BACHELOR THESIS

Petr Kouba

Study of the Lepton Flavor Violating Decays of the Higgs Boson at the ATLAS Experiment

Institute of Particle and Nuclear Physics

Supervisor of the bachelor thesis: Mgr. Daniel Scheirich, Ph.D.
Study programme: Physics
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Title: Study of the Lepton Flavor Violating Decays of the Higgs Boson at the ATLAS Experiment

Author: Petr Kouba

Institute: Institute of Particle and Nuclear Physics

Supervisor: Mgr. Daniel Scheirich, Ph.D., Institute of Particle and Nuclear Physics

Abstract: The thesis contains an analysis of the potential lepton flavor violating Higgs boson decays performed on the data acquired by the ATLAS experiment during the Run II period of the LHC. The analysis comprised of an event selection aiming at the reduction of the backgrounds, while keeping the highest possible amount of the signal events. An estimate of the leptons misidentified by the reconstruction algorithms of the ATLAS experiment was included in the analysis. For the selected events, invariant mass was reconstructed in the collinear approximation. The distribution of the invariant mass according to the MMC was provided for reference purposes.

Keywords: Higgs boson, ATLAS, collinear approximation
I would like to express deep gratitude to my supervisor, Dr. Daniel Scheirich, for his advices and for his patient and human approach, while guiding me throughout this thesis.
# Contents

1 Introduction ........................................... 2

2 Theoretical Background ................................. 3
   2.1 The Standard Model ................................ 3
      2.1.1 Leptons ........................................... 3
      2.1.2 Quarks ............................................ 4
      2.1.3 Bosons ............................................. 5
   2.2 Decay Modes of the Higgs Boson and Corresponding Background Processes ................. 6
      2.2.1 Decay Modes of the SM Higgs Boson ................ 6
      2.2.2 BSM Higgs Boson ................................ 6
      2.2.3 Background Events ................................. 7
   2.3 Particle Collisions .................................. 7
      2.3.1 Cross Section and Luminosity ...................... 7
      2.3.2 Kinematics ........................................ 9

3 Data Acquisition ........................................ 12
   3.1 The Large Hadron Collider ......................... 12
   3.2 The ATLAS Detector ................................. 13
      3.2.1 Inner Detector ................................. 13
      3.2.2 Calorimeters ................................. 14
      3.2.3 Muon Detector ................................. 14
      3.2.4 Triggers ........................................ 14

4 Data Analysis .......................................... 16
   4.1 Event Selection .................................. 16
      4.1.1 Trigger Selection ............................ 16
      4.1.2 Other Selection Criteria ...................... 17
      4.1.3 Misidentified Leptons - "Fakes" ............... 19
   4.2 Results ........................................... 20
      4.2.1 Invariant Mass Histograms ..................... 20
      4.2.2 Statistical Processing ......................... 22

5 Summary .............................................. 23

Bibliography ........................................... 24

List of Figures ......................................... 26
1. Introduction

The most widely accepted theory describing our current knowledge of microcosmos is the so called Standard Model (SM). It classifies all known elementary particles and describes three out of four fundamental forces - electromagnetism, weak interaction and strong interaction, with only gravity not being included in the SM\cite{16}. The reason for the high credibility of the theory lies in numerous experimental tests it has passed during its existence, with no experiment directly disproving the model so far. The greatest triumph of the SM is considered to be the discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC) in CERN, which confirmed the prediction included in the SM since 1970s.

Despite its remarkable achievements, the SM cannot be considered to be the complete theory of microcosmos, since there are various phenomena being left unexplained by the theory. As mentioned above, one of those phenomena is gravity. Other unexplained phenomena are for example the dark matter and neutrino oscillations. To explain the aforementioned, there is a need to further extend the model, often described as beyond Standard Model (BSM) search. While looking beyond the Standard Model, it is desirable to put the current predictions of SM to further experimental tests.

