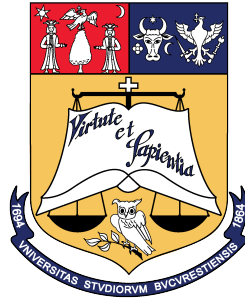


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**SEARCH FOR HBSM DOUBLE CHARGED SCALAR
BOSONS IN MULTI-LEPTONS FINAL STATES USING
PROTON-PROTON COLLISIONS AT $\sqrt{s} = 13$ TeV WITH
THE ATLAS DETECTOR**

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DECLARATION

I declare that this thesis entitled, “Search for HBSM double charged scalar bosons in multi-leptons final states using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector” was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified. The data presented was obtained in the ATLAS experiment carried out by the CERN in Geneva, Switzerland. I played my role in analyzing and interpreting the data and the results obtained were presented within collaboration. Any contributions from other colleagues such as diagrams or calibrations are patently cited in the text.

SULMAN YOUNAS

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Chapter 1

Introduction

The details about the kinetics of the subatomic particles and amalgamation of three fundamental forces of nature except gravity is precisely furnished by the Standard Model of Particle Physics (SM). The validity of the SM is being estimated through the present experiments specifically through Large Hadron Collider (LHC) experiments which have been providing enough quantification in this regard. The recent uncovering of the Higgs boson by the ATLAS [39] and CMS [40] collaborations at the LHC in the year 2012 accomplished the most recent landmark in the way of triumph of this model.

The SM is more of an estimation of the fundamental hypothesis of nature as being advocated by theoretical and experimental deliberations. The one of the aims of the high energy physics is to discover this theory. Being still deficient in the terms of providing direct discoveries of new matter particles or new force carriers, this model is consistent with the predictions in the field of experimental particle physics.

The Higgs boson is a paramount to evaluate the predictions of the SM and it settles at the core of the model by coupling to various independent parameters. At the same instant, the Higgs boson is intensely connected with the intrinsic theoretical problems of the SM and quite a few trails were executed to extend the SM to furnish the explanation about dark matter that turns into a subsequent transformation of the Higgs boson's properties as compared to the SM speculations [1]. In the wake of that, an accurate ascertainment of all the Higgs boson's properties is crucial that could probe new physics evidently.

The ATLAS and CMS experiments have observed the coupling strengths of the Higgs boson to the other elementary particles as being speculated by the SM. However the coupling of the Higgs boson to fermions of first and second generation is obscure for now. The coupling of the Higgs boson with the third generation fermions have manifested the consistency with the hypotheses of the SM that falls within relative uncertainties of about 20% [2]. Likewise the couplings of the Higgs boson to vector bosons are estimated to be consistent with the SM within relative uncertainties of $\sim 10\%$ [2].

Besides the computations of the extensive coupling strengths, the evaluation of differential entities for instance the transverse momentum distribution of the Higgs boson

i.e. $d\sigma/dp_T^H$ is pertinent. In spite of the fact that collision energy of the LHC is not that sufficient to investigate new physics at the moment but the SM can distinctively be adapted in accordance with required changes at high p_T^H . These substantial fluctuations would not affect the already measured couplings, even though the cross-sections are relatively low in this regime.

The collider with the adequate luminosity and the rather high centre-of-mass energy $\sqrt{s}$ is requisite to yield a sufficient amount of Higgs bosons for such kind of assessments at the LHC, colliding hadrons i.e. protons at $\sqrt{s} = 13$ TeV. The huge collision data collected by the ATLAS experiment at $139fb^{-1}$ during the second operational run of the LHC, is pioneering to great opportunities to execute the measurements in such low cross-sections areas.

This thesis entails the latest measurements on the Higgs boson production in association with heavy vector bosons i.e. W and Z . The experimental signatures with the two leptons together with the same electric charge or mutli-lepton final states have been employed in the searches for physics beyond the Standard Model (BSM) at LHC. The various models detect heavy BSM particles yielded during proton-proton collisions and then get decayed into multiple massive SM electroweak gauge bosons or top quarks. The signatures with the two leptons of same charge or three or four leptons with various charge combinations have been exploited by the ATLAS and CMS experiments in order to investigate possible SM extensions and phenomenology.

The riveting expansion among the preferred SM extensions is instigating SM sector of the weak gauge triplet of scalar fields along with non-zero vacuum expectation value of the neutral component that leads to the neutrino masses through the type-II seesaw mechanism [138]. The phenomenology of the doubly charged scalar bosons ($H^{\pm\pm}$) that can be produced in pairs and then decay into W bosons with the same charge and singly charged scalar bosons ($H^\pm$) decay into W along with Z bosons are taken in consideration.

The structure of thesis is as follows:

Chapter. 2 covers the theoretical background of the Standard Model and its limits are briefly identified. In addition, extensions of the SM that includes Higgs sector beyond SM, SUSY and it extensions are concisely described.

Chapter. 3 presents an introduction to the CERN's experiments in general and ATLAS experiment in particular.

Chapter. 4 describes details about object reconstruction at ATLAS experiment. The various objects i.e. electron, photons, muons and jets reconstruction is entailed.

Chapter. 5 concludes my contribution towards efficiency and its uncertainties measurements. The first part entails the measurement methodology used by the ATLAS inner detector to perform the efficiency measurement for the reconstruction algorithm [122]. The brief description of the *tag-and-probe* method that permits to select an unbiased sample of electrons in data, and estimation of the residual background contributions for

the efficiency measurement is provided. Then the results about statistical uncertainties measurements through pseudo-experiments are dispensed. The scale factors measurement for AF2 samples in release 21 with release 21 framework's setup are given. The re-implementation of methodology for electron reconstruction efficiency in release 22 framework and the proof of correctness of that work and comparison of scale factors in either versions of frameworks i.e. Rel21 & Rel22 is also provided.

Chapter. 6 aims at signal searches to extend the scalar sector of the Standard Model with a scalar triplet, directing to a phenomenology which comprehends singly and doubly charged Higgs bosons. This chapter presents the topologies used for the analysis and gives us the details of theoretical framework. The Monte Carlo simulations used for various selection variables are documented and the signal regions used for the different mass hypotheses of $H^{\pm\pm}$ & $H^\pm$ are described in order to distinguish signatures of BSM processes from SM backgrounds. The preliminary results obtained for each pre-selection channel i.e. 2L, 3L and 4L are concluded as well.

Chapter. 7 summarizes all the work carried through out for this dissertation.

Chapter 2

Theoretical foundations

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The summary of the Standard Model of Particle Physics (SM) is given in the Section. 2.1. The achievements and limitations of the SM are extended in the Section. 2.6. The brief description on Physics Beyond Standard Model stressing Higgs sector, Supersymmetry and encouragement to the extension of the Higgs sector and SUSY is encapsulated in the Section. 2.7. The drawbacks of the BSM Higgs bosons at LHC are furnished in the Section. 2.8.

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In this chapter, the presented Feynman diagrams are sketched by using TikZ-Feynman LaTeX package [27].

2.1 The Standard Model of Particle Physics

The details of the matter particles and their interactions is described by the theoretical model termed as Standard Model (SM). The gravity is not being considered by the SM yet. The Standard Model with all particles is summarised in the Fig. 2.1.

The SM is Lorentz invariant and is to be classified into matter constituents in accordance with their quantum number i.e. charges. The kinetics of their interactions is determined through the local gauge invariance as in relation;

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

Where the subscript refers to charge with respect to each symmetry group. The strong force is carried out through the $SU(3)_C$ group with respect to charge referred as "color" (C). The term $SU(2)_L \times U(1)_Y$ describes electromagnetic and weak interactions which are characterised by hypercharge (Y) and the isospin for each symmetry group. The subscript "L" points to the $SU(2)$ generators which interact with fermions i.e. left handed and antifermions i.e. right handed.

The two classification of the fermions are considered in the SM i.e. quarks and leptons. They are found in three generations and hold electric & color charge i.e. red, blue and green distinctively. The formation of the stable matter in the nature is revolving around charged fermions i.e. first generation candidates. The two consecutive families of the fermions are distinguished through their masses. Being unstable they get decayed into other fermions of the lower generations after certain life time which are then recreated in particle collisions. The leptons particularly do not contribute in the strong interactions as they do not comprises any color charge.

The quarks however are categorised on the basis of their charge for instance quarks holding $+2/3$ charge categorised as "up quarks" while those with $-1/3$ are classified as "down quarks". The quarks contribute to all the fundamental interactions in the SM.

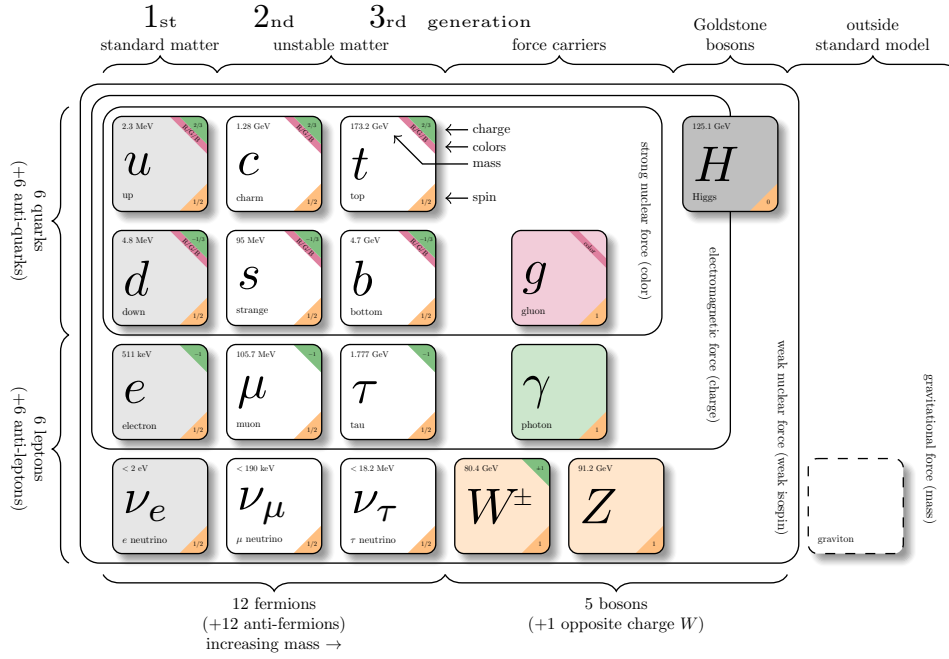


Figure 2.1: An outline of the SM constituents comprising matter particles and force carriers. Adapted from Ref. [3]

2.1.1 The Electromagnetic force

The charge particles i.e. electrons, muons etc are carried through the electromagnetic interaction and are interceded by electrically neutral particle i.e. photon (γ). The electromagnetic force has a wide range as the photons have no mass. Hence this interaction is referred as Quantum electrodynamics (QED).

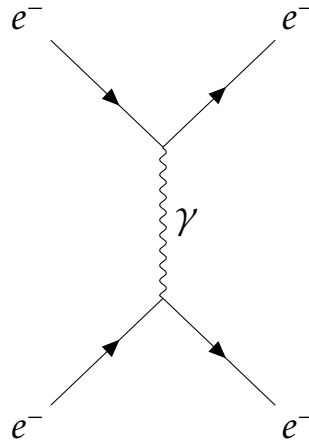


Figure 2.2: An overview of the first order Feynman diagram elucidating an electron-electron scattering through photon exchange.

Quantum electrodynamics

Having said that Quantum electrodynamics (QED) is the theoretical model encapsulating electromagnetic interactions. It encompasses Maxwell's equations that is taken as kinematic term along with the Dirac term to characterise equations on the free fermions e.g; electrons. The Lagrangian density can be adapted from Ref. [4, 5] for the free spin-1/2 field ψ with mass m of a fermion as:

$$\mathcal{L} = \bar{\psi}(x)(i\gamma^\mu \partial_\mu \psi - m)\psi(x) \quad (2.2)$$

where ∂_μ refers to gradient containing $\mu = 0, 1, 2, 3$ i.e. Dirac matrices. The first bit indicates the time dependent and rest of three bits are referring to spatial entities.

The Lagrangian acts as invariant under a global $U(1)$ transformation where the field transforms as;

$$\psi(x) \rightarrow \psi(x)' = e^{iq\theta} \psi(x) \quad (2.3)$$

It is deductive under the a local phase transformation in which the entity θ revolves around the space-time coordinate and the field is altered as;

$$\bar{\psi}(x) \rightarrow \bar{\psi}(x)' = \bar{\psi}(x)e^{-iq\theta} \quad (2.4)$$

By substituting covariant derivative in the Lagrangian, the invariance under the local transformation becomes;

$$D_\mu \equiv \partial_\mu + iqA_\mu(x) \quad (2.5)$$

where $A_\mu(x)$ is a vector field and turns into after transformation;

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \theta(x) \quad (2.6)$$

The QED Lagrangian can be recorded then by introducing new vector field as;

$$\mathcal{L}_{QED} = \underbrace{\bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi}_{\text{free electron Lagrangian}} - \underbrace{q\bar{\psi}\gamma^\mu \psi A_\mu}_{\text{interaction term}} - \underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{free photon Lagrangian}} \quad (2.7)$$

With

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad (2.8)$$

The component given in the brackets in Eq. 2.7 refers the free fermionic field that includes kinetic energy term (the first part) and mass term (second part). The third term indicates an interaction between fermionic field and vector field i.e. A_μ referring to photon field. The kinematics of the photon is determined by the free-field Lagrangian which refers to the last term in the Eq. 2.7. Now all the components in the equation become invariant under the combination of gauge transformations referred in Eqs. 2.3 & 2.6.

2.1.2 The strong force

The massless gluons are mediator to the strong interactions and they are found in eight variations: color and anti color states that refers to $SU(3)$ part of the gauge group as given in the Eq. 2.1. These gluons go through the interactions among themselves that accounts for *asymptotic freedom* and *confinement*. Where the idea of asymptotic freedom indicates that the coupling constant α_s for the strong interaction turns to weaker at short distances or large momentum transfer distinctively. The confinement on the other hand associated with the growth of the interaction strength at substantially large distances or small momentum transfer.

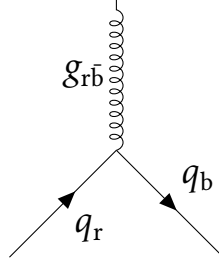


Figure 2.3: The depiction of the Feynman diagram elucidating a quark-gluon interaction.

Quantum chromodynamics

The QCD comes from the $SU(3)_C$ gauge group and its 8 kind of generators are termed as Gell-Mann matrices i.e. λ^a . The QCD Lagrangian of a fermion by Dirac including kinematic term can be written as;

$$\mathcal{L}_{QCD} = \sum_f \bar{\psi}_f (i\gamma_\mu D^\mu - m_f) \psi_f - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \quad (2.9)$$

where the sum f iterate over all the color possibilities of the quark fields while $\bar{\psi}_f$ refers to a spinor triplet. The covariant derivative D_μ is enclosed as;

$$D_\mu \equiv \partial_\mu + ig_s \frac{\lambda^a}{2} G_\mu^a \quad (2.10)$$

where g_s is referred as $SU(3)_C$ coupling constant and G_μ^a indicates eight gluon fields. Nevertheless, the field strength tensors $G_{\mu\nu}^a$ are encapsulated as:

$$G_{\mu\nu}^a = \partial^\mu G_\nu^a - \partial^\nu G_\mu^a - \underbrace{g_s f^{abc} G_\mu^b G_\nu^c}_{\text{self-interaction terms}} \quad (2.11)$$

Where f^{abc} refers to the constants coming from the $SU(3)_C$. The term responsible for the strong interaction between quarks and gluons is written as;

$$-g \bar{\psi}_j G_\mu^a \frac{\lambda_{ij}^a}{2} \gamma^\mu \psi_i \quad (2.12)$$

The relation elucidates the interaction carried out by a quark and conversion of color state i.e. $i \rightarrow j$ through a gluon. The depiction of that interaction through Feynman diagram is given in the Fig. 2.3.

2.1.3 The electroweak unification

The four gauge bosons indicating W_μ^1 , W_μ^2 , W_μ^3 , and B_μ fields are coming from the $SU(2)_L \times U(1)_Y$ symmetry group. The weak interaction is being carried out by the $W^\pm$ and Z^0 bosons and the speculation about their masses is interpreted through the Higgs mechanism described in the Section. 2.4. The eigen states of the mass of the gauge bosons are acquired by joining electroweak eigen states as;

$$W^\pm_\mu = \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2) \quad (2.13)$$

$$A_\mu = W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \quad (2.14)$$

$$Z_\mu = W_\mu^3 \cos \theta_W + B_\mu \sin \theta_W \quad (2.15)$$

where $W_\mu^\pm$ and Z_μ are the fields referring to the $W^\pm$ and Z bosons while A_μ is identified as the photon field as described in the previous sections. The fermion electric charge Q can be evaluated through the $SU(2)_L \times U(1)_Y$ gauge symmetries as;

$$Q = I_3 + \frac{Y}{2} \quad (2.16)$$

It has been determined through experiment that fermions interacting through weak force just couple with left-handed fermions. Thus, the fields of these interacting particles are categorized into left- and right- handed projections as;

$$\psi = \frac{1 - \gamma^5}{2} \psi + \frac{1 + \gamma^5}{2} \psi = \psi_L + \psi_R \quad (2.17)$$

The associated charge for the weak interaction is weak isospin I and its constituent along axis I_3 remain conserved in a weak interaction.

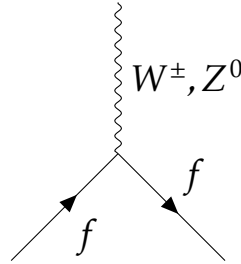


Figure 2.4: An overview of the Feynman diagram depicting interaction between fermions via weak interaction by an exchange of a weak gauge boson.

The Lagrangian for the complete electroweak interaction can be recorded as:

$$\mathcal{L}_{\text{electroweak}} = i \bar{\psi} \gamma^\mu D_\mu \psi - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^k W_k^{\mu\nu} \quad (2.18)$$

The mass term i.e. $m(\bar{\psi}_L + \bar{\psi}_R)(\psi_L + \psi_R)$ is to be incorporated with either of the handedness just because of the terms i.e. $\bar{\psi}_L \psi_L$ and $\bar{\psi}_R \psi_R$ becomes negligible. The final result can be interpreted as:

$$\begin{aligned}
m\bar{\psi}\psi &= \frac{1}{4}m\bar{\psi}(1-\gamma^5)(1-\gamma^5)\psi + \frac{1}{4}m\bar{\psi}(1+\gamma^5)(1+\gamma^5)\psi \\
&= m\bar{\psi}_R\psi_L + m\bar{\psi}_L\psi_R, \quad \text{gauge invariant only if } m = 0
\end{aligned} \tag{2.19}$$

The mechanism of gauge fields mediated through weak interaction and SM fermions obtaining mass in the Standard Model is detailed in the Section. 2.4.

2.2 The cross sections and particle decays

The decay rates and cross sections are indispensable for the measurements in experimental particle physics sector. Considering the fact, the measurements are performed, gathering information during an experimental phenomena where an initial particle decays into a final state during an interaction with the help of SM.

Cross sections

The cross section indicates the likelihood of a given to be occurred. For the annihilation process depicted in Fig.2.2 & Fig.2.5, the differential cross section is evaluated as;

$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi(p_1 + p_2; p_3, p_4) \tag{2.20}$$

The terms p_1 , p_2 , m_1 , and m_2 indicates four momenta and masses of initial state particles whereas p_3 and p_4 points to the four-momenta of the final state particles. The factor $d\Phi$ describes the unoccupied states available to be occupied by the final state candidates and matrix element $|\mathcal{M}|$ gives dynamics of the interaction.

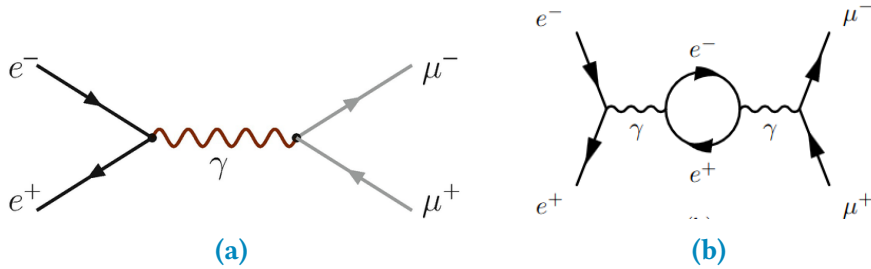


Figure 2.5: The first order (a) and second order (b) Feynman diagram depicting the scattering of e^-e^+ to $\mu^-\mu^+$ pair. Taken from the Ref. [43].

Using perturbation theory, matrix element can be computed for the given process. Here we have two scenarios explained with the help of Feynman diagrams. The Fig. 2.5a comprises two vertices for QED interaction where each impart a factor $e \propto \sqrt{\alpha}$ to the matrix element as demonstrated in Eq. 2.7. Overall, it contributes a factor α which indicates lowest order term in perturbation for scattering phenomenon. The Fig. 2.5b represents a second order scattering process with four vertices which offers a factor α^2 to the matrix element.

Likewise, the diagrams can be formulated showing incremental increase in the order of α , and matrix element i.e. computed as the sum of all accompanying interaction terms with a condition that the coupling constant remains smaller than 1 and terms in the series becomes negligible. The coupling constant for QED is quite small for the series and lowest order term is eventually suppressed by the matrix element. Given that strong coupling constant in QCD is smaller than 1 that, perturbative method is just applicable at short distances. Considering, disparate integrals while loop over momenta in high order processes, a re-normalised coupling constant is instigated which can eliminate infinite values. This constant as function of re-normalisation scale μ_R varies with momentum transfer Q^2 and hence eliminate infinities at this scale.

Decay rates

The common feature about overall fundamental particles is their ability to decay into other particles for instance the light weight decaying constituents which is being governed by the laws of conservation of SM. These laws of conservation in terms of energy and electric charge prevent electron from decaying as being the lightest fermion in standard model. On the same grounds, the proton being lightest but comprises baryon number i.e. non zero is considered as stable.

The decay Γ rate of the unstable particles is written as;

$$\Gamma = \frac{1}{\tau} \propto \frac{1}{2M} \int |\mathcal{M}|^2 d\Phi_n(P; p_1, \dots, p_n) \quad (2.21)$$

where M and P corresponds to mass and the four-momentum of the respective particle, $|\mathcal{M}|$ indicates the matrix element, p_i point to four momenta of the decaying constituents and $d\Phi$ corresponds to phase-space factor. Taking inverse of the decay rate gives us mean proper lifetime (τ) for an unstable candidate. Taking mean lifetime into consideration, the particle's probability to stay live for a considerable amount of time (t) prior to decay is computed through relation as;

$$P(t) = e^{-t/\gamma\tau} \quad (2.22)$$

where γ points to the Lorentz factor in this case.

The various elementary and composite particles in the SM exhibit extensive range of lifetimes as demonstrated in Fig.2.6. These lifetimes are controlled by coupling and the phase space entities for instance the hadrons in most of the cases are allowed to decay through the strong interaction which imparts a short lifetime in the order of 10^{-23} s. Nonetheless, the decay could be mediated through weak interaction in the absence of lighter hadrons with identical quarks, and hence particle will exhibit a longer lifetime. The neutron decay possibility arises when a negligibly small momentum transfer occurs with respect to mediator mass during weak interactions. Usually, during the neutron decay the mass differences between neutron and its decaying constituents i.e. electron, proton, and antineutrino is significantly small. The weak interaction is suppressed due to the virtuality (off-shell) of mediator, which implies that energy and momentum do not depend on the surface designated by energy mass equivalence i.e. $E^2 - p^2 = m^2$.

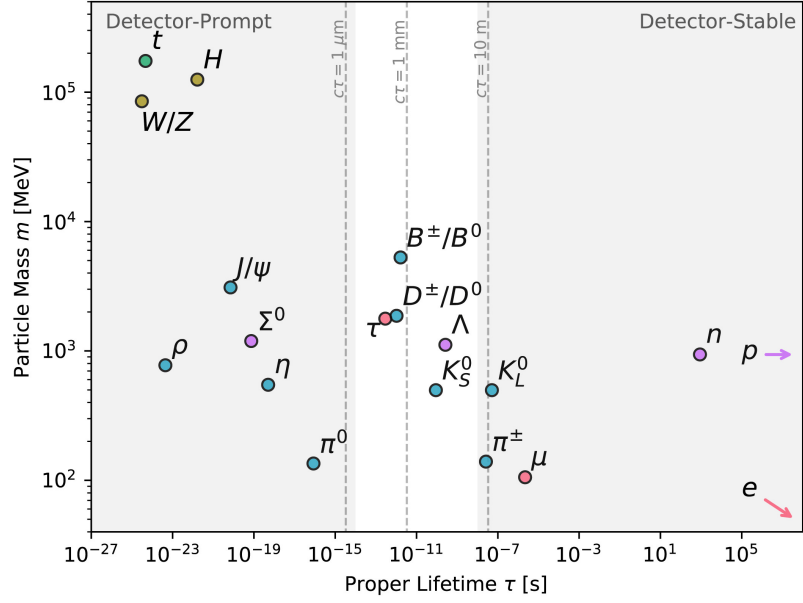


Figure 2.6: A depiction of the SM particle spectrum as a function of mass and proper lifetime. Taken from Ref.[44]

2.3 Paradigm of proton-proton collisions

The understanding of proton-proton collisions at LHC at high energy is a paramount within the field of particle physics. Considering the structure of proton, is a convoluted object constitute three valence quarks (uud), which hold a part of the proton's momentum, sea quarks and gluons. Together they are termed as partons which at significantly high Q^2 effectuates fundamental interaction between them during pp collisions i.e. inelastic. These phenomena are known as hard interactions, which however is complex collision as it entails several QCD and QED processes additionally. An outline of a pp collision is shown in Fig.2.7. The green colored ellipses with arrows pointing outward indicates the colliding protons and the filled red circles point towards hard interaction. The blue curly lines are pointing to the *initial state radiation* (ISR) and the red curly lines refers to the *final state radiation* (FSR).

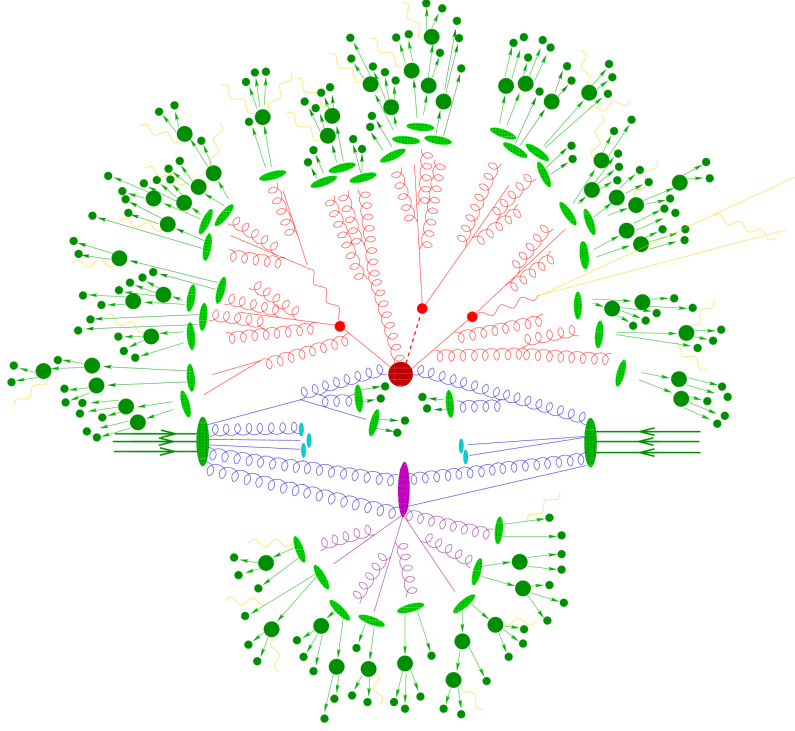


Figure 2.7: A detailed sketch of proton-proton collision Ref.[45]

During these processes colored particles in their initial and final states, radiate gluon which in turn come apart into quark-antiquarks pairs. The electrically charged particles could radiate photons which is pictorially demonstrated by yellow lines. On the top of these processes, the remaining interactions between partons are instantiated through purple ellipse. The factorised form for computing cross section for a process where two protons strike and emerge into a final state (O) is written as;

$$\sigma_{pp \rightarrow O} = \sum_{i,j} \int_0^1 dx_i \int_0^1 dx_j f_i(x_i, \mu_F^2) f_j(x_j, \mu_F^2) \times \hat{\sigma}_{ij \rightarrow O}(x_i p_i, x_j p_j, \mu_F^2, \mu_R^2) \quad (2.23)$$

Where, $f_i(x, Q)$ and $f_j(x, Q)$ are termed as *parton distribution functions* (PDFs), $\hat{\sigma}_{ij \rightarrow O}$ refers to the cross section of parton summing up over i and j partons which play part towards the interaction. In order to specify the probability of a parton in the proton holding a fraction x of the proton's momentum can be estimated by employing factorisation scale (μ_F)¹. Consequently, the PDFs performs over energy and the factorisation scale and set up a cut-off at which the inconsistencies can be eliminated. The PDFs should be acquired from the experimental evaluations [46, 47] and to be computed at particular scales which then are envisaged to energy pattern associated to a certain physics process. The estimation is controlled by the DGLAP evolution equations which yield PDFs from one scale to another [48]. The illustrations of proton PDFs are given in Fig.2.8.

¹A scale designed to evaluate the cross section to treat infrared divergencies in the matrix element which arises from the contributions from the particles with substantially small energies

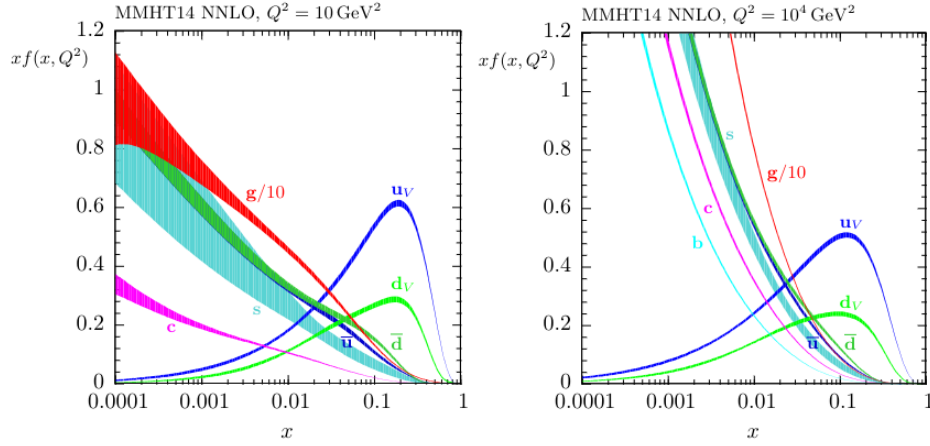


Figure 2.8: The parton distribution functions provided by NNPDF collaboration and demonstrated as a function of x for two different scales μ^2 . The value of x is obtained from combined fit to data and scaling is computed by employing DGLAP evolution. Taken from Ref.[42]

2.4 Particle masses and Higgs boson

The introduction of mass terms in SM Lagrangian defies local gauge invariance for the masses of fermions including W^- and Z boson. To this matter, P. Higgs, R. Brout and F. Englert came up with a model named Brout-Englert-Higgs (BEH) mechanism in 1964. They have realised together with T. Kibble, C. Hagan and G. Guralnik [33] that the mechanism would not only generate the needed mass terms for the heavy vector bosons but conserve the local gauge invariance simultaneously. This phenomenon is also known as electroweak symmetry breaking (EWSB) mechanism [34].

The BEH mechanism

The extension of SM Lagrangian is given by;

$$\mathcal{L}_{Higgs} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 (\phi^\dagger \phi) - \lambda (\phi^\dagger \phi)^2 \quad (2.24)$$

where ϕ is introduced as a $SU(2)_L$ doublet of complex scalar field with hypercharge $Y = 1$:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.25)$$

The potential $V(\phi)$ carries two independent variables, μ and λ . They are selected in a way that $\mu_2 < 0$ and $\lambda > 0$ which generates the Mexican-hat shaped potential depicted in Fig. 2.9. The minimal of $V(\phi)$ sets at non-zeros values of ϕ that satisfies;

$$\phi^\dagger \phi = \frac{1}{2} (\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{\lambda} \quad (2.26)$$

Considering the generality, the values of the field are to be set minimally at $\phi_1 = \phi_2 = \phi_4 = 0$ and $\phi_3 = \nu$, where $\nu = \sqrt{-2\frac{\mu^2}{\lambda}}$ that corresponds the vacuum expectation value of the Higgs field. The field can be extended with derivations $\{H, \phi_1, \phi_2, \phi_3\}$ varying around the minimum:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \theta_1(x) + i\theta_2(x) \\ \nu + H(x) + i\theta_4(x) \end{pmatrix} \approx \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H(x) \end{pmatrix} e^{i\frac{\sigma_j}{2} \frac{\theta_j^{(x)}}{\nu}} \quad (2.27)$$

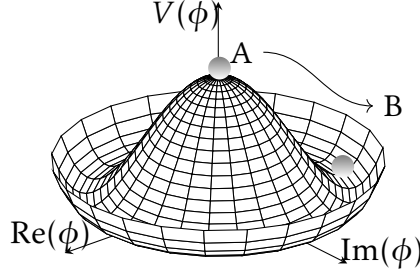


Figure 2.9: A depiction of the Higgs potential $V(\phi)$ as a function of the real and imaginary parts of a complex singlet field ϕ .

Eventually, the Goldstone field θ_j are resulted into a factor that could be estimated through transforms of the vector fields. Considering above parameters, the Higgs Lagrangian thus takes a form;

$$\begin{aligned} \mathcal{L}_{Higgs} = & \frac{1}{2} (\partial_\mu H \partial^\mu H) + \frac{g^2}{4} (\nu + H)^2 W_\mu^+ W^{-\mu} + \frac{1}{8} \frac{g^2}{\cos(\theta_W)^2} (\nu + H)^2 Z_\mu Z^\mu + \\ & + 0 A_\mu A^\mu + \frac{\mu^2}{2} (\nu + H)^2 - \frac{\lambda}{4} (\nu + H)^4 \end{aligned} \quad (2.28)$$

By setting minimum at i.e. $\phi \neq 0$, mass terms for the physical fields $W_\mu^\pm$, Z_μ and recently added expansion H are originated. These physical fields along with photon field A_μ can be acquired by exploiting fundamental fields;

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2) \quad , \\ \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} &= \begin{pmatrix} \cos(\theta_W) & -\sin(\theta_W) \\ \sin(\theta_W) & \cos(\theta_W) \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} \end{aligned} \quad (2.29)$$

The masses of $W_\mu^\pm$, Z , γ and H are obtained as:

$$m_W = \frac{vg}{2}, \quad m_Z = \frac{m_W}{\cos(\theta_W)}, \quad m_\gamma = 0, \quad m_H = \sqrt{-2\mu^2} \quad (2.30)$$

The excited physical Higgs field H is termed as Higgs boson with a mass depending on μ . The two independent parameters defining the Higgs potential in BEH mechanism are μ and λ . The Higgs boson mass m_H and the vacuum expectation value ν is re-stated through these two degrees of freedom.

The heavy vector bosons are created when Higgs field attains a non-zero vacuum expectation value through symmetry breaking. Nevertheless, electroweak SM Lagrangian at $\phi = 0$ remain invariant under $SU(2)_L \times U(1)_Y$. The vacuum expectation value $\phi_0 = \frac{1}{\sqrt{2}}(0, v)^T$ is ordained to be electrically neutral ($Q = 0$), which keeps the $U(1)_{QED}$ symmetry unbroken and photon massless consequently.

2.5 The SM Higgs boson

The discussion about the Higgs field in the previous Section. 2.4 helps to understand the massive vector bosons in the SM. The coupling of Higgs boson to the SM particles can be comprehended through vacuum expectation value which is proportionate with the mass of the particle. Nevertheless, the Higgs boson's mass is an independent parameter of theory, which must be computed through an experiment. The discovery of the Higgs bosons at ATLAS [39] and CMS [40] experiments at LHC in the year 2012 and the experimental observations have established that its mass is $m_H = 125.09 \pm 0.24$ [41] which is consistent with neutral scalar SM Higgs bosons [34]. This section covers the detailed SM predictions about the cross-sections and branching fractions of the production and decays modes at LHC.

Higgs bosons production and cross-sections

The predictions of the cross-section modes for a SM Higgs boson observed in pp collisions at centre-of-mass energies ($\sqrt{s}$) at LHC are expounded in the Fig. 2.10a. On the other hand, the production cross-sections of the Higgs boson as a function of its mass at a fixed centre-of-mass energy i.e. $\sqrt{s} = 14$ TeV is given in the Fig. 2.10b. The gluon-fusion (ggF) is a governing production phenomenon at LHC and dominates through the virtual top-quark loops while coupling with Higgs boson strongly due to large Y_t . The cross-section of this process is $\sim 20 - 50$ pb for $\sqrt{s} = 8 - 13$ TeV with uncertainties of the order of 7%. Another prevalent production mode with a cross-section of $O(10^{-1})$ here is an effect of vector-boson fusion (VBF) as demonstrated in Fig. 2.11 (b). The two quark jets along the beam-line are the by products of this process. The next dominant phenomenon in line is, vector-boson associated Higgs boson production (VH) associated with either Z or $W^\pm$ bosons as demonstrated in Fig. 2.12.

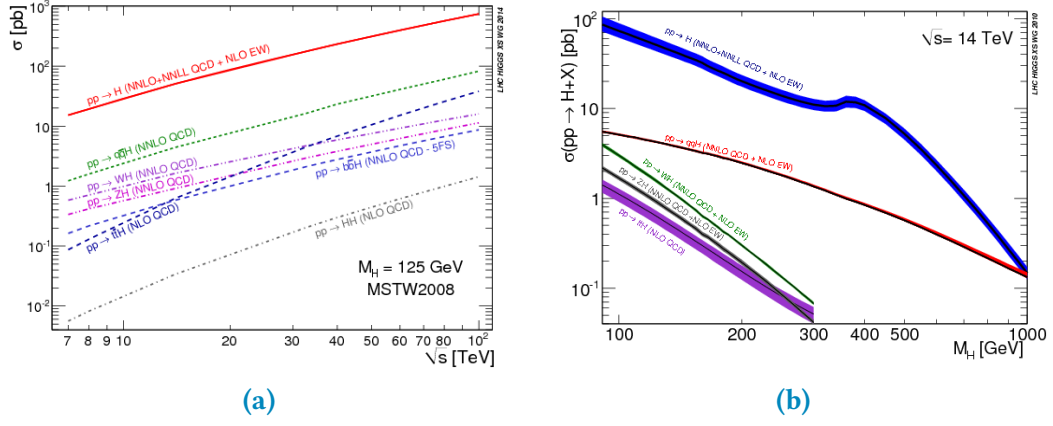


Figure 2.10: An overview of the production mode cross-section of a SM Higgs boson with mass $m_H = 125$ GeV (a) at varying pp collision energies whereas the distribution of cross-section with varying mass m_H at fixed pp collision energy i.e. $\sqrt{s} = 14$ TeV. Taken from Refs. [8, 9].

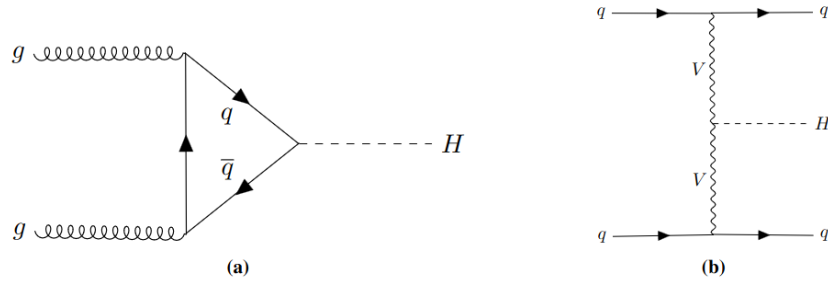


Figure 2.11: A depiction of leading-order Feynman diagram for Higgs boson production via (a) gluon-fusion (ggF) and (b) vector-boson-fusion (VBF).

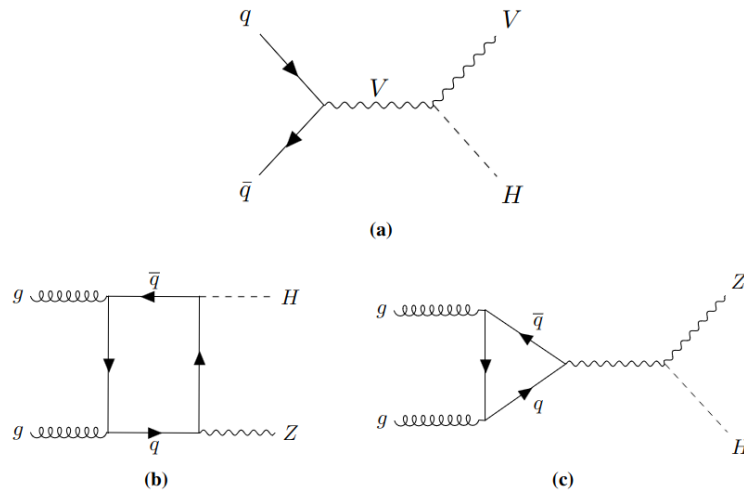


Figure 2.12: The leading-order Feynman diagrams for the Higgs boson associated production (VH) via vector-boson associated with (a) $W^\pm$ or Z (b) Z bosons

The highest Higgs boson cross-section can be achieved through coupling with quarks from third generation for instance, t -associated Higgs boson production ($t\bar{t}H$) and b -associated Higgs boson production ($b\bar{b}H$). The cross-section of both production modes are quite close to each other i.e. $\sim 0.5\text{pb}$ at $\sqrt{s} = 13\text{ TeV}$. The single t -associated Higgs boson production (tH) produced with an EW vertex with low cross-section of about 90 fb at $\sqrt{s} = 13\text{ TeV}$ is demonstrated in Fig. 2.13.

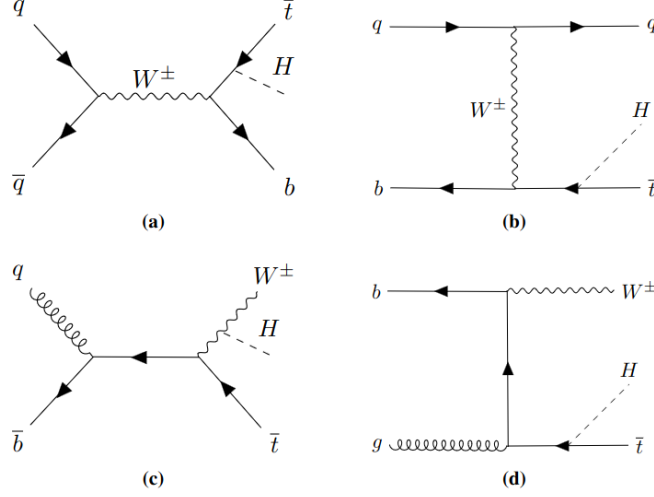


Figure 2.13: The leading-order Feynman diagrams for the Higgs boson associated production (tH) via single t -quark (a & b) associated with $W^\pm$ boson and light quark (c & d)

The Higgs boson cross-section get enlarged with centre-of-mass energy of the pp collisions as a function of it and becomes less sensitive towards a discovery. This is because of the high cross-sections of other processes for instance, $t\bar{t}$ production at the LHC preside over the total cross section and causes a large source of background for Higgs boson measurements. Taking it into consideration, a comparison of the measurements of cross-sections for various processes by ATLAS at several centre-of-mass energies i.e. $\sqrt{s} = 7, 8, 13\text{ GeV}$ is shown in Fig. 2.14. A good agreement between predicted cross-section and observed measurements within uncertainties is noticed and experimental uncertainties are prevalent in most of the scenarios.

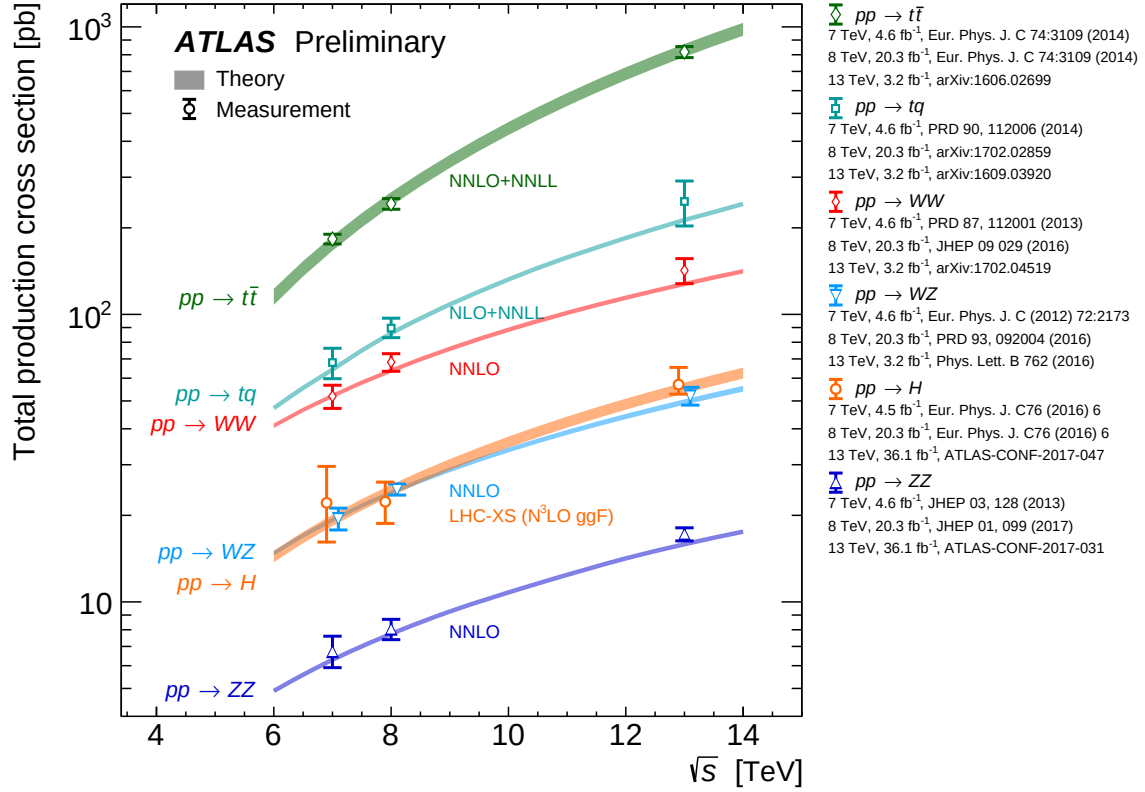


Figure 2.14: The summary of the total cross-sections measurements performed at $\sqrt{s} = 7, 8, 13$ TeV in pp collisions for various SM processes by ATLAS. Some markers are displaced horizontally for better visibility. Taken from Ref. [49]

Higgs boson decay widths and branching fractions

The decay of the Higgs boson to SM particles are computed through branching fractions which are proportionate with a particle's mass. The Section. 2.4 explicates the coupling strengths of Higgs boson to the vector bosons i.e. $W^\pm$ and Z given in Eq. 2.30. The branching fractions for Higgs boson with a mass of ~ 125 GeV are demonstrated in Fig. 2.15a and the broad range of Higgs masses is depicted in Fig. 2.15b. The branching ratio obtained for $H \rightarrow b\bar{b}$ for the 125 GeV Higgs boson is around 58% and to comprehend this signature is bit complicated because of massive QCD background. The branching ratios for the sensitive decay channels for instance, $H \rightarrow llll$ ($\sim 0.01\%$ with $l \neq \tau$) and $H \rightarrow \gamma\gamma$ ($\sim 0.2\%$), is being suppressed due to equipping clean signature from their final states. The $H \rightarrow \gamma\gamma$ decay cannot be happened as the photons are massless and are unable to couple with Higgs boson straightly. The representation of the Higgs boson decay to photon pairs through quark and vector-boson loops is demonstrated in Fig. 2.16.

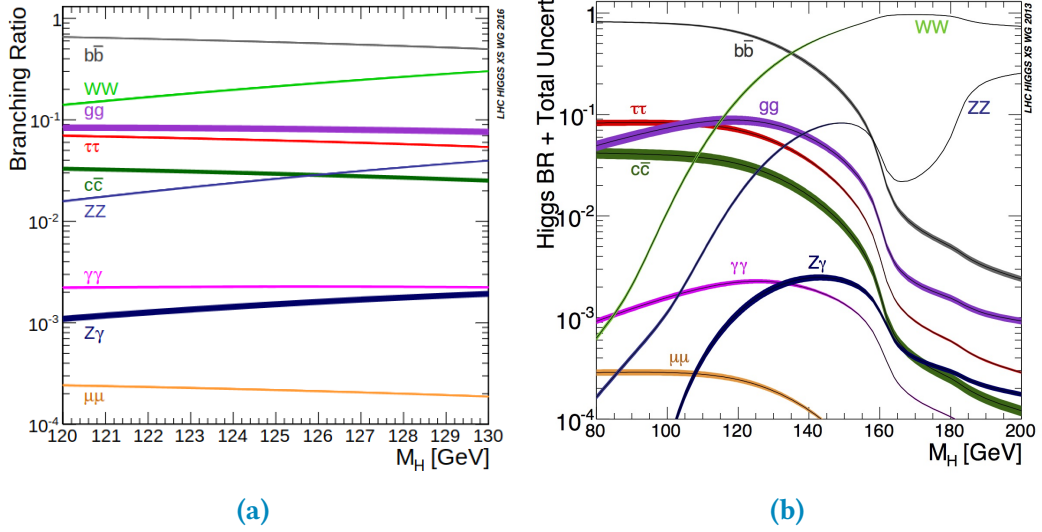


Figure 2.15: Branching ratios of a SM Higgs boson with a mass (a) $m_H \equiv 125$ GeV [10] and (b) $m_H \in [80, 100]$ GeV [11].

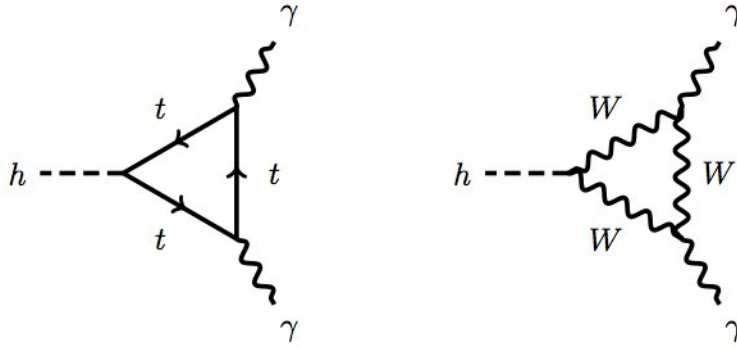


Figure 2.16: Representation of Higgs boson decay to two photons via top quark or W-boson loop.

The comparison of the measured coupling strengths with respect to particle mass for fermions (scaled linearly) and vector bosons (scaled quadratically) are shown in the Fig. 2.17. The computations are in favor with the SM suppositions.

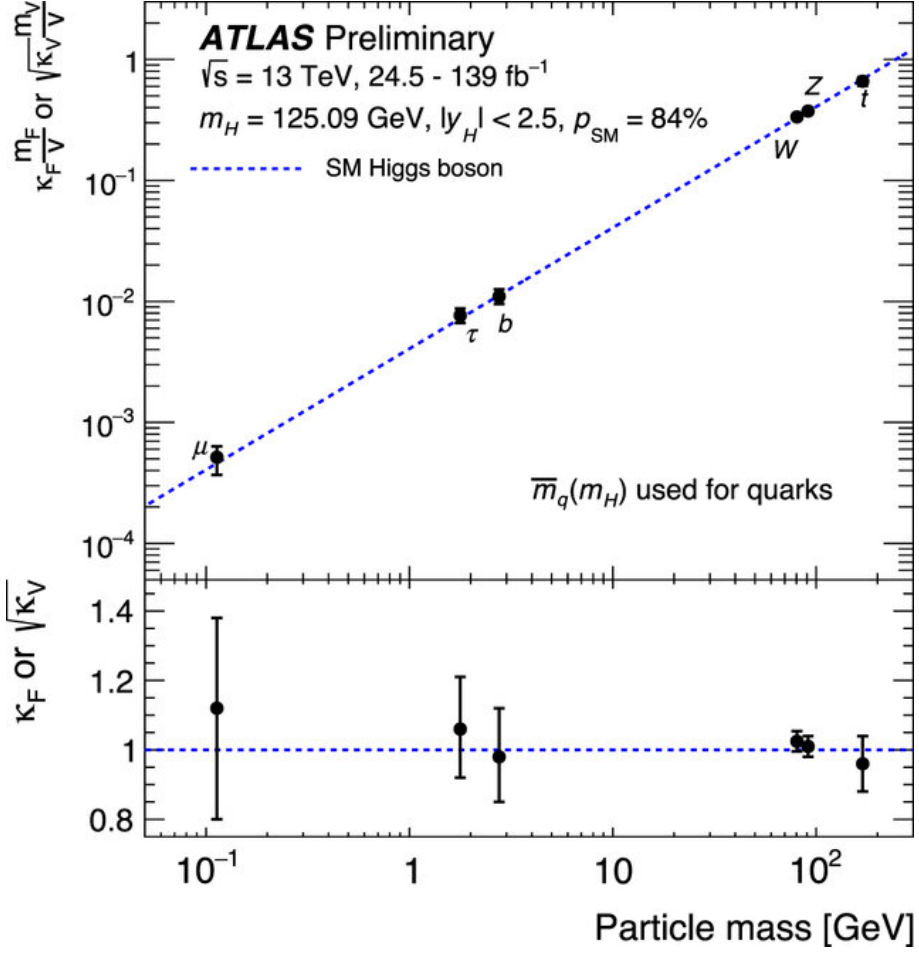


Figure 2.17: Reduced coupling-strength modifiers $\kappa_F \frac{m_F}{v}$ for fermions ($F = t, b, \tau, \mu$) and $\kappa_V \frac{m_V}{v}$ for weak gauge bosons ($V = W, Z$) as a function of their masses m_F and m_V , respectively. The vacuum expectation value of the Higgs field $v = 246$ GeV. Reproduced from [12].

