A Search for Lepton Flavor Violation in Z decays with the CMS Experiment

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Chapter 1

Introduction

The standard model of particle physics is a theory that has passed many experimental precision tests. However, there are still fundamental questions and observations that cannot be answered or explained by it. One example is neutrino oscillation. The standard model Lagrangian explicitly conserves lepton flavor in any given interaction. This feature does not arise from a gauge principle as for example momentum conservation; it was put in by hand because no violation was seen at the time. The observation of neutrino oscillation demonstrates that there is a violation of lepton flavor in the neutral sector. One open question is: is there Lepton Flavor Violation (LFV) in the charged sector as well?

This analysis focuses on Lepton Flavor Violation in decays of the Z boson, in particular on the decay $Z \rightarrow e\mu$. The branching ratio of this decay as predicted by incorporating neutrino oscillation is undetectable by any current or near-future experiment ($\mathcal{B}(Z \rightarrow e\mu) < 4 \cdot 10^{-60}$ [1]), turning its observation into a direct proof of new physics. Low-energy experiments looking for decays such as $\mu \rightarrow 3e$ [2] already set very stringent indirect limits on the branching ratio ($\mathcal{B}(Z \rightarrow e\mu) < 5 \cdot 10^{-13}$ [3]). However, a confirmation of such results with a direct search in the new environment provided by the LHC is important.

This thesis will shortly discuss the theoretical foundation of modern particle physics, the “STANDARD MODEL” (SM), as well as the implementation of neutrino oscillation and its implications. The CMS detector and the LHC will be described to illustrate the experimental setup. Next, the reconstruction and selection of events is presented and systematic uncertainties are evaluated. The number of selected events is statistically interpreted in terms of an exclusion limit on the branching ratio.

Conventions used in this thesis

As is customary in high energy physics, in this analysis the system of natural units is utilized where

$$\hbar = c = 1.$$ 

This statement allows the expression of the following quantities in terms of electronvolt (eV)

$$[\text{Energy}] = [\text{Momentum}] = [\text{Mass}] = [\text{Time}]^{-1} = [\text{Length}]^{-1} = \text{eV},$$

where one eV corresponds to the energy retained by an electron traversing a potential difference of 1 V. In some cases, the SI-system is used to exemplify dimensions. The conversion between the two systems is done via the relation

$$hc = 197.327 \text{ MeV fm}.$$
Chapter 2

Theoretical Foundation

This chapter introduces the reader to the standard model of particle physics. Furthermore, neutrino oscillation and its consequences regarding the violation of lepton flavor are discussed.

2.1 The Standard Model of Particle Physics

The standard model of particle physics is a theory that describes the fundamental particles of the universe and their interactions. These fundamental particles can be classified into two groups: bosons and fermions (see Tables 2.1, 2.2 and Figure 2.1). While fermions make up all of the visible matter in the universe and are particles of spin 1/2, bosons (integer spin) are responsible for their interactions, namely the strong and electroweak force. As there is no description of gravitation in terms of a quantum field theory to this date, it is not implemented in the standard model. Since gravitation has a very minor impact at (sub)atomic scales, it can be neglected in high energy physics experiments.

Table 2.1: Interactions described by the standard model including their symmetry groups, gauge-mediators (bosons) and their characteristics. $rgb/\bar{r}\bar{g}\bar{b}$ denotes combinations of color and anti-color. In total there are eight linearly independent combinations, yielding eight gluons.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Symmetry group</th>
<th>Mediator</th>
<th>Mass/GeV</th>
<th>Q / e</th>
<th>T_3</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>electromagnetic</td>
<td>U(1)</td>
<td>$\gamma$ (photon)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>weak</td>
<td>SU(2)</td>
<td>$Z$</td>
<td>90.2</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>strong</td>
<td>SU(3)</td>
<td>$\gamma$ (8 gluons)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$rgb/\bar{r}\bar{g}\bar{b}$</td>
</tr>
</tbody>
</table>

The strong interaction couples to particles with the quantum number color and is responsible for keeping these particles in bound states. The interaction is transmitted via massless gauge bosons (spin 1) called gluons and described by a locally gauge invariant Lagrangian based on a SU(3) symmetry group. Every gluon carries color and anti-color. There are eight linearly independent combinations of the three colors red, green and blue yielding eight gluons in total.

The electroweak interaction is a unification of the electromagnetic and the weak force, and it is based on the combined symmetry groups U(1) and SU(2), respectively: SU(2) × U(1). The electromagnetic interaction is transmitted by the massless photon (spin 1), while particle decays are mediated by an electrically neutral and two charged massive bosons of spin 1 (Z
and W$^{\pm}$) [4, 5]. However, the fact that the gauge bosons of the weak interaction are massive is incompatible with local gauge invariance of the Lagrangian. This issue is resolved by spontaneous breaking of the SU(2)$\times$U(1) symmetry below a certain energy scale conserving gauge invariance. Massless bosons of the SU(2)$\times$U(1) mix with each other, yielding the two charged W bosons as well as one massive (Z) and one massless ($\gamma$) neutral boson. This process (Brout-Engelert-Higgs mechanism [6, 7]) enforces the existence of a new particle: a boson of spin 0, the so called Higgs boson. This boson couples to the weak gauge bosons depending on their masses. Similarly, couplings relative to the fermion masses can be introduced (Yukawa couplings). It is important to note that neutrinos stay massless in the standard model contrary to experimental evidence [8], which is discussed in Section 2.2. Searches for the Higgs boson have been carried out for over two decades, and recently a promising discovery has been made by both, the ATLAS and CMS Collaborations: a spinless boson with a mass of roughly 125 GeV [9, 10]. Still, many measurements are needed to ascertain whether this boson actually is the standard model Higgs boson.

The fermionic sector can further be subdivided into particles carrying color – quarks – and particles that do not: leptons. For each fermion, there is an antifermion that differs only in charge-like quantum numbers. These antiparticles are – unless stated otherwise – omitted from here on. While matter is mostly made up of electrons and combinations of the up and down quark, unstable and heavier copies have been found in cosmic radiation and particle collisions. In total, there are six leptons and six quarks ordered by type and mass into three families (also called generations or flavor).

Table 2.2: Fermions in the standard model. Shown are the three families of leptons and quarks together with their charge-like quantum numbers: electric charge $Q$, the third component of the weak isospin $T_3$ and color. Moreover, both quarks and leptons are split into left-handed doublets and right-handed singlets with respect to the weak interaction.

<table>
<thead>
<tr>
<th>Quark families</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Q/e</th>
<th>$T_3$</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>($u^\prime$, $d^\prime$) $L$</td>
<td>($c^\prime$, $s^\prime$) $L$</td>
<td>($t$, $b^\prime$) $L$</td>
<td>+2/3</td>
<td>+1/2</td>
<td>rgb</td>
<td></td>
</tr>
<tr>
<td>$u_R$</td>
<td>$c_R$</td>
<td>$t_R$</td>
<td>$-1/3$</td>
<td>$-1/2$</td>
<td>rgb</td>
<td></td>
</tr>
<tr>
<td>$d_R$</td>
<td>$s_R$</td>
<td>$b_R$</td>
<td>$-1/3$</td>
<td>0</td>
<td>rgb</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lepton families</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Q/e</th>
<th>$T_3$</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>($\nu_e$, $e^-$) $L$</td>
<td>($\nu_\mu$, $\mu^-$) $L$</td>
<td>($\nu_\tau$, $\tau^-$) $L$</td>
<td>0</td>
<td>+1/2</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>$\nu_{e,R}$</td>
<td>$\nu_{\mu,R}$</td>
<td>$\nu_{\tau,R}$</td>
<td>$-1$</td>
<td>$-1/2$</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>$e^-_R$</td>
<td>$\mu^-_R$</td>
<td>$\tau^-_R$</td>
<td>$-1$</td>
<td>0</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Additionally to color, quarks differ from leptons by having non-integer electric charge. The absence of color in the leptonic sector is the reason why leptons do not partake in the strong interaction, and thus are observable in unbound states. Quantum chromodynamics (QCD) disallows colored final states by introducing the so called confinement. Whenever any given number of quarks is separated (e.g., a proton is broken up), the field energy of the strong
interaction increases until there is enough energy to create quark-antiquark pairs. This process continues until all quarks are bound in color-neutral states (hadronization), which are called hadrons and can consist of either a quark and an antiquark or three (anti)quarks. The former are called mesons (e.g., $\pi^+ = u \bar{d}$ or $K^- = \bar{u}s$) and the latter baryons (e.g., $p = uud$ or $\Omega^- = sss$).

As mentioned, particles from generations two and three are unstable and decay into other quarks including those from different families. This presents another difference between leptons and quarks, namely the conservation of family number during these decays. In the standard model, family number is strictly conserved for leptons, while the mass eigenstates of quarks are mixed by the Cabibbo-Kobayashi-Maskawa-matrix \[12, 13\] to form the weak eigenstates (see Equation 2.1). Globally, the number of both, leptons and quarks, is conserved during any interaction ($V_{\text{CKM}}^\dagger V_{\text{CKM}} = \mathbb{1}_3$).

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

A similar mixing of leptons in the neutrino sector is observed in various experiments through neutrino oscillation. This mechanism and its implications are discussed below.

### 2.2 Lepton Flavor Violation

Observations of the solar neutrino flux showed discrepancies from predictions made by the generally accepted model of the sun. A significantly lower flux was measured than anticipated \[14\]. In later years, several other experiments confirmed this deficit \[15–17\]. One possible explanation of this result is neutrino oscillation: an electron neutrino changes its flavor during flight. This oscillation implies a mixing in the leptonic sector similar to that of quarks, and has been proposed by S. Bilenky and B. Pontecorvo \[18\]. Such mixing requires massive neutrinos however, and the appropriate mixing matrix is shown in Equation 2.2. It is called Pontecorvo-Maki-Nakagawa-Sakata-matrix \[19\].
2. Theoretical Foundation

Figure 2.2: Feynman diagrams of $\mu \rightarrow e\gamma$ (left) and $\mu \rightarrow 3e$ (right).

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu_1} & U_{\mu_2} & U_{\mu_3} \\ U_{\tau_1} & U_{\tau_2} & U_{\tau_3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$ (2.2)

This matrix mixes the mass eigenstates of neutrinos and returns their flavor eigenstates. The first direct evidence of neutrino oscillation was found by the Sudbury Neutrino Observatory in the year 2002 [8]. Since then, various experiments have confirmed the oscillation of neutrinos of different flavors, and although neutrino masses have not been measured so far, mass differences of the three mass eigenstates have been shown to be finite [11].

If neutrino oscillation is taken into account, lepton number is no longer conserved for individual families and thus, many new decay modes become possible. Examples for decays accessible to low-energy experiments are $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ (see Figure 2.2) and $\tau \rightarrow \mu\gamma$. Due to the tiny mass ratio of the neutrino and the vector boson $W^\pm$, such decays are heavily suppressed [20].

At higher energies where the $Z$ boson becomes more important for neutral current interactions, another decay is possible: the decay of a $Z$ boson to two leptons of different flavor (see Figure 2.3). Again, the branching ratios of these decays are predicted to be undetectable by any experiment (e.g., $B(Z \rightarrow e\mu) \approx B(Z \rightarrow e\tau) < 4 \cdot 10^{-6}$ [1]). The observation of such a decay would hence be a clear sign of new physics (e.g., [21–24]), and to that end, searches for Lepton Flavor Violating $Z$ decays were performed by the four LEP$^1$ experiments in electron-positron collisions. The results are limits set on the branching ratio at 95% confidence level [25, 26]:

- $B(Z \rightarrow e\mu) < 1.7 \cdot 10^{-6}$
- $B(Z \rightarrow e\tau) < 1.2 \cdot 10^{-5}$
- $B(Z \rightarrow e\mu) < 9.8 \cdot 10^{-6}$

While LEP was built to produce $Z$ and $W$ bosons, the large luminosity and center-of-mass energy at the LHC provide a significantly higher amount of such events. Coupled with the good identification of leptons, a competitive measurement is expected. Therefore, in this thesis, the decay $Z \rightarrow e\mu$ is investigated using the CMS detector.

\(^1\)Large Electron Positron collider
2.2. Lepton Flavor Violation

Figure 2.3: Four possible Feynman diagrams of the decays $Z \rightarrow \ell_1 \ell_2$ taken from [1], where the complete set can be found.
Chapter 3

Experimental Setup

The measurement performed in this thesis uses data delivered by the *Large Hadron Collider* (LHC), and recorded by the *Compact Muon Solenoid* (CMS). Both, the collider and the detector, are described in the following sections.