The key role in this plays the LHC. In the data it has gathered during Run I - its first period of data acquisition - a minor hint at possible $H \rightarrow \tau\mu$ decay was spotted by the CMS experiment\cite{3}. Such a decay would violate the lepton number conservation and thus oppose the SM. However, the statistics of Run I is insufficient to be considered as an evidence of lepton flavor violation. The second period of data acquisition at the LHC - the Run II - provides us with more data which can be used to further examine the potential lepton flavor violating decays of the Higgs boson. The aim of this thesis is to examine such decays by analysing the data provided by the ATLAS experiment at LHC in CERN.
2. Theoretical Background

In this chapter we are going to briefly introduce the theoretical background behind the analysis of the Higgs Boson decays. Firstly, we will talk about the Standard Model and the decay channels of the Higgs boson with the corresponding background processes. At the end of this chapter a short summary of the physics of particle collisions will be provided.

2.1 The Standard Model

The Standard Model (SM) is a theory that classifies all of the so far known elementary particles. For a table summary of the elementary particles according to the SM see Figure 2.1

![Summary of the Standard Model](image)

Figure 2.1: Summary of the Standard Model

2.1.1 Leptons

Leptons are elementary particles with a half-integer spin, as such they belong to the group of fermions. They can be further divided according to their charge to charged leptons and neutral leptons. The charged leptons are $\tau$, $\mu$ and $e$, they carry negative elementary charge. Their respective antiparticles carry positive elementary charge. Their respective antiparticles carry positive elementary charge. The neutral leptons are neutrinos, there are three types of neutrinos $\nu_\tau$, $\nu_\mu$ and $\nu_e$, each having its own antineutrino. We say that each of the charged leptons, its corresponding neutrino and their antiparticles form a generation. Generally, leptons only interact through gravity and weak interaction, in case of charged leptons electromagnetic interaction is possible as well [5].
Lepton Number Conservation

The so-called lepton number (also called "lepton flavour") is an additive quantum number associated with leptons. According to the SM, the lepton number should be conserved within each of the lepton generations (with the exception of neutrino oscillations). Each lepton has a lepton number set equal to +1 and each antilepton has a lepton number set equal to -1. We will illustrate the lepton number conservation on an example [5]:

Let us denote the total lepton number by $L$ and the lepton numbers associated to the lepton generations by $L_{\tau}$, $L_{\mu}$, $L_{e}$. Now let us look at the decay of $\mu$:

$$\mu \rightarrow e + \bar{\nu}_{e} + \nu_{\mu} \tag{2.1}$$

For total lepton number we have:

$$L : 1 = 1 - 1 + 1$$

Within each generation we have:

$$L_{\tau} : 0 = 0 + 0 + 0$$
$$L_{\mu} : 1 = 0 + 0 + 1$$
$$L_{e} : 0 = 1 - 1 + 0$$

From the above, we can see that the lepton number conservation for (2.1) holds.

2.1.2 Quarks

Another group of elementary particles are quarks. Quarks exist in 6 different types - so-called flavours, we denote them as $u$, $d$, $c$, $s$, $t$ and $b$. They carry electric charge, mass and spin, for the respective values see Figure 2.1. Based on their half-integer spin number, quarks belong to fermions. Quarks can interact via all of the four fundamental interactions. For every quark there exists an antiquark. For each of the quark flavours a unique additive quantum number, called flavour number, is defined. By convention, we define that the flavour number of a quark, has the same sign as the electric charge of the quark. For antiquarks, the value of the flavour number as well as of the value of an electric charge has the opposite sign.

Quark Confinement

Apart from the flavour number and spin, other quantum numbers can be associated with quarks as well, one of such is the so-called "color" (or "color charge"). We define 3 different colors: "red", "green" and "blue". Antiquarks have anticolors: "antired", "antigreen" and "antiblue". Quarks can change their color via strong interaction, however the total color that goes into a reaction has to be conserved. According to the Noethers theorem, there is a symmetry behind this conservation law. It is an SU(3) symmetry that demands, that if cyclic permutation was performed with all of the three colors and the same with anticolors, it could not be observed on the outside [10].
Another important property of quarks is called “quark confinement”. This property causes that an isolated quark cannot be observed. Quarks always have to be bound together to form composite particles, called hadrons. Hadrons are “colorless particles”. We say that particle is ”colorless” either if it comprises of quarks and antiquarks whose colors and anticolors cancel out or if it contains same amount of all of the colors, so that the described SU(3) symmetry holds on the outside.

