

Electroweak physics and evidence for a Higgs boson decaying to a pair of tau leptons with the CMS detector

by

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Abstract

Studies of the electroweak interactions using final states with leptons in proton-proton collisions at the Large Hadron Collider at $\sqrt{s} = 7$ TeV, $\sqrt{s} = 8$ TeV, and $\sqrt{s} = 13$ TeV center-of-mass energies are described. Measurements of total inclusive and fiducial W and Z boson production cross sections and their ratios are performed. The W and Z bosons are observed via their decays to electrons and muons. An indirect determination of the total width of the W boson and the $\mathcal{B}(W \rightarrow \ell\nu)$ from the measured cross section ratios is described. The discovery of a new boson with a mass of 125 GeV at the Large Hadron Collider in 2012 sheds a new light on understanding the nature of electroweak symmetry breaking. A question of great significance is whether the new field couples to fermions through a Yukawa coupling interaction predicted in the standard model of particles. Evidence of the 125 GeV Higgs boson decay to a pair of tau leptons with an observed significance of 3.1 standard deviations is established. The nature of the Higgs sector is probed through searches for neutral resonances decaying to a pair of tau leptons in gluon-fusion and b-quark associated production modes with no observation of a significant excess. In addition, the feasibility of measuring the standard model Higgs boson self-coupling with an expected data sample corresponding to an integrated luminosity of 3000 fb⁻¹ is studied.

Thesis Supervisor: Professor Markus Klute
Title: Associate Professor

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Chapter 1

Introduction

The Standard Model (SM) theory of elementary particles provides a remarkably successful description of many experimental results up to the currently accessible energies. Leptons and colored quarks are the building blocks of matter and the SM provides a fundamental theory of strong [1, 2] and electroweak interactions [3, 4, 5]. The strong interactions are mediated by massless gluons. The force carriers of the electroweak interactions are the massless photon and the massive W and Z bosons. The SM is a renormalizable gauge theory based on the symmetry group $SU(3) \times SU(2) \times U(1)$. However, the massive W and Z gauge bosons and the massless photon indicate that the electroweak symmetry is broken. It was shown that the masses can be generated through spontaneous symmetry breaking introduced by adding a complex scalar field to the model [6, 7, 8, 9, 10, 11]. A neutral heavy scalar boson, the SM Higgs boson (H), remains after the spontaneous symmetry breaking by adding a complex scalar Higgs doublet. The scalar field can also account for the fundamental fermion masses. Postulated Yukawa couplings of the Higgs field to the fundamental fermions introduces the fermion mass terms after the same spontaneous symmetry breaking mechanism that gives masses to the W and Z gauge bosons.

The mass of the SM Higgs boson (m_H) is a free parameter in the theory. However the m_H should be smaller than about 1 TeV to retain the perturbative unitarity of the longitudinal W/Z boson scattering amplitudes at higher center-of-mass energies [12, 13, 14, 15]. Previous direct and model-independent searches at the LEP e^+e^- collider

excluded the existence of a Higgs boson with a mass less than 114.4 GeV at e^+e^- center-of-mass energies between 90 and 209 GeV at 95% Confidence Level (C.L.) [16]. Direct searches were performed at the Tevatron collider in proton-antiproton collisions at center-of-mass energy of 1.96 TeV excluding the existence of a SM Higgs boson in the mass regions of 90 – 109 GeV and 149 – 182 GeV, and reporting a broad excess in the mass regions of 115 – 140 GeV with a significance of 2.8 standard deviations [17]. The significance is not corrected for the so called look-elsewhere effect [18]. Moreover, indirect constraints from a global fit of the precision electroweak data at LEP, SLC, and the Tevatron colliders suggest $m_H = 89^{+22}_{-18}$ GeV, or $m_H < 127$ GeV at 90% (C.L.) [19]. It has to be noted that the global fit includes the Tevatron measurement of the W mass citeAaltonen:2013iut that is 1.5 standard deviation higher than the SM best fit value.

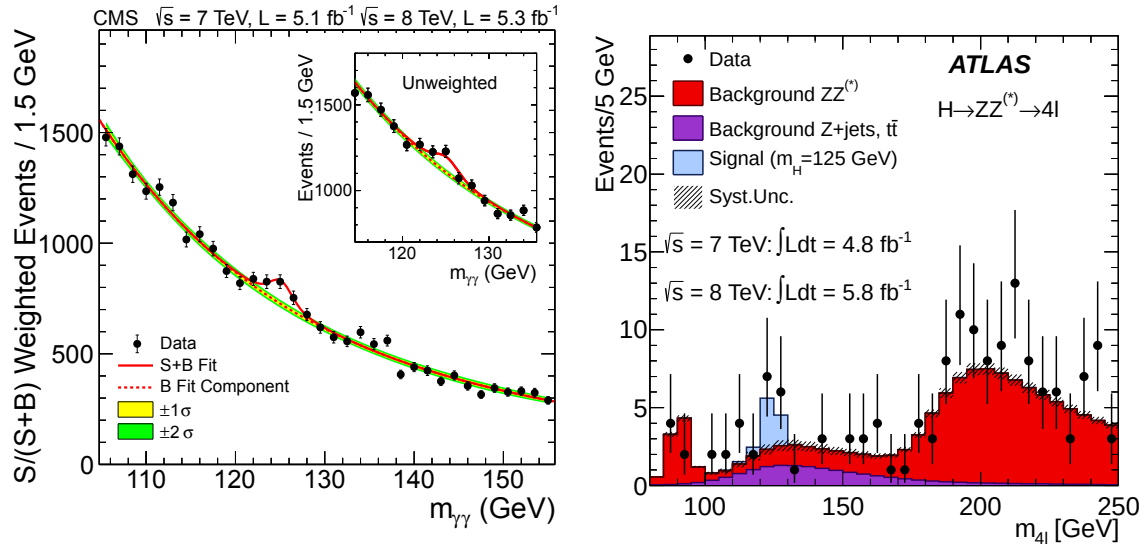


Figure 1-1: Distributions of the CMS diphoton invariant mass with each event weighted by $S/(S + B)$ value (left panel) and the ATLAS four-lepton invariant mass for the $ZZ \rightarrow 4\ell$ decays (right panel) [20].

The search for the SM Higgs boson has been one of the highlights of the Large Hadron Collider (LHC) [21]. In July 2012, the ATLAS and CMS collaborations announced the observation of a narrow resonance with a mass of about 125 GeV with properties consistent with the SM Higgs boson [22, 20]. Significant excesses were

observed in $\gamma\gamma$ and ZZ decay modes with rates consistent with the SM predictions. There were also strong hints in the data that the new particle decays to W^+W^- final state. The observed decay channels indicate that the new particle is a boson. Figure 1-1 shows the distributions of the diphoton invariant mass (weighted by the signal-to-background ratio) and four-lepton invariant mass for the $ZZ \rightarrow 4\ell$ decays in the CMS and ATLAS results, respectively. The ATLAS and CMS continued to take data after the discovery announcement. Subsequent measurements of the Higgs boson production and decay rates, combining the ATLAS and CMS results, with proton-proton collisions at center-of-mass energies of 7 and 8 TeV show a consistent picture with the SM Higgs boson predictions [23]. The combined measured mass of the discovered boson is $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV [24]. The spin and CP properties of the new boson are also consistent with those expected of the SM Higgs boson [25, 26, 27].

The measurement of the Higgs boson decays to $b\bar{b}$ and $\tau^+\tau^-$ is essential for identifying if the new boson is the SM Higgs boson. Both decay modes provide a direct probe of the Higgs Yukawa coupling to fermions. The $\tau^+\tau^-$ decay mode is currently the most promising final state to study the SM Higgs coupling to leptons.

1.1 Overview of the Standard Model

1.1.1 Quantum Chromodynamics

The gauge group of the strong interactions of the colored quarks and gluons is $SU(3)$. The most general gauge invariant and renormalizable Lagrangian of the quantum chromodynamics (QCD) is given by:

$$\mathcal{L} = \bar{\psi}_{f,\alpha}(i\gamma^\mu\partial_\mu\delta_{\alpha\beta} - g_s\gamma^\mu t_{\alpha\beta}^a A_\mu^a - m_f\delta_{\alpha\beta})\psi_{f,\beta} - \frac{1}{4}F_{\mu\nu}^b F^{b,\mu\nu} - \theta\frac{g_s^2}{72\pi^2}\epsilon_{\mu\nu\rho\sigma}F^{c,\mu\nu}F^{c,\rho\sigma}, \quad (1.1)$$

where repeated indices are summed over. The $\psi_{f,\alpha}$ are the quark-field Dirac spinors of flavor f , color α , and mass m_f . There are 6 quark flavors, the up (u), charm (c), and top (t), each carrying an electric charge of $+2e/3$, and the down (d), strange

(s), and bottom (b), each carrying an electric charge of $-e/3$. Each quark flavor comes in three "colors" transforming according to the fundamental representation of the $SU(3)$ color group. The A_μ^a denotes the massless gluon field vector potentials transforming according to the adjoint representation of the $SU(3)$ color group with a running from 1 to $N_c^2 - 1 = 8$ (8 gluons). The $t_{\alpha\beta}^a$ are the eight generators of the color group represented by 3×3 Hermitian traceless matrices. The g_s (or $\alpha_s = \frac{g_s}{4\pi}$) is the strong interaction coupling constant, the γ^μ are the Dirac matrices, and the gauge field tensor is given by:

$$\begin{aligned} F_{\mu\nu}^a &= \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f_{abc} A_\mu^b A_\nu^c, \\ [t^a, t^b] &= i f_{abc} t^c, \end{aligned} \tag{1.2}$$

where f_{abc} are the structure constants of the $SU(3)$. The non-Abelian structure of the $SU(3)$ group means that the Feynman rules of QCD involve 3-gluon and 4-gluon vertices in addition to the quark-antiquark-gluon vertex. The last term in the Lagrangian in Equation (1.1) can induce an electric dipole moment for the neutron resulting in a CP violation. However, the experimental limits on the electric dipole moment constrain the θ parameter to be smaller than 10^{-10} [19]. This is known as the strong CP problem with a possible resolution given by the Peccei-Quinn theory predicting the existence of a hypothetical particle Axion [28]. There are 7 fundamental parameters in the QCD Lagrangian (not counting the θ parameter): the 6 quark masses and the strong coupling g_s constant. Predictions utilizing perturbative QCD (pQCD) calculations are expressed in terms of the renormalized coupling constant $g_s(\mu_R)$ as a function of a non-physical renormalization scale μ_R . The renormalization group equation to three-loop order is given by:

$$\mu \frac{d}{d\mu} g_s \mu_R = -(\beta_0 \frac{g_s^3(\mu_R)}{16\pi^2} + \beta_1 \frac{g_s^5(\mu_R)}{128\pi^4} + \beta_2 \frac{g_s^7(\mu_R)}{8192\pi^6}), \tag{1.3}$$

where the loop coefficients β_i are:

$$\begin{aligned}\beta_0 &= 11 - \frac{2}{3}n_f, \\ \beta_1 &= 51 - \frac{19}{3}n_f, \\ \beta_2 &= 2857 - \frac{5033}{9}n_f - \frac{325}{27}n_f^2,\end{aligned}\tag{1.4}$$

and n_f is the number of quark flavors with masses below the energies of interest [19]. The minus sign in Equation (1.3) is the source of the asymptotic freedom and as can be seen in Equation (1.4) the theory is asymptotically free as long as there are less than 16 quark flavors below the energy scale of interest. Setting the renormalization scale near the momentum transfer Q of a given process gives the effective strength of the strong coupling. Thus the strong coupling becomes weak for larger Q and $\alpha_s \approx 0.1$ for momentum transfers near 100 GeV. Free quarks and gluons have not been observed experimentally. The asymptotic freedom implies that the strong coupling increases at low energies (large distances) and only color-singlet combinations of quarks, massless gluons, and anti-quarks, referred as hadrons, can be observed.

1.1.2 Electroweak Model

The gauge group of the electroweak interactions is $SU(2) \times U(1)$ with the corresponding gauge bosons $\vec{W}_\mu$ and B_μ , respectively. The $SU(2)$ part of the gauge group is chiral, i.e. it only acts on the left-handed components of the quark and lepton fields. The left handed fermion fields transform as doublets under $SU(2)$ and are given by:

$$\Psi = \begin{pmatrix} \nu_f \\ \ell_f \end{pmatrix}, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix},\tag{1.5}$$

for each lepton generation and by:

$$\Psi = \begin{pmatrix} u \\ d' \end{pmatrix}, \quad \begin{pmatrix} c \\ s' \end{pmatrix}, \quad \begin{pmatrix} t \\ b' \end{pmatrix},\tag{1.6}$$

for the three quark flavors. The d' , s' , and b' are given by:

$$\begin{aligned} d' &= V_{ud}d + V_{us}s + V_{ub}b \\ s' &= V_{cd}d + V_{cs}s + V_{cb}b \\ b' &= V_{td}d + V_{ts}s + V_{tb}b, \end{aligned} \tag{1.7}$$

where V is the unitary Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [29, 30]. The right handed fermion fields are $SU(2)$ singlets. The most general gauge invariant and renormalizable Lagrangian for the fermion fields ψ_i is given by:

$$\mathcal{L} = \sum_i \bar{\psi}_i \gamma^\mu (i\partial_\mu - \frac{g'}{2}Y B_\mu) \psi_i - \bar{\Psi}_i \gamma^\mu \frac{g}{2} \vec{\sigma} \cdot \vec{W}_\mu \Psi_i - \frac{1}{4} \vec{W}_{\mu\nu} \cdot \vec{W}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}, \tag{1.8}$$

where g' and g are the gauge coupling constants of the $U(1)$ and $SU(2)$, respectively. Thus the $\frac{Y}{2}$, where Y is the weak hypercharge, and the $\frac{1}{2}\vec{\sigma}$, where σ_i are the Pauli matrices, are the generators of the $U(1)$ and $SU(2)$, respectively. The gauge field tensors are given by:

$$\begin{aligned} B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\ \vec{W}_{\mu\nu} &= \partial_\mu \vec{W}_\nu - \partial_\nu \vec{W}_\mu + g \vec{W}^\mu \times \vec{W}^\nu. \end{aligned} \tag{1.9}$$

The hypercharge is normalized such that the electric charge $Q = \frac{1}{2}\sigma^3 + \frac{Y}{2}$. The vector fields corresponding to particles with spin 1 and definite mass are the charged $W_\mu^\pm$ bosons, the neutral Z_μ boson and the photon A_μ given in terms of the gauge fields as:

$$\begin{aligned} A_\mu &= B_\mu \cos \theta + W_\mu^3 \sin \theta \\ Z_\mu &= -B_\mu \sin \theta + W_\mu^3 \cos \theta \\ W_\mu^\pm &= W_\mu^1 \mp iW_\mu^2, \end{aligned} \tag{1.10}$$

where θ is the weak angle related to the gauge coupling constants by:

$$\begin{aligned}\sin \theta &= \frac{g'}{\sqrt{g^2 + g'^2}} \\ \cos \theta &= \frac{g}{\sqrt{g^2 + g'^2}}.\end{aligned}\tag{1.11}$$

However this theory of the electroweak interactions given in Equation (1.8) is not satisfactory. It contains four massless bosons whereas only the photon is massless in nature. Attempting to add mass terms of the form $-M_Z^2 Z_\mu Z^\mu$ for the vector boson fields in the Lagrangian breaks the gauge invariance. Furthermore introducing explicit mass terms for the spin-1 boson fields makes the theory non-renormalizable. There are also no mass terms in the Lagrangian for the fermion fields. The Dirac fermion mass terms link the left and right-handed components of the fields:

$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L).\tag{1.12}$$

This breaks the symmetry as the left and right-handed components transform differently under the $SU(2)$ and $U(1)$. Spontaneous symmetry breaking mechanism leaving the underlying gauge symmetry intact was the solution to the conundrum on how the gauge bosons can acquire mass.

1.1.3 The SM Higgs Mechanism

Spontaneous symmetry breaking occurs when the ground state (vacuum) does not exhibit the symmetry of the theory. A key aspect is that the vacuum is degenerate and it can not be predicted in advance which state will be chosen. Taking a precedence from the superconductivity phenomenon it was reasoned that the gauge symmetry can be broken through spontaneous symmetry breaking [31, 32]. The main difficulty is the appearance of the massless spin-0 Nambu-Goldstone bosons after the spontaneous symmetry breaking (the Goldstone theorem [33]) as no such particles are observed. Englert, Brout, Higgs, Guralnik, Hagen, and Kibble showed that the theorem does not apply to the gauge theories [6, 7, 8, 9, 10, 11]. Taking these ideas Weinberg and

Salam completed the electroweak unification started by Glashow [3, 4, 5]. They also added the possibility to generate the fermion masses through the same spontaneous symmetry breaking. Finally, it was proved by t'Hooft and Veltman that this model is renormalizable [34]. The $SU(2)$ symmetry is broken by introducing a scalar field (Higgs) in the spinor representation of the $SU(2)$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ \phi_0 + ia^0 \end{pmatrix}, \quad (1.13)$$

with four real degrees of freedom in the complex doublet and weak hypercharge of $Y = 1$. The most general renormalizable Lagrangian of the scalar field consistent with $SU(2) \times U(1)$ is given by

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2, \quad (1.14)$$

with $\lambda > 0$. The covariant derivative, given by

$$D_\mu \Phi = (\partial_\mu + \frac{1}{2}ig\vec{\sigma} \cdot \vec{W}_\mu + \frac{1}{2}g'YB_\mu)\Phi, \quad (1.15)$$

is responsible for the Higgs field couplings to the $\vec{W}_\mu$ and B_μ gauge fields. There is a tree-approximation non-zero vacuum expectation value (VEV) for $\mu^2 < 0$ given by:

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\nu \end{pmatrix}, \quad (1.16)$$

with VEV $\nu^2 = -\frac{\mu^2}{\lambda}$. A $SU(2) \times U(1)$ gauge transformation was performed in Equation (1.16) to a unitary gauge in which $\phi^+ = 0$, and $a^0 = 0$ leaving a positive $\langle \phi^0 \rangle$. Defining $\phi^0 = H + \nu$ in the Lagrangian in Equation (1.8) induces the spontaneous breaking of the SM gauge symmetry $SU(2) \times U(1)$ into $U(1)_{em}$ group. The generator of the $U(1)_{em}$ gauge group is the electric charge $Q = \frac{1}{2}\sigma^3 + \frac{Y}{2}$. Thus the photon field

A_μ remains massless and the Higgs Lagrangian is given by

$$\begin{aligned}\mathcal{L}_H = & \frac{1}{2}\partial_\mu H\partial^\mu H - \frac{1}{2}m_H^2 H^2 - \frac{1}{2}m_W^2 W_\mu^+ W^{-\mu} - \frac{1}{2}m_Z^2 Z_\mu Z^\mu \\ & + \frac{m_H^2}{2\nu} H^3 + \frac{m_H^2}{8\nu^2} H^4 + \frac{m_Z^2}{\nu} Z_\mu Z^\mu H + \frac{2m_W^2}{\nu} W_\mu^+ W^{-\mu} H \\ & + \frac{m_Z^2}{2\nu^2} Z_\mu Z^\mu H^2 + \frac{m_W^2}{\nu^2} W_\mu^+ W^{-\mu} H^2,\end{aligned}\tag{1.17}$$

where the Lagrangian is expressed in terms of the $W_\mu^\pm$ and Z_μ fields given in Equation (1.10) and

$$\begin{aligned}m_H &= \sqrt{-2\mu^2} \\ m_W &= \frac{1}{2}g\nu = \cos\theta m_Z \\ m_Z &= \frac{1}{2}\sqrt{g^2 + g'^2}\nu \\ m_A &= 0.\end{aligned}\tag{1.18}$$

Thus, the spin-1 gauge bosons $W_\mu^\pm$ and Z_μ have acquired mass. The Higgs boson H is also massive. The three scalar fields in Equation (1.13) are "eaten" by the $W_\mu^\pm$ and Z_μ fields and the fourth remains as the neutral Higgs field. One can see that the Higgs couplings to the spin-1 vector bosons are proportional to the mass squared of the bosons. The Higgs trilinear and quartic self couplings are proportional to the m_H^2 .

The final item needed to complete the theory is to add a mechanism for generating the fermion masses. The fermions acquire mass through a Yukawa type interactions between the Higgs scalar field and the fermions. The Yukawa Lagrangian before the electroweak symmetry is given by:

$$\mathcal{L}_Y = -h_{d_{ij}}\bar{q}_{Li}\Phi d_{Rj} - h_{u_{ij}}\bar{q}_{Li}i\sigma^2\Phi^* d_{Rj} - h_{\ell_{ij}}\bar{\ell}_L\Phi e_{Rj} + \text{h.c.},\tag{1.19}$$

where the q_L (ℓ_L) and u_R , d_R (e_R) are the quark (lepton) $SU(2)$ doublets (singlets) and the 3×3 matrices are the couplings [19]. After the electroweak symmetry breaking and rotating to the fermion mass eigenstate basis the coupling matrices are diagonalized

and the fermions acquire masses given by $m_f = \frac{h_f \nu}{\sqrt{2}}$. The Higgs to fermion coupling term becomes $\frac{m_f}{\nu} \bar{f} f H$. Thus, the fermions have acquired mass and the Higgs coupling to the fermions is proportional to the mass of the fermion in question. The Dirac neutrino masses can also be included in this framework if one considers the right handed neutrinos. It has to be noted that the fermion mass parameters have been replaced by the Yukawa couplings. Finally the Lagrangian for the fermion fields ψ_i after the electroweak symmetry breaking reads:

$$\begin{aligned} \mathcal{L}_{\mathcal{F}} = & \sum_i \bar{\psi}_i (i\partial - m_i - \frac{m_i H}{\nu}) \psi_i - \frac{g}{2\sqrt{2}} \sum_i \bar{\Psi}_i \gamma^\mu (1 - \gamma^5) (T^+ W_\mu^+ + T^- W_\mu^-) \Psi_i \\ & - e \sum_i Q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu - \frac{g}{2 \cos \theta} \sum_i \bar{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z_\mu, \end{aligned} \quad (1.20)$$

where $e = g \sin \theta$ is the magnitude of the electron electric charge. The vector and axial-vector couplings are given as $g_A^i = t_3^i$ and $g_V^i = t_3^i - 2Q^i \sin^2 \theta$, where the t_3^i is the weak isospin of fermion i . The $T^\pm$ are the weak isospin raising and lowering operators. The source of the CP violation in the Lagrangian is encoded in the CKM matrix.

It is interesting to consider the number of free parameters in the SM (ignoring the neutrino masses). There are 9 Yukawa couplings for each fermion. The CKM matrix is unitary and thus has 4 parameters. The 3 coupling constants for each gauge component: g_s, g, g' , the vacuum expectation value (ν), the self coupling parameter λ of the Higgs field, and the θ in the QCD Lagrangian are the remaining parameters. Thus, there are 19 free parameters in the SM theory of elementary particles.

1.1.4 Extended Higgs Sector

The SM theory of elementary particles has been remarkably successful in describing the present experimental observations. However, there are number of undesirable aspects of the theory necessitating an effort to improve our understanding of nature. The large number of free parameters in the model (19), the strong CP problem, the naturalness problem, the inclusion of gravity in the SM, and understanding the

generation of the neutrino masses are few examples to consider. There is also no candidate for the non-baryonic dark matter in the SM.

The SM Higgs boson is a scalar particle and is therefore susceptible to the ultraviolet (UV) divergent radiative quadratic loop corrections. For example, a Dirac fermion loop introduces a correction to the Higgs boson mass given by:

$$m_{SM}^2 = m_{\text{bare}}^2 - \frac{|\lambda_f|^2}{16\pi^2} \Lambda^2, \quad (1.21)$$

where the λ_f is the Yukawa coupling and Λ is the ultraviolet cut-off scale. If the cut-off scale is at the Planck scale of 10^{19} GeV then dramatic cancellations (fine tuning) are required on the right hand side of the Equation (1.21) to achieve a Higgs boson mass of the order of the electroweak scale. Supersymmetry is one of the proposed solutions to this naturalness problem where one introduces a new symmetry in nature between the bosons and fermions [35, 36]. A detailed introduction to the supersymmetry can be found in [37]. The quadratic corrections to the Higgs boson mass have opposite signs for the fermion and boson loop corrections. In supersymmetry theories every SM fermion (boson) has a super-partner boson (fermion) providing a natural cancelation of the quadratic loop divergences. The supersymmetry is a broken symmetry as there are no hints of the super-partners in the experimental data. The naturalness problem is still a concern if the scale at which the symmetry breaks is larger than 1 TeV.

The Minimal Supersymmetric Standard Model (MSSM) is the simplest extension of the SM to include the ideas of the supersymmetry [38, 39]. The Higgs sector in the MSSM considers an additional scalar Higgs doublet (2HDM) with hypercharge of $Y = -1$ given by:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^0 + ia_1^0 \\ \sqrt{2}\phi_1^- \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_2^+ \\ \phi_2^0 + ia_2^0 \end{pmatrix}. \quad (1.22)$$

Analogous to the SM case, the scalar fields acquire vacuum expectation values as the electroweak symmetry is spontaneously broken. There are eight degrees of freedom in the two doublets leading to five physical Higgs bosons after the electroweak symmetry

breaking:

$$\begin{aligned}
H^\pm &= \sin \beta \phi_1^\pm + \cos \beta \phi_2^\pm \\
A &= \sin \beta \text{Im} \phi_1^0 + \cos \beta \text{Im} \phi_2^0 \\
H &= \cos \alpha (\text{Re} \phi_1^0 - \nu_1) + \sin \alpha (\text{Re} \phi_2^0 - \nu_2) \\
h &= -\sin \alpha (\text{Re} \phi_1^0 - \nu_1) + \cos \alpha (\text{Re} \phi_2^0 - \nu_2),
\end{aligned} \tag{1.23}$$

where $\nu_i = \langle \phi_i^0 \rangle$ are the vacuum expectation values satisfying the requirement $\nu_{SM}^2 = \nu_1^2 + \nu_2^2$. Thus, there are two neutral CP-even states h and H , and one neutral CP-odd state A . There is also a charged Higgs boson pair $H^\pm$. The mixing angle is related to the ratio of the vacuum expectation values: $\tan \beta = \frac{\nu_2}{\nu_1}$. The h (H) denotes the light (heavy) CP-even Higgs boson. The couplings of the H and A bosons to the down type quarks and leptons have an additional factor of $\tan \beta$ enhancing the decay of the heavy neutral bosons to down type fermions for large $\tan \beta$ values. At tree level the MSSM Higgs sector is determined by two parameters: $\tan \beta$ and the mass of one of the Higgs bosons (m_A is typically chosen). The mass spectrum is given by:

$$\begin{aligned}
m_{H,h}^2 &= \frac{1}{2} \left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta} \right), \\
m_{H^\pm}^2 &= m_A^2 + m_W^2.
\end{aligned} \tag{1.24}$$

For m_A much larger than the mass of the Z boson (decoupling limit) the heavy scalars are almost degenerate $m_H \approx m_{H^\pm} \approx m_A$. There is also an upper bound on the lightest Higgs boson given by $m_h \leq m_Z \cos 2\beta$. However, the radiative corrections are important and an upper bound of about 135 GeV is possible [40]. The strategy in interpreting the experimental results in the MSSM is to fix the parameters that enter through the radiative corrections (benchmark scenarios) and explore the parameter space in $m_A - \tan \beta$ plane. The discovery of the Higgs boson at mass of 125 GeV invites to interpret the h as the discovered boson and search for the heavier scalars appearing in the MSSM. Few benchmark scenarios are considered in the results [41, 42].

1.2 The Large Hadron Collider

The LHC [21] is a circular proton-proton collider located at the European Organization for Nuclear Research (CERN). The tunnel housing the LHC has a circumference of 26.7 km and previously hosted the Large Electron-Positron (LEP) [43, 44] collider. Located at the border of France and Switzerland, the tunnel lies between 45 m and 170 m below the surface. The LHC is designed to collide beams of protons at center-of-mass energy $\sqrt{s}$ of up to 14 TeV. While the LHC is primarily a proton-proton collider, lead (Pb) ion beams of energy of up to 2.3 TeV per nucleon are used to produce lead-lead and proton-lead collisions.

Figure 1-2 shows a schematic representation of the accelerator complex at CERN. Ionized hydrogen atoms are accelerated to an energy of 50 MeV in the Linac 2 linear accelerator. Thereafter, they are injected into the Proton Synchrotron Booster (PSB) and Super Proton Synchrotron (SPS) raising the energy to 25 GeV and 450 GeV, respectively. From the SPS the protons are injected into two separate rings in discrete bunches. At the design bunch spacing of 25 ns there are up to 2808 proton bunches per beam.

The LHC operates as a synchrotron where the design beam energy is achieved with 1232 dipole magnets (15 meters in length) with a peak dipole field of 8.33 Tesla. Quadrupole magnets (492) of 5–7 meters in length are used to focus the beams. Two beam pipes with counter rotating beams are required as the LHC is a particle-particle accelerator. Space limitations in the tunnels led to the adoption of the twin-bore [46] magnet design where the beam pipes are magnetically coupled and the magnets share the same mechanical structure and cryostat. The target magnetic field is achieved using niobium-titanium superconducting electromagnets with operating temperatures of 1.9 K. Superfluid helium is used to cool the magnets to the operating temperature. The rate of events generated in the LHC collisions is given by

$$N = \sigma L, \tag{1.25}$$

where σ is the cross section of the event under study and L is the luminosity.

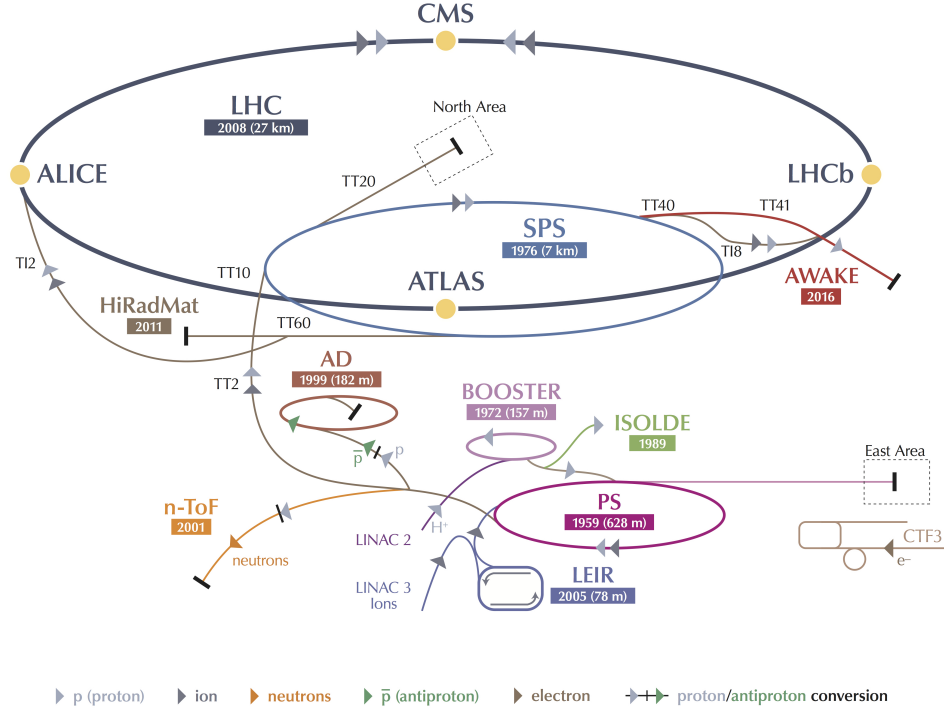


Figure 1-2: A schematic representation of the CERN accelerator complex [45].

Figure 1-3 shows the production cross sections of various SM processes as a function of $\sqrt{s}$ in proton-proton and proton-antiproton collisions. The rare processes of interest at the LHC are orders of magnitude smaller than the total inelastic cross section. Therefore, in addition to high beam energies, high beam intensities are required. The design peak luminosity at the LHC is $10^{34} \text{ cm}^2\text{s}^{-1}$ for the proton-proton collisions. The large beam intensity requirement excludes the feasibility of using proton-antiproton collisions at the LHC.

For a Gaussian beam distribution the machine luminosity is given by:

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F, \quad (1.26)$$

where N_b is the number of particle per bunch ($\mathcal{O}(10^{11})$), n_b is the number of bunches per beam, f_{rev} is the revolution frequency, γ_r is the Lorentz factor, ϵ_n is the normalized transverse beam emittance, β^* is the beta function, related to the beam transverse

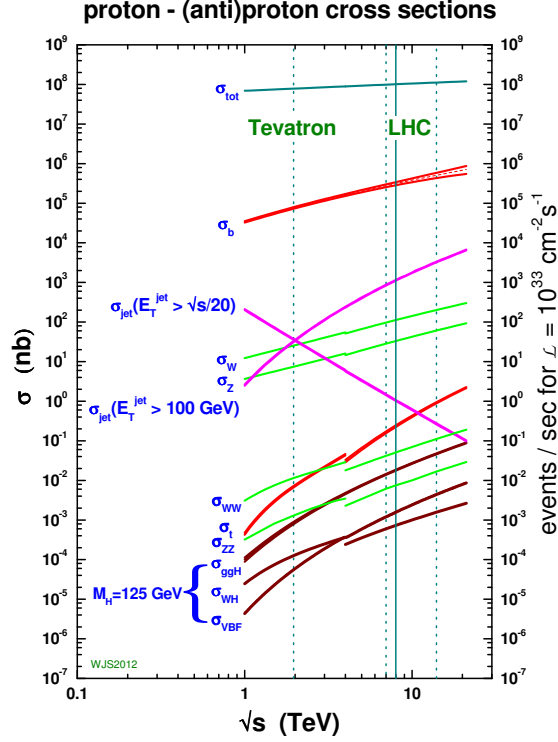


Figure 1-3: Cross sections of various SM processes as a function of $\sqrt{s}$ in proton-proton and proton-antiproton collisions [47]. The total hadronic cross section is based on a parameterization from Particle Data Group [19]. The remaining cross sections are calculated at NLO or NNLO using MSTW2008 parton distributions [48]. The discontinuities illustrate the differences in cross sections between the proton-proton and proton-antiproton collisions.

size at the collision point, and F is the geometric luminosity reduction factor due to the crossing angle at the interaction point. The LHC has four interaction points that host the ALICE [50], ATLAS [51], CMS [52], and LHCb [53] detectors. The ATLAS and CMS are general purpose, high luminosity experiments. The LHCb is a forward detector specializing in heavy flavor physics. The ALICE experiment is designed to study heavy-ion collisions.

Figure 1-4 shows the total integrated luminosity delivered to CMS during stable beams from October, 2010 to October, 2016 data taking periods. The LHC delivered proton-proton collisions at $\sqrt{s}$ of 7 TeV during 2010 and 2011. The total integrated luminosity delivered in 2011 was 6.1 fb^{-1} with a peak instantaneous luminosity of

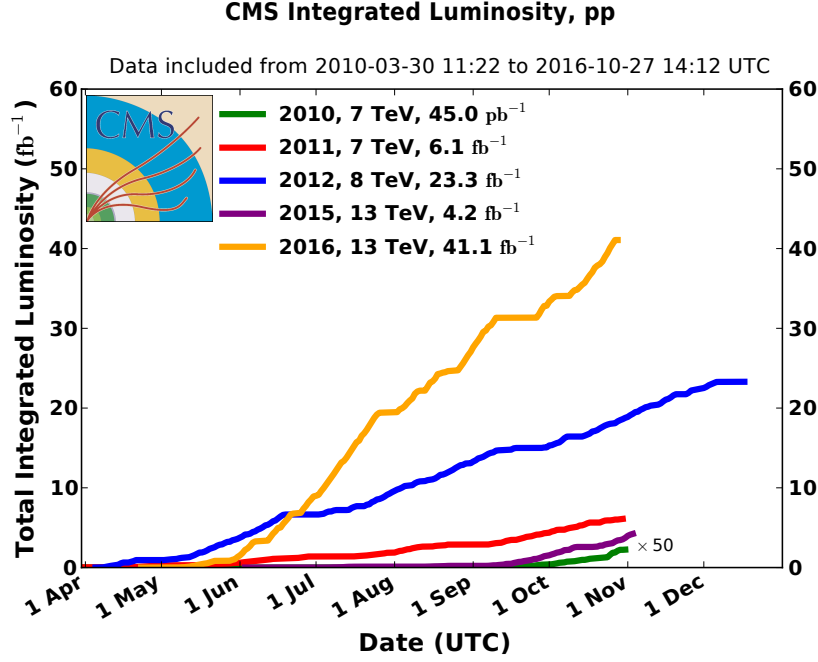


Figure 1-4: The total integrated luminosity delivered to CMS during stable beams in proton-proton collisions [49]. It is shown for 2010 (green), 2011 (red), 2012 (blue), 2015 (purple), and 2016 (orange) data taking periods.

$4.0 \times 10^{33} \text{ cm}^2 \text{ s}^{-1}$. The luminosity recorded and certified, where all the detector sub-components are confirmed to operate normally, for physics results was 5.1 fb^{-1} . $\sqrt{s}$ was increased to 8 TeV in 2012 with 23.3 fb^{-1} total integrated luminosity delivered to CMS with a peak instantaneous luminosity of $7.7 \times 10^{33} \text{ cm}^2 \text{ s}^{-1}$. The total certified data amounted to 19.7 fb^{-1} . A bunch spacing of 50 ns was used in the 2011 and 2012 data taking periods.

The LHC entered the Long Shutdown 1 (LS1) in 2013 for maintenance and upgrades during which the CMS detector was upgraded as well. The data taking resumed in 2015 with 4.2 fb^{-1} total integrated luminosity delivered to CMS with a peak instantaneous luminosity of $5.1 \times 10^{33} \text{ cm}^2 \text{ s}^{-1}$. The LHC started to operate with the nominal bunch spacing of 25 ns during this period. The total certified data for the nominal CMS operation and bunch spacing of 25 ns amounted to 2.3 fb^{-1} . The data taking continued in 2016 with an excellent performance by the LHC with significantly lower transverse beam sizes. This was achieved using a new bunch production scheme which resulted in a peak luminosity of $1.5 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$. Total

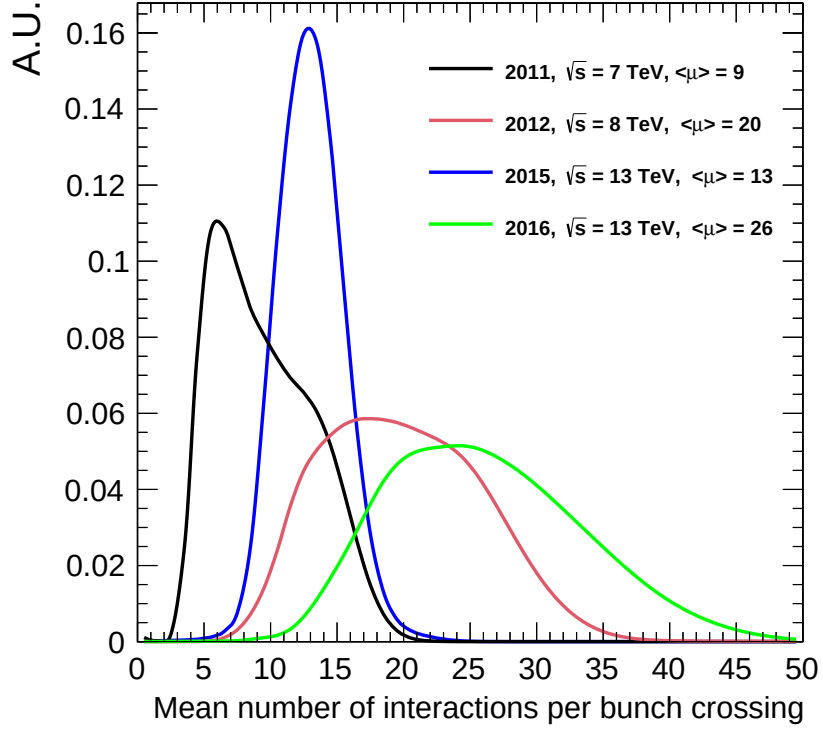


Figure 1-5: Mean number of interactions per bunch crossing in proton-proton collisions. A detailed description of the luminosity measurements in CMS can be found here [54, 55]. The distributions are shown for 2011 (black), 2012 (red), 2015 (blue), and 2016 (green) data taking periods.

integrated luminosity of 41.1 fb^{-1} was delivered. Figure 1-5 shows the mean number of additional inelastic proton-proton interactions per bunch crossing (pileup) for 2011 (black), 2012 (red), 2015 (blue), and 2016 (green) data taking periods. The additional pileup interactions in events present challenges in reconstruction and identification of the particles originating from the hard scattering process of interest. The average number of pileup interactions in 2011 was nine as the instantaneous luminosity continuously increased during the year. The average number of pileup interactions further increased to twenty in 2012 and reached to twenty four during 2016. While higher instantaneous luminosities are desired to enhance the production of the events of interest, the effects of pileup need to be mitigated to maximize the sensitivity of the results.

1.3 Proton-Proton Collisions and Event Simulation

The W , Z , and Higgs bosons are produced via the interactions of the quarks and gluons (referred as partons) inside the protons of the LHC colliding proton beams [56, 57].

The cross section of a process is given by:

$$\begin{aligned} \sigma_{p_a p_b \rightarrow n} = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, \mu_F^2) f_{b/B}(x_b, \mu_F^2) \\ \times [\hat{\sigma}_{LO}(x_a x_b s, \mu_R^2, \mu_F^2) + \alpha_s(\mu_R^2) \hat{\sigma}_{NLO}(x_a x_b s, \mu_R^2, \mu_F^2) + \dots], \end{aligned} \quad (1.27)$$

where $f_{a/A}$, $f_{b/B}$ are the parton distribution functions (PDFs) for the quarks and gluons inside the proton, x_i is the relative parton momentum in the direction of proton (Bjorken- x), and $\hat{\sigma}$ denote the parton-parton cross section at the center-of-mass energy $\sqrt{x_a x_b s}$, where s is the squared of the proton-proton center-of-mass energy. This is illustrated in Figure 1-6 for the Z boson production. The PDFs can not be described through perturbative calculations. However, the collinear factorization theorem can be applied to separate the perturbative and non-perturbative regimes in Equation (1.27) [58]. The scale at which this separation happens is denoted as the factorization scale μ_F . The basic idea is to absorb the large logarithms appearing in the calculations due to collinear emissions of the parton into the PDFs. This scale dependence of the PDFs is described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) parton evolution equations allowing to evolve a given PDF parametrization to a desired scale [59, 60, 61]. Parameterized functional forms are fitted to data and then evolved to a scale of interest by solving the DGLAP equations either at leading-order (LO), next-to-leading-order (NLO) or NNLO accuracy in perturbative QCD. PDF fits by several collaborations are used in the results.

The matrix elements (ME) needed to evaluate the partonic cross sections are performed using a Monte Carlo (MC) sampling to integrate the phase space. The QCD ME calculations are done up to a fixed number of final state partons. The transverse momenta of the bosons are zero at LO calculations. The real emissions in the higher order QCD corrections can explain the observed p_T distributions of the

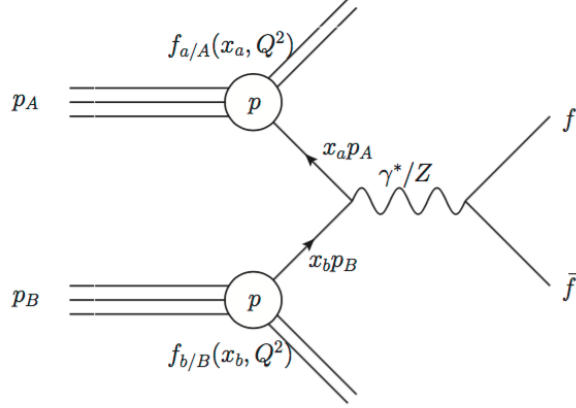


Figure 1-6: Illustration of the Z boson production in proton-proton collisions. The parton momenta are given by $x_a p_a$ and $x_b p_b$ [62].

W and Z bosons for example (there is also a very small boson p_T due to a small transverse momentum of the partons inside the proton). Thus, the measurement of the p_T distributions of these bosons provides new constraints in understanding the higher order QCD (and electroweak) corrections. Large logarithmic corrections appear in the fixed order calculations at small vector boson p_T due to collinear gluon emissions. These logarithmic corrections due to these emissions cancel with the virtual corrections for the inclusive calculations. Resummation can be carried out to provide accurate predictions of the vector boson p_T at the low values of the p_T [63].

ME calculations at fixed orders break down for soft momenta and collinear final state partons. Parton shower models are used to evolve the partons from the hard scales to the non-perturbative hadron scales. The parton showers are modeled as a sequence of branchings: $q \rightarrow qg$, $g \rightarrow q\bar{q}$, and $g \rightarrow gg$ in QCD and $q \rightarrow q\gamma$ and $\ell \rightarrow \ell\gamma$ in quantum electrodynamics (QED), where q , g , ℓ , and γ denote a quark, gluon, lepton, and photon, respectively [62]. The branchings from the initial and final partons add additional outgoing partons in the event. It has to be noted that unlike the ME approach, the parton method does not include the spin effects.

The parton showering is continued up to the scale $\Lambda_{QCD} \approx 200$ MeV. The final partons are hadronized into color-neutral hadrons to obtain the full generated event simulation. The models are tuned to the data. The unstable hadrons (trav-

eling less than few mm) are decayed according to the branching ratios. Additional parton-parton interactions in the colliding protons, known as multi-parton interactions (MPI), are included as well. The specific software tools utilized to generate the simulated events used in the results are referenced in chapter 4.

1.4 The W, Z , and Higgs Boson Productions at the LHC

The production of the electroweak gauge bosons at the LHC proton-proton collisions proceeds mainly via the Drell-Yan process [64]. At least one sea quark is required to produce the gauge bosons in the proton-proton collisions and it is dominated by $u\bar{d} \rightarrow W^+$, $d\bar{u} \rightarrow W^-$, and $u\bar{u}, d\bar{d} \rightarrow Z$ processes. The relations between the mass M and rapidity y of the vector boson and the kinematics of the colliding partons are given by:

$$\begin{aligned} M^2 &= x_1 x_2 s, \\ y &= \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) = \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right), \\ x_{1/2} &= \frac{M}{\sqrt{s}} \exp(\pm y). \end{aligned} \tag{1.28}$$

This is illustrated in Figure 1-7. Hence, for the W and Z boson production with masses of $\mathcal{O}(100 \text{ GeV})$ and rapidity $|y| < 2.5$ the Bjorken- x values are in the range of 10^{-3} to 0.1. Theoretical predictions of the inclusive W and Z production cross sections are available at NNLO in perturbative QCD [65, 66, 67, 68, 69]. The precision of the predictions is limited by the uncertainties in the PDFs and higher order QCD and electroweak (EWK) corrections. The energy scale of the process means that the sea quarks in the protons are mainly due to the gluon splitting, $g \rightarrow q\bar{q}$, and therefore the uncertainty of the gluon PDFs plays a role as well.