3.1 The Large Hadron Collider

The *Large Hadron Collider* (Fig. 3.1), which was constructed in a tunnel of roughly 27 km circumference and about 100 m below the surface, is located at CERN\(^1\) and accelerates hadrons to very high energies. While the LHC is also used to collide protons with lead, and lead with lead, the main focus lies on proton-proton collisions. Designed with a nominal beam energy of 7 TeV and a rate of one bunch crossing every 25 ns \([27]\), the LHC ran with 3.5 TeV and 4 TeV in the years 2011 and 2012, respectively, and a bunch spacing of 50 ns.

![Figure 3.1: A schematic illustration of the LHC, its pre-accelerators and experiments related to CERN and the LHC. The picture is taken from [28].](image)

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\(^{1}\)Conseil Européen pour la Recherche Nucléaire (European Council for Nuclear Research)
3. Experimental Setup

Protons are injected from a bottle of hydrogen gas into a series of pre-accelerators consisting of a linear accelerator (LINAC<sup>2</sup>) and three synchrotrons (PSB<sup>3</sup>, PS<sup>4</sup> and SPS<sup>5</sup>), receiving an increase in kinetic energy of 450 GeV before being injected into the main ring, the LHC. During the pre-acceleration, bunches of 10<sup>11</sup> protons are created and the LHC is filled with one bunch every 50 ns amounting to an average of 1374 bunches per fill [29] (design values are 25 ns and 2808 bunches [27]). With this setup, an instantaneous luminosity of 7 · 10<sup>33</sup> cm<sup>-2</sup> s<sup>-1</sup> was reached during 2012 (see Figure 3.2), already coming close to the design value of \( \mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \).

The two beams are kept in orbit by a large number of different magnets. The most powerful magnets are the 1232 dipoles with a peak magnetic field of 8.33 T, operating at a temperature of 1.9 K. Magnets of higher order focus the beams and direct them to the four collision points, where the main experiments

- ALICE [31] - A Large Ion Collider Experiment
- ATLAS [32] - A Large Toroidal LHC Apparatus
- CMS [33] - Compact Muon Solenoid
- LHCb [34] - Large Hadron Collider beauty

are located. While ATLAS and CMS are multi-purpose detectors built for a variety of physics analyses, ALICE and LHCb specialize in heavy ion collisions and B-meson physics, respectively. Furthermore, there are two experiments located around the collision points of ATLAS and CMS called LHCf<sup>6</sup> [35] and TOTEM<sup>7</sup> [36]. The former experiment measures particles in...
the very forward direction of the beam in order to calibrate hadronization models used for the investigation of extremely high-energetic cosmic rays, while the latter tries to measure the total cross section of proton-proton collisions.

The goal of the LHC physics program is to explore physics at the tera-scale where many theories predict new particles. One of the main objectives is the discovery or exclusion of the Higgs boson. Although this objective might be nearing completion in light of the recent discovery of a spinless boson mentioned in Section 2.1, there are still many interesting analyses possible with the 25 fb$^{-1}$ of data collected so far. After the current long shutdown, the LHC will start up in 2015 with a center-of-mass energy close to its design value of 14 TeV.

3.2 The Compact Muon Solenoid

The COMPACT MUON SOLENOID (Fig. 3.3) is one of the two large multi-purpose detectors. Since this analysis makes use of the CMS detector, a description of it is given in this section. Figures and facts concerning the detector are all taken from its description in [33] and its technical design report [37], except where stated otherwise.

With a length of 21.6 m, a diameter of 14.6 m and a weight of 14 000 t (see [39]) the detector is relatively heavy compared to, e.g., the ATLAS detector (44 m length, 25 m diameter and 7000 t weight [32]). Additionally, very little space is left between the different components and thus, the attribute compact was chosen. Advantages of this architecture are a large coverage of the 4$\pi$ solid angle and the maximal exploitation of the magnetic field for momentum and charge measurements of charged particles.
In order to meet the goals of the LHC physics program, the CMS Collaboration focused on excellent muon reconstruction. The fact that muons are minimum-ionizing particles and hence are able to traverse the whole detector without losing significant amounts of energy in the calorimeters allows for good discrimination against other particles. A dedicated muon system and the tracker accomplish this objective justifying the use of muon in the detectors’ name.

The measurement of charged particles’ transverse momenta requires a magnetic field bending their trajectories. Moreover, the charge of any particle is measured by analyzing the bending. In case of high energetic particles, this measurement can become ambiguous and a very large field is needed. CMS employs a solenoid designed to reach a magnetic field of up to 4 T, enabling it to identify a particles’ charge up to a TeV.

The detector is oriented such that its center coincides with the nominal interaction point. The coordinate system is defined as follows: the \( x \) axis points towards the center of the LHC, the \( y \) axis towards the surface and thus, the \( z \) axis along the beam pipe. The azimuth angle \( \phi \) in spherical coordinates is defined in the \( x − y \) plane and the polar angle \( \theta \) as zero in the positive and \( \pi \) in the negative \( z \) direction. Since \( \theta \) is not Lorentz-invariant, instead the quantity \( \eta \) defined as

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

is commonly used. It is referred to as pseudorapidity and is in good approximation Lorentz-invariant for particles with high energies or negligible masses.

CMS is made up of two detector regions, the barrel and endcap region. These cover different solid angles. The central region (\( |\eta| < 1.48 \)) is covered by subdetectors in a cylindrical layout. The innermost component is the tracker consisting of a silicon pixel and a silicon strip detector responsible for the reconstruction of charged tracks. The tracker is followed by the electromagnetic and hadronic calorimeters, which are designed to stop particles emerging from the collision and measure their energy deposition. The solenoid is placed around the aforementioned subsystems, and surrounding the magnet, there are four layers of muon chambers embedded into an iron return yoke. The fact that the calorimeters are placed inside the solenoid results in less scattering and thus, a better energy resolution. The endcap region (\( 1.48 < |\eta| < 3.0 \)) has essentially the same configuration with the exception of the solenoid, which only encompasses tracker and calorimeters in the barrel region. In order to obtain an even higher geometrical acceptance, forward calorimeters are installed next to the endcaps yielding a coverage of jets up to \( |\eta| < 5.2 \).

This analysis makes use of the tracker, both calorimeters, the magnet and the muon system in both barrel and endcap. Therefore, a more detailed description of these components is given in Section 3.2.1.

### 3.2.1 The Silicon Tracker

New physics is mostly expected to present itself in decays to fermions of the third generation, namely the tau lepton and the top quark. While the top quark decays to a W boson and a bottom quark very quickly, the tau lepton features several decay modes ranging from decays to one charged particle and one (two in case of leptons) neutrino (“1-prong”) to ones with three or even five charged hadrons and a neutrino (“3-prong” and “5-prong”). Both modes may be accompanied by multiple neutral hadrons. To access both, the top and the tau, the decay vertices of tau and hadrons from the top decay (designated secondary vertices)
3.2. The Compact Muon Solenoid

Figure 3.4: An illustration of the CMS pixel tracker [37].

need to be reconstructed precisely. Other challenges to the tracking system arise from the extremely high radiation exposure caused by around 100 particles per vertex penetrating the detector simultaneously every 25 ns at the design luminosity of $\mathcal{L} = 10^{34} \text{cm}^{-2} \text{s}^{-1}$. The CMS collaboration chose to build a tracker based solely on silicon technology to overcome these challenges. To minimize the damaging effects of radiation and the self heating of silicon, the whole tracker is operated at $-10^\circ\text{C}$. The expected degradation of the tracker after 10 years of operation will require the operation temperature to be reduced to $-27^\circ\text{C}$, needing its material to withstand temperature differences ranging from $30^\circ\text{C}$ to about $60^\circ\text{C}$. The innermost layer is expected to survive two years at design luminosity, at which point it will have to be replaced.

In the barrel, three layers of silicon pixel modules were implemented parallel to the beam with an area of $100 \times 150 \mu\text{m}^2$ per pixel. The first layer is secured 4.4 cm away from the interaction point, the subsequent layers are located at radii of 7.3 cm and 10.2 cm. All layers have a length of 53 cm each, and host a total of 48 million silicon pixels corresponding to an active area of 0.78 m$^2$. Those three layers are supplemented by two disks orthogonal to the beam on both sides of the tracker ($z = \pm 34.5 \text{ cm}$ and $z = \pm 46.5 \text{ cm}$) with 18 million channels in total, and an active area of 0.28 m$^2$ (see Figure 3.4). The geometrical acceptance of the pixel tracker is limited by $|\eta| < 2.5$.

Following the pixel tracker is the silicon strip tracker consisting of three different types in the barrel. The tracker inner barrel (TIB) extends from $r = 20 \text{ cm}$ up to 55 cm in the form of four layers of silicon strip modules. The strips are aligned parallel to the beam axis. The TIB is assisted by three disks with their strips oriented radially to the beam axis called tracker inner disks (TID). The TIB/TID system is enclosed in the tracker outer barrel (TOB) composed of six layers of the same modules as employed by the TIB, and extends up to a radius of 116 cm. The tracker system in the barrel has a length of 336 cm in total. Further silicon strip modules
are installed on disks in the region $124 \text{ cm} < |z| < 282 \text{ cm}$. The composition of 18 of these disks (nine in each $z$ direction) is called tracker endcaps (TEC), enabling a coverage with nine hits in $|\eta|$ up to 2.4 (see Figure 3.5). The first two layers and disks of the TIB/TOB and TID/TEC, respectively, are each equipped with two silicon strip modules back-to-back with an angle of 100 mrad yielding an additional measurement of either the $z$ coordinate in the barrel layers or the $r$ coordinate in the disks. The whole strip tracker is comprised of 9.3 million strips built on 15 148 moduls resulting in an active area of 198 m$^2$.

The resulting single point resolution of the whole tracker system ranges from $15 - 20 \mu m$ for the pixel detector to $35 - 53 \mu m$ for the TOB, and $230 \mu m$ and $530 \mu m$ for the $z$ coordinate in the TIB and TOB, respectively, yielding an expected primary vertex resolution of $10 - 50 \mu m$.

### 3.2.2 The Calorimeters

The calorimeter system of the CMS detector consists of two major parts: the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). While the ECAL is supposed to completely stop any particles interacting electromagnetically and measure their energy, the HCAL quantifies the energy of strongly interacting particles such as pions or neutrons.

#### The Electromagnetic Calorimeter

75 848 lead tungstate (PbWO$_4$) crystals were assembled to form the ECAL – 61 200 for the barrel region and 7324 for each of the endcaps. The system is extended by a preshower detector mounted on the ECAL endcaps (EE) responsible for a better discrimination of neutral pions. A region of $1.653 < |\eta| < 2.6$ is instrumented by the preshower detector, while the whole ECAL system covers $|\eta|$ up to a value of 3.0. The ECAL barrel (EB) extends radially from 129 cm to 177 cm, and the whole ECAL up to 315.4 cm in $z$ direction.

The high density of the PbWO$_4$ crystals (8.28 g/cm$^3$) entails a short radiation length (0.89 cm) and a small Molière radius (2.2 cm). The radiation length $X_0$ is defined as the distance needed for an electron to be decelerated to a fraction $1/e$ of its initial kinetic energy. This obviously

![Figure 3.5: A schematic of the CMS tracker system [33].](image)
depends heavily on the material in question. The Molière radius is defined by

$$R_M = \sqrt{\frac{4\pi}{\alpha} m_e^2 \frac{X_0}{E_C}} \approx 21 \text{ MeV} \frac{X_0}{E_C}, \quad (3.1)$$

where $E_C$ is the energy at which the electron’s energy equals its energy loss through ionization per radiation length. Within a cylinder of radius $R_M$ around the particles’ track an average of 90% of its energy is deposited [11]. Besides the fine stopping power of the ECAL crystals they provide another feature: they are scintillators with a decay time comparable to that of the design bunch crossing rate of 25 ns. At an operating temperature of 18 °C this yields 4.5 photoelectrons per MeV deposited energy. The output is amplified and read out by avalanche photo diodes (APDs) in the barrel region, and by vacuum phototriodes (VPTs) in the endcap region. VPTs are photomultipliers with only one gain stage and a copper mesh anode with 10 µm pitch enabling operation even within extremely large magnetic fields, while APDs are intrinsically resistant to magnetic fields as they are made from silicon. One VPT is mounted on each endcap crystal having an active area of roughly 280 mm$^2$, and two APDs are glued to each crystal in the barrel amounting to an active area of $2 \times 5 \times 5$ mm$^2$ (see Figure 3.6).