2.6 Accomplishments and drawbacks of the SM

The standard model has been successful model to envisage and validate the outcomes of particle physics experiments for the last few decades. Several experimental predictions about particles and discoveries have manifested their existence and furnish evidences about the validity of the model. For instance, the recent discovery of the W and Z bosons in 1983 [35, 36] and top quark in 1995 [37, 38] along with unveiling of the Higgs boson at the LHC in 2012 [40, 39]. The recent discoveries are evident to the presence of all the particles in the SM. Moreover, all the measurements performed on SM observables are in accordance with observations envisaged by the model. The measurements of cross sections for several production modes at different energies are summarised in Fig.2.18. The formidable rapport of these measurements with the ones deduced theoretically by the SM model is recorded and that consistency of the model is perceivable in Fig.2.19. For instance, the masses of W boson and top quark estimated by a SM fit are consistent with electroweak precision data. While performing these measurements excluding the ones with Higgs mass, the curbs of the SM have indicated a negligible perimeter extended by

the top and W masses. By including computations on Higgs mass would just dwindle this indicated area by the SM due to the fact that indirect calculations are in true agreement with the direct ones which compliments the constancy of the SM. It is evident that SM has stipulated all recent experimental measurements of particles and their interactions remarkably. Nevertheless, the extensions to the SM is required to answer the questions that has been left unsettled so far this realm.

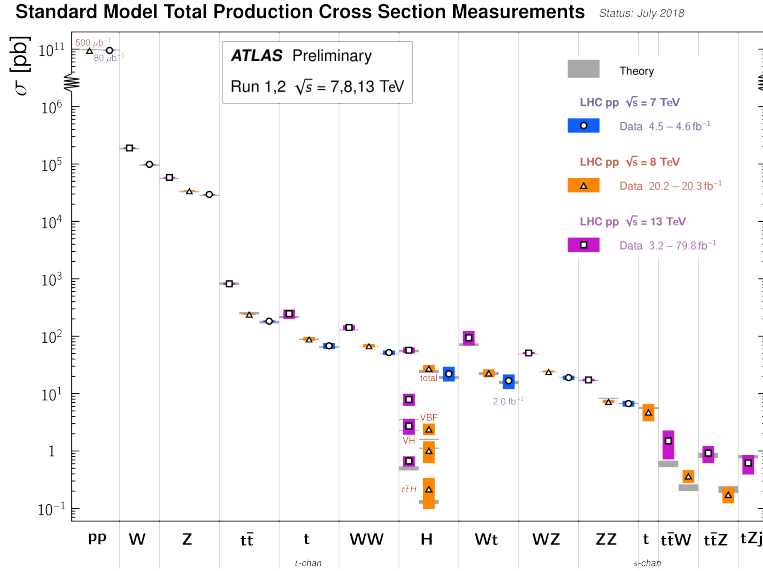


Figure 2.18: Summary of several Standard Model total production cross section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations. Taken from Ref.[49]

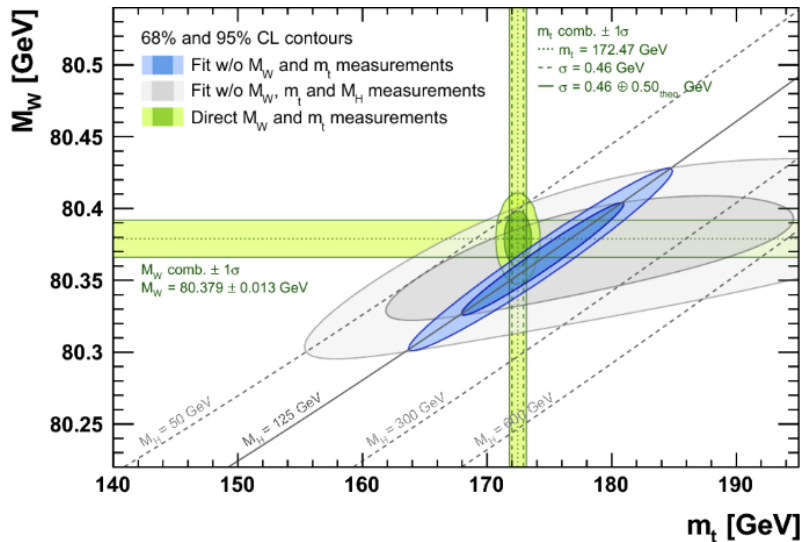


Figure 2.19: Contours at 68 and 95% CL obtained from scans of M_W versus m_t for the fit including (blue) and excluding the M_H measurement (grey), as compared to the direct measurements (green vertical and horizontal 1σ bands, and two-dimensional 1σ and 2σ ellipses). The direct measurements of M_W and m_t are excluded from the fits [50].

Dark matter

The astrophysical studies open on to the paradox that provide a support for the need of physics beyond the SM. The riveting confirmation about the formation of universal matter from non-luminous i.e. with a probability of weakly interacting matter which indicates the existence of Dark Matter which out of scope of SM. As a matter of fact, the observations conducted on Cosmic Microwave Background (CMB) concludes that $\sim 15\%$ of the matter in universe incorporates regular SM particles, whereas the rest is holding up the Dark Matter [51]. However, there are not any conclusive evidences available to comprehend the nature of dark matter particles but there are some hints being provided by the astrophysical measurements. Only possibility of the interaction with these particles is their mass, they should be massive enough so that they can interact with SM particle weakly which in turn should be stable on time scales within universal life span. Overly, the most of dark matter candidates being observed are termed as weakly interacting massive particle (WIMP) which somewhat matches all the needed requirements. In the WIMP context, the dark matter can be formulated thermally in the early universes just like to the existing particles of SM. To make the yield of WIMPs possible to date, requires to have the mass within the range of 100-1000 GeV. Consequently, the WIMP could be comprehended as an existent candidate for dark matter which must showed up at electroweak scale and can be attainable for the searches at LHC through its weak coupling to SM particles.

Neutrinos masses

The SM stipulated that neutrinos are mass less particles which contradicts neutrino oscillations [52] observations which confirms that neutrinos contain non-zero masses. This evokes the gap in SM for the neutrinos masses to be added considering SM as an effective theory. Nonetheless, it is still vague if neutrinos are Majorana or Dirac particles. It open up a motivation to extend the neutrinos sector in order to comprehend the phenomenon delivering masses to them.

Matter-Antimatter asymmetry

The predicament about matter-antimatter asymmetry reveals that discernible universe contains matter only and all the antimatter that would have been created at Big Bang time must has dissolved. This constraint about asymmetry give forth the presence of CP-violation mechanism that could distinguish between matter and antimatter [53]. The present methods in the SM are insufficient to grasp the matter-antimatter asymmetry and couldn't provide enough explanation.

Hierarchy problem

The hierarchy problem suggests that the electroweak sector that includes scalar sector of Higgs boson, is pragmatic to the cut-off criterion Λ where the supposed behaviour of the model is swapped due to the the chance of new physics. The loop-level profiles are therefore required to perform measurement on the physical mass of the Higgs boson. A scenario about those diagrams is manifested in Fig.2.20. This imparts radiative correction

terms to the lowest order diagram in accordance with,

$$m_h^2 = m_{h,0}^2 + \Delta m_h^2 \quad (2.31)$$

where $m_{h,0}$ refers to the reputed *bare* Higgs mass of the SM Lagrangian. These amendments are consistent with the cut-off scale and can be arranged as;

$$\Delta m_h^2 = -\frac{\lambda_f^2}{16\pi^2} \left[2\Lambda^2 + O\left(m_f^2 \ln\left(\frac{\Lambda}{m_f}\right)\right) \right] \quad (2.32)$$

where λ_f indicates the coupling variable to the given fermion field, and m_f refers to the fermion mass. These corrections are outstretched by adjusting the value of the cut-off equivalent to an energy corresponding to the Planck mass i.e. $M_p \equiv 10^{19}\text{GeV}$ where the gravity becomes homogeneous to other fundamental forces. In order to dissolve those radiative corrections that give rise to observed Higgs mass of 125 GeV, the bare Higgs mass is to be tuned finely. This implies that all models in physics must be executed without having any need of fine-tuning and have some standardised foundation for such dissolution of parametric values.

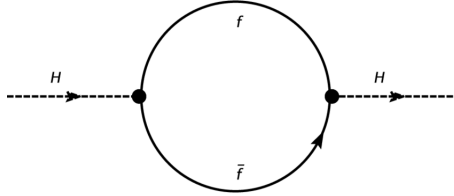


Figure 2.20: The fermionic radiative correction of scalar Higgs mass in One-loop.

Grand unification

The SM deals with almost 26 independent variables that evaluate the particle's masses and the coupling of interactions between them. It suggests to have a general philosophy in physics that in turn have a fundamental theory composing laws and a few independent parameters minimally. This persuades the chase of a Grand Unified Theory where the electroweak and strong interactions are consolidated as a single force, that disentangle theory from complexity. Employing the conceptualisation of SM, these fundamental interactions could be coupled pretty much at the same point targeting high energies.

2.7 The Higgs sector beyond the Standard Model

The adjustments to the Higgs boson mass term from fermionic loops (i.e. from massive *top* quark in discrete) which could enlarge its mass up to the Planck's scale. To have a light Higgs boson mass term i.e. 125 GeV as speculated, the adjustments are to be canceled which nevertheless requires a fine tuning over 30 orders of magnitude in the SM. The recent studies have observed that a theory outside SM scope based on the strong and EW couplings is the utmost requirement. The is investigated that the EM and weak interactions are coming from the electroweak forces originated from $SU(2)_L \times U(1)_Y$. Likewise, the unification of strong force with the electroweak force is being speculated

and could be achieved somewhat at high-energy scales i.e. the Grand Unified Theory (GUT) scale as discussed in Section. 2.6.

The Higgs sector is the right way to explore answers to the unresolved problems by the SM. As the dark matter is assumed to have mass via BEH mechanism and can get coupled with the Higgs boson. To comprehend the massive particles, the extension of the Higgs sector is indispensable as it is speculated by the SM that Higgs sector is a single Higgs doublet. The good approach to expand the Higgs sector, is to include Higgs doublet in so called Two-Higgs-Doublet-Models (2HDMs) [14, 16]. The extra DOFs in these models will bring forth an additional Higgs bosons, one of which is already discovered with the mass 125 GeV. The details are provided in the Section. 2.7.2.

Another motivation for considering 2HDMs comes from supersymmetry (SUSY) [13]. The optimistic solution to the hierarchy problem and the prospective dark matter particles, is delivered through the the hypotheses on physics beyond the SM (BSM) i.e. Supersymmetry or SUSY. This is formulated on the basis of already present SM framework which envisages an extension of particle spectrum with the possibility of various new particle's states. A preamble to SUSY is given here to comprehend the background and inspiration for the analyses. Presenting common aspects of SUSY with an explanation about existence of new particles i.e. originating from pp collisions at the LHC. Many instances in SUSY have provided hypotheses on the extant of new particles while decaying into SM particles through a suppressed decay i.e. turns out as long-lived particles. The details are provided in the Section. 2.7.1. A simplest extension to the SUSY model compatible with the SM is the Minimal Supersymmetric extension to the Standard Model (MSSM) discussed in the Section. 2.7.3.

2.7.1 Supersymmetry

SUSY is the theoretical model being formulated on the basis of SM which come up with a new proposed symmetry between bosons and fermions. Strictly speaking, it permits transformations between the fields affiliated to matter along with their associations with the forces. Mathematically, it is established by instigating the SUSY generator $\hat{Q}$, which transform fermionic states into bosonic ones and contrariwise:

$$\begin{aligned}\hat{Q}|\text{boson}\rangle &= |\text{fermion}\rangle \\ \hat{Q}|\text{fermion}\rangle &= |\text{boson}\rangle\end{aligned}\tag{2.33}$$

The novel symmetry is a space-time symmetry and its generator is fermionic which implies that it contains spin-1/2 as contradicts the bosonic generators of the symmetries in the SM. As a result, each SM boson has a fermionic super-partner and each SM fermion has a bosonic super-partner. These SUSY particles termed as *sparticles* comprises identical internal quantum numbers as their SM counterparts besides the spin which is different in either case. The novel super-partners of the SM leptons and quarks are spin-0 sleptons and squarks whilst the super-partners of the SM gauge bosons are spin-1/2 gauginos. To differentiate super-partners from their counterparts, they are symbolised with a tilde notation.

The main idea for the SUSY is to furnish an extension to the SM with addition of the new candidates to resolve the hierarchy problem. While evaluating the Higgs mass, loop corrections employ new scalar super-partners of the fermions, as demonstrated in

Fig.2.21 need to be considered. Considering the following expression to correct the mass term for each scalar S ;

$$(\Delta m_h^2)_S = \frac{\lambda_S^2}{16\pi^2} \left[2\Lambda^2 - O\left(m_S^2 \ln\left(\frac{\Lambda}{m_S}\right)\right) \right] \quad (2.34)$$

where the term λ_S refers to the coupling of the scalar to the Higgs field and Λ corresponds to cut-off scale of the theory. In comparison of Eq.2.34 with Eq.2.32, it is evident that disparate contributions to the masses in the SM are revoked by the novel terms as long as SUSY imparts homogeneous coupling and masses to the particles and sparticles. Accordingly, the SUSY is capable to provide a mechanism where disparate terms can be neutralised and discard the necessity for the fine-tuning. The current experiments could give signatures for sparticles of the SM particles only if they are consistent with masses, otherwise SUSY has not been revealed by the Nature so far. Just like electroweak symmetry breaking, the SUSY in any form can be broken down spontaneously but the rejection of the radiative correction terms in the Higgs mass withstand. This revealed that this breaking of SUSY is soft [54] and associated mass variables for this breaking are not bigger than a few TeV. A ton of the models are in line to describe the SUSY breaking mechanism but this extension of the SM demands minimal states for novel particles and their interaction which leads us to Super-symmetric Standard Model (MSSM).

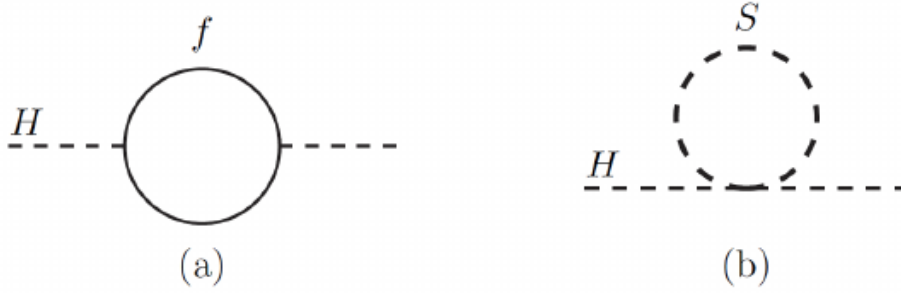


Figure 2.21: Fermion f (a) and scalar S (b) one-loop quantum corrections to the Higgs mass parameter m_H^2 [13].

2.7.2 Two-Higgs-Doublet-Models

The Two-Higgs-Doublet-Models (2HDM) is a nominal extension to the SM Higgs sector. This extension might lead to the intricacies in the Higgs sector which permits flavour-changing neutral currents (FCNCs) at tree-level. The 2HDMs can be investigated by employing outcomes inferred by Glashow and Weinberg [15] which discovered that Higgs boson mediated FCNCs are non-existent at tree-level in case of the fermions with particular charge coupling with one Higgs doublet. By selecting, reasonable Higgs-fermion couplings, FCNCs can be taken out from the models and hence, the Higgs sector can be able to conserve CP considerably. Considering two Higgs doublets i.e. Φ_1 and Φ_2 and scalar potential [14] $V(\Phi_1, \Phi_2)$ obeying simplified model, the VEVs of each doublet i.e. ν_1 and ν_2 can be thought of as real and positive, with $\nu = \sqrt{\nu_1^2 + \nu_2^2} \approx 246$ GeV. The complex doublets can be expressed to the minimum after EWSB as;

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (\nu_a + \rho_a + i\chi_a)/\sqrt{2} \end{pmatrix} \text{ for } a = (1, 2) \quad (2.35)$$

where ϕ^+ are complex fields, and ρ_a, χ_a are real fields. The eight degree of freedoms in Higgs sector are considered and after selecting appropriate gauge, three out of eight are taken up by the longitudinal polarisation of massive gauge bosons. The remaining five are physical scalar Higgs fields with respect to scalar bosons: two charged Higgs ($H^\pm$), one neutral CP-odd Higgs (A^0) and two neutral CP-even Higgs i.e. h^0 and H^0 where $m_{h^0} < m_{H^0}$. Then taking six independent variables in 2HDM Higgs sector into consideration, which are four Higgs masses (where $m_H^+ = m_H^-$), ratios of VEVs i.e. $\tan\beta \equiv \frac{v_2}{v_1}$ and the mixing angle of the neutral CP-even Higgs bosons (α). The physical mass eigenstates of the Higgs fields can be expressed as linear pairs of the above fields,

$$h^0 = \rho_1 \sin\alpha - \rho_2 \cos\alpha \quad (2.36)$$

$$H^0 = -\rho_2 \sin\alpha - \rho_1 \cos\alpha \quad (2.37)$$

$$A^0 = \chi_1 \sin\beta - \chi_2 \cos\beta \quad (2.38)$$

$$H^\pm = \phi_1^\pm \sin\beta - \phi_2^\pm \cos\beta \quad (2.39)$$

Given that, fermions and vector bosons masses in the SM are characterised by their relation to the VEV i.e. $m_W^2 = \frac{g^2 v^2}{2} = \frac{g^2 (v_1^2 + v_2^2)}{2}$. Likewise, the coupling strengths are computed through the interaction terms of the particle fields with the Higgs fields. The neutral couplings recognised in the vector boson sector, are of the form $h^0 VV$, $H^0 VV$, $ZA^0 h^0$, and $ZA^0 H^0$ with one missing term i.e. $A^0 VV$. As a result, the strength of the Higgs di-boson vertex with respect to the SM coupling strength g_{HVV}^{SM} can be enclosed as;

$$\xi_{VV}^{H^0} \equiv \frac{g_{H^0 VV}}{g_{HVV}^{SM}} = \cos(\beta - \alpha) \quad (2.40)$$

$$\xi_{VV}^{h^0} \equiv \frac{g_{h^0 VV}}{g_{HVV}^{SM}} = \sin(\beta - \alpha) \quad (2.41)$$

where ξ is being elucidated as a scalar factor to the Higgs-gauge coupling strength with respect to the SM. In case of having h^0 presumed to be SM Higgs that comprises 125 GeV mass, the H^0 get perturbed at $\cos(\beta - \alpha) \approx 0$ as given in Eq. 2.40. It turns out that zero superscript is to be removed from terms h^0 , H^0 and A^0 and final terms must be symbolised as h the SM-like Higgs, H the heavy CP-even Higgs and A the CP-odd. The correct coupling of fermions with identical quantum states to same Higgs doublets can avoid not only tree-level FCNCs but provides four different possibilities through which Higgs-fermionic coupling could be settled. The first possibility is termed as *Type – I* 2HDM, where all fermions get coupled with one scalar doublet i.e. Φ_2 while on the contrary, vector bosons get coupled to other doublet i.e. Φ_1 . In the *Type – I* 2HDM, all down-type fermions are paired up with Φ_1 and up-type quarks are coupled with Φ_2 . In either cases, the down category of the fermions are coupling to the same Higgs doublet. In the next two possibilities, these requirements are reversed i.e. up-and-down-type quarks swap their couplings with doublets. For instance in the *Lepton – specific* model, the up- and down-type quarks are paired up to Φ_2 whilst, down-type leptons couple to Φ_1 . During the last possibility, the down-type leptons and up-type quarks paired up with Φ_2 whereas down-type quarks are coupled to Φ_1 which described as, *Flipped* 2HDM. The summary of these models is given in Table. 2.1.

Model	Type-I	Type-II	Flipped	Lepton-specific
vector bosons	Φ_1	Φ_1	Φ_1	Φ_1
up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
down-type quarks	Φ_2	Φ_1	Φ_1	Φ_2
leptons	Φ_2	Φ_1	Φ_2	Φ_1

Table 2.1: The coupling of 2HDM Higgs doublets to SM fermions in the four models without FCNCs. Adapted from Ref. [14].

2.7.3 The Minimal Supersymmetric Standard Model

In the extended SM of the super-symmetry, each super-partner could be placed together with its field, just like its supermultiplet on which then SUSY algebraic operations can be applied. Considering the categories of these supermultiplet, they are classified into two; (1) chiral supermultiplets where spin-1/2 and spin-0 fields are paired up (2) gauge supermultiplets which gets spin-1 and spin-1/2 fields coupled. The features of the gauge transformation along with information of the MSSM is encapsulated in Tables.2.2 & 2.3. Characterizing the vector boson fields as gauge and fermions as chiral supermultiplets. However, fermions show different features for gauge transformation as they have different chirality that implies they should hold complex scalar partner. Therefore, the fermion super-partners are termed as *sfermions* which are further categorised as *squarks* and *sleptons* in the SM.

Names		Spin-0	Spin-1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
Squarks, Quarks ($\times 3$ generations)	Q	$(\tilde{u}_L \ \tilde{d}_L)$	$(u_L \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{3})$
	$\tilde{u}$	$\tilde{u}_R^*$	$\tilde{u}_R^+$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{4}{3})$
	$\tilde{d}$	$\tilde{d}_R^*$	$\tilde{d}_R^+$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3})$
Sleptons, Leptons ($\times 3$ generations)	L	$(\tilde{\nu} \ \tilde{e}_L)$	$(\nu \ e_L)$	$(\mathbf{1}, \mathbf{2}, -1)$
	$\tilde{e}$	$\tilde{e}_R^*$	$\tilde{e}_R^+$	$(\mathbf{1}, \mathbf{1}, 2)$
Higgs, Higgsino	H_u	$(H_u^+ \ H_u^0)$	$(\tilde{H}_u^+ \ \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +1)$
	H_d	$(H_d^0 \ H_d^-)$	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -1)$

Table 2.2: The chiral supermultiplets in the MSSM. Adapted from Ref. [13].

Names	Spin-1/2	Spin-1	$SU(3)_C, SU(2)_L, U(1)_Y$
Gluino, Gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
Winos, W-bosons	$\tilde{W}^\pm \quad \tilde{W}^0$	$W^\pm \quad W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
Bino, B-boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Table 2.3: The Gauge supermultiplets in the MSSM. Adapted from Ref. [13].

On the other hand, the SM Higgs boson is coupled with spin-1/2 super-partner i.e. higgsino in a chiral supermultiplet. As a result of having single Higgs chiral supermultiplet brings up gauge anomalies in hypothesis. These abnormalities get rejected between quarks and leptons but with one higgsino being incorporated in the MSSM, brings forth extra terms which couldn't be neglected. The way of solving this problem is to have at least two oppositely charged Higgs supermultiplets. The additional particles from the MSSM are added into the evolution of the existing coupling constants i.e. appear to unify at a singular point at $O(10^{16})$ GeV as demonstrated in the Fig. 2.22.

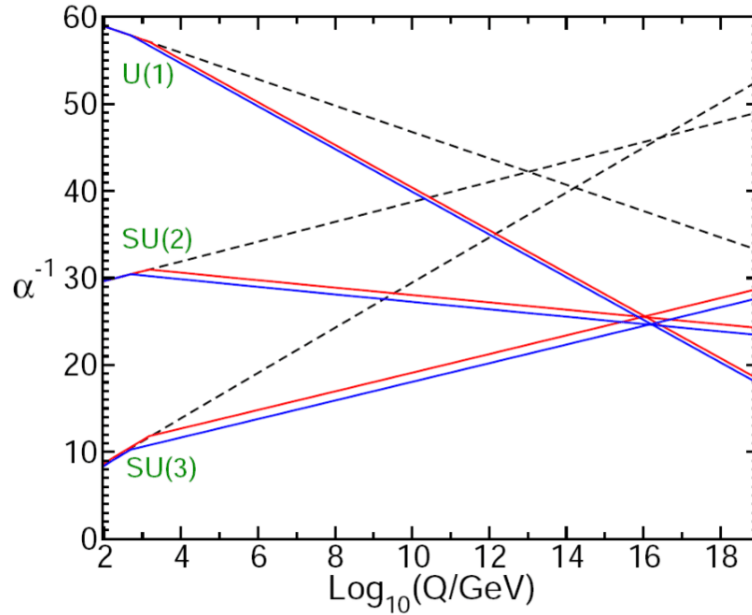


Figure 2.22: Two-loop re-normalisation group evolution of the inverse gauge couplings α^{-1} in the Standard Model (dashed lines) and the MSSM (solid lines) [13].

2.7.4 Charged Higgs boson production

The production of the charged Higgs at LHC is revolving around its mass i.e. $m_H^\pm$ and can be categorised into three regions. In case of light $m_H^\pm$, the primary production must be executed through the top-quark decay i.e. $t \rightarrow H^+ b$ as demonstrated in Fig. 2.23 (a). Considering the computation of $H^\pm$ cross-section from the $t\bar{t}$ multiplied by the speculated $t \rightarrow H^+ b$ branching fraction where top-quarks are on-shell and the effect from

top-quark off-shell can be eliminated at lowest mass range i.e. $m_{H^\pm} \lesssim 160$ GeV. The prevalent production mode is accompanied with top-quark at the high mass range i.e. $m_{H^\pm} \gtrsim 200$ GeV as depicted in Fig. 2.23(b). This mode neglects associated production of $W^\pm$ at LO and the final state is $pp \rightarrow \bar{t}bH^+$. Within the range $145 \lesssim m_{H^\pm} \lesssim 200$ GeV, the outcomes from non resonant(shown in Fig. 2.23 (c)), single resonant and double resonant top-quarks considerably affects the result so the full $pp \rightarrow H^\pm W^\pm b\bar{b}$ process is taken into consideration [17].

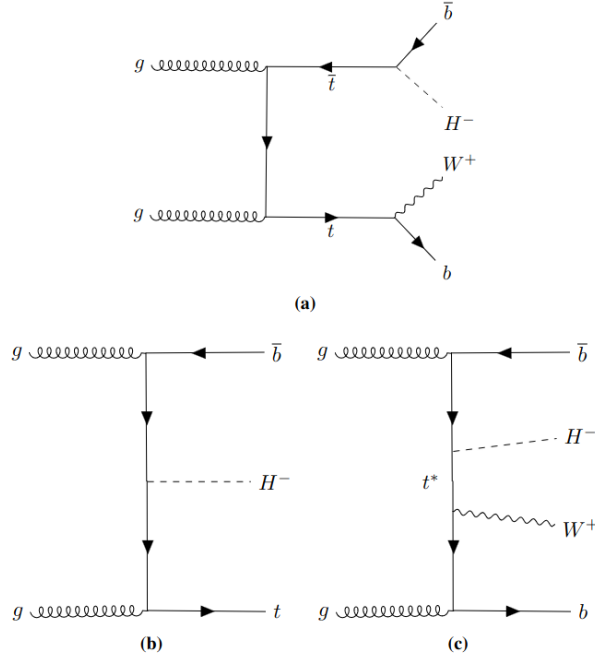


Figure 2.23: Feynman diagrams of the LO charged Higgs boson production for the (a) light (b) heavy and (c) intermediate (with non resonant top-quark) mass range.

The latest research work from the Ref. [17] dispenses cross section measurements in the intermediate mass region performed at NLO precision. The total cross-section of charged Higgs boson from Type-II 2HDM is demonstrated in Fig. 2.24. To furnish the measurements for the cross-sections for different cases, the 2HDM NLO cross-sections are need to be revised by the MSSM Yukawa coupling terms by considering SUSY-QCD effects. Just like neutral Higgs, the branching ratios for charged Higgs boson are evaluated with FEYNHIGGS or HDECAY.

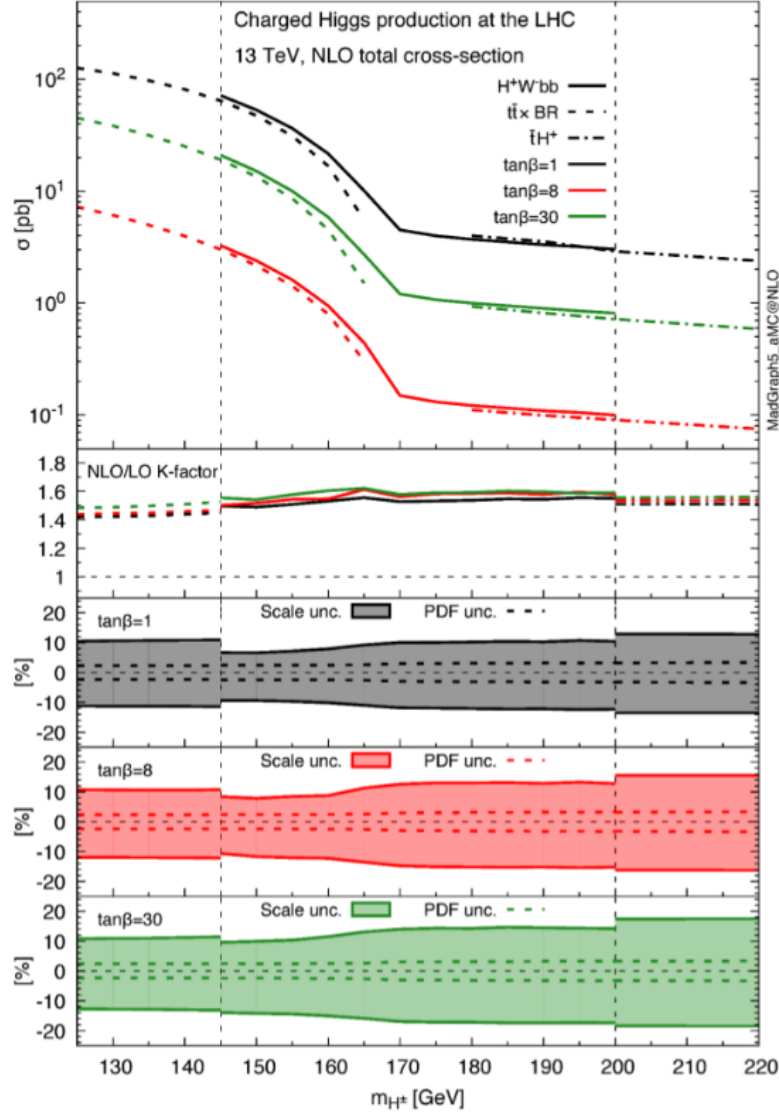


Figure 2.24: The total cross-section, K-factors and uncertainties for charged Higgs boson production at 13 TeV from a Type-II 2HDM at different values of $\tan\beta$ exhibiting low, intermediate and high masses [17].

2.8 Limitations of BSM Higgs bosons at LHC

The LHC has been able to probe the prompt signatures dispensed by the minimal extensions of Higgs sector for the aforementioned models i.e. 2HDM and MSSM with an exception that they required additional Higgs bosons which could be investigated straightly. The bunch of searches for the additional scalars have been furnished in the ATLAS Run-1 and Run-2 data and constraints are being placed on them in order to compare them with previous cross-section predictions as discussed in earlier sections. For instance, the Fig. 2.25 represents 95% confidence level (CL) limits from Run-1 in the hMSSM plane of $m_A - \tan\beta$. The constraints depicted are from direct searches of heavy Higgs boson at $\sqrt{s} = 8$ TeV and 20.3 fb^{-1} in pp collisions for processes: $A/H \rightarrow \tau\tau$ [20],

$A \rightarrow hZ$ [21], $H \rightarrow VV$ [22, 23] and $H^\pm \rightarrow \tau\nu$ [24]. Nevertheless, the indirect computations for instance the coupling of 125 GeV Higgs boson which seems inconsistent with certain regions of phase-space put constraints on the 2HDM and MSSM models. The consistency between the coupling of 125 GeV Higgs boson with the SM particles was examined in Run-1 and that has put restrictions on various BSM models [18]. Likewise, the Fig. 2.26 demonstrates the constraints put in Run-2 on the hMSSM during reinterpreting 125 GeV Higgs boson coupling measurement for the various physics processes. The limits are iterated at 95% CL, referring to data (solid lines) and the expectation for the SM Higgs sector (dashed lines).

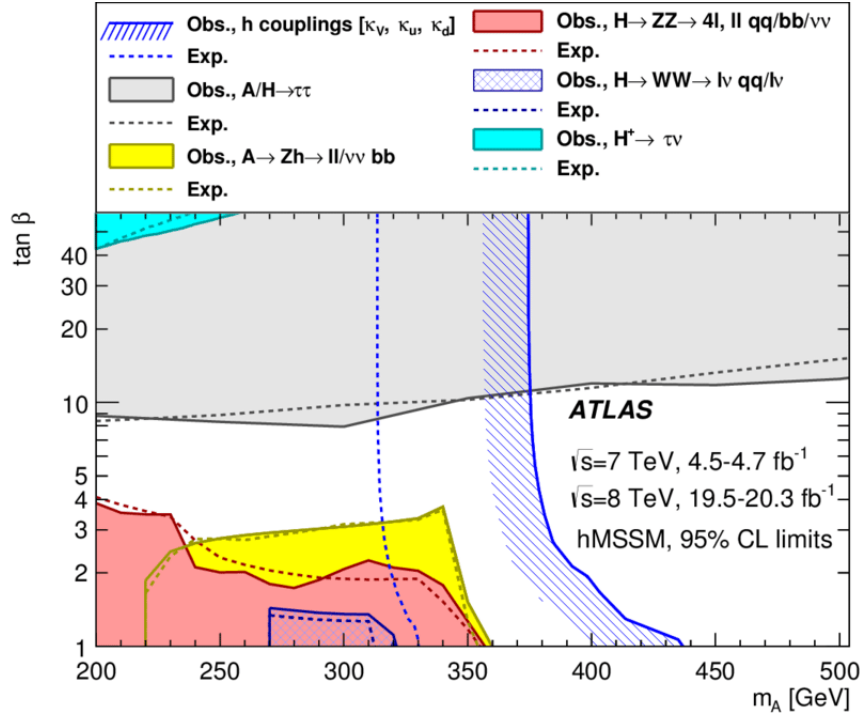


Figure 2.25: A demonstration of expected and observed excluded limits at 95% in the hMSSM model via direct searches for heavy Higgs bosons in Run-1 and fits to the measured rates of observed Higgs boson production and decays [18].

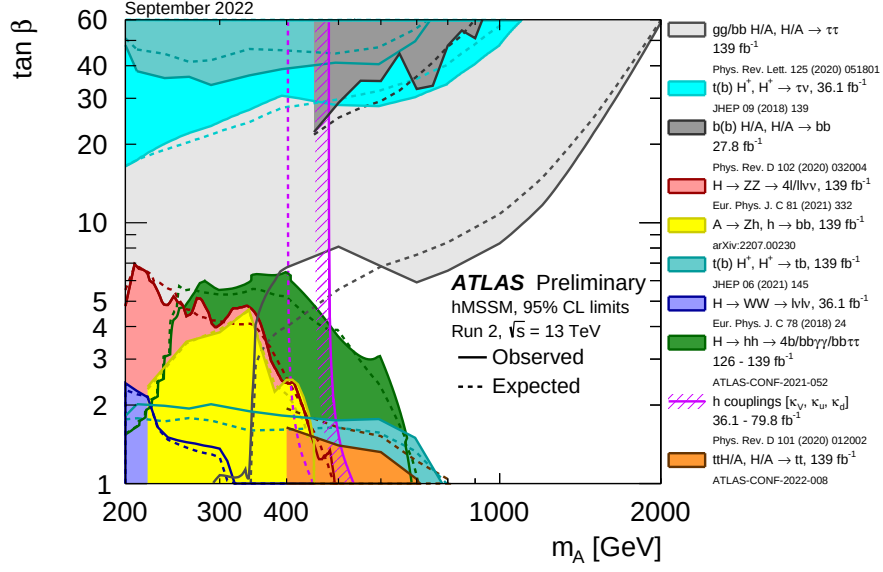


Figure 2.26: The expected and observed exclusion limits at 95% in the hMSSM model via direct searches for heavy Higgs bosons in Run-2 and fits to the measured rates of observed Higgs boson production and decays [19].

It is evident that to measuring the BSM Higgs sector, reliance on the both SM estimates and direct searches are indispensable. The searches for associated production of BSM Higgs boson in the $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ and $H^{\pm} \rightarrow W^{\pm}Z$ channels are entailed in this thesis. The details are provided in the Chapter. 6.

Chapter 3

The ATLAS Experiment at LHC

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3.1 The CERN and LHC

In December 1951, at intergovernmental conference of UNESCO in Paris, the first intention regarding the foundation of a European Council for Nuclear Research (in French *Conseil Européen pour la Recherche Nucléaire*) was approved [55]. Later, an agreement was signed establishing the provisional council, and acronym CERN was originated. In 1957, CERN's first accelerator named synchro-cyclotron (SC) cranked up, with particle beams for the CERN's first particle and nuclear physics experiments. The most remarkable thing about CERN is its Collider Physics Programme. Varied unprecedented collider have been constructed at CERN, starting with CERN's first synchrotron, the Proton Synchrotron (PS) which was built on 24 Nov, 1959 with a circumference of 628m [56]. The PS accelerated particles up to 25 GeV and bend particle beams into circle by using network of the room temperature electromagnets with the aim to supply beams for next experiments. Eventually, many colliders have been built with larger circumference to accelerate particles to higher level of energies. The project of Super Proton Synchrotron (SPS) was later accomplished in 1976. This machine enabled the beams of the protons to achieve energy of 400 GeV [57]. Later years, SPS was refurbished for the collisions between protons and antiprotons delivering centre of mass energy up to 900 GeV. Afterwards, the name of SPS was replaced by Sp^pS and more experiments were designed to detect the W and Z bosons forecasted by Glashow, Weinberg and Salam in 1968 (which won them the Nobel prize in 1979 [58]). After the victorious run of SPS, another project called Large Electron Positron Collider (LEP) was launched. It took more than 2 years to bore it 100m below the ground in a tunnel of 27km circumference. It was operated for 7 years initially around the mass of Z boson at $\sqrt{s}$ energy about 100 GeV. Observing the decaying process of short-term ¹ Z boson was the primarily test of the standard model. The LEP was refurbished later in 1995 to achieve double of that energy in order to probe collisions which could produce pair of W-bosons [59]. Eventually, LEP would have risen its energy up to 209 GeV in 2000. The Large Electron Positron Collider was shut down after the year 2000 and new circular hadron collider "The Large Hadron Collider or the LHC" was aimed to build up in the same tunnels.

¹A life time of 10^{-25} s

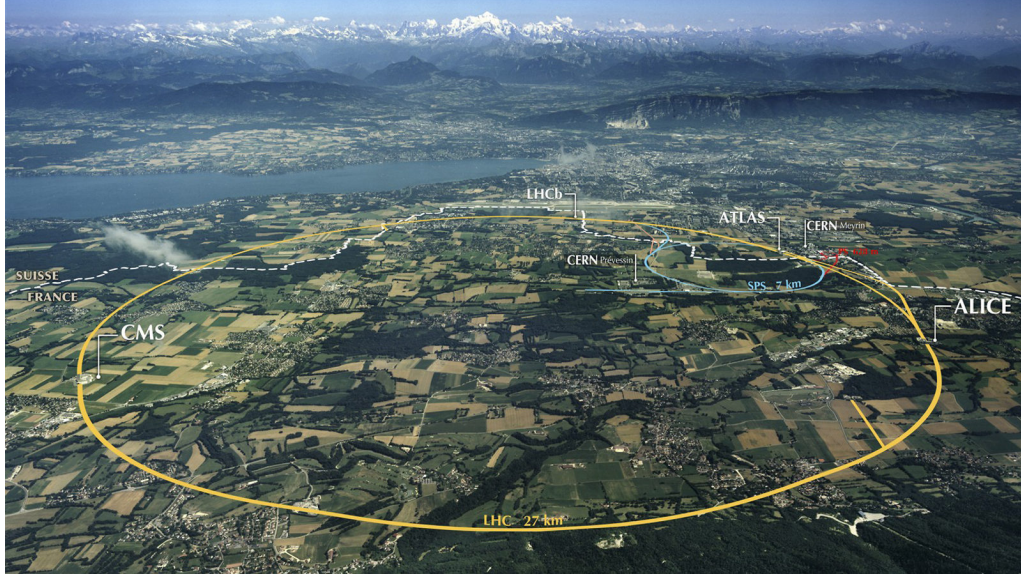


Figure 3.1: Sight of the Swiss/French border above the LHC tunnel. The ATLAS detector cavern is stationed at point 1. The ALICE, CMS & LHCb cavern are housed at points 2, 5 and 8, respectively.

3.2 The Large Hadron Collider

LHC stand for Large Hadron Collider. **Large** due to its size (approximately 27km in circumference), **Hadron** because it accelerates protons or ions, which are hadrons, and **Collider** because it forms two beams travelling in opposite directions, which collide at four points where the two rings of the machine intersect [60]. The large Hadron Collider (LHC), is a 27 km particle accelerator stationed at the European Organization for Nuclear Research (CERN) along the France/Switzerland border near Geneva. Its tunnel was pierced in the 80s to house the Large Electron-Positron Collider (LEP) [61], which finished operations in the year 2000 to allow construction of the LHC.

The four big experiments with their detectors built around the collision points are, A Large Ion Collider Experiment (ALICE) [62] whose main aim is to replicate the conditions of the early universe with their own experimental caverns and collision points. A Toroidal LHC Apparatus (ATLAS) [63], and the Compact Muon Solenoid (CMS) [66] the general-purpose discovery experiments; the Large Hadron Collider beauty (LHCb) experiment [67] designed to record composite particles with b-quarks in them. The remaining three experiments are called Total Elastic and diffractive cross-section Measurement (TOTEM) [69] located in the vicinity of the CMS interaction point, Large Hadron Collider forward (LHCf) [68] installed nearby ATLAS and the Monopole and Exotics Detector at the LHC (MoEDAL) experiment [70] close to the LHCb detector. All these detector points in the LHC tunnel are depicted in the Fig. 3.1.

The LHC is designed to accelerate protons from an initial energy of 450 GeV. On top of that, single protons are found within hydrogen-1 atoms, which are electrically neutral and cannot be electromagnetically accelerated. On that account, a few preparation stages are required for upstream of injection into the LHC's rings.

The LHC is hadron Collider primarily used to collide beams of protons. It has also seen special runs of proton–lead, lead–lead, and xenon–xenon collisions. The first run

of the LHC provided the first ever particle collisions at the centre of mass energy of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV between 2009 and 2013 [71, 72]. The Run 2 of LHC was started in 2015 and would continue till 2018 after long shut down of 2 years. During this period ATLAS collected 139 fb^{-1} of data: 3.2 fb^{-1} in 2015, 33.0 fb^{-1} in 2016, 44.3 fb^{-1} in 2017 and 58.5 fb^{-1} in 2018 [73]. The LHC proton beams were accelerated to 6.5 TeV during run 2, providing collision centre of mass energy of $\sqrt{s} = 13$ TeV, very closed to the designed value.

3.2.1 The LHC Acceleration Chain

The acceleration process at LHC is done in different stages that subsequently escalate the energy of the colliding beams via the CERN accelerator complex sketched in Fig. 3.2. This process of acceleration is based on succession of lower energy accelerators that inject their beams in higher energy accelerator to hit the targeted beam energy. The LHC protons are collected from the container of hydrogen gas from where the molecules of gas are acceded to an intense electric field, snapping them into protons and electrons. The protons are first accelerated in the LINAC 2 linear accelerator (which started operation in 1978 and now it is replaced by new LINAC 4, hitting energy of 50 MeV. They are then injected into the proton synchrotron booster (PSB), which accelerates them to an energy of 1.4 GeV, before introducing them into proton synchrotron (PS). The PS accelerate protons up to an energy of 25 GeV. After PS, they are injected into 7km long Super Proton Synchrotron (SPS) and accelerated to an energy of 450 GeV. At this point, the protons are injected in the LHC ring where they are accelerated to multi-TeV energies. The layout of the CERN collider complex, including each of these injectors, is represented in Fig. 3.2. The lead ions are accelerated in LINAC 3, followed by the Low Energy Ion Ring (LEIR), PS and SPS before launch into LHC [74].

3.2.1.1 Beam Structure

The LHC comprises two adjoining beam lines into which hadrons are introduced either clockwise and anti-clockwise in order to collide them. The proton beam is not continuous and divided into bunches. A bunch is a cluster of particles that get clanged around the particle which is synchronized with the RF Cavity. Then, the particles are accelerated by the RF cavities. The LHC beam consists of ~ 2808 bunches at full intensity, with each bunch comprising 1.1×10^{16} protons with a spacing of 25ns [75]. Each proton beam takes 11245 turns per second resulting nearly equal to 1 billion collisions per second at ATLAS. A scheme of LHC bunch structure is shown in Fig. 3.3.

3.2.1.2 Luminosity and Pileup

The luminosity (L) is the quantity that measures the ability of a particle accelerator to produce the required number of interactions. It is defined by the following relation;

$$L = \frac{1}{\sigma} \times \frac{dN}{dt} \quad (3.1)$$

Where σ corresponds to the interaction cross-section and N is the no of events that are recorded in the given time t . The unit of luminosity is $[\text{length}]^{-2}[\text{time}]^{-1}$.

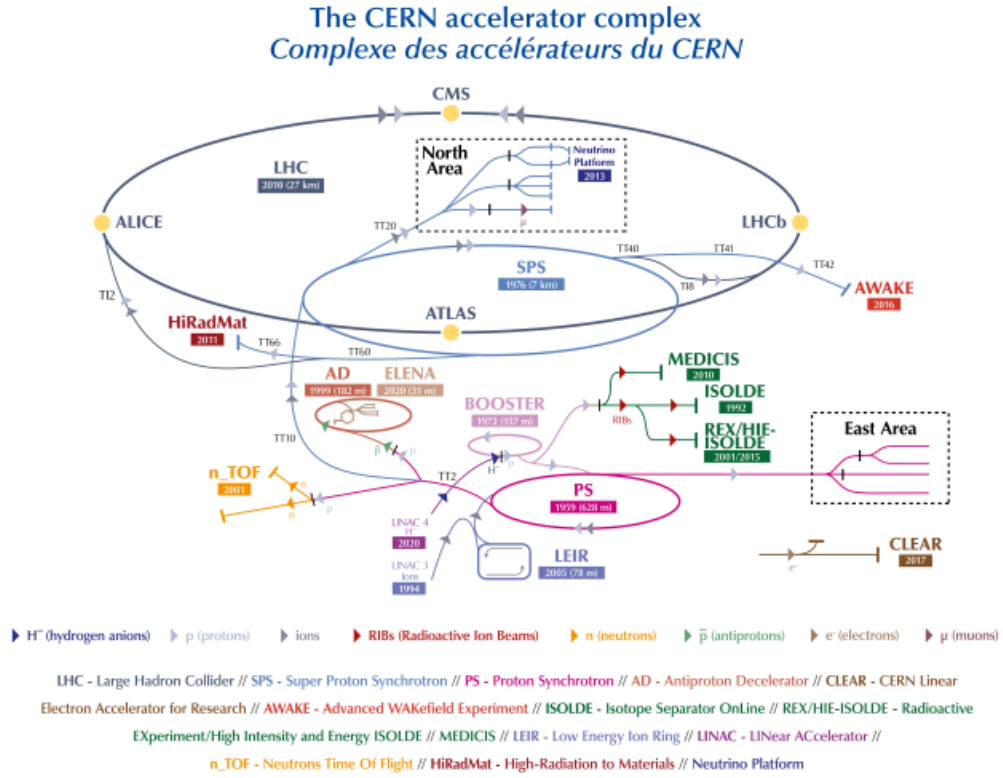


Figure 3.2: The layout of CERN's Accelerator Complex.

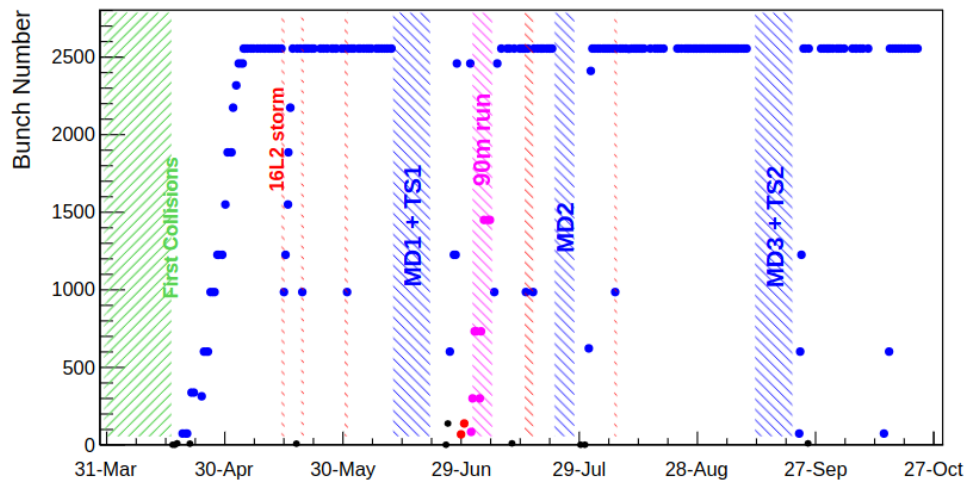


Figure 3.3: The number of bunches during 2018 proton operation [76].

The rate of events of a process in a particle accelerator designated by a cross-section σ_{event} is given by;

$$\frac{dN_{event}}{dt} = L_i \sigma_{event} \quad (3.2)$$

where the quantity L_i is the instantaneous luminosity, which depends only on beam parameters and can be written as;

$$L_i = \frac{N_b^2 K_b f \gamma}{4\pi \sigma_x \sigma_y} \times F [cm^{-2}s^{-1}] \quad (3.3)$$

The N_b is the number of particles per bunch and K_b is the number of bunches per beam. The γ is the relativistic factor of the accelerated particles and f is the revolution frequency of the accelerator. The σ_x and σ_y are the horizontal and vertical beam size. The F is the geometric luminosity reduction factor due to the crossing angle at the interaction point (IP).

The exact information of luminosity is vital for the performance of the experiments. The luminosity is the major systematic, especially the case in precision measurement of the cross section. In order to achieve this, the LHC experiments use dedicated detectors, called luminometers. During Run 2, the primary bunch-by-bunch luminosity measurement in ATLAS is given by the LUCID 2 Cherenkov detector [77], placed approximately at ± 17 m from interaction point. The beam condition monitor (BCM) [81] also measures luminosity at bunch crossing level, adding complimentary information coming from LUCID 2. The absolute calibration method is required to relate luminosity measurements of two detectors. This action is performed during special LHC fills in each data-taking year, called van der Meer (vdM) scans [82]. The overspread of two beams in transversal plane is scanned through vdM method and the relative interaction rates based on beam separation scans are measured. The development of the peak instantaneous luminosity over time during 2018 can be seen in Fig. 3.4a. The LHC has shown an outstanding performance throughout its operation, hitting its design value of $2 \times 10^{34} cm^{-2}s^{-1}$. The integrated luminosity collected in Run 2 as a function of time is depicted in Fig. 3.4b. A total integrated luminosity of $156 fb^{-1}$ which is 6 times more than Run 1 was delivered in Run 2. The ATLAS detector recorded $147 fb^{-1}$ of the data, exhibiting an impressive efficacy of 95%. Out of recorded data, only data fulfilling strict quality criterion can be used in physics analyses. In Run 2, $139 fb^{-1}$ of the recorded data is compatible for analysis.

The increase in instantaneous luminosity is explicitly favourable for the LHC as more data can be gathered in short period of time. Hence it develops an increase in number of interactions occur in a given bunch crossing. As the matter of the fact is, LHC experiments are only interested in a single interaction of a bunch crossing, with the interaction which is high in potential of physics. This interaction is thus named as hard-scatter interaction, while the supplementary activity is termed as pile-up.

Pile-up can be categorized as in-time pileup and out-of-time pileup. In-time pileup arises from additional collisions happening within the same bunch as that of the hard scattering whereas out-of-time pileup takes place in preceding bunch crossing associated to the hard scattering.

The existence of the pile-up hence collapses the performance of the detectors, because of the emerging particles from the pile-up interaction could tarnish hard-scatter

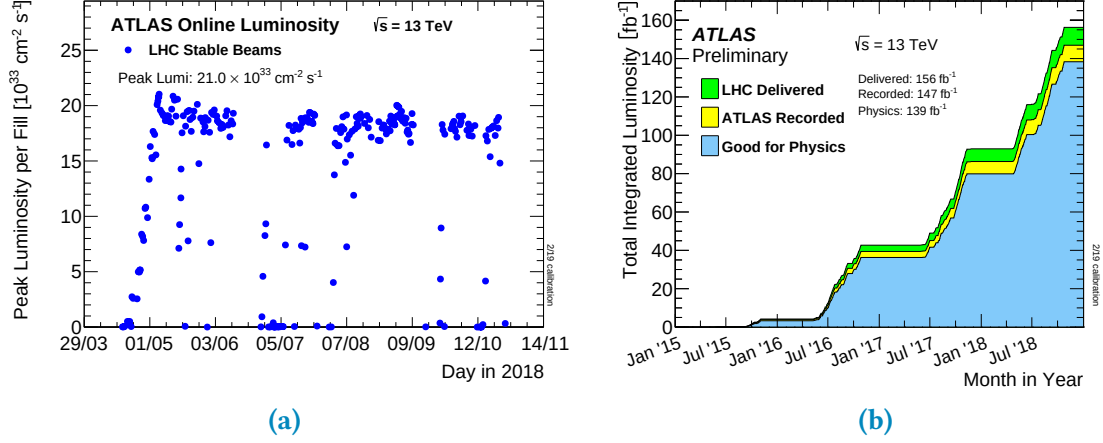


Figure 3.4: The plot (a) represents the distribution of peak instantaneous luminosity delivered to ATLAS as a function of time for 2018 data-taking period whereas plot (b) shows the same distribution for integrated luminosity versus time delivered to ATLAS (green) and recorded by ATLAS (yellow) during stable beams for pp collisions at 13 TeV centre- of-mass energy in the LHC Run 2 [83] .

events. Thus, the number of pile-up interactions per bunch crossing can be revealed by the formula;

$$\mu = \frac{L \times \sigma_{inel}}{N_b f} \quad (3.4)$$

Where σ_{inel} is the proton-proton inelastic cross-section. Fig. 3.5 represents the distribution of $\langle \mu \rangle$ for each year of the Run 2 pp collisions.

It was great challenge to project LHC as hadron accelerator and collider, because of huge radiative energy losses of accelerating electrons in a circular trajectory. As the charged particle accelerated radially by the energy losses in accordance with the relation,

$$\frac{dE}{dt} \propto \frac{E^4}{m^4 R} \quad (3.5)$$

Where E is the energy, m is mass of the particle and R is the orbit radius. The above equation conforms that energy loss is notably higher for electrons at the fixed energy and collider orbit radius which is $(m_p/m_e)^4$ would be 1013 times greater than for the protons.