The leptonic decays of the W and Z bosons provide a large dataset of relatively pure and isolated leptonic events. $Z \rightarrow \ell\ell$ events can be used to calibrate the detector

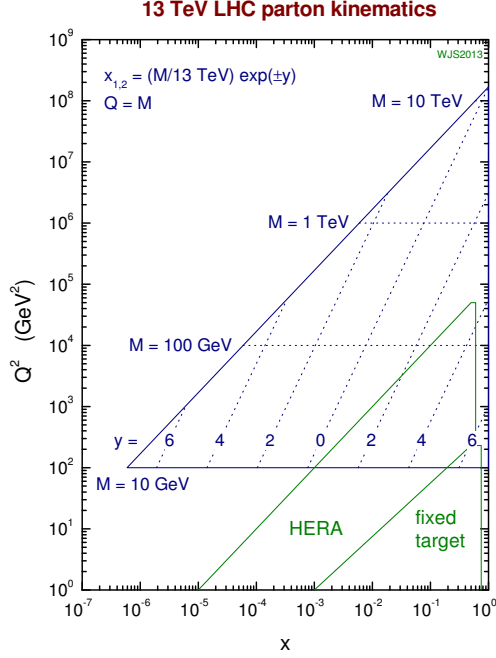


Figure 1-7: Available kinematic plane in Bjorken- x and the scale of the process Q^2 at the LHC center-of-mass energy $\sqrt{s} = 13$ TeV. M and y are the mass and rapidity of the final state parton. The corresponding plane for the deep inelastic experiments is shown in green [47].

as well as the stability of the luminosity measurement of the proton-proton collisions. The inclusive total cross section measurements and ratios test the perturbative higher order corrections and constrain the PDFs of the protons. The importance of the higher order QCD corrections on the boson transverse momenta distribution was discussed in the last section. Better understanding of these effects allows to make precise measurements of the fundamental electroweak parameters such as the mass of the W boson and the electroweak mixing angle. In addition, the W and Z boson production is a background source for the SM Higgs boson studies and many BSM physics searches.

Figure 1-8 shows the main leading order Feynman diagrams contributing to the SM Higgs boson production at the LHC. The gluon fusion production, where the Higgs boson is produced from an intermediate quark loop, is the dominant mode [70]. It is

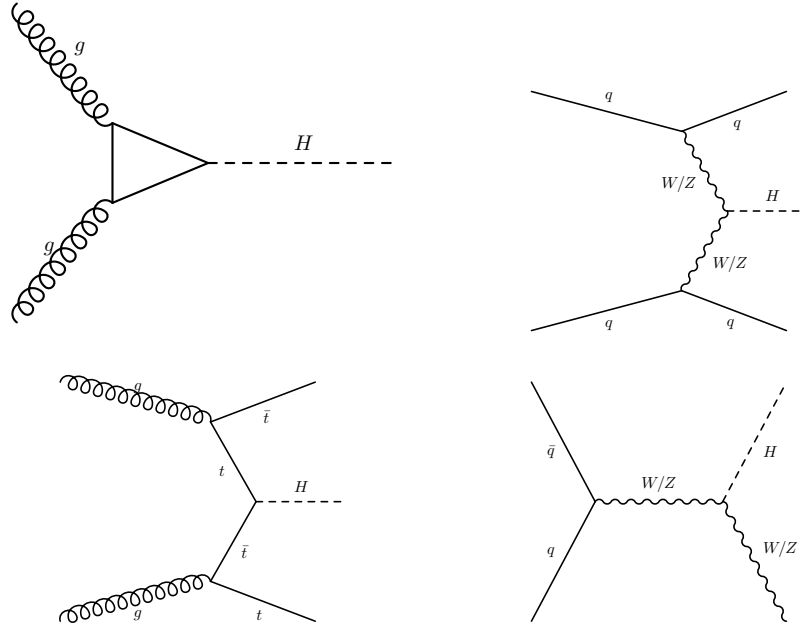


Figure 1-8: Leading order Feynman diagrams contributing to the SM Higgs boson production at the LHC in gluon fusion (top left), vector boson fusion (top right), Higgsstrahlung (bottom left), and top quark associated production (bottom right).

dominated by the top quark loop as the Higgs coupling to fermions is proportional to the mass of the fermion in question. The Vector Boson Fusion (VBF) production [71], where the Higgs boson is produced from an intermediate W/Z bosons radiated from the colliding quarks, has an interesting experimental signature that can be exploited. The VBF produced Higgs boson events are produced in association with two high energy forward jets (jets are discussed in chapter 3) in the opposite regions of the detector. There is typically very little hadronic activity in the central region of the detector as there is no "color flow" between the quarks. Higgsstrahlung [72], where the Higgs boson is radiated from a W or Z boson produced in s channel at leading order, is the next largest Higgs boson production mode. The Higgs bosons produced in VBF and Higgsstrahlung processes tend to have higher transverse momenta compared to Higgs bosons produced in the gluon fusion mode. The Higgs boson can also be produced in association with a top and anti-top pair [73, 74, 75, 76]. There are other Higgs boson production modes, not relevant for the current Higgs boson studies, that will be important to consider at higher integrated luminosities at the LHC. The

SM Higgs boson production cross sections are shown in Figure 1-9 as a function of the Higgs boson mass at $\sqrt{s} = 8$ TeV and as a function of $\sqrt{s}$ for the Higgs boson mass of 125 GeV. The individual cross sections for the four Higgs boson production mechanisms discussed above are shown. The calculations are done up to NNLO in QCD and NLO in EWK [77, 78, 79]. The gluon fusion predictions are also resummed to next-to-next to leading logarithmic (NNLL) accuracy. The total production cross section is 22.3 pb at $\sqrt{s} = 8$ TeV and 50.6 pb at $\sqrt{s} = 13$ TeV for the Higgs boson mass of 125 GeV. Recent calculations with N^3LO accuracy in QCD for the gluon fusion [80] and VBF production modes [81] have become available.

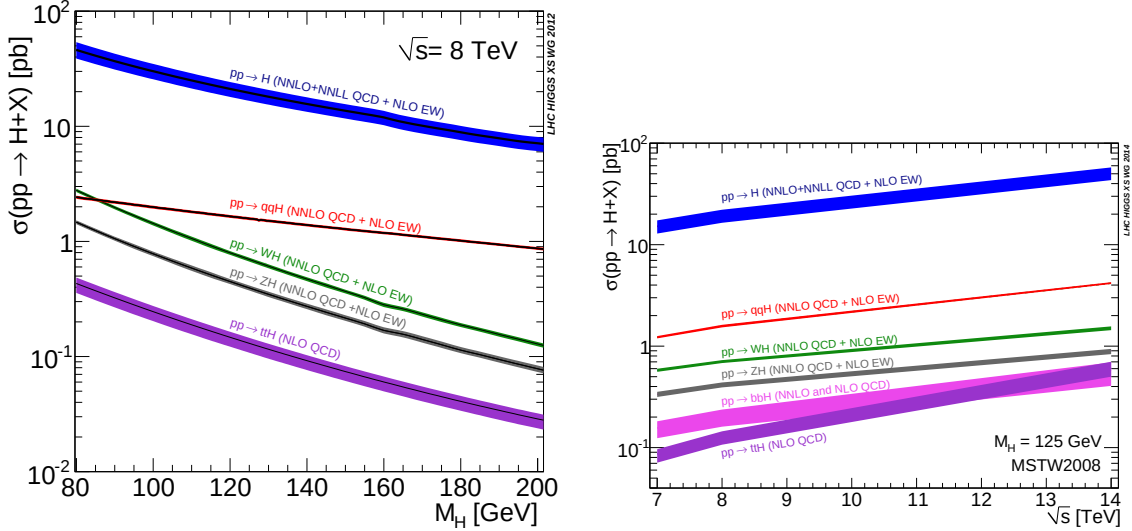


Figure 1-9: Higgs boson production cross sections for the different production modes as a function of the Higgs boson mass at $\sqrt{s} = 8$ TeV (left panel) and center-of-mass energy $\sqrt{s}$ for the Higgs boson mass of 125 GeV (right panel) [77, 78, 79].

The SM Higgs boson branching fractions and the total width are shown as a function of the mass in Figure 1-10. The total width is at the order of few MeV for the low Higgs boson masses. Higgs boson decays to $b\bar{b}$, $\tau^+\tau^-$ and $c\bar{c}$ are the dominating decay modes at very low Higgs boson mass as there is no phase space available for the Higgs boson decays to W^+W^- and ZZ . Decays to gg , $\gamma\gamma$, and $Z\gamma$ are possible through loops. For the $\gamma\gamma$ and $Z\gamma$ mode there is an interference between the fermion and W loops. At the Higgs boson mass of 125 GeV the branching ratio to the $\tau^+\tau^-$ final state is 0.063.

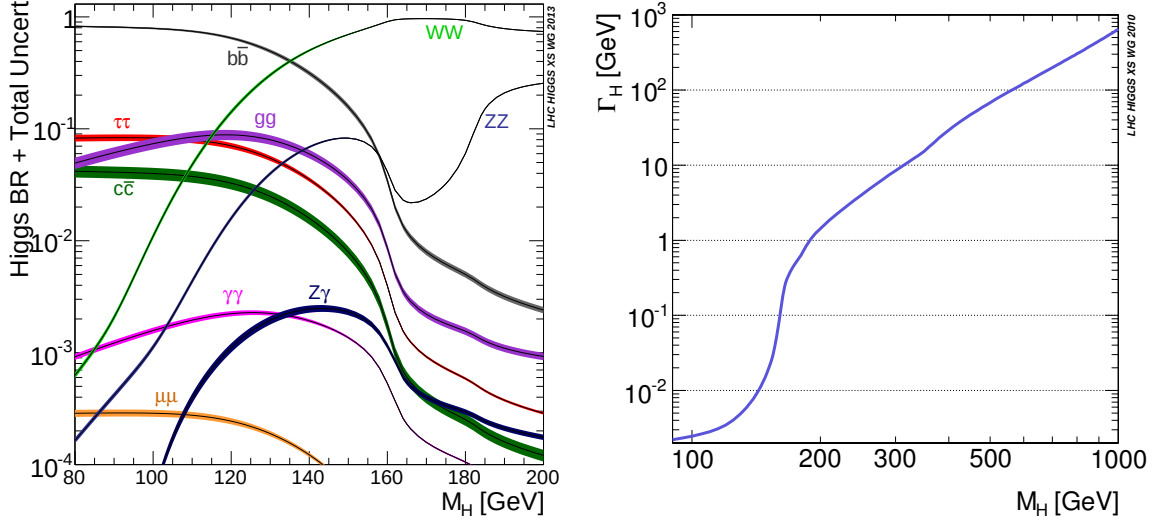


Figure 1-10: The largest Higgs boson branching ratios as a function (left panel) and total width as a function of the Higgs boson mass. The bands show the uncertainties in the branching fractions [77, 78, 79].

It is also possible to study the SM Higgs trilinear coupling by considering the Higgs boson pair-production as can be deduced from the Lagrangian in Equation (1.17) [82, 83, 84, 85, 86, 87, 88]. This measurement would directly probe the potential of the Higgs field. The process is also sensitive to other BSM effects, as BSM physics can modify the rate of the production. Figure 1-11 shows the dominant Feynman diagrams for the gluon fusion production mode. Higgs boson pairs can be produced via a box diagram (left) and through the Higgs self-coupling contribution. The two processes interfere destructively. In fact, the cross section is larger by a factor of two if only the box diagram is considered. The gluon fusion production cross section for the Higgs boson pair production has been calculated to NNLO accuracy in QCD [89, 90]. The cross section is 40.7 fb at $\sqrt{s} = 14$ TeV. One can see that the SM Higgs boson pair production cross section is an order of magnitude smaller than the single Higgs boson production. Therefore, this process can be measured at the LHC only with very high integrated luminosities.

The main MSSM Higgs boson production modes are shown in Figure 1-12. The gluon fusion and associated b quark production modes dominate. The production cross sections of the three neutral Higgs bosons h , H , and A for one of the commonly

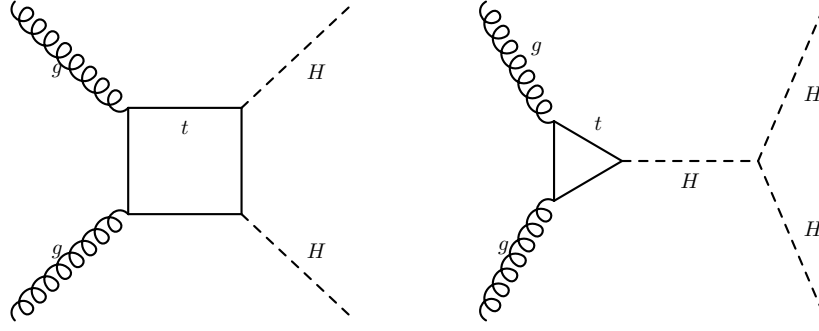


Figure 1-11: Leading order Feynman diagrams contributing to the gluon fusion Higgs boson pair production at the LHC. The right diagram is the Higgs self-coupling contribution to the Higgs boson pair production.

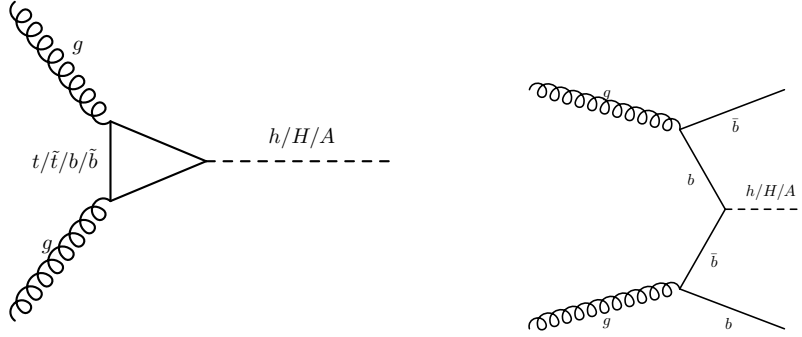


Figure 1-12: Leading order Feynman diagrams contributing to the production of the MSSM Higgs bosons in gluon fusion (left) and b quark associated production (right).

used benchmark scenarios are shown in Figure 1-13 at $\sqrt{s} = 8$ TeV as a function of the CP-odd Higgs boson mass. The left (right) panel shows the cross sections with $\tan\beta = 5$ ($\tan\beta = 30$). The b quark associated production cross section is enhanced for larger $\tan\beta$ values as the coupling of the neutral MSSM Higgs bosons to fermions scales with $\tan\beta$. Correspondingly, the heavy neutral bosons H and A mainly decay to $b\bar{b}$ and $\tau^+\tau^-$ final states for large values of $\tan\beta$. Figure 1-14 shows the branching fractions of the CP-odd Higgs boson as a function of the mass with $\tan\beta = 5$ (left) and $\tan\beta = 30$ (right). Thus, the search for the MSSM heavy neutral Higgs bosons with $\tau^+\tau^-$ decay channel is strongly motivated taking into account the experimental difficulties of the corresponding searches using the $b\bar{b}$ decay channel.

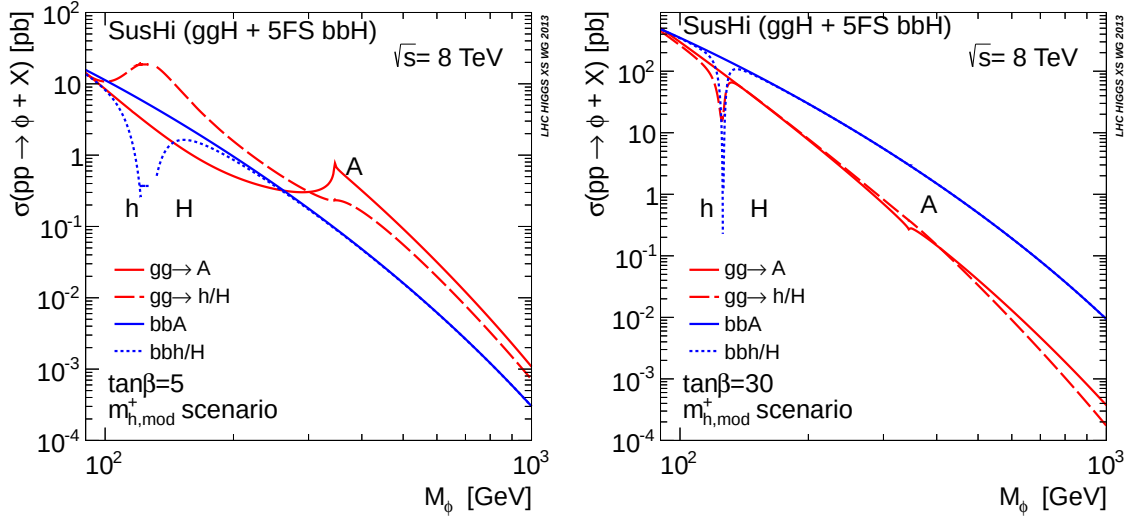


Figure 1-13: Neutral Higgs boson production cross sections as a function of the CP-odd Higgs boson mass in the m_h^{mod+} benchmark scenario with $\tan\beta = 5$ (left panel) and $\tan\beta = 30$ (right panel) [77, 78, 79].

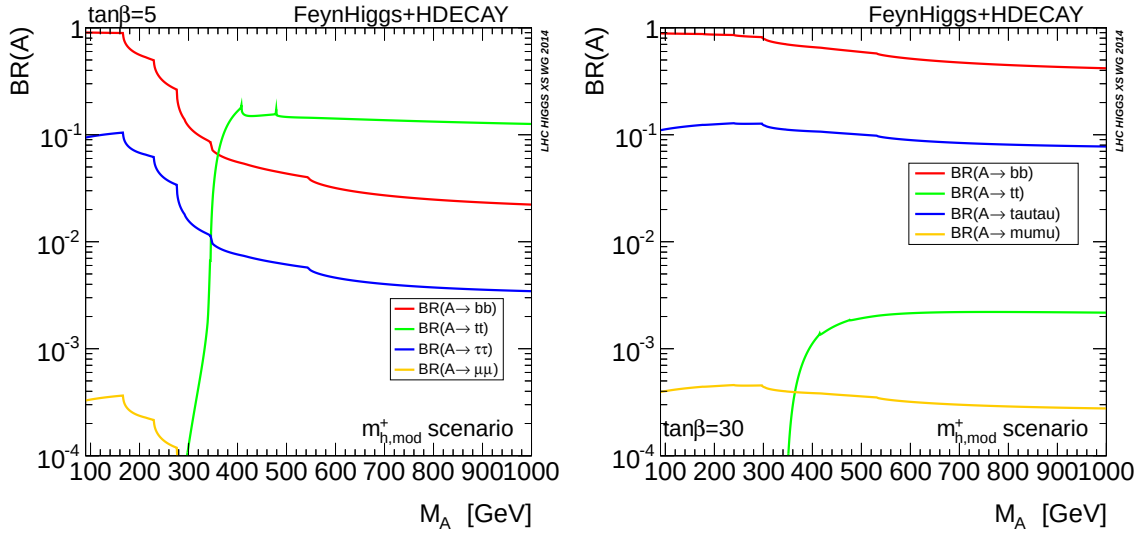


Figure 1-14: Neutral CP-odd Higgs boson branching fractions as a function of the mass in the m_h^{mod+} benchmark scenario with $\tan\beta = 5$ (left panel) and $\tan\beta = 30$ (right panel) [77, 78, 79].

Chapter 2

The CMS Experiment

The major goal of the CMS detector [52] is to elucidate the EWSB through the discovery of the Higgs boson. However, CMS is a general purpose detector, enabling to perform precision SM measurements as well BSM physics searches at the TeV scale. The detector requirements, driven by the physics program, include good reconstruction efficiency and momentum resolution of charged particles, good electromagnetic energy resolution, as well as good di-jet mass and missing energy resolutions. The large number of charged particles per interactions and the additional pileup interactions require a high granularity detector to be able to reconstruct all the individual charged particles. Furthermore, a bunch spacing of 25 ns requires a detector with good time resolution to be able to resolve the individual bunch crossings.

The overall layout of the CMS detector is shown in Figure 2-1. The detector is composed of several sub-detector layers with a length of 22 m and a diameter of 15 m. It has a cylindrical geometry with concentric barrel shaped detectors in the central region and disc shaped detectors in the forward region. The main feature of the CMS detector is a 3.8 Tesla superconducting solenoid magnet that provides a large bending power to the charged particles. The length of the solenoid is 13 m and the inner diameter is 6 m. The inner tracking detectors, electromagnetic, and hadron calorimeters are located inside the solenoid. The muon detectors are embedded in the steel flux-return yoke of the magnet providing a sufficient magnetic field for a large bending power of the muons inside the muon detectors. The total weight of the CMS

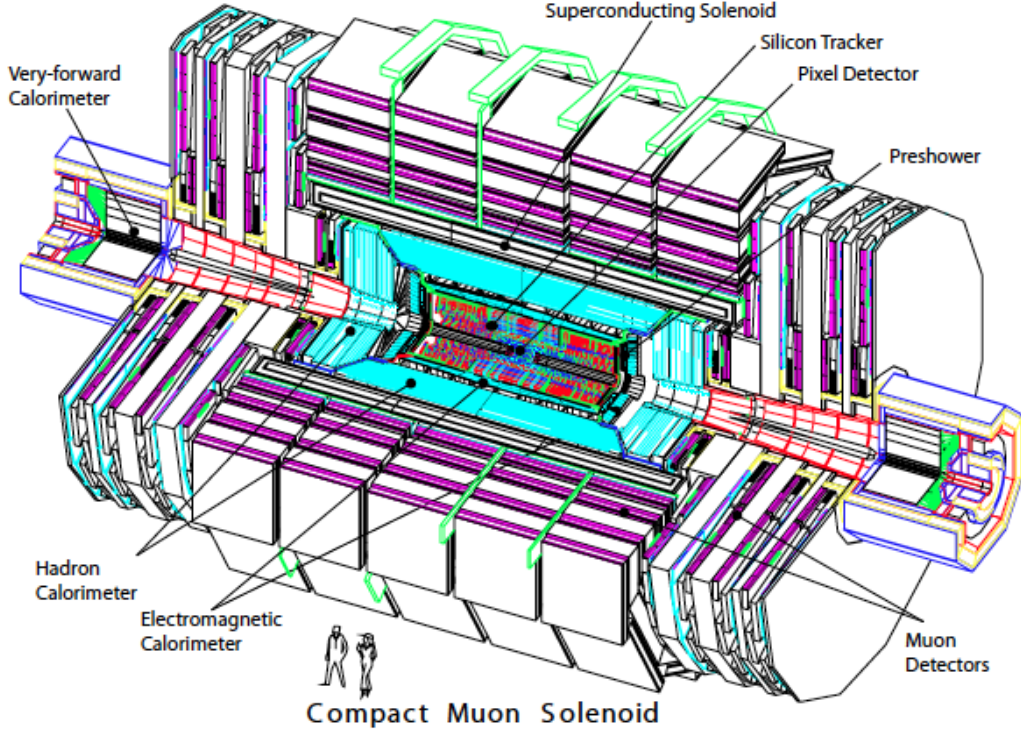


Figure 2-1: A cutaway diagram of the CMS detector. The labels identify the different sub-detectors and the solenoid.

detector is 12500 tonnes.

CMS uses the right-handed coordinate system. The origin is centered at the nominal collision point, x-axis is in the horizontal plane pointing towards the center of the LHC tunnel, y-axis points vertically upwards, and the z-axis points along the beam direction toward the Jura mountains. It is convenient to employ the spherical coordinate system. The polar angle θ is measured with respect to the positive z-axis and the azimuthal angle ϕ is measured from the positive x-axis in the x-y coordinate plane. The pseudorapidity is defined as $\eta = -\ln \tan(\frac{\theta}{2})$. A useful consequence of this definition is that the difference between the pseudorapidities of two particles is Lorentz invariant with respect to a boost in the beam direction. The separation of two particles is defined by $\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)}$. The momentum and energy transverse to the beam direction are denoted p_T and E_T , respectively. The imbalance of the measured transverse energy is defined as a missing energy and denoted by E_T^{miss} .

2.1 Inner Tracking Detectors

The inner tracking system [91, 92] surrounds the interaction point and has a length of 5.8 m and a diameter of 2.5 m. The goal of the inner tracking system is to make a precise and efficient measurement of the trajectories of charged particles as well as their momenta. In addition, a precise reconstruction of secondary vertices is needed for the identification of heavy-flavor particle decays. Tau lepton decays are identified by looking for one-prong and three-prong topologies, where prong refers to the number of charged particles, in the inner tracker. A homogenous solenoidal magnetic field of 3.8 Tesla over the full volume of the tracker is provided by the CMS solenoid.

There are $\mathcal{O}(1000)$ particles emerging from the interaction region at the nominal LHC luminosity for every 25 ns bunch crossing. Therefore, a high granular, fast, and radiation hard detector is required. On the other hand, this implies a large power density of electronics and the corresponding cabling and cooling systems which increases the amount of material, thereby enhancing multiple scattering, photon conversions, and bremsstrahlung processes. Silicon technology was chosen given the above considerations. Figure 2-2 shows a schematic view of the inner tracking system in $r - z$ plane. The inner tracking detector covers a pseudorapidity range of up to $|\eta| = 2.5$ and provides an average of 13 – 17 measurements per charged particle depending on the η region.

A pixelated detector has to be used close to the interaction region to keep the occupancy levels to less than 1%. Each pixel is a $p-n$ semiconductor junction. When a charged particle passes through the depletion region of the junction an electron-hole pairs are created and subsequently collected by the readout electronics. The tracking system consists of three barrel layers and two endcap disks. The barrel layers are located at radii of 4.4, 7.3, and 10.2 cm with a length of 53 cm. The endcap pixel layers are located at $z = \pm 34.5$ and $z = \pm 46.5$ cm covering approximately 6 to 15 cm in the radial direction. The pixel detector consists of 66 million pixel elements covering a surface area of approximately of 1 m². The pixel element size is $100 \times 150 \mu\text{m}^2$ providing a similar track resolution in both $r - \phi$ and $r - z$ directions. The

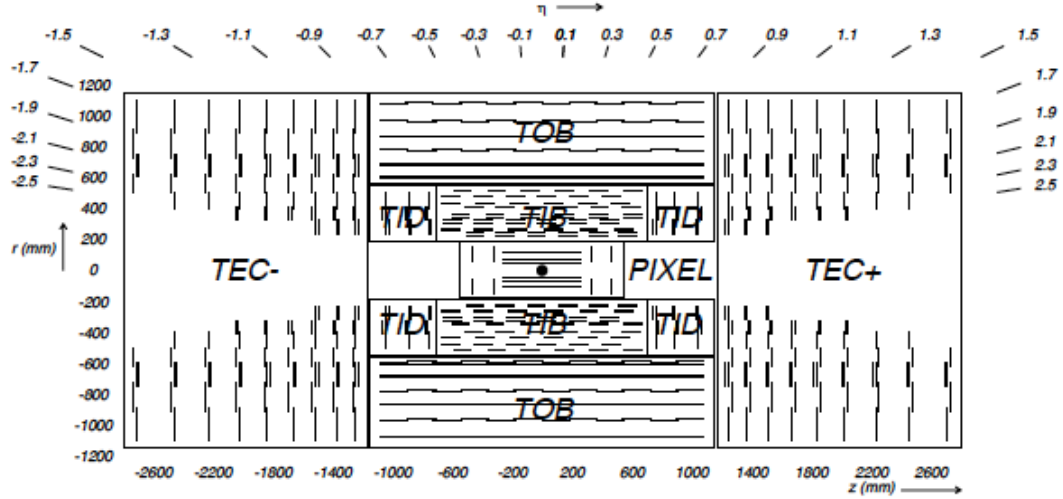


Figure 2-2: A schematic view of the CMS tracking system. Silicon pixel and strip detectors are shown. The double lines show back-to-back modules that deliver stereo hits.

Lorentz drift in the CMS magnetic field leads to a charge spreading of the collected signal charge between adjacent pixels. Using an analog pulse height read out the charge sharing allows to reduce a single hit spatial resolution to $15 - 20 \mu\text{m}$.

The outer tracker is occupied by a silicon strip tracker allowing two-dimensional measurements. Majority of the strips are oriented perpendicular to the ϕ direction, parallel to the beam direction in the barrel region and aligned radially in the endcap region. The tracker Inner Barrel (TIB) is located in the barrel region and extends from 20 cm to 55 cm in the radial direction. There are 6 additional layers with an outer radius of 116 cm composing the Tracker Outer Barrel (TOB) and extending in $|z|$ to 118 cm. The Tracker Disk (TID) consists of 3 layers located from $|z|$ of 80 to 90 cm. The Tracker EndCap (TEC) has nine layers and covers the region between $|z|$ of 124 and 282 cm. These radial strips provide up to 9 ϕ measurements for each trajectory. The silicon strip tracker has a total of 9.3 million strips and covers a surface area of 198 m^2 . The strip pitch varies between 80 and $184 \mu\text{m}$ depending on the region of interest. In addition, there is a second strip module mounted back-to-back with a stereo angle of 100 mrad in the first layers. This allows a measurement of the z and r coordinates in the barrel and disks, respectively. The corresponding

resolution in z coordinate is 230 to 530 μm in TIB and TOB, respectively.

2.2 Electromagnetic Calorimeter

The goal of the CMS electromagnetic calorimeter (ECAL) [93, 94] is to measure the energy of electrons and photons. ECAL is a homogeneous and hermetic calorimeter made of 61200 lead tungstate (PbWO_4) crystals in the central barrel region (EB) and 14648 crystals in the endcap region (EE). A homogeneous calorimeter was chosen to achieve the best energy resolution as one of the driving criteria was the precise measurement of the decay of the Higgs boson to two photons. Incident photons and electrons initiate an electromagnetic shower in the PbWO_4 crystals. The particles in the shower produce blue-green scintillation light as they excite the crystals and the scintillation light is measured by the photodetectors to determine the energy deposited in the crystals.

Lead tungstate high density (8.3 g/cm^3) crystals were chosen to satisfy the challenging operational requirements at the LHC. The scintillation decay time of these crystals is of the same order as the LHC bunch crossing with 80% of the light emitted in 25 ns. A short radiation length of $X_0 = 0.89 \text{ cm}$ and a small Moliere radius of 2.2 cm allows to have a fine granular and a compact calorimeter while still containing the electromagnetic showers in longitudinal and transverse directions. The crystals are radiation hard but there is a transparency loss under exposure to an ionizing radiation with a dynamical recovery when there are no collisions. The transparency loss is corrected with a dedicated laser monitoring system. Additional residual corrections are performed as well.

Figure 2-3 shows the layout of the ECAL. The 61200 crystals in EB are arranged in a $170 \times 360 \eta - \phi$ grid with a coverage up to $|\eta| = 1.479$ in pseudorapidity. The crystal front face cross section is approximately 0.0174×0.0174 in $\eta - \phi$ ($22 - 22 \text{ mm}^2$) and $26 - 26 \text{ mm}^2$ at the rear face. The increase in cross sectional area of the rear face is consistent with the small Moliere radius allowing to contain the transverse development of the electromagnetic shower within few crystals with respect to the

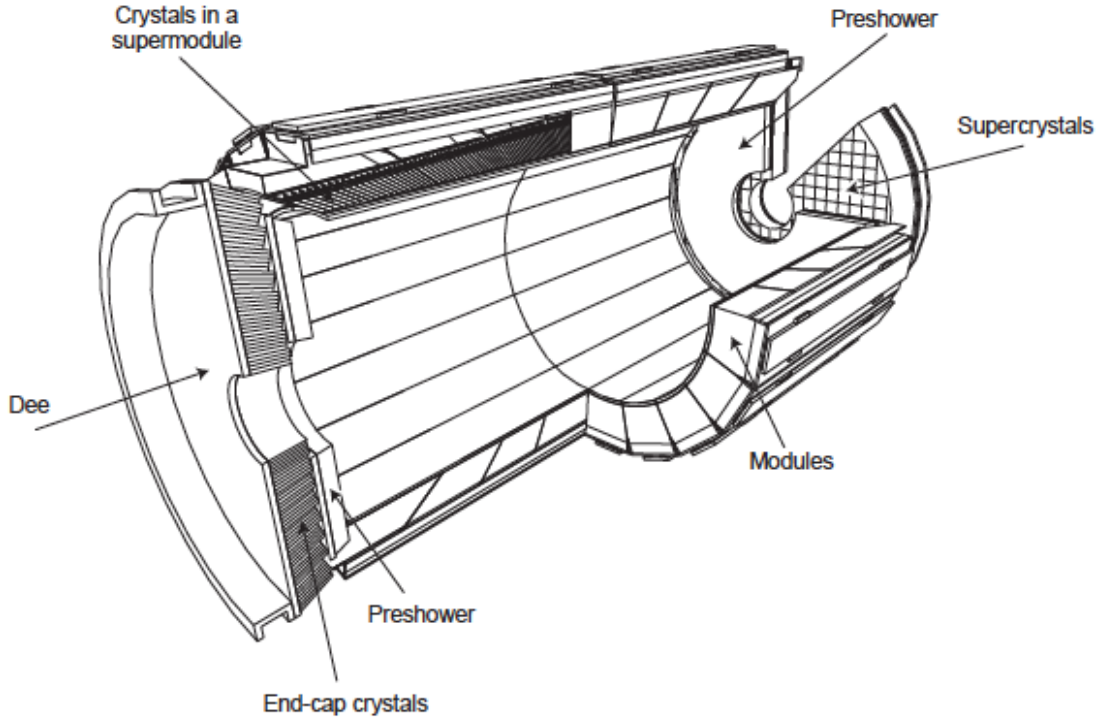


Figure 2-3: The layout of the CMS electromagnetic calorimeter. The barrel and endcap calorimeters are shown. The pre-shower detector sits in front of the endcap ecal.

central crystal. Each crystal has a length of 230 mm corresponding to 25.8 radiation lengths allowing to contain the longitudinal shower development with negligible levels of leakage. The crystals make an angle of 3 degrees with respect to the particle trajectories incident from the interaction vertex to avoid cracks aligned with the trajectories. Two avalanche photodiodes (APDs) with an active area of $5 \times 5 \text{ mm}^2$ are connected to the back of the crystals to convert the scintillation light to photoelectrons.

The 14648 crystals in EE are arranged in an $x - y$ grid with a front face cross section of $28.62 \times 28.62 \text{ mm}^2$ and a rear face cross section of $30 \times 30 \text{ mm}^2$. The length of the crystals is 220 mm corresponding to 24.7 radiation lengths. Vacuum phototriodes (VPTs) with an active area of approximately 280 mm^2 , allowing large surface coverage, are used as photodetectors. An anode of very fine copper mesh

allows to operate these devices in the 3.8 Tesla magnetic field with only slight loss in gain. The EE extends the ECAL coverage from $|\eta| = 1.479$ to $|\eta| = 3.0$. A sampling preshower detector sits in front of the EE allowing the identification of neutral pions from $|\eta| = 1.7$ to $|\eta| = 2.6$. Two alternating layers of passive lead and active silicon layers form a sampling calorimeter with approximately 3 radiation lengths of the absorber material.

The energy resolution of the ECAL can be parameterized as

$$\frac{\sigma}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C, \quad (2.1)$$

where E is the energy of the incident particle, S is the stochastic term, N is the noise term, and C is the constant term. The longitudinal shower leakage is assumed to be negligible in (2.1). Event-to-event fluctuations in the lateral shower containment and the photo-statistics of 2.1% contribute to the stochastic term. The noise term is mostly due to the electronic and digitization noise while the constant term comes from intercalibration errors and a non-uniform light collection. Typical values found at an electron test beam are $S = 0.029 \text{ GeV}^{\frac{1}{2}}$, $N = 0.12 \text{ GeV}$, and $C = 0.003$.

2.3 Hadron Calorimeter

The goal of the CMS hadron calorimeter (HCAL) [95] is to measure the energy of charged and neutral hadrons. This is particularly important for the measurement of hadronic jets and transverse missing energy. Figure 2-4 shows the layout of the hadron calorimeter components in the $r - z$ coordinate plane. The HCAL barrel calorimeter (HB) sits behind the ECAL between a radius of $r = 1.77 \text{ m}$ and the inner extend of the magnetic coil ($r = 2.95 \text{ m}$). The HB is a sampling calorimeter extending to $|\eta| = 1.3$ in pseudorapidity with 0.087×0.087 segmentation in $\eta - \phi$. The first layer of the absorbing material is a 40 mm thick steel plate followed by eight 50.5 mm thick brass plates with a last layer of 75 mm thick steel plate. The chemical composition of the non-magnetic brass is 70% Cu and 30% Zn with a radiation length

of 1.49 cm. Thus the total absorber thickness is 5.8 interaction lengths (λ_I) at $\eta = 0$ and increasing to $10.6 \lambda_I$ at $|\eta| = 1.3$. It has to be noted that the ECAL in front of HB adds about $1.1 \lambda_I$ of additional material.

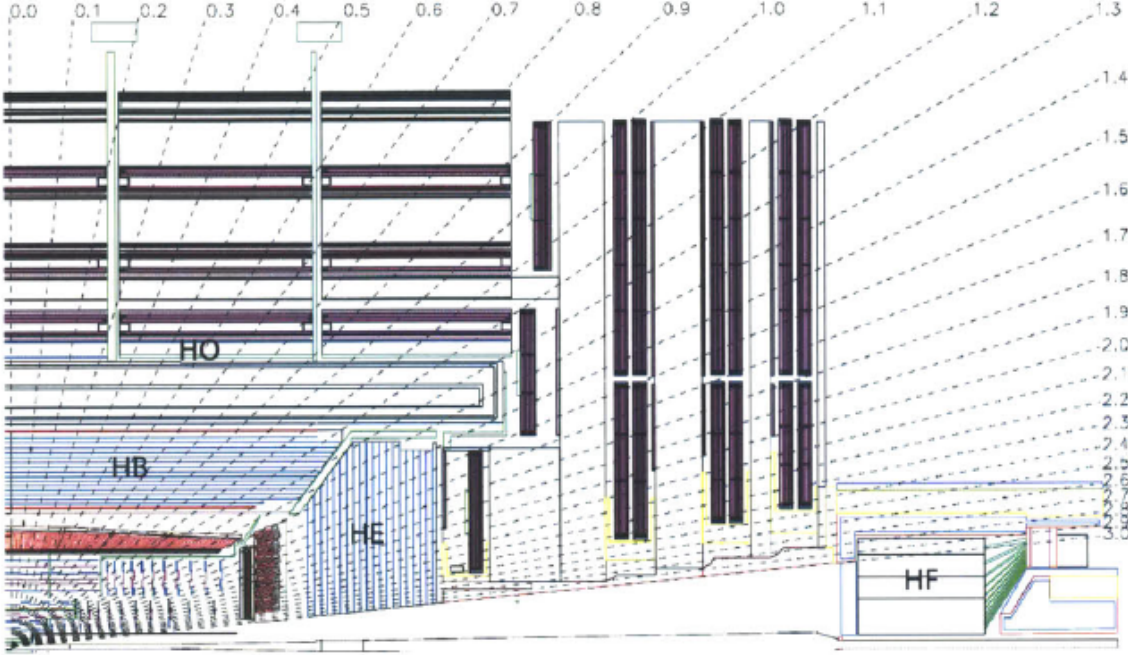


Figure 2-4: The layout of the CMS detector in the $r - z$ coordinate plane showing the location of the hadron barrel, endcap, outer, and forward calorimeters. The dashed lines show the extend of the coverage in pseudorapidity.

Plastic scintillators (3.7 mm thick) are used for the active layers using a tile and wavelength shifting fiber setup to bring out the light. The first and last layers of the scintillators are 9 mm thick where the latter serves to correct for the late developing hadron showers leaking out the back of the HB while the former serves to sample the hadron showers developed in the inert material between the EB and HB. Clear fibers are spliced onto the wavelength shifting fibers which are connected to optical fibers that take the light to an optical decoding unit (ODU). The role of the ODU is to arrange the fibers into read-out towers and bring the light to the hybrid photodiodes (HPDs) [96]. The central component of the HPD is a photocathode held at a high voltage of -8 kV from a pixelated silicon photodiode. The accelerated photo-electron from the cathode produces an ionization in the diode (3.3 mm away) with an overall gain of about 2000.

The hadron endcap (HE) extends the pseudorapidity coverage to $|\eta| = 3.0$ providing about $10 \lambda_I$ interaction lengths (including the ECAL crystals). The granularity of the HE is 0.087×0.087 in $\eta - \phi$ for $|\eta| < 1.6$ and 0.17×0.17 for $|\eta| \geq 1.6$. The EB and HB absorbing power does not provide sufficient containment of the hadronic showers. An additional outer calorimeter (HO) that utilizes the solenoid as an absorbing material is placed in the iron yoke (radial distance of 4.1 m) that returns the solenoid magnetic field. There is an additional sensitive layer at a radial distance of 3.8 m at $\eta = 0$ as the HB has minimal absorbing length there. The total absorber thickness is increased to a maximum of $11.8 \lambda_I$ through the inclusion of the HO.

The forward calorimeter (HF) extends the pseudorapidity coverage to $|\eta| = 5.2$. The HF is also responsible for the measurement of electromagnetic energy since the coverage of ECAL extends only to $|\eta| = 3.0$. The particle flux in this region is extremely high; presenting hostile conditions for the detector and requiring a radiation hard active material. Steel absorber layers and scintillating quartz fibers are used as the passive and active materials, respectively. The absorption depth is approximately $10 \lambda_I$. Cherenkov light is generated in the quartz fibers when the charged shower particles are above the Cherenkov threshold. Thus the HF is mostly sensitive to the electromagnetic component of the showers. The HF has a longitudinal segmentation of two segments that allows to distinguish between incident electrons/photons and hadrons. This is accomplished by having two sets of fibers where one set only starts at a depth of 22 cm from the front end of the detector. The transverse segmentation is 0.175×0.175 in $\eta - \phi$. The Cherenkov light is measured by a standard bialkaline high-gain photomultiplier tube with a borosilicate glass in the fringe magnetic field of the solenoid.

2.3.1 HCAL Upgrades

There is a comprehensive program to upgrade the HCAL detectors to take advantage of technologies that have become available since the original design of the detector [97]. The Phase 1 upgrade of the CMS HCAL is designed to improve the performance of the calorimeters at high luminosities with a mean number of about 50 pileup events

expected at the LHC. The HPDs in the HB and HE will be replaced by silicon photomultiplier (SIPM) devices while the single-channel phototubes in the HF will be replaced by multi-anode phototubes operated in a dual-anode configuration to reject spurious signals present in the single-channel phototubes of the initial HF detector. The readout detectors of all the calorimeter detectors will be replaced as well.

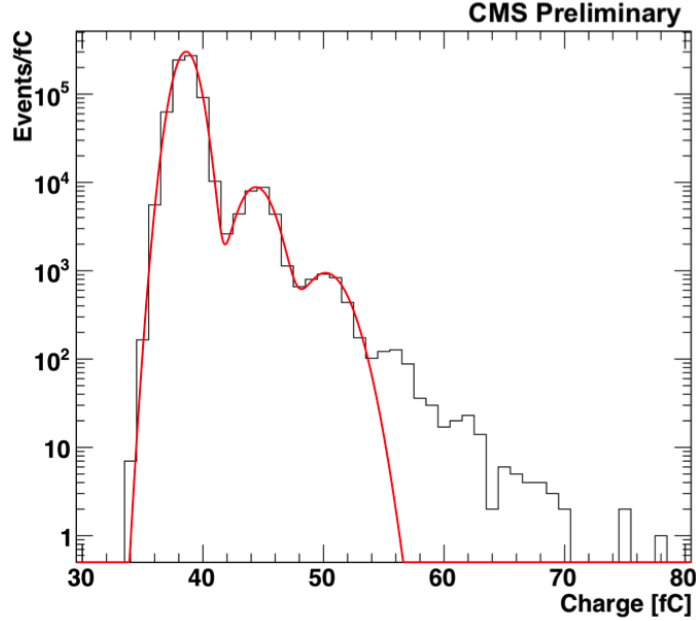


Figure 2-5: Charge distribution in a SIPM for events with no incident photons [98]. The first peak is due to the leakage current while the subsequent peaks show the thermal avalanches of individual pixels. The red curve is a fit to the charge distribution.

The Phase 1 upgrade program will be completed during the long shutdown 2 (LS2) starting in 2018. However, the HPDs in the HO calorimeter were already replaced by SIPMs during LS1. SIPMs are pixel arrays of avalanche photodiodes each operating in Geiger mode. Adding the signal of all the pixels together gives a measurement of the number of incident photons. SIPMs are compact devices that operate at about 2 orders of magnitude lower voltages compared to the HPDs. The gain is similar to that of photomultipliers, but the quantum efficiencies are a factor of two higher compared to the HPDs. In addition, the SIPMs are not affected by magnetic fields of up to 4 Tesla while about 10% of the HPDs experience rapid breakdown at lower magnetic fields affecting the HO calorimeter in the fringe fields outside of the solenoid.

SIPMs have an order of magnitude higher signal to noise ratios compared to the HPDs. The low signal to noise ratio is evident in Figure 2-5 showing the thermal avalanches of individual pixels. The performance of the SIPM devices allows to increase the depth segmentation of the HB and HE calorimeters. The current depth segmentation is summarized in Figure 2-6. The current HB calorimeter has a single longitudinal readout for most of the towers.

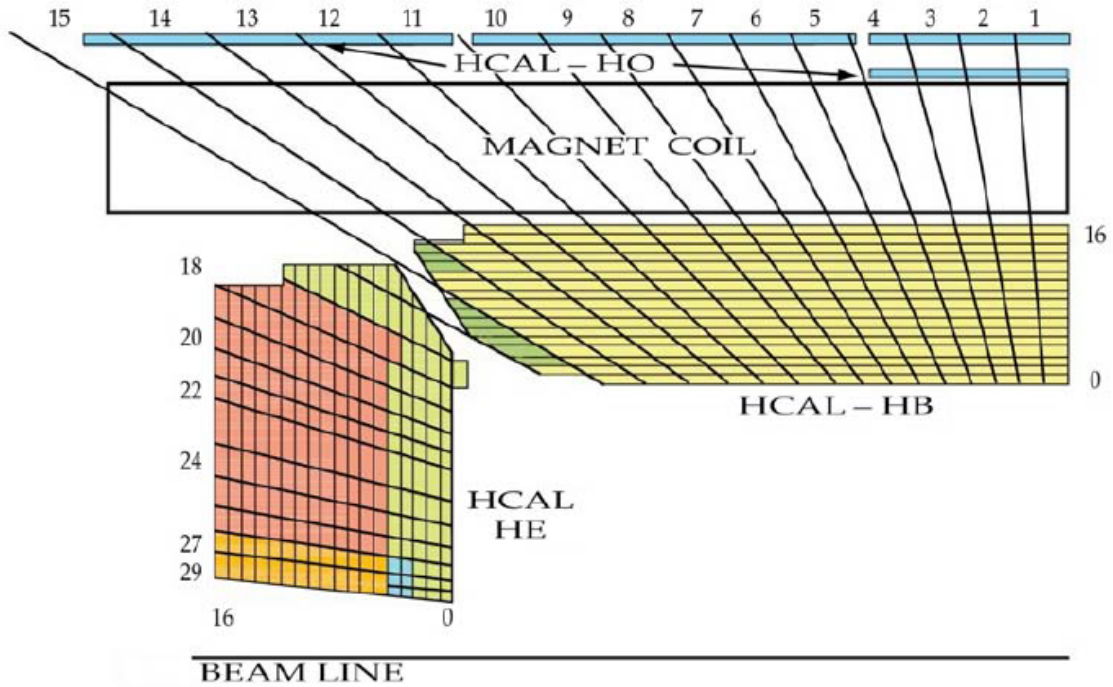


Figure 2-6: The current HCAL segmentation in the $r - z$ coordinate plane. The grouping of colors represents the optical grouping of the scintillator layers into different readouts.