The crystals themselves are built such that their cross section is quadratic with dimensions at their side facing the center of the detector of $22 \times 22$ mm$^2$ and $28.62 \times 28.62$ mm$^2$ in the barrel and endcaps, respectively. The backside mounted to the readout has a surface of $26 \times 26$ mm$^2$ and $30 \times 30$ mm$^2$, respectively. The ECAL in the barrel hence features a slightly better granularity, and at the same time a better stopping power compared to the ECAL endcaps owing to a small difference in crystal length (230 mm compared to 220 mm).

The preshower detector is built as a sampling calorimeter comprised of two layers of lead radiators and two layers of silicon strip detectors with their strips oriented orthogonally with respect to each other. In total, the system is 20 cm thick with the first layer of lead corresponding to $2 X_0$, and the second to $1 X_0$. Differences in shower shapes from photons and neutral pions allow the discrimination between the two through the use of this detector component.

The energy resolution of the ECAL is driven by three parameters. The first is a stochastic term arising mainly from the fact that photons are counted individually at the back of each crystal and is inversely proportional to $\sqrt{E}$. $E$ denotes the energy of the particle. The second term
3. Experimental Setup

is related to the noise created by electronics and multiple interactions in a bunch crossing. It is inversely proportional to the energy. The third term is a constant including effects from intercalibration, energy leakage at the back of the crystals, and the crystals’ longitudinal uniformity. The impact of these three parameters on the energy resolution has been studied using electron beams with energies ranging from 20 – 250 GeV. The result was a typical resolution of

\[
\left( \frac{\sigma}{E} \right)^2 = \left( \frac{2.8\%}{\sqrt{E}} \right)^2 + \left( \frac{0.12\%}{E} \right)^2 + (0.30\%)^2 \quad (E \text{ in GeV}), \quad (3.2)
\]

where \( E \) is reconstructed summing up the energy of 3 \( \times \) 3 crystals. The testing further revealed a total energy resolution of 0.45\% for electrons with an energy of 120 GeV reconstructed with 3 \( \times \) 3 or 5 \( \times \) 5 crystals.

The Hadronic Calorimeter

The HCAL is separated into four subdetectors constructed as sampling calorimeters. The barrel region is instrumented by the HCAL barrel (HB), which is located between solenoid and ECAL as well as by HCAL outer barrel (HO) outside of the magnet, which acts as a tail-catcher of hadrons with large enough energies to punch through HB and solenoid. Both, HB and HO cover a region up to |\( \eta \)| < 1.3. Between 1.3 < |\( \eta \)| < 3.0, the HCAL endcaps (HE) measure and stop hadrons. To increase coverage even further to |\( \eta \)| < 5.2, the HCAL forward (HF) is placed 11.2 m from the detectors’ center along the beam pipe. A large coverage of the HCAL is necessary in order to minimize the amount of particles lost to the detector and thus increases the resolution of missing energy due to neutrinos leaving CMS undetected.

The HB is constructed from 36 wedges (Fig. 3.7) composed of 14 brass plates (70% Cu, 30% Zn) lined with plastic scintillators. Each of these wedges is fixed between two steel plates giving an absorber thickness of 5.82 interaction lengths (\( \lambda \), analogous to \( X_0 \)) at \( \theta = \pi/2 \), increasing with \( 1/\sin(\theta) \) to 10.6 \( \lambda \) at \( \eta = 1.3 \). Another 1.1 \( \lambda \) originating from the ECAL have to be considered as well. The plastic scintillators are read out by hybrid photo diodes (HPDs) connected to them with wavelength shifting fibres. In total, there are 17 scintillator tiles built into one HCAL wedge.

![Figure 3.7: A picture of the HCAL wedges [33].](image)

The HE employs the same technique of sampling calorimetry as the HB. However, instead of being a composition of several smaller constructs, it is produced as a monolithic structure. Again, the front and back plates are made from steel but the brass plates are bolted together
leaving space for the insertion of the scintillator tiles (see Figure 3.8). The absorber thickness amounts to an average of 10.5 $\lambda$ not including the ECAL [40].

The granularity of the HCAL varies from $0.087 \times 0.087$ for $|\eta| < 1.6$ to $0.17 \times 0.17$ for $|\eta| \geq 1.6$ in the $\eta - \phi$ plane. Subjecting the calorimeter to testbeams of electrons, protons, pions and muons, it was concluded that an energy resolution of

$$\left( \frac{\sigma}{E} \right)^2 = \left( \frac{100\%}{E} \right)^2 + (4.5\%)^2 \quad (E \text{ in GeV})$$

(3.3)

is possible for energies between 30 GeV and 1 TeV [40].

The HF is situated in the harshest environment of the detector where it is hit by about $10^6$ particles per cm$^2$ and second, reaching roughly 10 MGy of deposited energy after 10 years of operation. Since the design goal was the survival of the detector for at least a decade, steel was chosen as absorber material. Steel plates of 5 mm thickness were grooved to house the active material: quartz fibres. Those fibres react to Cherenkov light and thus limit the detection capability of the HF to charged particles. The fibres are read out by photomultipliers (PMTs) shielded by a combination of 42.5 cm steel, lead and polyethylene. This calorimeter is one of the main sources of information for luminosity measurements performed by CMS.

A schematic view of the HCAL system within the CMS detector is depicted in Figure 3.9.
3.2.3 The Solenoid

One design goal of CMS was the unambiguous measurement of the muon-charge up to transverse momenta of 1 TeV. To meet this requirement, a solenoid capable of producing a magnetic field of up to 4 T was constructed. This solenoid is 12.5 m long and 6.3 m in diameter weighing 220 t. The coil is made of a four-layer winding of superconducting NbTi amounting to an inductance of 14.2 H. The superconductor operates at a temperature of 4.6 K and stores 2.6 GJ which is equivalent to an energy density of 11.6 kJ/kg. The nominal current during operation is 19.14 kA. An artistic drawing of the coil is shown in Figure 3.10. The return yoke of the magnet is constructed from iron and constitutes 71% of the detectors’ mass with a weight of 10 000 t. The yoke itself consists of five barrel wheels and six endcap disks, which are each able to host up to four muon detector components described in Section 3.2.4.

Figure 3.10: An illustration of the CMS solenoid [33].

3.2.4 The Muon System

The measurement of muons is a key aspect of the CMS detector demanding a dedicated system yielding excellent resolution and efficiency. To satisfy the design goals, three gas-based detector types were developed: the Drift Tube chambers (DTs), Cathode Strip Chambers (CSCs), and Resistive Plate Chambers (RPCs). In the barrel region, DTs are used in conjunction with RPCs to increase time resolution while the endcaps are instrumented with CSCs, again supplemented with RPCs (see Figure 3.11).

The DT chambers are composed of many individual cells. Each cell contains a gold-plated stainless-steel wire with a diameter of 50 µm serving as the anode. Field electrodes are glued to top and bottom, and cathode strips to both sides of a cell. Both electrodes and cathodes are made of 50 µm thick aluminium and connected to voltages of +1.8 kV and −1.2 kV, respectively. A voltage of +3.6 kV is applied to the anode and the cell is filled with a gas mixture of 85% argon and 15% carbon dioxide. Several of these cells are combined to layers. Four layers describe a superlayer, and one DT chamber is made up of either two or three superlayers. Each barrel wheel is supplied with four DT chambers from inside to outside, one between solenoid and return yoke, two within, and one outside of the yoke. Completing one revolution, this results in a total of 250 DT chambers. It should be noted that the distance between anode and cathodes is relatively large (21 mm, see Figure 3.12), which implies a relatively poor time resolution. However, both, the expected rate of particles entering the muon system, as well as the magnetic field strength are relatively low, making this still a viable option.
The endcaps are equipped with 468 trapezoidal CSCs covering a range of up to $|\eta| < 2.4$. In principle, CSCs are multiwire proportional chambers that consist of six anode wire planes between seven cathode planes. The wires run along $\phi$ and are thus a representation of the radial coordinate (see Figure 3.12). Here, copper of 36 $\mu$m thickness is used for the cathode planes and 50 $\mu$m thick gold-plated tungsten wires represent the anodes. The gas mixture introduced into this system is a combination of 40% argon, 50% carbon dioxide and 10% fluorine. The operation voltage lies at 3.6 kV for all of the modules except the ones attached to the HCAL endcaps. The CSCs mounted here have slightly different design parameters requiring a lower operation voltage of 2.9 kV. The gap between the cathodes is of the order of mm and thus much smaller than the ones in the DTs, yielding a better time resolution.
The RPCs are made of two bakelite plates (each 2 mm thick) kept at a distance of 2 mm with read-out strips between them (see Figure 3.12). The gap is then filled with a gas mixture of 96.2% $\text{C}_2\text{H}_2\text{F}_4$, 3.5% $\text{C}_4\text{H}_{10}$ and 0.3% $\text{SF}_6$, and a high voltage of up to 12 kV is applied. The short distance between the two bakelite plates yields a very good time resolution of a few nanoseconds making them an ideal candidate for triggering, and for that very reason 480 RPCs were installed in the barrel and 3 large RPC stations in each of the endcaps complementing the DT chambers and CSCs, respectively. However, unlike the CSCs, the RPC stations in the endcap regions only supply a coverage of $|\eta| < 1.6$.

### 3.2.5 The Trigger System

The extremely high rate of bunch crossings (40 MHz at design parameters) and the number of collisions per crossing (roughly 20) result in huge amounts of data that cannot be saved due to lack of storage capacity and, more prominently, insufficient time. In order to reduce the rate of events saved to permanent storage devices, a trigger system was devised that consists of two stages.

The Level-1 trigger (L1) is a hardware trigger that receives information from the calorimeters and the muon chambers. The information obtained is used to determine trigger objects such as muons, electrons or jets. The trigger objects are then ranked by energy or momentum and the confidence in these parameters, and passed to the third stage of the Level-1 trigger, which takes into account the status of all detector components and the data acquisition. Each event is buffered for 3.2 $\mu$s after which it is discarded or forwarded to the High-Level trigger. This process reduces the rate of data to 100 kHz which is still too large to be stored by a factor of roughly 25.

Events selected by the Level-1 trigger are sent to the second stage, a farm of approximately a thousand commercial processing units called High-Level trigger (HLT). This system has access to the full detector information, as well as more time to process it, and can therefore employ much more sophisticated algorithms to reduce the rate to levels manageable by modern recording technology. In order to perform its task as quickly as possible, a sequential filter is applied that is able to reject events after each of its many steps. In case of an electron, the calorimeter clusters are reconstructed and matched to a particle track, which itself is a matching of pixel and strip hits in the tracker. Each of these steps is able to discard a sizeable fraction of events passing the previous ones. There are many different “HLT-menus” suited to the needs of common physics analyses. Events passing the HLT are written to storage devices at a rate of about 400 Hz with a size of not more than 1 MB per event [11].
Chapter 4

Data and Simulated Data

The estimation of backgrounds and signals in high energy physics experiments is usually done using simulation techniques. This chapter describes how the output of the CMS detector is emulated for simulated data and how the output of both data and simulation is used to create a collection of physics objects. Moreover, the (simulated) data samples are listed and the production of the simulated signal sample is explained.

4.1 Data Simulation

The data simulated for a certain process need to have the same format as events actually recorded by the detector to make sure that the subsequent reconstruction (see Section 4.2) is done consistently in both cases. Multiple steps are taken in order to produce such events.

Event generation: The first step is the generation of the hard interaction, which is modeled by quantum electro– and chromodynamics, and is referred to as the GEN-step. There is a variety of different tools available for this purpose (e.g., PYTHIA [42], MADGRAPH [43] or POWHEG [44–46]). These tools are commonly referred to as Monte-Carlo generators, as they make use of the Monte-Carlo technique [47]. Data generated this way are therefore often called Monte-Carlo (MC) samples. Higher-order generators also take initial and final state radiation into account. The so called underlying event (UE) describes the proton remnants after the collision and is simulated together with the hadronization of initial and final state radiation by PYTHIA, for example. Other possibilities are the programs HERWIG [48] and SHERPA [49]. The decay of tau leptons is modeled using TAUOLA [50]. In each bunch crossing, many proton interactions occur and there is usually more than one collision that contributes to the particles recorded by the detector. This is called pileup, and it is emulated by adding a random number of simulated soft interactions distributed according to the expected mean number of interactions per bunch crossing.