Nevertheless, protons are not the elementary particles but are hadrons made up of partons (quarks or gluons) which carry only a fraction of the total momentum of the proton. In this scenario there are two possible types of interactions: soft or hard collisions.

Soft Collisions

The frequent interactions are emerged in LHC bunch crossing through distant collisions in which protons behave like elementary particles. Therefore, small transverse momentum is carried by the final state particles.

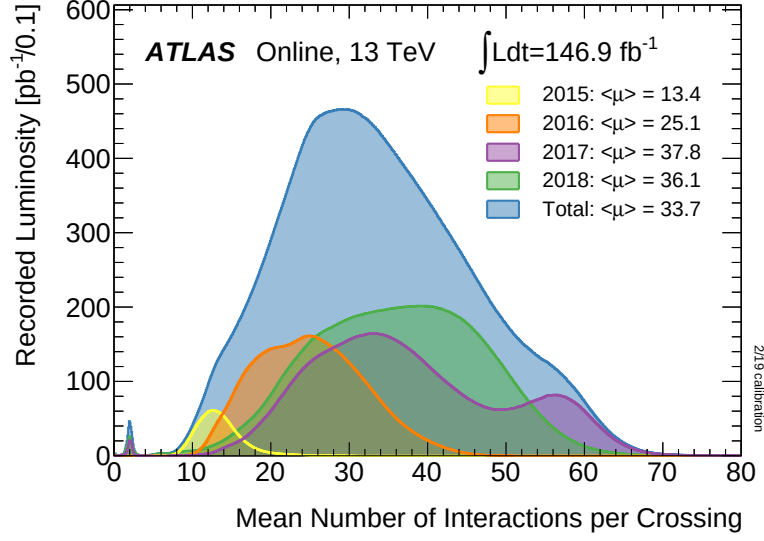


Figure 3.5: Distribution of mean number of interactions per bunch-crossing for each year of the Run 2 pp collisions data at 13 TeV centre of mass energy [83].

Hard collisions

The rare and most interesting interactions are hard collision in experimental point of view. Indeed, they are short distance collisions but can probe final state particles with high transverse momentum and mass.

3.3 The ATLAS Detector

ATLAS (A Toroidal LHC ApparatuS) [63] is one of the seven experiments on the LHC's ring. It is the largest collaboration of over 3000 active scientists and 180 institutions from 38 different countries. The core of the ATLAS experiment is its detector. It is cylindrical in shape, having diameter about 25 metres and 46 metres long and comprising weight roughly seven kilo tonnes. A schematic view of the ATLAS detector is shown in Fig. 3.6. The ATLAS detector is composed of several subsystems, which are enfolded concentrically around the beam and interaction point (IP) in the middle of the detector. Its various components record the paths, momentum and energy of the particles, allowing them to be independently identified. The components of the detector are briefly described below;

- **Magnetic system** It bends the charged particles, assisting in their separation, charge and momentum computation. It consists of two parts: a solenoid magnet providing a 2T field to the inner detector, and a pair of toroid magnets where muon spectrometer is employed.
- **Inner Detector** It is interior portion of the ATLAS detector, comprising various high granularity tracking layers and enumerate trajectories with momentum of the charged particles using solenoidal magnetic field. Furthermore, it reconstructs the interaction vertices of each bunch-crossing.

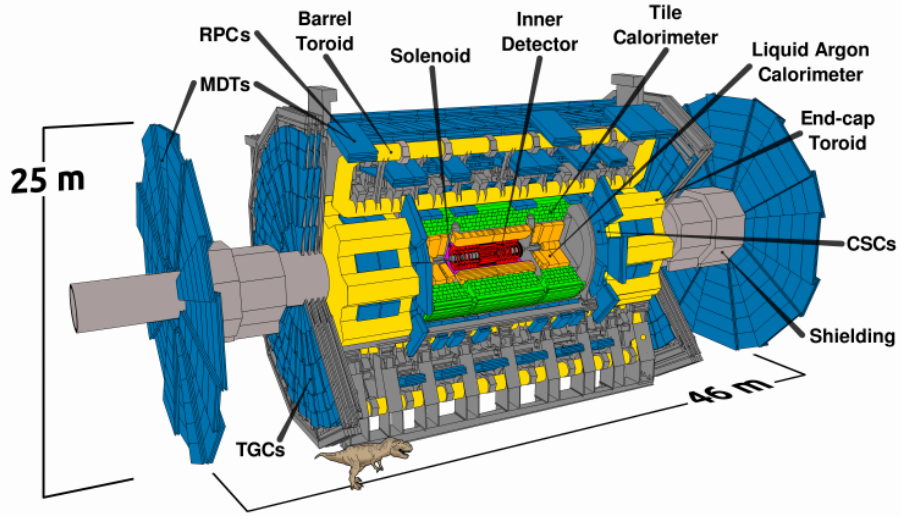


Figure 3.6: Graphical depiction of the ATLAS detector and its various subdetectors. Figure adapted from Ref. [84].

- **Calorimeter** They are located outside the solenoid magnet and are supposed to measure energy deposited by particles.
- **Muon System** The muonic spectrometer is a tracking system of gaseous chambers. Muons pass all the way through other components of the detector without being absorbed and hence deposit energy in the muon system. That is how, the momentum of the muons can be estimated by using toroidal magnets.

As the ATLAS is a general-purpose detector, it was developed to explore numerous candidates of new physics, and in addition perform standard model measurements precisely. On top of that was the search of Higgs boson in 2012.

3.3.1 The ATLAS coordinate system

ATLAS detector uses a right-handed coordinate system, depicted in the Fig. 3.7 having origin at nominal interaction point. The z-axis is representing beam pipe direction, the x-axis points towards the centre of the LHC ring and y-axis depicts the direction of the detector upward. The cylindrical coordinates (z, ϕ, θ) are most often used. The ' ϕ ' is the azimuthal angle around the beam pipe (x-y plane which is perpendicular to the beam direction) whereas ' θ ' is the polar angle with respect to the z-axis. All the transverse parameters i.e. p_T, E_T, E_T^{miss} are defined in x-y plane.

A range of $-\pi < \phi < \pi$ is specified while ' θ ' can be replaced by the distance 'r' to the beam axis at a position z. In particle physics, azimuthal angle ' θ ' and the pseudorapidity ' η ' defined as the function of polar angle ' θ ';

$$\eta = -\log \tan\left(\frac{\theta}{2}\right) \quad (3.6)$$

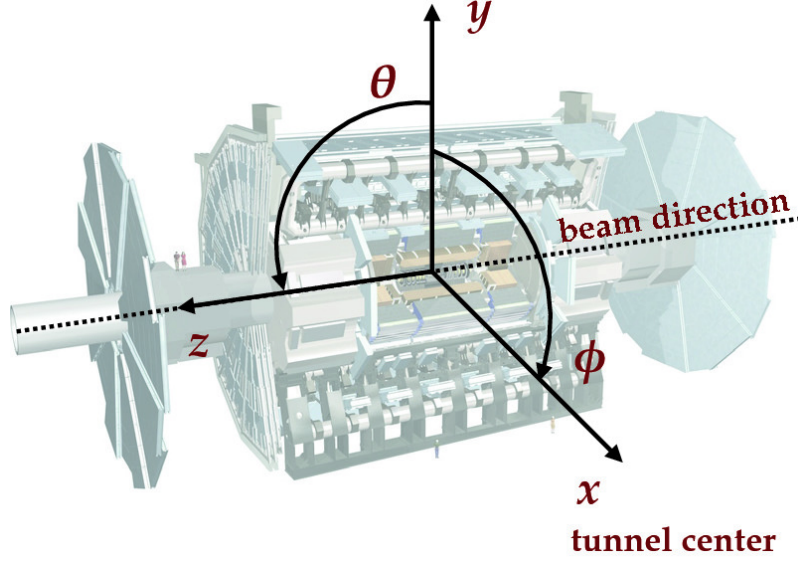


Figure 3.7: A scheme of right-handed coordinate system followed by the ATLAS detector.

A pseudo rapidity of $\eta = 0$ points to the centre of the detector, whereas $\eta \rightarrow \infty$ corresponds to the beam axis. As per assumed that a particle speed is nearly approaches to speed of the light in hardon collider physics, pseudo-rapidity is usually given preference over the polar angle ' θ '. The divergence in pseudo-rapidity ' η ' is invariant under boosts along beam axis.

In case of particles with greater mass, rapidity $y = \frac{1}{2} \times \log[(E + p_z)(E - p_z)]$ can be used, where E is the energy and p_z is the z -component of momentum. The angular distance between two objects in the detector can be estimated by using quantity ΔR , which is determined as $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$.

3.3.2 ATLAS Magnet System

The ATLAS detector comprises four gigantic superconducting magnetic systems:

Solenoidal

The inner most part of the magnetic system is *central solenoid magnet*. It is installed around inner detector and wounded with a total of 9 km of superconducting wires creating magnetic field of 2T at a nominal current of 7.73 kA. It has length of about 5.3 metres, with diameter of 2.4 m and it is cooled at 4.5 K. A layout of the magnetic system of ATLAS detector can be seen in the Fig. 3.8 The basic aim of solenoidal magnet is to bend the trajectories of the charged particles in inner tracking.

Toroidal

The ATLAS toroidal system of magnets is developed by barrel toroid, comprising 8 separate coils with nominal electric current of 20.5 kA and two end-caps toroid's', that provide a field of 0.5 T and 1T in the central and end-cap regions. The magnets are placed outer space of calorimeters. The dimensions of barrel with its outer diameter are 20.1 m,

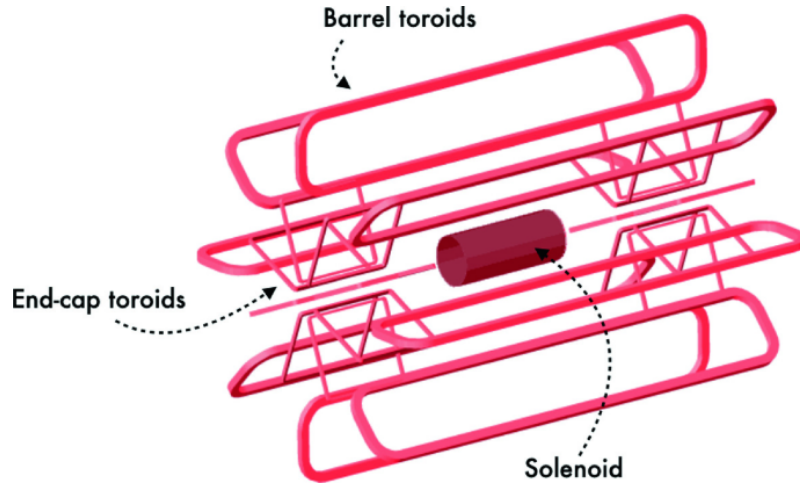


Figure 3.8: A schematic view of the magnetic system at ATLAS. Figure adapted from Ref. [85]

and length 25.3 m. The endcap toroid's are supposed to create a magnetic field near the beam axis, with aim to deflect the particles with small polar angles. Each of the toroid's are wound with 8 superconducting coils with diameter of 10.7m and width of 5m. A view of barrel toroid with its 8 coils is depicted in the Fig. 3.9.



Figure 3.9: A sketch of ATLAS detector barrel toroid model [86].

3.3.3 Particle identification with the ATLAS detector

The ATLAS detector has a system of detecting particles through the trails leave by them while passing through it. For instance, Fig. 3.10 instantiates the signatures of particles when they stretch across the ATLAS detector. The charged particles can be detected and identified through their potential signatures by detector. These candidates are holding an electrical charge and thus leave energy deposits normally named as hits in inner de-

tector (ID). Electrons are stopped by electromagnetic calorimeter once they impart all the energy and elicit a shower with a signal proportionate to their total energy. Photons on the other hand, elicit similar calorimeter signatures like electrons, but leave no characteristic trails while traveling through ID as they don't have an electrical charge. Protons leave a bent track in the ID being a charged particle like electrons and deposit all of their energy in the hadronic calorimeter since they are categorised as hadrons. Conversely, neutrons leave no potential tracks in the ID as being a neutral particle. Muons leave minimal traces of their energy deposit in the ID and electromagnetic calorimeter without launching a shower. They are heavier particle than electron and deposit some of their energy (hits) while crossing the Muon Spectrometer. Neutrinos pass through the ATLAS detector without being detected.

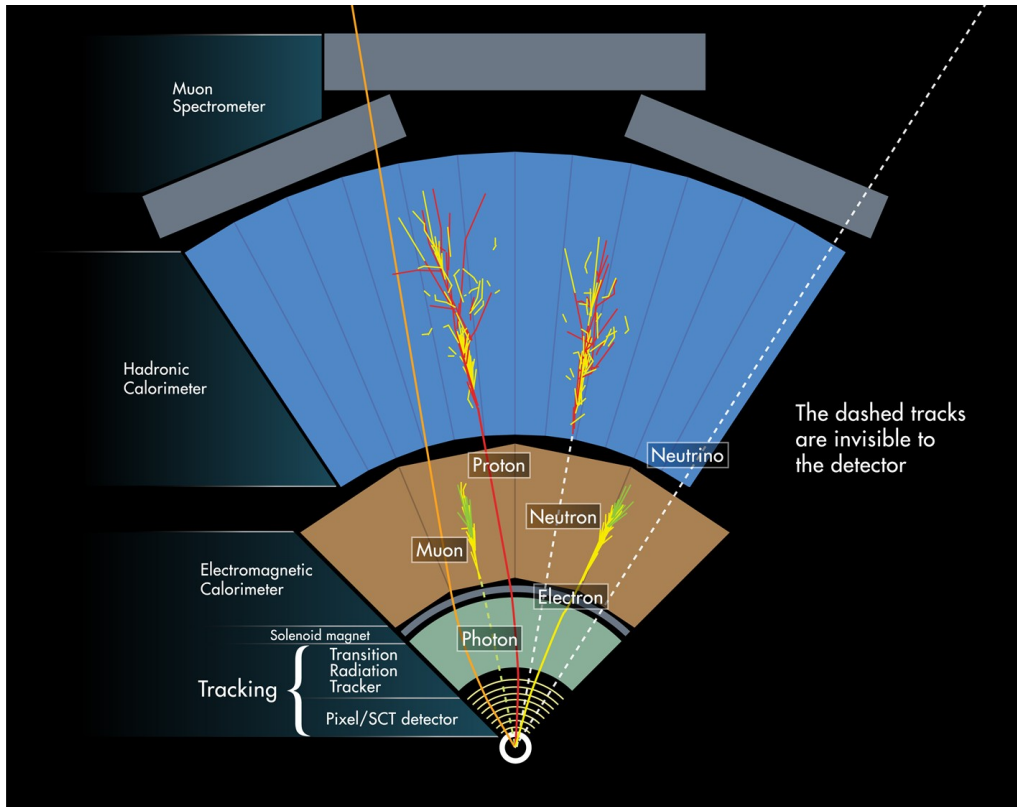


Figure 3.10: Cutaway view of the ATLAS detector demonstrating potential signatures of various particles inside the ATLAS detector [90].

3.3.4 The Inner Detector

The configuration of ATLAS inner detector is depicted in the Fig. 3.11. The ID constitutes the first detector layers around the beam pipe and interaction point. The particles originating from pp collisions can interact with this component of the ATLAS detector. It consists of three sub-detector systems, namely pixel detector [87], the semiconductor tracker (SCT) [88], covering $|\eta| < 2.5$ and the Transition Radiation Tracker (TRT) [89] covering $|\eta| < 2.0$. It is designed to observe all the possible decay products of the interaction between subatomic particles. It is capable to reconstruct both primary and secondary vertices and delivers outstanding momentum resolution of charged particles.

The momentum resolution has direct correspondence with curvature of the particles (i.e. performance collapses when p_T increases). The relation between expected resolution and particle p_T can be expressed as;

$$\frac{\sigma_{p_T}}{p_T} = \alpha p_T [GeV] \oplus b \quad (3.7)$$

Where ‘ α ’ is the intrinsic resolution of the momentum measurement in a magnetic field and ‘ b ’ is term which shows association with the effects produced by multiple scattering. The Inner detector is surrounded by the following four sub-detectors;

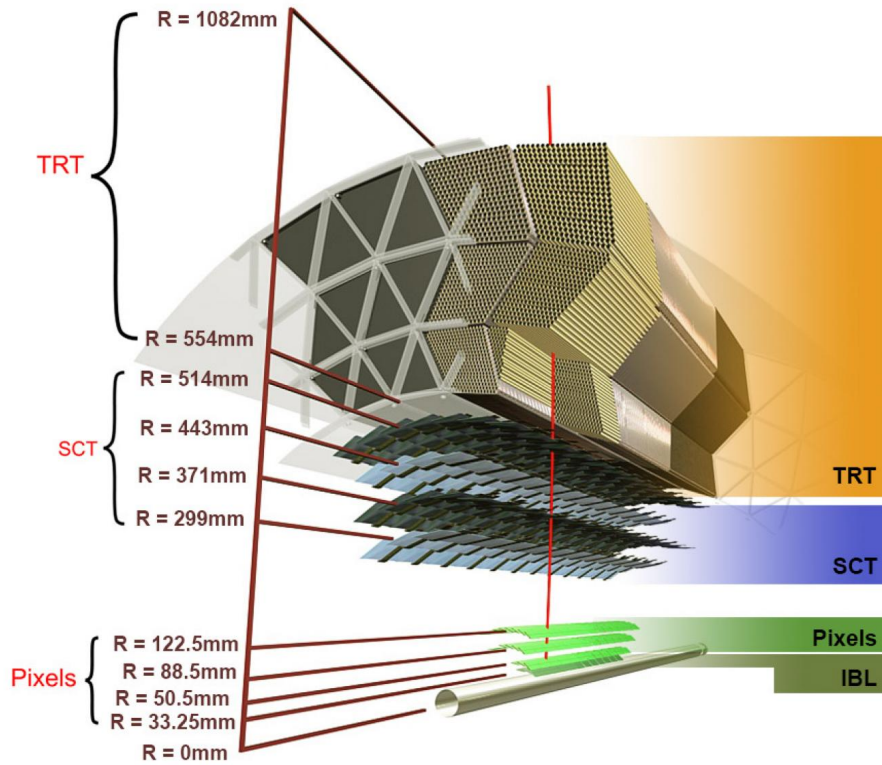


Figure 3.11: A radial cross section of the inner detector barrel

The Insertable B-Layer (IBL)

The innermost section of silicon pixel detectors is ATLAS Insertable B-Layer (IBL) [91]. The electric field created by reverse biasing of p-n junction of the semiconductor devices help to detect the particles. The electron and hole pairs are produced when a particle traverses sensor. Hence, a signal is established due to the movement of such charge carriers. With the aim to provide measurements adjacent to the interaction point, the IBL was installed during shutdown between Run-1 and Run-2. This layer was placed between the beam-pipe and the pixel detector and proposed for the identification of b-jets to ensure high quality of the track and vertex reconstruction on account of radiation damages by existing pixel detector. The IBL modules comprises two different types of pixel sensors i.e ; planar and 3D sensors with the dimension of $50 \times 250 \mu m^2$.

Pixel Detector

The next segment to IBL is the pixel detector. It comprises three coaxial layers on the barrel of the detector and three disks on each end-cap. Three-barrel coverings are placed at the distances of 50.5 mm, 88.5 mm and 122.5 mm from the beam pipe, respectively as depicted in the Fig. 3.12. In case of two end-caps, three disks are positioned at radial distances of 49.5 mm, 58.0 mm and 65.0 mm respectively. The detectors composed of pixel sensors, containing 1744 in numbers. Each of them correlates with semiconductor (Si) sensor with dimensions $50 \times 400 \mu\text{m}$. The pixels provide high resolution track and vertex reconstruction and counts 80 million channels approximately.

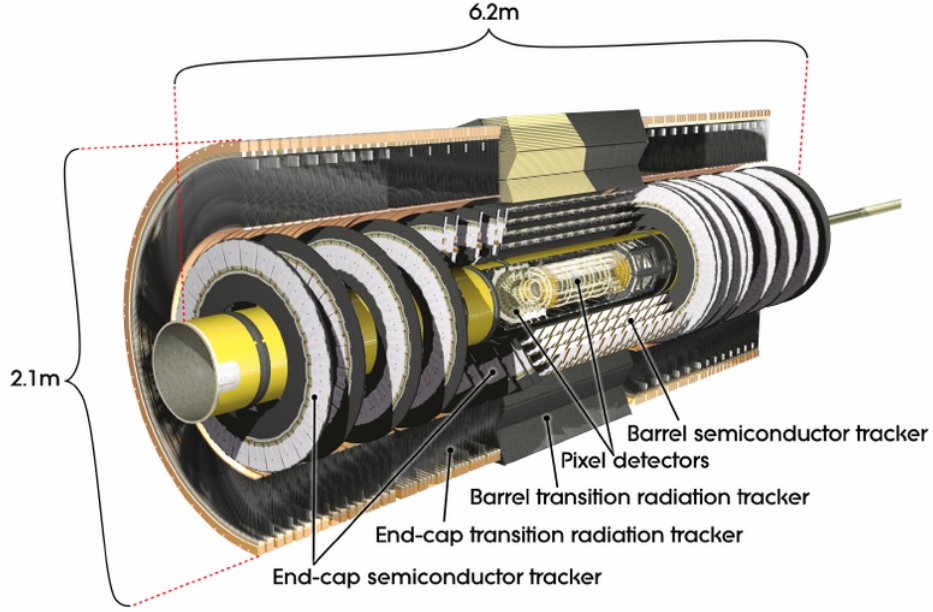


Figure 3.12: The cut away view of the inner detector.

Semiconductor Tracker

The semiconductor tracker is located around pixel detector and comprises four cylindrical layers in the barrel region and nine disks in the end-caps stretched in the radius of 290 mm to 560 mm. The layers hold silicon microstrip modules distant at average of $80 \mu\text{m}$. Each of the module is surrounded by two sensor layers positioned at an angle of 40 mrad allowing 2D hit reconstruction in the plane. The barrel region covers $|\eta| < 1.4$ and the end-cap region equipped with modules covering $1.4 < |\eta| < 2.5$ range. For the particles traveling from interaction point, the SCT imparts measurements in four space points that counts eight microstrip's hits. The SCT provides a resolution of $17 \times 580 \mu\text{m}^2$ in the plane of $r - \phi \times z$ for barrel and $580 \times 17 \mu\text{m}^2$ for end-caps region. The hit details are recorded in binary format when pulse surpasses a threshold inside channel.

The Transition Radiation Tracker

This is the final and outermost layer of the ATLAS ID. The TRT comprises straws which are filled with gas mixture having diameter of 4 mm with a wire in the center that collects

the electric charge. These tubes are elongated with an extension of 144 cm towards barrel region and have assembly of 72 layers leveled with the beam pipe. The tubes are further stretched out 37 cm in length towards end-caps and sit perpendicular to the beam pipe dispensing tracking up to $|\eta| < 2.0$ to charged particles. It imparts precision of $130 \mu\text{m}$ in $r-\phi$ for the barrel and $z-\phi$ for the end-caps. When a charged particle hits the TRT, it gets ionized because of the gas mixture present inside tube. The TRT has been operated with Xenon gas during Run 1 however, it was replaced with cheaper Argon gas mixture in Run 2 due to irremediable leaks. This change of mixture has affected identification of particle as Argon gas is not quite efficient with an absorbed photon [93].

3.3.5 The Calorimeter

The ATLAS Calorimeters are designed to estimate the energy and position of particles i.e. electrons, photons, jets, neutrons and missing transverse energy E_T . It is meant for incorporating energy of the particles originated from a collision and measure them within the detector. A schematic of calorimeter system within the ATLAS detector is demonstrated in Fig. 3.13. This system of calorimeters is surrounded by electromagnetic calorimeter (ECAL) and hadronic calorimeter (HCAL) to compute the energy of showers originating through electrons or hadrons interactions. The calorimeters cover the range $|\eta| < 4.9$ around the beam axis. Various sub-systems are put in place in three cryostats, one barrel and two end-caps. The electromagnetic barrel calorimeter is located in the barrel cryostat, whereas electromagnetic end-cap (EMEC), hadronic end-cap calorimeter (HEC) and the forward calorimeter (FCal) are stationed in each of the two end-cap cryostats covering proximate beam region. The measurements are performed in terms of energy within forward calorimeter (FCal) utilising Liquid Argon (LAr). The LAr is being nominated as an active material for it has stable response, radiation hardness and linear behaviour in order to measure the energy of particles intrinsically.

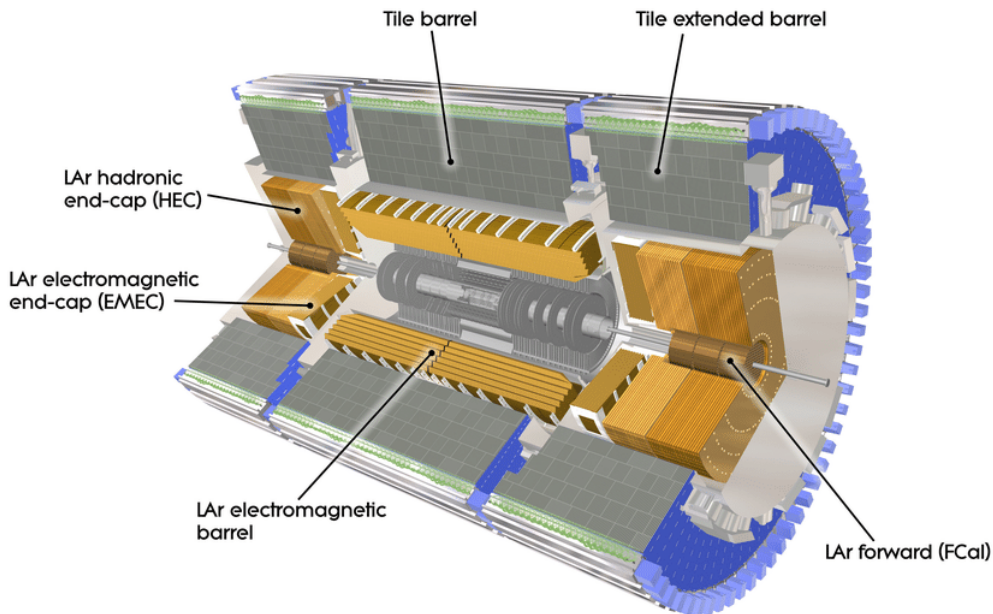


Figure 3.13: An overview of the ATLAS calorimeter system [63].

3.3.5.1 Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) exploits liquid Argon (LAr) as an active medium and lead as an absorber to generate an electromagnetic shower. The selection of the passive medium or absorber is based on the bremsstrahlung or pair production of electrons and photons at high energy which dispenses large area of cross-section of the ECAL. It is located at the rear of superconducting solenoid in the barrel and contains two cylinders (coaxial) partitioned by a gap at $z = 0$ covering region $|\eta| = 1.475$. The growth of EM shower depends entirely on radiation length (X_0)². The following expression computes incident energy of the particle in terms of radiation length;

$$E = E_0 e^{-x/X_0} \quad (3.8)$$

The electromagnetic calorimeter (ECAL) with electrodes and absorber adapt an accordion geometry as demonstrated in Fig. 3.14 which imparts full azimuthal symmetry and covers crack-less region. The signal is created at high voltage when charged particles ionize through interaction with the layers of liquid argon. The thickness is extended to $24 X_0$ in the barrel and $26 X_0$ in the end-caps, in order to meet the requirements of physics analyses i.e an object is required to be within $|\eta| < 2.5$ for measurements.

The barrel ECAL readout split up into three different layers dependent on ϕ and η segmentation which are used to supply information about shape of particle showers. The innermost layer is extended up to 4 radiation lengths X_0 comprising thin strips of $\Delta\phi \times \Delta\eta = 0.01 \times 0.003$ to distinguish between charged and neutral pions. The middle layer is $16X_0$ long and contains cells with dimension of $\Delta\phi \times \Delta\eta = 0.0245 \times 0.025$. Being an extensive layer of electromagnetic calorimeter, this measures directions of both photons and electrons. To discriminate electromagnetic showers from hadronic showers and estimate the fraction of EM showers reaching hadronic calorimeter³, the outermost layer is extended up to $2X_0$.

In order to minimize energy losses due to the material, thin layers of pre-sampler are put in place before the ECAL in several regions of barrel and end-cap. The relative resolution of energy of the ECAL is $\sigma E/E = 10\%/\sqrt{E[GeV]} \oplus 0.7\%$.

3.3.5.2 Hadronic Calorimeter

The hadronic calorimeter (HCAL) is placed at the rear of ECAL and is a momentous for energy measurements of hadronic showers. This comprises three calorimeters which exploit active and passive media determined by the performances and radiation hardness. The energy resolution fashioned for the hadronic calorimeter is $\sigma E/E = 50\%/\sqrt{E[GeV]} \oplus 3\%$ for the barrel and end-cap, aggravating up to $\sigma E/E = 100\%/\sqrt{E[GeV]} \oplus 10\%$ for the forward calorimeter.

Tile calorimeter

The tile calorimeter incorporates barrel having length 5.8 m and two 2.6 m prolonged barrels i.e. extended in the η region between the barrel and the end-caps. They furnish η

²A mean length or distance a particle needs to cover in order to reduce its energy by the factor $\frac{1}{e}$

³To eliminate this fraction in the EM cluster such that energy calibration could be corrected for the missing part

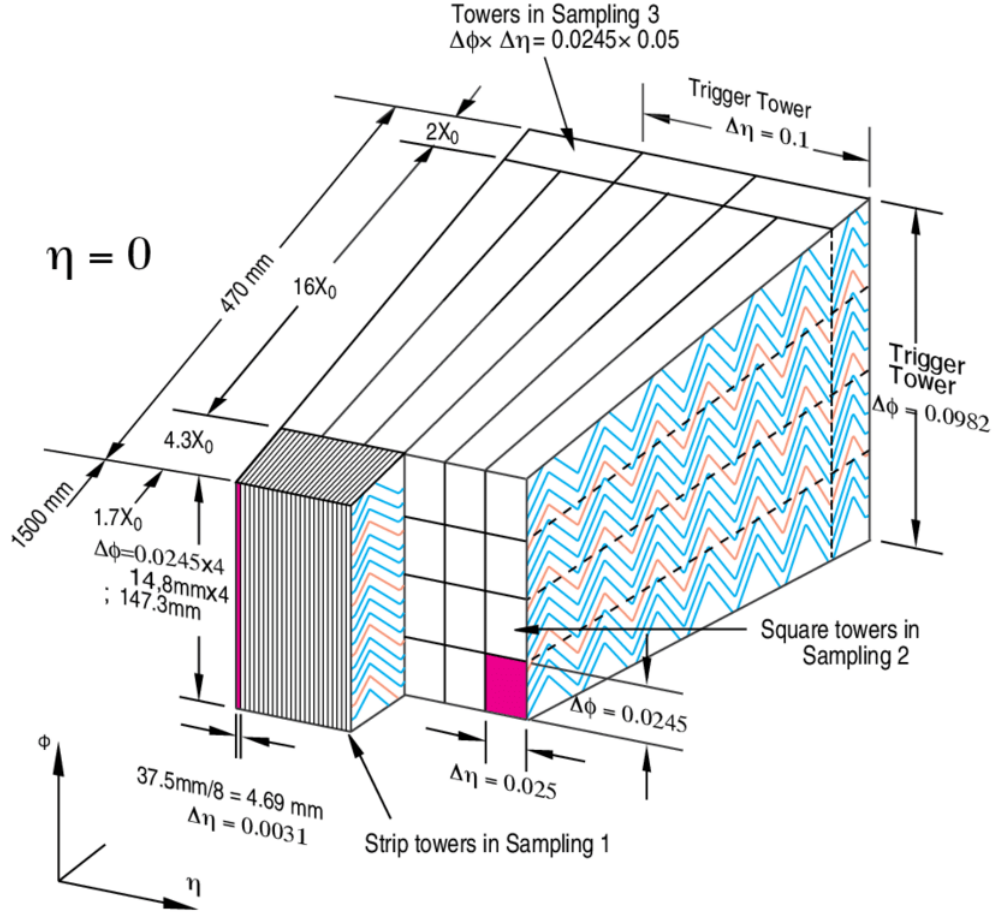


Figure 3.14: A schematic of the electromagnetic barrel LAr calorimeters. The granularity of η and ϕ with accordion geometry in three layers of ECAL is demonstrated on the side of Trigger Tower [65].

coverage in the regions of $|\eta| < 1.0$ and $0.8 < |\eta| < 1.7$. The tile calorimeter is segregated into three layers which are extended in the barrel with interaction lengths of 1.5, 1.4 and 1.8λ while the extended barrel are stretched out with 1.5, 2.6 and 3.3λ layers. The cells in each of the layers are markedly bigger than the cells in electromagnetic calorimeter with dimension of $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ to dispense the localization of hadronic showers. The whole detector contains thickness of about 9.7λ for tile region at $\eta = 0$ retrieving the energy losses between two barrel regions with gap scintillators positioned along extended barrel.

LAr hadronic end-cap calorimeter

The LAr hadronic end-cap calorimeter is being placed at the rear of end-cap of the ECAL carving up same cryostats. The end-cap comprises wheels constituting modules in the plane to exploit LAr as active medium and copper as an absorber. Each wheel is composed of 32 wedge-shaped modules split up into 2 longitudinal portions neighbouring four layers per end-cap consequently. They are imparting η coverage within range of $1.5 < |\eta| < 3.2$. The central region employs readout cells with dimension of $\Delta\phi \times \Delta\eta \equiv 0.1 \times 0.1$ just like the tile calorimeter. Moving away from the interaction

point, the granularity gets turned down effectively. However, in the forward regions of the detectors, the use of LAr as an active medium is advantageous due to the reason that it is resistive to radiation and its ability to substitute the liquid in case of performance collapses.

LAr forward calorimeter

The LAr forward calorimeter is stationed in the forward region of the detector and covers region of $3.1 < |\eta| < 4.9$ close to the beam pipe. The FCAL detects hadronic jets at angle $> 1^\circ$ from beam axis and is extended 10 interaction lengths with divisions of three modules in either of the end-caps as shown in Fig. 3.15. Each module comprises metal matrix, with equally spaced channels equipped with electrode containing rods and tubes in parallel to the beam axis. There is gap between the rod and tube which is filled with LAr as an active medium. Usually, the gap establish a quick signal with an ability to handle the irregularities due to the collisions in forward region. The first module holds copper as passive medium to dispense electromagnetic measurements whereas, other two contain tungsten as passive medium to estimate energy coming through hadronic interactions. The HCAL referring to about 7.4 radiation lengths sits radially outward at $\eta = 0$ from the interaction point coming up with enough material to make sure of hermetic closure. This imparts stable measurements for energy in transversal plane and provide insulation to Muon Spectrometer from particles other than muons and neutrinos.

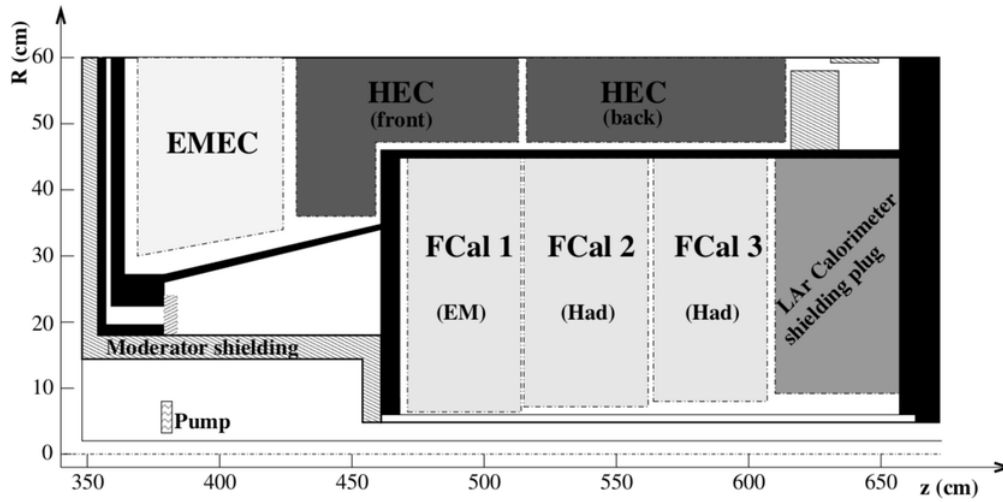


Figure 3.15: A schematic diagram presenting three FCAL modules placed in the end-cap cryostat which also includes the material at front of FCAL and shielding plug at the rear. The black regions depict structural parts of the cryostat [63].

3.3.6 The Muon Spectrometer

The Muon Spectrometer (MS) is positioned in the outer part of the ATLAS detector as depicted in Fig. 3.16 and designated to measure muons when passing through it. They are further reconstructed with combined information from inner detector, hits (energy deposits) in the calorimeter and MS. It is basically a tracking detector and aimed to dispense precise momentum measurements for muons in terms of energy (a few TeV). Muons lose

less energy through ionisation as compared to other particles and aren't obstructed by the calorimeters. Having a short mean lifetime of about $2.2\mu s$, they escape the ATLAS detector before get decayed. As, all SM particles except neutrino, don't get through the calorimeter so the track in the MS is only the indication of muon. It established an individual magnetic system that builds up a field in which muons can be bent. This system creates 4T magnetic field to divert them along η direction to cover up a region of $|\eta| = 1.4$. However, another pair of small toroid magnets establish the magnetic effect of $\sim 3.5T$ [64] together to cover up a range of $1.6 < |\eta| < 2.7$ in the barrel region. The idea of having two separate magnetic field installed is to have more bending volume so that momentum resolution can be augmented.

It consists of four subcomponents that provide a coverage of $|\eta| < 2.7$. The precise measurement of the track coordinates in the bending direction of magnetic field is supplied by **Monitored Drift Tubes** (MDT). Going beyond $2 < |\eta| < 2.7$ the range of pseudorapidity, the precision measurements are taken care of by the **Cathode Strip Chambers** (CSC). Then, exploiting **Resistive Plate Chambers** (RPC) in the barrel and **Thin Gap Chambers**(TGC) in the end-caps, trigger system can cover up a region of $|\eta| < 2.4$.

The trigger system is also employed to dispense bunch-crossing identification, signatures beyond selected p_T thresholds and estimates muon coordinates perpendicular to the tracking chambers. The relevant parameters of the MS's sub-detectors are enlisted in the Table. 3.1

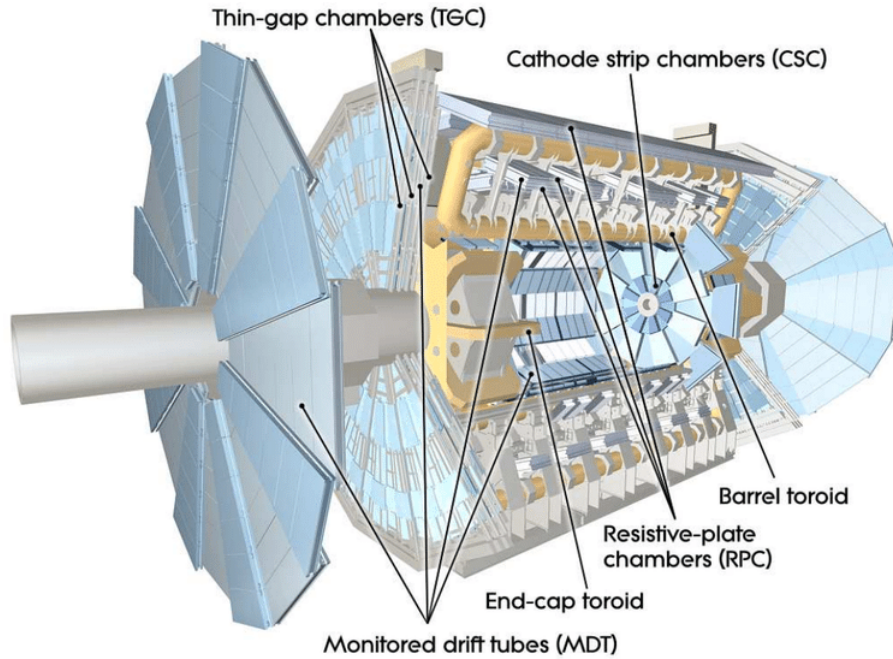


Figure 3.16: Schematic view of the ATLAS muon spectrometer and its components [63].

Type	Chamber resolution in			Track/Measurements		Number of	
	z/R	ϕ	time	barrel	end-cap	chambers	channels
MDT	35 μm (z)	—	—	20	20	1088	339k
CSC	40 μm (R)	5 mm	7 ns	—	4	32	30.7k
RPC	10 mm (z)	10 mm	1.5 ns	6	—	544	359k
TGC	2-6 mm (R)	3-7 mm	4 ns	—	9	3588	318k

Table 3.1: The specification of the four sub-systems of the muon detector. The information about spatial resolution provided in column 2, 3 exclude uncertainties for chamber alignment. The intrinsic time resolution of each chamber type is listed in column 4, where signal propagation contributions and electronics artifacts are to be added. Adapted from Ref. [63]

Monitored Drift Tubes

The MDTs are composed of 2 multi-layered drift tubes of 30 mm diameter which function with a mixtures of argon (93%) and carbon-dioxide (3%) gas. First layer provides a coverage up to $|\eta| < 2.0$ and the other two layers can cover up to $|\eta| < 2.7$. It contains 0.05 mm tungsten-rhenium wire of diameter 50 μm in the center which collects electrons radiated through ionization. The wire is positioned with ends of the tube to ensure wire-tube have same center and provide an accuracy of $\sigma < 10 \mu m$. This wire is also held responsible for back and forth movement of the gas in tube. As a handicap, this mixture of Ar/CO_2 affect the spatial resolution at high voltages because of the disturbed electric field due to the presence of positively charged ions. Nevertheless, this non-linearity of the gas mixture causes an erratic shift in space-time relation which elongates the period of drift relative to other gases.

Cathode Strip Chambers

This CSC's contain a chamber holding wires in the direction parallel with beam axis which deliver precise momentum resolution within pseudorapidity range of $2.0 < |\eta| < 2.7$. Each chamber is filled with 80% Ar and 20% CO_2 . The cathodes are partitioned in a way that permits measurements longitudinally or transversely. The track position is determined through extrapolation between the deposited charge on neighbouring cathode strips. To achieve, a comparable resolution i.e. 80 μm of a MDT tube layer, a readout pitch of 5.31 mm and 5.56 mm for large and small chambers in the bending direction is taken into account. This way, CSC hits a resolution ⁴ of 60 μm per plane. The CSC's are divided into chambers of different sizes in ϕ which dispense independent measurements in η and ϕ along the track. The region where particles are highly populated, CSC's overcome MDT's by performance. For instance, in the end-cap region of $\eta > 2$, CSC's provide transparency in track resolution in case of multiple tracks (ambiguous), time resolution of 7 ns per plane and low neutron sensitivity.

⁴It depends on the signal-to-noise ratio and readout pitch. The latter is premier cost-driving factor for the readout electronics

Resistive Plate Chambers

The trigger system comprises resistive plate chambers (RPC's) which are composed of cylindrical layers i.e. concentric around the beam axis. This three trigger stations containing RPC's are shown in Fig. 3.17. The middle RPC's requires a threshold to provide momentum tracks above 10 GeV (i.e. high p_T trigger) while in contrast other two RPC's are to bring forth low p_T trigger i.e. below 10 GeV. Each station contains two detector layers independently, which deliver measurements in η and ϕ . This way, a track traversing all the three stations furnishes six measurements in η and ϕ . The track superfluity i.e. repetitions in the track assessment enables to employ 3-out-of-4 concurrences in either projections for the low p_T trigger i.e. RPC1 and RPC2 stations and 1-out-of-2 for the high p_T trigger (i.e. RPC3 station). Strategically, these concurrences discard fake tracks from noise hits and meliorates the trigger efficiency along with the inaccuracies present. RPCs contain 370000 readout channels and are positioned inside every MDT barrel layer which provide a coverage of $|\eta| < 1.05$. Each channel has cathode strips perpendicular to anode strips in a chamber which is filled with a gaseous mixture of $C_2H_2F_4$ / Iso- C_4H_{10} / SF_6 . This mixture is non-flammable, inexpensive and can be operated at low voltages. The muons traveling through them deliver a stable plateau for avalanche operation and give rise to ionized electrons which get multiplied into avalanches with an effect of electric field i.e. about 5kV per mm.

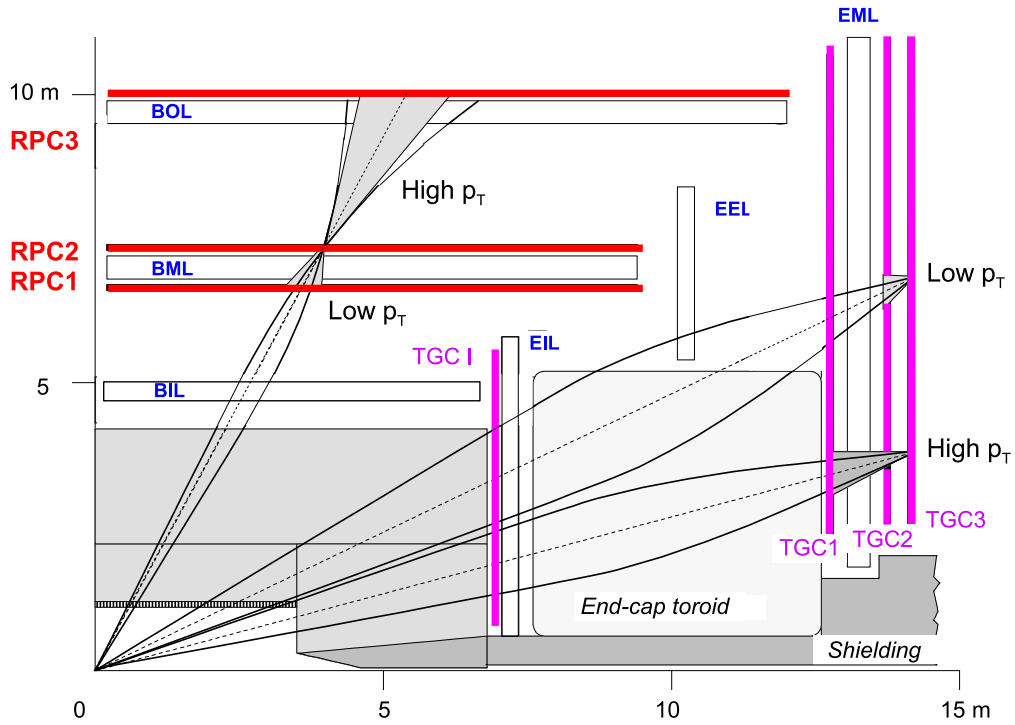


Figure 3.17: An overview of the ATLAS muon trigger system [63]. The pivot or reference planes for barrel and end-cap are RPC2 and TGC3.

Thin Gap Chambers

TGC's are primarily functioning in the end-caps of MS aiming at delivering trigger proficiency and azimuthal coordinate measurements which is an adjunct to MDT's estimates

in radial direction. The seven layers of TGC's are accompanied with a middle layer of MDT's in the end-cap of electromagnetic wheel while on the contrary, inner layer of MDT's is supported by two layers of TGC's. The TGC's requires good time resolution in order to achieve high efficiency ($> 99\%$) with beam crossing being marked and to deliver sharp cut-off for triggered muon. The TGC's are basically multi-wire chambers partitioned radially into end-cap region and forward region.

They are characterized with a wire-to-cathode distance of 1.4 mm which is smaller than wire-to-wire distance of 1.8 mm. To meet all physics prerequisites on the momentum resolution, the length of the grouped wires fluctuates between 6 and 31 mm as a function of η which is correlated with width of the wires ranging from 10.8 mm to 55.8 mm. The TGC's are filled with quenching gas mixture of CO_2 and $\text{n-C}_5\text{H}_{12}$ (n-pentane) allowing operation to achieve a gas gain of $\sim 3 \times 10^5$. Comparatively, this seems lower gas gain to prior implementations of the TGC's and make it limited in use. However, this mixture of gas can still be useful to prevent the contingencies in case of streamers in all operating conditions.

3.3.7 Forward detectors

In order to cover large pseudo rapidity region i.e. $|\eta| < 4.9$ which is overlooked by the central detectors, an additional sets of detectors are put in place in the forward region. The complete ATLAS forward detector system is demonstrated in Fig. 3.18. On the basis of the distance from the point of interaction (IP), three sets of detectors are defined in the forward region. The first in the list is Cerenkov detector called LUCID (LUMinosity measurement using Cerenkov Integrating Detector) which is nearest to the TAS (Target Absorber Secondaries) collimator and positioned at a distance of ± 17 m from IP. The second one is Zero-Degree Calorimeter (ZDC), which is installed at the distance of ± 140 m from IP and is encapsulated in TAN (Target Absorber Neutral). Third in the row is, absolute luminosity detector ALFA (Absolute Luminosity For ATLAS) which is a faraway detector maintaining a distance of about ± 240 m from IP.

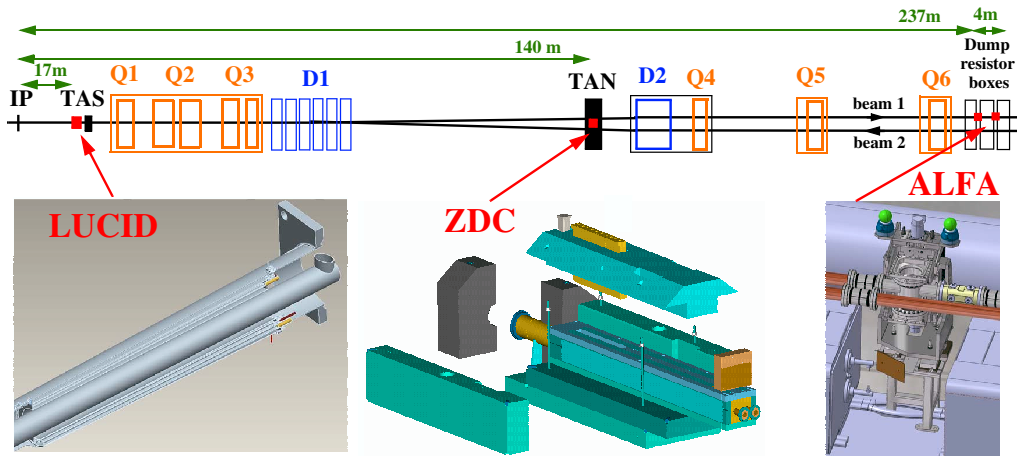


Figure 3.18: Installation of ATLAS Forward detectors along the beam line and their corresponding distances from the point of interaction [63].

To detect those particles outside the scope of the central region i.e. $|\eta| = 2.5$, the forward detectors come up with its system of detecting and measuring them. The following

detectors playing their role in forward region are briefly explained below;

- **LUCID** is a Cherenkov detector comprises two modules placed along the direction to the beam pipe. This is designed to compute relative luminosity within region of $5.6 < |\eta| < 5.9$. Each module contains photo multiplier tubes⁵ (PMT's) surrounded by the beam pipe, along with thin quartz being used as an active medium. When a charged particle travels through it, Cherenkov light is emitted and read as a signal or hit is registered if it is above the threshold level. The LUCID [77] detector's function is coordinated with electronics committed to provide hit counts for every colliding bunch.
- **MBTS** is the ATLAS Minimum Bias Triggers which comprises scintillators disks installed on either sides of the interaction point at the distance of ~ 3.6 m along the beam pipe. This covers the pseudo rapidity region within $2.1 < |\eta| < 3.8$ with wavelength shifting fibres installed at the boundaries of counters (outer and inner η counters). These fibers employ the same electronics as in Tile hadronic calorimeter to read out signals from PMTs which are then shaped and augmented in a way that pulse amplitude is in line with energy deposited in the counter. Being placed on each side of TileCal module, the PMTs inside or outside them accumulate light from the scintillators [78].
- **BCM** detector is composed of 4 diamond sensors in two groups which are aligned in a cross pattern on each side of the interaction point, being located at distance of ± 184 cm along z direction and $R = 5.5$ cm. They are designed to record particle fluxes close to the beam pipe for keeping the ATLAS inner subsystems safe from unrestrained radiations. The BCM furnishes measurements on interaction rate, instantaneous luminosity of the signals coming from instable beams and to discriminate signals from backgrounds.
- **ZDC** is meant for measuring neutrons or other neutral particles originated from heavy ion or proton-proton collisions and covers the pseudo rapidity range with $|\eta| > 8.3$. Being stationed at the point where the beam-pipe is segregated into two independent pipes with a placement of four ZDC modules i.e. one EM module and three hadronic modules. Each of the EM modules contains 11 tungsten plates which are orthogonal to the beam direction. In addition to that, they have two kinds of quartz radiator which are used to dispense energy and position measurements.
- **ALFA** Being located away from the interaction point, it covers large pseudo rapidity region i.e. $11 < |\eta| < 14$ to measure protons scattered at small-angles. They are designed for measuring distance of protons deflected from the beam elastically. In principle, the absolute luminosity is evaluated at ATLAS or general-purpose detectors via elastic scattering at small angles in coulomb nuclear interference. An angle of $3\mu\text{rad}$ which is seemingly smaller than beam divergence, so specific beam requirements for instance high-beta optics and contracted beam radiance are indispensable.

⁵these are proposed to measure the light emitted from the scintillators and generate a readout signal

- **AFP** is ATLAS Forward Proton was installed in Run2 in the spectrometers to get precised (proton) measurements on positions and directions and is distant at $\pm 220\text{m}$ and $\pm 420\text{m}$ from the point of interaction at ATLAS. Aiming at precised momentum loses which can be employed for mass computation using relation $M^2 = s\xi_1\xi_2$. The acceptance (ξ) of AFP detectors supplies a mass acceptance ranging from 80 GeV to 1 TeV with a target of new physics searches e.g. SM, MSSM, NMSSM Higgs boson, pair production of W boson, etc. To attain a good acceptance and mass resolution, the advanced 3D silicon technology is taken into account. In order to estimate the arrival time of protons with a precision of $\sim 10\text{ps}$, time-of-flight (ToF) detectors are used which can isolate the vertex of interest from pile-up vertices.