Based on the mechanism of achieving colorlessness, hadrons can be separated into two basic groups. Not taking into account any exotic hadrons, these groups are mesons and baryons. Mesons are hadrons which are formed by a quark and an antiquark with opposite colors. Baryons are formed by three quarks with different colors [5].

2.1.3 Bosons

Bosons are particles with an integer spin number. Bosons can be either composite particles (such as mesons, mentioned above) or elementary particles. In the context of the SM when referring to bosons, we will have in mind the elementary ones. Those are: gluons ($g$), photons ($\gamma$), $Z$, $W^+$, $W^-$ and the Higgs boson ($H$). We can further distinguish between the so-called gauge bosons ($g$, $\gamma$, $Z$, $W^\pm$) carrying spin number 1 and the Scalar boson ($H$) carrying spin number 0.

The Gauge Bosons

The gauge bosons transmit fundamental interactions. The electromagnetic interaction is intermediated by $\gamma$, the strong interaction is intermediated by $g$ and the weak interaction is intermediated by $W^\pm$ and $Z$. The $W^\pm$ and $Z$ bosons are often commonly referred to as the ”vector bosons”.

The Scalar Boson

Based on the assumed symmetries of the SM, all gauge bosons should have zero mass. However, experiments have shown that $W^\pm$ and $Z$ carry non-zero mass. This can be explained by the existence of the Higgs field, which gives mass to $W^\pm$ and $Z$ bosons via the so-called Brout-Englert-Higgs mechanism (Higgs mechanism, for short) [5]. More about the Higgs mechanism can be found in [13]. The Higgs boson is a particle that intermediates the interaction of the Higgs field with other particles. The mass of the Higgs boson is a free parameter of the theory and thus it has to be measured by experiment. According to the most recent experiments carried out by the ATLAS collaboration, the invariant mass of the Higgs boson is $m_H = (125.09 \pm 0.21{\text{stat.}}\pm0.11{\text{syst.}})\text{GeV}$ [1].
2.2 Decay Modes of the Higgs Boson and Corresponding Background Processes

2.2.1 Decay Modes of the SM Higgs Boson

The lifetime of the Higgs boson is $\sim 10^{-22}$ s [1], as such it is impossible to detect it directly. It can only be observed through the detection of its longer-living decay products. For the reconstruction of the Higgs boson, it is necessary to know the decay channels into which it can decay. The decay modes, that are predicted by the SM are listed together with their respective branching ratios in Table 2.1.

Table 2.1: Higgs Boson ($m_H = 125.09 GeV$) Decay Modes Branching Ratios [2]

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$5.81 \times 10^{-1}$</td>
<td>$+2.14%$ $-2.18%$</td>
</tr>
<tr>
<td>$H \rightarrow \tau \bar{\tau}$</td>
<td>$6.26 \times 10^{-2}$</td>
<td>$+2.77%$ $-2.74%$</td>
</tr>
<tr>
<td>$H \rightarrow \mu \bar{\mu}$</td>
<td>$2.12 \times 10^{-4}$</td>
<td>$+2.80%$ $-2.86%$</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td>$2.88 \times 10^{-2}$</td>
<td>$+7.73%$ $-3.39%$</td>
</tr>
<tr>
<td>$H \rightarrow g\bar{g}$</td>
<td>$8.18 \times 10^{-2}$</td>
<td>$+8.22%$ $-8.14%$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$2.27 \times 10^{-3}$</td>
<td>$+3.36%$ $-3.27%$</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$1.54 \times 10^{-3}$</td>
<td>$+7.20%$ $-7.35%$</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^-$</td>
<td>$2.15 \times 10^{-1}$</td>
<td>$+2.61%$ $-2.59%$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$2.64 \times 10^{-2}$</td>
<td>$+2.61%$ $-2.59%$</td>
</tr>
</tbody>
</table>

2.2.2 BSM Higgs Boson

Other decays then those listed in (2.1) are not predicted by the SM and are the subject of the BSM search. Two of such decay channels which are examined in this thesis are:

$$H \rightarrow \bar{\tau} + \mu \quad \text{or} \quad H \rightarrow \tau + \bar{\mu} \quad (2.2)$$

$$H \rightarrow \bar{\tau} + e \quad \text{or} \quad H \rightarrow \tau + \bar{e} \quad (2.3)$$

The reason for these decays not being predicted by the SM is that they oppose the lepton flavour conservation, as illustrated on the example of $\mu$ decay following (2.1).