Detector simulation and response: Once the particles are generated, their interaction with the detector environment is simulated using the software framework GEANT4 [51]. This step is called the SIM-step and it returns digitized data. In order to simulate the trigger response, the data needs to be converted back into the RAW format (DIGI2RAW) which corresponds to the detector output of real data. From here on out, the real and simulated data have the same format.

Trigger simulation: The Level-1 and High-Level trigger decisions are simulated next after which the dataformat is (re)digitized in the RAW2DIGI-step. Now, the reconstruction of the event can start. Treatment of real and simulated data is exactly the same.
4.2 Processing of the Detector Output

In order to obtain a collection of physics objects, different algorithms are applied to each event. These algorithms are developed by the so called Physics Object Groups (POGs) within the CMS Collaboration. There are separate algorithms for the reconstruction of muons, electrons and photons, as well as jets and missing transverse energy. To give the analyst as much freedom as possible, objects are usually reconstructed several times by different algorithms with varying requirements on efficiency and purity. While most reconstruction algorithms look for certain event topologies in the detector response and try to match them to a particle hypothesis, there is one algorithm that works differently. This algorithm uses information of the tracker, calorimeters and muon chambers, associates them to objects and examines these objects with respect to different particle hypotheses. The way this algorithm works has given it the name Particle-Flow algorithm. At this point, there is still the possibility of several object candidates being associated to the same detector hits. Although there is an option to resolve these ambiguities, it needs to be invoked by the analyst. This option is called top projection and works as follows: the analyst defines a list of objects ordered by importance to the respective analysis. Usually, muons are at the top of such a list. Following this example, the Particle-Flow algorithm takes the muon collection it has previously produced and removes all entries in the detector related to this collection. Particle Flow is executed again and object collections are compiled. Now, the entries from the second object on the analysts list are removed from the event and Particle Flow is run again. This cycle is repeated until an unambiguous collection of objects is available [52–54]. This analysis does not make use of the top projections. Instead, a manual cleaning of the objects of interest is done.

The event content after the reconstruction described above is called RECO and contains the complete output of the different reconstruction algorithms. A subset of this data needed by standard analyses reduces the amount of information to a level better manageable by the end user. This format is designated AOD (Analysis Object Data). This data is evaluated using the software framework ROOT [55], which specializes in the treatment of large amounts of data and supplies the user with a variety of easy-to-use functions frequently needed in high energy physics.

4.3 Data Samples

This analysis uses the full dataset of proton-proton collisions gathered by the CMS detector during 2012 at a center-of-mass energy of 8 TeV. The dataset is composed of four different runs adding up to a recorded integrated luminosity of $L_{\text{int}} = 21.79 \text{ fb}^{-1}$. The data sets used in this analysis are listed in Table 4.1. Only data-taking periods in which all detector components except the HO were working properly are selected, effectively reducing the amount of data available to the analysis together with the chosen trigger path to 19.8 $\text{fb}^{-1}$.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Run range</th>
</tr>
</thead>
<tbody>
<tr>
<td>MuEG/Run2012A-22Jan2013-v1/AOD</td>
<td>190456-193621</td>
</tr>
<tr>
<td>MuEG/Run2012B-22Jan2013-v1/AOD</td>
<td>193833-196531</td>
</tr>
<tr>
<td>MuEG/Run2012C-22Jan2013-v1/AOD</td>
<td>198022-203742</td>
</tr>
<tr>
<td>MuEG/Run2012D-22Jan2013-v1/AOD</td>
<td>203777-208686</td>
</tr>
</tbody>
</table>

Table 4.1: Data sets used.
4.4 Simulated Samples

4.4.1 Signal

The inclusive production cross section of Drell-Yan events and the current best upper limit on the branching ratio of $Z \to e\mu$ by the OPAL collaboration ($\sigma = 33.3 \text{ nb}$ for $60 < m_Z < 120 \text{ GeV}$ [11, 56] and $B (Z \to e\mu) < 1.7 \cdot 10^{-6}$ @95%CL [25], respectively) are used to estimate the number of signal events produced by the LHC. This yields an upper estimate of

$$N = L_{\text{int}} \cdot \sigma (pp \to ZX) \cdot B (Z \to e\mu) \approx 1128$$

(4.1)
events in the complete 2012 dataset.

A simulated data sample needs to be generated with a sufficient amount of events to get a handle on the behavior of the signal process. For this purpose, the event generator PYTHIA 6 is used in conjunction with the CMS software framework CMSSW [37]. However, Lepton Flavor Violating decays are not implemented in PYTHIA by default. One can solve this problem by introducing a new decay mode consisting of the desired final state, an electron and a muon. As this produces only one charge combination, $Z \to e^+\mu^-$ or $Z \to e^-\mu^+$, the event generation has to be carried out separately for both combinations. 100,000 signal events are produced in this manner – 50,000 of each charge combination. In order to check whether the custom simulation can be trusted, control plots are made. Figure 4.1(a) shows the simulated mass of the Z boson, while Figures 4.1(b) and 4.1(c) show the comparison of the transverse momentum and the pseudorapidity of the Z boson generated by MADGRAPH (official sample), and generated by PYTHIA (generated for this analysis) each normalized to 1.

Figure 4.1: Comparison of the PYTHIA (custom MC) and MADGRAPH (official MC) generator: mass (a), transverse momentum (b) and pseudorapidity (C) of the generated Z boson. All distributions are normalized to 1.

All distributions show some discrepancies between the two generators which is to be expected as PYTHIA is a leading-order and MADGRAPH a higher-order generator. The overall behavior, however, is reproduced satisfactory by the private simulation to use it. A systematic uncertainty depending on the different modeling of the transverse momentum is evaluated in Section 6.5, since this variable is essential to the selection in Section 5.5.3.
4. Data and Simulated Data

4.4.2 Background

All simulated data samples used for background estimation in this analysis are shown in Table 4.2. It should be noted that background coming from Drell-Yan events is modeled for an invariant dilepton mass larger than 50 GeV only. A more detailed description of each background, as well as a description of the data-driven method used to derive an estimate of contributions from QCD multijet and W(Z)+jets events, is given in Section 5.3.

Table 4.2: Simulated data samples used for background estimation. All of the samples listed were produced with CMSSW_5_3_X and the pileup scenario of the Summer 2012 campaign. The integrated luminosity is calculated using the cross section used for normalization and the generated number of events.

<table>
<thead>
<tr>
<th>Process</th>
<th>Sample Name</th>
<th>$\mathcal{L}_{\text{int}} / \text{fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>DYJetsToLL_M-50_TuneZ2Star_8TeV-madgraph-tarball</td>
<td>8.7</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>TT_CT10_TuneZ2star_8TeV-powheg-tauola</td>
<td>88.2</td>
</tr>
<tr>
<td>$tW$</td>
<td>T_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola</td>
<td>44.8</td>
</tr>
<tr>
<td>$\bar{t}W$</td>
<td>Tbar_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola</td>
<td>44.6</td>
</tr>
<tr>
<td>$WW \rightarrow 2\ell 2\nu$</td>
<td>WWJetsTo2L2Nu_TuneZ2star_8TeV-madgraph-tauola</td>
<td>260.7</td>
</tr>
<tr>
<td>$WZ \rightarrow 3\ell 1\nu$</td>
<td>WZTo3LNu_TuneZ2star_8TeV_pythia6_tauola</td>
<td>3683.1</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>ZZ_TuneZ2star_8TeV_pythia6_tauola</td>
<td>1166.7</td>
</tr>
</tbody>
</table>
Chapter 5

Event Reconstruction

This chapter describes the selection of events by the High-Level trigger, as well as the following offline object reconstruction and identification. Moreover, the background estimation and cut-based event selection is explained. A window around the nominal Z-boson mass (91.1876 GeV [11]) is blinded, meaning that data events within this window (83 – 98 GeV) are not available for study. This is done in order to prevent any possible bias due to the analyst. Only once systematic studies have been performed (Chapter 6), will the complete data be available.

5.1 Trigger Paths

Because of the nature of the desired final state, triggers requiring a muon and an electron are chosen. They are listed in Table 5.1 together with their L1 seeds where the paths delivering the bulk of the luminosity (main paths) are marked by an asterisk. The main HLT_Mu8_Ele17 path is seeded by the Level-1 triggers Mu3p5_EG12 or MuOpen_EG12. The former demands a muon with a transverse momentum greater than 3.5 GeV and an electron with $E_T$ larger than 12 GeV, the latter an electron with $E_T \geq 12$ GeV and any muon. There are no explicit requirements on either pseudorapidity or isolation of these objects. However, there are implicit $|\eta|$-restrictions by the detectors’ geometrical acceptance. The HLT then imposes additional criteria. In this case, the $p_T$ of the muon should be at least 8 GeV and the transverse energy of the electron at least 17 GeV. Furthermore, the identification of the electron reconstructed in the ECAL has to pass tight criteria, whereas isolation in the ECAL as well as the track identification and isolation are only subject to very loose requirements. The main HLT_Mu17_Ele8 path is seeded by the L1_Mu12_EG7 trigger, which involves one muon with $p_T \geq 12$ GeV and one electron with $E_T \geq 7$ GeV. Again, there are no explicit restrictions concerning $\eta$ or isolation. As before, the HLT imposes further constraints. The thresholds are increased to 17 GeV and 8 GeV, respectively, and the same identification and isolation requirements as for the HLT_Mu8_Ele17 path are used. In principle this choice of triggers allows for low $p_T$ and $E_T$ thresholds of muons and electrons, respectively. Features in some kinematic distributions of both leptons below 20 GeV were not understood completely. Therefore, a cut on both, $p_T$ of the muon and $E_T$ of the electron of 20 GeV is used to exclude these events.

Imperfect simulation and varying run conditions are expected to cause some discrepancies between selection and reconstruction efficiencies in data and Monte-Carlo simulation. To measure those discrepancies, a Tag&Probe method has been implemented by the $H \rightarrow \tau\tau$ working group [57]. For the muon leg, the tag muon is required to pass a single isolated muon trigger and both, tag and probe muon have to pass the ID requirements described in section 5.2.2. Furthermore, the analysed event needs to fulfill the $Z \rightarrow \mu\mu$ hypothesis within
Table 5.1: Triggers used in this analysis.

<table>
<thead>
<tr>
<th>HLT path</th>
<th>L1 seed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mu8 Ele17 CaloIdL</td>
<td>MuOpen EG12</td>
</tr>
<tr>
<td>Mu8 Ele17 CaloIdT CaloIsoVL</td>
<td>MuOpen EG12</td>
</tr>
<tr>
<td>*Mu8 Ele17 CaloIdT CaloIsoVL TrkIdVL TrkIsoVL</td>
<td>Mu3p5 EG12 OR MuOpen EG12</td>
</tr>
<tr>
<td>Mu17 Ele8 CaloIdL</td>
<td>Mu7 EG5</td>
</tr>
<tr>
<td>Mu17 Ele8 CaloIdT CaloIsoVL</td>
<td>Mu12 EG5</td>
</tr>
<tr>
<td>*Mu17 Ele8 CaloIdT CaloIsoVL TrkIdVL TrkIsoVL</td>
<td>Mu12 EG7</td>
</tr>
</tbody>
</table>

a mass window of 60 – 120 GeV. This is measured in both data and simulated events. The ratio of both efficiencies as a function of transverse momentum and pseudorapidity is placed as an event weight on the simulation. The electron leg is measured analogously. The event weights of both trigger legs were measured in Z → ττ events by the CMS H → ττ working group, and are applied to the distributions throughout this document. A typical scale factor for the muon leg is 0.970, corresponding to trigger efficiencies of 0.932 in data and 0.961 in simulation. For the electron leg, efficiencies of 0.903 in data and 0.928 in simulation give a typical scale factor of 0.973.

5.2 Object Reconstruction and Identification

5.2.1 Vertex Selection

During each bunch crossing, many collisions occur (pileup) and one has to find the vertex which has produced the signal objects. A vertex should not be located farther than ±24 cm away from the center of the detector in z direction to still be inside the barrel pixel tracker. Additionally, its transverse displacement must be less than 2 cm (must be within the beam pipe), and the vertex should have tracks associated to it with proper fit parameters ($\chi^2 \neq 0$ & ndof $\neq 0$). Moreover, the number of degrees of freedom of the vertex fit is required to be greater than 4. The vertex with highest sum of squared track-$p_T$ passing all these requirements is chosen as the primary vertex of the event.