3.4 Trigger, data acquisition and control systems

The LHC is producing a great amount of data every second with a collision frequency of $\sim 40\text{MHz}$, and around 30 interactions per bunch crossing. This seems quite tricky to analyse that big amount of data and for that reason ATLAS requires a swift system that can process all the information at the rate of collision frequency and can make prompt decision about selection of events for analyses. The complicated system termed as trigger and data acquisition (TDAQ) is established by ATLAS, which can manage online event selection and can steer readout of selected data events. The complete system of triggers and data acquisition is demonstrated in Fig. 3.19

The ATLAS comprises a trigger system [79] which operates in two steps, the Level-1 Trigger (L1) and the High-Level Trigger (HLT). Level-1 trigger is a hardware system that uses information from a subset of detectors, calorimeters and muon system to dispense high- p_T physics objects such as muons, electrons, jets or missing transverse energy. The L1 trigger executed in about $2.5\ \mu\text{s}$ and reduces the rate of events from 40 MHz to 100 kHz.

By defining region of interest (ROI), the Level-1 Trigger (L1) selects event containing interesting information about η and ϕ are then passed to the HLT. The software based HLT system then carries out partly reconstruction on the data accessible in the ROI and access the information from ID as well. The final step in the HLT includes offline event reconstruction employing event filtration. With an execution of this step, the event rate is turned down at $\sim 1\ \text{kHz}$ and selected events are forwarded to the CERN on-site computing center named Tier-0 for full reconstruction.

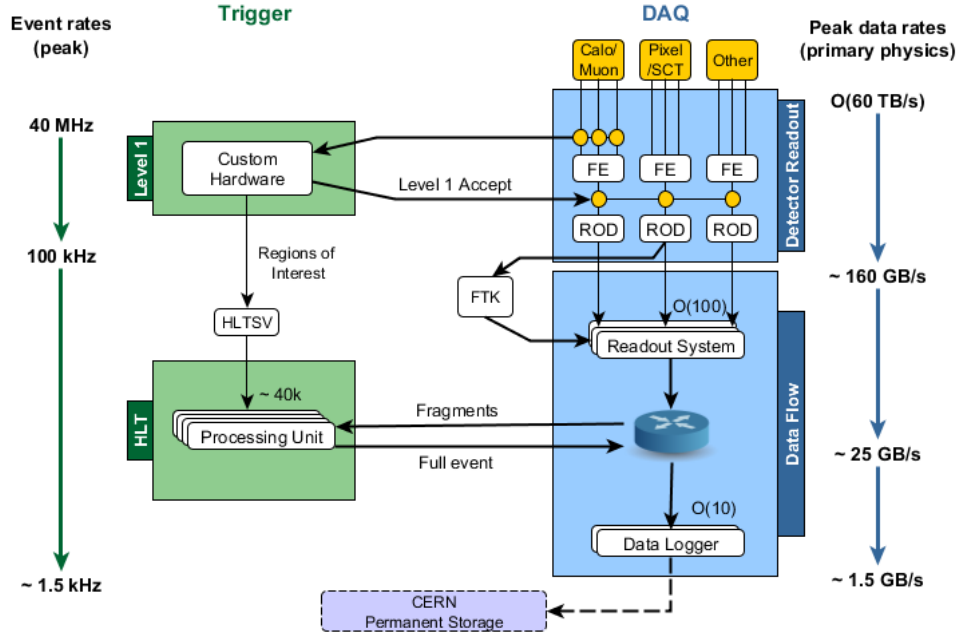


Figure 3.19: A schematics of ATLAS trigger and data acquisition system in Run 2 [80].

The ATLAS data taking process is executed in runs, which generally correspond to one LHC fill. Each run is divided into luminosity blocks (LBs) which constitutes small partitions of time in which instantaneous luminosity is considered constant. The conditions of triggers and detector itself remain same and data events are registered within a LB having a length of 60s. The corresponding integrated luminosity is then summed up as;

$$L = \sum_{LBs} \mathcal{L}_{LB} \cdot \Delta t_{LB} \quad (3.9)$$

where $\mathcal{L}$ indicates constant luminosity within LB and Δt_{LB} correspond to duration of the LB and sum is performed over all the LBs in the given time frame.

Chapter 4

Object Reconstruction in the ATLAS detector

4.1	Track and vertex reconstruction	63
4.2	Electron and photons	65
4.2.1	Reconstruction	65
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4.3	Muons	72
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4.5	Missing transverse energy	75

This chapter explains the reconstruction, identification and measurement performance of the final state objects used for different physics analyses at ATLAS experiment. The objects reconstructed, identified and measured by the inner subsystem of the detector are electrons, photons, muons, jets, tau leptons and missing transverse energy.

The chapter contains information from the following citations:

- Valente, Marco, "ATLAS Object Reconstruction" Cited. [94]
- ATLAS Collaboration, "Performance of the ATLAS Track Reconstruction Algorithms in Dense Environments in LHC Run2" Cited. [95]
- R. Frühwirth, "Application of Kalman filtering to track and vertex fitting" Cited. [96]
- ATLAS Collaboration, "Electron efficiency measurements with the ATLAS detector using the 2015 LHC proton-proton collision data" Cited. [97]
- W. Lampl et al., "Calorimeter clustering algorithms: Description and performance" Cited. [98]
- T.G. Cornelissen et al., "The global χ^2 track fitter in ATLAS" Cited. [99]
- ATLAS Collaboration, "Improved electron reconstruction in ATLAS using the Gaussian Sum Filter-based model for bremsstrahlung" Cited. [100]

- The ALICE collaboration., Acharya, S., Adamová, D. et al., "Underlying Event properties in pp collisions at $\sqrt{s} = 13$ TeV" Cited. [101]
- A.Hoecker et al., "TMVA - Toolkit for Multivariate Data Analysis" Cited. [102]
- L. Devroye, "Non-Uniform Random Variate Generation" Cited. [103]
- Aaboud, M., Aad, G., Abbott, B. et al., "Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016" Cited. [104]
- ATLAS Collaboration, "auxiliary material attached to Eur. Phys. J. C **79** (2019) 639" Cited. [105]
- ATLAS Collaboration, "auxiliary material attached to JINST **14** (2019) P12006" Cited. [106]
- ATLAS Collaboration, Aad, G., Abbott, B. et al., "Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV" Cited. [107]
- ATLAS Collaboration., Aad, G., Abbott, B. et al. "Electron performance measurements with the ATLAS detector using the 2010 LHC proton-proton collision data" Cited. [114]
- Oreglia, M., "A Study of the Reactions $\psi' \rightarrow \gamma\gamma\psi$ " Cited. [115]
- "Electroweak Model and Constraints on New Physics" Cited. [116]
- "Status of Higgs Boson Physics" Cited. [117]
- L. Evans and P. Bryant, "LHC Machine" Cited. [118]
- ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider" Cited. [119]
- CMS Collaboration, "The CMS experiment at the CERN LHC" Cited. [120]
- ATLAS Collaboration, "Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at $\sqrt{s}=13$ TeV" Cited. [121]

4.1 Track and vertex reconstruction

In the ATLAS inner detector, the charged particles passes through the magnetic field. They are twisted by the effect of that field and obtain an helical shape as shown in Fig. 4.1 The trajectory of the particles can be described by the following parameters;

- The polar and azimuthal angles θ and ϕ .
- The transverse impact parameter d_0 , which is defined as closest point of the track to the beam axis.

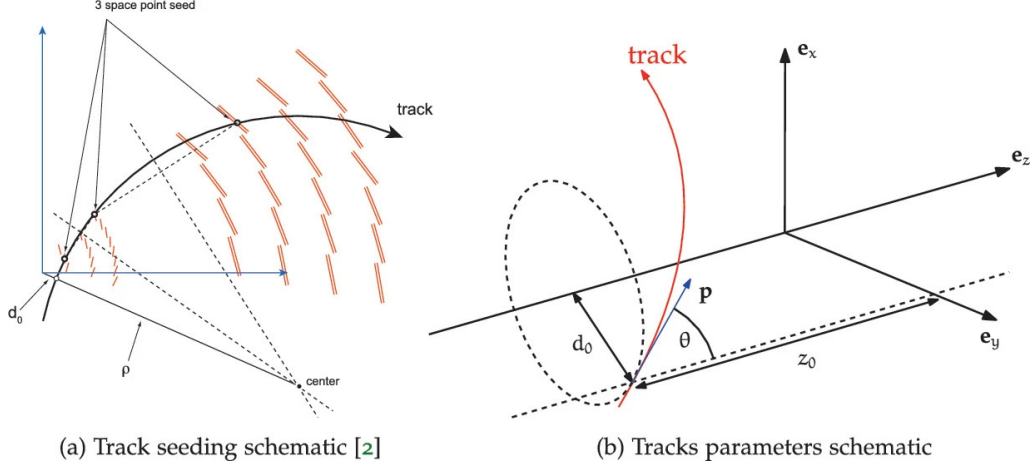


Figure 4.1: Schematics of tracking inside-out approach [94]

- The longitudinal impact parameter z_0 , refers the distance from the transverse plane (x-y plane) containing the closest point of the track to the beam axis to the primary vertex.
- The ratio of charge q and momentum p of the reconstructed track i.e. q/p

For the reconstruction of tracks, staged pattern-recognition approach Ref. [95] is used. Starting with iterative track-finding algorithm based on track seeds that requires a set of three space-points from the hits in pixel detector and first layer of SCT. Track seeds are formed by grouping such space-points.

A combinatorial Kalman filter Ref. [96] is then run to build track candidates by adding the hits which show compatibility with the first estimate. The fake tracks associated to these space-points are also removed during this step.

Since, multiple tracks could be associated to same space-point therefore, an ambiguity algorithm is run to distinguish them. This way, a score is assigned to each track based on χ^2 track fit (track quality), its p_T , η and other selections on the number of pixels and SCT clusters. Track candidates must fulfill the quality criteria mentioned in the Table. 4.1.

Requirements
$p_T > 500 \text{ MeV}$
$ \eta < 2.5$
Minimum of 7 clusters in pixel or SCT detector
≤ 2 holes in pixel or SCT detector
≤ 1 holes in pixel detector
$ d_0^{BL} < 2\text{mm}$ with respect to the beam-line
$ z_{\sin\theta} < 3\text{mm}$ with respect to the beam-line

Table 4.1: Track quality requirements

If all the requirements are matched, a high-resolution fit is performed to the track using full information from ID. The primary vertices are then obtained by the extrapolation of the tracks. The primary vertex with highest sum of the square of transverse momenta is considered in an event, while others are taken in pileup vertices.

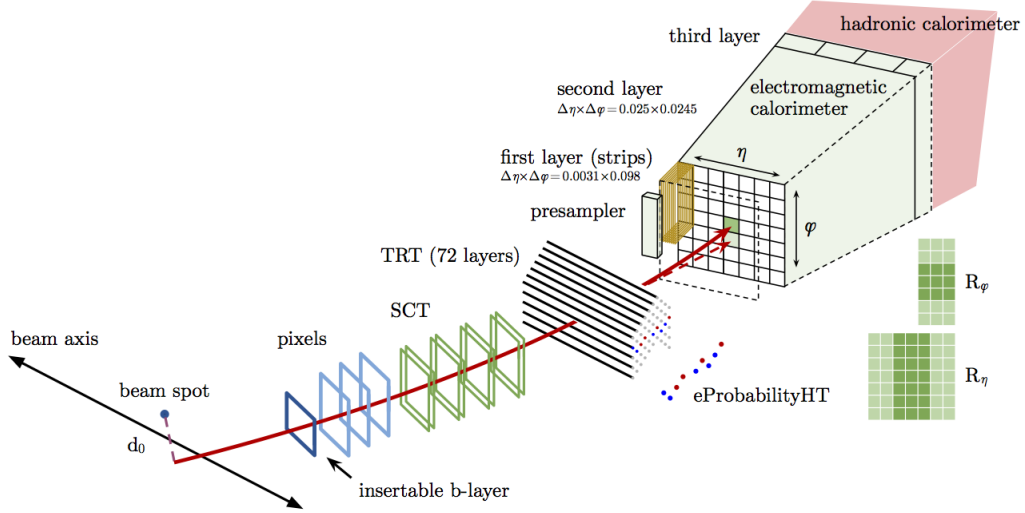


Figure 4.2: A depiction of electron path through the detector. The red line shows an electron path, which first traverses detector's tracking system which involves pixel detectors, silicon strip detectors (SCT) and transition radiation tracker (TRT). Then it enters the electromagnetic calorimeter. The dashed red trajectory points the path of a photon created by the effect of an electron's interaction with the material in tracking system [121]

4.2 Electron and photons

In all the analyses explained in this thesis, we use electrons¹ and photons reconstructed within the ID acceptance ($|\eta| < 2.5$). In the ATLAS detector, the electrons and photons deposit their energy in the EM calorimeter. Electrons have an associated track but photons (except converted photons) do not have any characteristics track.

The reconstruction of an electron requires information from ID in order to define the angular direction at the interaction point and for their energy measurement from EM calorimeter. The electron lose its energy due to bremsstrahlung, when traverses the detector's material during interaction. The radiated photon produced within this process, converts into an electron-positron pair. In result, a single electron creates multiple tracks and thus generates an electromagnetic shower. The secondary particles produced in this process are matched to the same EM cluster.

The Fig. 4.2 represent a sketch of the sub-detectors involved in the reconstruction of electron and photon. The procedure for photon reconstruction is same as for electron.

4.2.1 Reconstruction

In ATLAS, electron reconstruction in the central region of the detector ($|\eta| < 2.47$) proceeds in several different steps which includes seed-cluster reconstruction, track reconstruction, electron track-fit and electron candidate reconstruction Ref.[97]. The clusters are built in the EM calorimeter using $\eta \times \phi$ space, divided into a grid of 200×256 with towers having granularity $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. This space is used to search electron "seeds" as longitudinal towers with total cluster transverse energy above 2.5 GeV.

¹refers to both electrons and positrons

For each element, the energy of the cells in all longitudinal layers i.e. front, middle, and back layers of the calorimeter as well as region $|\eta| < 1.8$ (presampler) is added into the tower energy. The clusters in EM calorimeter are then formed around the seeds using clustering algorithm [98], allowing to remove the duplicates. If two of the candidates are spotted within an assumed area of $\Delta\eta \times \Delta\phi = 5 \times 9$ units, the one with high E_T is selected with a presumption that its transverse energy must be 10% greater than other cluster. If that is not the case, the cluster with the highest E_T central tower is considered. This phenomenon thus gives a reconstruction efficiency ranges from 95% $E_T = 7\text{ GeV}$ to more than 99% above $E_T = 15\text{ GeV}$. The measurements on the electron reconstruction efficiency are briefly explained in chapter 5.

The track information extracted from ID is proceeded in two ways; (1) Pattern-recognition (2) Ambiguity resolution to fit track. For the pattern-recognition, the standard ATLAS algorithm called pion hypothesis is used for the model of energy loss from interactions of object with the material of detector. The seeds of track should have hits ≤ 3 in IBL, pixel and SCT detector shown in Fig. 4.2 with momentum greater than 1 GeV. If a track seed with $p_T > 1\text{ GeV}$, cannot be outstretched eventually to a full track of having at least 7 hits in SCT detector but falls in the interested region of EM cluster, another attempt is performed under electron hypothesis. However, this second attempt allows up to 30% energy loss due to bremsstrahlung. The tracks are then fitted using ATLAS Global χ^2 Track Fitter [99] taking electron and pion hypotheses into consideration.

The EM clusters(or tracks) are then matched to the distance considered in the space of $\eta - \phi$ ². An optimised Gaussian Sum Filter (GSF) [100] is used to fit the tracks associated to electron clusters having precision hits ≥ 4 in SCT, which also considers the energy loss due to bremsstrahlung.

The step which finalise the electron reconstruction is, matching of the GSF-track candidate to the candidate's cluster seed in EM calorimeter. This shares the similar matching technique as mentioned above but repeated with more strict conditions for the refit track. Taking a cluster-track distance R calculation (using various hypotheses on momentum computation, hits in the pixel detector and hit produced in the first silicon layer) into consideration, an algorithm is used to choose "primary" tracks, in case of several tracks fulfilling the matching criteria. The electron candidates with no associated precision hit tracks are eliminated and considered to be photons. In Run-2, the measurements with electron candidates are conducted with an associated track consistent with the primary interaction vertex of hard collision [101].

4.2.2 Identification

In order to distinguish electron candidates from the backgrounds (arises from hadronic decays, photon conversions, heavy flavor decays) mimicking real electron candidates, an identification method is designed [121]. This method is based on multivariate likelihood technique which selects the prompt electrons i.e. from the decays of W, Z and H bosons, entering in the central region of detector ($|\eta| < 2.47$). A set of variables designated for electrons are taken into account, which apprehend information from all three layers of the EM calorimeter, hadron leakage, track related entities in inner detector and track-cluster matching. All these variables are listed in the Table 4.2.

²The separation of the cluster-barycentre position and track extrapolated from perigee to the second layer of the calorimeter satisfying, $|\eta_{cluster} - \eta_{track}| < 0.05$

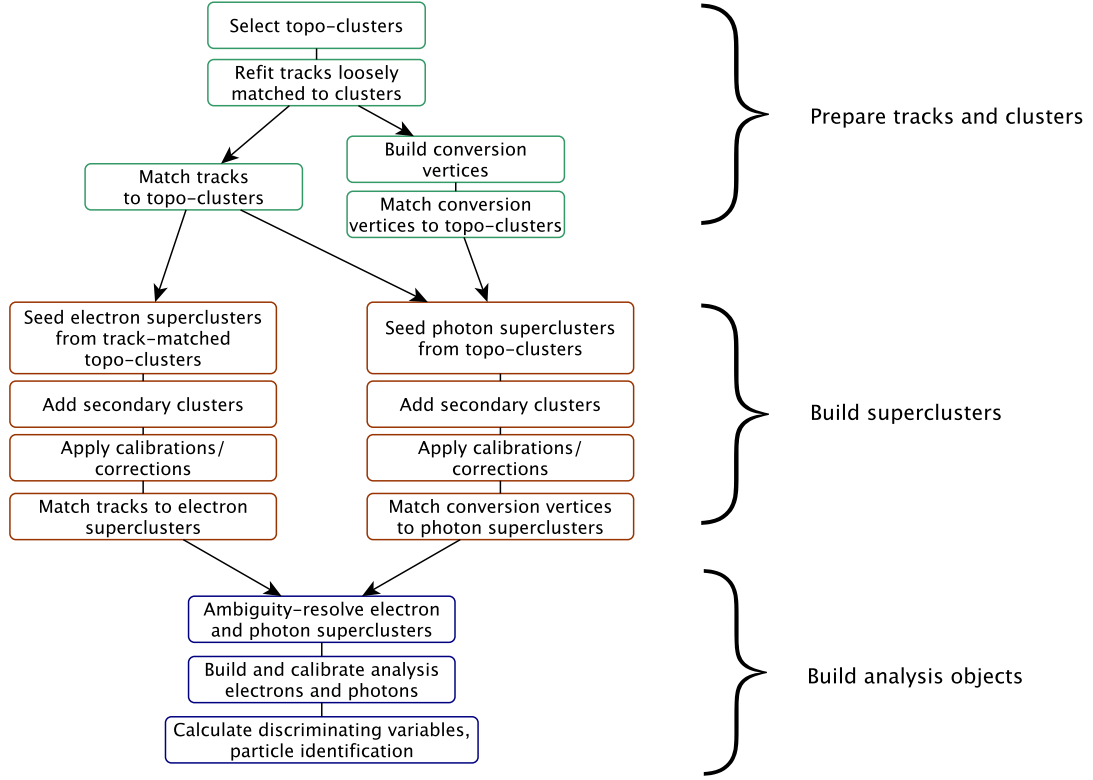


Figure 4.3: A flow diagram of an algorithm showing reconstruction of electron and photon.

The electron LH based on the products for signal, L_S , and for the background, L_B , of n pdfs (P) is written as;

$$L_{S(B)}(\mathbf{x}) = \prod_{i=1}^n P_{S(b),i}(x_i) \quad (4.1)$$

where $\mathbf{x}$ is the vector of discriminating variable values and $P_{S,i}x_i$ is the of the signal probability density function of i^{th} variable at x_i . Likewise, $P_{b,i}x_i$ refers to the background probability density function.

For each electron candidate, a discriminant (d_L) is established:

$$d_L = \frac{L_S}{L_S + L_B}; \quad (4.2)$$

This discriminant d_L response has a sharp peak at unity for signal and zero for background, which is not convenient to select working points (Tight, medium, loose) as it requires finer binning. Therefore, an inverse sigmoid function is used to transform the distribution of discriminant of Eq. 4.2:

$$d'_L = -\tau^{-1} \ln(d'_L - 1) \quad (4.3)$$

The value of τ is set to 15 according to Ref. [102]. Consequently, the range of transformed discriminant values do not vary between zero and unity anymore. The value of

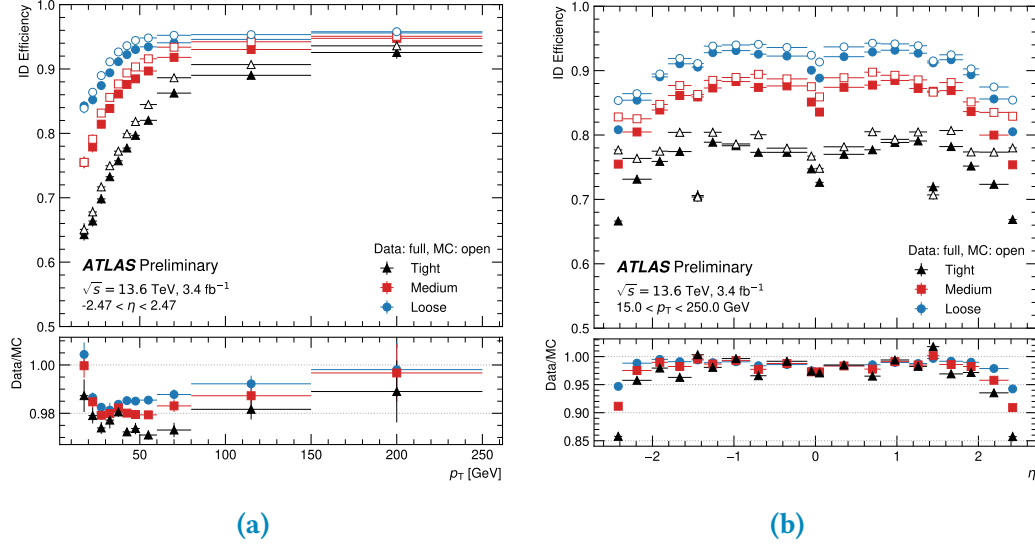


Figure 4.4: The electron ID efficiencies in data and MC events of $Z \rightarrow e^+e^-$ for three working points based on LH i.e. Tight (black triangle), Medium (red square), and Loose with B-layer requirement (blue circle) as a function of p_T and η in range $-2.47 < |\eta| < 2.47$ (a) whereas transverse momentum in range $15 < p_T < 250$ GeV (b). The data shown here was recorded in year 2022 for p-p collisions at $\sqrt{s} = 13.6$ TeV, corresponding to integrated luminosity of 3.4 fb^{-1} . The error bars indicate the total uncertainties includes statistical and systematic components. In both plots, the bottom panel shows data to MC ratio [105].

transformed discriminant is assigned to each working point: the candidates with values greater than the value of are considered signal. Thus, the method ensures the better background rejection than a "cut based" algorithm (which uses selection criteria on each variable progressively) for a certain signal efficiency. For each of the three working points, the efficiencies of electron LH based identification were measured for Run 3 early data and given in Fig. 4.4.

The prompt photons in hadronic collisions are identified in the ATLAS experiment by applying some selections on quantities illustrating the shape and properties of EM showers by having them to be isolated from other events of particles. These selections are augmented for those candidates of photons that convert into an electron-positron pair, reaching EM calorimeter (converted photons) and those candidates which are not associated to a conversion (unconverted photons). The efficiency of the tight photon identification (ϵ_{ID}) is computed using various techniques: Radiative Z decays, Electron extrapolation and Inclusive photons. The electron extrapolation technique uses electron showers in EM calorimeter, which originates from $Z \rightarrow e^+e^-$ decays, identified by tag-and-probe method 5.2.1. To match the properties of photon showers, these EM showers improve their shape using Smirnov transform [103]. Then, they are used to measure the (ϵ_{ID}) in the E_T region, $25 < E_T < 150$ GeV where we have enough statistics for electron candidates coming from Z decays.

The shower-shape variables in EM calorimeter layers (middle & strip) for photons are listed in Table 4.2. The simulation is used to correct the differences between the distributions of photon and electron. The efficiencies (ϵ_{ID}) measured in data for two of the methods are depicted in Fig. 4.5 for unconverted and converted photons Ref. [104].

Category	Description	Name	Usage
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the ranges $ \eta < 0.8$ and $ \eta > 1.37$)	R_{had_1}	e/γ
	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}	e/γ
EM third layer	Ratio of the energy in the third layer to the total energy in the EM calorimeter	f_3	e
EM second layer	Ratio of the sum of the energies of the cells contained in a $3 \times 7 \eta \times \phi$ rectangle (measured in cell units) to the sum of the cell energies in a 7×7 rectangle, both centred around the most energetic cell	R_η	e/γ
	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_{η_2}	e/γ
	Ratio of the sum of the energies of the cells contained in a $3 \times 3 \eta \times \phi$ rectangle (measured in cell units) to the sum of the cell energies in a 3×7 rectangle, both centred around the most energetic cell	R_ϕ	e/γ
EM first layer	Total lateral shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all cells in a window of $\Delta\eta \approx 0.0625$ and i_{max} is the index of the highest-energy cell	$w_{s \text{ tot}}$	e/γ
	Lateral shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all cells in a window of 3 cells around the highest-energy cell	$w_{s \ 3}$	γ
	Energy fraction outside core of three central cells, within seven cells	f_{side}	γ
	Difference between the energy of the cell associated with the second maximum, and the energy reconstructed in the cell with the smallest value found between the first and second maxima	ΔE_s	γ
	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}	e/γ
	Ratio of the energy measured in the first layer of the electromagnetic calorimeter to the total energy of the EM cluster	f_1	e/γ
Track conditions	Number of hits in the innermost pixel layer	$n_{\text{innermost}}$	e
	Number of hits in the pixel detector	n_{Pixel}	e
	Total number of hits in the pixel and SCT detectors	n_{Si}	e
	Transverse impact parameter relative to the beam-line	d_0	e
	Significance of transverse impact parameter defined as the ratio of d_0 to its uncertainty	$ d_0/\sigma(d_0) $	e
	Momentum lost by the track between the perigee and the last measurement point divided by the momentum at perigee	$\Delta p/p$	e
	Likelihood probability based on transition radiation in the TRT	$e\text{ProbabilityHT}$	e
Track-cluster matching	$\Delta\eta$ between the cluster position in the first layer of the EM calorimeter and the extrapolated track	$\Delta\eta_1$	e
	$\Delta\phi$ between the cluster position in the second layer of the EM calorimeter and the momentum-rescaled track, extrapolated from the perigee, times the charge q	$\Delta\phi_{\text{res}}$	e
	Ratio of the cluster energy to the measured track momentum	E/p	e

Table 4.2: The variables based on the LH discriminant used for the identification of electron and photon. The column named "usage" points whether variables are used for the identification of electrons, photons or both. For the variables computed in the first layer of EM calorimeter, if cluster having more than one cell unit in window of $\Delta\eta \times \Delta\phi$, the two of the cells closer to cluster in ϕ are merged. The definitions in the table are provided for this merged cell. The " d_0 " referring the coordinates of the transversal perigee i.e. $(x_0, y_0) = (-d_0 \sin\phi, d_0 \cos\phi)$ is chosen, where ϕ is the azimuthal angle of track momentum at perigee Ref. [122].

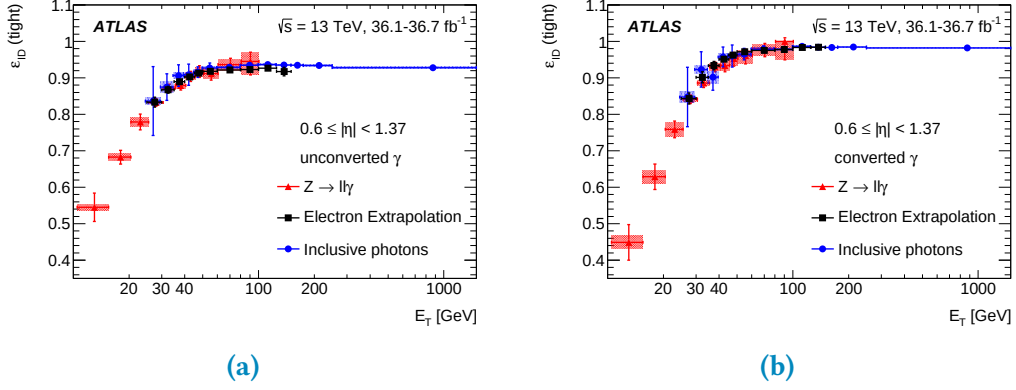


Figure 4.5: A comparison of ID efficiencies through data-driven measurements for unconverted photons (a) and converted photons (b) as a function of E_T , for pseudorapidity interval $0.6 < |\eta| < 1.37$. The error bars indicate the quadrature sum of statistical and systematic uncertainties in each method. The shaded areas show statistical uncertainties.

4.2.3 Isolation

To discriminate signal from backgrounds, an isolation criteria is further set up in most of ATLAS physics analyses. The several isolation working points are needed to calibrate particle's energy³ and allow to extract the prompt electrons (coming from W & Z decays) from non-isolated electron candidates e.g; converted photons decays, heavy flavour and light flavour hadronic decays. For that reason, two categories of variables are introduced:

- Calorimetric isolation energy ($E_T^{cone0.2}$): delineated as the sum of transverse energies of all the EM topo-clusters within a cone of radius $\Delta R = 0.2$ around cluster of subjected candidate. The sum is computed with the clusters having positive reconstructed energy. A correction depending on E_T and η estimates, is further applied to count electron energy leakage outside the cluster.
- Track isolation ($p_T^{varcone0.2}$): described as the total of transverse momenta of all the tracks, fulfilling track quality selections within a cone of radius $\Delta R = \min(0.2, 10\text{GeV}/E_T)$ around the track of electron candidate. The requirements for track quality such as; $p_T > 1\text{ GeV}$, $|\eta| > 2.5$, at least 7 precision hits in pixel & SCT detectors with one shared hit and 1 missing hits in the SCT and pixel. In order to minimize the pile-up effect, the longitudinal impact parameter should be $|z_{sin\theta}| < 3\text{mm}$.

The electron isolation efficiency depicted in the Fig. 4.6 is measured with data taken in year 2018. The data-to-MC ratios are also shown as a function of electron E_T and η for the isolation selection criteria encapsulated in Table 4.3. The probe electron fulfilling Tight identification selection are given in the results, obtained using events of $Z \rightarrow e^+e^-$ taken in 2018.

The photon isolation working points are designated in Table 4.4 based on the selection requirements on the calorimeter and track isolation observables. An inconsistency

³rejecting candidates which deposit energy in a cone around the actual electron candidate as it exceeds particular threshold i.e. dependent on electron p_T

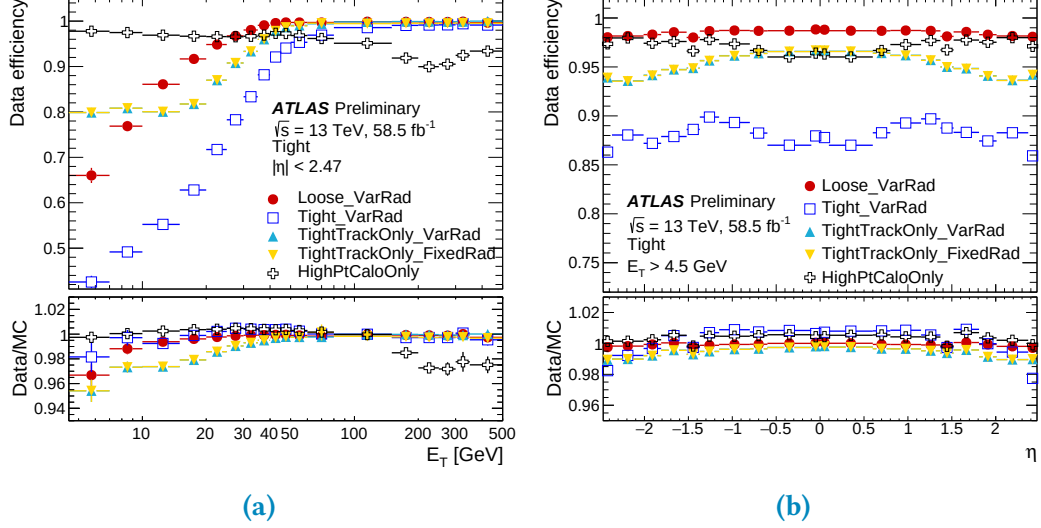


Figure 4.6: An electron efficiency measurement for different isolation working points (shown in Table 4.3) for year 2018 Run 2 data in $Z \rightarrow e^+e^-$ as function of pseudo-rapidity η . The electron candidates fulfilling Tight LH based identification selection, are shown. The plots include total uncertainties referring statistical and systematic components. The lower pads represent ratio efficiencies of data and MC Ref. [106].

Selection criteria	Calorimetric isolation	Track isolation
HighPtCaloOnly	$E_T^{cone20} < \max(0.015 \times p_T, 3.5) \text{ GeV}$	—
TightTrackOnly_VarRad	—	$\frac{p_T^{varcone30}}{p_T} < 0.06$
TightTrackOnly_FixedRad	—	$\frac{p_T^{varcone30}}{p_T} < 0.06$ for $E_T < 50 \text{ GeV}$ $\frac{p_T^{varcone20}}{p_T} < 0.06$ for $E_T < 50 \text{ GeV}$
Tight_VarRad	$\frac{E_T^{cone20}}{p_T} < 0.06$	$\frac{p_T^{varcone30}}{p_T} < 0.06$
Loose_VarRad	$\frac{E_T^{cone20}}{p_T} < 0.20$	$\frac{p_T^{varcone30}}{p_T} < 0.15$

Table 4.3: Definition of the electron isolation selection criteria. All the working points use a cone size of $\Delta R = 0.2$ for calorimetric isolation, and $\Delta R_{max} = 0.3$ or 0.2 for track isolation.

has been noticed between distribution of determined (data) and simulated (MC) distributions in Run 1 [114], which leads to divergency in shower shapes in electromagnetic calorimeter. Subsequently, the photon isolation efficiencies in determined and simulated events contradicts, which cause scale factors to deviate from 1 markedly. These inconsistencies are alleviated in Run 2 by deploying data-driven shifts to isolation variables in simulated events of photons. The segments influenced by the real photon in collision data and simulated events, these shifted could be acquired by carrying out fits on distribution of isolation variable through Crystal Ball pdfs [115]. These fits are carried out individually for isolation variables (E_T^{cone20} , E_T^{cone40}) in photon's η & E_T bins. Thus, a shift value is obtained by subtracting peak values of data and MC in fitted region, which later would sum up to the isolation values in simulated events of photon. The efficiency of photon isolation is normally carried out with two main scenarios: radiative Z decays within range $10 < E_T < 100 \text{ GeV}$, inclusive photons inside range $25 \text{ GeV} < E_T < 1.5 \text{ TeV}$.

The isolation efficiencies for photon are computed for working points mentioned in Table 4.4 considering the same methodology as for photon identification. The isolation efficiency computation done in 2017 data as a function of η & E_T are demonstrated in Fig. 4.7 depicts along with data-to-MC efficiency ratio.

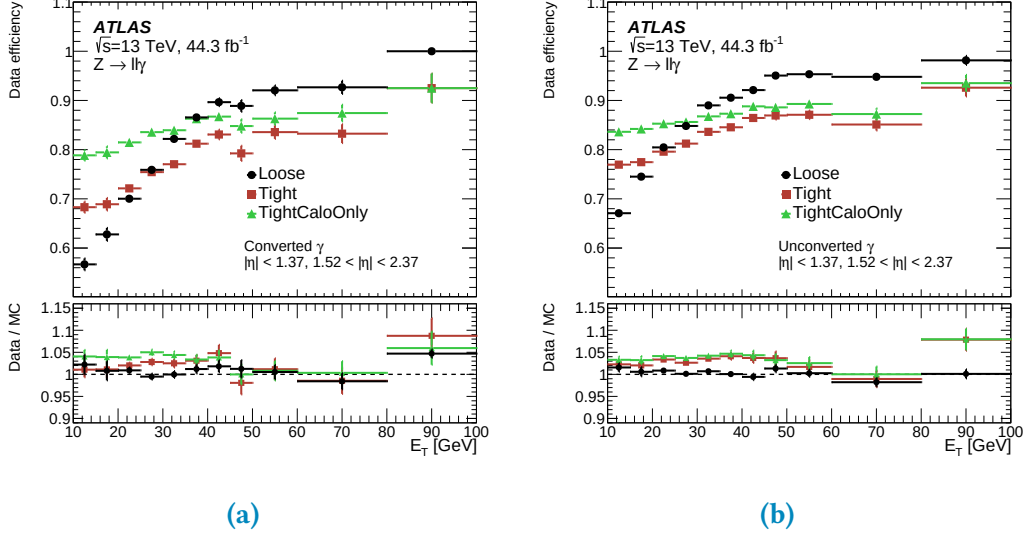


Figure 4.7: Representation of efficiency for topology $Z \rightarrow ll\gamma$ for isolation working points listed in Table 4.4, for converted photons (a) and unconverted photons (b) as a function of η (top pad), E_T (bottom pad). The bottom pad represents the ratio efficiencies in data and MC including statistical and systematic uncertainties [122].

Selection working point	Calorimetric isolation	Track isolation
Loose	$E_T^{cone20} < 0.065 \times E_T \text{ GeV}$	$\frac{p_T^{cone20}}{E_T} < 0.05$
Tight	$E_T^{cone40} < 0.022 \times E_T + 2.45 \text{ GeV}$	$\frac{p_T^{cone20}}{E_T} < 0.05$
TightCaloOnly	$E_T^{cone40} < 0.022 \times E_T + 2.45 \text{ GeV}$	—

Table 4.4: Definition of the photon isolation selection working points.

4.3 Muons

Muons are charged particles just like electrons and arise out of the particles decay during collision of p-p collisions in the ATLAS detector. For their detection, muon spectrometer i.e: the outermost section of the ATLAS detector is being used. This measures the energy, direction and momentum of these particles with great precision. For measuring the muon tracks, a system of drift tube chambers comprising several layers of such tubes are used. The muons leave behind characteristic trails in these tubes while interaction with atoms of gas filled in them.

Reconstruction and identification

Muon reconstruction is carried out, based on the track details provided by the inner detector (ID) and muon spectrometer (MS) along with calorimeters. The reconstruction procedure is executed by defining categories of muons i.e: combined (CB), inside-out combined (IO), extrapolated muon spectrometer (ME), segmented-tagged (ST), and calorimeter-tagged (CT).

- **CB muon:** A fit is performed on combined track from ID and MS, in order to reconstruct and distinguish muon track candidates. By upgrading the track hits in MS, a fit can be performed again to improve its quality. To form silicon-associated forward (SiF) muons, these tracks in muon spectrometer are joined with short track segments built from the pixel and SCT detectors hits at $|\eta| = 2.5$.
- **IO combined muon:** These muons are reconstructed by employing an inside-out algorithm, extracting tracks from ID to MS with at least 3 loosely-aligned MS hits requirement. This will benefit low- p_T muons, and those traversing regions with minimal MS coverage, to gain some efficiency.
- **ME muon:** This type can be defined when a track from MS wouldn't be matched to an ID track by extending its parameters to the interaction point. To exploit the full coverage inside $|\eta| = 2.7$, these muons are thus stretched to the outer region of ID.
- **ST muon:** This category of muons are distinguished by involving ID tracks embedded to MS, which must fulfil tight selection on angular matching on one of the reconstructed MS segment. The final matched ID track identified through this process is called ST muon.
- **CT muon:** These are extracted from energy deposits in the calorimeters, showing consistency with particle having least ionization. By extracting muon parameters from ID track fit, such deposits benefit to label these track as muon. On contrary, reconstruction of other muon algorithms operate with tracks having $p_T > 2$ GeV, but for the reconstruction of this category of muons, requires $p_T > 5$ GeV to reject the large background available at low p_T .

After reconstructing them, these candidates are nominated for further checks on the number of precision hits in various subsections of the ID and MS, characteristics of track fit, and observables determining the correctness of measurements in these subsystems. In order to minimize the background contributions from non prompt-muons (includes light hadrons decays & heavy flavor decays), different identification operating points are introduced. There are three standard operating points (OP's) established, to meet the necessity of most of the physics analyses. These OP's are named as Loose, Medium, and Tight. They are subset of each other for instance, tight is subset of Medium and Medium is subset of Loose. In addition to them, two more operating points on the selections are designated, to achieve the targeted regions in extreme phase. These are specified as; High- p_T & low- p_T . The former one, guarantees fine measurements of muon's momentum with $p_T > 100$ GeV and best rejection of loosely reconstructed tracks greatly inflicted by the effect of uncertainties.

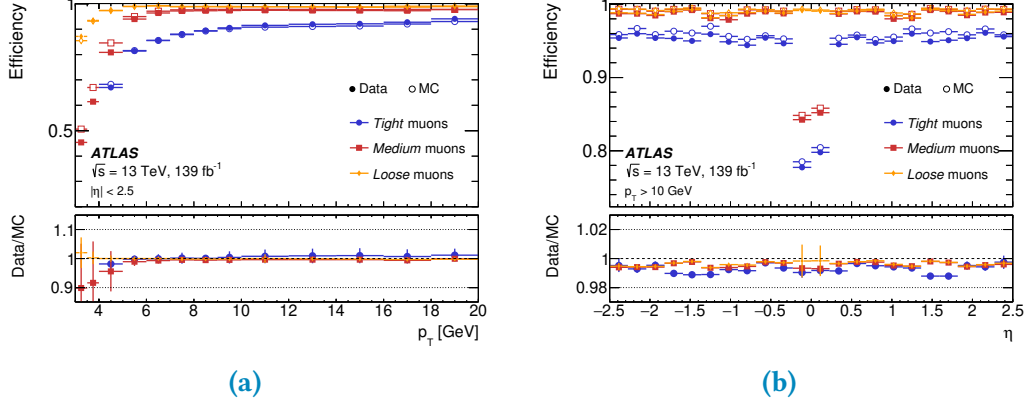


Figure 4.8: Muon reconstruction and identification efficiencies for operating points, Loose, Medium and Tight. The left plot presents efficiency measurement in $J/\psi \rightarrow \mu\mu$ as function of p_T whereas, the right plot depicts the measurements in $Z \rightarrow \mu\mu$ for muons having $p_T > 10$ GeV. The efficiencies in simulation are shown with open markers, whilst measurements in collision data are illustrated with filled markers. The bottom pad represents the ratio of the data and MC efficiencies, including statistical and systematic uncertainties [107].

The low- p_T on the other hand, intended to hit muons with lowest p_T which has less chances to be reconstructed as full tracks in muon spectrometer. To that account, identification is essentially required in those MS components. To maintain high efficiency, this operating point thus manoeuvres, a set of observables imparting a good separation between prompt and non-prompt muons with consideration of large background contribution. This can further be translated into two sets: a cut-based selection which minimizes efficiencies from backgrounds and a multivariate WP, which enhances performance inclusively. The Fig. 4.8 represent muon reconstruction and identification efficiencies measured in events $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ for all of three identification operating points.

4.4 Jets

The particles produced in pp collisions are termed as final state quarks and gluons which decay instantly into other hadrons for instance pions or kaons. This gives forth to a shower of particles equivalent with the momentum of the parent particle. This sprinkling of the particles refer to *jet* which is being reconstructed in ATLAS by employing an algorithm based on the particle's flow [108]. This particle-flow strategy incorporates the tracks information in the ID and energy deposits in the calorimeter. In that sense, a jet can be characterized as a coupling of 4-vectors which corresponds to either calorimeter clusters i.e. a calorimetric jet or ID tracks i.e. track jet. The specified algorithms execute this coupling that give rise to reconstructed jets as a final state particle which then establishes an information about partons involved in the emergence of the jet [109]. Based on these facts, a jet algorithm must be flexible and doesn't affect jet reconstruction by low energy and primary emission of parton.

Algorithms for jet reconstruction

In general, the jets clustering is performed by employing anti- k_t algorithm [110]. The clusters or tracks from calorimeter in terms of 4-vectors are employed to the cluster's algorithm as an input. The interval (d_{ij}) between pair of objects i.e. i and j can be expressed as;

$$d_{ij} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right) \times \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \quad (4.4)$$

The term Δy_{ij} refers to the difference of rapidity between the particles i and j whereas $\Delta\phi_{ij}$ corresponds to difference in azimuthal angle and $p_{T,i(j)}$ refers to transverse momentum. The term R is referred as a free parameter of the algorithm. The least distance for the individual object i can be evaluated as;

$$d_{min} = \min(d_{iB}, d_{ij}) \text{ with } d_{iB} = \frac{1}{p_{T,i}^2} \quad (4.5)$$

In situation where $d_{min} = d_{ij}$, the two objects i and j are grouped together and the intervals are meant to be re-computed whereas in the case of $d_{min} = d_{iB}$, the object i is referred as a jet. The anti- k_t algorithm give rise to jets in y - ϕ space having a radius established by the free parameter R if and only if that jet event is properly disentangled. An illustration of the anti- k_t jets in the y - ϕ plane is demonstrated in Fig.4.9

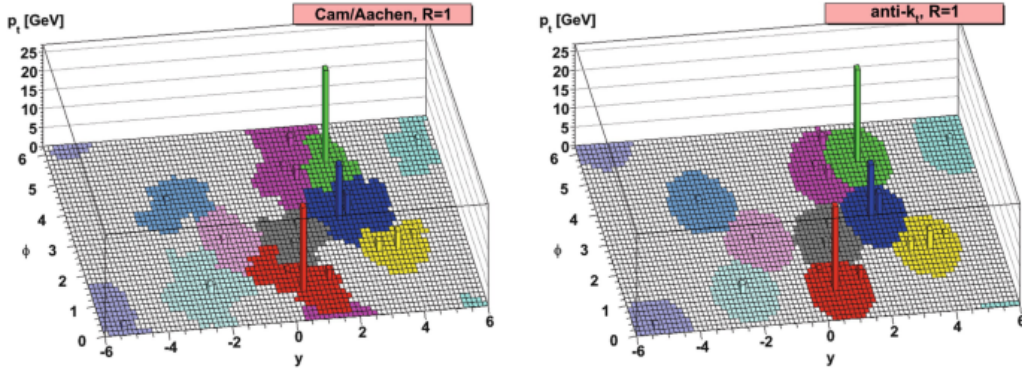


Figure 4.9: A depiction of jet reconstruction that depends on k_t (left) and anti- k_t (right) algorithms [110]

The shapes of the jet determined by the k_t algorithm seem irregular as compared to anti- k_t as depicted in Fig.4.9. It implies that anti- k_t algorithm is employed for the jet clustering around hard seeds whereas for the clustering of the soft particles the k_t an energy dependent algorithm is employed [111] and for the clustering independent of energy, the Cambridge or Aachen algorithm [112] is taken into account.

4.5 Missing transverse energy

The neutrinos particles are undetectable by the ATLAS and they only interact through the weak interactions that leads into small cross-sections. By employing energy and momentum conservation in the transverse plane, the information about their existence

can be extrapolated (indirectly). The fine approximation about them is that the partons coming in, do not hold any transverse momentum, so that the vector sum of all the particles in the transverse plane should be equal to zero. Any sort of momentum imbalance in transverse plane is characterized by the entity E_T^{miss} which is computed through its components along x and y-axes as;

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2} \quad (4.6)$$

The components E_x^{miss} and E_y^{miss} can be estimated by summing up all the contributions coming from the final state objects. By considering additional track-based soft term [113] that measures the tracks which are not correlated with any object but are consistent with the primary vertex:

$$E_{x/y}^{miss} = -E_{x/y}^{miss,soft} - \sum_{i \in \text{objects}} E_{x/y}^{miss,i} \quad (4.7)$$

In order to reject the signatures counted as double i.e. identified as multiple objects, an overlap removal is requested. The systematic uncertainties on all the objects contributing to E_T^{miss} evaluation are hence proliferated through the re-computation of E_T^{miss} for each uncertainty. Moreover, uncertainties associated with the track-based soft term are computed from the processes having no E_T^{miss} for instance, $Z \rightarrow ll$ comprises not jets in the event. The scaling parameter of the E_T^{miss} soft term is evaluated in those cases where E_T^{miss} withstand Z boson reconstruction in the transverse plane.

Chapter 5

Electron reconstruction efficiency measurements

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The information identified in this chapter is partly taken from the following citations:

- ATLAS Collaboration, "Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton-proton collision data" Cited. [122]
- CMS Collaboration, "Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC" Cited. [123]

- ATLAS Collaboration, "Electron efficiency measurements with the ATLAS detector using 2012 LHC proton–proton collision data" Cited. [124]
- ATLAS Collaboration, "auxiliary material attached to Eur. Phys. J. C **79** (2019) 639" Cited. [125]
- C. Hensel and K. Kröninger, "Data Analysis in High Energy Physics" Cited. [126]
- G. Tarna, "Studies of the Higgs boson properties and search for new physics beyond the standard model in the top sector with the ATLAS detector" Cited. [127]
- Di C. Lucia et al., "Support Note for Electron ID: efficiency measurements" Cited. [129]
- Ehrke, Lukas Fabian, "Electron Identification using Deep Neural Networks" Cited. [130]
- ATLAS, EGAM, "TagAndProbeFrame Framework" Cited. [133]
- ATLAS, EGAM, "TagAndProbe Framework" Cited. [134]
- Y. Sulman, "Reconstruction Efficiency Module" Cited. [135]
- A. Christos et al., "Support Note for Electron ID: electron reconstruction and identification" Cited. [137]

The results presented in this chapter is my own contribution towards the analysis. The results for statistical uncertainties through pseudo-experiments were already published in a journal [163] whereas the measurements for electron reconstruction efficiency, scale factors and associated uncertainties were already documented in an ATLAS internal note .[128].

5.1 Introduction

The analysis is based on reconstructed electrons from electromagnetic energy deposits which has to match the tracks in the inner detector. A reconstructed electron is defined as an object consisting of a cluster built from energy deposits from calorimeter (super-cluster) and a matched track (or tracks). For the electron candidates to be distinguished from other particles, identification and isolation criteria are applied with background rejection and signal efficiency. These candidates are categorized as signal electrons which are coming from Z decay while backgrounds consist of misidentified hadrons, photon conversions and heavy flavour decays. Therefore, it is crucial to measure how well those candidates are reconstructed in the detector. To see a good agreement of data and MC, efficiencies are computed based on tag-and-probe method using Z resonances.

In the first part of this chapter (Section 5.2), the measurement methodology used by the ATLAS experiment to perform the efficiency measurement for the reconstruction algorithm [122] is reviewed. Here we describe how the *tag-and-probe* method allows to select an unbiased sample of electrons in data for this measurement, and how the residual background contribution is estimated.

The Section 5.4 is dedicated to the measurement of statistical uncertainties through pseudoexperiments. Since statistical uncertainties in published results are estimated using first-order approximations only, the Sections 5.4 and 5.4.2 are devoted to study the

accuracy of those approximations by comparing them to the dispersion of repeated pseudoexperiments.

Results are presented in Section 5.4.2 for various representative choices of the available number of events for the measurement and the level and shape of the residual background. Concluding remarks are provided in Section 5.7.

The scale factors measurement for AF2 samples in release 21 with old framework and the results are shown in Section 5.5. Then, the methodology for electron reconstruction efficiency is re-implemented in new framework and the proof of correctness of that work and comparison of scale factors in either versions of frameworks i.e. Rel21 & Rel22 is provided in Section 5.6.

5.2 The methodology of electron reconstruction efficiency measurement

In the method tag-and-probe [126] one of the electron candidate named tag has strict selection and the other one has loose selection is called probe. The efficiencies namely reconstruction, identification, isolation and trigger are calculated from probe electrons after subtracting residual background contamination. The efficiency is the fraction of the probes fulfilling the test criteria. The efficiencies depend on the interactions of electron candidates with the detector. This is characterized by its energy E_T and pseudorapidity (η). Therefore, measurements for reconstruction efficiencies are performed double differentially in bins of (E_T , η) designated in Tables 5.1 and 5.2.

Table 5.1: Measurement bins in electron transverse energy E_T

Bin boundaries in E_T [GeV]										
15	20	25	30	35	40	45	50	60	80	150

Table 5.2: Measurement bins in electron pseudo-rapidity η

Bin boundaries in η									
-2.47	-2.37	-2.01	-1.81	-1.52	-1.37	-1.15	-0.08	-0.60	-0.10
0.10	0.60	0.80	1.15	1.37	1.52	1.81	2.01	2.37	2.47

5.2.1 Tag and Probe Method

The tag-probe pair passing selection requirement should have an invariant mass close to that of the Z boson, $m_z \approx 91$ GeV. In Ref. [122], the $Z \rightarrow e^+e^-$ process is used for measuring all efficiencies within range $15 < E_T < 150$ GeV. Reconstruction scale factors are measured between 15 GeV and 150 GeV. Below 15 GeV the scale factor is 1 and an uncertainty of 2% (5%) in the barrel (endcap) is applied. Above 150 GeV, the values from the highest measurement bin are used.

Before computing efficiencies, any kind of contributions from background needs to be subtracted. To estimate background, the truth information is used in Monte Carlo simulations. For data, different approaches are being used. For low transverse energies $E_T < 30$ GeV, background subtraction becomes particularly important.

Name of Template	Definition
FailTwoMultilepton	Fail two Multilepton cuts $\frac{E_T^{cone30}}{E_T} > 0.02$ pass track quality cuts
FailTwoLoose05	Fail two Loose cuts $\frac{E_T^{cone40}}{E_T} > 0.05$ pass track quality cuts
FailTwoLoose20	$\frac{E_T^{cone40}}{E_T} > 0.20$

Table 5.3: The background templates used, based on the Z_{mass} method. Used are one FailTwoMultilepton template and two FailTwoLoose templates. The numbers in the the FailTwoLoose template names indicate the ratio of the calorimeter isolation E_T^{coneR} in a cone of $\Delta R = 0.3$ or $\Delta R = 0.4$ around the electron and E_T of the electron candidate. All template selections apply a cut on such a ratio and all candidates need to pass the track quality cuts defined in Section 5.2.2. The FailTwoLoose templates are defined by an inversion of the cut-based Loose ID criteria, while at least two of the Loose cuts need to fail. The Multilepton and Loose criteria are defined in Ref. [124].

