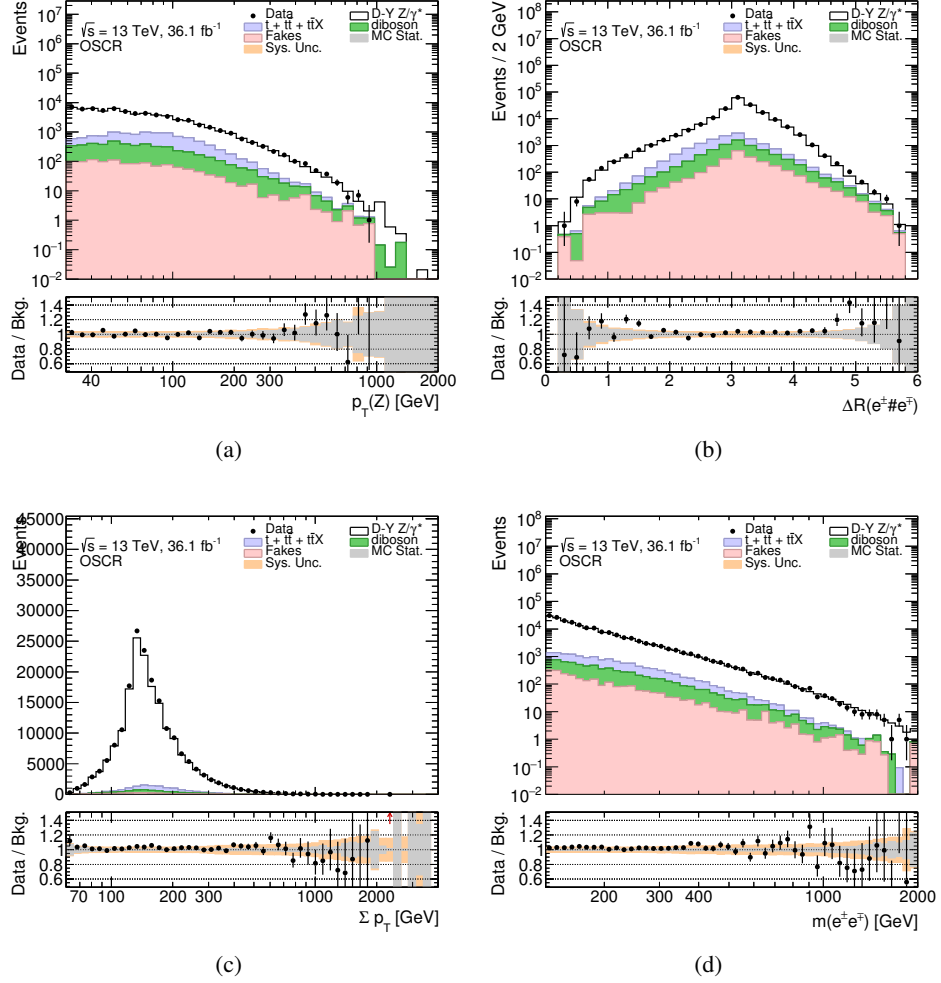


Figure F.9: Pre-fit event distributions in the diboson control region of the electron channel: (a) $p_T(e^\pm, e^\pm)$ of the same-sign electrons, (b) $\Delta R(e^\pm, e^\pm)$ separation of the same-sign electrons, (c) $\sum |p_T|$ distribution of all electrons in the event (d) and invariant mass $m(e^\pm, e^\pm)$ of the same-sign electron pair.

F.2 Opposite-charge Control Region (OCCR)

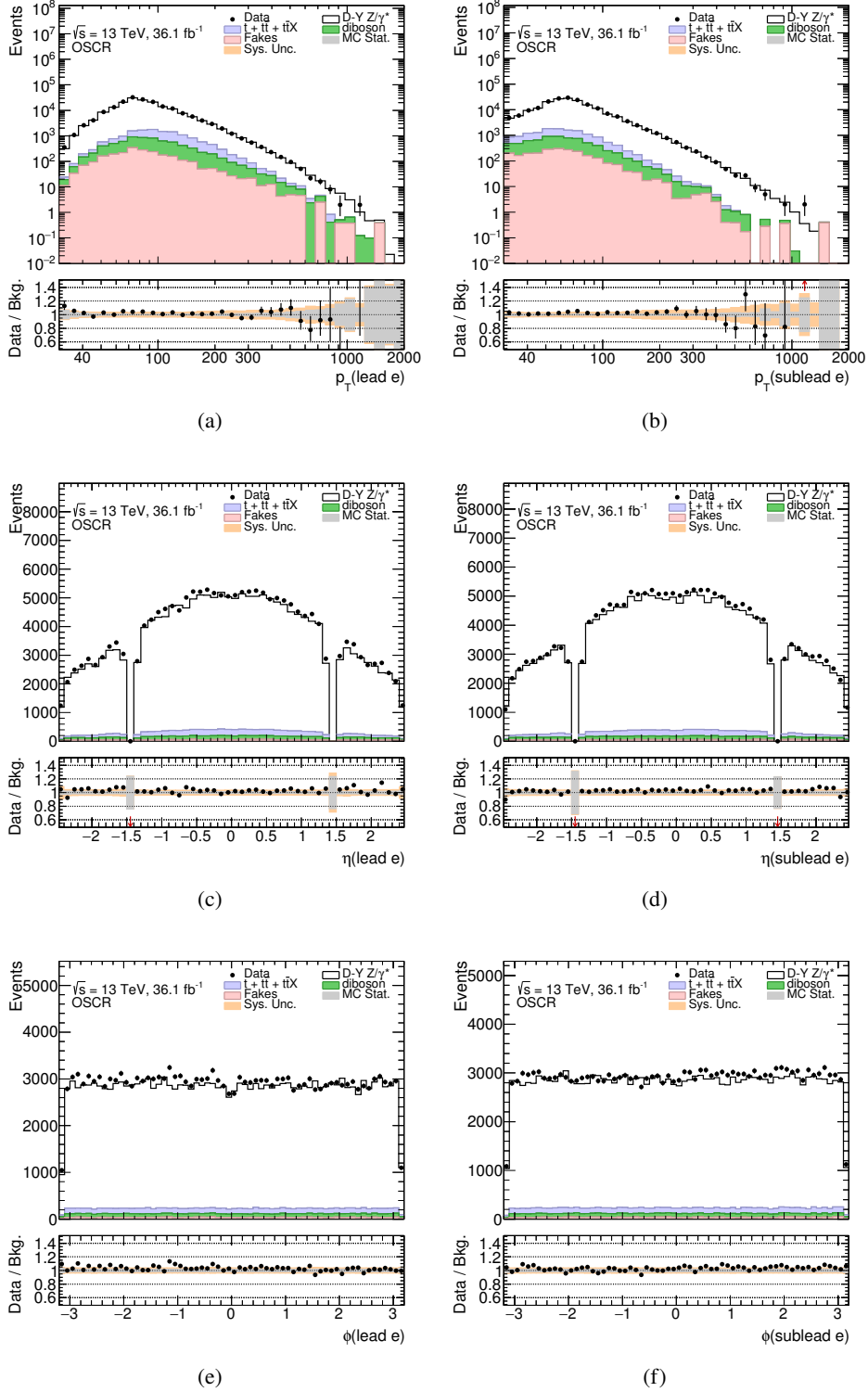


Figure F.10: Pre-fit kinematic distributions in the diboson control region of the electron channel referred to the electrons in the same-sign pair: (a) p_T distribution of the leading electron, (b) p_T distribution of the sub-leading electron, (c) η distribution of the leading electron, (d) η distribution of the sub-leading electron, (e) ϕ distribution of the leading electron (f) and ϕ distribution of the sub-leading electron.

F.3 Same-charge Validation Region (SCVR)

The purpose of SCVRs is to validate the fake estimation, outlined in Section 7.2.1, and diboson background in events with two leptons. In the electron channel, the SCVR is also used to test the model of the charge-flip background mostly due to $Z \rightarrow ee$ events. Distributions in this region for the electron channel are shown in Figures F.11 and F.12. Distributions in the mixed channel are reported in Figures F.13 and F.14 and the corresponding ones of the muon channel are presented in Figures F.15 and F.16.

F.3.1 Electron Channel SCVR plots

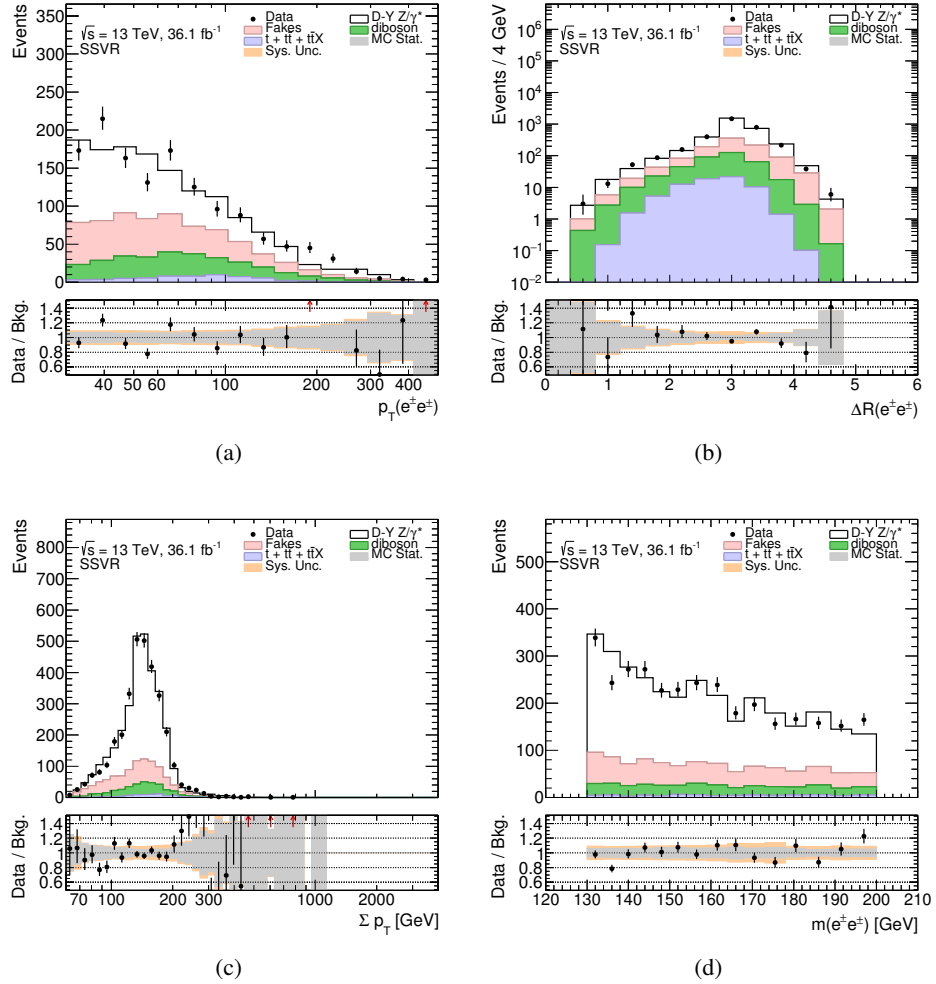


Figure F.11: Event distributions in the same-sign validation region of the electron channel: (a) $p_T(e^{\pm}, e^{\pm})$ of the same-sign electrons, (b) $\Delta R(e^{\pm}, e^{\pm})$ separation of the same-sign electrons, (c) $\sum |p_T|$ distribution of all electrons in the event (d) and invariant mass $m(e^{\pm}, e^{\pm})$ of the same-sign electron pair.

F.3 Same-charge Validation Region (SCVR)

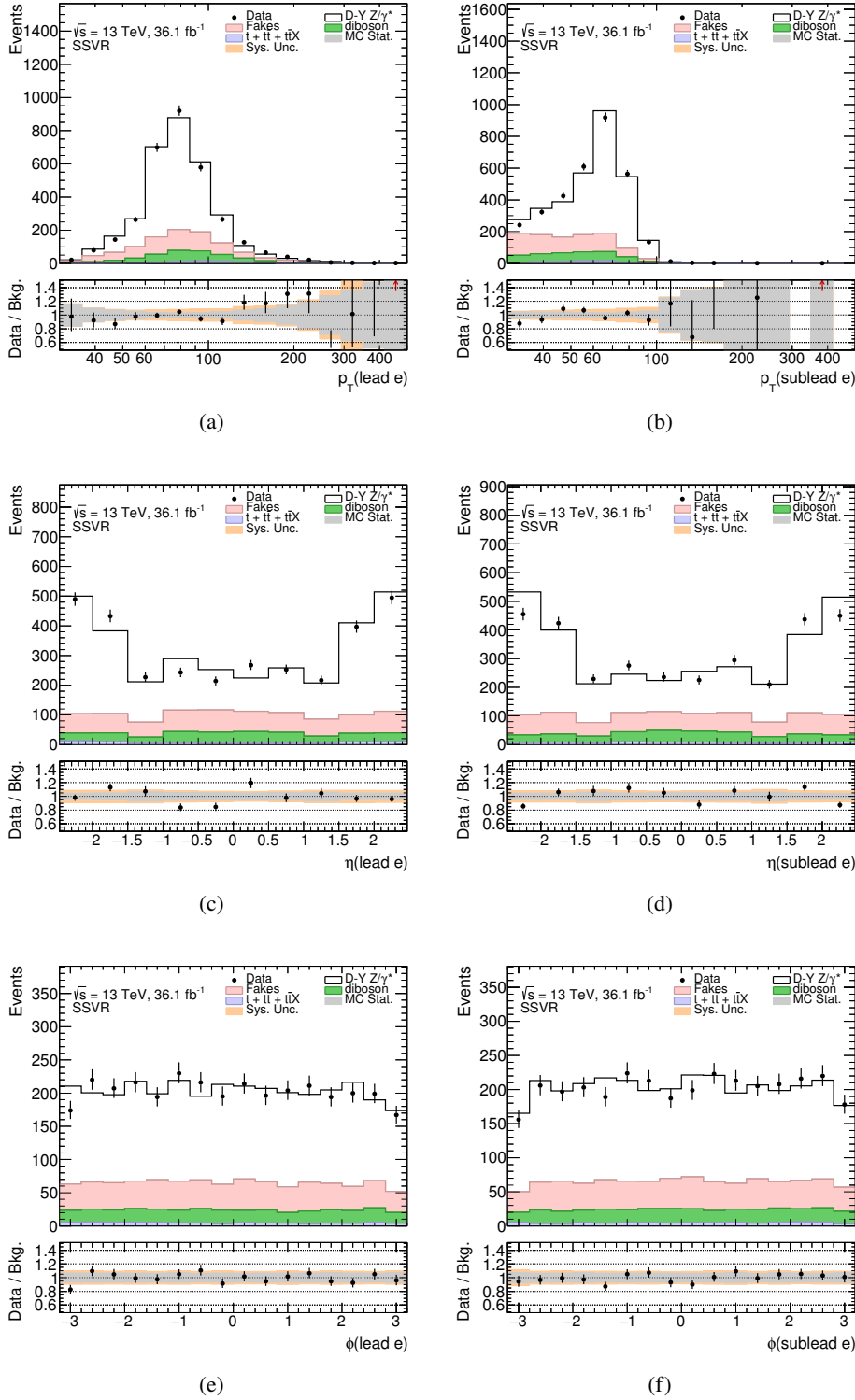


Figure F.12: Kinematic distributions in the same-sign validation region of the electron channel: (a) p_T distribution of the leading electron, (b) p_T distribution of the sub-leading electron, (c) η distribution of the leading electron, (d) η distribution of the sub-leading electron, (e) ϕ distribution of the leading electron (f) ϕ distribution of the sub-leading electron.

F.3.2 Mixed Channel SCVR plots

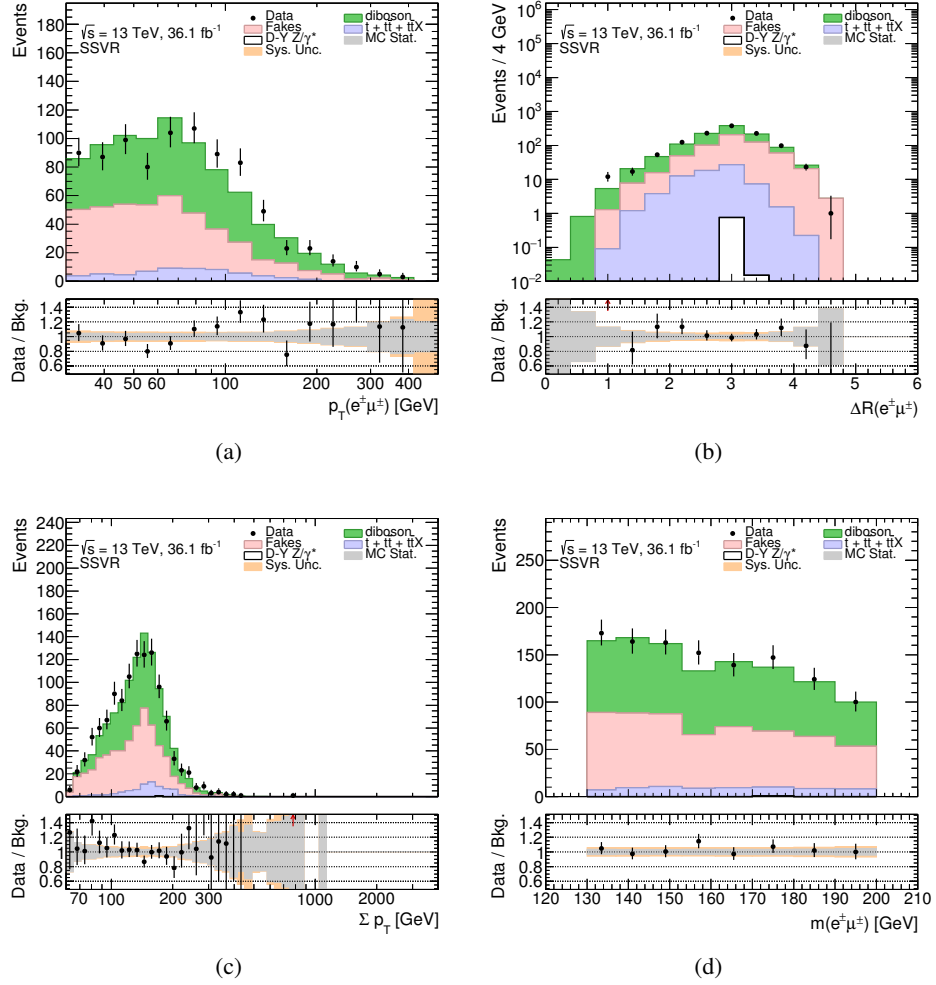


Figure F.13: Event distributions in the same-sign validation region of the mixed channel: (a) $p_T(e^{\pm}, \mu^{\pm})$ of the same-sign leptons, (b) $\Delta R(e^{\pm}, \mu^{\pm})$ separation of the same-sign leptons, (c) $\sum |p_T|$ distribution of all leptons in the event (d) and invariant mass $m(e^{\pm}, \mu^{\pm})$ of the same-sign lepton pair.

F.3 Same-charge Validation Region (SCVR)

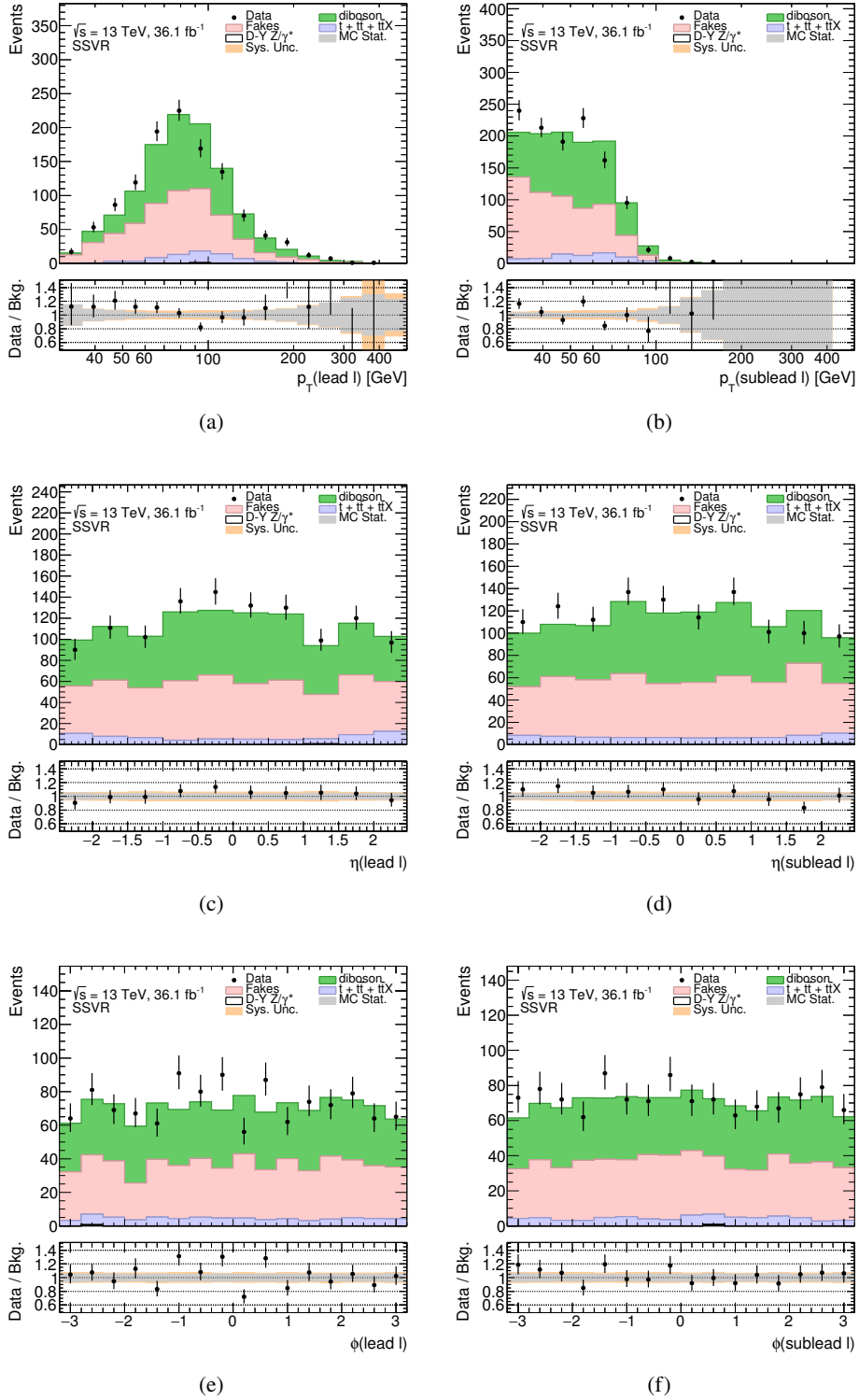


Figure F.14: Kinematic distributions in the same-sign validation region of the mixed channel: (a) p_T distribution of the leading lepton, (b) p_T distribution of the sub-leading lepton, (c) η distribution of the leading lepton, (d) η distribution of the sub-leading lepton, (e) ϕ distribution of the leading lepton (f) and ϕ distribution of the sub-leading lepton.