To correct the number of pileup vertices in simulation, an event-based reweighting of the simulation is done. This reweighting procedure is seeded by the distribution of the number of reconstructed vertices in simulation and measurements in data using minimum-bias events. The distribution of the number of reconstructed primary vertices is depicted in Figure 5.1 and shows good agreement within uncertainties. Here, and in the following distributions, backgrounds modeled by simulation are scaled according to the integrated luminosity and their respective cross sections. Electroweak backgrounds are WW → 2ℓ2ν, WZ → 3ℓ1ν, ZZ and Z → ee/µµ.

5.2.2 Muons

Muon reconstruction

Muons are minimum-ionizing particles (MIPs) and thus able to pass the calorimeters, which are followed by a dedicated muon system. A muon can be reconstructed in three different ways: as stand-alone, global or tracker muon. Stand-alone muons are reconstructed in

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1Events recorded with very loose trigger requirements
the muon system only, while the other two are reconstructed using information from both, tracker and muon stations. The outside-in approach (global muon) is seeded by the muon chamber hits and associates them to a track measured by the tracker using a fit. The inside-out approach uses the information of the tracker to extrapolate the track to the muon system. Multiple scattering and energy loss are taken into account. If the extrapolated track matches at least one hit in the muon stations, it is classified as a tracker muon [58].

**Muon identification**

Muons in this analysis have to be reconstructed both by the global-muon fit with a \( \chi^2 / ndof < 10 \) and at least one hit in the muon system, and by the Particle-Flow algorithm (see Section 4.2). Additionally, at least two muon chamber segments have to be matched to the muon track and there have to be at least one pixel and six tracker-layer hits. Furthermore, requirements on the transverse and longitudinal impact parameters of the muon candidate are imposed as \( d_{xy} < 0.2 \text{ cm} \) and \( d_z < 0.5 \text{ cm} \), respectively. All these requirements are comprised in the so called tight identification (ID) [58]. Any muon passing the tight ID also has to have a transverse momentum greater than 20 GeV, and a pseudorapidity \( |\eta| < 2.1 \). Moreover, the recommended values of the impact parameters have been tightened to 0.02 cm and 0.2 cm, respectively, to match the muon identification of the CMS H \( \rightarrow \tau\tau \) working group [57]. Restricting the pseudorapidity and tightening the requirements on the impact parameters is necessary to apply the data-driven estimation of W(Z)+jets and QCD multijet events as explained in Section 5.3.1. Finally, the muon should be isolated to reduce contamination from leptonic quark decays. The relative isolation is defined as

\[
I_{rel} = \frac{\sum p_T \text{ (charged)} + \max (\sum E_T \text{ (neutral)} + \sum E_T \text{ (photon)} - \Delta \beta, 0)}{p_T (\mu)}, \tag{5.1}
\]

where \( p_T \) (charged) corresponds to the transverse momentum of any charged particle, \( E_T \) (neutral/photon) to the transverse energy of any neutral particle or photon, and \( \Delta \beta \) to the estimated neutral energy from pileup, all in an isolation cone of \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4 \). The \( \Delta \beta \) correction is calculated by removing the energy of all charged particles within the
Table 5.2: MVA ID requirements on electrons.

<table>
<thead>
<tr>
<th>$\eta$ range</th>
<th>MVA discriminator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$0.8 \leq</td>
<td>\eta</td>
</tr>
<tr>
<td>$1.479 \leq</td>
<td>\eta</td>
</tr>
</tbody>
</table>

isolation cone not associated to the primary vertex and multiplying this number by 0.5 [59]. As discriminants, $I_{rel} < 0.15$ ($0.10$) for $|\eta| < 1.479$ ($\geq 1.479$) are chosen. Should more than one muon pass the identification, the one with the highest transverse momentum is selected as the signal candidate.

5.2.3 Electrons

Electron reconstruction

The reconstruction of electrons employs two detector components: the ECAL and the tracker. In cases where the electron is low energetic, the reconstruction is seeded by the tracker. Since this analysis uses electrons coming from Z-boson decays, the more relevant reconstruction technique is the one seeded by so-called superclusters in the ECAL. Adjacent crystals measuring energy deposits above a certain threshold ($E_T \geq 1$ GeV) form a cluster, and adjacent clusters form a supercluster. Due to bremsstrahlung caused by the magnetic field, energy in a range of $\Delta \phi = \pm 0.3$ rad around the start cluster is summed up. The weighted mean position of the supercluster is then used to extrapolate a track back to the pixel detector incorporating both charge hypotheses, looking for a pixel hit in the first barrel layer with loose requirements on $\Delta \phi$ and $\Delta z$. Once such a hit is found, a second pixel hit is sought with more stringent requirements on longitudinal and azimuthal location. These two pixel hits are used to seed the track fit [37]. A special track fit is employed to account for effects of bremsstrahlung and multiple scattering. This fit is called Gaussian-sum filter and electrons reconstructed this way GsfElectrons [60].

Electron identification

Electrons are required to be reconstructed as GsfElectrons and have to fulfill $E_T > 20$ GeV, as well as $|\eta| < 2.3$. To identify electrons, the loose multivariate analysis (MVA) ID based on a boosted decision tree (BDT) by the EGamma POG is chosen [61]. To train the BDT and calculate the MVA output, a total of 19 different variables are used. These variables are related to the track fit, ECAL shower shapes, geometry and energy-matching. The requirements on the MVA discriminator depending on pseudorapidity are listed in Table 5.2. The isolation is calculated analogously to Equation 5.1 but using $\rho$ instead of $\Delta \beta$ corrections. These corrections consist of average transverse momenta per unit area $\rho$ that are expected from pileup [62]. The thresholds are identical to those of the muon. Only isolated electrons with a $\Delta R > 0.2$ with respect to the previously selected muon are evaluated. Should more than one electron pass these requirements, again the one with the highest $p_T$ is chosen.

Lepton ID and Isolation Efficiency

As described in Section 5.1, imperfections of the simulation can cause differences between data and simulated events. This also holds for the identification of leptons. These ID and isolation efficiencies have been measured by the $H \rightarrow \tau \tau$ working group [57] using $Z \rightarrow \ell \ell$ events and checking dependencies of the efficiencies as functions of $p_T$, $\eta$ and the number
of reconstructed primary vertices. The scale factors obtained by the H → ττ working group are applied to all distributions in this analysis. Typical efficiencies for muons are 0.804 in MC and 0.789 in data, resulting in a scale factor of 0.981. The corresponding values for electrons are 0.613, 0.534 and 0.871, respectively.

The kinematic variables of the selected electron and muon, \( p_T \) and \( \eta \), are checked for consistency between data and simulation. Figure 5.2 shows these distributions. While in case of the muon the agreement is good, the pseudorapidity of the electron shows a significant deviation of data from the background estimate in regions where \( |\eta| > 1.5 \). This corresponds to the endcap region of the detector. As of yet, it is not understood where this discrepancy comes from and electrons with \( |\eta| > 1.479 \) are therefore excluded for the moment. 91% of all signal electrons are reconstructed in the barrel. Most of the electrons from backgrounds are reconstructed there, as well with the exception of W(Z)+jets and QCD multijet events. Here, only 56% pass the \( \eta \) constraint.

5.2.4 Jets

During the hard interaction, gluons may be radiated either as initial state or as final state radiation (ISR or FSR), and single quarks may appear. Because of the confinement introduced by QCD, they are not permitted to remain free. Instead, they hadronize and color-neutral mesons and baryons are formed. Ideally, these particles in sum have the same trajectory as the original quark or gluon. However, during hadronization the emerging particles interact with each other and transfer momentum such that a cone of particles appears. This is called a jet. The components of a jet can be measured by both the tracker and the calorimeters, depending on whether they are charged or neutral objects. However, the association of particles to a certain jet is ambiguous and clearly affects the outcome of the measurement. Different algorithms have been developed to cluster particles into jets. At CMS, the anti-\( k_T \) algorithm is used frequently.

The anti-\( k_T \) algorithm

Distances \( d_{ij} \) and \( d_B \) are introduced where \( i \) and \( j \) are the entities (particles or pseudojets) and \( B \) denotes the beam. These distances are computed via

\[
d_{ij} = \min \left( k_{ti i}^2, k_{ij}^2 \right) \frac{\Delta_{ij}^2}{R^2},
\]

\[
d_B = k_{ti i}^2,
\]

where \( k_{ti i} \) corresponds to the transverse momentum, \( \Delta_{ij} \) to the distance \( \sqrt{\Delta_\eta_{ij}^2 + \Delta_\phi_{ij}^2} \) of the entities \( i \) and \( j \). \( R \) is the radius parameter, which governs when the algorithm stops taking particles into account. The parameter \( p \) influences the impact of the entities’ energy on the distances and is in principle arbitrary. However, if \( p = 1 \) or \( p = 0 \), either the \( k_T \) or Cambridge/Aachen algorithm is recovered, respectively. In case of the anti-\( k_T \) algorithm, \( p \) is set to \(-1\) [63]. The advantage is that due to the negative \( p \), entities with smaller momentum are clustered mainly with entities that have a high transverse momentum, which in the absence of multiple high energetic jets within \( 2R \) of the original candidate produces conical jets. Should there be two or more hard entities with \( R < \Delta_{ij} < 2R \) with respect to the first hard particle “1”, the shape of the resulting jet(s) depends on the ratio \( k_{ti i}/k_{ij} \). If the ratio is much larger than one, jet 1 will be conical, and jet \( j \) only in part, while if the ratio is equal to one, neither jet will be conical but instead, the overlap between them will be separated by
Figure 5.2: $p_T$ and $\eta$ of the muon (top) and the electron (bottom).

a straight line. In case $k_{11} \sim k_{1j}$, the boundary will be more complex. If $\Delta_{1j} < R$, both hard particles will be clustered into one single jet where the shape again depends on the ratio of their transverse momenta. Hence, the shape of the jets solely depends on the momenta of the hard particles and not of any soft particles [63]. This advantage is displayed in Figure 5.3.

This analysis uses jets reconstructed by the Particle-Flow algorithm, which takes all of the detector components into account and employs the anti-$k_T$ algorithm with a radius of $R = 0.5$. Uncertainties arising from mismeasurement of jet energies by the calorimeters have been measured by the JetMET POG, and corrections are available [64]. Here, pileup (L1), relative $\eta$ (L2) and absolute scale corrections (L3) are applied to simulation, while for data additional small $\eta$– and $p_T$-dependent residual corrections are applied (L2L3Residuals).
5.2. Object Reconstruction and Identification

5.2.5 Missing Transverse Energy

The negative vector sum of all reconstructed particles’ transverse momenta is called missing transverse energy ($E_T^{\text{miss}}$ or MET). It quantifies the amount of energy carried by neutrinos or other particles that have not been detected. Since it is the last physics object to be reconstructed, it is highly dependent on any uncertainties from previous object reconstructions.

The largest contribution to the misreconstruction of $E_T^{\text{miss}}$ is due to jet energy uncertainties. To reduce this bias, a “type-1” correction is applied [64]:

$$E_T^{\text{miss}} = E_T^{\text{miss,raw}} - \sum \left( \vec{p}_T^{\text{jet}} - \vec{p}_T^{\text{raw,jet}} \right). \quad (5.4)$$

Other uncertainties arise from pileup where the sum of transverse momenta of charged and neutral particles is expected to be balanced. However, due to energy thresholds in the calorimeters and non-linearity, neutral particles are measured with less accuracy leading to $E_T^{\text{miss}}$ pointing in the direction of the $\vec{p}_T$-sum of neutral particles. A correction for this is also available and called “type-0” [64].

This analysis uses both, type-0 and type-1 corrected missing transverse energy reconstructed by the Particle-Flow algorithm as it is recommended by the JetMET POG (see Fig. 5.4).
5.3 Background Estimation

In a search, understanding and correctly modeling the background is a key aspect. Backgrounds are processes that have an event topology in the final state similar to that of the signal. Backgrounds that have the same final state but characteristics that enable us to separate them from the signal are called reducible backgrounds. Those processes showing analogous behavior as the signal are irreducible backgrounds, and processes that lead to characteristics similar to those of the signal due to misidentification are called fake backgrounds. The main backgrounds of this analysis are listed and described in detail below. Additionally, possible Feynman diagrams of these processes are depicted in Figure 5.5.