5.2.2 Event and Object Level Selections

The events having one primary vertex including at least 2 tracks is the selection for event level. The events must be selected from single lepton trigger and at least two electron candidates are required, which in the TagAndProbeFrame framework includes objects coming from either the electron or photon xAOD container.

In addition some strict criteria is applied on tag electron and loose selection is imposed on probe electron candidates individually. The tag electron is required to have a transverse energy $E_T > 25$ GeV, be matched to a trigger object and be outside the transition region between barrel and endcap of the electromagnetic calorimeter i.e. $1.37 < |\eta| < 1.52$.

Furthermore, it has to pass the tight identification criteria. The probes must have $E_T > 15$ GeV and pass the track quality criteria (TQ) i.e. at least 7 precision hits SCT+pixel with at least 1 pixel hit. The invariant mass of the tag-probe system is required to be close to the nominal mass of the Z boson, $75 < m_{ee} < 105$ GeV. The selections for the both objects i.e. tag and probe are listed in Table 5.4.

Table 5.4: Object level selections for tag and probe system

Tag	Probe
TightID (baseline)	!Tag
$ \eta \leq 2.47$ (exclude $1.37 \leq \eta \leq 1.52$)	$ \eta \leq 2.47$
$E_T \geq 25$ GeV	$E_T \geq 15$ GeV
Pass OQ	Pass OQ (only at Numerator)
Trigger Matched	Pass EGamma Ambiguity Selection ¹
Truth Match to Z (MC)	Truth Match to Z (MC)
Track Isolation ($p_{Tcone20}/p_T < 0.1$)	Jet Veto (pass if $nCloseJets < 2$) (probe isolated from AntKt4 jet with $E_T > 20$ GeV within $\Delta R = 0.4$)
–	passEMcluster: $dR(\text{photon probe, any e with track}) < 0.15$ ²

¹EGamma Ambiguity Selection refers to the ambiguity in the identification of an object as an electron or a photon candidate. This tool will allow probes with track (electrons) coming from electron container. But in case of ambiguous track, the tool will pass probe without track (photons) from photon container.

²The minimum ΔR requirement between the photon and the closest-by electron, where ΔR is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Furthermore, all the electrons in the container *Electrons* are used (if this container is not available) and any value can be set to select this requirement in the TagAndProbe framework.

When multiple electrons within one event satisfy the tag requirements, tag-probe pairs are formed independently for each viable tag (matched to the probe candidate yielding the highest pair invariant mass), such that a single event may contribute to the measurement with a multiplicity greater than one.

5.2.3 Efficiency

The reconstruction efficiency [124] is defined as the ratio of probes fully reconstructed as electrons (cluster matching a track which also satisfies some quality criteria) over all probes. It can be written as:

$$\varepsilon_{reco} = \frac{N_{pass}^{sig}}{N_{pass}^{sig} + N_{fail}^{sig}} = \frac{N_p^e - B_p^e}{(N_p^e - B_p^e) + (N_F^e - B_F^e) + (N^\gamma - B^\gamma)} \quad (5.1)$$

where N_p^e and N_F^e are the number of probes reconstructed as electrons and passing/failing the extra track quality requirements, and B_p^e , B_F^e are the corresponding background estimates. N^γ is the number of non-reconstructed probes, in other words clusters with no matched tracks, and B^γ the corresponding background estimate [129].

5.2.4 Background estimation

Different methods are used to estimate the backgrounds for probes reconstructed as electrons (B_p^e , B_F^e), or for clusters with no matching tracks (B^γ), described in the following two sections.

5.2.4.1 Background template for electron candidates with an associated track

The background coming from this category of probes (B_p^e , B_F^e) is estimated using templates of the invariant mass distribution obtained from suitable data events [122]. They are built by inverting isolation and identification selections (as shown in Table 5.5) of the probe candidate. This is done to minimize the contribution of real electrons to the templates. They are scaled in order to match the number of events with regular tag and probe selections in an m_{ee} region away from m_Z , which is considered to be signal free. Such a region is typically chosen to be the interval $120 < m_{ee} < 250$ GeV. The remaining signal in the template or in the normalization region is subtracted using MC simulations. The estimation of the background coming from probes with track either passing or failing quality criteria is thus given by the relation;

$$B^e = (N_{peak}^{template} - N_{peak}^{template,MC}) \times \frac{N_{tail}^e - N_{tail}^{MC}}{N_{tail}^{template} - N_{tail}^{template,MC}} \quad (5.2)$$

where B^e is the number of background in the signal region (Z peak), N^e and $N^{template}$ are the number of the probes selected in data for the measurement or in the background template, respectively. Whereas, N_{peak} and N_{tail} refer to the signal and normalization regions. Terms with an MC superscript correspond to the subtracted signal contribution evaluated with simulation.

Fig. 5.1 represents two invariant mass distributions for the electron candidates passing (left) / failing (right) the track quality (TQ) conditions. The background estimates (red line) for the electron candidates passing the track quality matches well the high and low mass region. The estimation of background in the signal region i.e. Z mass peak is concurring the total expected (signal MC + background template) and the data. The background estimates for the electron candidates failing the track quality is less precise because of limited statistics, but in turn does not affect significantly the final results.

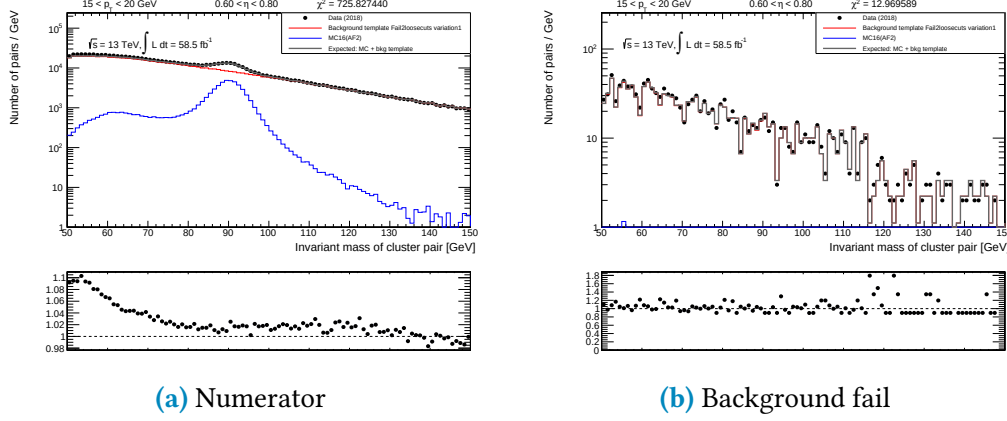


Figure 5.1: The plot (a) represents the distribution of invariant mass for electron candidates passing TQ conditions whereas plot (b) shows the distribution for candidates failing TQ requirement and background estimation in corresponding bin of E_T , $15 < E_T < 20\text{GeV}$ for $0.60 < \eta < 0.80$.

Table 5.5: Details of the templates used for background estimation for electrons with track

Template		Variation 1	Variation 2
Inverted cuts		Fail at least 2 <i>cut-based Loose cuts</i> 5.3	
Isolation requirements	$E_T < 30\text{GeV}$	$\frac{E_T^{\text{cone30}}}{E_T} > 0.02$	$\frac{E_T^{\text{cone30}}}{E_T} > 0.02$
	$E_T \geq 30\text{GeV}$	$\frac{E_T^{\text{cone40}}}{E_T} > 0.05$	$\frac{E_T^{\text{cone40}}}{E_T} > 0.20$
Control region	$E_T < 30\text{GeV}$	$120 < m_{ee} < 250\text{GeV}$	$60 < m_{ee} < 70\text{GeV}$
	$E_T \geq 30\text{GeV}$	$120 < m_{ee} < 250\text{GeV}$	$120 < m_{ee} < 250\text{GeV}$

5.2.4.2 Background template for electron candidates having no associated track

For candidates not reconstructed as electrons, i.e. clusters with no matched tracks, the background is instead estimated with a third-order polynomial interpolation of the observed data yields as function of the invariant mass m_{ee} , excluding the signal-rich region near m_Z . A binned modified χ^2 fit is performed to determine the coefficients of the polynomial. The background estimation is then given by integrating the fitted function in the signal region. Using the exposition and notations from Ref. [127], the polynomial

function can be written as following:

$$f(m) = \sum_{i=0}^3 k_i m^i \quad (5.3)$$

And the modified χ^2 is defined as:

$$\chi^2 = \sum_{i=1}^N (n_i - f(m_i))^2 \quad (5.4)$$

where n_i is the number of events and m_i the invariant mass in the center of the bin i . Bins have $\Delta m = 5$ GeV width. This bin width is chosen to have sufficient statistics to avoid instabilities in the fit. Signal contamination is then subtracted for each bin based on the simulation. Minimizing χ^2 with respect to its four free parameters leads to the following system of linear equations:

$$\sum_{i=1}^N \left(n_i - \sum_{j=0}^3 k_j m_i^j \right) m_i^q = 0 \quad (5.5)$$

where N is the number of bins.

Defining $S_{\alpha\beta} = \sum_{i=1}^N m_i^\alpha n_i^\beta$ and a matrix M with $M_{ij} = S_{(i+j)(0)}$ ($0 \leq i, j \leq 3$), the solution is:

$$\begin{pmatrix} k_0 \\ k_1 \\ k_2 \\ k_3 \end{pmatrix} = M^{-1} \begin{pmatrix} S_{01} \\ S_{11} \\ S_{21} \\ S_{31} \end{pmatrix} \quad (5.6)$$

Then the number of background events is obtained by integrating the fitted function in the peak region $[m_{peak\ low}, m_{peak\ up}]$:

$$B^{\gamma} = k_0 \delta^{(1)} + \frac{k_1}{2} \delta^{(2)} + \frac{k_2}{3} \delta^{(3)} + \frac{k_3}{4} \delta^{(4)} \quad \text{with } \delta^i = m_{peak\ up}^i - m_{peak\ low}^i \quad (5.7)$$

Fig. 5.2 is showing plots for denominator term (i.e. probes without any track requirements) for low E_T , $15 < E_T < 20$ GeV (left) and high E_T , $40 < E_T < 45$ GeV (right). At low E_T , the contribution from the electrons with no associated track term to the signal is negligible as the corresponding term (dark blue line) is at the same level as the fit terms (dashed yellow lines). Whereas, at higher E_T the no associated track term peaks around the Z mass above the estimated background from the sidebands fit. This distinction refers to the signal electrons (real candidates) with no matched track.

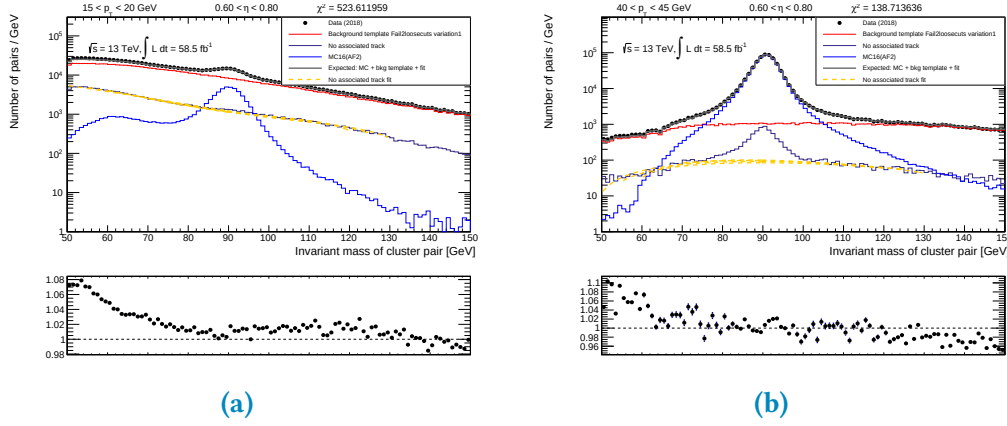


Figure 5.2: The plot (a) shows the distribution of invariant mass at denominator level for reconstructed electron, non-reconstructed electron candidates (photon probes) and background estimation in corresponding bins of low E_T , $15 < E_T < 20\text{ GeV}$ and the plot (b) represents the same distribution for high E_T , $40 < E_T < 45\text{ GeV}$ for $0.60 < \eta < 0.80$.

5.3 Systematic uncertainties

Systematic uncertainties are estimated by applying variations on the selection procedure.

Variations on the tag identification: Three different tag ID are chosen: *Tight*, *Tight* with $E_T^{\text{cone40}} < 5\text{ GeV}$ and *Medium* with $E_T^{\text{cone40}} < 5\text{ GeV}$. This allows to modify the amount and composition of background (proportion of events with a real isolated electron from W/Z +jets and QCD events without real electron).

Variations on the Z-mass peak window: The $]80, 100[$, $]75, 105[$ and $]85, 95[$ GeV allow the variation of some identification criteria efficiencies depending on the invariant mass (low mass region rich in bremsstrahlung electrons).

The background template variations, described in Table 5.5, to change contamination signal proportions.

Variations of electron-photon m_{ee} intervals used to fit photon background: $[70, 80] \cup [100, 110]$, $[60, 80] \cup [100, 120]$, $[50, 80] \cup [100, 130]$, and $[55, 70] \cup [110, 125]$ GeV to ensure the stability of the analytic form.

Applying all of those variations results in 72 terms of efficiencies and scale factors. The final efficiency and statistical uncertainties are computed as the average of the systematic variations and the corresponding systematic uncertainty is the root mean square (RMS) value of the 72 values for the efficiency.

5.4 The measurement of statistical uncertainties through pseudo-experiments

In the published measurements [121, 122], the statistical uncertainties are evaluated simply by propagating Poisson fluctuations of the observed data yields with a first-order approximation. For convenience, Eq. 5.1 is re-expressed by splitting all observables into

uncorrelated components:

$$\begin{aligned}\varepsilon_{reco} &= \frac{P - T \frac{P_H}{T_H}}{P - T \frac{P_H}{T_H} + F - U \frac{F_H}{U_H} + \Gamma} \\ &= \frac{U_H(S T_H - T S_H)}{U_H(S T_H - T S_H) + T_H(R U_H - U R_H) + \Gamma T_H U_H}\end{aligned}\quad (5.8)$$

with P/F the number of candidates passing / failing the track quality requirements, T/U the number of probes in templates passing / failing the same requirements. Γ is the number of non-reconstructed candidates after background subtraction. The index H stands for the normalization region, at high invariant mass. The right hand side, has independent variables, used for the error propagation. S is defined as $P - T$, $S_H = P_H - T_H$, $R = F - U$ and $R_H = F_H - U_H$.

The statistical uncertainty is then given by the formula:

$$\begin{aligned}\Delta \varepsilon^2 &= \frac{T_H^2 (S T_H - T S_H)^2}{(denom)^4} \times \\ &\times \left[U^2 R_H^2 \Delta U_H^2 + U_H^2 (U_H^2 \Delta R^2 + U_H^2 \Delta \Gamma^2 + U^2 \Delta R_H^2 + R_H^2 \Delta U^2) \right] + \\ &+ \frac{U_H^2 (R U_H - U R_H + \Gamma U_H)^2}{(denom)^4} \times \\ &\times \left[T^2 S_H^2 \Delta T_H^2 + T_H^2 (T_H^2 \Delta S^2 + T^2 \Delta S_H^2 + S_H^2 \Delta T^2) \right]\end{aligned}\quad (5.9)$$

Where "denom" stands for the denominator of Eq. 5.8. Δ is the Poisson uncertainty in the relevant observable. The $\Delta \Gamma$ term is more involved because $\Gamma = N^\gamma - B^\gamma$, $(\Delta \Gamma)^2 = (\Delta N^\gamma)^2 + (\Delta B^\gamma)^2$. ΔN^γ is the Poisson uncertainty on the number of non-reconstructed probes whereas ΔB^γ is the statistical uncertainty on the associated background estimated from the fit. ΔB^γ is also obtained by error propagation on the number of events in each bin used for the fit. It reads at leading order:

$$(\Delta B^\gamma)^2 = \sum_i \left(\frac{\partial B^\gamma}{\partial n_i} \right)^2 \times (\Delta n_i^{(stat)})^2 \quad (5.10)$$

Where $\Delta n_i^{(stat)}$ is the Poisson uncertainty on the number of events in the i^{th} bin.

5.4.1 The principle of pseudo-experiments

We verify the accuracy of Eq. 5.8 under various conditions, with the help of pseudoexperiments in which we fluctuate independently, and according to Poisson density functions, all the independent observables entering Eq. 5.8. Repeated for a large number of times (N), this provides us with a set of efficiencies $\varepsilon(i)$, where $i=1, \dots, N$. The empirical statistical uncertainty is then calculated from the root mean square error of efficiencies in this set:

$$\Delta \varepsilon_{rms} = \sqrt{\frac{1}{N} \sum \varepsilon(i)^2 - \left(\frac{1}{N} \sum \varepsilon(i) \right)^2} \quad (5.11)$$

which can be compared to the approximation provided by Eq. 5.9.

The pseudoexperiments are performed for various assumed number of signal events, level of background, and shape of the background distribution as function of the invariant mass. Realistic values are chosen for the latter two parameters, as well as for other (fixed) parameters necessary to determine all the terms in Eq. 5.8. These are as follows:

- the number of signal events in the peak region (taken as $80 < m_{ee} < 100$ GeV) are varied from 50 to 10^6 ;
- the reconstruction efficiency is set to either 97, 98 or 99%, based on Refs. [121, 122];
- the number of signal probes non reconstructed as electrons or reconstructed but failing the track quality requirements, are equal, a mostly arbitrary choice with partial support from Fig. 2a in Ref. [121].
- the number of signal events leaking into the template normalization region is set to 0.5% of the corresponding number in the peak region, based e.g. on aux. Fig. 3 in Ref. [125], and regardless of the probe selection;
- no signal is assumed to leak into the templates;
- the ratio β between the number of background and signal events in the peak region, for an inclusive probe selection, is set to either 5, 10, 50, 100 or 200%, based on Refs. [121, 125].
- the total background is split between the three categories of probes such that the level of background in the peak region, relatively to the number of signal events in the same category and region, are in proportion 1 : 2 : 6 between the three categories, based on Fig. 3.5 in Ref. [127];
- the background shape, as function of the invariant mass m , follows an exponentially-decaying distribution $e^{-\alpha m}$ with α set to either 0, 0.01 or 0.025, based on distributions shown in Refs. [121, 125, 122];
- the fraction of background events also entering in the template is 80%.

5.4.2 Results

The results are plotted using different configurations for background level ($\beta = 5\%, 10\%, 50\%, 100\%, 200\%$) and shape ($\alpha = 0.0, 0.01, 0.025$). The values of α give us different exponential shapes for various invariant mass bins (m) in GeV e.g: 60, 80, 100 & 120 as shown in Fig. 5.3. This helps us to estimate our background for clusters without matching track in the denominator as explained in Section 5.2.3. The results are taken from Ref. [163].

The uncertainties vary with number of events (n) and efficiencies (ϵ). We consider $5 \times 10^1, 1 \times 10^2, 1 \times 10^3, 1 \times 10^4, 1 \times 10^5, 1 \times 10^6$ events for each set of efficiency percentage i.e. 97%, 98%, 99%. Hence, we have in total 270 configurations to be considered for this studies of uncertainty measurement.

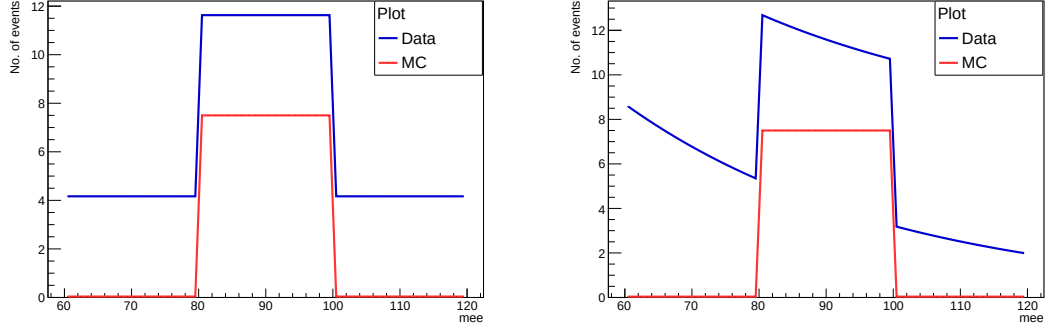


Figure 5.3: The plots are showing bins of various invariant masses filled for data and mc at different background levels (β), efficiency (ϵ), events (n) and alpha (α) values. The left plot is representing the bins filled for data (signal+background) and mc (signal) histograms at $\beta = 10\%$, $\epsilon = 97\%$, $n = 10^4$ & $\alpha = 0.0$. The right plot is representing the same scenario for bins filling at $\beta = 10\%$, $\epsilon = 97\%$, $n = 10^4$ & $\alpha = 0.025$.

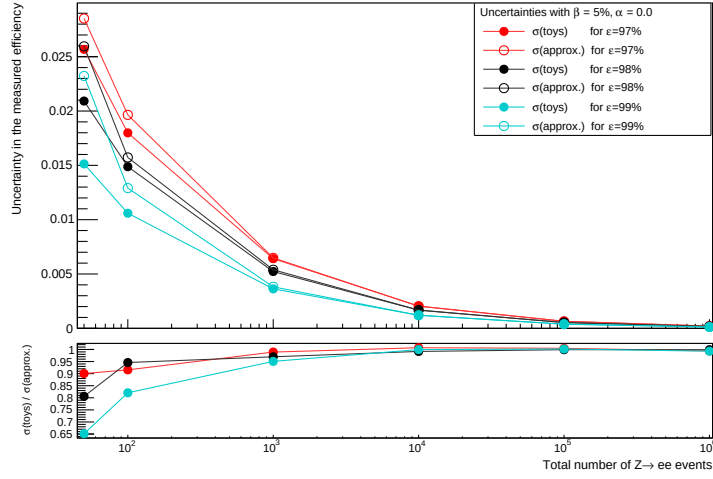


Figure 5.4: The upper pad of plot represents uncertainties in efficiencies (ϵ) for $\beta = 5\%$ and $\alpha = 0.0$. The full circle markers show uncertainties evaluated with pseudoexperiments (σ_{toys}) while the open markers correspond to uncertainties calculated with Eq. 5.9 ($\sigma_{approx.}$). Different colours are used for different choices of the efficiency (97%, 98%, 99%). The lower pad shows the ratio of $\sigma(toys)$ and $\sigma(approx.)$ for each set of two curves from the upper pad.

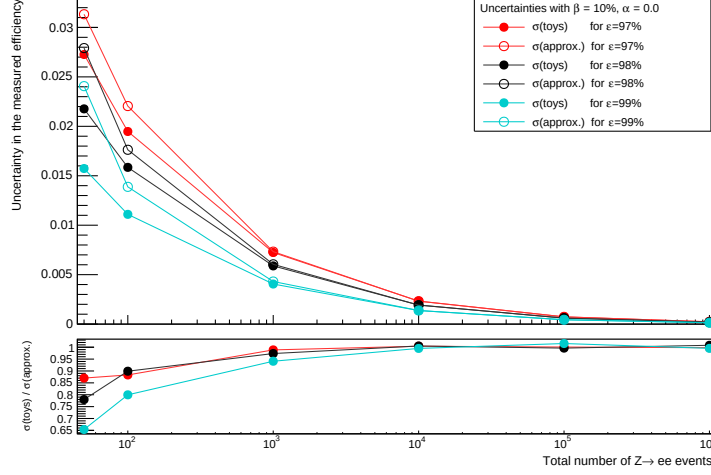


Figure 5.5: The upper pad of plot represents uncertainties in efficiencies (ϵ) for $\beta = 10\%$ and $\alpha = 0.0$. The full circle markers show uncertainties evaluated with pseudoexperiments (σ_{toys}) while the open markers correspond to uncertainties calculated with Eq. 5.9 ($\sigma_{\text{approx.}}$). Different colours are used for different choices of the efficiency (97%, 98%, 99%). The lower pad shows the ratio of $\sigma(\text{toys})$ and $\sigma(\text{approx.})$ for each set of two curves from the upper pad.

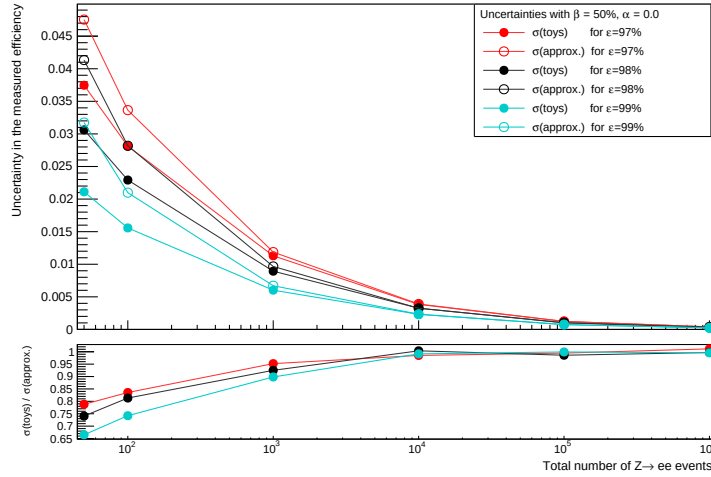


Figure 5.6: The upper pad of plot represents uncertainties in efficiencies (ϵ) for $\beta = 50\%$ and $\alpha = 0.0$. The full circle markers show uncertainties evaluated with pseudoexperiments (σ_{toys}) while the open markers correspond to uncertainties calculated with Eq. 5.9 ($\sigma_{\text{approx.}}$). Different colours are used for different choices of the efficiency (97%, 98%, 99%). The lower pad shows the ratio of $\sigma(\text{toys})$ and $\sigma(\text{approx.})$ for each set of two curves from the upper pad.

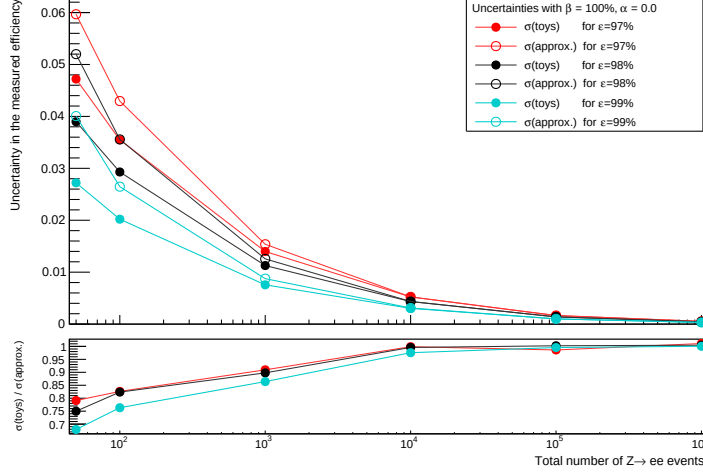


Figure 5.7: The upper pad of plot represents uncertainties in efficiencies (ϵ) for $\beta = 100\%$ and $\alpha = 0.0$. The full circle markers show uncertainties evaluated with pseudo-experiments (σ_{toys}) while the open markers correspond to uncertainties calculated with Eq. 5.9 ($\sigma_{\text{approx.}}$). Different colours are used for different choices of the efficiency (97%, 98%, 99%). The lower pad shows the ratio of $\sigma(\text{toys})$ and $\sigma(\text{approx.})$ for each set of two curves from the upper pad.

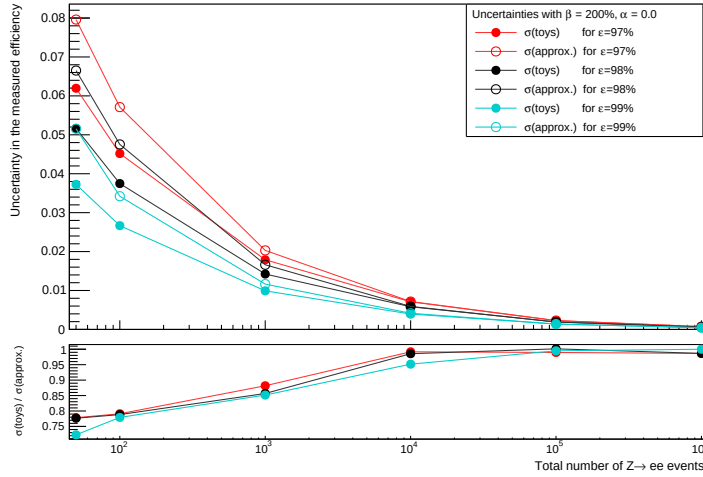


Figure 5.8: The upper pad of plot represents uncertainties in efficiencies (ϵ) for $\beta = 200\%$ and $\alpha = 0.0$. The full circle markers show uncertainties evaluated with pseudo-experiments (σ_{toys}) while the open markers correspond to uncertainties calculated with Eq. 5.9 ($\sigma_{\text{approx.}}$). Different colours are used for different choices of the efficiency (97%, 98%, 99%). The lower pad shows the ratio of $\sigma(\text{toys})$ and $\sigma(\text{approx.})$ for each set of two curves from the upper pad.

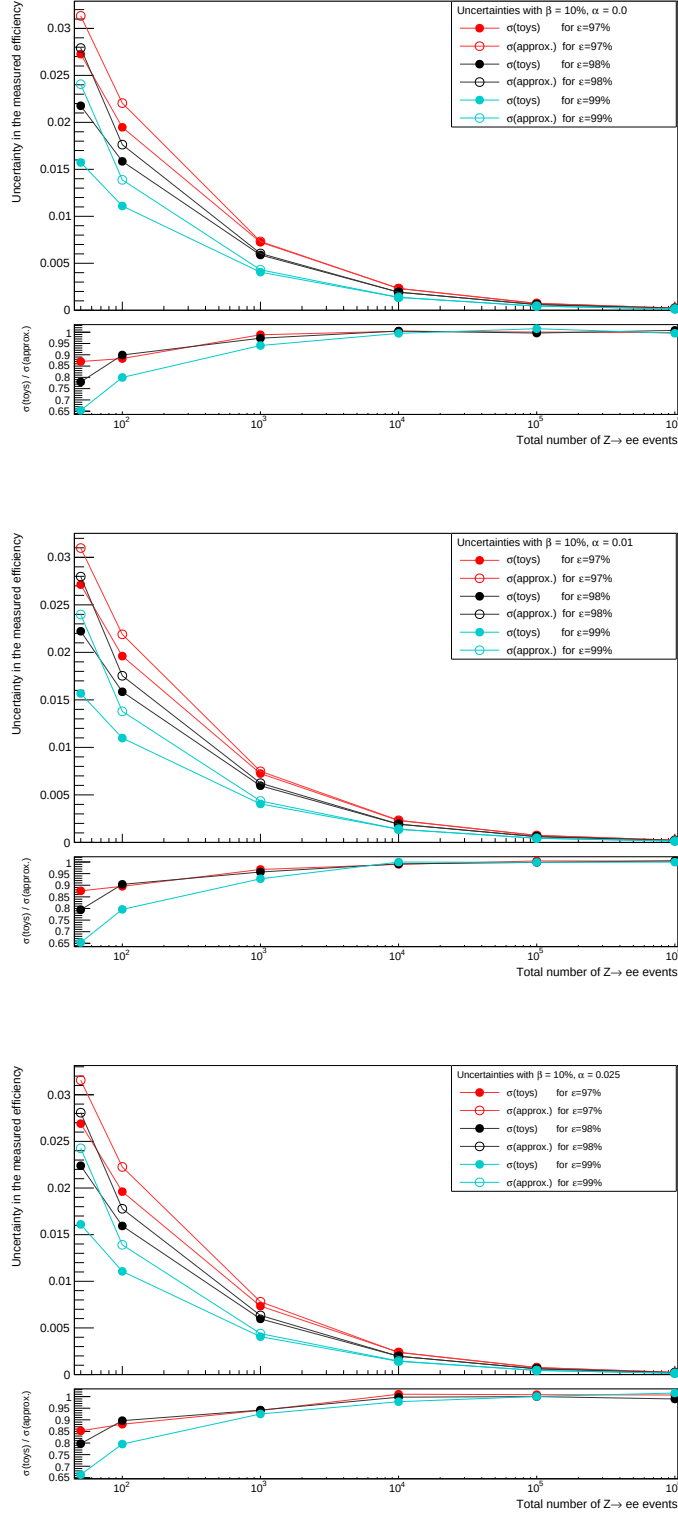


Figure 5.9: The upper pad of all the plots represents uncertainties in efficiencies (ϵ) for $\beta = 10\%$ with $\alpha = 0.0$ (top), $\alpha = 0.01$ (middle), $\alpha = 0.025$ (bottom). The red curves correspond to uncertainties in 97% efficiency, the black curves correspond to 98% efficiency & cyan curves indicate uncertainties in efficiencies 99%. The lower pad in all plots shows the ratio of $\sigma(\text{toys})$ and $\sigma(\text{approx.})$ for each set of two curves from the upper pads in each plot.

From Figs. 5.4 to 5.8 we overall comprehend that, at low background fractions the ratio between $\sigma(\text{toys})$ and $\sigma(\text{approx.})$ is below 1 for small number of events $5 \times 10^1, 10^2, 10^3$, indicating that the approximation is a bit conservative. However, at large number of events $10^4, 10^5, 10^6$ differences between the measurements of both are very small and ratio sits closer to 1 for all efficiencies.

In Fig. 5.9, we present three different scenarios for the values of alpha. The numbers are reasonably close to each other for each set of efficiencies and comparison between uncertainties of toys and approximate formula is showing same trend in each case. On that account, other combinations of background and alpha giving us similar observations are not shown here.

These are my own results and they are already published in Ref. [163].

5.5 Run2 AtlasFast2 recommendations in Rel21

The efficiency measurements were performed for Run2 data for AF2³ samples and comparison was done with full simulation (FS) and previous recommendations. The scale factors are calculated in TagandProbeFrame Framework [133] by using following commands:

Selection Step : `python ZRecoRun.py --config-file ZRecoConfigs --configs March2021 --datasetfile SFGridFiles --datasets rel21_EGAM1_[dataset_year]_ptag --dir[name of directory] --selection --grid --gridSuffix`

Calculation Step : `python ZRecoRun.py --config-file ZRecoConfigs --configs March2021 --datasetfile SFGridFiles --datasets rel21_EGAM1_[dataset_year]_ptag --dir[name of directory] --calculate`

where `[dataset_year]` could be 2015, 2016, 2017 and 2018.

The output of the selection step stored into two root files i.e. `merged-hist-mc.root` and `merged-hist-data.root` that store histograms of numerator and denominator needed for MC and data efficiencies. While the calculation step compute desired efficiencies and scale factors ($SF = \text{data} / \text{MC}$) providing the final root files `ScaleFactors.root` and `variation_reference.root`.

The results for the measurement of efficiency and scale factors carried out with AF2 samples are depicted in the Fig. 5.10 and comparison is done with data efficiency of full simulation to calculate correct scale factors i.e.

$$SF (AF2) = Data\ Eff (FS) / MC\ Eff (AF2)$$

Overall, high efficiency (98%) is measured for both data and MC except crack region. The scale factors are closer to one, with spike less than 1.08% in crack region. The uncertainties in scale factors are dominated by systematics at low E_T by 2.5% and are below 0.5% in general.

The measured efficiencies with data and MC and SF for all E_T bins for years 2015+16, 2017 and 2018 are shown in Fig. 5.12. On the other hand, the uncertainties in scale factors

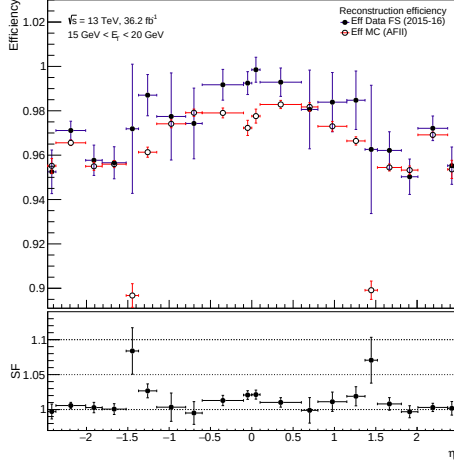
³ Atlfast-II which uses FastCaloSim in the calorimeter. The detail is provided in Ref. [131].

Table 5.6: The datasamples used for measurements with data for complete Run2 and MC for the years 2015+2016, 2017 and 2018

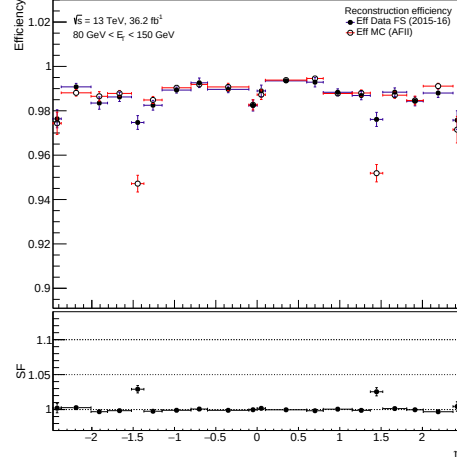
Datasets	Signal $Z \rightarrow ee$
Data Samples (R21)	data15_13TeV.periodAllYear.physics_Main.PhysCont.DA0D _EGAM1.grp15_v01_p4332 data16_13TeV.periodAllYear.physics_Main.PhysCont.DA0D _EGAM1.grp16_v01_p4332 data17_13TeV.periodAllYear.physics_Main.PhysCont.DA0D _EGAM1.grp17_v01_p4332 data18_13TeV.periodAllYear.physics_Main.PhysCont.DA0D _EGAM1.grp18_v01_p4332
MC Samples (R21)	mc16_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DA0D _EGAM1.e3601_a875_r9364_p3918 mc16_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DA0D _EGAM1.e3601_a875_r10201_p3918 mc16_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DA0D _EGAM1.e3601_a875_r10724_p3918

for those years are given in Fig. 5.14. The scale factors are very close to one in all years. The SF uncertainties are higher at low E_T and systematic uncertainties are dominated by 3.25% in 2015+2016, 2.5% in 2017 and 1.8% in 2018 data.

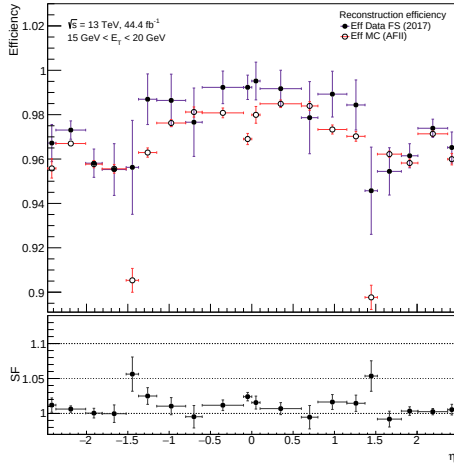
The results are taken from my ATLAS authorship qualification project report Ref.[128].



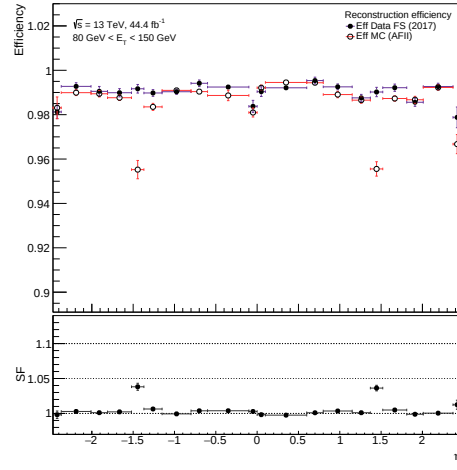
(a)



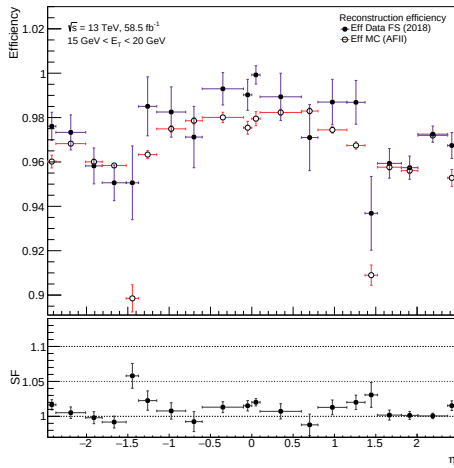
(b)



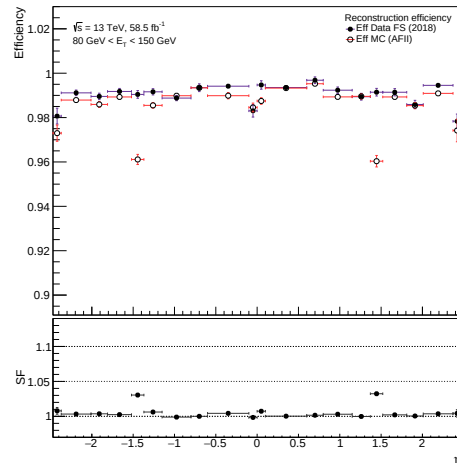
(c)



(d)



(e)



(f)

Figure 5.10: The plots a(b) represent the comparison of data efficiency of full simulation with MC efficiency of AF2 in low E_T bin $15 < E_T < 20\text{GeV}$ and high E_T bin $80 < E_T < 150\text{GeV}$ for years 2015+2016. Whereas the plots c(d) show comparison of data & MC efficiencies for FS & AF2 for low/high E_T bins $15 < E_T < 20\text{GeV}$ / $80 < E_T < 150\text{GeV}$ for the year 2017. The plots e(f) depict the same comparison of efficiencies in data, MC & SF for year 2018.

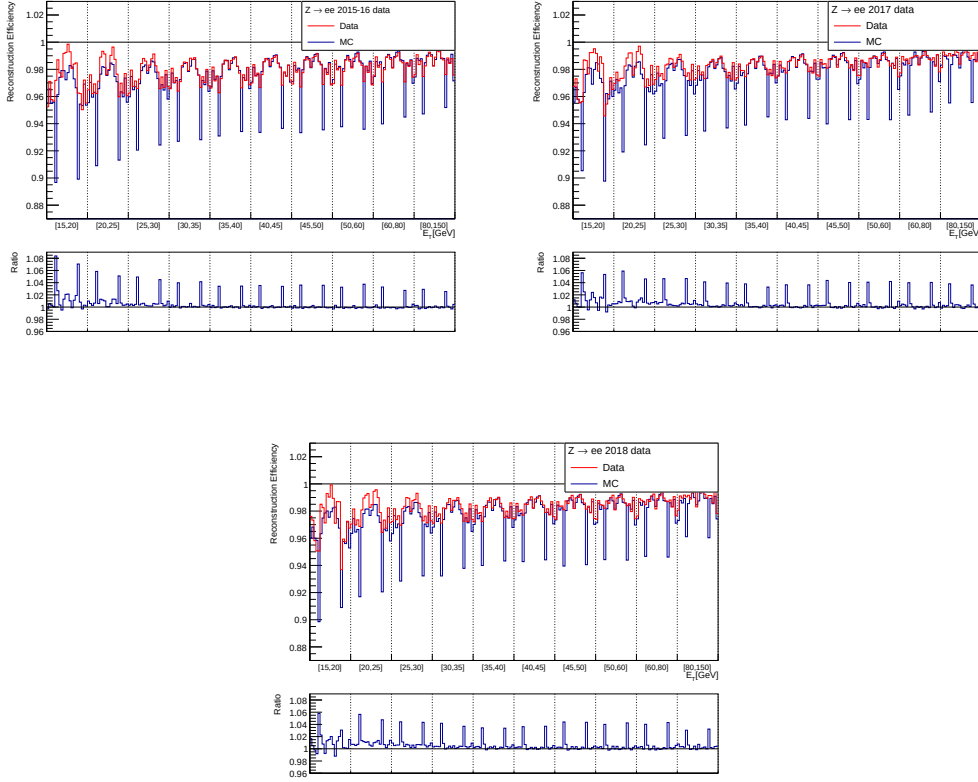


Figure 5.12: The overview of the measured efficiencies and scale factors (top left plot) for reconstruction efficiency as function of E_T and η for $15 < E_T < 150\text{GeV}$ for 2015-16 datasets, whereas plot (top right) shows the same trend of efficiencies and SF for year 2017 for all bins of E_T and bottom plot represents the efficiencies for data & MC and SF for year 2018.

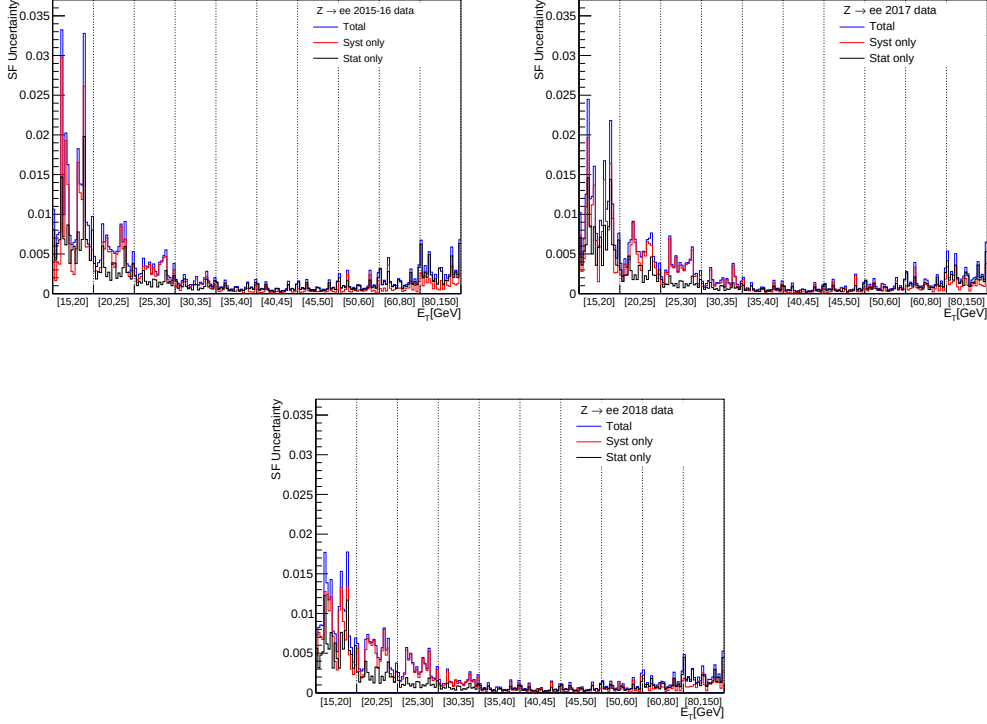


Figure 5.14: The plot (top left) represents the uncertainties in scale factors for year 2015+2016 as function of E_T and η . The plot (top right) shows the same trend of uncertainties for year 2017 for all bin of E_T and η i.e. $15 < E_T < 150\text{GeV}$ and $-2.47 < \eta < 2.47$. The plot (bottom) depicts the same comparison of total, systematics and statistical uncertainties for all bins of E_T and η for the year 2018.

5.5.1 Comparison with previous recommendations

The comparison of reconstruction efficiency for data and MC, is done with 2015+2016 and 2017 AF2 samples. A comparison of data, MC efficiencies and scale factors for 2015-16 and 2017 with previous recommendations is shown in Fig. 5.16 and Fig. 5.18. The decrease in the data and MC efficiencies in last η bins is observed to small extent, but the overall behavior of the efficiencies in all other bins is preserved.

The MC efficiencies show rise in transition region i.e. $1.37 < |\eta| < 1.52$ of the detector overall, because MC efficiency of FS is used for signal contamination subtraction which leads to almost less (or no drops) in crack region at low E_T . In Fig. 5.16, Data AF2 refers to which data efficiency was used to derive AF2 scale factors. The blue curve in top left plot is representing new recommendation for data (AF2) efficiency labelled as, "Data AF2 new" calculated with MC efficiency of FS whereas red curve is showing old recommendation for data (AF2) efficiency labelled as, "Data AF2 old" calculated with MC efficiency of AF2.

In top right plot, the blue curve shows the new recommendation for MC (AF2) efficiency labelled as, "MC AF2 new" and red curve represents old recommendation for MC (AF2) efficiency labelled as, "MC AF2 old". The bottom plot is showing comparison between scale factors of new recommendation (blue curve) and scale factors of old recommendation (red curve).

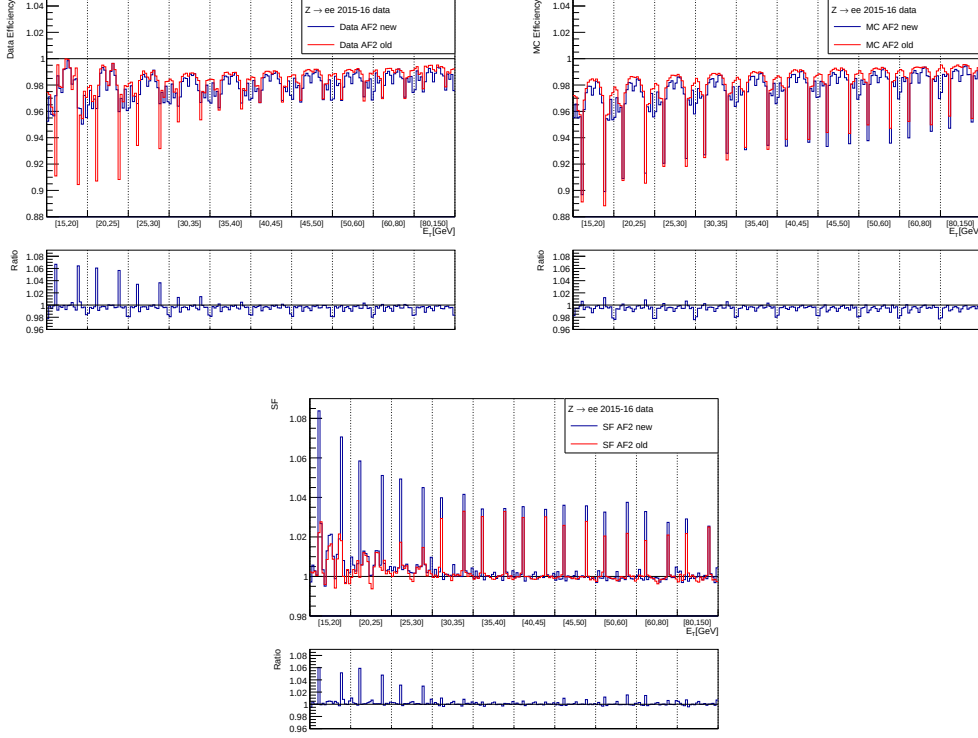


Figure 5.16: The plot (top left) shows the overview of electron reconstruction (data) efficiencies as function of E_T and η for $15 < E_T < 150\text{GeV}$ for 2015-16 datasets. The plot (top right) shows the same trend of (MC) efficiencies for all bins of E_T and η while plot (bottom) represents the scale factors for 2015-16 AF2 samples.

The scale factor measurements are defined as;

$$SF\ AF2\ (new\ recommendation) = Data\ Eff\ (FS) / MC\ Eff\ (AF2)$$

$$SF\ AF2\ (previous\ recommendation) = Data\ Eff\ (AF2) / MC\ Eff\ (AF2)$$

Where $Data\ Eff\ (FS)$ is used for new recommendations because $Data\ Eff\ (AF2)$ was not accurate.

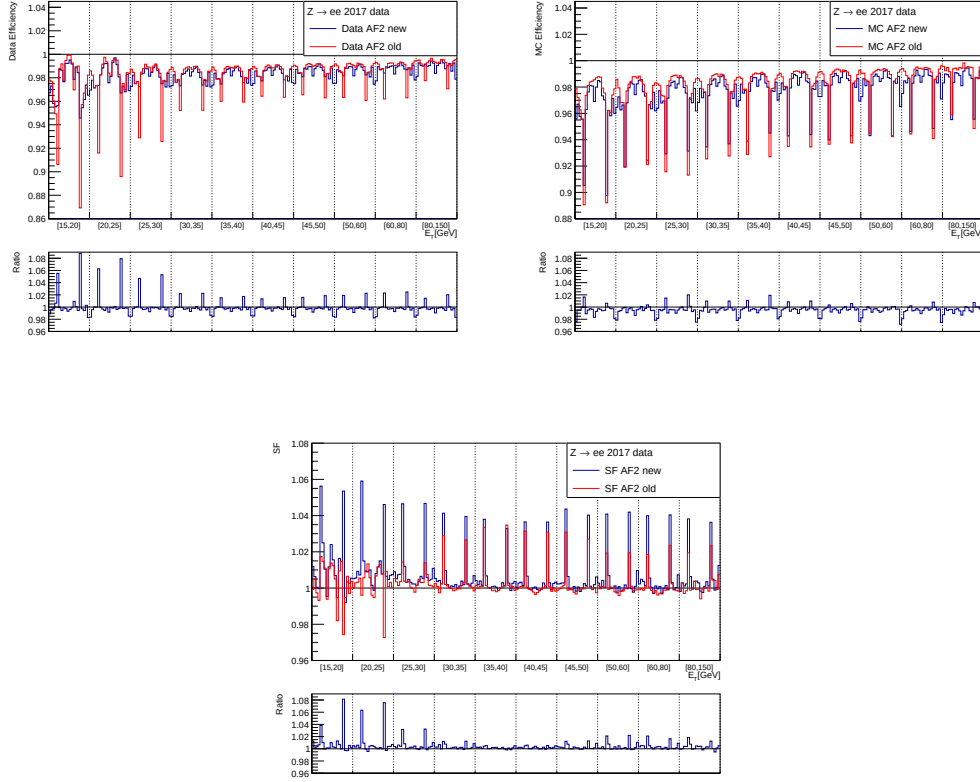


Figure 5.18: The plot (top left) shows the overview of electron reconstruction (data) efficiencies as function of E_T and η for $15 < E_T < 150$ GeV for 2017 datasets. The plot (top right) shows the same trend of (MC) efficiencies for all bins of E_T and η whereas plot (bottom) shows the scale factors for 2017 AF2 samples.

5.6 Electron reconstruction efficiency measurement in Rel22

The TagandProbeFrame framework in release 21 had little quality control and many developments were never merged into a common branch. Therefore, another software was needed for the sake of higher configurability, flexibility and the migration to release 22 setup. The discussed releases in this analysis are detailed in the Ref. [132].

The TagandProbe framework is designed to measure efficiencies like reconstruction, isolation, identification and trigger for physics processes for instance $Z \rightarrow ee$ and $J/\psi \rightarrow ee$. In order to calculate the reconstruction efficiency in TagAndProbe framework, photons as probe object with some primary selections had to be implemented first Ref. [134]. Based on the *CutFlow* comparison in either frameworks, the selection requirements at Event & Object level had to be placed for the efficiency measurement. For example, isolation variables had to be implemented in order to build background templates by inverting some isolation variables.