F.3.3 Muon Channel SCVR plots

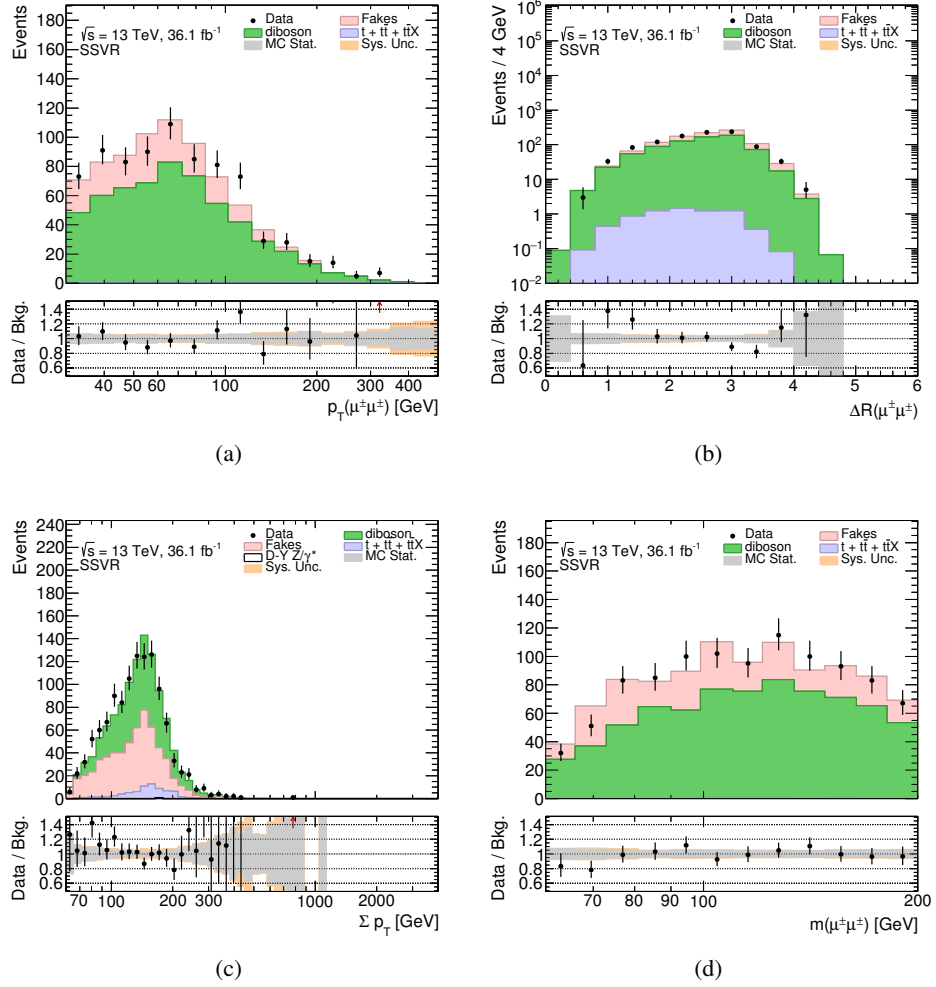


Figure F.15: Event distributions in the same-sign validation region of the muon channel: (a) $p_T(\mu^\pm, \mu^\pm)$ of the same-sign muons, (b) $\Delta R(\mu^\pm, \mu^\pm)$ separation of the same-sign muons, (c) $\sum |p_T|$ distribution of all muons in the event (d) and invariant mass $m(\mu^\pm, \mu^\pm)$ of the same-sign muon pair.

F.3 Same-charge Validation Region (SCVR)

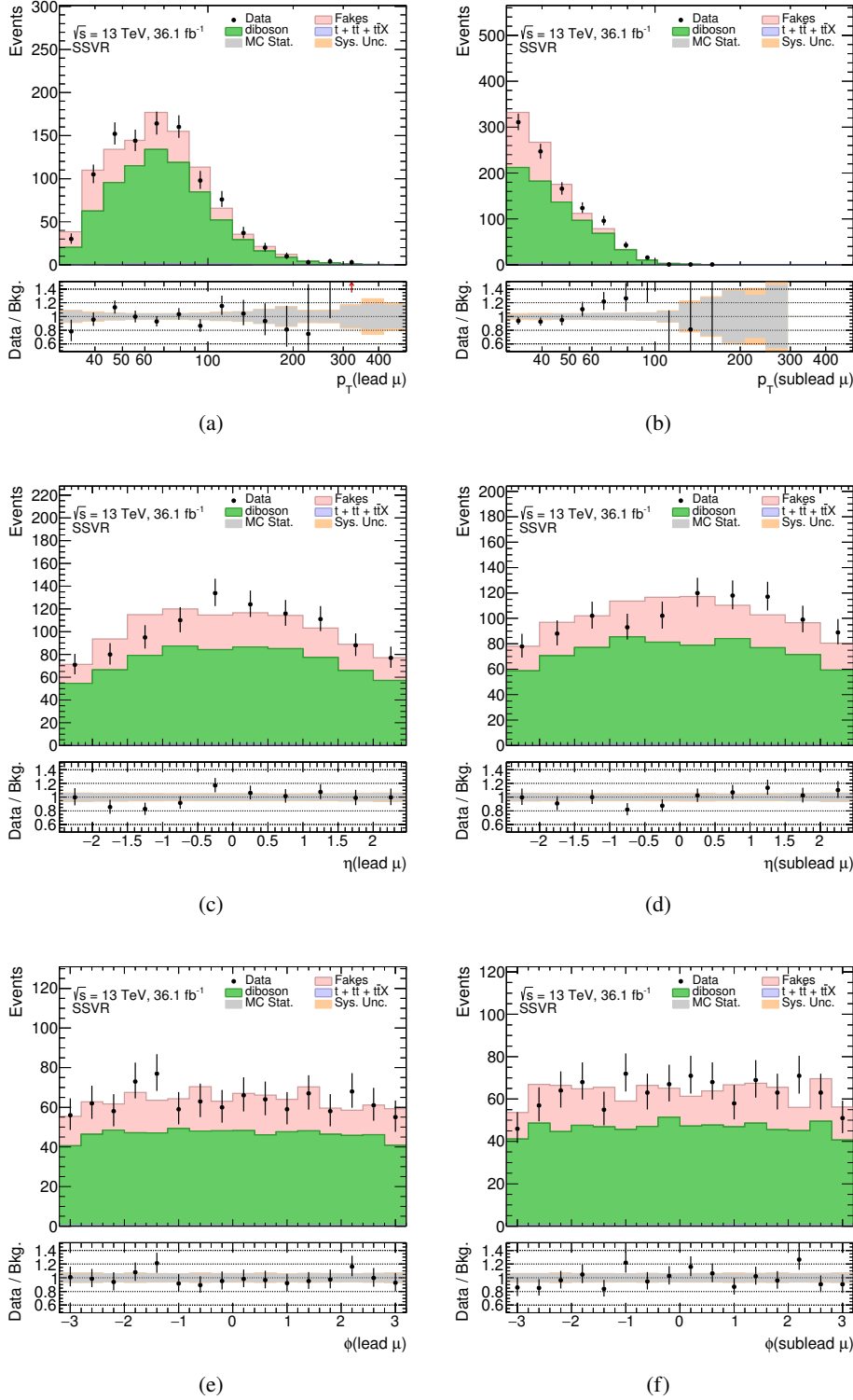


Figure F.16: Kinematic distributions in the same-sign validation region of the muon channel: (a) p_T distribution of the leading muon, (b) p_T distribution of the sub-leading muon, (c) η distribution of the leading muon, (d) η distribution of the sub-leading muon, (e) ϕ distribution of the leading muon (f) and ϕ distribution of the sub-leading muon.

F.4 Three-leptons Validation Region (3LVR)

The three lepton validation region 3LVR is defined to test the modeling of the diboson background in events with three leptons. Distributions in this region for the electron channel are reported in Figures F.17 and F.18. Distributions in the mixed channel are illustrated in Figures F.19 and F.20 and the muon channel distributions are shown in Figures F.21 and F.22.

F.4.1 Electron Channel 3LVR plots

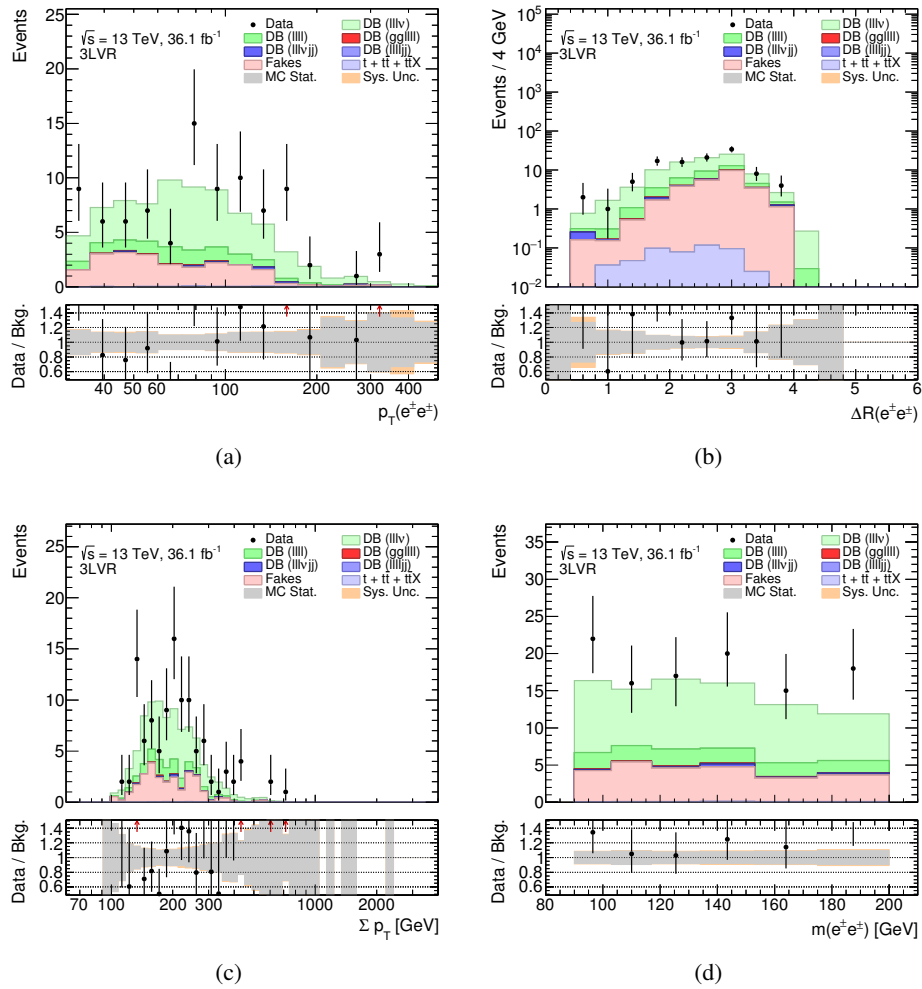


Figure F.17: Event distributions in the three lepton validation region of the mixed channel: (a) $p_T(e^{\pm}, e^{\pm})$ of the same-sign electrons, (b) $\Delta R(e^{\pm}, e^{\pm})$ separation of the same-sign electrons, (c) $\sum |p_T|$ distribution of all electrons in the event (d) and invariant mass $m(e^{\pm}, e^{\pm})$ of the same-sign electron pair.

F.4 Three-leptons Validation Region (3LVR)

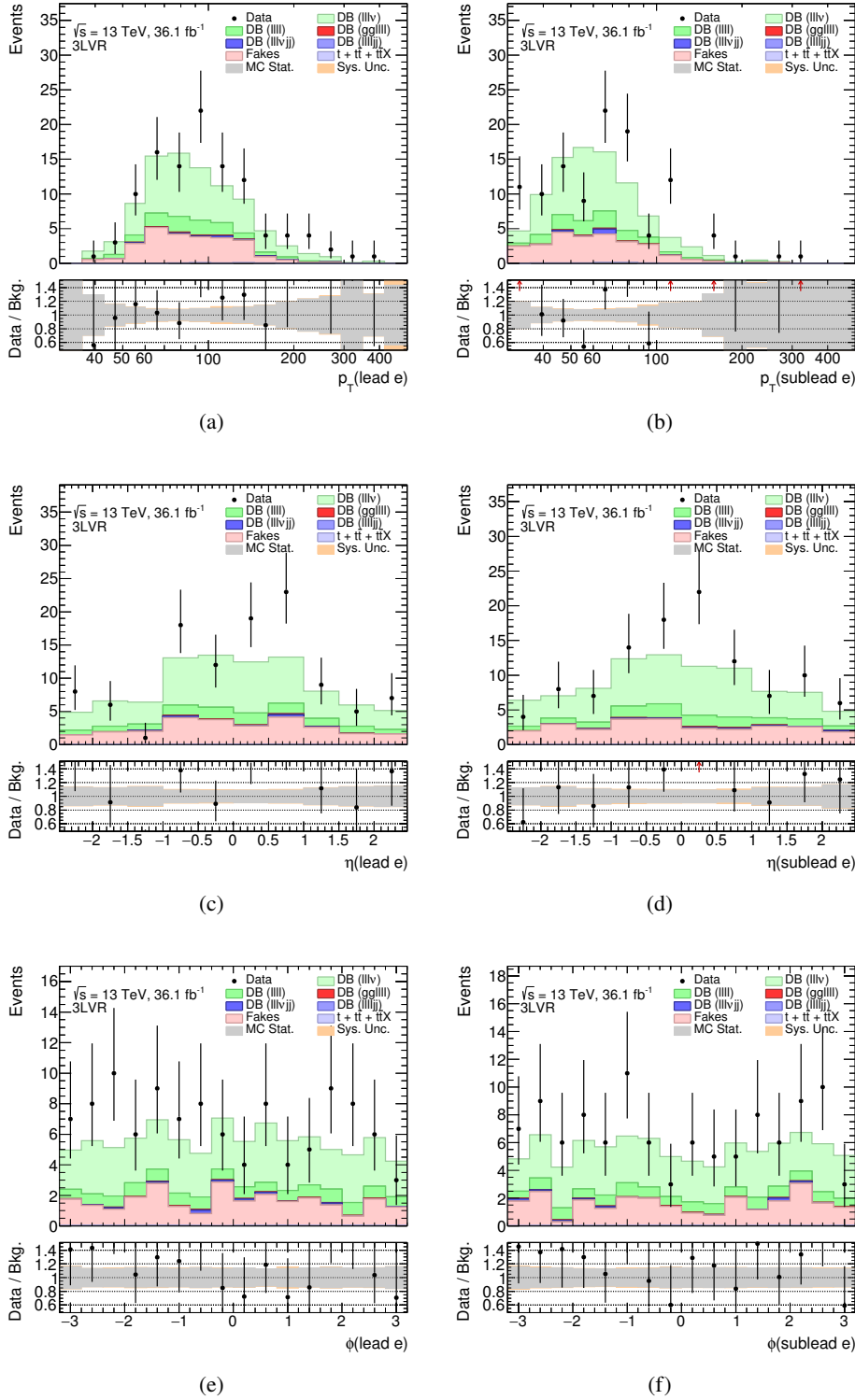


Figure F.18: Kinematic distributions in the three-lepton validation region of the mixed channel referred to the electrons in the same-sign pair: (a) p_T distribution of the leading electron, (b) p_T distribution of the sub-leading electron, (c) η distribution of the leading electron, (d) η distribution of the sub-leading electron, (e) ϕ distribution of the leading electron (f) and ϕ distribution of the sub-leading electron.

F.4.2 Mixed Channel 3LVR plots

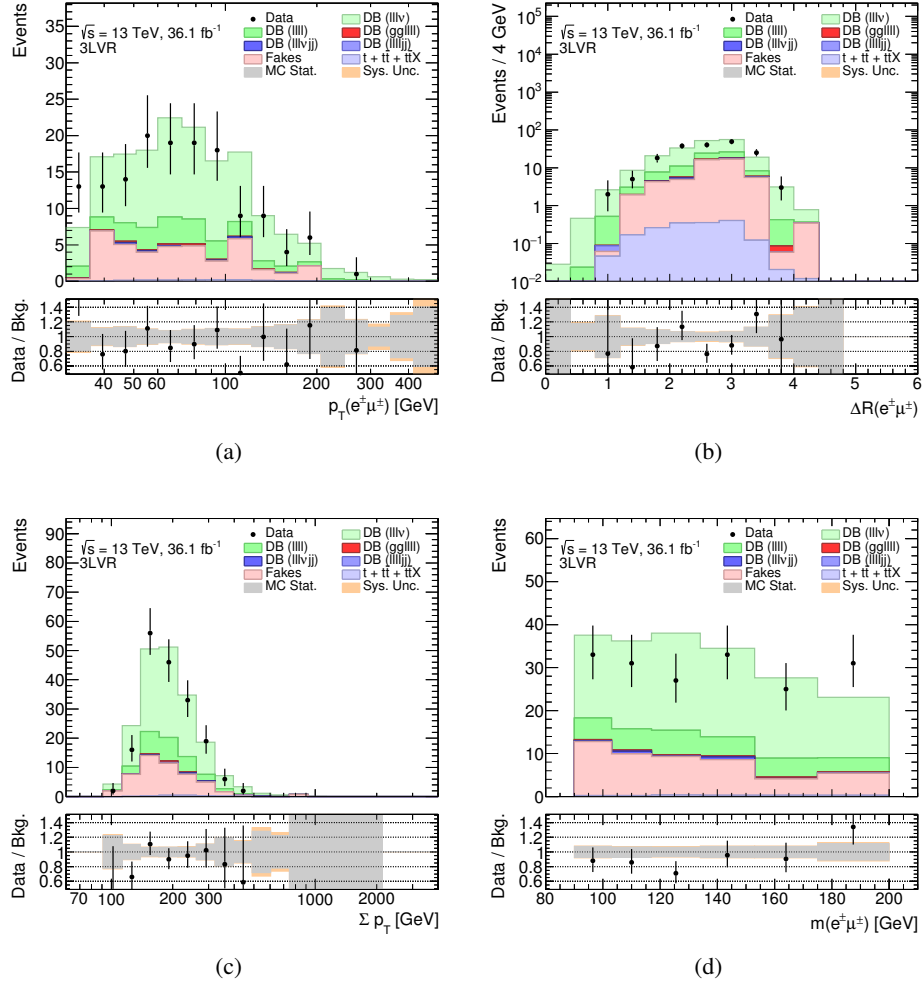


Figure F.19: Event distributions in the three lepton validation region of the mixed channel: (a) $p_T(e^\pm, \mu^\pm)$ of the same-sign leptons, (b) $\Delta R(e^\pm, \mu^\pm)$ separation of the same-sign leptons, (c) $\sum |p_T|$ distribution of all leptons in the event (d) and invariant mass $m(e^\pm, \mu^\pm)$ of the same-sign lepton pair.

F.4 Three-leptons Validation Region (3LVR)

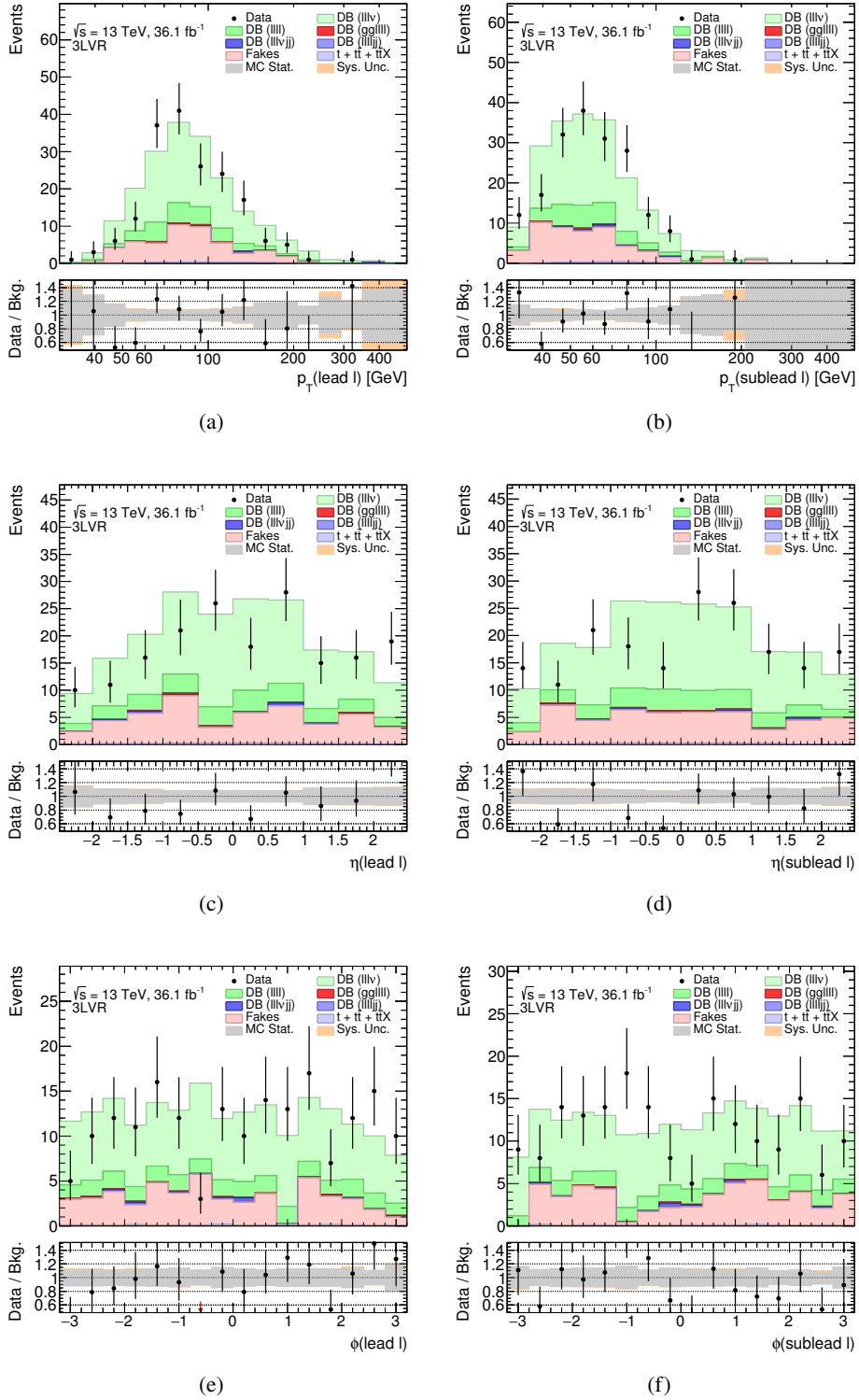


Figure F.20: Kinematic distributions in the three-lepton validation region of the mixed channel, referred to the leptons in the same-sign pair: (a) p_T distribution of the leading lepton, (b) p_T distribution of the sub-leading lepton, (c) η distribution of the leading lepton, (d) η distribution of the sub-leading lepton, (e) ϕ distribution of the leading lepton (f) and ϕ distribution of the sub-leading lepton.

F.4.3 Muon Channel 3LVR plots

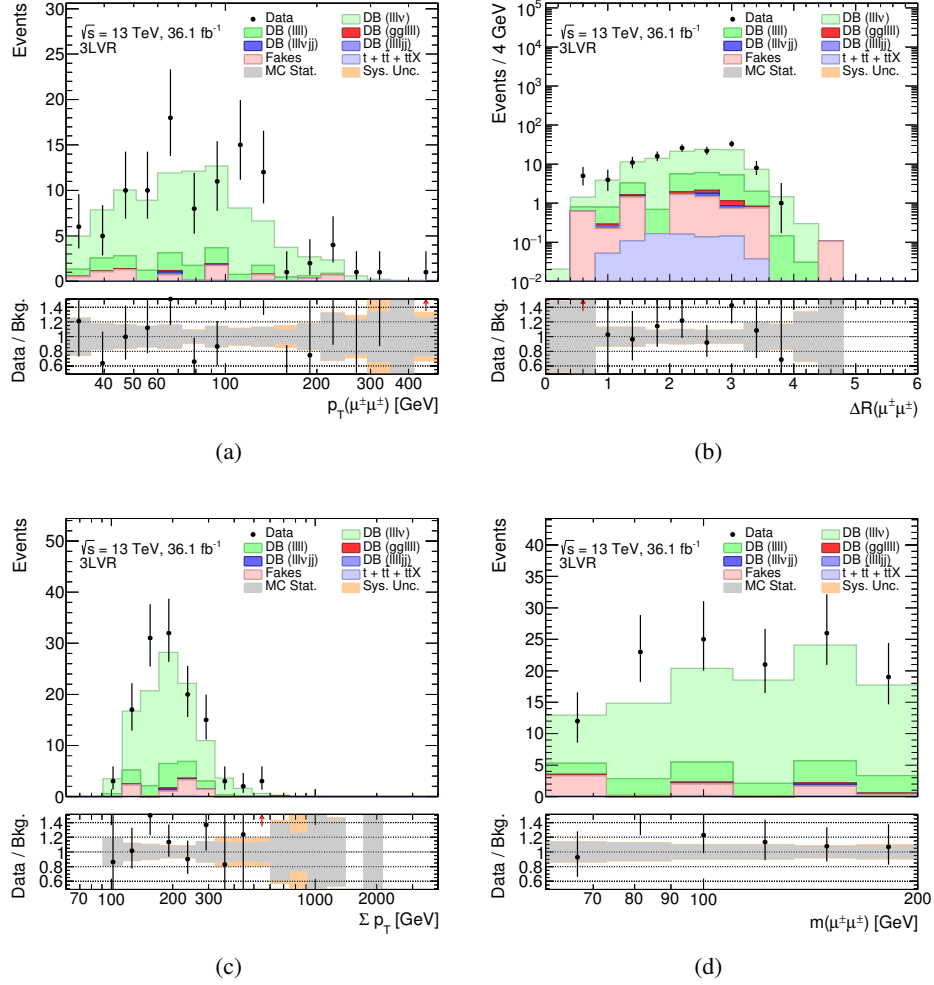


Figure F.21: Event distributions in the three lepton validation region of the mixed channel: (a) $p_T(\mu^\pm, \mu^\pm)$ of the same-sign muons, (b) $\Delta R(\mu^\pm, \mu^\pm)$ separation of the same-sign muons, (c) $\sum |p_T|$ distribution of all muons in the event (d) and invariant mass $m(\mu^\pm, \mu^\pm)$ of the same-sign muon pair.