**Drell-Yan (DY) + jets** ($\sigma = 33.3$ nb for $60 < m_Z < 120$ GeV [11, 56]): The Z boson is produced via quark-antiquark annihilation while jets can be produced by initial state radiation. The subsequent decay of the Z boson to two tau leptons, which then decay to an electron and a muon, respectively, is especially important as it is irreducible. The only means of discriminating against it is a cut on the invariant mass, since the energy of the four neutrinos emerging during tau decays cannot be detected. Contributions from $Z \rightarrow \mu\mu$, where a muon radiates a photon which is then misreconstructed as an electron, and from $Z$+jets where a jet fakes a lepton, are also expected.

**W + jets** ($\sigma = 110.0$ nb [11, 56]): A W boson in association with $\geq 0$ jets is produced in the hard interaction and decays leptonically. In case the jet is misidentified as a lepton, this process mimics the signal.

**Top-pairs** ($\sigma = 245.8$ pb [65]): Since top quarks decay into a W boson and a bottom quark with a branching ratio of almost 100%, their contribution to the background originates from real electrons and muons in the final state, but also from jets faking leptons. Due to the large mass of the top quark, these leptons are boosted and thus have very high transverse momenta. Moreover, top-pair production and the following decay is accompanied by at least two high-energetic jets. Both aspects present us with a handle on reducing this background.
5.3. Background Estimation

(a) Drell-Yan + jets
(b) top-pair production
(c) Single top + W
(d) W + jets
(e) WW
(f) WZ
(g) ZZ

Figure 5.5: Possible Feynman diagrams of background processes.

\( tW/\bar{t}W \) (\( \sigma = 22.2\text{ pb} \))

The signature of this background is similar to that of \( tt \) events with the exception of a different boost. Moreover, its cross section is an order of magnitude smaller.

\( WW \) (\( \sigma = 69.9\text{ pb} \))

The decay of two W bosons to leptons describes another irreducible background. The reconstructed invariant mass is expected to be distributed evenly in the signal window making it difficult to get rid of these events. However, this in turn means that a possible resonance in the signal window is not expected to originate from this process.

\( WZ(ZZ) \) (\( \sigma = 24.61(8.4)\text{ pb} \))

These diboson processes also contribute to the background in cases where one or two of the produced leptons are not measured by the detector, or when a jet fakes one of the leptons (\( ZZ \rightarrow 2\ell 2q \)).

**QCD multijet:** This background consists of jets being misidentified as leptons. Although the rate at which both leptons are misidentified is assumed to be very low, the large cross section of this background forces us to consider it.

While diboson, top-pair and Drell-Yan events are estimated from simulated data samples produced by the CMS Collaboration (see Table 4.2), backgrounds from W(Z)+jets and QCD multijet events are estimated from data using the fake rate method described in Section 5.3.1.

5.3.1 The Fake Rate Method

The fake rate method quantifies the likelihood of a jet faking an electron or a muon. It is determined by selecting leptons via a set of identification criteria (so called fake ID) in a background-enriched data sample recorded by a multijet trigger, and checking whether those leptons also pass the tighter ID requirements as described in Sections 5.2.2 and 5.2.3. The ratio defines the rate of a jet faking a lepton. Measuring these fake rates thus enables us to model W+jets, QCD multijet and even Z+jets events. One should keep in mind that this does not cover Drell-Yan events where one muon radiates a photon, which can fake an electron. This background is still modeled using simulation.

The fake rate method is used in the \( H \rightarrow \tau\tau \)-analysis in the electron-muon channel [57], and these measured fake rates can be used within the CMS Collaboration. Since the final
state is the same, the possibility to use the measurement mentioned above presents itself. The requirements for the fake IDs have been taken from the $H \to \tau\tau$ analysis and some requirements of the official identification recommendations have been tightened according to the same analysis to avoid compatibility issues. Table 5.3 states the requirements on the leptons in order to pass the fake ID, where the isolation is calculated as described in Sections 5.2.2 and 5.2.3.

Table 5.3: Fake ID requirements on the leptons.

| Electron | reconstructed as GsfElectron  
no conversions  
$p_T > 20 \text{GeV}$  
$|\eta| \leq 2.5$  
$|d_z| < 0.1 \text{ cm}$  
$|d_{xy}| < 0.03 \text{ cm}$  
$I_{rel} < 0.2$ |
|---|---|
| Muon | reconstructed as global muon  
$p_T > 10 \text{GeV}$  
$|\eta| < 2.1$  
$|d_{xy}| < 0.2 \text{ cm}$  
$I_{rel} < 0.4 \ (p_T < 20 \text{GeV}), \ I_{abs} < 8 \ (p_T \geq 20 \text{GeV})$ |

The fake rates are applied as weights to events in data with two selected lepton candidates that have the same charge and in which one or both leptons pass the fake but not the tight ID. Since we assume no charge correlation between the real and the fake lepton in $W(Z)+jets$ and QCD multijet events, these events are then passed to later stages of the analysis as though they had opposite charge.

### 5.4 Quality Cuts

Three requirements are imposed on events passing the object selection. These requirements are not optimized with respect to the signal-to-background ratio or the expected limit as is the case with the selection cuts in Section 5.5. They are intended to remove events with multiple leptons, same charge and fake leptons.

Two vetos are applied to each event. The first veto takes effect if there is an additional muon with a transverse momentum larger than 3 GeV and $|\eta| < 2.4$ within a cone of $\Delta R = 0.3$ with respect to the selected electron candidate. This muon should be reconstructed as a global and a Particle-Flow muon. Its aim is to suppress backgrounds where two muons are produced and one of them radiates a photon, which then converts to an electron-positron pair (e.g., $Z \to \mu\mu + q$). It is referred to as dimuon veto. The second veto tries to minimize backgrounds where more than two real leptons are produced (e.g., $WZ \to 3\ell 1\nu$ or $ZZ \to 4\ell$), or where a jet is reconstructed as a lepton (e.g., $Z \to ee/\mu\mu + q$ or $ZZ \to 2\ell 2q$). To trigger this tri-lepton veto, there has to be another electron or muon with a transverse momentum greater than 10 GeV, a relative isolation smaller than 0.3 and $|\eta| < 2.5 \text{ or } 2.4$, respectively. Furthermore,
this lepton has to have impact parameters $|d_{xy}|$ smaller than 0.045 cm and $|dz| < 0.2$ cm, as well as pass the loose MVA ID in case of being reconstructed as an electron or the tight ID in case of a muon.

The last cut in this category is placed on the charge-sum of the two selected leptons. Since charge is conserved, the sum of both charges has to equal zero. This is the case for all signal events and all background events with one real electron and one real muon. All other backgrounds – namely $WZ \rightarrow 3\ell 1\nu$, $ZZ$, and $Z \rightarrow ee/\mu\mu$ – are suppressed by this cut. The efficiencies of the individual cuts are displayed in Table 5.4.

Table 5.4: Relative efficiencies of quality cuts with respect to events that passed the previous cuts. All events in this table passed the object identification and thus, $Z \rightarrow ee/\mu\mu$ events listed here contain at least one fake lepton. Note that due to the way of obtaining the QCD/W(Z)+jets background, its efficiency for the cut on the charge sum is 1 (see Section 5.3.1).

<table>
<thead>
<tr>
<th>Cut</th>
<th>Signal</th>
<th>Data</th>
<th>$Z \rightarrow \tau \tau$</th>
<th>$t\bar{t}$</th>
<th>$tW$</th>
<th>QCD/W(Z)+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimuon veto</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tri-lepton veto</td>
<td>1</td>
<td>0.99</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.88</td>
</tr>
<tr>
<td>$q_e + q_\mu = 0$</td>
<td>1</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Electroweak**

<table>
<thead>
<tr>
<th>Cut</th>
<th>WW $\rightarrow 2\ell 2\nu$</th>
<th>WZ $\rightarrow 3\ell 1\nu$</th>
<th>ZZ</th>
<th>$Z \rightarrow ee/\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di-muon veto</td>
<td>1</td>
<td>1</td>
<td>0.99</td>
<td>0.66</td>
</tr>
<tr>
<td>Tri-lepton veto</td>
<td>1</td>
<td>0.50</td>
<td>0.31</td>
<td>0.71</td>
</tr>
<tr>
<td>$q_e + q_\mu = 0$</td>
<td>0.99</td>
<td>0.50</td>
<td>0.54</td>
<td>0.65</td>
</tr>
</tbody>
</table>

A glance at the invariant-mass distribution after all the above shows good agreement between data and the background estimation (see Fig. 5.6).
5. Event Selection

A set of cuts is placed on each event to suppress background that preferably affects the signal yield only slightly, if at all. This section motivates and describes each cut.

5.5.1 The Jet Veto

Due to its relatively large cross section, top-pair production up to this point is the second largest background. However, top pairs produce two b jets during their decay which, in cases where the top pair is not boosted along the beam direction, presents one with at least these two jets. This can be exploited to discriminate against such events and to that end, a jet veto is designed.

As a first step, only jets are processed further that do not have any tracks overlapping with either of the selected lepton candidates in the $\eta - \phi$ plane. Next, it is checked whether the leading tracks of the remaining jets are compatible with the selected primary vertex by matching them to tracks associated to this vertex. Of those jets, the two with the highest transverse momentum are selected, the sum of those momenta is calculated and a cut is placed on it. Should there be only one jet coming from the vertex, a cut is placed on its $p_T$. The values for this cut and the ones following are deduced by studying the corresponding distributions (in this case Figure 5.7), and picking a value by eye. Then, it is checked whether this value results in a good signal-to-background ratio. If it does, the value is varied in steps up to $\pm 10$ GeV and the behaviour of the expected limit (see Section 7.2) is observed. The number resulting in the best expected limit is used as the final cut value. In case of the jet veto, this method delivers 70 GeV for the $p_T$-sum and 40 GeV for the single jet $p_T$. The efficiencies depending on the different processes are listed in Table 5.5.

As expected, the veto works very well against top-pair events. However, it also suppresses backgrounds from hadronically decaying ZZ and tW events. There is also moderate reduction of leptonic backgrounds with additional jet contribution from initial state radiation or...

Figure 5.7: $p_T$ sum of two hardest jets (left); $p_T$ of jet if there is only one coming from the vertex (right).
5.5. Event Selection

Table 5.5: Relative efficiencies of the different selection cuts with respect to previously passed cuts.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Jet veto</th>
<th>$m_T^\mu &lt; 50$ GeV</th>
<th>$p_T^\mu &lt; 20$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>0.47</td>
<td>0.58</td>
<td>0.68</td>
</tr>
<tr>
<td>Signal</td>
<td>0.90</td>
<td>0.81</td>
<td>0.78</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>0.85</td>
<td>0.87</td>
<td>0.87</td>
</tr>
<tr>
<td>$WW \rightarrow 2\ell 2\nu$</td>
<td>0.72</td>
<td>0.33</td>
<td>0.36</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.23</td>
<td>0.28</td>
<td>0.08</td>
</tr>
<tr>
<td>QCD/W(Z)+jets</td>
<td>0.60</td>
<td>0.56</td>
<td>0.48</td>
</tr>
<tr>
<td>$Z \rightarrow ee/\mu\mu$</td>
<td>0.71</td>
<td>0.77</td>
<td>0.79</td>
</tr>
<tr>
<td>$tW$</td>
<td>0.40</td>
<td>0.28</td>
<td>0.10</td>
</tr>
<tr>
<td>$WZ \rightarrow 3\ell 1\nu$</td>
<td>0.60</td>
<td>0.32</td>
<td>0.21</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.43</td>
<td>0.60</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Figure 5.8: Distribution of the invariant electron-muon mass before (left) and after (right) the jet veto.

misidentification. Since all events have passed the lepton identification at this point, the difference between signal and $Z \rightarrow \tau\tau$ simulation is most likely caused by higher order calculations used to generate the Drell-Yan events. Thus, the signal efficiency may be slightly overestimated. Nevertheless, both, signal and $Z \rightarrow \tau\tau$ events experience only minor effects from the jet veto as intended. Data reproduce the behavior of the combined backgrounds well. A look at the distribution of the invariant electron-muon mass (Fig. 5.8) demonstrates the effect of this cut.
5. Event Reconstruction

5.5.2 Transverse Mass

Since some of the backgrounds (e.g., WW → 2ℓ2ν or t¯t) involve W bosons decaying to a charged lepton and a neutrino, large missing transverse energy is expected in these decays. To use this circumstance to our advantage, the transverse mass of the muon candidate is used to filter such events. The transverse mass is defined as

\[ m_\mu^T = \sqrt{2 \cdot p_\mu^T E_{\text{miss}}^T \left(1 - \cos(\Delta \phi)\right)} , \]

where \( \Delta \phi \) is the angle between the muon candidate and \( E_{\text{miss}} \) in the transverse plane. The actual cut value is determined with respect to the optimal signal-to-background ratio, and the best expected limit to be 50 GeV. At this point, signal and Drell-Yan background decrease, while electroweak and top-related backgrounds rise (Fig. 5.9). The efficiencies of this cut are shown in Table 5.5. This variable yields good discrimination against backgrounds involving one or two W bosons and moderate to minor discrimination against backgrounds from Z bosons or (multi)jet events. The behavior of data corresponds well to the combination of all backgrounds.

