

Search for the Higgs Boson in its Decay into Tau Leptons at CMS

by

Matthew Hans Chan

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

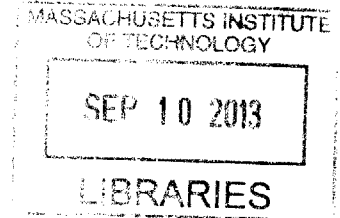
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Abstract

A search for the Standard Model Higgs boson in the $H \rightarrow \tau\tau$ channel is presented. The search is performed on proton collision data collected by the Compact Muon Solenoid at the Large Hadron Collider. The data corresponds to 4.9 fb^{-1} of proton collisions at $\sqrt{s} = 7\text{ TeV}$ and 19.5 fb^{-1} at $\sqrt{s} = 8\text{ TeV}$. The search is based on di-tau events in which one tau decays into an electron or muon, and the other tau decays into hadrons. The search focuses on Higgs masses between 110 GeV and 145 GeV . The analysis reveals no statistically significant excess in the data over the Standard Model backgrounds. Upper limits on the Higgs production cross section at the 95% confidence level are established. The observed limit is statistically consistent with the expected limit in the background-only hypothesis but does not exclude any Higgs mass.

Thesis Supervisor: Prof. Steven C. Nahn
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Chapter 1

Introduction

The Standard Model of particle physics is a theory of the elementary particles of matter and the forces between them. The Standard Model (SM) is a quantum field theory obeying both the principles of quantum mechanics and the special theory of relativity. Particles are treated as observable excitations of underlying quantum fields. Hence, the existence of a quantum field implies a corresponding particle that can be created and observed in an experiment. The SM describes the electromagnetic force, the strong nuclear force, and the weak nuclear force. The SM has been well verified by experiment. The most recent particle of the SM to be experimentally supported is the Higgs boson, which enables the particles of the SM to have mass.

The concept of the Higgs boson arises from electroweak theory. The electroweak theory was postulated in 1967 [1,2] and predicts the existence of the W and Z vector bosons, as well as the scalar Higgs field which confers mass to the weak vector bosons in a gauge invariant way. In the decades following the proposal of electroweak theory, both the W and Z bosons were observed experimentally [3,4]. However, the Higgs boson eluded detection for several more decades. During that time, it was considered to be the last remaining piece of the SM to be experimentally verified. The Higgs boson was finally observed in 2012 at the Large Hadron Collider (LHC) by the Compact Muon Solenoid (CMS) [5] and A Toroidal LHC Apparatus (ATLAS) [6].

This thesis describes a search for the Higgs boson through its decay into taus, using data collected by the CMS detector. The theoretical motivations for the Higgs

boson are given in this chapter. Chapter 2 describes the Large Hadron Collider and the CMS detector. Chapter 3 describes how proton collision events are reconstructed from the raw detector data collected by CMS. Chapter 4 defines which events are selected as $H \rightarrow \tau\tau$ candidates. Chapters 5 and 6 explain the measurement of selection efficiencies and the modeling of signal and background processes. Chapter 7 describes the statistical analysis of the observed data and its results. Finally, Chapter 8 provides concluding remarks about the search for the Higgs boson.

1.1 The Standard Model

The Standard Model of particle physics is a theory that describes the fundamental constituents of matter and their interactions. All elementary particles of matter are spin 1/2 fermions, comprising two groups:

- *Leptons*, consisting of the electron (e), muon (μ), tau (τ), and their corresponding neutrinos ν_e , ν_μ , and ν_τ .
- *Quarks*, consisting of the up quark (u), down quark (d), charm quark (c), strange quark (s), top quark (t), and bottom quark (b).

In the SM, interactions between particles of matter are mediated by spin 1 bosons. The SM describes three of the four fundamental forces: 1) the electromagnetic force, mediated by the photon, 2) the strong nuclear force, mediated by the gluon, and 3) the weak nuclear force, mediated by the $W^\pm$ and Z bosons. The SM does not include the gravitational force, which is much weaker than the other three forces.

The dynamics of the Standard Model are dictated by the SM Lagrangian, $\mathcal{L}_{\text{SM}}$. The SM Lagrangian defines the quantum fields which underlie the particles of the SM and the interactions between these fields. A hypothetical Lagrangian is constructed by starting with the free Lagrangian of the fermionic fields and making it symmetric under a proposed set of gauge transformations. The procedure of imposing local gauge symmetry on the Lagrangian involves introducing gauge fields that couple with the fermionic fields in such a way as to preserve the Lagrangian under the chosen set of

gauge transformations. This can be done by replacing all partial derivatives in the Lagrangian with the *covariant derivative*,

$$\partial_\mu \rightarrow \mathcal{D}_\mu \equiv \partial_\mu + igT_i G_\mu^i \quad (1.1)$$

where T_i are the generators of the gauge transformation, G_μ^i are the gauge fields, and g is the coupling constant between the fermions and the gauge field. The SM Lagrangian is based on the symmetry group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ [7], where $SU(3)_c$ corresponds to the color symmetry of the strong force, $SU(2)_L$ is the symmetry of weak isospin (“L” refers to the left-handed chiral states coupled by weak isospin), and $U(1)_Y$ is the symmetry of weak hypercharge. The relationship between the strong force and $SU(3)_c$ symmetry is explained elsewhere [8]. The origin of the Higgs field begins with the electroweak theory of the SM.

1.1.1 Electroweak Theory

The electromagnetic and weak forces are combined in the Glashow-Weinberg-Salam (GWS) theory of electroweak unification [1,9]. Electroweak interactions are based on the symmetry group $SU(2)_L \otimes U(1)_Y$. The $SU(2)_L$ transformations operate only on left-handed weak isospin doublets while $U(1)_Y$ transformations operate on both left and right-handed components. The leptons can be arranged into three left-handed weak isospin doublets,

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L, \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L, \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L, \quad (1.2)$$

and three right-handed singlets,

$$e_R, \mu_R, \tau_R. \quad (1.3)$$

Neutrinos are considered massless in the SM and therefore do not have right-handed components.

The quarks can be structured in a similar manner, forming three left-handed

doublets,

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L, \quad (1.4)$$

and six right-handed singlets,

$$u_R, d'_R, c_R, s'_R, t_R, b'_R. \quad (1.5)$$

The prime notation signifies the weak eigenstates of the quarks, defined as

$$d'_i = \sum_{j=1}^N U_{ij} d_j \quad (1.6)$$

where U_{ij} is the Cabibbo-Kobayashi-Maskawa matrix [10].

For a left-handed doublet χ_L and right-handed singlet ψ_R , the $SU(2)_L \otimes U(1)_Y$ transformations are

$$\chi_L \rightarrow e^{i\boldsymbol{\alpha}(x) \cdot \boldsymbol{\tau} + i\beta(x)Y} \chi_L, \quad (1.7)$$

$$\psi_R \rightarrow e^{i\beta(x)Y} \psi_R, \quad (1.8)$$

where $\boldsymbol{\alpha}(x)$ and $\beta(x)$ parameterize the transformation, the components of $\boldsymbol{\tau}$ are the Pauli matrices (the generators of $SU(2)_L$), and Y is the hypercharge operator (the generator of $U(1)_Y$).

The electroweak Lagrangian is obtained by requiring local $SU(2)_L \otimes U(1)_Y$ gauge invariance. To accomplish this, it necessary to introduce the weak isospin gauge fields $\mathbf{W}_\mu = (W_\mu^1, W_\mu^2, W_\mu^3)$ and the weak hypercharge gauge field B_μ . The infinitesimal transformations of these gauge fields are

$$\mathbf{W}_\mu \rightarrow \mathbf{W}_\mu - \frac{1}{g} \partial_\mu \boldsymbol{\alpha}(x) - \boldsymbol{\alpha}(x) \times \mathbf{W}_\mu, \quad (1.9)$$

$$B_\mu \rightarrow B_\mu + \frac{1}{g'} \partial_\mu \beta(x), \quad (1.10)$$

where g and g' are the electroweak coupling constants to $\mathbf{W}_\mu$ and B_μ , respectively.

The covariant derivative for the left-handed doublets is

$$\partial_\mu \rightarrow \mathcal{D} \equiv \partial_\mu + i\frac{g}{2}\boldsymbol{\tau} \cdot \mathbf{W}_\mu + i\frac{g'}{2}YB_\mu. \quad (1.11)$$

The covariant derivative for the right-handed singlets is

$$\partial_\mu \rightarrow \mathcal{D} \equiv \partial_\mu + i\frac{g'}{2}YB_\mu. \quad (1.12)$$

The electroweak Lagrangian, formulated to be invariant under $SU(2)_L \otimes U(1)_Y$ transformations, is

$$\begin{aligned} \mathcal{L}_{\text{ewk}} = & \sum_{\chi_L} \bar{\chi}_L \gamma^\mu \left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau} \cdot \mathbf{W}_\mu - \frac{g'}{2}YB_\mu \right) \chi_L \\ & + \sum_{\psi_R} \bar{\psi}_R \gamma^\mu \left(i\partial_\mu - \frac{g'}{2}YB_\mu \right) \psi_R \\ & - \frac{1}{4} \mathbf{W}_{\mu\nu} \cdot \mathbf{W}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}, \end{aligned} \quad (1.13)$$

where γ^μ are the Dirac matrices. The first two lines of Eq. 1.13 define the interaction of the fermions with the gauge fields. The third line contains the kinetic terms of the gauge fields, with the tensors $\mathbf{W}_{\mu\nu}$ and $B_{\mu\nu}$ defined as

$$\mathbf{W}_{\mu\nu} = \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu - g \mathbf{W}_\mu \times \mathbf{W}_\nu \quad (1.14)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu. \quad (1.15)$$

The Lagrangian $\mathcal{L}_{\text{ewk}}$ dictates the dynamics of the fermions and the gauge bosons within electroweak theory. However, the fermions and gauge bosons are all massless. Any boson mass terms of the form $-\frac{1}{2}M_B^2 B_\mu B^\mu$ or $-\frac{1}{2}(M_W \cdot \mathbf{W})^2$ (where M_W is a diagonal mass matrix) would violate the $SU(2)_L \otimes U(1)_Y$ gauge symmetry of the Lagrangian. Fermion mass terms are also excluded by $SU(2)_L$ symmetry. A fermion mass term takes the form

$$-m\bar{\psi}\psi = -m(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R). \quad (1.16)$$

Since ψ_L belongs to a weak isospin doublet while ψ_R is a singlet, the fermion mass term is not invariant under $SU(2)_L$ transformations and therefore cannot be included in $\mathcal{L}_{\text{ewk}}$. The absence of mass terms in the Lagrangian may seem to contradict the experimental observation of massive fermions and bosons. However, this dilemma is solved by the Higgs mechanism, which “generates” mass in a gauge invariant manner.

1.1.2 The Higgs Mechanism

The Higgs mechanism [11–13] confers mass to particles without violating local gauge symmetry. It involves introducing “Higgs” fields which have a non-zero vacuum expectation value and reformulating the Lagrangian in terms of fields that have been shifted to a minimum of the Higgs potential. The end result is that the interaction of fermions and bosons with the Higgs fields leads to mass terms for those particles. In the context of electroweak symmetry breaking, the Higgs fields form a weak isospin doublet with weak hypercharge $Y = 1$,

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad (1.17)$$

where ϕ^+ and ϕ^0 are complex scalar fields. As a weak isospin doublet, ϕ transforms as

$$\phi \rightarrow e^{i\alpha(x)\cdot\boldsymbol{\tau}/2+i\beta(x)}\phi. \quad (1.18)$$

The Higgs field ϕ is added to the electroweak Lagrangian as

$$\mathcal{L}_H = \left| \left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau} \cdot \mathbf{W}_\mu - \frac{g'}{2}YB_\mu \right) \phi \right|^2 - V(\phi), \quad (1.19)$$

where $V(\phi)$ is the Higgs potential,

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2, \quad (1.20)$$

with parameters $\mu^2 < 0$ and $\lambda > 0$. Due to the sign of μ^2 , $\phi = 0$ does not correspond to the ground state of ϕ , i.e. ϕ has a non-zero vacuum expectation value. The minima of $V(\phi)$ occur where

$$\phi^\dagger \phi = -\frac{\mu^2}{2\lambda}. \quad (1.21)$$

In order to perform perturbative calculations, ϕ must be expanded about one of these minima of $V(\phi)$. The $SU(2)_L \otimes U(1)_Y$ symmetry ensures that any choice of minimum is equally valid and leads to the same physical result. A convenient choice is

$$\langle \phi \rangle_0 = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad (1.22)$$

$$v^2 \equiv -\frac{\mu^2}{\lambda}. \quad (1.23)$$

The next step is to recast ϕ in terms of fields which have zero vacuum expectation value, so that they are suitable for perturbative calculations:

$$\phi(x) = \begin{pmatrix} \xi(x) \\ v + \eta(x) \end{pmatrix}. \quad (1.24)$$

If Eq. 1.24 were inserted into Eq. 1.19, massless Goldstone boson would appear in the Lagrangian [14]. Since these Goldstone bosons are non-physical, one further step must be taken to eliminate them. Rather than use Eq. 1.24, a more sophisticated formulation of ϕ is employed:

$$\phi(x) = e^{i\boldsymbol{\tau} \cdot \boldsymbol{\theta}(x)/v} \begin{pmatrix} 0 \\ \frac{v+h(x)}{\sqrt{2}} \end{pmatrix} \quad (1.25)$$

$$\approx \sqrt{\frac{1}{2}} \begin{pmatrix} \theta_2(x) + i\theta_1(x) \\ v + h(x) - i\theta_3(x) \end{pmatrix}, \quad (1.26)$$

where $\boldsymbol{\theta}(x)$ and $h(x)$ are real fields. The second equation, Eq. 1.26, merely demonstrates that in the perturbative limit, Eq. 1.25 contains all the necessary degrees of freedom to express a doublet of complex scalar fields, that is, Eq. 1.25 is as general as

Eq. 1.24. Because of the $SU(2)_L \otimes U(1)_Y$ local gauge symmetry of the Lagrangian, the factor $e^{i\boldsymbol{\tau} \cdot \boldsymbol{\theta}(x)/v}$ can be eliminated from Eq. 1.25 by an appropriate local gauge transformation, leading to

$$\phi(x) = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \quad (1.27)$$

In other words, local gauge symmetry allows $\xi(x)$ to be eliminated (or more accurately, $\xi(x)$ is merged with $\eta(x)$ to make $h(x)$). This is the final form of ϕ which will be inserted into the electroweak Lagrangian to generate the masses of the $W^\pm$ and Z bosons.

W and Z Boson Masses

The boson masses are obtained by substituting Eq. 1.27 into Eq. 1.19. Ignoring terms involving $h(x)$, the interaction between ϕ and the gauge bosons becomes

$$\begin{aligned} \left| \left(-i\frac{g}{2}\boldsymbol{\tau} \cdot \mathbf{W}_\mu - i\frac{g'}{2}B_\mu \right) \phi \right|^2 &= \frac{1}{8}v^2g^2 \left[(W_\mu^1)^2 + (W_\mu^2)^2 \right] \\ &\quad + \frac{1}{8}v^2 (g'B_\mu - gW_\mu^3) (g'B^\mu - gW^{3\mu}) \\ &= \left(\frac{vg}{2} \right)^2 W_\mu^+ W^{-\mu} + \frac{1}{2} \left(\frac{v}{2} \right)^2 (gW_\mu^3 - g'B_\mu)^2, \end{aligned} \quad (1.28)$$

where $W_\mu^\pm$ is defined as

$$W_\mu^\pm = \sqrt{\frac{1}{2}} (W_\mu^1 \mp iW_\mu^2). \quad (1.29)$$

The mass of the W boson is given by the square root of the coefficient of $W_\mu^+ W^{-\mu}$ in Eq. 1.28,

$$M_W = \frac{vg}{2}. \quad (1.30)$$

The mass of the Z boson is less apparent because the Z boson is a linear combination of W_μ^3 and B ,

$$Z_\mu = \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}}. \quad (1.31)$$

By comparing Z_μ defined in Eq. 1.31 to the term $\frac{1}{2} \left(\frac{v}{2}\right)^2 (gW_\mu^3 - g'B_\mu)^2$ from Eq. 1.28, the Z boson mass is seen to be

$$M_Z = \frac{v}{2} \sqrt{g^2 + g'^2}. \quad (1.32)$$

The expression orthogonal to Eq. 1.31 corresponds to the photon field,

$$A_\mu = \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2 + g'^2}}. \quad (1.33)$$

There is no mass term for A_μ so the photon is massless, as expected.

The Higgs mass can be extracted from the Higgs potential, Eq. 1.20, and is given by

$$m_h^2 = 2v^2\lambda. \quad (1.34)$$

Since λ is unknown, the Higgs mass is not predicted by the SM and must be measured experimentally.

Fermion Masses

In the SM, the same Higgs doublet ϕ responsible for the W and Z boson masses also confers mass to the fermions. This is achieved by adding to the Lagrangian a Yukawa coupling to the Higgs for each fermion:

$$\mathcal{L}_f = -\frac{m\sqrt{2}}{v} (\overline{\chi}_L \phi \psi_R + \overline{\psi}_R \phi \chi_L). \quad (1.35)$$

Substituting ϕ from Eq. 1.27 into Eq. 1.35 yields

$$\mathcal{L}_f = -m(\overline{\psi}_L \psi_R + \overline{\psi}_R \psi_L) - \frac{m}{v} (\overline{\psi}_L \psi_R + \overline{\psi}_R \psi_L) h \quad (1.36)$$

$$= -m\overline{\psi}\psi - \frac{m}{v} \overline{\psi}\psi h. \quad (1.37)$$

This Lagrangian now contains a mass term for the fermion, $-m\overline{\psi}\psi$, as well as a coupling between the fermion and the Higgs field, $-\frac{m}{v}\overline{\psi}\psi h$. The coupling between

the Higgs boson and a fermion is proportional to the fermion’s mass, meaning the heavier fermions (such as the tau and the b quark) couple more strongly to the Higgs than the lighter fermions.

1.2 Higgs Production at the LHC

The Large Hadron Collider (Section 2.1) collides protons at the TeV energy scale. In a high-energy proton collision, particles are produced by the interaction between the quarks and gluons which make up the colliding protons. The dominant production mode of the Higgs boson in a proton collision is *gluon fusion*, where two gluons interact via a fermion loop to produce a Higgs boson (Figure 1-1a). The largest contribution to the fermion loop comes from the top quark, which is the heaviest fermion. The Higgs boson can also be produced by the interaction of two vector bosons (Figure 1-1b) in a process called *vector boson fusion* (VBF). Although the cross section for VBF is an order of magnitude smaller than for gluon fusion, a Higgs boson produced in the VBF process is accompanied by two jets in the forward/backward regions of the detector; these two jets, in addition to the Higgs boson decay products themselves, help identify the Higgs event. Two other Higgs production channels are “Higgs-strahlung”, where the Higgs is emitted from a vector boson (Figure 1-1c), and associated production with $t\bar{t}$ (Figure 1-1d). These two production channels have much smaller cross sections than the gluon fusion and vector boson fusion channels and play a smaller role in Higgs searches. The cross sections for the aforementioned Higgs production processes are shown in Figure 1-2 for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV proton collisions, as functions of the Higgs mass.

After a Higgs boson is produced in a proton collision, it immediately decays according to its couplings to other particles. Figure 1-3 shows the branching ratios of prominent Higgs decay channels. Since the Higgs does not couple to massless particles like the photon or gluon, the $H \rightarrow \gamma\gamma$, $H \rightarrow gg$, and $H \rightarrow Z\gamma$ channels proceed through fermion or massive boson loops. Of particular interest is the decay of the Higgs boson into a pair of taus, which has the second largest branching ratio among

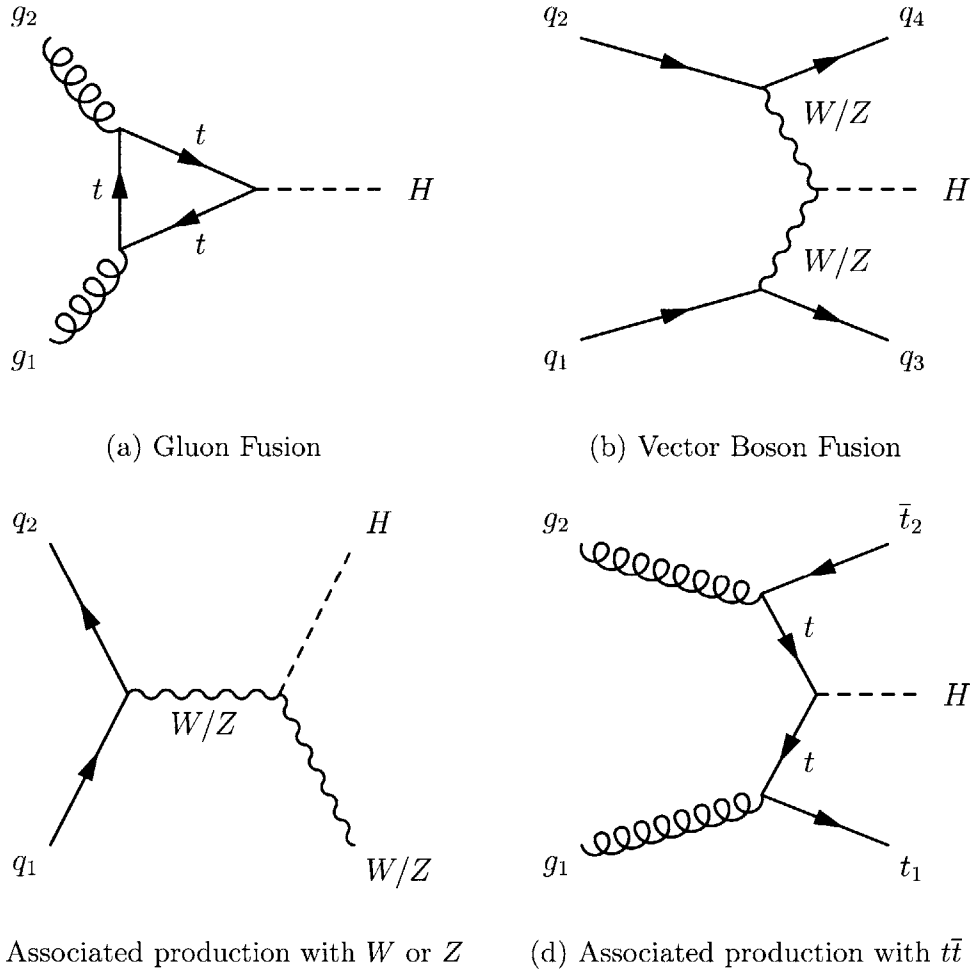
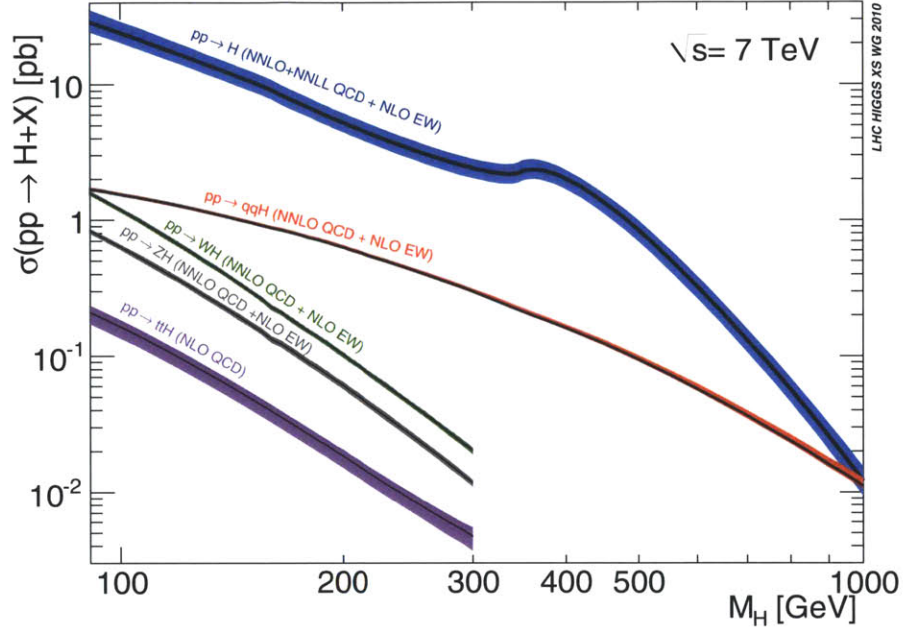


Figure 1-1: Higgs production diagrams.

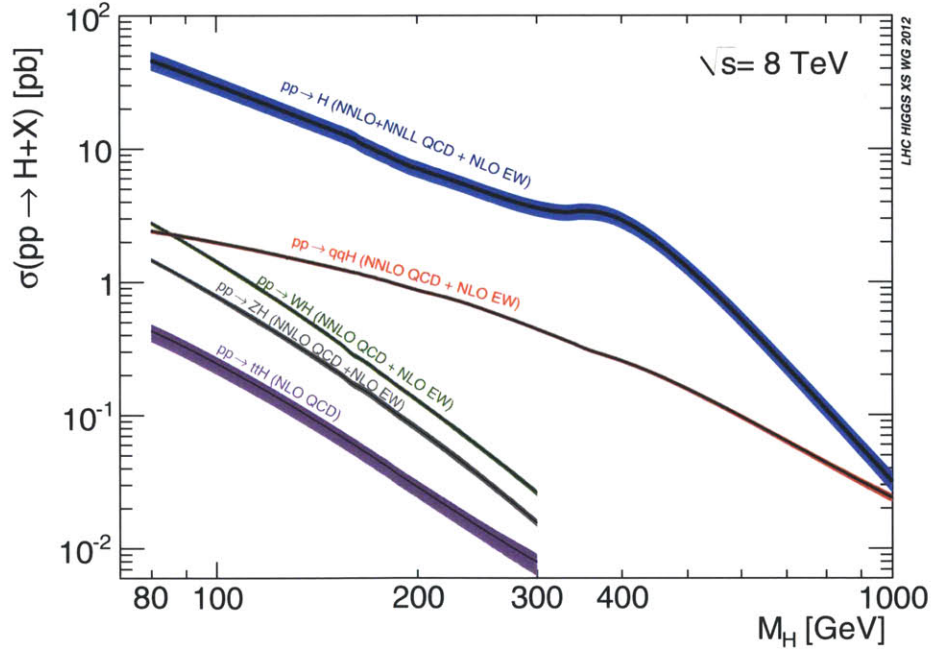
Higgs decays into fermions. Searching for the Higgs boson in the $H \rightarrow \tau\tau$ channel is the subject of this thesis.

1.3 Decay of the Higgs Boson into Taus

The tau is the most massive of the leptons, with a mass of 1776.8 MeV. The large mass means that its coupling to the Higgs boson is relatively strong, but it also means the tau has a short life time, 2.9×10^{-13} s. The production of a tau is inferred by detecting its stable decay products. A tau can decay either leptonically via $\tau \rightarrow e\nu_e\nu_\tau$ or $\tau \rightarrow \mu\nu_\mu\nu_\tau$, or hadronically via $\tau \rightarrow \tau_h\nu_\tau$, where τ_h represents a combination of



(a) $\sqrt{s} = 7$ TeV



(b) $\sqrt{s} = 8$ TeV

Figure 1-2: Higgs production cross section as a function of the Higgs mass [15, 16].

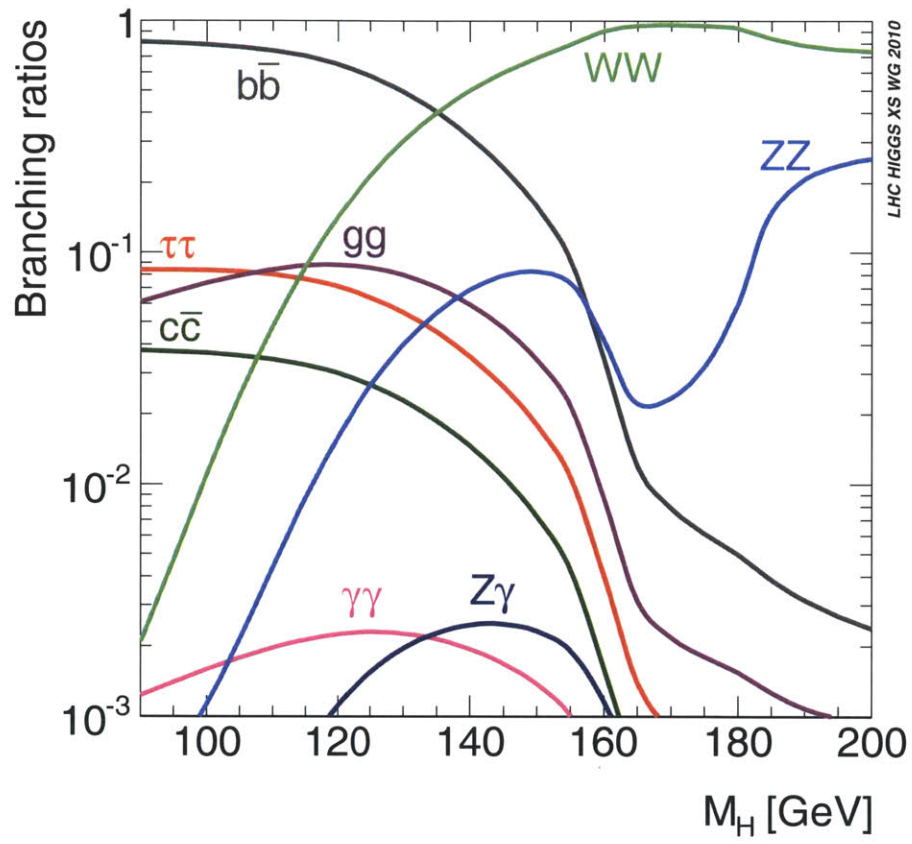


Figure 1-3: Higgs branching ratios [15].

hadrons. The leptonic decay channels have branching ratios of 17.83% for $\tau \rightarrow e\nu_e\nu_\tau$ and 17.41% for $\tau \rightarrow \mu\nu_\mu\nu_\tau$ [17]. The remaining 65.76% of the branching ratio consists of hadronic modes. The predominant hadronic decays are $\pi^\pm\nu_\tau$ (10.83%), $\pi^\pm\pi^0\nu_\tau$ (25.52%), $\pi^\pm\pi^+\pi^-\nu_\tau$ (8.99%), and $\pi^\pm\pi^0\pi^0\nu_\tau$ (9.30%), where the percentages in parentheses are given with respect to the total decay width of the tau. A search for $H \rightarrow \tau\tau$ involves detecting one or more of the possible final states of the tau pair:

1. $\tau\tau \rightarrow ee\nu_e\nu_e\nu_\tau$ (3.2%),
2. $\tau\tau \rightarrow \mu\mu\nu_\mu\nu_\mu\nu_\tau$ (3.0%),
3. $\tau\tau \rightarrow e\mu\nu_e\nu_\mu\nu_\tau$ (6.2%),
4. $\tau\tau \rightarrow e\tau_h\nu_e\nu_\tau$ (23.1%),
5. $\tau\tau \rightarrow \mu\tau_h\nu_\mu\nu_\tau$ (22.6%),
6. $\tau\tau \rightarrow \tau_h\tau_h\nu_\tau\nu_\tau$ (41.9%).

The analysis presented in this thesis makes use of the fourth and fifth $\tau\tau$ decay channels, that is, $\tau\tau \rightarrow e\tau_h\nu_e\nu_\tau$ and $\tau\tau \rightarrow \mu\tau_h\nu_\mu\nu_\tau$. An analysis combining all the tau decay modes (except $\tau\tau \rightarrow ee\nu_e\nu_e\nu_\tau$) has been studied by the CMS collaboration [18].

1.3.1 Analysis Strategy

The general approach of this analysis is to identify events that contain either an electron or muon along with a hadron jet that has been identified as coming from the decay of a tau. Events in data are compared with theoretical predictions calculated using Monte Carlo (MC) techniques (Section 6.1), wherein large samples of simulated proton collisions are used to estimate the expected distributions of event variables. Simulations are used in the design and optimization of the analysis, taking into account all relevant background physics processes, and to assess the systematic uncertainties associated with various analysis choices.

The search for $H \rightarrow \tau\tau$ involves dealing with large SM backgrounds. The backgrounds include Drell-Yan [19], W bosons, multi-jet events from QCD processes, $t\bar{t}$

events, single top events, and di-boson events. The final state particles in these background events are the same or appear to be same as the final state particles of $H \rightarrow \tau\tau$. The main purpose of the event selection criteria (Chapter 4) is to reduce backgrounds as much as possible while maintaining high signal efficiency. These include cuts on individual event objects as well as cuts on event configurations. The event selection significantly reduces the background but the Higgs signal is still small compared to the remaining background. In order to search for an excess in the data corresponding to a signal, the backgrounds must be modeled accurately (Chapter 6) and compared to the selected data. The statistical significance of any excess is evaluated and could potentially lead to either an observation (statistically significant excess) or an upper limit on the signal cross section (no excess).

1.4 Previous Searches for the Higgs Boson

Prior to the LHC, constraints on the Higgs boson mass were obtained by investigating higher order electroweak corrections due to the Higgs field. Precision electroweak measurements from experiments at the Large Electron Positron Collider (LEP), the Tevatron, and the Stanford Linear Accelerator Center (SLAC) favored a low mass Higgs [20]. Experiments at LEP and the Tevatron were also able to conduct direct searches for the Higgs boson. LEP experiments excluded Higgs masses less than 114.4 GeV, while experiments at the Tevatrons excluded the Higgs mass range 147 GeV – 179 GeV [21]. Figure 1-4 shows the theoretically favored range of the Higgs mass based on a fit to precision electroweak measurements, as well as the Higgs mass intervals excluded by direct searches. In 2012, the CDF and D0 experiments at the Tevatron observed a significant excess in the mass range $115 \text{ GeV} < m_H < 140 \text{ GeV}$, with a significance of 2.9 standard deviations in the $H \rightarrow b\bar{b}$ channel [22].

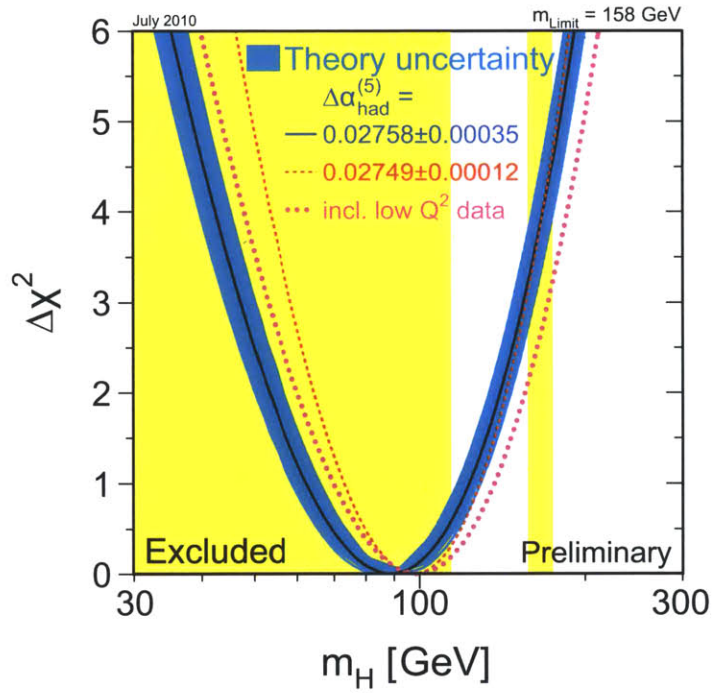


Figure 1-4: $\Delta\chi^2$ as a function of the Higgs mass for a combined fit to electroweak measurements. The yellow band up to 114.4 GeV represents the LEP exclusion. The yellow band from 158 GeV to 175 GeV represents the exclusion from a 2010 Higgs search by experiments at the Tevatron [20].

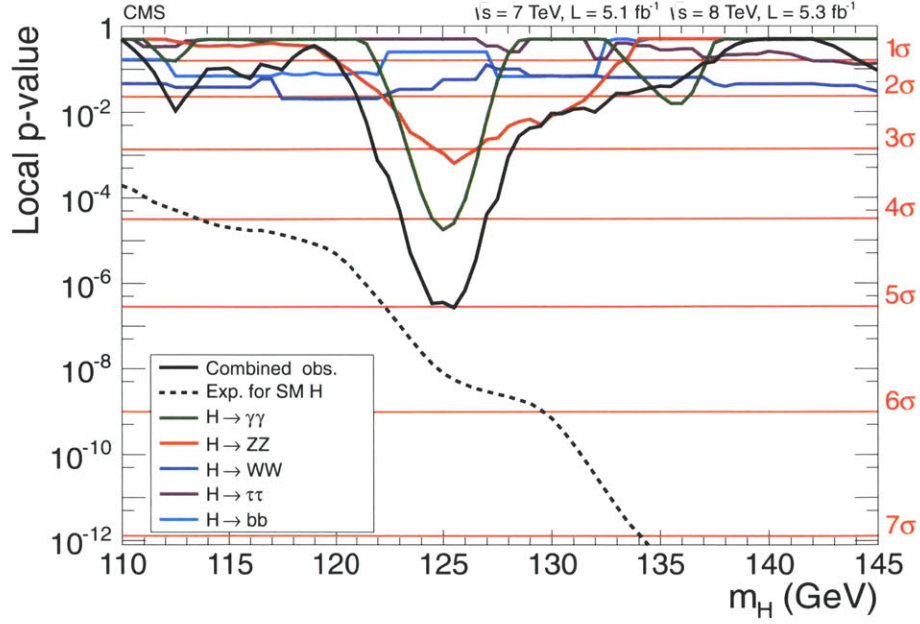


Figure 1-5: The observed local p -values from the CMS Higgs search performed in July, 2012. The p -values are shown for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$, $H \rightarrow b\bar{b}$, and their combination, as a function of the Higgs mass. The dashed line shows the expected local p -values for a SM Higgs boson [5].

1.5 Observation of a Higgs-Like Boson

When LHC operations began in 2009, the CMS and ATLAS experiments continued the search for the Higgs boson. In July of 2012, CMS and ATLAS claimed an observation of a new boson with a mass near 125 GeV, believed to be the Higgs boson [5,6]. The Higgs searches were performed in the decay modes $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$, and $H \rightarrow b\bar{b}$. CMS observed an excess with a local significance of 5.0 standard deviations while ATLAS observed an excess with a significance of 5.9 standard deviations. The p -values measured by CMS are shown in Figure 1-5. Within experimental precision, the observed particle was found to be consistent with the SM Higgs boson in terms of its couplings, spin, and parity. The search described in this thesis is closely aligned with the $H \rightarrow \tau\tau$ search conducted by CMS [18].

Chapter 2

Experimental Apparatus

2.1 Large Hadron Collider

The Large Hadron Collider (LHC) [23] is a proton accelerator located at the European Organization for Nuclear Research (CERN), near Geneva, Switzerland. The LHC has a circumference of 26.7 km, with eight straight sections and eight arcs. The LHC accelerates two proton beams in opposite directions that are brought to collide at the interaction points, where the experiments are located. The LHC is host to four major experiments: CMS, ATLAS, LHCb, and ALICE. Figure 2-1 shows the location of the experiments along the LHC ring. In addition to accelerating protons, the LHC is capable of accelerating and colliding ions for heavy-ion experiments.

Before entering the LHC, the proton beams are accelerated by a series of smaller accelerators, starting with the Linac2 linear accelerator and moving onto the Proton Synchrotron Booster (1.4 GeV), the Proton Synchrotron (25 GeV), and the Super Proton Synchrotron (450 GeV). Figure 2-2 shows the accelerators that make up the LHC injection chain. Once in the LHC, each proton beam is accelerated by eight radio frequency cavities, which impart 16 MeV per turn around the ring. The beams are guided around the LHC ring by 1,232 superconducting Nb-Ti dipole magnets, which are capable of generating magnetic fields up to 8.33 T. The dipole magnets are cooled to 1.9 K by superfluid helium. The protons are grouped into bunches, each containing $O(10^{11})$ protons. The LHC is designed to circulate 2,808 bunches per

beam with a bunch separation of 25 ns. The instantaneous luminosity of a circular collider is given by

$$\mathcal{L} = \frac{N_p^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F, \quad (2.1)$$

where N_p is the number of protons per bunch, n_b is the number of bunches per beam, f_{rev} is the revolution frequency, γ_r is the relativistic gamma factor E_{beam}/m_p , $\epsilon_n = 3.75 \mu\text{m}$ is the emittance, $\beta^* \approx 0.5 \text{ m}^{-1}$ is the beta function at the collision point, and F is a geometric factor that accounts for the crossing angle of the beams [17]. The design luminosity of the LHC is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

Stable proton collisions at the LHC began in 2009 and continued until the end of 2012, when it shut down for upgrades and maintenance. During this time, the LHC circulated up to 1,380 bunches per beam with a bunch separation of 50 ns. In 2011, the LHC operated at a collision energy of 7 TeV and achieved a peak instantaneous luminosity of $3.6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, delivering 6.1 fb^{-1} of proton collision data. In 2012, the collision energy was increased to 8 TeV. The LHC reached a peak instantaneous luminosity of $7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ and delivered 23.3 fb^{-1} of collision data in 2012. Figure 2-3 plots the integrated luminosity for proton-proton physics runs in 2010, 2011, and 2012 (note that this analysis only uses data from 2011 and 2012).

2.1.1 Pileup

Due to the high instantaneous luminosity of the LHC, multiple non-elastic pp interactions can occur during a single bunch crossing. These additional pp interactions are called *pileup* interactions. Pileup interactions create stray particles that may obscure the event signature of the main interaction. Pileup is addressed by designing event selection techniques that mitigate its effect and by properly simulating it in the Monte Carlo (Section 6.1.1). The average number of pileup interactions was 9.5 in 2011 and 19.0 in 2012.

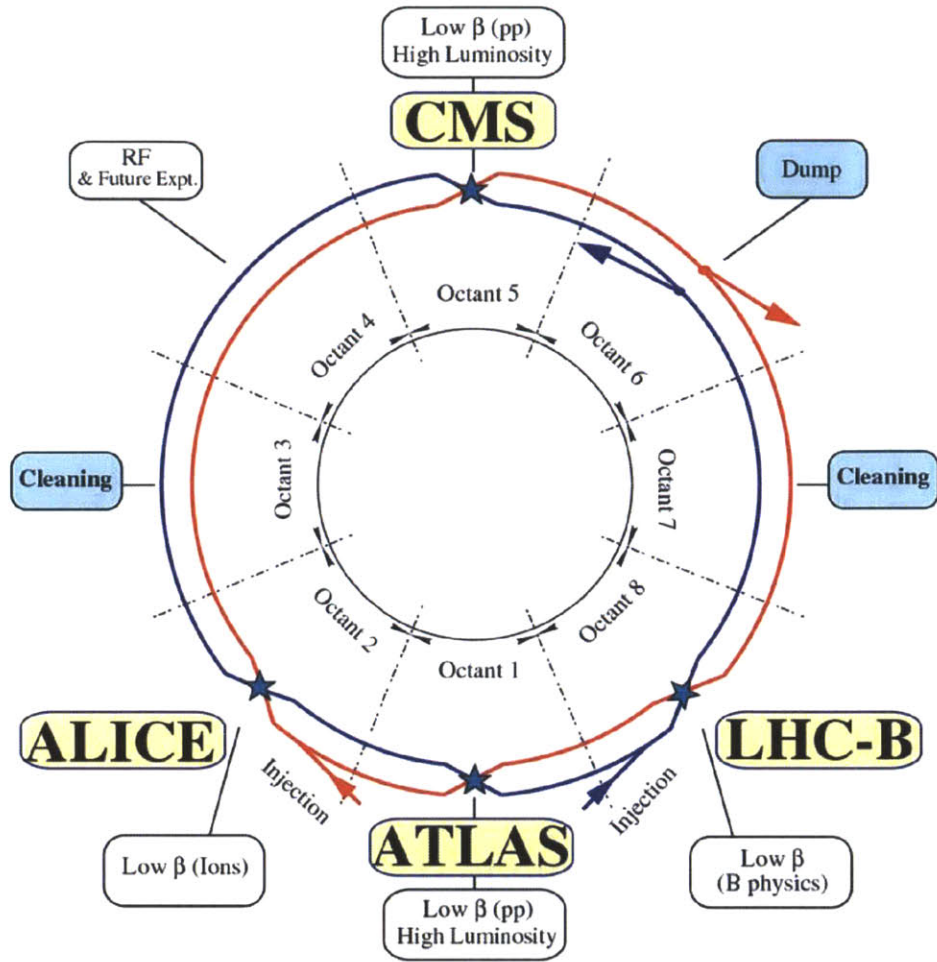


Figure 2-1: Location of experiments on the LHC ring.

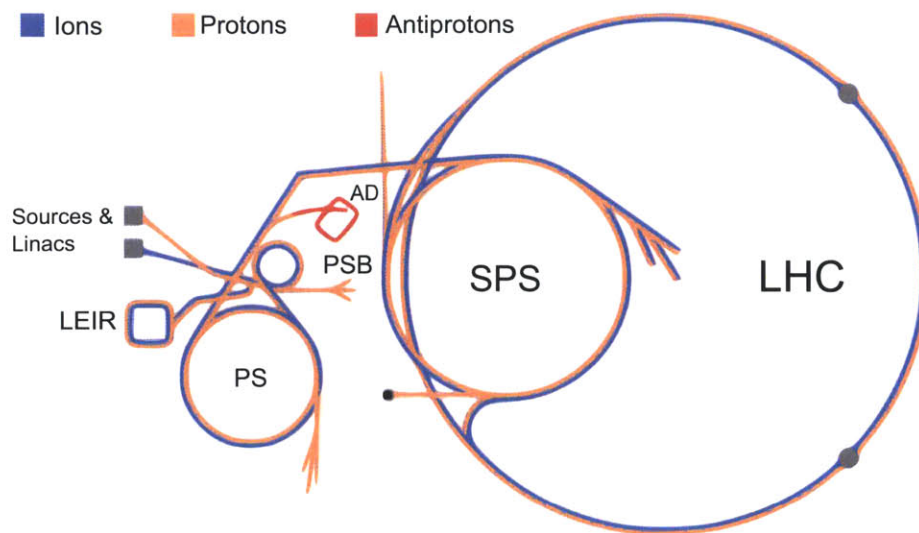


Figure 2-2: LHC proton injection chain.

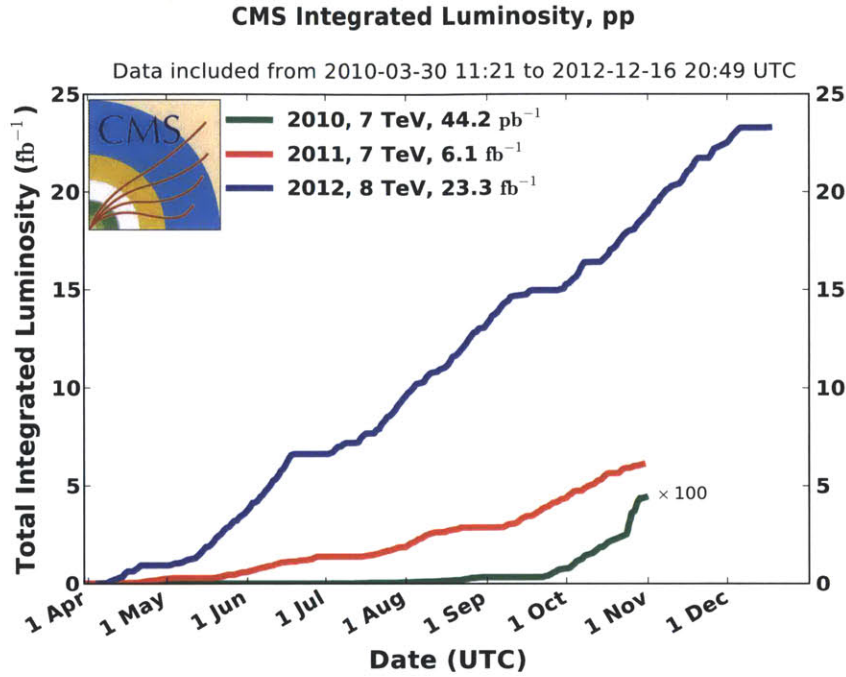


Figure 2-3: Integrated luminosity of proton collisions delivered by the LHC in 2010, 2011, and 2012.

2.2 Compact Muon Solenoid

The Compact Muon Solenoid (CMS) [24,25] is a general purpose particle detector located 100 m underground at Point 5 of the LHC ring, in the French commune of Cessy. The CMS detector has a cylindrical geometry, with a length of 21.6 m, a diameter of 14.6 m, and a weight of 12500 tons. The detector is aligned along the beam axis, with the collision point at the center. CMS is composed of several concentric sub-detectors: the silicon tracker, the electromagnetic calorimeter, the hadronic calorimeter, and the muon tracking system. CMS also contains a 3.8 T superconducting solenoid whose magnetic field bends the trajectory of charged particles and enables the measurement of their momenta. Figure 2-4 is a diagram of the sub-detectors within CMS. Figure 2-5 summarizes how various types of particles are identified by CMS. The CMS sub-detectors and solenoid are described in greater detail in the following sections. The trigger system and luminosity measurement are described at the end of this chapter.

The nominal pp interaction point is treated as the origin of the CMS coordinate system. Coordinates in CMS are parameterized either using the Cartesian or cylindri-

cal coordinate system. In Cartesian coordinates, x points towards the center of the ring and y points upward; the z -axis is along the beam line, with positive z corresponding to the counter-clockwise direction of the LHC ring. In cylindrical coordinates, the z -axis is the same as in the Cartesian coordinate system (i.e. along the beam line), θ is the polar angle from the z -axis, and ϕ is the azimuthal angle from the x -axis. The polar angle is often re-parameterized in terms of *pseudorapidity*,

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]. \quad (2.2)$$

For a particle whose momentum is much greater than its mass, the pseudorapidity is an approximation of *longitudinal rapidity*,

$$y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right), \quad (2.3)$$

where E is the energy of the particle and p_L is its longitudinal momentum. Longitudinal rapidity is invariant to boosts along the longitudinal direction, making pseudorapidity approximately invariant to such boosts for high momentum particles. Note that pseudorapidity depends only on θ and not on the actual momentum four-vector of a particle. The cylindrical coordinate system is more commonly used than the Cartesian system when describing particle trajectories.

2.2.1 Solenoid

The CMS magnet is a 12.5 m long superconducting solenoid with an inner radius of 6.3 m. The solenoid's inner volume contains the silicon tracker, the electromagnetic calorimeter, and the hadronic calorimeter. The solenoid generates a 3.8 T magnetic field by passing 18160 A through four winding layers of Nb-Ti coils, cooled to superconductance by liquid helium. The solenoid is supported by an aluminum structure that counteracts the stress exerted by the magnetic field on the solenoid's own coils.

The purpose of the solenoid is to apply a Lorentz force on charged particles as they travel through the detector. A particle with charge ze and transverse momentum p_T

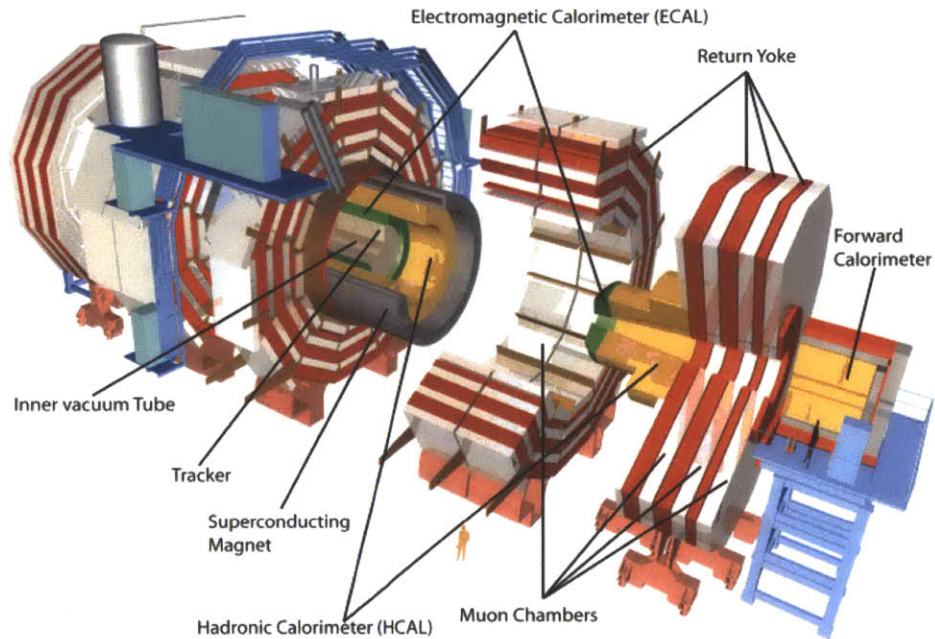


Figure 2-4: Layout and geometry of the sub-detectors within CMS.

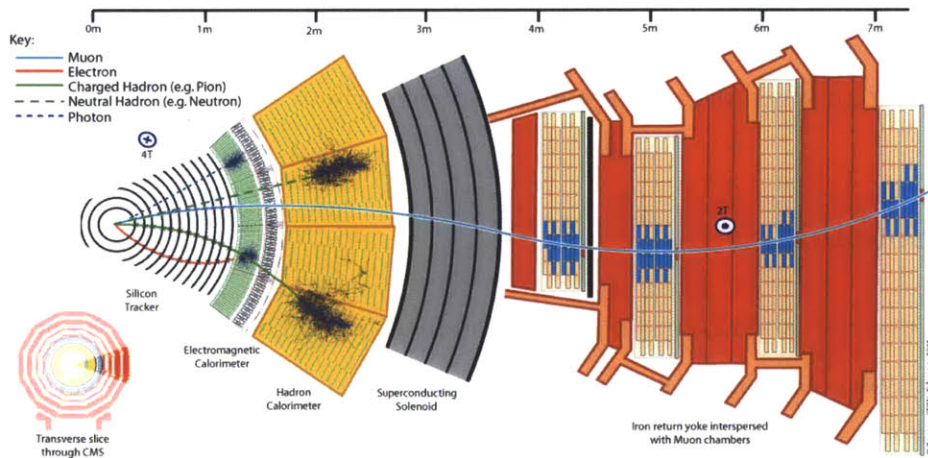


Figure 2-5: Different types of particles create distinct signatures within the CMS detector. Charged particles have curved trajectories due to the magnetic field and leave hits in the tracker. Electrons and photons are absorbed by the ECAL. Hadrons are absorbed by the HCAL. Muons traverse the entire detector and leave hits in the muon chambers.

moving through a magnetic field of strength B will have a radius of curvature given by

$$R = \frac{p_T}{0.3 \frac{\text{GeV}}{\text{c}\cdot\text{T}\cdot\text{m}} z B}. \quad (2.4)$$

This relationship allows the transverse momentum of a charged particle to be deduced from the curvature of its path, which is measured in the tracker. The momentum resolution is inversely proportional to the magnetic field strength [17],

$$\sigma_p \propto \frac{1}{\sqrt{B}}. \quad (2.5)$$

It follows that a stronger magnetic field enables more precise momentum measurements. The 3.8 T magnetic field generated by the solenoid is one of the hallmarks of CMS. The CMS magnet has an exceptional energy-to-mass ratio of 11.6 kJ/kg, exceeding all previous detector magnets.

2.2.2 Tracker

The tracker is the innermost sub-detector of CMS and is composed of an inner pixel detector and an outer strip detector. The tracker measures the momenta of charged particles. The active components of the tracker are composed of silicon. As a charged particle passes through a silicon pixel or strip, it creates electron-hole pairs that are collected and read out as an electronic signal, referred to as a *hit*. The positions of these hits are linked together to form a *track* that traces the path of the particle through the tracker. The curvature of a track indicates a particle's charge and momentum. In order to reduce thermal noise in the active silicon, the tracker is cooled to -10°C by perfluorohexane (C_6F_{14}) and nitrogen gas (N_2). The detection coverage of the tracker extends to $|\eta| = 2.5$.