The first step in an efficiency computation is to run the event and object level selections to retrieve the output of the event framework. For each tag-probe pair, selection of interest can be loaded in the specific configuration by providing the name of the run directory and the unique identifier for the corresponding tag-probe pair. This provides an access to both, the selection configuration file and the results inside the run directory. The observables of interest can be read easily by analysis packages, once a selection is loaded.

A model has to be specified for each type of efficiency, which is to be computed. This component stores information of all variations for instance invariant mass windows, tag identification and template variations that are used to obtain the efficiency value. In addition, each variation, is defined by the histograms used to obtain the output of selections performed for numerator and denominator terms.

A configuration for efficiency measurement is written to plug all histograms from `rundir` obtained by `tp analyse` step. The results of efficiencies for different variations are stored in pickle files obtained through `tp efficiency` step. To ensure the validity of the module for reconstruction efficiency, input histograms from (old) TagAndProbe framework Ref. [135] were placed into efficiency module. Then, the methodology is validated by comparing the outputs of efficiencies and scale factors from TagAndProbe-Frame framework with implementation in TagAndProbe framework. The results of efficiencies and scale factors are shown in Section 5.6.2.

5.6.1 Comparison between cut based loose ID and likelihood based templates

The *cut-based Loose ID* background templates as explained in Section 5.2.4.1 were being used for old measurements of efficiencies in release 21. Figs. 5.20 to 5.30 show the invariant mass distribution at low E_T , with the background estimation performed using fail at least two loose cuts (*Fail2LooseCut*) and likelihood based i.e. *VeryLooseLLH* and *UltraLooseLLH* background templates for both variations as listed in Table. 5.7.

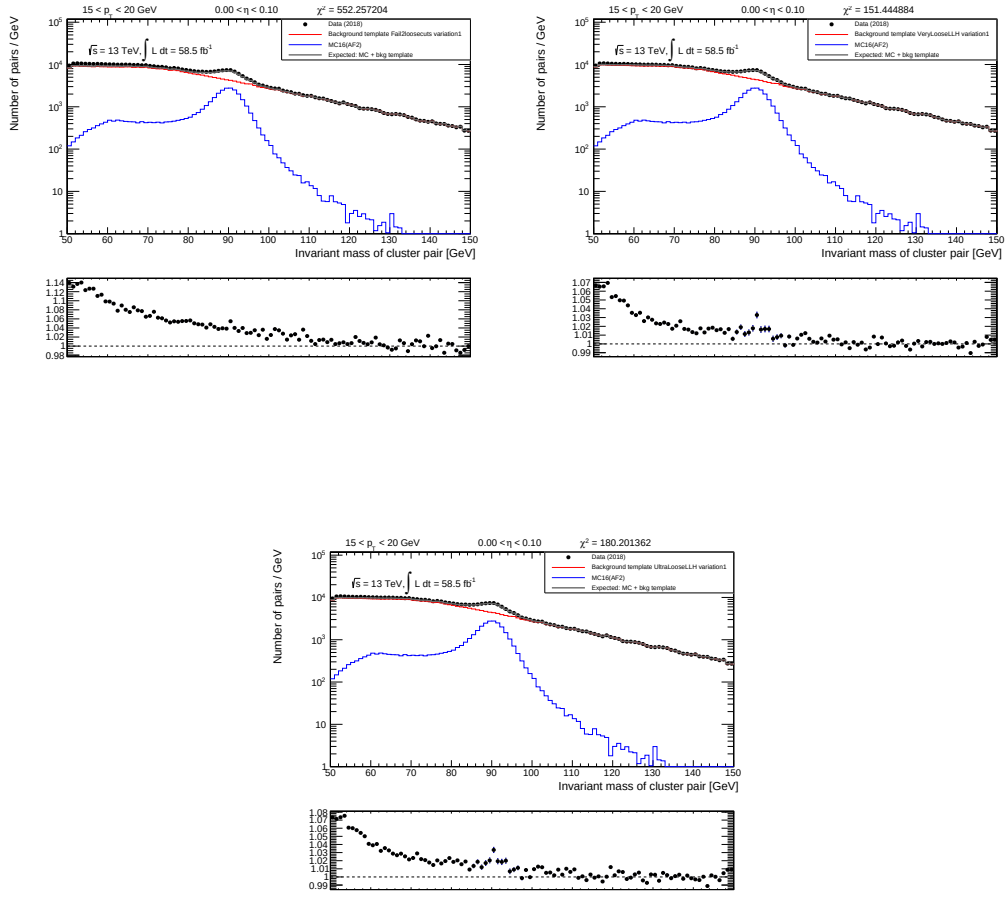
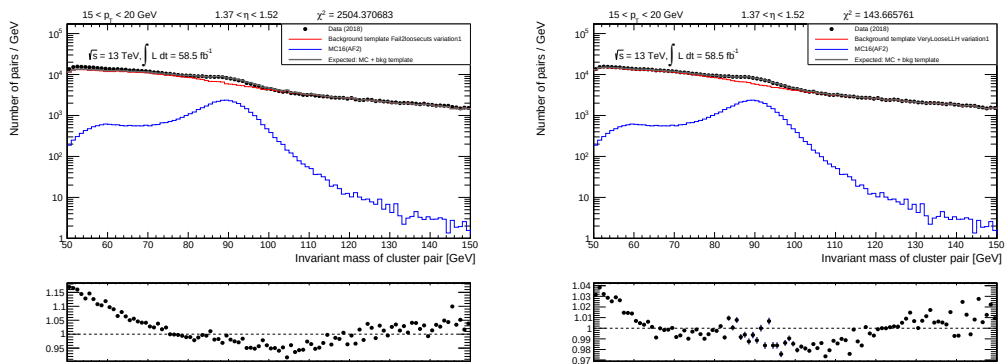


Figure 5.20: The plot (top left) shows the invariant mass distribution at numerator level for *Fail2LooseCut* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and η , $0.0 < \eta < 0.1$. The plots (top right) represent the distribution of invariant mass for numerator term for *VeryLooseLLH* in same bins of E_T and η . The plot (bottom) depicts invariant mass distribution at numerator level for *UltraLooseLLH* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and $0.0 < \eta < 0.1$ for variation 1.



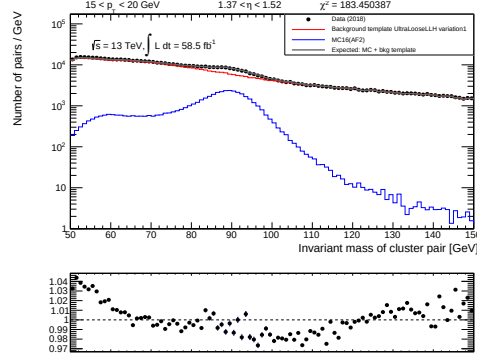


Figure 5.22: The plot (top left) shows the invariant mass distribution at numerator level for *Fail2LooseCut* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and η , $1.37 < \eta < 1.52$. The plots (top right) represent the distribution of invariant mass for numerator term for *VeryLooseLLH* in same bins of E_T and η . The plot (bottom) depicts invariant mass distribution at numerator level for *UltraLooseLLH* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and $1.37 < \eta < 1.52$ for variation 1.

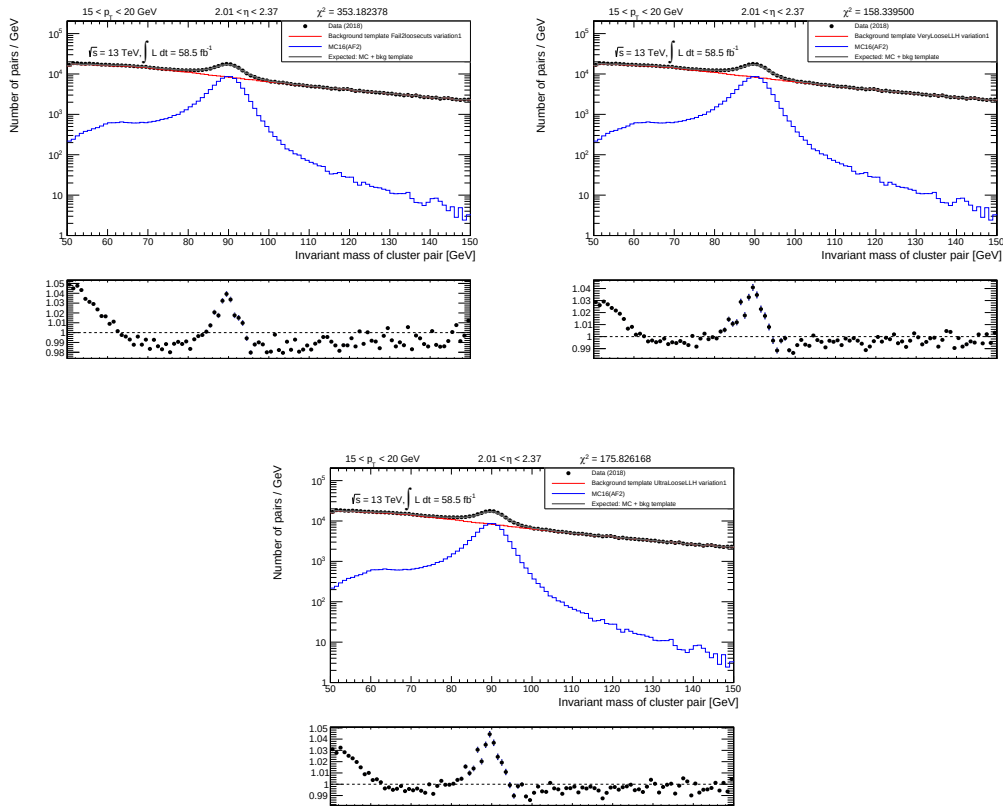


Figure 5.24: The plot (top left) shows the invariant mass distribution at numerator level for *Fail2LooseCut* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and η , $2.01 < \eta < 2.37$. The plots (top right) represent the distribution of invariant mass for numerator term for *VeryLooseLLH* in same bins of E_T and η . The plot (bottom) depicts invariant mass distribution at numerator level for *UltraLooseLLH* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and $2.01 < \eta < 2.37$ for variation 1.

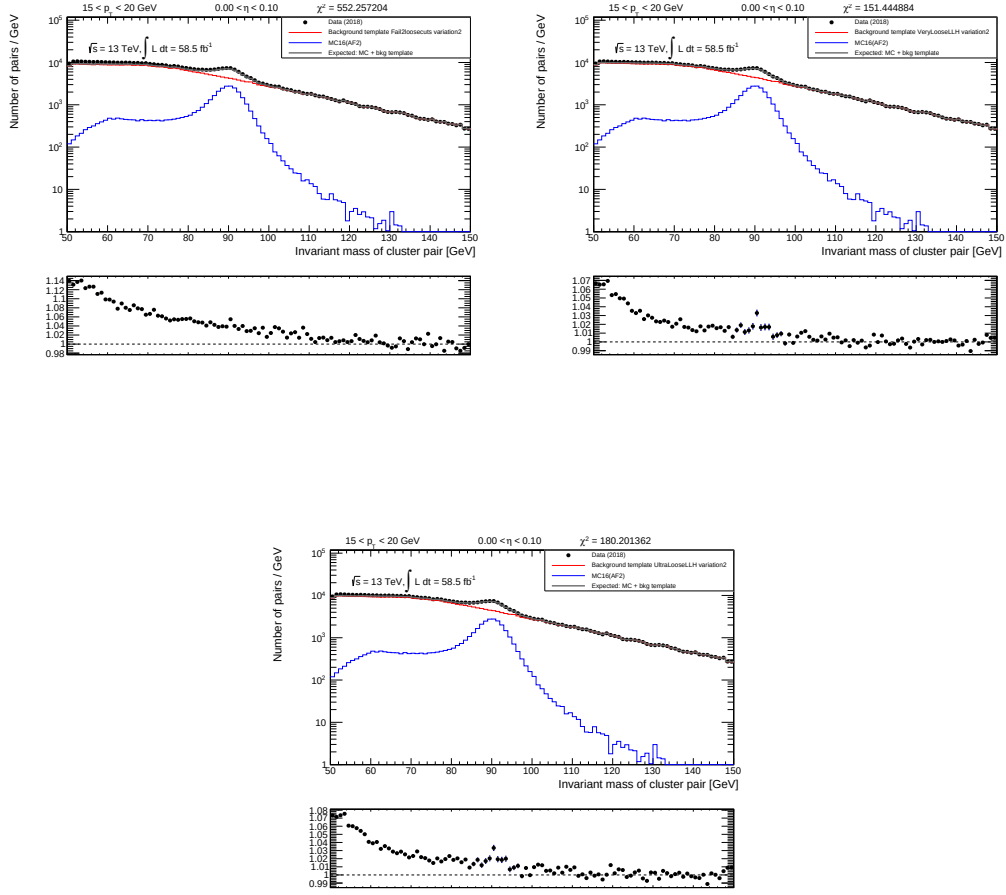
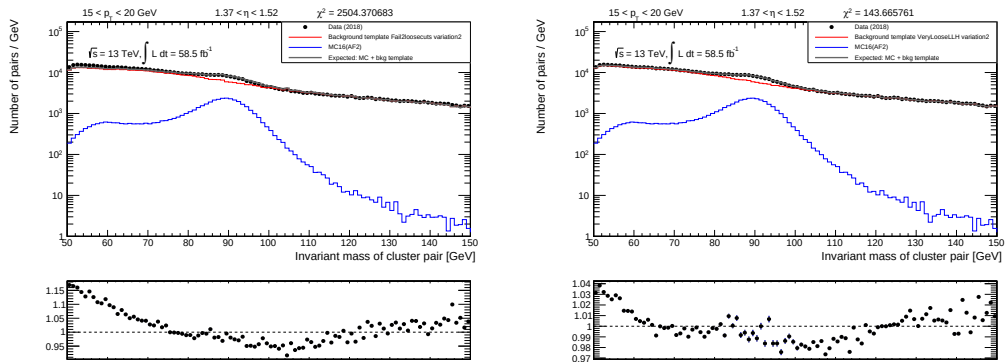


Figure 5.26: The plot (top left) shows the invariant mass distribution at numerator level for *Fail2LooseCut* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and η , $0.0 < \eta < 0.1$. The plots (top right) represent the distribution of invariant mass for numerator term for *VeryLooseLLH* in same bins of E_T and η . The plot (bottom) depicts invariant mass distribution at numerator level for *UltraLooseLLH* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and $0.0 < \eta < 0.1$ for variation 2.



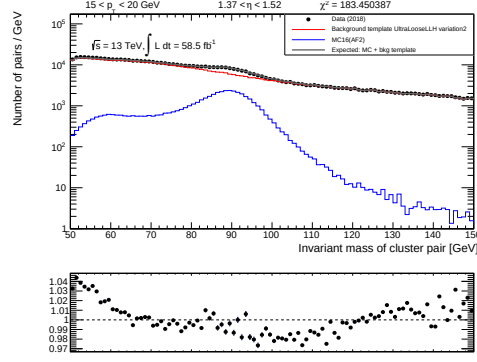


Figure 5.28: The plot (top left) shows the invariant mass distribution at numerator level for *Fail2LooseCut* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and η , $1.37 < \eta < 1.52$. The plots (top right) represent the distribution of invariant mass for numerator term for *VeryLooseLLH* in same bins of E_T and η . The plot (bottom) depicts invariant mass distribution at numerator level for *UltraLooseLLH* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and $1.37 < \eta < 1.52$ for variation 2.

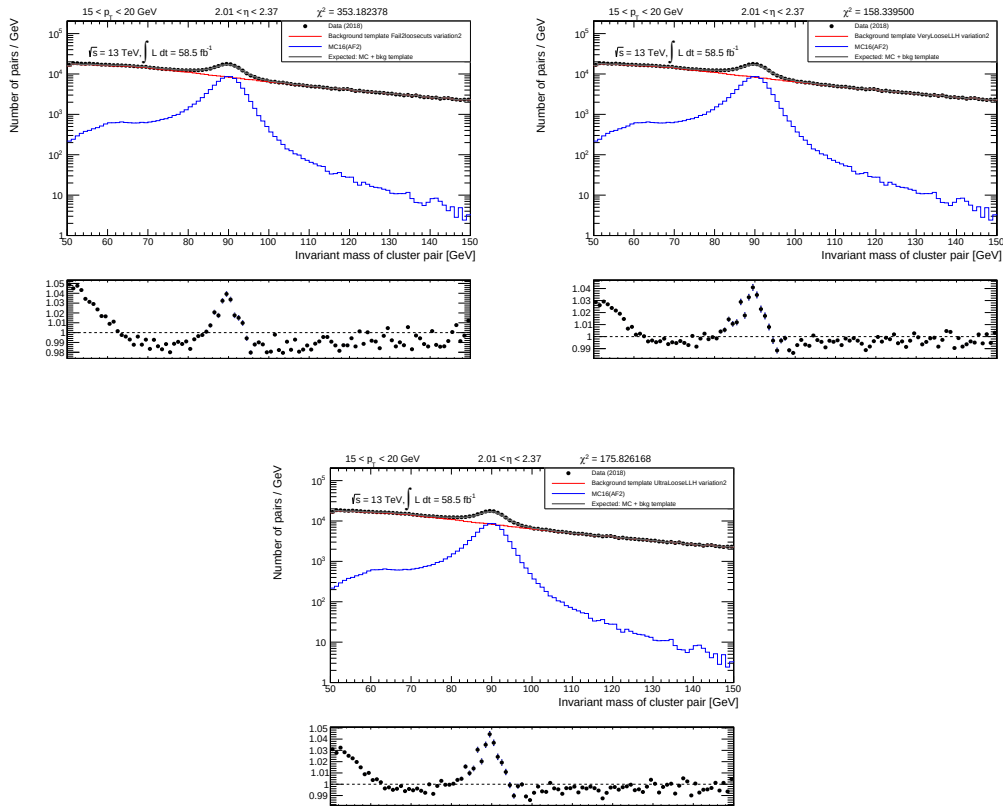
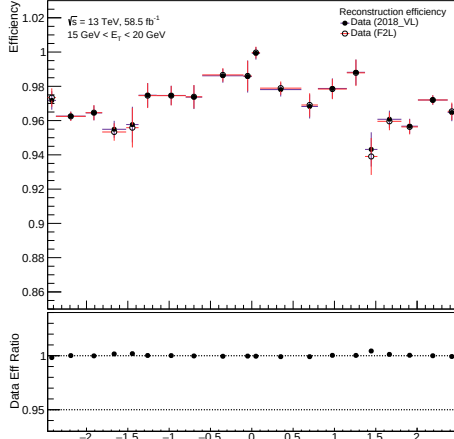
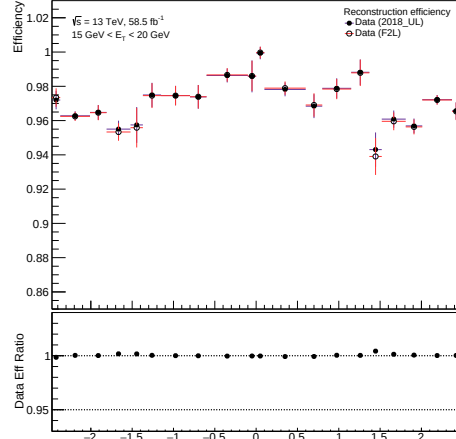


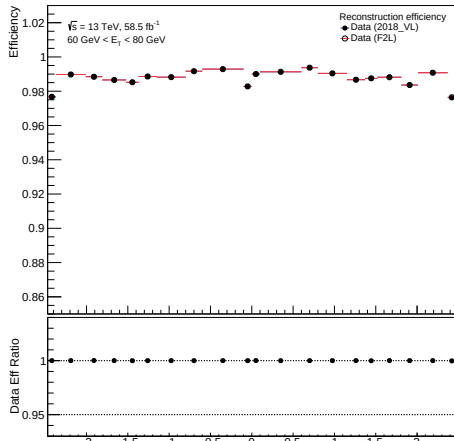
Figure 5.30: The plot (top left) shows the invariant mass distribution at numerator level for *Fail2LooseCut* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and η , $2.01 < \eta < 2.37$. The plots (top right) represent the distribution of invariant mass for numerator term for *VeryLooseLLH* in same bins of E_T and η . The plot (bottom) depicts invariant mass distribution at numerator level for *UltraLooseLLH* background template in bins E_T , $15 < E_T < 20\text{GeV}$ and $2.01 < \eta < 2.37$ for variation 2.



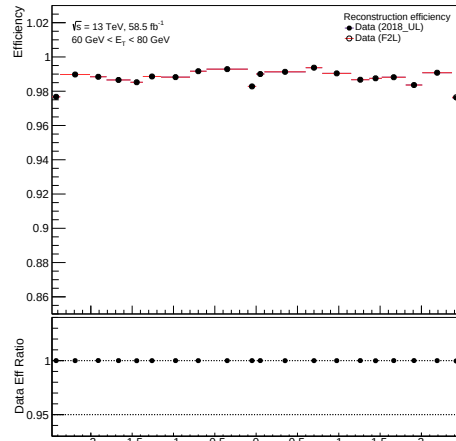
(a)



(b)

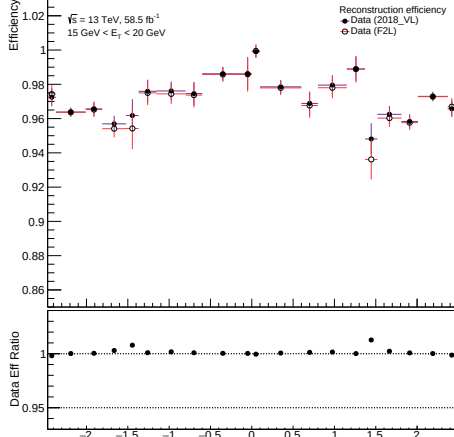


(c)

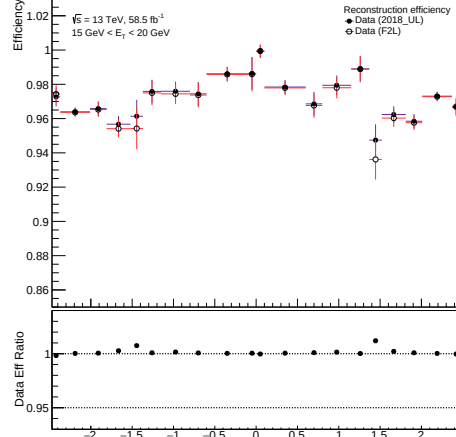


(d)

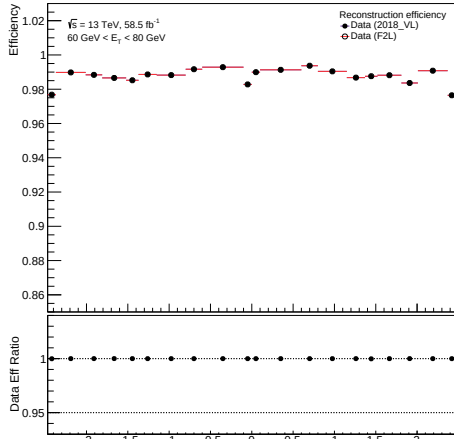
Figure 5.31: The plots a(b) represent the comparison between data efficiencies for background templates *VeryLooseLLH* and *Fail2LooseCut* (*UltraLooseLLH*, *Fail2LooseCut*) for low E_T bin, $15 < E_T < 20$ GeV for FS 2018 datasample (variation 1). The plots c(d) represent the ratio of data efficiencies for high E_T bin, $60 < E_T < 80$ GeV and $\eta > 0$ for same background templates for FS 2018 datasample (variation 1).



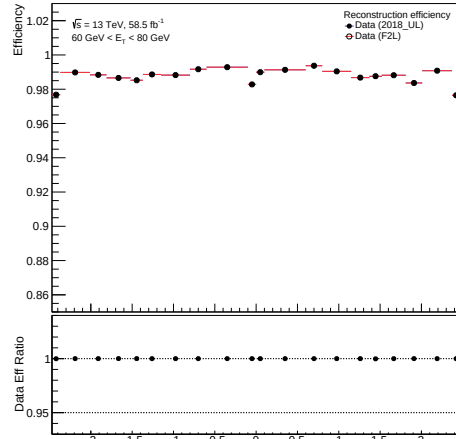
(a)



(b)



(c)



(d)

Figure 5.32: The plots a(b) represent the comparison between data efficiencies for background templates *VeryLooseLLH* and *Fail2LooseCut* (*UltraLooseLLH*, *Fail2LooseCut*) for low E_T bin, $15 < E_T < 20\text{GeV}$ for FS 2018 datasample (variation 2). The plots c(d) represent the ratio of data efficiencies for high E_T bin, $60 < E_T < 80\text{GeV}$ and $\eta > 0$ for same background templates for FS 2018 datasample (variation 2).

Table 5.7: Details of the LH based templates used for background estimation for electrons with track

Template	Variation 1		Variation 2
Inverted cuts	Likelihood based (VeryLooseLLH and UltraLooseLLH)		
Isolation requirements	$E_T < 30\text{GeV}$	$E_{T\text{cone}30}/E_T > 0.02$	$E_{T\text{cone}30}/E_T > 0.02$
	$E_T \geq 30\text{GeV}$	$E_{T\text{cone}40}/E_T > 0.05\text{GeV}$	$E_{T\text{cone}40}/E_T > 0.20$
Control region	$E_T < 30\text{GeV}$	$120 < m_{ee} < 250\text{GeV}$	$60 < m_{ee} < 70\text{GeV}$
	$E_T \geq 30\text{GeV}$	$120 < m_{ee} < 250\text{GeV}$	$120 < m_{ee} < 250\text{GeV}$

From Figs. 5.20 to 5.30, (the lower pad in ratio plots showing ratio between **data** i.e. signal + background (**black curve**) and **Expected** i.e. MC + background template (*gray curve*)) it is clear that for LH based templates, the ratio looks better and the deviations from unity are very small. The χ^2 values shown in the plots in above figures are very small for LH based templates than *cut-based Loose* ID background templates (specifically in case of *VeryLooseLLH*). So, smaller the χ^2 value, the better is the agreement between **data** and **Expected**.

Also, from Figs. 5.31 & 5.32, the ratio between data efficiencies of *VeryLooseLLH* (**black data points**) & *Fail2LooseCut* (*red data points*) background templates seems better, as data efficiency is improved at low E_T because of high fraction of background. The data efficiency in crack region i.e. $1.37 \leq |\eta| \leq 1.52$ is improved the most in this ratio. Therefore, LH based templates should be preferred over *cut-based Loose* ID background templates. To be explicit, *VerLooseLLH* should preferably be used for new measurements in release 22 setup.

5.6.2 Comparison between Rel22 and Rel21 efficiencies measurements in TagAndProbe framework

The comparison between efficiencies (measured in Rel22 and Rel21 frameworks) is done using release 21 samples. The methodology is implemented in TagAndProbe framework for Rel22 and hence validated by comparing efficiencies and scale factors for different variations with TagAndProbeFrame framework developed for Run2 in Rel21.

Fig. 5.33 shows the comparison between new and old efficiencies measured in central values, statistical errors and their scale factors for variation 1.

For the data and mc efficiencies in background template variation 2, two normalization regions i.e. low and high tail invariant mass regions around Z peak region are considered. The background template is normalized in both regions shown in Table. 5.5. The comparison between new and old efficiencies in central values, statistical uncertainties and their scale factors for variation 2 are shown in Fig. 5.34. The overall differences between efficiencies estimated in data and MC in new & old framework for both background template variations are very small i.e. values fall within numerical precision of float data type. Hence, the perfect agreement can be seen between efficiencies measured in Rel22 & Rel21 setup.

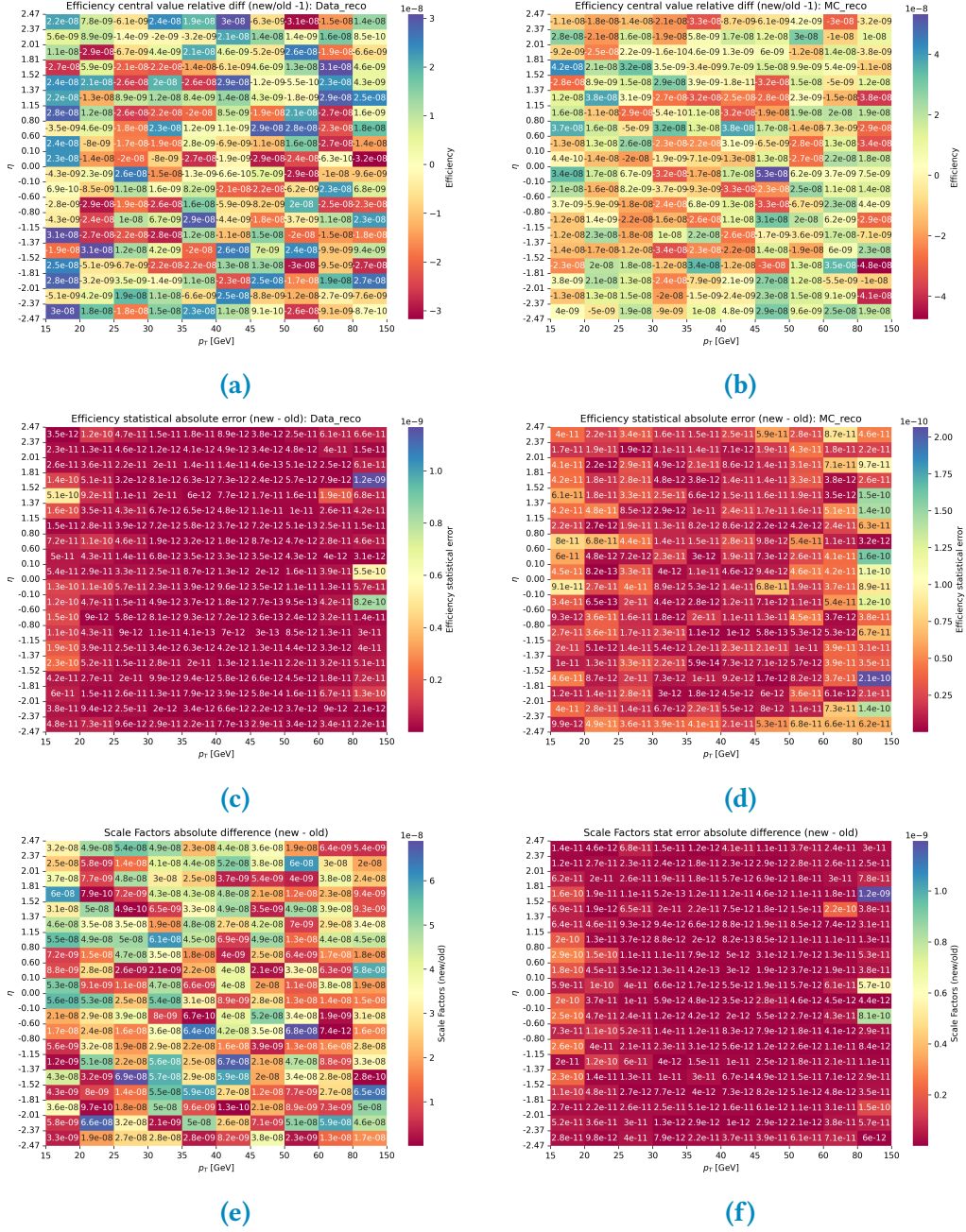


Figure 5.33: The plots a(b) show 2D map of ratio of new and old efficiencies measured in central values for data(MC). The plots c(d) represent the 2D map of absolute differences of efficiencies in statistical uncertainties for data(MC). Whereas the plots e(f) shows the absolute differences of scale factors measured in central values(statistical uncertainties) for variation 1.

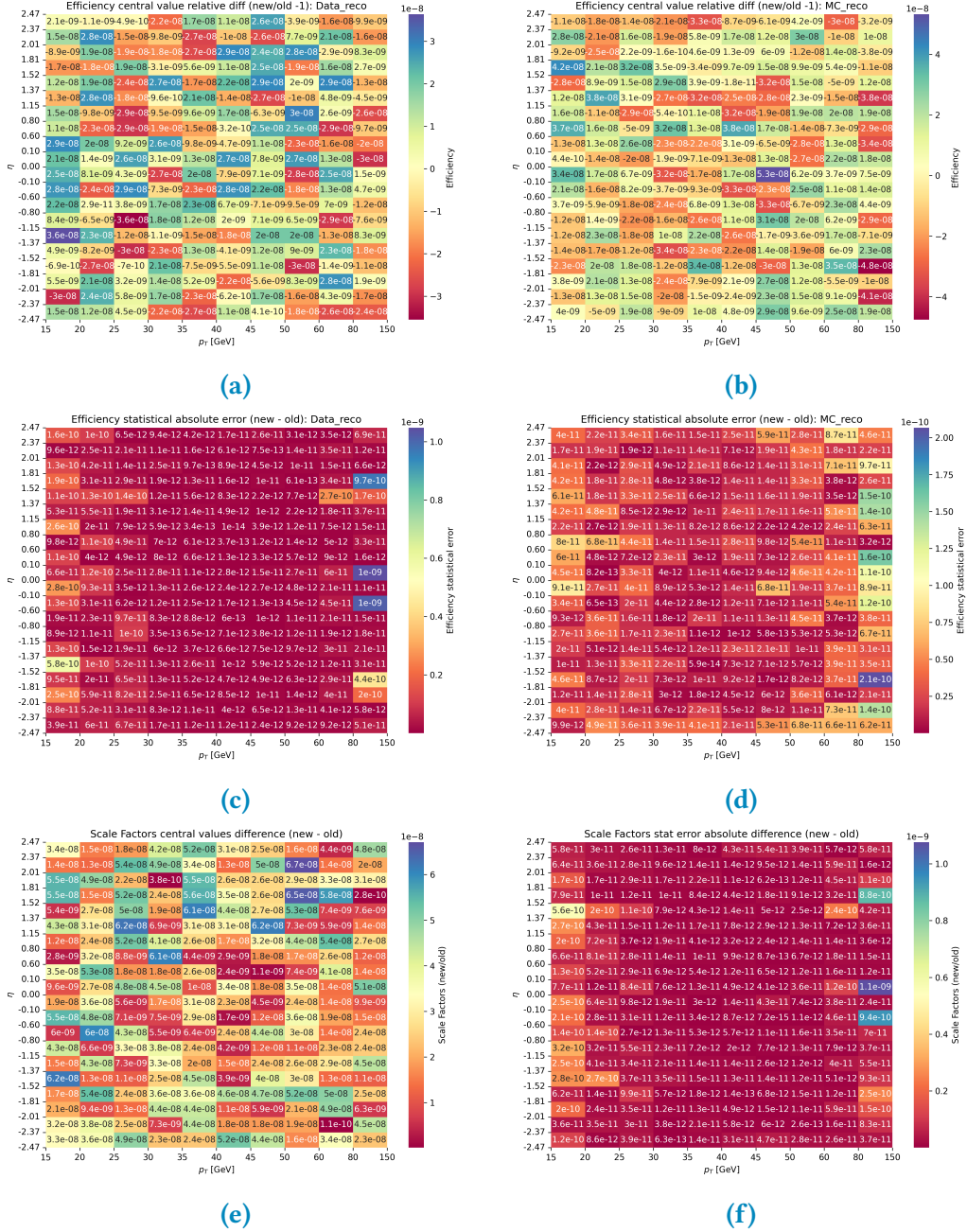


Figure 5.34: The plots a(b) show 2D maps of ratio of new and old efficiencies measured in central values for data(MC). The plots c(d) represents the 2D map of absolute differences of efficiencies in statistical uncertainties for data(MC). Whereas the plots e(f) shows the absolute differences of scale factors measured in central values(statistical uncertainties) for variation 2.

5.6.3 Average efficiencies and systematics measurement

For the measurement of systematic uncertainties in TagAndProbe framework, total of 72 variations are implemented i.e. 3 tag identification, 3 Z-mass peak windows, 2 electron background templates and 4 sidebands variations for fit of photon background are considered. The comparison of the calculated efficiencies and their uncertainties (i.e. statistical, systematics and total uncertainties) are taken into account Ref. [135]. The results of average efficiencies in central values, statistical uncertainties, systematic uncertainties and total errors are shown in Fig. 5.35 and Fig. 5.36

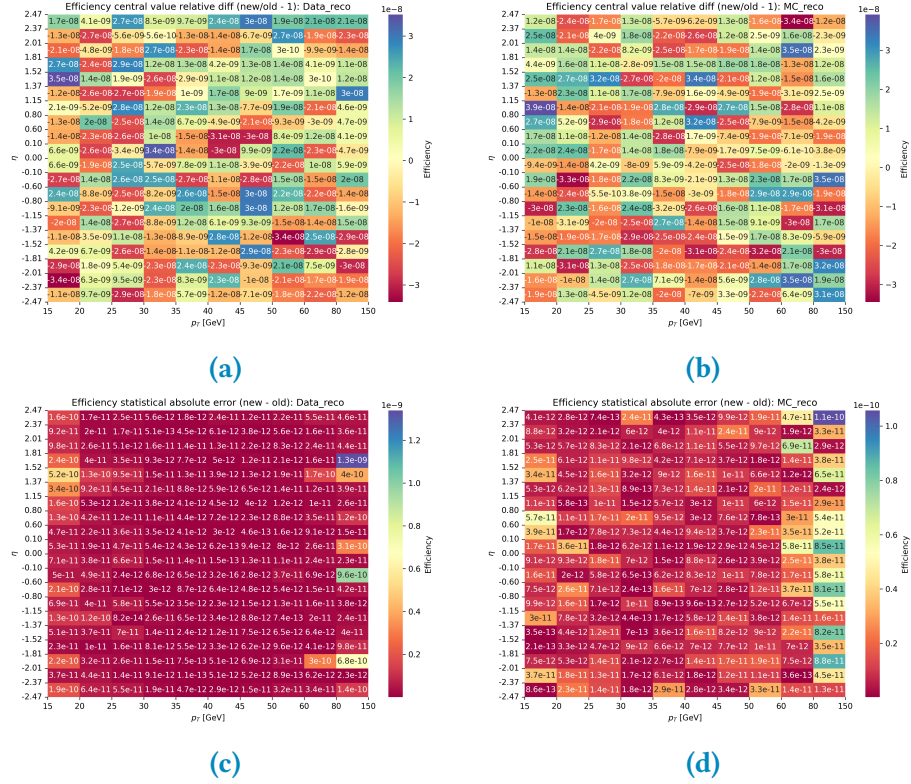


Figure 5.35: The plots a(b) present 2D map of ratio of new and old averaged efficiencies in central values for data(MC). The plots c(d) show the absolute differences of averaged efficiencies in statistical uncertainties for data(MC).

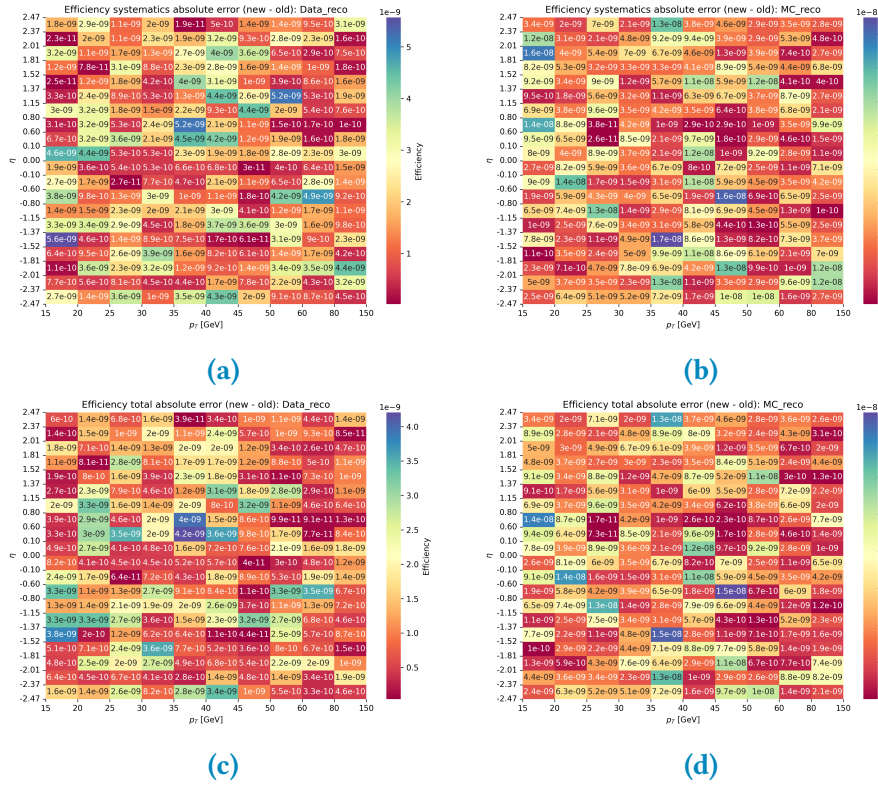


Figure 5.36: The plots a(b) represent 2D map of absolute differences in systematic uncertainties for data(MC). The plots c(d) show 2D map of absolute differences of averaged efficiencies in total errors for data(MC) in new and old framework.

5.6.4 Computation of averaged scale factors

The central value of the scale factor is obtained averaging on all the SF's systematic variations. The averaged scale factors are represented in Fig. 5.37 and Fig. 5.38.

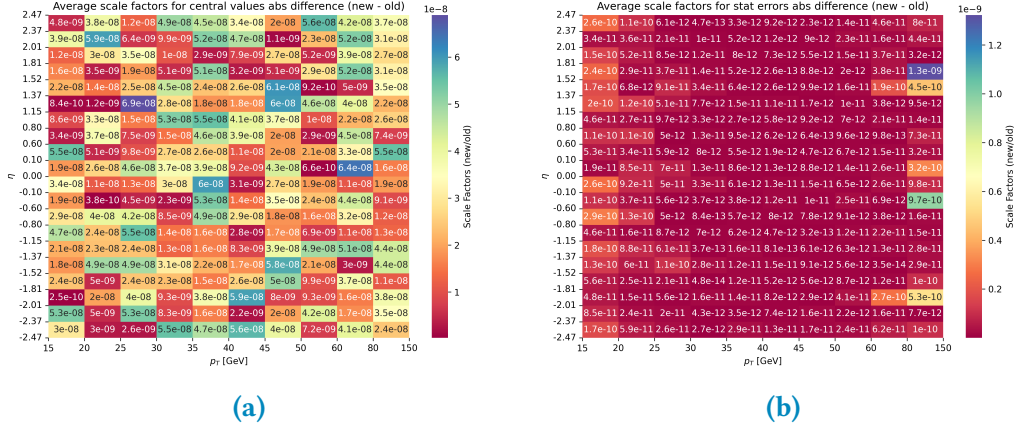


Figure 5.37: The plot (a) shows the 2D map of absolute differences of new and old averaged scale factors measured in central values. Whereas, plot (b) represents the 2D map of absolute differences of averaged scale factors measured in statistical uncertainties.

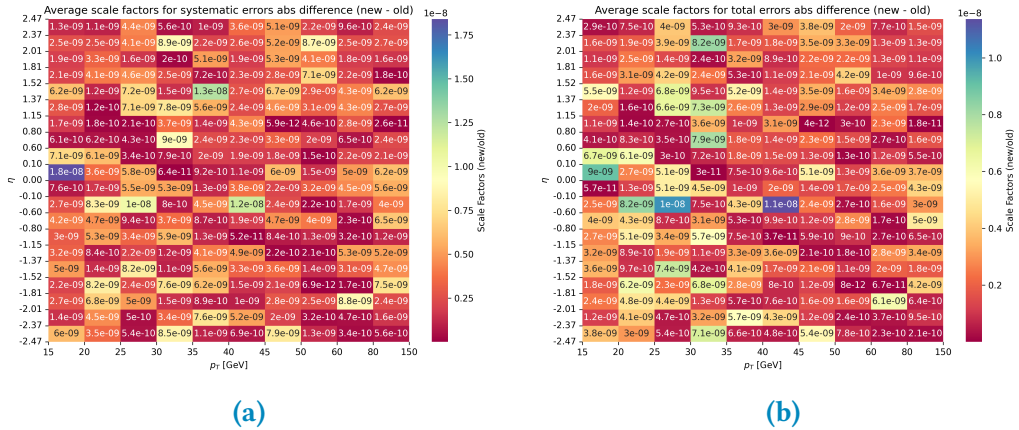


Figure 5.38: The plot (a) presents 2D map of absolute differences of averaged scale factors measured in systematic uncertainties. Whereas plot (b) shows the absolute differences of averaged scale factors measured in total errors in new and old framework.

5.7 Conclusion

The results presented in this chapter represents my own contribution towards the analysis.

The methodology of the electron reconstruction efficiency measurement is briefly explained in Section 5.2. The approximation formula being used for the statistical uncertainties in the measurements published by the ATLAS collaboration was explained explicitly in Section 5.4. In Section 5.4.1, the principle of the assessment of their accuracy through pseudo experiments was briefly explained. The studies were performed with different assumed target efficiencies, number of events available for the measurement, and level and shape of the background. This novel studies of uncertainties measurements through pseudo experiments was described in Section 5.4.2.

We conclude through this studies that, the first-order approximation is very accurate for low level of background for instance 5% or large number of events e.g. 10^4 , 10^5 , 10^6 . Even for more difficult scenarios with small available statistics or large background, the approximation remains acceptable: differences rather exceed 30%, and furthermore the approximated uncertainty is always larger than the one determined though pseudoexperiments. The usage of the approximation is therefore conservative and largely justified.

The results of electron reconstruction efficiency, scale factors measured with AF2 release 21 samples and the comparison with previous recommendations were precisely explained and shown in Sections 5.5, 5.5.1. The methodology is re-implemented in TagAndProbe framework for release 22 setup.

The comparison between measurements performed in Rel22 and Rel21 frameworks was done, by computing the efficiencies once in Rel22 setup and then comparing them with results measured in Rel21 setup. The results are shown in Section 5.6.2. All results of efficiencies and scale factors in central values, statistical, systematic & total uncertainties are validated. They match exactly with old values measured in TagAndProbeFrame framework, and fall within the numerical precision (10^{-8}) of float data type.

Chapter 6

The searches for associated production of BSM Higgs boson in the $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ and $H^{\pm} \rightarrow W^{\pm}Z$ channels

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The analysis presented here is aimed to search the signals of *Type – II* SeeSaw model [139] that extends the scalar sector of the Standard Model with a scalar triplet, directing to a phenomenology which comprehends singly and doubly charged Higgs bosons. The associated production of doubly charged $H^{\pm\pm}$ and singly charged $H^{\pm}$ bosons are investigated through the analysis.

Section 6.1 presents the topologies used for the analysis and Section 6.2 gives us the details of theoretical framework. The Monte Carlo simulations used for various selection variables are listed in Section 6.3.2. In Section 6.4.4 the signal regions used for the different mass hypotheses of $H^{\pm\pm}$ & $H^\pm$ are described in order to distinguish signatures of BSM processes from SM backgrounds. The results for associated production of charged Higgs's signal are concluded in Section 6.7 and the validation plots are given in Section 6.6.

The general introduction of chapter is compiled on the information available in following citations;

- A. Melfo et al., "Type II neutrino seesaw mechanism at the LHC: The roadmap" Cited. [139]
- P. Fileviez Perez, T. Han, G.- y. Huang, T. Li and K. Wang, "Neutrino masses and the CERN LHC: Testing the type II seesaw mechanism" Cited. [140]
- A. Arhrib, R. Benbrik et al., "Higgs potential in the type II seesaw model" Cited. [141]
- S. Kanemura, M. Kikuchi, K. Yagyu and H. Yokoya, "Bounds on the mass of doubly charged Higgs bosons in the same-sign diboson decay scenario" Cited. [142]
- T.P. Cheng and L.-F. Li, "Neutrino masses, mixings, and oscillations in $SU(2) \times U(1)$ models of electroweak interactions" Cited. [143]
- ATLAS Collaboration, "Monte Carlo Generators for the Production of a W or Z/γ^* Boson in Association with Jets at ATLAS in Run2" Cited. [144]
- ATLAS Collaboration, "Multi-Boson Simulation for 13 TeV ATLAS Analyses" Cited. [145]
- J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations" Cited. [146]
- The NNPDF collaboration., "Parton distributions for the LHC Run II" Cited. [147]
- T. Sjöstrand et al., "An Introduction to PYTHIA 8.2" Cited. [148]
- ATLAS Collaboration, "ATLAS Pythia 8 tunes to 7 TeV data" Cited. [149]
- ATLAS Collaboration, " Measurement of $W^\pm Z$ production cross sections and gauge boson polarisation in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector" Cited. [150]
- ATLAS collaboration., Aad, G., Abbott, B. et al., "Search for doubly and singly charged Higgs bosons decaying into vector bosons in multi-lepton final states with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV" Cited. [152]
- ATLAS collaboration, "Search for doubly charged scalar bosons decaying into same-sign W boson pairs with the ATLAS detector" Cited. [162]

The results presented in this chapter are my own finding.

6.1 Analysis Strategy

The significance of scalar sector of Standard Model at high energy at LHC, to have new particles and forces beyond existing SM particles along with the accurate calculations of the Higgs boson couplings is pivotal for searches of new scalars. The scarce and delicate event to quartic and triple gauge pairings of standard model is the production of three massive vector bosons in p-p collisions. The see-saw models are consequential to apprehend the non-zero mass of neutrinos and masses within electroweak scale range which are being detectable at LHC [140, 141, 142]. The seven scalar bosons i.e. $H^{\pm\pm}$, $H^\pm$, A^0 (CP odd), H^0 (CP even) and h^0 (CP even) are being considered in type-II seesaw model after the electroweak symmetry breaking. The two leptons of same charge, three or four leptons channels with a multiple charge combinations are employed to examine the possible SM extensions and phenomenology [140]. The different predictions for $H^{\pm\pm}$ masses between 200 and 600 GeV are taken into account for signal processes. The decay of $H^{\pm\pm}$ boson into a $W^\pm W^\pm$ pair and the $H^\pm$ boson into a $W^\pm Z$ pair is taken into consideration. The final states comprises four gauge-bosons which are distinguished by the charged leptons i.e. electrons or muons, missing transverse momentum and hadronic jets. The analysis operates three final states categorized in accordance with number of leptons i.e. two same sign leptons ($2l^{SS}$), three leptons (3l), and four leptons (4l). The multi-lepton topologies for the same-sign di-lepton events with missing transverse energy and multi-jets is depicted in Fig. 6.1. The topologies for Tri-lepton events with missing transverse energy and jets and Four-lepton events with missing transverse energy is given in Fig. 6.2.

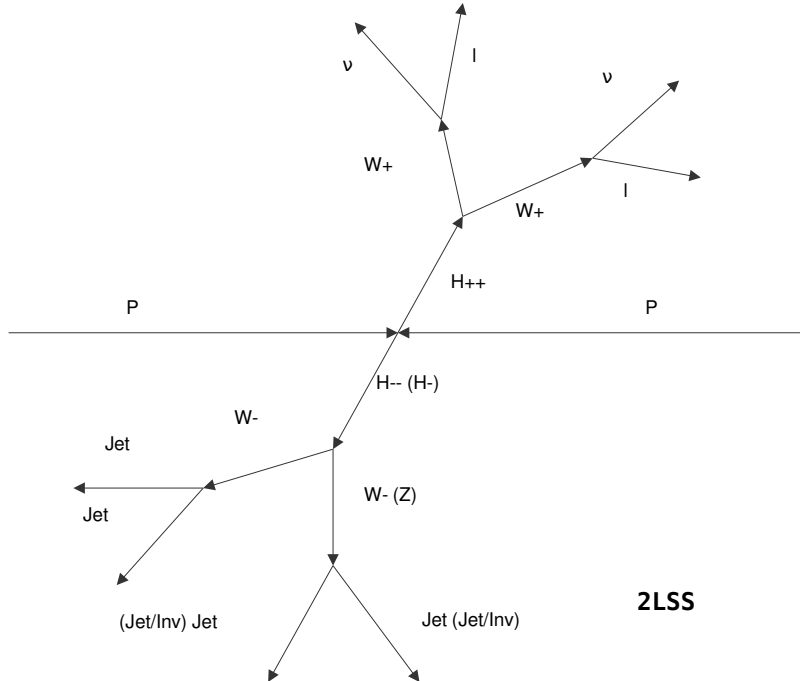


Figure 6.1: The pair production and associated production of charged higgs for same-sign di-lepton events with missing transverse energy and multi-jets.

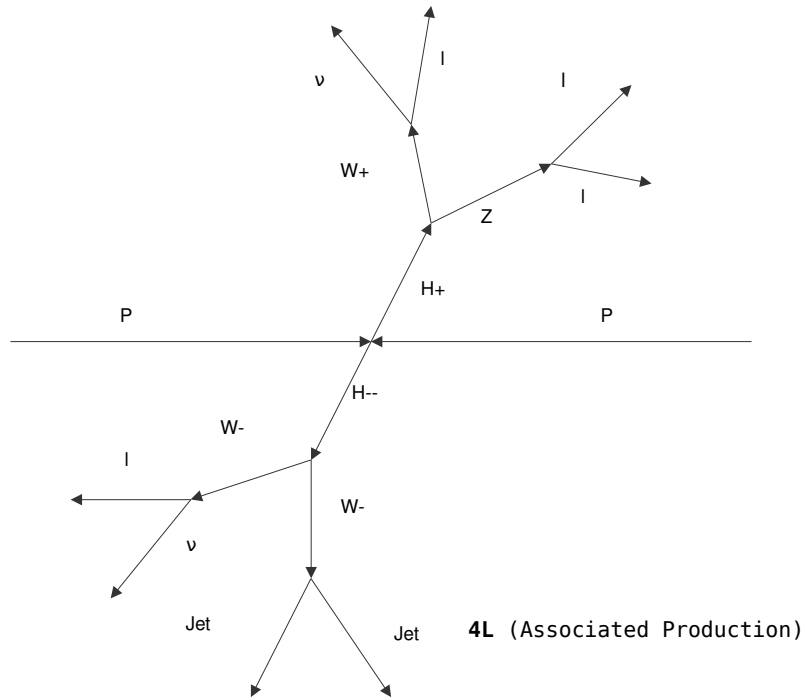
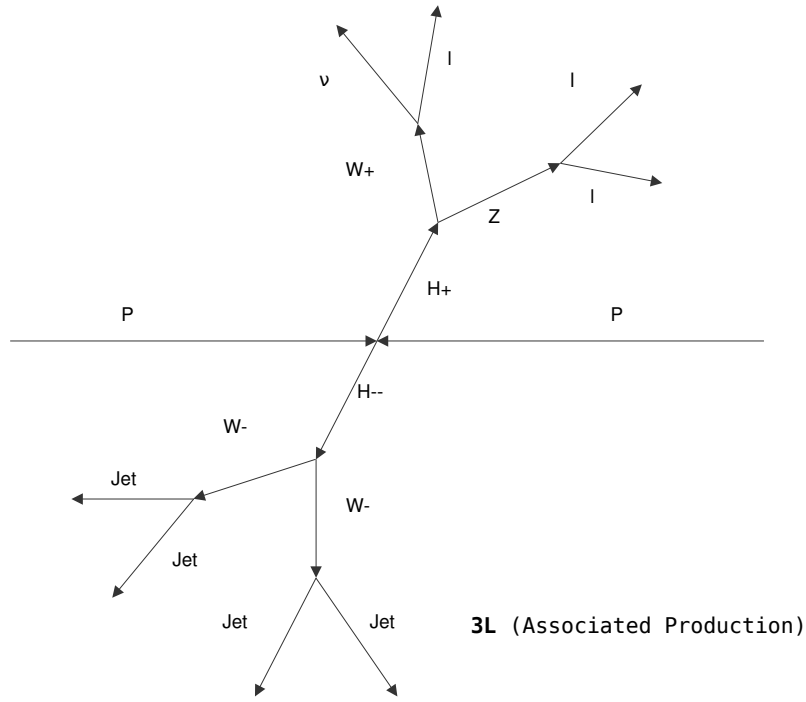


Figure 6.2: The associated production of charged Higgs ($H^{\pm\pm}$, $H^\pm$) for Tri-lepton events with missing transverse energy and multi-jets (top) whereas Four-lepton events with missing transverse energy (bottom).