F.4 Three-leptons Validation Region (3LVR)

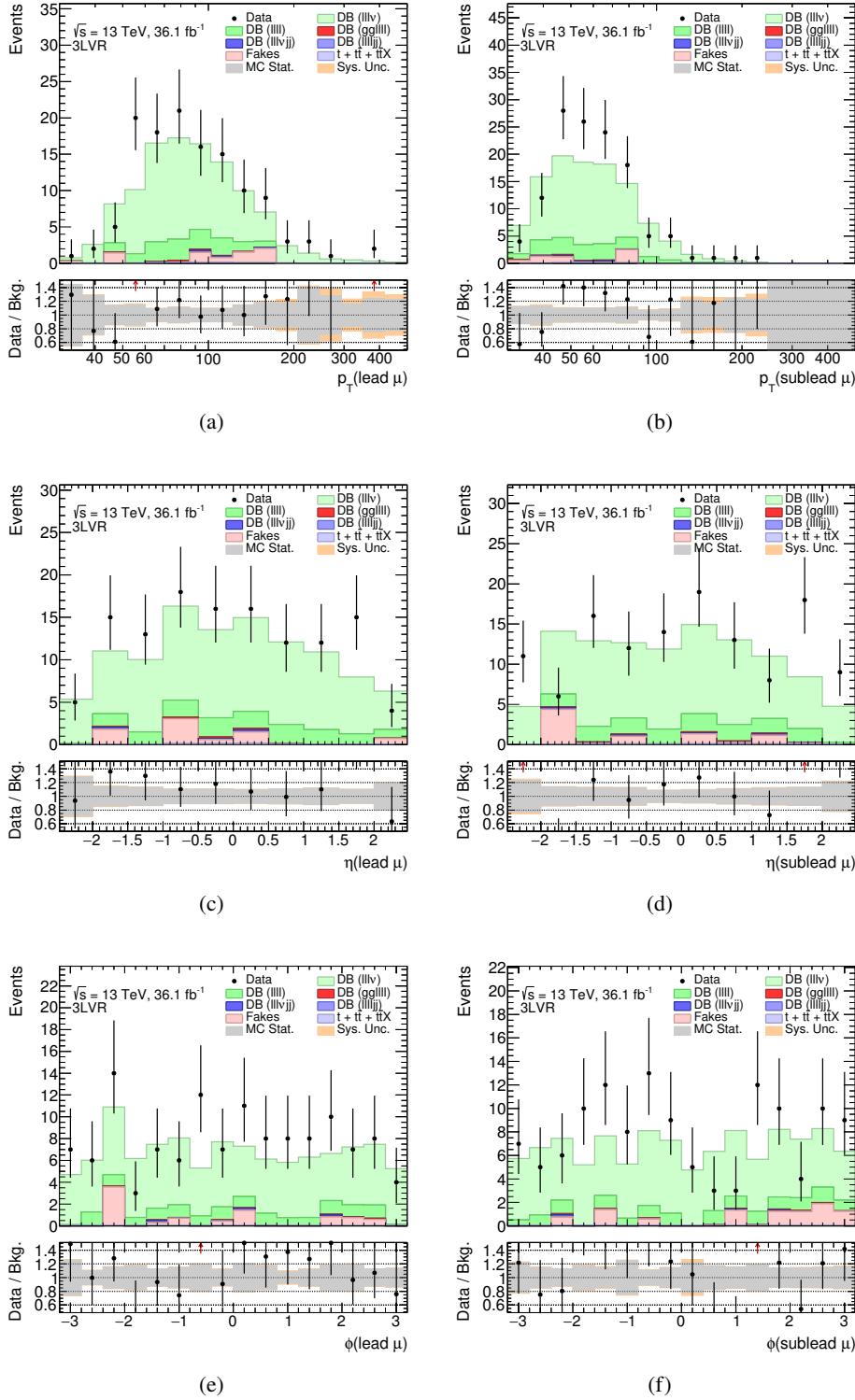


Figure F.22: Kinematic distributions in the three-lepton validation region of the mixed channel referred to the muons in the same-sign pair: (a) p_T distribution of the leading muon, (b) p_T distribution of the sub-leading muon, (c) η distribution of the leading muon, (d) η distribution of the sub-leading muon, (e) ϕ distribution of the leading muon (f) and ϕ distribution of the sub-leading muon.

F.4.4 Mixed Channel 3LVR plots with a same-flavor same-charge pair

These validation regions, namely $e^\pm e^\pm \mu^\mp$ and $\mu^\pm \mu^\pm e^\mp$ test fake estimation in a phase space with three leptons where the same-charge lepton also have the same flavor. Invariant masses of the same-charge lepton pairs in this validation region are shown in Fig F.23.

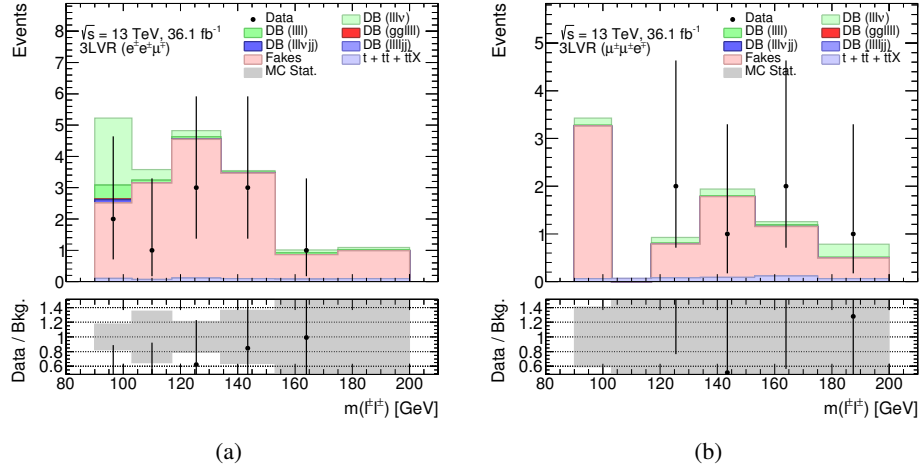


Figure F.23: Invariant mass distributions of same-charge lepton pairs in the same-flavor mixed 3LVR: (a) $e^\pm e^\pm \mu^\mp$ candidates. (b) $\mu^\pm \mu^\pm e^\mp$ candidates.

G Detailed distributions of the heavy N_R and W_R search analysis regions

G.1 Control regions

The electron and muon control regions are used to constrain the normalization of the $Z \rightarrow ee$ and the diboson background in the fit. For the electron channel, the Drell–Yan process is one of the dominant background due to charge-misidentification. Since charge-misidentification for muons is negligible, the main prompt background in the muon channel is the diboson process. Yield of the Drell–Yan process is extracted from the electron channel and yield of the diboson process is extracted simultaneously from electron and muon control regions. Pre-fit distributions are presented in Figures [G.1](#) and [G.2](#) for the electron channel and Figures [G.3](#) and [G.4](#) for the muon channel

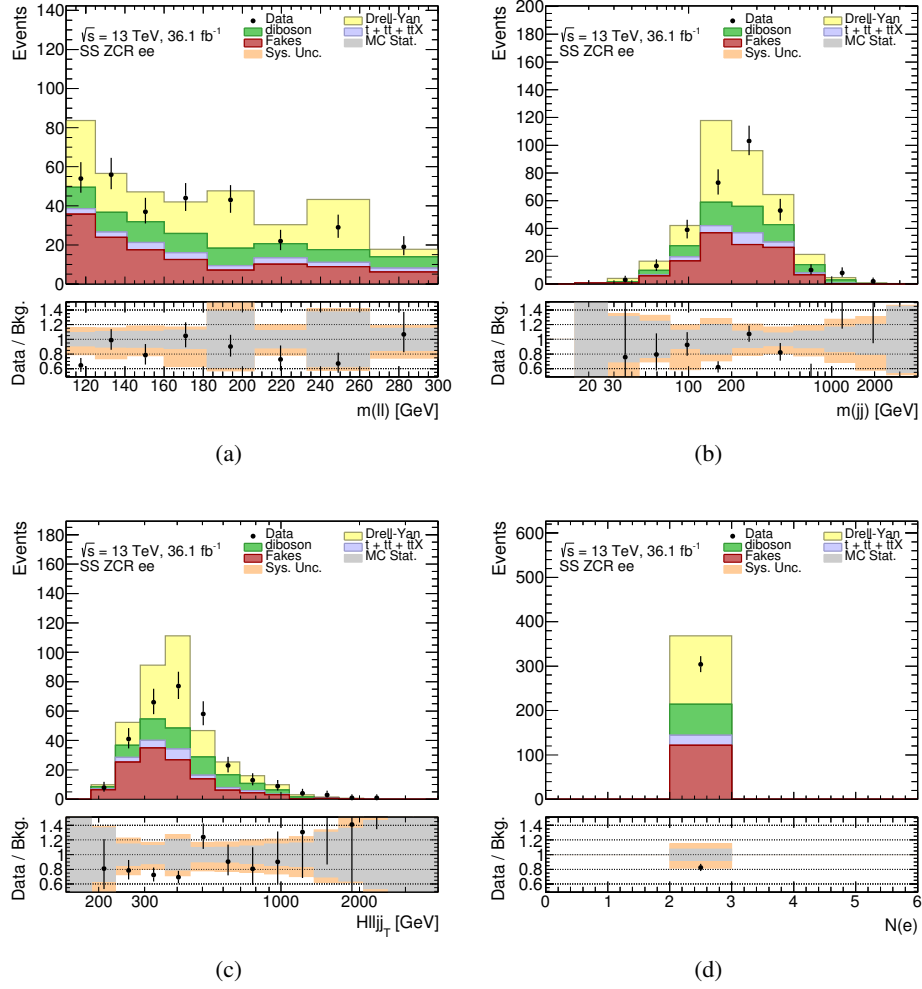


Figure G.1: Distributions for data and SM background predictions in the electron channel control region: (a) invariant mass of the two leptons, (b) invariant mass of the two leading jets, (c) scalar sum of the p_T of leptons and two leading jets, and (d) total number of events in the region.

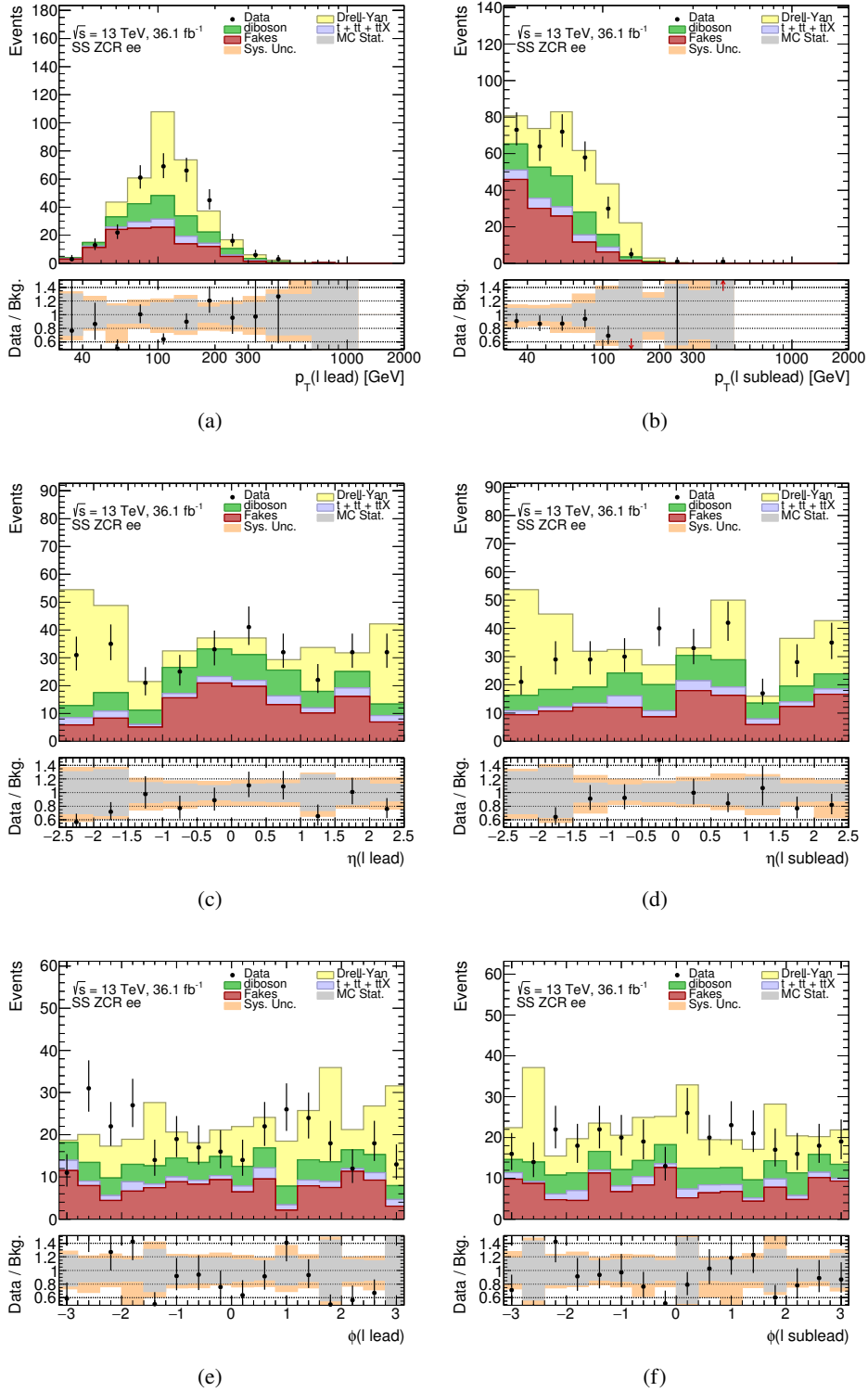


Figure G.2: Distributions for data and SM background predictions in the electron channel control region: (a) leading electron p_T , (b) subleading electron p_T , (c) leading electron η , (d) subleading electron η , (e) leading electron ϕ , and (f) subleading electron ϕ .

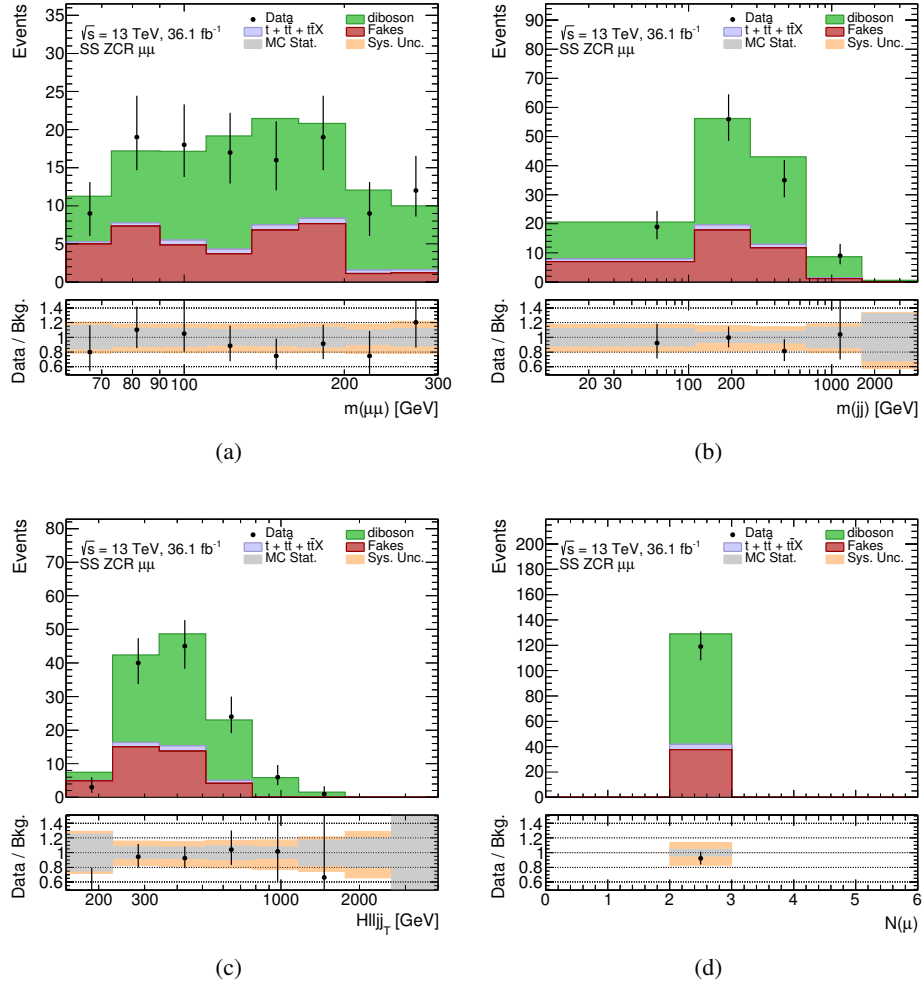


Figure G.3: Distributions for data and SM background predictions in the muon channel control region: (a) invariant mass of the two leptons, (b) invariant mass of the two leading jets, (c) scalar sum of the p_T of leptons and two leading jets, and (d) total number of events in the region.

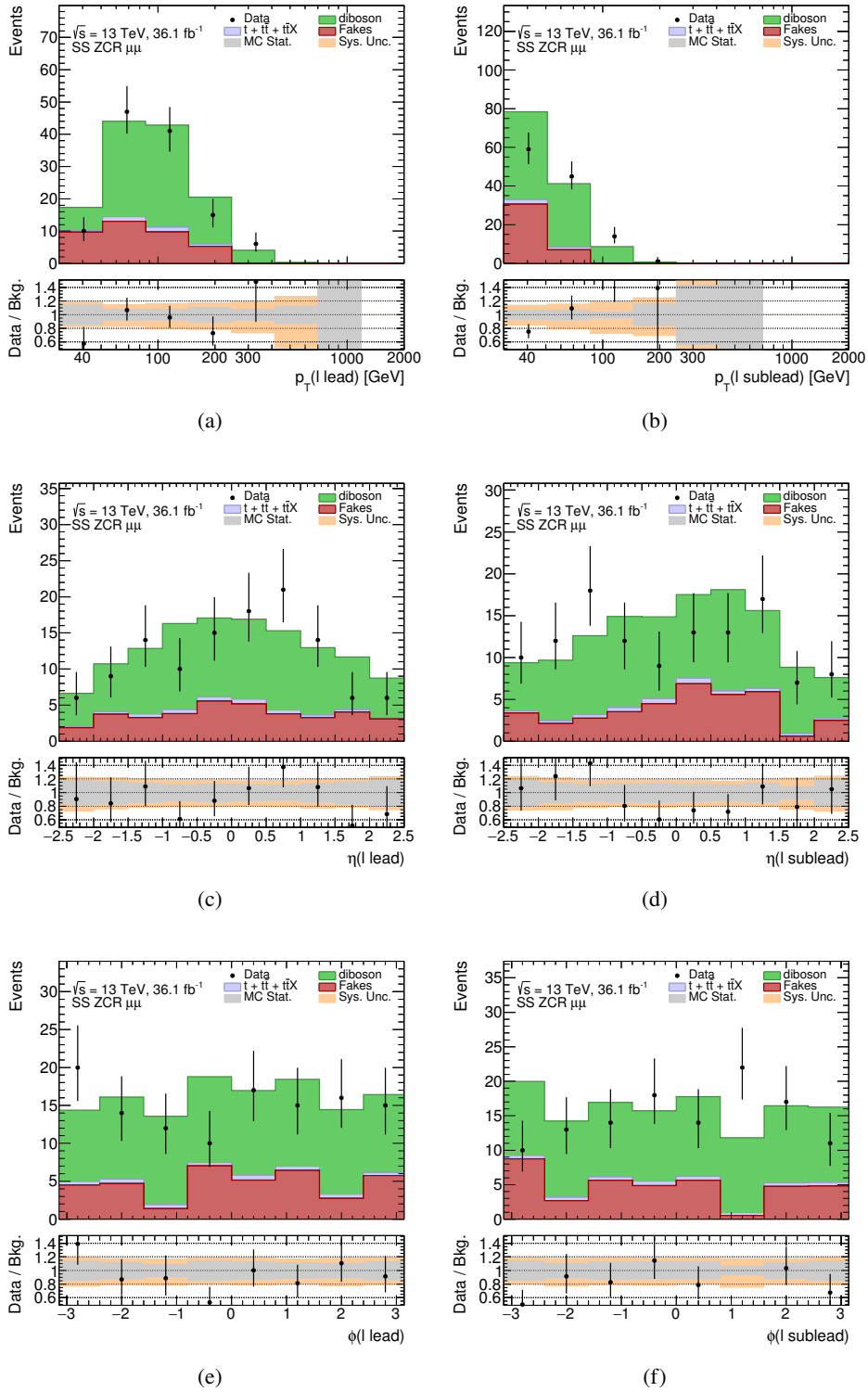


Figure G.4: Distributions for data and SM background predictions in the muon channel control region: (a) leading muon p_T , (b) subleading muon p_T , (c) leading muon η , (d) subleading muon η , (e) leading muon ϕ , and (f) subleading muon ϕ .

G.2 Validation regions

The purpose of the validation regions is to validate the data-driven background estimation techniques, namely the fake factor method and the charge misidentification scale factors in topologies with two high- p_T jets. Pre-fit distributions are presented in Figures G.5 and G.6 for the electron channel and Figures G.7 and G.8 for the muon channel.