2.4 Muon Detectors

The goal of the CMS muon detectors [99] is threefold: muon triggering, identification, and the momentum measurement. Muons with $\mathcal{O}(10)$ GeV energies are minimum ionizing particles and there is little energy loss due to bremsstrahlung as muons have about 200 times larger mass than electrons. Muons are detected in gas-ionization detectors embedded in the the steel return yoke outside of the solenoid. An appearance

of a charged particle in the muon detectors is a strong indication of a muon particle as the charged hadrons, electrons, and photons are effectively stopped by the ECAL and HCAL.

The layout of the CMS muon system is shown in Figure 2-7 providing a pseudo-rapidity coverage to $|\eta| = 2.4$. Drift tube (DT) chambers with rectangular drift cells are used in the central barrel region with a pseudorapidity coverage to $|\eta| = 1.2$. There are 4 stations cylindrically interspersed in the layers of the flux return plates where the first 3 stations contain 8 chambers measuring the muon coordinate in the $r - \phi$ plane and 4 chambers providing a measurement in the z direction along the beam-line. The last station does not have the z measurement plates. The gas used in the drift cells is a mixture of argon and carbon dioxide. The maximum drift time is 380 ns in this mixture corresponding to a drift length of 21 mm.

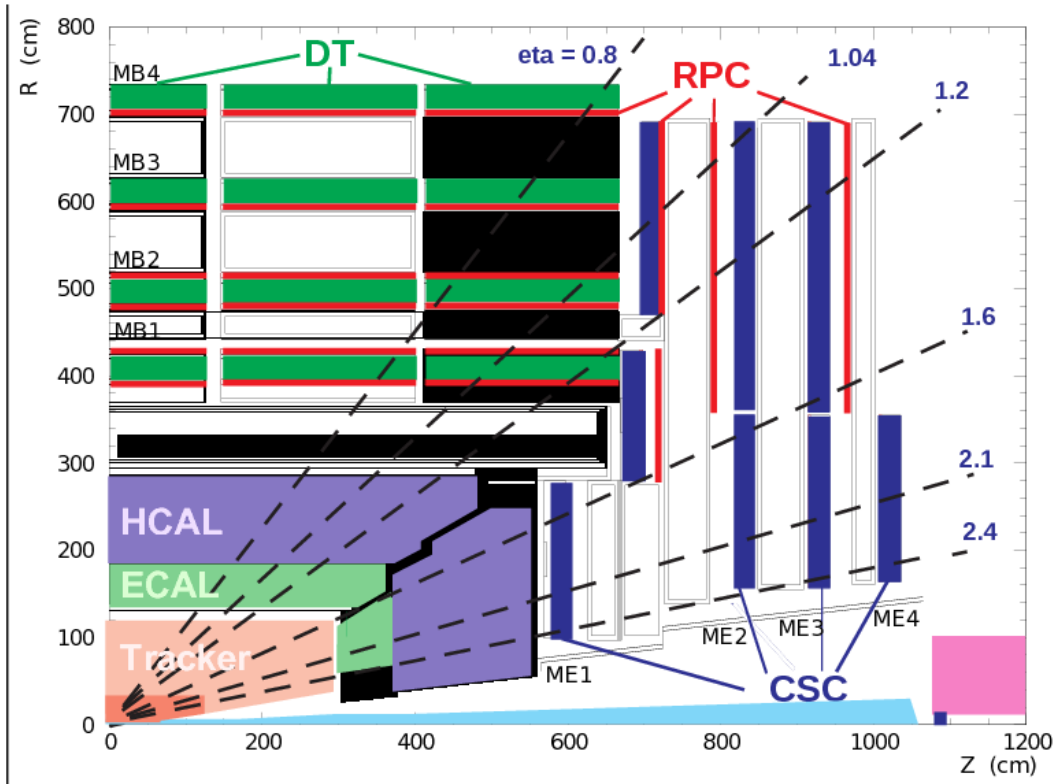


Figure 2-7: The layout of the CMS detector in the $r - z$ coordinate plane showing the location of the four DT chambers in the barrel (MB1-MB4) and the four CSC chambers in the endcap (ME1-ME4). The RPC stations are shown in red [100]. The dashed lines show the extend of the coverage in the pseudorapidity.

Cathode strip chambers (CSCs) are used in the endcap region, where the muon rates and background levels are higher, with a pseudorapidity coverage from $|\eta| = 0.9$ to $|\eta| = 2.4$. The CSCs are radiation resistant and have a fast response time and fine segmentation. There are 4 stations with chambers positioned perpendicular to the beam line with the cathode strips of each chamber running radially outward to provide measurements in the $r - \phi$ plane. The anode wires are also read out. They run perpendicular to the strips and provide measurements in η .

A dedicated trigger system consisting of resistive plate chambers (RPCs) is added covering up to $|\eta| = 1.6$ in pseudorapidity. The RPCs are double-gap chambers that operate in avalanche mode. The response is very fast with a time resolution of about 1 ns. They serve as an independent muon trigger system that can identify the correct bunch crossing time at the LHC nominal instantaneous luminosity. The position resolution of the RPCs is poorer than the DTs and CSCs.

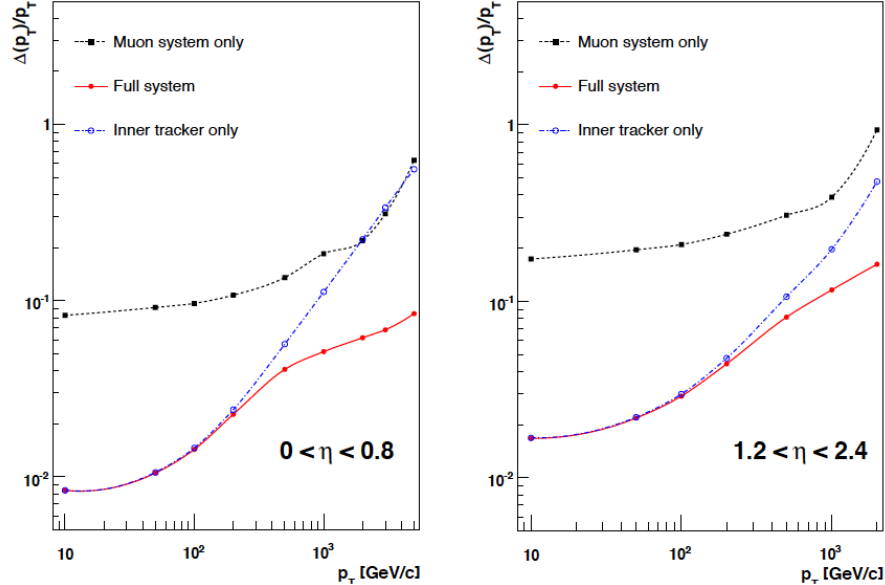


Figure 2-8: The expected muon transverse momentum resolution as a function of the transverse momentum for $|\eta| < 0.8$ (left panel) and $1.2 < |\eta| < 2.4$ (right panel) [52]. The performance for the muon system only (black), the inner tracker only (blue), and the full system (red) is shown.

Figure 2-8 shows the expected muon transverse momentum resolution using the standalone muon system (black) and the inner tracking system (blue). A muon reso-

lution of about 9% for muon transverse momenta up to 200 GeV is achieved. Multiple-scattering in the detector material before the first muon station limits the resolution achieved by the standalone muon system. An order of magnitude improvement in resolution is achieved using the inner tracker information in a global momentum fit, as described in the next chapter (the red curves in Figure 2-8).

2.5 Triggering and Data Acquisition

The design 25 ns bunch spacing at the LHC translates to a bunch crossing rate of 40 MHz. This results in a total inelastic collision rate of order of 1 GHz taking the additional inelastic proton-proton interactions per bunch crossing into account. A drastic rate reduction has to be achieved as it is impossible to store and process the resulting large amount of data. This is achieved by the triggering system. The triggering of the events in the CMS is achieved in two steps designated as Level One Trigger (L1) [101, 102] and High-Level Trigger (HLT) [102, 103, 104]. The L1 trigger consists of a custom designed and largely programmable electronics while the HLT is a software system consisting of a farm of about one thousand commercial processors having a few thousand CPU cores. The L1 trigger takes the decision to either reject or accept the event for further evaluation by the HLT. Thus the events are readout and fully assembled only for the events that pass the L1 trigger. The readiness of the sub-detectors and the data acquisition (DAQ) system are considered in the L1 decision through the Timing, Trigger, and Control (TTC) system [105]. Finally, the events are either discarded or passed to the offline computing system for storage and reconstruction depending on the HLT decision. The nominal output rate of the L1 trigger is 100 kHz limited by the CMS readout electronic speed. The HLT nominally selected an average rate of 400 Hz for storage and processing during the 2011 and 2012 data taking period. However, HLT accept rates of up to several kHz were possible if the data was not processed promptly. An extra 300 – 400 Hz data was collected through special "parked" data stream [106] during the 2012 data taking period and reconstructed only at the end of the run. Average HLT accept rates of 2 kHz and

higher were achieved after the LS1. The overall output rate of the L1 trigger and HLT can also be adjusted by applying a pre-scale on the number of events that satisfy the selection criteria of specific HLT algorithms.

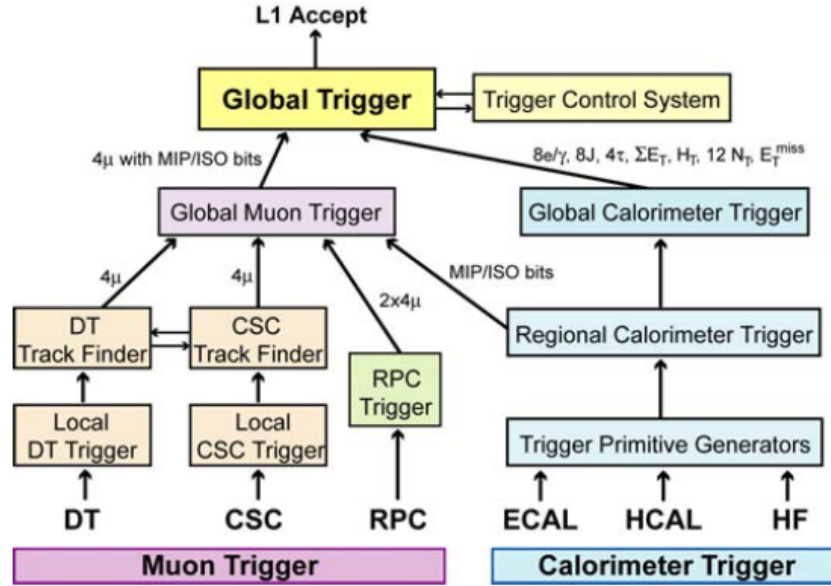


Figure 2-9: Level-1 trigger architecture showing the components of the trigger [52] .

The L1 trigger uses coarsely segmented data from the calorimeters and the muon system. The full detector information is retained in the pipelined memory buffers of the front-end read-out electronics pending the L1 trigger decision. It has to be noted that no information from the inner tracking system is used in the L1 trigger as the number of channels and the speed of the readout electronics of the inner tracking detectors is currently prohibitive. The L1 hardware is implemented in combination of Field Programmable Gate Arrays (FPGAs) and Application Specific Integrated Circuits (ASICs). A programmable memory lookup table (LUT) is also used where density and radiation requirements are important. The allowed latency is $3.2 \mu s$. Figure 2-9 shows the L1 trigger architecture and the information flow toward the L1 decision. The L1 trigger objects consist of clusters of the ECAL and HCAL deposits (photons/electrons, hadrons), muons, and global event information such as the summed transverse energy or the missing transverse energy.

The HLT has access to the complete read-out data including the hit patterns

from the inner tracking detector. Thus better position and momentum resolutions can be used compared to the L1 trigger objects. The HLT uses identical software framework to the one used in the offline processing. However, optimized algorithms and configurations are used to manage the input rate of 100 kHz. For example, reconstruction of the tracks in the inner tracking system is only performed after other selection criteria based on the calorimeter and muon detector information to reduce the CPU usage. In addition, the data is reconstructed in the regions of interest, defined by the L1 trigger information, to further reduce the processing time. The output rate of the HLT is limited by event sizes and the capacity of the downstream systems to process the events.

The LHC experiments utilize the Worldwide LHC Computing Grid (WLCG) global computing infrastructure to store, distribute, and analyze the data generated by the LHC. The computing facilities from the universities and research centers, collaborating at the LHC, are integrated into the WLCG. Multiple copies of data are kept at different sites allowing access to the data independent of geographical location.

2.6 Detector Simulation

A full detector simulation is performed using Geant 4 [107, 108]. The simulation includes the propagation of the final state particles in the CMS magnetic field as well as the passage of the particles in the passive and active elements of the detector. The readout electronics are simulated including the effects of the noise. The output of the simulation has the same format as the collision data. Thus, a complete simulation is obtained starting from the generated events described in Section 1.3, and adding the simulated detector response. The effects of the pileup interactions are modeled by including additional inelastic proton-proton collisions in the event according to a distribution of pileup events expected in data. The simulated events are then reconstructed using the same reconstruction software used for the collision data events.

Chapter 3

Event Reconstruction

The $W^\pm$ and Z boson cross section measurements and $H \rightarrow \tau\tau$ searches rely on the precise reconstruction of the decay products. The presence of neutrinos in the leptonic $W^\pm$ boson decays and also in τ lepton decays requires an accurate reconstruction of all the detector deposits to infer the presence of the neutrinos from the momentum imbalance in the transverse plane. In addition, reconstruction of jets is important to capture the different production modes of the Higgs boson. The additional pileup interactions in the events present a challenge for a precise reconstruction of the events. This chapter summarizes the event reconstruction emphasizing the components relevant for the results that follow.

3.1 Track Reconstruction

The goal of the track reconstruction is to estimate the position and momentum parameters of charged particles from the reconstructed hits in the inner tracking detector. Reconstructing tracks at the LHC nominal instantaneous luminosities is a computationally challenging task due to a high occupancy environment. About 1000 charged particles transverse the inner tracking detectors at each bunch crossing. Charged particles from prior or later bunch crossings can also be present due to finite detector time resolution. The track reconstruction starts by clustering of zero-suppressed signals in the pixel and strip detectors into hits. Each hit provides an estimate of the

cluster position and the corresponding uncertainty. The CMS track reconstruction algorithm is referred to as combinational track finder (CTF) [109, 110]. The CTF is an adaptation of the combinatorial Kalman filter [111, 112, 113], which is an extension of the Kalman filter [114], combining pattern recognition and track fitting in the same framework.

The CTF is performed iteratively six times to determine the collection of the tracks in an event. The aim of this iterative tracking is to first find the tracks that are easiest to find (tracks with high p_T and near the interaction region) with subsequent iterations searching for the more challenging tracks (tracks with low p_T and displaced from the interaction region). Hits associated with tracks are removed after each iteration thereby reducing the computational complexity. Each iteration has four steps:

- **Seed generation:** Initial track candidates are found using only two or three hits in the inner part of the tracker. One has to note that the seeds are not constructed from the outermost regions of the tracker where the track density is small. The high granularity of the pixel detector ensures that the channel occupancy is lower than the channel occupancy of the outer strip layers. In addition, significant fraction of charged pions undergo inelastic interaction in the track detectors while many electrons lose significant energy due to bremsstrahlung radiation as they transverse the inner tracker. Five parameters are needed to define the helical trajectory of the charged particles in the approximately uniform magnetic field. Two or three hits in combination with a constrain on the origin of the charged particle to be near the beam spot (the three dimensional profile of the luminous region of the collisions) is sufficient to extract these parameters.
- **Track finding:** The Kalman filter algorithm is used to provide a coarse estimate of the track parameters starting from the seeds. A track candidate is built by adding hits from successive detector layers. A fast analytical propagator is used to find the hit layers. The track parameters are updated each time a new hit is found.

- **Track fitting:** The full information needed for the trajectory is only available once all the hits of the trajectory are identified. Therefore, the trajectory is once again re-fitted using a Kalman filter and smoother. A fourth-order Runge-Kutta method is used to extrapolate the trajectory between the successive hits. Material and inhomogeneous magnetic field effects are included.
- **Track selection:** Quality requirements are applied to reject fake tracks not originating from charged particles.

The track reconstruction is effectively fully efficient for isolated muons with 2.5% resolution in p_T for p_T of about 100 GeV [110]. The longitudinal (with respect to the z axis) and transverse impact parameter resolutions are 30 μm and 10 μm , respectively. The efficiency for charged particles of p_T greater than 0.9 GeV in simulated $t\bar{t}$ events is 94% (85%) in the pseudorapidity region of $|\eta| < 0.9$ ($0.9 < |\eta| < 2.4$). The main cause of the inefficiency is due to the hadrons undergoing nuclear interactions in the tracker material.

3.2 Primary Vertex Reconstruction

The goal of the primary vertex reconstruction is to measure the position of each proton-proton interaction vertex in each event. The vertex reconstruction starts from the collection of the reconstructed tracks consistent with being produced near the beam spot. Additional quality requirements on the number of inner tracker layers associated to the track and the quality of the CTF fit are applied. There is no requirement on the p_T of the tracks ensuring high vertex reconstruction efficiency.

A clustering algorithm based on the z coordinates of closest approach of the tracks to the beam spot is used to resolve the vertices. The tradeoff is to be able to resolve the nearby vertices against the accidental splitting of a single vertex into more than one cluster of tracks. A deterministic annealing (DA) algorithm [115] is used for the clustering where the most probable vertex positions are found through a minimization

of "free energy" F at "temperature" T [110],

$$F = -T \sum_i^{N_T} \ln \sum_j^{N_V} p_{ij} \rho_j \exp \left[-\frac{1}{T} \frac{(z_i^T - z_j^V)^2}{\sigma_i^{z2}} \right], \quad (3.1)$$

where z_i^T and σ_i^z are the z coordinates of the points of the closest approach of the tracks to the z and the corresponding uncertainties, z_j^V are the vertex positions with vertex weights ρ_j , and p_{ij} is the probability of assigning the track i to the vertex j . The assignment of the probabilities is such that at very low temperatures every track is compatible with a single vertex while at very high temperatures all the tracks become compatible with a single vertex. The algorithm starts at a high temperature that gradually decreases (F is minimized at each step) until a pre-defined minimum temperature is reached. Thereafter the temperature is further decreased to $T = 1$ for the final assignment without further splitting of the vertices.

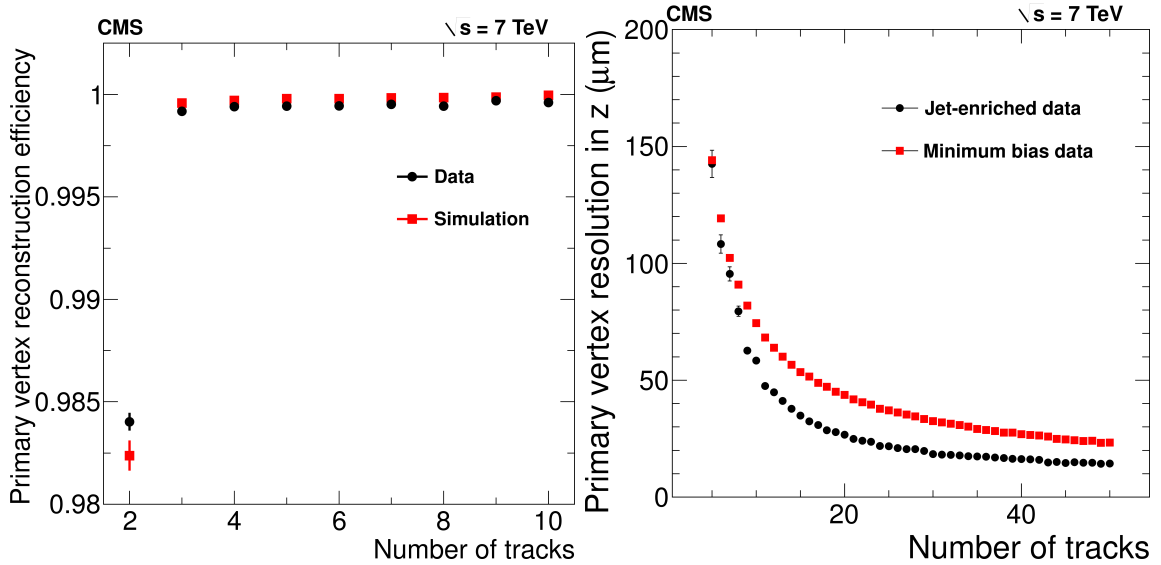


Figure 3-1: Vertex reconstruction efficiency (left panel) as a function of the number of tracks in the vertex measured in minimum-bias data and in simulation. Vertex resolution (right panel) in the z coordinate as a function of the number of tracks measured in minimum bias events (red) and jet-enriched events (black) [110].

The candidate vertices determined by the DA clustering that contain at least two tracks are fitted using an adaptive vertex fitter [116] to determine all the vertex parameters, including the x , y , and z positions. Figure 3-1 shows the vertex recon-

struction efficiency (left) and vertex resolution in z coordinate as a function of the number of tracks used to fit the vertex. The reconstruction efficiency is close to 100% when there are more than two tracks used to reconstruct the vertex. The vertex resolution also depends on the number of tracks as well as the p_T of the tracks. The vertex resolutions are shown for minimum bias data events (red), where loose triggers select inelastic pp collisions with as little bias as possible, and jet enriched data events, where the events are required to have a reconstructed jet with a transverse energy E_T greater than 20 GeV (black). The tracks in the jet enriched events have higher p_T resulting in better vertex resolution. A resolution of approximately 10 μm is achieved for high p_T vertices with at least 50 tracks.

The vertex with the largest sum of the p_T^2 is defined to be the true hard-scattered pp vertex and is denoted as the primary vertex. The other vertices in the event are assumed to originate from the additional pileup interactions in the bunch crossing. Beam induced backgrounds can be rejected by applying compatibility requirements on the primary vertex with the nominal interaction point (the origin of the CMS coordinate system). The distance of the primary vertex in the z direction (transverse direction) to the nominal interaction point is required to be less than 24 cm (2 cm). The number of degrees of freedom of the primary vertex fit is also required to be greater than three.

3.3 Muon Reconstruction and Identification

Muon tracks are reconstructed not only in the CMS inner tracker but also independently in the muon system [100]. The latter tracks are called standalone muon tracks. The standalone muon tracks are reconstructed from the hits in the muon chambers in a combined track fit using a Kalman filter. The "global muon" reconstruction refers to the combination and matching of the standalone muon tracks with the inner tracker tracks. A global muon track is fitted from these tracks again using a Kalman filter technique. The expected energy loss in the solenoid and support structures is taken into account in the fit. The global fit improves the momentum resolution for

muons with p_T greater than 200 GeV compared to the inner tracker only resolution as demonstrated in Figure 2-8.

Another independent algorithm starts from the inner tracker and proceeds outward in the radial direction matching the hits in the muons chambers. This "tracker muon" reconstruction is more efficient for low momentum muons ($p < 5$ GeV) compared to the global muon reconstruction as it only requires one muon segment hit in the muon chambers. The tracker muon reconstruction considers all the inner tracker tracks with p_T greater than 0.5 GeV as possible muon candidates. The average expected energy loses and multiple Coulomb scattering in the detector material are taken into account for the extrapolation to the muon system.

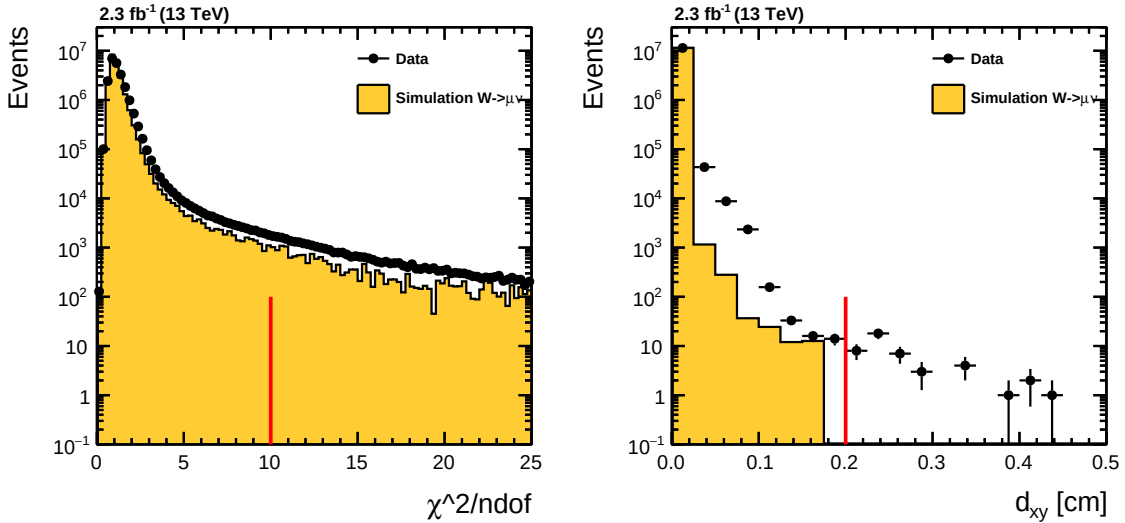


Figure 3-2: Distribution of χ^2 per degree of freedom (left panel) and transverse impact parameter d_{xy} (right panel) for data at $\sqrt{s} = 13$ TeV taken during 2015 data taking period. Simulated $W \rightarrow \mu\nu$ signal process normalized to the number of observed data events is shown for comparison. The events satisfy all other selection requirements (including the isolation requirement to be discussed in Section 3.8) except that on the shown variable. The red line illustrates the requirement on the variable for a selection optimized for that data-taking period.

Muon candidates selected in the results are required to be a global muon. Approximately 99% of the muons in the fiducial volume (the geometrical acceptance) of the muon system are identified as either a tracker or a global muon. Muon candidates identified as both a global and a tracker muon are merged into a single candidate.

Additional quality requirements are imposed to reduce misidentified muon candidates and so called non-prompt muons. Non-prompt muons originate from in-flight decays of light hadrons and semi-leptonic decays of the heavy flavor quarks. The misidentified muon candidates originate from the punch-through of hadron showers to the muon system. The contribution is generally small for the global muons due to the minimum number of muon segment hits requirement.

Figure 3-2 shows the distributions of few of the muon variables used for reduction of the non-prompt and misidentified muons. The χ^2 per degree of freedom of the global track fit is required to be less than 10. At least one segment in the muon stations must be included in the global fit to reduce the punch-through hadrons. The muons are required to have track segments in at least two muon stations. In addition, at least one hit in the pixel tracker and at least five tracking layers are required. Background originating from cosmic-ray muons transversing the CMS detector in coincidence with a pp collision is reduced by the impact parameter requirement. Figure 3-2 (right panel) shows the transverse impact parameter distribution d_{xy} calculated with respect to the primary vertex. The candidates with large d_{xy} originate mainly from the cosmic-ray muons. The excess of events with respect to the $W \rightarrow \mu\nu$ simulation is due to the in-flight decays of long lived particles in the QCD multi-jet background. There is also a requirement on the longitudinal impact parameter d_z calculated with respect to the primary vertex of the event.

3.4 Electron Reconstruction and Identification

Electrons are reconstructed by looking for a track in the inner tracker that is matched to energy deposits in the ECAL. Electron reconstruction is complicated due to bremsstrahlung radiation emitted as the electrons transverse the inner tracker detector. These bremsstrahlung photons can subsequently undergo a pair-conversion before reaching the ECAL. As a result the electron energy reaching the ECAL is significantly spread in the azimuthal direction ϕ due to bending of the trajectories in the CMS magnetic field. Approximately 35% of electrons radiate more than 70% of their

initial energy before reaching the ECAL [110, 117]. A dedicated clustering algorithms are used to collect the bremsstrahlung energy taking the spreading in the ϕ direction into account [118]. The spread in the η direction is mostly negligible except for very low p_T (less than 5 GeV).

In the ECAL barrel region the energy is collected in a small η window with an extended window in ϕ . An array of 5×1 crystals in $\eta - \phi$ are formed around a seed crystal with transverse energy $E_T > 1$ GeV. The arrays are extended in both ϕ directions centered at the seed crystals up to $\Delta\phi$ of radius of 0.3. The arrays with $E_T > 0.1$ GeV are grouped to form a supercluster. In the ECAL endcap the supercluster is seeded by a 5×5 cluster in $\eta - \phi$ centered at the seed crystal. The supercluster energy corresponds to the sum of the energies of its clusters.

Inner tracker seeds compatible with a reconstructed supercluster are searched in the pixel tracker (also in TEC to improve the efficiency). Electrons that suffer a small amount of bremsstrahlung radiation loss can be identified by extrapolating a standard reconstructed track to the ECAL and checking if it passes close to an ECAL cluster. On the other hand, a poor χ^2 or few associated hits in the reconstructed tracks may come from an electron that suffered a significant bremsstrahlung energy loss. A modified version of the Kalman filter is used to perform the final fit of the track parameters as the Kalman filter is only optimal for Gaussian uncertainties whereas the bremsstrahlung energy loss is modeled by Bethe-Heitler model. A gaussian approximation to the Bethe-Heitler model is crude and therefore a Gaussian-Sum filter (GSF) [119] method is employed that approximates the Bethe-Heitler energy loss by a sum of Gaussian functions. The final electron momentum is derived from a weighted mean of the inner tracker measurements and the supercluster energy.

There are few sources of electron backgrounds. An overlapping charged and neutral pions inside a hadronic jet or a charged pion showering early in the ECAL can be misidentified as an electrons. Figure 3-3 shows the distributions of few of the electron identification variables used for reduction of these background processes:

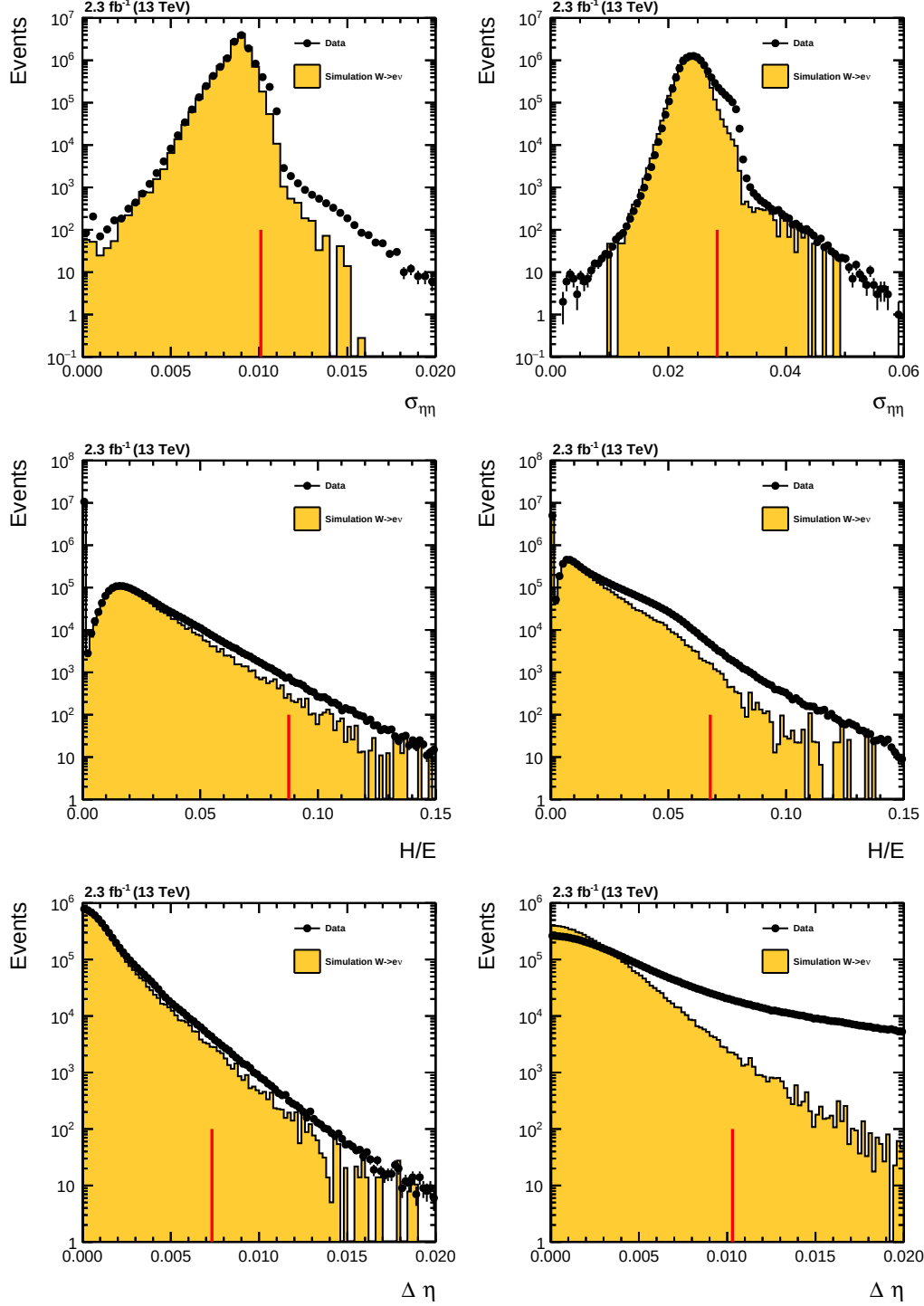


Figure 3-3: Distribution of shower shape $\sigma_{\eta\eta}$, H/E , and $\Delta\eta$ for data at $\sqrt{s} = 13$ TeV taken during 2015 data taking period for the barrel (left) and endcap (right). Simulated $W \rightarrow e\nu$ signal process normalized to the number of observed data events is shown for comparison. The events satisfy all other selection requirements (including the isolation requirement to be discussed in Section 3.8) except that on the shown variable. The red line illustrates the requirement on the variable for a selection optimized for that data-taking period.

- $\sigma_{\eta\eta}$ is the energy weighted η width of the cluster. As can be seen it is small for genuine electrons.
- H/E is the ratio of the energy deposited in the HCAL to the electromagnetic energy near the seed cluster.
- $\frac{1}{E} - \frac{1}{p}$ quantifies the energy and momentum compatibility measured in the ECAL and inner tracker, respectively.
- $\Delta\eta$ and $\Delta\phi$ are the separations between the supercluster and track directions evaluated at the primary vertex in the η and ϕ directions, respectively.

The conversion of a photon into an electron-positron pair is another source of background. Electron candidates with missing hits in the innermost layers of the inner tracker indicate a photon conversion. The identification of a vertex with a pair of tracks with no hits in the tracker layers between the vertex and the interaction point is also used to further suppress this background.

3.5 Jet Reconstruction

Quarks and gluons produced at the LHC fragment and hadronize nearly immediately to a collimated spray of hadrons, known as jets. Jets may originate from a $2 \rightarrow 2$ scattering of the partons inside the colliding protons, decay of a heavy object, such as a top quark or a Higgs boson, and emission of gluons off some other partons in the event. Measuring the jet energy and direction provides information of the original parton. A detailed review of jet finding algorithms, a set of rules for grouping the hadrons into jets, at hadron colliders can be found in [120]. So called sequential recombination jet algorithms are used at CMS as implemented in the FastJet package [121]. The usual approach of these algorithms is to introduce two distance measures d_{ij} and d_{iB} defined as:

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \quad (3.2)$$

$$d_{iB} = p_{ti}^{2p}, \quad (3.3)$$

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and k_{ti} , y_i , and ϕ_i are the transverse momentum, rapidity, and azimuth of object i in the event. R is the distance parameter and p is the power of the energy scale. From the above definitions it can be seen that d_{ij} and d_{iB} are invariant under a boost along the beam direction. The algorithm proceeds to identify the smallest distance measures in the events. If d_{ij} is the smallest for a given pair of objects, then the two objects are combined into a single object by adding the momenta of the i and j objects. If d_{iB} is the smallest distance then the object i is denoted as a jet and removed from further consideration in the algorithm. The algorithm continues until there are no objects remaining in the event. The anti- k_t algorithm [122] with $p = -1$ is used for the results shown here. A distance parameter of $R = 0.5$ or $R = 0.4$ is used. The anti- k_t algorithm grows outward from hard "seeds" resulting in a cone-like jets in $\eta - \phi$. The resulting jet boundaries are resilient with respect to soft radiation while the algorithm is infra-red and collinear safe.

3.5.1 Jet Energy Scale

The jet energy needs to be calibrated to obtain a more accurate estimate of the original parton energy. Corrections are needed to account for the additional energy due to pileup, non-uniformities in the detector response, and detector noise. The effect of additional energy due to pileup and detector noise is corrected on per-jet basis for each event using the median energy density ρ and the jet area [123]. The pseudorapidity and the jet transverse momentum dependent corrections are derived in simulated events with and without pileup overlay. "Zero-bias" triggered events (from randomly selected non-empty LHC bunch crossings) are used to correct for the residual differences between data and detector simulation. The average jet energy scale is calibrated using the MC truth in simulation [124, 125]. Corrections are then applied to account for residual differences between the detector simulation and data using the transverse momentum balancing in di-jet, γ -jet, and Z -jet events. The di-jet p_T balancing method is used to correct the relative scale using the barrel region $|\eta| < 1.3$ as a reference. The absolute scale is corrected using γ -jet and Z -jet events exploiting the excellent p_T resolution of photons and leptons.

Figure 3-4 shows the summary of jet energy scale uncertainties as a function of jet p_T and η at $\sqrt{s} = 8$ TeV data taking period. Jets selected for majority of the physics results are required to have a transverse momentum greater than 30 GeV (the p_T requirement is lower for jets originating from b quarks) with $|\eta| < 4.7$. The uncertainties in the jet energy scale are below 3% across the phase space considered by most analyses and below 1% in the barrel region when excluding the uncertainties due to jet flavor differences in the events used to derive the different stages of the jet energy scale corrections.

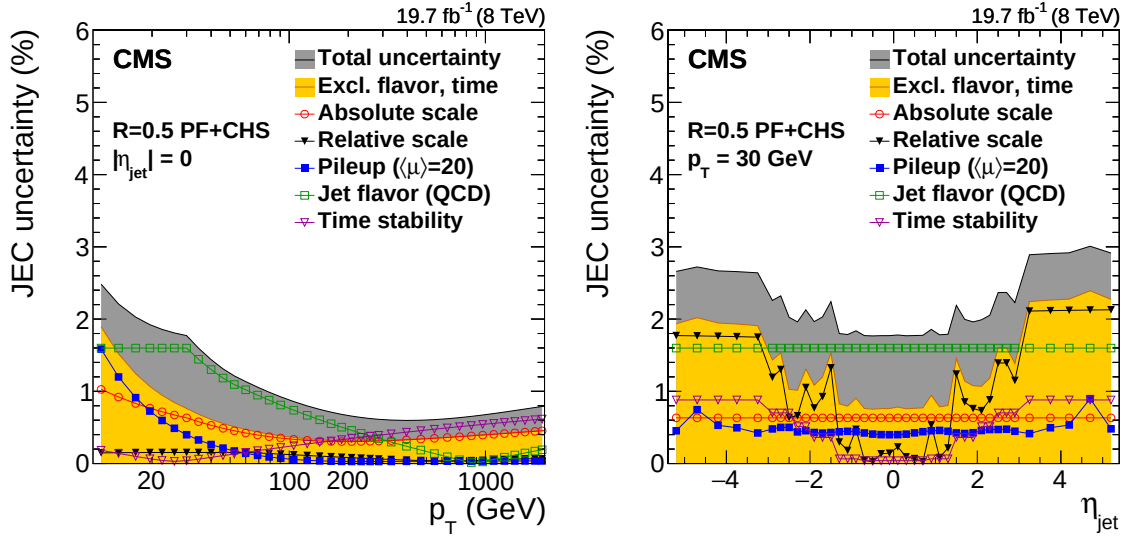


Figure 3-4: Summary of jet energy scale systematics as a function of jet p_T for $|\eta| = 0$ (left) and of jet η for $p_T = 30$ GeV at $\sqrt{s} = 8$ TeV data taking period. The markers show the single effect of different sources and the gray dark band shows the cumulative total uncertainty. The total uncertainty, when excluding the effects of time dependence and flavor, is also shown in yellow light [125].

3.5.2 Pileup Jet Identification

The particles originating from pileup interactions can cluster into jets. The p_T density due to pileup particles is roughly 0.7 GeV per unit area in $\eta - \phi$ plane for one reconstructed primary vertex. While the pileup jets have low p_T it is possible for these low p_T jets to overlap and form a single jet with relatively large p_T . The number of overlapping jets grows roughly quadratically with the number of pileup

interactions and jet area [126].

The goal of the pileup jet identification algorithm is to mitigate the background events due to the pileup jets. The charged particles in pileup jets generally do not point to the primary vertex of the event. In addition, jets originating from pileup tend to be more diffuse in shape compared to the jets from the hard scattering. These two characteristic signatures of the pileup jets are exploited. A Boosted Decision Tree (BDT) discriminant implemented in TMVA [127] is used. It takes as an input the compatibility of the tracks inside the jet with the primary vertex of the event, variables exploiting the jet shape, and the number of charged and neutral constituents of the jet. The most discriminating track related variable (β^*) and jet shape variable ($\langle \Delta R^2 \rangle$) are defined as:

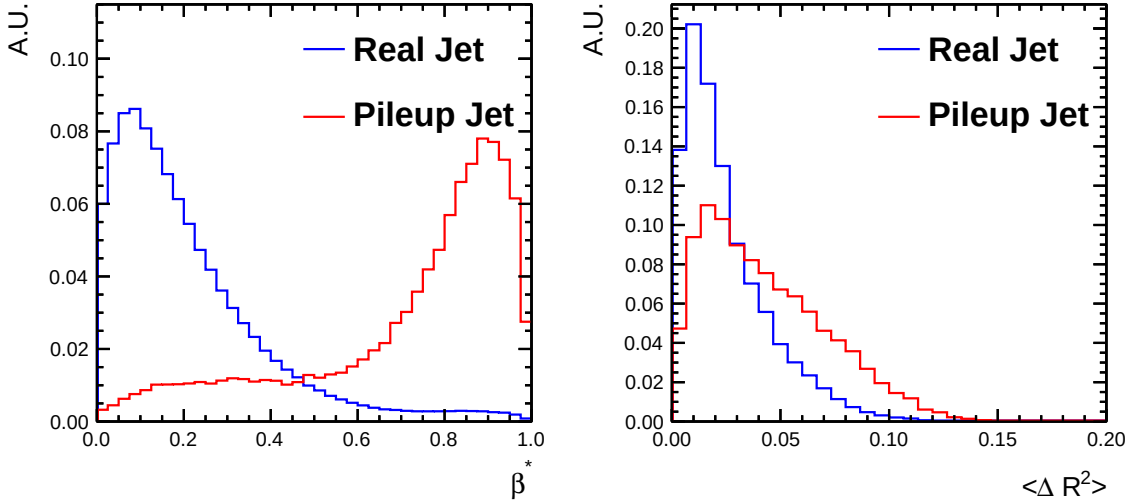


Figure 3-5: Distributions of the β^* (left panel) and $\langle \Delta R^2 \rangle$ (right panel) variables in simulation for jets matched to MC truth jet within a radius of $\Delta R < 0.25$ (blue) and for jets with no match (red). Jets are required to have a p_T greater than 25 GeV and $|\eta| < 2.5$ (left), and $|\eta| > 3.0$ (right).

$$\beta^* = \frac{\sum_{i \notin \text{PV}} p_{Ti}}{\sum_i p_{Ti}}, \quad (3.4)$$

$$\langle \Delta R^2 \rangle = \frac{\sum_{i \in \text{jet}} \Delta R^2 p_{Ti}^2}{\sum_{i \in \text{jet}} p_{Ti}^2}, \quad (3.5)$$

where the charged particle is defined to be coming from the primary vertex if $\Delta z < 0.2$

cm in the β^* definition and ΔR is the distance of the particle to the jet axis in the $< \Delta R^2 >$ definition. The distributions of these variables for "real" and pileup jets are shown in Figure 3-5. The $< \Delta R^2 >$ distributions are shown for jets with $|\eta| > 3.0$ where there is a degradation of separation due to the coarse granularity of the HF calorimeter.

The BDT discriminator is almost fully efficient for jets with $p_T > 30\text{GeV}$ in the inner tracker geometric acceptance ($|\eta| < 2.4$) region with a pileup jet rejection rate of approximately 87%. The efficiency degrades outside of the inner tracker volume. It is about 90% for "real" jets with a pileup jet rejection rate of about 40% for jets with $3.0 < |\eta| < 5.0$.

3.5.3 b-jet Identification

The identification of jets originating from bottom quark hadronization (b-jet) is crucial to reduce the overwhelming background from processes involving jets originating from gluons, light flavored quarks, and charm quarks (c-jets). b-jets are important signatures to study the top quark decays, the Higgs boson, and in searches for new physics. The main idea is to exploit the long lifetimes of the bottom and charm quarks and their relatively large mass. As a result, one can look for secondary vertices and/or tracks with large impact parameters. For example, the CMS inner tracking detector allows to achieve an impact parameter resolution of about 15 (30) μm for a track with p_T of 100 (5) GeV while typical impact parameter values for tracks from the b-jets are at a level of a few 100 μm [128].

The so called Combined Secondary Vertex (CSV) algorithm [128] is used to identify the b-jets. A likelihood discriminant is formed combining information about track impact parameters and secondary vertices. This means that the b-jets can only be identified within the inner tracker geometrical acceptance ($|\eta| < 2.4$). A b-jet identification efficiency of about 75% is achieved with a light-flavor jet misidentification rate of about 1%.

3.6 Particle Flow

CMS uses the so called particle flow (PF) approach to calorimetry [129, 130, 131]. The basic idea of the PF approach is to combine information from all sub-detectors in order to reconstruct all the particles in the event using the best measurements possible. This is especially useful for jet energy measurements as roughly 62% of the jet energy is carried by charged particles (mainly hadrons), around 27% by photons, about 10% by long lived neutral hadrons, and around 1.5% by neutrinos [132]. Thus, one can exploit the superior momentum (energy) resolution of the inner tracker (ECAL) to obtain the most accurate measurements for the charged hadrons (photons) inside the jet and within the inner tracker (ECAL) geometric acceptance. In addition, the high granularity ECAL makes it possible to separate photons from charged particle energy deposits.

The basic elements of the PF algorithm are tracks in the inner tracker, muon segments in the muon system, and energy clusters from the calorimeters. The calorimeter clustering allows to separate the neutral particles from the energy deposits of charged hadrons as well as to reconstruct and identify the electrons and the corresponding bremsstrahlung photons. The clustering starts from the cluster seed defined as a local energy maxima. The clusters are then grown from the seeds by including neighboring cells, with an energy in excess of a defined threshold, in the cluster. The threshold is defined to be two standard deviation of the electronic noise of the ECAL (80 MeV in the barrel and approximately 300 MeV in the endcap) and 800 MeV in the HCAL. A linking algorithm is required as a given particle will result in several PF elements. This is achieved by defining a distance measure between each pair of PF elements. For example, the ECAL clusters of bremsstrahlung photons emitted by an electron are linked by extrapolating the tangents of the track at each intersection point with an inner tracking detector layer to the ECAL to form a PF block. It has to be noted that due to high granularity of the CMS detector the linked blocks typically contain only 1 – 3 elements. The PF candidates are identified from these blocks.