Pixel Tracker

The pixel tracker is the innermost sub-detector of CMS. It provides fine granularity tracking at a radial distance where the particle flux is highest. A pixel is a $100 \times$

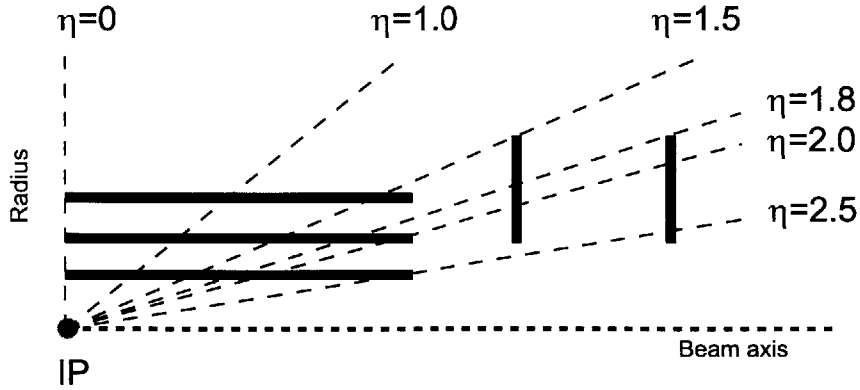


Figure 2-6: Geometrical layout of the pixel layers and disks, in the $r - \eta$ plane.

$150 \mu\text{m}^2$ p-n junction which produces an electrical signal when traversed by a charged particle. The pixel tracker contains 66 million pixels, covering an area of 1 m^2 .

The Barrel Pixel Detector (BPix) is 57 cm long and consists of three cylindrical layers of silicon pixels at radii of 4.4 cm, 7.3 cm, and 10.2 cm. It contains 800 detector modules controlling a total of 48 million pixels. Each module has 8 to 16 read-out chips that amplify and process signals from 52×80 pixels. A High Density Interconnect provides power and control signals to the read-out chips.

The forward regions are covered by the Forward Pixel Detectors (FPix), placed at $z = \pm 34.5 \text{ cm}$ and $z = \pm 46.5 \text{ cm}$. The FPix is segmented into 672 *plaquettes*. Each plaquette contains a pixel sensor bonded with read-out chips and a very-high-density-interconnect. Three to four plaquettes are mounted on each pedal-shaped panel. The panels are arranged into FPix disks which are located at either end of the BPix. The FPix contains 9 million pixels per endcap.

The arrangement of the pixel layers in the $r - \eta$ plane is illustrated in Figure 2-6. Figure 2-7 is a cutaway diagram of the pixel detector. The pixel tracker is especially important in providing seeds for track fitting. Doublets or triplets of pixel hits are used to seed the iterative track finding algorithm (Section 3.1). The pixel detector achieves a spatial resolution of $15 - 20 \mu\text{m}$ when making use of charge sharing to interpolate hit positions between pixels.

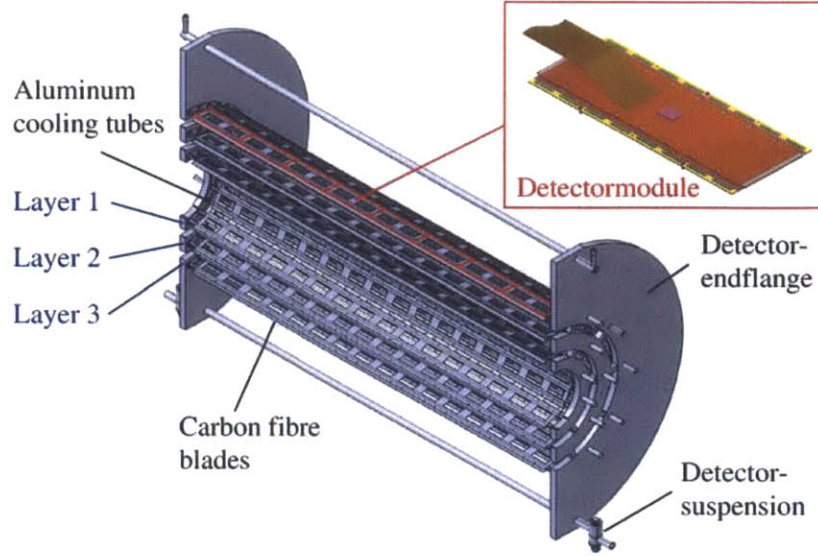


Figure 2-7: Cutaway diagram of the pixel detector.

Strip Tracker

The strip tracker operates under the same principles as the pixel tracker but uses 10 – 20 cm long, 80 – 120 μm wide silicon strips instead of pixels. The use of strips allows coverage of a larger area for a given number of channels but does not provide precise measurements along the length of the strip. The strips are thin p-doped silicon segments embedded in an n-doped bulk. The strip tracker is made of four distinct sections (Figure 2-8). The barrel section is composed of the Tracker Inner Barrel (TIB), the Tracker Inner Disks (TID), and the Tracker Outer Barrel (TOB). The Tracker Endcaps (TEC) are located in the forward regions.

The TIB and TID form the inner barrel section of the strip tracker, in the radial range 20–55 cm. The TIB comprises four cylindrical layers covering the central region. At each end of the TIB are three disks which form the TID. The silicon strips are 320 μm thick and arranged parallel to the beam axis in the TIB and radially in the TID. In the TIB, the strip pitch ranges from 80 μm to 120 μm . In the TID, the pitch ranges from 100 μm to 141 μm . The TOB surrounds the TIB and TID. It consists of 6 cylindrical layers and is 236 cm long, with an inner radius of 55 cm and an outer radius of 116 cm. The strips are 500 μm thick and have a pitch of 122 – 183 μm . The strip tracker is capped at each end by the TEC. The outer radius of the TEC is 1.1 m.

Each endcap contains 9 disks, with up to 7 rings per disk. The strips have a thickness of $320\text{ }\mu\text{m}$ and a pitch of $97 - 184\text{ }\mu\text{m}$.

The strips are built into encapsulated units called modules. Each module contains 512 or 768 strips. In the TIB and TOB, the modules are rectangular; in the TID and TEC, the modules are wedge-shaped. The modules contain read-out chips and electronics that distribute power and control signals (Figure 2-9). The silicon strip tracker contains 15,148 modules in total. Readout is performed by APV chips. Each APV chip is connected to 128 strips. The APV chip can be operated in *peak mode*, in which it yields the maximum of the 50 ns pulse from a strip, or *deconvolution mode*, in which the output is the weighted sum of three consecutive samples, reducing the effective pulse width to 25 ns. Peak mode is used for calibration studies while deconvolution mode is used for taking physics data. From the APV, data is sent via optical fibers to the off-detector Front End Drivers (FED), which perform analog-to-digital conversion, pedestal and common-mode subtraction, and zero-suppression. Each FED processes data from up to 192 APV chips.

Because a strip is 10–20 cm long, it individually does not provide a precise position measurement along its length. The use of double-sided modules helps remedy this problem. A double-sided module is made of two single-sided modules placed back-to-back with a stereo angle of 100 mrad. When a particle traverses a double-sided module, each side will register a hit. Since the strips are angled by 100 mrad with respect to one another, the intersection of the two impinged strips provides a position measurement along the length of the module. Double-sided modules are installed in the first two layers/rings of the TIB, TID, and TOB, and in rings 1, 2, and 5 of the TEC.

2.2.3 Electromagnetic Calorimeter

The Electromagnetic Calorimeter (ECAL) [26] is responsible for the detection of photons and electrons. The ECAL detects particles via scintillation: photons and electrons which enter a *scintillator* are absorbed and re-emitted as photons of a specific wavelength, which are then collected by photodetectors. In practice, a photon

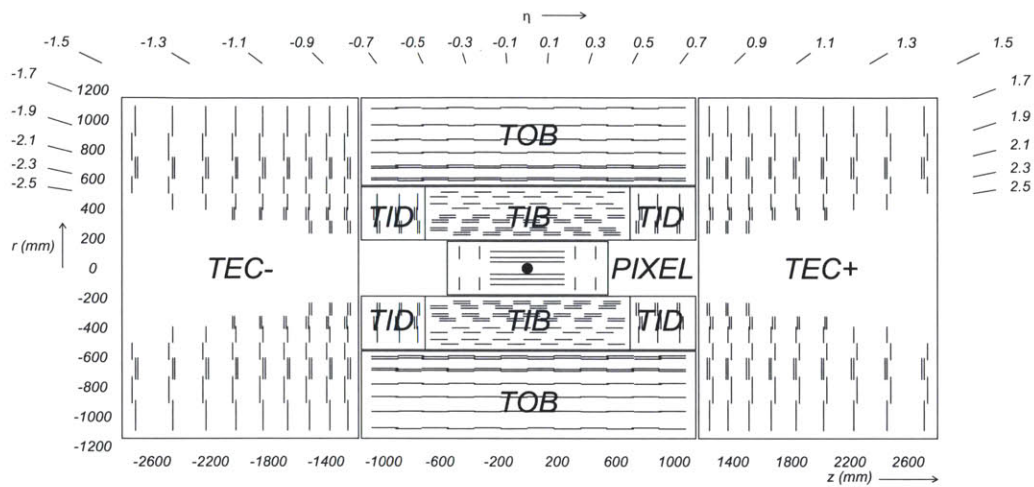


Figure 2-8: Layout of the tracker partitions, in the $r - \eta$ plane.

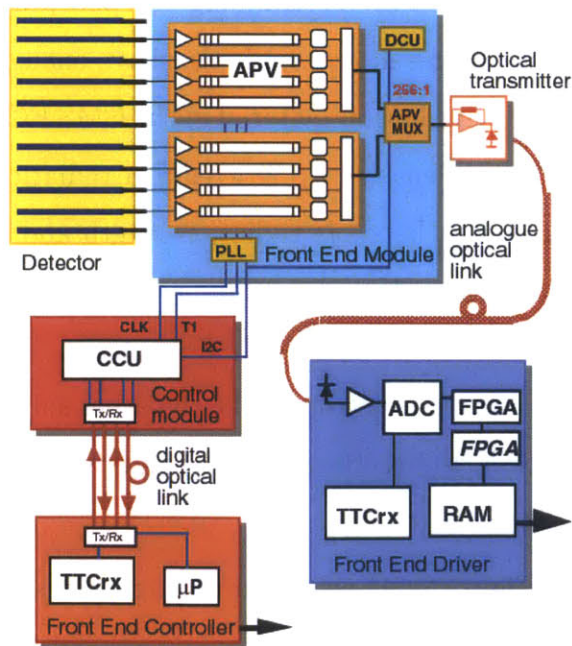


Figure 2-9: Schematic of the silicon strip readout electronics.

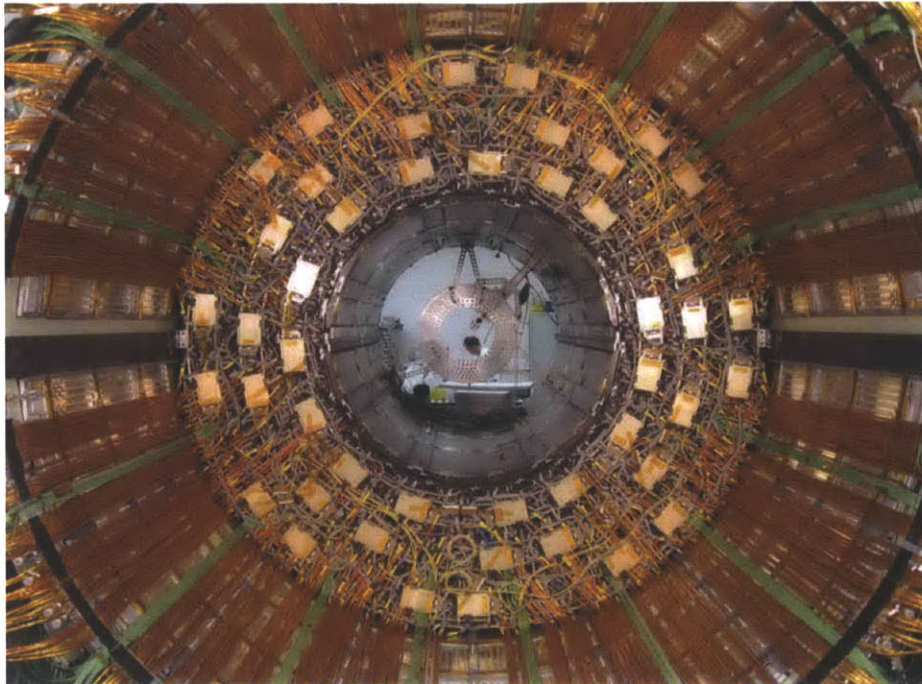


Figure 2-10: A photo of one half of the TOB.

or electron is not immediately absorbed but rather cascades into an electromagnetic shower of lower energy particles via bremsstrahlung and pair production. The shower tapers off when the photons in the shower no longer have enough energy to produce electron-positron pairs. The scintillation material in the CMS ECAL is lead-tungstate (PbWO_4) crystal, which has a density of 8.28 g/cm^3 , a radiation length of 0.89 cm , and a Molière radius of 2.2 cm . The short radiation length and small Molière radius enable the ECAL to have effective shower containment and fine granularity. Furthermore, 80% of the scintillation light is emitted within 25 ns . The scintillation light wavelength peaks in the range $420 - 430 \text{ nm}$. Like the other sub-detectors, the ECAL is divided into a barrel section (ECAL Barrel or EB) and two endcaps (ECAL Endcap or EE).

The PbWO_4 crystals (Figure 2-11) are 230 mm long, corresponding to 28.5 radiation lengths. In the barrel, the crystals have a cross sectional area of $22 \times 22 \text{ mm}^2$ at the front face and $26 \times 26 \text{ mm}^2$ at the rear face. In the endcap, the crystals have an area of $28.62 \times 28.62 \text{ mm}^2$ at the front face and $30 \times 30 \text{ mm}^2$ at the rear face. There are $61,200$ crystals in the barrel and $7,324$ crystals in each endcap. The crystals are

arranged to have 360-fold segmentation in ϕ and 2×854 -fold segmentation in η . The arrangement of crystals within the ECAL is illustrated in Figure 2-12. In order to maintain the stability of scintillation emission, the ECAL is kept at a temperature of $18.00 \pm 0.05^\circ\text{C}$ by a water cooling system.

The EB covers the central region, $|\eta| < 1.479$. In the EB, crystals are grouped into *modules* of 400 to 500 crystals. Four modules form a supermodule. The scintillation light from each crystal is measured by a pair of avalanche photodiodes (APD). Each APD has an active area of $5 \times 5 \text{ mm}^2$ and is operated at $340 - 430 \text{ V}$, yielding a gain of ~ 50 . A temperature sensor is embedded in every tenth APD.

The EE covers the forward regions of the detector, from $|\eta| = 1.479$ to $|\eta| = 3$. The inner radius of the EE is 1.29 m. The crystals in the EE are grouped into 5×5 units called *supercrystals*. The scintillation light in the EE is measured using vacuum phototriodes (VPT), which have a lower gain (10.2) than APDs but a larger surface area (280 mm^2). The VPT has a quantum efficiency of 22% at the scintillation wavelength of 430 nm. A thermometer is embedded in each supercrystal.

Data readout is performed in units of trigger towers. In the EB, a trigger tower is a 5×5 grid of crystals. In the EE, a trigger tower is made of 5 *pseudo-strips* of 5 contiguous crystals. The on-detector readout electronics for each trigger tower consists of 5 Very-Front-End (VFE) boards and 1 Front-End (FE) board. A VFE board reads out data from a group of 5 crystals. The data from the 5 VFEs is transmitted to the FE, which stores data in a 256-word pipeline. The FE also sums the energy deposited in the trigger tower to be used as a trigger primitive. After processing by the FE, the data is transferred off-detector to the Trigger Concentration Cards (TCC) and the Data Concentration Cards (DCC). A TCC collects trigger data from 68 FE boards in the barrel or 48 FE boards in the endcap. A DCC collects and processes data from up to 68 FE boards.

As the crystals are irradiated, they form color centers that absorb scintillation light, reducing the optical output of the crystals [27]. This transparency loss is measured *in-situ* by a laser monitoring system. Two wavelengths are used: 440 nm light is used to emulate the scintillation frequency and 796 nm light is used to verify the

stability of the electronics. The light intensity of each laser is checked by a PN photodiode. By precisely measuring the laser light intensity with the PN photodiode and then shining the laser through a crystal, changes in crystal opacity can be measured and tracked over time. These transparency measurements are used to calculate corrections to the ECAL output to account for radiation damage.

The Preshower sub-detector is installed in the forward regions, covering $1.653 < |\eta| < 2.6$. The Preshower is a sampling detector made of a lead radiator followed by two layers of silicon sensors. The Preshower helps identify neutral pions in the forward region.

The energy resolution of an electromagnetic calorimeter can be parameterized as

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2, \quad (2.6)$$

where S represents stochastic fluctuations, N represents electronic noise, and C is a constant baseline. In the CMS ECAL, the stochastic term is influenced by lateral shower containment (1.5%) and photostatistics (2.1%). The noise term is caused by fluctuations in the electronics and digitization process; it is 40 MeV/channel. The constant term has contributions from the non-uniformity of longitudinal light collection, calibration errors, and radiation leakage from the back of the crystal; it has an approximate value of 0.3%. Thus, the energy resolution of the CMS ECAL is given by

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2, \quad (2.7)$$

where E is measured in GeV.

2.2.4 Hadronic Calorimeter

While the ECAL specializes in detecting electrons and photons, the Hadronic Calorimeter (HCAL) is designed to detect hadrons via strong interactions with the nuclei of an absorber material. The HCAL is a sampling calorimeter with brass and steel radiators interleaved with plastic scintillators [28]. The radiator layers interact with

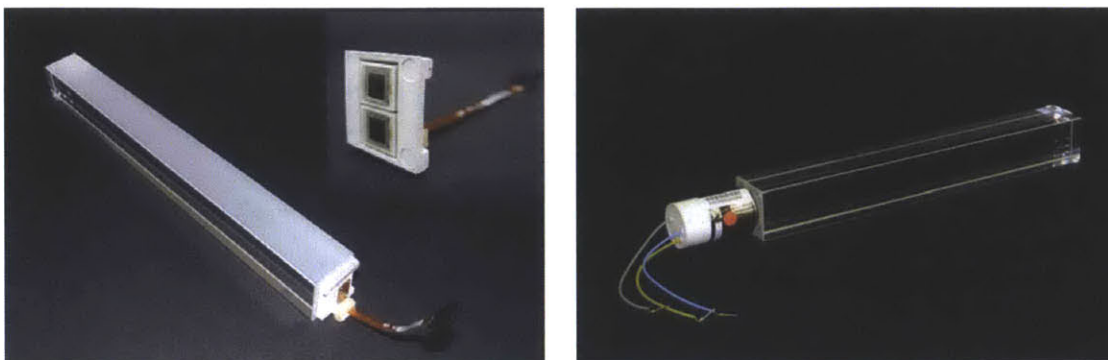


Figure 2-11: PbWO_4 crystals from the ECAL barrel (left) and ECAL endcap (right).

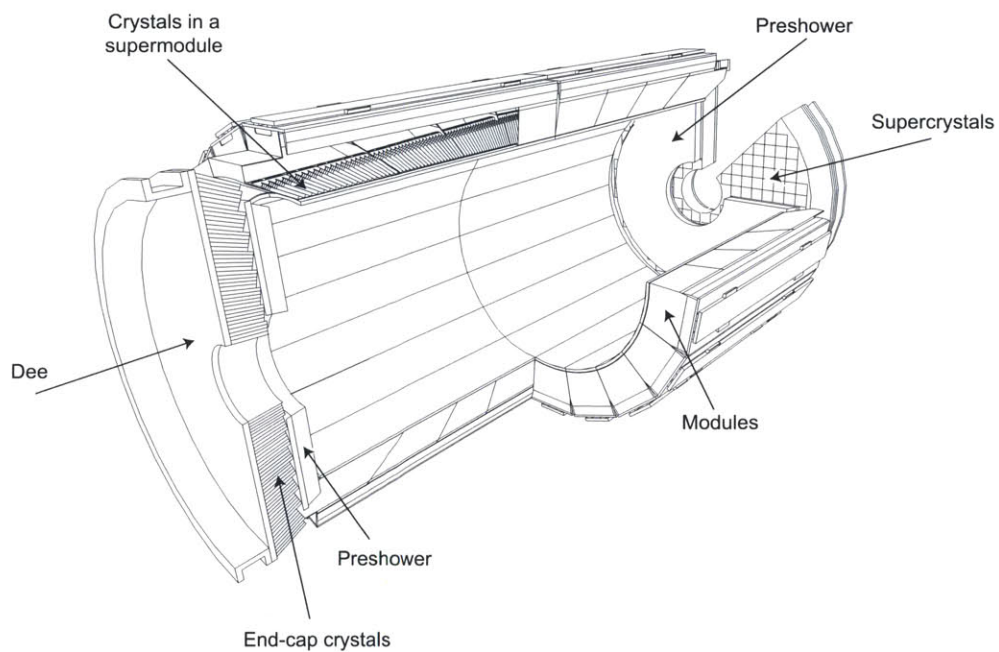


Figure 2-12: Schematic of the ECAL, showing the arrangement of crystal modules, supermodules, and supercrystals, as well as the placement of the Preshower.

high-energy hadrons and convert them into showers of lower energy hadrons. As the low energy hadrons pass through a scintillator layer, they are absorbed and re-emitted as photons. The photons are collected by wavelength-shifting optical fibers and guided into photodetectors. The number of detected photons is roughly proportional to the original energy of the hadron.

The HCAL is divided into four partitions: the HCAL Barrel (HB), the Outer HCAL (HO), the HCAL Endcap (HE), and the Forward HCAL (HF). The HB is located in the barrel region between the ECAL and the solenoid. The HO is located outside the solenoid and catches hadrons that are not stopped by the HB. The HE and HF extend coverage to the forward regions of CMS. Figure 2-13 shows the layout of the HCAL partitions.

The HB has an inner radius of 1.77 m and an outer radius of 2.95 m. It covers the pseudorapidity range $|\eta| < 1.3$. The HB is segmented into 72 ϕ sectors by 16 η sectors. The absorber layers consist of a 40 mm thick steel plate, fourteen 50.5–56.5 mm thick brass plates, and a 75 mm thick steel back plate. In terms of interaction lengths (λ_I), the thickness of the absorbers varies from 5.82 λ_I at $\eta = 0$ to 10.6 λ_I at $|\eta| = 1.3$. The HB contains 70,000 scintillator tiles. The main scintillator tiles are made of Kuraray SCSN81 plastic scintillator and are 3.7 mm thick. In addition, a special 9 mm scintillator layer made of Bicron BC408 is placed in front of the first steel plate. The scintillation light is guided out of the scintillator by green wavelength shifting (WLS) fiber. The WLS fiber is bonded to clear optical fibers that lead into hybrid photodiodes (HPD). An HPD is a photocathode paired with a pixelated silicon photodiode. The device produces a gain of ~ 2000 .

The HO provides additional hadron absorption in the pseudorapidity region $|\eta| < 1.3$. Since the size of the HB is limited by the radius of the solenoid, the HO is necessary for capturing hadrons that are not absorbed by the HB. The HO scintillation layers are embedded in the iron yoke surrounding the solenoid. The iron yoke itself is used as the absorber. There are two scintillator layers in the central iron yoke ring, at $r = 3.82$ m and $r = 4.07$ m, on either side of a 19.5 cm layer of iron. The two iron yoke rings at the ends of the barrel each have one scintillator layer, at $r = 4.07$ m.

The scintillator tiles are made of Bicron BC408 and are 10 mm thick. Like the HB, the HO tiles form towers with granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$. The HO extends the absorption depth of the HCAL to $11.8 \lambda_I$.

The HE detects hadrons in the pseudorapidity range $1.3 < |\eta| < 3$. Each endcap has 17 absorber layers made of 79 mm thick brass plates. The HE and the preceding ECAL correspond to ~ 10 interaction lengths. The scintillator material is the same as for the HB (Kuraray SCSN81 plastic scintillator and Bicron BC408). In total, the HE contains 20,916 scintillator tiles. Within $|\eta| < 1.6$, the granularity of the HE is $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$; beyond that the granularity is $\Delta\eta \times \Delta\phi = 0.17 \times 0.17$.

The HF covers the region $4.5 < |\eta| < 5.2$. It is located 11.2 m from the interaction point, and has an inner radius of 12.5 cm and an outer radius of 130 cm. The active material of the HF is made of quartz fiber. Shower particles are detected using the principle of Cherenkov radiation. A charged particle traveling faster than the speed of light in the quartz generates Cherenkov radiation, which is guided by internal reflections along the fiber to a photomultiplier tube. The number of detected photons gives a measure of the shower energy. The quartz fibers are embedded in a steel absorber structure and run parallel to the beam line. The fibers have a diameter of $600 \pm 10 \mu\text{m}$ and are spaced 5.0 mm apart from each other in a square grid. The absorber is 165 cm long, corresponding to $10 \lambda_I$. Half of the fibers run the entire length of the absorber while the remaining fibers start 22 cm from the front face of the HF. These two sets of fibers are read out separately. Since showers created by photons and electrons attenuate more quickly than showers created by hadrons, the full-length fibers absorb showers created by all particles while the truncated fibers primarily measure the longer showers created by hadrons. This setup helps the HF distinguish hadrons from electromagnetic particles.

The energy resolution of the HCAL for single pions has been measured in test beam studies [29] and is approximately

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{115\%}{\sqrt{E}}\right)^2 + (5.5\%)^2. \quad (2.8)$$

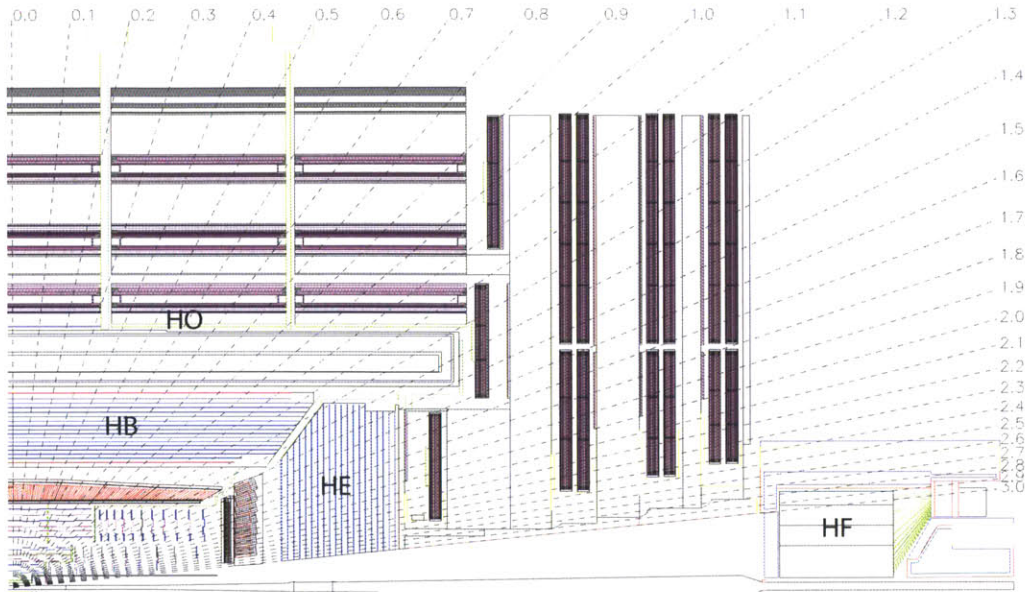


Figure 2-13: Layout of the HCAL in the $r - \phi$ plane showing the positions of the HCAL partitions.

2.2.5 Muon Chambers

The muon detectors form the outermost detection layer of CMS. Most types of particles produced in pp interactions are stopped within the 16 interaction lengths of material in front of the muon detectors. Muons are the only particles that regularly reach the muon detection layers. There are three types of muon detectors: 1) Drift Tubes (DT), 2) Cathode Strip Chambers (CSC), and 3) Resistive Plate Chambers (RPC). Drift Tubes detect muons in the central rapidity region while Cathode Strip Chambers detect muons in the forward regions. Resistive Plate Chambers mainly serve as fast-response detectors for the trigger system. The muon detectors are designed to both identify muons and measure their momenta. As with the other sub-detectors, the muon detectors are divided into a cylindrical barrel section and disk-shaped end-caps. The momentum resolution of muons reconstructed only in the muon system (without the silicon tracker) is $\sim 9\%$ for muons with $p_T < 200 \text{ GeV}$. Including the track from the inner tracking system improves the resolution to 1%.

Drift Tubes

The DT system detects muons in the pseudorapidity region $|\eta| < 1.2$. The DT system is divided into 4 cylindrical layers, called stations (Figure 2-14). Each station contains 12 DT chambers. A chamber is composed of 2 or 3 superlayers, each of which contains 4 layers of DT cells. A DT cell is a long, rectangular volume (cross sectional area $13 \times 42 \text{ mm}^2$) filled with Ar/CO₂ gas (Figure 2-15). A $50 \mu\text{m}$ diameter anode wire runs through the center of each DT cell. When a muon passes through a cell, it ionizes the gas. The free electrons drift toward the anode wire and are read out as an electrical signal. Two superlayers in a chamber are aligned with the beam axis, providing measurements in ϕ , while one superlayer is aligned perpendicular to the others, providing measurements in z . The chambers of the fourth station only have two superlayers, both measuring the ϕ coordinate. The position resolution of a single wire is $250 \mu\text{m}$, while a full chamber has a resolution of approximately $100 \mu\text{m}$. The wires are operated at 3600 V and the cathode strips at -1200 V . The gas provides a gain of 10^5 .

Cathode Strip Chambers

The CSCs form the endcaps of the muon system, with a pseudorapidity range of $0.9 < |\eta| < 2.4$. A CSC is a wedge-shaped ($10^\circ - 20^\circ$) multiwire proportional chamber with 6 anode wire planes interleaved among 7 cathode panels (Figure 2-16). The anode wires are azimuthally aligned and measure the r coordinate of a muon hit. The cathode strips are oriented radially and measure the ϕ coordinate. The anodes are gold-plated tungsten wires with a diameter of $50 \mu\text{m}$ and a length up to 1.2 m. They are spaced apart at about 3.2 mm. The gas gaps between the cathode panels are 9.5 mm wide and are filled with Ar/CO₂/CF₄ gas in the ratio 4/5/1. The CSCs are operated at 3.6 kV and yield a gain of 7×10^4 . The spatial resolution of a single CSC is approximately $80 \mu\text{m}$. The CSC system contains 468 CSCs in total. Figure 2-17 shows a CSC station.

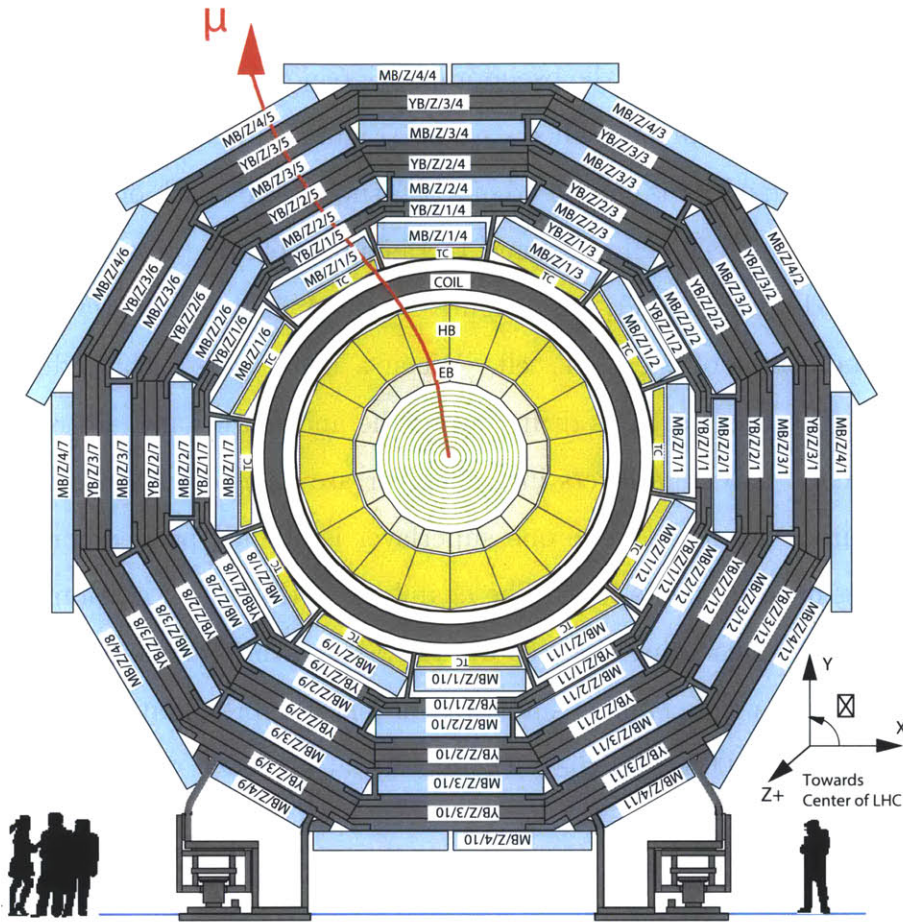


Figure 2-14: Layout of the drift tube system in one wheel.

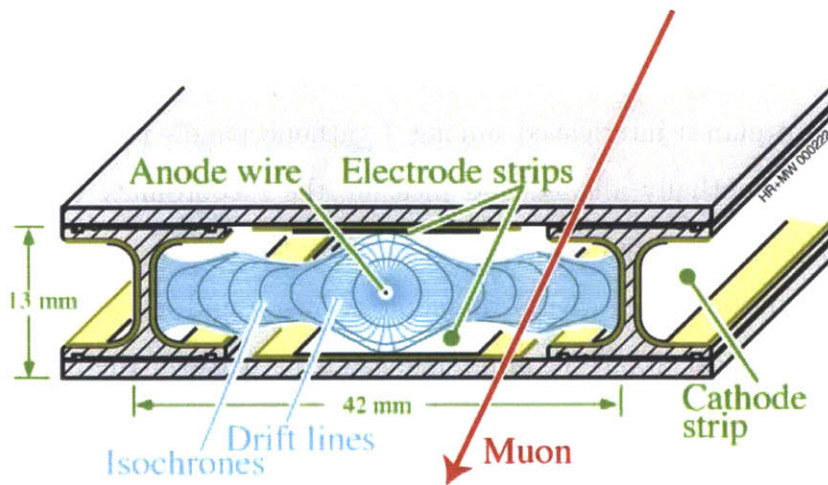


Figure 2-15: Drift tube cell containing gas volume, anode wire, cathode strips, and electrode strips.



Figure 2-16: A CSC consists of seven panels forming six gas gaps. The radial cathode strips and azimuthal anode wires are shown (only a few anode wires are drawn).

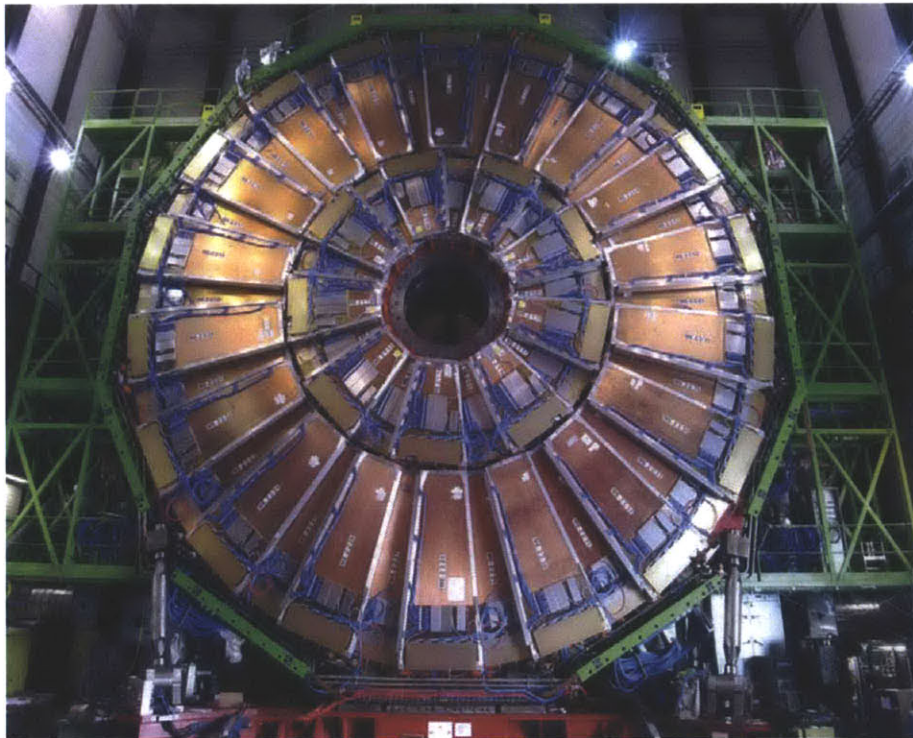


Figure 2-17: Photo of a CSC station. The outer ring consists of 36 chambers; the inner ring consists of 18 chambers.

Resistive Plate Chambers

Resistive Plate Chambers form a dedicated trigger system in the pseudorapidity region $|\eta| < 1.6$. The fast response time of the RPCs enable the trigger system to associate a muon with the correct bunch crossing. The RPCs follow a double-gap design, each containing two gas gaps operated in avalanche mode. An RPC double-gap module is made of 2 mm thick bakelite plates forming two 2 mm gaps. The gas is a mixture of 96.2% $\text{C}_2\text{H}_2\text{F}_2$, 3.5% $i\text{C}_4\text{H}_{10}$, and 0.3% SF_6 . Incident muons ionize the gas and create electrons that are accelerated by the electric field across the gap. The accelerated electrons cause additional ionization, leading to an amplification of signal charge. The charge in both gaps is collected and read out by a common set of aluminum strips located in between the two gaps.

There are 480 RPC chambers in the barrel, arranged into 6 layers. The chambers are 2455 mm long and are aligned along the beam axis. Each chamber contains 2 or 3 double-gap RPC modules. The RPC chambers collectively cover a surface area of 2400 m^2 .

2.2.6 Trigger System

In 2011 and 2012, the LHC ran at a bunch crossing rate of 20 MHz. However, only $O(100)$ events can be recorded per second due to data processing limitations. This limitation necessitates a trigger system that can quickly decide which collisions to record and which to ignore. The CMS Trigger System is divided into two stages of ascending complexity: the Level-1 Trigger (L1) and the High Level Trigger (HLT).

The Level-1 trigger is implemented in low-level electronics and firmware. It filters events down to a rate of 100 kHz. The Level-1 trigger only uses trigger primitives from the calorimeters and muon system (notably, information from the tracker is not used). Data from the ECAL consists of the energy sum of 5×5 groupings of crystals (“towers”), as well as the number of crystals per tower that exceed a pre-determined energy threshold. The ECAL deposits form seeds for reconstructing photons and electrons. Similarly, the HCAL provides the L1 Trigger system with estimates of the

energy deposited in coarse groupings of HCAL towers. The HCAL deposits seed the reconstruction of hadrons. Muon candidates are derived from rudimentary tracking in the muon system. The algorithms that accept or reject an event are designed to make a decision quickly and are constrained by computational and time limits.

If an event is accepted by the L1 Trigger, it is passed onto the HLT. The HLT is implemented in software and can therefore make use of more sophisticated algorithms than those used by the L1 Trigger. The HLT can also use information from the inner tracking system. Momentum and position measurements have better resolution in the HLT than in the L1 Trigger system. In many cases, the HLT implements a simplified version of offline reconstruction algorithms. For example, hadronic tau decays are reconstructed using a simplified Particle Flow algorithm (Section 3.5).

As the instantaneous luminosity increased during the course of LHC physics operations, the trigger table was adjusted in both the L1 and HLT to keep the trigger rate at a manageable level. This usually involved raising p_T thresholds and applying more stringent identification requirements on reconstructed trigger objects. Alternatively, the rate of a trigger path could be reduced by accepting it only the n -th time it is fired; such a scheme is called a *prescale*.

2.2.7 Luminosity

The luminosity delivered by the LHC to CMS is monitored with one of two methods: 1) monitoring activity in the HF [30], and 2) counting pixel clusters [31, 32]. HF activity is parameterized as the fraction of towers containing energy deposits. Both HF activity and the number of pixel clusters are expected to be proportional to the instantaneous luminosity. However, the HF technique suffers from additional sources of systematic uncertainty, such as the “afterglow effect” (energy remains in the HF from a previous bunch crossing) and non-linearity of the HF response. Hence, the pixel cluster counting method has smaller uncertainty and is preferred when available.

The proportionality constant between the instantaneous luminosity and the HF/pixel response is calibrated by performing an absolute luminosity measurement. For a

beam-beam collider, the instantaneous luminosity is given by

$$\mathcal{L} = \frac{N_1 N_2 n_b f_{\text{orbit}}}{2\pi \sigma_x^{\text{eff}} \sigma_y^{\text{eff}}}, \quad (2.9)$$

where N_1 and N_2 are the number of protons per bunch in the two beams, n_b is the number of colliding bunches, f_{orbit} is the orbit frequency, σ_x^{eff} and σ_y^{eff} are the effective widths of the beam in the x and y dimensions, and $2\pi\sigma_x^{\text{eff}}\sigma_y^{\text{eff}}$ is the effective overlapping area of the two beams. The measured electric current of the beam gives N_1 and N_2 , and the bunch filling scheme determines n_b . The orbit frequency f_{orbit} is fixed at 11246 Hz. The effective beams widths σ_x^{eff} and σ_y^{eff} are measured in a special run called a *Van der Meer scan* [33]. In a Van der Meer scan, the proton density profile is obtained by incrementally displacing the beams along either the x or y axis and measuring the counting rate (either HF or pixel). The function of the counting rate with respect to the displacement is fit with the sum of two Gaussians. The effective width σ_i is given by the integral of the curve divided by the peak value. Thus, all the variables of Eq. 2.9 are obtained and an absolute luminosity measurement can be made. The proportionality constant between HF towers/pixel clusters and luminosity is calculated as the ratio of the absolute luminosity to the HF/pixel activity during the Van der Meer scan. Once this ratio is known, the instantaneous luminosity can be monitored during a physics run by measuring the HF/pixel activity in events collected with zero-bias triggers.

The integrated luminosities for the 2011 and 2012 physics runs were measured using the pixel cluster counting technique. The integrated luminosity available for analysis is reduced with respect to the delivered luminosity because of detector down-time. The usable $\sqrt{s} = 7$ TeV pp collision data recorded by CMS in 2011 corresponds to an integrated luminosity of 4.9 fb^{-1} , with an uncertainty of 2.2%. The usable $\sqrt{s} = 8$ TeV pp collision data recorded in 2012 corresponds to an integrated luminosity of 19.5 fb^{-1} , with an uncertainty of 4.4%.

Chapter 3

Event Reconstruction

3.1 Tracks

Charged particle tracks are reconstructed by connecting hits in the silicon tracker. The path of a charged particle in the solenoidal magnetic field of the CMS magnet is a helix. The reconstruction of a track starts with a doublet or triplet of pixel hits. The track is extrapolated outward using the *Kalman filter* [34]. The Kalman filter estimates the track parameters based on the hits currently in the track and predicts the path of the particle. At the next layer of the silicon tracker, hits that are compatible with the predicted path are added to the track and the track parameters are updated with information from the new hits. A new path prediction is computed using the updated track parameters and the next layer of the tracker is checked for compatible hits. This process repeats until the track has been extrapolated through the entire silicon tracker. Once the track is complete, the associated hits are removed from the hit collection and the tracking algorithm searches for another track based on the remaining hits. The tracking algorithm continues until all hits have been associated with a track or determined to be spurious.

Tracking efficiency has been studied in simulations of pions and muons. Noise and occupancy effects are taken into account by embedding the simulated tracks into events collected with a minimum-bias trigger [35]. This embedding method allows acceptance and reconstruction effects to be studied separately by measuring the

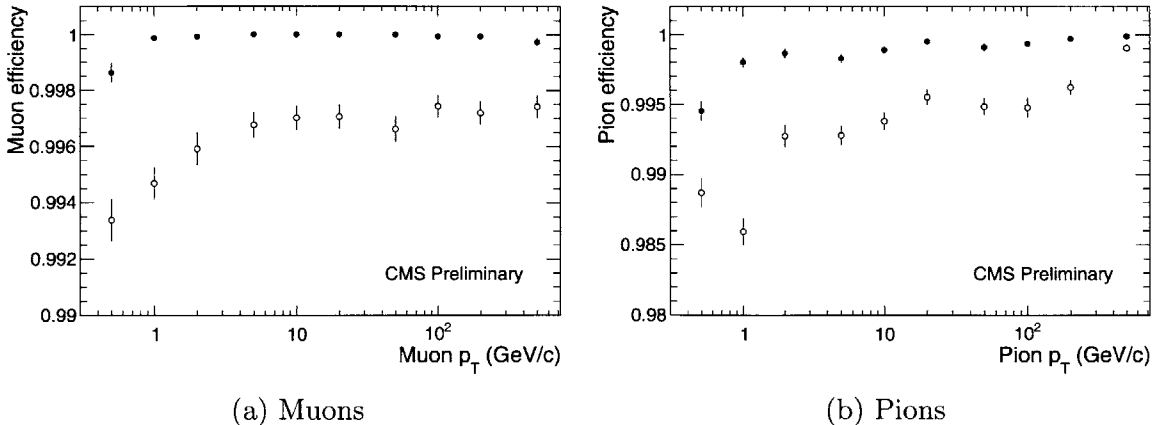


Figure 3-1: Tracking efficiency of simulated (a) muons and (b) pions. Solid circles represent the tracking efficiency in completely simulated events. Open circles represent the tracking efficiency of simulated muons and pions embedded in minimum-bias events [35].

efficiency before and after embedding the track into a minimum-bias event. Figure 3-1 shows the tracking efficiency of pions and muons. Tracking efficiency remains above 99% for muons and 98.5% for pions even after embedding the tracks into minimum-bias events.

Track momentum resolution has been measured from muons in $J/\psi \rightarrow \mu\mu$ events [36]. Track momentum resolution is measured by fitting a Crystal Ball convoluted with a Gaussian, plus an exponential background, to the $J/\psi \rightarrow \mu\mu$ lineshape. A narrower mass peak indicates better momentum resolution, while a broader peak indicates lower resolution. Figure 3-2 shows the momentum resolution derived in this manner; the resolution was found to be 1 – 2% in the central detector region and 3% in the forward regions.

3.2 Primary Vertex

Since the bunch length at the LHC is ~ 8 cm, there is a relatively large longitudinal range within which the pp hard scatter of a bunch crossing can occur. The primary vertex is defined as the position of the pp hard scatter within the beam spot. The primary vertex is reconstructed from the tracks of charged particles produced in

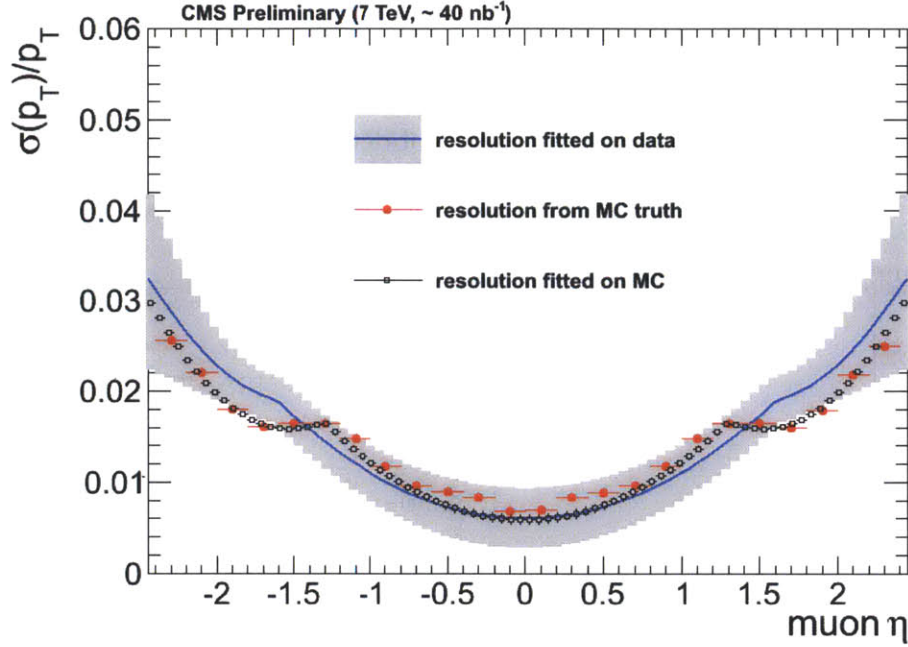


Figure 3-2: Momentum resolution obtained from a fit of the $J/\psi \rightarrow \mu\mu$ mass peak, in data and Monte Carlo simulation.

the collision. The primary vertex is reconstructed by clustering tracks using the *deterministic annealing method* [37] and then fitting each track cluster to find the common origin point of its tracks. The primary vertex is required to pass the quality cuts listed in Table 3.1. If multiple primary vertices are found in an event, the one with the highest scalar sum of track p_T is selected.

Primary vertex resolution was studied in early 7 TeV data [38]. The resolution of the transverse and longitudinal position is shown in Figure 3-3. For primary vertices with over 30 tracks, the resolution is $\sim 25 \mu\text{m}$. Precise determination of vertex position and separation between vertices is an important component of dealing with pileup interactions. The association of tracks with the correct vertex is crucial in reducing the effect of pileup on lepton isolation, jet energy, and missing transverse energy.

Primary Vertex Variable		
Number of degrees of freedom in fit	$\geq$	4
$ z_{\text{vtx}} $	$\leq$	24 cm
Distance from nominal origin of detector	$\leq$	2 cm

Table 3.1: Primary vertex selection requirements.

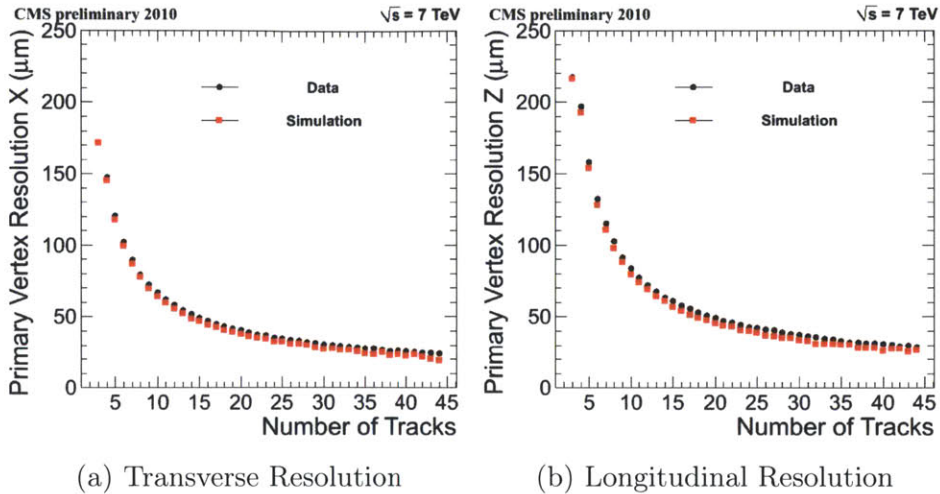


Figure 3-3: Position resolution of primary vertex reconstruction in early 7 TeV collision data in the transverse and longitudinal directions [38].

3.3 Electron Reconstruction

Electron reconstruction [39] starts with superclusters, groups of crystal clusters in the ECAL. In the barrel, a supercluster is seeded by a 5×1 crystal cluster, oriented along η , which surpasses the seed energy threshold. Because electrons and positrons within the electromagnetic shower will spread out in the ϕ direction, the initial supercluster is iteratively expanded to include adjacent 5×1 clusters along ϕ in order to capture the full energy of the shower. In the endcap, a supercluster starts as a 5×5 crystal cluster centered on a seed crystal. If a crystal on the supercluster's perimeter contains a large amount of energy (implying the shower is larger than the initial supercluster), a 5×5 crystal array centered on that crystal is added to the supercluster; this procedure is repeated until no perimeter crystal exceeds the given energy threshold. On average, a supercluster contains more than 97% of the energy deposited by a showering particle.

In addition to depositing its energy in the ECAL, an electron also creates a track in the silicon tracker. An electron passing through the tracker has non-Gaussian

energy loss due to bremsstrahlung. Thus, the Kalman filter, which assumes Gaussian uncertainties, does not perform optimally for electron tracking. Instead of the Kalman Filter, electron tracking is done by the Gaussian Sum Filter, which uses a sum of Gaussian distributions as an uncertainty model. Electron tracks reconstructed using the Gaussian Sum Filter (*GSF tracks*) are better able to take into account the energy loss described by the Bethe-Heitler model. GSF tracks are seeded by pixel hits that are close to superclusters in $\eta - \phi$ space. If the GSF track propagates to the supercluster, the GSF track and supercluster are combined to form a *GSF electron*. The GSF electron energy is taken as the weighted mean of the track momentum and the ECAL energy; in case of significant disagreements between the two quantities, the momentum is taken from the track for low momentum electrons, otherwise the ECAL energy takes precedence. GSF electrons form the basis for further selection of electron candidates.

3.4 Muon Reconstruction

Muons are reconstructed by linking hits in the muon stations to form segments. The segments are then assembled into muon tracks using the Kalman filter. *Standalone muons* are reconstructed using only hits in the muon system. A *global muon* is created from a standalone muon by finding a matching track in the silicon tracker. The kinematic parameters of a global muon are determined by a fit to both the muon system hits and the silicon tracker hits. As an alternative to the standalone and global muons, a *tracker muon* is a muon candidate that starts with a track in the silicon tracker which is matched to a segment in a muon station. The parameters of a tracker muon are based solely on the track within the silicon tracker. Muon selection can require that muons are reconstructed as any or all of these three muon candidate types.

Muon tracking efficiency has been studied in $J/\psi \rightarrow \mu\mu$ events [35]. Figure 3-4 shows the muon efficiency as a function of muon pseudorapidity. For muons with $p_T > 1.5 \text{ GeV}$, muon tracking efficiency was found to be above 98% in all regions of

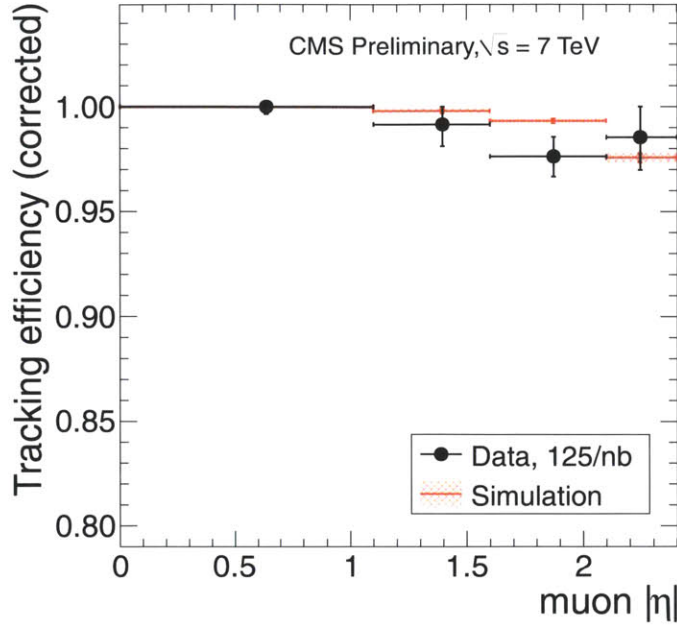


Figure 3-4: Muon efficiency measured in $J/\psi \rightarrow \mu\mu$ events as a function muon pseudorapidity [35].

the tracker.

3.5 Particle Flow

The Particle Flow (PF) framework is an attempt to reconstruct and identify every stable particle in an event by combining information across all sub-detectors [40]. The particles reconstructed by the PF algorithm are called *PF candidates*. There are five types of PF candidates: 1) charged hadrons, 2) neutral hadrons, 3) electrons, 4) muons, and 5) photons.

Particle Flow was designed for the reconstruction of jets and missing transverse energy, both of which involve measuring a mixture of charged and neutral hadrons. Particle flow attempts to resolve the individual constituents of a jet so that the momenta of charged hadrons and electromagnetic particles can be measured with high resolution by the silicon tracker and ECAL, respectively, while only neutral hadrons need to be measured by the relatively low resolution HCAL. This requires advanced algorithms to disentangle the energy deposited in the calorimeters by different par-

ticles so that particle energy is not double-counted. This approach also has the advantage of ensuring that the reconstructed particles are mutually exclusive and do not overlap.

The Particle Flow algorithm begins by constructing particle components in each sub-detector that will later be linked together. In the silicon tracker, a track constitutes a single component. In the calorimeters, crystals/towers are grouped into *Particle Flow clusters*, each corresponding to a single particle. A Particle Flow cluster is seeded by a crystal/tower that exceeds a given energy threshold. The cluster is iteratively expanded by incorporating adjacent crystals/towers whose energy is twice the noise level. In the muon system, muon segments are treated as PF components.