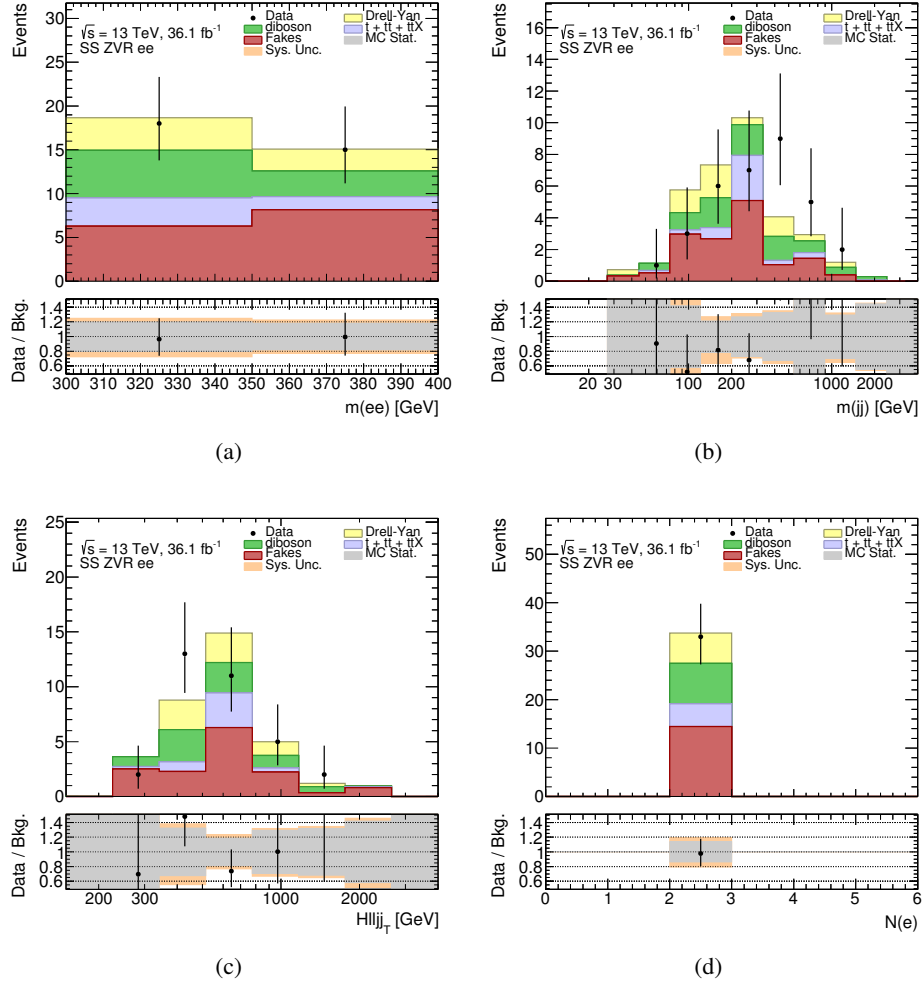


Figure G.5: Distributions for data and SM background predictions in the electron channel validation region: (a) invariant mass of the two leptons, (b) invariant mass of the two leading jets, (c) scalar sum of the p_T of the leptons and two leading jets, and (d) total number of events in the region.

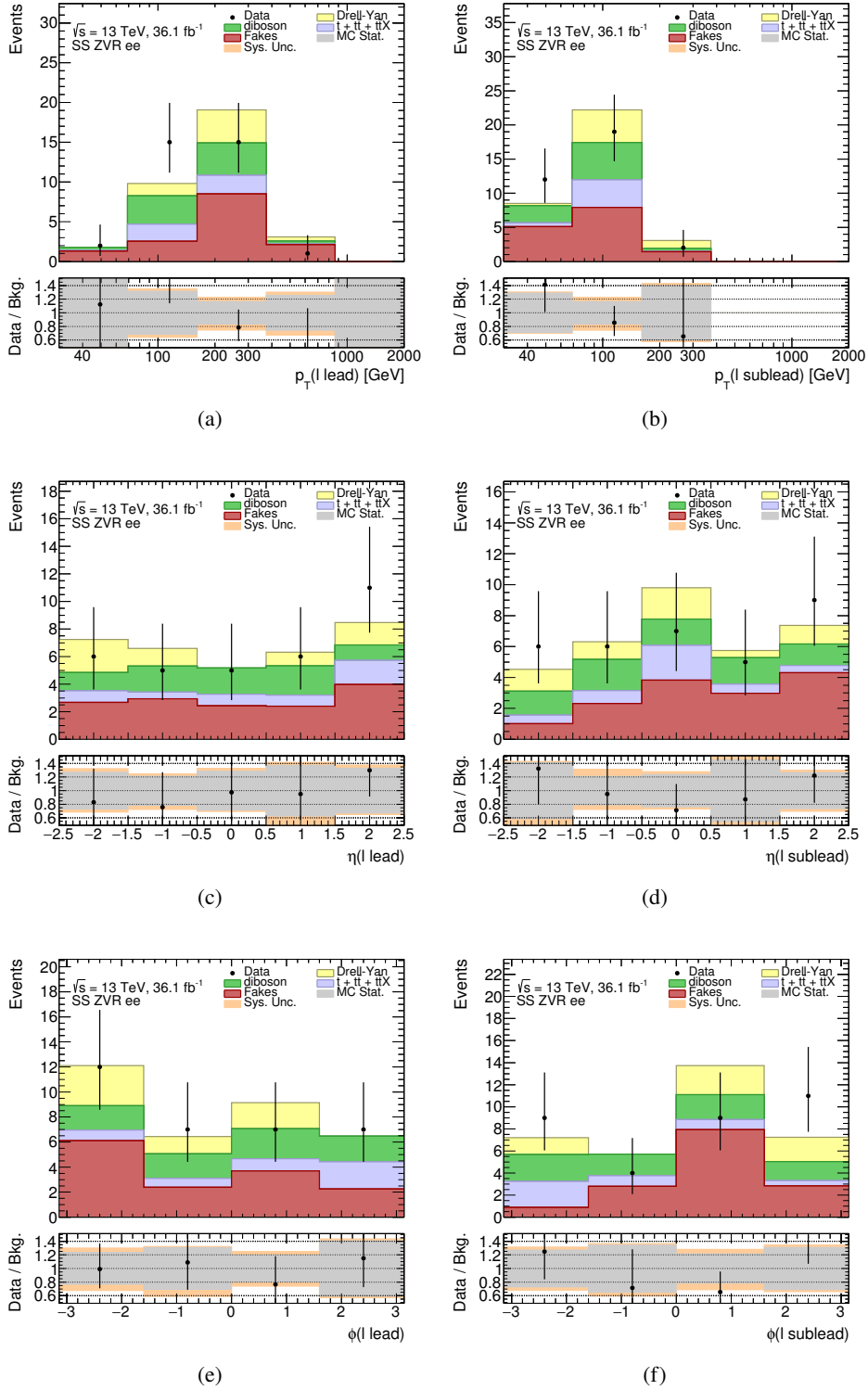


Figure G.6: Distributions for data and SM background predictions in the electron channel validation region: (a) leading electron p_T , (b) subleading electron p_T , (c) leading electron η , (d) subleading electron η , (e) leading electron ϕ , and (f) subleading electron ϕ .

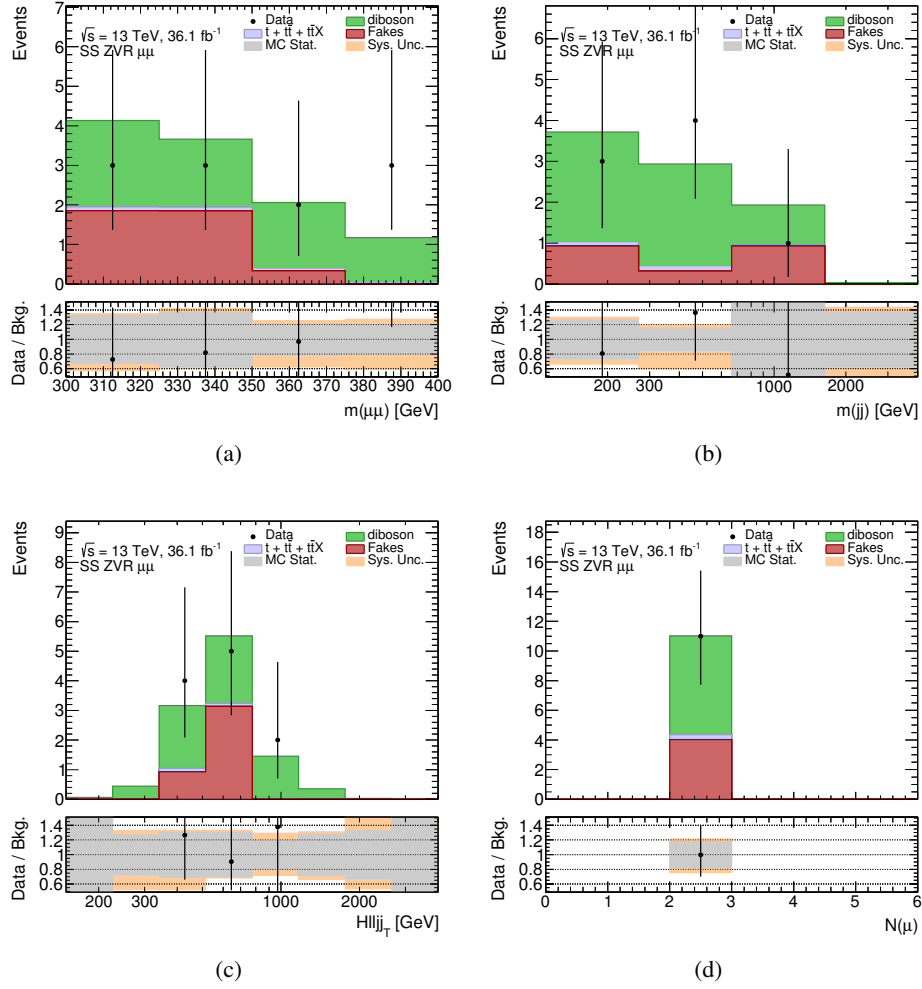


Figure G.7: Distributions for data and SM background predictions in the muon channel validation region: (a) invariant mass of the two leptons, (b) invariant mass of the two leading jets, (c) scalar sum of the p_T of leptons and two leading jets, and (d) total number of events in the region.

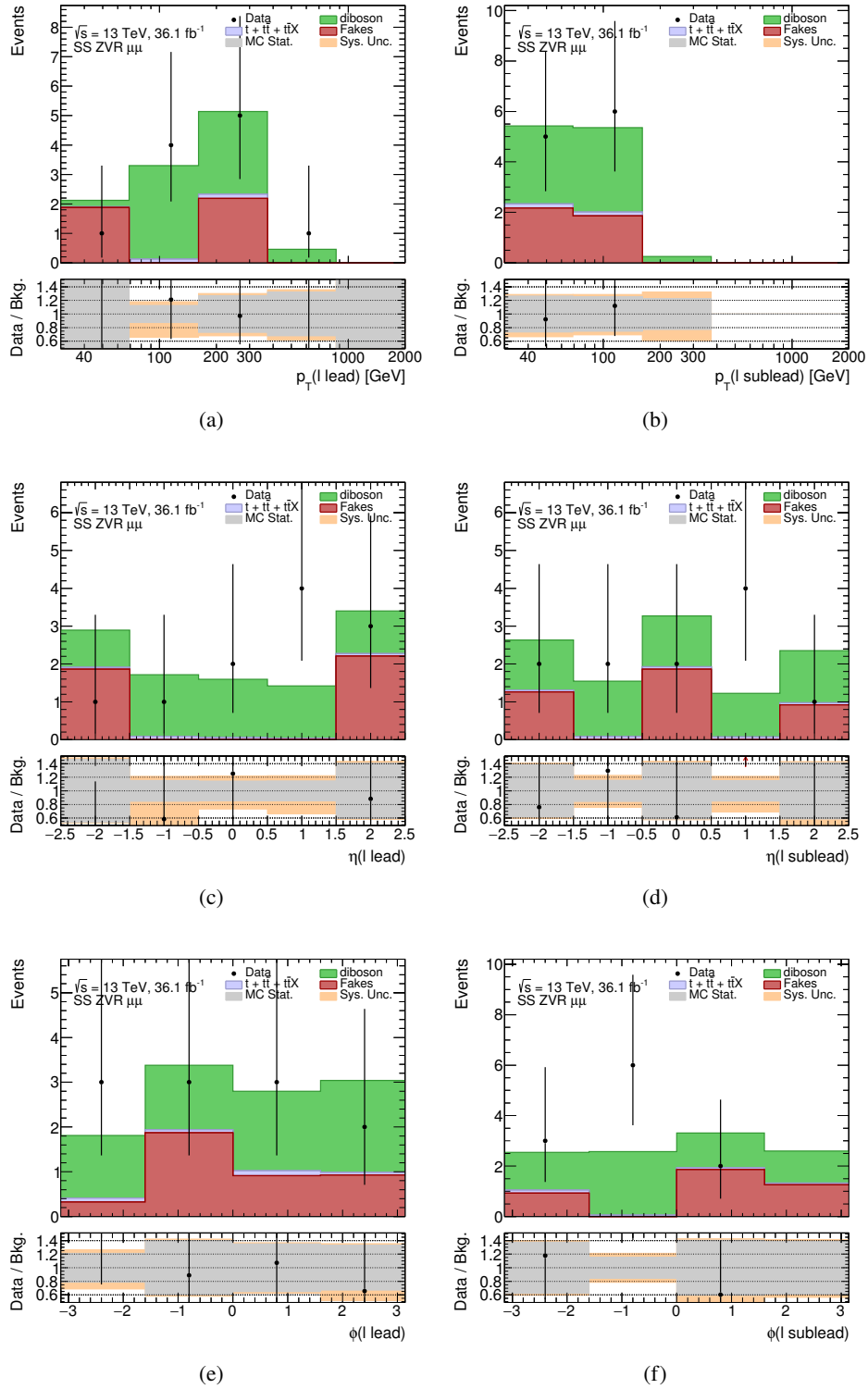


Figure G.8: Distributions for data and SM background predictions in the muon channel validation region: (a) leading muon p_T , (b) subleading muon p_T , (c) leading muon η , (d) subleading muon η , (e) leading muon ϕ , and (f) subleading muon ϕ .

G.3 Signal regions

Signal regions are defined by the presence of two high- p_T jets, two same-flavor and same-charge leptons with invariant mass above 400 GeV in a high-energetic event ($H_T > 400$ GeV). The distribution of data events presented in the $m(W_R) \times m(N_R)$ plane along with the SM prediction is shown in Figure G.9. The event with the highest invariant masses was observed in the electron channel and corresponds to $m(W_R) \sim 3500$ GeV and $m(N_R) \sim 2000$ GeV.

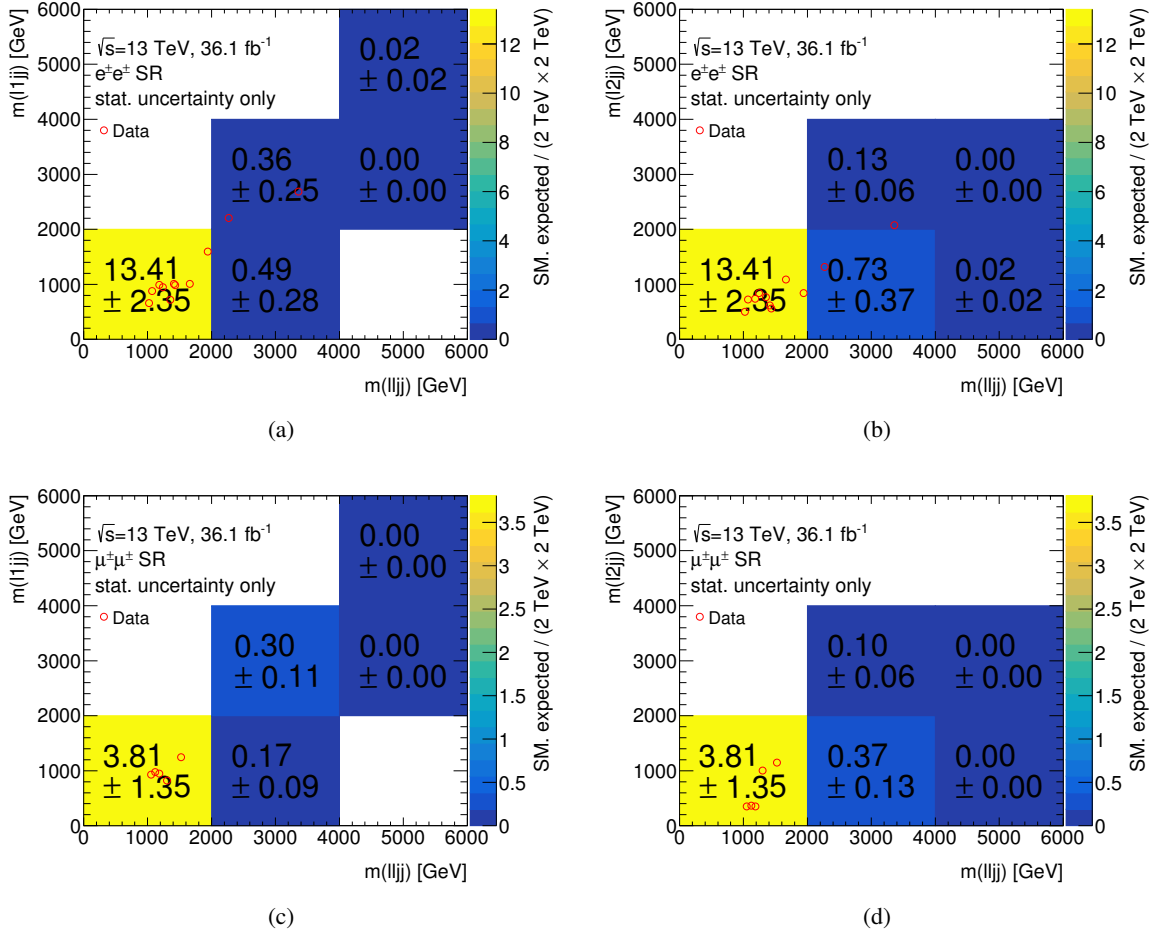


Figure G.9: Distributions for data events and the corresponding SM background prediction with the stat. uncertainty only in the $m(W_R) \times m(N_R)$ plane: (a) $m(ee jj)$ vs. $m(e_1 jj)$, (b) $m(ee jj)$ vs. $m(e_2 jj)$, (c) $m(\mu\mu jj)$ vs. $m(\mu_1 jj)$, and (d) $m(\mu\mu jj)$ vs. $m(\mu_2 jj)$, where the index (1 or 2) indicates the leading and the subleading lepton.

Figures G.10 and G.11 and Figures G.12 and G.13 show the signal regions, respectively for the electron and the muon channel, with the expected SM background prediction together with two signal samples both in the $m(W_R) > m(N_R)$ and the $m(N_R) > m(W_R)$ hierarchies. The H_T portrays a strong sensitivity for the predicted signal with both mass hierarchies and was chosen as the fitted SR distribution in the likelihood fit (see Section 9).

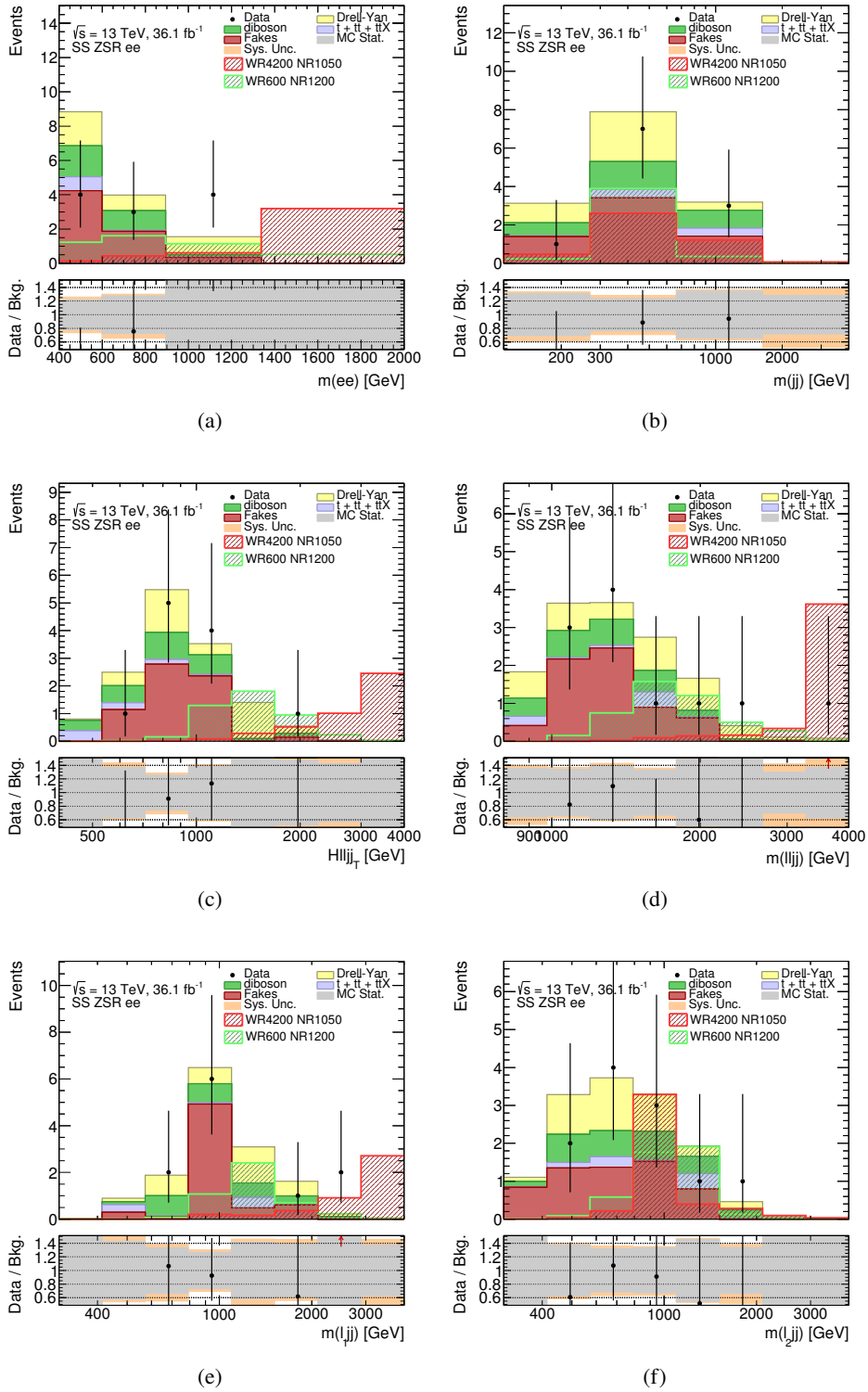


Figure G.10: Distributions for data and SM background predictions in the electron channel signal region: (a) invariant mass of the two leptons, (b) invariant mass of the two leading jets, (c) scalar sum of the p_T of leptons and two leading jets, (d) invariant mass of the four selected objects, (e) invariant mass of the two jets and the leading lepton, and (f) invariant mass of the two jets and the subleading lepton.

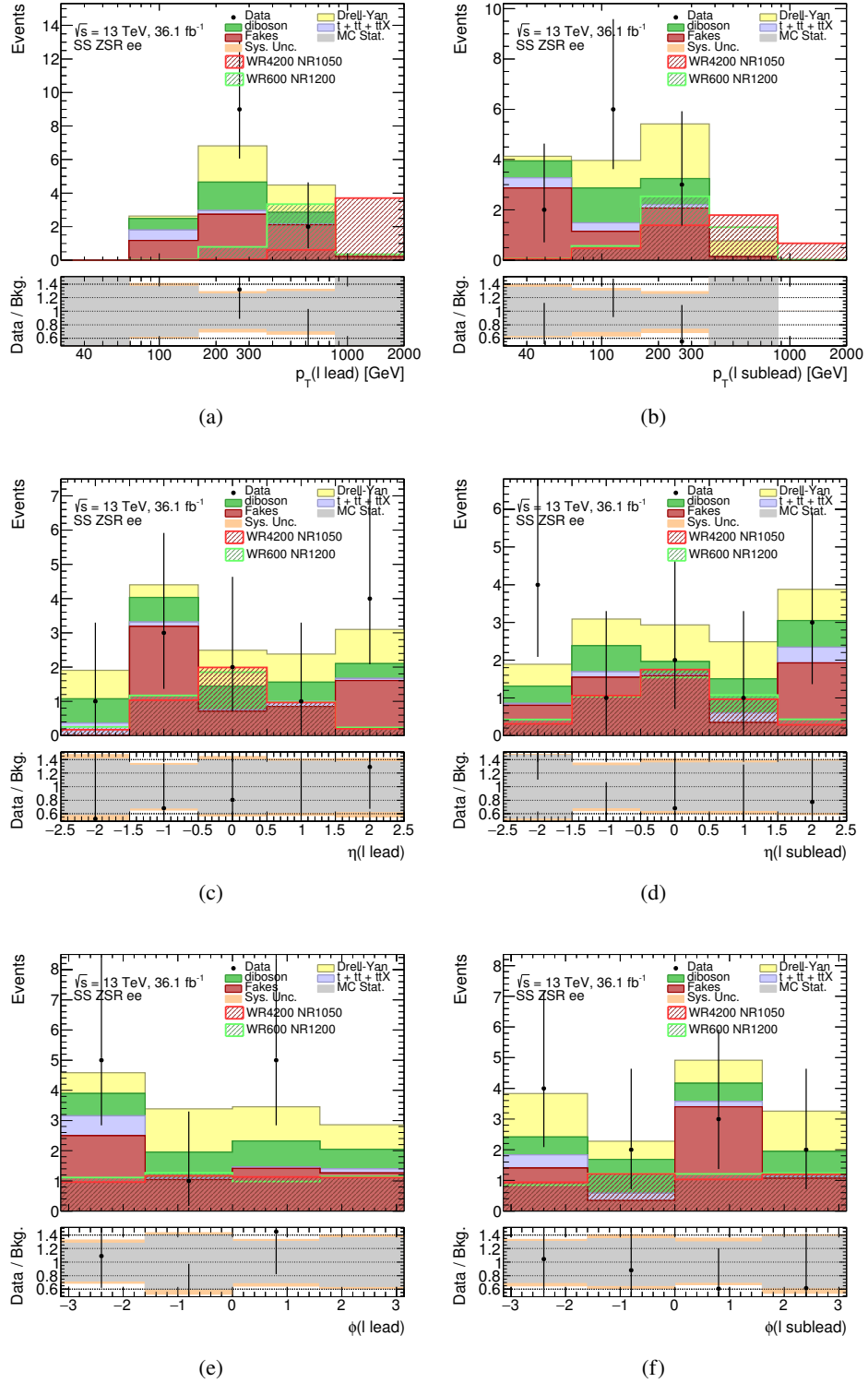


Figure G.11: Distributions for data and SM background predictions in the electron channel signal region: (a) leading electron p_T , (b) subleading electron p_T , (c) leading electron η , (d) subleading electron η , (e) leading electron ϕ , and (f) subleading electron ϕ .