The existence of the decay (2.2) or (2.3) would indicate that the SM in its current form is not valid. However, there are already theories that are extending the current SM in which lepton flavour conservation is not demanded from the Higgs boson decays. Some of these theories work with the SM being extended by the existence of a second Higgs doublet, some rely on the existence of extra dimensions and some models suggest that the Higgs boson is not an elementary particle but a composite one [10]. An observation of any lepton flavour violating Higgs boson decay would encourage further examination of the aforementioned models.
2.2.3 Background Events

The $\tau$ leptons lifetime is $2.9 \cdot 10^{-13}$ s, approximating their velocity at LHC by the light velocity $c$, we see that their mean path before decay in their reference frame is $87\,\mu m$. Passing only this small distance, they decay inside of the beam pipe of the LHC [9]. In our analysis, we can therefore only reconstruct them by detecting their decay products, which can be both hadrons as well as leptons. In our analysis we will examine the (2.2) and (2.3) decay channels, where $\tau$ decays leptonically as $\tau \rightarrow \mu + \nu_\tau + \bar{\nu}_\mu$ or $\tau \rightarrow e + \nu_\tau + \bar{\nu}_e$.

There are various events that are recorded through the detection of two leptons, the Higgs boson decay only being one of them. Therefore, when trying to observe the Higgs boson decay, we need to deal with background events. The most significant background processes in our analysis are:

- **Z boson decay**
  Z boson can decay into two same flavoured leptons

- **Top quark (t quark) decay**
  Top quark can decay into lepton, neutrino and a b-hadron (hadron containing b quark). The b-hadron can further produce a single lepton and a neutrino. Furthermore, top quarks are usually produced in pairs of a top and an antitop quark, resulting in potentially high lepton-multiplicity events.

- **Vector boson interaction**
  Production of pairs WW, WZ or ZZ can further produce two detectable leptons accompanied by neutrinos, in case the bosons decay leptonically.

- **Fake decays**
  Events where one lepton from the boson decay is combined with a lepton coming from the decay of a heavy hadron (e.g. containing b or c quark). More information on the fake decays is provided in Section 4.1.3.

2.3 Particle Collisions

2.3.1 Cross Section and Luminosity

In this section we are going to introduce quantities which are essential for the description of particle collisions.

**Cross Section**

Cross section is a quantity defined for a collision of a particle with a general target (which can be another particle). It is the effective transverse area that needs to be hit by the particle in order for the particle to interact with the target. Since cross section is defined as an area, its unit is $m^2$. For practical reasons new unit called "barn" [b] is defined. The conversion relation is $1\,b = 10^{-28}\,m^2$ [5].
Luminosity

If we know the cross section $\sigma$ of certain event occurring during particle collisions in a particle collider, we can calculate the event rate according to the following equation [11]:

$$\frac{dN}{dt} = L \cdot \sigma$$  \hspace{1cm} (2.4)

Where $\frac{dN}{dt}$ is the number of events per second and the proportionality factor $L$ defines a new quantity called "luminosity".

For head-on collision of two particle bunches, luminosity $L$ can be calculated from the following equation [17]:

$$L = f_{coll} \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}$$  \hspace{1cm} (2.5)

Where $f_{coll}$ is the collision frequency of two bunches containing $n_1$ and $n_2$ particles, $\sigma_x$ and $\sigma_y$ are the root mean squares (RMS) of the Gaussian particle distributions in the plane perpendicular to the bunch trajectories.

In an actual experiment the luminosity is a function of time because the beam intensity decays with time. For calculation of the number of events that occurred during the time of run of a particle collider, it is practical to define "integrated luminosity" $L_{int}$ [11]:

$$L_{int} = \int_{t_1}^{t_2} L(t) dt$$  \hspace{1cm} (2.6)

Where $t_1$ is the start of the run of the particle collider and $t_2$ is the end of this period.