6.2 Signal model

A doublet triplet model (DTM), enclosing the scalar sector of the SM expanded with a hypercharge $Y = 2$ scalar triplet Δ [140, 141, 143] is considered. The symmetry breaking of electroweak sector (EWSB) could be established at the dispense of vacuum expectation values i.e. ν_d, ν_t acquired by the neutral components of H and Δ . Through mixing these fields after EWSB, the resultant scalar bosons obtained are: $H^{\pm\pm}, H^\pm, A^0$ (CP odd), H^0 (CP even) and h^0 (CP even). The h^0 boson obtained by mixing between the CP-even scalars is recognized as SM Higgs boson. Consequently, the triplet-neutrino Yukawa term yields masses of neutrino which corresponds to the vacuum expectation value of ν_t . The curbs from the accurate electroweak measurements thus give rise to an upper limit of 2.5 GeV on ν_t . This suggests the requirement of lower bound on the ν_t values (neutrinos mass dependent) as the value is pretty less than electroweak scale.

In this analysis, only the associated production of singly ($H^\pm$) and doubly charged ($H^{\pm\pm}$) Higgs boson through diagram delineated in Fig. 6.3 is investigated. Taking into account just the bosonic decays of singly charged bosons i.e. $H^\pm \rightarrow W^\pm Z$, the branching ratio fluctuates in between 40% and 60% as shown in the Table. 6.2. The branching fractions are notably less for the specific mass point of $H^{\pm\pm}$ than the other observed mass points. This could eventually be the cause of its great dependence on the mass of the scalar triplet. Other possible decays of singly charged higgs ($H^\pm$) could be $H^\pm \rightarrow t\bar{b}$ and $H^\pm \rightarrow W^\pm h^0$ [140]. The contribution from the other possible $H^\pm$ decays is somewhat suppressed by employing the requirement of having at least two same-charge leptons or minimum three leptons with no b-jets. The different control regions are employed in the analysis to reach out the comparable results. For the associated production of singly ($H^\pm$) and doubly charged ($H^{\pm\pm}$) bosons, branching fraction multiplied cross-section is computed for on-shell W and Z bosons. That is why, mass region greater than 200 GeV is taken in account throughout.

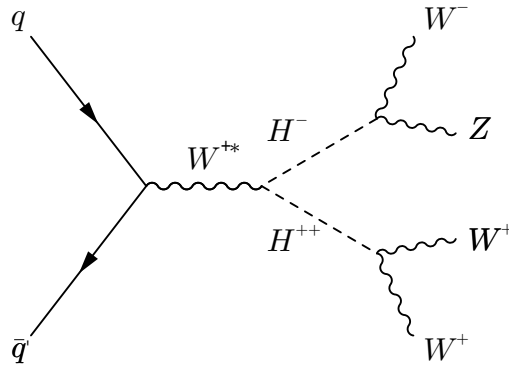


Figure 6.3: A illustration of associated production and decays $H^{\pm\pm}$ and $H^\pm$ bosons through Feynman diagrams.

6.3 Samples used for the analysis

6.3.1 Data

The data used for the analysis is recorded for luminosity 139 fb^{-1} in proton-proton collision of ATLAS detector at $\sqrt{s} = 13 \text{ TeV}$ center of mass energy from 2015 to 2018. The data sets used are given below:

- data15_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_PHYS.grp15_v01_p5631
- data16_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_PHYS.grp16_v01_p5631
- data17_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_PHYS.grp17_v01_p5631
- data18_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_PHYS.grp18_v01_p5631

6.3.2 Monte Carlo simulation

The monte carlo (MC) generators are being used for simulating signal and background events in p-p collisions. The events are generated for associated production of signal $H^{\pm\pm}H^{\pm}$ processes at partonic level with MadGraph5_aMCNLO [146] using leading order (LO) matrix elements (ME) and NNPDF3.0NNLO [147]. The events were scattered eventually using Pythia 8 [148] with combination of tuned specifications named as A14 tune [149]. The signal processes used for different mass suppositions falls between 200 and 600 GeV. The cross section for the associated production drops abruptly with the charged Higgs boson's mass as listed in Table. 6.2. By probing computations on next-to-leading (NLO), the events samples are normalized and NLO K-factor raises event production by a factor of 1.0 expectantly.

Process	Generator	PDF	Parton Shower	Tune
VH	POWHEGPYTHIA8	NNPDF30	PYTHIA8	default
VVV	SHERPA 222	NNPDF30NNLO	SHERPA	default
$V+jets$	SHERPA 2211	NNPDF30NNLO	SHERPA	default
ttZ, ttW	PYTHIA8_A14N23LO	MEN30NLO	PYTHIA8	A14
tZ	MADGRAPH	—	PYTHIA8	A14
$Wt, Ttbar$	POWHEGPYTHIA	—	PYTHIA8	A14
ttH	POWHEGPYTHIA8	NNPDF30ME	PYTHIA8	A14NNPDF23
WZ, WW, ZZ	SHERPA 221/222	NNPDF30NNLO	SHERPA	default
tWZ	PYTHIA8_aMCNLO	—	PYTHIA8	default
$TtbarWW, 3top$	MADGRAPH	—	PYTHIA8	A14NNPDF23LO
$4top$	PYTHIA8_aMCNLO	—	PYTHIA8	A14NNPDF23LO
$single\ top$	POWHEGPYTHIA	—	PYTHIA8	A14NNPDF23LO
$V+\gamma$	SHERPA 2211	NNPDF30NNLO	SHERPA	default
$Dijets$	PYTHIA8	—	PYTHIA8	A14NNPDF23LO
$Drell-Yan$	SHERPA 2211	—	SHERPA	default

Table 6.1: Overview of event generators, PDF configurations and parton showers used for simulated events of background processes. The letter V indicates an electroweak gauge boson production (W or Z/γ^*). The term 'default' advises the default parameter set by event generator.

The Table. 6.1 summarizes background simulation with MC event generators. The triboson (VVV) events and the simulated events for electroweak gauge boson in association with jets (V+jets) were produced with the *Sherpa* v2.2.1 mc generator using NNPDF30NNLO configuration. For the prompt contributions, the processes resulting in three leptons as final states are taken into consideration. The non-prompt (fake) lepton background computation is done by employing methods based on data and V+jets MC simulations. The MC simulations used for the background processes used for the analysis are depicted in Section. C.1, C.2, C.3 & C.4 in Appendix. C.

Signal MC Samples

The LHE files from release 19 are used for job options (JO's) submission in release 21 setup i.e. 21.6.98,AthGeneration. The 10k events are produced in release 21 setup using Madgraph 2.9.5. The LHE files used are listed in Table. 6.3.

$m_{H^{\pm\pm}}$ [GeV]	200	220	300	400	450	500	550	600
$m_{H^\pm}$ [GeV]	196	215	295	395	445	496	545	602
$\mathcal{B}(H^{\pm\pm} \rightarrow W^\pm W^\pm)$ [%]	100	100	100	100	100	100	100	100
$\mathcal{B}(H^\pm \rightarrow W^\pm Z)$ [%]	58.8	44.3	37.3	44.7	45.9	45.7	48.4	50.8
Cross section [fb]								
$(H^{\pm\pm} H^\pm \text{ associated production})$	88.7	44.5	9.5	3.0	1.9	1.2	0.8	0.5
Filter efficiency	0.6523	0.6543	0.6829	0.7039	0.7069	0.7178	0.7184	0.7259
DSID	450619	451889	450620	450621	451890	450622	451891	450623

Table 6.2: Details of the cross sections (NNPDF, k-factor = 1.0 for NLO correction), filter efficiencies, DSIDs of AFIII signal samples for $H^{\pm\pm}$ and $H^\pm$ associated production modes. The branching fractions ($\mathcal{B}$) of the charged Higgs bosons decaying to $W^\pm W^\pm$ or $W^\pm Z$ are also shown.

LHE files (release 19)
group.phys-gener:group.phys-gener.MadGraph5.450619.HppHp3WpZ_Hpp200_NNPDF30_13TeV.TXT.mc15_v1
group.phys-gener:group.phys-gener.MadGraph5.451889.HppHp3WpZ_Hpp220_NNPDF30_13TeV.TXT.mc15_v2
group.phys-gener:group.phys-gener.MadGraph5.450620.HppHp3WpZ_Hpp300_NNPDF30_13TeV.TXT.mc15_v1
group.phys-gener:group.phys-gener.MadGraph5.450621.HppHp3WpZ_Hpp400_NNPDF30_13TeV.TXT.mc15_v1
group.phys-gener:group.phys-gener.MadGraph5.451890.HppHp3WpZ_Hpp450_NNPDF30_13TeV.TXT.mc15_v2
group.phys-gener:group.phys-gener.MadGraph5.450622.HppHp3WpZ_Hpp500_NNPDF30_13TeV.TXT.mc15_v1
group.phys-gener:group.phys-gener.MadGraph5.451891.HppHp3WpZ_Hpp550_NNPDF30_13TeV.TXT.mc15_v2
group.phys-gener:group.phys-gener.MadGraph5.450623.HppHp3WpZ_Hpp600_NNPDF30_13TeV.TXT.mc15_v1

Table 6.3: The LHE files used for JO's in release 21 with AFIII samples in compaigns mc20a, mc20d and mc20e.

The results are produced for the variables based on reco-like and Truth particles with some object collection given in Table.6.4 and are presented in the Section. 6.7.

6.4 Event Selection

The two steps: the pre-selection and signal regions (SR's) selection are considered for the event-level selection. The definition of preselection for 2L, 3L and 4L channels is listed in Table. 6.5. Selection of events will be executed if numerical sum of charges of the leptons

Object Collection	
Initial Leptons	no p_T / η requirements applied; no ID, no ISO
Taus	no p_T / η , no ID, no ISO (no other cleaning cuts)
Baseline electrons	$p_T > 4.5$ GeV, $ \eta < 2.47$, ELooseBLLH, ED0Sigma5, EZ05mm (no isolation) b-jet aware below 100 GeV for electron - electron, electron - muon & electron - jet, and p_T dependent OR applied
Baseline muons	$p_T > 3$ GeV, $ \eta < 2.5$, MuMedium, MuZ05mm, MuQoPSignificance, MuNotCosmic (no isolation) muon - jet (p_T dependent) OR applied
Signal electrons	baseline collection + $p_T > 8$ GeV, EMediumLH ID, ElsoLoose
Signal muons	baseline collection + $p_T > 8$ GeV, MuD0Sigma3, MulsoPflowLoose_VarRad
Jets	$p_T > 20$ GeV, $ \eta < 2.8$, JVTight, LooseBadJet
b-jets	jet collection with 5 GeV cut instead of 20 GeV + $ \eta < 2.5$ and BTag85DL1r

Table 6.4: The object collection used for the variables for the signal given in Table.6.2.

is two & one or two & zero for each topology. For 2L, the lepton p_T is required to be greater than 20 GeV and either of two leptons must be tight. Likewise in 3L channel, each lepton object from the tight leptons pair must have same charge and holds $p_T > 20$ GeV. On the top of that, some additional requirements for preselection are employed on missing transverse energy (E_T^{miss}), jet multiplicity (N_{jets}) and number of b-jets (N_{b-jet}). The minimum value of E_T^{miss} required for 3L and 4L channels is 30 GeV whereas for 2L channel it has to be 70 GeV minimally. For 2L topology, veto on Z-boson invariant mass is employed to minimize the contributions from electron charge misidentification. The invariant mass for SFOS lepton pair events should diverge the Z-boson nominal mass by the numerical value of 10 GeV. An invariant mass of larger than 15 GeV is additionally required to reduce background effects from Drell-Yan processes for 3L and 4L topologies.

Selection criteria	2L	3L	4L
At least one offline tight lepton having $p_T^l \geq 20$ GeV which triggered the event			
N_l (type L)	= 2	= 3	= 4
N_l (type L*)	—	—	= 4
N_l (type T)	= 2	$\geq 2(l_{1,2})$	≥ 1
$ \sum Q_l $	= 2	= 1	$\neq 4$
Lepton p_T	$p_T^{l_1, l_2} > 30, 20$ GeV	$p_T^{l_0, l_1, l_2} > 10, 20, 20$ GeV	$p_T^{l_1, l_2, l_3, l_4} > 10$ GeV
E_T^{miss}	> 70 GeV	> 30 GeV	> 30 GeV
N_{jets}	≥ 3	≥ 2	—
N_{b-jets}	= 0		
Low SFOS m_{ll} veto	—	$m_{ll}^{OC} > 15$ GeV	
Z boson decay veto	$ m_{ee}^{SC} - m_Z > 10$ GeV	$ m_{ll}^{OC} - m_Z > 10$ GeV	

Table 6.5: The preselection criteria for 2L, 3L and 4L channels. The Loose (L), Loose & slightly isolated (L*) and Tight identification selection must be passed by the leptons. The notations l_1, l_2 indicates the two same sign leptons whilst l_0 represents the leptons with a charge opposite to the total lepton's charge. The symbol 'Q' points to the charge of each lepton [152].

6.4.1 Object definition

The analysis employs light leptons i.e. electron and muons with working points on identification algorithms and isolation which are being used as requirements on them. They are briefly described in the Chapter. 4 in Sections. 4.2.2 & 4.2.3. To characterise four leptons classifications i.e. Tight, Loose, Loose with isolation and baseline, these selections

are joined with impact parameters with respect to the primary vertex (PV), transverse and longitudinal to the beam-line. The baseline leptons are specified before overlap removal with most loose requirements. The nominated isolation WPs for electrons and muons are defined in isolation selection tool [153]. As the background contribution of electrons from the photon conversions cannot be neglected in the same-sign channel therefore requirements on the Egamma Author and DFCommonAddAmbiguity are included discussed in Ref. [154, 155]. The Author cut on Egamma is specified in all three preselection channels i.e. 2L, 3L and 4L however, the DFCommonAddAmbiguity electron cut is being applied just in 2L channel. In order to eliminate electron charge mis-ID background, the Charge mis-ID Tagger [158] is employed (Loose WP). The conditions for loose, tight and loose with iso definitions for electrons and muons are summarised in Table.6.6 & 6.7.

Lepton	Electrons			
Condition	baseline	loose	LooseWithIso	tight
p_T	$p_T^e > 10 \text{ GeV}$			$p_T^e > 20 \text{ GeV}$
Pseudo-rapidity	$ \eta_e < 2.47$ excluding crack region			
Identification WP	LHLoose	LHLooseBL	LHLooseBL	PLVTight
Isolation WP	No	No	FCLoose	PLVTight
Charged mis-ID Tagger WP	No	Loose	Loose	Loose
Egamma Author	No	Yes	Yes	Yes
Impact parameters	$ z_0 \sin\theta < 0.5\text{mm}$ and $ d_0/\sigma(d_0) < 5$			

Table 6.6: Definition of the electron selection criteria used in the analysis. The working points (WPs) recommendations are taken from Ref. [156, 157, 158].

Lepton	Muons			
Condition	baseline	loose	LooseWithIso	tight
p_T	$p_T^e > 10 \text{ GeV}$			$p_T^e > 20 \text{ GeV}$
Pseudo-rapidity	$ \eta_e < 2.5$			
Identification WP	Medium	Medium	Medium	Medium
Isolation WP	No	No	FCLoose_FixedRad	PLVTight
$ z_0 \sin\theta $	$ z_0 \sin\theta < 0.5\text{mm}$			
$ d_0/\sigma(d_0) $	< 10		< 3	

Table 6.7: Definition of the muon selection criteria used in the analysis. The working points (WPs) recommendations are taken from Ref. [159].

6.4.2 Triggers

The samples used for the analysis are being collected through the single lepton triggers (unprescaled) designated in the Table. 6.8.

2015	2016	2017-2018
HLT_2e12_lhloose_L12EM10VH	HLT_2e17_lhvloose_nod0	HLT_2e24_lhvloose_nod0
HLT_mu18_mu8noL1	HLT_mu22_mu8noL1	HLT_mu22_mu8noL1
HLT_e17_lhloose_mu14	HLT_e17_lhloose_nod0_mu14	HLT_e17_lhloose_nod0_mu14

Table 6.8: Overview of the triggers used for the analysis.

All the samples including selections entail requirement of the single lepton triggers i.e. at least one of the leptons to be matched the triggers requirement along with the cut on transverse momentum ($p_T > 30$ GeV) to confirm a high trigger efficiency. The tight leptons as given in Table.6.6 & 6.7 are employed for the trigger matching such that *loose leptons bias* arising from the triggers with *ivarloose* / *ivarmedium* isolation working point can be rejected.

6.4.3 Event cleaning and selection

- **Jet Cleaning:** The events with a *Loose* set of cleaning selections as recommended by the $\text{Jet-}E_T^{\text{miss}}$ [160] are necessitate and executed in the DF `eventClean` flags. In case of `eventClean` flag is equal to 0, the event is discarded.
- **Primary Vertex:** The events are needed to execute a primary vertex requirement i.e. at least one of the reconstructed vertices should be categorised as `xAOD :: VxType :: PriVtx`.
- **Bad Muon Veto:** The events comprising minimum one pre-selected muon fulfilling $\sigma(q/p)/|q/p| > 0.2$ are to be terminated prior the overlap removal. This also includes the muons which are labeled as *Bad Muons* comply with recommendations from the Muon CP group [161].
- **Muons reconstructed as Jets:** The PFlow algorithm is executed on the full muon container since they are considered as pions and need to be subtracted from calorimeter and hence from particle flow jets. These fake jets mimic themselves as muons which overlap with the reconstructed muon. The overlap removal tool thus employs `orFlags.doMuPFJetOR = true` flag as in Ref. [160].
- **Two same-sign, 2LSS:** The events of two leptons with the same electric charge must be required for this classification. The two tight leptons must create same-sign pair depending on the flavor and three channel are thus categorised as: ee , $\mu\mu$, $e\mu$.
- **Three leptons, 3L:** The events with the three leptons with a total charge of ± 1 are selected. A veto is applied on the events for which at least one same-flavor-opposite-sign (SFOS) lepton pair must hold an invariant mass of 10 GeV around Z boson mass window.
- **Four leptons, 4L:** The events with the four leptons with a total charge of ± 2 are requested. A veto is applied on the events which comprise at least one same-flavor-opposite-sign (SFOS) lepton pair with an invariant mass of 10 GeV around Z boson mass window ($M_Z = 91.2$ GeV). The cut on the 4L mass i.e. $M_{4L} > 100$ GeV is then executed.

6.4.4 Definition of Signal Regions

The signal regions are defined using following variables:

- The definite invariant masses of all leptons involved in 2L, 3L, 4L channels are recognized by the variable " m_{xl} " where 'x' corresponds to l_2, l_3, l_4 .
- The variable referring the invariant mass of all involved jets in the process is designated as m_{jets} . The leading jets will only be considered in the case of having > 4 jets involved in process i.e. 2L channel.
- The 2L and 3L channels employ the distance of $\eta - \phi$ between two same-sign leptons to refer $\Delta R_{l^\pm l^\pm}$ variable. The two variables $\Delta R_{l^\pm l^\pm}^{max}$, $\Delta R_{l^\pm l^\pm}^{min}$ are separately computed in 4L channels for the sake of signal region.
- The transverse momentum of leading jet (highest- p_T jet) referring $p_T^{leadjet}$ variable is used to characterize signal regions in 3L channel.
- The transverse momentum of leading lepton (highest- p_T lepton) referring $p_T^{leadlepton}$ variable is used to characterize signal regions in 4L channel.
- The azimuthal interval between the system of two leptons and E_T^{miss} delineated as $\Delta\phi_{ll, E_T^{miss}}$. The variable is designated to define signal region in 2L channel.
- The minimal interval of $\eta - \phi$ between opposite-sign lepton and nearest jet which is probably leading jet refers to $\Delta R_{l^\pm - lead-jet}$. This variable is considered to define SR's in 3L channel.
- In order to distinguish a variable named as 'S' in 2L channel which exploits the intervals between azimuths of leptons, E_T^{miss} and jets. This is characterized as root mean square (R.M.S) of ϕ 's of leptons and E_T^{miss} multiplied by ϕ 's of jets divided by R.M.S of the ϕ 's of leptons, E_T^{miss} together with that of jets. It reads as:

$$S = \frac{\mathcal{R}(\phi_{l_1}, \phi_{l_2}, \phi_{E_T^{miss}}) \times \mathcal{R}(\phi_{j_1}, \phi_{j_2}, \dots)}{\mathcal{R}(\phi_{l_1}, \phi_{l_2}, \phi_{E_T^{miss}}, \phi_{j_1}, \phi_{j_2}, \dots)} \quad (6.1)$$

where $\mathcal{R}$ is identified as root mean square which estimates the spread, $\mathcal{R}(\phi_1, \dots, \phi_n) = \sqrt{\frac{1}{n} \sum_{i=1}^n (\phi_i - \bar{\phi})^2}$

The SR's are designated in Table. 6.9 and characterized for each topology. All these variables are able to distinguish between signal and backgrounds. The SR's were formulated by using mass hypotheses $m_{H^{\pm\pm}} = 200, 300, 400, 500$ GeV for $H^\pm$ associated production mode. Considering the fact discriminating strength for signal doesn't fluctuate notably in this procedure, additional mass suppositions are also taken in account while defining signal regions. The mass suppositions $m_{H^{\pm\pm}} = 200, 300, 400, 500$ GeV are distinctively employed to specify the signal regions for $m_{H^{\pm\pm}} = 220, 450, 550$ GeV in associated production mode of $H^\pm$ and $H^{\pm\pm}$.

Charged Higgs boson masses	$m_{H^{\pm\pm}} = 200$	$m_{H^{\pm\pm}} = 300$	$m_{H^{\pm\pm}} = 400$	$m_{H^{\pm\pm}} = 500$
Selection criteria	2L			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
$\Delta R_{l^\pm l^\pm}$	< 1.9	< 2.1	< 2.2	< 2.4
$\Delta\phi_{ll, E_T^{miss}}$	< 0.7	< 0.9	< 1.0	< 1.0
m_{xl} [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
E_T^{miss} [GeV]	> 100	> 130	> 170	> 200
Selection criteria	3L			
$\Delta R_{l^\pm l^\pm}$	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$\Delta R_{l^\pm - lead-jet}$	[0.1, 1.5]	[0.1, 2.0]	[0.1, 2.3]	[0.5, 2.3]
E_T^{miss} [GeV]	> 30	> 55	> 80	> 90
$p_T^{leadjet}$ [GeV]	> 40	> 70	> 100	> 95
Selection criteria	4L			
$\Delta R_{l^\pm l^\pm}^{max}$	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]
$\Delta R_{l^\pm l^\pm}^{min}$	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
E_T^{miss} [GeV]	> 60	> 60	> 60	> 60
$p_T^{leadlepton}$ [GeV]	> 65	> 80	> 110	> 130

Table 6.9: A detail of signal features developed on the basis of various mass suppositions of $H^\pm$ and $H^{\pm\pm}$. The criteria is set together with preselection designated in Table. 6.5. The SR's for $m_{H^{\pm\pm}} = 220, 450, 550$ GeV were also used for $m_{H^{\pm\pm}} = 220, 450, 550$ GeV in associated production of $H^\pm$ and $H^{\pm\pm}$. The variables are delineated already in Section. 6.4.4 and in Ref. [152].

6.4.5 The WZ control and validation region

WZ	Three tight leptons, p_T at least 20 GeV At least one pair of same-flavour opposite-sign leptons with $ M_{ll} - MZ < 10$ GeV B-jet Veto(DL1 r_7 0) and E_T^{miss} at least 30 GeV $M_{lll} > 100$ GeV
----	--

Table 6.10: Selections for WZ validation region.

WZ	At least one pair of same-flavour opposite-sign leptons with $ M_{ll} - MZ < 10$ GeV (Z-selection) B-jet Veto(DL1 r_7 0) and E_T^{miss} and $N_{jets} \geq 2$
----	---

Table 6.11: Definition of the WZ (≥ 2 jets) control region used to obtain WZ normalisation factor.

The results for the background estimation in the WZ control region including selection from Table. 6.11 are given in Section. A.1 and for the WZ validation region including selection from Table. 6.10 are demonstrated in Section. A.2.

6.5 Background estimation

The source of backgrounds are normally grouped into two main types i.e. (1) SM backgrounds or prompt lepton (2) non-prompt leptons. The first classification contains SM background events based on reconstructed leptons which are coming from W and Z bosons decays termed as prompt candidates. The second classification depends on the non-prompt leptons which corresponds to the contributions of heavy flavor decays i.e. b-hadron or c-hadrons decays and fake electrons¹. This category might involve the contribution of backgrounds from the photons which are radiated from the hadronic decays and give signature for electrons. The candidates reconstructed from these sources hold isolation characteristics which implies to have comparatively significant impact parameters with the respect to the primary vertex but they might not able to meet identification criteria for leptons as given in Section. 4.2.2.

The contributions of the backgrounds from SM processes considered in this thesis are listed in Table.6.1 and are computed with the MC simulations, besides the background from the WZ production mode because the normalisation is evaluated using data events in the control region (CR). To estimate the contributions for background from non-prompt leptons or electron charge-flip, the data driven methods are being employed. The $V\gamma$ mode might add to the background contribution minimally only if the photons get transformed into a pair of an electron-positron. The WW production mode however contributes to backgrounds with condition on the electric charge i.e. background in the case of two same sign W boson must be computed through the simulations and it is estimated from data in other way around. The contribution is coming through the non-prompt or electron charge-flip in the second-mentioned scenario.

6.5.1 Background from WZ

In multiple analyses in the ATLAS Collaboration, it is being noticed that WZ processes are not fashioned properly inside regions having jets ≥ 2 . The role of reweighting based on jet multiplicity thus becomes vital for such analyses. To measure the correct normalization factor in each bin, a measurement is performed to reweight the WZ processes. A scale factor is calculated in each jet multiplicity bin using relation [150]:

$$K_{WZ}^{REW} = \frac{f_{data} - f_{MC-WZ}}{f_{WZ}} \quad (6.2)$$

where f_{data} represents the events observed, f_{MC-WZ} indicates output with events from all MC processes excluding WZ events, and f_{WZ} points the events coming from WZ process. This computation is done in the defined WZ control region². The jet multiplicity distribution in this WZ CR region is depicted in Fig. 6.4a after reweighting factor applied. The distribution with 3l preselection region with reweighting is also illustrated in Fig. 6.4b. A good agreement between data and background estimates from different processes can be seen.

¹The candidates that mimic real electron signatures

²At least one pair of same-flavour opposite-sign leptons with $|M_{ll} - M_Z| < 10$ GeV (Zmass Window selection), B-jet Veto, $N_{jets} \geq 2$ and $p_T \geq 25$ GeV

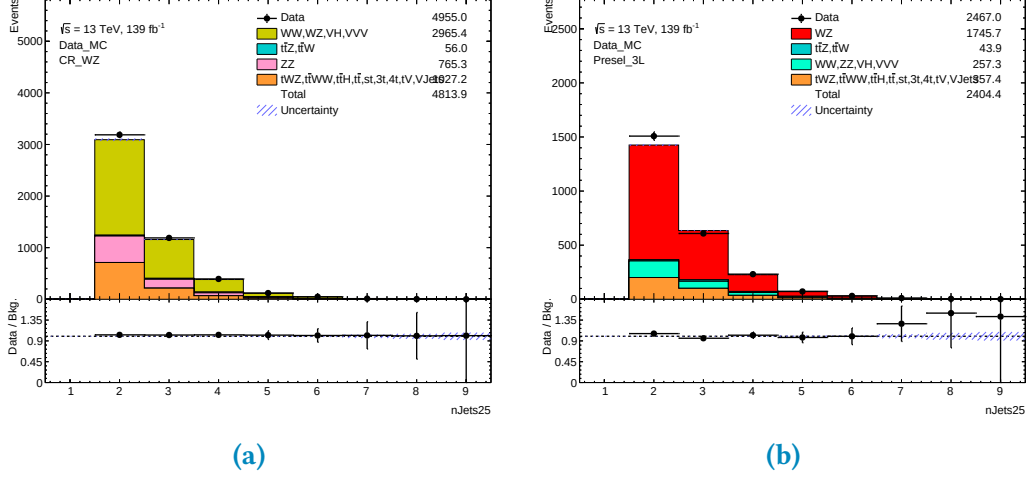


Figure 6.4: The plot (a) represents the distribution of jet multiplicity in the WZ control region with normalization factor applied in each bin whereas plot (b) shows the same distribution for jet multiplicity in 3L preselection region with the normalization factor applied. The comparison is shown between data (dots) and expected contributions for backgrounds from SM processes and reducible background. The total uncertainty includes statistical component.

6.5.2 Background from other sources

The contribution from the fake leptons in SR's varies for each topology i.e. 2L, 3L and 4L and various methods are being considered for that. In the 2L and 3L case, this kind of background is estimated by employing fake-factor method [162], whereas in 4L case it is computed by using data and MC simulations. For computing fake factor in 2L pre-selection channel, the control region is specified by utilising selection kinematics for pre-selection or the signal regions are parameterised by using selection cuts on leptons. For 3L channel, the similar technique is employed with a condition that opposite charge leptons (l_0) must pass loose criterion and it is to be presumed as a prompt candidates. For 4L pre-selection channel, the non-prompt contributions are computed by taking scale factors in the control region i.e. abundant with non-prompt candidates which are rectified with the help of simulations and small events from data. The principal origin of these leptons are coming from hadrons i.e b-hadron and c-hadron including small contribution from light flavor hadrons. The contribution from fake leptons is not taken into consideration for the results given in this chapter.

6.6 Background validation

Same sign di-lepton channel

The di-lepton events are categorised into three channels as per flavours of the two leptons i.e. ee , $\mu\mu$ & $e\mu$. The event selection designated in Table. 6.5 is described as the event pre-selection. The leading lepton is needed to have $p_T > 30 \text{ GeV}$ such that the triggers are to be employed at the plateau region of the efficiency curves. In order to reject the charge flip background, a cut on the invariant mass between the electron pair

(excluding $\mu\mu$ & $e\mu$ channels) is considered.

The background contributions in the 2L channel at pre-selection stage is largely coming from $t\bar{t}$, W +Jets, $V\gamma$ (fake/non-prompt source of leptons) WZ , $W^\pm W^\pm$ and $t\bar{t}+V$ (prompt source of leptons) with V referring to W and Z vector bosons. The contributions from WZ , ZZ , $W^\pm W^\pm$ etc. are included from the MC simulations. The modeling of two substantial backgrounds i.e. WZ and $t\bar{t}$ is verified through the control regions as described in Section. 6.4.5.

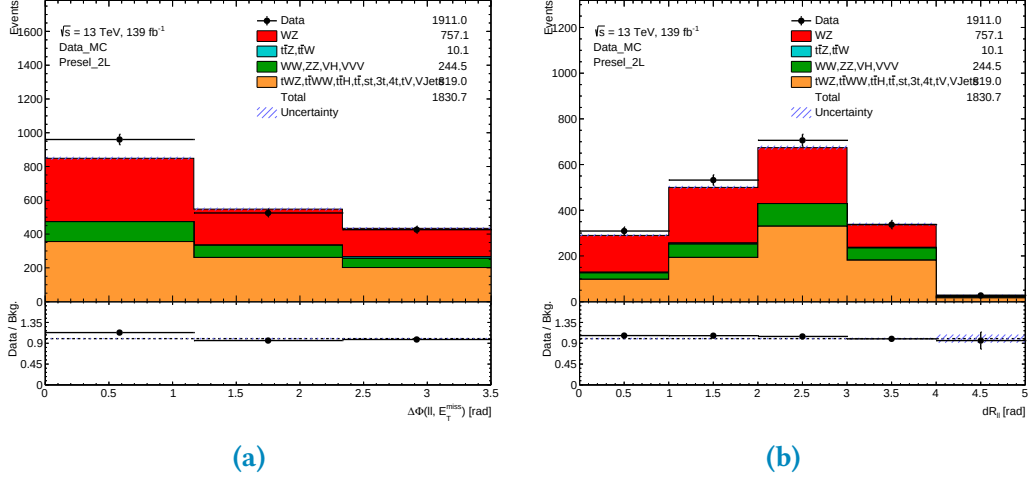
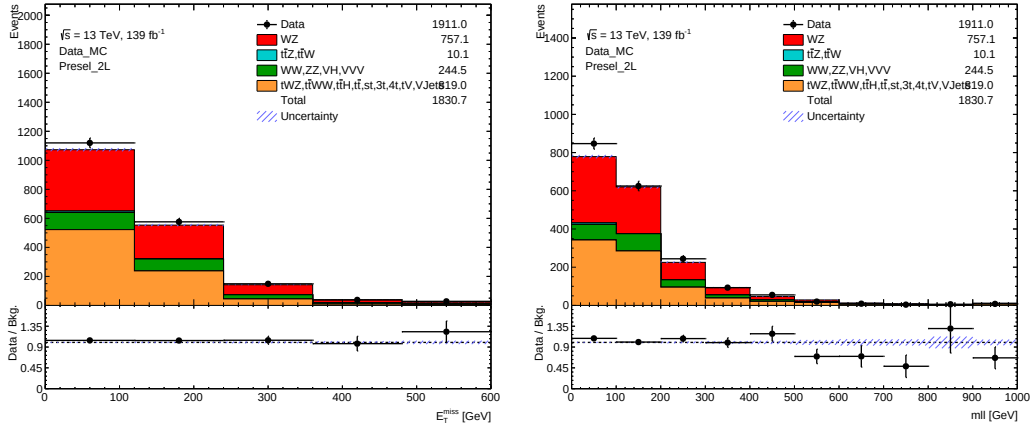


Figure 6.5: The angular-related discriminating distributions defining SR for 2L channel are shown at the preselection defined in Table. 6.5. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.



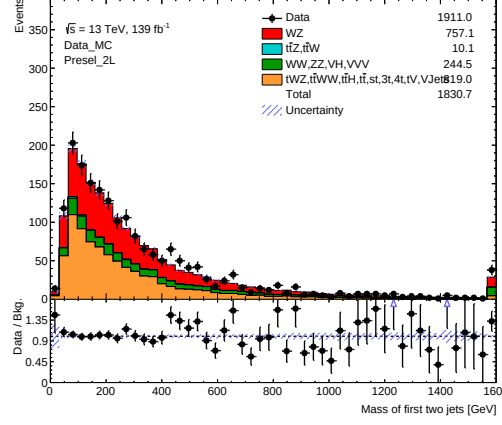


Figure 6.7: The mass-related discriminating variables defining SR for 2L channel are shown at the pre-selection defined in Table. 6.5. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.

The validation of the backgrounds estimates relying on methods based on collision data is conducted by comparing data outputs with extrapolation of backgrounds, together with MC estimates for SM processes including prompt leptons. The distributions for the variables describing signal features for 2L pre-selection channel are delineated in Figs. 6.5 & 6.7. Overall, a good rapport is observed between data and MC background extrapolations from SM processes which favours to precised estimates for background contributions in the shapes. The variables are obtained for 2L channel which hold all the pre-selection criteria as explained in Table. 6.5.

Tri-lepton (3L) channel

The event pre-selection for 3L channel is encapsulated in Table. 6.5 and depends on the following steps:

- Tri-lepton selection: three loose leptons possessing total charge (i.e. sum of the three leptons) of ± 1 are required in each event. The lepton must pass the trigger matching selection i.e. it must comprises $p_T > 30$ GeV and should pass the tight requirements from the Tables. 6.6 & 6.7. Two of out of the three leptons creating SS pair have to match the tight lepton definition as these leptons possibly are fake or non-prompt. The rest one must satisfies the loose lepton selection.
- The notations l_1, l_2 indicates the two same sign leptons whilst l_0 represents the leptons with a charge opposite to the total lepton's charge. Where lepton (l_2) should be closer to lepton (l_0) i.e. $\Delta R(l_0, l_2) < \Delta R(l_0, l_1)$.
- The possible final states or sub-channels are **SFOS0** and **SFOS12**. The **SFOS0** channel comprises zero same-flavor-opposite-sign lepton pairs i.e. $e^\mp \mu^\pm \mu^\pm, \mu^\mp e^\pm e^\pm$. While the **SFOS12** contains 1 or 2 same-flavor-opposite-sign lepton pairs i.e. $e^\mp e^\pm \mu^\pm, \mu^\mp \mu^\pm e^\pm, e^\mp e^\pm e^\pm$ & $\mu^\mp \mu^\pm \mu^\pm$.

- A veto is requested, entailing events with all SFOS lepton pairs outside the Z mass window which is $|m_{ee}^{SC} - m_Z| > 10$ GeV.
- The low mass Drell-Yann processes are discarded by having events with all SFOS lepton pairs that satisfy $m_{ll}^{OC} > 15$ GeV.
- The events with notable missing transverse energy $E_T^{miss} > 30$ GeV are chosen as demonstrated in the Fig. 6.8d & 6.9d.

The distributions for the variables describing signal features for 3L pre-selection with categorised sub channels are delineated in Figs. 6.8 and 6.9.

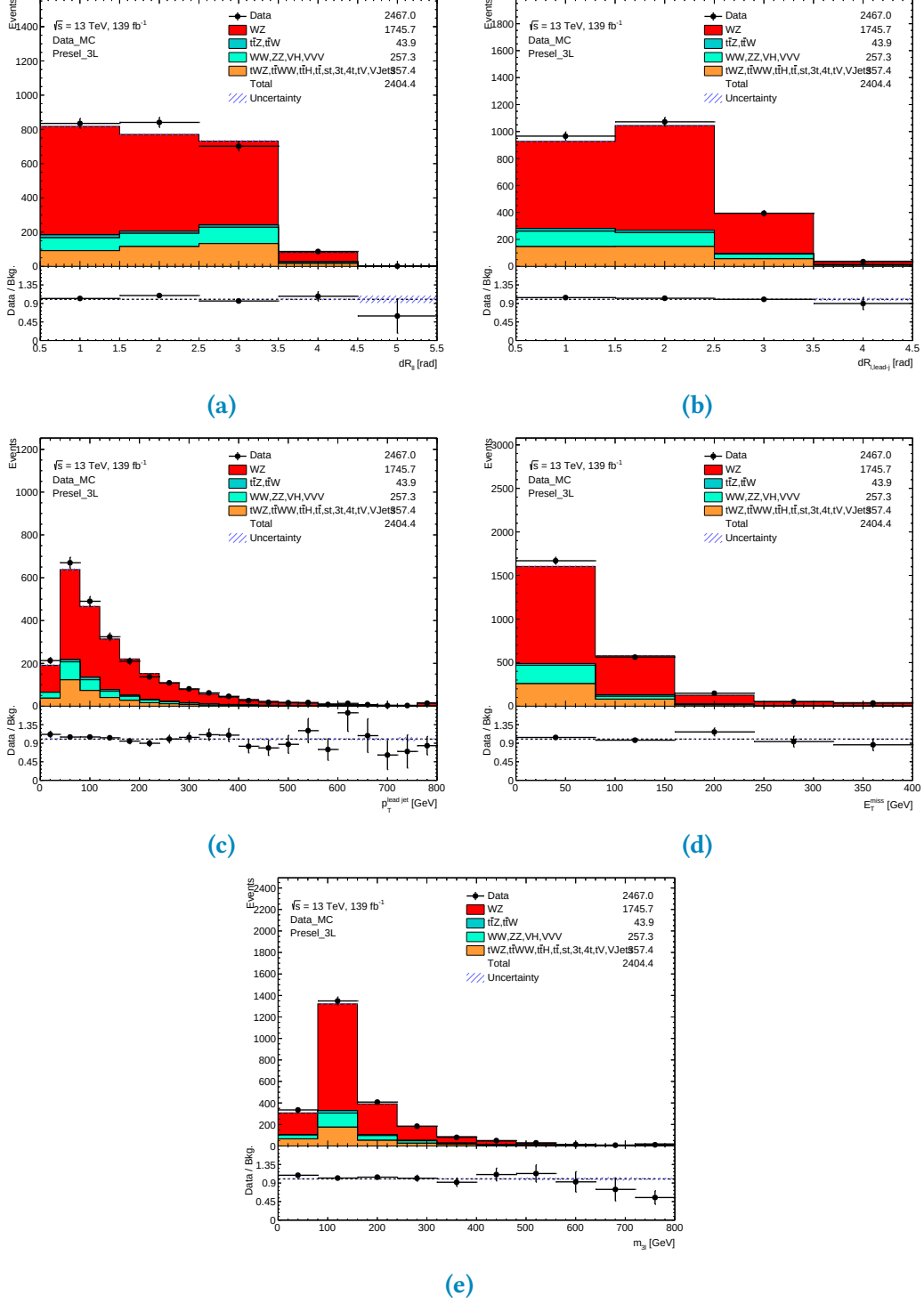


Figure 6.8: The plots describing selected variables employed to characterize the SR's for 3L SFOS0 channel are shown at the preselection defined in Table. 6.5. The variables shown from left top are the ΔR between same-sign leptons, ΔR between lepton-jet, p_T of the leading jet, E_T^{miss} and tri-lepton mass. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.

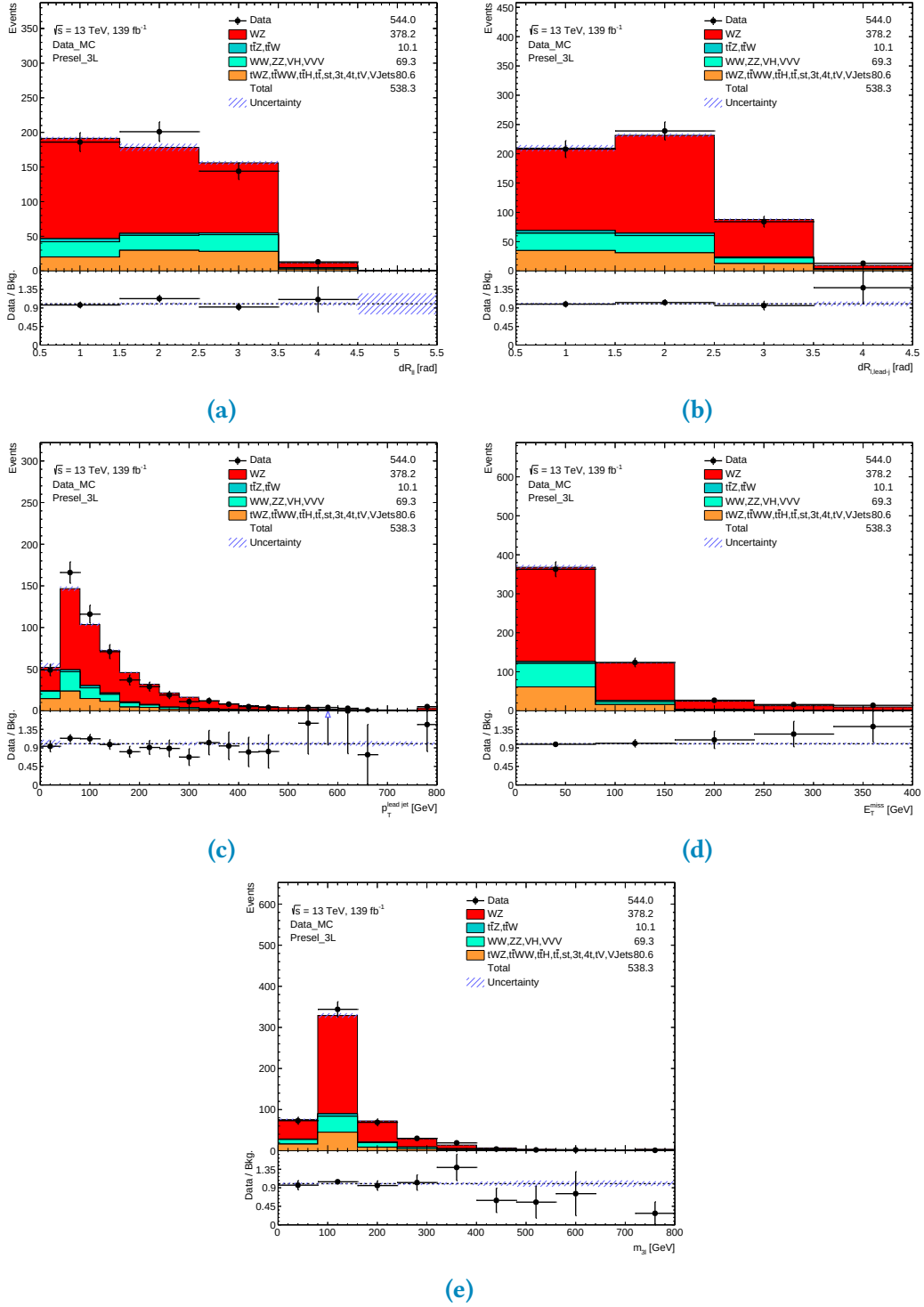


Figure 6.9: The plots describing selected variables employed to characterize the SR's for 3L SFOS12 channel are shown at the preselection defined in Table. 6.5. The variables shown from left top are the ΔR between same-sign leptons, ΔR between lepton-jet, p_T of the leading jet, E_T^{miss} and tri-lepton mass. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.

Four-lepton (4L) channel

In the four leptons channel, the background contribution is lower than in the three leptons expectantly. The SM contributions are envisaged to be dominated by the ZZ production and each Z boson get decayed into di-leptons at the same time. The smaller contributions are from the rare processes for example ttZ , ttH , four tops, etc. but those processes give rise to several hadronic jets in the event. Just like the 2L, 3L the analysis in the 4L channel executed in the various steps:

- To select the events with four leptons (electrons and muons) a pre-selection criterion is to be defined. The leptons are designated in the descending order of their p_T e.g. the index 1 refers to the lepton with highest p_T and index 4 indicates the lepton with the lowest p_T .
- The total electric charge for the four leptons must be equal to 0 or ± 2 and have to pass the looseWithIso lepton requirements as given in the Tables. 6.6 & 6.7.
- To minimise the Z +jets backgrounds, a veto is applied on the events containing at least one SFOS lepton pair around the Z mass ($M_Z = 91.2\text{GeV}$) with an invariant mass within 10 GeV window i.e. $|m_{ee}^{SC} - m_Z| > 10\text{ GeV}$.
- The low mass Drell-Yann processes are discarded by having events with all SFOS lepton pairs that satisfy $m_{ll}^{OC} > 15\text{ GeV}$.
- To diminish inclusive Z +jets production further, the $E_T^{miss} > 30\text{ GeV}$ is required.
- The final cut on the 4L mass is executed i.e. $M_{4l} > 100\text{ GeV}$ to minimise even more background.

After the pre-selection, the main prompt background remains ZZ followed by the ttV and ttH processes. The distributions for the variables describing signal features for 4L pre selection channel are delineated in Figs. 6.10.

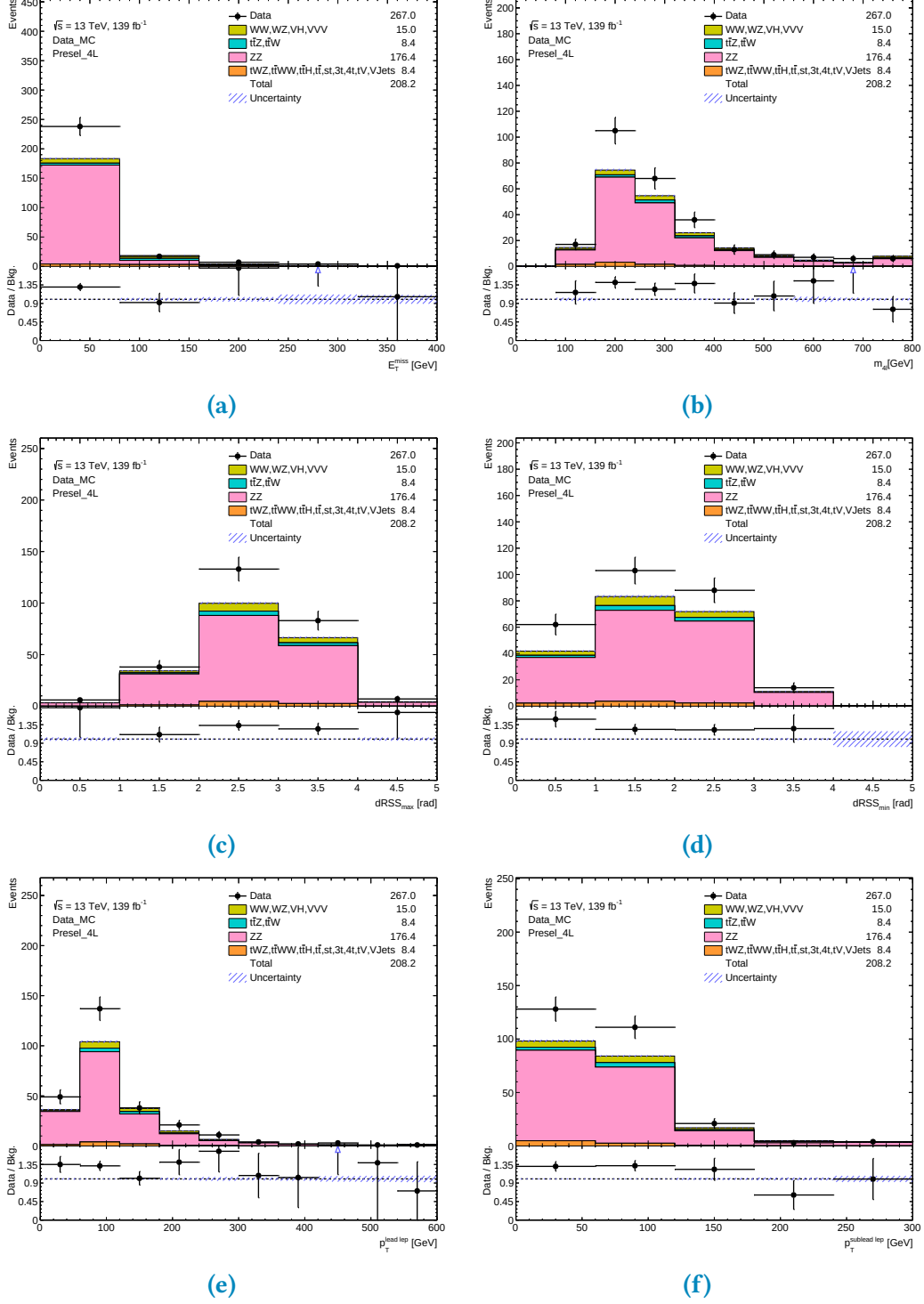


Figure 6.10: The plots describing selected variables employed to characterize the SR's for 4L channel are shown at the preselection defined in Table. 6.5. The variables shown from left top are the E_T^{miss} , four-lepton mass, ΔR_{max} between same-sign leptons, ΔR_{min} between same-sign leptons, p_T of the leading lepton and p_T of the sub-leading lepton. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.

6.7 Charged Higgs Signal

The different variables for the reco-like and truth particle collection are shown in the Figs. 6.11, 6.12, 6.14 & 6.15. The variables are obtained after applying the object selection on them as given in Table.6.4. Each variable represents five different curves for each signal or mass point for singly ($H^\pm$) and doubly charged ($H^{\pm\pm}$) Higgs boson. The corresponding signal mass points 200, 300, 400, 500 & 600 GeV for associated production of charged higgs in all three channel are shown inclusively and the explanations of the results are given in the conclusions of this chapter.