The block and the corresponding PF elements are iteratively removed from fur-

ther consideration once a PF candidate has been identified. A global muon is denoted as a PF muon if a track element is compatible with the global muon. The track is removed from further consideration and the expected energy deposits in the calorimeters are subtracted from the corresponding calorimeter clusters. The GSF electron tracks are linked to the ECAL clusters using a discriminator against charged pions that utilizes information from the inner tracker and the ECAL. A PF electron is formed from the GSF tracks and the ECAL clusters (including the clusters identified as bremsstrahlung photons) in case of a positive match. The remaining inner tracker tracks are identified as charged hadrons. If the linked calorimeter cluster energy exceeds the tracker momentum (taking the relevant measurement uncertainties into account), the corresponding energy excess is identified as a neutral particle. In addition, a PF photon is identified if the excess energy is larger than the linked ECAL cluster while the remaining energy is assigned to a neutral hadron. The remaining ECAL (HCAL) clusters that do not have a linked track are denoted as PF photons (PF neutral hadrons).

The output of the PF algorithm are denoted as particle flow candidates and are classified as electrons, photons, muons, charged hadrons, or neutral hadrons. The particle flow candidates are used for the reconstruction of jets (referred as PF jets) described in the previous section. A special version of the PF algorithm is used in the HLT optimized to the HLT requirements.

3.7 Hadronic Tau Decays

The τ lepton with a mass of 1.777 GeV [19] is the only lepton sufficiently heavy to be able to decay to hadrons. Hadronic tau decays proceed via weak interaction into one or three charged pions or kaons with up to two neutral pions, and one tau neutrino (ν_τ). The ν_τ escapes the detector resulting in a missing energy in the event. The π_0 meson decays almost exclusively to a pair of photons. Table 3.1 summarizes the most common hadronic tau decays. The mean lifetime of the τ lepton is 2.9×10^{-13} s [19] resulting in a significant (compared to the transverse impact parameter and

secondary vertex resolution) displacement of the decay vertex from the production vertex for energetic taus. The hadronic tau decays are denoted as τ_h henceforth. The tau decays to muons and electrons are denoted as τ_μ and τ_e , respectively. The

Decay Mode	Resonance	Branching fraction [%]
$\tau^\pm \rightarrow h^\pm \nu_\tau$		11.5
$\tau^\pm \rightarrow h^\pm \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^\pm \rightarrow h^\pm \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^\pm \rightarrow h^\pm h^\pm h^\mp \nu_\tau$	$a_1(1260)$	9.8
$\tau^\pm \rightarrow h^\pm h^\pm h^\mp \pi^0 \nu_\tau$		4.8
Other hadronic modes		1.8
All hadronic modes		64.8

Table 3.1: Approximate branching fractions of hadronic tau decay modes [19]. The intermediate meson resonances are indicated where appropriate. The symbol h represents a charged pion or kaon.

visible decay products in the τ_h decays result in collimated jets with a relatively low particle multiplicity. The main idea of the τ_h reconstruction algorithm is to reconstruct the individual decay modes listed in Table 3.1. The hadron-plus-strip (HPS) algorithm [133] takes advantage of the PF algorithm using the reconstructed charged and neutral PF candidates. The HPS algorithm starts with a PF jet of p_T greater than 14 GeV and $|\eta| < 2.5$ using the anti- k_T algorithm with distance parameter of $R = 0.5$. The photons produced in $\pi^0 \rightarrow \gamma\gamma$ decays are likely to convert to an electron-positron pair within the volume of the inner tracker. This is taken into account by clustering the electrons and photons (with $p_T > 0.5$ GeV) in the jet into strips in the $\eta - \phi$ plane with a window size of 0.05×0.20 taking the direction of the bending of the charged trajectories into account. Strips with total p_T sum larger than 2.5 GeV are identified as π^0 candidates.

τ_h candidates are formed by combining the clustered strips with the charged candidate constituents of the jets. The charged particles are required to have a p_T greater than 0.5 GeV. The distance of closest approach to the charged particle of highest p_T in the jet has to be less than 0.4 cm in the z direction and 0.03 cm in the transverse plane [134]. The following decay hypotheses are considered:

- $h^\pm$: A single charged particle with no π^0 candidates.
- $h^\pm\pi^0$: One charged particle and one strip with a system mass of $0.3 < m_{\tau_h} < 1.3$ GeV for $p_T < 200$ GeV. The size of the mass window is enlarged for τ_h candidates with high p_T to account for the inner tracker momentum resolution degradation. The mass cut utilizes the intermediate meson resonance ($\rho(770)$) mass in the decay.
- $h^\pm\pi^0\pi^0$: One charged particle combined with two strips. The mass cut requirement is $0.4 < m_{\tau_h} < 1.2$ GeV for $p_T < 200$ GeV targeting the intermediate meson resonance decay of $a_1(1260)$. The size of the mass window is enlarged for τ_h candidates with high p_T .
- $h^\pm h^\pm h^\mp$: A combination of three charged particles with a system mass of $0.8 < m_{\tau_h} < 1.5$ GeV. The sum of the charges is required to be 1. The charged tracks are required to originate from the same event vertex ($\Delta z < 4$ mm).

An additional requirement is imposed on the separation of the charged hadrons and strips. All the charged hadrons and strips are required to be within a narrow cone of $\Delta R = 3.0/p_T$ [GeV] around the jet axis to exploit the collimation of the decay products of energetic taus. When ΔR is smaller than 0.05 or exceeds 0.10, a cone size of 0.05 or 0.10 is used, respectively. Figure 3-6 shows the distribution of the mass of τ_h for $Z/\gamma^* \rightarrow \tau\tau$ events at $\sqrt{s} = 8$ TeV data taking period. The individual decay modes are highlighted by splitting the simulated $Z/\gamma^* \rightarrow \tau\tau$ events according to the reconstructed τ_h decay mode. As one can see the m_{τ_h} distribution peaks around the intermediate meson resonance masses of $\rho(770)$ and $a_1(1260)$. The narrow peak near the charged pion mass is due to the single charged particle decay mode.

Jets originating from quarks and gluons remain a large background to the τ_h reconstruction. This background is further reduced by requiring the selected τ_h candidates to be isolated. The τ_h candidate isolation is discussed in the next section. It is also possible for an electron or muon to be misidentified as a τ_h candidate. For example, an electron with a radiated bremsstrahlung photon that undergoes a pair conversion

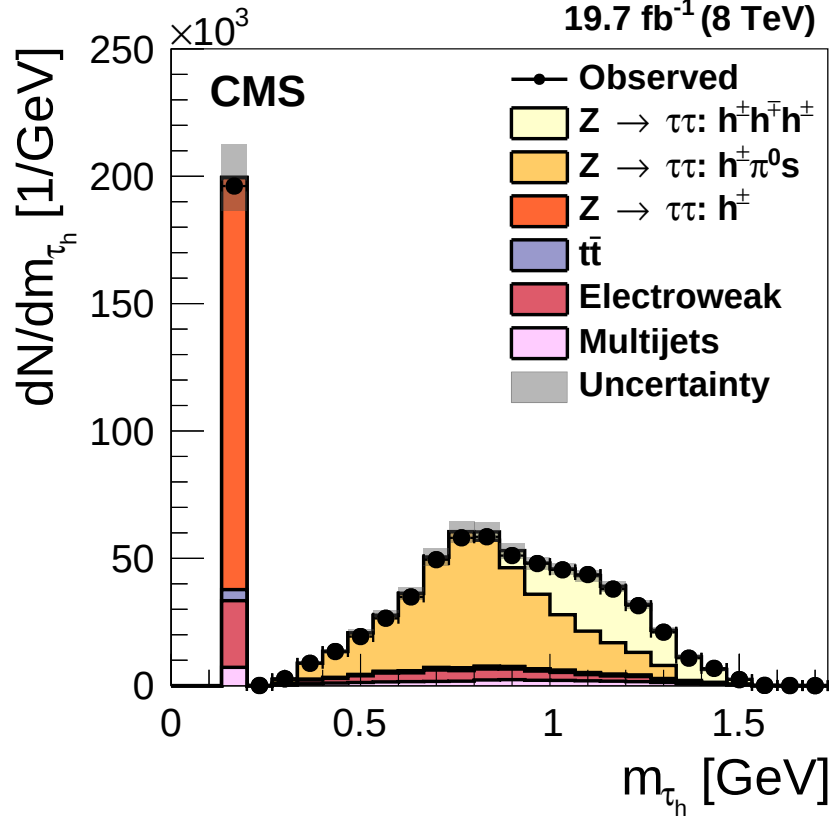


Figure 3-6: Distribution of the τ_h masses in $Z/\gamma^* \rightarrow \tau\tau$ events selected in data during $\sqrt{s} = 8$ TeV data taking period. Expected predictions from the simulation are also shown. The $Z \rightarrow \tau\tau$ prediction is split into the different expected τ_h decay modes. The electroweak background is mainly due to W +jets production [134].

is likely to be reconstructed as a $h^\pm\pi^0$ decay mode. misidentified muons are rejected if track segments are found in at least two muon stations consistent with the direction of the τ_h candidate. There are also additional requirements on the expected energy deposits in the ECAL and HCAL. misidentified electrons are rejected by considering variables sensitive to the distribution of the energy deposits in the ECAL and the particle multiplicities to distinguish electromagnetic and hadron showers. Variables sensitive to the bremsstrahlung radiation are also considered. For example, the amount of bremsstrahlung radiation can be quantified by $\frac{p_{in}-p_{out}}{p_{in}}$ where p_{in} (p_{out}) is the measured momentum at the innermost (outermost) region of the inner tracker. A BDT discriminant is implemented taking as an input these variables. More details can be found in [134].

3.8 Lepton Isolation

Leptons originating from the decays of the W , Z , and Higgs bosons are expected to be isolated from additional hadronic activity in the vicinity of the lepton. On the other hand, the leptons originating from the decays of the bottom and charm quarks and in-flight decays of the kaons and pions are surrounded by a significant contribution of additional hadrons present inside the jet. It is also possible for a charged hadron inside a jet to be miss-reconstructed as a lepton. Thus, in either of these cases the lepton candidates have a significant energy flow in the vicinity of the lepton trajectory and a requirement on the isolation reduces these lepton backgrounds.

The PF candidates are used to define the isolation metric as this ensures that the most accurate measurements are used. Moreover, the use of the PF candidates avoids a possible double counting where the energy deposits of the same particle in different sub-detectors are included in the isolation metric. The isolation metric for the muons and electrons is defined as:

$$I_\ell = \sum_{i \in \text{PV}} p_{iT}^{\text{charged}} + \sum_i (p_{iT}^{\text{neutral}} + p_{iT}^\gamma) - p_T^{\text{PU}}, \quad (3.6)$$

where the charged and neutral particles are required to be within a cone of radius $\Delta R = 0.4$ around the lepton direction. The lepton, the neutral hadrons, and photons in the innermost region of the cone ($\Delta R < 0.01$) are excluded from the isolation sum to take into account the radiation off the lepton. The isolation metric defined in Equation (3.6) is susceptible to the additional pileup interactions present in the event. The contribution of the charged particles originating from the pileup interactions are removed by considering only the charged particles associated to the primary vertex of the event. This is achieved by only including the charged particles within 0.1 cm of the closest approach of the corresponding track to the primary vertex in the z coordinate.

The last term in Equation (3.6) denotes the contribution of the neutral particles originating from the pileup interactions. Two methods are used to estimate the p_T^{PU} . The first method is based on the observation that the rate of the charged particles

originating from the pileup interactions is about two times larger than the corresponding rate of the neutral particles. Thus, the contribution due to the neutral particles originating from the pileup interactions can be estimated by determining the contribution of the charged particles not associated to the primary vertex:

$$p_T^{\text{PU}} = \frac{1}{2} \sum_{i \notin \text{PV}} p_{iT}^{\text{charged}}. \quad (3.7)$$

Only the charged particle contribution is included in the isolation sum in Equation (3.6) if the magnitude of the p_T^{PU} is larger than the neutral contributions. The second method is based on calculating the median energy density ρ of the pileup interactions in the isolation cone similar to the jet area method discussed in Section 3.5.1. This method is used for the electron isolation metric [135]. Selected electrons and muons are required to be isolated by applying a requirement on the relative isolation $\frac{I_\ell}{p_T}$ where p_T is the lepton transverse momentum. A relative isolation values less than 0.10 to 0.15 are typically required for the selected lepton candidates depending on the η region. The exact values are optimized for each data taking period.

The charged hadrons used to reconstruct the tau hadronic decays and the electrons and photons used to form the strips are excluded from the isolation sum for the τ_h isolation. The Equation (3.8) is slightly modified for the τ_h isolation definition:

$$I_{\tau_h} = \sum_{i \in \text{PV}} p_{iT}^{\text{charged}} + \max(0, \sum_i p_{iT}^\gamma - 0.46 \sum_{i \notin \text{PV}} p_{iT}^{\text{charged}}), \quad (3.8)$$

where a cone size of $\Delta R = 0.5$ around the τ_h direction is used and the p_T of the charged hadrons and photons is required to be greater than 0.5 GeV. The track distance requirement to the primary vertex is 0.2 cm in the z direction and $\Delta r < 0.03$ cm in the transverse direction. A cone size of $\Delta R = 0.8$ around the τ_h direction is used to compute the contribution of the charged particles originating from the pileup interactions. The factor 0.46 minimizes the dependance of the efficiency of the isolation to the pileup interactions. Figure 3-7 shows the distribution of the I_{τ_h} for $\tau^+ \tau^-$ candidate events with a muon and τ_h final state with $p_T > 20$ GeV. Events

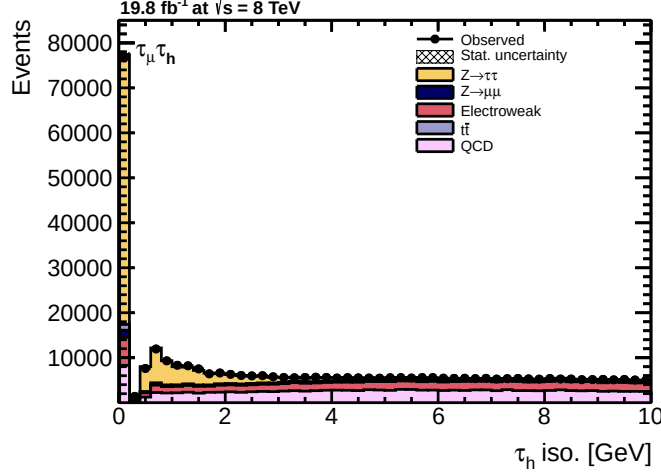


Figure 3-7: Distribution of τ_h isolation for $\tau^+\tau^-$ candidates events with a muon and τ_h final state with $p_T > 20$ GeV. Points represent the data and the histograms show the expected contribution from different SM processes. The muon selection requirement on the isolation is $I_{\text{rel}} < 0.1$. The QCD multi-jet process contributions is estimated from same-sign charged muon and τ_h and the electroweak background is mainly due to W +jets production. The W +jet contribution is suppressed here by a selection requirement on the transverse mass of the muon and missing transverse energy system as discussed in the next chapter.

with large I_{τ_h} values mainly come from QCD multi-jet background and W +jet events where the W boson decays to a muon and a jet is misidentified as a τ_h . The W +jet contribution is suppressed here by a selection requirement on the transverse mass of the muon and missing transverse energy system as discussed in the next chapter. The selected τ_h candidates are required to have I_{τ_h} values less than 1.0 GeV for the $\tau_h\tau_h$ final states and 1.5 GeV for the $\tau_\ell\tau_h$ final states. The efficiency to select the τ_h candidates ranges from 60% to 70% with a jet misidentification probability of about 1% [134]. Figure 3-7 shows that relaxing the requirements on the lepton isolation provides a useful control region enriched with the background processes with a jet is misidentified as a lepton.

3.9 Missing Transverse Energy

Neutrinos and hypothetical neutral weakly interacting particles produce a momentum imbalance in the plane perpendicular to the beam direction. The missing transverse

momentum $\vec{E}_T^{miss}$ is defined as the negative vectorial sum of all the visible particle transverse momenta in the event. The magnitude E_T^{miss} is referred to as the missing transverse energy. A precise measurement of E_T^{miss} is crucial for the W boson cross section measurements and plays a key role in the Higgs boson searches decaying to $\tau^+\tau^-$ final states. Precise calibration of all the reconstructed physics objects in the event is important for an accurate $\vec{E}_T^{miss}$ measurement. Therefore, the PF candidates are used to reconstruct the $\vec{E}_T^{miss}$:

$$\vec{E}_T^{miss} = - \sum_{i \in \text{PF candidates}} \vec{p}_{Ti}, \quad (3.9)$$

denoted as PF $\vec{E}_T^{miss}$.

The $\vec{E}_T^{miss}$ response and resolution can be degraded due to minimum energy thresholds and non-linear response in the calorimeters, and p_T thresholds and inefficiencies in the inner tracker. By correcting the jet energy scale as described above one can reduce the biases in the response of $\vec{E}_T^{miss}$ introduced by these effects [136]. In addition, the $\vec{E}_T^{miss}$ is sensitive to the additional pileup interactions in the event. While contribution of genuine $\vec{E}_T^{miss}$ from the pileup interactions is small due to small probability to produce neutrinos in the inelastic pp collisions, the nonlinearity and minimum thresholds of the calorimeters cause the $\vec{E}_T^{miss}$ to point on average in the direction of the vectorial $\vec{p}_T$ sum of the neutral particles. Each additional pileup interaction in a given event degrades the resolution of the PF $\vec{E}_T^{miss}$ by about 3.5 GeV added in quadrature [136]. On the other hand the impact on the response of the PF $\vec{E}_T^{miss}$ is small as the additional pileup interactions are isotropic.

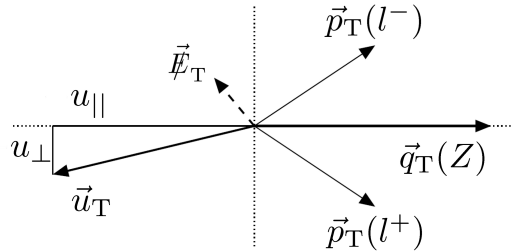


Figure 3-8: Illustration of the recoil $\vec{u}_T$ definition in the transverse plane for $Z \rightarrow \ell\ell$ events [136].

Thus, it is crucial to mitigate the effect of the pileup interactions on the resolution of the $\vec{E}_T^{miss}$. Two methods are employed in the results shown in the next chapter. The main approach in both of these methods is to identify the particles that are likely to originate from the pileup interactions and the particles that are likely to originate from the hard scattering of interest. MVA PF $\vec{E}_T^{miss}$ method relies on a BDT regression algorithm as implemented in TMVA [127]. Consider a $W \rightarrow \ell\nu$ event. The hadronic recoil is defined as:

$$\vec{u}_T = -\vec{q}_T - \vec{E}_T^{miss}, \quad (3.10)$$

where $\vec{q}_T$ is the transverse momentum of the W boson. The recoil can be identically defined for the $Z \rightarrow \ell\ell$ events even though there is no genuine $\vec{E}_T^{miss}$ in this process. The Z boson can be well measured in these events allowing to better understand the response and resolution of the recoil. The $\vec{q}_T$ of the Z boson defines a unique axis in the event. The hadronic recoil is projected onto this axis to obtain the parallel $u_{\parallel}$ and perpendicular $u_{\perp}$ components of the recoil. This is illustrated in Figure 3-8. The BDT regression first corrects the recoil direction to the true hadronic recoil direction. The magnitude of the $\vec{u}_T$ is corrected in the second step using simulated $Z \rightarrow \mu\mu$ and γ +jets events. The BDT utilizes 5 different constructions of the recoil ($\vec{E}_T^{miss}$):

- The negative sum $\vec{p}_T$ of all the PF candidates, i.e. the PF $\vec{E}_T^{miss}$.
- The negative sum $\vec{p}_T$ of all the charged PF candidates associated to the primary vertex of the event.
- The negative sum $\vec{p}_T$ of all the charged PF candidates and all the neutral PF candidates inside jets satisfying the pileup jet identification requirement discussed in Section 3.5.2.
- The negative sum $\vec{p}_T$ of all the charged PF candidates not associated to the primary vertex of the event and all the neutral PF candidates within jets not satisfying the pileup jet identification requirement.

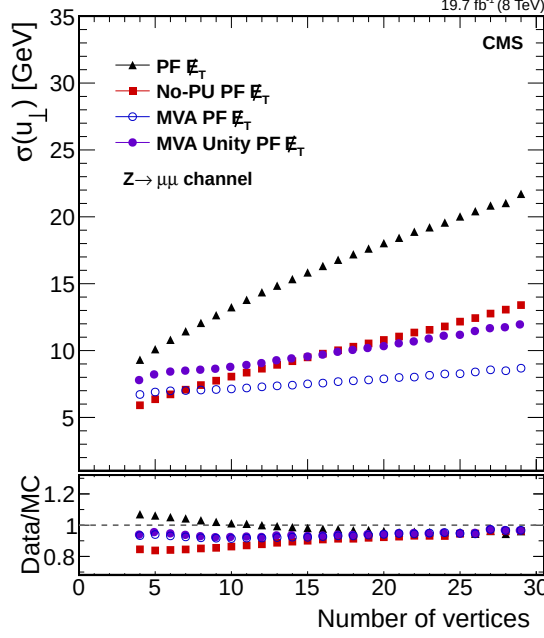


Figure 3-9: The resolution of the perpendicular component of the recoil as a function of the number of vertices for $Z \rightarrow \mu\mu$ data events shown for the PF $\vec{E}_T^{miss}$ in black triangles and MVA MVA PF $\vec{E}_T^{miss}$ in blue open circles for the $\sqrt{s} = 8$ TeV data taking period. The MVA Unity PF $\vec{E}_T^{miss}$ and No-PU PF $\vec{E}_T^{miss}$ are additional pileup mitigation techniques not discussed here [136].

- The negative sum $\vec{p}_T$ of all the charged PF candidates associated to the primary vertex of the event and all the neutral PF candidates. In addition, the PF candidates within jets not satisfying the pileup jet identification requirement are added to this sum $\vec{p}_T$.

Figure 3-9 shows the the resolution of the perpendicular component of the recoil as a function of the number of reconstructed vertices in $Z \rightarrow \mu\mu$ data events at $\sqrt{s} = 8$ TeV data taking period. The black triangles show the PF $\vec{E}_T^{miss}$ and the blue open circles show the MVA $\vec{E}_T^{miss}$. As it can be seen the resolution of the PF $\vec{E}_T^{miss}$ is significantly degraded with additional pileup interactions in the event while the MVA PF $\vec{E}_T^{miss}$ resolution is significantly better compared to the PF $\vec{E}_T^{miss}$ resolution. For example, for the $\sqrt{s} = 8$ TeV data taking period the average number of pileup interactions is 20 (Figure 1-5) resulting in the improvement of the MVA PF $\vec{E}_T^{miss}$ resolution by a factor of two with respect to the PF $\vec{E}_T^{miss}$ resolution.

The second method used to mitigate the effect of the additional pileup interactions

in the event is called pileup per particle identification (PUPPI) [137]. The main idea consists of defining a shape variable that encodes the collinear versus soft diffuse structure around a given particle. The charged particles within the inner tracker acceptance region not associated to the primary vertex are used to compute the shape variable distribution for each event. An assumption is made that this distribution is representative of all the particles originating from the pileup interactions. The shape variable is then used to define a weight associated with each particle giving the probability of that particle to originate from a pileup interaction. The charged particles associated to the primary vertex are assigned a weight of 1 while the charged particles not associated to the primary vertex are assigned a weight of 0. The weights are then used to rescale the four-momenta of the particles. The particles with very small weights or transverse momenta are discarded. The PUPPI $\vec{E}_T^{miss}$ is determined by the negative $\vec{p}_T$ sum of the rescaled four-momenta of the PF candidates. The PUPPI $\vec{E}_T^{miss}$ resolution is comparable to the resolution obtained using the MVA $\vec{E}_T^{miss}$ technique.

3.9.1 Recoil Calibration

Discrepancies between simulation and data in the response and resolution of the recoil are calibrated using the $Z \rightarrow \mu\mu$ data events. Figure 3-9 shows the simulation and data differences in the lower panel of the figure. The differences are due to imperfect simulation of the underlying event, and differences in the calorimeter response and resolution. The distributions of the parallel and perpendicular components of the recoil in the $Z \rightarrow \mu\mu$ data and simulation events are fitted with a double Gaussian. This is done as a function of the Z boson p_T and the number of reconstructed jets in the event. Figure 3-10 shows a typical fit for the recoil parallel (left panel) and perpendicular (right panel) components in the $Z \rightarrow \mu\mu$ data events at $\sqrt{s} = 13$ TeV data taking period. The ratios of the data to simulation fit parameters are used to calibrate the recoil response and resolution. For example, the recoil in $W \rightarrow \ell\nu$ or H simulated events are corrected in this way as a function of the simulated truth of the boson or scalar p_T . The $\vec{E}_T^{miss}$ is then obtained by adding back the energy of the

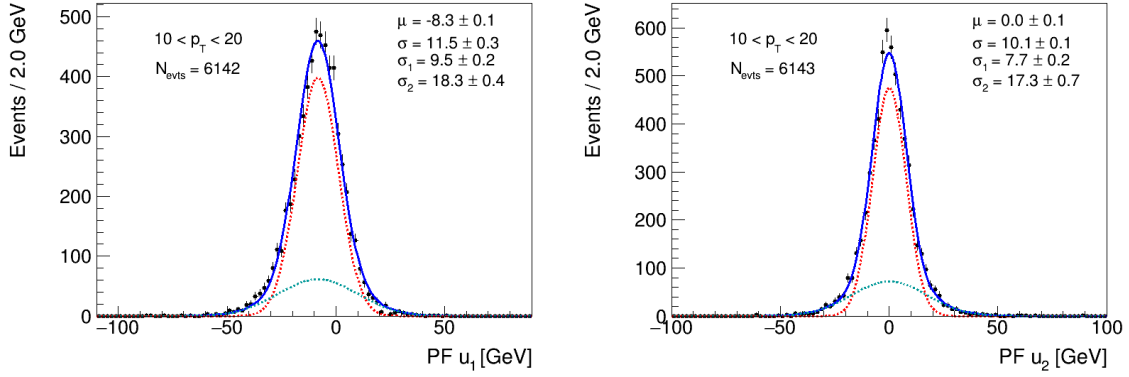


Figure 3-10: Double Gaussian fits to the distributions of the parallel (left panel, denoted as u_1) and perpendicular (right panel, denoted as u_2) components of the recoil in $Z \rightarrow \mu\mu$ data events at $\sqrt{s} = 13$ TeV data taking period. The fits are shown for the Z p_T in the range of 10 to 20 GeV. The PUPPI algorithm is used for the recoil distributions shown here. The σ_i and μ_i parameters are the standard deviations and means of the two Gaussian distributions, respectively. The σ and μ are the weighted average values of the σ_i and μ_i .

lepton to the corrected recoil. The statistical uncertainties of the fit parameters are propagated to the $\vec{E}_T^{\text{miss}}$ as a systematic uncertainty. The corrections are also derived as a function of the boson rapidity to take into account the differences in kinematics of the Z and W bosons. An additional systematic uncertainty is included to take these differences into account.

3.9.2 Covariance Matrix

The covariance matrix V of the $\vec{E}_T^{\text{miss}}$ is computed from the covariance matrix of each object in the event given by:

$$U_i = \begin{pmatrix} \sigma_{p_{iT}}^2 & 0 \\ 0 & p_{iT}^2 \sigma_{i\phi}^2 \end{pmatrix}, \quad (3.11)$$

where Gaussian uncertainties are assumed [138]. It is assumed that there is no correlation between the σ_{p_T} and σ_ϕ . This equation gives U_i in the coordinate system with one axis aligned with the direction of the $\vec{E}_{iT}$. A rotation in the ϕ direction is performed to obtain the covariance matrix V in the $x - y$ coordinate system of the

CMS detector:

$$V = \sum_i R(\phi_i) U_i R_i^{-1}, \quad (3.12)$$

where R is the rotation matrix.

3.10 Luminosity Calibration

The absolute calibration of the dataset is the leading systematic uncertainty of the W and Z cross section measurements. Several detectors are used to monitor and measure the instantaneous luminosity based on the rate of events recorded by these detectors during the LHC collisions. The count of the number of reconstructed clusters in the inner silicon pixel detector is used for the calibration of the total integrated luminosity recorded by CMS [54, 55]. The low occupancy and good stability of the pixel detector make it an ideal candidate for this measurement as the rate of the clusters is proportional to the instantaneous luminosity. The absolute calibration is performed by utilizing the Van der Meer (VdM) scan technique [139]. The proton beams are scanned by moving the beams in the transverse direction in a dedicated LHC machine setup. The beam profiles are determined by analyzing the collected data in the VdM scan determining the calibration constants relating the instantaneous luminosity to the rate of the reconstructed clusters in the pixel detector.

The pixel cluster acceptance effects can introduce time and pileup dependent variations of the calibration constants. There are also dependencies on the number of bunches of the beam and on the LHC filling schemes. These variations in the calibration constants are taken into account. The largest sources of the systematic uncertainties in the total integrated luminosity are due to the length-scale calibration of the beam-beam separation and the assumptions on the proton densities in each bunch during the VdM scans. The systematic uncertainty in the total integrated luminosity obtained with this technique is 2.2% for the 2011, 2.6% for the 2012, and 2.7% for the 2015 data taking periods.

Chapter 4

Results and Interpretations

This chapter summarizes four results using events recorded by the CMS detector at the LHC proton-proton collisions in 2011, 2012, and 2015 data taking periods. The measurements of inclusive W and Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV are described in Section 4.1. The total and fiducial inclusive production cross sections and ratios are reported. The measured cross section values agree with NNLO QCD calculations. The leptonic branching ratio and the total width of the W boson are extracted from the W/Z cross section ratio measurement. The search for the SM Higgs boson decaying into a pair of tau leptons in proton-proton collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV is described in Section 4.2. An excess of events with respect to the expected background contributions at the mass of the SM Higgs boson around 125 GeV are reported. The search for heavy neutral resonances decaying into a pair of tau leptons in the context of the MSSM Higgs bosons is described in Section 4.3. No excess is observed with respect to the background predictions and upper limits are set on the production cross sections times branching fractions for resonances produced in gluon fusion and b quark associated production modes. The results are interpreted in the context of the MSSM model with different benchmark scenarios.

4.1 Inclusive W and Z Production Cross Sections

The inclusive W and Z boson production cross sections and their ratios have been previously measured at the LHC by the ATLAS and CMS collaborations in the LHC proton-proton collisions at $\sqrt{s} = 7$ TeV [140, 141, 142]. The corresponding measurement performed in the LHC proton-proton collisions at $\sqrt{s} = 8$ TeV by CMS is described in this section [143]. ATLAS and CMS collaborations have also performed this measurement in the LHC proton-proton collisions at $\sqrt{s} = 13$ TeV [144, 145]. The CMS preliminary measurement in the LHC collisions at $\sqrt{s} = 13$ TeV is also described in this section. A systematic uncertainty of 4.8% in the total integrated luminosity was reported in [144]. An update to the total integrated luminosity reducing this systematic uncertainty to 2.7% was reported in [55]. The results shown in this section include the updated integrated luminosity value and the corresponding systematic uncertainty.

The electron and muon final states are used to observe the W and Z bosons. The Z boson candidates are required to have a dilepton mass in the range of 60 to 120 GeV. The inclusive total cross section is given by:

$$\sigma = \frac{N}{\varepsilon A \mathcal{L}}, \quad (4.1)$$

where A is the fiducial kinematic and geometric acceptance, ε is the efficiency to reconstruct and identify the boson candidate, N is the number of observed W or Z boson candidates, and $\mathcal{L}$ is the total integrated luminosity of the data sample (discussed in Section 3.10). The W and Z production cross sections and their ratios are also measured within the fiducial kinematic and geometric acceptance of the CMS detector.

Section 4.1.1 describes the data samples and simulation of the events used in the results and Section 4.1.2 describes the selection of the candidate W and Z events. The geometrical and kinematic acceptance and associated theory uncertainties are described in Section 4.1.3, whereas the measurements of the lepton reconstruction, selection, and trigger efficiencies are described in Section 4.1.4. The W and Z boson

signal extraction and the systematic uncertainties are described in Sections 4.1.5 and 4.1.6, respectively. The measured inclusive total and fiducial cross section measurements and ratios are summarized in Section 4.1.7.

4.1.1 Data and Simulated Samples

The W and Z candidate events in proton-proton collisions at $\sqrt{s} = 13$ TeV are selected from data samples collected in July 2015, corresponding to an integrated luminosity of $\mathcal{L} = 43.0 \pm 1.2 \text{ pb}^{-1}$. Data samples collected in May 2012, corresponding to an integrated luminosity of $\mathcal{L} = 18.2 \pm 0.5 \text{ pb}^{-1}$, are used to select the W and Z candidate events at $\sqrt{s} = 8$ TeV. The instantaneous luminosity reached at the LHC during the full 2012 data taking period presents a challenging environment to perform the $W \rightarrow \ell\nu$ cross section measurement due to the degradation of the E_T^{miss} resolution arising from the additional pileup interactions in the events (Figure 1-5). The impact of the pileup interactions on the E_T^{miss} resolution was discussed in Section 3.9. The collisions in May 2012 had low pileup with an average of 4 additional pileup interactions per bunch crossing compared with the average of 20 pileup interactions during the full data taking period. This was achieved in a special configuration where the separation of the proton beams was adjusted during the data taking to achieve a stable and low instantaneous luminosity. There were no special low pileup collisions in 2015 and the measurement was performed by employing the PUPPI pileup mitigation technique discussed in Section 3.9.

The candidate events selected by the CMS trigger require the presence of at least one electron or muon candidate with a threshold requirement on the energy and pseudorapidity. The muon candidates are triggered if there is at least one muon candidate present with transverse momentum p_T greater than 20 GeV (15 GeV) and with $|\eta|$ less than 2.4 (2.1) during the 2015 (2012) data taking period. There is a loose isolation and identification requirement for the 2015 data taking period to cope with the limited bandwidth for the data processing. The electron candidates are triggered if there is at least one electron candidate present with transverse energy E_T greater than 23 GeV (22 GeV) and with $|\eta| < 2.5$, during the 2015 (2012) data taking period.

with loose isolation and identification requirements.

Several MC event generators are used to simulate the W and Z boson and background processes. The signal samples used for the $\sqrt{s} = 13$ TeV measurement are generated using MadGraph5_aMC@NLO [146] generator with matrix element calculations having up to two extra partons in the final state with the NNPDF3.0 [147] NLO PDF set. The matrix element calculation is merged with the parton shower simulation using the FxFx merging scheme [148]. PYTHIA 8 [149, 150] with tune CUETP8M1 [151] is used for the simulation of the parton shower, hadronization, and the underlying event. The signal samples for the $\sqrt{s} = 8$ TeV measurement are generated using POWHEG [152, 153, 154, 155] generator, with the CT10 [156] NLO PDF set, interfaced with PYTHIA 6.4 [149]. The PYTHIA 6.4 parameters for the description of the underlying event are set to the $Z2^*$ tune [157]. The $\sqrt{s} = 13$ TeV ($\sqrt{s} = 8$ TeV) diboson background samples are generated with POWHEG and PYTHIA 8 (PYTHIA 6.4). The $t\bar{t}$ background is generated with MadGraph5_aMC@NLO. The PYTHIA 6.4 used for the $\sqrt{s} = 8$ TeV samples is interfaced with TAUOLA to simulate the decays of polarized tau leptons. For all the generated processes the additional pileup interactions and the detector response are simulated as described in Section 2.6.

4.1.2 Event Selection

The $Z \rightarrow \ell^+ \ell^-$ decays are characterized by two energetic and isolated leptons. The Z boson candidates are required to have a reconstructed dilepton mass between 60 to 120 GeV. $W \rightarrow \ell \nu$ decays are characterized by an energetic and isolated lepton with a significant missing transverse energy E_T^{miss} . There is no requirement on the minimum reconstructed E_T^{miss} in the event selection. The E_T^{miss} distribution is used as a discriminant against backgrounds from multi-jet events where a jet is misidentified as a lepton.

The muon and electron candidates are reconstructed and identified as described in Chapter 3. It is also required that the selected lepton candidate triggered the event in the $W \rightarrow \ell \nu$ candidate selection while at least one of the selected leptons is

required to trigger the event for the $Z \rightarrow \ell^+ \ell^-$ event candidates. The kinematic and geometric fiducial acceptance regions are defined as follows. The muon candidates are required to have a transverse momentum greater than 25 GeV and $|\eta| < 2.4$. The electron candidates are required to have a transverse energy E_T greater than 25 GeV with $|\eta| < 1.444$ and $1.556 < |\eta| < 2.5$. The transition region between the ECAL barrel and endcap regions, $1.444 < |\eta| < 1.556$, is excluded as the reconstructed ECAL clusters have lower quality there due to services and cables exiting between the ECAL barrel and endcap. The two muon candidates in the $Z \rightarrow \mu^+ \mu^-$ candidate selection are required to be oppositely charged.

The following background processes are considered:

- **QCD multi-jet:** The lepton isolation requirements reduce this background where a jet is misidentified as a lepton as discussed in Section 3.8.
- **Drell-Yan:** The Drell-Yan lepton pair where one of the leptons is not within the fiducial region or is not reconstructed is a background source for the $W \rightarrow \ell \nu$ candidate events. Events with a second lepton with $p_T > 10$ GeV and satisfying loose identification requirements in the $W \rightarrow \ell \nu$ candidate event selection are vetoed to reduce this background.
- **$W \rightarrow \tau \nu$ and $Z \rightarrow \tau^+ \tau^-$:** The leptonic decays of the τ lepton(s) from the W and Z boson decays constitutes a background.
- **Boson and top-quark pair:** The production of the WW , WZ , and ZZ processes constitutes a background as the W and Z bosons originating from these processes are not considered in the signal definition. There is also non-negligible contribution from the $t\bar{t}$ events with at least one lepton in the final state.

The QCD multi-jet process is the dominant background for the $W \rightarrow \ell \nu$ candidate events and is simply denoted as the "QCD" background. The other background processes, except the $t\bar{t}$ process, are denoted as the "EWK" background. The EWK and $t\bar{t}$ background contributions are estimated from the simulation. For the simulated background samples the calculated cross sections are taken at NNLO in QCD

if available (calculations at NLO accuracy is used otherwise). The Drell-Yan and $W \rightarrow \tau^+ \nu$ background processes have sizable contribution in the $W \rightarrow \ell \nu$ candidate events, while the $t\bar{t}$ and diboson contribution is small. The QCD multi-jet background contribution is negligible in the $Z \rightarrow \ell^+ \ell^-$ events with a dilepton mass between 60 to 120 GeV.

4.1.3 Efficiency

The efficiency of the lepton selection is a key component of the cross section measurement as can be seen from Equation (4.1). The single lepton efficiencies are measured from the $Z \rightarrow \ell^+ \ell^-$ data events referred to as the tag-and-probe method. The idea is to identify a "tag" lepton candidate satisfying the identification, isolation, and triggering requirements and a "probe" lepton candidate inside the dilepton mass window requirement. The mass window requirement gives a relatively pure selection of $Z \rightarrow \ell^+ \ell^-$ data events. The probe is required to pass a specific criteria depending on the efficiency under study. The efficiency ε is then given by:

$$\sigma = \frac{N_{\text{pass}}}{N_{\text{pass}} + N_{\text{fail}}}, \quad (4.2)$$

where N_{pass} and N_{fail} denote the number of passing and failing probes, respectively. The efficiencies are measured in data and in simulation. This allows to correct for the imperfect simulation through data-to-simulation scale factors.

The lepton efficiencies are measured as a function of the lepton transverse energy and η , allowing to propagate the efficiencies measured in the Z candidate events to the W cross section measurement. The muon and electron selection efficiencies are determined as follows:

$$\begin{aligned} \varepsilon_\mu &= \varepsilon_{\text{trig}} \varepsilon_{\text{sta}} \varepsilon_{\text{track-id}}, \\ \varepsilon_e &= \varepsilon_{\text{trig}} \varepsilon_{\text{gsf-id}}, \end{aligned} \quad (4.3)$$

where ε_μ and ε_e are the muon and electron selection efficiencies, respectively. The $\varepsilon_{\text{trig}}$ denotes the trigger efficiency with the probe lepton candidate satisfying the identifica-

tion and isolation requirement. The ε_{sta} denotes the standalone muon reconstruction efficiency where the probe lepton candidate is a track in the inner tracker. Similarly, the $\varepsilon_{\text{track-id}}$ denotes the muon track reconstruction (inner tracker), identification, and isolation efficiency where the probe lepton candidate is a standalone muon track (Section 3.3). The $\varepsilon_{\text{gsf-id}}$ denotes the electron reconstruction, identification, and isolation efficiency where the probe lepton candidate is an ECAL supercluster. The ECAL supercluster reconstruction efficiency is taken from the simulation as the $\frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{sim}}}$ ratio is found to be consistent with one.

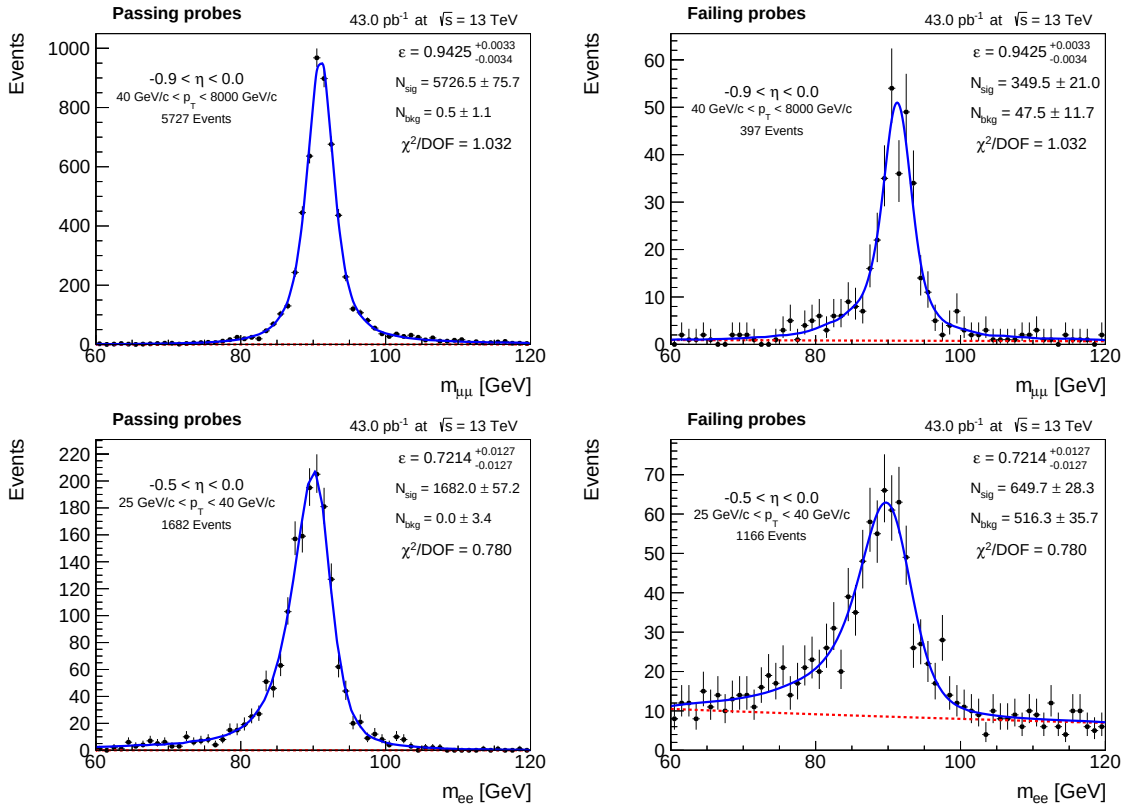


Figure 4-1: Examples of the fits to the dilepton mass distributions to determine the lepton reconstruction and identification efficiencies. The "passing" (left) and "failing" (right) probe categories of the simultaneous fits are shown for the $Z \rightarrow \mu^+\mu^-$ (top) and $Z \rightarrow e^+e^-$ (bottom) data events taken during the 2015 LHC data taking period. The fits for the electron probes with E_T in the range of 25 to 40 GeV and $-0.5 < \eta < 0.0$, and muon probes with p_T greater than 40 GeV and $-0.9 < \eta < 0.0$ are shown. The dashed red curves denote the fitted background contributions while the solid blue lines denote the sum of the fitted signal and background contributions.

The background contribution is negligible in the selected $Z \rightarrow \ell^+\ell^-$ candidate

events used to measure the trigger efficiency. For the remaining efficiencies defined in Equation (4.3) there is a sizable background contribution and a simultaneous fit to the dilepton mass distributions in the "passing" and "failing" event categories, where the probe passes and fails the criteria of interest, respectively, is performed. Figure 4-1 shows a representative example of the simultaneous fit for the $\varepsilon_{\text{track-id}}$ (top) and $\varepsilon_{\text{gsf-id}}$ (right) efficiencies in the $\sqrt{s} = 13$ TeV data events. The signal model is

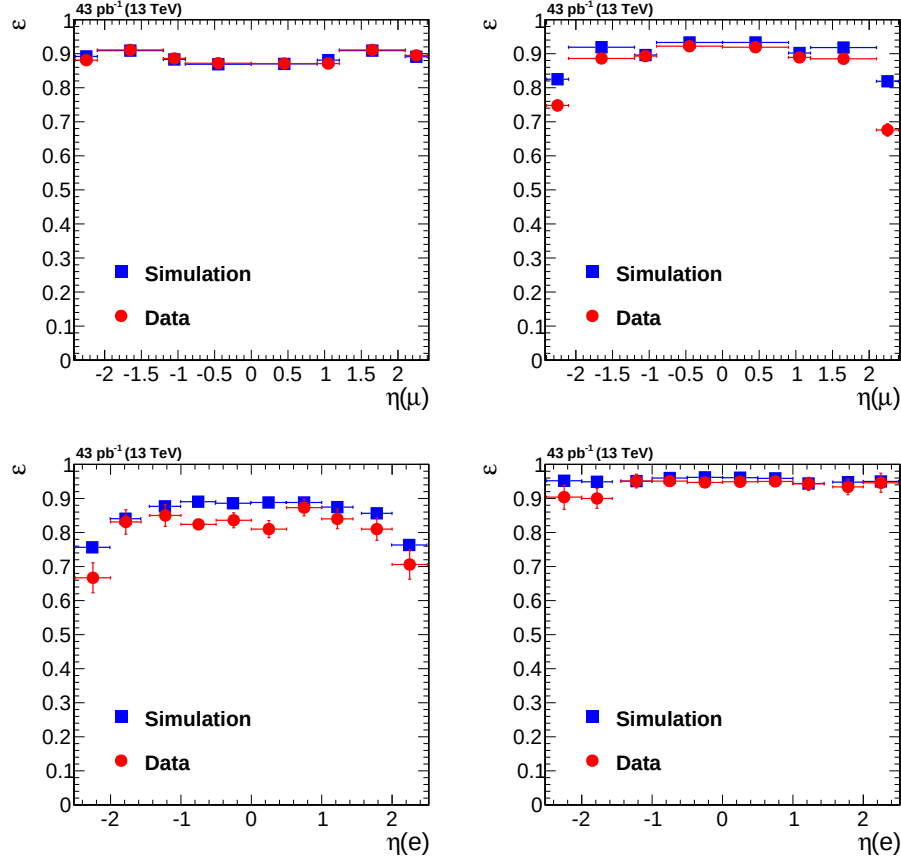


Figure 4-2: Single muon (top) and electron (bottom) efficiencies in data (red circle) and simulation (blue square) for the reconstruction, identification, and isolation (left) and trigger (right) as a function of the corresponding lepton pseudorapidities. The shown data events are taken during the 2015 LHC data taking period. The muon probes with $25 < p_T < 40$ GeV and electron $E_T > 55$ GeV are selected. Scale factors are derived to correct the simulated events used in the results.

derived by convolving the dilepton mass shape obtained from the simulation with a Gaussian distribution. Taking the mass shape from the simulation takes into account the detector and the lepton final state radiation effects on the distribution. The

convoluted Gaussian accounts for the imperfect simulation of the lepton resolution. An exponential function is used to model the background contribution. Figure 4-2 shows a representative example of the measured reconstruction, identification, and isolation (left) and trigger (right) efficiencies as a function of the probe pseudorapidity for the muon (top) and electron (bottom) candidates in 2015 data (red) and simulation (blue).