Considering that the cross section for certain event is time independent, total number of events $N$, characterised by cross section $\sigma$, occuring during the time of run of a particle collider can be obtained by integration of (2.4):

$$N = \sigma \cdot L_{int}$$  \hspace{1cm} (2.7)
2.3.2 Kinematics

In this section we will use the example pictured in Figure 2.2 to introduce quantities useful for the description of the kinematics of particle decays.

![Figure 2.2: Scheme of the Decay $H \rightarrow \bar{\mu} + \tau \rightarrow \bar{\mu} + e + \nu_\tau + \bar{\nu}_e$ in the Laboratory Reference Frame](image)

Transverse Variables

An important quantity describing the particle kinematics is the momentum $p$. However, only its component which is perpendicular to the beam axis is measured directly by the detectors. We call this component the transverse momentum $p_T$. Useful property of the $p_T$ is its invariance under the Lorentz transformation along the beam axis.

In the plane coordinates of the laboratory reference frame parametrized by the $z - axis$ (equivalent to the beam axis) and an angle $\theta$ (describing the angle between the $z - axis$ and the vector $\mathbf{p}$) the relation between $p$ and $p_T$ is:

$$p_T = p \cdot \sin \theta$$

In Figure 2.2, we denote the two neutrinos by only one trajectory. Since neutrinos cannot be detected, we do not know their momentum. However, we know that the initial $p_T$ of the particles moving along the beam is zero. By measuring the $p_T$ of all particles coming from a certain event, we can find out the $p_T$ we are missing in order for the momentum to stay conserved. We assign this missing $p_T$ to the undetected neutrinos and considering their negligible mass, we define the quantity ”missing transverse energy” $E_{T}^{\text{miss}}$, further referred to as MET [17]:

$$E_{T}^{\text{miss}} = -c \cdot \sum_i p_{T_i}$$

So far, we have described the decay in a plane. To describe it in the third dimension, additional coordinate needs to be introduced. Considering the cylindrical symmetry of the detector, we use the angle indicating rotation around the beam axis, we will denote the angle by $\phi$. Approximating the neutrinos trajectory by MET, we can think of the $\tau$ decay in Figure 2.2 as of a two-particle decay.
For a two-particle decay we can define missing transverse mass \( M_T \) of the original particle by the following relation \[17\]:

\[
M_T^2 \equiv (E_{T1} + E_{T2})^2 - (p_{T1} + p_{T2})^2 = m_1^2 + m_2^2 + 2[E_{T1} \cdot E_{T2} - p_{T1} \cdot p_{T2}] \quad (2.10)
\]

Where \( E \) stands for energy \( p \) for momentum, \( m \) for mass and indices 1 and 2 denote different decay products. A detailed derivation of a similar relation will be done in the section "Collinear Approximation".

In case where the decay products of the original particle are massless, \[2.10\] further simplifies as \[17\]:

\[
M_T^2 = 2|p_{T1}||p_{T2}|(1 - \cos \phi_{12}) \quad (2.11)
\]

Where \( \phi_{12} \) denotes the difference of the \( \phi \) coordinates of the \( p_{T1} \) and \( p_{T2} \) vectors.

**Pseudorapidity**

Instead of the use of the \( \theta \) coordinate as used in Figure 2.2, different coordinate is often used. This coordinate is called pseudorapidity \( (\eta) \) and its relation to \( \theta \) is \[5\]:

\[
\eta \equiv - \log(\tan \frac{\theta}{2}) \quad (2.12)
\]

**Collinear Approximation**

Having introduced MET, we can now represent the neutrinos in the decay in Figure 2.2 by their \( \phi \) coordinate and \( p_T \). However, we still need to assign pseudorapidity \( \eta \) to the MET to have a full description in 3 dimensions. Having no information about the \( \eta \) coordinate of the neutrinos, we need to make further approximation.

The simplest approximation is the so-called "collinear approximation". Based on the mass of the Higgs boson being expected to be significantly greater than the mass of the decay products \( (m_H >> m_\tau > m_\mu) \), we can neglect the mass of the decay products. In this approximation the momenta of the neutrinos have the same direction as the other \( \tau \) decay product \[5\]. Therefore, we can assign to the neutrinos the same \( \eta \) coordinate as measured for the detected product of the \( \tau \) lepton decay. In our case we assign to the neutrinos the same \( \eta \) coordinate as we measured for the detected electron. We can now describe the kinematics of both the electron and the neutrinos by \( p_T, \eta, \phi \) coordinates.