5.5.3 Transverse Momentum Balance

For the last discriminanting variable, the four-momenta of both signal particles are combined and a cut is placed on the transverse momentum of the vector sum. This value quantifies whether the signal leptons originate from a common mother particle at rest, and hence is efficient against backgrounds with a relatively high boost, e.g., t¯t or diboson events. As is shown in Section 4.4.1, as well as measured in [69], the transverse momentum of Z bosons produced at the LHC is small on average (see Figure 4.1(b)) making this a viable cut. The cut value is determined from Figure 5.9 to be 20 GeV. Efficiencies are listed in Table 5.5. Requiring \( p_T \) balance has a large impact on any diboson or top-related background. Especially large amounts of top-pair and single top events are rejected, while there is only a moderate
to small impact on Drell-Yan and signal events. The efficiency in data fits the background estimation well.

The distribution of the invariant mass after all of the cuts above (Fig. 5.10) shows a signal peak situated narrowly around the Z-boson mass on top of a falling Drell-Yan background. Thus, the signal window in which the number of signal, background and data events are extracted is defined as

$$88 \text{ GeV} \leq m_{\mu\mu} \leq 94 \text{ GeV}$$

(5.6)

to be within the range $m_Z \pm \Gamma_Z$. The final number of signal and background events is listed in Table 5.6. The background is dominated by the irreducible processes $Z \rightarrow \tau\tau$ and $WW \rightarrow 2\ell2\nu$. Smaller contributions come from $t\bar{t}$, $Z \rightarrow \mu\mu$, QCD/W(Z) + jets and tW/\bar{t}W. The remaining backgrounds contribute with less than 1 event per category. A look at Table 5.7 reveals the absolute signal efficiency of the analysis after different stages. The final signal efficiency is 6.1%.

Figure 5.10: Distribution of the invariant electron-muon mass after the complete selection. For emphasis, the signal is stacked on top of the background.
Table 5.6: Event yields normalized to luminosity and respective cross sections after different stages of the analysis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trigger &amp; ID</th>
<th>Quality Cuts</th>
<th>Jet Veto</th>
<th>$m_T^{\mu}$</th>
<th>$p_T^{e\mu}$</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>58849</td>
<td>57982</td>
<td>27100</td>
<td>15630</td>
<td>10682</td>
<td>x</td>
</tr>
<tr>
<td>Signal</td>
<td>183.2</td>
<td>183.2</td>
<td>164.4</td>
<td>132.8</td>
<td>104</td>
<td>68.5</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>14877.3</td>
<td>14870.9</td>
<td>12598.8</td>
<td>10924.1</td>
<td>9548.1</td>
<td>47.4</td>
</tr>
<tr>
<td>$WW \rightarrow 2\ell2\nu$</td>
<td>6767.4</td>
<td>6763.9</td>
<td>4865</td>
<td>1608.6</td>
<td>573.4</td>
<td>35.6</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>32237</td>
<td>32081</td>
<td>7290.8</td>
<td>2043.1</td>
<td>169.3</td>
<td>8.3</td>
</tr>
<tr>
<td>QCD/W(Z)+jets</td>
<td>1118.8</td>
<td>968.9</td>
<td>585.7</td>
<td>326.3</td>
<td>157.8</td>
<td>7.2</td>
</tr>
<tr>
<td>$Z \rightarrow ee/\mu\mu$</td>
<td>154</td>
<td>72</td>
<td>50.9</td>
<td>39.4</td>
<td>30.9</td>
<td>11.1</td>
</tr>
<tr>
<td>$tW$</td>
<td>3269.8</td>
<td>3257.5</td>
<td>1307.8</td>
<td>365.7</td>
<td>37.2</td>
<td>1.5</td>
</tr>
<tr>
<td>$WZ \rightarrow 3\ell1\nu$</td>
<td>498.7</td>
<td>247.9</td>
<td>147.5</td>
<td>47.2</td>
<td>9.9</td>
<td>0.6</td>
</tr>
<tr>
<td>ZZ</td>
<td>120.2</td>
<td>36.8</td>
<td>16</td>
<td>9.6</td>
<td>2.7</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 5.7: Absolute efficiencies after different stages of the analysis for signal and the two major backgrounds. Additionally, the signal-to-background ratio is shown.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Efficiency</th>
<th>$s/b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger &amp; preselection</td>
<td>42.0%</td>
<td>7.4 $\cdot$ 10^{-4}</td>
</tr>
<tr>
<td>Object identification</td>
<td>16.2%</td>
<td>3.1 $\cdot$ 10^{-3}</td>
</tr>
<tr>
<td>Quality cuts</td>
<td>16.2%</td>
<td>3.1 $\cdot$ 10^{-3}</td>
</tr>
<tr>
<td>Jet veto</td>
<td>14.6%</td>
<td>6.1 $\cdot$ 10^{-3}</td>
</tr>
<tr>
<td>Transverse mass cut</td>
<td>11.8%</td>
<td>8.6 $\cdot$ 10^{-3}</td>
</tr>
<tr>
<td>Transverse momentum balance</td>
<td>9.2%</td>
<td>9.9 $\cdot$ 10^{-3}</td>
</tr>
<tr>
<td>Mass window</td>
<td>6.1%</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Chapter 6

Systematic Uncertainties

A variety of systematic uncertainties is studied to further strengthen the robustness of the result of this analysis. Uncertainties evaluated below are used in the calculation of the limit in Chapter 7. Which uncertainties to study and the methods for obtaining them are decided upon before unblinding the data. Ideally, the numerical calculation of these uncertainties is done with active blinding. However, after unblinding, some features unrelated to the actual unblinding were noticed in the momentum distributions of the signal leptons, which lead to a cut on $p_T < 20$ GeV. Therefore, the systematics were recalculated.

6.1 Background Normalization

The modeling of most backgrounds is done using officially produced simulated data samples. Their normalization is set by their respective cross sections. Since the cross sections of all diboson processes have been measured by the CMS collaboration, they are used together with their statistical and systematic uncertainties. Background from $W(Z)+$jets and QCD multijets is estimated from data and thus its normalization is automatically correct, assuming the fake rate method works perfectly. As this has not been quantified, a large uncertainty of 50% is used for this background estimate.

The production cross section of top-pairs at the LHC has been calculated with precision at the percent level in [65] to be $\sigma(pp \rightarrow t\bar{t}) = 245.8^{+6.2}_{-8.4} \, (\text{scales})^{+6.2}_{-6.4} \, (\pdf) \, \text{pb}$. A slightly conservative 6% systematic uncertainty is used for this normalization. In case of the associated $tW$ production, the calculation in [66] yields an uncertainty of 7.6%.

The Drell-Yan background is normalized to the cross section calculated at next-to-next-to-leading-order for $m_{\ell\ell} > 50$ GeV of $\sigma(pp \rightarrow Z/\gamma \rightarrow \ell\ell) = 3503.71 \, \text{pb}$ using the code FEWZ (Fully Exclusive W and Z Production) [70]. To estimate the systematic uncertainty in the normalization, the distribution of the invariant electron-muon mass after the object identification is used. All backgrounds except $Z \rightarrow \tau\tau$ are subtracted from data and the resulting distribution is subject to a fit consisting of a Gaussian. The same function is fitted to the simulated sample, and the variation of the resulting area in the range of 50 – 80 GeV with respect to data is taken as the systematic bias. Figure 6.1 shows the parameters of interest. The areas corresponding to both fits differ by about 4%. Since the branching ratios of leptonic decays of the Z boson differ at the sub-percent level (see [11]), using this relative uncertainty for $Z \rightarrow \ell\ell$ is justified.

The relative systematic uncertainties for each background are listed in Table 6.1. As the number of events in the signal window is directly proportional to the normalization of the individual samples, the systematic uncertainty in the number of events in each background
6. Systematic Uncertainties

**Figure 6.1:** Distribution of $m_{e\mu}$ with all backgrounds subtracted except for $Z \to \tau\tau$.

**Table 6.1:** Relative systematic uncertainties in the normalization.

<table>
<thead>
<tr>
<th>Background process</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to \ell\ell$</td>
<td>4%</td>
</tr>
<tr>
<td>$WW \to 2\ell 2\nu$</td>
<td>10%</td>
</tr>
<tr>
<td>$t\bar{t}$ inclusive</td>
<td>6%</td>
</tr>
<tr>
<td>$tW/\bar{t}W$</td>
<td>7.6%</td>
</tr>
<tr>
<td>$WZ \to 3\ell 1\nu$</td>
<td>7%</td>
</tr>
<tr>
<td>ZZ inclusive</td>
<td>14%</td>
</tr>
<tr>
<td>$W(Z) +$ jets/QCD</td>
<td>50%</td>
</tr>
</tbody>
</table>

The measured luminosity directly affects the number of events that are expected and thus has a large impact on the result. The systematic uncertainty in the luminosity measured by CMS is documented in [71] and evaluated to be 4.4% for the whole 2012 dataset collected in proton-proton collisions. This uncertainty also directly translates into an uncertainty in the number of events in the signal window.

**6.2 Luminosity**

As stated in Section 5.1, trigger and ID efficiencies were measured by the $H \to \tau\tau$ working group and are used throughout this analysis. All efficiencies are individually shifted by their uncertainties to estimate the impact on the result arising from either the trigger or the identification. In order to quantify this impact, the difference in the number of signal and combined background events within the signal window is observed. The results are listed in Table 6.2. Since the impact of both, electron and muon ID is small, it is neglected.
Table 6.2: Relative systematic uncertainties in the trigger and identification efficiencies.

<table>
<thead>
<tr>
<th>Source</th>
<th>Background</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon trigger</td>
<td>1.4%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Muon ID</td>
<td>&lt; 0.1%</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Electron trigger</td>
<td>0.8%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Electron ID</td>
<td>&lt; 0.1%</td>
<td>&lt; 0.1%</td>
</tr>
</tbody>
</table>

Figure 6.2: Measurements of the muon and electron mass scale (a and b, respectively) from [73].

6.4 Lepton Scale and Resolution

Mismeasurement of lepton mass or momentum scales, as well as momentum and energy resolution, may influence the resulting number of events in the signal window. In order to estimate the influence of scale uncertainties, the muon momentum is shifted by ±0.2% as recommended in [72], and propagated through the whole analysis. In case of the momentum resolution, a value of 0.6% is used [72]. The uncertainties arising from the mass scale are neglected as they have been measured to be below 0.3% in [73] (see Figure 6.2(a)).

In case of the electron, effects due to mass scale uncertainties have to be taken into account. The reconstructed mass of the Z-boson candidate is varied as a function of the electrons \( p_T \) (see Figure 6.2(b)). An uncertainty of 2% on the electrons energy resolution is used to evaluate the resolutions’ impact on the result (see Figure 6.3). This is done by creating a Gaussian with mean zero and the resolution uncertainty as \( \sigma \). Now, a random number is taken from this distribution and added to the electrons’ energy in each event. To be able to recreate every step, the seed of the random number generator is set to a constant value before initializing the analysis. The resulting systematic uncertainties in signal and background estimation are listed in Table 6.3.
Table 6.3: Relative systematic uncertainties in the number of events within the signal window arising from lepton scales and resolution.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon $p_T$ scale</td>
<td>0.2%</td>
</tr>
<tr>
<td>Muon $p_T$ resolution</td>
<td>4.1%</td>
</tr>
<tr>
<td>Electron mass scale</td>
<td>4.2%</td>
</tr>
<tr>
<td>Electron energy resolution</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Figure 6.3: Electron energy resolution from [73].