The next step of the Particle Flow algorithm is to link together the components created in each sub-detector to form *Particle Flow blocks*. A track is linked to a Particle Flow cluster if the extrapolated position of the track falls within the boundaries of that cluster. A Particle Flow cluster in the ECAL is linked to a cluster in the HCAL if the center of the ECAL cluster is within the $\eta - \phi$ boundaries of the HCAL cluster. A segment in the muon system is linked to a track in the silicon tracker if a fit of the two tracks has a sufficiently low χ^2 .

After linking, blocks may have overlapping elements. These ambiguities are resolved by an iterative process of assigning blocks and their elements to distinct PF candidates, starting with the cleanest physics objects (leptons) and proceeding to the more ambiguous objects (hadrons). The PF candidate types are described in the following list:

- *PF muons* are seeded by global muons. The only additional requirement for PF muons is that the E_T sum of tracks and calorimeter deposits within $\Delta R < 0.3$ ($\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$) of the muon (but not associated with the muon itself) must be less than 10% of the muon p_T . The PF blocks matching a reconstructed muon are assigned to that muon and the associated PF elements are removed from all other PF blocks.
- *PF electrons* are seeded by GSF electrons. The block corresponding to the GSF

electron must contain a track and PF cluster, and must pass a multivariate discrimination algorithm trained to distinguish electrons from pions using track and calorimeter information. Bremsstrahlung photons are reconstructed by looking for PF clusters that follow the tangent of the track at each tracker layer. These bremsstrahlung photons are associated with the PF electron. The PF elements associated with the PF electron (both the electron itself and radiated photons) are removed from the other PF blocks.

- *PF charged hadrons* are constructed from the remaining PF blocks which contain both PF clusters and tracks. Each track leads to the creation of a PF charged hadron. If the PF cluster contains more energy than the total track momentum, then PF photons and PF neutral hadrons are created, depending on whether the energy excess is in the ECAL or HCAL. If the PF cluster contains less energy than the total track momentum, loose muons are identified and the associated track and energy are removed.
- *PF photons* are generated from PF clusters in the ECAL that are not linked with a track. *PF neutral hadrons* are generated from PF clusters in the HCAL that are not linked with a track.

The PF candidates of an event are used for lepton isolation, tau reconstruction, jet reconstruction, and missing energy measurements. Lepton selection in this analysis uses the dedicated reconstruction algorithms described in Sections 3.3 and 3.4 rather than their Particle Flow counterparts.

3.6 Jet Reconstruction

When a quark or gluon is emitted in a pp collision, it decays via QCD interactions into multiple hadrons. These hadrons collectively carry the same momentum as the original quark or gluon and the boost causes them to form a collimated stream of particles called a *jet*. Jets are reconstructed by clustering PF candidates using the anti- k_T algorithm [41]. The anti- k_T algorithm is an iterative clustering algorithm that

begins by computing the “distance” between every pair of particles and between every particle and the beam line,

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{\Delta R_{ij}^2}{R_0^2}, \quad (3.1)$$

$$d_{iB} = p_{T,i}^{-2}, \quad (3.2)$$

where d_{ij} is the distance between particles i and j , d_{iB} is the distance between particle i and the beam line, $\Delta R_{ij}^2 = \Delta\eta_{ij}^2 + \Delta\phi_{ij}^2$, and R_0 is a distance scale parameter, chosen to be 0.5. The smallest distance is found and the two particles i and j are combined into a pseudo-jet. If the smallest distance is d_{iB} , then entity i (which may be a particle or a pseudo-jet) is deemed a jet and removed from the collection of entities. This process repeats on the remaining particles and pseudo-jets until there is none left. Jets reconstructed from PF candidates are called *PF jets*.

Jet Energy Scale

The momentum of a PF jet is initially computed as the sum of the momenta of the PF candidates that make up the jet. The jet energy is then adjusted to compensate for non-linearities in detector response and to recover the original parton energy [42].

The jet energy correction is factorized into three steps:

1. The first correction is to remove energy from pileup particles. The pileup energy is estimated by dividing the (η, ϕ) space into tiles and computing the energy density in each tile [43]. The median energy density is labeled ρ and is taken as an estimate of the pileup energy density throughout the detector for that event. The jet energy is corrected for pileup by subtracting the product of ρ and the jet area in (η, ϕ) space [44, 45].
2. The second jet energy correction produces a flat η response. Jet energies are scaled to match (on average) jet energies measured in the central region $|\eta| < 1.3$.
3. The correction factors are derived in data by examining di-jet balance in multi-jet events.

3. The third jet energy correction produces a flat p_T response. The jet energy is corrected such that on average it is equal to the energy of the original quark or gluon. The correction factors are derived in data by examining transverse energy balance in $Z/\gamma + \text{jets}$ events.

After these corrections are applied, the jet energy scale uncertainty ranges from 1% to 3% for jets in the central detector region and rises to 5% for jets in the endcap ($|\eta| \gtrsim 2.3$) [46].

3.7 Hadronic Tau Decay

The majority of taus decay into hadrons (branching ratio $\approx 65\%$). These tau decays appear as streams of collimated hadrons similar to quark and gluon jets but typically contain fewer particles. The visible particles in a hadronic tau decay are denoted with the symbol τ_h . Tau reconstruction is based on searching PF jets for combinations of PF candidates that match tau decay patterns.

Reconstruction of hadronic tau decays is handled by the *Hadron-plus-Strips* (HPS) algorithm. The algorithm searches every PF jet for a combination of charged PF candidates and ECAL deposits (PF photons and electrons) that match a tau decay mode. The charged hadrons are the stable decay products of the tau, while the ECAL deposits are meant to reconstruct $\pi^0 \rightarrow \gamma\gamma$, including photons that have converted into electrons. Since the electrons from converted photons will be deflected in the ϕ direction by the CMS magnet, the ECAL deposits are searched for within geometric “strips” with $\eta \times \phi$ dimensions 0.05×0.20 (hence *strips* in the algorithm name Hadron-plus-Strips). The most common hadronic tau decays fall into three categories (Figure 3-5):

1. one charged hadron* (BR = 11.54%),
2. one charged hadron with one or more π^0 s (BR = 36.57%),
3. three charged hadrons (BR = 9.80%).

* *Charged hadron* here refers to either $\pi^\pm$ or $K^\pm$.

The first decay mode is simply a charged PF candidate. As most jets contain at least one charged hadron, identification of this decay mode relies heavily on the isolation requirement (see Section 4.2.6).

The second decay mode is characterized by one charged PF candidate along with ECAL deposits in one or two $\eta - \phi$ strips. If there is only one strip and it consists of multiple PF candidates, its mass is required to be in the range $50 \text{ MeV} < m_{\text{strip}} < 200 \text{ MeV}$, to be broadly consistent with the mass of the π^0 . Similarly, if there are two strips, the mass of both strips together is required to be within that interval; the photons from the π^0 are assumed to have separated enough to make two separate ECAL deposits. The mass of the hadron and EM strips together is required to be within $0.3 \text{ GeV} < m_\tau < 1.3 \text{ GeV}$ because this type of decay primarily proceeds through a $\rho(770)$ meson intermediary.

The third decay mode is characterized by three charged PF candidates and no EM strips. The tracks are required to be within $|d_z| < 0.2 \text{ cm}$ of each other, to ensure that they all originated from the same vertex. A mass cut of $0.8 < m_\tau < 1.5$ is applied to the tau decay system to match the $a(1260)$ resonance.

In addition to matching a tau decay mode, a potential tau candidate is required to be within $\Delta R < 0.1$ of the PF jet axis. The charge of the tau candidate (computed as the total charge of its constituents) must be ± 1 . Finally, the tau constituents must be contained within a cone whose radius depends on the p_T of the tau,

$$\Delta R = \begin{cases} 0.10 & p_T^{\tau_h} < 28 \text{ GeV} \\ \frac{2.8 \text{ GeV}}{p_T^{\tau_h}} & 28 \text{ GeV} < p_T^{\tau_h} < 56 \text{ GeV} \\ 0.05 & p_T^{\tau_h} > 56 \text{ GeV}. \end{cases} \quad (3.3)$$

If multiple tau candidates are found within a jet, the highest p_T tau candidate is taken. The other particles in the jet are used in determining whether the tau candidate is sufficiently isolated. The absolute efficiency of tau selection (including tau isolation, see Section 4.2.6) is approximately 60%. A more precise determination of the tau selection efficiency is given in Section 5.3.2.

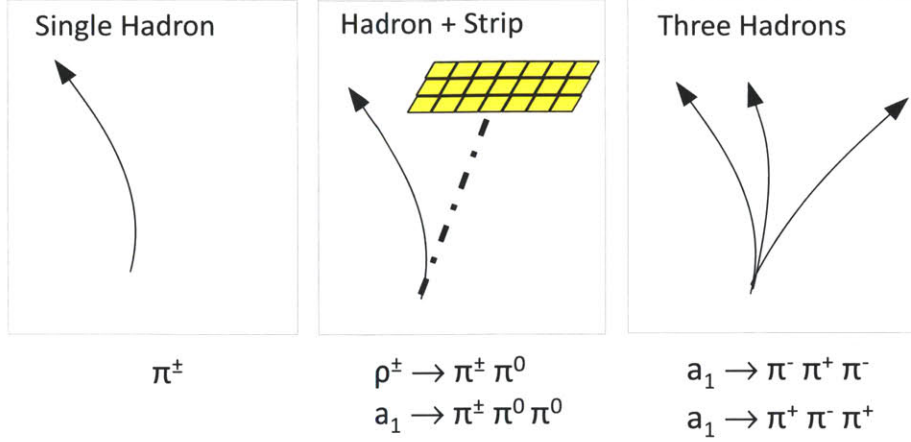


Figure 3-5: The HPS algorithm searches for three types of hadronic tau decays: one charged hadron (left), one charged hadron plus EM strips (middle), and three charged hadrons (right).

3.7.1 Tau Energy Scale

Due to differences between the detector simulation and the actual detector, the energy response to simulated taus in Monte Carlo events can differ from that in data. The energy response is parameterized as

$$E_\tau^{\text{data}} = \alpha_\tau E_\tau^{\text{MC}} \quad (3.4)$$

where E_τ^{data} and E_τ^{MC} are the tau energy measured in data and simulation, respectively, and α_τ is the tau energy scale.

The tau energy scale is measured in the m_{τ_h} distribution of $Z \rightarrow \tau_\mu \tau_h$ events. The $\tau_\mu \tau_h$ events are selected according to the requirements described in Chapter 4. Fit models for m_{τ_h} are generated using the methods described in Chapter 6 and are fit to the m_{τ_h} distribution in data, allowing α_τ to float as a free parameter in the fit. The fits are performed separately for each tau decay mode. The fit results are shown in Figures 3-6 and 3-7. The tau energy scales for 2011 data/MC are measured to be $\alpha_\tau = 1.0106 \pm 0.0028$ for tau decays with one charged hadron and $\alpha_\tau = 1.0099 \pm 0.0026$ for tau decays with three charged hadrons. The fit results for 2012 data are $\alpha_\tau = 1.0145 \pm 0.0015$ for tau decays with one charged hadron and $\alpha_\tau = 1.0096 \pm 0.0016$ for tau decays with three charged hadrons.

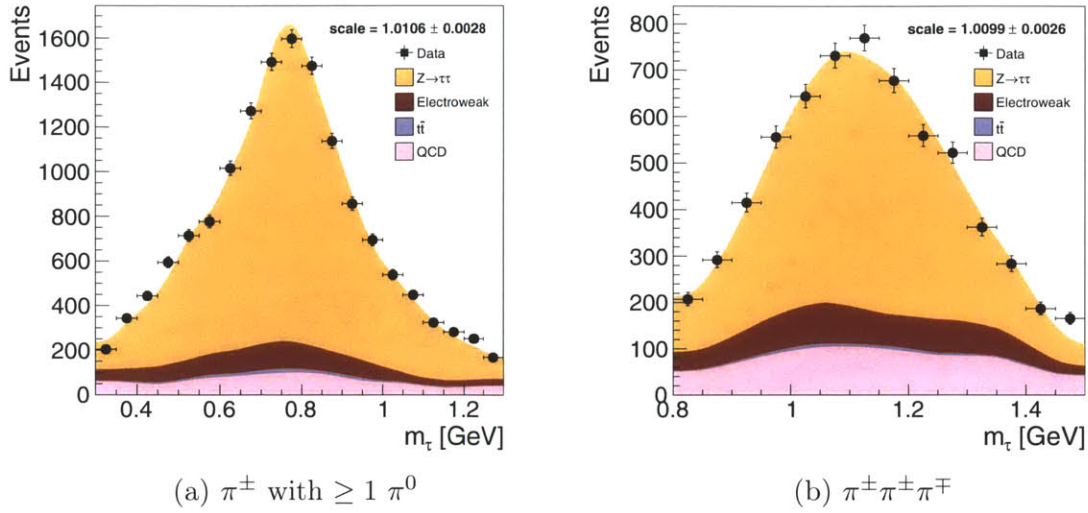


Figure 3-6: The tau energy scale is measured by fitting the m_{τ_h} distribution. A separate fit is performed for each tau decay mode. These results are for 2011 data and MC.

The systematic uncertainty due to the choice of parameterization is estimated by performing the fit with the $Z \rightarrow \tau\tau$ template convolved with a Gaussian resolution function, rather than using an energy scale parameter. Comparisons with the alternative fit give a systematic uncertainty of $\sim 2\%$.

3.8 Missing Transverse Energy

In a pp collision, the incoming particles have negligible transverse momentum. Therefore, the total transverse momentum of the collision products must be approximately zero, due to momentum conservation. Any significant deviations from zero transverse momentum indicate the presence of undetectable particles, such as neutrinos. The transverse energy that is needed to balance an event is called *missing transverse energy* and is denoted $\cancel{E}_T$. The missing transverse energy plays an important role in di-tau events because of the neutrinos in the final state. The missing transverse energy is used in the identification of di-tau events and to estimate the di-tau mass (Section 3.9).

The $\cancel{E}_T$ in this analysis is calculated using PF candidates. However, rather than

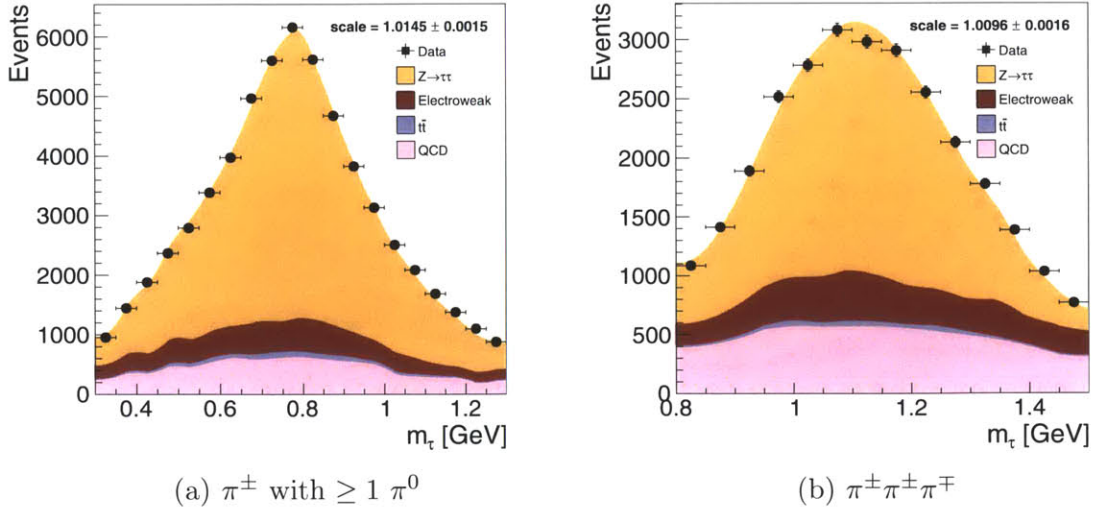


Figure 3-7: The tau energy scale is measured by fitting the m_{τ_h} distribution. A separate fit is performed for each tau decay mode. These results are for 2012 data and MC.

simply taking the negative vectorial p_T sum of all PF candidates, a multivariate regression is applied to compensate for errors due to mis-measurements of visible particles. Furthermore, the differences in the hadronic recoil (a large source of error for $\cancel{E}_T$) between data and Monte Carlo are measured in $Z \rightarrow \mu\mu$ events and the Monte Carlo is corrected to match the data.

Multivariate $\cancel{E}_T$ Regression

Ideally, $\cancel{E}_T$ would be exactly equal to the transverse momentum of the invisible particles (e.g. neutrinos) in an event. However, $\cancel{E}_T$ can also arise from poor measurements of visible particles, such as the case where a hadron does not deposit all of its energy in the calorimeters. These mis-measured particles generate “false” $\cancel{E}_T$ and degrade the accuracy of the $\cancel{E}_T$ measurement. Pileup interactions also add a random component to the missing transverse energy. To remedy these sources of error, a multivariate regression is employed to compute $\cancel{E}_T$. This method of computing the missing transverse energy is called MVA PF $\cancel{E}_T$.

The multivariate $\cancel{E}_T$ regression takes as input the vectorial and scalar p_T sums of the following classes of PF candidates:

1. All PF candidates,
2. Charged PF candidates from the primary vertex,
3. Charged PF candidates from the primary vertex plus neutral particles in jets that pass the jet ID (Section 4.2.7),
4. Charged PF candidates from pileup vertices plus neutral particles in jets that fail the jet ID,
5. Charged PF candidates from the selected primary vertex, plus neutral particles in jets that pass the jet ID, plus unclustered neutral particles.

In all cases, the two selected leptons of the event are excluded from the p_T sum. The MVA regression is trained on $Z \rightarrow \mu\mu$ events; the regression target is the vector which balances the di-lepton momentum (the true hadronic recoil momentum is the opposite of the di-lepton momentum). Both the direction and the magnitude of the hadronic recoil is regressed. The $\cancel{E}_T$ is then calculated as the negative vector sum of the regressed hadronic recoil $\mathbf{u}$ and the di-lepton momentum $\mathbf{q}$,

$$\cancel{E}_T = -(\mathbf{u} + \mathbf{q}). \quad (3.5)$$

In addition to the input variables listed above, the MVA PF $\cancel{E}_T$ also takes the four-vectors of the two highest p_T jets and the number of vertices in the event. The jet four-vectors provide additional information about the hadronic recoil. The number of vertices gives the MVA a measure of the amount of pileup in the event, helping it to better counteract the effect of pileup.

Recoil Corrections

Due to inaccuracies in the hadronic recoil simulation, a correction is applied to the scale and resolution of the MVA PF $\cancel{E}_T$ in Z , W , and Higgs MC samples. The hadronic recoil momentum $\mathbf{u}$ is measured in $Z \rightarrow \mu\mu$ events in data. The vector $\mathbf{u}$ is decomposed into a component parallel to the Z boson, $u_{\parallel}$, and a component

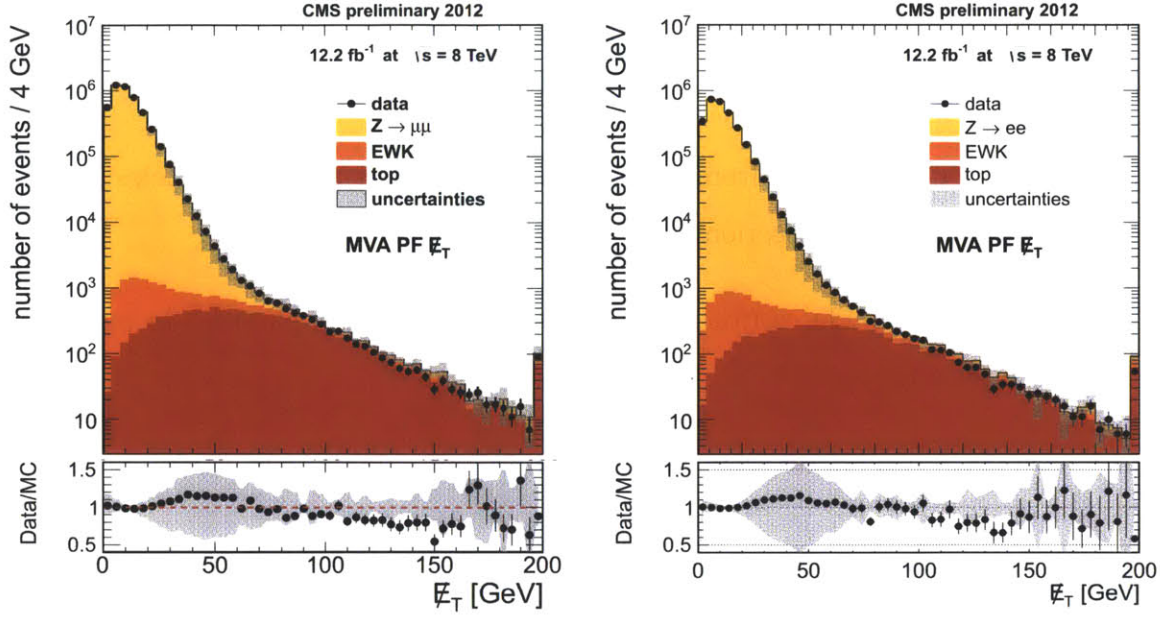


Figure 3-8: MVA PF $\cancel{E}_T$ in $Z \rightarrow \mu\mu$ events (left) and $Z \rightarrow ee$ events (right) [47]. Recoil corrections have been applied to the Monte Carlo.

perpendicular to the Z boson, $u_\perp$. The scale (i.e. average response) and resolution of $u_\parallel$ and $u_\perp$ are calculated in bins of p_T^Z and the number of jets. The scale is fit with a first-order polynomial in p_T^Z while the resolution is fit with a third-order polynomial in p_T^Z . The same procedure for measuring the scale and resolution of the recoil is repeated for a $Z \rightarrow \mu\mu$ Monte Carlo sample. A scale correction for the response is obtained by taking the ratio of the response function in data to the response function in Monte Carlo. A resolution correction is computed by subtracting the Monte Carlo resolution function in quadrature from the data resolution function. The scale and resolution corrections are applied to the hadronic recoil in Z , W , and Higgs Monte Carlo events as a function of the boson p_T and jet multiplicity. The $\cancel{E}_T$ in the simulation is then re-computed as the negative vectorial sum of the lepton p_T and the corrected hadronic recoil. Overall, the $\cancel{E}_T$ response in simulation is reduced by $\sim 4\%$ and the resolution is smeared by $\sim 6\%$ [47]. The distributions of MVA PF $\cancel{E}_T$ in $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events from 2012 data along with recoil-corrected simulation are shown in Figure 3-8.

3.9 Di-Tau Mass Reconstruction

The mass of the di-tau system would be a useful variable for distinguishing $H \rightarrow \tau\tau$ events from $Z \rightarrow \tau\tau$ events. However, because energy in a di-tau event escapes undetected via one or more neutrinos, it is impossible to compute exactly the mass of the original di-tau system. Alternatives to the di-tau mass include the visible mass (i.e. the mass of the visible tau decay products) or the collinear approximation [48], a calculation that assumes the neutrinos are collinear with the visible components of the tau. The disadvantage of the visible mass is that it does not take into account the missing transverse energy of the system and therefore tends to have a broader spectrum than methods which make use of the missing transverse energy. The disadvantage of the collinear approximation is that it breaks down for events in which the taus are back-to-back in the laboratory frame, as the system becomes under-determined.

Rather than use the visible mass or collinear approximation, this analysis uses a likelihood-based algorithm called *SVFit**. The SVFit algorithm estimates $m_{\tau\tau}$ by maximizing the likelihood of the tau decay kinematics, given measurements of the visible tau decay products and $\cancel{E}_T$. In a semi-leptonic tau decay, $\tau \rightarrow \tau_h \nu_\tau$, there are two unknown parameters:

1. the visible energy fraction, $x_h = E_{\tau_h}/E_\tau$,
2. the azimuthal angle ϕ_h of the visible decay products about the tau's direction of flight.

In a fully-leptonic tau decay, $\tau \rightarrow \ell \nu_\ell \nu_\tau$, there are three unknown parameters:

1. the visible energy fraction, $x_\ell = E_\ell/E_\tau$,
2. the mass of the two neutrinos, $m_{\nu\nu}$,
3. the azimuthal angle ϕ_ℓ of the lepton around the tau's direction of flight.

*SVFit stands for ‘‘Secondary Vertex Fit.’’ It was originally intended to fit the displaced vertices of tau decays but that functionality was never fully implemented.

The differential decay width for semi-leptonic decays is derived solely from phase-space considerations and is taken as a uniform distribution on the physically allowed range of x_h , $m_{\tau_h}^2/m_\tau^2 \leq x_h \leq 1$. The semi-leptonic decay width is hence

$$\frac{d\Gamma}{dx_h} = \frac{\Gamma_{\text{tot}}}{1 - m_{\tau_h}^2/m_\tau^2}, \quad (3.6)$$

where m_{τ_h} is the mass of the visible tau decay products and Γ_{tot} is the total decay width.

The decay width for fully-leptonic decays is more complicated because of the additional parameter $m_{\nu\nu}$ [49]. The decay width is given by

$$\frac{d\Gamma}{dx_\ell dm_{\nu\nu}} \propto \frac{m_{\nu\nu}}{4m_\tau^2} (m_\tau^2 + 2m_{\nu\nu}^2) (m_\tau^2 - m_{\nu\nu}^2). \quad (3.7)$$

The measured $\cancel{E}_T$ in an event also constrains the di-tau system. It approximates the sum p_T of the three neutrinos ν_ℓ , ν_τ , and $\bar{\nu}_\tau$. The uncertainty of the $\cancel{E}_T$ measurement is calculated by the MVA PF $\cancel{E}_T$ regression as a covariance matrix,

$$\mathbf{V} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix}, \quad (3.8)$$

where σ_{ij} is the covariance along the i and j axes. The missing transverse energy is incorporated into the SVFit likelihood as

$$L(\cancel{E}_T | x_h, x_\ell, m_{\nu\nu}, \phi_h, \phi_\ell) = \frac{1}{\sqrt{2\pi|\mathbf{V}|}} \exp \left[\frac{1}{2} \Delta \cancel{E}_T^T \mathbf{V}^{-1} \Delta \cancel{E}_T \right], \quad (3.9)$$

where $\Delta \cancel{E}_T$ is the vectorial difference between the measured $\cancel{E}_T$ and the sum p_T of the neutrinos,

$$\Delta \cancel{E}_T = \left(\cancel{E}_T - \sum \mathbf{p}_T^\nu \right), \quad (3.10)$$

which depends on the parameters x_h , x_ℓ , $m_{\nu\nu}$, ϕ_h , and ϕ_ℓ .

The overall SVFit likelihood is

$$L_{\text{SVFit}}(m_{\tau\tau}|\mathbf{p}_\ell, \mathbf{p}_\tau) = \int \frac{d\Gamma_1}{dx_h} \frac{d\Gamma_2}{dx_\ell dm_{\nu\nu}} \times L(\cancel{E}_T) \times \delta(m_{\tau\tau} - M_{\tau\tau}) dx_h dx_\ell dm_{\nu\nu} d\phi_h d\phi_\ell, \quad (3.11)$$

where $M_{\tau\tau}$ is the di-tau mass computed from $\mathbf{p}_\ell, \mathbf{p}_\tau$, and the hypothesized kinematic parameters x_ℓ, x_h , and $m_{\nu\nu}$. The decay width is assumed to be constant with respect to ϕ , i.e. $\frac{d\Gamma}{d\phi} = \frac{1}{2\pi}$, a constant multiplicative factor that can be ignored in the likelihood. The integral is numerically computed with the VEGAS program [50]. The $m_{\tau\tau}$ parameter is scanned in steps of 2.5 GeV from 0 to 100 GeV, then in steps of 2.5% up to 3 TeV. A quadratic fit is performed on the likelihood-maximizing value of $m_{\tau\tau}$ found in the scan and its two neighboring points. The value of $m_{\tau\tau}$ at the peak of the parabola is returned from the SVFit algorithm as the best estimate of $m_{\tau\tau}$. The SVFit mass has a resolution of 15 – 20%.

Chapter 4

Event Selection

Once events are reconstructed, events containing a lepton and an HPS tau are selected for further analysis. Event selection criteria are driven by the goal of choosing signal events and rejecting background events. The first step is to select events that have passed a relevant trigger path. The second step is to examine offline reconstructed physics objects, which contain more accurate information and have better resolution than the data available to the trigger system. Third, several event topology cuts are made to reject certain backgrounds. Events which pass the selection criteria are divided into categories based on their jet configuration and tau momentum; the use of these categories increases the search sensitivity.

4.1 Trigger

The event selection starts with selecting events that pass the desired trigger paths. The trigger paths for the $\tau_\ell\tau_h$ final state require two objects to be reconstructed by the HLT, one for the electron or muon and the other for the τ_h . For the $\tau_e\tau_h$ channel, the HLT reconstructs an electron based on track and ECAL information. The electron must satisfy identification and isolation requirements imposed on track and calorimeter variables. For $\tau_\mu\tau_h$, the HLT reconstructs a muon from silicon tracker and muon system data. The muon is required to be loosely isolated. The τ_h trigger object is based on a simplified version of the Particle Flow algorithm. The trigger

HLT Path	L1 Seed	Lumi [pb ⁻¹]
2011		
HLT_Ele15_*_LooseIsoPFTau15	L1_SingleEG12	168.8
HLT_Ele15_*_LooseIsoPFTau20	L1_SingleEG12	957.3
HLT_Ele15_*_TightIsoPFTau20	L1_SingleEG12	834.0
HLT_Ele18_*_MediumIsoPFTau20	L1_SingleEG12	2092.3
HLT_Ele20_*_MediumIsoPFTau20	L1_SingleEG18	883.3
* substitutes for CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT		
2012		
HLT_Ele20_*_LooseIsoPFTau20	L1_SingleIsoEG18er	895.5
	L1_SingleEG20	
HLT_Ele22_eta2p1_WP90Rho_LooseIsoPFTau20	L1_SingleIsoEG18er	18571.1
	L1_SingleIsoEG20er	
	L1_SingleEG22	
* substitutes for CaloIdVT_CaloIsoRhoT_TrkIdT_TrkIsoT		

Table 4.1: The HLT paths and L1 seeds for the $\tau_e\tau_h$ channel. The table also shows the integrated luminosity collected by each trigger path.

system treats any isolated jet with low particle multiplicity as a τ_h candidate. The τ_h trigger candidate is required to be adequately isolated.

The $\tau_e\tau_h$ trigger paths used in this analysis are given in Table 4.1. The $\tau_\mu\tau_h$ trigger paths are given in Table 4.2. The p_T thresholds were raised over time to maintain a reasonable trigger rate as the instantaneous luminosity of the LHC increased. Since electrons are more frequently faked than muons, the p_T , identification, and isolation requirements for the $\tau_e\tau_h$ triggers are generally more stringent than those of the $\tau_\mu\tau_h$ triggers.

In the Monte Carlo, only one trigger path is used per channel per year. Correction factors (Section 5.2) are applied to match the Monte Carlo trigger efficiency with the evolving trigger paths in data. The trigger paths used in Monte Carlo are summarized in Table 4.3.

4.2 Object Selection

After trigger selection, events are selected on the basis of the reconstructed objects they contain. The object reconstruction described in Chapter 3 provides the initial

HLT Path	L1 Seed	Lumi [pb ⁻¹]
2011		
HLT_IsoMu12_LooseIsoPFTau10	L1_SingleMu7	177.6
HLT_IsoMu15_LooseIsoPFTau15	L1_SingleMu10	2082.4
HLT_IsoMu15_eta2p1_LooseIsoPFTau20	L1_SingleMu14_Eta2p1	2674.6
2012		
HLT_IsoMu18_eta2p1_LooseIsoPFTau20	L1_SingleMu16er	895.5
HLT_IsoMu17_eta2p1_LooseIsoPFTau20	L1_SingleMu14er	18571.1

Table 4.2: The HLT paths and L1 seeds for the $\tau_\mu\tau_h$ channel. The table also shows the integrated luminosity collected by each trigger path.

Channel	Year	HLT Path
$\tau_e\tau_h$	2011	HLT_Ele18_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_MediumIsoPFTau20
	2012	HLT_Ele22_eta2p1_WP90Rho_LooseIsoPFTau20
$\tau_\mu\tau_h$	2011	HLT_IsoMu15_LooseIsoPFTau15
	2012	HLT_IsoMu17_eta2p1_LooseIsoPFTau20

Table 4.3: The HLT paths used in Monte Carlo simulation, by decay channel and year.

ingredients for understanding an event but does little to reject fakes and backgrounds. Leptons, HPS taus, and jets are required to pass additional requirements to reject fakes and ensure the quality of the reconstructed object.

Reconstructed electrons and muons are required to pass two selection steps before being considered for further analysis. The first step is called *identification* and examines the lepton object itself, including track quality and calorimeter deposits. The second step is called *isolation* and considers the particles surrounding the physics object to determine whether it is isolated; isolation is crucial in discriminating against jets that may have faked the lepton. Electrons and muons have separate identification requirements but share the same method of assessing isolation.

HPS taus also undergo identification and isolation procedures. The identification step is mainly to reject electrons and muons that may have faked the τ_h . The isolation requirement is the main technique for distinguishing a τ_h from a quark or gluon jet.

4.2.1 Boosted Decision Trees

Conventionally, object selection is based on applying cuts on object variables, e.g. requiring a variable to be above a given threshold. Cuts are a simple approach to selection but usually do not take advantage of correlations between variables. Multivariate methods, on the other hand, are able to take into account the joint distributions of multiple variables in a systematic way. One such method is the *boosted decision tree* (BDT) [51]. A single decision tree is a binary tree of cuts. An event (or object) is evaluated by starting at the root node and applying the corresponding cut; whether it passes or fails determines which of the two child nodes is next. The event traverses the tree until it reaches a leaf node, which contains a score indicating the likelihood that the event is signal. The cuts of the decision tree and the scores in its leaves are determined by “training” the decision tree on a sample of signal and background events. The training process finds for each node the cut that maximizes the S/B ratio; that cut is then assigned to the node. The process then repeats for the set of events which pass the cut and the set of events which fail the cut, creating the two child nodes. A leaf is created either at a pre-defined depth or when the number of training events falls below a pre-defined minimum. The S/B of the events which reach that leaf determines its score, with higher S/B corresponding to higher scores. A *boosted* decision tree is a collection of such decision trees, where each tree is trained with a different set of event weights. The event weights are determined by increasing the weights of events which have been mis-categorized by previously trained decision trees. This helps subsequent trees to properly categorize the more “difficult” events. The scores from all the trees are combined to produce a joint score for the event, which can be used for a final selection cut. BDTs are used in electron identification, tau identification, and tau isolation.

4.2.2 Electron Identification

Electron identification uses a BDT that has been trained to distinguish real electrons from jets. The BDT uses a multitude of variables related to the electron track and

Input Variables of the Electron ID BDT
f_{brem} , bremsstrahlung energy as a fraction of the electron energy
χ^2 of the Kalman Filter track fit
Number of hits in the Kalman Filter track
χ^2 of the GSF Track fit
Difference between the supercluster η and the η of the track at the vertex
Difference between the supercluster ϕ and the ϕ of the track at the vertex
Difference between the seed cluster η and the η of the track at the ECAL surface
$\sigma_{i\eta i\eta}$, a variable that characterizes the shower shape in the η direction
$\sigma_{i\phi i\phi}$, a variable that characterizes the shower shape in the ϕ direction
Supercluster width in η
Supercluster width in ϕ
Ratio of 1×5 seed cluster energy to 5×5 cluster energy
R_9 , the ratio of 3×3 cluster energy to 5×5 cluster energy
HCAL energy over ECAL energy
$\frac{1}{E_{\text{SC}}} - \frac{1}{P_{\text{track}}}$
Supercluster energy divided by the momentum of the track at the ECAL surface

Table 4.4: Input variables to the electron identification BDT.

supercluster; these input variables are summarized in Table 4.4. The BDT is trained on electrons from a $Z \rightarrow ee$ data sample as signal and jets from $W + \text{jets}$ Monte Carlo as background. Because the detector response has a dependence on the pseudorapidity of the electron, a separate BDT is trained for each of three η regions: the central section of the ECAL barrel ($|\eta| < 0.8$), the forward section of the ECAL barrel ($0.8 < |\eta| < 1.479$), and the ECAL endcap ($|\eta| > 1.479$). By training separately on each of the three regions, each BDT can optimize for the characteristics of its respective detector region.

In addition to the BDT, cuts are applied on the longitudinal and transverse impact parameters d_z and d_0 to ensure compatibility with the primary vertex. However, the impact parameter cuts are made loose enough to retain taus that propagate some distance from the primary vertex before decaying. The electron identification requirements are listed in Table 4.5.

Quantity	Requirement
Electron ID BDT Output, $ \eta < 0.8$	> 0.925
Electron ID BDT Output, $0.8 < \eta < 1.479$	> 0.975
Electron ID BDT Output, $ \eta > 1.479$	> 0.985
$ d_0 $	$< 0.045 \text{ cm}$
$ d_z $	$< 0.2 \text{ cm}$
missing inner hits	< 1

Table 4.5: Electron identification requirements.

Photon Conversion Rejection

A photon passing through the material of the tracker can interact with a nucleus and produce an electron-positron pair. These electrons can be mistaken for electrons produced in the pp interaction. Electrons from photon conversions are rejected in two ways:

- If a photon converts into electrons in the middle of the tracker volume, the electron tracks will be missing hits from the inner layers of the tracker. Electrons that are missing any expected inner hits are rejected as conversion electrons.
- A vertex fit is performed on every pair of co-planar, oppositely charged tracks. If the vertex is more than 2 cm from the primary vertex, the pair of tracks is tagged as a photon conversion and any electron that contains one of these tracks is rejected.

4.2.3 Muon Identification

Muons are easier to identify and less frequently faked than electrons, so the selection criteria are simpler. A muon is required to have been reconstructed as both a tracker muon and a global muon (Section 3.4). Cuts are made on the χ^2 of the global muon track fit, the number of hits and segments in the muon system, the number of hits in the silicon tracker, and the impact parameters d_0 and d_z . As in the case of electrons, the impact parameter cuts are relatively loose because taus can travel a short distance from the primary interaction before decaying. The muon identification cuts are listed in Table 4.6.

Quantity	Requirement
χ^2/ndf	< 10
valid hits	> 0
matching muon segments	> 1
pixel hits	> 0
tracker layers hit	> 5
$ d_0 $	< 0.045
$ d_z $	< 0.2

Table 4.6: Muon identification requirements.

4.2.4 Lepton Isolation

Electrons and muons in QCD multi-jet events tend to be accompanied by hadrons. For example, a muon from a B hadron decay will be surrounded by hadrons created in the decay cascade; a pion which fakes an electron is likely to have been produced as part of a collimated stream of hadrons. On the other hand, an electron or muon produced in a tau decay will usually be isolated from other particles. This distinction is used to further reject backgrounds by requiring electrons and muons to be isolated.

Lepton isolation is quantified by summing the p_T of nearby particles. If this sum is small, the lepton is considered to be isolated. The isolation p_T sum is computed by adding up the p_T of PF candidates within $\Delta R < 0.4$ of the lepton,

$$I_0^{\text{PF}} = \sum_{\substack{\text{PF cands} \\ \Delta R < 0.4}} p_T. \quad (4.1)$$

Depending on the PF candidate type, an inner veto cone (to avoid including the lepton itself) and minimum p_T requirement may be required. The cuts on isolation particles for electrons and muons are given in Tables 4.7 and 4.8, respectively.

Pileup interactions create particles that may enter the isolation cone and cause the rejection of otherwise isolated leptons, thereby reducing selection efficiency. To counteract this loss of efficiency, the isolation p_T sum is corrected for pileup effects. Charged pileup particles can be excluded from the isolation p_T sum by requiring them to have tracks which originate from the selected primary vertex. The association of a track to a vertex is based on the track clustering step of the vertex reconstruction

PF Type	Minimum ΔR
charged particles	0.01 (EB), 0.015 (EC)
neutral hadrons	0
photons	0.08

Table 4.7: Cuts on the PF candidates used in computing electron isolation. EB indicates cuts for electrons in the ECAL barrel; EC indicates cuts for electrons in the ECAL endcap.

algorithm (Section 3.2). Removing the neutral pileup contribution, on the other hand, is more difficult because neutral particles do not leave tracks. Instead of attempting to determine whether an individual neutral particle came from a pileup interaction, the overall neutral pileup contribution is estimated from the p_T of pileup tracks entering the cone (pileup tracks are defined as tracks which are not associated with the selected primary vertex). A charged-to-neutral energy ratio of 2 : 1 is assumed, due to the fact that there are two charged pions (π^+ and π^-) versus only one neutral pion (π^0), and all three types of pions are produced with roughly equal frequency. The neutral pileup contribution is estimated as 1/2 the p_T sum of pileup tracks entering the isolation cone. It is subtracted from the original isolation p_T sum to give the corrected isolation*,

$$I_{\Delta\beta}^{\text{PF}} = I_0^{\text{PF}} - \frac{1}{2} \sum_{\substack{\text{PU tracks} \\ \Delta R < 0.4}} p_T. \quad (4.2)$$

In Eq. 4.2, I_0^{PF} excludes charged pileup particles.

To normalize against the total energy of the hard scatter, the isolation quantity is divided by the lepton p_T , yielding the *relative isolation*,

$$I_{\text{rel}}^{\text{PF}} = I_{\Delta\beta}^{\text{PF}} / p_T^\ell. \quad (4.3)$$

The isolation requirement for electrons and muons is $I_{\text{rel}}^{\text{PF}} < 0.1$. Figure 4-1 illustrates this isolation requirement.

*This method of pileup correction is called the “ $\Delta\beta$ correction.”

PF Type	Minimum p_T [GeV]	Minimum ΔR
charged particles	0	0
neutral hadrons	0.5	0.01
photons	0.5	0.01

Table 4.8: Cuts on the PF candidates used in computing muon isolation.

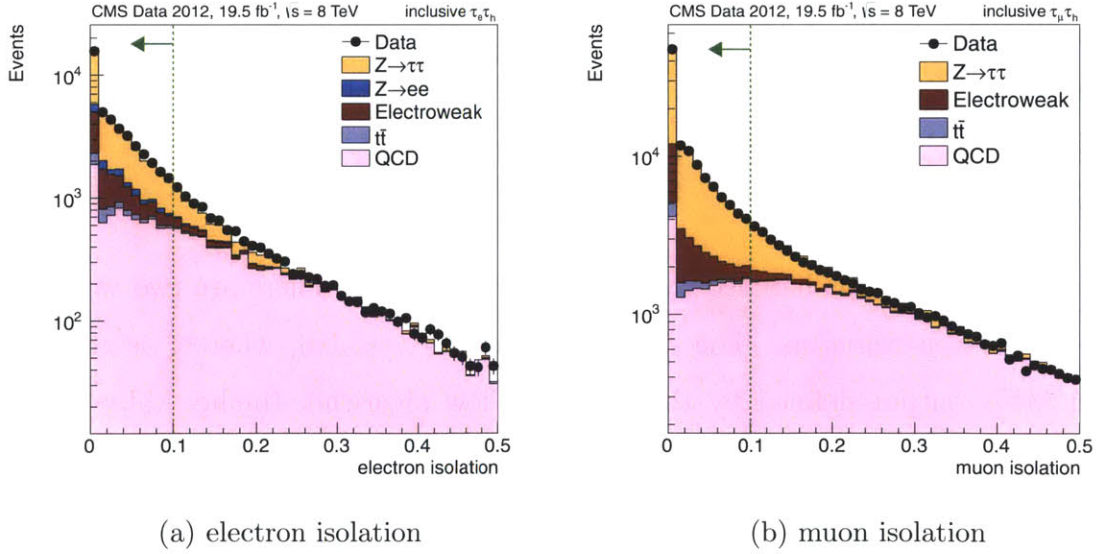


Figure 4-1: Distributions of the isolation quantity $I_{\text{rel}}^{\text{PF}}$ for electrons and muons. The dashed line indicates the isolation cut $I_{\text{rel}}^{\text{PF}} < 0.1$.

Input Variables of the Electron Rejection BDT
p_T , η , ϕ , and mass of HPS tau Angular distance between HPS tau and nearest ECAL crack Electromagnetic energy fraction Number of charged PF candidates in HPS tau Number of PF photons in HPS tau E_{HCAL}/P of highest p_T PF charged hadron in HPS tau E_{ECAL}/P of highest p_T PF charged hadron in HPS tau Electron-Pion MVA value of highest p_T PF charged hadron in HPS tau $\langle \Delta\eta^2 \rangle$ and $\langle \Delta\phi^2 \rangle$ of PF gamma candidates in HPS tau Energy of PF photons divided by p_T of HPS Tau Number of hits in KF and GSF tracks p_T , η , χ^2 , and σ_{p_T} of GSF track p_T , η , ϕ of matching GSF electron Bremsstrahlung energy fraction of matching GSF electron Momentum of matching GSF electron at inner and outer tracker surfaces Energy of supercluster

Table 4.9: Input variables of the electron rejection BDT.

4.2.5 Tau Identification

Tau identification is the process of rejecting HPS taus that have been faked by electrons or muons. Each type of lepton has its own rejection algorithm.

Electron Rejection

Rejecting $e \rightarrow \tau_h$ fakes is handled by multivariate methods. There are two working points for electron rejection. The *Loose* cut requires $\xi < 0.6$, where ξ is the PF electron MVA output defined by the Particle Flow algorithm (higher values of ξ indicate greater probability that the PF candidate is an electron). This cut has fairly weak rejection power and is only used in the $\tau_\mu\tau_h$ channel, where electrons are a small background. The *Tight* working point is handled by a BDT specially trained to distinguish τ_h from electrons. The BDT takes variables from the HPS tau and any matching electrons. The input variables of the BDT are summarized in Table 4.9. The BDT is trained on $Z \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ Monte Carlo samples as signal, and $Z \rightarrow ee$ and $t\bar{t}$ Monte Carlo samples as background. The electron rejection BDT has an efficiency of $\approx 77.22\%$ and an $e \rightarrow \tau_h$ fake rate of $\approx 0.12\%$.

Muon Rejection

Rejecting $\mu \rightarrow \tau_h$ fakes is based on matching the HPS tau with segments or hits in the muon system, as well as checking if the calorimeter deposits are consistent with a minimum ionizing particle. There are two working points for muon rejection:

1. *Loose Muon Rejection* requires that the leading charged PF candidate not be matched to a muon segment.
2. *Tight Muon Rejection* requires that the leading charged PF candidate not be matched to a muon chamber *hit*. Furthermore, if the HPS tau contains only a single charged PF candidate, that candidate must have deposited at least 20% of its energy in the calorimeters,

$$\frac{E_{\text{ECAL}} + E_{\text{HCAL}}}{p} > 0.2. \quad (4.4)$$

This calorimeter-based cut rejects PF candidates that appear to be minimum-ionizing particles, which are usually muons.

For the $\tau_\mu\tau_h$ channel, the τ_h candidate is required to pass the *Tight* working point, in order to reduce the $Z \rightarrow \mu\mu$ background. For the $\tau_e\tau_h$ channel, the τ_h candidate is only required to pass the *Loose* working point.

4.2.6 Tau Isolation

Unlike jets originating from quarks or gluons, tau jets tend to be highly collimated and isolated. Requiring the tau candidate to be isolated is a crucial step in tau identification. Rather than simply sum the p_T of PF candidates close to the tau candidate, the isolation is determined by a BDT, which is able to use information about the geometric distribution of energy deposits around the tau candidate. As can be seen in Figure 4-2, the distribution of energy deposits around a τ_h is qualitatively different from that of a quark/gluon jet. The difference in shape and quantity can be used by the BDT to distinguish taus from quark/gluon jets. The BDT is trained on the following samples:

Signal

The signal training sample consists of taus from simulated $Z \rightarrow \tau\tau$ events. The tau candidates are required to pass tau identification requirements.

Background

The background sample is a selection of jets from a jet-triggered data sample. Because these events are triggered by multi-jet triggers, most of them are QCD multi-jet events. Hence, it can be assumed that all tau candidates in these events are faked by quark/gluon jets. The tau candidates are required to pass tau identification requirements.

The main input variables to the BDT are the p_T sums of PF candidates in five rings of width $\Delta R = 0.1$ centered on the tau candidate. The p_T sums are computed for each of the three PF candidate types: 1) charged particles, 2) neutral hadrons, 3) photons. In addition to these p_T sums, the BDT is also given summary statistics about the geometric distribution of the isolation particles: $\langle\Delta\eta\rangle$, $\langle\Delta\phi\rangle$, $\langle\Delta\eta^2\rangle$, $\langle\Delta\phi^2\rangle$, and $\langle\Delta\eta\Delta\phi\rangle$, where the angles are computed with respect to the tau candidate axis. Finally, the BDT is given the average pileup energy density, ρ , so that it can compensate for the pileup in the event. The BDT contains 1000 trees, each with a maximum depth of 5. Training uses the gradient boosting method. The output of the BDT is a value from -1 to 1, with values closer to 1 indicating a higher likelihood that the tau candidate is from a tau decay. Figure 4-3 shows the BDT response for taus and quark/gluon jets. Figure 4-4 shows the BDT response for HPS taus in simulated background samples in the $\tau_\mu\tau_h$ channel. The threshold used in the analysis is 0.795. Figure 4-5 shows the efficiency of the tau isolation as a function of the p_T of the generated τ_h , computed from simulation.

4.2.7 Jet Identification

Jets are reconstructed from PF candidates using the anti- k_T clustering algorithm (Section 3.6). The jets used in this analysis are required to have $p_T > 30$ GeV and $|\eta| < 4.7$. These kinematic cuts significantly reduce the number of selected pileup

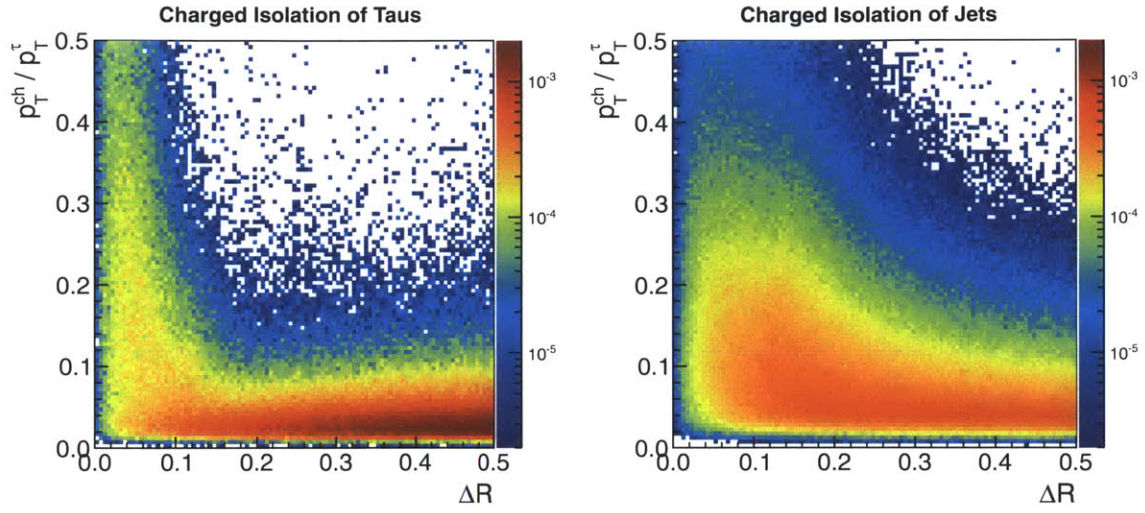


Figure 4-2: Probability density of charged isolation particles as a function of p_T^{PF}/p_T^τ and ΔR for taus (left) and jets (right).

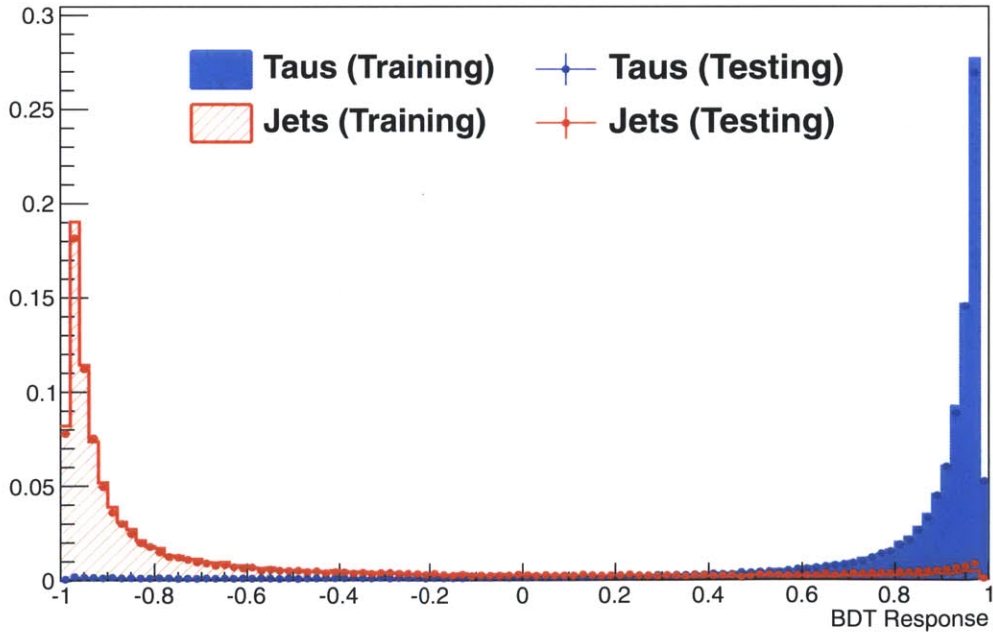


Figure 4-3: Response of tau isolation BDT for taus and jets.

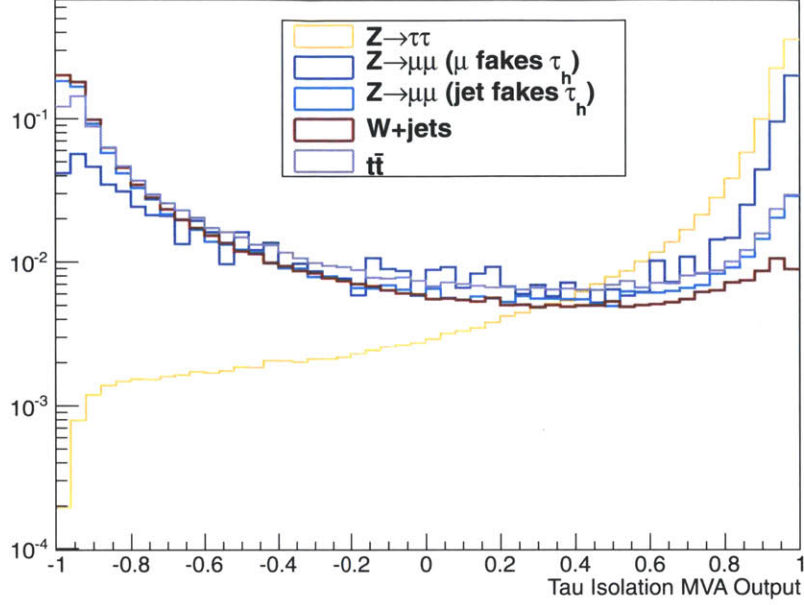


Figure 4-4: Comparison of the tau isolation MVA output for HPS taus in the $Z \rightarrow \tau\tau$ MC sample and several other background samples.

jets. Jets are required to be at least $\Delta R = 0.5$ away from the lepton and τ_h , to ensure that the jets are distinct from the tau decay products.

Jets must also pass a jet identification BDT that attempts to distinguish hard scatter jets from pileup jets. Jets from pileup interactions are usually soft but can sometimes overlap to form a high p_T jet. These composite jets have a more diffuse shape than jets from the hard-scatter. The variables that go into the jet identification BDT are:

- p_T -weighted average of the ΔR between the jet's constituents and the jet axis:

$$\langle \Delta R \rangle = \frac{1}{p_T^{\text{jet}}} \sum_{\text{PF}} p_T \Delta R, \quad (4.5)$$

where p_T^{jet} is the transverse momentum of the jet, p_T is the transverse momentum of the PF candidate, and ΔR is the angular distance between the PF candidate and the jet axis.