Using the collinear approximation, we will now reconstruct the invariant mass of the Higgs boson from the decay shown in Figure 2.2. We will work in the natural units, where \( c = 1 \). Based on the detection of \( \mu \) and \( e \), we can construct following vectors characterized by the \( p_T, \eta, \phi \) coordinates: \( p_\mu = (p_{T\mu}, \eta_\mu, \phi_\mu) \); \( p_e = (p_{Te}, \eta_e, \phi_e) \); \( p_{MET} = (MET, 0, \phi_{MET}) \).
Neglecting the neutrino mass and the electron mass, we can reconstruct the τ lepton momentum $p_{\tau} = p_e + (\hat{p}_e \cdot p_{MET})\hat{p}_e$. Where the $\hat{p}_e$ denotes the unit vector in the direction of $p_e$.

For the reconstruction of the Higgs boson mass from the known momenta $p_{\tau}$ and $p_\mu$, it is useful to realize the conversion between the $p_T$, $\eta$, $\phi$ coordinates and the Cartesian coordinates:

\[
\begin{align*}
  p_x &= p_T \cdot \cos \phi \\
  p_y &= p_T \cdot \sin \phi \\
  p_z &= p_T \cdot \sinh \eta
\end{align*}
\]

If we realize that $\sinh \eta = \cot \theta$ the conversion becomes clear.

For the Higgs boson mass ($m_H$) reconstruction, we first take the conservation law for four-momentum:

\[
\begin{pmatrix}
  E_H \\
  p_H
\end{pmatrix} = \begin{pmatrix}
  E_\mu \\
  p_\mu
\end{pmatrix} + \begin{pmatrix}
  E_\tau \\
  p_\tau
\end{pmatrix}
\]

(2.14)

By taking the square of (2.14) we get:

\[
m_H^2 = m_\mu^2 + m_\tau^2 + 2(E_\mu E_\tau + p_\mu \cdot p_\tau)
\]

(2.15)

By neglecting the mass of both leptons, their energy can be expressed by $E_\mu = |p_\mu|$ and $E_\tau = |p_\tau|$. The equation (2.15), simplifies as:

\[
m_H^2 = 2(|p_\mu||p_\tau| + p_\mu \cdot p_\tau)
\]

(2.16)

The conversion (2.13) helps us calculate the vector magnitudes and the dot product:

\[
m_H^2 = 2p_T p_T (\cosh \eta_\mu \cosh \eta_\tau - (\cos \phi_\mu \cos \phi_\tau + \sin \phi_\mu \sin \phi_\tau + \sinh \eta_\mu \sinh \eta_\tau))
\]

(2.17)

Using trigonometric and hyperbolic trigonometric identities we obtain the final equation:

\[
m_H^2 = 2p_T p_T (\cosh(\eta_\mu - \eta_\tau) - \cos(\phi_\mu - \phi_\tau))
\]

(2.18)
3. Data Acquisition

In order to be able to make a conclusion of the experiment and make a statement about the validity of the theoretical predictions, we have been provided both data gathered by the ATLAS experiment at LHC in CERN as well as various samples with Monte Carlo simulations, which stood for our idea of what is happening in the proton-proton collisions at LHC. In this chapter, we will introduce the way in which our data samples have been obtained.

3.1 The Large Hadron Collider

The LHC is the most powerful particle collider in the world, it has been built and is being maintained by CERN, the European Organisation for Nuclear Research. It is a circular device kept in a tunnel with circumference of about 26.7 km. Two directed particle beams are being accelerated and lead through the tunnel, each beam circulating on a different trajectory and heading in an opposite direction then the other beam. Both trajectories only intersect at four points of the LHC. Around those points seven detectors were build to gather information about the events caused by the particle collisions. The main four detectors are ATLAS, CMS, ALICE and LHCb.

Two kinds of particles are being accelerated by the LHC - lead nuclei and protons, each kind of particle being useful for different purpose. For the research of the Higgs boson decays, the study of proton-proton collisions is of interest. After several improvements were carried out, the device accelerates each beam to the energy of 6.5 TeV (designed up to 7 TeV). The injected proton beam is separated into maximum 2808 "bunches", the spacing of the bunches causes that two bunches collide every 25 ns at the collision points [8]. This period corresponds to the collision frequency of 40 MHz.
3.2 The ATLAS Detector

The data used in our analysis were acquired by the ATLAS detector (see Figure 3.1). The detector consists of several parts.