6.5 Signal Generation with Pythia

In Section 4.4.1 it is pointed out that there are differences between the private simulation of the signal and the officially produced DY simulation. These differences are due to higher order calculations done by MADGRAPH compared to PYTHIA. In order to estimate the impact on the signal efficiency, the transverse momentum of the reconstructed Z boson in signal events is reweighted bin-by-bin according to Figure 4.1(b). The variation of the number of signal events in the mass window is used as the systematic uncertainty and is found to be 2.3%. 

![Figure 6.3: Electron energy resolution from [73].](image-url)
Chapter 7

Statistical Interpretation

A statistical method is needed to interpret the number of measured events in terms of compatibility with the background-only or the signal hypothesis. The CMS Collaboration recommends using the so called $CL_s$-method, which is explained in the following section. Following that, the result of this analysis is presented and discussed.

7.1 The CLs-Method

Suppose an experiment is carried out, and for each event a certain variable is measured. This variable is then stored in a histogram of $N$ bins $n_j$, where $n_j$ is Poisson distributed with a parameter $\zeta s_j + b_j$. $s_j$ and $b_j$ denote the expected number of signal and background events, respectively, and $\zeta$ is the signal strength, which can be 1 for the expected signal yield, or 0 for the background-only hypothesis. Moreover, nuisance parameters $\theta$ which describe systematic uncertainties are evaluated and stored in a histogram. This histogram has $M$ bins $m_k$ that are also Poisson distributed with a parameter $u_k$ which can be derived from the nuisance parameters.

The CLs-method introduces a likelihood function which is composed of a product of Poisson distributions for each bin $j$ and $k$, respectively (Equation (6) in [74]):

$$L(\zeta, \theta) = \prod_{j=1}^{N} \left( \frac{(\zeta s_j + b_j)^{n_j}}{n_j!} \cdot e^{- (\mu s_j + b_j)} \right) \cdot \prod_{k=1}^{M} \left( \frac{u_k^{m_k}(\theta)}{m_k!} \cdot e^{-u_k} \right). \quad (7.1)$$

To test different hypotheses, the likelihood ratio is computed by dividing the respective likelihood functions for the signal and the background assumption. This ratio is called $\lambda(\zeta)$. It can be transformed to $t_\zeta = -2 \ln(\lambda)$ for convenience reasons, as it leads to a sum of likelihood functions instead of a product.

A quantitative statement about the compatibility of a measurement with some hypothesis can be made by calculating the p-value

$$p_\zeta = \int_{t_{\zeta,\text{obs}}}^{\infty} P(t_\zeta|\zeta) \, dt_\zeta, \quad (7.2)$$

with $P(t_\zeta|\zeta)$ being the probability density function of the likelihood ratio and $t_{\zeta,\text{obs}}$ the measured likelihood ratio of the chosen hypothesis. In this analysis, there are exactly two hypotheses:
• only background events are expected
• additionally, there are signal events expected

In case of setting an upper limit, the ratio

\[ \text{CL}_s \equiv \frac{P_{s+b}}{P_b} = \frac{P_{\zeta=1}}{P_{\zeta=0}} \tag{7.3} \]

is evaluated, instead of just \( P_{s+b} \). This is done to circumvent the possibility of excluding a hypothesis due to a downward background fluctuation without actually being sensitive to such values \([75]\). Since \( 0 \leq \zeta \leq 1 \), this limit is naturally more conservative. Different levels can be defined to quantify the confidence in the limit. Usually, at CMS, the so called 95% confidence level (CL) is computed, which corresponds to CL\(_s\) values smaller than 0.05. Statistical fluctuations of the background are accounted for in 1\(\sigma\) and 2\(\sigma\) bands that are calculated by varying the background expectation by \(\pm 1\sigma\) or \(\pm 2\sigma\), respectively.

To calculate the expected and observed limit, in this analysis the combine tool developed by both the ATLAS and the CMS Collaboration for the LHC Higgs Combination Group \([76, 77]\) is used. The signal strength is used such that it satisfies

\[ \sigma = \zeta \cdot \sigma_{\text{exp}} \tag{7.4} \]

where \(\sigma\) corresponds to the measured and \(\sigma_{\text{SM}}\) to the expected cross section. This translates into the number of expected events from background and signal: \(N = \zeta \cdot s + b\). The same logic can be applied in case of this measurement, where instead of the cross sections branching ratios are used:

\[ B(Z \to e\mu) = \zeta \cdot B(Z \to e\mu)_{\text{LEP}} \tag{7.5} \]

where \(B(Z \to e\mu)_{\text{LEP}}\) is the 95% CL limit on the branching ratio measured at LEP (see Section 2.2). Now, the CL\(_s\)-method can be used to set a limit on the signal strength.

If there is no possibility of exclusion or the observed CL\(_s\)-value deviates significantly from the expectation, one can look at the value of \(p_b\). The smaller this number, the worse the agreement of data with the background-only hypothesis. There are two commonly used values to categorize such a measurement. Should \(p_b\) be smaller than \(2.7 \cdot 10^{-3}\), one claims to have found evidence of a signal. A \(p_b\)-value smaller than \(5.7 \cdot 10^{-7}\) is called an observation. Both numbers are chosen such that they agree with the probability of observing a 3\(\sigma\) or 5\(\sigma\) deviation from the mean of a Gaussian. It is important to note that in case an observation is made using this method, it does not necessarily have to be the signal sought after.

7.2 Result

Only once the whole analysis is defined and set up, including the selection, study of systematic uncertainties and the choice of the statistical method for interpretation, is the data fully unblinded and the number of data events in the signal window available. Features in the momentum distributions of electron and muon that were not noticed before unblinding lead to a cut on \(p_T < 20\) GeV after the unblinding. This required a reevaluation of systematic uncertainties. This reevaluation entailed the numerical calculation only, however. No changes have been made to any of the methods. There are 116 events selected in data compared to 111.76 expected background and 68.5 signal events in the signal window after unblinding. The unblinded invariant mass is shown in Figure 7.1.
Figure 7.1: Unblinded distribution of $m_{\mu\tau}$.

Table 7.1: Numerical values entering the limit calculation. Systematic uncertainties in the normalization are not given here as they are evaluated for each background individually. They are listed in Table 6.1

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>116</td>
<td>68.5</td>
<td>111.76</td>
</tr>
<tr>
<td>Syst. uncertainties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger (e)</td>
<td>–</td>
<td>0.8%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Trigger (μ)</td>
<td>–</td>
<td>1.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Mass scale (e)</td>
<td>–</td>
<td>0.3%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Energy res. (e)</td>
<td>–</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>$p_T$ scale (μ)</td>
<td>–</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$p_T$ res. (μ)</td>
<td>–</td>
<td>1.1%</td>
<td>4.1%</td>
</tr>
<tr>
<td>$p_T$ reweighting</td>
<td>–</td>
<td>2.3%</td>
<td>–</td>
</tr>
</tbody>
</table>

Using the number of expected signal and background events, as well as all systematic uncertainties evaluated (Tab. 7.1), this yields an expected upper limit of

$$B (Z \to e\mu) < 0.46 \cdot B (Z \to e\mu)_{\text{LEP}} \at 95\% \text{ CL} \quad (\text{see Figure 7.2}), \quad (7.6)$$

which translates to

$$B (Z \to e\mu) < 7.38 \cdot 10^{-7} \at 95\% \text{ CL}. \quad (7.7)$$

An observed number of 116 events which is slightly above the expected total background of almost 112 events, yields an observed upper limit of

$$B (Z \to e\mu) < 8.41 \cdot 10^{-7} \at 95\% \text{ CL}. \quad (7.8)$$

There is a slight discrepancy between the value computed by the combine tool and the value read off Figure 7.2. This is due to the heavy computations by the tool requiring toy Monte-Carlo generation initialized with different seeds. The uncertainty introduced by the computation method amounts to 2%.
This analysis improves the limit measured by LEP by a factor 2 and thus sets the current world’s best limit. The small discrepancy between expectation and observation corresponds to a $p$-value of 0.35 and is most likely due to a statistical fluctuation. No sign of new physics or charged Lepton Flavor Violation is observed by this analysis and the standard model is confirmed once more.
Chapter 8

Conclusion and Outlook

The present search for the Lepton Flavor Violating process $Z \rightarrow e\mu$ is based on 19.8 fb$^{-1}$ of data from proton-proton collisions recorded with the CMS detector in the year 2012. A dedicated cut-and-count experiment with partially blinded data is conducted to derive an exclusion limit on the branching ratio $B(Z \rightarrow e\mu)$. In particular, the following results are achieved:

Signal simulation:
The signal decay is implemented in the Monte-Carlo generator PYTHIA to produce a simulated data sample. The sample is validated on reference Drell-Yan simulation.

Event selection:
A cut-based selection is used to separate signal from background with an absolute signal efficiency of $\epsilon = 6.1\%$ and a signal-to-background ratio of $s/b = 0.6$. The selection is optimized with respect to the upper limit on the branching ratio and an examination of agreement between real and simulated data is done in unblinded regions. The number of expected signal and background events in the blinded signal window around the nominal Z-boson mass amounts to 68.5 and 111.76, respectively.

Systematic uncertainties:
Several systematic uncertainties are studied, where the main contributions originate from the background normalization and muon momentum resolution, as well as from the electron mass scale and the luminosity uncertainty.

Exclusion limit:
116 real data events are found in the signal region after unblinding. The result is interpreted by means of the CL$_s$-method. An upper limit of

$$ B(Z \rightarrow e\mu) < 8.41 \cdot 10^{-7} \ @ 95\% \ CL $$

is set. This results in an improvement of the world’s best limit from direct searches at LEP by a factor 2.

Improvements of this result are possible by including electrons in the endcap region, as well as lowering the thresholds on the transverse momentum to $p_T \geq 10 \ GeV$ in case only one of the two triggers responds. In order to do both, a detailed investigation of the electron identification for $p_T < 20 \ GeV$ is necessary.
The uncertainties in the cross sections used for normalization should be studied further. A way to estimate more backgrounds from data could prove useful especially for the main background $Z \rightarrow \tau\tau$. This could be done by using so called embedded samples, where $Z \rightarrow \mu\mu$ events are measured in data and the kinematics are then used for a simulation of di-tau decays of the Z boson. These samples have been successfully used in $H \rightarrow \tau\tau$ analyses [57].

Shortly before finalizing this thesis, newer luminosity uncertainties have been published by the CMS Collaboration. Instead of 4.4%, an uncertainty of 2.6% is to be assumed [78]. New calculations are also available for the pileup reweighting method. Both changes would improve the limit.

Moreover, the signal simulation can be enhanced by using higher-order generators such as 

\textsc{madgraph} or \textsc{powheg}. A more realistic modeling of the signal would remove the systematic uncertainty in the signal efficiency introduced by the modeling of the Z bosons’ transverse momentum by \textsc{pythia}. Additionally, this might explain the difference of relative efficiencies between signal and $Z \rightarrow \tau\tau$ background observed in the selection.

Further systematic uncertainties may be evaluated. Examples are uncertainties caused by pileup, or by the parton density functions used to generate the simulated data samples. Additionally, jet energy and missing transverse energy resolution uncertainties can be incorporated in the result.

Finally, instead of counting events, a shape-based analysis could be implemented to make use of the fact that a resonance is expected on top of a declining background.

Once the LHC starts again in 2015, this analysis could be revisited. With the increased center-of-mass energy and higher instantaneous luminosity, and thus the larger cross section of Z-boson production, an even better upper limit should be achievable. Furthermore, such a study could probe a new energy regime.

Although the LHC and its largest detectors ATLAS and CMS were designed for searches in higher mass regimes, this analysis has shown that improvements can be achieved even in regions other colliders like LEP are in general more sensitive to.
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<th>Description</th>
<th>Page</th>
</tr>
</thead>
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<td>39</td>
</tr>
<tr>
<td>6.1</td>
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<td>42</td>
</tr>
<tr>
<td>6.2</td>
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<td>43</td>
</tr>
<tr>
<td>6.3</td>
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<td>44</td>
</tr>
<tr>
<td>7.1</td>
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<td>47</td>
</tr>
<tr>
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<td>48</td>
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</tbody>
</table>
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[30] “Public display of LHC luminosity measurements”.


[41] Bastian Kargoll. Private communication.


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Statement of Authorship

I declare that I have used no other sources and aids other than those indicated. All passages quoted from publications or paraphrased from these sources are indicated as such, i.e. cited and/or attributed. This thesis was not submitted in any form for another degree or diploma at any university or other institution of tertiary education.

Aachen, September 16 2013  
(Alexander Nehrkorn)