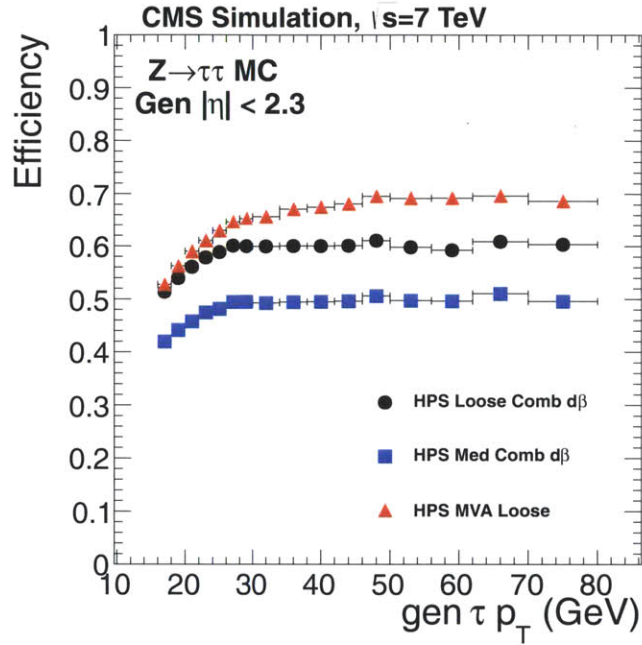


Figure 4-5: HPS tau efficiency for three types of isolation: MVA isolation (red), cut-based PF isolation at the loose working point (black), and cut-based PF isolation at the medium working point (blue). The “Loose MVA” corresponds to requiring the tau isolation BDT output to be greater than 0.795 and is the requirement used in this analysis. “Comb $d\beta$ ” refers to a cut-based isolation method using the sum p_T of all PF candidates with $\Delta\beta$ pileup correction. The cut-based isolation is not used in this analysis.

- p_T sums in four ΔR rings around the jet axis,

$$p_T^{\Delta R_i} = \frac{1}{p_T^{\text{jet}}} \sum_{\substack{\text{PF} \\ r_i < \Delta R < r_{i+1}}} p_T, \quad (4.6)$$

where r_i are five uniformly spaced boundaries in ΔR from 0.0 to 0.4 in steps of $\Delta R = 0.1$.

- The fraction of the jet’s charged particle momentum which comes from the primary vertex,

$$\beta = \frac{\sum_{\text{charged from PV}} p_T}{\sum_{\text{all charged}} p_T}, \quad (4.7)$$

where “charged from PV” refers to charged PF candidates whose tracks originate from the primary vertex.

- The complement of Eq. 4.7,

$$\beta^* = \frac{\sum_{\text{charged from PU}} p_T}{\sum_{\text{all charged}} p_T}, \quad (4.8)$$

where “charged from PU” refers to charged PF candidates whose tracks *do not* originate from the primary vertex.

- Charged and neutral particle multiplicities of the jet constituents.
- Jet kinematic variables p_T , η , and ϕ .

The jet identification BDT is trained on jets from a simulated $Z \rightarrow \mu\mu + \text{jets}$ sample. Non-pileup jets are those that are matched to jets built from generated particles; all other reconstructed jets are considered pileup jets. The jet identification BDT has an efficiency of 95% for jets with $p_T > 25 \text{ GeV}$ [47].

Jets from b Quarks

Jets originating from b quarks (b-jets) are identified by their displaced vertices, since B hadrons have relatively long lifetimes which allow them to travel a detectable distance

from the pp collision before decaying. This analysis uses the *Combined Secondary Vertex* (CSV) algorithm [52] to identify b-jets. When applied to a reconstructed jet, the CSV algorithm first attempts to reconstruct a secondary vertex and, if one is found, uses a likelihood ratio technique to verify that its characteristics match those of a b-jet. The input variables to the likelihood are:

- Invariant mass of tracks from the secondary vertex,
- Charged particle multiplicity of the secondary vertex,
- Flight distance significance of the secondary vertex in the transverse plane,
- Energy of the charged particles from the secondary vertex divided by the energy of all charged particles in the jet,
- Pseudorapidities between secondary vertex tracks and the jet axis,
- 3D impact parameter of each track in the jet.

The CSV algorithm produces a discrimination value for each jet such that higher values indicate a higher probability that the jet originated from a b quark. The distribution of the CSV output in QCD multi-jet events is shown in Figure 4-6. In this analysis, b-jets are used to reject $t\bar{t}$ events, which usually contain one or more b-jets. A PF jet is considered a b-jet if its CSV output value is greater than 0.679 (medium working point) and its p_T is greater than 20 GeV.

4.3 Tau Pair Selection

After object selection, events are selected according to one of the final states, $\tau_e\tau_h$ and $\tau_\mu\tau_h$. Taus tend to have soft (i.e. low p_T) visible decay products because energy is lost to neutrinos. It is therefore desirable to have as a low a p_T threshold as possible. However, p_T cuts at the trigger level impose a lower bound on the offline cut. The η requirements are driven by the trigger and the boundaries of the sub-detectors.

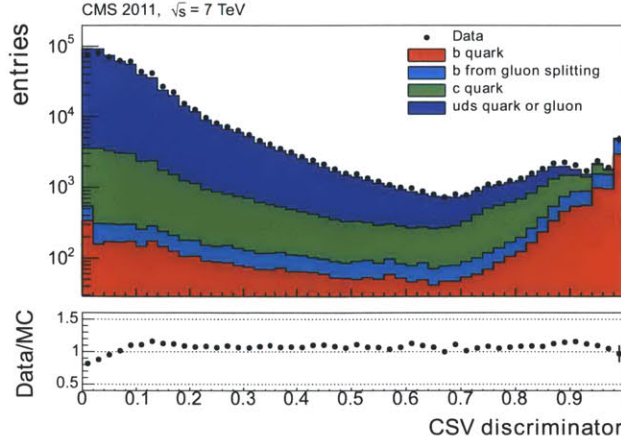


Figure 4-6: Output of the Combined Secondary Vertex algorithm in $\sqrt{s} = 7$ TeV data and simulation [52].

Selection of $\tau_e \tau_h$ Events

Events with one reconstructed electron and one HPS tau are selected for the $\tau_e \tau_h$ final state. The electron is required to be in the pseudorapidity range $|\eta| < 2.1$. The electron p_T cut is $p_T > 20$ GeV in 2011 and increases to $p_T > 24$ GeV in 2012, due to the rising p_T cut at the trigger level. The tau is required to have $p_T > 20$ GeV and be within the pseudorapidity region $|\eta| < 2.3$. The longitudinal impact parameter of the tau candidate is required to be less than 0.2 cm. The tau candidate must also pass the *Tight* electron rejection cut and the *Loose* muon rejection cut. The electron and HPS tau must have opposite charge.

Selection of $\tau_\mu \tau_h$ Events

Events with one reconstructed muon and one HPS tau are selected for the $\tau_\mu \tau_h$ final state. The muon is required to be in the pseudorapidity range $|\eta| < 2.1$. The muon p_T cut is $p_T > 17$ GeV in 2011 and increases to $p_T > 20$ GeV in 2012 due to an increase in the p_T threshold at trigger level. The tau is required to have $p_T > 20$ GeV and be within the pseudorapidity region $|\eta| < 2.3$. The longitudinal impact parameter of the tau candidate is required to be less than 0.2 cm. The tau candidate must also pass the *Tight* muon rejection cut and the *Loose* electron rejection cut. The muon and HPS tau must have opposite

charge.

4.3.1 W Rejection

In order to reject W + jets background, a cut is made on the transverse mass of the electron/muon and $\cancel{E}_T$. The transverse mass of the lepton and $\cancel{E}_T$ is defined as

$$M_T^2 = (E_T^\ell + \cancel{E}_T)^2 - (\mathbf{p}_T^\ell + \cancel{\mathbf{E}}_T)^2 \quad (4.9)$$

$$\approx 2E_T^\ell \cancel{E}_T (1 - \cos \Delta\phi), \quad (4.10)$$

where $\Delta\phi$ is the angle between the lepton and $\cancel{E}_T$ in the transverse plane. The approximation holds when the lepton momentum is much larger than the lepton mass.

In a $W \rightarrow \ell\nu$ event, M_T is approximately equal to the mass of the W multiplied by $\cos\theta$, where θ is the angle of the W from the transverse plane in the lab frame. Hence, M_T tends to be large for W events, peaking around 75 GeV, while M_T is small for Higgs events. The cut applied to reject W background is

$$M_T < 20 \text{ GeV}. \quad (4.11)$$

The cut value was chosen to optimize the expected limit on the Higgs cross section. The cut is illustrated in Figure 4-7.

4.3.2 Di-Lepton Veto

$Z \rightarrow \ell\ell$ events can fake a $Z \rightarrow \tau_\ell\tau_h$ event if one of the leptons is mistaken for a τ_h . To help reduce $Z \rightarrow \ell\ell$ background, events which contain an additional, loosely selected lepton are rejected. For the $\tau_e\tau_h$ channel, the loose electron selection used in the di-electron veto is summarized in Table 4.10. If a $\tau_e\tau_h$ event has an electron passing the loose selection with an opposite charge to an electron passing the main selection described in Section 4.2, the event is rejected as a $Z \rightarrow ee$ event. For the $\tau_\mu\tau_h$ final state, the second muon must be a tracker or global muon and satisfy a

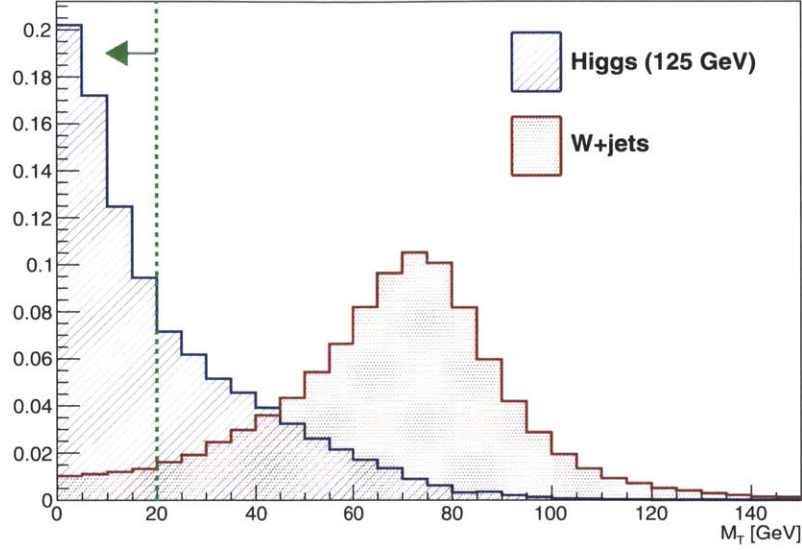


Figure 4-7: Transverse mass distributions of $\tau_\mu\tau_h$ events in the Higgs and $W + \text{jets}$ Monte Carlo samples (2012). Both histograms are normalized to one. The dashed line indicates the transverse mass cut $M_T < 20 \text{ GeV}$.

Variable		Barrel	Endcap
$ \sigma_{i\eta i\eta} $	$<$	0.01	0.03
$ \Delta\eta_{\text{in}} $	$<$	0.007	0.010
$ \Delta\phi_{\text{in}} $	$<$	0.8	0.7
$\left \frac{E_{\text{HCAL}}}{E_{\text{ECAL}}}\right $	$<$	0.15	N/A
$I_{\text{rel}}^{\text{PF}}$	$<$	0.3	0.3

Table 4.10: Electron selection requirements used in the di-electron veto.

relaxed isolation requirement of $I_{\text{rel}}^{\text{PF}} < 0.3$. An event containing a muon passing the main muon selection and a second muon of opposite charge passing the loose muon selection is rejected as a $Z \rightarrow \mu\mu$ event.

4.4 Event Categories

To increase the sensitivity of the Higgs search, events are separated into five categories based on jet topology and the p_T of the τ_h :

0-jet, low $p_T^{\tau_h}$

The event has no jets. The τ_h has $p_T < 40 \text{ GeV}$.

0-jet, high $p_T^{\tau_h}$

The event has no jets. The τ_h has $p_T > 40$ GeV.

1-jet, low $p_T^{\tau_h}$

The event has at least one jet but no b-jets. The τ_h has $p_T < 40$ GeV.

Due to the presence of jets, the Higgs boson is boosted and therefore the SVFit mass resolution is improved.

1-jet, high $p_T^{\tau_h}$

The event has at least one jet but no b-jets. The τ_h has $p_T > 40$ GeV.

Due to the presence of jets, the Higgs boson is boosted and therefore the SVFit mass resolution is improved. The p_T cut on the τ_h also increases the signal-to-background ratio because the Higgs boson, being more massive than the Z boson, produces taus with greater energy.

VBF

The event contains two jets with di-jet mass $m_{jj} > 500$ GeV and pseudorapidity separation $\Delta\eta > 3.5$. In the case of events with more than two jets, only the two jets with the highest p_T are used. Additionally, there must not be another jet between the two jets (*Central Jet Veto*).

This jet configuration is characteristic of Higgs events produced via vector boson fusion (Section 1.2). By requiring the two forward jets, the background is greatly reduced. An event which passes both the 1-jet requirements and the VBF requirements is assigned to the VBF category.

By dividing events in this manner, the analysis takes advantage of low-statistics, high S/B categories to search for signal while retaining high-statistics, low S/B as control regions for *in situ* measurements of efficiencies and background contributions. In particular, the 0-jet categories are not fit for signal; they are used only as control regions to constrain nuisance parameters of the background models. The categories are summarized in Figure 4-8.

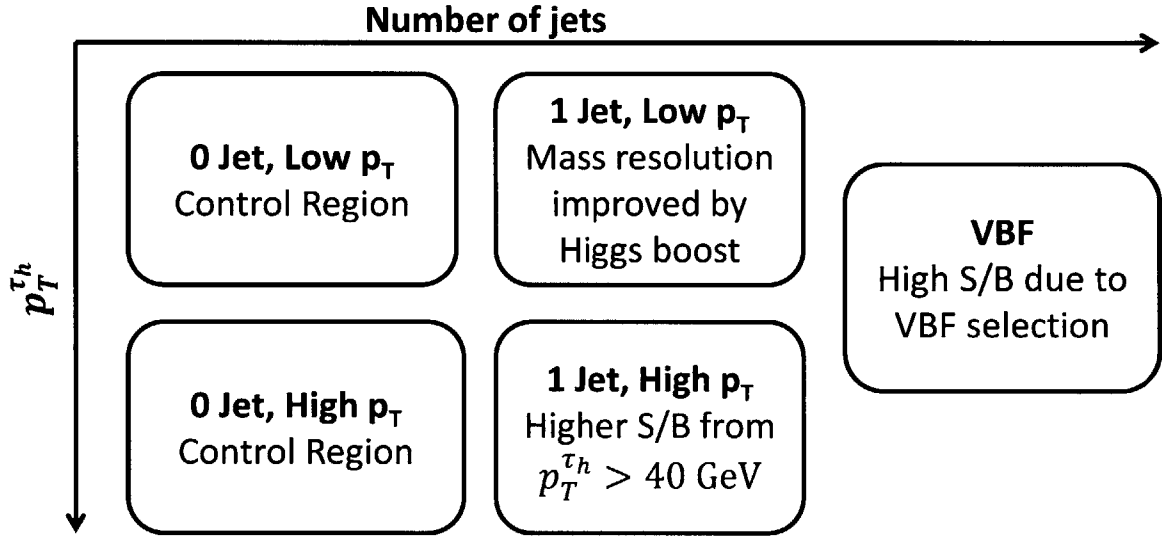


Figure 4-8: Summary of the event categories used in this analysis. Events are categorized by the presence of a jet and the p_T of the selected HPS tau. There is also a category for VBF events, identified by the presence of two forward jets.

Chapter 5

Selection Efficiency

In the context of this analysis, the *efficiency* of a selection requirement is defined as the probability that the desired physics object passes the requirement. Efficiencies can affect the normalization and shape of signal and background distributions. In most cases, efficiencies are provided by Monte Carlo simulation (Section 6.1), which simulates the traversal of particles through the CMS detector and performs the same event reconstruction as in data. However, the simulated efficiencies may sometimes be inaccurate, either because of a poorly modeled physical process or because of differences between the simulated detector and the real detector, often arising from changing conditions during data-taking. These inaccuracies in the simulation are corrected by measuring the efficiency in data and adjusting the simulated efficiency to match. These adjustments are implemented as event weights, defined as

$$\rho = \varepsilon_{\text{data}}/\varepsilon_{\text{MC}}, \tag{5.1}$$

where ρ is the correction factor (applied as an event weight), $\varepsilon_{\text{data}}$ is the efficiency measured in data, and ε_{MC} is the efficiency measured in Monte Carlo.

In data, the efficiency of selecting an object must be measured with respect to a more loosely selected object because an object which is not reconstructed at all cannot be used in a measurement. Hence, the efficiency measured in data is the conditional probability that an object of the desired type passes the selection requirement *given*

that it also passes a looser set of requirements. The *absolute* efficiency can only be obtained from Monte Carlo simulation, in which the original generated particles are known. All efficiencies in this section refer to conditional efficiencies. Efficiencies are measured for lepton and τ_h selection. Trigger and offline selection efficiencies are measured separately.

5.1 Tag and Probe

Efficiencies for lepton and τ_h selection are measured using the *tag-and-probe* method, a common technique for measuring lepton efficiencies in CMS analyses. The basic idea of the tag-and-probe method is to measure lepton efficiencies in di-lepton decays of the Z boson, where a constraint on the di-lepton mass ensures the purity of the selected events. One lepton, called the *tag*, is required to pass tight selection cuts so that it is selected with high purity. The other lepton, called the *probe*, is selected using a set of cuts that are looser than the selection whose efficiency is to be measured. The fraction of probe leptons that pass the full selection gives the efficiency of the full selection with respect to the probe selection. The end result of the tag-and-probe method is a measurement of the conditional probability that a lepton will pass the analysis selection given that it passes the probe selection. In cases where there are non-negligible backgrounds, a fit to the di-lepton mass spectrum is performed to subtract background contamination and determine the yield of true Z boson events.

5.2 Trigger Efficiency

The trigger efficiency is measured relative to the offline selection; that is, the trigger efficiency is the probability that a physics object will pass the trigger requirements, given that it is selected offline. Since the trigger paths used in this analysis involve two different trigger objects per event, the efficiency for each type of trigger object (electron, muon, or τ_h) is measured separately. To account for the evolution of the trigger paths during data-taking, the trigger efficiency for each trigger path is mea-

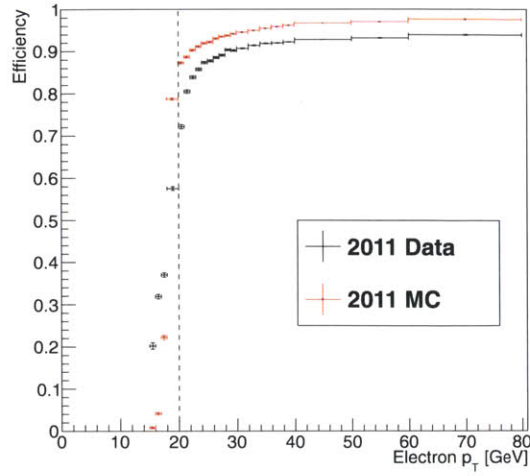
sured separately and then averaged together, weighted by the integrated luminosity for which the trigger path was active.

5.2.1 Electron and Muon Trigger Efficiency

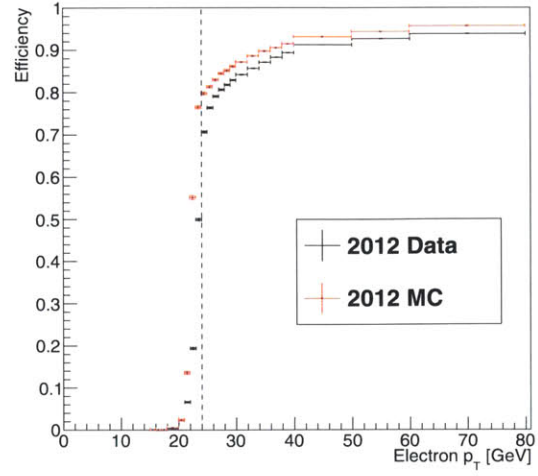
The electron and muon trigger efficiencies are measured using the tag-and-probe method in $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events, respectively. Single-lepton trigger paths are used because requiring the probe lepton to pass a trigger requirement would bias the efficiency measurement. Both the tag and probe leptons are required to satisfy the lepton identification and isolation requirements described in Section 4.2. The tag lepton is also required to match the single-lepton trigger object whereas the probe lepton does not have a trigger requirement. The probe lepton is tested by checking if it matches the lepton leg of the appropriate analysis trigger path (i.e. the electron leg of the $\tau_e\tau_h$ trigger or the muon leg of the $\tau_\mu\tau_h$ trigger). The fraction of probe leptons which are matched to the lepton trigger object gives the trigger efficiency. The trigger efficiency and correction factors are computed in bins of lepton p_T and η in order to account for dependencies on the lepton kinematics. The p_T projections of the electron and muon efficiencies are shown in Figures 5-1 and 5-2. The differences between data and Monte Carlo efficiencies are due to the evolution of the trigger paths during data-taking and to simulation discrepancies. The correction factors in $p_T - \eta$ bins are provided in Appendix A.

5.2.2 Tau Trigger Efficiency

The tau trigger efficiency is measured using tag-and-probe in $Z \rightarrow \tau_\mu\tau_h$ events. The tag is a muon from a tau decay and the probe is an HPS tau. The muon and HPS tau must pass the full object selection used in the analysis. Furthermore, the event must pass the di-lepton veto and the W rejection cut $M_T < 40$ GeV. Unlike for electrons and muons, this measurement is complicated by significant backgrounds. Because of these backgrounds, the probe taus are a mixture of τ_h and quark/gluon jets. To extract the trigger efficiency of τ_h alone, the trigger efficiency of quark/gluon jets is

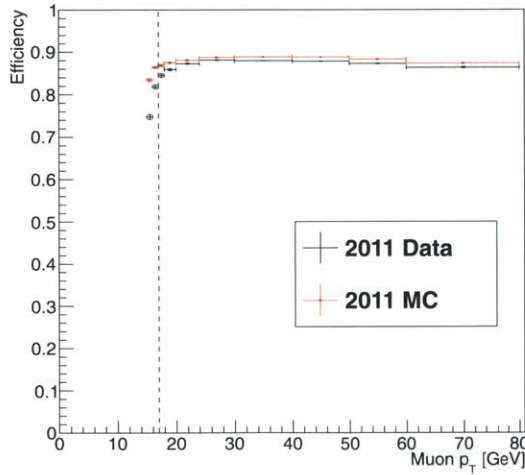


(a) 2011

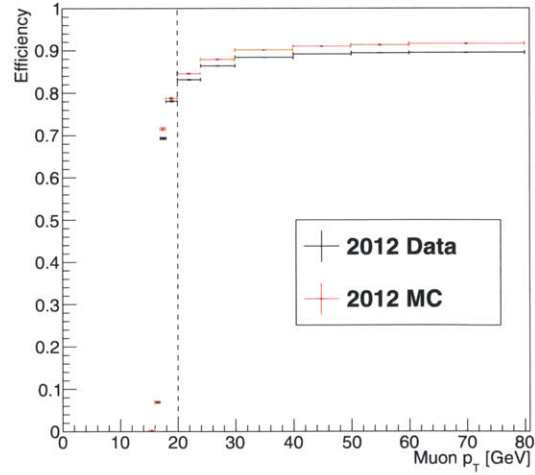


(b) 2012

Figure 5-1: Electron trigger efficiency measured in data and MC. The dashed line indicates the electron p_T cut. Note that the trigger paths used in data evolved over time whereas a single trigger path is used in the MC, so the efficiencies are not expected to be the same between data and MC, especially at low p_T .



(a) 2011



(b) 2012

Figure 5-2: Muon trigger efficiency measured in data and MC. The dashed line indicates the muon p_T cut. Note that the trigger paths used in data evolved over time whereas a single trigger path is used in the MC, so the efficiencies are not expected to be the same between data and MC, especially at low p_T .

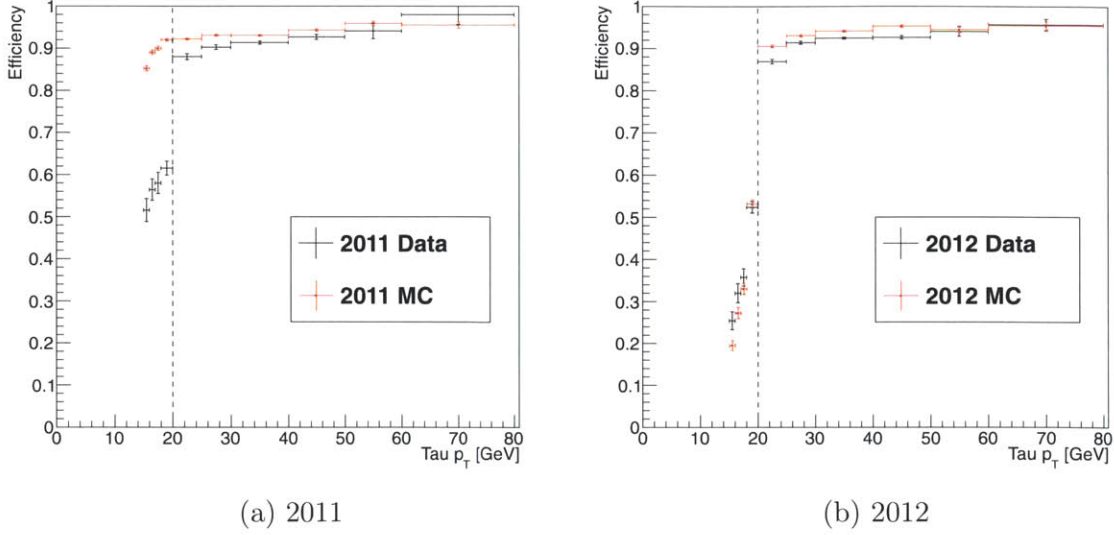


Figure 5-3: Tau trigger efficiency measured in data and MC. Note that the trigger paths used in data evolved over time whereas a single trigger path is used in the MC, so the efficiencies are not expected to be the same between data and MC, especially at low p_T .

measured in the $M_T > 60$ GeV sideband (which is dominated by $W + \text{jets}$ events) and inserted into the following formula:

$$\epsilon_{\tau_h} = \frac{\epsilon_{\text{data}} - (1 - f_Z)\epsilon_{\text{fakes}}}{f_Z}, \quad (5.2)$$

where ϵ_{data} is the efficiency measured in the $M_T < 40$ GeV signal region, ϵ_{fakes} is the efficiency measured in the $M_T > 60$ GeV sideband, and f_Z is the fraction of $Z \rightarrow \tau\tau$ events, estimated from Monte Carlo simulation. The trigger efficiency is computed in bins of p_T and η of the τ_h to account for efficiency variations due to the kinematics of the τ_h . The tau trigger efficiency as a function of p_T is shown in Figure 5-3. The correction factors in $p_T - \eta$ bins are provided in Appendix A.

5.3 Identification and Isolation Efficiency

Identification and isolation efficiencies are measured in single-lepton triggered events so that the probe is not biased by online HLT requirements. Unlike the case of the

trigger efficiency measurement, there are often non-negligible backgrounds and hence a fit is performed to estimate the yield of Z boson events. In the case of the electrons and muons, identification and isolation efficiencies are measured together.

5.3.1 Electron and Muon Identification/Isolation Efficiency

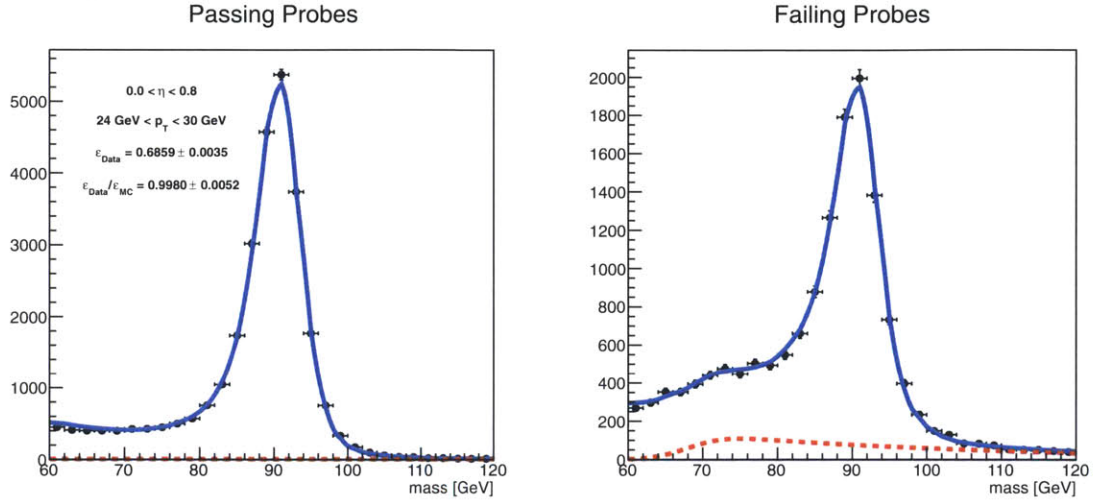
The efficiency of the lepton identification and isolation requirements are measured using tag-and-probe in $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events. The tag lepton must pass the full object selection. The probe lepton is a GSF electron (Section 3.3) in the case of electron efficiency and a global muon (Section 3.4) in the case of muon efficiency. The di-lepton mass must be in the range $60 \text{ GeV} < m_{\ell\ell} < 120 \text{ GeV}$. The fraction of probe leptons which pass the identification and isolation requirements gives the efficiency.

Although the backgrounds for $Z \rightarrow \mu\mu$ are negligible, there are significant backgrounds for $Z \rightarrow ee$ which must be taken into account. The background contribution is estimated by fitting the di-lepton mass distribution. Two mass distributions are fit simultaneously: 1) the di-lepton mass of the tag and probe pairs where the probe *passes* the full lepton selection, and 2) the di-lepton mass of the tag and probe pairs where the probe *fails* the full lepton selection. The signal model in both cases is a Monte Carlo-derived shape template convolved with a Gaussian resolution model. The background model depends on whether the probe passes or fails the full lepton selection: for probe leptons that pass the full selection, the background model is an exponential function, whereas for probe leptons that fail the full lepton selection, the background model is an exponential function multiplied by the complementary error function,

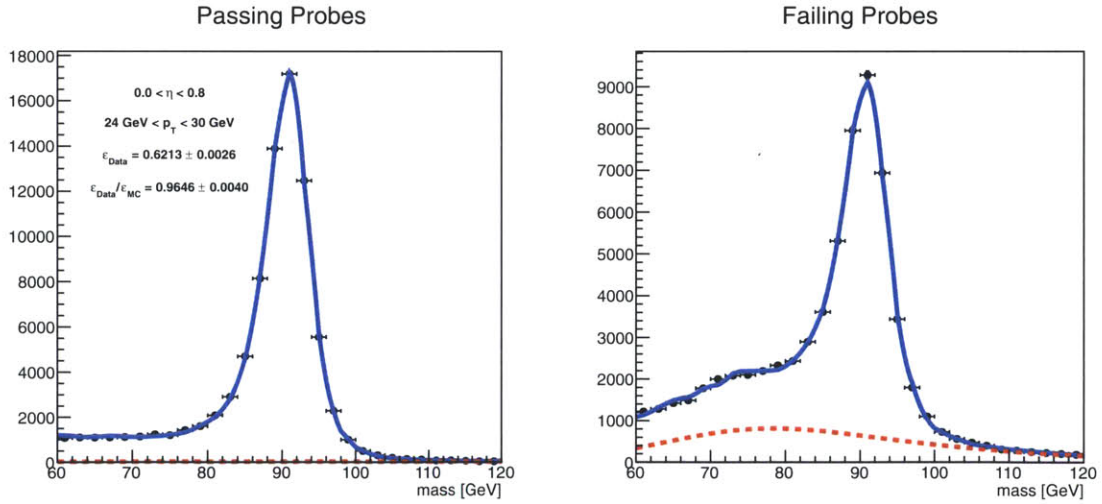
$$b(m) = \text{erfc}(\beta(\alpha - m)) \cdot \exp(-\gamma m). \quad (5.3)$$

The complementary error function emulates the kinematic turn-on caused by the p_T cut on the probe.

The fits are performed in bins of lepton p_T and η . Figures 5-4 and 5-5 are examples of fits to the mass distribution. Additional fit results and tables of efficiency correction factors are given in Appendix A.

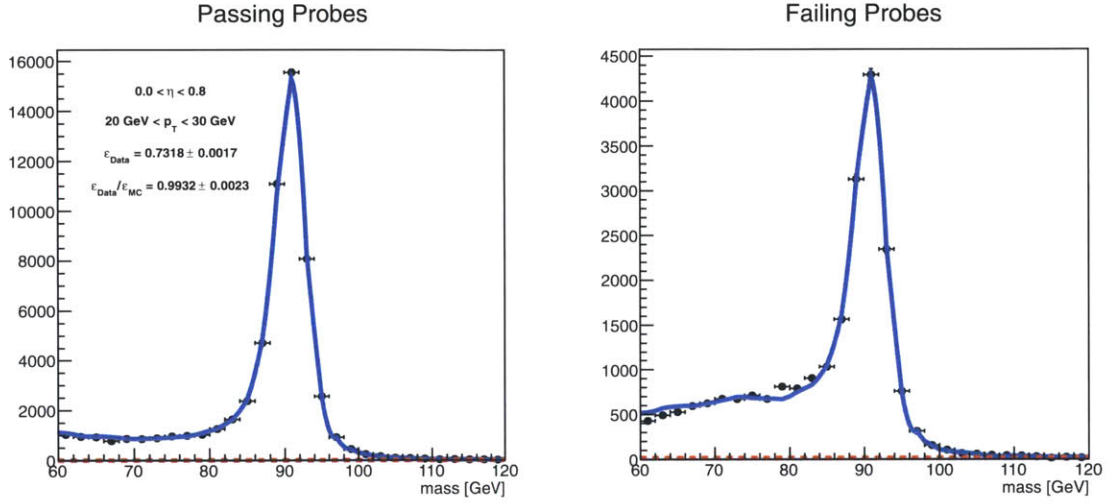


(a) 2011

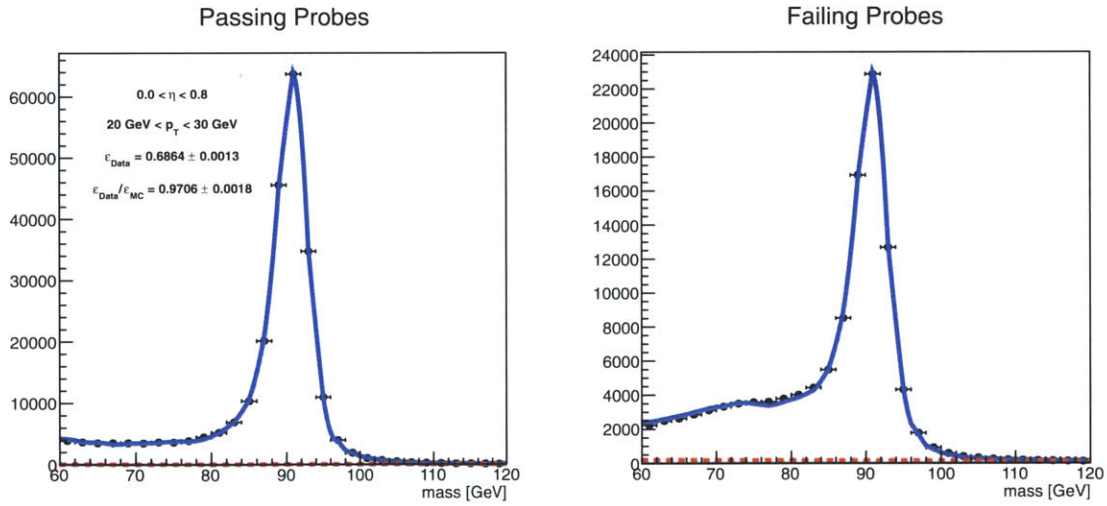


(b) 2012

Figure 5-4: Examples of fit results for the electron ID and isolation efficiency measurements. Other fit results are provided in Appendix A.



(a) 2011



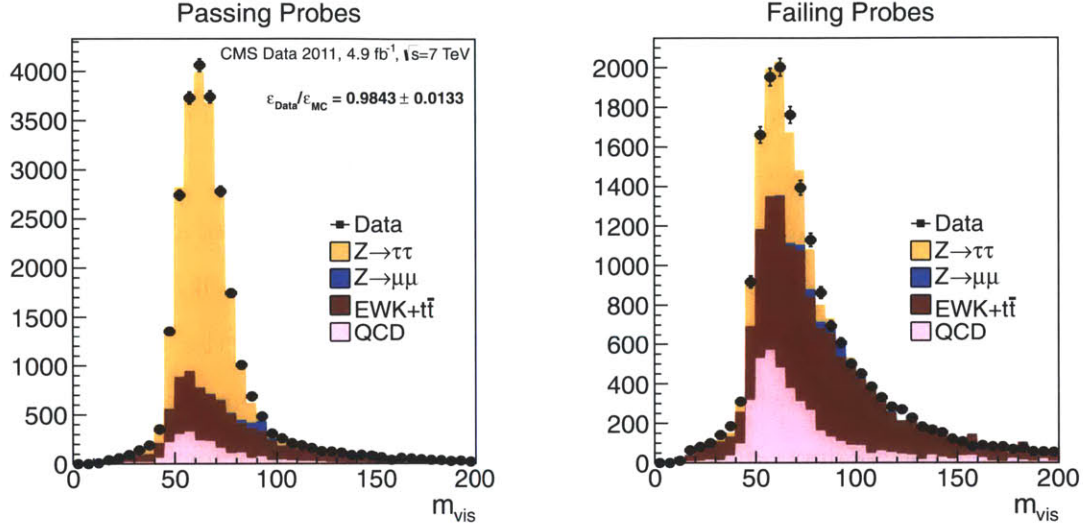
(b) 2012

Figure 5-5: Examples of fit results for muon ID and isolation efficiency measurements. Other fit results are provided in Appendix A.

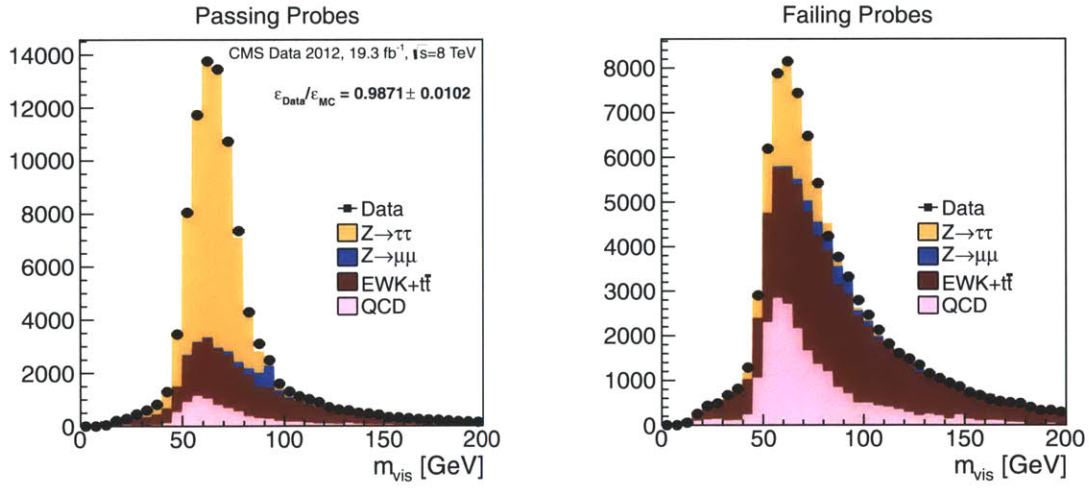
5.3.2 Tau Isolation Efficiency

The efficiency of the tau isolation is measured using the tag-and-probe method in $Z \rightarrow \tau_\mu \tau_h$ events. The tag is a muon that passes the full muon selection. The probe is defined as an HPS tau passing decay mode finding and lepton rejection cuts. The probe is also required to satisfy a minimal isolation cut of $I_{\tau_h}^{\text{BDT}} > 0$. The probe is considered to have passed the isolation requirement if $I_{\tau_h}^{\text{BDT}} > 0.795$ (the cut used in the main analysis). Events are also required to have $M_T < 30$ GeV in order to reject W background.

Backgrounds are estimated by fitting the visible mass of the $\mu + \tau_h$ system. Background models are derived using the methods described in Section 6.3. Figure 5-6 shows the fit results for 2011 and 2012. Due to limited statistics, the tau isolation efficiency is measured inclusively (i.e. for all p_T and η). The systematic uncertainty due to ignoring the p_T dependence is estimated by performing the efficiency measurement in bins of p_T ; the uncertainty is found to be $\sim 3\%$. Since the correction factors in 2011 and 2012 are statistically consistent, the average correction factor is applied for both years. The correction factor for the tau isolation efficiency is 0.986 ± 0.029 .



(a) 2011



(b) 2012

Figure 5-6: Fit results for the tau isolation efficiency measurement.

Chapter 6

Signal and Background Modeling

The vast majority of the events selected according to the procedure described in Chapter 4 come from known Standard Model backgrounds. The search for the Higgs boson depends on finding an excess of events over the background events that pass selection. A potential excess is determined by a fit to the di-tau mass distribution. This fit requires obtaining accurate predictions of the event yields and di-tau mass shapes for the Higgs signal and the relevant backgrounds. The main technique for modeling signal and background contributions is Monte Carlo simulation. For certain backgrounds, data-driven methods are employed to estimate the background directly from the data, thereby avoiding inaccuracies in the simulation. The methods used in modeling the signal and background are described in the following sections.

6.1 Monte Carlo

Monte Carlo simulation is used to model the Higgs signal and certain Standard Model backgrounds. Monte Carlo events are created in two steps: First, the initial particles created by the pp hard scatter are sampled according to matrix element calculations; second, the decay of these initial particles and the traversal of their stable decay products through the detector are simulated. Event generation is performed either by PYTHIA [53], POWHEG [54,55], or MADGRAPH [56]. PYTHIA is a leading-order (LO) generator that also computes leading-log parton showering and hadronization.

POWHEG is a next-to-leading-order (NLO) generator; however, it does not generate parton showers and must be linked to PYTHIA to handle parton showering. MADGRAPH is a LO generator but also includes parton emission diagrams for up to four emitted partons [57]. Because of these parton emission diagrams, MADGRAPH more accurately models jet multiplicity and the jet p_T spectrum than POWHEG. Like POWHEG, MADGRAPH must be linked to PYTHIA to handle parton showering. The decay of taus into stable particles is simulated by the software package TAUOLA [58].

The particles in the event are then propagated through a simulation of CMS by GEANT4 [59,60]. GEANT4 simulates the traversal of particles through the detector, taking into account interactions with the detector material and making a prediction of particle trajectories and energy losses. It also simulates the signals produced by the active detector components, thus producing event output in a format identical to the data obtained from real pp collisions. The simulated event output is run through the same event reconstruction procedure described in Section 3. A Monte Carlo event can then be analyzed in the same way as data.

The event selection can be run on a Monte Carlo sample to produce the expected variable distributions for a given physics process. The expected distributions are representative of real collision data to the extent that the event generation and simulation are accurate. Several corrections are applied to simulated events. Monte Carlo events are corrected according to selection efficiencies measured in collision data (Chapter 5). Also, the energy of simulated jets and taus are scaled to reflect energy scale measurements in data.

The selected events from a Monte Carlo sample are normalized according to the formula

$$N = \mathcal{L}\sigma\varepsilon, \tag{6.1}$$

where N is the normalization (i.e. expected number of events) of the sample, $\mathcal{L}$ is the integrated luminosity, σ is the cross section of the process, and ε is the selection efficiency $N_{\text{selected}}/N_{\text{total}}$ of the sample. The cross sections of the background samples used in this analysis are given in Table 6.1.

Process	Cross Section [pb]	
	7 TeV	8 TeV
$Z \rightarrow \ell\ell, \tau\tau$	3048	3504
$W + \text{jets}$	31314	36257
$t\bar{t}$	164.4	225.2
Single top	15.74	22.2
$ZZ \rightarrow 4\ell$	0.064	0.181
$ZZ \rightarrow 2\ell 2q$	0.777	2.502
$ZZ \rightarrow 2\ell 2\nu$	0.251	0.716
$WW \rightarrow \ell\nu\ell\nu$	4.783	5.824
$WZ \rightarrow 2\ell 2q$	1.789	2.207
$WZ \rightarrow 3\ell\nu$	0.857	1.058

Table 6.1: Cross sections of background samples, for $\sqrt{s} = 7$ TeV [61] and $\sqrt{s} = 8$ TeV [62].

6.1.1 Pileup Modeling

Pileup is incorporated into simulated events by superimposing minimum-bias events generated with PYTHIA. The simulated minimum-bias events are added to the original hard scatter event at the digitization level, i.e. the step during event simulation when detector output is simulated. The number of pileup interactions added to a simulated event follows an approximate prediction of the expected pileup in data. However, this prediction is made before data-taking and can differ considerably from the actual pileup distribution. After data-taking, the expected pileup distribution in data is computed from the instantaneous luminosity profile and the Monte Carlo samples are re-weighted to match this pileup distribution. The original pileup distribution used in Monte Carlo generation and the pileup distribution in data are shown in Figure 6-1.

6.2 Higgs Signal

The Higgs boson signal is modeled using Monte Carlo simulation. Samples are produced for a range of hypothetical Higgs masses. This $H \rightarrow \tau\tau$ search focuses on low Higgs mass because the $H \rightarrow \tau\tau$ branching fraction is maximal for $m_H \lesssim 150$ GeV. The Higgs masses that are studied in this analysis are the mass points from $m_H =$

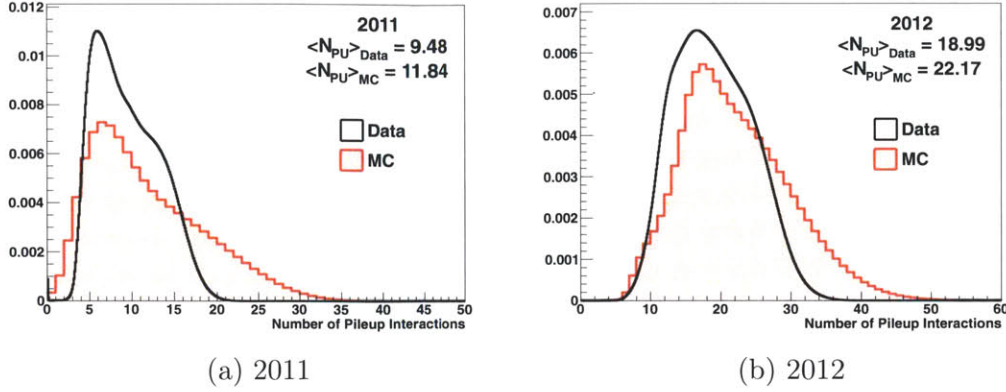


Figure 6-1: Distribution of pileup interactions in data and Monte Carlo for 2011 and 2012. The Monte Carlo is re-weighted to match the pileup distribution in data.

m_H [GeV]	Cross Sections				
	$gg \rightarrow H$	VBF	WH	ZH	$t\bar{t}H$
110	19.84	1.410	0.8754	0.4721	0.1257
115	18.14	1.344	0.7546	0.4107	0.1106
120	16.65	1.279	0.6561	0.3598	0.0976
125	15.32	1.222	0.5729	0.3158	0.0863
130	14.16	1.168	0.5008	0.2778	0.0766
135	13.11	1.117	0.4390	0.2453	0.0681
140	12.18	1.069	0.3857	0.2172	0.0607
145	11.33	1.023	0.3406	0.1930	0.0544

Table 6.2: Higgs cross sections for $\sqrt{s} = 7$ TeV [15].

110 GeV to $m_H = 145$ GeV in steps of 5 GeV.

Three Higgs production processes need to be generated: gluon fusion Higgs, vector boson fusion Higgs, and Higgs produced in association with W , Z , or $t\bar{t}$. Gluon fusion Higgs and VBF Higgs samples are generated with the NLO event generator POWHEG [63]. The Higgs p_T spectrum in the gluon fusion sample is re-weighted to match the NNLO + NNLL prediction from HQT [64] and FeHiPro [65] (FeHiPro is used for $p_T^H \gtrsim 130$ GeV). VH and $t\bar{t}H$ Monte Carlo samples are generated with PYTHIA. The Standard Model Higgs cross sections for 7 TeV and 8 TeV collisions are given in Tables 6.2 and 6.3. The $H \rightarrow \tau\tau$ branching ratios are given in Table 6.4.

m_H [GeV]	Cross Sections				
	$gg \rightarrow H$	VBF	WH	ZH	$t\bar{t}H$
110	25.04	1.809	1.432	0.7807	0.1887
115	22.96	1.729	1.060	0.5869	0.1663
120	21.13	1.649	0.7966	0.5117	0.1470
125	19.52	1.578	0.6966	0.4483	0.1302
130	18.07	1.511	0.6095	0.3943	0.1157
135	16.79	1.448	0.5351	0.3473	0.1031
140	15.63	1.389	0.4713	0.3074	0.09207
145	14.59	1.333	0.4164	0.2728	0.07403

Table 6.3: Higgs cross sections for $\sqrt{s} = 8$ TeV [16].

m_H [GeV]	BR($H \rightarrow \tau\tau$)
110	7.9×10^{-2}
115	7.5×10^{-2}
120	7.0×10^{-2}
125	6.3×10^{-2}
130	5.4×10^{-2}
135	4.4×10^{-2}
140	3.5×10^{-2}
145	2.6×10^{-2}

Table 6.4: $H \rightarrow \tau\tau$ branching ratios [15].

6.3 Backgrounds

Several SM processes have event signatures that contain or appear to contain a tau pair. The major backgrounds in the search for $H \rightarrow \tau\tau$ are:

- $Z \rightarrow \tau\tau$,
- $Z \rightarrow \ell\ell$ ($\ell = e$ or μ),
- W + jets,
- QCD multi-jet events,
- $t\bar{t}$ and single top,
- Di-Boson (WW , WZ , and ZZ).

In some of these processes, such as $Z \rightarrow \tau\tau$, the $\tau_\ell\tau_h$ pair is real and indistinguishable from $H \rightarrow \tau\tau$. In other processes, such as W + jets, the τ_ℓ and/or τ_h is faked by a similar physics object. Since the Higgs signal sits on top of these backgrounds, it is important to accurately predict the contribution of these background processes to the selected events. These backgrounds are estimated with a combination of Monte Carlo simulation and data-driven methods, described in the following sections.

6.3.1 $Z \rightarrow \tau\tau$

The largest background to $H \rightarrow \tau\tau$ is $Z \rightarrow \tau\tau$, which has the same final state particles as $H \rightarrow \tau\tau$. The $Z \rightarrow \tau\tau$ background model is based on two separate samples:

- Variable distributions are obtained from *embedded tau samples*, which are created by selecting di-muon events from collision data and replacing the reconstructed muons with simulated taus. The taus are decayed by TAUOLA and the standard GEANT4 simulation is run on the resulting stable particles. The advantage of embedded tau samples over pure Monte Carlo simulation is that all other aspects of the event besides the taus are taken from data, eliminating systematic uncertainties related to inaccuracies in the simulation. In particular, the modeling of jets and $\cancel{E}_T$ are improved versus pure Monte Carlo simulation. Jet kinematics and multiplicity play an important role in the categorization of

events (Section 4.4), while $\cancel{E}_T$ affects the efficiency of the M_T cut and the di-tau mass reconstruction.

- Overall event yield, including acceptance and efficiency, is computed from the $Z \rightarrow \tau\tau$ MADGRAPH Monte Carlo sample. The embedded tau samples cannot be used to measure acceptance because the original di-muon events are by definition already within the detector acceptance. Hence, it is necessary to use the pure Monte Carlo sample, which has a defined production cross section, for normalization. More specifically, the $Z \rightarrow \tau\tau$ background is normalized to the event yield of the $Z \rightarrow \tau\tau$ Monte Carlo after the tau pair selection but without the M_T cut.

6.3.2 $Z \rightarrow \ell\ell$

When a Z boson decays into two electrons or two muons, one lepton can be selected as the leptonic tau decay while the other lepton fakes a τ_h . Most $\ell \rightarrow \tau_h$ fakes are rejected by the lepton rejection requirements of the tau candidate (Section 4.2.5) and the di-lepton veto (Section 4.3.2). However, a significant number of $Z \rightarrow \ell\ell$ events still passes these cuts. The $Z \rightarrow \mu\mu$ contribution is relatively small in the $\tau_\mu\tau_h$ channel, because muons are fairly clean objects, but $Z \rightarrow ee$ constitutes a significant background for the $\tau_e\tau_h$ final state. $Z \rightarrow \ell\ell$ events can also be selected when one of the leptons goes undetected while a quark or gluon jet produced along with the Z boson fakes the τ_h . This background creates a non-resonant contribution to the SVFit mass distribution and it affects the $\tau_e\tau_h$ and $\tau_\mu\tau_h$ selections approximately equally. The $Z \rightarrow \ell\ell$ background is estimated with the Drell-Yan MADGRAPH Monte Carlo sample.

6.3.3 $W + \text{jets}$

$W + \text{jets}$ refers to events where a W boson and at least one jet are produced in a pp collision. A $W + \text{jets}$ event is selected if the W boson decays into an electron or muon while a jet fakes the τ_h , hence creating an event that appears to be $\tau_\ell\tau_h$. The

$M_T < 20 \text{ GeV}$ cut is dedicated to rejecting this background. The $W + \text{jets}$ events which pass this cut are modeled using a combination of data control regions and Monte Carlo. The variable distributions are taken from MADGRAPH Monte Carlo. The event yield is estimated by counting the number of events in the $M_T > 60 \text{ GeV}$ sideband in data, subtracting other background contributions (as predicted by Monte Carlo), and multiplying the result by the ratio of the number of $W + \text{jets}$ events in the sideband to the number of $W + \text{jets}$ events in the signal region ($M_T < 20 \text{ GeV}$); this ratio is computed from the Monte Carlo sample. The $W + \text{jets}$ event yield estimated by this procedure can be expressed as

$$N_W^{\text{est}} = \frac{N_W^{M_T < 20 \text{ GeV}}}{N_W^{M_T > 60 \text{ GeV}}} \left(N_{\text{data}}^{M_T > 60 \text{ GeV}} - N_{\text{non-W MC}}^{M_T > 60 \text{ GeV}} \right), \quad (6.2)$$

where N_W^{cut} is the W yield in Monte Carlo with the specified M_T cut, $N_{\text{data}}^{M_T > 60 \text{ GeV}}$ is the event count in the sideband in data, and $N_{\text{non-W MC}}^{M_T > 60 \text{ GeV}}$ is the event yield of non- W backgrounds predicted by Monte Carlo. This method for normalizing the $W + \text{jets}$ background essentially corrects the $\text{jet} \rightarrow \tau_h$ by measuring it in a sideband composed predominantly of $W + \text{jets}$ events and extrapolating the fake rate to the signal region. The signal region and sideband in the M_T distribution are illustrated in Figure 6-2.

6.3.4 QCD Multi-Jet Events

QCD interactions in a pp collision can result in an event with multiple high p_T jets. In these QCD multi-jet events, a jet can fake a τ_h while another jet fakes the lepton (in the case of the $\tau_\mu \tau_h$ channel, a muon is produced by a heavy-quark decay). The background due to QCD processes is estimated using events in data where the selected lepton and HPS tau have the same charge. Since the lepton and HPS tau in a QCD multi-jet event are actually jets that were coincidentally paired, there is expected to be only a small correlation between the charge of the two objects. Hence, the same-sign control region should have the same SVFit mass shape as the opposite-sign QCD events that pass the full selection.