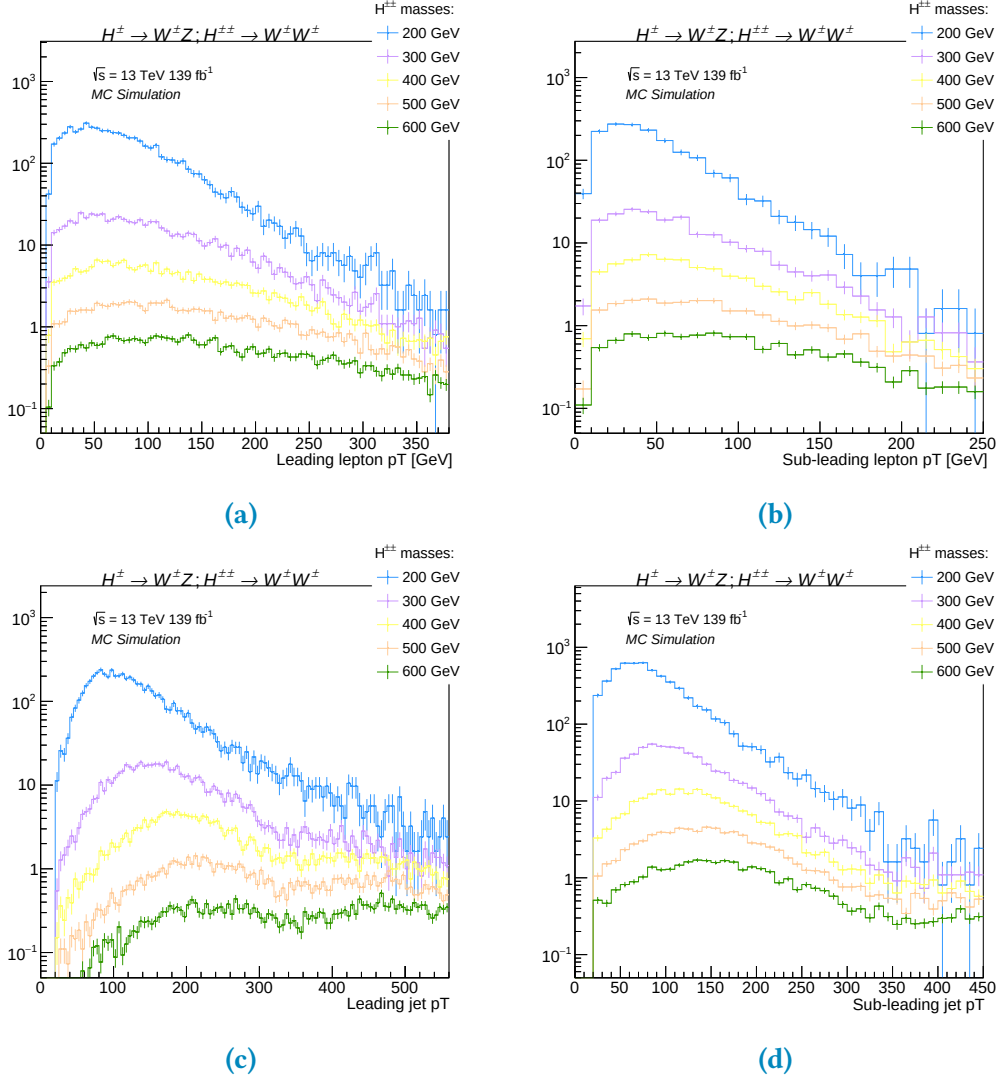


Figure 6.11: The plot (a) demonstrates the transverse momentum of leading lepton while plot (b) represents the transverse momentum of sub-leading lepton in all three channels. The plot (c) shows transverse momentum of leading jet whereas plot (d) depicts the transverse momentum of sub-leading jet for signal mass points (200, 300, 400, 500 & 600 GeV) for associated production of charged higgs in all three channels.

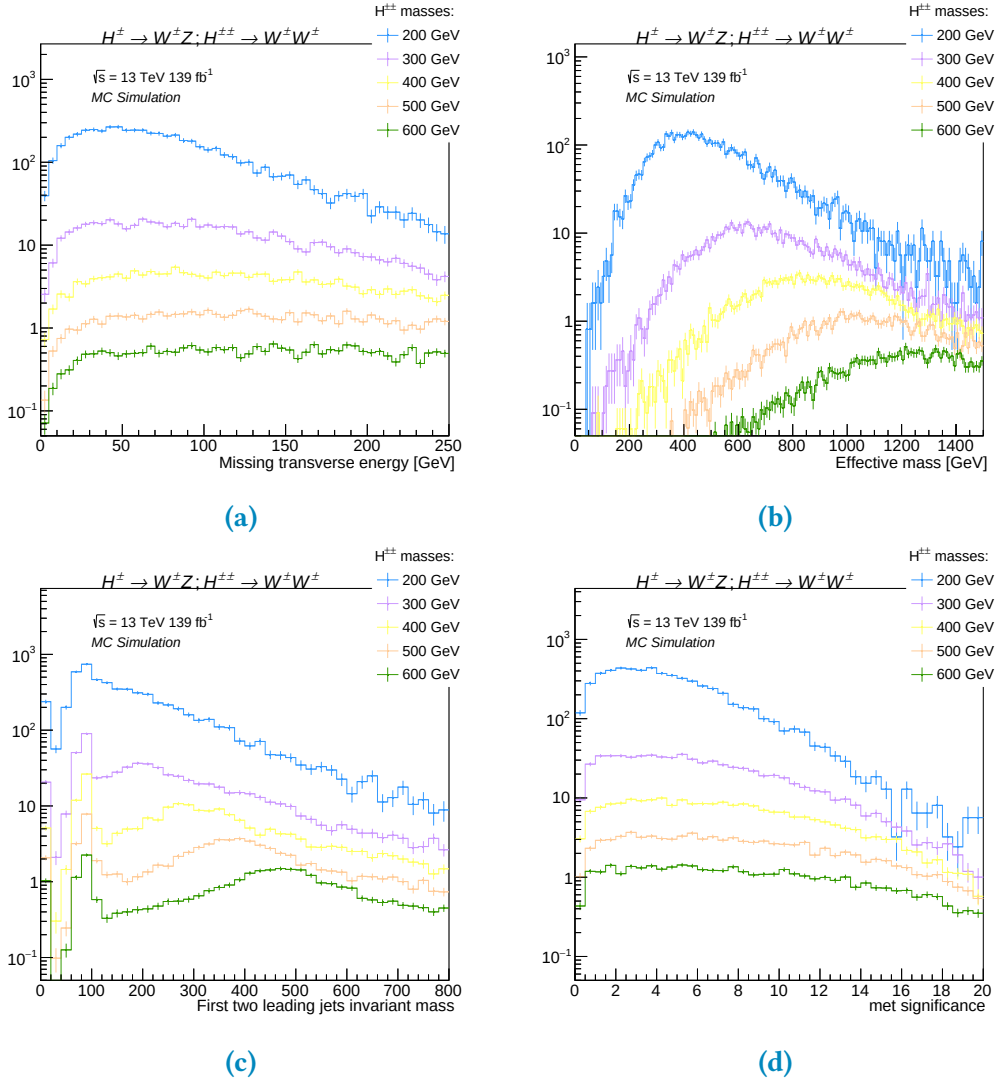
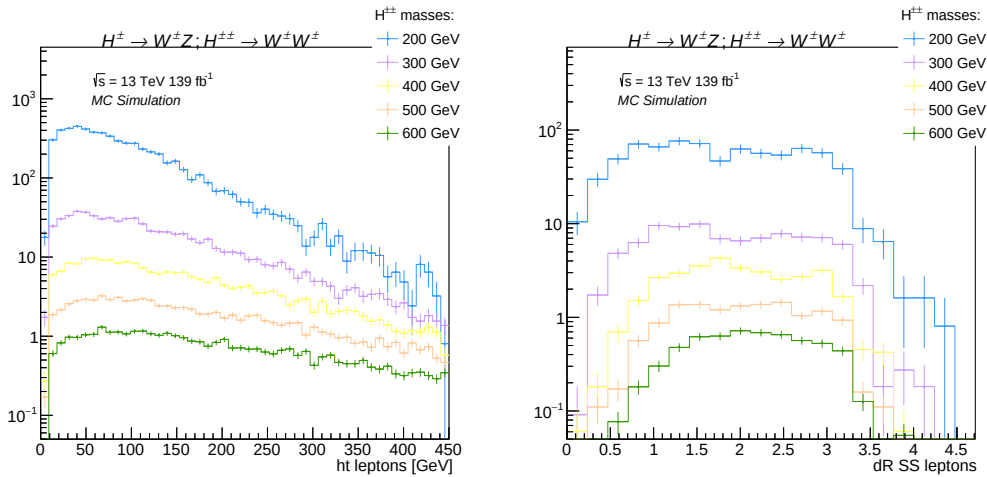


Figure 6.12: E_T^{miss} (a) and effective mass (b) distributions for signal mass points (200, 300, 400, 500 & 600 GeV) for associated production of charged higgs in all three channels. The distribution of invariant mass of first-two leading jets (c) and E_T^{miss} significance (d) for the given signal mass points in all three channels (associated production).



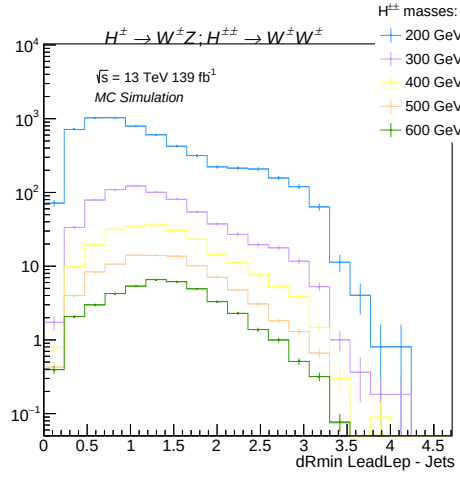


Figure 6.14: The distribution of high- p_T leptons (left) and distance between two same-sign leptons (right). The minimum distance between lepton and closest jet (bottom) for the given signal mass points in all three channels (associated production).

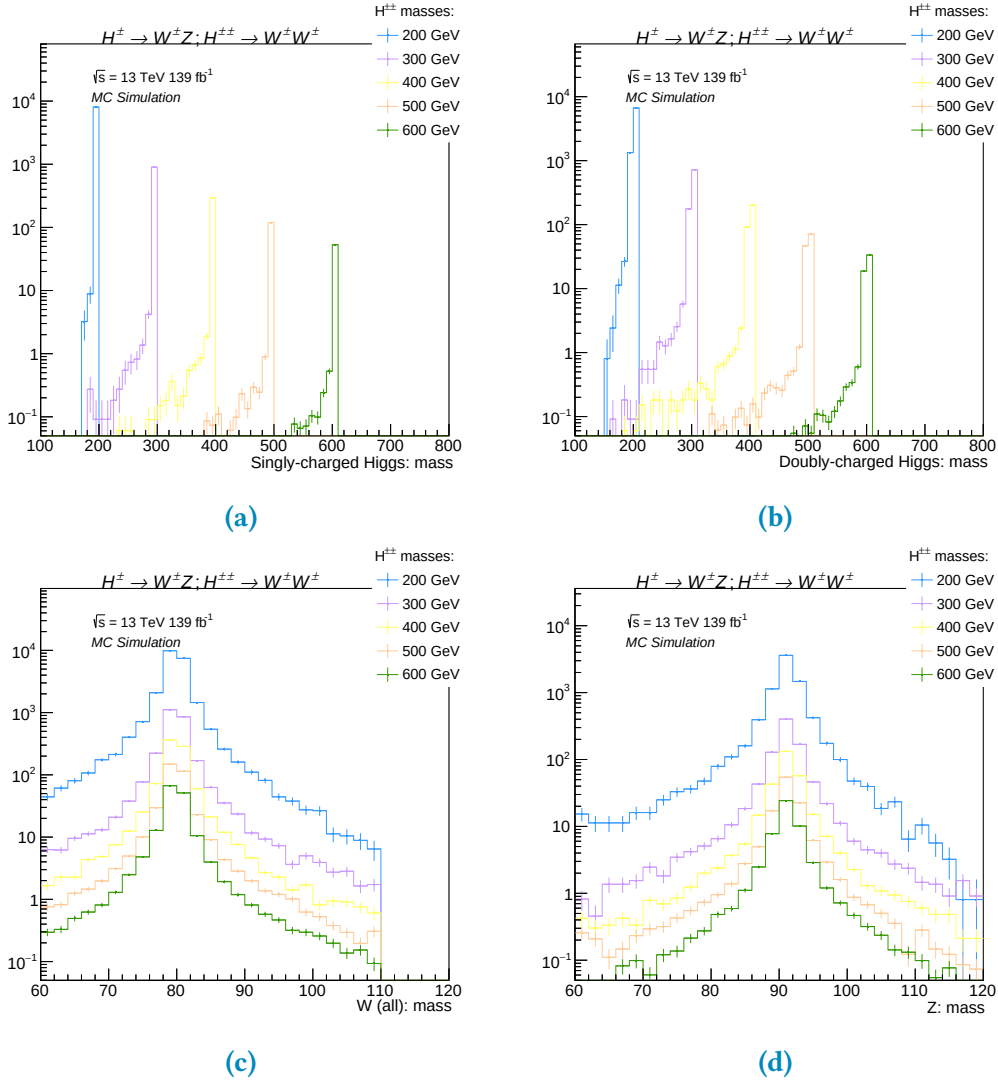


Figure 6.15: The distributions of singly charged higgs (a) doubly charged higgs invariant masses (b). The distribution of invariant mass of all W bosons (c) and Z boson (d) for the given signal mass points in all three channels (associated production).

6.8 Conclusions

The results for the validation of background are concluded in Section. 6.6 on the basis of the selections given in Table.6.5 and the specified regions for the WZ production mentioned in the Section. 6.4.5.

The distributions for the variables describing signal features for each preselection channel i.e. 2L, 3L & 4L were delineated in Figs. 6.5, 6.7, 6.8, 6.9 & 6.10. A good agreement is seen between data and MC background extrapolations from SM processes which favours to precised estimates for background contributions in the shapes. The variables were obtained for 2L, 3L & 4L channels after applying preselection criteria given in Table. 6.5.

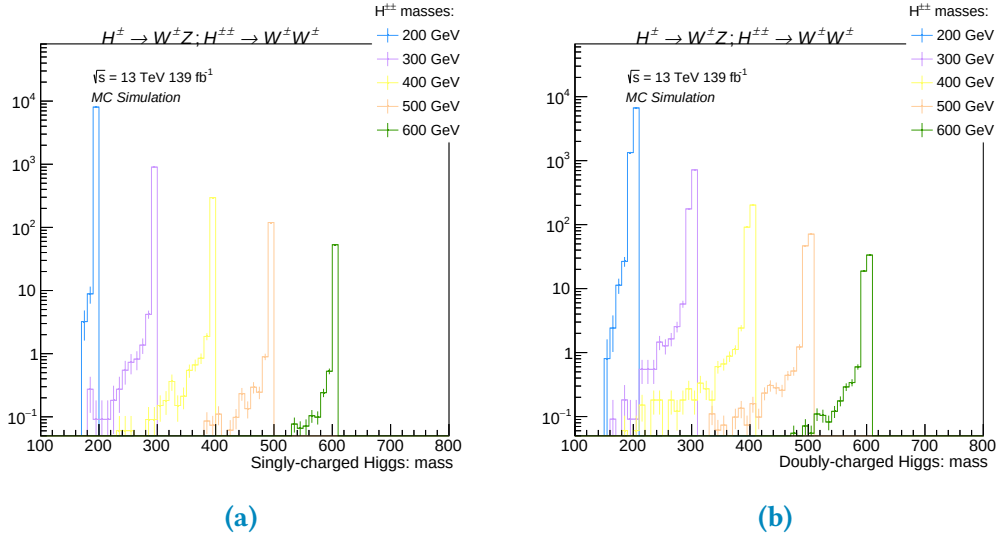


Figure 6.16: The distributions of singly charged higgs (a) doubly charged higgs invariant masses (b).

The results for the signal production of charged Higgs (associated production mode) for the various object collection are delineated in the Figs. 6.11, 6.12, 6.14 & 6.15. The variables were obtained after applying the object selection on them as given in Table. 6.4. In each variable case, five different curves representing signal mass point for singly ($H^\pm$) and doubly charged ($H^{\pm\pm}$) Higgs boson. The corresponding signal mass points 200, 300, 400, 500 & 600 GeV for associated production of charged higgs in all three channels are shown inclusively.

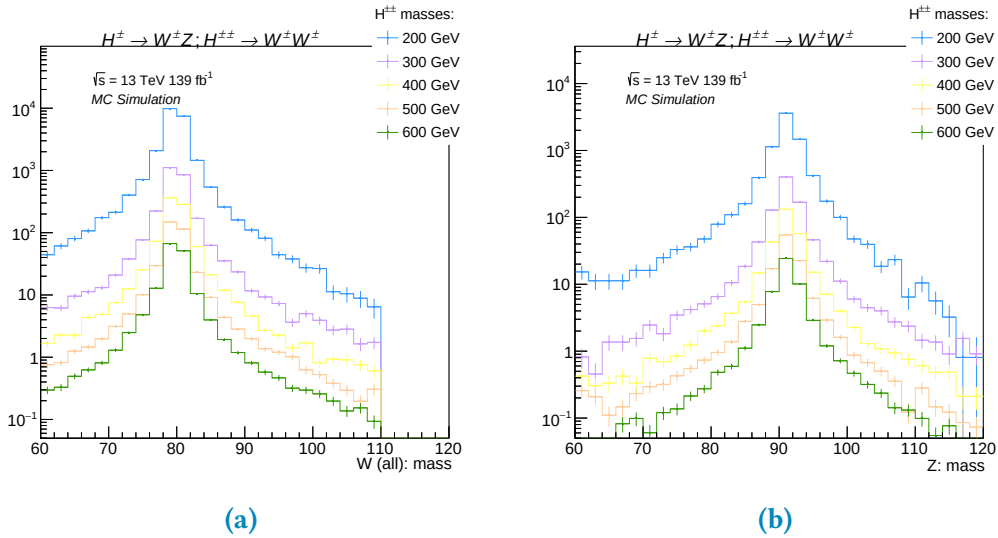


Figure 6.17: The distribution of invariant mass of all W bosons (a) and Z boson (b) for the given signal mass points in all three channels (associated production).

The results indicates masses of singly ($H^\pm$) and doubly charged ($H^{\pm\pm}$) Higgs bosons and the measurements were done correctly as depicted in the Fig. 6.16. The mass of all the W bosons and Z boson involved in the associated production mode of the Higgs as depicted in 6.1 & 6.2 were precisely measured and the results for their masses are given

in Fig. 6.17. The signal is not included in validations plots for the background comprehensively as the request for the signal production is in progress. But the preliminary results for the request of the signal production are shown. The contribution from fake leptons or non-prompt electrons is also not considered but this is supposedly to be done for the future studies. Overall, the preliminary results are included in this chapter.

Chapter 7

Concluding remarks

In this dissertation I have presented my own work on the ATLAS reconstruction efficiency measurement for full Run 2 data using two different release version of TagAndProbe framework and search for HBSM double and singly charged scalar bosons decaying into multi-leptons. The work is performed with proton proton collision datasets recorded by the ATLAS experiment in the LHC Run 2 correspond to years 2015-2018. Additionally, the checks for the Run 3 pre-production MC21 samples are done within ATLAS Egamma group and the results for the variables based on LH discriminant are also presented.

This thesis presents an overview of the Standard Model and physics beyond standard model i.e. Higgs physics within chapter 2. An introduction to the CERN's experiments in general and ATLAS experiment in particular is given in chapter 3. The details about object reconstruction at ATLAS experiment are given in chapter 4. The chapter 5 and 6 contain **my contribution** towards different measurements and performances towards ATLAS physics analyses. The major work about electron reconstruction efficiency measurements and singly and doubly charged Higgs searches at ATLAS experiment is done under groups i.e. Electron and Photon Performance Group [136] and Higgs and Diboson Searches [151].

The first part of the chapter 5 describes the measurement methodology used by the ATLAS experiment to perform the efficiency measurement for the reconstruction algorithm [122] given in Section 5.2. I have briefly described the *tag-and-probe* method that permits to select an unbiased sample of electrons in data, and estimation of the residual background contributions for the efficiency measurement. The dedicated Section 5.4 is to measure statistical uncertainties through pseudo-experiments. Since statistical uncertainties in published results are estimated using first-order approximations only, the Sections 5.4 and 5.4.2 are devoted to study the accuracy of those approximations by comparing them to the dispersion of repeated pseudo-experiments Ref.[163]. The results are presented in Section 5.4.2 for various representative choices of the available number of events for the measurement and the level and shape of the residual background and conclusions are provided in Section 5.7. The scale factors measurement for AF2 samples in release 21 with release 21 framework and the results are shown in Section 5.5. The re-implementation of methodology for electron reconstruction efficiency in release 22 framework and the proof of correctness of that work and comparison of scale factors in either versions of frameworks i.e. Rel21 & Rel22 is provided in Section 5.6.

Aiming at signal searches to extend the scalar sector of the Standard Model with a scalar triplet, directing to a phenomenology which comprehends singly and doubly charged Higgs bosons, the analysis is presented in chapter 6. The associated production of doubly charged $H^{\pm\pm}$ and singly charged $H^\pm$ bosons are investigated through the analysis. Section 6.1 presents the topologies used for the analysis and Section 6.2 gives us the details of theoretical framework. The Monte Carlo simulations used for various selection variables are listed in Section 6.3.2. In Section 6.4.4 the signal regions used for the different mass hypotheses of $H^{\pm\pm}$ & $H^\pm$ are described in order to distinguish signatures of BSM processes from SM backgrounds. The results obtained for the background validation are given the Section. 6.6 and the results obtained for the MC signal are concluded in Section 6.7.

Personal list of contributions

Published papers

1. S. Younas, *Methodology of electron reconstruction efficiency in situ calibration at high-energy colliders and accuracy of the associated statistical uncertainties*, [Rom. J. Phys. 68, 403 \(2023\)](#)
2. G. Aad, S. Younas, *et al.* ATLAS Collaboration, *Electron and photon efficiencies in LHC Run 2 with the ATLAS experiment*, submitted on Fri, 25 Aug 2023 to Journal of High Energy Physics, [arXiv:2308.13362 \[hep-ex\]](#)

International conferences

1. S. Younas, (2023), "PERFORMANCES OF ELECTRON RECONSTRUCTION AND IDENTIFICATION IN RUN 2 AND RUN 3 OF THE ATLAS EXPERIMENT", **Oral Presentation** at 21st International Balkan Workshop on Applied Physics and Materials Science, Constanta, Romania, 11-14, July, 2023, Published Abstracts: Ovidius University Press, list of accepted presentations [Accepted-Abstracts-IBWAP-2023.pdf](#)
2. S. Younas, (2022), "Performances of electron reconstruction + identification in Run 2 and preparation for Run 3", **Poster Presentation** at 51st International Symposium on Multi-particle Dynamics, Scotland, UK, July 31 - August 5, 2022, link to the conference indico page [ISMD2022](#)

Appendices

Appendix A

A.1 Background estimation for WZ Control region

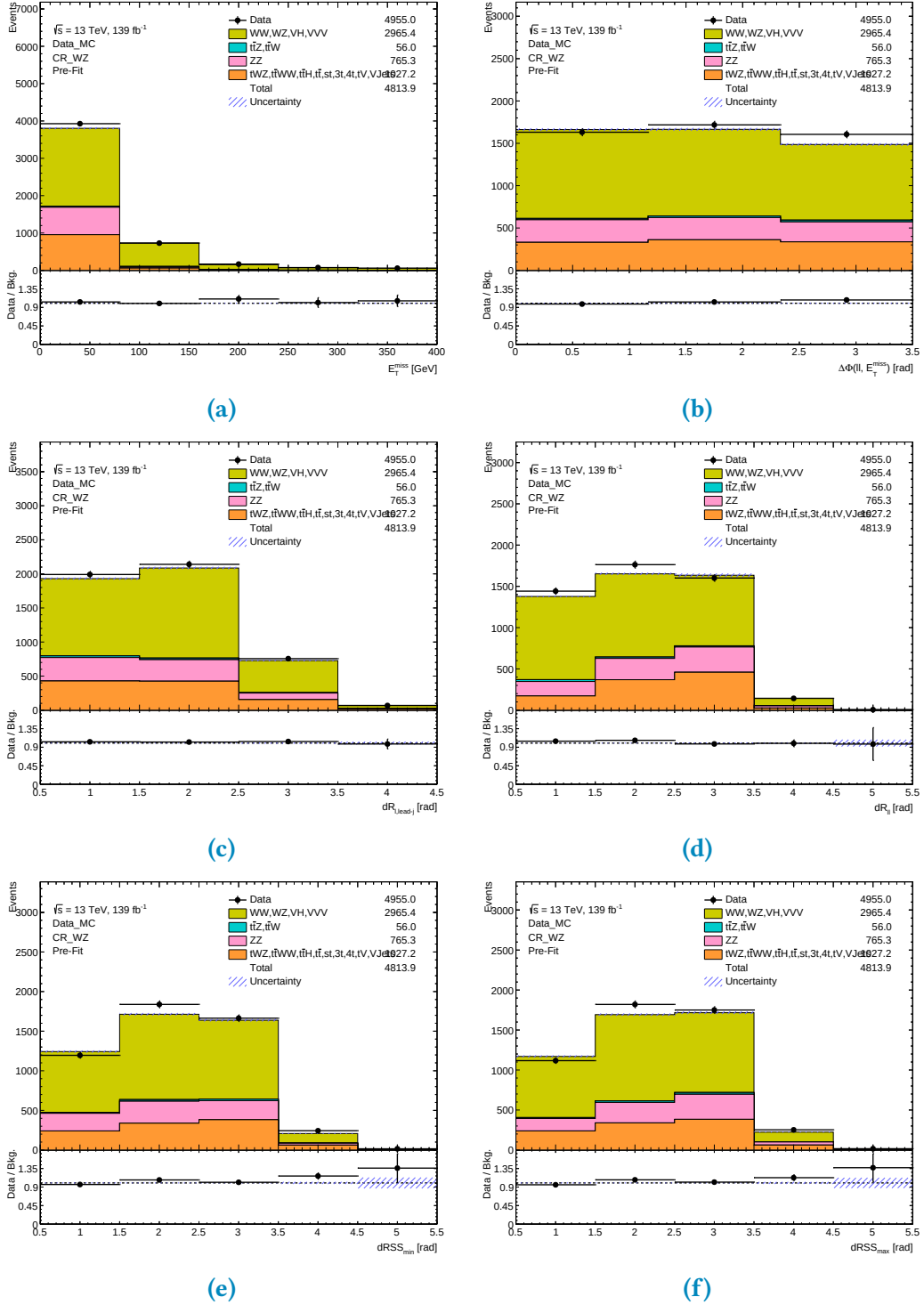


Figure A.1: The angular-related discriminating distributions and E_T^{miss} for WZ control region are shown at requirements defined in Table. 6.11. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.

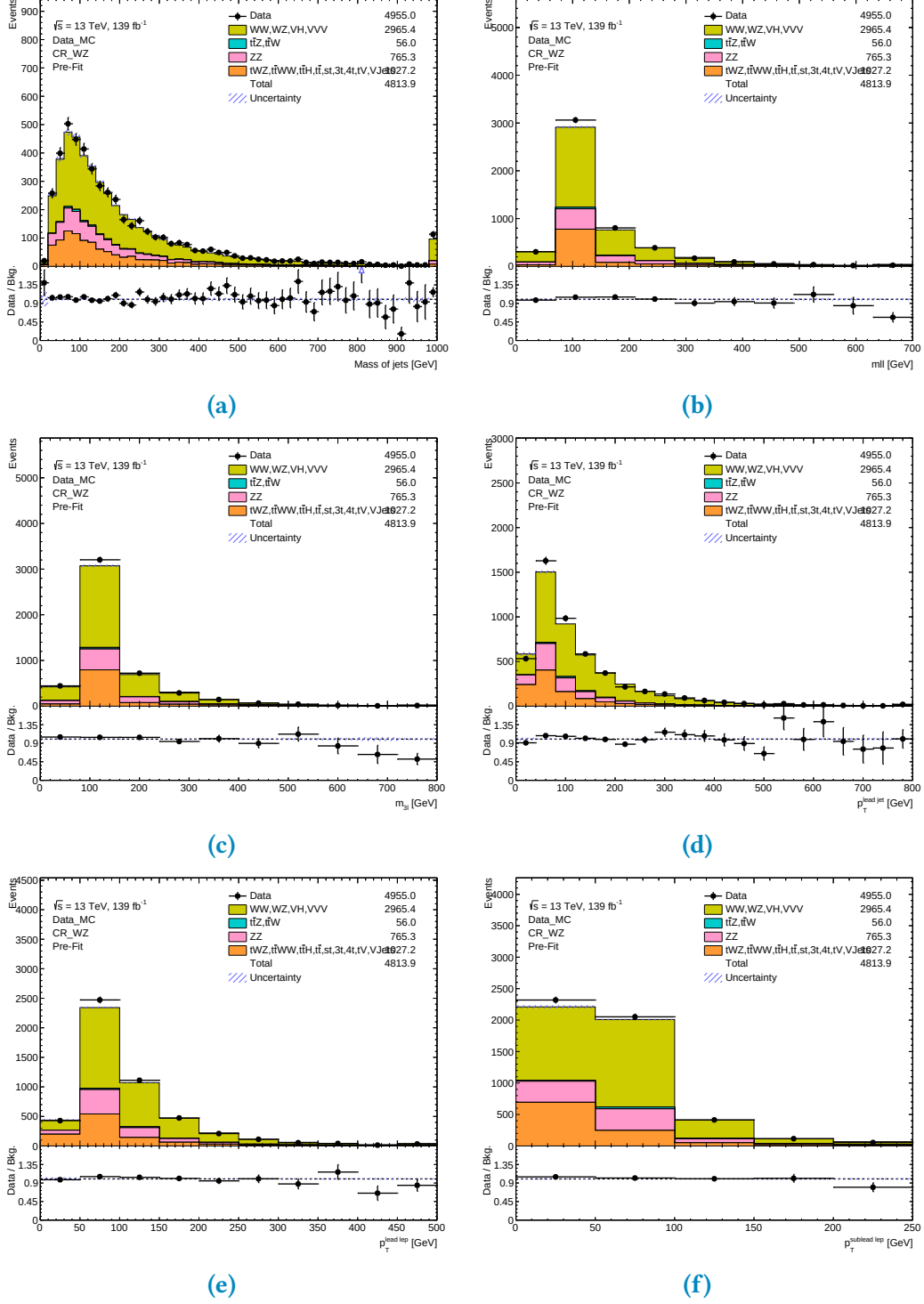


Figure A.2: The mass-related discriminating distributions for WZ control region are shown at requirements defined in Table. 6.11. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.

A.2 Background estimation for WZ Validation region

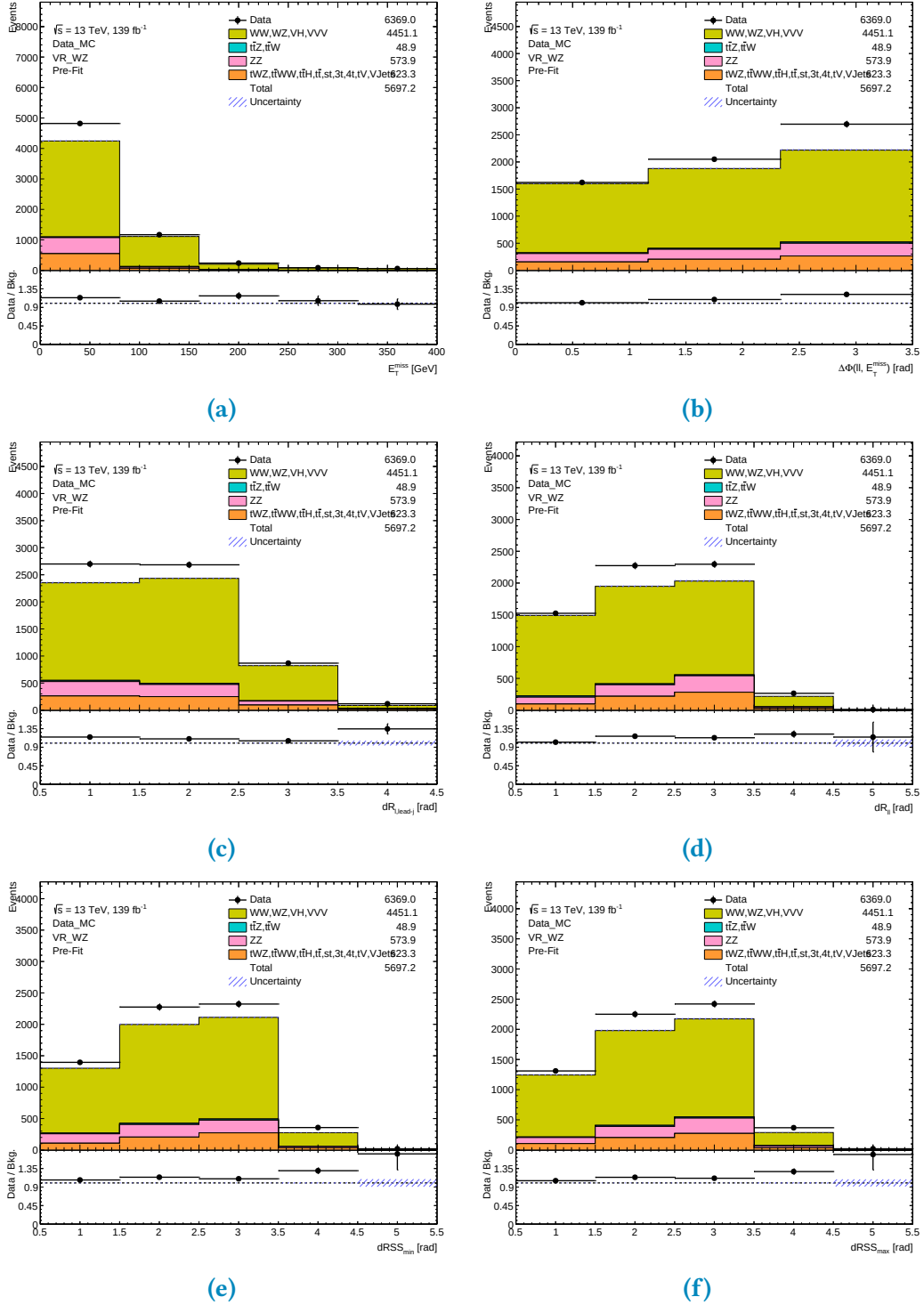


Figure A.3: The angular-related discriminating distributions and E_T^{miss} for WZ validation region are shown at requirements defined in Table 6.10. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.

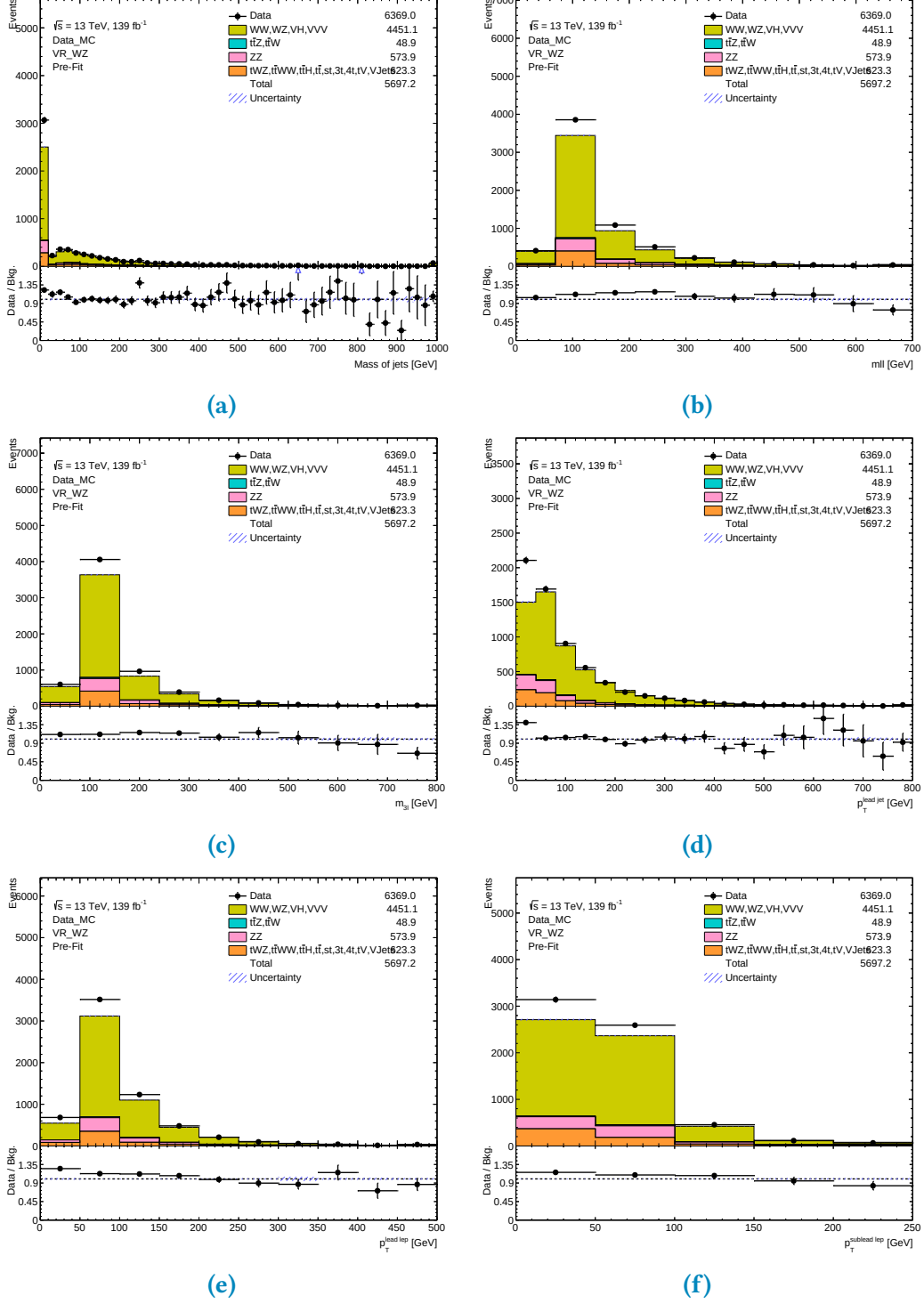


Figure A.4: The mass-related discriminating distributions for WZ validation region are shown at requirements defined in Table. 6.10. A comparison between the data (dots) and observed extrapolations from the involved background processes is depicted. The lower pad represent that comparison between data and MC simulated events in backgrounds. It also includes the statistical component of uncertainty for the background.

Appendix B

B.1 Run 3 pre-production MC21 samples Validations

Table B.1: The datasamples used for the validation of Run3 pre-production mc21 with Run 2 mc20 release 22 sample

Datasets	Signal $Z \rightarrow ee$
MC Samples (R22)	mc21_13p6TeV.601189.PyPy8EG_AZNLO_Zee.deriv.DA0D _EGAM1.e7400_s3775_r13504_r13491_p5034_tid28476407_00 mc20_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DA0D _EGAM1.e3601_s3681_r13145_p4940

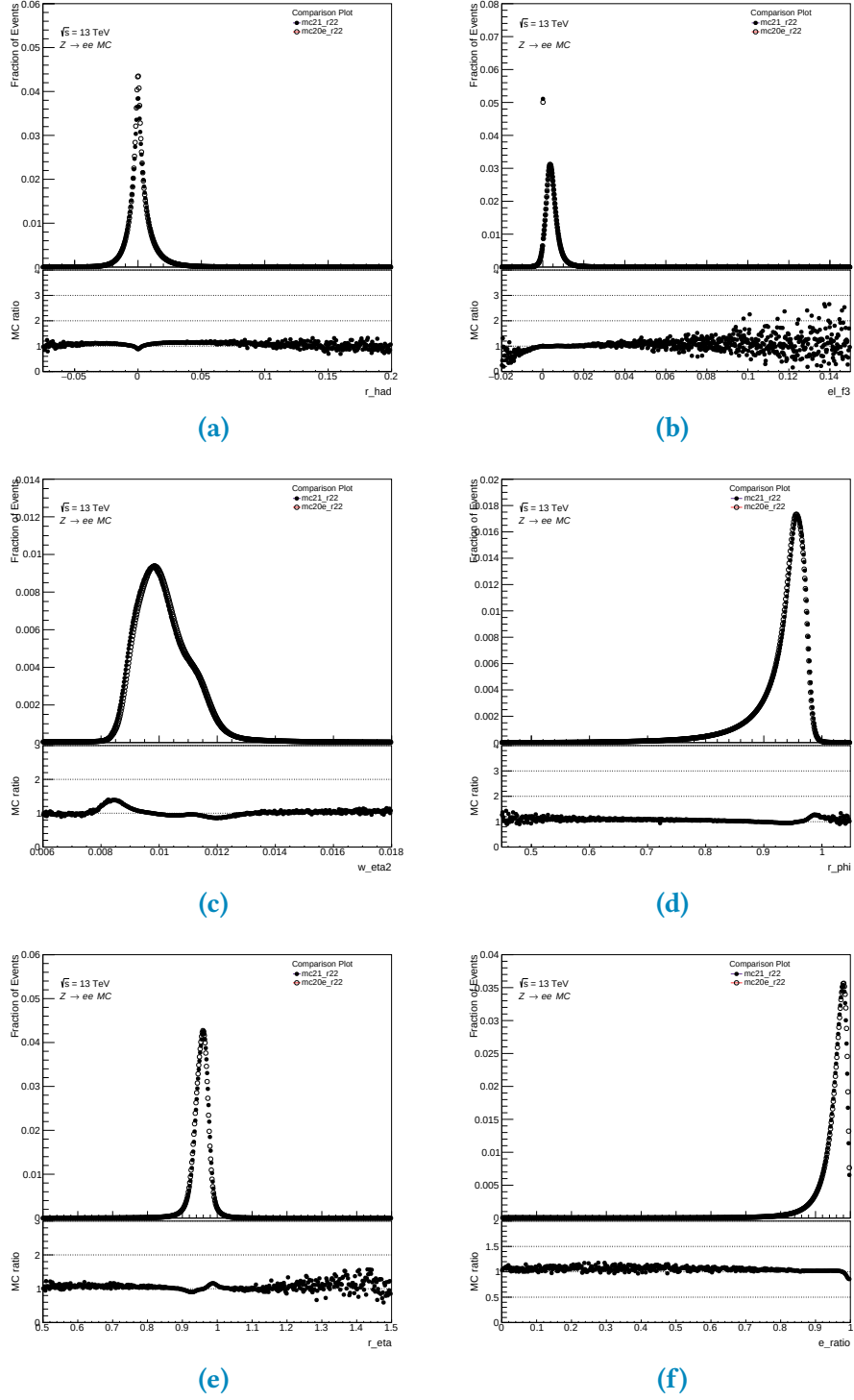
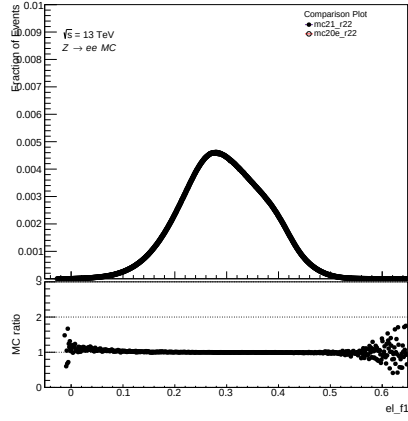
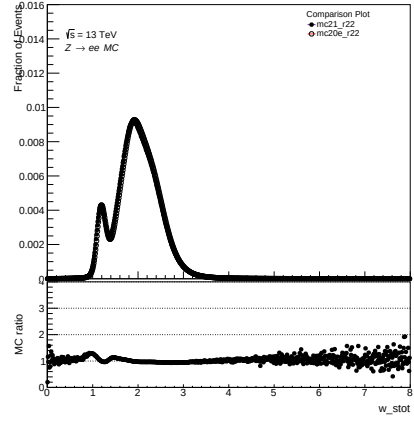


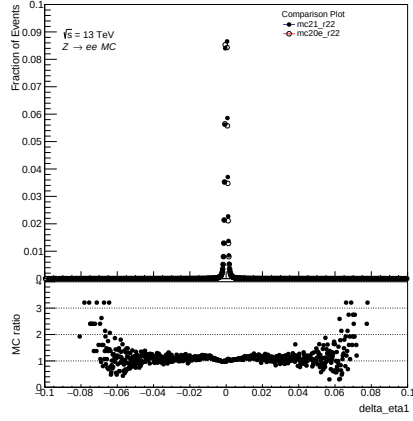
Figure B.1: The plots a(b) represent the comparison of variables $R_{had}(f_3)$ for mc21 and mc20e data samples in release 22. The plots c(d) show the ratio of variables $w_{\eta 2}(R_{phi})$ for mc21 and mc20e data samples in release 22. Whereas the plots e(f) show the comparison of variables $R_{\eta}(E_{ratio})$ for same datasets in release 22.



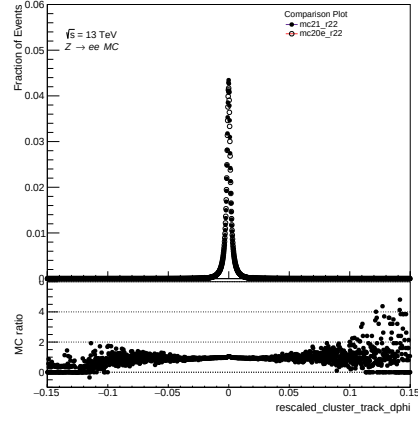
(a)



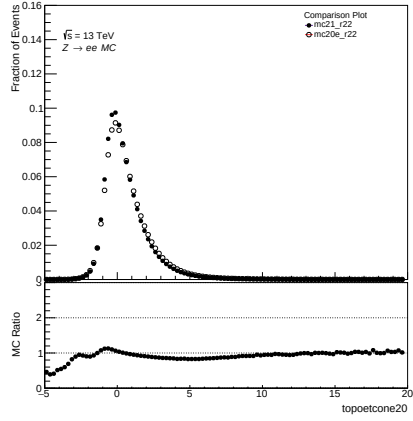
(b)



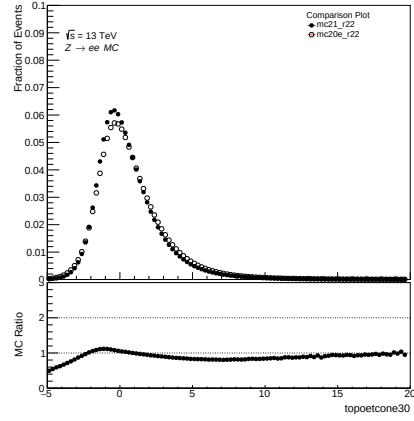
(c)



(d)



(e)



(f)

Figure B.2: The plots a(b) represent comparison of variables $f_1(w_{stot})$ for mc21 and mc20e data samples in release 22. Whereas, plots c(d) and e(f) show the comparison of variables $\Delta\eta_1$ ($\Delta\phi_{res}$) and $TopoE_T^{cone0.2}$ ($TopoE_T^{cone0.3}$) for mc21 and mc20e data samples in release 22.

Appendix C

C.1 MC background samples for VV, VH & ttW

DatasetID	Generator and ProcessInfo
WZ	
363358	Sherpa_221_NNPDF30NNLO_WqqZll
363489	Sherpa_221_NNPDF30NNLO_WlvZqq
364253	Sherpa_222_NNPDF30NNLO_lllv
364255	Sherpa_222_NNPDF30NNLO_lvvv
364284	Sherpa_222_NNPDF30NNLO_llvjj_EW6
364289	Sherpa_222_NNPDF30NNLO_lllv_lowMllPtComplement
WW	
363359	Sherpa_221_NNPDF30NNLO_WpqqWmlv
363360	Sherpa_221_NNPDF30NNLO_WplvWmq
364290	Sherpa_222_NNPDF30NNLO_llvv_lowMllPtComplement
345718	Sherpa_222_NNPDF30NNLO_ggllvvWW
364304	Sherpa_222_NNPDF30NNLO_ggWmlvWpq
364305	Sherpa_222_NNPDF30NNLO_ggWplvWmq
364286	Sherpa_222_NNPDF30NNLO_llvjj_ss_EW4
364287	Sherpa_222_NNPDF30NNLO_llvjj_ss_EW6
ZZ	
364250	Sherpa_222_NNPDF30NNLO_llll
364283	Sherpa_222_NNPDF30NNLO_lllljj_EW6
363355	Sherpa_221_NNPDF30NNLO_ZqqZvv
363356	Sherpa_221_NNPDF30NNLO_ZqqZll
345723	Sherpa_222_NNPDF30NNLO_ggllvvZ
345705	Sherpa_222_NNPDF30NNLO_ggllll_0M4l130
345706	Sherpa_222_NNPDF30NNLO_ggllll_130M4l
364288	Sherpa_222_NNPDF30NNLO_llll_lowMllPtComplement
345043	Sherpa_221_NNPDF30NNLO_ZbbZvv
345044	Sherpa_221_NNPDF30NNLO_ZbbZll
364302	Sherpa_222_NNPDF30NNLO_ggZllZqq
364303	Sherpa_222_NNPDF30NNLO_ggZvvZqq
NLO+ttW	
410155	aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttW
NLO+ttZ	
410218	aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttee
410219	aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttmumu
410220	aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_tttatau
410156	aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttZnunu
410157	aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttZqq
VH	
346310	PowhegPythia8EvtGen_NNPDF30_AZNLO_ZH125J_Zincl_H_incl_MINLO
346311	PowhegPythia8EvtGen_NNPDF30_AZNLO_WpH125J_Wincl_H_incl_MINLO
346312	PowhegPythia8EvtGen_NNPDF30_AZNLO_WmH125J_Wincl_H_incl_MINLO

Table C.1: The event samples simulated as background in 3l final state.

C.2 MC background processes tZ, ttH, TTbar, tops, VVV

DatasetID	Generator and ProcessInfo
tZ, Wt DS	
410560	MadGraphPythia8EvtGen_A14_tZ_4fl_tchan_noAllHad
410648	PowhegPythia8EvtGen_A14_Wt_DR_dilepton_top
410649	PowhegPythia8EvtGen_A14_Wt_DR_dilepton_antitop
ttH	
346343	PhPy8EG_A14NNPDF23_NNP30ME_ttH125_allhad
346344	PhPy8EG_A14NNPDF23_NNP30ME_ttH125_semlep
346345	PhPy8EG_A14NNPDF23_NNP30ME_ttH125_dilep
Ttbar, TtbarWW	
410470	PhPy8EG_A14_ttbar_hdamp258p75_nonallhad
410471	PhPy8EG_A14_ttbar_hdamp258p75_allhad
410472	PhPy8EG_A14_ttbar_hdamp258p75_dil
410081	MadGraphPythia8EvtGen_A14NNPDF23_ttbarWW
tWZ	
410408	aMcAtNloPythia8EvtGen_tWZ_Ztoll_minDR1
Single top, 3top, 4top	
410644	PowhegPythia8EvtGen_A14_singletop_schan_lept_top
410645	PowhegPythia8EvtGen_A14_singletop_schan_lept_antitop
410658	PhPy8EG_A14_tchan_BW50_lept_top
410659	PhPy8EG_A14_tchan_BW50_lept_antitop
304014	MadGraphPythia8EvtGen_A14NNPDF23_3top_SM
412043	aMcAtNloPythia8EvtGen_A14NNPDF31_SM4topsNLO
VVV	
364336	Sherpa_222_NNP30NNLO_WpWpWn_sslvjljj_EW6
364337	Sherpa_222_NNP30NNLO_WnWnWp_sslvjljj_EW6
364338	Sherpa_222_NNP30NNLO_WpWpWn_oslvjljj_EW6
364339	Sherpa_222_NNP30NNLO_WnWnWp_oslvjljj_EW6
364243	Sherpa_222_NNP30NNLO_WWZ_4l2v_EW6
364244	Sherpa_222_NNP30NNLO_WWZ_2l4v_EW6
364245	Sherpa_222_NNP30NNLO_WZZ_5l1v_EW6
364246	Sherpa_222_NNP30NNLO_WZZ_3l3v_EW6
364247	Sherpa_222_NNP30NNLO_ZZZ_6l0v_EW6
364248	Sherpa_222_NNP30NNLO_ZZZ_4l2v_EW6
364249	Sherpa_222_NNP30NNLO_ZZZ_2l4v_EW6

Table C.2: The MC derivations with tag p5631 is considered for background processes.

C.3 MC background processes $V\gamma$ & V +jets

DatasetID	Generator and ProcessInfo
$V+\gamma$	
700398	Sh_2211_mumugamma
700399	Sh_2211_eegamma
700400	Sh_2211_tautaugamma
700401	Sh_2211_nunugamma
700402	Sh_2211_munugamma
700403	Sh_2211_enugamma
700404	Sh_2211_taunugamma
V +jets	
700320	Sh_2211_Zee_maxHTpTV2_BFilter
700321	Sh_2211_Zee_maxHTpTV2_CFilterBVeto
700322	Sh_2211_Zee_maxHTpTV2_CVetoBVeto
700323	Sh_2211_Zmumu_maxHTpTV2_BFilter
700324	Sh_2211_Zmumu_maxHTpTV2_CFilterBVeto
700325	Sh_2211_Zmumu_maxHTpTV2_CVetoBVeto
700335	Sh_2211_Znunu_pTV2_BFilter
700336	Sh_2211_Znunu_pTV2_CFilterBVeto
700337	Sh_2211_Znunu_pTV2_CVetoBVeto
700338	Sh_2211_Wenu_maxHTpTV2_BFilter
700339	Sh_2211_Wenu_maxHTpTV2_CFilterBVeto
700340	Sh_2211_Wenu_maxHTpTV2_CVetoBVeto
700341	Sh_2211_Wmunu_maxHTpTV2_BFilter
700342	Sh_2211_Wmunu_maxHTpTV2_CFilterBVeto
700343	Sh_2211_Wmunu_maxHTpTV2_CVetoBVeto
700344	Sh_2211_Wtaunu_L_maxHTpTV2_BFilter
700345	Sh_2211_Wtaunu_L_maxHTpTV2_CFilterBVeto
700346	Sh_2211_Wtaunu_L_maxHTpTV2_CVetoBVeto
700347	Sh_2211_Wtaunu_H_maxHTpTV2_BFilter
700348	Sh_2211_Wtaunu_H_maxHTpTV2_CFilterBVeto
700349	Sh_2211_Wtaunu_H_maxHTpTV2_CVetoBVeto

Table C.3: The MC derivations with tag p5631 is considered for background processes.

C.4 MC background processes dijets & drell_yan

DatasetID	Generator and ProcessInfo
Dijets	
364700	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ0WithSW
364701	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ1WithSW
364702	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ2WithSW
364703	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ3WithSW
364704	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ4WithSW
364705	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ5WithSW
364706	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ6WithSW
364707	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ7WithSW
364708	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ8WithSW
364709	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ9WithSW
364710	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ10WithSW
364711	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ11WithSW
364712	Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ12WithSW
Drell_Yan	
700467	Sh_2211_Zee_maxHTpTV2_m10_40_pT5_BFilter
700468	Sh_2211_Zee_maxHTpTV2_m10_40_pT5_CFilterBVeto
700469	Sh_2211_Zee_maxHTpTV2_m10_40_pT5_CVetoBVeto
700470	Sh_2211_Zmumu_maxHTpTV2_m10_40_pT5_BFilter
700471	Sh_2211_Zmumu_maxHTpTV2_m10_40_pT5_CFilterBVeto
700472	Sh_2211_Zmumu_maxHTpTV2_m10_40_pT5_CVetoBVeto

Table C.4: The MC derivations with tag p5631 is considered for background processes.

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