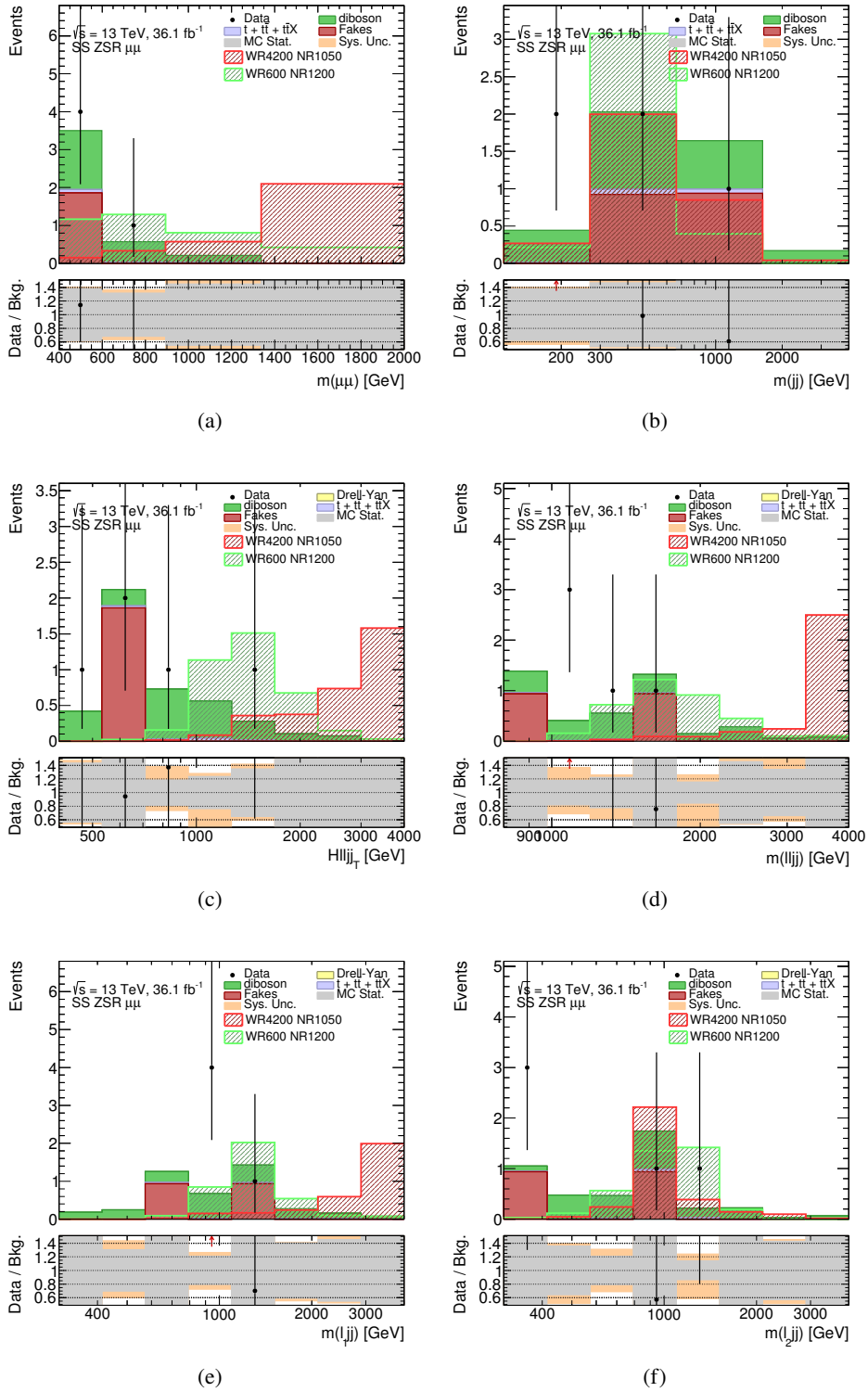


Figure G.12: Distributions for data and SM background predictions in the muon channel signal region: (a) invariant mass of the two leptons, (b) invariant mass of the two leading jets, (c) scalar sum of the p_T of leptons and two leading jets, (d) invariant mass of the four selected objects, (e) invariant mass of the two jets and the leading lepton, and (f) invariant mass of the two jets and the subleading lepton.

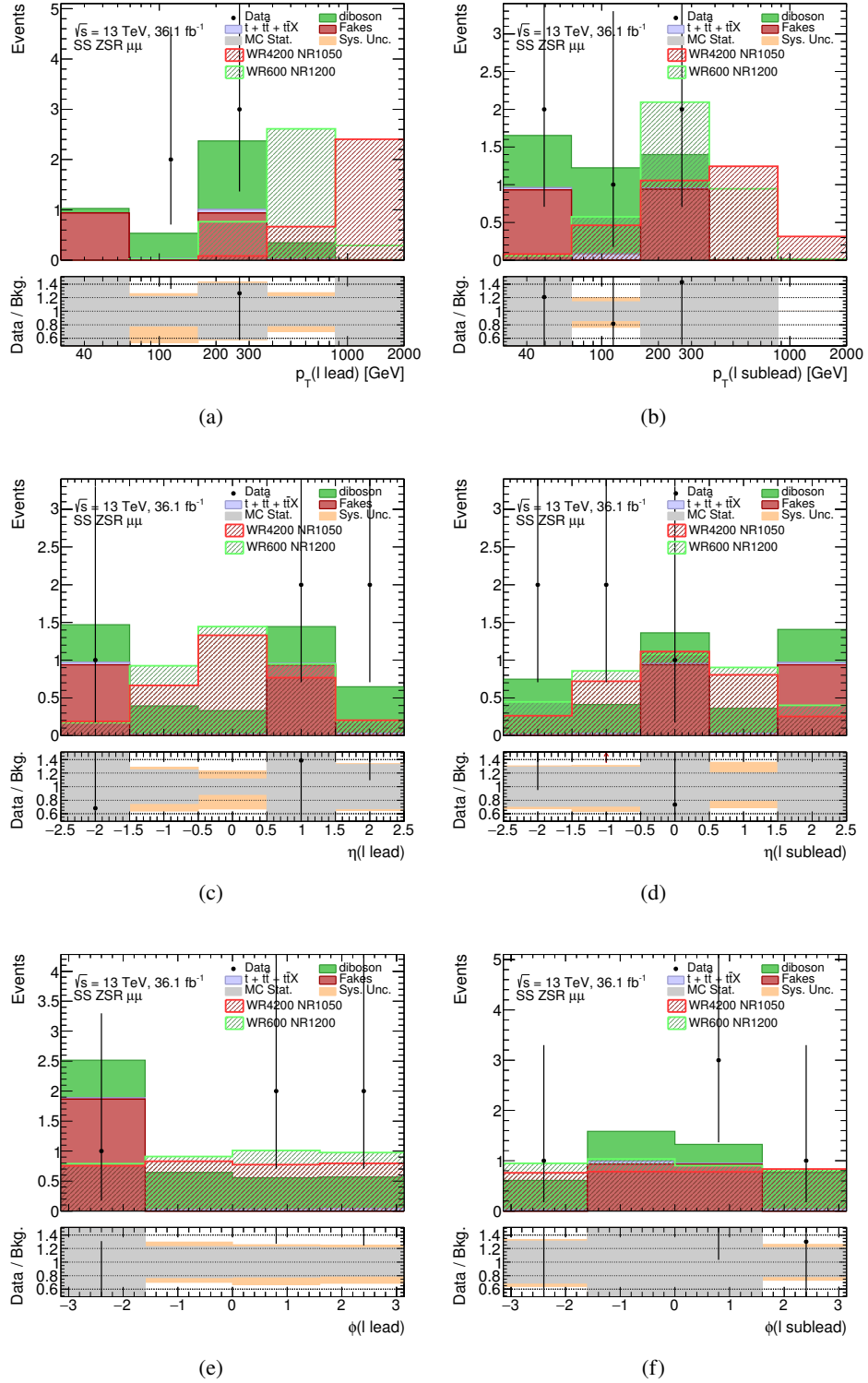


Figure G.13: Distributions for data and SM background predictions in the muon channel signal region: (a) leading muon p_T , (b) subleading muon p_T , (c) leading muon η , (d) subleading muon η , (e) leading muon ϕ , and (f) subleading muon ϕ .

H Detailed lower $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ mass limits

The lower mass limits of both $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ for all combinations of the three branching ratios that add up to less than 100 % are presented in Figures [H.1–H.3](#) for the expected limits and in Figures [H.4–H.6](#) for the observed limits.

H Detailed lower $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ mass limits

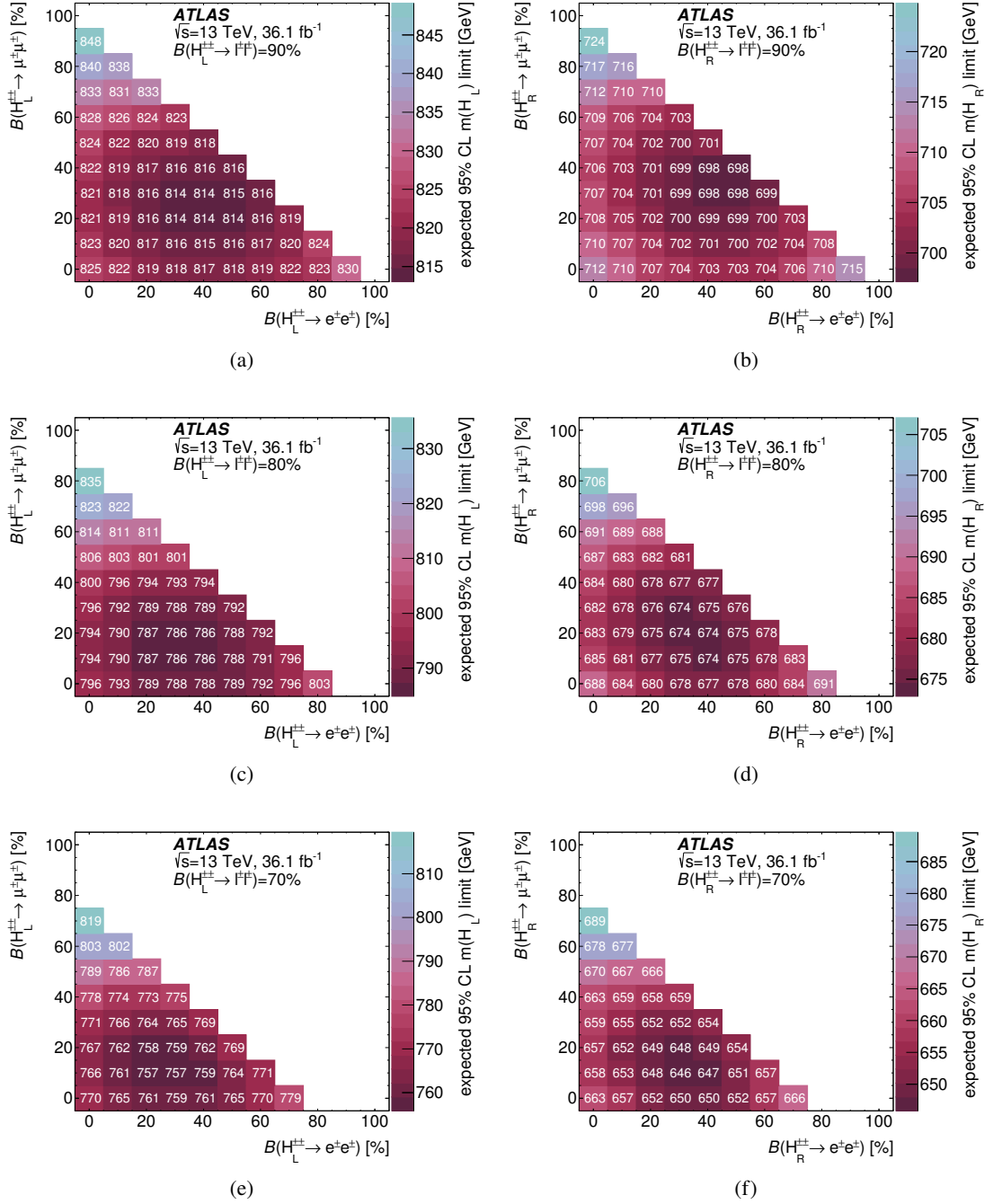


Figure H.1: Expected lower limit on the $H^{\pm\pm}$ mass for all branching ratio combinations ($B(e^{\pm}e^{\pm}), B(e^{\pm}\mu^{\pm}), B(\mu^{\pm}\mu^{\pm})$), for (a) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 90\%$, (b) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 90\%$, (c) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 80\%$, (d) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 80\%$, (e) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 70\%$, (f) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 70\%$. Taken from Ref. [93].

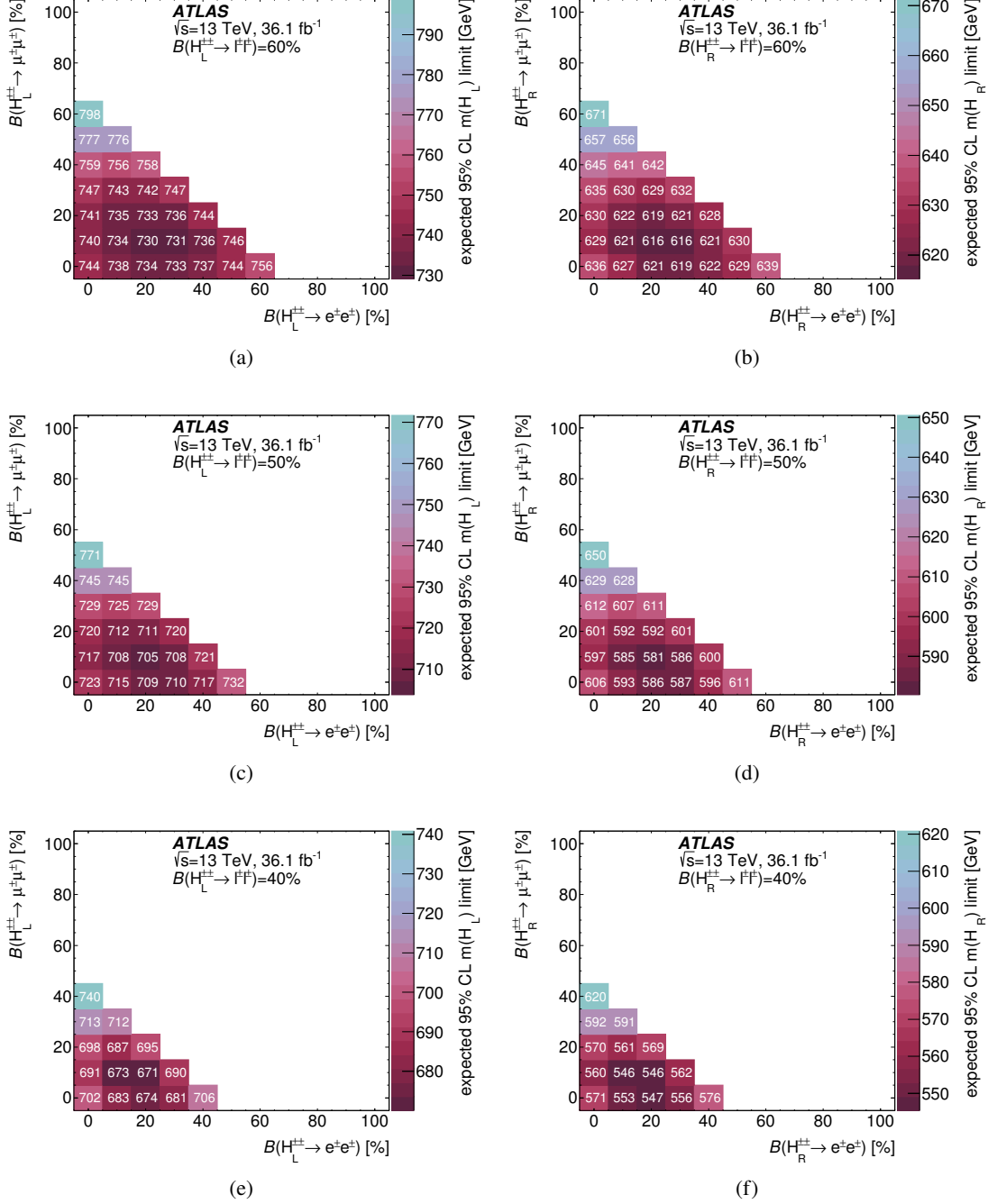


Figure H.2: Expected lower limit on the $H^{\pm\pm}$ mass for all branching ratio combinations ($B(e^{\pm}e^{\pm}), B(e^{\pm}\mu^{\pm}), B(\mu^{\pm}\mu^{\pm})$), for (a) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 60\%$, (b) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 60\%$, (c) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 50\%$, (d) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 50\%$, (e) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 40\%$, (f) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 40\%$. Taken from Ref. [93].

H Detailed lower $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ mass limits

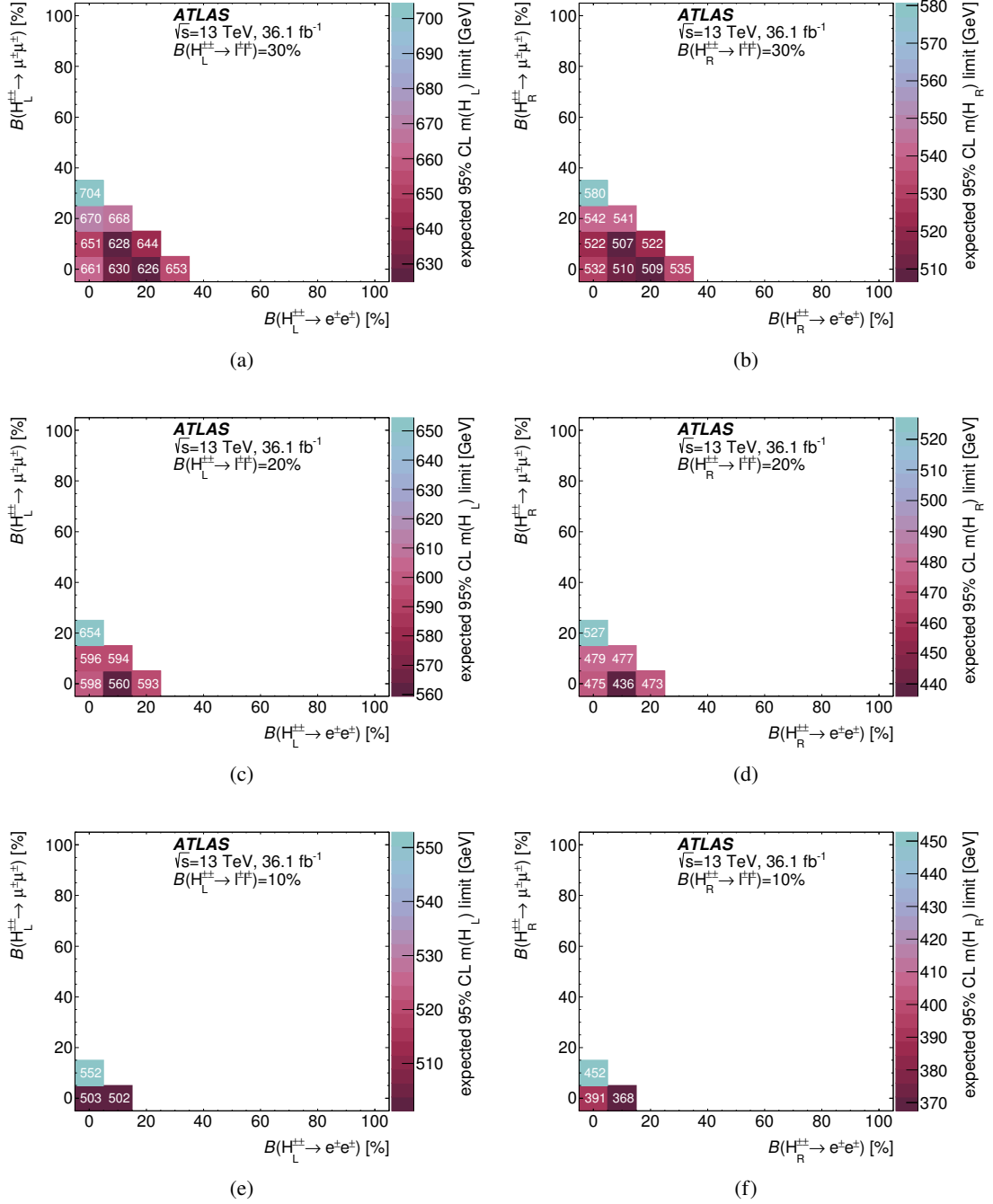


Figure H.3: Expected lower limit on the $H^{\pm\pm}$ mass for all branching ratio combinations ($B(e^{\pm}e^{\pm}), B(e^{\pm}\mu^{\pm}), B(\mu^{\pm}\mu^{\pm})$), for (a) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 30\%$, (b) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 30\%$, (c) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 20\%$, (d) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 20\%$, (e) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 10\%$, (f) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 10\%$. Taken from Ref. [93].