The SVFit mass and other variable distributions of the QCD multi-jet background

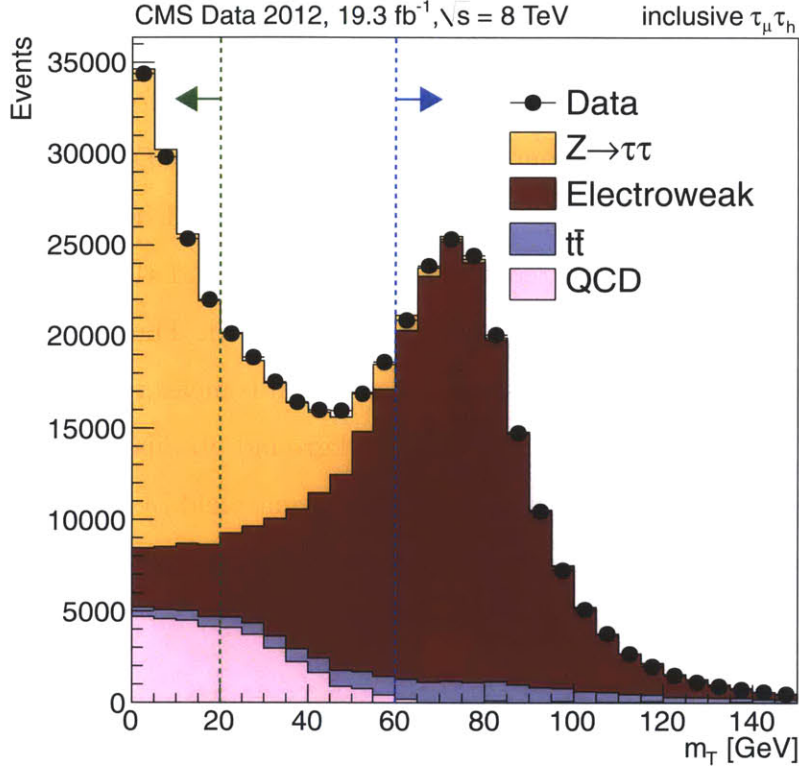


Figure 6-2: The normalization of the W background is derived from the $M_T > 60$ GeV sideband (indicated by the blue dashed line). The number of events in that sideband (minus other backgrounds) is extrapolated into the $M_T < 20$ GeV signal region (indicated by the green dashed line). The extrapolation factor is measured in Monte Carlo simulation. In the figure, this technique has already been applied to the normalization of the W background.

are derived by taking the distribution from same-sign $\tau_\ell\tau_h$ events and subtracting same-sign contributions from non-QCD backgrounds. The same-sign $W + \text{jets}$ contribution is estimated using the method described in Section 6.3.3 except using same-sign events instead of opposite-sign events. Other non-QCD backgrounds in the same-sign region are obtained from Monte Carlo simulation. The remaining same-sign events are used to estimate the shape of the QCD background. The same-sign control region for the SVFit mass is shown in Figure 6-3.

The normalization of the QCD estimate needs to be corrected for the fact that the opposite-sign QCD events are more numerous than same-sign QCD events. The ratio of opposite-sign to same-sign QCD events, $R_{\text{OS/SS}}$, is measured in the anti-isolated control region. The lepton is required to have $I_{\text{rel}}^{\text{PF}} > 0.3$ and the tau isolation is relaxed to $I_{\tau_h}^{\text{BDT}} > 0.7$. Non-QCD backgrounds are subtracted. The ratio of opposite-sign events to same-sign events in the anti-isolated region is measured to be $R_{\text{OS/SS}} = 1.09 \pm 0.05$ for both 2011 and 2012. The QCD background obtained from the same-sign region is normalized by multiplying its original event yield by $R_{\text{OS/SS}}$.

To compensate for a lack of statistics in some event categories, variations on the above method are used, depending on the category:

Inclusive and 0-jet

In the inclusive and 0-jet categories, the QCD background is estimated using the standard method described above.

1-jet

In the 1-jet category, the QCD background *normalization* is determined using the standard method described above. The shape is taken from the same-sign, anti-isolated ($I_{\text{rel}}^{\text{PF}} > 0.2$) control region.

VBF

In the VBF category, several cuts are relaxed to gain additional statistical precision. The QCD normalization is estimated by multiplying the isolated/anti-isolated ratio measured in the same-sign control region (no jet selection) with the number of anti-isolated ($I_{\text{rel}}^{\text{PF}} > 0.2$), same-sign events passing the VBF jet

selection, and multiplying by the opposite-sign/same-sign ratio,

$$N_{\text{QCD}}^{\text{est}} = \frac{N_{\text{SS-isolated}}}{N_{\text{SS-anti-isolated}}} N_{\text{SS-anti-isolated}}^{\text{VBF}} R_{\text{OS/SS}}. \quad (6.3)$$

The shape for the QCD background in the VBF category is taken from the same-sign, anti-isolated control region in data, but with the di-jet selection relaxed to $m_{jj} > 100 \text{ GeV}$ and $\Delta\eta > 1.0$.

6.3.5 Top

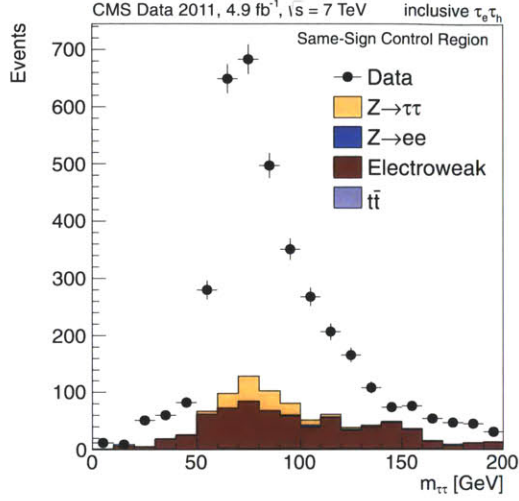
A $t\bar{t}$ event can contain multiple leptons and jets created in the decay cascade of the top quarks. A lepton and jet (either from a tau, quark, or gluon) produced in a $t\bar{t}$ event can cause it to be selected as a di-tau event. Similarly, the much rarer single top event can contain a lepton from a top or bottom quark decay along with jets that can fake a τ_h . The $t\bar{t}$ and single-top backgrounds are modeled with MADGRAPH and POWHEG Monte Carlo samples, respectively.

6.3.6 Di-Boson

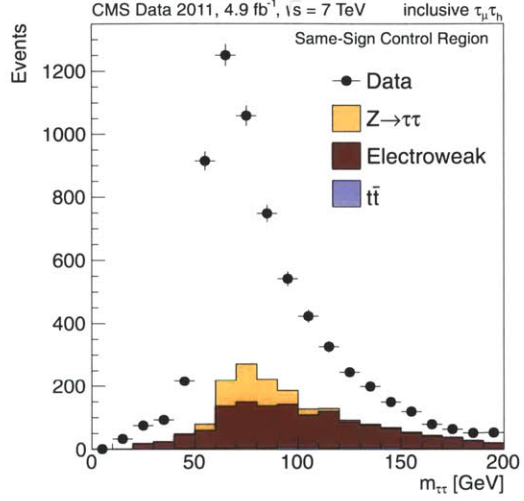
Di-boson backgrounds include WW , ZZ , and WZ events. The cross sections for these processes are small but vector bosons can decay into isolated leptons (including taus) that imitate the $\tau_\ell\tau_h$ final state. Di-boson backgrounds are modeled by MADGRAPH Monte Carlo simulation.

6.4 Comparison of Background Estimation with Data

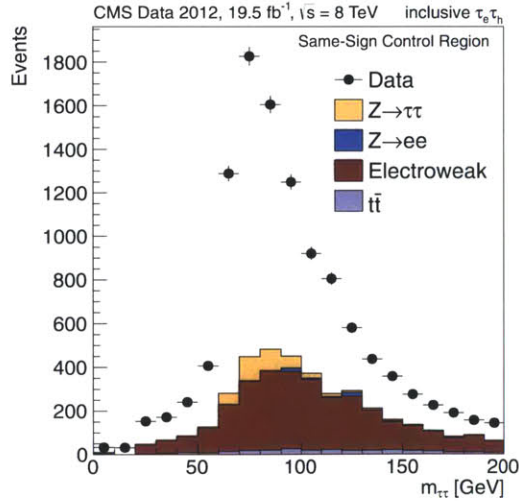
The validity of the background estimation methods can be gauged by examining variable distributions in the inclusive selection, i.e. all event categories combined. Under the inclusive selection, the Higgs signal is negligible compared to the backgrounds and therefore the data is expected to be compatible with the SM background. The p_T and η distributions of the electron, muon, and τ_h are shown in Figures 6-4 to 6-7.



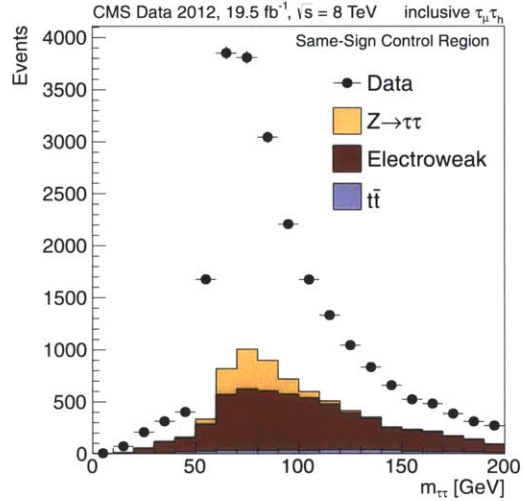
(a) Same-sign $\tau_e \tau_h$ in 2011



(b) Same-sign $\tau_\mu \tau_h$ in 2011



(c) Same-sign $\tau_e \tau_h$ in 2012



(d) Same-sign $\tau_\mu \tau_h$ in 2012

Figure 6-3: SVFit di-tau mass in the same-sign control region with Monte Carlo prediction of non-QCD backgrounds. The difference between the data and the non-QCD backgrounds is used as an estimate of the QCD background shape.

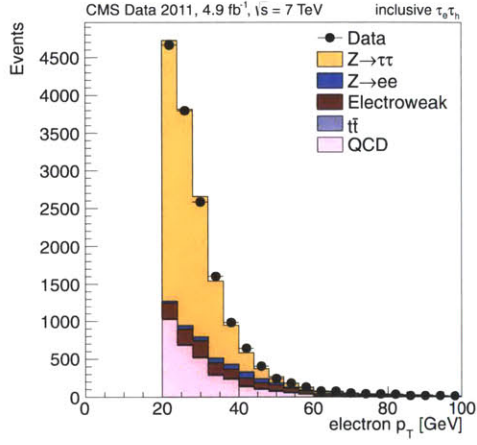
The transverse mass of the lepton and $\cancel{E}_T$, $M_T(\ell, \cancel{E}_T)$, is plotted in Figure 6-8; in these plots, the $M_T < 20 \text{ GeV}$ cut is removed so that the entire M_T range can be seen. Figure 6-9 shows the mass of the visible tau decay products, m_{vis} . The visible mass conveys how well the $\tau_\ell \tau_h$ correlations are modeled. Finally, the number of jets per event (jet multiplicity) is shown in Figure 6-10. Only jets with $p_T > 30 \text{ GeV}$ and passing the jet identification criteria (Section 4.2.7) are counted. These inclusive distributions show adequate agreement between the background estimation and data. In the next section, systematic uncertainties that account for some of the mis-modeling are discussed.

6.5 Systematic Uncertainties

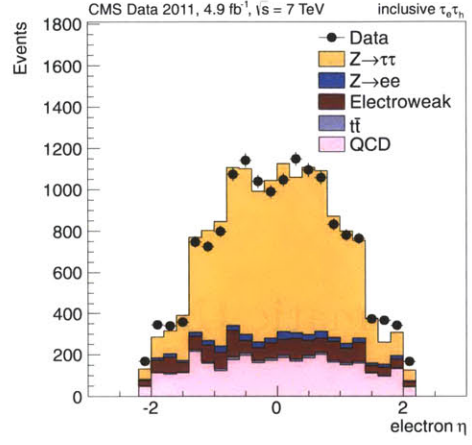
The predicted event yields and distributions of the signal and background models are subject to systematic uncertainties due to limited knowledge of detector conditions, simulation inaccuracies, limited statistics in control regions, etc. These uncertainties are incorporated in the statistical analysis as potential variations in the normalization and shape of the fit models (Section 7.1). The following is a summary of the major systematic uncertainties.

Theory Uncertainties on Higgs Production and Acceptance

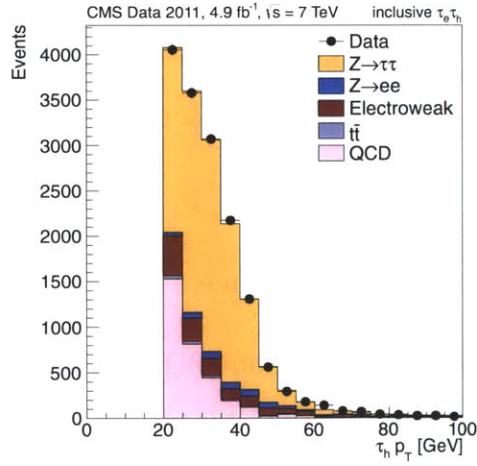
The Higgs cross section depends on the *parton distribution function* (PDF) [66] used in the Monte Carlo event generation. The PDF is empirically derived in electron-proton and proton-proton collision experiments [67] and has uncertainties on its parameters. The effect of these uncertainties are assessed by computing the Higgs cross section using a set of PDFs for which the individual parameters have been shifted according to their uncertainties. Additional uncertainties arise from the fact that there are several alternative methods for deriving the PDF. These uncertainties are estimated by calculating the Higgs cross section using alternative PDF sets (CT10, MSTW2008, and NNPDF [68,69]) and taking the largest difference as the overall uncertainty. The PDF uncertainties on $gg \rightarrow H$, VBF, and VH production are 8%, 3%, and 2%,



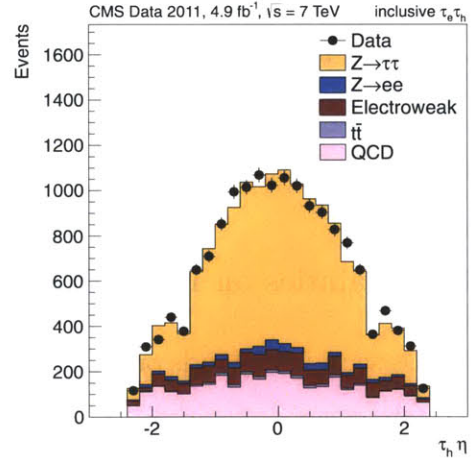
(a) electron p_T



(b) electron η

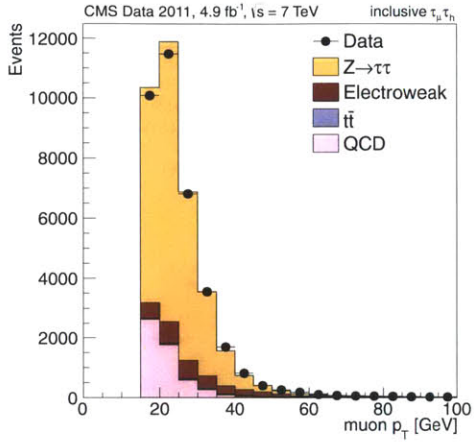


(c) $\tau_h p_T$

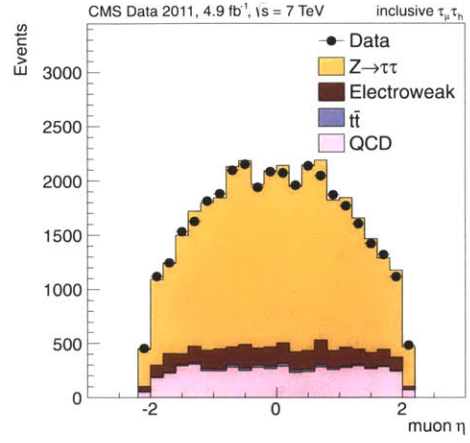


(d) $\tau_h \eta$

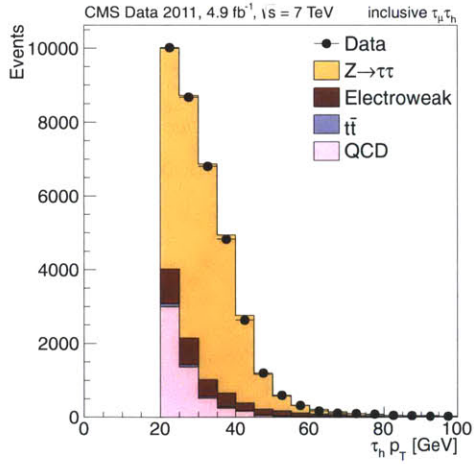
Figure 6-4: p_T and η distributions of the electron and τ_h in the $\tau_e \tau_h$ channel in 2011 data.



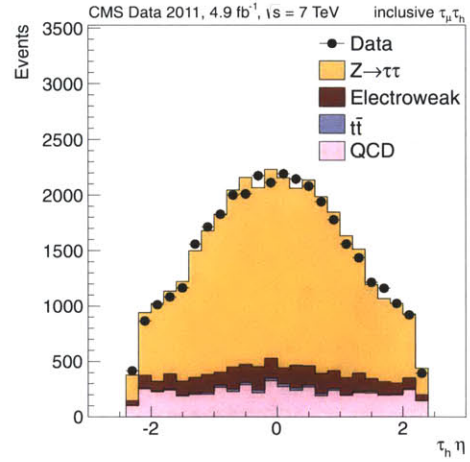
(a) muon p_T



(b) muon η

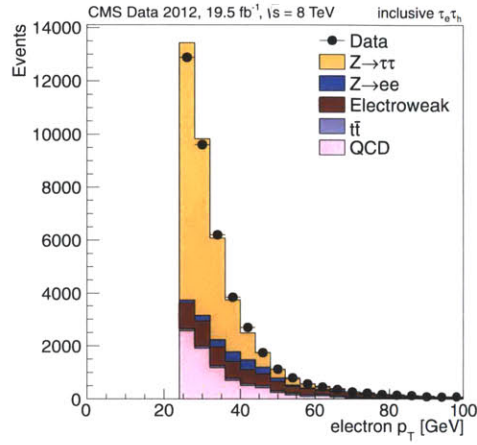


(c) $\tau_h p_T$

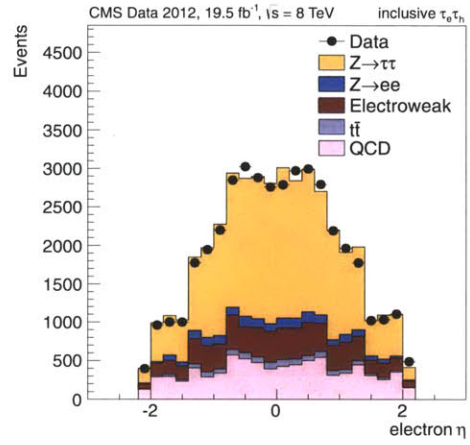


(d) $\tau_h \eta$

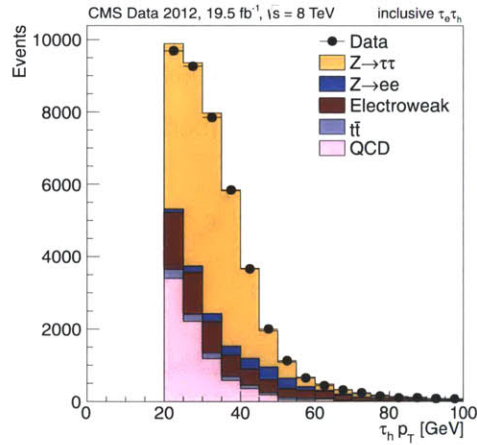
Figure 6-5: p_T and η distributions of the muon and τ_h in the $\tau_\mu \tau_h$ channel in 2011 data.



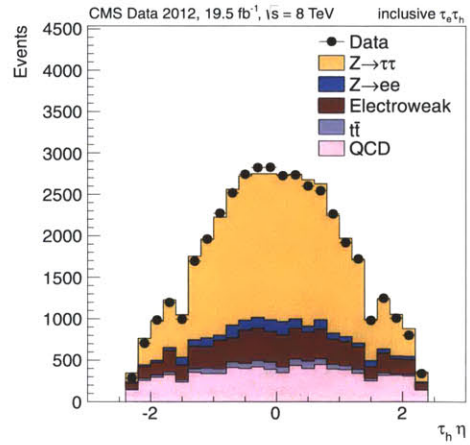
(a) electron p_T



(b) electron η

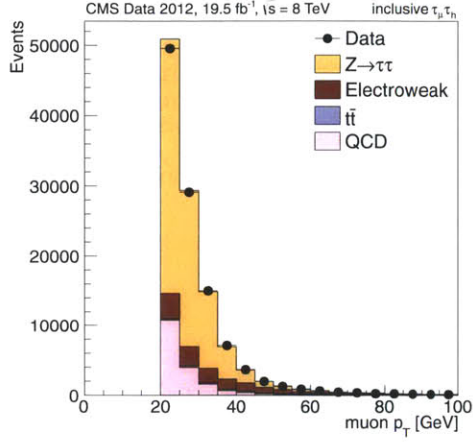


(c) $\tau_h p_T$

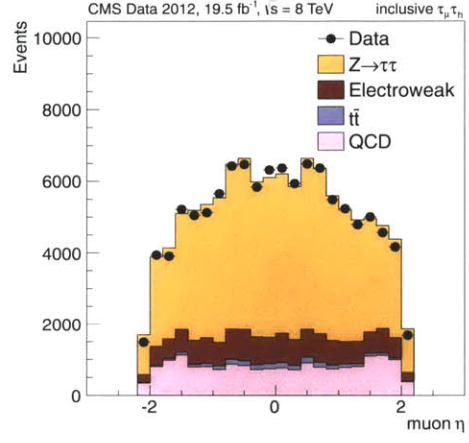


(d) $\tau_h \eta$

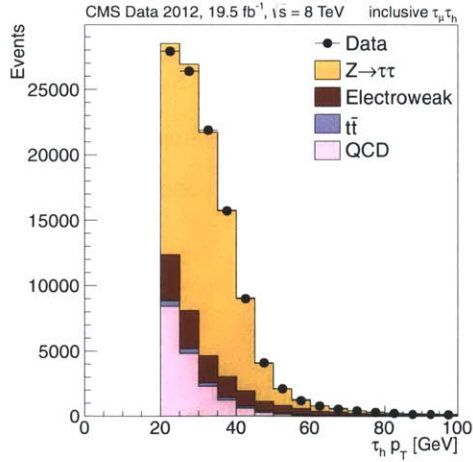
Figure 6-6: p_T and η distributions of the electron and τ_h in the $\tau_e \tau_h$ channel in 2012 data.



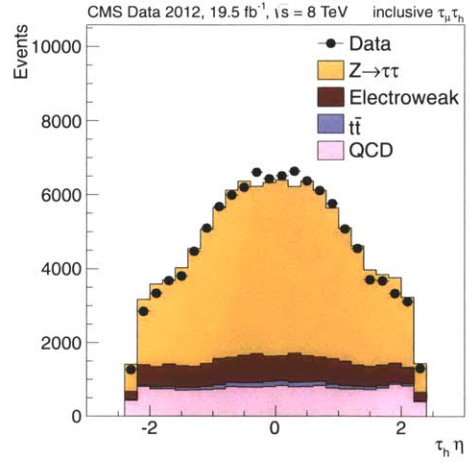
(a) muon p_T



(b) muon η

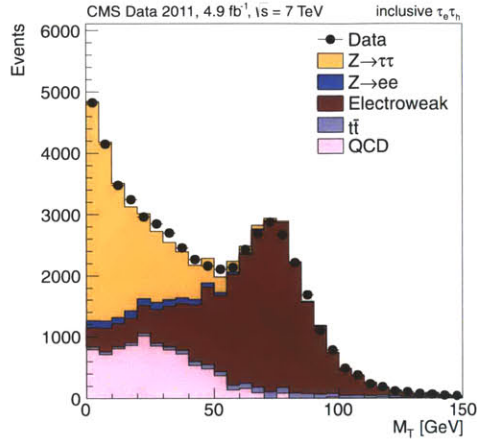


(c) $\tau_h p_T$

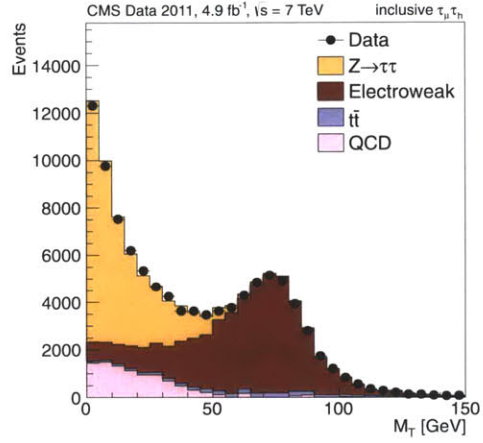


(d) $\tau_h \eta$

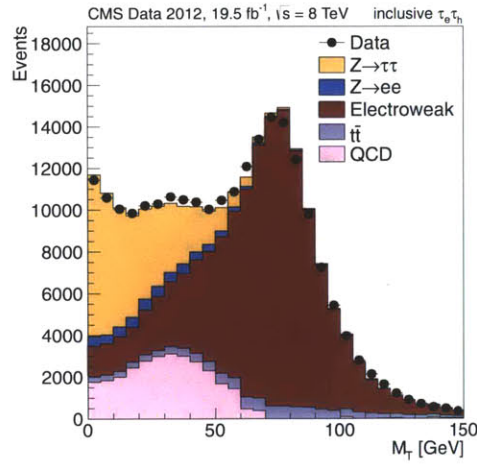
Figure 6-7: p_T and η distributions of the muon and τ_h in the $\tau_\mu \tau_h$ channel in 2012 data.



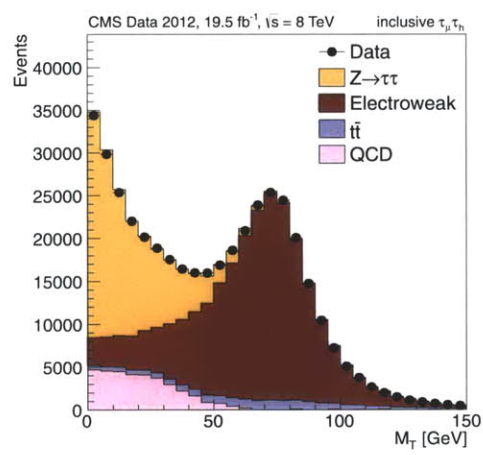
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

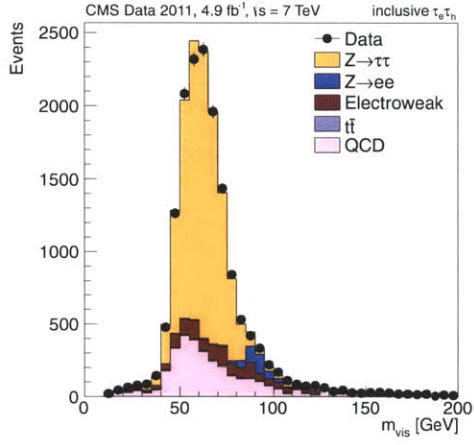


(c) $\tau_e \tau_h$, 2012

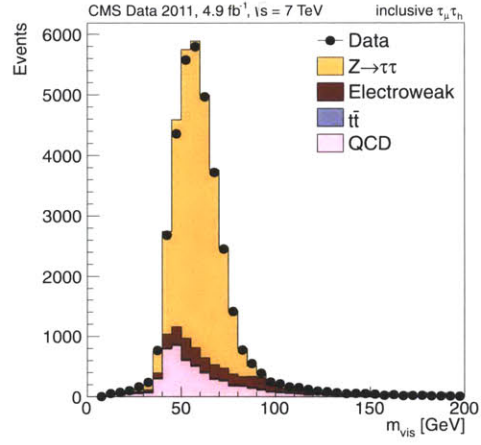


(d) $\tau_\mu \tau_h$, 2012

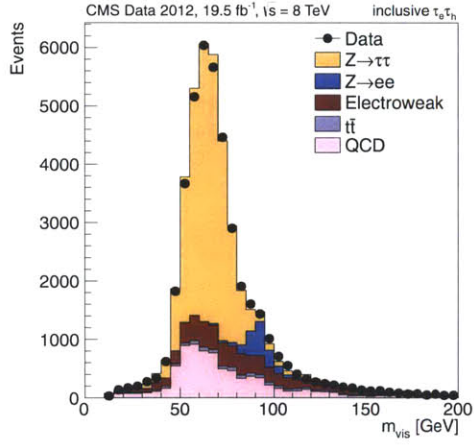
Figure 6-8: Transverse mass of the lepton and $\cancel{E}_T$.



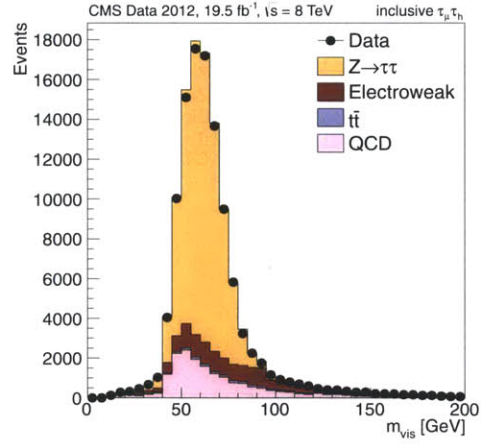
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

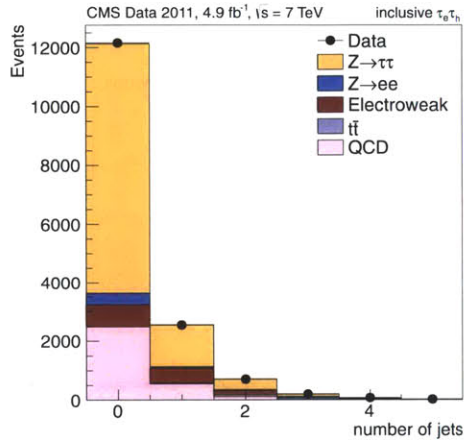


(c) $\tau_e \tau_h$, 2012

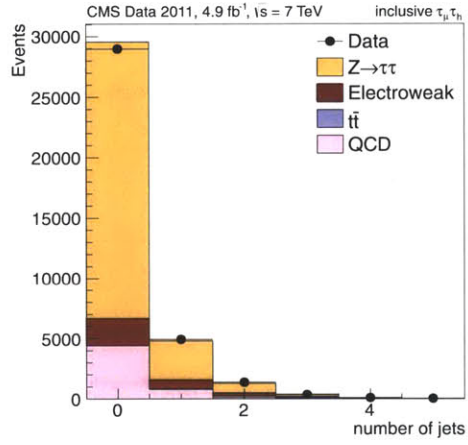


(d) $\tau_\mu \tau_h$, 2012

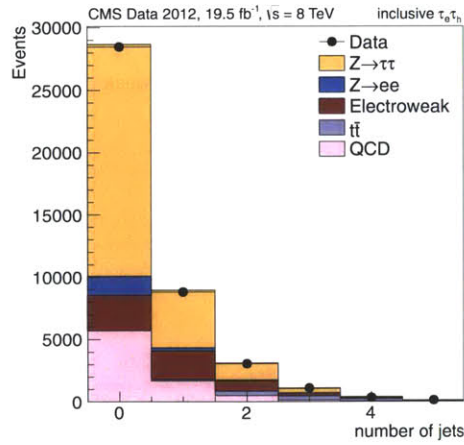
Figure 6-9: Visible mass of the tau pair.



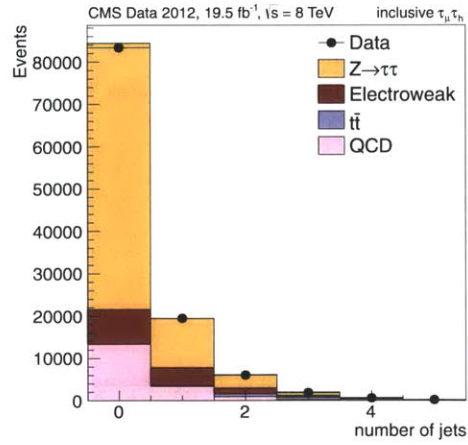
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011



(c) $\tau_e \tau_h$, 2012



(d) $\tau_\mu \tau_h$, 2012

Figure 6-10: Jet multiplicity.

respectively.

The rate of Higgs production also has a dependence on the strong coupling constant α_s , the renormalization scale μ_R , and the factorization scale μ_F , because the cross section is computed to fixed order. The production and acceptance uncertainties due to α_s [70, 71] and the missing higher order QCD corrections are estimated by varying α_s , μ_R , and μ_F and comparing changes in the Higgs event yield. The uncertainty on gluon fusion production is 8% in the 0-jet categories, 10% in the 1-jet categories, and 30% in the VBF category. The uncertainty on VBF production is 3.5% in the 0-jet categories and 4% in the other categories.

The underlying event [72, 73] and parton shower modeling affects the jet distribution and therefore the categorization of events. Variations of this modeling lead to a 4% uncertainty on the predicted Higgs event yield, anti-correlated between categories with jets and those without jets.

Luminosity

The expected event yield predicted by a Monte Carlo sample is given by Eq. 6.1, which is proportional to the integrated luminosity. The samples which depend on the luminosity measurement include the Z boson, $t\bar{t}$, single top, and di-boson backgrounds. The Higgs signal is also normalized based on the luminosity measurement. Any uncertainty in the measurement of the integrated luminosity corresponds to a proportional uncertainty on the normalization of these samples. Luminosity measurements are described in Section 2.2.7. The integrated luminosity in 2011 has an uncertainty of 2.2%; the integrated luminosity in 2012 has an uncertainty of 4.4%.

Lepton Selection Efficiency

The precision of the electron and muon efficiency corrections measured in Chapter 5 is limited by available statistics and uncertainty about the fit models. These uncertainties translate into a potential variation in the normalization of Monte Carlo simulated samples to which the efficiency corrections are applied. The total uncertainty on the trigger, identification, and isolation efficiencies for leptons is estimated to be 2% for

both electrons and muons.

Tau Selection Efficiency

The efficiency of selecting τ_h includes the trigger, identification, and isolation efficiencies. The trigger and isolation efficiencies were measured from data (Sections 5.2.2 and 5.3.2) and have uncertainties of 4% and 3%, respectively. The efficiency of the reconstruction and identification is determined *in situ* by the fit to the SVFit mass distribution when quantifying the Higgs excess. It is assigned an estimated uncertainty of 6%. The total uncertainty due to the τ_h efficiency is 8% and is applied to samples with genuine taus ($H \rightarrow \tau\tau$, $Z \rightarrow \tau\tau$, $t\bar{t}$, and di-boson samples).

Tau Energy Scale

The τ_h energy scale was measured in data (Section 3.7.1) but has systematic uncertainties due to the choice of fit model for the τ_h mass spectrum. The uncertainty is estimated to be 2%. This uncertainty affects the di-tau mass shape and is handled as a *shape* uncertainty: the di-tau mass shape is allowed to vary between two alternative templates generated with the energy of the τ_h shifted by $\pm 2\%$. The shifted mass shapes are illustrated in Figure 6-11.

Jet Energy Scale

The uncertainty on the jet energy scale affects the selection of jets and therefore the categorization of events. The effect on the event yield of each category is assessed by shifting the jet energy up and down by the jet energy scale uncertainty. In the 0-jet and 1-jet categories, the effect ranges from 2% to 4%, depending on the sample (samples that contain more jets on average, e.g. $t\bar{t}$, are more strongly affected). In the VBF category, the effect of the jet energy scale uncertainty on event yield ranges from 5% to 15%, depending on the sample. The effect of the uncertainty is anti-correlated between categories with jets and those without jets.

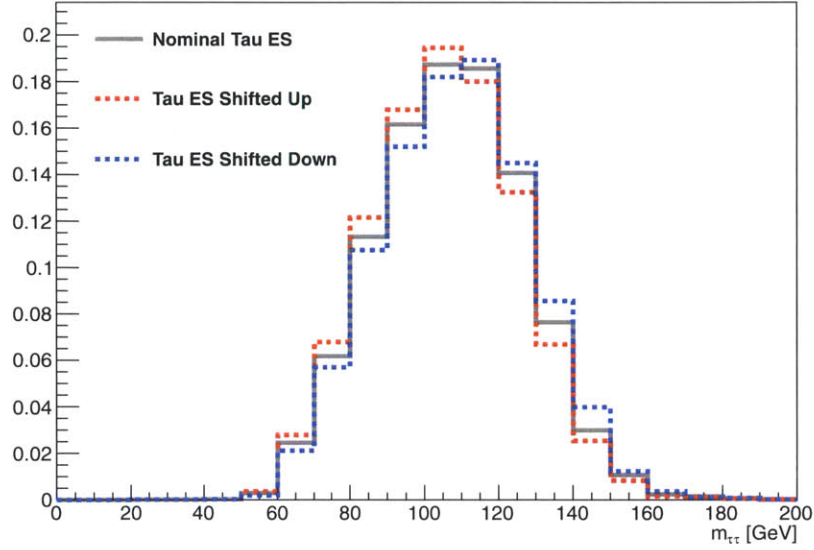


Figure 6-11: Comparison of the SVFit di-tau mass computed with the nominal tau energy scale and with the tau energy scale shifted up and down by 2%. The events are from a Higgs ($m_H = 125$ GeV) Monte Carlo sample, in the $\tau_\mu\tau_h$ channel. The histograms are normalized to one.

$\cancel{E}_T$ Scale

The efficiency of the M_T cut is affected by the $\cancel{E}_T$ scale uncertainty, which is taken from the $\cancel{E}_T$ recoil correction measurement (Section 3.8). The effect on predicted event yields is assessed by shifting the $\cancel{E}_T$ up and down by the uncertainty of the recoil correction. The effect on the predicted event yield is 2 – 7%, depending on sample and category. Only samples in which $\cancel{E}_T$ is simulated by Monte Carlo are affected; the embedded $Z \rightarrow \tau\tau$ and the QCD backgrounds are not affected by this uncertainty because they obtain their $\cancel{E}_T$ from data control regions.

$\ell \rightarrow \tau_h$ and jet $\rightarrow \tau_h$ Fake Rates in $Z \rightarrow \ell\ell$

The probability that an electron, muon, or jet will fake a τ_h affects the event yield of the $Z \rightarrow \ell\ell$ background. The $e \rightarrow \tau_h$ and $\mu \rightarrow \tau_h$ fake rates have an uncertainty of 20% and 30%, respectively. The jet $\rightarrow \tau_h$ fake rate has an uncertainty of 20%.

W Normalization

The normalization of the W + jets background is determined by the number of events in the $M_T > 60$ GeV sideband and the ratio of events with $M_T < 20$ GeV to events with $M_T > 60$ GeV in the W Monte Carlo. The uncertainty on the ratio is due to $\cancel{E}_T$ modeling and the jet energy scale. In the tighter categories (e.g. VBF), the sideband is statistically limited. The combined uncertainty due to these two factors is 10–20%, depending on the category.

QCD Normalization

The uncertainty of the QCD background normalization for the 0-jet and 1-jet categories is composed of two parts: 1) the statistical uncertainty of the same-sign sideband, 2) the systematic uncertainty of the opposite-sign/same-sign ratio. The statistical uncertainty of the sideband is 0.8 – 5%, depending on the channel, category, and year. The systematic uncertainty of the opposite-sign/same-sign ratio is estimated by varying the anti-isolation requirement on the lepton; this procedure yields an uncertainty of 6%.

In the VBF category, the QCD normalization procedure involves computing several efficiencies for various cuts (Section 6.3.4). A conservative uncertainty of 20–30%, depending on channel, is assigned to cover biases and statistical uncertainties in this procedure.

Top and Di-Boson Cross Sections and Jet Fake Rate

The predicted $t\bar{t}$ and di-boson event yields have an additional 10% and 15% uncertainty, respectively, due to the uncertainty on their cross sections and the jet $\rightarrow \tau_h$ fake rate. The uncertainty related to the jet fake rate is anti-correlated between categories with jets and those without jets.

Chapter 7

Analysis Results

The search for the Higgs boson involves finding a statistically significant excess of events in the data over the expected Standard Model background. Rather than simply counting events, this analysis assesses the significance of any potential excess in the data by performing a fit to the di-tau mass distribution. The fit allows backgrounds to be constrained by the shape of the di-tau mass spectrum and looks for an excess only in a mass region consistent with the hypothesized signal. The statistical methods used in testing the signal hypothesis against the background-only hypothesis are described in this chapter. Following that is a summary of the observed and expected event yields, as well as the di-tau mass distributions that result from the maximum likelihood fit. Finally, the upper limits on the Higgs cross section are presented.

7.1 Statistical Method

7.1.1 Likelihood

Any potential excess in the data is quantified by a binned *maximum likelihood fit* on the di-tau mass distribution. The likelihood function is parameterized by the expected number of signal and background events in each mass bin, as well as a signal strength

modifier μ and nuisance parameters $\boldsymbol{\theta}$. The likelihood function is given by

$$\mathcal{L}(\text{data}|\mu, \boldsymbol{\theta}) = \prod_i \frac{(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))^{n_i}}{n_i!} e^{-\mu s_i - b_i} \cdot p(\boldsymbol{\theta}), \quad (7.1)$$

where n_i , $s_i(\boldsymbol{\theta})$, and $b_i(\boldsymbol{\theta})$ are the number of observed events, expected signal events, and expected background events, in the i^{th} bin, respectively. The first part of the likelihood represents the Poisson probability of observing n_i events in a bin where the expected number of events is $\mu s_i + b_i$. The second part of the likelihood, $p(\boldsymbol{\theta})$, represents the constraints on the nuisance parameters.

The expected signal and background events are obtained from fit models generated by the methods described in Chapter 6. Since the fit models are binned, they are referred to as *templates*. The normalization and shape of the templates are allowed to vary according to their systematic uncertainties, which are incorporated into the fit as nuisance parameters. A nuisance parameter can modify either the normalization or shape of a template.

A nuisance parameter representing a normalization uncertainty can have one of two probability distributions:

1. If the effect of a nuisance parameter on the normalization is estimated from Monte Carlo simulation, that normalization is constrained by a log-normal distribution,

$$P(N) = \frac{N_0}{\sqrt{2\pi N \ln \kappa}} \exp \left[-\frac{(\ln(N/N_0))^2}{2(\ln \kappa)^2} \right], \quad (7.2)$$

where N is the normalization of the template, N_0 is the normalization estimated from Monte Carlo, and κ is the relative uncertainty, e.g. a 3% uncertainty on the event yield would correspond to $\kappa = 1.03$.

2. If the normalization of a template is derived from the event count in a data control region, the normalization of that template is modeled as a Gamma distribution,

$$P(N) = \frac{N^M}{\alpha^{M+1} \Gamma(M+1)} \exp(-N/\alpha), \quad (7.3)$$

where N is the normalization of the template, M is the number of events in the control region, αM is the expected normalization of the template, and Γ is the Gamma function.

Shape uncertainties are implemented by the *vertical morphing technique*. For each shape uncertainty, additional templates are provided where the nuisance parameter is shifted up or down by one standard deviation. The template is morphed by interpolating the nominal template bin-by-bin with the alternative templates. The interpolation is quadratic up to one standard deviation and then becomes linear for larger deviations. The shift parameter follows a standard normal distribution.

If there are multiple event categories, the categories are fit simultaneously. The total likelihood is the product of the individual likelihoods of the categories, except that the nuisance parameter term $p(\boldsymbol{\theta})$ is shared. In this analysis, all categories are used to constrain the nuisance parameters, but only the 1-jet and VBF categories are fit for signal. In the 0-jet categories, the Higgs signal is negligible and the di-tau mass resolution is poor; hence the signal is not included in the likelihoods of the 0-jet categories.

The likelihood is a key ingredient in testing the signal hypothesis against the background-only hypothesis. The actual test statistic is described in the next section.

7.1.2 Profile Likelihood Ratio

A significance or upper limit calculation is based on the *profile likelihood ratio*,

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}}_\mu)}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}, \quad (7.4)$$

where μ is the signal strength modifier, $\hat{\mu}$ is the *best fit* signal strength modifier, $\hat{\boldsymbol{\theta}}$ is a vector of best fit nuisance parameters, and $\hat{\boldsymbol{\theta}}_\mu$ is the vector of best fit nuisance parameters with the signal strength modifier constrained to μ . Rather than use the

profile likelihood ratio $\lambda(\mu)$ directly, it is more convenient to use the test statistic,

$$t_\mu = -2 \ln \lambda(\mu). \quad (7.5)$$

Low values of t_μ correspond to good compatibility between the data and the given value of μ while high values indicate incompatibility between the data and the hypothesized μ .

7.1.3 Limit Calculation

For upper limit calculations, two conditions are imposed on the profile likelihood ratio:

1. $\hat{\mu}$ is forced to be non-negative because negative signal strengths are unphysical.
2. If $\hat{\mu} > \mu$, the test statistic is automatically set to 0 (highest compatibility) because in the case of upper limits, only values of $\hat{\mu}$ that are smaller than μ should be treated as part of the rejection region of the test.

Putting these two conditions together, the test statistic (based on Eq. 7.5) becomes

$$\tilde{q}_\mu = \begin{cases} -2 \ln \frac{L(\mu, \hat{\theta}_\mu)}{L(0, \hat{\theta}_0)} & \hat{\mu} < 0 \\ -2 \ln \frac{L(\mu, \hat{\theta}_\mu)}{L(\hat{\mu}, \hat{\theta})} & 0 < \hat{\mu} < \mu \\ 0 & \hat{\mu} > \mu. \end{cases} \quad (7.6)$$

The probability distribution of $\tilde{q}_\mu$, $f(\tilde{q}_\mu | \mu s + b)$, is either computed by generating pseudo-data or approximated with the *asymptotic formula* [74]. The asymptotic formula uses the Wald approximation [75] for the profile likelihood ratio:

$$-2 \ln \lambda(\mu) \approx \frac{(\mu - \hat{\mu})^2}{\sigma^2}, \quad (7.7)$$

where $\hat{\mu}$ follows a normal distribution with mean μ and standard deviation σ . The standard deviation σ is estimated using the “Asimov” dataset [74, 76], which is the dataset where every data point is at its expected value.

The probability distribution $f(\tilde{q}_\mu|\mu s+b)$ is used to calculate the following p -values:

$$CL_{s+b}(\mu) = \int_{q_{\mu,\text{obs}}}^{\infty} f(q_\mu|\mu s+b) dq_\mu, \quad (7.8)$$

$$CL_b(\mu) = \int_{q_{\mu,\text{obs}}}^{\infty} f(q_\mu|b) dq_\mu, \quad (7.9)$$

$$CL_s = \frac{CL_{s+b}(\mu)}{CL_b(\mu)}. \quad (7.10)$$

CL_{s+b} is the p -value of the observed test statistic $q_{\mu,\text{obs}}$ in the signal-plus-background scenario whereas CL_b is the p -value in the background-only scenario. CL_s [77] is CL_{s+b} normalized with respect to CL_b ; it is not technically a p -value, but gives a more conservative limit and is less sensitive to background fluctuations than CL_{s+b} . An upper limit on μ with confidence $1 - \alpha$ (α is typically 0.05) is obtained by finding the value of μ for which $CL_s = \alpha$.

7.2 Event Yields

The observed and expected event yields by channel and year are tabulated in Tables 7.1, 7.2, 7.3, and 7.4. The expected event yields are given for each background process. The expected Higgs signal yield for $m_H = 125$ GeV is also shown for comparison (note that the signal is not included in the fit of the 0-jet categories and therefore is not shown for those categories). The uncertainties on the predicted yields are computed by summing the corresponding systematic uncertainties in quadrature. There is no significant excess in the number of observed events over the SM backgrounds. It should be noted that this analysis extracts the signal excess by a fit to the di-tau mass distribution, which greatly improves the search sensitivity over a simple counting analysis.

	0-jet, high $p_T^{\tau_h}$	0-jet, low $p_T^{\tau_h}$	1-jet, high $p_T^{\tau_h}$	1-jet, low $p_T^{\tau_h}$	VBF
$gg \rightarrow H$	-	-	6.7 ± 1.1	5.8 ± 1.1	0.16 ± 0.06
VBF H	-	-	1.2 ± 0.1	1.1 ± 0.1	0.86 ± 0.12
$VH + t\bar{t}H$	-	-	0.56 ± 0.07	0.54 ± 0.07	0.005 ± 0.001
$Z \rightarrow \tau\tau$	7086 ± 641	1371 ± 148	1321 ± 137	438 ± 47	7.6 ± 1.0
$Z \rightarrow \ell\ell$	291 ± 47	197 ± 37	176 ± 31	66 ± 10	5.7 ± 1.1
$W + \text{jets}$	401 ± 40	177 ± 18	339 ± 34	101 ± 10	3.7 ± 0.7
$t\bar{t}$	0.84 ± 0.12	0.58 ± 0.07	20 ± 3	9.7 ± 1.3	0.56 ± 0.13
Di-Boson	6.5 ± 1.3	5.7 ± 1.1	16 ± 3	8.7 ± 1.7	0.30 ± 0.32
QCD	2344 ± 128	147 ± 15	536 ± 36	70 ± 9	5.5 ± 1.6
$\sum \text{Bkg}$	10128 ± 657	1897 ± 154	2408 ± 149	693 ± 50	23 ± 2
Data	10148	1930	2385	722	23

Table 7.1: Expected and observed event yields in the $\tau_e\tau_h$ channel for 2011 data. The expected Higgs event yields are for $m_H = 125$ GeV.

	0-jet, high $p_T^{\tau_h}$	0-jet, low $p_T^{\tau_h}$	1-jet, high $p_T^{\tau_h}$	1-jet, low $p_T^{\tau_h}$	VBF
$gg \rightarrow H$	-	-	12 ± 2	11 ± 2	0.28 ± 0.11
VBF H	-	-	2.3 ± 0.3	2.2 ± 0.3	1.6 ± 0.2
$VH + t\bar{t}H$	-	-	1.1 ± 0.1	1.2 ± 0.1	0.002 ± 0.001
$Z \rightarrow \tau\tau$	19527 ± 1766	3283 ± 353	2878 ± 297	1038 ± 112	20 ± 3
$Z \rightarrow \ell\ell$	475 ± 84	129 ± 27	167 ± 33	57 ± 10	0.75 ± 0.24
$W + \text{jets}$	1180 ± 118	284 ± 28	584 ± 58	157 ± 16	9.3 ± 1.6
$t\bar{t}$	1.1 ± 0.1	1.2 ± 0.2	42 ± 6	21 ± 3	1.4 ± 0.3
Di-Boson	17 ± 3	13 ± 2	33 ± 6	19 ± 4	0.34 ± 0.15
QCD	4235 ± 222	170 ± 16	714 ± 45	116 ± 13	7.7 ± 1.7
$\sum \text{Bkg}$	25434 ± 1786	3880 ± 356	4418 ± 308	1407 ± 114	39 ± 4
Data	25052	3771	4553	1380	39

Table 7.2: Expected and observed event yields in the $\tau_\mu\tau_h$ channel for 2011 data. The expected Higgs event yields are for $m_H = 125$ GeV.

	0-jet, high $p_T^{\tau_h}$	0-jet, low $p_T^{\tau_h}$	1-jet, high $p_T^{\tau_h}$	1-jet, low $p_T^{\tau_h}$	VBF
$gg \rightarrow H$	-	-	26 ± 5	22 ± 4	0.68 ± 0.26
VBF H	-	-	4.5 ± 0.6	3.8 ± 0.5	3.9 ± 0.5
$VH + t\bar{t}H$	-	-	2.1 ± 0.3	2.3 ± 0.3	0.006 ± 0.001
$Z \rightarrow \tau\tau$	15084 ± 1467	3395 ± 385	4477 ± 490	1419 ± 169	44 ± 6
$Z \rightarrow \ell\ell$	845 ± 136	1057 ± 203	836 ± 150	267 ± 41	13 ± 3
$W + \text{jets}$	1323 ± 132	784 ± 78	1710 ± 171	584 ± 62	27 ± 3
$t\bar{t}$	0.99 ± 0.21	3.8 ± 0.7	153 ± 23	74 ± 13	5.2 ± 1.9
Di-Boson	17 ± 3	19 ± 4	85 ± 16	48 ± 10	1.4 ± 1.4
QCD	5176 ± 269	583 ± 38	1854 ± 103	155 ± 16	21 ± 6
$\sum \text{Bkg}$	22446 ± 1504	5841 ± 444	9116 ± 551	2547 ± 186	111 ± 10
Data	22200	6028	8986	2591	85

Table 7.3: Expected and observed event yields in the $\tau_e\tau_h$ channel for 2012 data. The expected Higgs event yields are for $m_H = 125$ GeV.

	0-jet, high $p_T^{\tau_h}$	0-jet, low $p_T^{\tau_h}$	1-jet, high $p_T^{\tau_h}$	1-jet, low $p_T^{\tau_h}$	VBF
$gg \rightarrow H$	-	-	54 ± 9	53 ± 9	2.4 ± 0.8
VBF H	-	-	9.0 ± 1.1	8.2 ± 1.0	7.0 ± 0.9
$VH + t\bar{t}H$	-	-	4.1 ± 0.5	4.9 ± 0.6	0.058 ± 0.011
$Z \rightarrow \tau\tau$	52795 ± 5136	9634 ± 1093	10840 ± 1186	3648 ± 414	92 ± 13
$Z \rightarrow \ell\ell$	1721 ± 306	575 ± 121	874 ± 161	213 ± 38	7.0 ± 2.7
$W + \text{jets}$	3785 ± 379	1376 ± 138	3307 ± 331	1076 ± 108	44 ± 4
$t\bar{t}$	2.3 ± 0.4	7.3 ± 1.2	282 ± 47	147 ± 24	5.7 ± 2.1
Di-Boson	56 ± 11	50 ± 10	176 ± 34	104 ± 20	1.6 ± 0.6
QCD	12396 ± 631	934 ± 57	3341 ± 178	356 ± 26	43 ± 9
$\sum \text{Bkg}$	70755 ± 5197	12577 ± 1109	18820 ± 1255	5545 ± 431	193 ± 17
Data	70002	12610	18587	5555	193

Table 7.4: Expected and observed event yields in the $\tau_\mu\tau_h$ channel for 2012 data. The expected Higgs event yields are for $m_H = 125$ GeV.

7.3 Di-Tau Mass Distributions

The maximum likelihood fit is performed on the di-tau mass distribution. The fit is restricted to the di-tau mass window $0 - 350$ GeV. Two binning schemes are used:

1. For high statistics channels/categories, the bin width is 10 GeV in the range $0 - 200$ GeV. The bin width is increased to 25 GeV in the range 200 GeV $- 350$ GeV.
2. For low statistics channels/categories, the bin width is 20 GeV in the range $0 - 200$ GeV. The bin width is increased to 50 GeV in the range $200 - 350$ GeV.

The di-tau mass distributions resulting from the maximum likelihood fit are shown in Figures 7-1, 7-2, 7-3, and 7-4. In these figures, each background model has been modified according to the nuisance parameter values that maximize the likelihood.

7.4 Upper Limit on Higgs Cross Section

The 95% confidence level ($CL_s = 0.05$) upper limit on the SM Higgs cross section is computed for eight Higgs mass points: $m_H = 110, 115, 120, 125, 130, 135, 140, 145$ GeV. The limits are derived from the combination of the $\tau_e\tau_h$ and $\tau_\mu\tau_h$ channels, using 4.9fb^{-1} of 7 TeV pp collision data and 19.3fb^{-1} of 8 TeV pp collision data. The observed and expected limits are plotted in Figure 7-5 and tabulated in Table 7.5. The expected limit shows that this analysis is most sensitive at $m_H = 120$ GeV and $m_H = 125$ GeV. The data do not exclude any Higgs mass point at the 95% confidence level. Limits computed separately for each channel and year are included in Appendix D.