Systematic uncertainties in the efficiency measurement are determined by considering alternative signal and background shape models. A Breit-Wigner with nominal Z mass and width convoluted with an asymmetric resolution function is used as an alternative signal model and a power law function is used as an alternative background model. The statistical uncertainties in the efficiency measurements are propagated as a systematic uncertainty in the cross section measurement. The biases in the efficiency measurement due to the tag lepton candidate selection and dilepton mass requirement are negligible. The systematic uncertainties are summarized in Section 4.1.6.

4.1.4 Acceptance

The kinematic and fiducial acceptance of the $W \rightarrow \ell\nu$ or $Z \rightarrow \ell^+\ell^-$ boson events is the fraction of generated events with the final state leptons satisfying the requirements on p_T and η . The Z boson events are generated with $60 < m_Z < 120$ GeV requirement. The muons are required to have a $p_T > 25$ GeV and $|\eta| < 2.4$. The electrons are required to have a $p_T > 25$ GeV and $|\eta| < 1.442$ or $1.566 < |\eta| < 2.5$. The lepton momenta are evaluated after the final state QED radiation (FSR). For the Z boson acceptance the dilepton invariant mass is required to be in the range of $60 < m_{\ell\ell} < 120$ GeV.

The acceptance is calculated using the MadGraph5_aMC@NLO (POWHEG) simulation at NLO in QCD with the NNPDF3.0 (CT10) PDF set and showered with PYTHIA 8 (6.4) in collisions at $\sqrt{s} = 13$ TeV ($\sqrt{s} = 8$ TeV). Thus, the nominal acceptance value is accurate up to NLO in perturbative QCD and up to the leading-logarithmic (LL) for soft and non-perturbative QCD effects. The systematic

Process	NNPDF3.0 [%]	MMHT2014 [%]	CT14 [%]
W^+	0.7	0.6	0.8
W^-	0.6	0.7	0.9
W	0.6	0.6	0.8
Z	0.7	0.9	1.1
W^+/W^-	0.6	0.4	0.6
W^+/Z	0.5	0.5	0.5
W^-/Z	0.4	0.4	0.5
W/Z	0.4	0.4	0.4

Table 4.1: The summary of the PDF uncertainties (68% CL) in the acceptance in the muon final state for the NNPDF3.0, MMHT2014 and CT14 PDF sets in collisions at $\sqrt{s} = 13\text{TeV}$.

uncertainties in the acceptance values arising from the uncertainties in the PDFs, and from missing higher order corrections in QCD and EWK are denoted as theoretical uncertainties in the cross section measurement.

The PDF uncertainties in the acceptance are estimated following the prescriptions of the individual PDF groups. The total PDF uncertainty includes the uncertainties in the α_s , where the Z mass is used as the central scale. Table 4.1 shows the summary of the PDF uncertainties in the acceptance in the muon final state for the NNPDF3.0, MMHT2014 [158], and CT14 [159] PDF sets in collisions at $\sqrt{s} = 13\text{ TeV}$. A good agreement is found in the acceptance values estimated with these 3 PDF sets. The CT14 PDF uncertainties are generally larger compared to the NNPDF3.0 and MMHT2014 PDF uncertainties. Similar results are obtained for the electron final state. The PDF uncertainties in the acceptance for the CT10 PDF set in the collisions at $\sqrt{s} = 8\text{ TeV}$ are about a factor of two larger compared to the $\sqrt{s} = 13\text{ TeV}$ uncertainties demonstrating the improvements in the PDF uncertainties with the inclusion of the results from the LHC Run 1 data in the PDF fits. The NNPDF3.0 and CT10 PDF uncertainties are propagated to the measured cross sections at $\sqrt{s} = 13\text{ TeV}$ and $\sqrt{s} = 8\text{ TeV}$, respectively.

The RESBOS [160] and DYRES [161, 162] generators provide a resummed calculation of the W and Z boson transverse momentum distributions accurate up to NNLL in QCD. The calculation is then combined with a fixed order calculation at

Process	NNLO+ISR [%]	μ_R, μ_F [%]	FSR [%]	EWK [%]	PDF [%]	Total [%]
W^+	1.2	0.2	0.6	0.2	0.7	1.6
W^-	1.0	0.3	0.3	0.6	0.6	1.4
W	1.1	0.2	0.5	0.2	0.6	1.4
Z	0.8	0.9	0.6	0.6	0.7	1.6
W^+/W^-	1.6	0.3	0.3	0.8	0.5	1.9
W^+/Z	1.2	0.9	1.1	0.7	0.5	1.9
W^-/Z	0.4	1.2	0.6	1.2	0.4	1.9
W/Z	0.5	1.0	0.8	0.8	0.4	1.7

Table 4.2: The summary of the theoretical uncertainties in the acceptance values in the electron final state in collisions at $\sqrt{s} = 13$ TeV. The uncertainties due to higher order QCD contributions, PDFs, FSR modeling, and missing EWK contributions are shown.

large values of the transverse momenta accurate to NNLO. The total inclusive cross section with NNLO accuracy is recovered by integrating the resulting boson transverse momentum distribution. The RESBOS and DYRES generators are used to estimate the impact of the soft, non-perturbative QCD effects, and QCD perturbative corrections at NNLO on the acceptance values. The differences in these acceptance values compared to the baseline MadGraph5_aMC@NLO (POWHEG) acceptance values is taken as a systematic uncertainty. The second column of the Table 4.2 shows the resulting systematic uncertainty in the electron final state in collisions at $\sqrt{s} = 13$ TeV. Similar results are obtained for the muon final state. The corresponding systematic uncertainties at $\sqrt{s} = 8$ TeV are found to be less than 1%.

The effect of the higher order perturbative QCD corrections (beyond the NNLO accuracy) are estimated by varying the renormalization (μ_R) and factorization (μ_F) scales up and down in a fixed order calculation accurate to NNLO in QCD using FEWZ [163, 164, 165]. The μ_R and μ_F values are set to the corresponding boson mass in the central value calculation and the differences in the acceptances when varying the scales up and down within a factor of two (keeping $\mu_R = \mu_F$) is taken as a systematic uncertainty. The third column of the Table 4.2 shows the uncertainties in the electron final state at $\sqrt{s} = 13$ TeV. Similar results are obtained for the muon final state and the corresponding $\sqrt{s} = 8$ TeV uncertainties.

The higher order EWK corrections are estimated using the HORACE generator [166, 167, 168, 169]. The initial and final state QED radiation in the baseline acceptance are modeled with PYTHIA with the parton shower method. The systematic uncertainty in the modeling of the final state QED radiation in PYTHIA is estimated by comparing to the acceptances of the HORACE generator FSR implementation. PHOTOS [170] is also used for additional checks. The effect of the virtual EWK corrections are estimated using HORACE. The fourth and fifth columns of Table 4.2 show the systematic uncertainties due to FSR modeling and EWK virtual corrections in the electron final state at $\sqrt{s} = 13$ TeV. Similar results are obtained for the muon final state and the corresponding $\sqrt{s} = 8$ TeV uncertainties.

4.1.5 Signal Extraction

The $Z \rightarrow \ell^+ \ell^-$ yields are obtained by counting the number of selected event candidates. The background contribution is estimated from the simulation to be about 0.6% (0.4%) in $\sqrt{s} = 13$ TeV ($\sqrt{s} = 8$ TeV) collisions and it is subtracted from the $Z \rightarrow \ell^+ \ell^-$ yields. A conservative systematic uncertainty of the same magnitude as the background contribution is propagated to the cross section measurement. The $Z \rightarrow \ell^+ \ell^-$ yields contain a contribution of about 3% from the γ^* mediated process (including the interference effects) as estimated with MCFM [171]. Figure 4-3 shows the dilepton mass distribution for the selected Z boson candidate events in the muon (left) and electron (right) final states in collisions at $\sqrt{s} = 13$ TeV. The energies of the leptons used in calculation of the dilepton mass are corrected for the energy scale effects by studying the dilepton mass peak and width. An additional resolution corrections (smearing), derived from the $Z \rightarrow \ell^+ \ell^-$ candidate events, are applied to the simulated samples. The $Z \rightarrow e^+ e^-$ candidate events with a tighter requirement on the dilepton mass range are used to study the charge misidentification rate in data and simulation. The corresponding uncertainty is not negligible for the W^+ / W^- cross section ratio measurement.

The $W \rightarrow \ell \nu$ yields are obtained by performing a maximum-likelihood fit to the E_T^{miss} distribution. The resolution of the E_T^{miss} measurement (Section 3.9) is essential

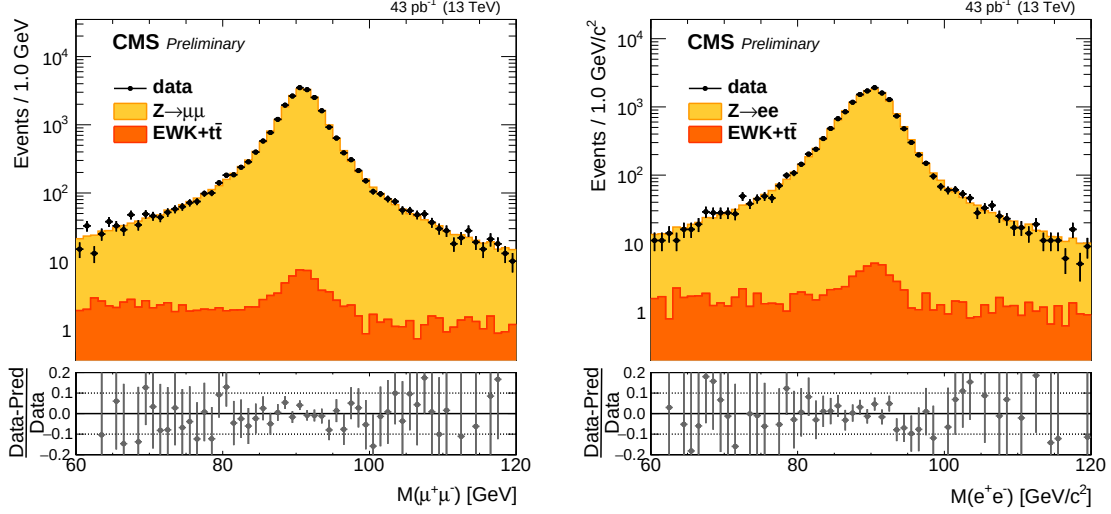


Figure 4-3: The dilepton mass distributions for the selected Z boson candidate events in the muon (left) and electron (right) final states in proton-proton collisions at $\sqrt{s} = 13$ TeV data taking period. The points with error bars represent the observed data events. The expected background contributions from the EWK and $t\bar{t}$ processes are shown superimposed with the expected Z boson signal distributions [144].

to distinguish the W candidate events from the QCD multi-jet background. The PF E_T^{miss} is used to extract the $W \rightarrow \ell\nu$ yields in collisions at $\sqrt{s} = 8$ TeV as the number of additional pileup interactions is low in the special low pileup LHC run.

The E_T^{miss} spectra of the W^+ and W^- candidates are fitted independently. The $W \rightarrow \ell\nu$ signal is modeled using simulation calibrated to the $Z \rightarrow \mu^+\mu^-$ candidate data events as described in Section 3.9.1. The $W \rightarrow \tau\nu$, $Z \rightarrow \ell^+\ell^-$, and $t\bar{t}$ background processes contribute significantly, about 10% of the signal yield, for large E_T^{miss} values. The EWK and $t\bar{t}$ backgrounds are modeled using simulation. The recoil is similarly calibrated to data for the main EWK backgrounds ($Z \rightarrow \ell^+\ell^-$ and $W \rightarrow \tau\nu$). The uncertainties in the recoil calibration are propagated to the E_T^{miss} distribution in the fit. The lepton energy scale/resolution corrections are propagated to the E_T^{miss} calculation as well. The QCD background is modeled by an analytic function. The functional shape is motivated from the well known fact that the length of a random (Gaussian distributed) two dimensional vector is described by the Rayleigh

distribution. A modified Rayleigh distribution is used given by:

$$f = E_T^{miss} \exp \left(-\frac{E_T^{miss,2}}{2(\sigma_0 + \sigma_1 E_T^{miss})^2} \right). \quad (4.4)$$

The shape parameters σ_0 and σ_1 are studied by a fit to control samples defined by inverting the truck-cluster matching, $\Delta\eta$ and $\Delta\phi$, requirements on the electron candidates and by inverting the isolation requirement on the muon candidates. A systematic uncertainty in the choice of the QCD shape is estimated by introducing an additional shape parameter σ_2 : $\sigma_0 + \sigma_1 E_T^{miss} + \sigma_2 E_T^{miss,2}$. Figure 4-4 shows the E_T^{miss} distributions for the W boson candidate events in the electron (left) and muon (right) final states in collisions at $\sqrt{s} = 8$ TeV with the superimposed results of the fit. The EWK and $t\bar{t}$ background contributions are normalized to the W boson

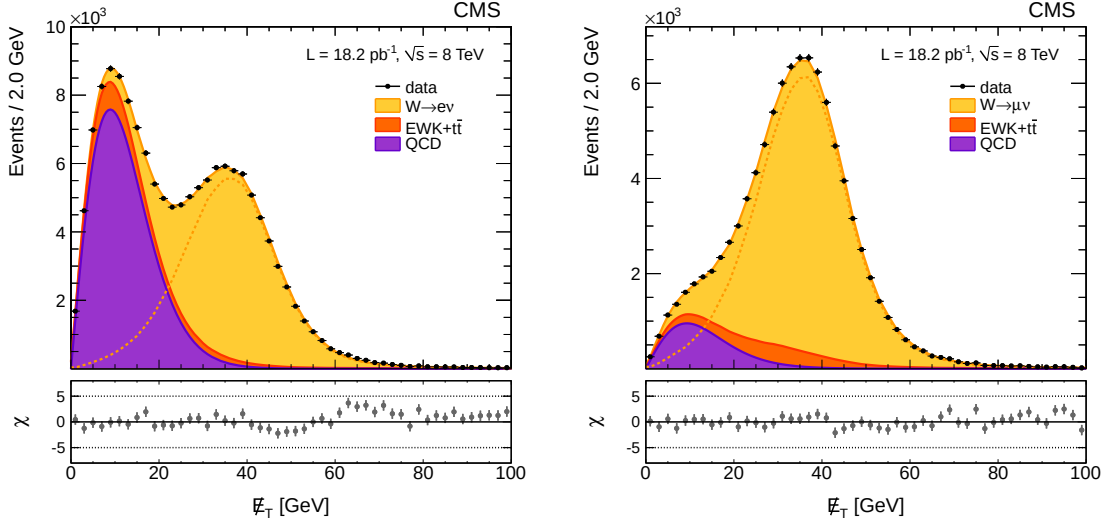


Figure 4-4: The missing transverse energy distributions for the W boson candidate events in the electron (left) and muon (right) final states in proton-proton collisions at $\sqrt{s} = 8$ TeV data taking period. The points with error bars represent the observed data events. The dotted orange lines shows the distribution of the W boson signal. The variable χ shown in the lower plot is defined as $(N_{\text{obs}} - N_{\text{exp}})/\sqrt{N_{\text{obs}}}$, where N_{obs} is the number of observed events and N_{exp} is the total of the fitted signal and background yields [143].

signal yield in the fit with ratios taken from the theoretical cross section predictions. The fit parameters are the QCD background yield, the W signal yield, and the shape

parameters σ_0 and σ_1 . A simultaneous fit including the muon control region, obtained by inverting the isolation requirement on the muon candidate, is also performed in the muon final state to improve the modeling of the QCD shape. The σ_1 shape parameter is constrained to be the same between the signal and control region in the simultaneous fit. The corresponding differences in the W boson signal yields are propagated as a systematic uncertainty in the background modeling.

PUPPI E_T^{miss} is used to fit for the W^+ and W^- candidates in collisions at $\sqrt{s} = 13$ TeV data taking period as the PF E_T^{miss} resolution is degraded significantly due to the additional pileup interactions. The PUPPI E_T^{miss} is measured using the PF candidates with $|\eta|$ less than 3.0. The PF candidates with $|\eta| > 3.0$ are measured by the HF calorimeter which was not fully commissioned for the analyzed data sample. The Figure 4-5 shows the corresponding E_T^{miss} distributions for the W^+ and W^- candidates with the fit results superimposed. Similarly to the $\sqrt{s} = 8$ TeV fits, the QCD shape is constrained from the control regions with the corresponding systematic uncertainties in the model propagated to the cross section results.

The summary of the signal yields, acceptances, and efficiencies are given in Table 4.3 and Table 4.4 for the $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV collisions, respectively. The uncertainties in the acceptances and efficiencies are the systematic uncertainties described in the previous two sections. The uncertainties in the signal yields are determined from the E_T^{miss} fit for the W boson candidates and from the Poisson statistics for the Z boson yields.

4.1.6 Systematic Uncertainties

The systematic uncertainties are summarized in Table 4.5 and Table 4.6, for the electron and muon final states, respectively in collisions at $\sqrt{s} = 13$ TeV. The leading experimental uncertainty in the inclusive total cross section measurement is due to the uncertainty in the integrated luminosity of the data sample (2.7%). This uncertainty cancels in the measurement of the cross section ratios. The lepton reconstruction and identification uncertainties are the second leading uncertainties in the total inclusive cross section measurement. This uncertainty is larger in the electron final state dom-

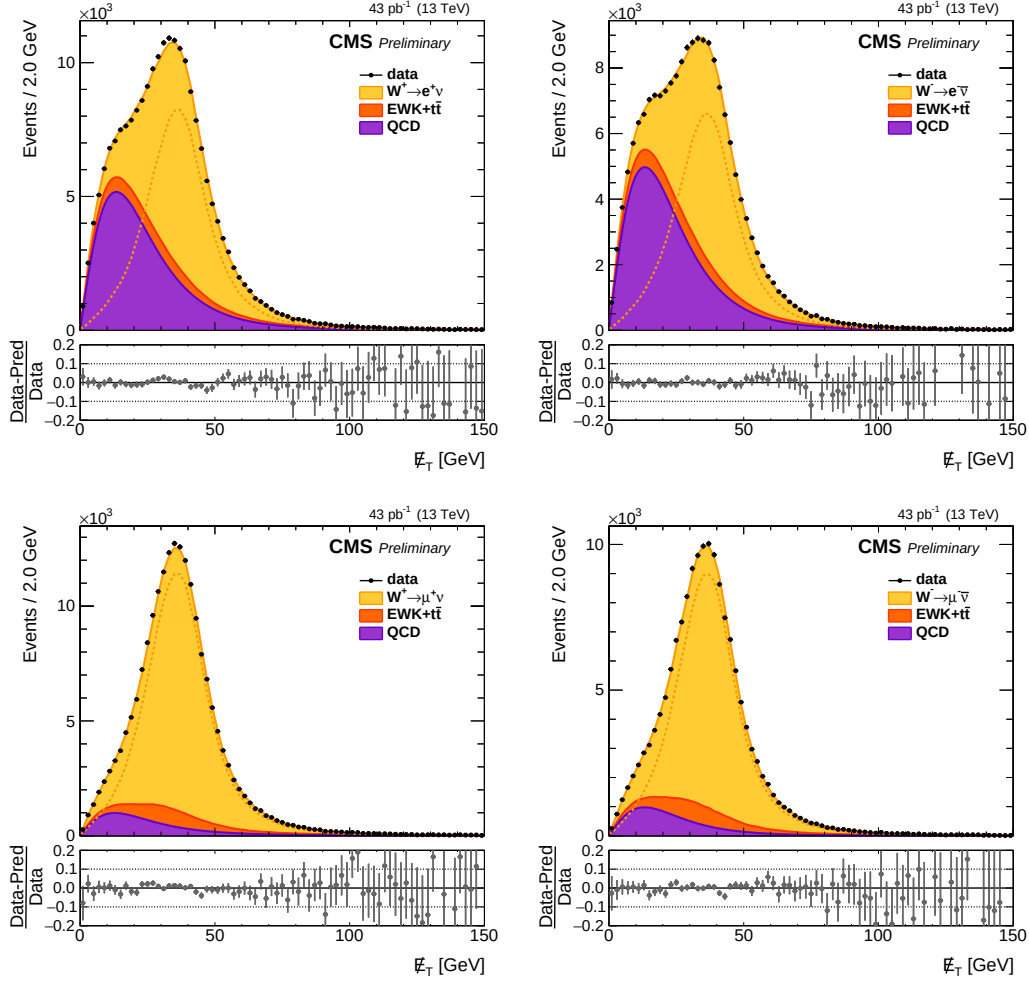


Figure 4-5: The missing transverse energy distributions for W^+ (left) and W^- (right) boson candidate events in the electron (top) and muon (bottom) final states in proton-proton collisions at $\sqrt{s} = 13$ TeV data taking period. The points with error bars represent the observed data events. The dotted orange lines shows the distribution of the W boson signal [144].

Source	$Z \rightarrow e^+e^-$	$W^+ \rightarrow e^+\nu$	$W^- \rightarrow e^-\bar{\nu}$
Yields	4790 ± 70	44190 ± 220	30860 ± 190
Acceptance	0.41 ± 0.01	0.48 ± 0.01	0.47 ± 0.01
Efficiency	0.59 ± 0.02	0.69 ± 0.02	0.71 ± 0.02
Source	$Z \rightarrow \mu^+\mu^-$	$W^+ \rightarrow \mu^+\nu$	$W^- \rightarrow \mu^-\bar{\nu}$
Yields	5920 ± 80	47640 ± 220	33840 ± 180
Acceptance	0.35 ± 0.01	0.44 ± 0.01	0.44 ± 0.01
Efficiency	0.81 ± 0.01	0.84 ± 0.01	0.83 ± 0.01

Table 4.3: The background subtracted signal yields, acceptances, and efficiencies for the Z , W^+ , and W^- boson candidates in collisions at $\sqrt{s} = 8$ TeV. The Z boson yield uncertainties are given by Poisson statistics, while the W boson yield uncertainties are determined from the fit. Uncertainties in the acceptances and efficiencies are discussed in Sections 4.1.3 and 4.1.4, respectively.

Source	$Z \rightarrow e^+e^-$	$W^+ \rightarrow e^+\nu$	$W^- \rightarrow e^-\bar{\nu}$
Yields	15290 ± 120	122320 ± 980	98200 ± 950
Acceptance	0.33 ± 0.01	0.43 ± 0.01	0.44 ± 0.01
Efficiency	0.56 ± 0.01	0.58 ± 0.01	0.60 ± 0.01
Source	$Z \rightarrow \mu^+\mu^-$	$W^+ \rightarrow \mu^+\nu$	$W^- \rightarrow \mu^-\bar{\nu}$
Yields	23670 ± 150	167710 ± 830	131250 ± 910
Acceptance	0.36 ± 0.01	0.44 ± 0.01	0.46 ± 0.01
Efficiency	0.80 ± 0.02	0.78 ± 0.01	0.79 ± 0.01

Table 4.4: The background subtracted signal yields, acceptances, and efficiencies for the Z , W^+ , and W^- boson candidates in collisions at $\sqrt{s} = 13$ TeV. The Z boson yield uncertainties are given by Poisson statistics, while the W boson yield uncertainties are determined from the fit. Uncertainties in the acceptances and efficiencies are discussed in Sections 4.1.3 and 4.1.4, respectively.

inated by the uncertainty in the modeling of the signal and background shapes in the efficiency fits. The correlations of the lepton efficiencies are taken into account in the cross section ratio measurements. The systematic uncertainties due to the recoil calibrations and lepton scale/resolution affect the shape of the E_T^{miss} distribution. These uncertainties are included in the maximum-likelihood fit via a smooth morphing of the shape as a function of the corresponding uncertainty parameter. The correlation of the theoretical uncertainties is taken into account in the cross section ratio measurement. The systematic uncertainties in the measurement at $\sqrt{s} = 8$ TeV are

Source	W^+	W^-	W	W^+/W^-	Z	W^+/Z	W^-/Z	W/Z
Lepton charge, reco. & id. [%]	2.1	2.0	2.1	0.6	2.5	1.2	1.0	1.0
Bkg. subtraction / modeling [%]	1.4	1.4	1.4	0.9	0.6	1.5	1.5	1.5
E_T^{miss} scale and resolution			shape		NA		shape	
Electron scale and resolution			shape		NA		shape	
Total experimental [%]	2.5	2.5	2.5	1.1	2.6	1.9	1.8	1.8
Theoretical uncertainty [%]	1.6	1.4	1.4	1.9	1.6	1.9	1.9	1.7
Lumi [%]	2.7	2.7	2.7	NA	2.7	NA	NA	NA
Total [%]	4.0	3.9	3.9	2.1	4.1	2.7	2.6	2.5

Table 4.5: Systematic uncertainties in percent for the electron final state in collisions at $\sqrt{s} = 13$ TeV. “NA” means that the source either does not apply or is negligible.

Source	W^+	W^-	W	W^+/W^-	Z	W^+/Z	W^-/Z	W/Z
Lepton charge, reco. & id. [%]	1.9	1.7	1.8	0.3	2.2	0.6	0.6	0.6
Bkg. subtraction / modeling [%]	0.6	0.6	0.6	0.4	0.6	0.8	0.8	0.8
E_T^{miss} scale and resolution			shape		NA		shape	
Muon scale and resolution			shape		NA		shape	
Total experimental [%]	2.0	1.8	1.9	0.5	2.3	1.1	1.1	1.1
Theoretical Uncertainty [%]	2.0	1.7	1.3	2.3	1.5	2.0	1.9	1.6
Lumi [%]	2.7	2.7	2.7	NA	2.7	NA	NA	NA
Total [%]	3.9	3.6	3.6	2.3	3.9	2.3	2.2	1.9

Table 4.6: Systematic uncertainties in percent for the muon final state in collisions at $\sqrt{s} = 13$ TeV. “NA” means that the source either does not apply or is negligible.

summarized in Table 4.7. The leading systematic uncertainty in the electron channel is due to the lepton reconstruction and identification efficiency measurements. The size of the Z boson candidate data sample is larger at $\sqrt{s} = 13$ TeV providing a better understanding of these uncertainties at $\sqrt{s} = 13$ TeV. The leading systematic uncertainty in the muon final state is due to the uncertainty in the integrated luminosity of the data sample (2.6%).

	W^+		W^-		W		W^+/W^-		Z		W/Z	
Sources	e	μ	e	μ	e	μ	e	μ	e	μ	e	μ
Lepton charge, reco. & id. [%]	2.8	1.0	2.5	0.9	2.5	1.0	3.8	1.2	2.8	1.1	3.8	1.5
Bkg. subtraction / modeling [%]	0.2	0.2	0.3	0.1	0.3	0.1	0.1	0.2	0.4	0.4	0.5	0.4
E_T^{miss} scale & resolution	0.8	0.5	0.7	0.5	0.8	0.5	0.3	0.1	NA	NA	0.8	0.5
Momentum scale & resolution	0.4	0.3	0.7	0.3	0.5	0.3	0.3	0.1	NA	NA	0.5	0.3
Total experimental	3.0	1.2	2.7	1.1	2.7	1.2	3.8	1.2	2.8	1.2	3.9	1.7
Theoretical uncertainty	2.1	2.0	2.6	2.5	2.7	2.2	1.5	1.4	2.6	1.9	2.0	2.5
Luminosity	2.6	2.6	2.6	2.6	2.6	2.6	NA	NA	2.6	2.6	NA	NA
Total	4.5	3.5	4.6	3.8	4.6	3.6	4.1	1.8	4.6	3.4	4.4	3.0

Table 4.7: Systematic uncertainties in percent for the electron and muon final states in collisions at $\sqrt{s} = 8$ TeV. "NA" means that the source either does not apply or is negligible [143].

4.1.7 Results

The inclusive total and fiducial production cross sections and ratios are shown separately for the muon and electron final states. The fiducial cross section measurement uncertainties are reduced as the theoretical uncertainties do not enter the measurement since no extrapolation from the fiducial region to the full phase space is performed (the acceptance). The fiducial cross section measurements in the muon and electron final states are not combined as the fiducial requirements are not the same. The total cross section measurements in the muon and electron final states are combined assuming lepton universality of the W and Z boson couplings to leptons. The two decay modes are combined by taking the average value weighted by their statistical and systematic uncertainties. The luminosity uncertainty is taken as fully correlated in the combination while the other uncertainties are treated as uncorrelated. The prediction of the total cross sections and their ratios is estimated using FEWZ [163, 164, 165] providing a fixed order calculation with NNLO accuracy in QCD. The calculation is also accurate to NLO in EWK for the Z boson production. The factorization and renormalization scales and the scale of the $\alpha_s(Q^2)$ are set to the corresponding boson mass. For the W boson production cross section calculation the $\Gamma(W \rightarrow \ell\nu)$ is set to the experimental PDG value [19] instead of the SM prediction to reduce the EWK effects on the calculation. The predictions are estimated with MSTW2008 [48] NNLO PDF set for the $\sqrt{s} = 8$ TeV collisions and NNPDF3.0 PDF set for the $\sqrt{s} = 13$ TeV collisions. The uncertainties are due to the PDF

	NNPDF3.0	CT14	MMHT2014	ABM12LHC	HERAPDF15
$\sigma_{W^+}^{tot}$ [pb]	11330 ⁺³²⁰ ₋₂₇₀	11500 ⁺³³⁰ ₋₃₁₀	11580 ⁺²⁶⁰ ₋₂₁₀	11730 ⁺¹⁵⁰ ₋₁₃₀	11780 ⁺⁵⁷⁰ ₋₂₅₀
$\sigma_{W^-}^{tot}$ [pb]	8370 ⁺²⁴⁰ ₋₂₁₀	8520 ⁺²³⁰ ₋₂₄₀	8590 ⁺¹⁹⁰ ₋₁₇₀	8550 ⁺¹¹⁰ ₋₉₀	8700 ⁺⁴⁰⁰ ₋₁₇₀
σ_W^{tot} [pb]	19700 ⁺⁵⁶⁰ ₋₄₇₀	20020 ⁺⁵⁶⁰ ₋₅₅₀	20170 ⁺⁴³⁰ ₋₃₉₀	20280 ⁺²⁶⁰ ₋₂₂₀	20480 ⁺⁹⁶⁰ ₋₄₁₀
σ_Z^{tot} [pb]	1870 ⁺⁵⁰ ₋₄₀	1900 ⁺⁵⁰ ₋₅₀	1920 ⁺⁴⁰ ₋₄₀	1920 ⁺²⁰ ₋₂₀	1930 ⁺⁹⁰ ₋₄₀
$\sigma_{W^+}^{tot}/\sigma_{W^-}^{tot}$	1.354 ^{+0.011} _{-0.012}	1.350 ^{+0.014} _{-0.014}	1.348 ^{+0.011} _{-0.008}	1.371 ^{+0.003} _{-0.004}	1.353 ^{+0.014} _{-0.013}
$\sigma_{W^+}^{tot}/\sigma_Z^{tot}$	6.06 ^{+0.04} _{-0.05}	6.06 ^{+0.06} _{-0.06}	6.04 ^{+0.05} _{-0.05}	6.11 ^{+0.02} _{-0.01}	6.10 ^{+0.06} _{-0.06}
$\sigma_{W^-}^{tot}/\sigma_Z^{tot}$	4.48 ^{+0.03} _{-0.02}	4.49 ^{+0.03} _{-0.03}	4.48 ^{+0.03} _{-0.04}	4.46 ^{+0.02} _{-0.01}	4.51 ^{+0.04} _{-0.03}
$\sigma_W^{tot}/\sigma_Z^{tot}$	10.55 ^{+0.07} _{-0.06}	10.55 ^{+0.09} _{-0.09}	10.53 ^{+0.08} _{-0.09}	10.56 ^{+0.04} _{-0.02}	10.61 ^{+0.11} _{-0.09}

Table 4.8: Summary of predicted total inclusive cross sections and their ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV. The predictions were calculated with FEWZ at NNLO accuracy in QCD, and NLO accuracy in EWK for the Z bosons only. The given uncertainties for each prediction are the combined PDF and scale uncertainties [144].

and α_s uncertainties, as well as the missing effects of the higher order corrections estimated by varying the factorization and renormalization scales within a factor of two (keeping $\mu_R = \mu_F$). In addition, the production cross sections and their ratios are calculated with CT14, MMHT2014, ABM12LHC [172], and HERAPDF15 [173] PDF sets. The predictions of the inclusive total production cross sections and their ratios using these PDF sets for the proton-proton collisions at $\sqrt{s} = 13$ TeV are summarized in Table 4.8.

The ratio of the W and Z measured cross sections is given by:

$$\frac{\sigma_W}{\sigma_Z} = \frac{N_W}{N_Z} \frac{\varepsilon_Z}{\varepsilon_W} \frac{A_Z}{A_W}. \quad (4.5)$$

Similar expressions are obtained for the other cross section ratios. Table 4.9 summarizes the measured total inclusive W^+ , W^- , W , and Z boson production cross section times branching fractions, W^+ , W^- , and W to Z and W^+ to W^- ratios and the theoretical prediction with the NNPDF3.0 PDF set in proton-proton collisions at $\sqrt{s} = 13$ TeV. The values measured in the electron and muon final states are also shown separately. Figure 4-6 shows the ratio of the measured total cross section (and their ratios) and the theoretical predictions. The fiducial cross section results in collisions at $\sqrt{s} = 13$ TeV are summarized in Figure 4-7. As pointed out above the theoretical uncertainties are not relevant for the fiducial measurement. The fiducial pre-

Channel		$\sigma \times \mathcal{B}$ [pb] (total)	NNLO [pb]
W^+	$e^+\nu$	$11330 \pm 90(\text{stat}) \pm 340(\text{syst}) \pm 310(\text{lumi})$	11330^{+320}_{-270}
	$\mu^+\nu$	$11290 \pm 60(\text{stat}) \pm 320(\text{syst}) \pm 300(\text{lumi})$	
	$\ell^+\nu$	$11310 \pm 50(\text{stat}) \pm 230(\text{syst}) \pm 300(\text{lumi})$	
W^-	$e^-\nu$	$8630 \pm 80(\text{stat}) \pm 240(\text{syst}) \pm 230(\text{lumi})$	8370^{+240}_{-210}
	$\mu^-\nu$	$8470 \pm 60(\text{stat}) \pm 210(\text{syst}) \pm 230(\text{lumi})$	
	$\ell^-\nu$	$8540 \pm 50(\text{stat}) \pm 160(\text{syst}) \pm 230(\text{lumi})$	
W	$e\nu$	$19970 \pm 120(\text{stat}) \pm 570(\text{syst}) \pm 540(\text{lumi})$	19700^{+560}_{-470}
	$\mu\nu$	$19760 \pm 80(\text{stat}) \pm 460(\text{syst}) \pm 530(\text{lumi})$	
	$\ell\nu$	$19840 \pm 70(\text{stat}) \pm 360(\text{syst}) \pm 540(\text{lumi})$	
Z	e^+e^-	$1910 \pm 10(\text{stat}) \pm 60(\text{syst}) \pm 50(\text{lumi})$	1870^{+50}_{-40}
	$\mu^+\mu^-$	$1890 \pm 10(\text{stat}) \pm 50(\text{syst}) \pm 50(\text{lumi})$	
	$\ell^+\ell^-$	$1900 \pm 10(\text{stat}) \pm 40(\text{syst}) \pm 50(\text{lumi})$	
Quantity		Ratio (total)	NNLO
R_{W^+/W^-}	e	$1.313 \pm 0.016(\text{stat}) \pm 0.028(\text{syst})$	$1.354^{+0.011}_{-0.012}$
	μ	$1.334 \pm 0.011(\text{stat}) \pm 0.031(\text{syst})$	
	ℓ	$1.323 \pm 0.010(\text{stat}) \pm 0.021(\text{syst})$	
$R_{W^+/Z}$	e	$5.94 \pm 0.07(\text{stat}) \pm 0.16(\text{syst})$	$6.06^{+0.04}_{-0.05}$
	μ	$5.98 \pm 0.05(\text{stat}) \pm 0.14(\text{syst})$	
	ℓ	$5.96 \pm 0.04(\text{stat}) \pm 0.10(\text{syst})$	
$R_{W^-/Z}$	e	$4.52 \pm 0.06(\text{stat}) \pm 0.12(\text{syst})$	$4.48^{+0.03}_{-0.02}$
	μ	$4.49 \pm 0.04(\text{stat}) \pm 0.10(\text{syst})$	
	ℓ	$4.50 \pm 0.03(\text{stat}) \pm 0.08(\text{syst})$	
$R_{W/Z}$	e	$10.46 \pm 0.11(\text{stat}) \pm 0.26(\text{syst})$	$10.55^{+0.07}_{-0.06}$
	μ	$10.47 \pm 0.08(\text{stat}) \pm 0.20(\text{syst})$	
	ℓ	$10.46 \pm 0.06(\text{stat}) \pm 0.16(\text{syst})$	

Table 4.9: Summary of total inclusive W^+ , W^- , W , and Z production cross sections times branching fractions, W^+ , W^- , and W to Z and W^+ to W^- ratios, and their theoretical predictions in proton-proton collisions at $\sqrt{s} = 13$ TeV. The values in the electron and muon final states are also shown individually.

dictions are computed by multiplying the NNLO FEWZ predictions for the total inclusive cross sections by the acceptance estimated with the MadGraph5_aMC@NLO. The theoretical uncertainties in the acceptance and the NNLO cross section predictions are assumed to be uncorrelated. The measured total inclusive W^+ , W^- , W , and Z production cross sections times branching fractions, W to Z , and W^+ to W^- ratios and the theoretical predictions in collisions at $\sqrt{s} = 8$ TeV are summarized in Table 4.10 and Figure 4-8. The measured values in collisions at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV are consistent with the SM predictions accurate to NNLO in QCD. The individual measurements in the muon and electron final states separately are compatible.

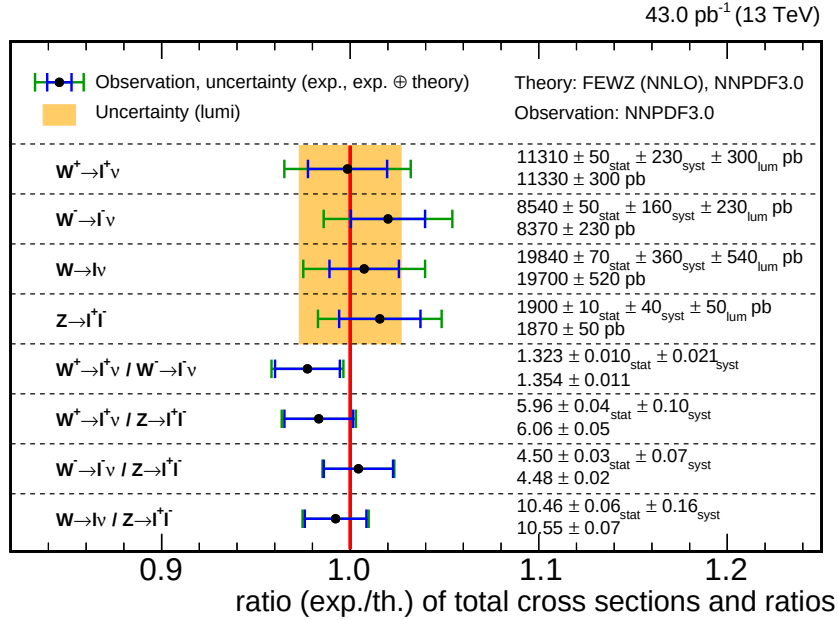


Figure 4-6: Summary of the total inclusive W^+ , W^- , W , and Z production cross sections times branching fractions and W^+ to W^- , and W to Z ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV. The theoretical predictions with FEWZ using the NNPDF3.0 PDF set are also shown. The inner error bars (blue) represent the measurement uncertainties while the outer error bars (green) also include the uncertainties in the theoretical predictions. The shaded box denotes the uncertainty in the total integrated luminosity measurement.

It is also interesting to compare the measured production cross sections and their ratios to the predictions with different PDF sets given in Table 4.8. Figure 4-9 shows

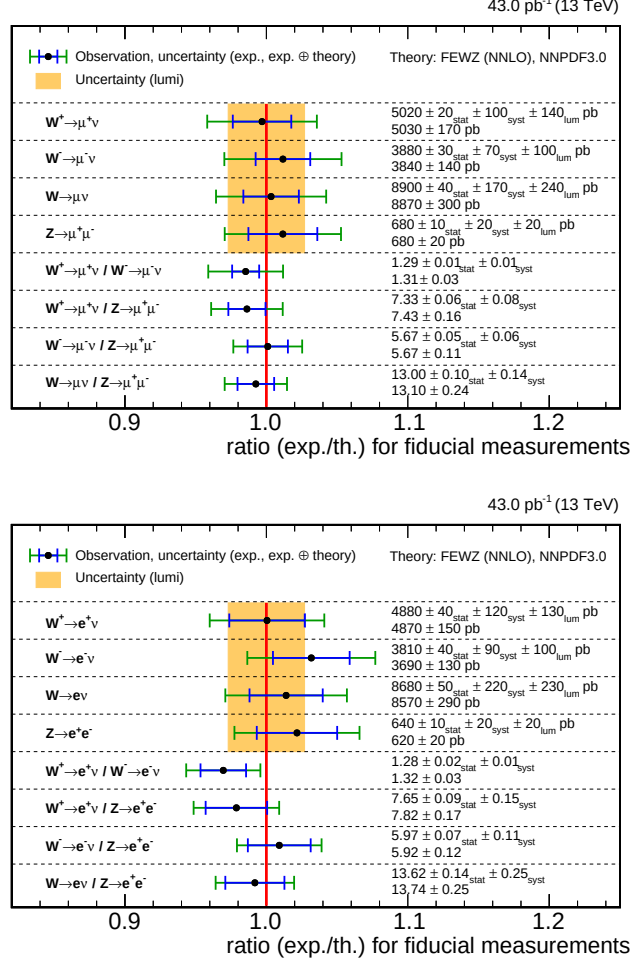


Figure 4-7: Summary of the fiducial inclusive W^+ , W^- , W , and Z production cross sections times branching fractions and W^+ to W^- , and W to Z ratios for the muon (top) and electron (bottom) final states in proton-proton collisions at $\sqrt{s} = 13$ TeV. The acceptance used in the theory prediction is taken from the MadGraph5_aMC@NLO while the inclusive total production cross section prediction is taken from FEWZ. The inner error bars (blue) represent the measurement uncertainties while the outer error bars (green) also include the uncertainties in the theoretical predictions. The shaded box denotes the uncertainty in the total integrated luminosity measurement.

Channel		$\sigma \times \mathcal{B}$ [pb] (total)	NNLO [pb]
W^+	$e^+\nu$	$7310 \pm 40(\text{stat}) \pm 260(\text{syst}) \pm 190(\text{lumi})$	7120 ± 200
	$\mu^+\nu$	$7040 \pm 30(\text{stat}) \pm 160(\text{syst}) \pm 180(\text{lumi})$	
	$\ell^+\nu$	$7110 \pm 30(\text{stat}) \pm 140(\text{syst}) \pm 180(\text{lumi})$	
W^-	$e^-\nu$	$5080 \pm 30(\text{stat}) \pm 190(\text{syst}) \pm 130(\text{lumi})$	5060 ± 130
	$\mu^-\nu$	$5090 \pm 30(\text{stat}) \pm 140(\text{syst}) \pm 130(\text{lumi})$	
	$\ell^-\nu$	$5090 \pm 20(\text{stat}) \pm 110(\text{syst}) \pm 130(\text{lumi})$	
W	$e\nu$	$12390 \pm 50(\text{stat}) \pm 440(\text{syst}) \pm 320(\text{lumi})$	12180 ± 320
	$\mu\nu$	$12130 \pm 40(\text{stat}) \pm 290(\text{syst}) \pm 320(\text{lumi})$	
	$\ell\nu$	$12210 \pm 30(\text{stat}) \pm 240(\text{syst}) \pm 320(\text{lumi})$	
Z	e^+e^-	$1130 \pm 20(\text{stat}) \pm 50(\text{syst}) \pm 30(\text{lumi})$	1130 ± 40
	$\mu^+\mu^-$	$1160 \pm 20(\text{stat}) \pm 30(\text{syst}) \pm 30(\text{lumi})$	
	$\ell^+\ell^-$	$1150 \pm 10(\text{stat}) \pm 20(\text{syst}) \pm 30(\text{lumi})$	
Quantity		Ratio (total)	NNLO
R_{W^+/W^-}	e	$1.44 \pm 0.01(\text{stat}) \pm 0.05(\text{syst})$	1.41 ± 0.01
	μ	$1.38 \pm 0.01(\text{stat}) \pm 0.03(\text{syst})$	
	ℓ	$1.39 \pm 0.01(\text{stat}) \pm 0.02(\text{syst})$	
$R_{W/Z}$	e	$10.99 \pm 0.16(\text{stat}) \pm 0.43(\text{syst})$	10.74 ± 0.04
	μ	$10.44 \pm 0.14(\text{stat}) \pm 0.30(\text{syst})$	
	ℓ	$10.63 \pm 0.11(\text{stat}) \pm 0.25(\text{syst})$	

Table 4.10: Summary of total inclusive W^+ , W^- , W , and Z production cross sections times branching fractions, W to Z and W^+ to W^- ratios, and their theoretical predictions in proton-proton collisions at $\sqrt{s} = 8$ TeV. The values in the electron and muon final states are also shown individually.