![Scheme of the ATLAS Detector](image)

Figure 3.1: Scheme of the ATLAS Detector [7]

3.2.1 Inner Detector

The inner detector consists of Transition Radiation Tracker (TRT), Semiconductor Tracker (SCT) and Pixel Detector. Closest to the collision point is the pixel detector. Being placed in three layers, with its high resolution of 80 million pixels it provides us with relatively precise measurement of the direction from which the detected particle came [20]. The entire inner detector is surrounded by toroidal and solenoid magnets, which cause the curvature of trajectories of the charged particles leaving the collision point. The direction of curve provides us with information about whether the charge of the particle is positive or negative and the measurement of the degree of curvature tells us the momentum of the charged particle.

To be able to reconstruct the trajectory, SCT is of great importance. Consisting of four double layers of silicon strips it works similar as the pixel detector, yet covers significantly longer part of the particle trajectory [14]. The TRT consists of tubes, which are 4 mm in diameter and contain gas which gets ionised by a charged particle passing through. Between the tubes are placed materials producing transition radiation in response to passing particle. The intensity of the signal recorded by ionisation is proportional to the speed of the particle. Since for fixed energy the lighter particles are faster than the heavier, the TRTs main function is to assign recorded trajectories to the recorded particles based on their mass [12].
3.2.2 Calorimeters

Around the solenoidal magnets, calorimeters are placed. Their task is to measure the energy of the passing particle by absorbing part of its energy. The inner calorimeter is electromagnetic (EM), its purpose is to measure the energies of the particles that interact via EM interaction and create EM showers in the calorimeter. In Figure 3.1, the EM calorimeter is described as Liquid Argon Calorimeter, because liquid argon is used to measure the energy of EM showers. The outer calorimeter is a hadron calorimeter, aiming at the energy measurement of the particles interacting via strong interaction. In Figure 3.1 it is described as the Tile Calorimeter.

3.2.3 Muon Detector

Because muons do not interact via strong nuclear force, any interaction with a nucleus, for example in the calorimeters, is rather unlikely to occur. Although, muons can - just like electrons - interact via EM interaction, they are more than 200 times heavier than electrons and thus only lose small fraction of their energy in collisions with electrons \[17\]. Their mass being higher then electrons also causes that their radiation losses are, in comparison to electrons, much lower. Since muons do not interact too easily, large fraction of the muons produced in the collisions passes through the inner detector and calorimeters without leaving behind enough traces for their tracking.

To be able to track the muons with high transverse momentum a specialized detector is needed. In the ATLAS detector the muon detector, also called the muon spectrometer, surrounds the calorimeters and occupies the majority of the detector volume. Otherwise it works similarly to the inner detector.

3.2.4 Triggers

As we already mentioned before, protons at the LHC are grouped into so-called “bunches”. In each bunch there is around \(1.15 \cdot 10^{11}\) protons. Around 20 protons collide per each bunch collision \[18\]. With 40 MHz frequency of bunch collisions and with circa 2 MB of raw data per proton-proton collision event \[19\] we are getting around 1.6 PB of data every second. It is not possible to store such a large amount of data. Since some events are more interesting for our purposes then others, there is a system of so-called triggers that choose the events which will be stored based on being potentially interesting.

The ATLAS trigger system in Run 2 is organised into two levels: Level 1 trigger (L1) comprises of fast electronics, which coarsely chooses events occurring in our high energy region of interest (RoI). L1 only has 2.5 \(\mu s\) to decide whether the event will be passed to the next level trigger or whether it will be ignored \[19\]. Within this short time it can only make its decision based on information from the calorimeter and muon detectors without accessing the information from the inner detector. The events that pass the L1 are passed to the next level trigger.
The next trigger is the so-called High level trigger (HLT). Thanks to the L1 pass rate of 100 kHz HLT has more time to evaluate the events - approximately 200 ms. This amount of time is sufficient for the HLT to utilise information from all of the detector levels and to use fast algorithms, which enable doing a more detailed analysis. The events that pass the HLT are then stored. The pass rate of the HLT is around 1 kHz [19].
4. Data Analysis

The analysis of the experiment is based on the comparison of the data acquired by the detectors with our prediction of the observed events. Our prediction comprises of MC simulations of the expected background events mentioned in Section 2.2.3 as well as of estimated "Fakes", that are based on real data. More detailed description of "Fakes" will be provided in this chapter in Section 4.1.3.