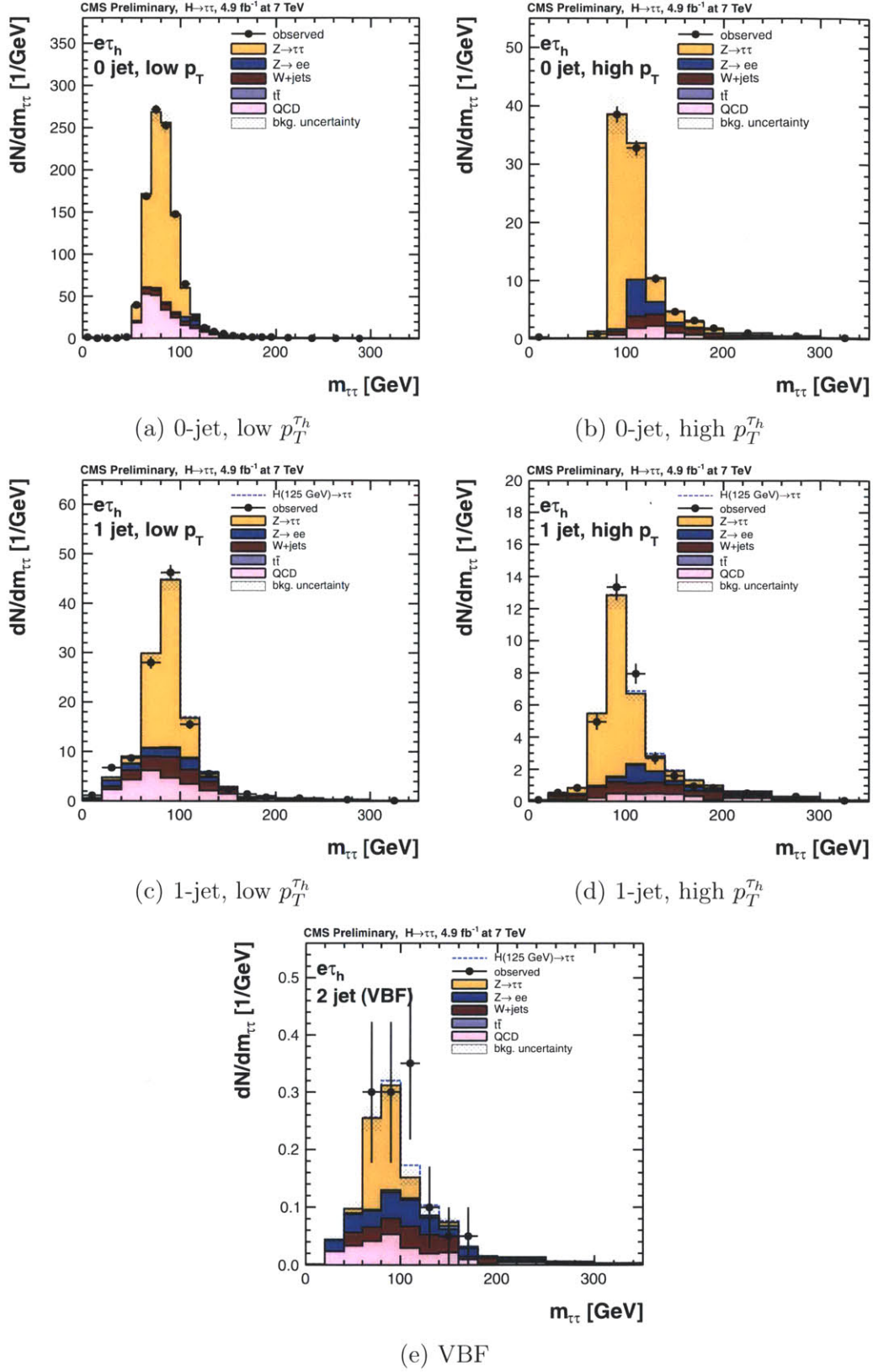


Figure 7-1: Di-tau mass distributions in the $\tau_e \tau_h$ channel in 2011 data.

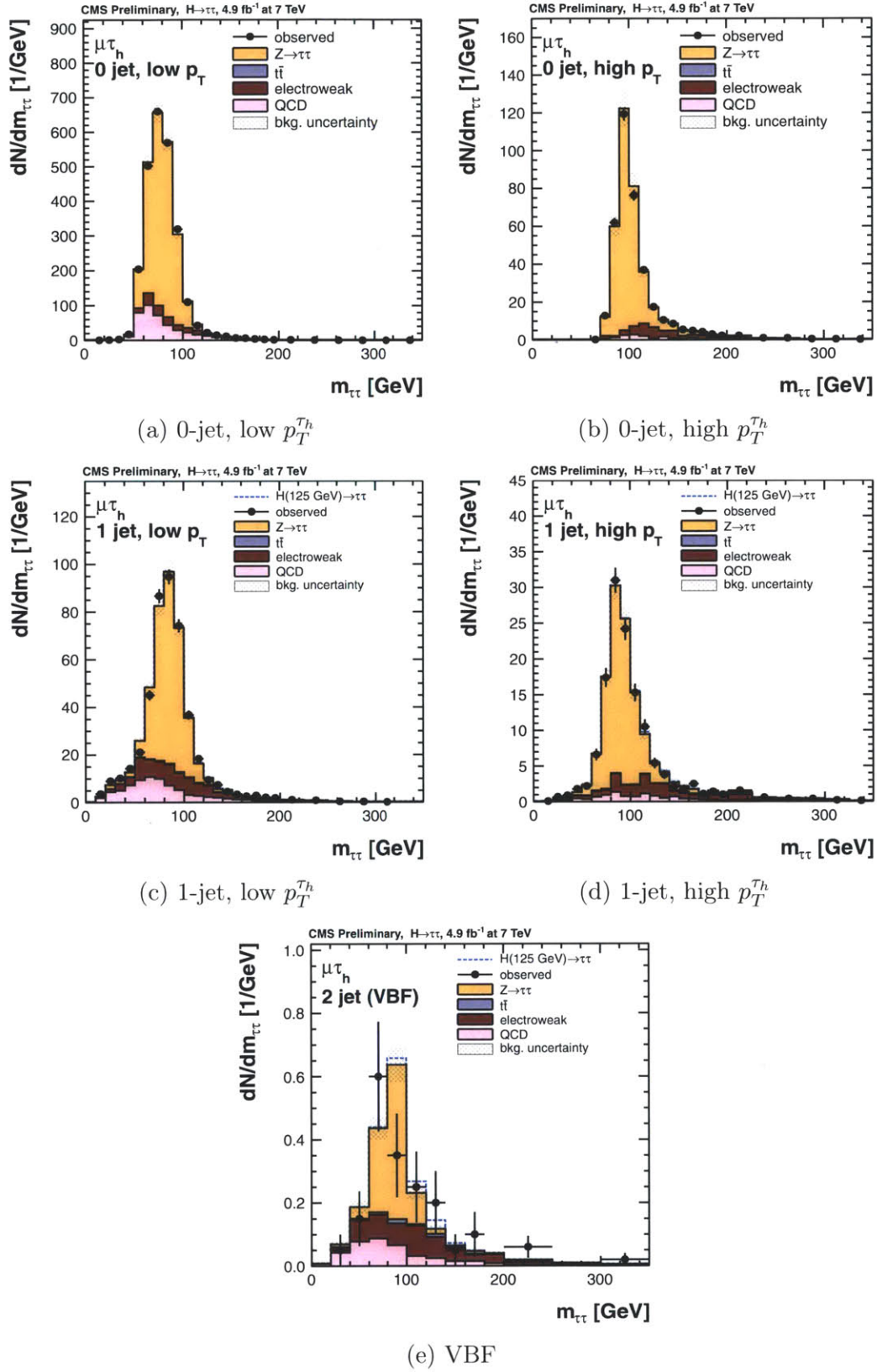
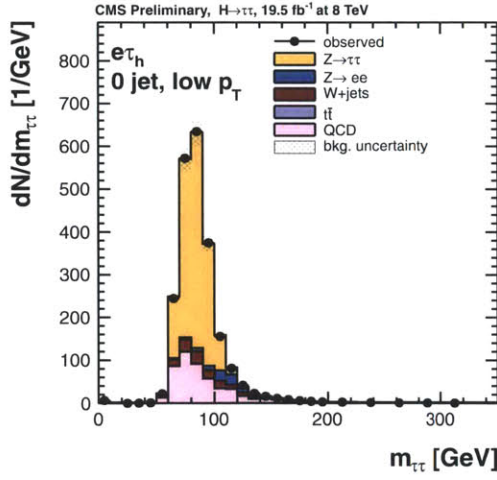
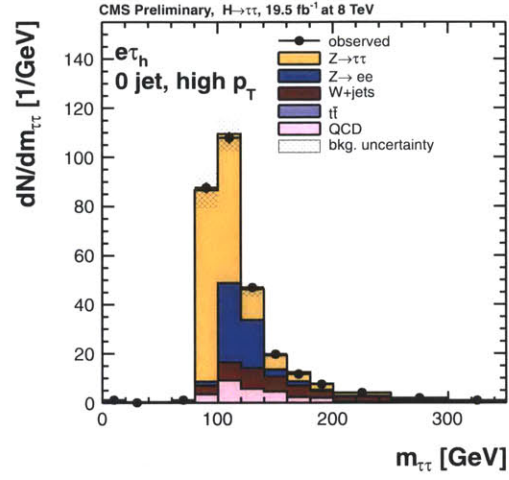


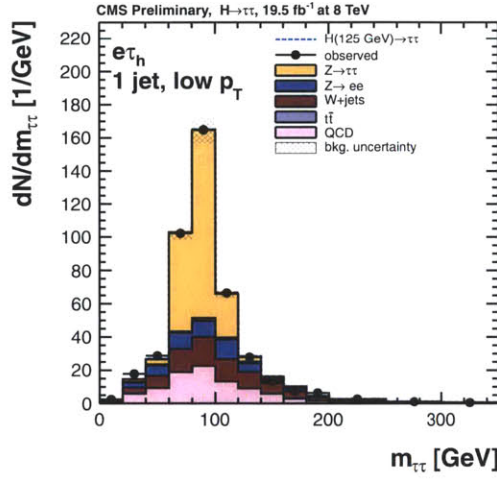
Figure 7-2: Di-tau mass distributions in the $\tau_\mu\tau_h$ channel in 2011 data.



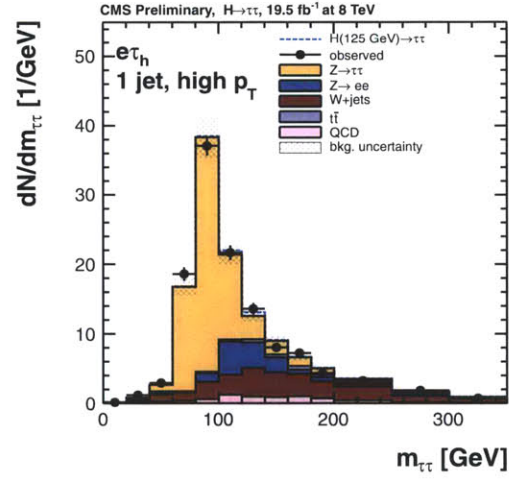
(a) 0-jet, low p_T^h



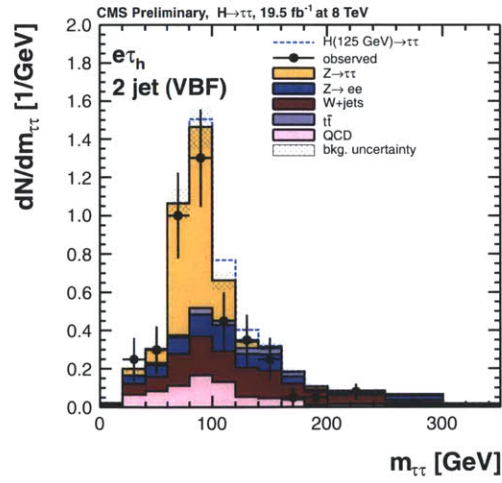
(b) 0-jet, high p_T^h



(c) 1-jet, low p_T^h



(d) 1-jet, high p_T^h



(e) VBF

Figure 7-3: Di-tau mass distributions in the $\tau_e\tau_h$ channel in 2012 data.

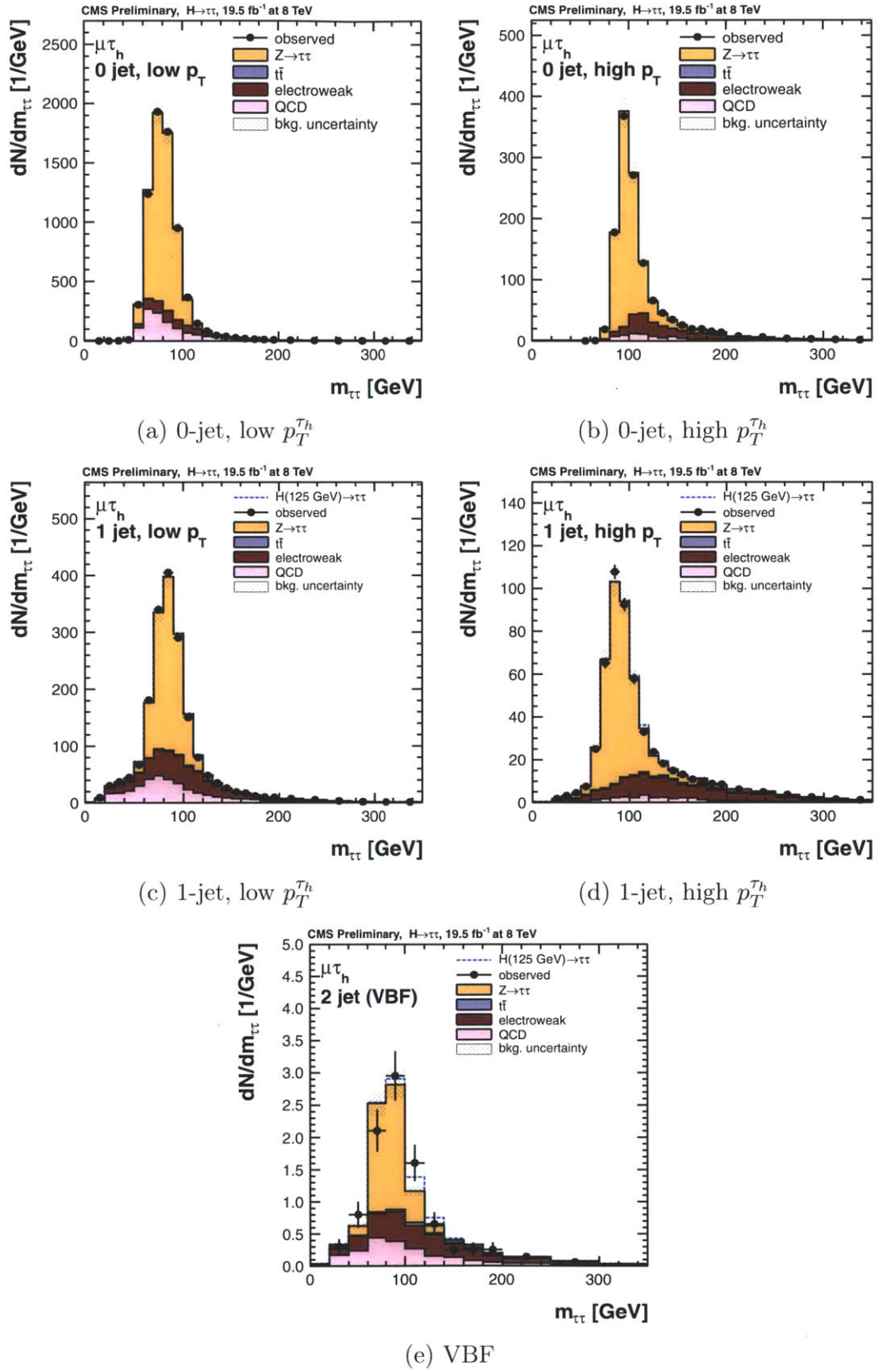


Figure 7-4: Di-tau mass distribution in the $\tau_\mu \tau_h$ channel in 2012 data.

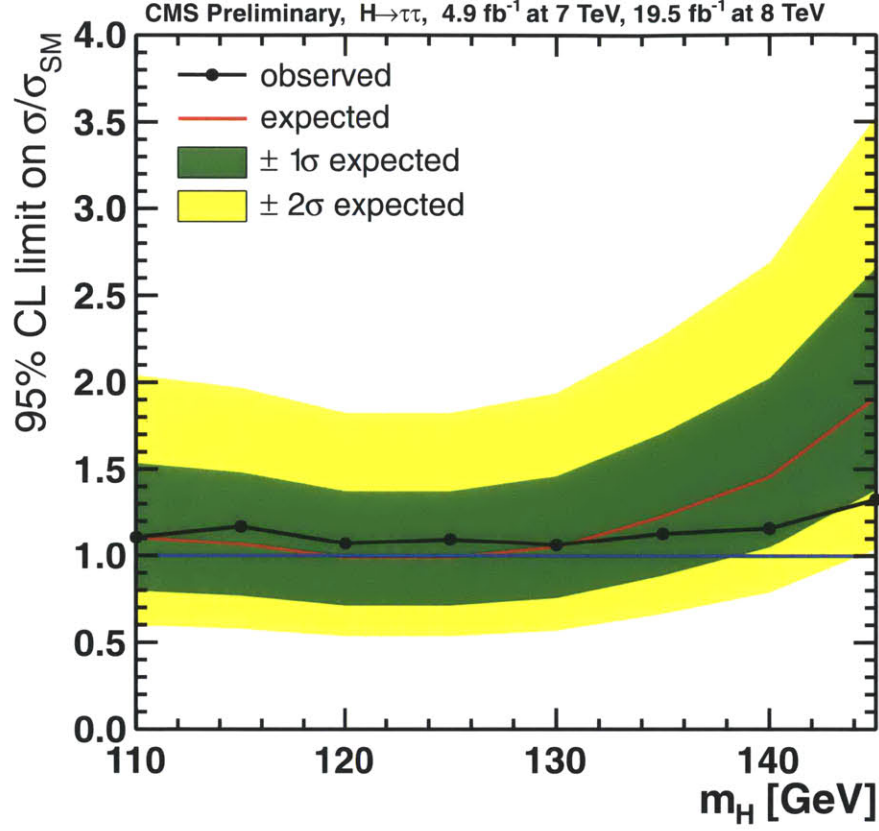


Figure 7-5: Expected and observed upper limits on the Higgs cross section measured in the $H \rightarrow \tau\tau \rightarrow \ell\tau_h\nu_\ell\nu_\tau$ channel. The $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands for the expected limit are also shown.

m_H	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Obs. Limit
110 GeV	0.60	0.80	1.11	1.54	2.04	1.11
115 GeV	0.58	0.77	1.07	1.48	1.97	1.17
120 GeV	0.54	0.71	0.99	1.37	1.82	1.07
125 GeV	0.54	0.71	0.99	1.37	1.82	1.09
130 GeV	0.57	0.76	1.05	1.46	1.94	1.06
135 GeV	0.67	0.89	1.23	1.71	2.27	1.13
140 GeV	0.79	1.05	1.46	2.02	2.69	1.16
145 GeV	1.04	1.38	1.91	2.66	3.53	1.33

Table 7.5: Expected and observed upper limits on the Higgs cross section for $m_H = 110 - 145$ GeV. The upper limit for each Higgs mass is expressed as a ratio to the SM Higgs cross section. The $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands for the expected limit are also provided.

Chapter 8

Conclusion

A search for the Higgs boson was performed in the $H \rightarrow \tau\tau$ channel, where one tau decays leptonically and the other tau decays hadronically. The search used 24.4 fb^{-1} of proton collision data collected by CMS in 2011 and 2012; 4.9 fb^{-1} of data was taken at $\sqrt{s} = 7 \text{ TeV}$ and 19.5 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. Events with a light charged lepton (i.e. electron or muon) and a τ_h candidate were selected for analysis. A notable challenge was the efficient and accurate identification of τ_h candidates, as quark/gluon jets are frequently produced in proton collisions. The mass of the di-tau system was estimated by a likelihood-based algorithm using the kinematics of the visible tau decay products and the missing transverse energy. The significance of any excess corresponding to the Higgs boson was evaluated by a fit to the di-tau mass spectrum. The sensitivity of the statistical analysis was enhanced by classifying events into categories according to the Higgs production mode (as indicated by the jet configuration) and τ_h momentum. The analysis focused on the low Higgs mass range, where the $H \rightarrow \tau\tau$ branching ratio is maximal. No significant excess was observed in the Higgs mass range from 110 GeV to 145 GeV . An upper limit on the Higgs production cross section (assuming SM branching ratios) was computed for $m_H = 110 - 145 \text{ GeV}$. The observed limit is well within the uncertainties of the expected limit in the background-only hypothesis but does not exclude any Higgs mass.

The $H \rightarrow \tau\tau$ channel, with one leptonic tau decay and one hadronic tau decay, is not expected to be able to directly detect the Higgs boson given the available CMS

data. However, the CMS analysis involving all the tau decay modes (except $\tau_e\tau_e$) observes an excess with a significance of 2.85σ for $m_H = 125\text{ GeV}$ [18]. An analysis of ATLAS data using 4.6 fb^{-1} at $\sqrt{s} = 7\text{ TeV}$ and 13.0 fb^{-1} at $\sqrt{s} = 8\text{ TeV}$ observes an excess with a significance of 1.1σ [78].

As discussed in Section 1.5, a CMS Higgs search using data corresponding to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV observed a Higgs-like boson with a mass near 125 GeV. The properties of this new boson have been measured using the full 2011 and 2012 datasets [79]. The mass of the boson was measured to be $125.7 \pm 0.4\text{ GeV}$. The boson mass was measured in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ channels, which have the highest mass resolution. Figure 8-1 illustrates the results of the mass measurement in these two channels. The signal strength modifier, $\mu = \sigma/\sigma_{\text{SM}}$, obtained from a combination of Higgs decay channels was found to be 0.80 ± 0.14 , consistent with the SM expectation. Furthermore, a test of the spin and parity found the new boson to be consistent with a scalar particle and disfavored the pseudoscalar and spin-2 hypotheses. These results provide evidence that the newly discovered particle is indeed the SM Higgs boson.

Although the $H \rightarrow \gamma\gamma$ [80] and $H \rightarrow ZZ$ [81] channels are more sensitive to the Higgs boson, evidence for the Higgs in the $H \rightarrow \tau\tau$ channel would directly demonstrate couplings between the leptons and the Higgs boson. The LHC will restart physics operations in 2015 at higher collision energy and over the course of a few years will provide enough data to directly detect the Higgs boson in the $H \rightarrow \tau\tau$ channel.

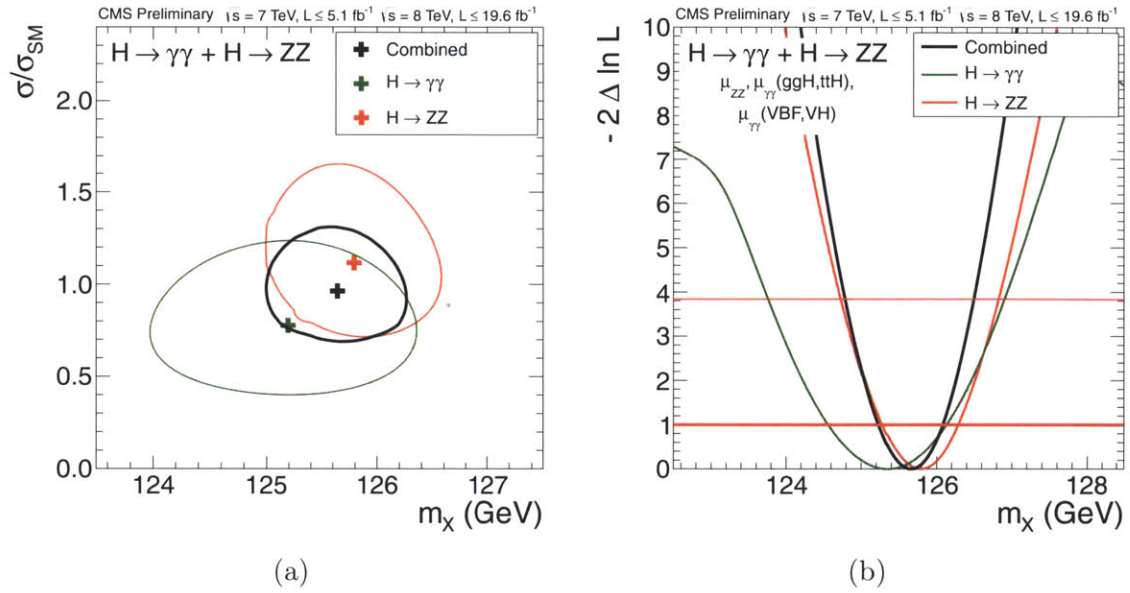


Figure 8-1: The results of the Higgs mass measurement in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ channels using the full 2011 and 2012 CMS datasets. (a) The 68% CL contours for the signal strength $\sigma/\sigma_{\text{SM}}$ versus the boson mass m_X for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, and their combination. (b) The test statistic $-2\Delta \ln L$ versus boson mass m_X for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, and their combination [79].

Appendix A

Efficiency Correction Factors

This appendix contains tables of correction factors for the trigger and identification/isolation efficiency in Monte Carlo samples. This appendix also contains the fit results for the identification/isolation efficiency measurements.

	$0.0 < \eta < 0.4$	$0.4 < \eta < 0.8$	$0.8 < \eta < 1.2$	$1.2 < \eta < 1.5$	$1.5 < \eta < 2.1$
$20 < p_T < 21$	0.8130 ± 0.0064	0.8591 ± 0.0056	0.8480 ± 0.0061	0.8548 ± 0.0071	0.7039 ± 0.0055
$21 < p_T < 22$	0.9430 ± 0.0059	0.9291 ± 0.0053	0.9238 ± 0.0057	0.9061 ± 0.0066	0.7783 ± 0.0052
$22 < p_T < 23$	0.9425 ± 0.0055	0.9527 ± 0.0049	0.9333 ± 0.0051	0.9489 ± 0.0060	0.8328 ± 0.0049
$23 < p_T < 24$	0.9473 ± 0.0049	0.9439 ± 0.0044	0.9428 ± 0.0047	0.9548 ± 0.0056	0.8951 ± 0.0047
$24 < p_T < 25$	0.9452 ± 0.0044	0.9567 ± 0.0040	0.9507 ± 0.0044	0.9378 ± 0.0048	0.9420 ± 0.0046
$25 < p_T < 26$	0.9576 ± 0.0039	0.9466 ± 0.0037	0.9533 ± 0.0041	0.9604 ± 0.0047	0.9266 ± 0.0043
$26 < p_T < 27$	0.9559 ± 0.0035	0.9554 ± 0.0034	0.9496 ± 0.0037	0.9486 ± 0.0044	0.9345 ± 0.0039
$27 < p_T < 28$	0.9483 ± 0.0032	0.9552 ± 0.0032	0.9546 ± 0.0035	0.9576 ± 0.0042	0.9450 ± 0.0037
$28 < p_T < 29$	0.9610 ± 0.0030	0.9627 ± 0.0030	0.9661 ± 0.0033	0.9691 ± 0.0040	0.9567 ± 0.0035
$29 < p_T < 30$	0.9617 ± 0.0028	0.9532 ± 0.0028	0.9572 ± 0.0030	0.9607 ± 0.0038	0.9537 ± 0.0033
$30 < p_T < 32$	0.9600 ± 0.0018	0.9606 ± 0.0018	0.9622 ± 0.0020	0.9576 ± 0.0024	0.9515 ± 0.0022
$32 < p_T < 34$	0.9627 ± 0.0016	0.9638 ± 0.0016	0.9587 ± 0.0018	0.9671 ± 0.0023	0.9589 ± 0.0020
$34 < p_T < 36$	0.9587 ± 0.0014	0.9616 ± 0.0015	0.9657 ± 0.0016	0.9647 ± 0.0021	0.9637 ± 0.0019
$36 < p_T < 38$	0.9570 ± 0.0013	0.9599 ± 0.0013	0.9624 ± 0.0015	0.9650 ± 0.0020	0.9543 ± 0.0017
$38 < p_T < 40$	0.9568 ± 0.0012	0.9620 ± 0.0012	0.9564 ± 0.0014	0.9625 ± 0.0018	0.9580 ± 0.0017
$40 < p_T < 50$	0.9568 ± 0.0005	0.9606 ± 0.0005	0.9605 ± 0.0006	0.9644 ± 0.0008	0.9589 ± 0.0008
$50 < p_T < 60$	0.9609 ± 0.0011	0.9602 ± 0.0012	0.9613 ± 0.0013	0.9662 ± 0.0018	0.9578 ± 0.0015
$60 < p_T < 80$	0.9620 ± 0.0019	0.9638 ± 0.0019	0.9631 ± 0.0022	0.9678 ± 0.0029	0.9584 ± 0.0025
$80 < p_T < 100$	0.9542 ± 0.0039	0.9611 ± 0.0040	0.9654 ± 0.0047	0.9640 ± 0.0063	0.9612 ± 0.0056
$100 < p_T$	0.9606 ± 0.0050	0.9706 ± 0.0053	0.9493 ± 0.0055	0.9458 ± 0.0080	0.9599 ± 0.0071

Table A.1: Electron trigger efficiency scale factors, 2011.

	$0.0 < \eta < 0.4$	$0.4 < \eta < 0.8$	$0.8 < \eta < 1.2$	$1.2 < \eta < 1.5$	$1.5 < \eta < 2.1$
$17 < p_T < 18$	0.9745 ± 0.0081	0.9744 ± 0.0067	0.9773 ± 0.0059	0.9295 ± 0.0063	0.9711 ± 0.0048
$18 < p_T < 20$	0.9706 ± 0.0047	0.9865 ± 0.0039	0.9928 ± 0.0037	0.9468 ± 0.0041	0.9755 ± 0.0030
$20 < p_T < 24$	0.9808 ± 0.0024	0.9887 ± 0.0020	0.9955 ± 0.0020	0.9727 ± 0.0023	0.9945 ± 0.0017
$24 < p_T < 30$	0.9785 ± 0.0012	0.9858 ± 0.0011	0.9910 ± 0.0012	0.9768 ± 0.0014	1.0176 ± 0.0011
$30 < p_T < 40$	0.9779 ± 0.0006	0.9846 ± 0.0006	0.9858 ± 0.0007	0.9797 ± 0.0008	1.0193 ± 0.0006
$40 < p_T < 50$	0.9771 ± 0.0005	0.9839 ± 0.0005	0.9834 ± 0.0006	0.9822 ± 0.0007	1.0171 ± 0.0006
$50 < p_T < 60$	0.9741 ± 0.0011	0.9831 ± 0.0011	0.9846 ± 0.0012	0.9756 ± 0.0015	1.0206 ± 0.0013
$60 < p_T < 80$	0.9728 ± 0.0018	0.9857 ± 0.0018	0.9824 ± 0.0019	0.9782 ± 0.0024	1.0274 ± 0.0021
$80 < p_T < 100$	0.9760 ± 0.0038	0.9859 ± 0.0038	0.9842 ± 0.0042	0.9758 ± 0.0052	1.0108 ± 0.0045
$100 < p_T$	0.9865 ± 0.0050	0.9721 ± 0.0050	0.9902 ± 0.0055	0.9660 ± 0.0069	1.0316 ± 0.0065

Table A.2: Muon trigger efficiency scale factors, 2011.

	$0.0 < \eta < 0.8$	$0.8 < \eta < 1.5$	$1.5 < \eta < 2.3$
$20 < p_T < 25$	0.9793 ± 0.0032	0.9599 ± 0.0038	0.9042 ± 0.0043
$25 < p_T < 30$	0.9776 ± 0.0033	0.9585 ± 0.0039	0.9666 ± 0.0047
$30 < p_T < 40$	0.9861 ± 0.0027	0.9811 ± 0.0034	0.9735 ± 0.0042
$40 < p_T < 50$	0.9780 ± 0.0049	0.9925 ± 0.0060	0.9807 ± 0.0079
$50 < p_T < 60$	1.0165 ± 0.0110	0.9649 ± 0.0135	0.9487 ± 0.0168
$60 < p_T < 80$	0.9947 ± 0.0151	0.9742 ± 0.0174	1.0583 ± 0.0252
$80 < p_T < 100$	0.9775 ± 0.0235	0.9707 ± 0.0278	1.0162 ± 0.0445
$100 < p_T$	1.0097 ± 0.0271	0.9013 ± 0.0373	1.0268 ± 0.0532

Table A.3: Tau trigger efficiency scale factors, 2011.

	$0.0 < \eta < 0.4$	$0.4 < \eta < 0.8$	$0.8 < \eta < 1.2$	$1.2 < \eta < 1.5$	$1.5 < \eta < 2.1$
$24 < p_T < 25$	0.9561 ± 0.0040	0.9108 ± 0.0038	0.8568 ± 0.0040	0.7565 ± 0.0039	0.8859 ± 0.0046
$25 < p_T < 26$	0.9550 ± 0.0037	0.9471 ± 0.0037	0.9292 ± 0.0038	0.8595 ± 0.0041	0.9749 ± 0.0046
$26 < p_T < 27$	0.9654 ± 0.0034	0.9596 ± 0.0034	0.9486 ± 0.0036	0.9045 ± 0.0040	0.9638 ± 0.0040
$27 < p_T < 28$	0.9530 ± 0.0031	0.9596 ± 0.0030	0.9491 ± 0.0032	0.9182 ± 0.0038	0.9844 ± 0.0038
$28 < p_T < 29$	0.9619 ± 0.0028	0.9603 ± 0.0028	0.9600 ± 0.0030	0.9277 ± 0.0035	0.9824 ± 0.0035
$29 < p_T < 30$	0.9727 ± 0.0026	0.9645 ± 0.0026	0.9559 ± 0.0028	0.9230 ± 0.0032	0.9822 ± 0.0032
$30 < p_T < 32$	0.9700 ± 0.0016	0.9585 ± 0.0016	0.9655 ± 0.0018	0.9393 ± 0.0021	0.9877 ± 0.0021
$32 < p_T < 34$	0.9640 ± 0.0014	0.9642 ± 0.0014	0.9634 ± 0.0016	0.9486 ± 0.0019	0.9958 ± 0.0019
$34 < p_T < 36$	0.9705 ± 0.0012	0.9659 ± 0.0013	0.9642 ± 0.0014	0.9538 ± 0.0018	0.9998 ± 0.0017
$36 < p_T < 38$	0.9747 ± 0.0011	0.9695 ± 0.0011	0.9703 ± 0.0013	0.9631 ± 0.0017	1.0006 ± 0.0016
$38 < p_T < 40$	0.9757 ± 0.0010	0.9719 ± 0.0010	0.9719 ± 0.0012	0.9664 ± 0.0015	1.0051 ± 0.0015
$40 < p_T < 50$	0.9770 ± 0.0004	0.9773 ± 0.0005	0.9759 ± 0.0005	0.9679 ± 0.0007	1.0058 ± 0.0007
$50 < p_T < 60$	0.9777 ± 0.0009	0.9803 ± 0.0010	0.9810 ± 0.0011	0.9746 ± 0.0015	1.0031 ± 0.0013
$60 < p_T < 80$	0.9788 ± 0.0016	0.9772 ± 0.0016	0.9819 ± 0.0019	0.9783 ± 0.0025	0.9919 ± 0.0023
$80 < p_T < 100$	0.9783 ± 0.0037	0.9767 ± 0.0038	0.9827 ± 0.0043	0.9802 ± 0.0058	0.9948 ± 0.0054
$100 < p_T$	0.9785 ± 0.0044	0.9803 ± 0.0045	0.9796 ± 0.0050	0.9892 ± 0.0068	0.9958 ± 0.0065

Table A.4: Electron trigger efficiency scale factors, 2012.

	$0.0 < \eta < 0.4$	$0.4 < \eta < 0.8$	$0.8 < \eta < 1.2$	$1.2 < \eta < 1.5$	$1.5 < \eta < 2.1$
$20 < p_T < 24$	0.9678 ± 0.0018	0.9859 ± 0.0016	0.9590 ± 0.0016	0.9766 ± 0.0019	1.0105 ± 0.0014
$24 < p_T < 30$	0.9722 ± 0.0009	0.9882 ± 0.0009	0.9692 ± 0.0009	0.9731 ± 0.0011	1.0016 ± 0.0008
$30 < p_T < 40$	0.9766 ± 0.0004	0.9887 ± 0.0004	0.9622 ± 0.0005	0.9665 ± 0.0006	1.0001 ± 0.0005
$40 < p_T < 50$	0.9771 ± 0.0004	0.9889 ± 0.0004	0.9632 ± 0.0004	0.9659 ± 0.0005	0.9977 ± 0.0004
$50 < p_T < 60$	0.9793 ± 0.0008	0.9886 ± 0.0008	0.9613 ± 0.0009	0.9645 ± 0.0011	0.9949 ± 0.0009
$60 < p_T < 80$	0.9785 ± 0.0013	0.9893 ± 0.0013	0.9585 ± 0.0014	0.9566 ± 0.0018	0.9921 ± 0.0015
$80 < p_T < 100$	0.9746 ± 0.0029	0.9922 ± 0.0029	0.9616 ± 0.0031	0.9624 ± 0.0039	0.9861 ± 0.0033
$100 < p_T$	0.9759 ± 0.0036	0.9878 ± 0.0036	0.9626 ± 0.0039	0.9524 ± 0.0050	0.9787 ± 0.0043

Table A.5: Muon trigger efficiency scale factors, 2012.

	$0.0 < \eta < 0.8$	$0.8 < \eta < 1.5$	$1.5 < \eta < 2.3$
$20 < p_T < 25$	0.9681 ± 0.0049	0.9390 ± 0.0060	0.9782 ± 0.0066
$25 < p_T < 30$	0.9844 ± 0.0049	0.9899 ± 0.0060	0.9697 ± 0.0069
$30 < p_T < 40$	0.9762 ± 0.0039	0.9909 ± 0.0048	0.9859 ± 0.0060
$40 < p_T < 50$	0.9655 ± 0.0066	0.9735 ± 0.0083	0.9878 ± 0.0106
$50 < p_T < 60$	0.9852 ± 0.0145	1.0026 ± 0.0206	1.0355 ± 0.0249
$60 < p_T < 80$	1.0007 ± 0.0190	0.9455 ± 0.0216	1.0727 ± 0.0321
$80 < p_T < 100$	0.9615 ± 0.0352	0.9862 ± 0.0402	1.0100 ± 0.0592
$100 < p_T$	0.9888 ± 0.0347	0.8476 ± 0.0428	0.8996 ± 0.0696

Table A.6: Tau trigger efficiency scale factors, 2012.

	$20 < p_T < 24$	$24 < p_T < 30$	$30 < p_T$
$-2.1 < \eta < -1.5$	0.9773 ± 0.0190	1.0099 ± 0.0101	1.0070 ± 0.0002
$-1.5 < \eta < -0.8$	0.9444 ± 0.0184	0.9888 ± 0.0104	0.9803 ± 0.0009
$-0.8 < \eta < 0.0$	0.9735 ± 0.0115	0.9954 ± 0.0049	0.9867 ± 0.0001
$0.0 < \eta < 0.8$	0.9890 ± 0.0082	0.9980 ± 0.0052	0.9905 ± 0.0005
$0.8 < \eta < 1.5$	0.9632 ± 0.0127	1.0063 ± 0.0065	0.9848 ± 0.0001
$1.5 < \eta < 2.1$	1.0072 ± 0.0158	1.0390 ± 0.0428	1.0231 ± 0.0002

Table A.7: Electron identification and isolation efficiency scale factors, 2011.

	$17 < p_T < 20$	$20 < p_T < 30$	$30 < p_T$
$-2.1 < \eta < -1.2$	0.9656 ± 0.0082	0.9849 ± 0.0020	1.0027 ± 0.0001
$-1.2 < \eta < -0.8$	0.9931 ± 0.0127	0.9888 ± 0.0035	1.0005 ± 0.0001
$-0.8 < \eta < 0.0$	0.9931 ± 0.0132	0.9916 ± 0.0007	1.0030 ± 0.0001
$0.0 < \eta < 0.8$	1.0146 ± 0.0109	0.9932 ± 0.0023	1.0049 ± 0.0001
$0.8 < \eta < 1.2$	0.9773 ± 0.0128	0.9937 ± 0.0036	1.0013 ± 0.0001
$1.2 < \eta < 2.1$	0.9691 ± 0.0081	0.9983 ± 0.0021	1.0083 ± 0.0001

Table A.8: Muon identification and isolation efficiency scale factors, 2011.

	$24 < p_T < 30$	$30 < p_T$
$-2.1 < \eta < -1.5$	0.9192 ± 0.0001	0.9481 ± 0.0013
$-1.5 < \eta < -0.8$	0.9393 ± 0.0051	0.9500 ± 0.0001
$-0.8 < \eta < 0.0$	0.9472 ± 0.0039	0.9558 ± 0.0001
$0.0 < \eta < 0.8$	0.9646 ± 0.0040	0.9601 ± 0.0001
$0.8 < \eta < 1.5$	0.9379 ± 0.0048	0.9509 ± 0.0001
$1.5 < \eta < 2.1$	0.9595 ± 0.0079	0.9537 ± 0.0005

Table A.9: Electron identification and isolation efficiency scale factors, 2012.

	$20 < p_T < 30$	$30 < p_T$
$-2.1 < \eta < -1.2$	0.9989 ± 0.0010	0.9978 ± 0.0003
$-1.2 < \eta < -0.8$	0.9783 ± 0.0022	0.9841 ± 0.0001
$-0.8 < \eta < 0.0$	0.9643 ± 0.0014	0.9820 ± 0.0001
$0.0 < \eta < 0.8$	0.9703 ± 0.0016	0.9840 ± 0.0001
$0.8 < \eta < 1.2$	0.9802 ± 0.0019	0.9831 ± 0.0001
$1.2 < \eta < 2.1$	1.0026 ± 0.0012	0.9998 ± 0.0001

Table A.10: Muon identification and isolation efficiency scale factors, 2012.

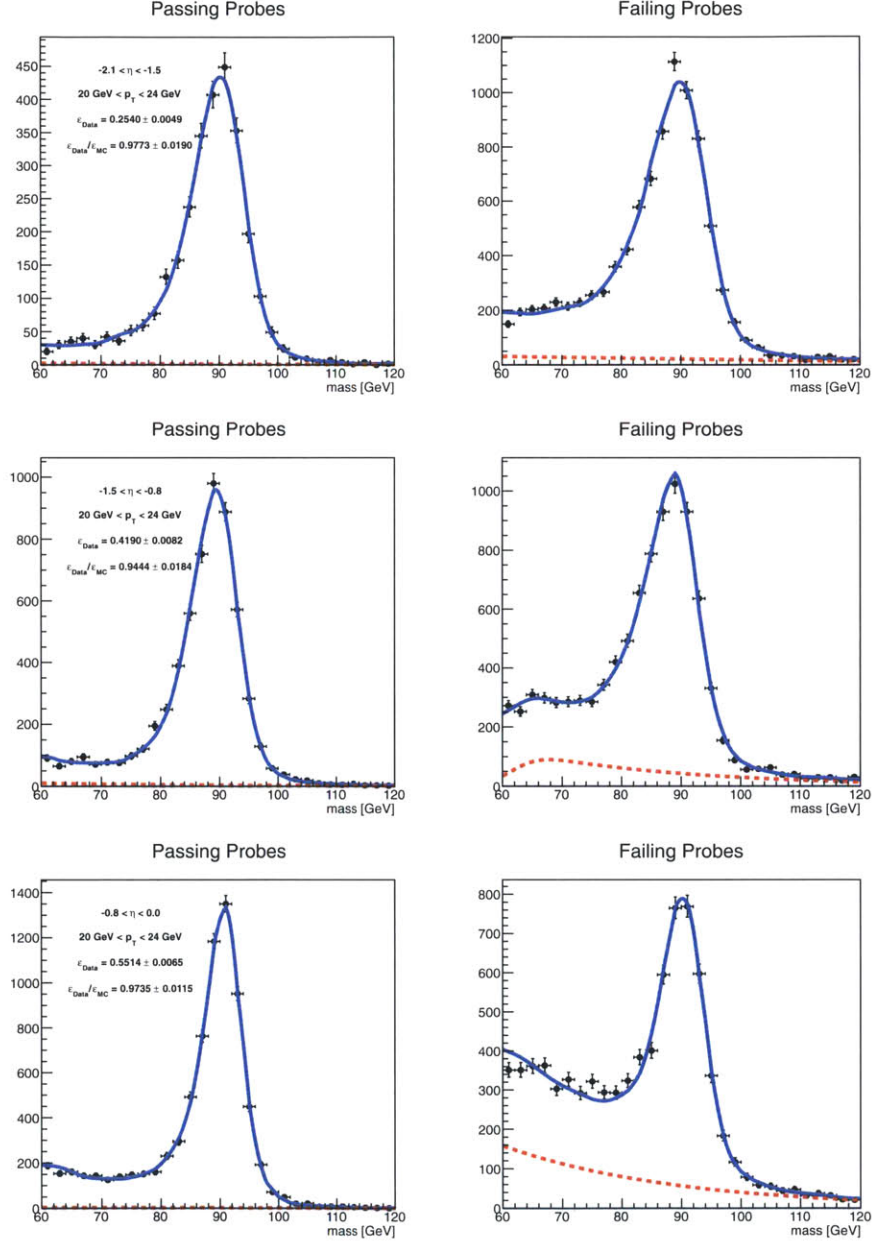


Figure A-1: Electron identification and isolation efficiency fits, $20 \text{ GeV} < p_T < 24 \text{ GeV}$, $-2.1 < \eta < 0$, 2011.

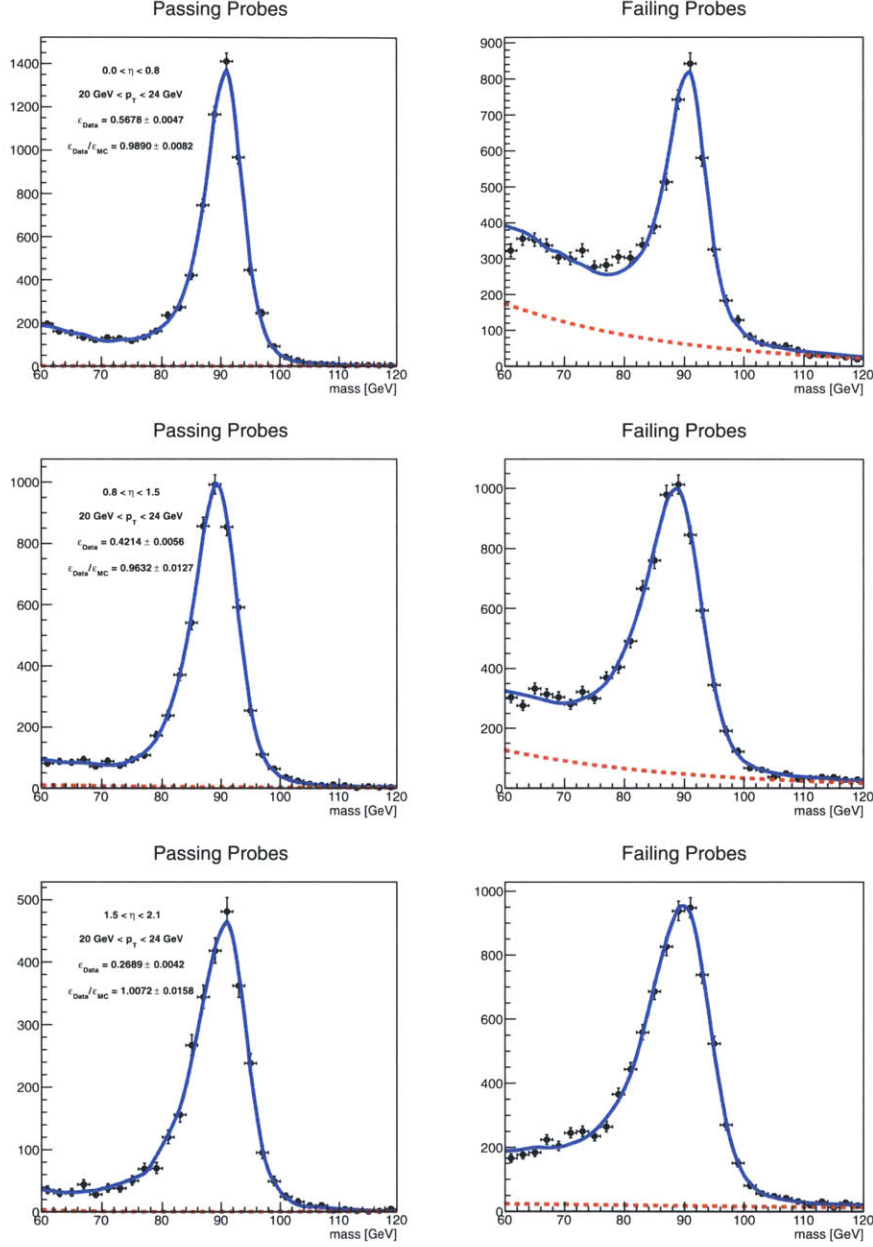


Figure A-2: Electron identification and isolation efficiency fits, $20 \text{ GeV} < p_T < 24 \text{ GeV}$, $0 < \eta < 2.1$, 2011.

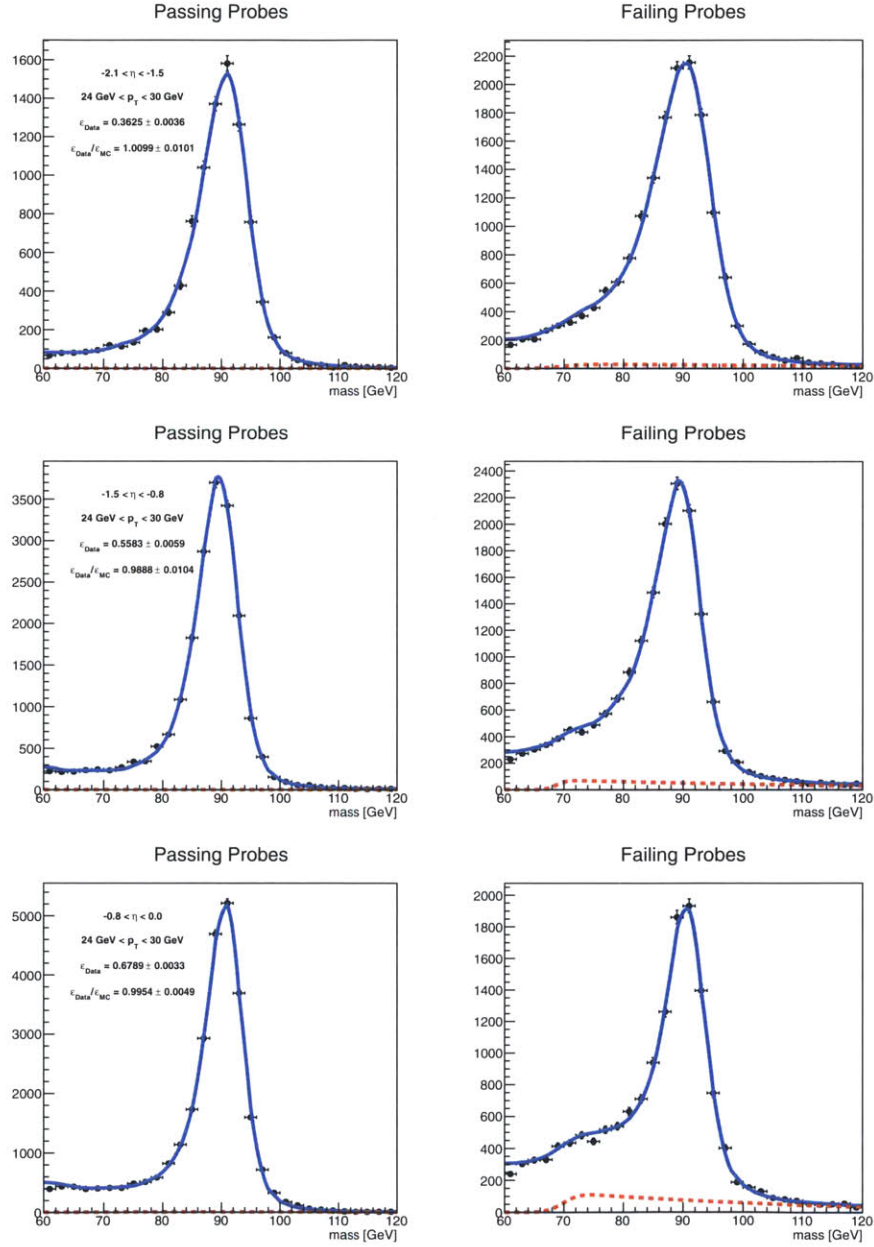


Figure A-3: Electron identification and isolation efficiency fits, 24 GeV < p_T < 30 GeV, $-2.1 < \eta < 0$, 2011.

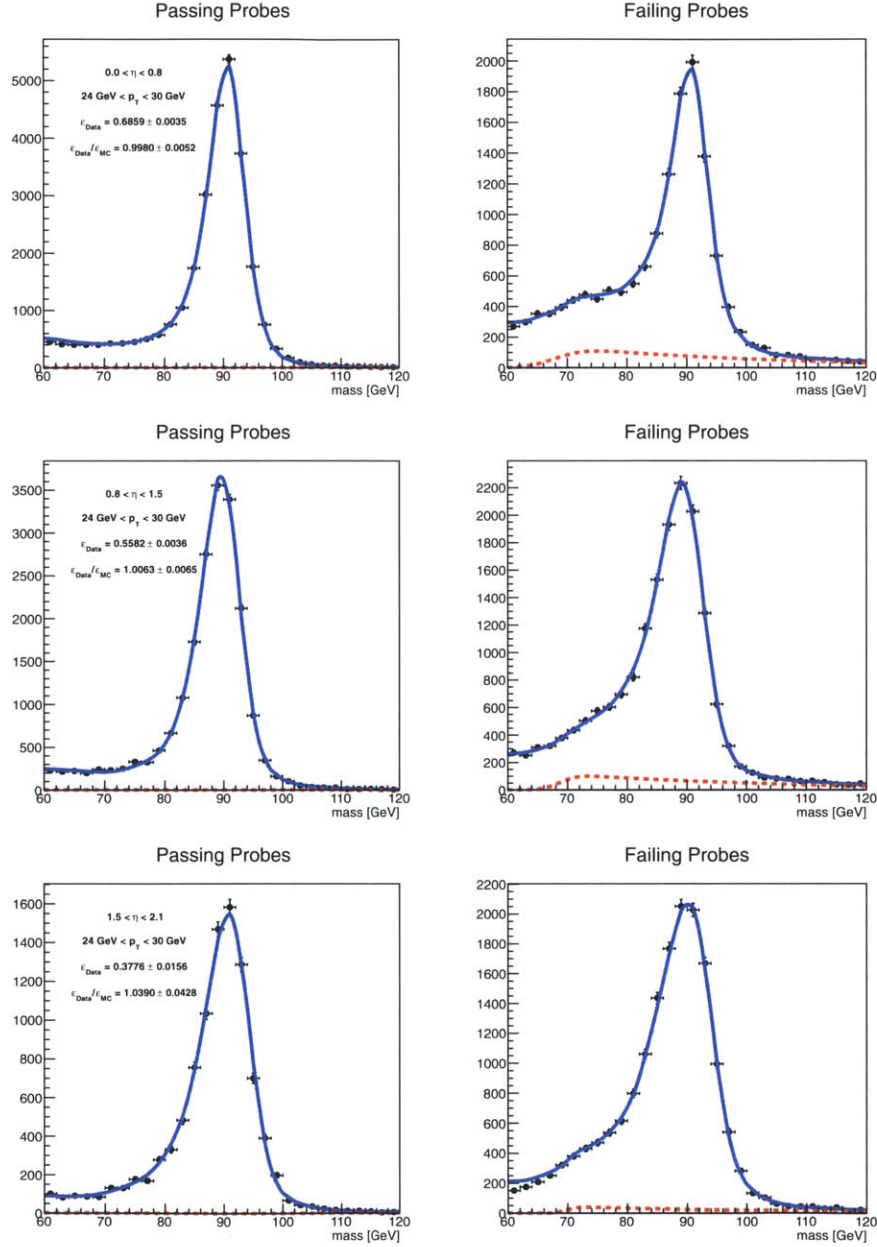


Figure A-4: Electron identification and isolation efficiency fits, $24 \text{ GeV} < p_T < 30 \text{ GeV}$, $0 < \eta < 2.1$, 2011.