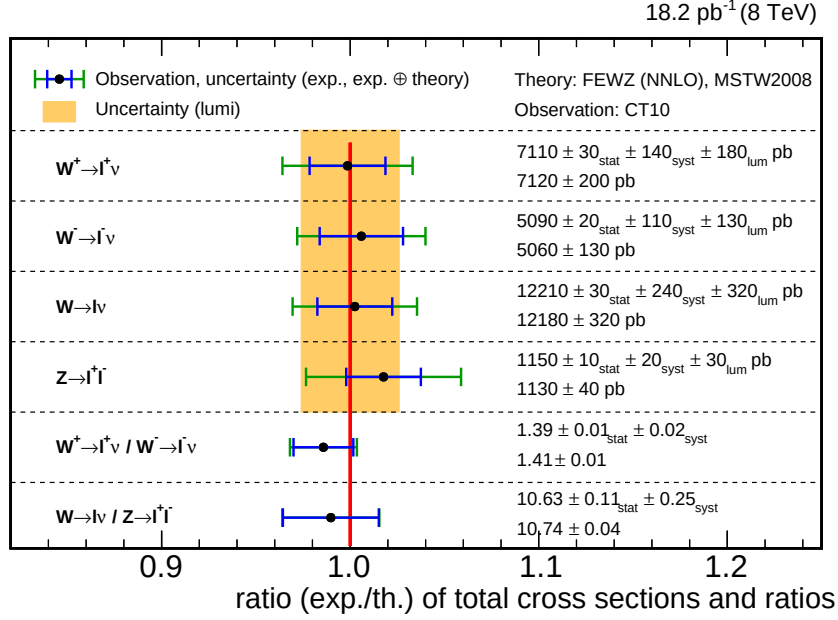


Figure 4-8: Summary of the total inclusive W^+ , W^- , W , and Z production cross sections times branching fractions and W^+ to W^- , and W to Z ratios in proton-proton collisions at $\sqrt{s} = 8$ TeV. The theoretical predictions with FEWZ using the MSTW2008 PDF set are also shown. The inner error bars (blue) represent the measurement uncertainties while the outer error bars (green) also include the uncertainties in the theoretical predictions. The shaded box denotes the uncertainty in the total integrated luminosity measurement.

the comparison of the measured inclusive total cross sections with the predictions in collisions at $\sqrt{s} = 13$ TeV. The corresponding comparison of the cross section ratios is shown in Figure 4-10. The measurements are consistent with the predictions with different PDF sets. Figure 4-11 shows the measurements of the total W^+ , W^- , W , and Z production cross sections times branching fractions as a function of the center of mass energy for the measurements performed by CMS and experiments at lower-energy colliders [174, 175, 176, 177, 178, 179]. The cross section is predicted to increase with $\sqrt{s}$. The increase is confirmed by these measurements.

4.1.8 $\mathcal{B}(W \rightarrow \ell \nu)$ and Γ_W

Indirect measurement of the $\mathcal{B}(W \rightarrow \ell \nu)$ and Γ_W SM parameters can be performed using the W to Z cross section ratio measurement. The argument given here follows

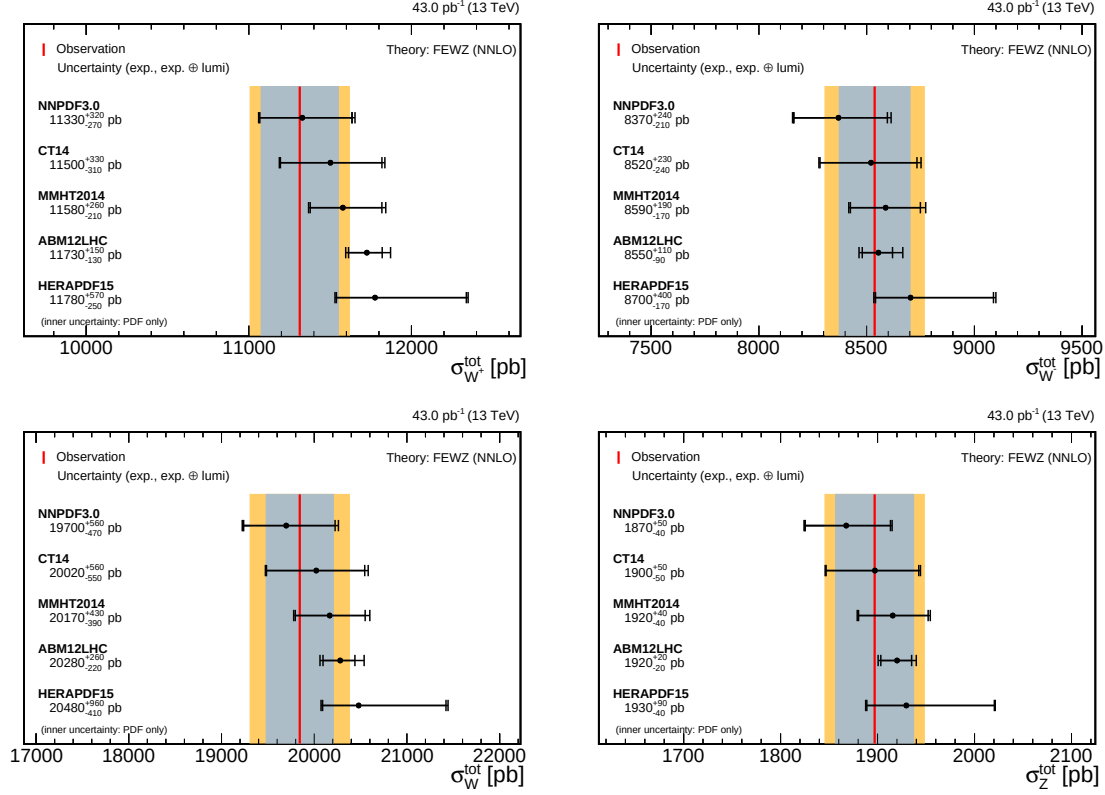


Figure 4-9: Comparison of the measured inclusive total cross sections with the predictions using five PDF sets: NNPDF30, C14, MMHT2014, ABM12LHC, and HERAPDF15. The comparison is shown for the W^+ (top left), W^- (top right), W (bottom left), and Z (bottom right) production cross sections in collisions at $\sqrt{s} = 13$ TeV.

closely to [140]. The measured cross section ratio at $\sqrt{s} = 13$ TeV is $R_{W/Z} = 10.46 \pm 0.06(\text{stat}) \pm 0.16(\text{syst})$. The $R_{W/Z}$ can be written as:

$$R_{W/Z} = \frac{\sigma_W}{\sigma_Z} \frac{\mathcal{B}(W \rightarrow \ell\nu)}{\mathcal{B}(Z \rightarrow \ell\ell)}, \quad (4.6)$$

where $\frac{\sigma_W}{\sigma_Z}$ is the predicted ratio of the W to Z cross sections. The measured value of the $\mathcal{B}(Z \rightarrow \ell\ell)$ is taken from the PDG: 0.033658 ± 0.000023 [19]. The predicted ratio of the inclusive total W to Z boson cross sections is calculated with NNLO accuracy in QCD (NLO accuracy in EWK for the Z cross section) with NNPDF3.0 PDF set. The predicted value is 3.27 ± 0.02 where the uncertainty is due to the PDF and missing higher order corrections. It is important to note that the uncertainties in the CKM elements in the W boson cross section are not negligible [180]. From

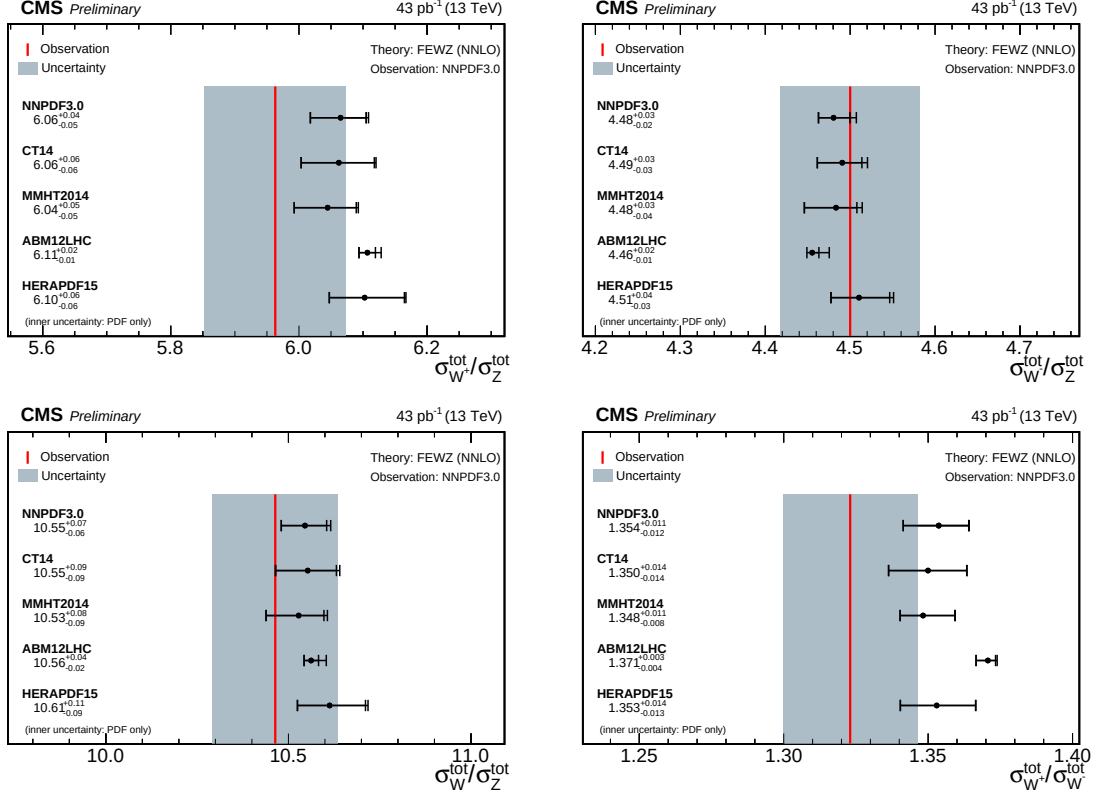


Figure 4-10: Comparison of the measured inclusive total cross section ratios with the predictions using five PDF sets: NNPDF30, C14, MMHT2014, ABM12LHC, and HERAPDF15. The comparison is shown for the W^+ (top left), W^- (top right), and W (bottom left) to Z , and W^+ to W^- (bottom right) cross section ratios in collisions at $\sqrt{s} = 13$ TeV [144].

Equation (4.6) and the values discussed above indirect determination of $\mathcal{B}(W \rightarrow \ell\nu) = 0.1076 \pm 0.0013$ is made. The obtained value is in agreement with the current PDG value: $\mathcal{B}(W \rightarrow \ell\nu) = 0.1086 \pm 0.0009$ [19].

The total width of the W boson can be extracted using the SM value of the leptonic partial decay width $\Gamma(W \rightarrow \ell\nu) = 226.6 \pm 0.2$ MeV [181, 180], where the uncertainty is dominated by the uncertainty on the mass of the W boson. The total width is given by:

$$\Gamma_W = \frac{\Gamma(W \rightarrow \ell\nu)}{\mathcal{B}(W \rightarrow \ell\nu)}. \quad (4.7)$$

Thus, $\Gamma_W = 2105 \pm 37$ MeV is obtained from the above values in agreement with the PDG value of 2085 ± 42 MeV and with the SM prediction of 2093 ± 2 MeV [180].

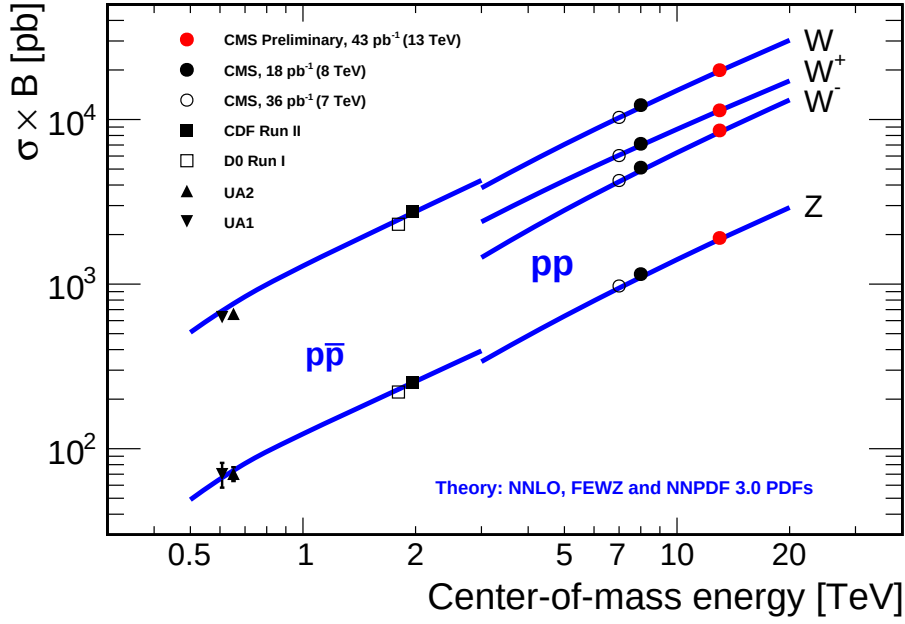


Figure 4-11: Measurements of the total W^+ , W^- , W , and Z production cross sections times branching fractions as a function of the center of mass energy. The measurements performed by CMS and experiments at lower-energy colliders are shown. The blue lines show the predictions by FEWZ with NNPDF3.0.

To summarize, the measurement of the W/Z production cross section ratio leads to indirect determination of the $\mathcal{B}(W \rightarrow \ell\nu)$ and Γ_W :

$$\begin{aligned}\mathcal{B}(W \rightarrow \ell\nu) &= 0.1076 \pm 0.0013, \\ \Gamma(W) &= 2105 \pm 37 \text{ MeV}.\end{aligned}\tag{4.8}$$

The quoted uncertainties include only the uncertainties in the PDF and higher order corrections for the σ_W prediction.

4.2 Evidence for a Higgs Boson in Tau Decays

Searches for the SM Higgs boson decaying to a tau pair final state have previously been performed at the LEP and Tevatron colliders. The main SM Higgs boson production mode at the LEP e^+e^- colliders was the associated production with a Z boson via the Higgsstrahlung. No significant excess of events with respect to the

predicted background processes was observed [182, 183, 184, 185]. The CDF and D0 collaborations also saw no significant excess of events with respect to the expected SM background predictions in the SM $H \rightarrow \tau^+\tau^-$ searches at $p\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV. Upper limits at 95% CL on the production cross section times branching fraction of 16 and 14 times the SM expected $\sigma \times \mathcal{B}$ were set by the CDF [186] and D0 [187] collaborations, respectively.

The ATLAS and CMS collaborations have reported evidence of $H \rightarrow \tau^+\tau^-$ events near a Higgs boson mass of 125 GeV with each collaboration reporting significances larger than three standard deviations [188, 189]. All the $\tau^+\tau^-$ final states are used targeting the main Higgs boson production modes (Figure 1-8) including dedicated final states targeting the WH or ZH production modes where the W and Z bosons decay into final states with electrons or muons. The CMS results are described in this section focusing on the $\tau_\mu\tau_h$, $\tau_h\tau_h$, and $\tau_e\tau_h$ final states. These are the leading final states in the expected sensitivity to the $H \rightarrow \tau^+\tau^-$ signal with a Higgs boson mass hypothesis of 125 GeV.

Section 4.2.2 describes the data samples and simulation of the events used in the results and Section 4.2.2 describes the selection of the $H \rightarrow \tau^+\tau^-$ candidate events. The τ pair mass reconstruction is described in Section 4.2.3, whereas the background estimation is described in Section 4.2.4. Sections 4.2.5 and 4.2.6 summarize the systematic uncertainties and the results, respectively.

4.2.1 Data Samples and Simulation

The $H \rightarrow \tau^+\tau^-$ candidate events in proton-proton collisions at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV are selected from the full data samples collected in 2012 and 2011, respectively. This corresponds to a total integrated luminosity of $\mathcal{L} = 19.7 \pm 0.5 \text{ fb}^{-1}$ and $\mathcal{L} = 4.9 \pm 0.1 \text{ fb}^{-1}$ in collisions at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV, respectively. The candidate events selected by the CMS trigger require the presence of an electron/muon and τ_h candidate in the $\tau_\mu\tau_h$ and $\tau_e\tau_h$ final states, and the presence of two τ_h candidates in the $\tau_h\tau_h$ final state.

The L1 trigger requires a presence of at least one muon or electron candidate in

the $\tau_\mu\tau_h$ and $\tau_e\tau_h$ final states, respectively. A selection of an additional τ_h candidate, not overlapping with the electron or muon candidate in ΔR distance, is required in the HLT. A simplified version of the PF algorithm is utilized to reconstruct the τ_h and the isolation sum. The electron, muon, and τ_h candidates are required to be loosely identified and isolated. The transverse momentum p_T thresholds of the trigger selection was increased continuously during the data taking to cope with the higher rate of triggering of events due to the additional pileup interactions coming from the increased instantaneous luminosity. The muon candidate p_T threshold ranged from 12 to 20 GeV and the τ_h candidate p_T threshold ranged from 10 to 20 GeV in the $\tau_\mu\tau_h$ final state. The electron candidate p_T threshold ranged from 15 to 22 GeV and the τ_h candidate p_T threshold ranged from 15 to 20 GeV. The efficiency of triggering the candidate events were measured with the tag-and-probe technique (described in detail in Section 4.1.3) in $Z \rightarrow \mu^+\mu^-$, $Z \rightarrow e^+e^-$, and $Z \rightarrow \tau_\mu\tau_h$ candidate data events for the muon, electron, and τ_h single lepton efficiencies, respectively. The efficiencies are also measured in the simulated events.

The rate of a single τ_h trigger is prohibitively high for the transverse momenta of interest in the $\tau_h\tau_h$ final state. Instead, the trigger selection in the $\tau_h\tau_h$ final state starts with a L1 trigger selection of either two calorimeter jets (clustered using the energy deposits in the calorimeters) with $p_T > 64$ GeV and $|\eta| < 3.0$ or two narrow calorimeter jets (τ_h candidate signature) with $p_T > 44$ GeV and $|\eta| < 2.17$. It has to be noted that the L1 trigger uses only coarsely segmented data from the calorimeters as discussed in Chapter 2. The trigger was only available during the 2012 data taking period. The HLT selects two loosely isolated PF taus with $p_T > 30$ GeV and $|\eta| < 2.1$. There is also a requirement of an additional central jet with p_T greater than 30 GeV and $|\eta| < 3.0$ to reduce the trigger rate. Thus, the triggering of the $\tau_h\tau_h$ final state consists of selecting two τ_h candidates with an additional central jet. In addition, the measurement of the trigger selection efficiency with the tag-and-probe technique is more complicated as the requirement of the two τ_h candidates at the L1 trigger means there is no suitable independent data sample to perform the efficiency measurement. The $\tau_h\tau_h$ final state benefited from the special parked data stream

(discussed in Section 2.5) reconstructed only at the end of the 2012 data taking period. In this data sample the HLT selects two loosely isolated PF taus with $p_T > 35$ GeV and $|\eta| < 2.1$ and without the additional central jet requirement. There is also a $\tau_\mu\tau_h$ trigger selection in the parked dataset requiring a muon with $p_T > 18$ GeV and a τ_h with $p_T > 25$ GeV, where the reconstructed τ_h candidate in the HLT is identical to the τ_h candidate in the above $\tau_h\tau_h$ trigger selection. This allows to perform the single τ_h triggering efficiency measurement with the tag-and-probe technique using $Z \rightarrow \tau_\mu\tau_h$ candidate data events. The efficiency in data reaches a plateau of about 80% above the fully reconstructed τ_h p_T of 60 GeV. The total luminosity of the inclusive $\tau_h\tau_h$ trigger in the parked data sample is only 18.3 fb^{-1} as the trigger was not included for the full data taking period. Therefore, the $\tau_h\tau_h$ +jet trigger is also used to recover the candidate events not selected by the inclusive trigger.

The SM Higgs boson events produced via the gluon fusion and VBF processes are generated using POWHEG [152, 153, 154, 155] generator, with the CT10 [156] NLO PDF set, interfaced with PYTHIA 6.4 [149]. The PYTHIA 6.4 is used to generate the SM Higgs boson events produced in association with a W or Z boson, or with a $t\bar{t}$ pair. The MadGraph5_aMC@NLO [146] generator at LO perturbative QCD accuracy, with matrix element calculations having up to four extra partons in the final state, is used to generate the Z +jets and W +jets background processes. The $t\bar{t}$, and diboson background processes are also generated with MadGraph5_aMC@NLO at LO accuracy in perturbative QCD. The single top process is produced with POWHEG. The PYTHIA parameters for the description of the underlying event are set to the $Z2$ tune for the 7 TeV samples and $Z2^*$ tune for the 8 TeV samples [157]. The PYTHIA 6.4 is interfaced with TAUOLA to simulate the decays of polarized tau leptons. For all the generated processes the additional pileup interactions and the detector response are simulated as described in Section 2.6.

The SM Higgs boson gluon-gluon fusion p_T spectrum is corrected to the resummed calculation up to NNLL in QCD using HRES [190]. The calculation is then combined with a fixed order calculation at large values of the transverse momenta accurate to NNLO. An additional correction is applied to account for the effects of the finite

top quark mass with accuracy up to NLO in perturbative QCD [191]. The SM Higgs boson production cross sections and the branching fractions are taken from [77, 78, 79] as shown in Figure 1-9 and Figure 1-10.

4.2.2 Event Selection and Categorization

The $H \rightarrow \tau^+\tau^-$ decays are characterized by two energetic, isolated and opposite-charge tau leptons. The muon, electron and τ_h candidates in the $\tau_\mu\tau_h$, $\tau_e\tau_h$, and $\tau_h\tau_h$ final states are reconstructed and identified as described in detail in Chapter 4. The selected candidate events are required to contain at least one well reconstructed primary vertex. Figure 4-12 shows the number of reconstructed vertices in the selected $\tau_\mu\tau_h$ final state candidate events in collisions at $\sqrt{s} = 8$ TeV. The simulated events are weighted to the pileup distribution in data in each data-taking period (Figure 1-5). The tau lepton candidates are selected as follows:

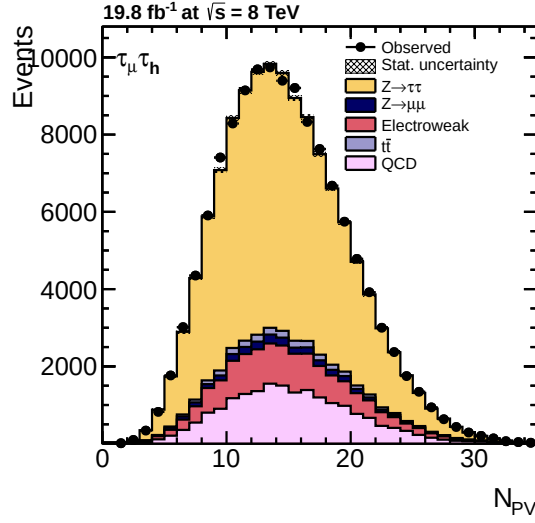


Figure 4-12: Distribution of the number of reconstructed vertices for the selected $\tau_\mu\tau_h$ final state candidate events in collisions at $\sqrt{s} = 8$ TeV. The points with error bars represent the data. Superimposed are the expected SM background distributions. The shaded area shows the statistical uncertainty in the background predictions. The simulated events are weighted to the pileup distribution.

- $\tau_\mu\tau_h$: The muon candidate is required to have a transverse momentum greater than 20 GeV (17 GeV) with $|\eta| < 2.1$ in collisions at $\sqrt{s} = 8$ TeV ($\sqrt{s} = 7$ TeV). The

τ_h candidate is required to have a transverse momentum greater than 30 GeV with $|\eta| < 2.4$. Selected events containing loosely identified and isolated muon pair with the muon transverse momenta greater than 15 GeV are rejected.

- $\tau_e\tau_h$: The electron candidate is required to have a transverse momentum greater than 24 GeV (20 GeV) with $|\eta| < 2.1$ in collisions at $\sqrt{s} = 8$ TeV ($\sqrt{s} = 7$ TeV). The τ_h candidate is required to have a transverse momentum greater than 30 GeV with $|\eta| < 2.4$. Selected events containing loosely identified and isolated electron pair with the electron transverse momenta greater than 15 GeV are rejected.
- $\tau_h\tau_h$: The τ_h candidates are required to have transverse momenta greater than 45 GeV with $|\eta| < 2.1$. Selected events containing a loosely identified and isolated muon or electron with transverse momentum greater than 10 GeV are rejected.

The selected events with an additional electrons or muons are rejected to reduce the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ background contributions where a jet is misidentified as a τ_h candidate. In addition, these requirements ensure that there is no overlap of the selected candidate events between these final states and the final states targeting the WH or ZH production mode where the W/Z bosons decay to an electrons or muons.

The efficiencies of the electron, muon, and τ_h candidate selection are measured with the tag-and-probe technique in $Z \rightarrow \ell^+\ell^-$ events as discussed in Section 4.1.3. The simulated events are corrected for the differences in the simulation and data. The differences in the energy scale of the τ_h candidates in the simulation and data are measured from a fit to the τ_h mass distribution shown in Figure 3-6. The tau energy scale is a fit parameter affecting the shape of the distribution. Tau energy scale correction of 1.2% is applied to the simulated events for the $h^\pm\pi^0$, $h^\pm\pi^0\pi^0$, and $h^\pm h^\mp h^\pm \tau_h$ decay modes.

The following background processes are considered:

- $Z \rightarrow \tau\tau$: The Drell-Yan tau pair production. Constitutes a dominant irreducible

background. Tau pair invariant mass is used to separate the signal candidate events from the $Z \rightarrow \tau^+\tau^-$ events.

- **$Z \rightarrow \ell\ell$:** The Drell-Yan e^+e^- and $\mu^+\mu^-$ pair production where an electron (muon) is misidentified as a τ_h candidate in the $\tau_e\tau_h$ ($\tau_\mu\tau_h$) final state. This is an important background for the $\tau_e\tau_h$ final state but is small for the $\tau_\mu\tau_h$ and $\tau_h\tau_h$ final states.
- **W +jets:** The $W \rightarrow e\nu$ ($W \rightarrow \mu\nu$) where a jet is misidentified as a τ_h candidate constitutes a background in the $\tau_e\tau_h$ ($\tau_\mu\tau_h$) final state. It also constitutes a non-negligible background in the $\tau_h\tau_h$ final state dominated with events where jets are misidentified as τ_h candidates.
- **QCD multi-jet:** Constitutes a background where the jets are misidentified as a τ_h candidate or an electron/muon. An important background process for the $\tau_h\tau_h$ final state.
- **$t\bar{t}$ and single top:** Rejecting events with one or more b-tagged jets reduces the contributions of these background processes.
- **Boson pair:** The production of the WW , WZ , and ZZ processes constitutes a small background.

The neutrinos produced in the τ lepton decays coming from the $Z \rightarrow \tau^+\tau^-$ or $H \rightarrow \tau^+\tau^-$ decays are collinear with the visible decay products as the corresponding τ energy is much larger than the mass of the tau lepton. On the other hand, the neutrino in the $W \rightarrow \ell\nu$ decays is mostly in the opposite direction to the lepton in the transverse plane due to the high mass of the W boson. Thus, the large W +jets background in the $\tau_\ell\tau_h$ final states is reduced by considering the transverse mass m_T defined as:

$$m_T = \sqrt{2p_T^\ell E_T^{miss}(1 - \cos(\Delta\phi))}, \quad (4.9)$$

where the p_T^ℓ is the transverse momentum of the muon or electron candidate, and the $\Delta\phi$ is the difference in azimuthal angle between the $\vec{p}_T^\ell$ and $\vec{E}_T^{miss}$. Figure 4-13

shows the m_T distribution for the selected $\tau_\mu\tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV. The "QCD" in Figure 4-13 denotes the contribution of the QCD multi-

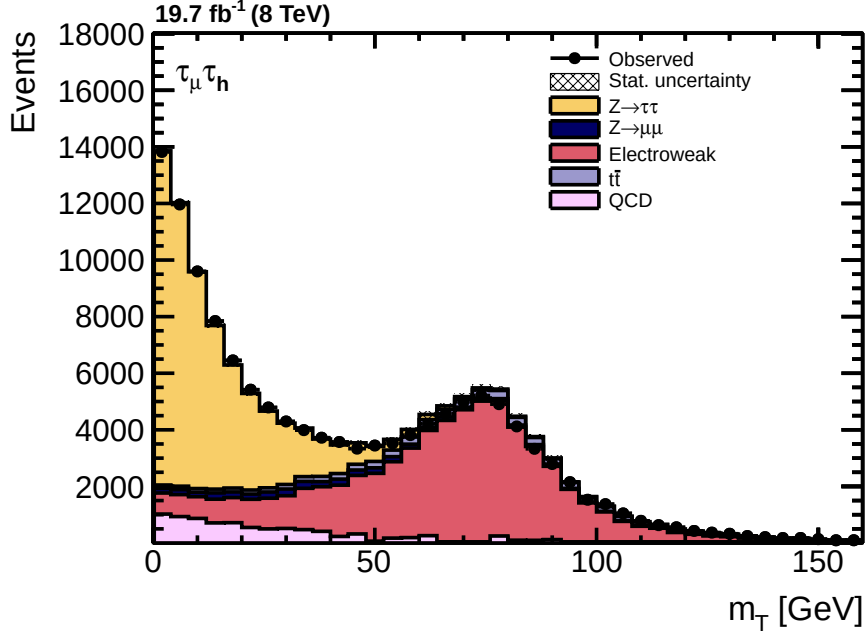


Figure 4-13: The transverse mass m_T distribution for the selected $\tau_\mu\tau_h$ final state candidates before the $m_T < 30$ GeV requirement in collisions at $\sqrt{s} = 8$ TeV. The points with error bars represent the data. Superimposed are the SM background distributions obtained from the fit. The shaded area shows the statistical uncertainty in the background predictions. The region with $m_T > 70$ GeV defines a control region used to estimate the W +jet background contribution.

jet background. The contributions of the W +jet, boson-pair, and single top processes are denoted as the "Electroweak" background. The selected events in the $\tau_\ell\tau_h$ final states are required to have $m_T < 30$ GeV. The E_T^{miss} used in the results is the MVA $\vec{E}_T^{miss}$ to reduce the impact of the pileup interactions on the E_T^{miss} resolution as discussed in Section 3.9. The $\vec{E}_T^{miss}$ resolution is essential to separate the SM Higgs boson signal from the $Z \rightarrow \tau^+\tau^-$ irreducible background (discussed in the next section). The recoil in the simulation is also calibrated to data as discussed in Section 3.9.1.

The candidate $\tau^+\tau^-$ events are split into mutually exclusive categories to improve the sensitivity of the events to the presence of the SM Higgs boson signal with a mass in the range of 110 to 145 GeV. An important aspect of this categorization is

to exploit the signatures of different SM Higgs boson production modes (Figure 1-8). The first step is to classify the events according to the number of reconstructed jets with $p_T > 30$ GeV and $|\eta| < 4.7$. The jets are clustered from the PF candidates as discussed in Chapter 3. The jets originating from the pileup interactions are rejected utilizing the pileup jet identification technique described in Section 3.5.2. The selected jets are required to be separated from the selected tau candidates by a distance ΔR larger than 0.5. The $t\bar{t}$ and single top backgrounds are reduced by rejecting the $\tau^+\tau^-$ candidate events containing at least one b-tagged jets with $p_T > 20$ GeV and $|\eta| < 2.4$. The CSV algorithm described in Section 3.5.3 is used to identify the b-tagged jets. The efficiency of the b-jet identification and misidentification of the light-flavor jets as b-jets are measured in data and simulation [128]. The simulation is corrected for the differences between the data and simulation in the efficiencies and misidentification probabilities.

Events with at least two selected jets can be used to exploit the SM Higgs boson VBF production signature. Figure 4-14 shows the distributions of the dijet mass M_{jj} (left) and the distance between the two jets in $|\Delta\eta_{jj}|$ for the selected $\tau_\mu\tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV. The corresponding distributions are also shown for the SM Higgs boson signal, with mass 125 GeV, produced in gluon fusion (red) and VBF (blue) production modes. The VBF produced SM Higgs boson events are produced in association with two high energy forward jets in the opposite regions of the detector as can be seen from the large separation of the two jets in $|\Delta\eta_{jj}|$. The two jets also tend to have a large invariant mass M_{jj} for the VBF produced SM Higgs boson events. The VBF category is defined by requiring $M_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 3.5$. There is typically very little hadronic activity in the central region of the detector as there is no "color flow" between the quarks in the VBF produced Higgs boson events. Events with a central jet between the pseudorapidity gap of the two highest p_T jets are not selected in the VBF category. The VBF category is split into "tight" and "loose" categories for the $\tau_\ell\tau_h$ final states in collisions at $\sqrt{s} = 8$ TeV by defining a tight category satisfying the $M_{jj} > 700$ GeV and $|\Delta\eta_{jj}| > 4.0$ requirements. The $Z \rightarrow \tau^+\tau^-$ background is suppressed in the VBF categories as the initial state

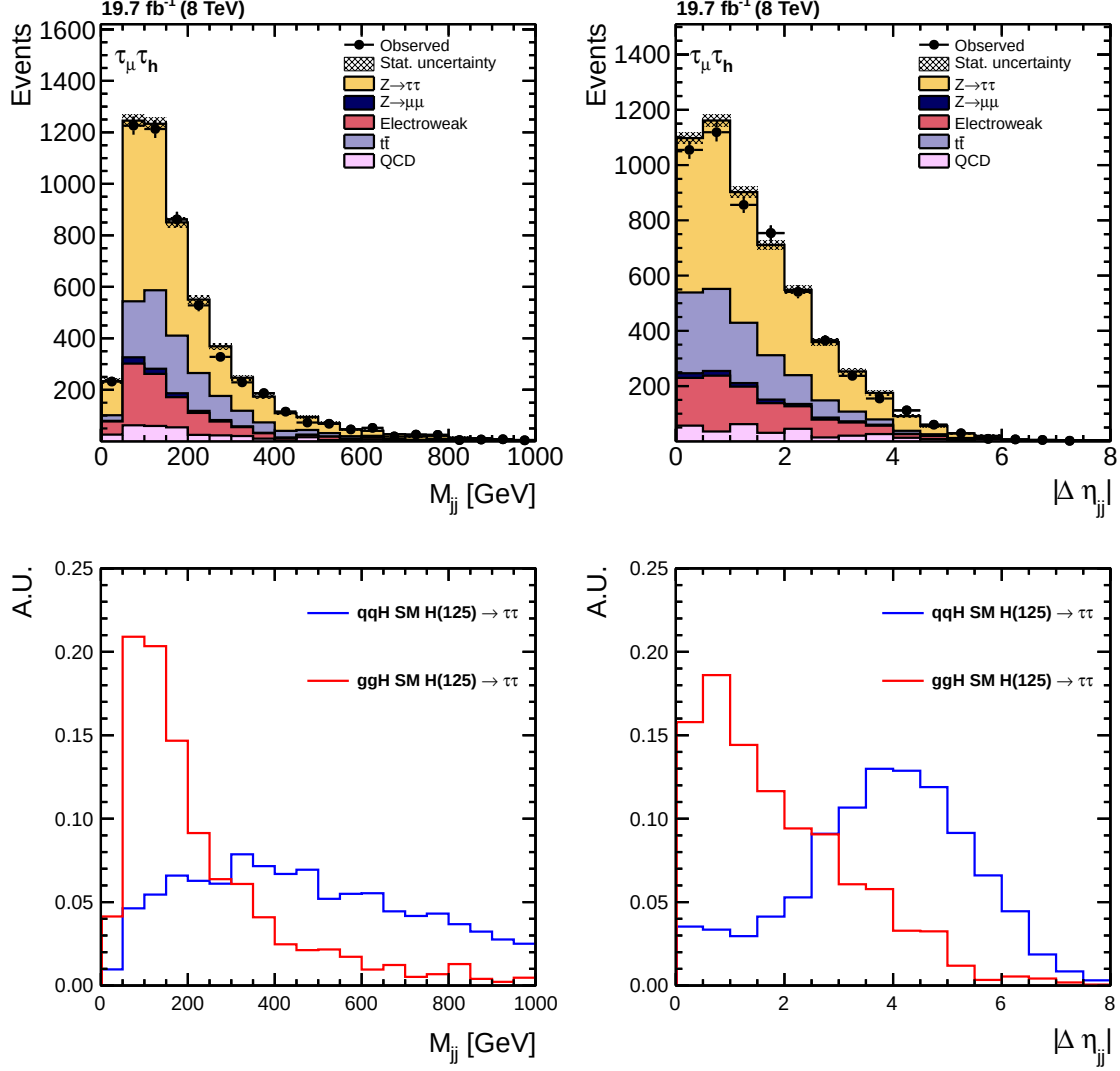


Figure 4-14: Distributions of the dijet mass M_{jj} (top left) and the distance between the two jets in pseudorapidity $|\Delta\eta_{jj}|$ (top right) for the selected $\tau_\mu\tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV. The points with error bars represent the data. Superimposed are the expected SM background distributions. The shaded area shows the statistical uncertainty in the background predictions. The corresponding normalized distributions for the SM Higgs boson with mass 125 GeV are shown (bottom) for the gluon fusion (red) and VBF (blue) production.

gluon radiated jets with $p_T > 30$ GeV tend to be in the central region. The M_{jj} of the two radiated jets also tends to be smaller compared to the VBF jets originating mostly from the valence quarks in the colliding protons. On the other hand the contribution of the $Z + 2\text{jet}$ production from purely electroweak processes is very small [192]. The events with two jets but failing the VBF category requirements are placed in the 1-jet category.

The 1-jet and VBF categories are further divided according to the transverse momentum of the Higgs boson candidate $p_T^{\tau\tau}$, defined as:

$$p_T^{\tau\tau} = |\vec{p}_T^{\tau_1} + \vec{p}_T^{\tau_2} + \vec{E}_T^{miss}|, \quad (4.10)$$

where the $\vec{p}_T^{\tau_i}$ denote the transverse momenta of the two tau candidates. The candidate events in the VBF tight category are required to have $p_T^{\tau\tau} > 100$ GeV. The 1-jet $\tau_\ell\tau_h$ category is divided into two categories by requiring $p_T^{\tau\tau} > 100$ GeV. The category satisfying the $p_T^{\tau\tau} > 100$ GeV requirement is denoted as "boosted". The selection on the $p_T^{\tau\tau}$ reduces the QCD and $W + \text{jet}$ backgrounds since the jets misidentified as τ_h candidates typically have softer spectra. The 1-jet category in the $\tau_h\tau_h$ final state is split into two categories with $p_T^{\tau\tau} > 170$ GeV and $100 < p_T^{\tau\tau} < 170$ GeV requirements denoted as "1-jet highly boosted" and "1-jet boosted" categories, respectively. No additional categories are defined for the $\tau_h\tau_h$ final state as the "0-jet" and "1-jet not-boosted" categories are completely dominated by the QCD background.

The 0-jet and 1-jet categories in the $\tau_\ell\tau_h$ final states are further divided by introducing the $p_T^{\tau_h} > 45$ GeV requirement. The τ leptons coming from the Higgs bosons with masses larger than the Z mass tend to have larger transverse momenta compared to the tau leptons coming from the Z boson. The resulting categories are denoted as the "0-jet low $p_T^{\tau_h}$ " and "0-jet high $p_T^{\tau_h}$ " in the 0-jet category and "1-jet low $p_T^{\tau_h}$ ", "1-jet high $p_T^{\tau_h}$ ", and "1-jet high $p_T^{\tau_h}$ boosted" in the 1-jet category. Figure 4-15 shows the distributions of the τ_h candidate (left) and $p_T^{\tau\tau}$ (right) for the selected $\tau_\mu\tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV. The $Z \rightarrow e^-e^+$ background in the $\tau_e\tau_h$ final state is further suppressed by requiring the E_T^{miss} to be larger than 30 GeV

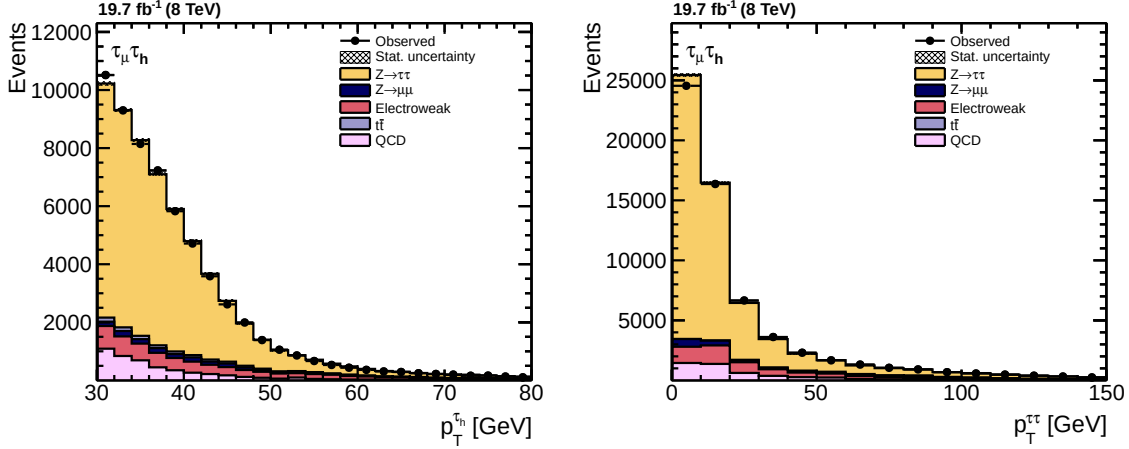


Figure 4-15: Distributions of the transverse momentum of the τ_h candidate (left) and the transverse momentum of the Higgs boson candidate (right) for the selected $\tau_\mu\tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV. The points with error bars represent the data. Superimposed are the expected SM background distributions. The shaded area shows the statistical uncertainty in the background predictions.

in the 1-jet categories. It is important to suppress this background with a large contribution peaking in the signal search region. The extra requirement on the E_T^{miss} reduces the sensitivity of the "1-jet high $p_T^{\tau h}$ " category defined with a $p_T^{\tau\tau} < 100$ GeV requirement. Therefore, this category is not considered in the $\tau_e\tau_h$ final state. The E_T^{miss} requirement is not applied in the 0-jet categories as the sensitivity to the signal is very low. In fact, a large contribution of the $Z \rightarrow e^-e^+$ events in the 0-jet categories allows to better understand the systematic uncertainties in the prediction of this background.

4.2.3 τ -Pair Invariant Mass Reconstruction

The di-tau invariant mass is used to separate the $H \rightarrow \tau^+\tau^-$ signal events from the irreducible $Z \rightarrow \tau^+\tau^-$ background events. As a first approximation one can use the visible tau decay products to reconstruct the di-tau invariant mass. However, the separation power of the visible di-tau mass, denoted as m_{vis} , is limited as the neutrinos from the tau decays can make a large fraction of the tau energy invisible to the detector. However, the $\vec{E}_T^{miss}$ vector in the transverse plane with respect to the beam direction provides an additional information on the neutrino kinematics.

The hadronic tau lepton decay can be specified by 6 parameters as the tau and neutrino masses provide two constraints ($m_\tau = 1.777$ GeV and $m_\nu = 0$ GeV). These 6 parameters can be chosen as the polar and azimuthal angles of the τ_h in the tau lepton rest frame, the three parameters needed to define the boost from the tau lepton rest frame to the laboratory frame, and finally the mass of the τ_h . There are two neutrinos in the leptonic tau decays and the neutrino mass constrain is no longer valid. There are 7 parameters needed for the leptonic tau decays and the mass of the two neutrino system, $m_{\nu\nu}$ can be chosen as the additional parameter. Thus, there are 2 and 3 unknown parameters for the hadronic and leptonic tau decays, respectively, given the observed 4-momenta of the visible decay products. The unknown parameters are chosen to be:

- x : the fraction of the tau lepton "visible" energy in the laboratory frame.
- ϕ : the azimuthal angle of the tau lepton in the laboratory frame.
- $m_{\nu\nu}$: the invariant mass of the two-neutrino system for the leptonic decays of the tau lepton.