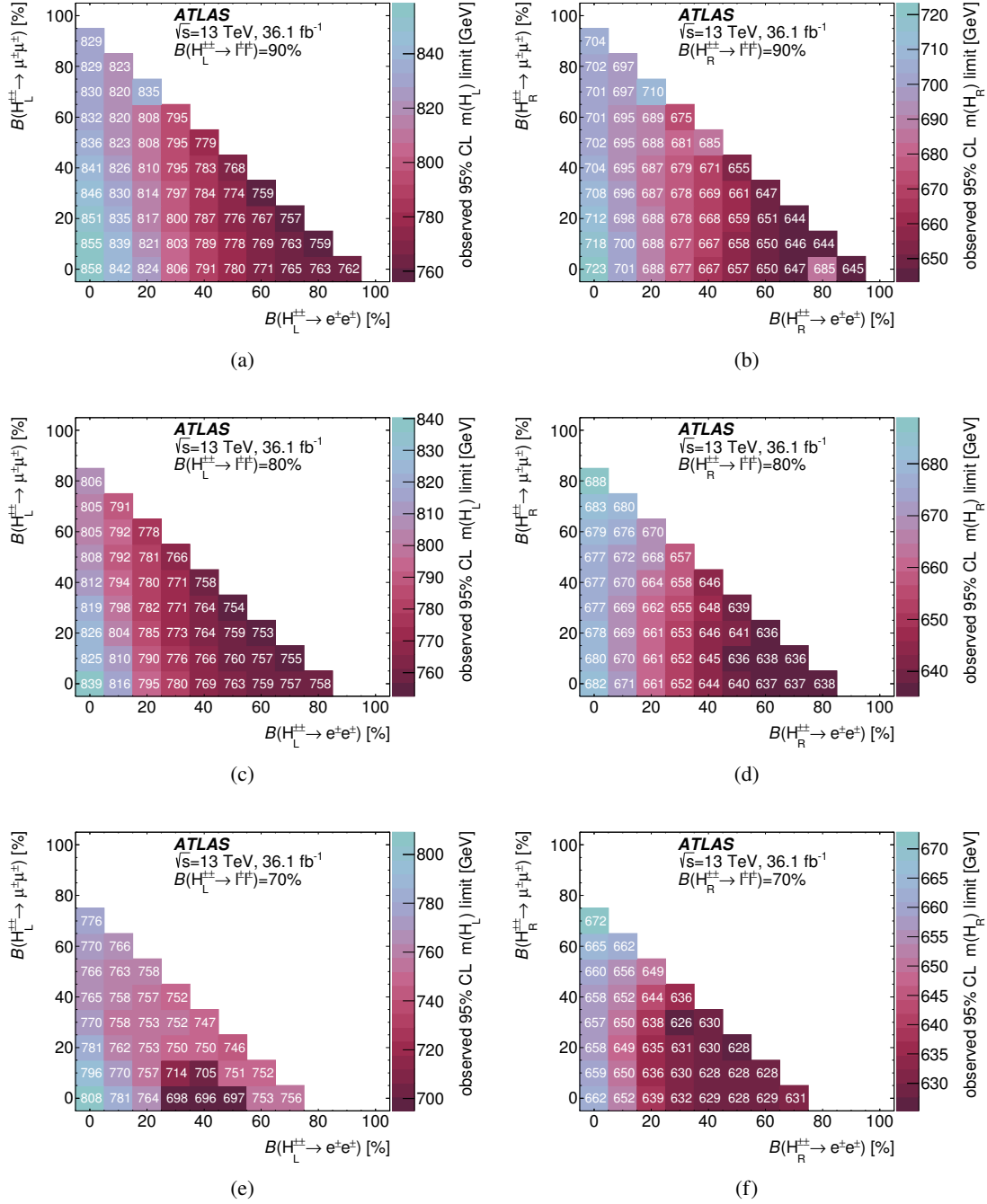


Figure H.4: Observed lower limit on the $H^{\pm\pm}$ mass for all branching ratio combinations ($B(e^{\pm}e^{\pm}), B(e^{\pm}\mu^{\pm}), B(\mu^{\pm}\mu^{\pm})$), for (a) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 90\%$, (b) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 90\%$, (c) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 80\%$, (d) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 80\%$, (e) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 70\%$, (f) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 70\%$. Taken from Ref. [93].

H Detailed lower $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ mass limits

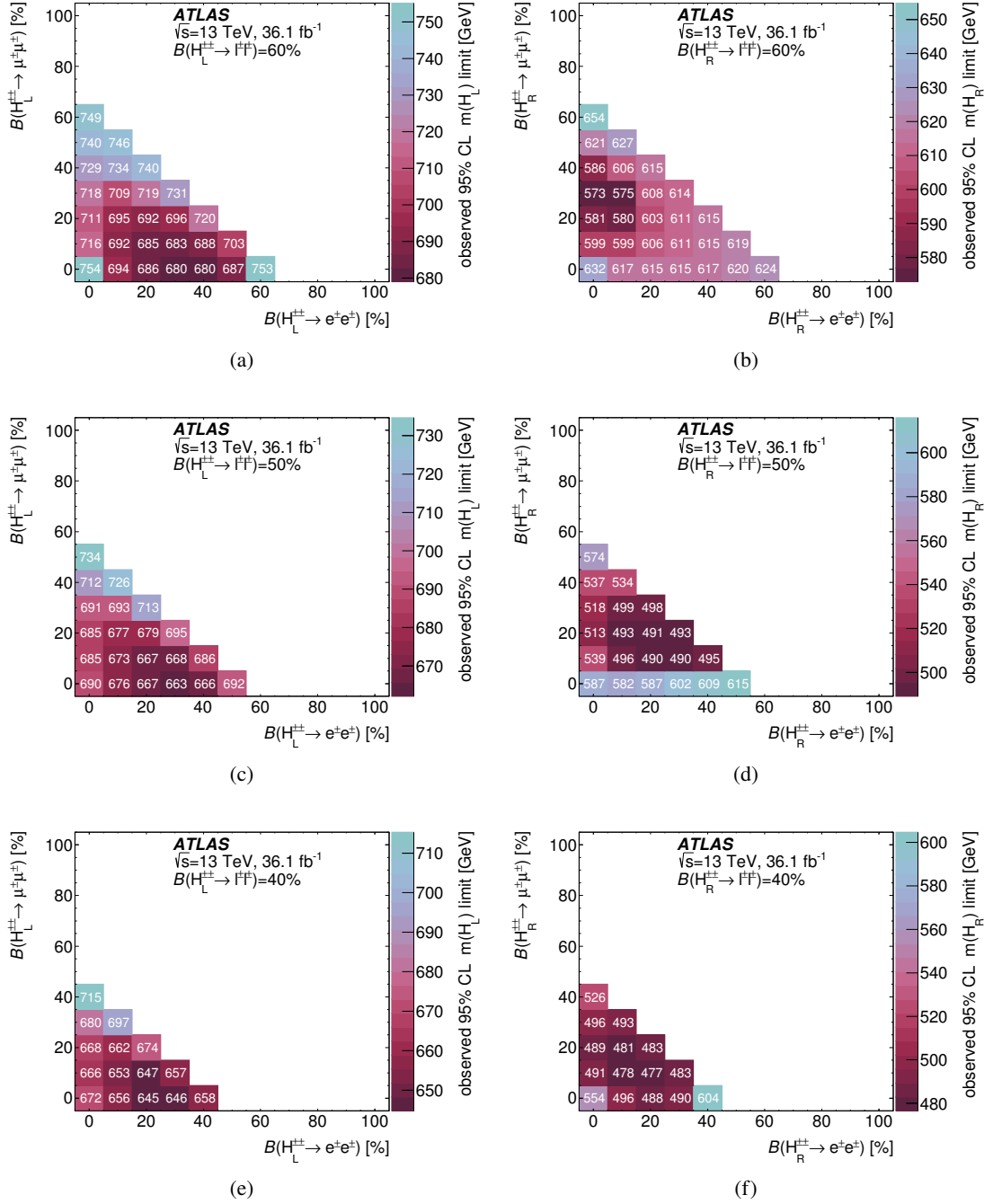


Figure H.5: Observed lower limit on the $H^{\pm\pm}$ mass for all branching ratio combinations ($B(e^{\pm}e^{\pm}), B(e^{\pm}\mu^{\pm}), B(\mu^{\pm}\mu^{\pm})$), for (a) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 60\%$, (b) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 60\%$, (c) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 50\%$, (d) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 50\%$, (e) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 40\%$, (f) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 40\%$. Taken from Ref. [93].

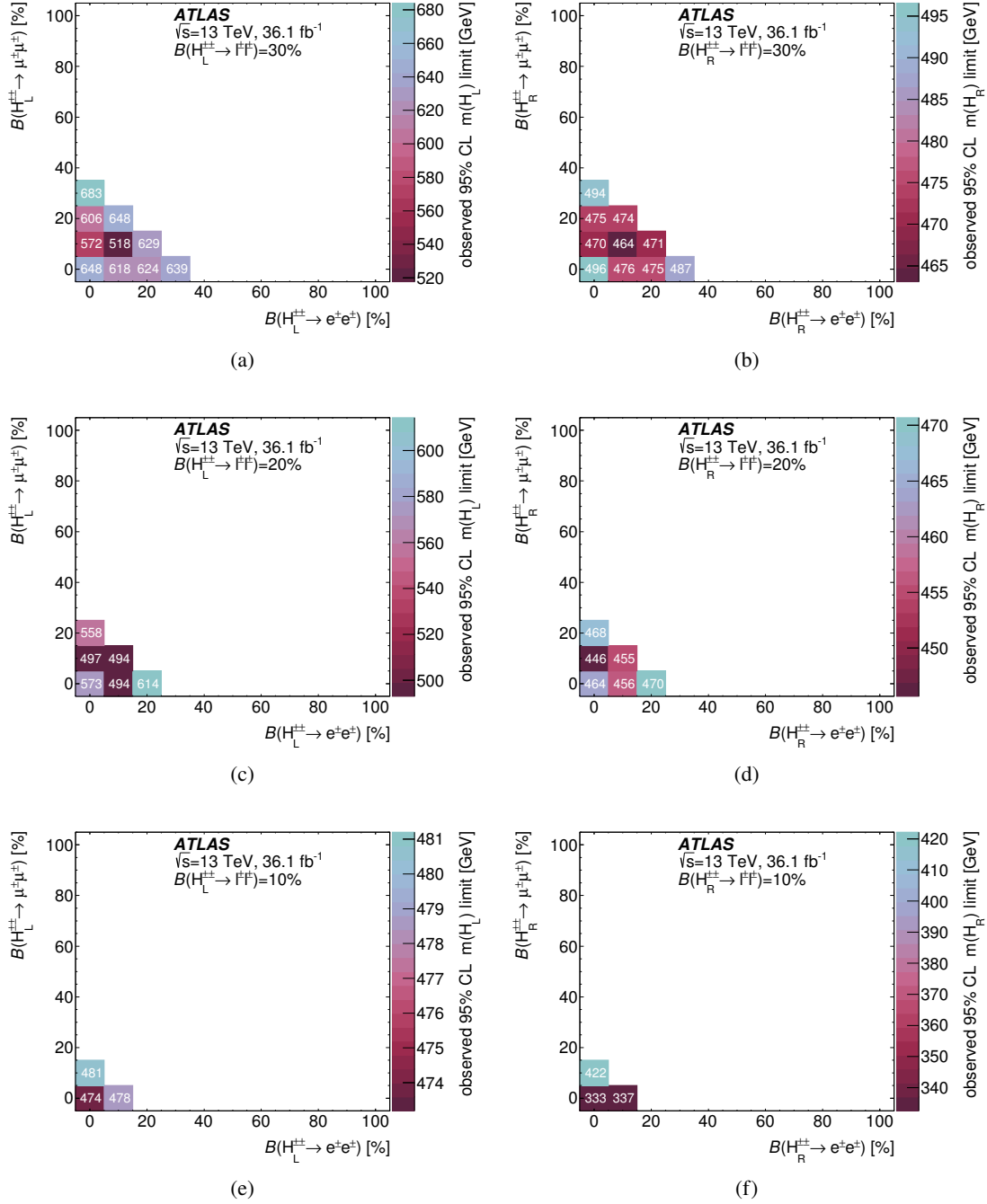


Figure H.6: Observed lower limit on the $H^{\pm\pm}$ mass for all branching ratio combinations ($B(e^{\pm}e^{\pm}), B(e^{\pm}\mu^{\pm}), B(\mu^{\pm}\mu^{\pm})$), for (a) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 30\%$, (b) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 30\%$, (c) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 20\%$, (d) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 20\%$, (e) $m(H_L^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 10\%$, (f) $m(H_R^{\pm\pm})$ and $B(\ell^{\pm}\ell^{\pm}) = 10\%$. Taken from Ref. [93].

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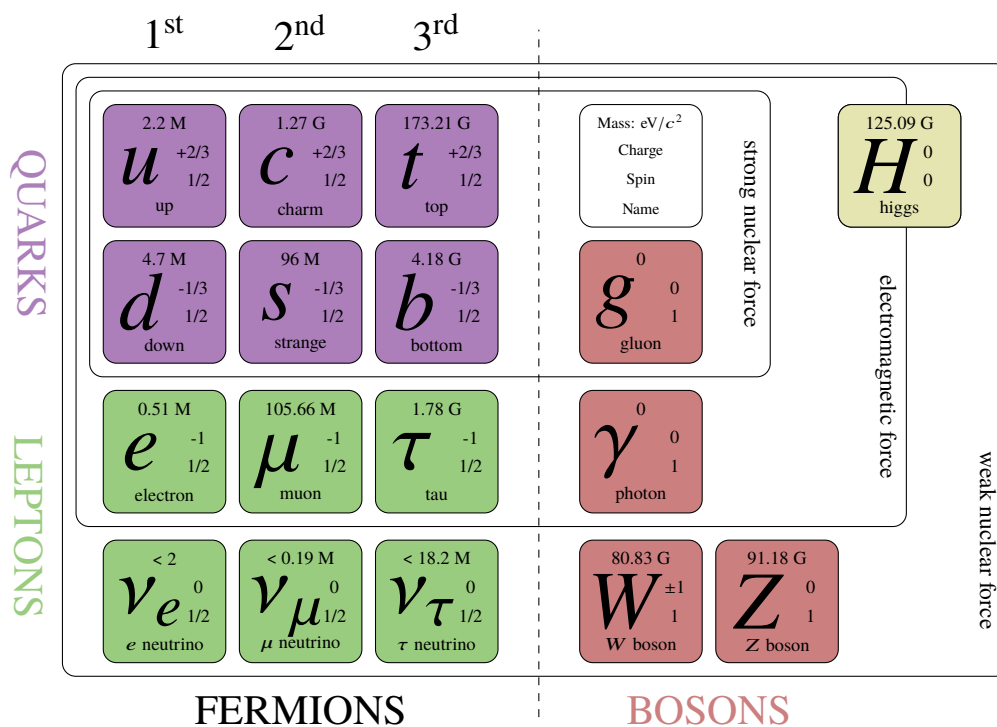
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Razširjeni povzetek v slovenskem jeziku

Standardni model [1–4] elektrošibke in močne interakcije (SM) je teorija fizike osnovnih delcev, ki opisuje močno, šibko in elektromagnetno silo kot tudi osnovne delce, ki sestavljajo snov. Njen edinstveni gradnik je Brout–Englert–Higgsov (BEH) mehanizem¹, ki razloži izvor mase fermionov in umeritvenih bozonov. Standardni model temelji na Yang–Millsovi teoriji [5] in je grajen na podlagi kvantne teorije polja [6, 7]. Sklada se s kvantno mehaniko in s posebno teorijo relativnosti, vendar ne vsebuje opisa gravitacije in torej ne upošteva zakonitosti splošne teorije relativnosti. Implementiran je z uporabo simetrijske grupe $SU(3) \otimes SU(2) \otimes U(1)$. Standardni model in pripadajoča matematična orodja so do potankosti opisana v mnogih knjigah kot npr. [14, 15, 209], v tem povzetku pa so navedene samo osnove. Lastnosti osnovnih delcev Standardnega modela so prikazane na Sliki 1.



Slika 1: Osnovni delci Standardnega modela in njihove lastnosti. Delijo se na fermione, umeritvene bozone in Higgsov bozon. V okvirčku vsakega delca je podana masa, električni naboj, spin in njegovo angleško ime. Prav tako so označene tri osnovne sile v naravi in delci, s katerimi te sile interagirajo.

¹ Imenovan po prejemnikoma Nobelove nagrade za fiziko leta 2013: François Englert in Peter Higgs, ter po soavtorju Englerta, Robertu Broutu, ki nagrade ni mogel prejeti.

Osnovni delci se delijo na tri družine fermionov s polovičnim spinom ($1/2$) in na bozone s celoštevilčnim spinom. V vsaki družini fermionov sta nabiti lepton in njegov pripadajoči nevtrino, kvark tipa gor in kvark tipa dol. Nabiti leptoni imajo naboj -1 ² in so razen različne mase med seboj popolnoma enaki. Najlažji je elektron (e), sledi mu mion (μ), najtežji je lepton tau (τ). Ustrezni nevtrini ν_e , ν_μ in ν_τ so leptoni brez električnega naboja in so v okviru Standardnega modela brez mase. Kvarki tipa gor (ang. *up-type quarks*) imajo električni naboj $2/3$, kvarki tipa dol (ang. *down-type quarks*) pa imajo naboj $-1/3$. Vsi fermioni imajo antidelce, ki imajo enako maso in nasprotno elektromagnetne lastnosti (npr. naboj $-1 \rightarrow +1$).

Umeritveni bozoni so nosilci osnovnih interakcij, npr. nosilec elektromagnetne sile foton (γ) interagira z delci z električnim nabojem. Fotoni so brezmasni in zato potujejo s svetlobno hitrostjo kot je opisano v posebni teoriji relativnosti. Posledično ima elektromagnetna interakcija neskončen doseg. Nosilci šibke sile so bozoni Z^0 in bozoni $W^\pm$. Bozoni Z imajo maso 91.2 GeV in bozoni W imajo maso 80.4 GeV [18]. Zaradi njihove velike mase ima šibka interakcija omejen doseg. Kvantno število, povezano s šibko interakcijo, je šibki izospin I_w . Prenašalci močne sile so gluoni (g); to so brezmasni umeritveni bozoni, ki se vežejo na barvni naboj. V nasprotju z ostalimi interakcijami imajo gluoni tudi sami barvni naboj (npr. fotoni nimajo električnega naboja) in tako lahko interagirajo sami s seboj. Obstajajo trije barvni naboji: rdeči, zeleni in modri, ki tvorijo skupaj osem možnih različnih stanj gluonov. Poleg gluonov imajo barvni naboj tudi kvarki in oboji skupaj tvorijo hadrone, kot sta proton in nevtron.

Standardni model vsebuje še en bozon — Higgsov bozon H . To je bozon s spinom 0 , ki je brez električnega in barvnega naboja ter ima šibki izospin $I_w^H = 1/2$. Njegova masa je $m(H) = 125 \text{ GeV}$ [19] in je zadnji odkriti osnovni delec. Odkrili sta ga kolaboraciji CMS [8] in ATLAS [9] leta 2012. Od takrat naprej velja Standardni model za zaključeno teorijo. Vse fermione lahko združimo v skupine (multiplete), ki nastopajo enakovredno v šibkih interakcijah. Fermioni z negativno kiralnostjo imajo izospin enak $1/2$ in jih lahko združimo v skupine po dva (dublet) s tretjo komponento izospina $\pm 1/2$. Fermioni s pozitivno kiralnostjo imajo šibki izospin enak 0 , tvorijo singlete in niso podvrženi šibkim interakcijam.

Standardni model izredno dobro opiše meritve vseh dosedanjih eksperimentov v fiziki osnovnih delcev, vendar ga je potrebno dopolniti, da bi dobili *teorijo vsega* – to je teorija, ki poenoti vse osnovne sile, med njimi tudi gravitacijo. Nekateri indirektni eksperimenti poročajo tudi o meritvah, ki niso popolnoma v skladu s Standardnim modelom. Poleg temne snovi in gravitacije je morda največja šibka točka izmerjena neničelna masa nevtrinov. Eksperimenta Super-Kamiokande [55] in SNO [56] sta predstavila meritve, ki potrjujejo, da nevtrini niso brezmasni kot napoveduje Standardni model. Vendar je izvor mase nevtrinov popolnoma neznan. Lahko bi jo implementirali na enak način kot maso vseh ostalih fermionov preko mehanizma BEH, vendar bi bil za to potreben obstoj desnosučnih nevtrinov, ki pa jih do sedaj nismo opazili in bi zaradi tega morali biti sterilni (interagirajo samo z Higgsovim poljem). Nevtrini, ki bi dobili maso na ta "klasičen" način, se imenujejo Diracovi nevtrini. Druga možnost so Majoranovi nevtrini. Imenujejo se po fiziku Ettore Majorani, ki je leta 1937 prvi izpostavil [57], da desnosučni fermioni pravzaprav niso potrebni za pojasnitev njihove mase. Majoranovi nevtrini so sami sebi antidelci in se konstruirajo kot $\nu = \nu_L + \nu_L^C$. Masni člen za levosučne Majoranove nevtrine lahko zapišemo kot $\mathcal{L}_{\text{Majorana}} = 1/2 m_L (\bar{\nu}_L^C \nu_L + \bar{\nu}_L \nu_L^C)$. Edini problem

² Električni naboj je podan v enotah naboja elektrona $q_e = -1.602 \times 10^{-19} \text{ C}$ [18].

je, da ta člen spremeni šibki hipernaboj ($Y = 2(q - I_3)$) za dve enoti, česar pa Higgsov bozon v Standardnem modelu ni zmožen prenesti, saj ima šibki hipernaboj enak 1.

Ogromno teorij nove fizike napove in opiše maso nevtrinov. Med njimi je tudi model levo-desne simetrije (LRSM) [58–60], ki Higgsov sektor nadgradi z bi-dubletom Φ in dvema $SU(2)_{L,R}$ tripletoma $\Delta_{L,R}$. Tripleta vsebujeta eno nevtralno stanje ($\Delta_{L,R}^0$) in dve nabiti stanji z električnim nabojem ena in dva: $\Delta_{L,R}^\pm$ ter $\Delta_{L,R}^{\pm\pm}$. Poleg tega simetrizira šibki sektor tako, da imajo levosučni in desnosučni enakovredno interakcijo s šibko silo, kar doseže z dodatnim umeritvenim poljem, ki je enakovredno umeritvenemu polju za levosučne fermione, s simetrijo $SU(2)_R$, in interagira samo z desnosučnimi fermioni. To polje ima pripadajoče desnosučne umeritvene bozone $W_R^\pm$ ter Z_R^0 . Zaradi dosedanjih meritev, ki izključujejo lažja stanja, morajo biti ti bozoni težki (vsaj nekaj TeV). Elektrošibka simetrija Standardnega modela je tako povzdignjena na $SU(2)_R \times SU(2)_L \times U(1)_Y$ in moč obeh šibkih interakcij je enaka, $g = g_L = g_R$. Povezava med električnim nabojem in šibkim izospinom se zapiše kot $q = I_{3L} + I_{3R} + (B - L)/2$, kjer sta B in L barionsko in leptonsko kvantno število. Levosučni in desnosučni fermioni dobijo enako maso preko sklopitve z bi-dubletom Φ , vendar pa mora biti ta simetrija zlomljena, saj desnosučnih nevtrinov še nismo opazili. Tripleta $\Delta_{L,R}$ zavzameta neničelno vakumsko pričakovano vrednost $v_{L,R}$, bi-dublet pa $\langle \Phi \rangle = 1/\sqrt{2} \times \text{diag}(\kappa_1, \kappa_2)$, povezava med njimi pa je $v_L \propto v^2/v_R$ [60, 65, 210], kjer je $v^2 = \kappa_1^2 + \kappa_2^2$. Natančne meritve parametra $\rho = m(W_L)^2/\cos^2 \theta_W m(Z)^2$, $\rho = 1.00037 \pm 0.00023$ [18], omejijo v_L na nizke vrednosti, saj bi ta spremenil maso šibkih bozonov. Vrednost v_L mora biti tako $v_L \lesssim 1 \text{ GeV}$ in vodi do hierarhije $v_R > v > v_L$.

V modelu levo-desne simetrije dobijo nevtrini tako Diracovo kot Majoranovo maso. Člen za Diracovo maso nastopi preko interakcije nevtrinov z bi-dubletom Φ in se zapiše kot $\mathcal{L}_{\text{Yukawa}}^{\text{neutrino}} = -(\bar{\nu}_L^i \Gamma_{ij} \nu_R^j + \bar{\nu}_L^i \Theta_{ij} \nu_R^j + h.c.)$, kjer so Γ_{ij} in Θ_{ij} neznani parametri, povezani z močjo sklopitve bi-dubleta in nevtrinov, $\nu_{L,R}^i$ pa so levosučni ali desnosučni nevtrini iz i -te družine. Nevtrini dobijo Majoranovo maso preko sklopitve s tripletoma $\Delta_{L,R}$. Po diagonalizaciji masne matrike (dimenzije 6×6) dobimo masno matriko za lahke nevtrine $m_\nu = M_L - m M_R^{-1} m^T$ [68], kjer je m Diracova masna matrika, $M_{L,R}$ pa so Majoranovi masni členi, sorazmerni s sklopitvijo s tripletoma $\Delta_{L,R}$. Ker je $M_L \propto v_L$ in $M_R \propto v_R$, so ti nevtrini lahki in lahko pojasnijo maso opaženih levosučnih nevtrinov. Na ta način lahko pojasnimo njihovo majhno maso preko težkih desnosučnih Majoranovih nevtrinov, kar se imenuje tudi gugalni mehanizem. V primeru sklopitve nevtrinov s skalarnim tripletom gre za gugalni mehanizem tipa II.