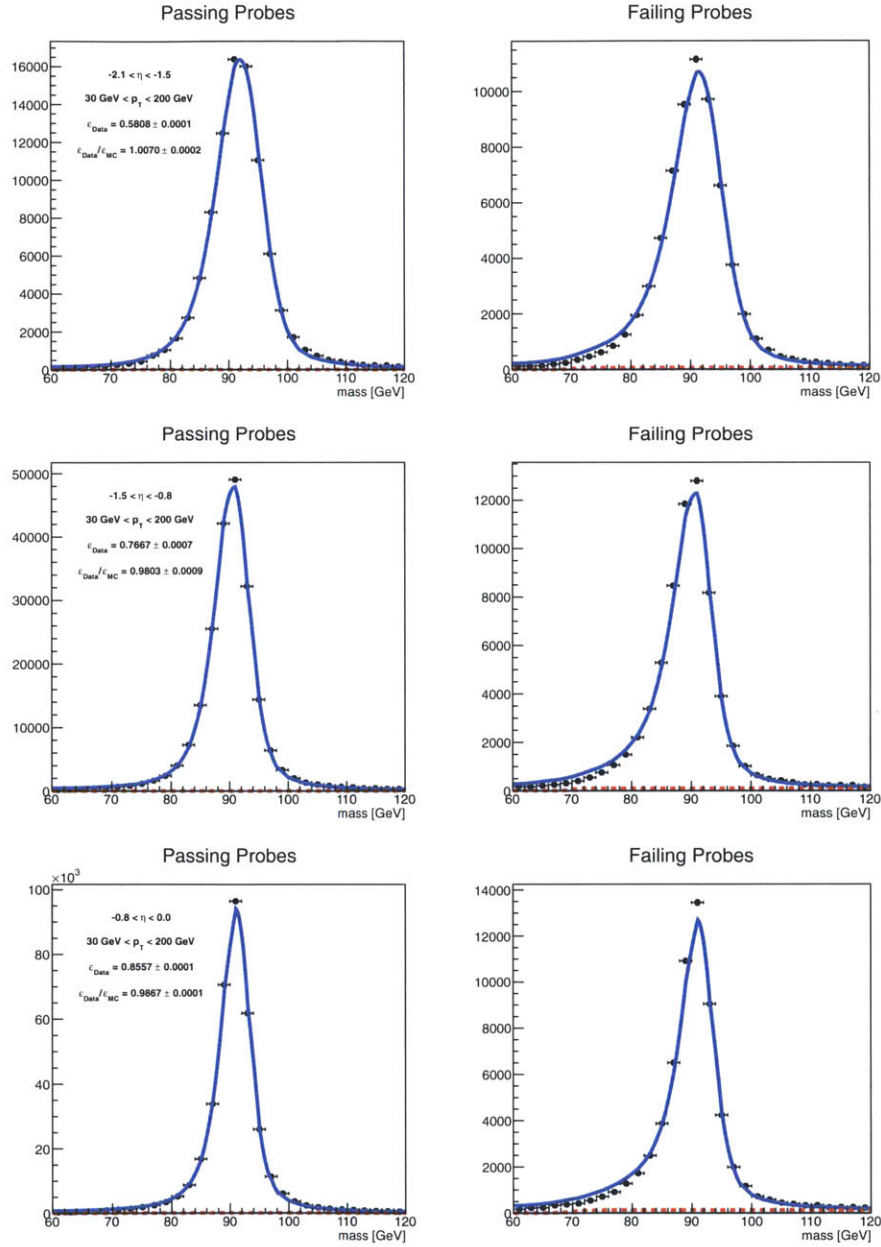


Figure A-5: Electron identification and isolation efficiency fits, $p_T > 30$ GeV, $-2.1 < \eta < 0$, 2011.

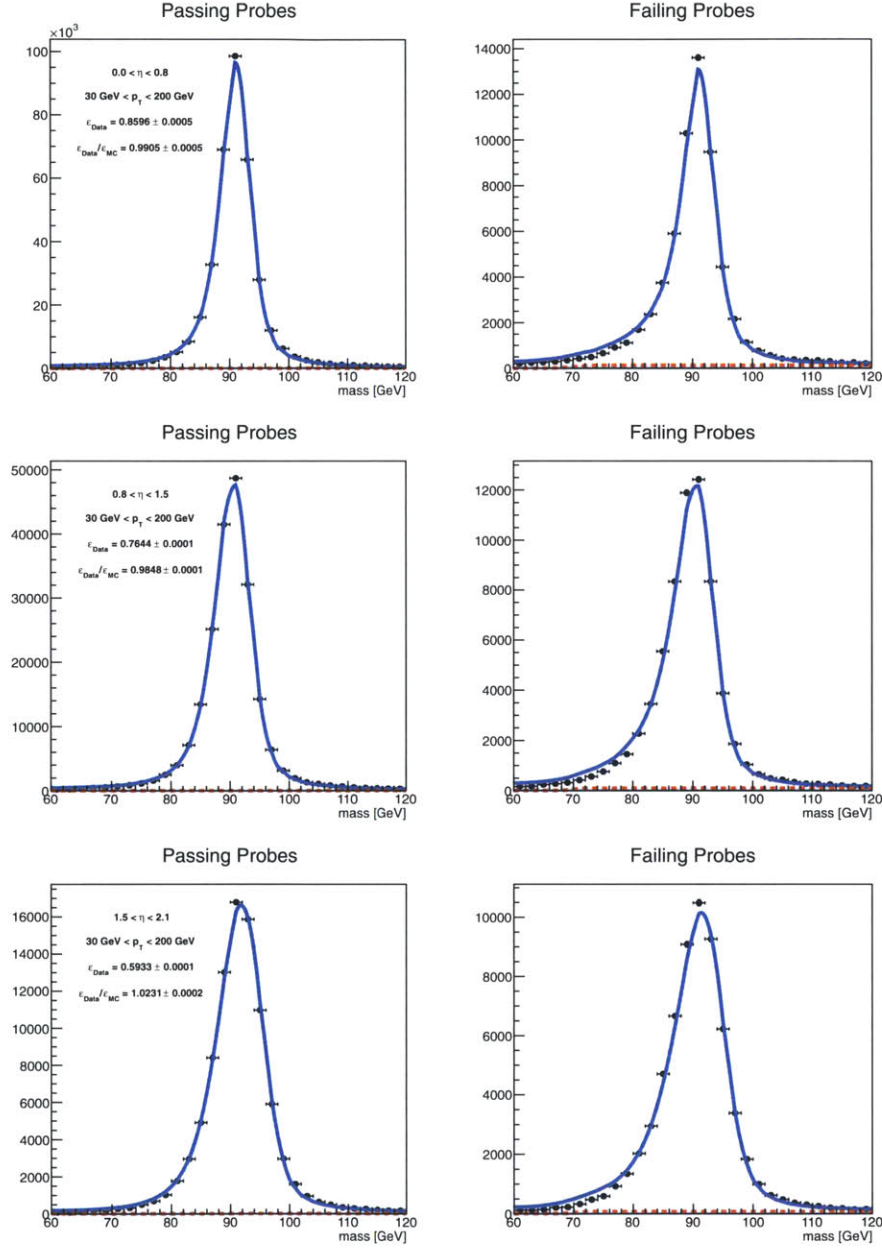


Figure A-6: Electron identification and isolation efficiency fits, $p_T > 30$ GeV, $0 < \eta < 2.1$, 2011.

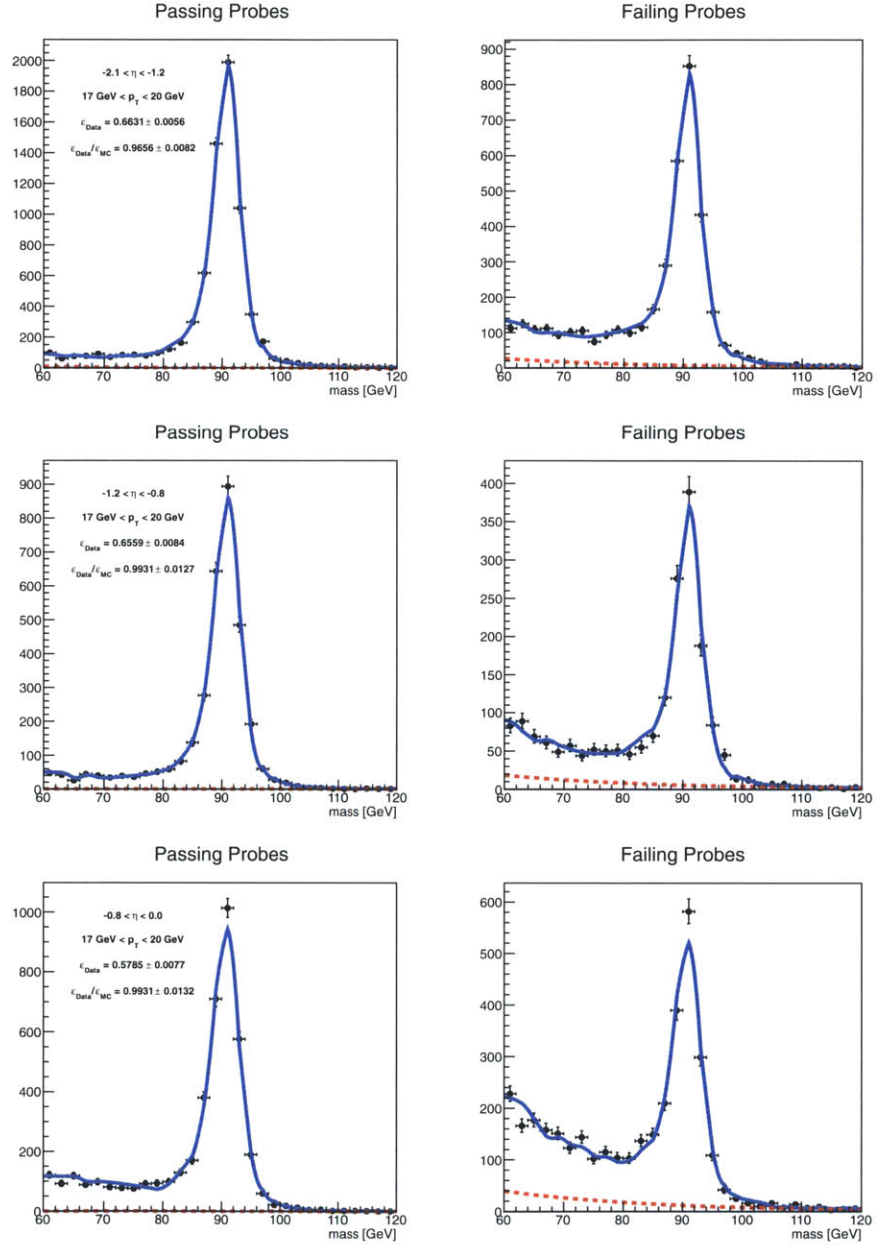


Figure A-7: Muon identification and isolation efficiency fits, $17 \text{ GeV} < p_T < 20 \text{ GeV}$, $-2.1 < \eta < 0$, 2011.

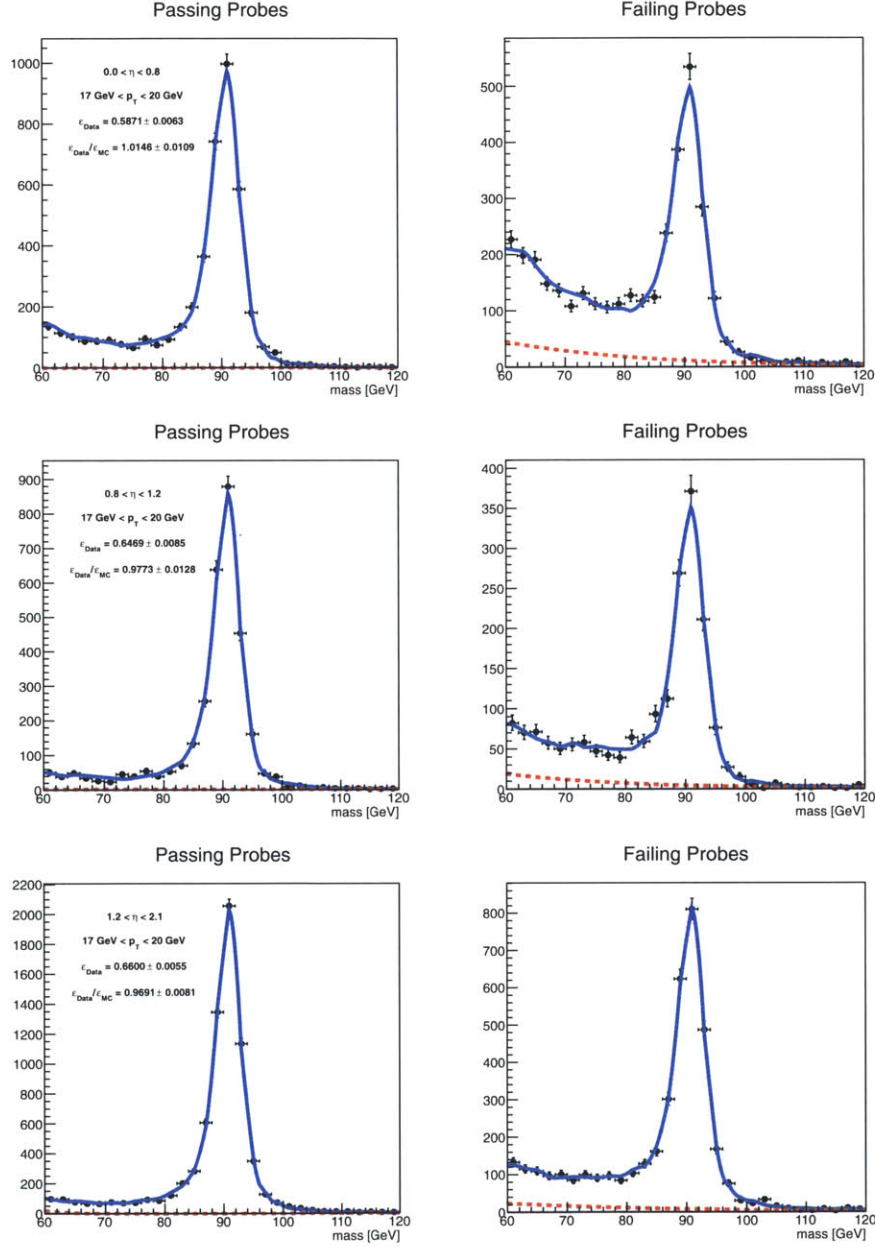


Figure A-8: Muon identification and isolation efficiency fits, $17 \text{ GeV} < p_T < 20 \text{ GeV}$, $0 < \eta < 2.1$, 2011.

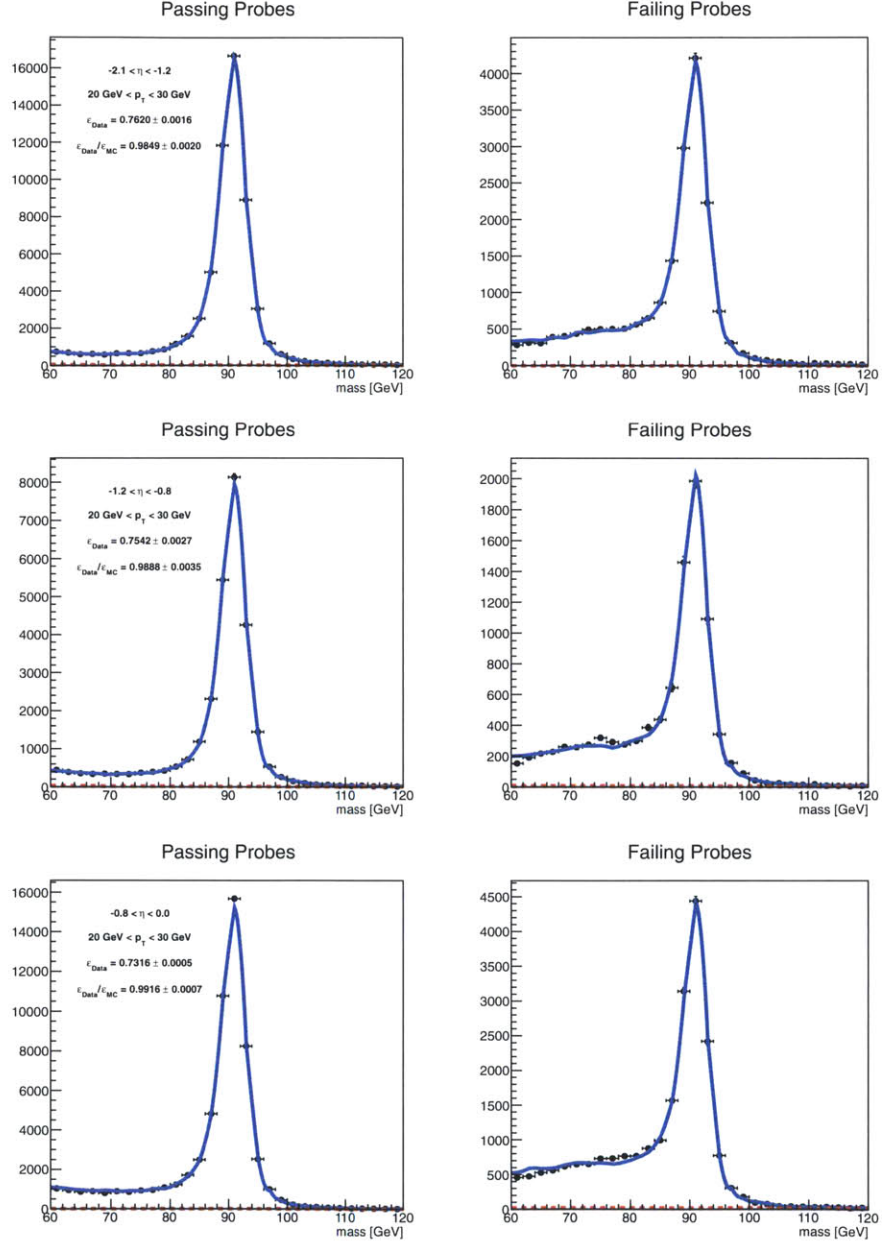


Figure A-9: Muon identification and isolation efficiency fits, $20 \text{ GeV} < p_T < 30 \text{ GeV}$, $-2.1 < \eta < 0$, 2011.

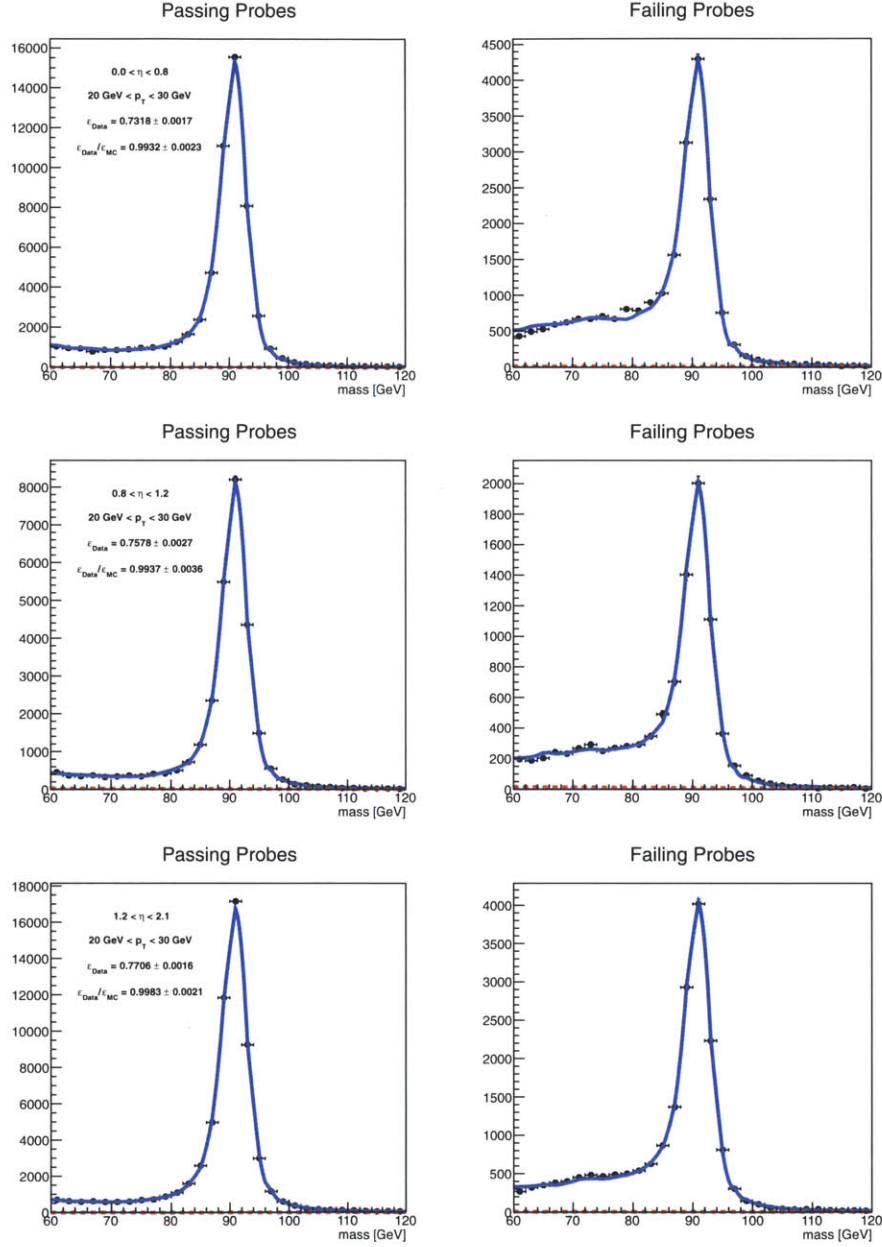


Figure A-10: Muon identification and isolation efficiency fits, $20 \text{ GeV} < p_T < 30 \text{ GeV}$, $0 < \eta < 2.1$, 2011.

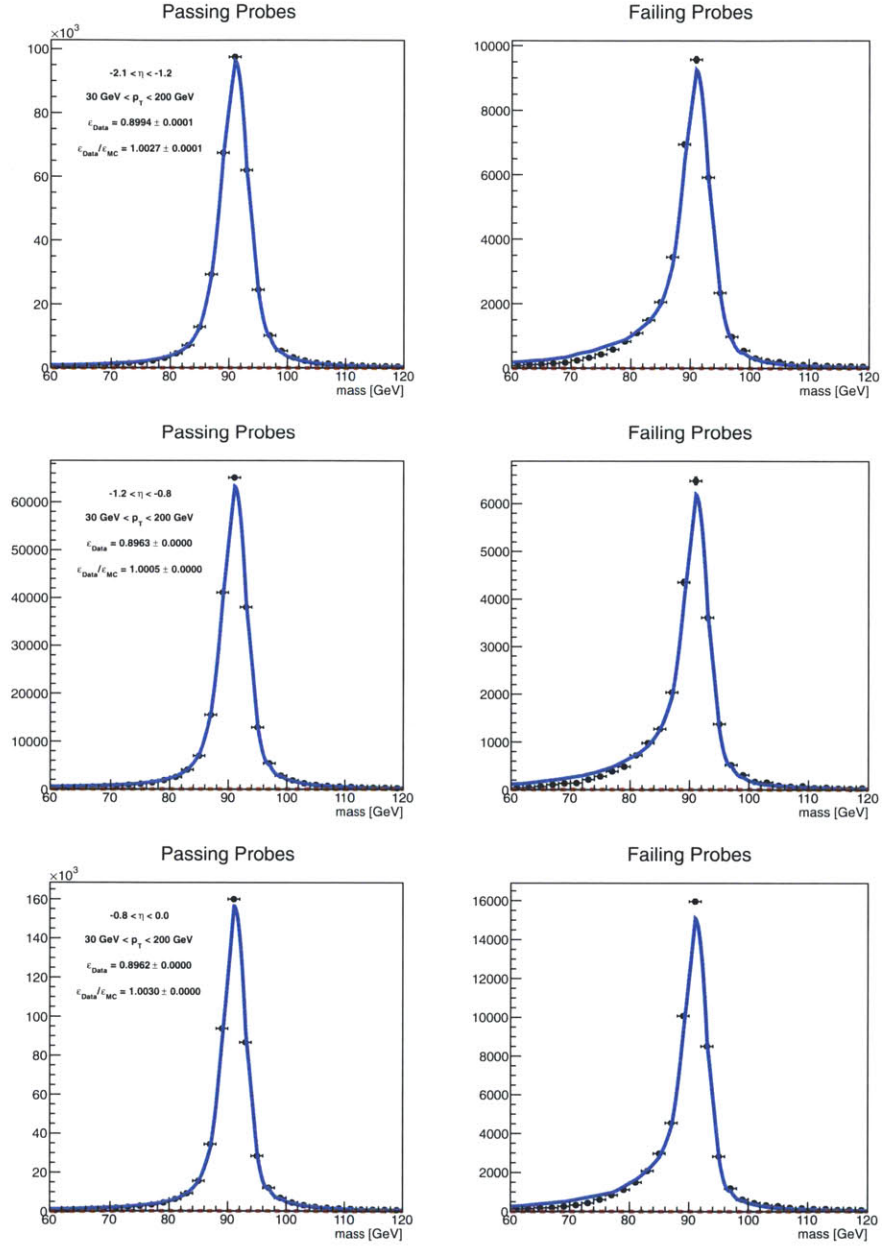


Figure A-11: Muon identification and isolation efficiency fits, $p_T > 30$ GeV, $-2.1 < \eta < 0$, 2011.

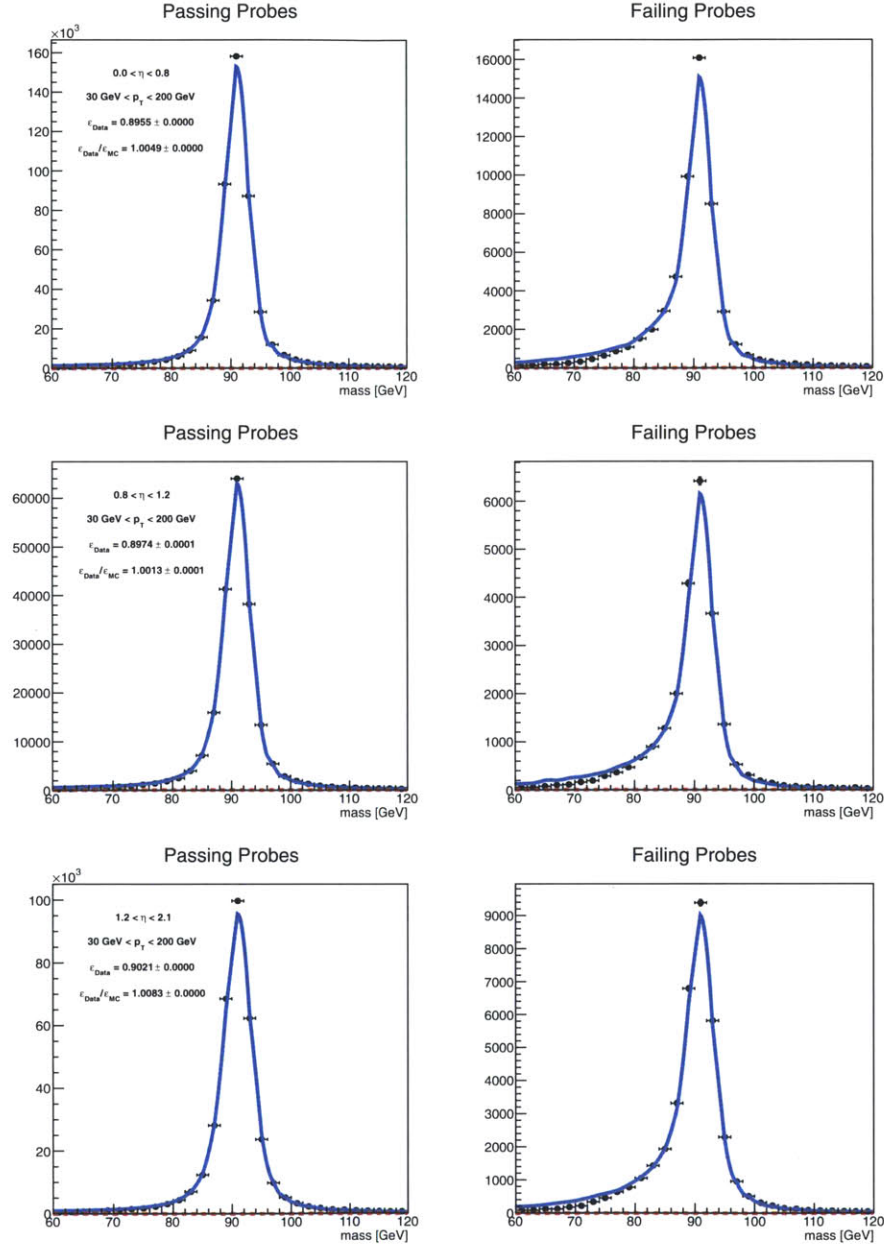


Figure A-12: Muon identification and isolation efficiency fits, $p_T > 30$ GeV, $0 < \eta < 2.1$, 2011.

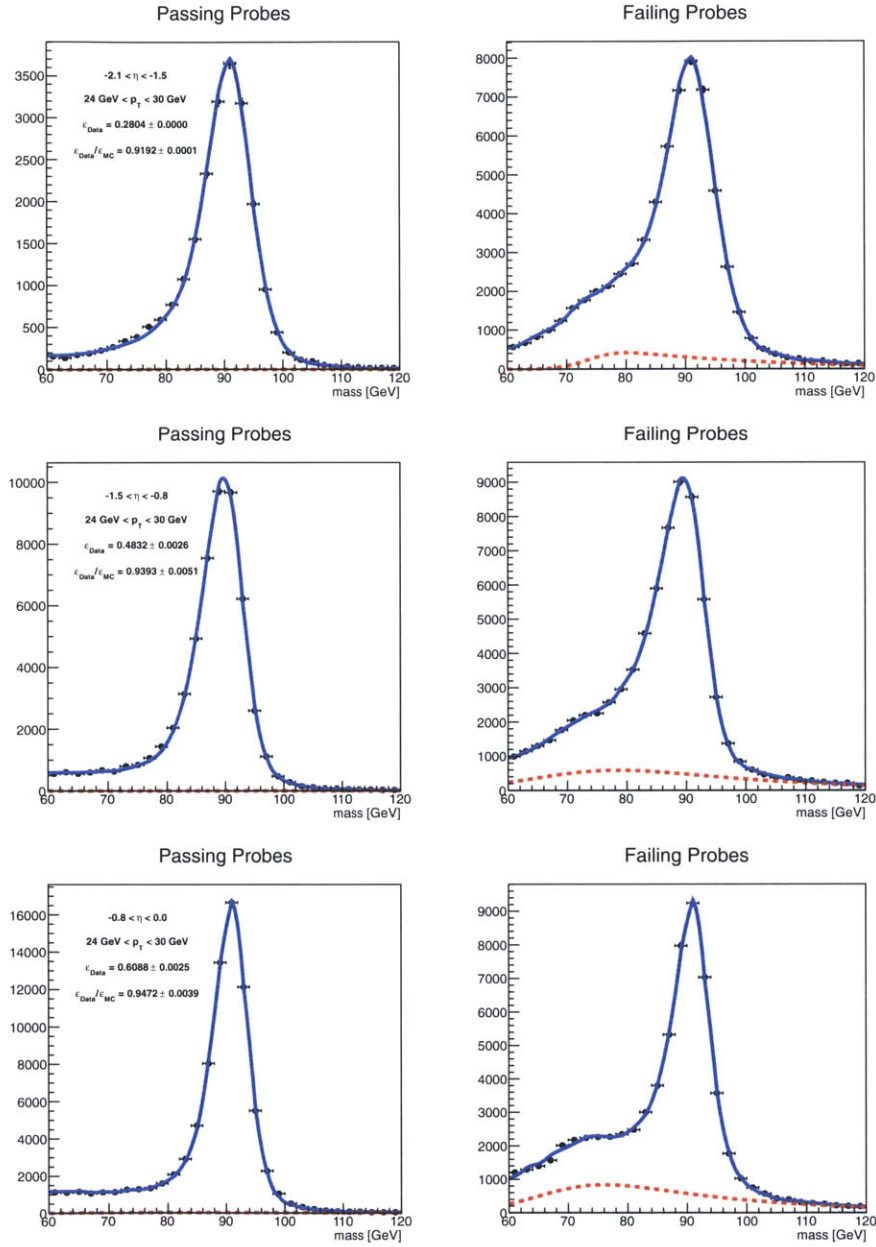


Figure A-13: Electron identification and isolation efficiency fits, $24 \text{ GeV} < p_T < 30 \text{ GeV}$, $-2.1 < \eta < 0$, 2012.

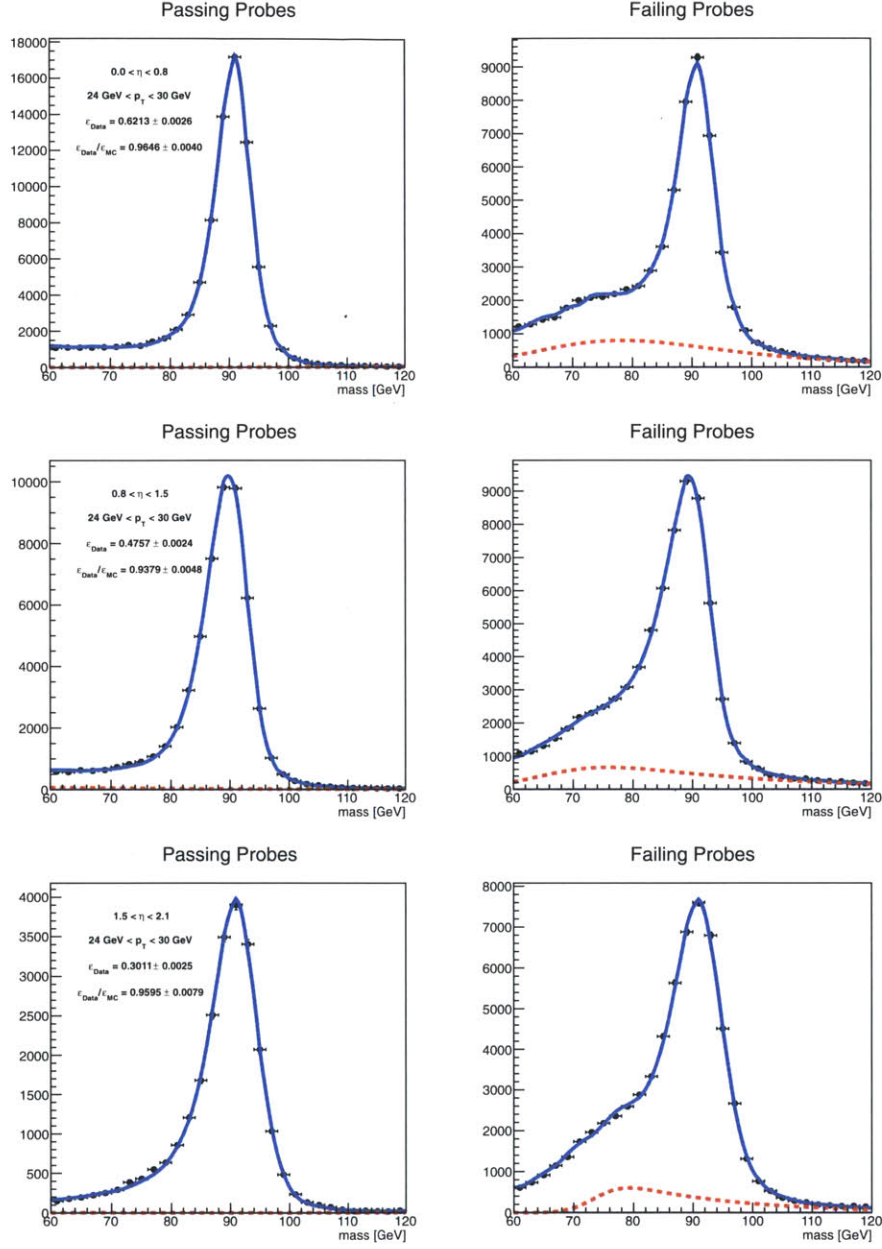


Figure A-14: Electron identification and isolation efficiency fits, 24 GeV < p_T < 30 GeV, $0 < \eta < 2.1$, 2012.

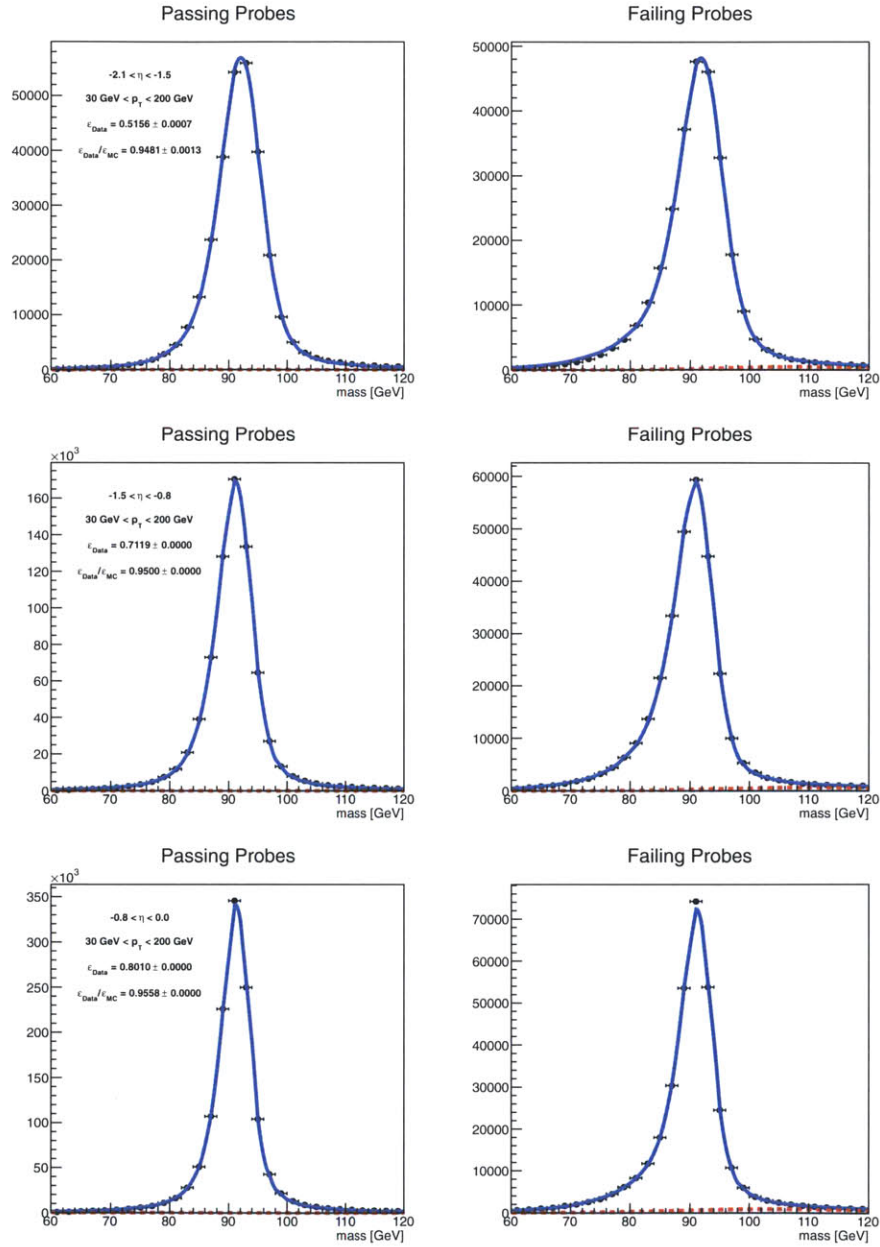


Figure A-15: Electron identification and isolation efficiency fits, $p_T > 30 \text{ GeV}$, $-2.1 < \eta < 0$, 2012.

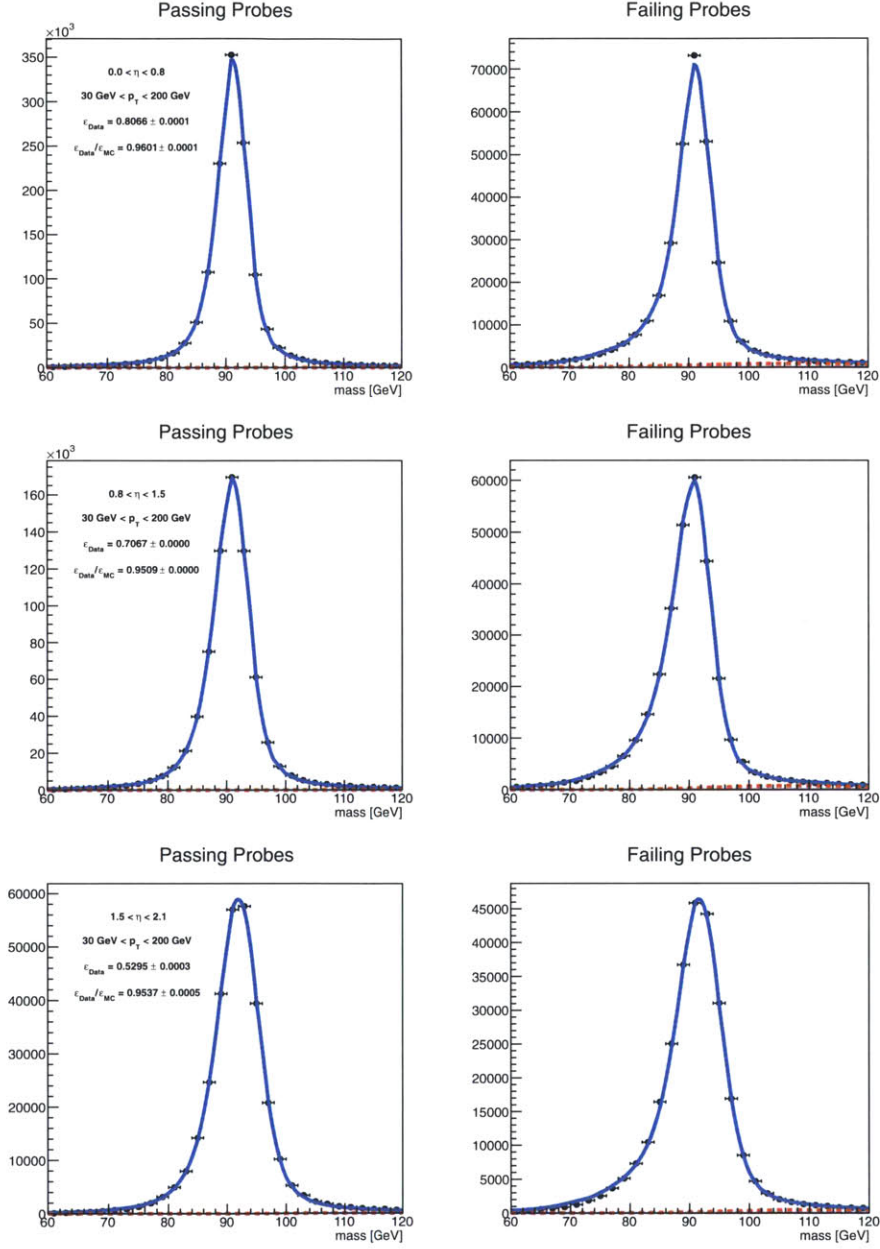


Figure A-16: Electron identification and isolation efficiency fits, $p_T > 30$ GeV, $0 < \eta < 2.1$, 2012.

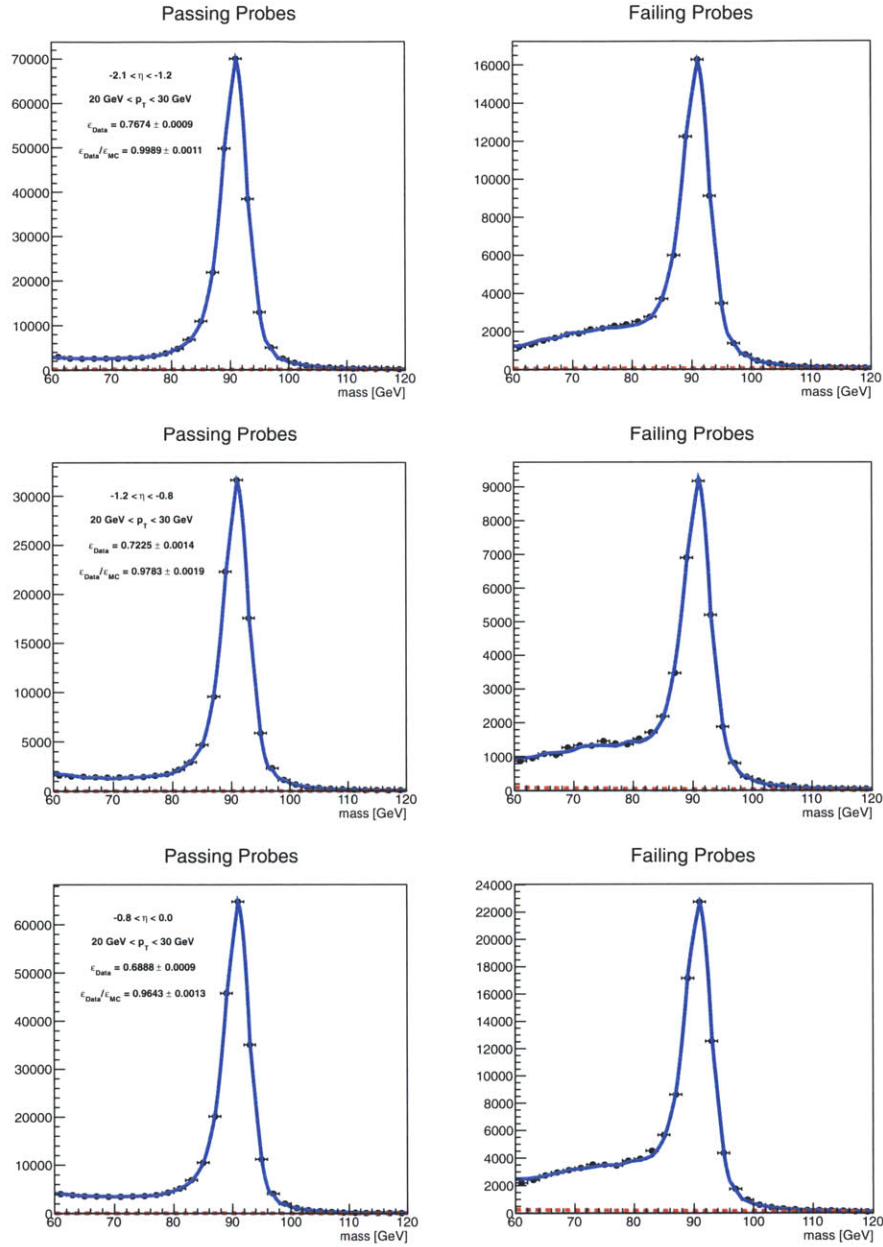


Figure A-17: Muon identification and isolation efficiency fits, $20 \text{ GeV} < p_T < 30 \text{ GeV}$, $-2.1 < \eta < 0$, 2012.

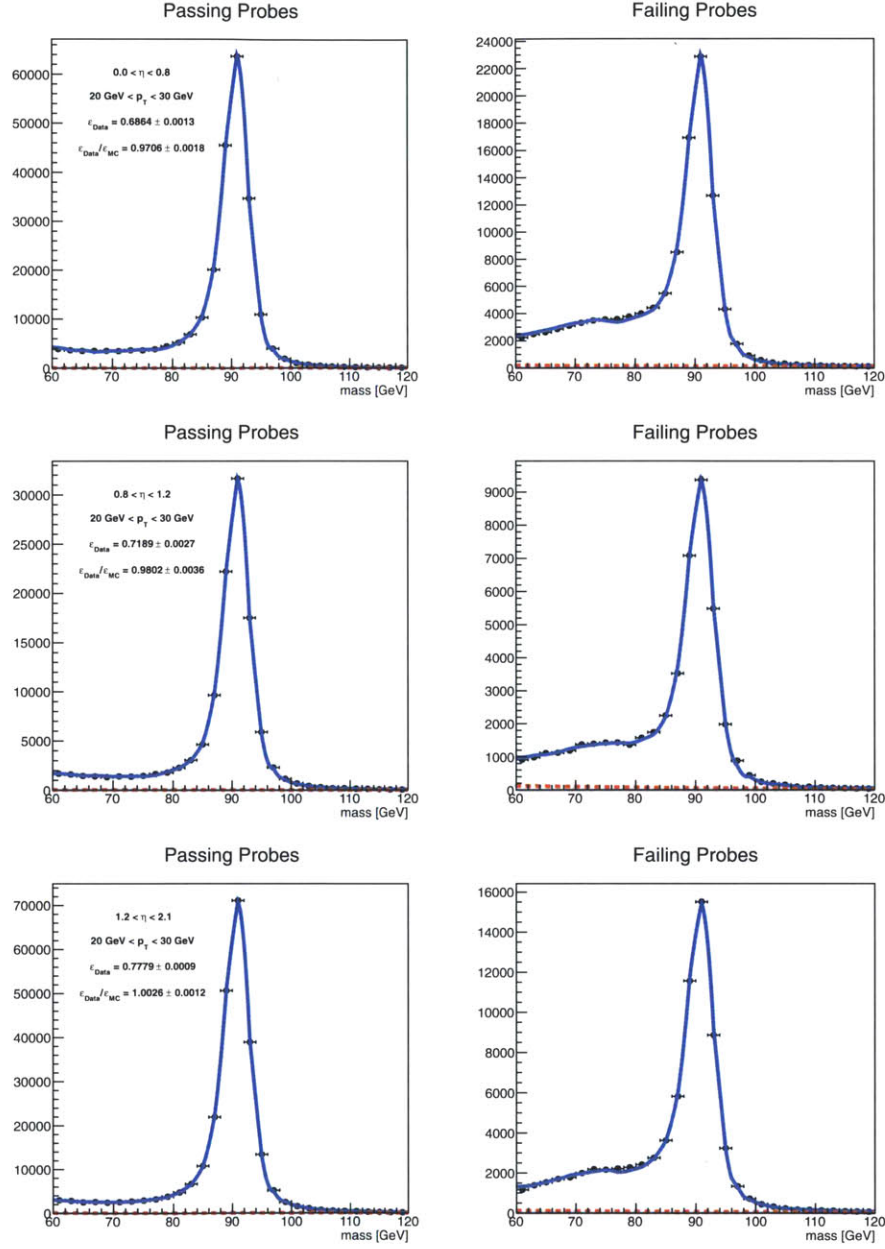


Figure A-18: Muon identification and isolation efficiency fits, $20 \text{ GeV} < p_T < 30 \text{ GeV}$, $0 < \eta < 2.1$, 2012.

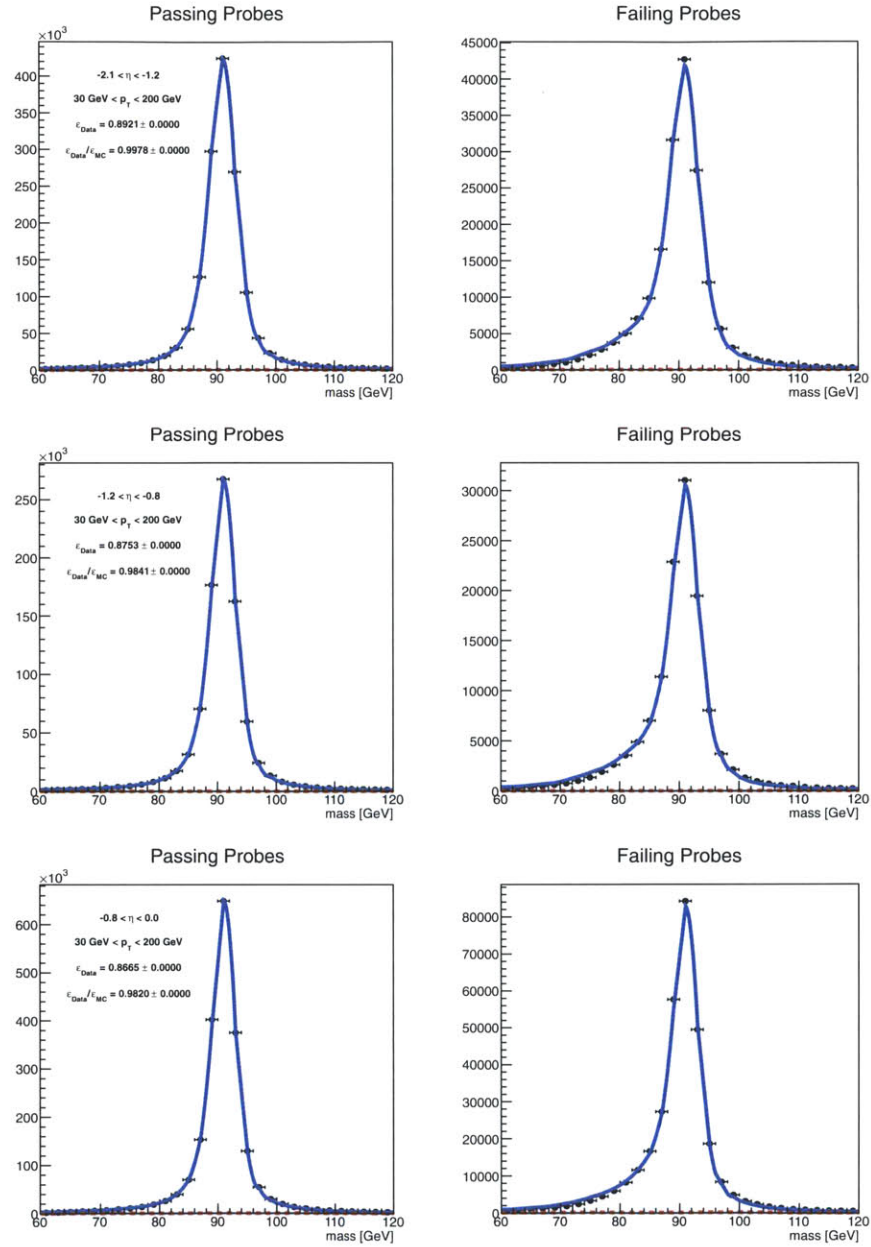


Figure A-19: Muon identification and isolation efficiency fits, $p_T > 30$ GeV, $-2.1 < \eta < 0$, 2012.

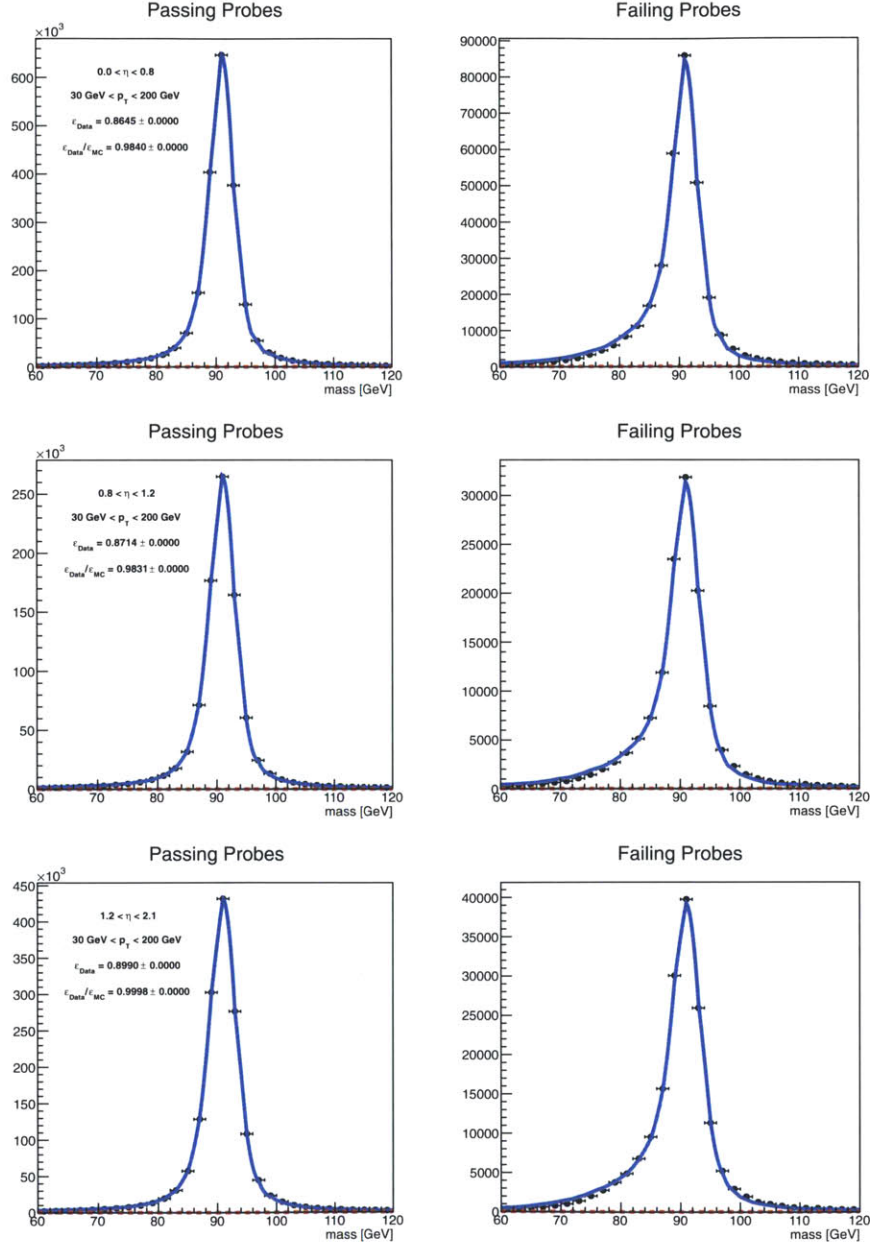
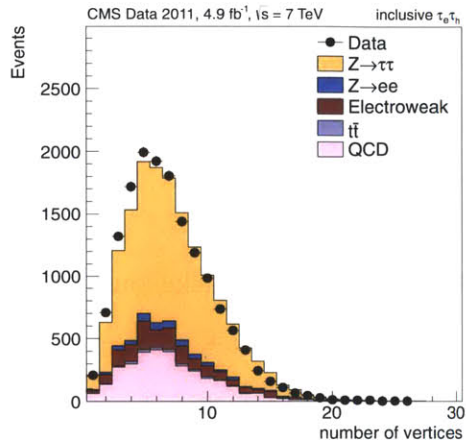


Figure A-20: Muon identification and isolation efficiency fits, $p_T > 30 \text{ GeV}$, $0 < \eta < 2.1$, 2012.