The measurement of the $\vec{E}_T^{miss}$ provides two additional constraints. Thus, the kinematics of the tau pair system is undetermined with 2 and 4 unknown parameters in the $\tau_h\tau_h$ and $\tau_\ell\tau_h$ final states, respectively. The system can be solved for the $m_{\tau\tau}$ by introducing an assumption that the neutrinos from the tau decays are collinear with the corresponding visible decay products. This simple approximation, known as the collinear approximation and first proposed here [193], yields unphysical solutions for events where the two tau leptons are traveling back-to-back (i.e. the di-tau system is not boosted). Instead, a maximum likelihood based method is used to solve for the $m_{\tau\tau}$ in these results. The likelihood function is defined by $f(\vec{E}_T^{miss}, \vec{y}, \vec{a}_1, \vec{a}_2)$, where the $\vec{y} = (p_1^{\text{vis}}, p_2^{\text{vis}})$ denotes the four-momenta of the visible tau decay products, and the $\vec{a}_i = (x_i, \phi_i, m_{\nu\nu,i})$ denotes the unknown decay parameters. The probability is defined as:

$$P(m_{\tau\tau}) = \int \delta(m_{\tau\tau} - m_{\tau\tau}(\vec{y}, \vec{a}_1, \vec{a}_2)) f(\vec{E}_T^{miss}, \vec{y}, \vec{a}_1, \vec{a}_2) d\vec{a}_1 d\vec{a}_2. \quad (4.11)$$

The best estimate of the $m_{\tau\tau}$ is taken to be the value that maximizes the $P(m_{\tau\tau})$. The likelihood function $f(\vec{E}_T^{miss}, \vec{y}, \vec{a}_1, \vec{a}_2)$ is a product of three likelihood functions: one for each of the tau lepton decays and one for the compatibility of the di-tau pair decay with the observed $\vec{E}_T^{miss}$. The likelihood function of the leptonic tau decay is modeled by the matrix element of the leptonic decay of an unpolarized tau lepton [194]. The likelihood $\mathcal{L}_{\tau,\ell}$ is given by:

$$\mathcal{L}_{\tau,\ell} = \frac{d\Gamma}{dx dm_{\nu\nu} d\phi} \propto \frac{m_{\nu\nu}}{4m_\tau^2} [(m_\tau^2 + 2m_{\nu\nu}^2)(m_\tau^2 - m_{\nu\nu}^2)], \quad (4.12)$$

where the allowed regions are given by $0 < x < 1$ and $0 < m_{\nu\nu} < m_\tau \sqrt{1-x}$. The two body phase-space is used to model the likelihood function of the hadronic tau decays [19]. The likelihood $\mathcal{L}_{\tau_h}$ is given by:

$$\mathcal{L}_{\tau_h} = \frac{d\Gamma}{dx d\phi} \propto \frac{1}{1 - m_{\text{vis}}^2/m_\tau^2}, \quad (4.13)$$

where the allowed region is given by $\frac{m_{\text{vis}}}{m_\tau} \leq x \leq 1$. The TAUOLA simulation is used to verify that the two body phase-space model is an adequate parameterization of the hadronic tau decay. The $\mathcal{L}_{\tau,\ell}$ and $\mathcal{L}_{\tau_h}$ do not explicitly depend on the x_i or ϕ_i parameters. The x_i parameter defines the integration limits in Equation (4.11). The ϕ_i parameters enter the likelihood function for the measured $\vec{E}_T^{miss}$ given by:

$$\mathcal{L}_\nu(E_x^{\text{miss}}, E_y^{\text{miss}}) = \frac{1}{2\pi\sqrt{|V|}} \exp \left[-\frac{1}{2} \begin{pmatrix} E_x^{\text{miss}} - \sum p_x^\nu \\ E_y^{\text{miss}} - \sum p_y^\nu \end{pmatrix}^T V^{-1} \begin{pmatrix} E_x^{\text{miss}} - \sum p_x^\nu \\ E_y^{\text{miss}} - \sum p_y^\nu \end{pmatrix} \right], \quad (4.14)$$

where the expected $\vec{E}_T^{miss}$ resolution is represented by the covariance matrix defined in Equation (3.12). The obtained relative $m_{\tau\tau}$ resolution is about 10% and 15% for the $\tau_h\tau_h$ and $\tau_\ell\tau_h$ final states, respectively. The resolution varies between the event categories defined in the previous section with the boosted categories having better $m_{\tau\tau}$ relative resolution due to the more accurate $\vec{E}_T^{miss}$ measurement. Thus, the categorization of the events in $p_T^{\tau_h}$ and $p_T^{\tau\tau}$ additionally provides a better separation of the SM Higgs boson and $Z \rightarrow \tau^+\tau^-$ candidate events in the boosted categories due

to the improved $m_{\tau\tau}$ reconstruction. Figure 4-16 shows the distributions of the visible

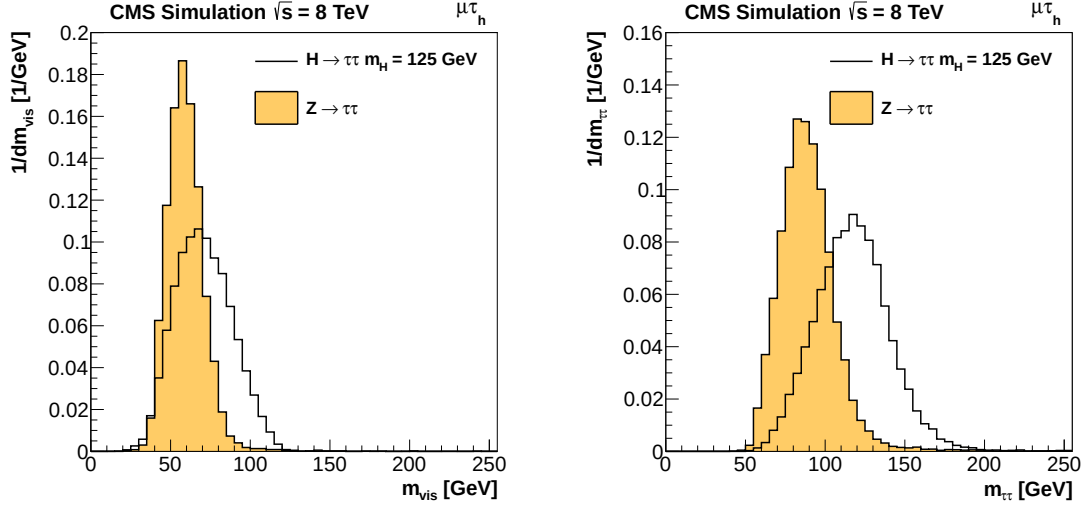


Figure 4-16: Distributions of the invariant mass of the tau pair visible decay products (left) and the likelihood based reconstruction (right) in $Z \rightarrow \tau^+\tau^-$ and $H \rightarrow \tau^+\tau^-$ selected candidate events in simulation. The distributions are normalized to unit area for the $\tau_h\tau_\mu$ final state [189].

di-tau invariant mass (left) and the likelihood based di-tau invariant mass (right) in the $\tau_\mu\tau_h$ final state for simulated $Z \rightarrow \tau^+\tau^-$ and SM Higgs boson, with a mass of 125 GeV, events. The likelihood based $m_{\tau\tau}$ provides a better separation between the signal and background. The overall improvement in the expected sensitivity of the results to the SM Higgs boson with a mass of 125 GeV is about 40% with respect to the results obtained with the visible mass.

4.2.4 Background Estimation

The major background contributions are estimated from data. The largest source of the background events is the Drell-Yan tau pair production. This background is modeled by the so called "embedding" technique using $Z \rightarrow \mu^+\mu^-$ candidate events selected with loose identification and isolation requirements on the muon candidates. The candidate muons are replaced with simulated τ leptons with identical four-momenta with the corresponding observed muons. The simulated taus are decayed with TAUOLA and passed through the full CMS detector simulation and

reconstruction. The muons in the $Z \rightarrow \mu^+\mu^-$ data events are replaced with the reconstructed visible decay products of the simulated tau leptons. The E_T^{miss} , the jets, the τ_h candidates, and the isolation sums are then computed. The embedded samples are normalized to the inclusive $Z \rightarrow \mu^+\mu^-$ observed events. Thus, the systematic uncertainties in the E_T^{miss} , jet energy scale, and the luminosity measurement are negligible as the events are taken from "real" collision data. Systematic uncertainties due to extrapolation to the different event categories are considered. The uncertainties due to the reconstruction and acceptance of the embedded events are estimated by performing the embedding procedure on the $Z \rightarrow \tau^+\tau^-$ simulated events. Statistical uncertainties due to the limited number of events in the categories are also included. The $Z \rightarrow \ell^+\ell^-$ is a smaller but non-negligible background in the $\tau_\ell\tau_h$ final states. This background contribution is estimated from the simulation with the normalization taken from $Z \rightarrow \mu^+\mu^-$ data. There is a small contribution from $Z \rightarrow \ell^+\ell^-$ events where one of the leptons is not within the fiducial region and a jet is misidentified as a τ_h candidate. This contribution is taken from the simulation.

The W +jet background shape is modeled using simulation. The normalization is determined from data using the high- m_T control region defined with $m_T > 70$ GeV requirement (Figure 4-13) in the $\tau_\ell\tau_h$ final states. This is done in each category by normalizing the W +jet predicted yield to the observed data. The small contribution from other background sources in the high- m_T control region is subtracted from the observed number of events. In the VBF categories, with limited number of simulated W +jet events, the requirements on the M_{jj} and $|\Delta\eta_{jj}|$ are relaxed to obtain smooth templates for the $m_{\tau\tau}$ distribution. The bias introduced in the $m_{\tau\tau}$ shape is found to be negligible. $\tau_\mu\tau_h$ control region with the same categories as in the $\tau_h\tau_h$ final state is used to obtain a simulation-to-data scale factor for the W +jet contribution in the high- m_T control region. The scale factor is then used to scale the W +jet background contribution obtained from the simulation in the $\tau_h\tau_h$ final state. The extrapolation factor from the high- m_T control region to the signal region is obtained from simulation. An uncertainty of 10 to 25% is estimated in the extrapolation factor by studying the differences in the $Z \rightarrow \mu^+\mu^-$ data and simulated events where one of

the muons is removed from the event to obtain W +jet like events. The extrapolation uncertainty is 30% in the $\tau_h\tau_h$ final state.

The $t\bar{t}$ background contribution is taken from the simulation. The expected yield in the simulation is corrected to the observed data using a $t\bar{t}$ enriched control region by requiring b-tagged jets in the final state. The small contributions from the diboson and single top background processes are taken from the simulation.

The QCD multi-jet events are estimated by exploiting the same charged events in the $\tau_\ell\tau_h$ final state. In the 0-jet and 1-jet low $p_T^{\tau_h}$ categories the normalization and the shape of the QCD background contribution is obtained from the same charge control region. The Drell-Yan, $t\bar{t}$, and W +jets background process contributions are subtracted from the observed event yields in this control region. The expected QCD background contribution in the opposite charge signal region is then derived by rescaling the yield in the same-charge control region by a factor of 1.06. This factor is measured in an anti-isolated control region where the isolation requirements on the ℓ and τ_h are inverted. An uncertainty of 10% is assigned in the extrapolation factor accounting for the $p_T^{\tau_h}$ dependence and the statistical uncertainties. In the VBF-tagged and 1-jet high $p_T^{\tau_h}$ boosted categories the number of selected events in the same-charge control region is too small to determine the QCD background contribution with the above method. Instead, the QCD yield is determined by multiplying the QCD yield in the inclusive $\tau_\ell\tau_h$ selection (determined by the method described above) and the efficiency of the corresponding category selection. The efficiency of the category selection is determined in the anti-isolated same charge control region while the shape of the QCD background is taken from the anti-isolated selection. An additional shape uncertainty is included to account for the shape differences between the control and signal regions. The QCD background in the $\tau_h\tau_h$ final state is estimated from a control region with relaxed τ_h isolation requirements. The QCD multi-jet background shape is taken from this control region after subtracting the contributions from the Drell-Yan, $t\bar{t}$, and W +jet processes. The yield in the signal region is estimated by multiplying the yield in the control region by an extrapolation factor obtained in the same charge $\tau_h\tau_h$ candidate events. The assumption that the

QCD shapes in the control and signal regions are the same is verified in the same-charge selection. An uncertainty of 35% is assigned to the QCD prediction coming from the limited number of events and the uncertainties in the expected contributions of the subtracted backgrounds in the control regions.

4.2.5 Systematic Uncertainties

The systematic uncertainties can be categorized into three sources. The theoretical uncertainties affect the expected signal yields and the diboson background processes with the predictions taken from the simulation. The experimental uncertainties come from the uncertainties in the electron, muon or τ_h candidate reconstruction and identification, and from the uncertainties in the background estimation as discussed in the last section. The systematic uncertainties can affect the rates and the shapes of the $m_{\tau\tau}$ distributions.

The leading experimental uncertainty in the $\tau_\ell\tau_h$ and $\tau_h\tau_h$ final states comes from the uncertainty in the τ_h candidate reconstruction and identification. The systematic uncertainty in the τ_h energy scale is obtained from the template fit to the mass of the τ_h candidate as described in Section 4.2.2. An uncertainty of 3% in the energy scale of each τ_h candidate is propagated to the result. This uncertainty affects the rate and the shape of the relevant signal and background processes. The uncertainty due to the identification and trigger efficiencies per τ_h candidate is about 10% estimated from the tag-and-probe measurement. An additional 3% uncertainty is assigned for the high $p_T^{\tau_h}$ candidates to take into account the small tag-and-probe selected sample size. The efficiency of the electron, muon, or jet candidate to be misidentified as a τ_h candidate in the $Z \rightarrow \ell^+\ell^-$ events has an uncertainty of up to 80% dominated by the statistical uncertainties due to limited number of simulated events. The identification, isolation, and trigger efficiency simulation to data scale factors have uncertainties up to 2% for the $\tau_\ell\tau_h$ final states. The effect of the electron and muon energy scale is negligible compared to the effect of the τ_h energy scale on the $m_{\tau\tau}$ distribution.

The uncertainty in the E_T^{miss} scale of 5% affects the $\tau_\ell\tau_h$ final states due to the $m_T < 30$ GeV selection requirement. The uncertainty also affects the 1-jet categories

Uncertainty	Affected processes	Change in acceptance
Tau energy scale	signal & sim. backgrounds	1–29%
Tau ID (& trigger)	signal & sim. backgrounds	6–19%
e misidentified as τ_h	$Z \rightarrow e^+e^-$	20–74%
μ misidentified as τ_h	$Z \rightarrow \mu\mu$	30%
Jet misidentified as τ_h	$Z + jets$	20–80%
Electron ID & trigger	signal & sim. backgrounds	2–6%
Muon ID & trigger	signal & sim. backgrounds	2–4%
Jet energy scale	signal & sim. backgrounds	up to 20%
E_T^{miss} scale	signal & sim. backgrounds	1–12%
$\varepsilon_{b\text{-tag}}$ b jets	signal & sim. backgrounds	up to 8%
$\varepsilon_{b\text{-tag}}$ light-flavoured jets	signal & sim. backgrounds	1–3%
Norm. Z production	Z	3%
$Z \rightarrow \tau^+\tau^-$ category	$Z \rightarrow \tau^+\tau^-$	2–14%
Norm. $W + jets$	$W + jets$	10–100%
Norm. $t\bar{t}$	$t\bar{t}$	8–35%
Norm. diboson	diboson	6–45%
Norm. QCD multijet	QCD multijet	6–70%
Shape QCD multijet	QCD multijet	shape only
Norm. reducible background	Reducible bkg.	15–30%
Shape reducible background	Reducible bkg.	shape only
Luminosity 7 TeV(8 TeV)	signal & sim. backgrounds	2.2% (2.6%)
PDF (qq)	signal & sim. backgrounds	4–5%
PDF (gg)	signal & sim. backgrounds	10%
Norm. ZZ/WZ	ZZ/WZ	4–8%
Norm. $t\bar{t} + Z$	$t\bar{t} + Z$	50%
Scale variation	signal	3–41%
Underlying event & parton shower	signal	2–10%
Limited number of events	all	shape only

Table 4.11: The systematic uncertainties, the corresponding processes, and the impact in the acceptances. Several systematic uncertainties are treated as (partially) correlated for the different final states and/or categories. Adapted from [189].

in the $\tau_e\tau_h$ final state due to the $E_T^{miss} > 30$ GeV requirement. The 5% uncertainty comes from the recoil calibration and translates to yield uncertainties between 1 to 12% depending on the final state and category. The uncertainty in the jet energy scale results in the signal rate uncertainty of up to 20% in the VBF categories. The uncertainty in the b-tagged jet veto results in the $t\bar{t}$ rate uncertainties of up to 10%. The uncertainties in the background estimations were discussed in the last section. The theoretical uncertainties in the SM Higgs boson production due to the PDFs, renormalization and factorization scale variations, as well as the uncertainties in the

underlying event and parton shower are considered. The uncertainties in the Higgs boson p_T spectrum due to the scale of the resummation and missing higher order corrections in perturbative QCD are propagated as a shape uncertainty. The systematic uncertainties and the corresponding changes in the acceptances are summarized in Table 4.11. The uncertainties due to limited number of simulated events or due to limited number of data events in the control regions are included in the maximum likelihood fits following the method proposed in [195].

4.2.6 Results

A simultaneous maximum-likelihood fit of the $m_{\tau\tau}$ distribution in all the categories and final state is performed to extract the SM Higgs boson signal. The systematic uncertainties discussed in the last section are represented by nuisance parameters entering the likelihood via their probability density functions. The nuisance parameters only affecting the normalization of the corresponding background contributions are modeled by log-normal probability density functions. The log-normal probability functions are chosen to avoid having negative background contributions after the fit. The nuisance parameters for the systematic uncertainties also affecting the shape of the $m_{\tau\tau}$ templates are modeled by a Gaussian probability distribution function. The variation of these nuisance parameters results in a smooth morphing of the given template [196].

The nuisance parameters affect the background processes in multiple categories. For example, the nuisance parameters corresponding to the tau identification efficiency and energy scale are correlated across all the categories of a given final state. This allows for these uncertainties to be constrained by the 0-jet and 1-jet categories where the number of $Z \rightarrow \tau^+\tau^-$ events is large. Thus, the $Z \rightarrow \tau^+\tau^-$ background prediction in the VBF categories, for example, is constrained resulting in enhanced sensitivity of these categories. The nuisance parameters corresponding to the systematic uncertainties coming from the limited number of events for a particular category are only constrained within that category in the fit.

Figures 4-17, 4-18, and 4-19 show the $m_{\tau\tau}$ distributions for the selected candidates

in the $\tau_\mu\tau_h$, $\tau_e\tau_h$, and $\tau_h\tau_h$ final states, respectively in collisions at $\sqrt{s} = 8$ TeV. All the categories considered in the fit are shown. The SM background predictions are obtained from the maximum likelihood fit described above. The expected contribution of the SM Higgs boson with a mass of 125 GeV is also shown. The corresponding event yields for the observed and predicted events are summarized in Table 4.12 (adapted from [189]). The predicted background contribution yield is taken from the maximum likelihood fit. An indication of excess of events with respect to the background contributions is visible. Figure 4-20 shows the 95% CL upper limits on

Event category	SM Higgs ($m_{\text{H}} = 125 \text{ GeV}$)				Background	Data	$\frac{S}{S+B}$	σ_{eff} (GeV)
	ggH	VBF	VH	Σ signal				
$\mu\tau_h$								
0-jet low- $p_T^{\tau_h}$ 8 TeV	83.0	0.8	0.4	85.0 ± 11.0	40800 ± 1900	40353	0.003	16.3
0-jet high- $p_T^{\tau_h}$ 8 TeV	66.2	0.7	0.6	67.5 ± 9.3	5990 ± 250	5789	0.020	15.2
1-jet low- $p_T^{\tau_h}$ 8 TeV	36.0	6.0	3.0	45.0 ± 6.0	9030 ± 360	9010	0.010	18.6
1-jet high- $p_T^{\tau_h}$ 8 TeV	29.6	4.3	2.4	36.3 ± 4.6	3180 ± 130	3160	0.029	19.7
1-jet high- $p_T^{\tau_h}$ boosted 8 TeV	11.5	2.9	2.0	16.5 ± 2.6	1265 ± 62	1253	0.072	17.2
Loose VBF tag 8 TeV	1.1	3.4	—	4.5 ± 0.4	81 ± 7	76	0.17	17.0
Tight VBF tag 8 TeV	0.3	2.0	—	2.4 ± 0.2	15 ± 2	20	0.49	18.1
$e\tau_h$								
0-jet low- $p_T^{\tau_h}$ 8 TeV	33.4	0.3	0.2	34.0 ± 4.6	16750 ± 750	17109	0.002	15.8
0-jet high- $p_T^{\tau_h}$ 8 TeV	31.4	0.3	0.3	32.1 ± 4.4	4380 ± 170	4536	0.010	15.4
1-jet low- $p_T^{\tau_h}$ 8 TeV	9.1	1.8	1.0	11.9 ± 1.6	1200 ± 56	1214	0.025	16.5
1-jet high- $p_T^{\tau_h}$ boosted 8 TeV	5.1	1.4	0.9	7.5 ± 1.1	497 ± 27	476	0.11	15.5
Loose VBF tag 8 TeV	0.6	1.8	—	2.4 ± 0.2	45 ± 4	40	0.14	16.7
Tight VBF tag 8 TeV	0.3	1.3	—	1.6 ± 0.1	9 ± 2	7	0.51	16.2
$\tau_h\tau_h$								
1-jet boosted 8 TeV	7.2	2.1	1.0	10.3 ± 1.7	1133 ± 49	1120	0.054	15.2
1-jet highly-boosted 8 TeV	5.6	1.6	1.2	8.4 ± 1.2	380 ± 23	366	0.14	13.1
VBF tag 8 TeV	0.5	2.4	—	3.0 ± 0.3	29 ± 4	34	0.32	14.3

Table 4.12: Observed and predicted event yields in all event categories of the $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$ final states in the full $m_{\tau\tau}$ mass range. The event yields of the predicted background distributions correspond to the result of the global fit. The signal yields, on the other hand, are normalized to the standard model prediction. The $\frac{S}{S+B}$ variable denotes the ratio of the signal and the signal-plus-background yields in the central $m_{\tau\tau}$ range containing 68% of the signal events for $m_H = 125$ GeV. The σ_{eff} variable denotes the standard deviation of the $m_{\tau\tau}$ distribution for corresponding signal events. Adapted from [189].

the SM Higgs boson cross section times branching fraction relative to the predicted SM value as a function of the Higgs boson mass hypothesis ranging from 90 to 145 GeV for the $\tau_h\tau_h$ (top left), $\tau_e\tau_h$ (top right), and $\tau_\mu\tau_h$ (bottom) final states in collisions at $\sqrt{s} = 8$ TeV. The limits are obtained using the modified frequentist construction CL_s [197, 198]. The expected limits are obtained from the background only hypothesis. An

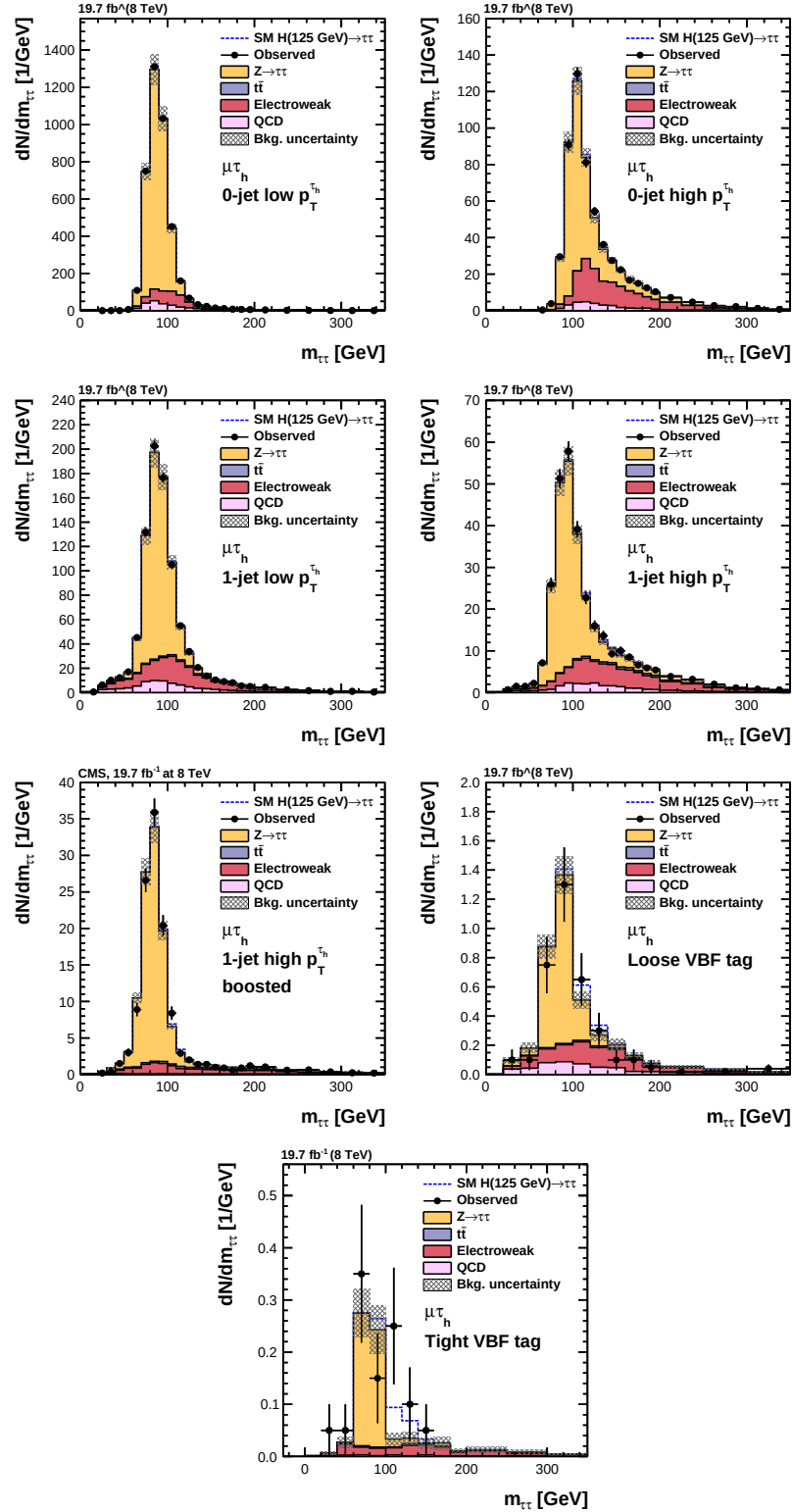


Figure 4-17: The $m_{\tau\tau}$ distributions for the selected $\tau_\mu\tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV. The points with error bars represent the data. Superimposed are the SM background distributions obtained from the fit. The shaded area is the uncertainty in the background predictions after the fit. The SM Higgs boson, with a mass of 125 GeV, contribution added to the background is shown in blue.

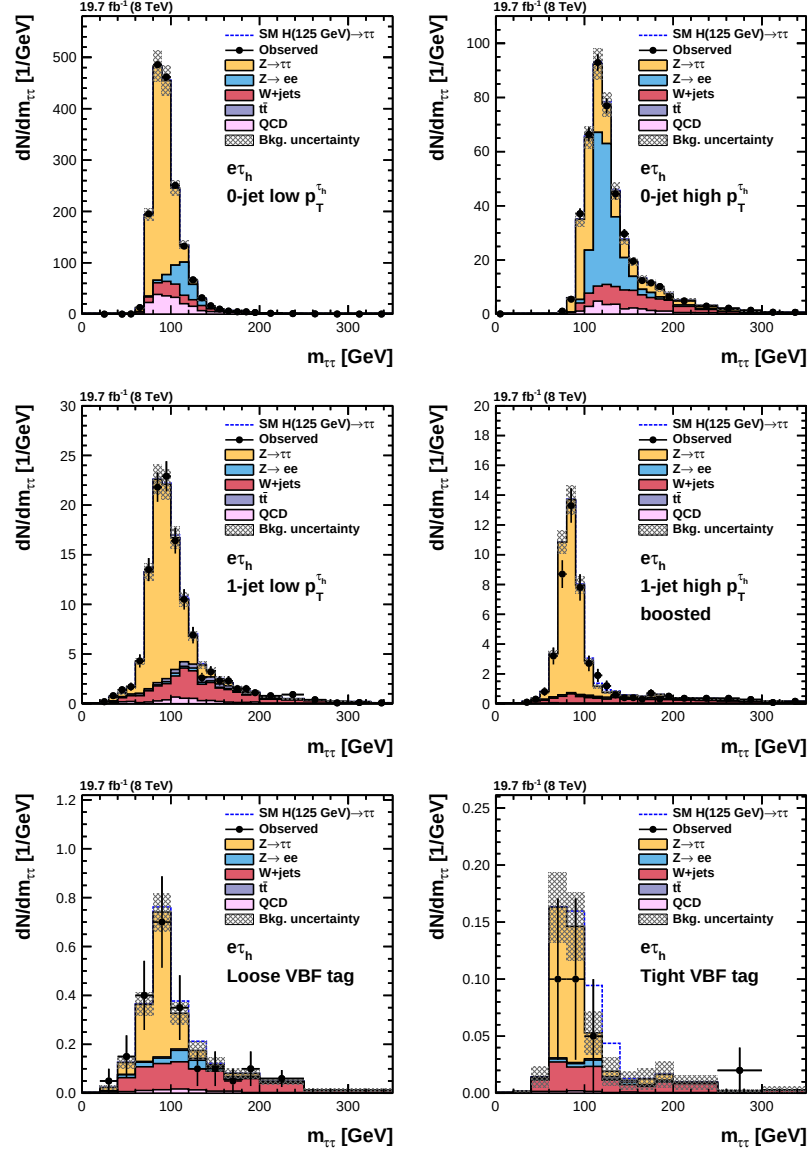


Figure 4-18: The $m_{\tau\tau}$ distributions for the selected $\tau_e\tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV. The points with error bars represent the data. Superimposed are the SM background distributions obtained from the fit. The shaded area is the uncertainty in the background predictions after the fit. The SM Higgs boson, with a mass of 125 GeV, contribution added to the background is shown in blue.

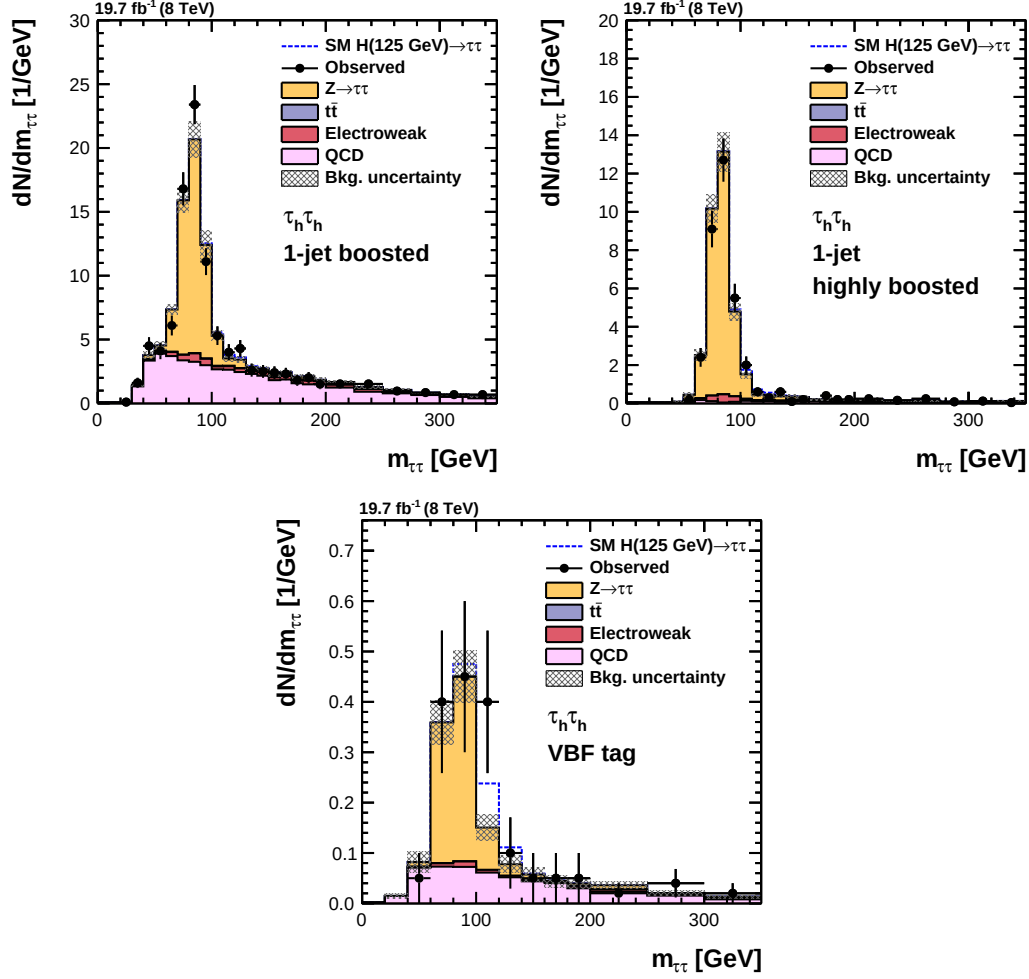


Figure 4-19: The $m_{\tau\tau}$ distributions for the selected $\tau_h\tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV. The points with error bars represent the data. Superimposed are the SM background distributions obtained from the fit. The shaded area is the uncertainty in the background predictions after the fit. The SM Higgs boson, with a mass of 125 GeV, contribution added to the background is shown in blue.

excess of events with respect to the background predictions is visible in the $\tau_\mu\tau_h$ and $\tau_h\tau_h$ final states at $\sqrt{s} = 8$ TeV. Figure 4-21 shows the expected 95% CL upper

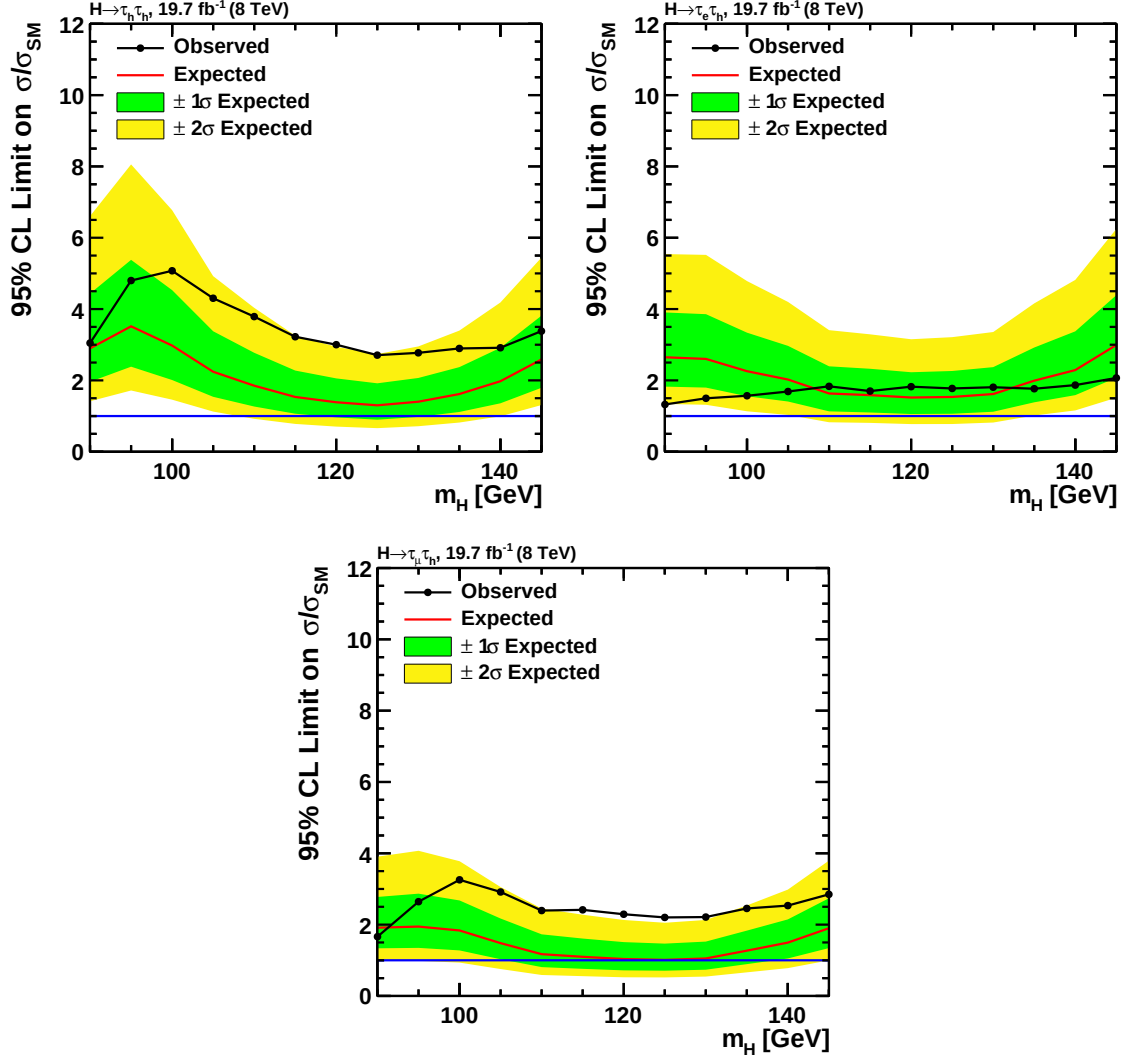


Figure 4-20: The expected and observed 95% CL upper limits on the $\frac{\sigma}{\sigma_{SM}}$ parameter for the $\tau_h\tau_h$ (top left), $\tau_e\tau_h$ (top right), and $\tau_\mu\tau_h$ (bottom) final states in collisions at $\sqrt{s} = 8$ TeV. The bands show the expected one (two) standard deviation intervals around the expected limit.

limits (left) on the $\frac{\sigma}{\sigma_{SM}}$ parameter for the background only hypothesis at $\sqrt{s} = 8$ TeV demonstrating the expected sensitivity of the individual final states to the presence of a SM Higgs boson. The observed and expected 95% CL upper limits are also shown (right) in the combination of the three final states at $\sqrt{s} = 8$ TeV.

Figure 4-22 shows the observed and expected $m_{\tau\tau}$ distributions combining all the

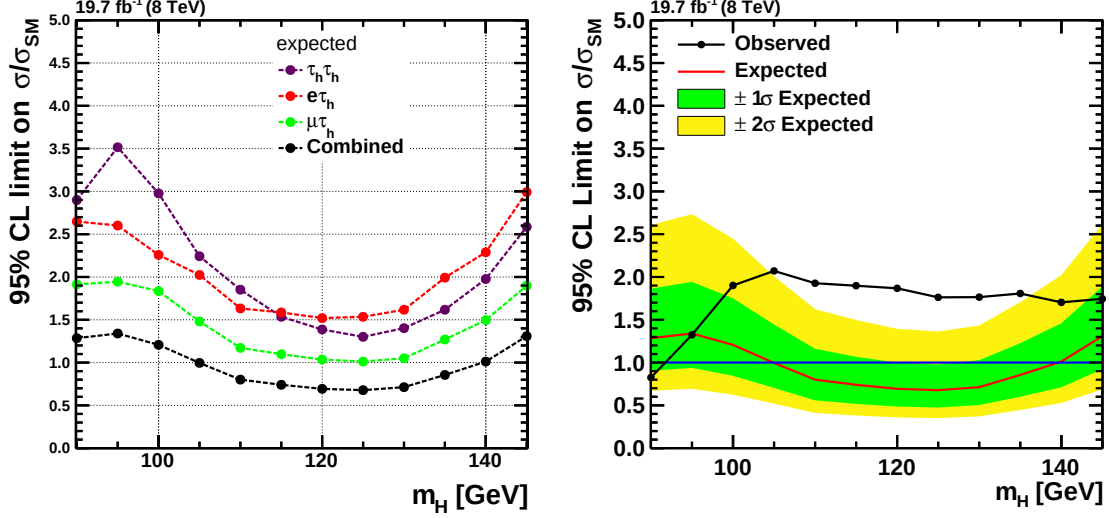


Figure 4-21: Expected 95% CL upper limits on the $\frac{\sigma}{\sigma_{SM}}$ parameter for the $\tau_h\tau_h$, $\tau_e\tau_h$, $\tau_\mu\tau_h$ final states shown separately and compared to the combined limit (left) in collisions at $\sqrt{s} = 8$ TeV. The plot on the right shows the expected and observed 95% CL upper limits on the $\frac{\sigma}{\sigma_{SM}}$ parameter for the combination of the $\tau_h\tau_h$, $\tau_e\tau_h$, $\tau_\mu\tau_h$ final states in collisions at $\sqrt{s} = 8$ TeV. The bands show the expected one (two) standard deviation intervals around the expected limit.

categories in the $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$, and $\tau_e\tau_\mu$ final states in collisions at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV. The distributions are weighted by $S/(S + B)$ in each category to better visualize the agreement of the data and SM background predictions in the more sensitive categories. Here the S is the expected contribution of the SM Higgs boson with a mass of 125 GeV and B is the predicted background yield obtained from the maximum likelihood fit. The $S/(S + B)$ weight is obtained from the $m_{\tau\tau}$ region containing the 68% of the SM Higgs boson events. The insert shows the difference between the observed data and background prediction with SM Higgs boson contribution, with a mass of 125 GeV, superimposed in shaded red. The excess of the observed events with respect to the background predictions is compatible with a SM Higgs boson with a mass of 125 GeV.

The excess of events is quantified by the observed p-value as a function of the SM Higgs boson mass hypothesis shown in Figure 4-23. All the possible tau pair final states are used to obtain the p-value. The dashed line shows the expected p-value for a SM Higgs boson with a mass m_H . The observed p-value is minimal at

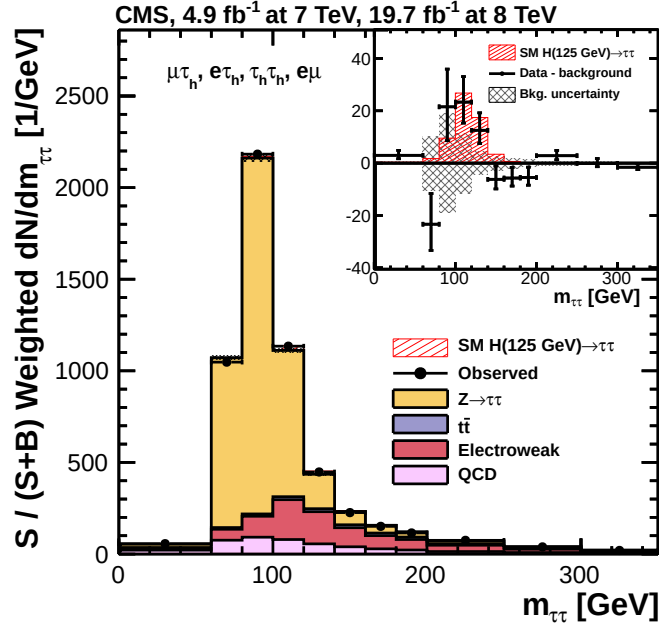


Figure 4-22: The $m_{\tau\tau}$ weighted distribution for the $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$, and $\tau_e\tau_\mu$ tau pair final states for the observed data and predicted SM backgrounds obtained from the fit. The weights for the distributions in each channel and in each category are obtained from the ratio between the expected signal contribution and signal-plus-background yields in the $m_{\tau\tau}$ interval containing 68% of the SM Higgs boson candidate events. The insert shows the difference between the observed data and the background prediction. The expected SM Higgs boson contribution, with mass of 125 GeV, is shown in red [189].

the $m_H = 120$ GeV mass hypothesis with a significance of 3.3 standard deviations. The observed standard deviation is 3.2 for the $m_H = 125$ GeV mass hypothesis. The p-values are not corrected to account for the look-elsewhere effect.

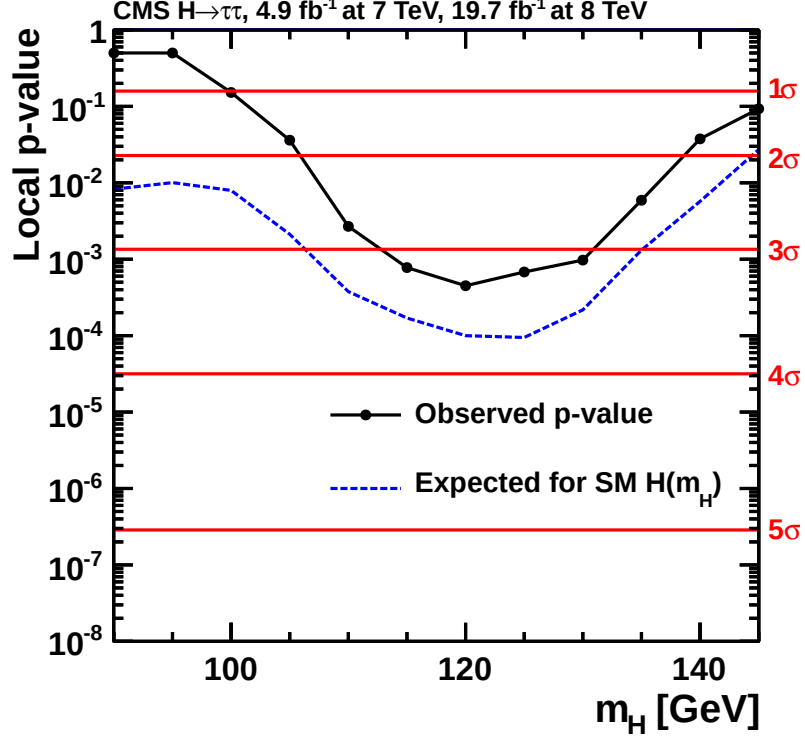


Figure 4-23: The observed p-value as a function of the SM Higgs boson mass hypothesis in combination of all the $\tau^+\tau^-$ final states. The dashed line shows the expected p-value for a SM Higgs boson with a mass m_H [189]. The shown significance is not corrected for the so called look-elsewhere effect [18].

4.3 MSSM Higgs Boson Search in Tau Decays

Searches for MSSM neutral Higgs bosons have previously been performed at the LEP [199] and Tevatron [200, 201, 202, 203] colliders in e^+e^- and $p\bar{p}$ collisions, respectively with no significant excess of events with respect to the SM background predictions. This section describes the search for neutral MSSM Higgs bosons decaying to a τ lepton pair performed by the CMS collaboration [204]. The CMS $h, H, A \rightarrow \tau^+\tau^-$ search is performed in the $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$, $\tau_e\tau_\mu$, and $\tau_\mu\tau_\mu$ final states.

The analysis is closely related to the SM Higgs boson search described in the previous section with similar $\tau^+\tau^-$ candidate selection, background estimation, and signal extraction. The differences are described in this section.

The search strategy is to exploit the production mechanism of the MSSM neutral Higgs bosons as shown in Figure 1-12. The selected $\tau^+\tau^-$ candidates are split into two mutually exclusive categories as follows:

- **b-tag:** At least one b-tagged jet with $p_T > 20$ GeV and $|\eta| < 2.4$ is required with no more than one jet with $p_T > 30$ GeV and $|\eta| < 4.7$. This category exploits the b quark associated production that is enhanced for large $\tan\beta$ values. The requirement on the additional jet reduces the $t\bar{t}$ background contribution.
- **no b-tag:** Events are required to have no b-tagged jets with $p_T > 20$ GeV and $|\eta| < 2.4$. This event category is sensitive to the gluon fusion production.

No additional categories to enhance the expected sensitivity to the presence of the heavy neutral Higgs bosons are considered. This allows to interpret the results with reduced model dependencies. For example, the requirements on the $p_T^{\tau\tau}$ and $p_T^{\tau_h}$ will have different impacts for various MSSM benchmark scenarios. The p_T requirement on the τ_h candidate in the $\tau_\ell\tau_h$ final states is also reduced to 20 GeV with respect to the 30 GeV requirement in the selection for the SM Higgs boson search. The MSSM Higgs boson signal samples are modeled by PYTHIA 6.4. The data samples used in the results are the same as for the SM Higgs boson searches with one important difference in the $\tau_h\tau_h$ final state. Only the inclusive $\tau_h\tau_h$ trigger in the parked data sample is used in this final state corresponding to a total integrated luminosity of 18.3 fb^{-1} .

The background contributions and the corresponding uncertainties are estimated with the methods described in the previous section. One notable difference is related to the $Z \rightarrow \tau^+\tau^-$ background estimation with the embedding technique. The $Z \rightarrow \mu^+\mu^-$ data events in the b-tag category are contaminated by the $t\bar{t}$ background events. The contribution of the $t\bar{t}$ background process is not negligible and is taken into account in the background prediction.

An analytic function is used to model the important background processes in the high $m_{\tau\tau}$ region as the background predictions obtained from the simulation is difficult due to the limited number of simulated events. The functional form used is given by:

$$f(m_{\tau\tau}) = \exp\left(-\frac{m_{\tau\tau}}{a + bm_{\tau\tau}}\right), \quad (4.15)$$

where the a and b parameters are determined from a fit to the data in the $m_{\tau\tau}$ region above 150 GeV. The uncertainties in the a and b parameters from the fit are propagated as shape uncertainties in the background shape.

4.3.1 Results and Interpretations

A simultaneous maximum-likelihood fit of the $m_{\tau\tau}$ distribution in the b-tag and no-btag categories for all the final states is performed to extract the signal contribution. Figures 4-24 and 4-25 show the $m_{\tau\tau}$ distributions for the observed and predicted events in the $\tau_h\tau_h$ and $\tau_\mu\tau_h$ final states, respectively at $\sqrt{s} = 8$ TeV. The background contributions and the corresponding uncertainties are obtained from the maximum likelihood fit. The MSSM signal prediction is shown in blue for the $m_A = 160$ GeV and $\tan\beta = 8$ parameters in the m_h^{mod+} benchmark scenario (Section 1.1.4).

No significant excess of data events with respect to the background predictions is observed. Upper limits at 95% CL are set on production times branching fraction for the gluon fusion and b-quark associated narrow resonance $\phi \rightarrow \tau^+\tau^-$. Figure 4-26 shows the observed and expected 95% CL upper limits on the $\sigma(gg\phi) \times \mathcal{B}(\phi \rightarrow \tau\tau)$ (left) and $\sigma(bb\phi) \times \mathcal{B}(\phi \rightarrow \tau\tau)$ (right) as a function of the ϕ mass hypothesis in collisions at $\sqrt{s} = 8$ TeV. The expected limits are derived using a SM background hypothesis where the SM Higgs boson with mass of 125 GeV is included. The ϕ production in gluon fusion (b-quark associated) mode is treated as a nuisance parameter in the extraction of the b-quark associated (gluon fusion) expected limits.