Hipotezo obstoja levo-desne simetrije lahko neposredno testiramo z Velikim hadronskim trkalnikom (LHC) [76], kar je osrednja tema te doktorske disertacije. Stanja $\Delta_{L,R}^{\pm\pm}$ tripletov $\Delta_{L,R}$ lahko nastaneta v trkih protonov. Ta hipotetični delec se imenuje dvojno nabiti Higgsov bozon in se označi s $H_{L,R}^{\pm\pm}$. Sklaplja se z leptoni in umeritvenimi bozoni W , kot je izpeljano v referenci [73]. Sklopitev z bozoni je sorazmerna s parametroma $v_{L,R}$ in je torej zaradi vrednosti parametra ρ šibka med bozonoma $H_{L,R}^{\pm\pm}$ in $W_L^\pm$. Bozon $H_R^{\pm\pm}$ se lahko sklaplja z bozoni $W_R^\pm$, vendar je tudi ta interakcija šibka zaradi potrebne visoke mase bozonov $W_R^\pm$. V tem doktorskem delu privzamemo, da bozon $H_{L,R}^{\pm\pm}$ interagira samo z leptoni in v tem primeru je razpadna širina

$$\Gamma(H^{\pm\pm} \rightarrow \ell^\pm \ell'^\pm) = k \frac{h_{\ell\ell'}^2}{16\pi} m(H^{\pm\pm}), \quad (1)$$

kjer je $k = 2$ za pare leptonov z enakim okusom ($\ell = \ell'$) in $k = 1$ za pare z različnim okusom. Dominantni proces nastanka bozonov $H_{L,R}^{\pm\pm}$ s trki protonov je torej nastanek v paru, $pp \rightarrow H^{++}H^{--}$, preko umeritvenega bozona Z ali γ , v končnem stanju pa so štirje leptoni. Pari enako nabitih leptonov imajo invariantno maso, ki ustreza masi hipotetičnega delca $H^{\pm\pm}$, $m(\ell^+\ell^+) = m(\ell^-\ell^-) = m(H^{\pm\pm})$. V nadaljevanju je predstavljena optimizirana analiza za takšen proces.

Levo-desno simetrijo lahko neposredno izmerimo tudi preko Keung-Senjanovičevega (KS) procesa [72], kjer bi s trki protonov nastali težki desnosučni Majoranovi nevtrini: $pp \rightarrow W_R \rightarrow \ell N_R \rightarrow \ell\ell W_R$. Končno stanje, najbolj občutljivo na ta proces, sta dva leptona z enakim ali nasprotnim nabojem, in dva pljuska z rekonstruirano maso bozona W_R . V tej disertaciji je predstavljena tudi analiza za ta proces. Ločena je na dva razpadna kanala: na enako-značni (SS) in nasprotno-značni (OS) kanal, v odvisnosti od nabojev dveh leptonov (enaka ali nasprotna). Doktorsko delo vsebuje kanal SS in statistično kombinacijo obeh kanalov. Kanal OS v tem delu ni opisan v podrobnosti, je pa predstavljen v celoti v referenci [190]. V primeru, kjer so težki desnoručni nevtrini Majoranovi delci, bodo v KS procesu tvorili 50 % končnih stanj z enako-značnimi leptoni in 50 % končnih stanj z nasprotno-značnimi leptoni, kjer pa so to Diracovi nevtrini, bodo v končnem stanju samo nasprotno-značnimi leptoni. Z meritvijo naboja leptonov v končnem stanju lahko tako v primeru odkritja sklepamo o tipu novih nevtrinov v okviru modela levo-desne simetrije.

Obe hipotezi ($H^{\pm\pm}$ in W_R/N_R) smo preverili z razpadi novih delcev na elektrone in mione. Razpad na leptone τ ni bil eksplicitno preverjen z rekonstrukcijo hadronskih τ objektov, vendar analiza podatkov za hipotezo $H^{\pm\pm}$ vključuje primere, kjer bozon $H^{\pm\pm}$ razpade tudi na delce X , ki niso zajeti v analizi. Ti delci ustrezajo npr. bozonom W ali leptonom τ . Privzeti razpad bozona $H^{\pm\pm}$ se lahko torej zapiše kot $B(H^{\pm\pm} \rightarrow e^\pm e^\pm) + B(H^{\pm\pm} \rightarrow e^\pm \mu^\pm) + B(H^{\pm\pm} \rightarrow \mu^\pm \mu^\pm) + B(H^{\pm\pm} \rightarrow X) = B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) + B(H^{\pm\pm} \rightarrow X) = 100\%$. Podrobni opisi obeh analiz in rezultati so objavljeni v referencah [93] in [190]. V obeh primerih je glavna sestavina analize končno stanje s pari enako-značnih leptonov, ki nastanejo zelo redko v procesih Standardnega modela. Model LRSM napove povišano tvorbo parov enako-značnih leptonov in tako analiza tega končnega stanja omogoča neposredno meritev hipotetičnih procesov nove fizike.

Predstavljeni analizi zajemata podatke, izmerjene z detektorjem ATLAS [79] na LHC. LHC je največji pospeševalnik na svetu z obsegom 27 km, ki proizvede trke protonov s težiščno energijo $\sqrt{s} = 13$ TeV. Eksperiment ATLAS je eden izmed štirih glavnih eksperimentov na pospeševalnem obroču Velikega hadronskega trkalnika, kot je prikazano na Sliki 2. Uporabljeni podatki so bili zapisani med letoma 2015 in 2016 v tako imenovanem obdobju "Run 2", pri težiščni energiji $\sqrt{s} = 13$ TeV in ustrezajo integrirani luminoznosti 36.1 fb^{-1} . Detektor ATLAS je večnamenski detektor s cilindrično simetrijo okoli interakcijske točke in skoraj popolnim pokritjem prostorskega kota³. Sestavljen je iz Notranjega detektorja (ID), ki je obdan s superprevodnim solenoidom z magnetnim poljem 2 T v smeri osi z , elektromagnetnimi (EM) in hadronskimi kalorimetri ter z Mionskim spektrometrom (MS). ID pokriva območje do $|\eta| < 2.5$ in je sestavljen iz silicijevih "pixel" detektorjev, silicijevih "micro-strip" detektorjev in detektorjev prehodnega sevanja. Pred začetkom zajemanja podatkov v Run 2

³ V ATLAS-u uporabljamo desnoručni koordinatni sistem z izhodiščem v interakcijski točki (IP) v središču detektorja in z -osjo v smeri žarka protonov. Os x kaže iz IP proti centru obroča LHC in os y kaže navpično navzgor. Cilindrične koordinate (r, ϕ) se uporabljajo v transverzalni ravnini, kjer je ϕ azimut glede na os z . Pogosto uporabljena količina je psevdorapidnost, ki je definirana kot $\eta = -\ln \tan(\theta/2)$. Kotna razdalja med dvema točkama se meri v enotah $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Transverzalna gibalna količina delcev je $p_T = \sqrt{p_x^2 + p_y^2}$.

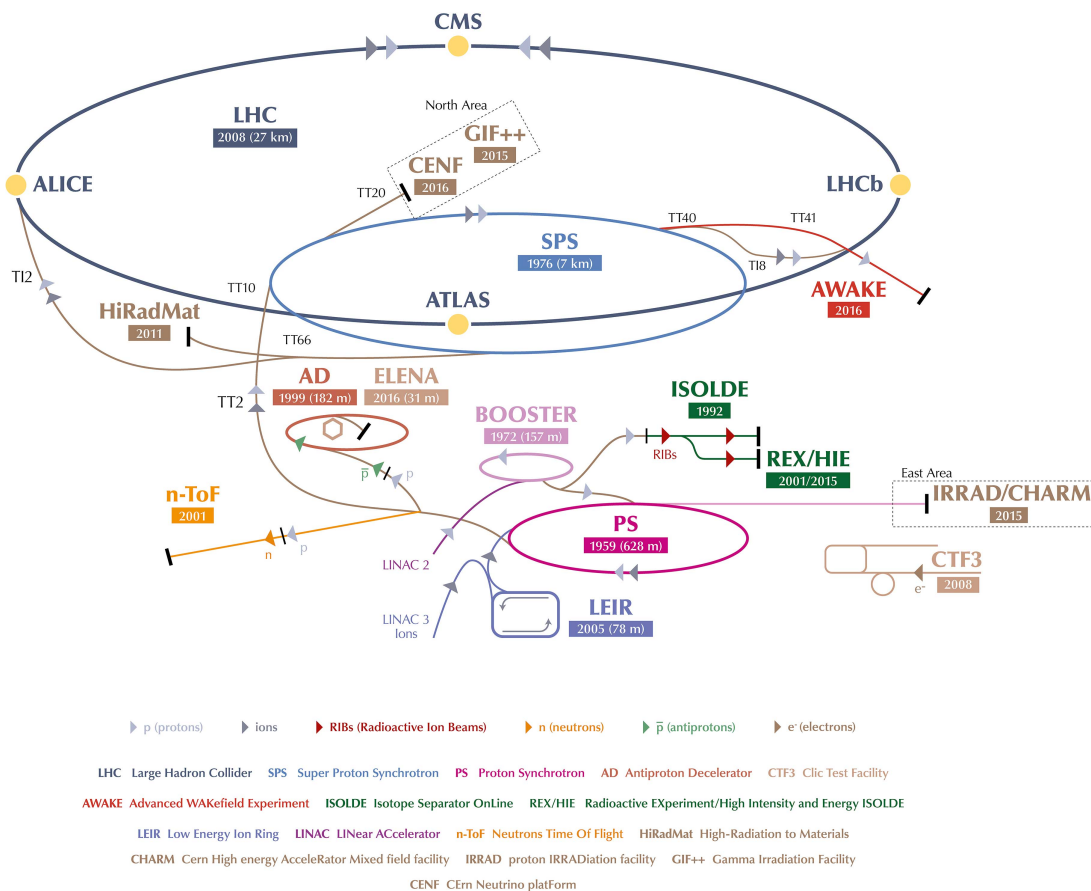
je bil dodan tudi nov notranji sloj detektorja Pixel, IBL [81]. Kalorimetri se delijo na kalorimetre "LAr" (kalorimetri s kombinacijo svinca in tekočega argona) in na kalorimetre "Tile". Kalorimetri Tile se uporabljajo izključno za hadronske meritve, ki pokrivajo območje do $|\eta| < 1.7$, kalorimetri LAr pa se uporabljajo za elektromagnetne in hadronske meritve ter pokrivajo območje do $|\eta| < 4.9$. Najbolj zunanji del detektorja ATLAS je MS, ki ima tri superprevodne toroidalne magnete z močjo ukrivljanja med 2.0 do 6.0 T m. Podatki so zajeti s pomočjo dvo-nivojskega prožilca, ki izbere samo določene trke protonov [87]. Prvi nivo (L1) je zelo hiter in izbira trke protonov s frekvenco 40 MHz, sledi pa mu digitalni (HLT) prožilec, ki omogoča frekvenco zajemanja trkov protonov okoli 1 kHz.

ATLAS in CMS sta že opravila podobne analize hipoteze bozona $H^{\pm\pm}$: kolaboracija ATLAS s trki pri energiji $\sqrt{s} = 7$ TeV [178, 179] in $\sqrt{s} = 8$ TeV [180]. Kolaboracija CMS ima objavo samo z $\sqrt{s} = 7$ TeV [181] podatki. Hipoteza je bila vselej zavrnjena in najmočnejše izključitvene limite je postavila analiza opisana v članku [180]. V odvisnosti od končnega stanja, spodnja meja s stopnjo zaupanja 95 % mase Higgsovega bozona variira od 465 GeV do 550 GeV pod predpostavko $B(H_L^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$. Prav tako sta ATLAS in CMS že analizirala hipotezo procesa KS: pri energiji trkov protonov $\sqrt{s} = 7$ TeV [182, 183], $\sqrt{s} = 8$ TeV [184, 185] in $\sqrt{s} = 13$ TeV [186]. Kolaboracija CMS ima tudi analizo s hadronskimi τ leptoni v končnem stanju pri energiji trkov $\sqrt{s} = 13$ TeV [187, 188]. Do sedaj ni nobenih sledi novih delcev bozona W_R in nevtrina N_R in prejšnja najmočnejša limita izhaja iz objave kolaboracije CMS [186]. Analizi predstavljeni v tem doktorskem delu nadgradita prejšnje analize kolaboracije ATLAS in ob zavrnitni hipoteze novih delcev postavita najmočnejše limite za te procese do sedaj.

Ključnega pomena pri analizi podatkov je primerjava izmerjenih trkov protonov s teoretično napovedjo Standardnega modela in procesov nove fizike. Za to primerjavo je potrebna numerična simulacija interakcije nastalih delcev in detektorja, saj je odziv detektorja netrivialen in nelinearen. V ta namen se uporabljajo računalniški programi na podlagi Monte-Carlo (MC) metod, ki naključno generirajo trke protonov z željenim rezultatom. MC metode se uporabijo tudi za simulacijo interakcij generiranih delcev z detektorjem ATLAS in za simulacijo analognega odziva detektorja. V tej disertaciji smo za simulacijo uporabili računalniški program GEANT 4 [91]. Izmerjeni podatki in simulirani dogodki so bili rekonstruirani z istim ATLAS-ovim programskim paketom za rekonstrukcijo dogodkov [92].

Za generacijo signalnih dogodkov $pp \rightarrow H^{++}H^{--}$ smo uporabili paket LRSM programa PYTHIA 8.186 [94]. Ta implementacija levo-desne simetrije temelji na opisu v referenci [113]. Parametri $h_{\ell\ell'}$ iz Enačbe 1 so bili postavljeni na enako vrednost in sklopitev bozona $H^{\pm\pm}$ z bozoni W je bila izklopljena ($v_L = 0$). Sipalni presek za ta proces je bil prvotno izračunan za $\sqrt{s} = 14$ TeV, nato pa so avtorji reference [114] izračunali sipalni presek tudi za $\sqrt{s} = 13$ TeV do reda ene zanke (ang. *next-to-leading order*). Za generacijo procesa KS smo uporabili program MG5_AMC@NLO 2.2.2 [97, 98]. Implementacija modela LRSM je opisana v referenci [118], ki pa je bila nato izboljšana, kot je opisano v referencah [69] in [70]. Generirani so bili samo N_R nevtrini v Majoranovi hipotezi, vendar lahko iste dogodke uporabimo za Diracovo hipotezo, če uporabimo samo nasprotno-značne dogodke in jih pomnožimo s faktorjem 2. Moč šibkih interakcij v generiranih dogodkih je enaka ($g_L = g_R$). Zaradi možnosti različnih mas nevtrinov N_R^e in N_R^μ je analiza opravljena samo s hipotezo enega težkega N_R nevtrina hkrati (predpostavimo, da obstaja samo eden N_R nevtrino pri dosegljivih energijah hkrati).

Pri predstavljenih analizah so glavni viri ozadja procesi, ki tvorijo pare enako nabitih leptonov. Ti procesi se delijo na neposredne, posredne in lažne. Najbolj pogosti neposredni procesi, ki sestavljajo



Slika 2: Pospeševalnik LHC je zadnji obroč (temno modra črta) v kompleksnem sistemu pospeševalnikov delcev. Manjši pospeševalniki se uporabljajo za postopno pospeševanje protonov do visokih energij. LHC trči protone na štirih točkah, ki ustrezajo glavnim eksperimentom, ALICE, ATLAS, CMS, in LHCb. Vzeto iz reference [77].

ozadje v tej analizi, so hkratna tvorba dveh vektorskih bozonov V ($V = Z, W$), ki razpadejo na leptone. Sledi jim proces $t\bar{t}V$, kjer lahko prav tako nastanejo neposredni pari enako nabitih leptonov. Doprinos neposrednih procesov Standardnega modela k ozadju smo ocenili z MC simulacijo na enak način kot doprinos signalnih dogodkov. Da izmed vseh izmerjenih podatkov izluščimo čimveč neposrednih in morebitnih signalnih dogodkov smo uporabili t.i. identifikacijske kriterije za leptone. To so izpeljane spremenljivke iz večih osnovnih spremenljivk, ki dobro ločijo med neposrednimi in posrednimi ter lažnimi leptoni. Izbrani identifikacijski kriteriji so navedeni v poglavju 6.3.1 v angleškem delu, vendar so kljub temu neposredni in lažni leptoni znatni del ozadja v predstavljeni analizi.

Posredni leptoni izvirajo iz razpadov dolgoživih delcev, in sicer večinoma iz semi-leptonskih razpadov težkih hadronov (vsebujejo kvarke b ali c). Posredni leptoni lahko s kombinacijo vektorskih bozonov povzročijo končno stanje dveh enako nabitih leptonov. Lažni leptoni so objekti, rekonstruirani kot leptoni, ki v resnici niso leptoni. Hadroni, ki se prekrivajo s pljuski, lahko v detektorju ATLAS povzročijo podoben odziv kot leptoni in so tako pomotoma rekonstruirani kot neposredni leptoni.

Simulacija takšnih dogodkov je zahtevna zaradi potrebnega zelo natančnega modeliranja močne interakcije, interakcije delcev z detektorjem in odziva detektorja. Poleg tega bi zaradi majhne verjetnosti napačne rekonstrukcije bilo potrebno simulirati tudi nedostopno visoko število takšnih dogodkov. Zaradi navedenih izzivov smo v doktorskem delu uporabili metodo, ki temelji na izmerjenih podatkih in se imenuje metoda "Fake-Factor". V večji obsežnosti je opisana v angleškem delu disertacije in v referenci [93]. Temelji na dvostopenjski identifikaciji leptonov, kjer leptone razdelimo na dve ortogonalni množici z imenoma "tight" (T) in "loose" (L). Množica "tight" vsebuje leptone, ki so uporabljeni za strukturo vseh signalnih območij v analizi, množica "loose" pa vsebuje leptone, ki niso dosegli potrebne ravni identifikacije za množico "tight", so pa dosegli določen znižan kriterij, zadosten za množico "loose". Metoda Fake-Factor nato omogoča ekstrapolacijo iz *stranskih* območij, izmerjenih s trki protonov, v signalna območja. Stranska območja so definirana na enak način kot signalna območja, vendar vsi leptoni niso dosegli zadostnega kriterija identifikacije. Ekstrapolacija je narejena s t.i. "Fake Factor"-ji ($F(p_T, \eta, \text{okus})$), ki so določeni izključno z izmerjenimi podatki. Število dogodkov, kjer je vsaj eden izmed leptonov neposreden ali lažen, se nato izrazi kot

$$N^{\text{fake}} = \sum_{i=1}^{N_{\text{SB}}^{\text{data}}} (-1)^{N_{L,i}+1} \prod_{l=1}^{N_{L,i}} F_l - \sum_{i=1}^{N_{\text{SB}}^{\text{MC}}} (-1)^{N_{L,i}+1} \prod_{l=1}^{N_{L,i}} F_l,$$

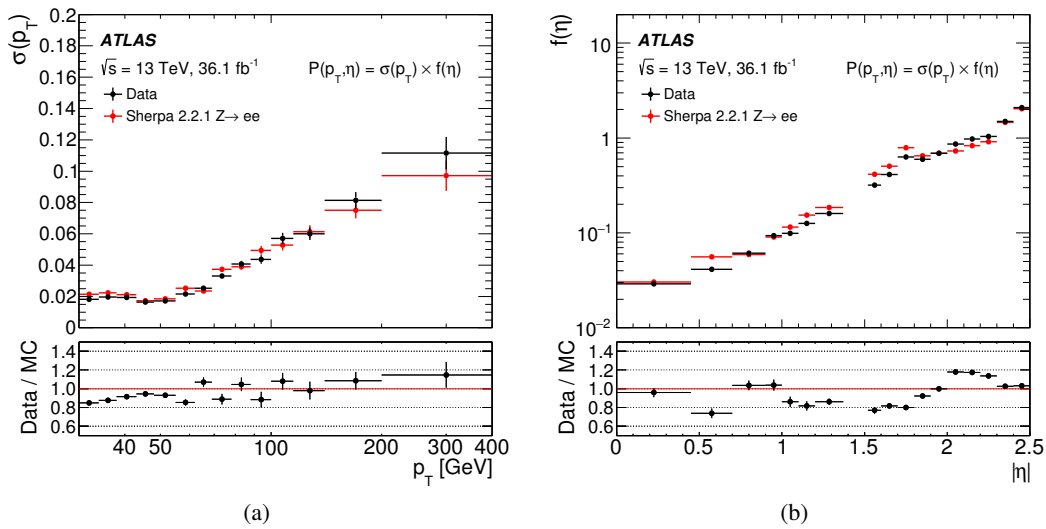
kjer je $N_{\text{SB}}^{\text{data}}$ število izmerjenih dogodkov v tem stranskem območju in $N_{L,i}$ število leptonov v i -tem dogodku stranskega območja iz množice "loose". Vsak tak lepton ima svoj pripadajoč $F(p_T, \eta, \text{okus})$, ki je povezan z verjetnostjo, da je tak lepton narobe identificiran kot lažen ali neposreden lepton.

Dodaten vir ozadja so elektroni, ki smo jim narobe izmerili naboj ($\pm \rightarrow \mp$)⁴. Ta tip ozadja je podoben lažnemu ozadju, saj sta oba posledica interakcij v detektorskem materialu; narobe izmerjen naboj je posledica končne resolucije in pomanjkljivosti detektorja. Leptoni z visoko transversalno gibalno količino imajo toge sledi, ki jim je težko določiti ukrivljenost, kar lahko vodi do narobe določenega naboja. Leptoni lahko tudi izsevajo foton, ki nato reagira z atomskim jedrom detektorskega materiala in tvori par elektron-pozitron. Ti trije leptoni so ponavadi zelo kolimirani in razmažejo naboj prvotnega leptona, kar lahko vodi do napake pri meritvi naboja. To ozadje najbolj pogosto nastopi ob produkciji bozona Z , kjer je naboj enega izmed leptonov narobe rekonstruiran ($Z \rightarrow e^+ e^- \rightarrow e^\pm e^\pm$). Simulacija tega ozadja se zaradi kompleksnosti pojava ni najbolje ujemala z izmerjenimi podatki. V doktorskem delu sem raziskoval pojave, ki vodijo do napačne rekonstrukcije naboja elektrona (poglavje 5 v angleškem delu), in izpeljal popravke, ki jih apliciramo na simulirane dogodke in izboljšamo ujemanje med simulacijo ter meritvijo.

Popravki za rekonstrukcijo naboja elektrona so izpeljani s primerjavo verjetnosti za napačno rekonstrukcijo naboja v izmerjenih podatkih in simulaciji. Verjetnost je izmerjena v posebnem območju, ki ustreza razpadu $Z \rightarrow ee$. To so pari elektronov, ki dosežejo določeno invariantno maso glede na njihov naboj, $|m_{\text{OS}}(ee) - m(Z)| < 14.0 \text{ GeV}$ in $|m_{\text{SS}}(ee) - m(Z)| < 15.8 \text{ GeV}$. Število enako-značnih in nasprotno-značnih parov elektronov je $N^{ij} = N_{\text{SS}}^{ij} + N_{\text{OS}}^{ij}$, kjer indeksa i in j ustrezata dvema elektromoma. Verjetnost za narobe rekonstruiran naboj je nato izračunana kot $P = N_{\text{SS}}^{ij} / N^{ij}$. Običajno se ta verjetnost izrazi kot dvodimenzionalna verjetnost, $P = P(p_T, \eta)$, vendar pa je bila za analize v tem

⁴ Ta tip ozadja za mione ni prisoten, saj je naboj mionov zaradi njihove manj pogoste interakcije z detektorjem veliko bolj pogosto pravilno izmerjen kot pa za elektrone.

doktorskem delu prvič v eksperimentu ATLAS uporabljena parametrizacija $P(p_T, \eta) = \sigma(p_T) \times f(\eta)$. Transverzalna gibalna količina ustreza sipalnemu preseku za interakcijo elektrona z materialom detektorja ATLAS, kotna spremenljivka η pa opiše količino materiala, ki ga elektron prepotuje. Ta dva efekta sta v principu nekorelirana, kar je glavna motivacija za parametrizacijo $P(p_T, \eta) = \sigma(p_T) \times f(\eta)$. Prednost te parametrizacije pred običajno 2D parametrizacijo je manjše število prostih parametrov ($N_{p_T} + N_\eta$ namesto $N_{p_T} \times N_\eta$) in posledično omogoča meritev verjetnosti narobe rekonstruiranega naboja do višjih energij (okoli 300 GeV). To je ključnega pomena za predstavljene analize, ki iščejo pare enako nabitih elektronov pri visokih energijah. Rezultat meritev te verjetnosti je prikazan na Sliki 3 za simulacijo (rdeči krožci) in za izmerjene podatke (črni krožci). Razmerje med verjetnostjo v podatkih in simulacijo tvori popravke, ki jih v končni analizi apliciramo na vse elektrone v simulaciji. Elektroni z narobe rekonstruiranim nabojem dobijo popravek $P(\text{data})/P(\text{MC})$, elektroni s pravilno rekonstruiranim nabojem pa $(1 - P(\text{data}))/(1 - P(\text{MC}))$.