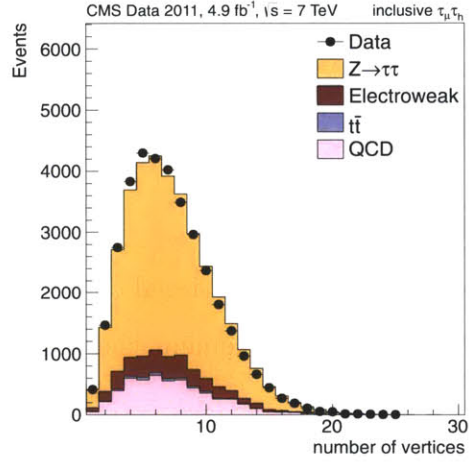
Appendix B

Additional Control Plots

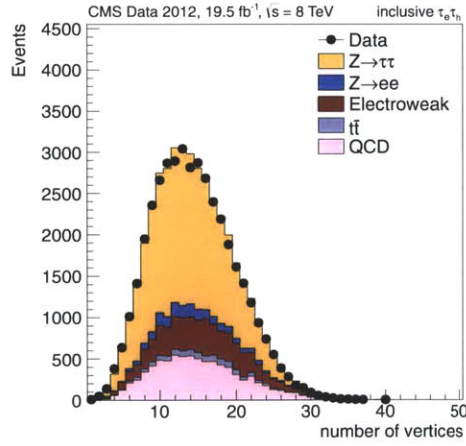
This appendix contains additional control plots that compare the background models to data. These plots supplement the figures provided in Section 6.4.



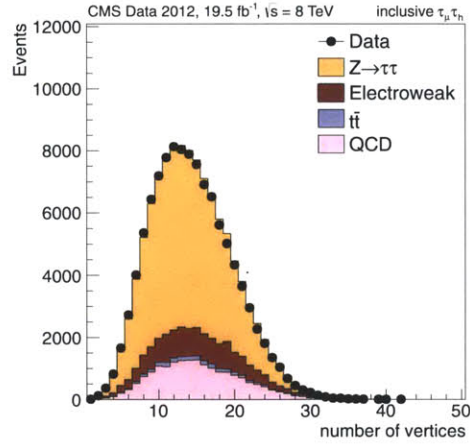
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

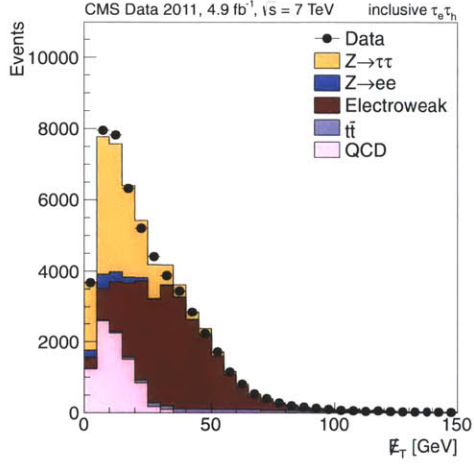


(c) $\tau_e \tau_h$, 2012

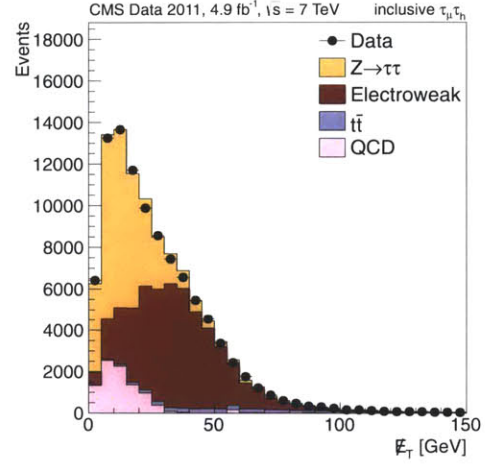


(d) $\tau_\mu \tau_h$, 2012

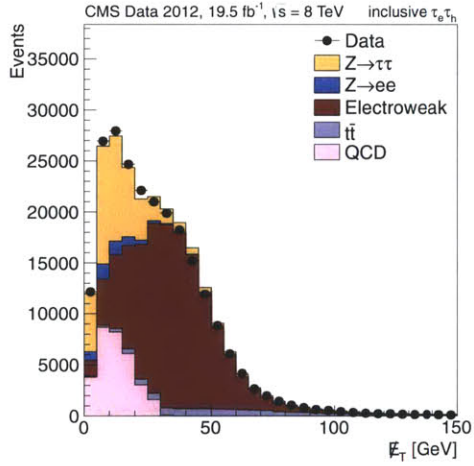
Figure B-1: Primary vertex multiplicity.



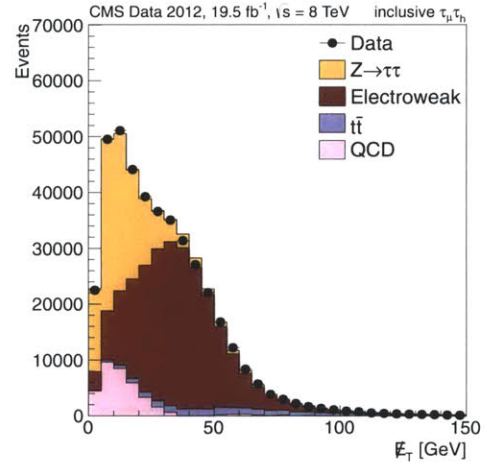
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

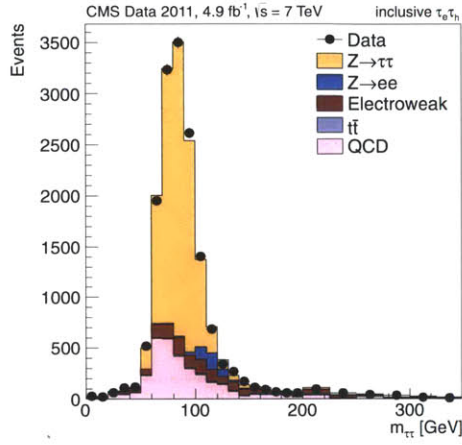


(c) $\tau_e \tau_h$, 2012

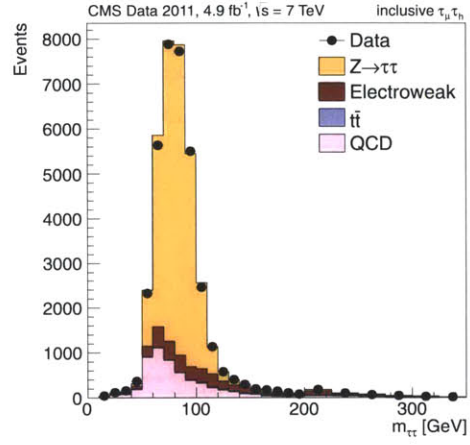


(d) $\tau_\mu \tau_h$, 2012

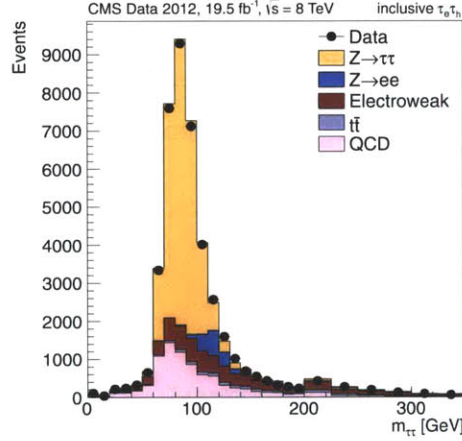
Figure B-2: Missing transverse energy.



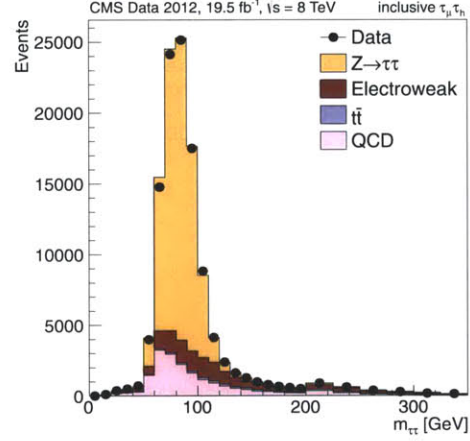
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

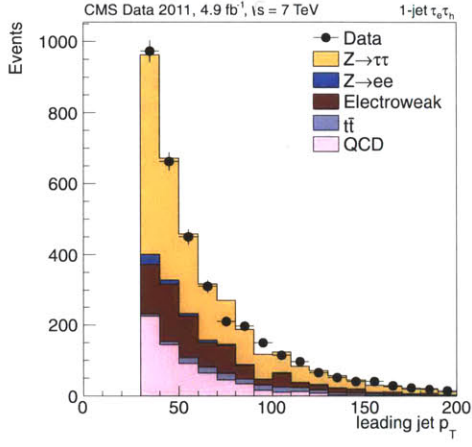


(c) $\tau_e \tau_h$, 2012

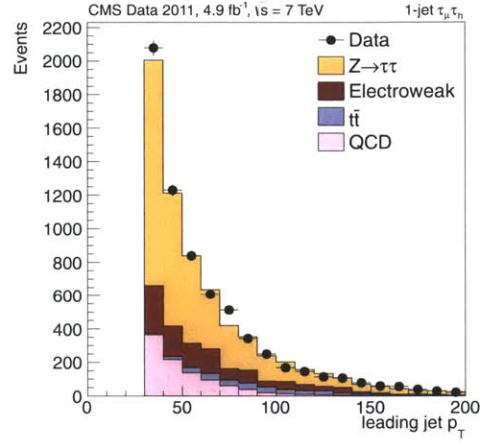


(d) $\tau_\mu \tau_h$, 2012

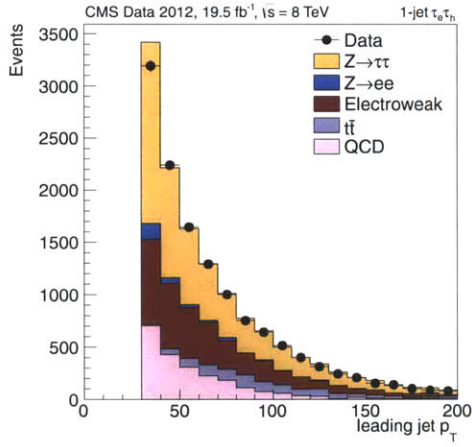
Figure B-3: SVFit di-tau mass.



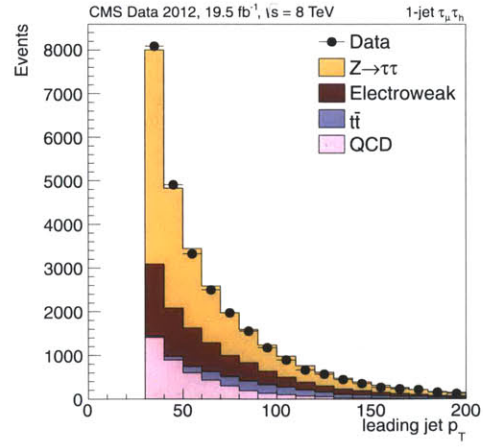
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

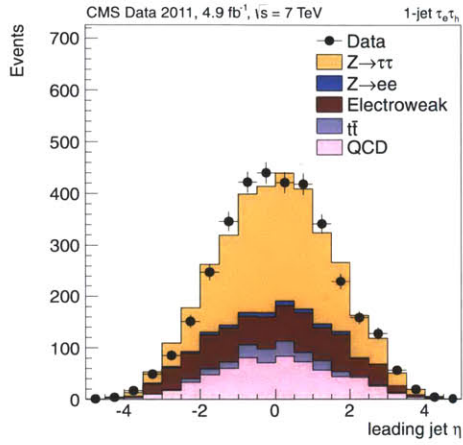


(c) $\tau_e \tau_h$, 2012

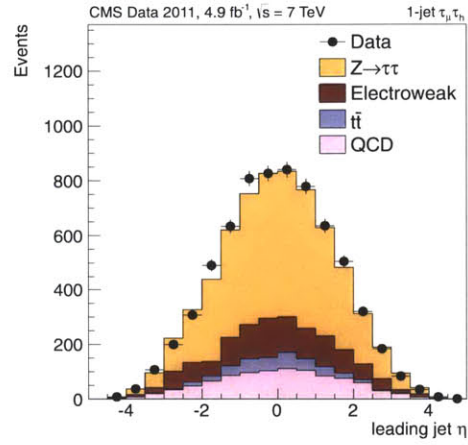


(d) $\tau_\mu \tau_h$, 2012

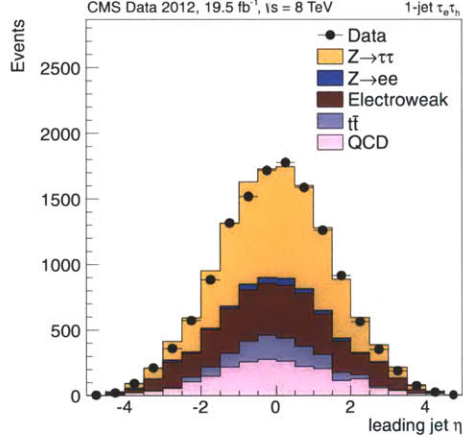
Figure B-4: p_T of leading jet in events with at least one jet.



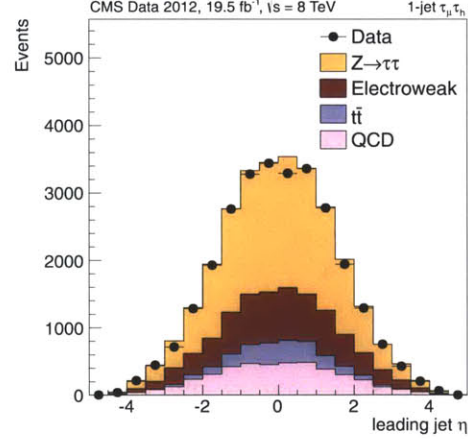
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

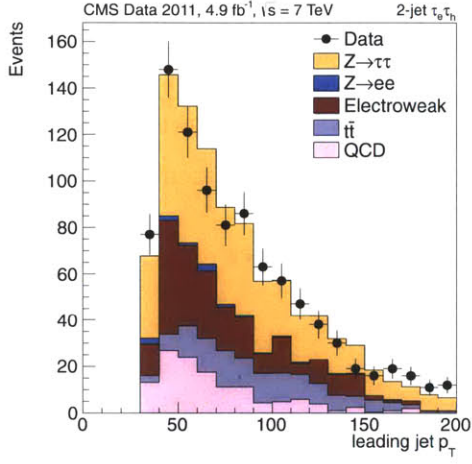


(c) $\tau_e \tau_h$, 2012

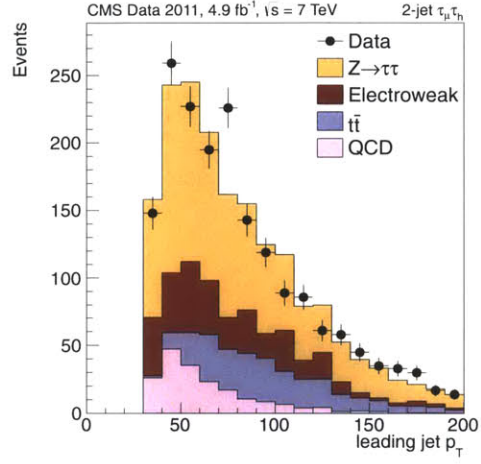


(d) $\tau_\mu \tau_h$, 2012

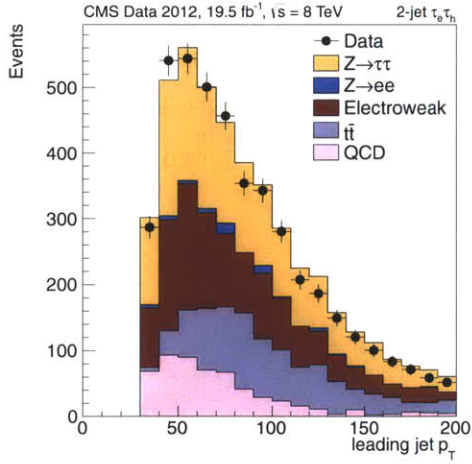
Figure B-5: η of leading jet in events with at least one jet.



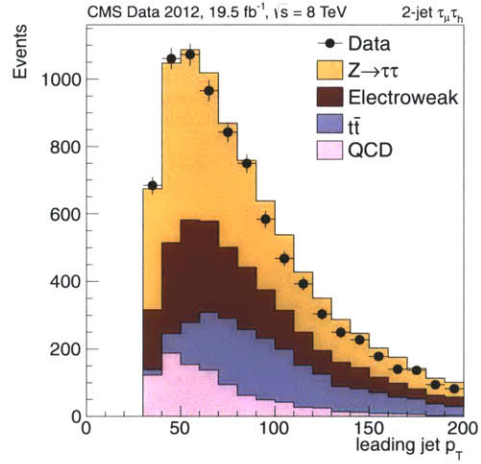
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

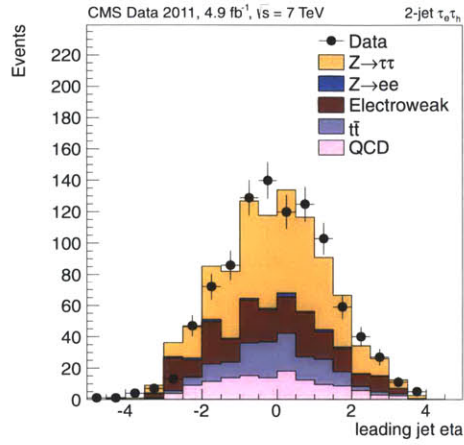


(c) $\tau_e \tau_h$, 2012

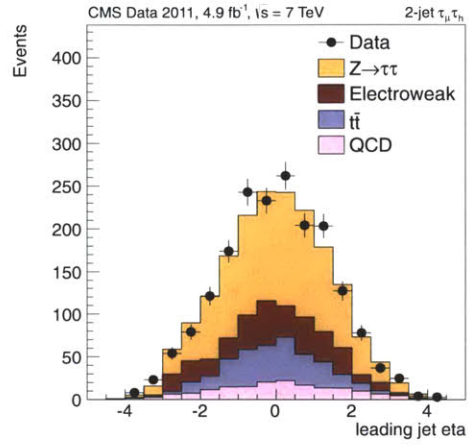


(d) $\tau_\mu \tau_h$, 2012

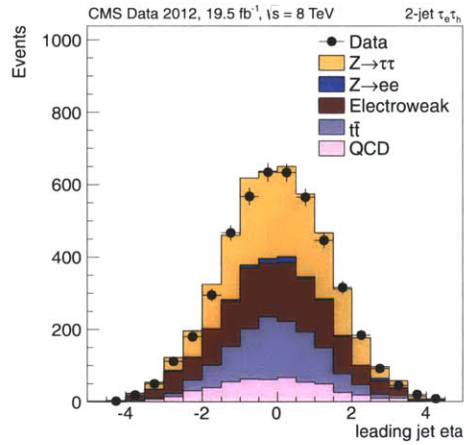
Figure B-6: p_T of leading jet in events with at least two jets.



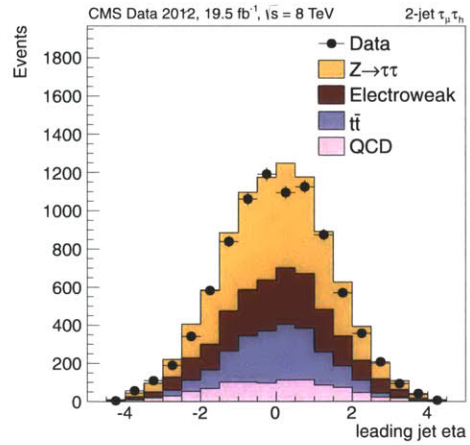
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

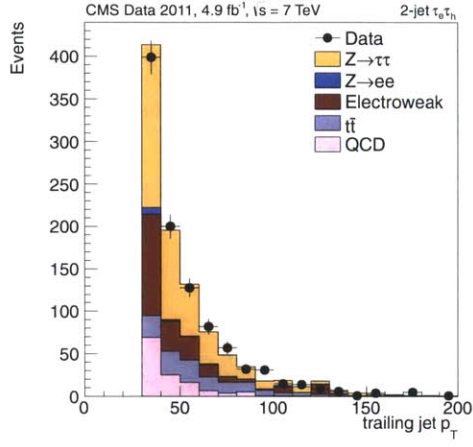


(c) $\tau_e \tau_h$, 2012

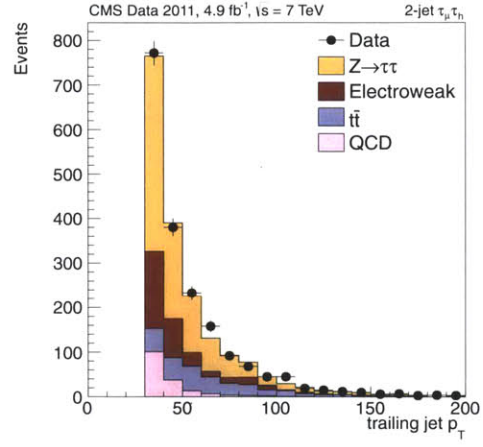


(d) $\tau_\mu \tau_h$, 2012

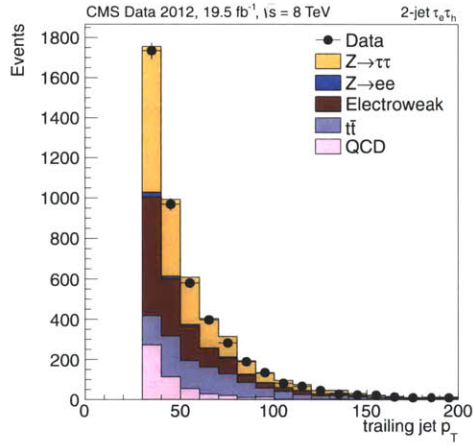
Figure B-7: η of leading jet in events with at least two jets.



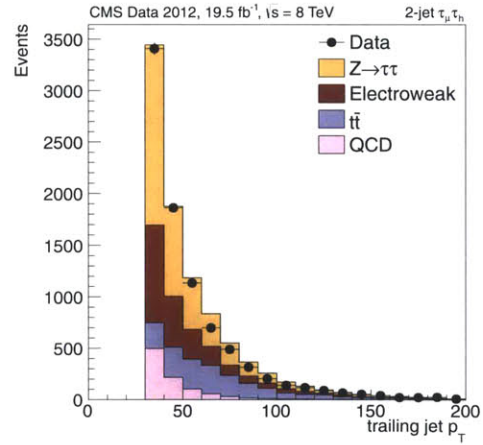
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

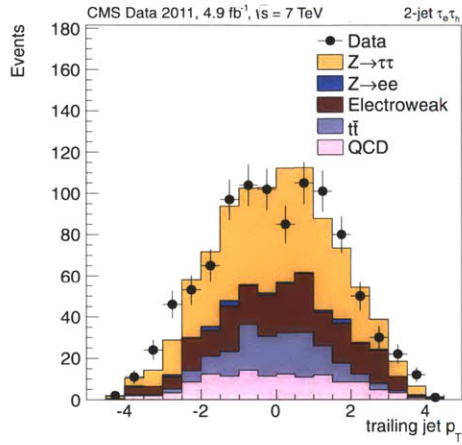


(c) $\tau_e \tau_h$, 2012

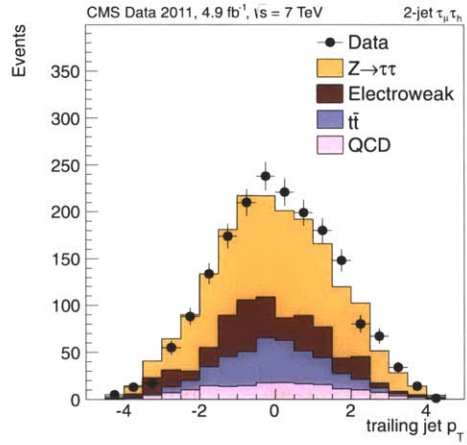


(d) $\tau_\mu \tau_h$, 2012

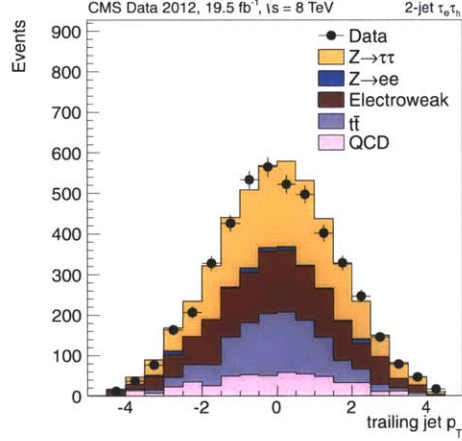
Figure B-8: p_T of sub-leading jet in events with at least two jets.



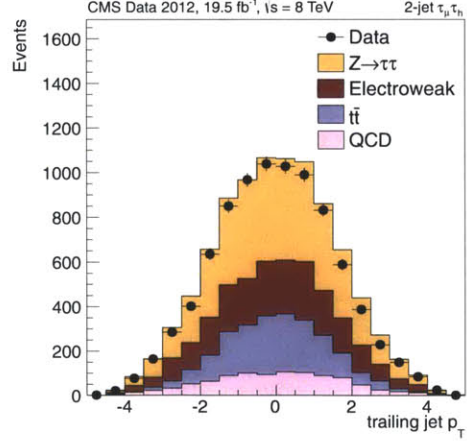
(a) $\tau_e\tau_h$, 2011



(b) $\tau_\mu\tau_h$, 2011

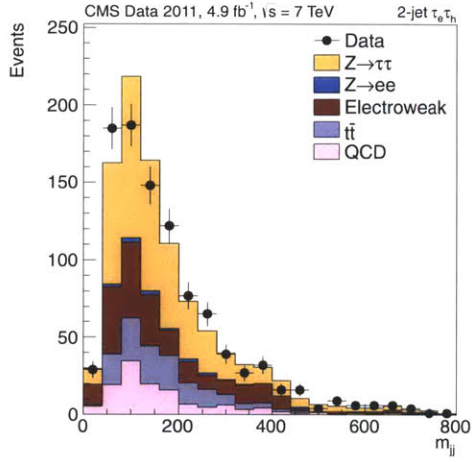


(c) $\tau_e\tau_h$, 2012

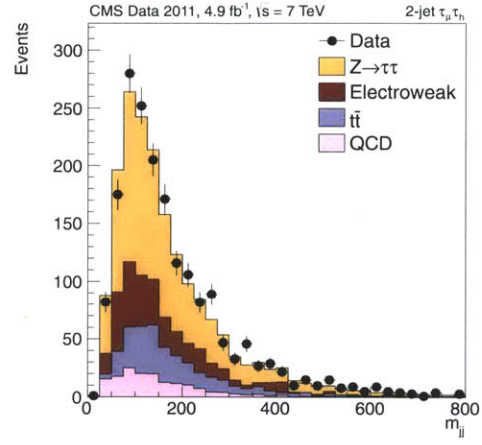


(d) $\tau_\mu\tau_h$, 2012

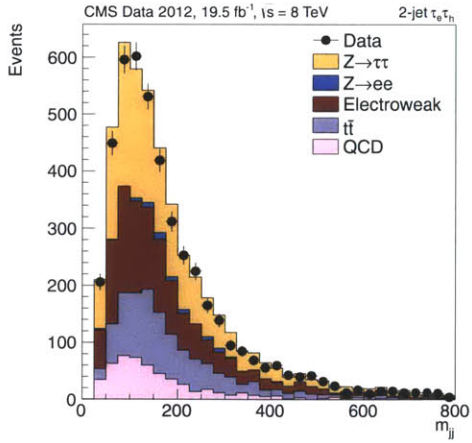
Figure B-9: η of sub-leading jet in events with at least two jets.



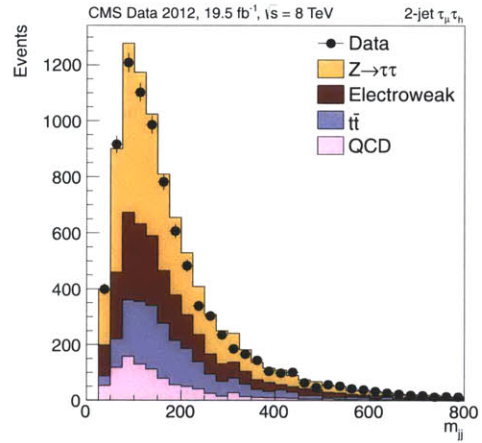
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011

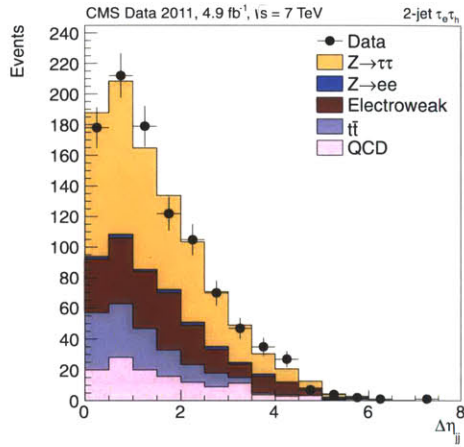


(c) $\tau_e \tau_h$, 2012

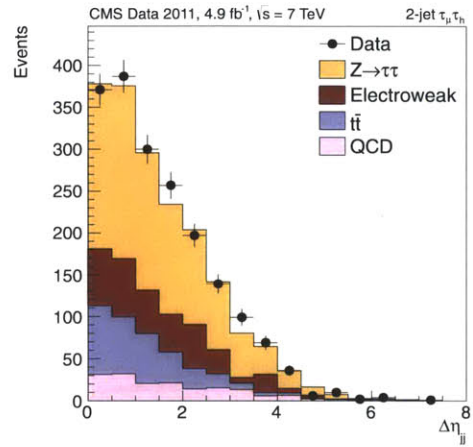


(d) $\tau_\mu \tau_h$, 2012

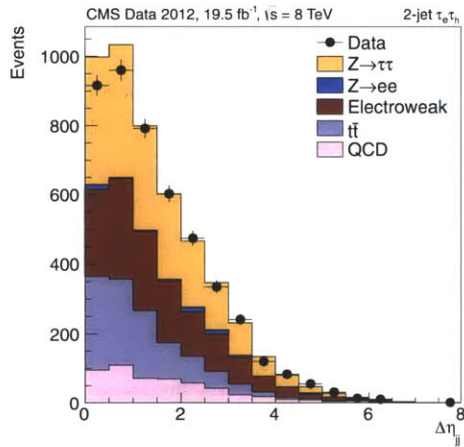
Figure B-10: Invariant mass of two highest p_T jets in events with at least two jets.



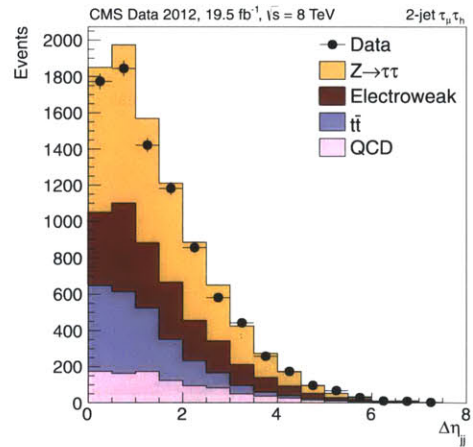
(a) $\tau_e \tau_h$, 2011



(b) $\tau_\mu \tau_h$, 2011



(c) $\tau_e \tau_h$, 2012



(d) $\tau_\mu \tau_h$, 2012

Figure B-11: $\Delta\eta$ between the two highest p_T jets in events with at least two jets.

Appendix C

Expected Higgs Boson Yields

This appendix contains tables of expected Higgs boson yields by channel and year.

	m_H [GeV]	1-jet, high $p_T^{\tau_h}$	1-jet, low $p_T^{\tau_h}$	VBF
$gg \rightarrow H$	110	8.2 ± 1.4	4.6 ± 0.8	0.12 ± 0.05
VBF H	110	1.6 ± 0.2	1.4 ± 0.2	1.1 ± 0.2
$VH + t\bar{t}H$	110	0.88 ± 0.11	0.84 ± 0.11	0
$gg \rightarrow H$	115	8.0 ± 1.4	6.0 ± 1.1	0.31 ± 0.12
VBF H	115	1.6 ± 0.2	1.3 ± 0.2	1.1 ± 0.1
$VH + t\bar{t}H$	115	0.82 ± 0.10	0.73 ± 0.10	0
$gg \rightarrow H$	120	6.5 ± 1.1	6.6 ± 1.2	0.19 ± 0.07
VBF H	120	1.4 ± 0.2	1.3 ± 0.2	1.0 ± 0.1
$VH + t\bar{t}H$	120	0.70 ± 0.08	0.70 ± 0.10	0.004 ± 0.001
$gg \rightarrow H$	125	6.7 ± 1.1	5.8 ± 1.1	0.16 ± 0.06
VBF H	125	1.2 ± 0.1	1.1 ± 0.1	0.86 ± 0.12
$VH + t\bar{t}H$	125	0.56 ± 0.07	0.54 ± 0.07	0.005 ± 0.001
$gg \rightarrow H$	130	5.4 ± 0.9	4.8 ± 0.9	0.092 ± 0.035
VBF H	130	0.97 ± 0.12	1.0 ± 0.1	0.74 ± 0.10
$VH + t\bar{t}H$	130	0.42 ± 0.05	0.52 ± 0.07	0.001 ± 0.001
$gg \rightarrow H$	135	3.7 ± 0.6	4.5 ± 0.8	0.11 ± 0.04
VBF H	135	0.79 ± 0.10	0.90 ± 0.11	0.63 ± 0.09
$VH + t\bar{t}H$	135	0.30 ± 0.04	0.40 ± 0.05	0.001 ± 0.001
$gg \rightarrow H$	140	2.9 ± 0.5	3.8 ± 0.7	0.085 ± 0.033
VBF H	140	0.54 ± 0.07	0.78 ± 0.10	0.54 ± 0.08
$VH + t\bar{t}H$	140	0.21 ± 0.03	0.29 ± 0.04	0.002 ± 0.001
$gg \rightarrow H$	145	1.9 ± 0.3	2.6 ± 0.5	0.054 ± 0.021
VBF H	145	0.42 ± 0.05	0.52 ± 0.07	0.34 ± 0.05
$VH + t\bar{t}H$	145	0.14 ± 0.02	0.21 ± 0.03	0.001 ± 0.001

Table C.1: Expected Higgs boson yields in the $\tau_e\tau_h$ channel in 2011 data.

	m_H [GeV]	1-jet, high $p_T^{\tau_h}$	1-jet, low $p_T^{\tau_h}$	VBF
$gg \rightarrow H$	110	19 ± 3	12 ± 2	0.38 ± 0.14
VBF H	110	3.1 ± 0.4	2.7 ± 0.3	2.2 ± 0.3
$VH + t\bar{t}H$	110	2.0 ± 0.3	1.7 ± 0.2	0.005 ± 0.001
$gg \rightarrow H$	115	18 ± 3	12 ± 2	0.37 ± 0.14
VBF H	115	3.3 ± 0.4	2.6 ± 0.3	2.0 ± 0.3
$VH + t\bar{t}H$	115	1.7 ± 0.2	1.5 ± 0.2	0.004 ± 0.001
$gg \rightarrow H$	120	15 ± 3	11 ± 2	0.21 ± 0.08
VBF H	120	2.6 ± 0.3	2.4 ± 0.3	1.8 ± 0.2
$VH + t\bar{t}H$	120	1.4 ± 0.2	1.3 ± 0.2	0.005 ± 0.001
$gg \rightarrow H$	125	12 ± 2	11 ± 2	0.28 ± 0.11
VBF H	125	2.3 ± 0.3	2.2 ± 0.3	1.6 ± 0.2
$VH + t\bar{t}H$	125	1.1 ± 0.1	1.2 ± 0.1	0.002 ± 0.001
$gg \rightarrow H$	130	9.6 ± 1.7	10 ± 2	0.23 ± 0.09
VBF H	130	1.9 ± 0.2	1.9 ± 0.2	1.4 ± 0.2
$VH + t\bar{t}H$	130	0.80 ± 0.10	0.95 ± 0.12	0.003 ± 0.001
$gg \rightarrow H$	135	7.7 ± 1.3	9.3 ± 1.6	0.25 ± 0.09
VBF H	135	1.5 ± 0.2	1.7 ± 0.2	1.1 ± 0.1
$VH + t\bar{t}H$	135	0.62 ± 0.08	0.72 ± 0.09	0.001 ± 0.001
$gg \rightarrow H$	140	6.0 ± 1.1	7.5 ± 1.3	0.20 ± 0.08
VBF H	140	1.1 ± 0.1	1.3 ± 0.2	0.90 ± 0.12
$VH + t\bar{t}H$	140	0.42 ± 0.05	0.56 ± 0.07	0.001 ± 0.001
$gg \rightarrow H$	145	3.8 ± 0.7	5.3 ± 0.9	0.16 ± 0.06
VBF H	145	0.79 ± 0.09	0.98 ± 0.12	0.68 ± 0.09
$VH + t\bar{t}H$	145	0.28 ± 0.04	0.38 ± 0.05	0.002 ± 0.001

Table C.2: Expected Higgs boson yields in the $\tau_\mu\tau_h$ channel in 2011 data.

	m_H [GeV]	1-jet, high $p_T^{\tau_h}$	1-jet, low $p_T^{\tau_h}$	VBF
$gg \rightarrow H$	110	40 ± 7	25 ± 5	1.5 ± 0.6
VBF H	110	6.0 ± 0.8	4.3 ± 0.6	4.8 ± 0.6
$VH + t\bar{t}H$	110	3.5 ± 0.5	2.9 ± 0.4	0.028 ± 0.005
$gg \rightarrow H$	115	36 ± 7	24 ± 5	1.1 ± 0.4
VBF H	115	5.8 ± 0.7	4.3 ± 0.6	4.5 ± 0.6
$VH + t\bar{t}H$	115	3.2 ± 0.4	2.8 ± 0.4	0.042 ± 0.008
$gg \rightarrow H$	120	32 ± 6	25 ± 5	1.1 ± 0.4
VBF H	120	5.3 ± 0.7	4.3 ± 0.6	4.2 ± 0.6
$VH + t\bar{t}H$	120	2.5 ± 0.3	2.6 ± 0.4	0
$gg \rightarrow H$	125	26 ± 5	22 ± 4	0.68 ± 0.26
VBF H	125	4.5 ± 0.6	3.8 ± 0.5	3.9 ± 0.5
$VH + t\bar{t}H$	125	2.1 ± 0.3	2.3 ± 0.3	0.006 ± 0.001
$gg \rightarrow H$	130	24 ± 4	22 ± 4	0.94 ± 0.36
VBF H	130	3.8 ± 0.5	3.6 ± 0.5	3.4 ± 0.5
$VH + t\bar{t}H$	130	1.6 ± 0.2	1.9 ± 0.3	0.016 ± 0.003
$gg \rightarrow H$	135	18 ± 3	19 ± 4	0.70 ± 0.27
VBF H	135	3.0 ± 0.4	3.1 ± 0.4	2.7 ± 0.4
$VH + t\bar{t}H$	135	1.3 ± 0.2	1.5 ± 0.2	0.001 ± 0.001
$gg \rightarrow H$	140	14 ± 3	17 ± 3	0.61 ± 0.24
VBF H	140	2.2 ± 0.3	2.6 ± 0.3	2.1 ± 0.3
$VH + t\bar{t}H$	140	0.82 ± 0.11	1.2 ± 0.2	0.003 ± 0.001
$gg \rightarrow H$	145	8.9 ± 1.6	13 ± 2	0.47 ± 0.18
VBF H	145	1.6 ± 0.2	2.0 ± 0.3	1.7 ± 0.2
$VH + t\bar{t}H$	145	0.62 ± 0.08	0.82 ± 0.11	0.014 ± 0.003

Table C.3: Expected Higgs boson yields in the $\tau_e\tau_h$ channel in 2012 data.

	m_H [GeV]	1-jet, high $p_T^{\tau_h}$	1-jet, low $p_T^{\tau_h}$	VBF
$gg \rightarrow H$	110	80 ± 14	51 ± 9	2.7 ± 0.9
VBF H	110	12 ± 1	9.0 ± 1.1	9.0 ± 1.2
$VH + t\bar{t}H$	110	7.4 ± 0.9	6.7 ± 0.8	0.062 ± 0.012
$gg \rightarrow H$	115	72 ± 12	51 ± 9	1.9 ± 0.7
VBF H	115	11 ± 1	9.2 ± 1.1	8.4 ± 1.1
$VH + t\bar{t}H$	115	6.6 ± 0.8	5.7 ± 0.7	0.052 ± 0.010
$gg \rightarrow H$	120	65 ± 11	52 ± 9	2.1 ± 0.7
VBF H	120	10 ± 1	8.8 ± 1.1	8.0 ± 1.1
$VH + t\bar{t}H$	120	5.0 ± 0.6	5.4 ± 0.7	0.035 ± 0.007
$gg \rightarrow H$	125	54 ± 9	53 ± 9	2.4 ± 0.8
VBF H	125	9.0 ± 1.1	8.2 ± 1.0	7.0 ± 0.9
$VH + t\bar{t}H$	125	4.1 ± 0.5	4.9 ± 0.6	0.058 ± 0.011
$gg \rightarrow H$	130	46 ± 8	46 ± 8	2.0 ± 0.7
VBF H	130	7.4 ± 0.9	7.3 ± 0.9	6.2 ± 0.8
$VH + t\bar{t}H$	130	3.3 ± 0.4	3.7 ± 0.5	0.032 ± 0.006
$gg \rightarrow H$	135	34 ± 6	38 ± 7	1.5 ± 0.5
VBF H	135	5.8 ± 0.7	6.2 ± 0.8	5.0 ± 0.7
$VH + t\bar{t}H$	135	2.5 ± 0.3	3.0 ± 0.4	0.030 ± 0.006
$gg \rightarrow H$	140	27 ± 5	33 ± 6	1.1 ± 0.4
VBF H	140	4.2 ± 0.5	5.0 ± 0.6	4.1 ± 0.5
$VH + t\bar{t}H$	140	1.6 ± 0.2	2.2 ± 0.3	0.016 ± 0.003
$gg \rightarrow H$	145	19 ± 3	26 ± 4	0.77 ± 0.26
VBF H	145	3.0 ± 0.4	3.8 ± 0.5	2.9 ± 0.4
$VH + t\bar{t}H$	145	1.2 ± 0.1	1.5 ± 0.2	0

Table C.4: Expected Higgs boson yields in the $\tau_\mu\tau_h$ channel in 2012 data.

Appendix D

Limits by Channel and Year

This appendix contains upper limits on the Higgs cross section computed using only one channel ($\tau_e\tau_h$ or $\tau_\mu\tau_h$) in one year of data (2011 or 2012).

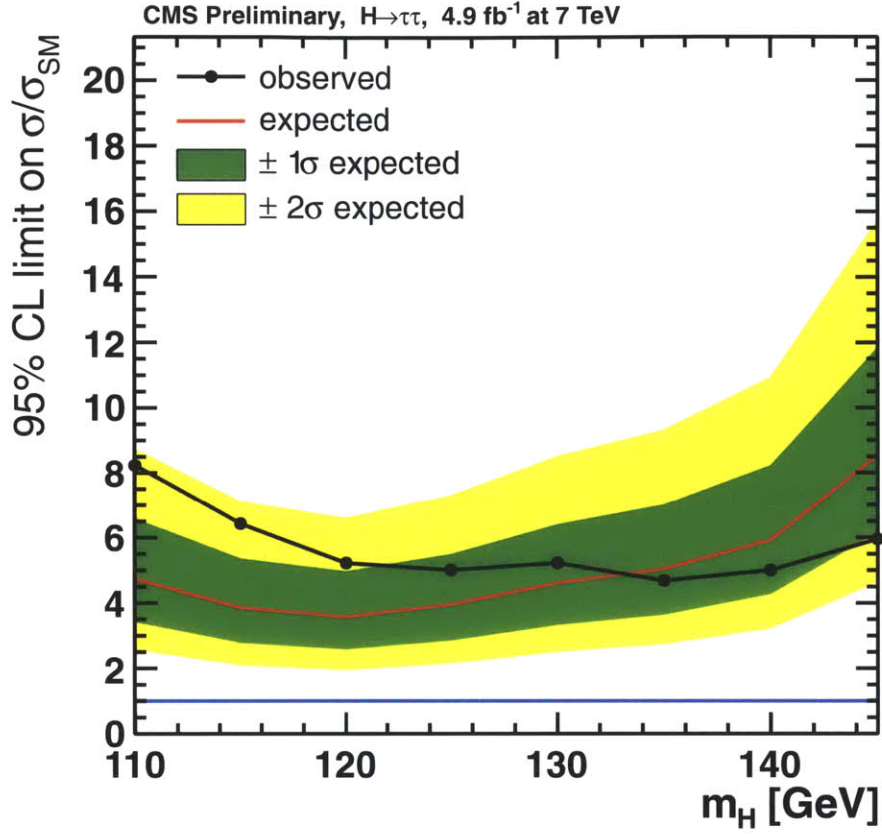


Figure D-1: Expected and observed upper limits on the Higgs cross section computed using only $\tau_e\tau_h$ channel in 2011 data.

m_H	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Obs. Limit
110 GeV	2.57	3.42	4.73	6.58	8.74	8.23
115 GeV	2.09	2.79	3.86	5.36	7.12	6.43
120 GeV	1.94	2.58	3.58	4.97	6.60	5.22
125 GeV	2.14	2.85	3.95	5.49	7.30	5.01
130 GeV	2.50	3.33	4.61	6.40	8.51	5.22
135 GeV	2.74	3.64	5.05	7.01	9.31	4.68
140 GeV	3.21	4.27	5.92	8.23	10.93	5.00
145 GeV	4.63	6.16	8.53	11.85	15.74	5.96

Table D.1: Expected and observed upper limits on the Higgs cross section computed using only $\tau_e\tau_h$ channel in 2011 data.

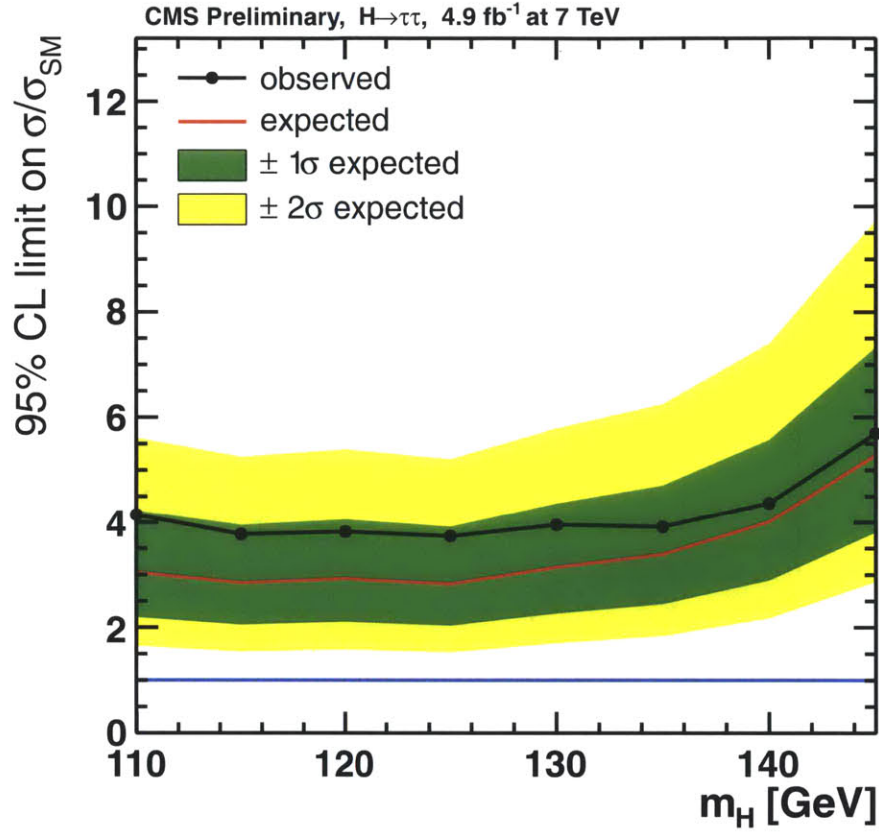


Figure D-2: Expected and observed upper limits on the Higgs cross section computed using only $\tau_\mu\tau_h$ channel in 2011 data.

m_H	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Obs. Limit
110 GeV	1.65	2.19	3.04	4.22	5.61	4.15
115 GeV	1.54	2.05	2.84	3.95	5.25	3.77
120 GeV	1.59	2.11	2.92	4.06	5.39	3.82
125 GeV	1.53	2.04	2.82	3.92	5.20	3.74
130 GeV	1.70	2.27	3.14	4.36	5.80	3.95
135 GeV	1.84	2.45	3.39	4.71	6.26	3.92
140 GeV	2.18	2.90	4.02	5.58	7.41	4.37
145 GeV	2.87	3.81	5.28	7.34	9.75	5.69

Table D.2: Expected and observed upper limits on the Higgs cross section computed using only $\tau_\mu\tau_h$ channel in 2011 data.

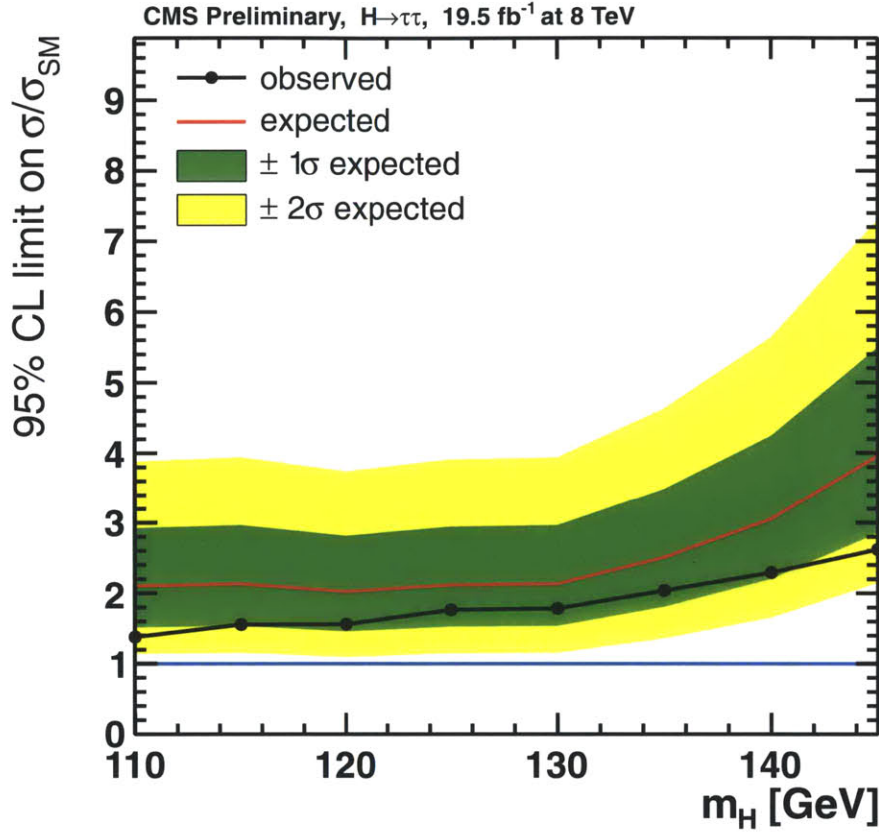


Figure D-3: Expected and observed upper limits on the Higgs cross section computed using only $\tau_e\tau_h$ channel in 2012 data.

m_H	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Obs. Limit
110 GeV	1.14	1.52	2.10	2.92	3.88	1.38
115 GeV	1.16	1.54	2.13	2.96	3.94	1.56
120 GeV	1.10	1.46	2.02	2.81	3.73	1.56
125 GeV	1.15	1.53	2.12	2.94	3.91	1.76
130 GeV	1.16	1.54	2.13	2.96	3.94	1.78
135 GeV	1.36	1.81	2.51	3.48	4.63	2.04
140 GeV	1.66	2.20	3.05	4.24	5.64	2.29
145 GeV	2.14	2.85	3.95	5.49	7.30	2.62

Table D.3: Expected and observed upper limits on the Higgs cross section computed using only $\tau_e\tau_h$ channel in 2012 data.

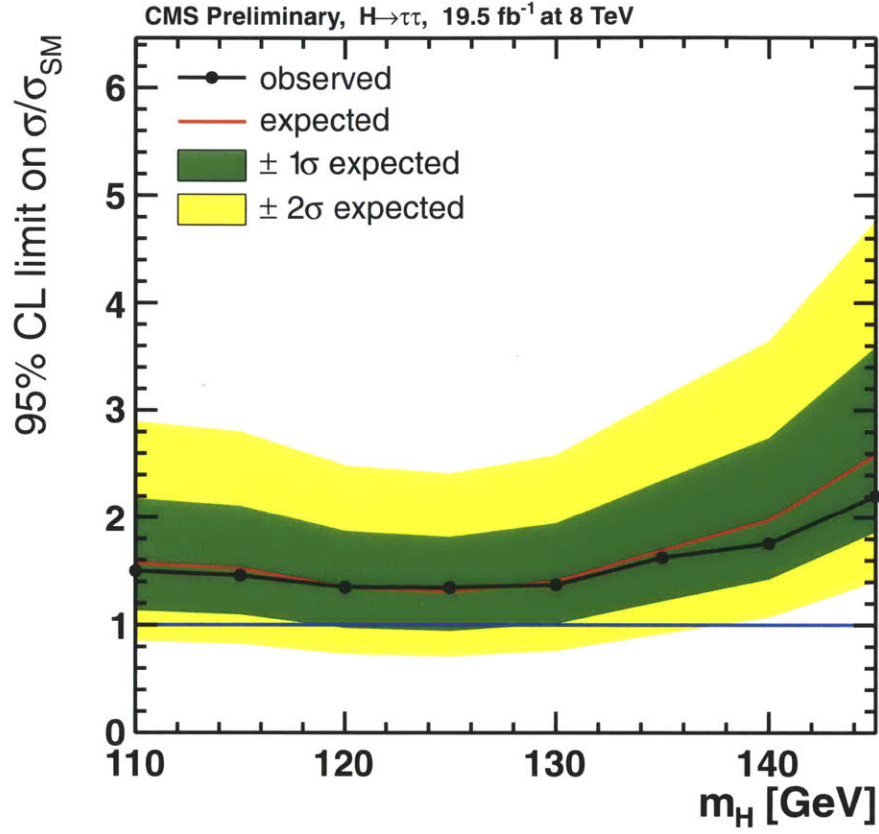


Figure D-4: Expected and observed upper limits on the Higgs cross section computed using only $\tau_\mu\tau_h$ channel in 2012 data.

m_H	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Obs. Limit
110 GeV	0.85	1.13	1.57	2.18	2.90	1.50
115 GeV	0.82	1.10	1.52	2.11	2.80	1.46
120 GeV	0.73	0.97	1.35	1.87	2.49	1.35
125 GeV	0.71	0.94	1.31	1.82	2.41	1.35
130 GeV	0.76	1.01	1.40	1.95	2.59	1.37
135 GeV	0.92	1.22	1.70	2.35	3.13	1.63
140 GeV	1.07	1.43	1.98	2.75	3.65	1.76
145 GeV	1.40	1.87	2.59	3.59	4.77	2.20

Table D.4: Expected and observed upper limits on the Higgs cross section computed using only $\tau_\mu\tau_h$ channel in 2012 data.

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