The results are also interpreted in the context of the MSSM neutral Higgs boson searches. The three neutral Higgs bosons contribute to the signal. Limits are derived by introducing a test statistic that tests the compatibility of the data to the MSSM

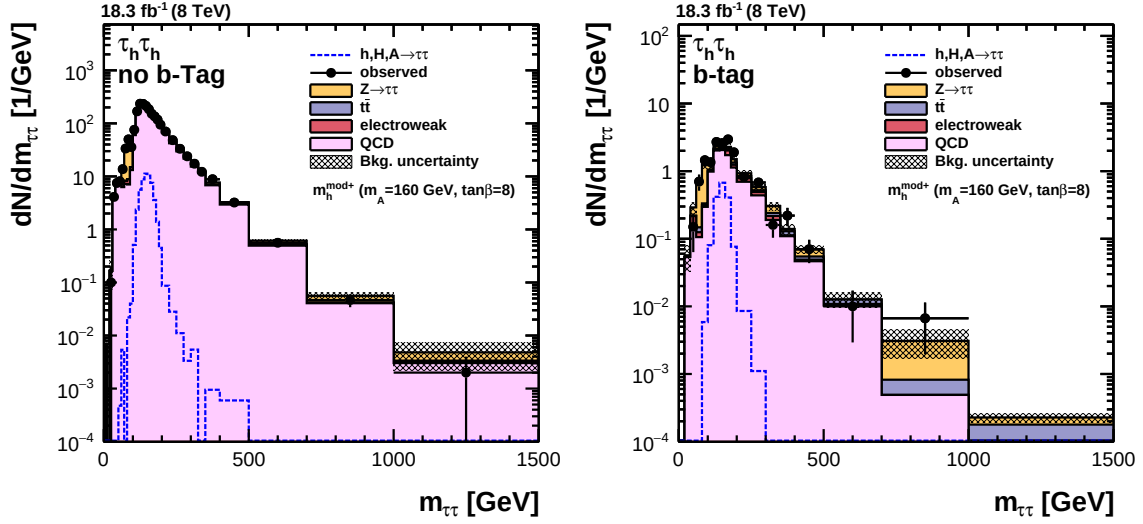


Figure 4-24: The $m_{\tau\tau}$ distributions for the selected $\tau_h \tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV showing the "no b-tag" (left) and "b-tag" (right) event categories. The points with error bars represent the data. Superimposed are the SM background distributions obtained from the fit. The shaded area is the uncertainty in the background predictions. The MSSM signal prediction is shown in blue for the $m_A = 160$ GeV and $\tan \beta = 8$ in m_h^{mod+} benchmark scenario.

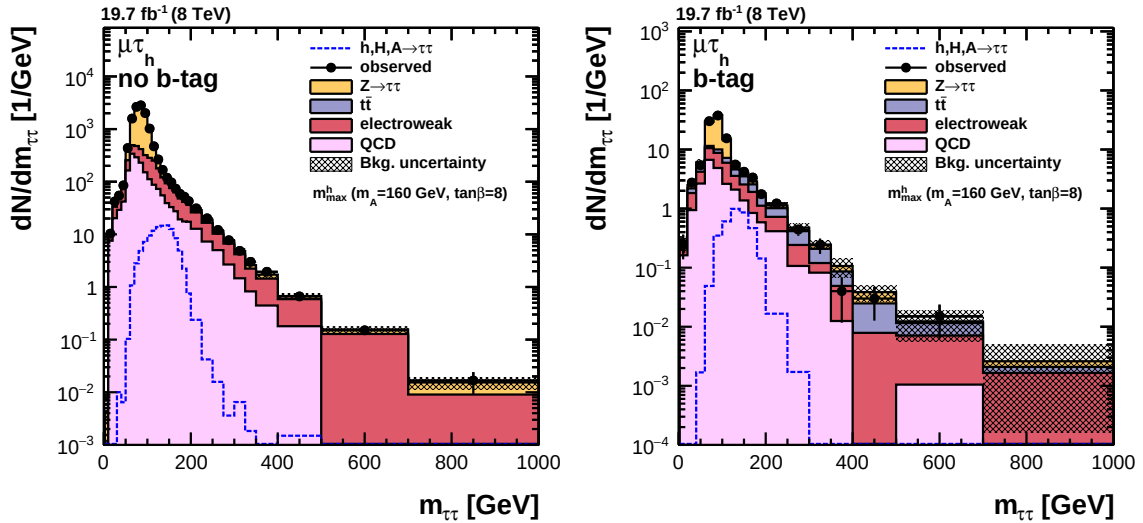


Figure 4-25: The $m_{\mu\tau}$ distributions for the selected $\mu_h \tau_h$ final state candidates in collisions at $\sqrt{s} = 8$ TeV showing the "no b-tag" (left) and "b-tag" (right) event categories. The points with error bars represent the data. Superimposed are the SM background distributions obtained from the fit. The shaded area is the uncertainty in the background predictions. The MSSM signal prediction is shown in blue for the $m_A = 160$ GeV and $\tan \beta = 8$ in m_h^{mod+} benchmark scenario.

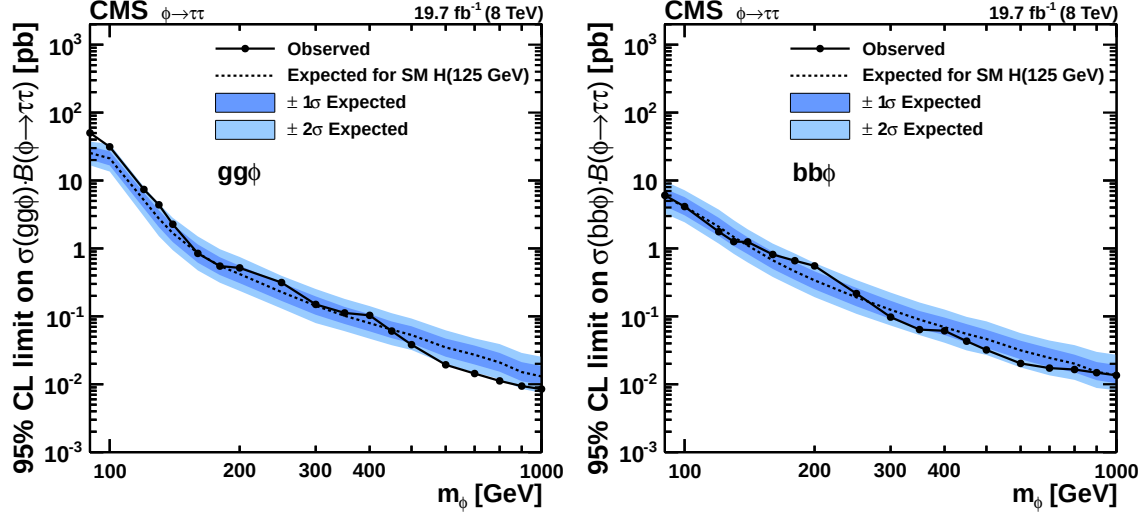


Figure 4-26: The expected and observed 95% CL upper limits on the $\sigma(gg\phi) \times \mathcal{B}(\phi \rightarrow \tau\tau)$ (left) and $\sigma(bb\phi) \times \mathcal{B}(\phi \rightarrow \tau\tau)$ (right) as a function of the ϕ mass hypothesis in collisions at $\sqrt{s} = 8$ TeV. The bands show the expected one (two) standard deviation intervals around the expected limit. The SM Higgs boson, with a mass of 125 GeV, expected contribution is included as a background. [204].

Higgs bosons compared to the SM Higgs boson hypothesis. Exclusion limits are set in the m_A and $\tan\beta$ plane at 95% CL in different MSSM benchmark scenarios. Figure 4-27 shows the expected and observed exclusion 95% CL limits in the m_A - $\tan\beta$ parameter space in the m_h^{max} (left) and m_h^{mod+} (right) benchmark scenarios. The m_h^{max} benchmark scenario was designed to maximize the mass of the light scalar Higgs boson in the MSSM reaching a mass value of 135 GeV. The discovery of the Higgs boson with mass of 125 GeV naturally invites to interpret the new discovered boson as the light CP-even MSSM state. However, this interpretation excludes a large parameter space in the m_A - $\tan\beta$ space as shown by the red lines. Only a small parameter space with $\tan\beta < 10$ for m_A masses larger than 200 GeV is compatible with a $m_h = 125$ GeV hypothesis within 3 GeV uncertainty coming from the theory uncertainties in the calculations. The m_h^{mod+} benchmark scenario shown in Figure 4-27 is obtained by changing the stop mixing parameter from 2 TeV to 1.5 TeV. This opens up a large parameter space in the m_A - $\tan\beta$ plane compatible with the 125 GeV boson discovery. Other interesting benchmark scenarios, not discussed here, are considered in [204].

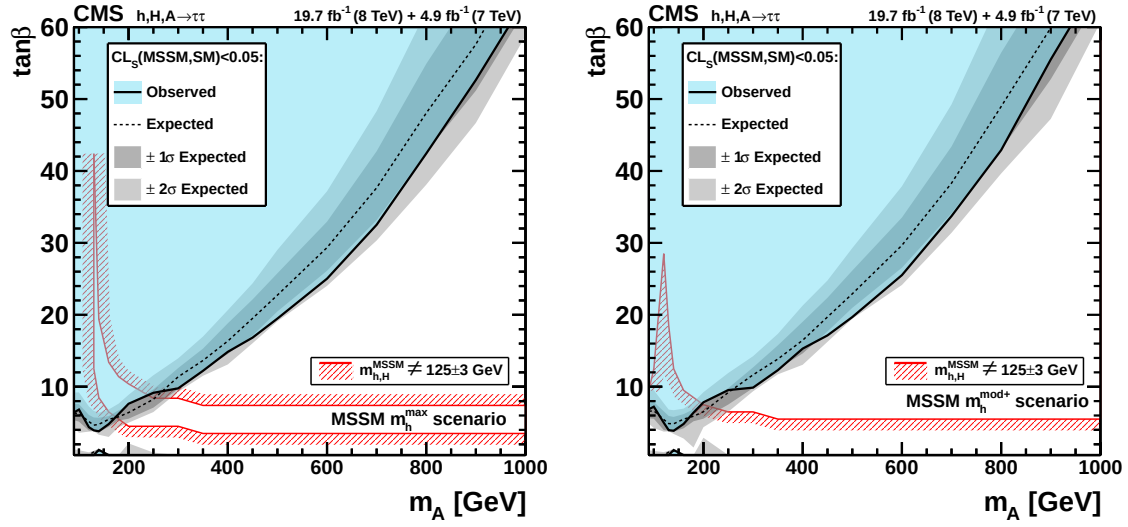


Figure 4-27: The expected and observed exclusion 95% CL limits in the $m_A - \tan \beta$ parameter space in the m_h^{max} (left) and m_h^{mod+} (right) benchmark scenarios. The red lines represent the regions where both neutral scalars, h and H , have a mass not compatible with the discovered 125 GeV boson. [204].

Chapter 5

Higgs Pair Production at the HL-LHC

The discovery of a Higgs boson opens a new era in particle physics, the era of precision Higgs physics studies. The LHC is expected to undergo major updates resulting in a significant increase in the instantaneous luminosity [205]. The injector chains will be upgraded to provide high intensity and low emittance bunches. The quadrupole magnets that focus the beam at the ATLAS and CMS interaction regions will also be upgraded along with additions of crab cavities to improve the bunch overlap at the interaction regions. These upgrades will allow proton-proton collisions with a peak instantaneous luminosity of $2 \times 10^{35} \text{ cm}^2 \text{ s}^{-1}$. This high luminosity operation period is known as the Phase-II or HL-LHC.

A total integrated luminosity of about 3000 fb^{-1} in proton-proton collisions at $\sqrt{s} = 14 \text{ TeV}$ is expected by the end of 2035. This large dataset will allow to make precise measurements of the Higgs couplings and search for its rare SM as well as BSM decays. The discovered boson has so far shown a consistent picture with the SM Higgs boson as discussed in Section 1.1. Figure 5-1 shows the current CMS Higgs coupling measurements (left) and the projected measurements of the couplings using the HL-LHC dataset (right) as a function of the the corresponding boson and fermion masses. A percent level measurement can be performed for the majority of the Higgs couplings. In addition, the Higgs coupling to the second generation fermions will be

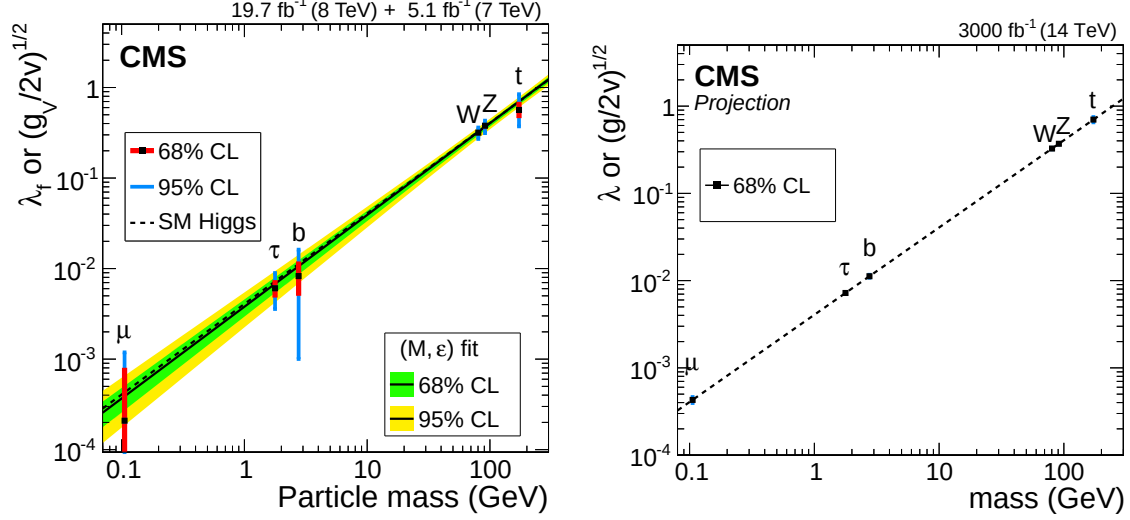


Figure 5-1: The SM Higgs couplings measured at the LHC Run 1 data taking period (left) and the projected measurements to 3000 fb⁻¹ expected luminosity at the HL-LHC (right) as a function of the corresponding boson and fermion masses [206].

accessible via the Higgs boson decays to the muon pair final state.

It is also possible to study the SM Higgs trilinear coupling by considering the Higgs boson pair production as discussed in Section 1.4. This chapter describes the studies of the Higgs boson pair production at the HL-LHC in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states with the upgraded CMS detector [207]. The gluon fusion production cross section for the Higgs boson pair production at a center of mass energy of 14 TeV has been calculated to next-to-next-to-leading-order to be 40.7 fb [89, 90]. Other production modes potentially add another 10% to the total production cross section, but have not been included in this study. Approximately 320 and 9000 signal events are expected to be produced per experiment at the HL-LHC for the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states, respectively.

5.1 CMS Phase-II Detector and Simulation

The increased instantaneous luminosity leads to a significant increase in the number of additional pileup interactions. The HL-LHC is expected to operate with an average of 140 pileup events per bunch crossing. This presents a serious challenge

to the experiments in their ability to deal with this increased level of activity and energy flow, and to preserve the detector performance under this environment. As part of a comprehensive strategy to address these issues, CMS has released a technical proposal for the Phase-II upgrade [206] program. The expected performance of this detector at the HL-LHC is assumed for these studies and is discussed in the following sections. The impact of some of the individual components of the Phase-II upgrade on the results are highlighted where it is appropriate. In addition, the $b\bar{b}\gamma\gamma$ results are also described assuming the detector performance of the so called Phase-I CMS upgrade [208] detector after an assumed integrated luminosity of 1000 fb^{-1} ; configuration hereafter denoted as “Phase-I aged”.

At present, the Phase-II detector simulation includes the upgraded outer tracker, muon systems, and calorimetry. The inner pixel detector upgrade, however, is still not finalized and the simulation contains the Phase-I pixel detector in the barrel and an extended version of the current pixel detector in the forward detector to provide an ability of tracking at higher $|\eta|$ values of up to 4.0. The primary and secondary vertex reconstruction and identification performance will certainly be better than what is assumed in these studies and should be viewed as a conservative estimate.

It is crucial that the Phase-II detector can cope with the challenging environment at the HL-LHC as pileup mitigation, b-tagging, tau reconstruction and identification, photon identification efficiencies, and mass resolutions are fundamental to perform these measurements. Triggers are assumed to be 100% efficient in these studies. The DELPHES fast simulation framework [209] can be used to model the Phase-II detector response. The parameterized response of the Phase-II detector in Delphes is taken from the corresponding GEANT4 based fully simulated samples. The $b\bar{b}\gamma\gamma$ analysis uses the MC generator truth information with smearing functions to model the response of the detector. A combination of the two approaches mentioned above is used for the $b\bar{b}\tau^+\tau^-$ final state.

The signal samples are generated using the MadGraph5_aMC@NLO generator with LO accuracy in QCD, using the results from [210]. PYTHIA 6 is used to model the parton showering and hadronization. The generator is also interfaced with

TAUOLA for the simulation of the tau lepton decays. The pileup events are simulated in the Delphes samples by randomly placing minimum-bias interactions along the beam axis according to the longitudinal spread of the minimum-bias interactions derived from the fully simulated samples.

5.2 $b\bar{b}\gamma\gamma$ Final State

The signal events of interest contain two high transverse momentum p_T photon candidates and two high p_T jets originating from b quarks. The photons are rejected if an electron is reconstructed within a distance ΔR of 0.1 to the photon. A p_T and η dependent efficiency is applied to the photons to model the identification and isolation efficiency. The efficiency is about 80% in the barrel, and about 55% in the endcap. The lower efficiency in the endcap is primarily due to the electron veto requirement. The jets are reconstructed using the anti-kt algorithm with a resolution parameter of 0.5. The processes involving jets faking photons are among the dominant backgrounds. The rate to misidentify photons is about 1×10^{-4} for gluon jets and about 5×10^{-4} for quark jets. The rate to misidentify electrons as photons is taken to be 1% (3%) in the barrel (endcap). Di-photon mass width of 1.2 GeV is achieved with the upgraded detector, for the events where both photons are in the barrel, using sophisticated multivariate techniques to calibrate the photon energy. Jets are tagged as originating from a b quark on the basis of the presence of secondary vertices and large impact parameter tracks, which are exploited for b-tagging in the CSV discriminator as discussed in Section 3.5.3. The chosen working point of the CSV discriminator gives, on average, b-tagging efficiencies of about 75% and 65% in the central and forward regions, respectively; with mistagging rates for light and charm jets of about 1% and 20%, respectively. Di-jet mass resolution of about 20 GeV is achieved with the upgraded detector.

Electrons and muon candidates with $p_T > 10$ GeV are selected for the purpose of vetoing events with signatures consistent with a Higgs boson produced in association with a top and anti top quark pair ($t\bar{t}H$). This process contributes significantly to the

total background after signal event selection requirements. A non-negligible fraction of such background events contain leptons and can be rejected on this basis. Very loose selection requirements with efficiency in the range between 90% and 95% are placed on the electron and muon candidates in order to suppress this background as much as possible.

5.2.1 Signal and Background Estimation

The signal process of interest is the production of two Higgs bosons, one of which decays to a pair of b quarks, and the other decaying to a pair of photons. The main resonant backgrounds are ZH , where a Higgs boson is produced in association with a Z boson which subsequently decays to two b-jets, $t\bar{t}H$, where a Higgs boson is produced in association with a top and anti-top quark pair, and $b\bar{b}H$, where a Higgs boson is produced in association with a b and anti-b quark pair. The non-resonant backgrounds include QCD production of $b\bar{b}\gamma\gamma$, QCD production of $jj\gamma\gamma$ with light jets mistagged as b-jets, QCD production of $b\bar{b}j\gamma$ and $b\bar{b}jj$ with one and two jets misidentified as photons, respectively, and QCD production of four jets with two jets misidentified as photons and two jets miss-tagged as b-jets, dominated by mistagged charm jets. These background processes have cross sections that are several orders of magnitude larger than the resonant backgrounds, but are suppressed by the low rate for mistaged b-jets and misidentified photons. It is computationally impossible to fully simulate these background events due to their large cross sections. Instead, generator particle truth level MC samples are produced and the events are weighted by the corresponding efficiencies and fake rates for selecting the constituent particles. Finally, the SM production of $t\bar{t}(\gamma)$ enters as background for the signal event selection for events where both top quarks decay semi-leptonically to electrons where one (or both) of the electrons are misidenified as photons. A sample of di-electron decays of the $t\bar{t}(\gamma)$ events are weighted by the corresponding electron to photon misidenification rates to estimate the background contribution.

5.2.2 Event Selection

Events containing two photons with p_T greater than 25 GeV and $|\eta| < 2.5$, and two b-tagged jets with p_T greater than 30 GeV and $|\eta| < 2.4$ are selected. While the Phase-II upgrades allow b-jet tagging capabilities up to $|\eta|$ of 3.0, the b-tagged jets with p_T greater than 30 GeV for the signal events are predominantly central and therefore b-tagged jets with $|\eta| < 2.4$ are selected. One of the two photons is required to have $p_T > 40$ GeV. Due to the large amount of background from jets faking photons in the endcap region of the detector the event sample is split into two categories: one with both photons in the barrel and one with at least one photon in the endcap. To suppress $t\bar{t}H$ background events, it is required that there are no electrons or muons passing the veto selection and that the number of jets with $p_T > 30$ GeV and $|\eta| < 2.5$ is less than four.

A number of different additional kinematic requirements were investigated in order to improve the signal to background ratio. It is required that the ΔR between the two photons and the ΔR between the two b-jets are less than 2.0, and that the minimum of the ΔR between photons and b-jets is larger than 1.5. With the above kinematic selection requirements, a signal to background ratio of about 1 : 3 is achieved.

The expected event yields for the signal and resonant background processes, and the non-resonant background processes for various stages of the event selection are shown in Table 5.1. For the event category with both photons in the barrel, the dominant backgrounds are $b\bar{b}\gamma\gamma$, $jj\gamma\gamma$ primarily consisting of mistagged charm jets, and $b\bar{b}j\gamma$ with one fake photon, while for the event category with at least one photon in the endcap the dominant backgrounds are $b\bar{b}j\gamma$ and $b\bar{b}jj$ with one or two fake photons.

5.2.3 Signal Extraction

To extract the signal cross section, the kinematic selection requirements from Section 5.2.2 are applied, and a two dimensional maximum likelihood fit on the di-photon and di-bjet mass distributions is performed. Probability density functions are derived

Process / Selection Stage	$HH \rightarrow bb\gamma\gamma$	$ZH \rightarrow bb\gamma\gamma$	$t\bar{t}H \rightarrow WWbb\gamma\gamma$	bbH
Object Selection & Fit Mass Window	23.8 (6.27)	30.5 (12.0)	184 (47.2)	6.53 (2.61)
Kinematic Selection	13.4 (3.27)	15.1 (4.44)	3.39 (1.04)	2.09 (0.78)
Mass Windows	9.00 (1.91)	3.39 (0.26)	1.57 (0.26)	0.78 (0.26)

Process / Selection Stage	$bb\gamma\gamma$	$jj\gamma\gamma$
Object Selection & Fit Mass Window	2767 (1363)	954 (552)
Kinematic Selection	162 (88.8)	30.2 (19.7)
Mass Windows	10.4 (5.70)	2.1 (1.2)

Process / Selection Stage	$bbj\gamma$	$c\bar{c}j\gamma$	$bbjj$	$c\bar{c}jj$	$t\bar{t}(\gamma)$
Object Selection & Fit Mass Window	1592 (5145)	27.2 (46.3)	279 (1622)	7.8 (44.4)	597 (705)
Kinematic Selection	96.9 (351)	0.7 (3.7)	19.6 (137)	0.2 (2.1)	21.5 (20.3)
Mass Windows	6.3 (17.2)	0.0 (0.2)	1.1 (7.9)	0.02 (0.1)	1.2 (1.2)

Table 5.1: The expected event yields of the signal and background processes for 3000 fb^{-1} of integrated luminosity at various stages of the cut-based selection for the category with both photons in the barrel. The event yields for the category with at least one photon in the endcap are shown inside the brackets. A large fit mass window, 105 GeV to 145 GeV for $M_{\gamma\gamma}$ and 70 GeV to 200 GeV for M_{bb} , is used for the likelihood fit analysis described in Section 5.2.3.

for the di-photon mass, $M_{\gamma\gamma}$, and di-bjet mass, M_{bb} , distributions for the signal, the resonant background, and the non-resonant background by fitting the distributions from the simulated samples to a particular parametrization of the line-shape for $M_{\gamma\gamma}$ and M_{bb} . The distributions of the signal and resonant backgrounds are fitted with a Crystal Ball distribution, while for the non-resonant backgrounds are fitted to a decaying exponential. The jet energy resolution parameter is then appropriately increased to model the degraded jet energy resolution under the HL-LHC pileup conditions,

The correlations between $M_{\gamma\gamma}$ and M_{bb} are assumed to be negligible. Therefore, the two dimensional probability distribution functions are simply the product of the one dimensional probability distribution functions. The expected number of events within the fit mass window is used to normalize the probability distributions functions for the signal, the resonant background, and the non-resonant background.

Toy MC experiments are randomly drawn from the full model and two dimensional fits are performed, where the yields of the signal, the resonant background, and the

non-resonant background are the fit parameters. Figure 5-2 shows the projection of one example toy experiment and the fitted result. The average fit uncertainty of the cross section measurement using the two dimensional fit is about 67%. The expected significance is about 1.6 standard deviations. The statistical uncertainties

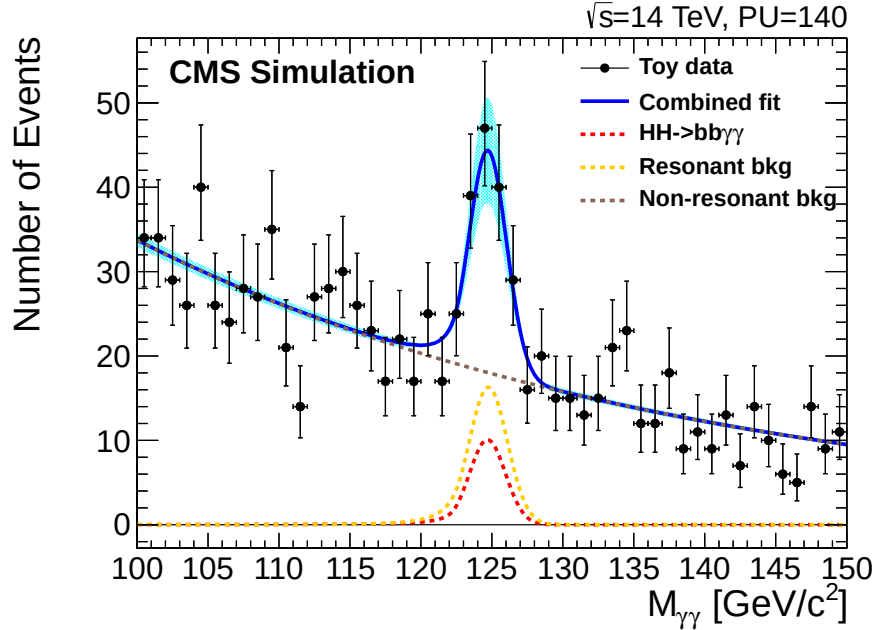


Figure 5-2: Projection of a two dimensional fit on the di-photon mass for one representative toy experiment is shown. The signal, the resonant background, and the non-resonant background components are shown in red, yellow, and gray, respectively.

dominate over the systematic uncertainties with 3000 fb^{-1} of integrated luminosity. The systematic uncertainty in the non-resonant background modeling is evaluated by performing toy MC experiments where the assumed non-resonant background model used is the product of an exponential and a fourth-degree polynomial fitted to the expected non-resonant background distribution, while an exponential function is used to perform the fit. This results in an average bias of about 12%. The theoretical uncertainties in the Higgs boson pair production cross section coming from the missing higher order perturbative corrections, uncertainties in the α_s and the PDFs [88] is about 11%. The systematic uncertainties in the jet and photon energy resolutions are negligible compared to the statistical uncertainty.

5.2.4 Upgrade Scenarios

It is critical to achieve a robust reconstruction of the detector objects at the HL-LHC pileup condition as discussed in Section 5.1. As the measurement is primarily limited by the number of selected signal candidate events, improving the object selection efficiency is very important to improve the results. To explore the effect of the object selection efficiencies and to provide a general goal for the detector upgrade, Figure 5-3 shows the sensitivity as a function of the relative improvement on the photon selection efficiency and the b-tagging efficiency, respectively, over the current performance estimate at the HL-LHC pileup conditions. It is seen that the measurement can be significantly improved with even a modest improvement in the photon candidate selection efficiency or b-tagging efficiency. Finally, the sensitivity of the result as a function of the total integrated luminosity (left) and the relative contribution of the non-resonant background contribution (right) is shown in Figure 5-4.

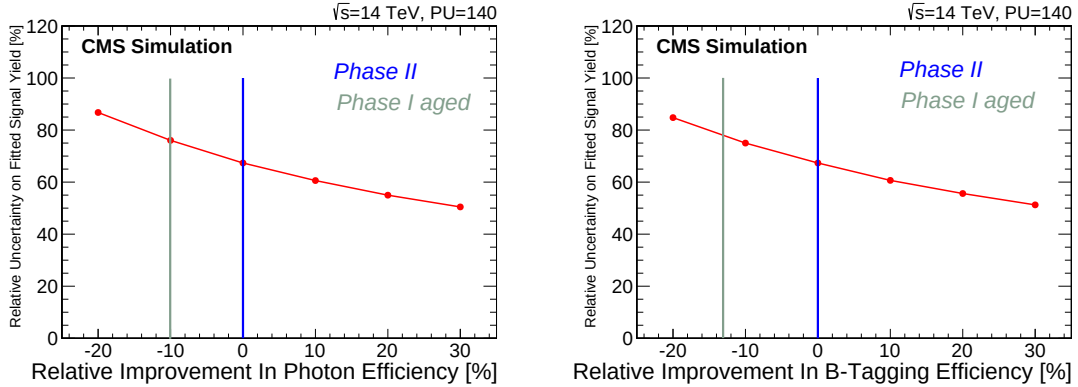


Figure 5-3: The average expected relative uncertainty in the Higgs boson pair production cross section measurement as a function of the relative improvement in the photon (left) and b-tagging (right) selection efficiency with respect to the current performance estimate at the HL-LHC pileup conditions.

5.3 $b\bar{b}\tau^+\tau^-$ Final State

The signal events of interest contain two high p_T taus and two high p_T jets originating from b quarks. Di-tau final states $\tau_\mu\tau_h$ and $\tau_h\tau_h$ are considered. The jets are recon-

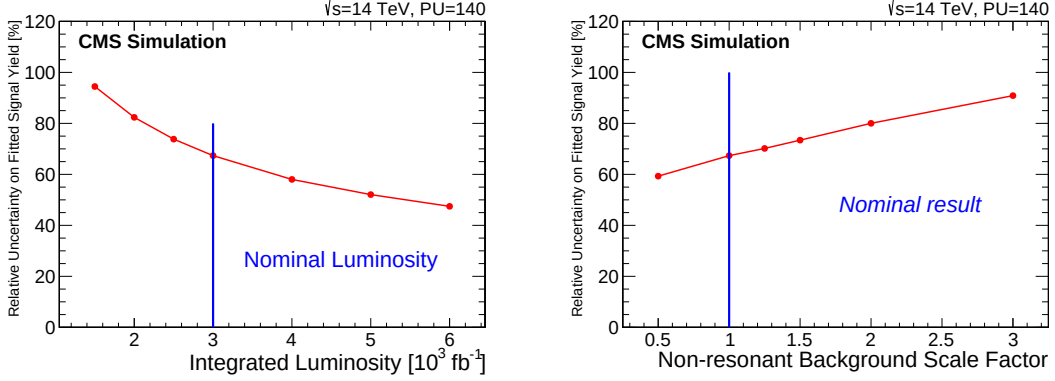


Figure 5-4: The average expected relative uncertainty in the Higgs boson pair production cross section measurement is shown as a function of the integrated luminosity (left) and the relative contribution of the non-resonant background.

structured using the anti-kt algorithm with a resolution parameter of 0.4. A simple jet pileup identification is developed in Delphes using the track related and jet shape variables described in Section 3.5.2. The efficiency of the jet pileup identification is 0.95 with a pileup jet rate of 0.20. Without pileup mitigation the PF $\vec{E}_T^{miss}$ resolution is on average 50 GeV with 140 pileup interactions. With the PUPPI pileup mitigation the $\vec{E}_T^{miss}$ resolution in Delphes is reduced to about 25 GeV. The efficiency of selecting jets originating from b quarks and tau hadronic decays are parameterized in Delphes. To further reduce the background events with light jets mimicking the hadronic tau decays it is required that jets originating from hadronic tau decays contain an isolated track. With the upgraded Phase-II detector and the τ_h selection described here, a selection efficiency of about 55% is possible while keeping the mistag rates to be less than 0.5%. The working point used for the b-tagging has an average efficiency of 0.68 with 0.1 and 0.01 mistag rates from the c-quarks and light quarks, respectively. The muon efficiencies and resolutions are parameterized in Delphes and efficiencies of about 95% are assumed.

5.3.1 Event Selection and Background Estimation

Events are selected containing two b-tagged jets with $p_T > 30$ GeV and $|\eta| < 2.4$, and two τ_h candidates with $p_T > 60$ GeV, or $p_T > 90$ GeV for the leading τ_h candidate

and $p_T > 45$ GeV for sub-leading τ_h candidate, and $|\eta| < 2.1$ for the $\tau_h\tau_h$ di-tau final state, $p_T > 30$ GeV and $|\eta| < 2.1$ for the τ_h and $p_T > 30$ GeV and $|\eta| < 2.5$ for the τ_μ in $\tau_\mu\tau_h$ di-tau final states.

The background samples are simulated using the techniques that were developed for the Snowmass 2013 Energy Frontier for the future hadron colliders [211]. The existing generated samples were reconstructed using Delphes. A similar approach to the $b\bar{b}\gamma\gamma$ analysis is adopted by producing a generator particle level $t\bar{t}$ sample and weighting the events by their corresponding efficiencies for selecting the constituent particles. The resolution effects of the detector are also taken into account. The main background is $t\bar{t}$ production with fully leptonic decays. Another source of large background is the Drell-Yan production of a Z boson decaying into a pair of tau leptons produced in association with jets, where the light jets are mistagged as b-jets. The important single Higgs boson backgrounds are the ZH and $t\bar{t}H$ processes. The remaining backgrounds considered are the single top and $t\bar{t}$ produced in association with a vector boson, and di-boson processes. The QCD multi-jet background is negligible in the signal region as verified by studying the LHC data available at $\sqrt{s} = 8$ TeV.

5.3.2 Signal Extraction

Selections are applied on the di-tau mass, $m_{\tau^+\tau^-}$, and the di-b-jet mass, m_{bb} , distributions to identify the Higgs boson decays to tau and b pairs, respectively. The requirement for the m_{bb} is $90 \text{ GeV} < m_{bb} < 130 \text{ GeV}$, and $110 \text{ GeV} < m_{\tau^+\tau^-} < 140 \text{ GeV}$ for the $m_{\tau^+\tau^-}$. The event selection is summarized in Table 5.2

Event selection
≥ 2 b-tagged jets with $p_T > 30$ GeV, $ \eta < 2.4$
$\tau_h\tau_h$ final state
≥ 2 isolated τ_h -s with $p_T > 60$ GeV or $p_T > 90/45$ GeV, $ \eta < 2.1$
$\tau_\mu\tau_h$ final state
An isolated τ_h with $p_T > 30$ GeV, $ \eta < 2.1$ and an isolated τ_μ with $p_T > 30$ GeV, $ \eta < 2.5$
$90 \text{ GeV} < m_{bb} < 130 \text{ GeV}$ and $110 \text{ GeV} < m_{\tau^+\tau^-} < 140 \text{ GeV}$

Table 5.2: Event selection summary for the $b\bar{b}\tau^+\tau^-$ final state.

A kinematic bounding variable, m_{T2} , is introduced to further discriminate the dominant $t\bar{t}$ background from the Higgs boson pair signal [212]. By construction, m_{T2} is bounded above by the top quark mass for $t\bar{t}$ background events while it is unbounded for di-Higgs boson signal events. For the $\tau_\mu\tau_h$ final states a boosted decision tree (BDT) discriminant was trained to further exploit the boosted kinematics of the Higgs boson pair production. The input variables are the masses, transverse momenta, and ΔR distances of the di-tau, di-b-jet, and di-Higgs systems. The m_{T2} variable is also included in the training.

Figure 5-5 shows the predicted distributions of the m_{T2} variable (left) for the $\tau_h\tau_h$ final state and the BDT discriminant variable (right) for the $\tau_h\tau_\mu$ final state after the mass window requirements. Both variables provide good discrimination between the signal and background. As expected the $t\bar{t}$ background is bounded above by the top quark mass taking into account the detector resolution effects. Table 5.3 and Table 5.4 show the expected event yields with 3000fb^{-1} integrated luminosity at various stages of the event selection for the $\tau_h\tau_h$, and $\tau_\mu\tau_h$ final states, respectively.

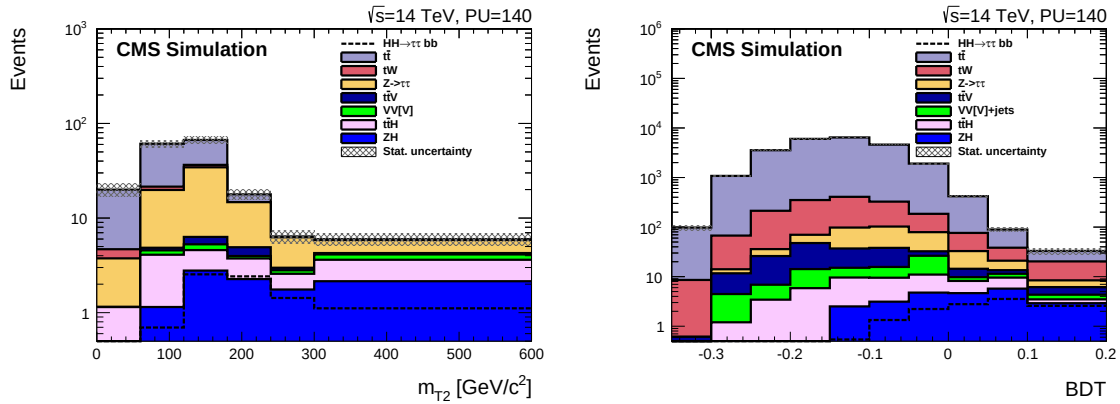


Figure 5-5: m_{T2} (left) and BDT score (right) distributions in the $\tau_h\tau_h$ and $\tau_\mu\tau_h$ final states, respectively. The yields are the expected SM contributions.

The expected significance for the Higgs boson pair production is 0.5 and 0.7 standard deviations for the $\tau_\mu\tau_h$ and $\tau_h\tau_h$ di-tau final states, respectively. The combined expected significance is 0.9 standard deviations. The resulting expected uncertainty in the cross section measurement is approximately 105%. Theoretical uncertainties

Selection	HH	ZH	$t\bar{t}H$	$Z \rightarrow \tau^+\tau^-$
Baseline selection	23.6 ± 0.5	104.7 ± 3.5	204.6 ± 5.8	479.3 ± 7.7
Mass windows	8.3 ± 0.3	10.1 ± 1.0	9.8 ± 1.3	60.3 ± 3.3
Signal	4.9 ± 0.2	6.2 ± 0.8	3.8 ± 0.8	14.7 ± 1.6

Selection	$t\bar{t}$	tW	$t\bar{t}V$	$VV(V)$
Baseline selection	7662 ± 69	734.4 ± 19.4	189.4 ± 10.0	128.9 ± 16.7
Mass windows	88.4 ± 7.5	4.8 ± 1.6	2.7 ± 0.9	2.1 ± 0.7
Signal	3.2 ± 1.4	0.1 ± 0.1	1.3 ± 0.7	1.0 ± 0.5

Table 5.3: The expected signal yields at 3000 fb^{-1} of integrated luminosity are shown at various stages of the selection in the $\tau_h\tau_h$ channel. A loose mass window cut is applied on the $t\bar{t}$ sample at the generation level. For the signal selection stage the m_{T2} is required to be greater than 180 GeV. The full m_{T2} distribution is used for the signal extraction.

Selection	HH	ZH	$t\bar{t}H$	$Z \rightarrow \tau^+\tau^-$
Baseline selection	39.2 ± 0.6	213.7 ± 4.7	1175.8 ± 12.9	3711.7 ± 34.1
Mass window	13.1 ± 0.4	24.4 ± 1.5	37.7 ± 2.3	234.5 ± 8.6
Signal	6.1 ± 0.3	8.6 ± 0.9	4.5 ± 0.8	9.7 ± 1.7

Selection	$t\bar{t}$	tW	$t\bar{t}V$	$VV(V)$
Baseline selection	$(3.84 \pm 0.00) \times 10^5$	$(3.72 \pm 0.00) \times 10^4$	4154 ± 39	1418 ± 90
Mass window	$(2.3 \pm 0.0) \times 10^4$	1232 ± 33	119.4 ± 7.4	49.6 ± 2.3
Signal	63.5 ± 7.3	29.2 ± 4.8	3.9 ± 1.3	2.7 ± 0.7

Table 5.4: The expected signal yields at 3000 fb^{-1} of integrated luminosity are shown at various stages of the selection in the $\tau_\mu\tau_h$ channel. A loose mass window cut is applied on the $t\bar{t}$ sample at the generation level. For the signal selection stage we require the BDT variable to be greater than 0.05. The full BDT distribution is used for the signal extraction.

in the Higgs boson production are included in this result. Renormalization and factorization scale uncertainties in the Higgs boson pair-production signal are 20% for NNLO calculation. The PDF uncertainty is 9%. The systematic uncertainty in the luminosity is taken to be 2.6%. Energy scale uncertainties in jets, tau leptons, and missing energy are also included. A scale uncertainty of 2% is assumed which is comparable to the corresponding uncertainty with the current CMS detector performance. The effect of the jet energy scale uncertainty in the result is about 5%.

5.3.3 Trigger Performance

The performance of the trigger system is crucial to achieve the result described above, in particular the capability to trigger on charged particles at L1 trigger. For the $\tau_h\tau_h$ final state, the di-tau trigger has an offline threshold of 56 GeV on both tau legs, and the single tau trigger threshold is 88 GeV for the L1 trigger of the Phase-II upgraded detector [206]. These thresholds are significantly higher without the inclusion of tracks in the L1 trigger (track trigger), 95 GeV on both tau legs for the di-tau trigger and 138 GeV for the single tau trigger. Considering these less performant thresholds, the signal and background yields are reduced by about a factor of two. For the $\tau_\mu\tau_h$ final state the situation is similar. The single-muon trigger threshold is 18 GeV with the track trigger and 50 GeV without the track trigger. The thresholds for the muon-tau trigger legs are significantly higher as well. Again, the signal and background yields are reduced by a factor of two by requiring 50 GeV cut on the p_T of the muon and τ_h . Thus, in both final states the effect of the trigger performance on the sensitivity of this analysis is significant. The overall sensitivity is reduced by 40%, the equivalent of using only half of 3000 fb⁻¹.

5.4 Results and Summary

A combination of the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ results is performed by using a simultaneous fit to the generated pseudo-data. The expected uncertainty in the signal yield is approximately 54%. The combined expected significance is 1.9 standard deviations. The studies are performed assuming the operational conditions of the HL-LHC, with an integrated luminosity of 3000 fb⁻¹, and the upgraded CMS detector. The benefits of the CMS Phase-II upgrades to meet the challenges presented by the high luminosity environment are emphasized. Further improvements of the sensitivity are possible by using more sophisticated reconstruction and analysis techniques. Additional Higgs boson pair production boson production and decay modes remain unexplored. Among these the bbbb final state promises the largest potential for improvement.

Chapter 6

Conclusions and Outlook

Measurements of total inclusive and fiducial W and Z boson production cross sections at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV center-of-mass energies are described. Muon and electron final states are considered in a data sample corresponding to an integrated luminosity of 18.2 pb^{-1} at 8 TeV and 43 pb^{-1} at 13 TeV. A dilepton mass in the range of 60 to 120 GeV is required for the Z boson results. The measured total inclusive cross sections times branching fractions agree with next-to-next-to-leading-order QCD cross section calculations. Ratios of cross sections with a precision of 2% are also reported. Indirect determination of the total W boson width and $\mathcal{B}(W \rightarrow \ell\nu)$ is performed.

A search for a Standard Model Higgs boson decaying to a pair of tau leptons produced in proton-proton collisions at the Large Hadron Collider at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV center-of-mass energies is described. Final states with at least one hadronic tau are described with a data sample collected with the CMS detector corresponding to an integrated luminosity of 19.7 fb^{-1} at 8 TeV and 4.9 fb^{-1} at 7 TeV. A statistically significant excess of events with respect to the background prediction is observed corresponding to 3.1 standard deviations for a Higgs boson mass hypothesis of 125 GeV. This result establishes evidence of the 125 GeV Higgs boson decay to a pair of tau leptons.

Additional searches for neutral resonances decaying to a pair of tau leptons in gluon-fusion and b-quark associated production modes are performed. No significant

excess of events is observed and exclusion limits on the production cross section times branching ratios are given for neutral resonances with mass hypotheses ranging from 90 GeV to 1 TeV. The results are also interpreted in the context of neutral Higgs boson production in the minimal supersymmetric extension of the Standard Model.

Studies of the Standard Model Higgs boson pair production at the High-Luminosity LHC with an expected data sample corresponding to an integrated luminosity of 3000 fb^{-1} are described. Higgs boson decays resulting in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states are considered. These are the first detailed studies of the Higgs boson pair production assuming the expected performance of the upgraded CMS detector at the High-Luminosity LHC. The expected significance for the Standard Model Higgs boson pair production signal is 1.9 standard deviations corresponding to an expected uncertainty of 54% in the signal yield.

The discovery of the new boson with a SM-like Higgs boson properties opens a new era towards our understanding of the fundamental interactions. The LHC will continue to explore the nature of the electroweak symmetry breaking in the coming years. Performing precise measurements of the observed SM-like Higgs boson is one of the main goals of the HL-LHC. Deviations from the SM predictions will provide hints on the BSM physics. Indeed, the SM theory of elementary particles has so far been remarkably successful in describing the present experimental observations. There are number of existing BSM theories, introduced to explain the limitations of the SM, patiently waiting for an opportunity to step forward. But perhaps, non of the existing BSM theories provides the correct fundamental equations describing nature. It is feasible that we will discover something unexpected that will guide us toward the ultimate theory of nature.

Who ordered that?

I. I. Rabi

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