Slika 3: Verjetnost za narobe rekonstruiran naboj izmerjena v simulaciji (rdeči krožci) in podatkih (črni krožci): (a) p_T odvisnost in (b) η odvisnost. Razmerje obeh verjetnosti (spodnji del) ustrezajo popravkom, ki jih apliciramo na simulirane elektrone v končni analizi. Vzeto iz reference [93].

Sistematične napake, ki spremljajo napoved ozadja in signala, se delijo ne teoretske in eksperimentalne. Teoretske sistematične napake izvirajo iz končnega reda (ponavadi do ene zanke) generiranih dogodkov in nepopolnega poznavanja Standardnega modela. Teoretske napake so višje v primeru analize Keung-Senjanovičevega (KS) procesa, saj ta vsebuje dva pljuska v končnem stanju in so tako procesi ozadja bolj podvrženi izbiri renormalizacijske in faktorizacijske skale (μ_R in μ_F). Na primer, teoretska napaka v napovedi števila dogodkov v končnem stanju $\ell\ell jj$ lahko sega do 40 % za tvorbo parov dveh vektorskih bozonov. Eksperimentalne sistematične napake izvirajo iz neujemanja simulacije in meritev pri kalibraciji ter identifikaciji leptonov in pljuskov. Pri predstavljenih analizah so te napake manjše v primerjavi z ostalimi. Dodatne eksperimentalne napake izvirajo iz napovedi ozadja s "Fake-Factor" metodo in iz popravkov za rekonstrukcijo naboja (Slika 3). Izmerjeni $F(p_T, \eta, \text{okus})$ privzamejo, da imajo vsi tipi lažnih in neposrednih leptonov enako verjetnost za nepravilno rekonstrukcijo elektrona, vendar to ni popolnoma res. Dodatna napaka izvira iz končnega števila dogodkov,

uporabljenih za meritev $F(p_T, \eta, \text{okus})$. Oba vira skupaj tvorita sistematično napako na $F(p_T, \eta, \text{okus})$ od 5 do 40 % v odvisnosti od energije leptonov in števila pljuskov v dogodku. Sistematična napaka popravkov za rekonstruiran naboj izvira predvsem iz končne statistike dogodkov, uporabljenih za meritev verjetnosti za narobe rekonstruiran naboj elektrona, in znaša od 5 do 20 %.

Statistično obdelavo podatkov smo naredili s programom HISTFITTER [211], ki nudi implementacijo metode maksimalne zanesljivosti (ang. *maximum-likelihood fit*). Statistična analizo smo opravili ločeno za hipotezo bozona $H^{\pm\pm}$ in za proces KS. Verjetnost, ki jo maksimiramo, je sestavljena kot produkt Poissonove verjetnosti za opis izmerjenega števila dogodkov v nekem območju in Gaussove verjetnosti za modeliranje prostih parametrov, ki ustrezajo sistematični napaki. Širina Gaussove porazdelitve ustreza jakosti vsake posamične sistematične napake. Poleg tega so dodani Poissonovi členi za statistično napako zaradi končnega števila simuliranih MC dogodkov in pa prosti parametri za normalizacijo vodilnih neposrednih ozadij: Drell–Yanov proces ($Z \rightarrow ee$) in tvorba dveh vektorskih bozonov. Po maksimirani verjetnosti smo primerjali izmerjene podatke s pričakovanim ozadjem in nismo opazili nobenega statistično signifikantnega odstopanja. Posledično smo izpeljali gornjo mejo za sipalni presek procesa $pp \rightarrow H^{++}H^{--}$ in procesa KS s stopnjo zaupanja 95 % z metodo CL_s [212].

Območja, uporabljena za statistično obdelavo, se delijo na tri tipe: kontrolna območja (CR), preverjalna območja (VR) in signalna območja (SR). V maksimiranju verjetnosti smo uporabili kontrolna in signalna območja, maksimirane vrednosti (sistematična napaka in normalizacija nekega ozadja) pa smo nato ekstrapolirali v preverjalna območja. Razlika med kontrolnimi in signalnimi območji je, da se za normalizacijo ozadja uporabijo samo kontrolna območja, signalna območja pa se uporabijo za normalizacijo hipotetičnega signala. Kontrolna območja smo optimizirali tako, da vsebujejo čimveč nekega tipa ozadja (npr. samo Drell–Yanov proces). Namen preverjalnih območij je preveriti veljavnost določenega tipa ozadja, npr. izračunanega ozadja z metodo "Fake-Factor" ali ozadja napačne rekonstrukcije naboja elektrona. Definiciji območij obeh analiz sta podani v Tabeli 1 za iskanje bozonov $H^{\pm\pm}$ in v Tabeli 2 za analizo procesa KS. V obeh analizah igra ključno vlogo invariantna masa enako-značnih leptonov, saj signal pričakujemo pri višjih masah. Prav tako je v obeh primerih zahtevana visoka transverzalna energija nastalih produktov $H_T = \sum |p_T(\ell)|$ in odsotnost pljuskov, identificiranih kot pljuski, ki vsebujejo težke hadrone s kvarki b (ang. *b-jet veto*).

Tabela 1: Definicija območij v analizi $pp \rightarrow H^{++}H^{--}$. Tabela je razdeljena na tri dele: zgornji prikazuje končno stanje, srednji prikazuje zahtevano invariantno maso enako nabitih leptonov v tem območju in spodnji prikazuje dodatne selekcijske kriterije. Kriteriji, ki so uporabljeni v določenem območju, so označeni s kljukico (✓). Vzeto iz reference [93].

	Control Regions			Validation Regions			Signal Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
Electron channel	$e^{\pm}e^{\mp}$	$e^{\pm}e^{\pm}e^{\mp}$		$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$		$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$	
Mixed channel	-	$e^{\pm}\mu^{\pm}\ell^{\mp}$	$\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$	$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell^{\mp}$	$\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$	$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell^{\mp}$	$\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$
Muon channel	-	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$	
$m(e^{\pm}e^{\pm})$ [GeV]	[130, 2000]	[90, 200)		[130, 200)	[90, 200)		[200, ∞)	[200, ∞)	
$m(\ell^{\pm}\ell^{\pm})$ [GeV]	-	[90, 200)	[60, 150)	[130, 200)	[90, 200)	[150, 200)	[200, ∞)	[200, ∞)	[200, ∞)
$m(\mu^{\pm}\mu^{\pm})$ [GeV]	-	[60, 200)		[60, 200)	[60, 200)		[200, ∞)	[200, ∞)	
b -jet veto	✓	✓	✓	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-	-	✓	✓
$\Delta R(\ell^{\pm}, \ell^{\pm}) < 3.5$	-	-	-	-	-	-	✓	✓	-
$p_T(\ell^{\pm}\ell^{\pm}) > 100$ GeV	-	-	-	-	-	-	✓	✓	-
$\sum p_T(\ell) > 300$ GeV	-	-	-	-	-	-	✓	✓	-
$\Delta M/\bar{M}$ requirement	-	-	-	-	-	-	-	-	✓

Tabela 2: Definicija območij v analizi procesa KS. Analiza je razdeljena na kanala OS in SS, kot je prikazano v tabeli. Gornji del prikazuje zahtevano invariantno maso para leptonov, spodnji del pa dodatne selekcijske kriterije. Vzeto iz reference [190].

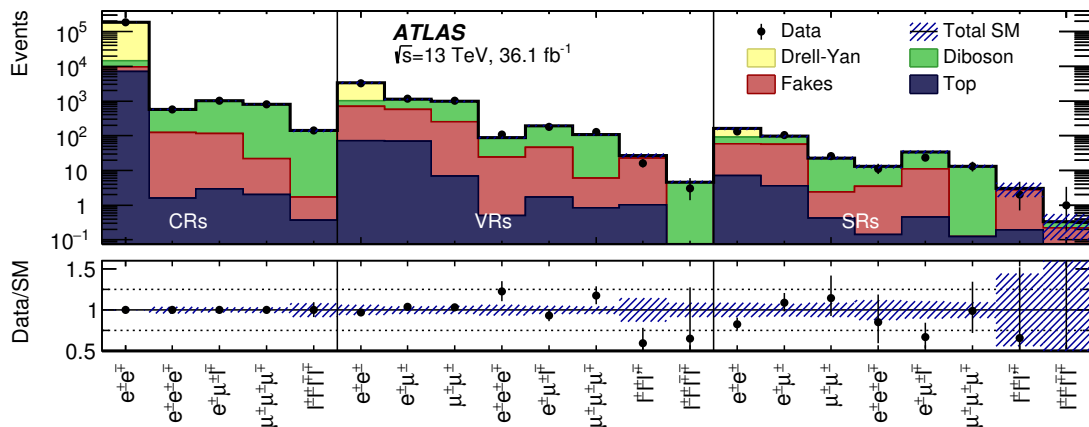
Region	Control region			Validation region		Signal region	
Channel	CR($\ell^{\pm}\ell^{\mp}$)	CR($\ell^{\pm}\ell'^{\mp}$)	CR($\ell^{\pm}\ell^{\pm}$)	VR($\ell^{\pm}\ell^{\mp}$)	VR($\ell^{\pm}\ell^{\pm}$)	SR($\ell^{\pm}\ell^{\mp}$)	SR($\ell^{\pm}\ell^{\pm}$)
m_{ee} [GeV]	[60, 110]	—	[110, 300]	[110, 400]	[300, 400]	> 400	> 400
$m_{\mu\mu}$ [GeV]	[60, 110]	—	[60, 300]	[110, 400]	[300, 400]	> 400	> 400
$m_{e\mu}$ [GeV]	—	> 400	—	—	—	—	—
H_T [GeV]	> 400	> 400	—	> 400	—	> 400	> 400
$m(jj)$ [GeV]	> 110	> 110	—	> 110	—	> 110	> 110
jet p_T [GeV]	> 100	> 100	> 50	> 100	> 50	> 100	> 100

Signalna območja analize bozona $H^{\pm\pm}$ so razdeljena na območja z dvema, tremi in štirimi leptoni v končnem stanju. Ta klasifikacija omogoča občutljivost na ves spekter razvejitenega razmerja $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$ in zviša statistično občutljivost, kadar ne rekonstruiramo vseh nastalih signalnih leptonov. V območju s štirimi leptoni "2P4L" smo dodali tudi zahtevo po določeni razliki invariantnih mas obeh parov enako nabitih leptonov $\Delta M/\bar{M}$ v odvisnosti od mase parov in okusa leptonov. To ustreza hipotetičnemu signalu, kjer nastaneta dva bozona $H^{\pm\pm}$ z enako maso v paru. Skupna učinkovitost rekonstrukcije signalnih dogodkov $pp \rightarrow H^{++}H^{--}$ je odvisna predvsem od razmerja $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$ in mase bozona $H^{\pm\pm}$. variira od 0 za $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 0$ do 70 % za $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100$ %. Ozadje Drell–Yanovega procesa je normirano v območju "OCCR", proces nastanka dveh vektorskih bozonov v območjih "DBCR" in proces nastanka dveh vektorskih bozonov s štirimi leptoni v končnem stanju v območju "4LCR". Analiza ima tri tipe preverjalnih območij: "SCVR" za območja z dvema leptonoma, "3LVR" za tri leptone in "4LVR" za štiri leptone v končnem stanju.

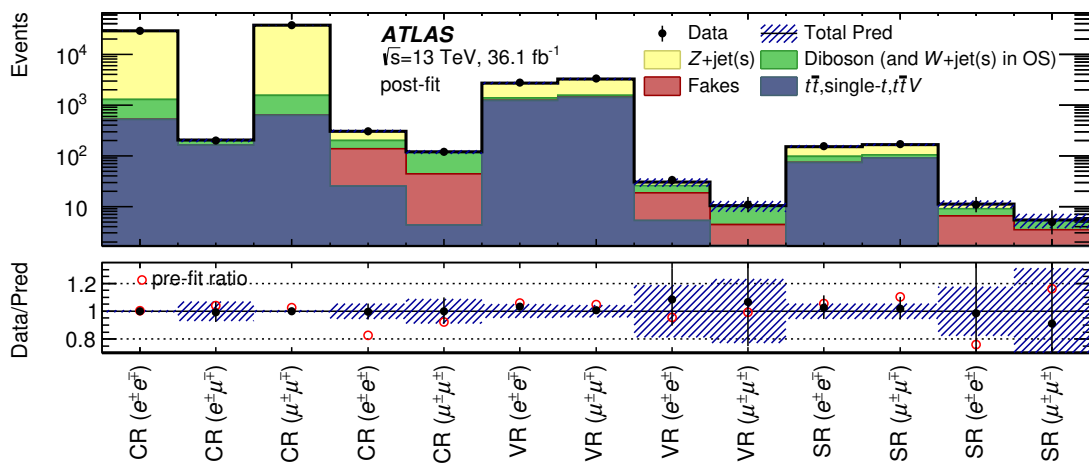
Pri iskanju procesa KS se območja delijo na kanala SS in OS. V končnem stanju zahtevamo dva leptona in dva pljuska. Ker pljuska izhajata iz težkega bozona W_R , smo postavili zahtevo po visoki invariantni masi dveh pljuskov. Prav tako smo podali zahtevo po visoki transverzalni energiji pljuskov v dogodku. V kanalu SS je ozadje Drell–Yanovega procesa normirano v območju " $CR(e^\pm e^\pm)$ ", proces nastanka dveh vektorskih bozonov pa v dveh območjih " $CR(e^\pm e^\pm)$ " in " $CR(\mu^\pm \mu^\pm)$ ". Učinkovitost rekonstrukcije procesa KS s to definicijo signalnih območij variira od nekaj procentov za nizke mase bozona W_R in nevtrina N_R , ki so že izključeni s prejšnjimi analizami, do 50 % za višje mase.

V opisanem maksimiranju verjetnosti ne nastopajo samo števila dogodkov v določenem območju, vendar celotne porazdelitve izbrane spremenljivke. V analizi $H^{\pm\pm}$ je ta spremenljivka vedno invariantna masa enako-značnih leptonov v dogodku, v kanalu SS analize procesa KS pa je ta spremenljivka skalarna vsota transverzalnih količin objektov v dogodku H_T . Izmerjeno in pričakovano število dogodkov v vseh območjih analize je podano v Sliki 4. Pričakovana števila ustrezajo vrednostim, ki jih dobimo po maksimiranju verjetnosti, kot je opisano v besedilu. V obeh analizah se meritev sklada s Standardnim modelom in hipoteza novih delcev je bila zavrnjena. Prav tako je ujemanje med napovedjo in meritvijo skladno v preverjalnih območjih, kar poviša verodostojnost meritev in uporabljenih metode za napoved ozadja.

Ob zavrnitvi hipoteze signala je končni rezultat analize zgornja meja s stopnjo zaupanja 95 % na sipalnem preseku za nastanek tega signala. Za hipotezo bozona $H^{\pm\pm}$ so rezultati podani v strnjeni obliki na Sliki 5, ločeno za delca $H_L^{\pm\pm}$ in $H_R^{\pm\pm}$. Razlika med njima je samo sipalni presek za nastanek v paru, saj se bozon $H_R^{\pm\pm}$ ne sklaplja s šibkim bozonom Z in tako nastane samo preko razpada bozona γ . Limito smo izračunali za vse kombinacije razvejitenih razmerij $B(H^{\pm\pm} \rightarrow e^\pm e^\pm)$, $B(H^{\pm\pm} \rightarrow e^\pm \mu^\pm)$ in $B(H^{\pm\pm} \rightarrow \mu^\pm \mu^\pm)$, ki se seštejejo v nek $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$. Rezultat je nato podan kot funkcija $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$, kjer je za vsako vrednost podana najšibkejša limita izmed vseh in tako velja za vse kombinacije. Rezultati analize procesa KS so prikazani na Sliki 6. Slika prikazuje izmerjeno (polna črta) in pričakovano (črtkana črta) spodnjo mejo v odvisnosti od mase bozona W_R in nevtrina N_R . Limito smo podali ločeno za kanala SS in OS in za statistično kombinacijo. V statistični kombinaciji je vselej predpostavljena Majoranova narava nevtrinov, ki tako tvorijo obe končni stanji z verjetnostjo 50 %. Slika hkrati prikazuje, da je kanal SS statistično močnejši od kanala OS, kar pa je posledica mnogo manjšega ozadja Standardnega modela v končnih stanjih s pari enako-značnih leptonov.

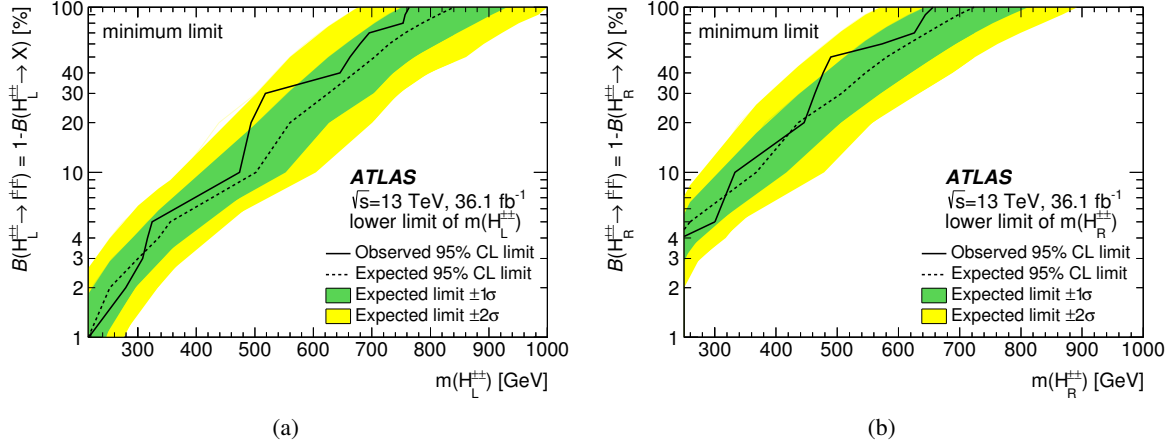


(a)

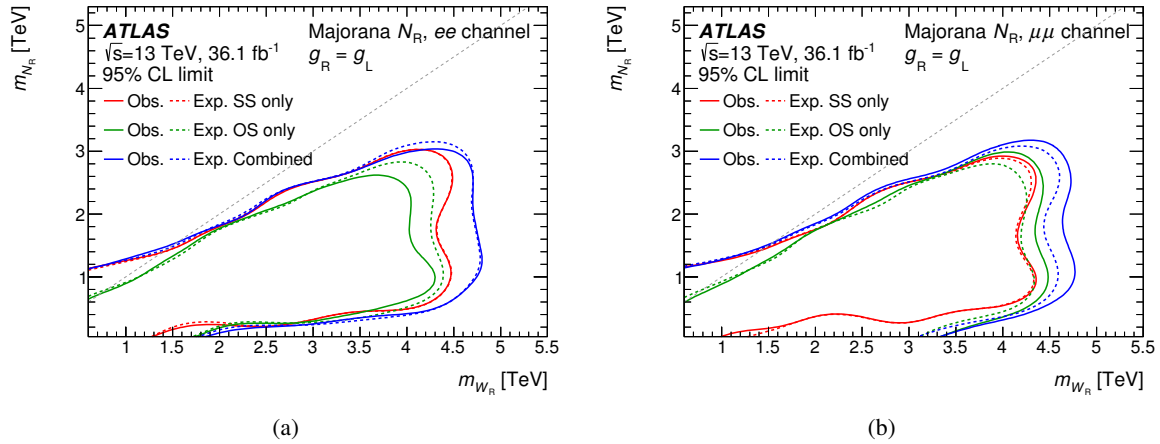


(b)

Slika 4: Število izmerjenih in pričakovanih dogodkov v vseh območjih v analizi: (a) območja v analizi bozona $H^{\pm\pm}$ in (b) območja v analizi procesa KS. Pričakovano število dogodkov ozadja (Total SM) je podano po maksimiranju verjetnosti, kot je opisano v besedilu. Šrafirani vzorec vsebuje vse sistematične napake z upoštevanimi korelacijami po maksimirani verjetnosti. Vzeto iz referenc [93] in [190].



Slika 5: Spodnja meja s stopnjo zaupanja 95 % za maso bozona $H^{\pm\pm}$. Limita je izračunana za vse kombinacije razvejitenih razmerij $B(H^{\pm\pm} \rightarrow e^\pm e^\pm)$, $B(H^{\pm\pm} \rightarrow e^\pm \mu^\pm)$ in $B(H^{\pm\pm} \rightarrow \mu^\pm \mu^\pm)$, ki se seštejejo v $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$. Za vsak $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$ podana najšibkejša limita in tako velja za vse kombinacije. Vzeto iz reference [93].



Slika 6: Izmerjena (polna črta) in pričakovana (črtkana črta) spodnja meja z gotovostjo 95 % v odvisnosti mase bozona W_R in nevtrina N_R . Rezultati so podani ločeno za oba kanala, SS in OS, in za statistično kombinacijo: (a) za končno stanje z dvema elektronoma in (b) za končno stanje z dvema mionoma. Vzeto iz reference [190].

Predstavljeni analizi podatkov predstavljata najmočnejše limite modela LRSM do sedaj. Spodnja meja za maso hipotetičnega bozona $H_L^{\pm\pm}$ variira od 770 do 870 GeV za predpostavko $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ in je še vedno nad 450 GeV za $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \geq 10\%$ za vse kombinacije razvejitenih razmerij. Za hipotetičen bozon $H_R^{\pm\pm}$ sega limita pri $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ od 660 do 760 GeV in je najmanj 320 GeV za $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \geq 10\%$. Limite za maso delca $H_L^{\pm\pm}$ in predpostavko $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 100\%$ so za 300 GeV višje od prejšnjih najmočnejših. Analiza procesa KS in iskanje bozona W_R ter nevtrina N_R se je prav tako končala z zavrnitvijo hipoteze in je izboljšala najmočnejše spodnje meje mase teh delcev do sedaj. Spodnja meja sega do $m(W_R) = 4.7$ TeV za $m(N_R) = 1.2$ TeV. V drugi smeri sega do $m(N_R) = 2.8$ TeV (za $m(W_R) = 3.7$ TeV) v elektronskem kanalu in $m(N_R) = 3.2$ TeV (za $m(W_R) = 4.1$ TeV) v mionskem kanalu. V območju $m(N_R) > m(W_R)$ je spodnja meja mase nevtrina N_R okoli 1.5 TeV. Ti rezultati izboljšajo prejšnje najmočnejše za 1 do 2 TeV in so prvi tovrstni rezultati za hipotezo $m(N_R) > m(W_R)$. Predstavljeni analizi pokažeta tudi moč končnih stanj s pari enako-značnih leptonov in eksperimentalne metode, uporabljene za napoved ozadja v takšnih končnih stanjih. Uporabljena metoda za korekcijo rekonstrukcije naboja elektrona je v tej disertaciji objavljena prvič in izboljša prejšnjo metodo, predvsem za elektrone z visoko energijo nad 200 GeV.