Our analysis also includes MC simulations of the sought for Higgs boson decays. Unlike the simulations of the well known background events whose free parameters of the theory are determined by experiment, some of the parameters for the signal events simulations, such as their cross sections times branching fractions, had to be estimated. In order to keep our analysis relevant towards the decays of our interest, careful event selection is essential. The following section provides us with the explanation of our event selection methodology.

4.1 Event Selection

Our data samples contain evidence of several different physical processes, our aim is to study the Higgs boson decays $H \rightarrow \tau\mu$ and $H \rightarrow \tau e$. In order to study the decays of our interest, we are going to apply various selection criteria, which would enable us to suppress the background, while keeping the most of the relevant events. In this chapter we will introduce the selection criteria we have applied.

4.1.1 Trigger Selection

Different High Level Triggers decide about whether the observed event should be stored or not. Based on the flavour of the leading lepton and eventually based on the $p_T$ of the subleading lepton, we require the fulfillment of the criteria of different HLTs. Electron triggers are given priority over the muon ones, because of their better efficiency. The subleading $p_T$ thresholds differ based on the year of data acquisition. Because of the luminosity increase in 2016, the thresholds for the 2016 data are more severe.

2015 Datasets

- **HLT mu20**
  
  Fulfillment of this trigger required for events, where leading lepton is a muon and the subleading electron has $p_T < 25$ GeV

- **HLT e24**
  
  Required otherwise
2016 Datasets

- **HLT mu26**
  Fulfillment of this trigger required for events, where leading lepton is a muon and the subleading electron has $p_T < 27$ GeV

- **HLT e26**
  Required otherwise

### 4.1.2 Other Selection Criteria

When handling the datasets, which come from an actual experiment, we need to check, whether the examined event was acquired while all of the detectors were working properly.

The following selection criteria were applied to both actual data samples as well as to simulations.

- **Number of primary vertices $> 0$**
  When two bunches collide, several proton proton collisions occur. The places where the proton-proton collisions took place are called vertices. The vertex from which came the particles with the largest sum of $p_T^2$ is called the primary vertex. This condition requires that for the examined event a primary vertex was successfully reconstructed based on the recorded data.

- **Number of electrons + number of muons $= 2$**
  Because of the decay channels we are examining, the expected particles that should be recorded by the detector are electrons or muons, their total number should be 2.

- **Opposite charge**
  Since Higgs boson, which we are looking for, has zero charge and we are looking for decay products of two charged leptons, we require that the leptons which we detect have an opposite sign, so that charge is conserved.

- **Different flavour**
  When looking for the decays $H \to \tau + \mu$ and $H \to \tau + e$, where $\tau$ decays as $\tau \to \mu + \nu + \bar{\nu}$ or $\tau \to e + \nu + \bar{\nu}$ recorded pairs of same flavour leptons as well as different flavour leptons could be of interest. However, when a pair of electrons or muons is detected, it is most likely a product of $Z \to e+\bar{e}$ or $Z \to \mu + \bar{\mu}$ respectively. This criterion is therefore aimed at suppressing the Z boson background.

- **Leading lepton $p_T > 45$ GeV/c and subleading lepton $p_T > 15$ GeV/c**
  The lepton $p_T$ thresholds are based on the mass of the Higgs boson. If we neglect the mass of the leading lepton compared to the mass of the Higgs boson $m_H$, we can expect that momentum of the leading lepton should roughly correspond to $\frac{1}{2} m_H/c$. Taking into account that not all of the

\[1\] Here we denote the leptons generally, without indicating the charged antileptons and without indicating the neutrino flavours.
momenta is transversal leads us to lowering the threshold for \( p_T \). For the subleading lepton \( p_T \) threshold the estimated neutrino and antineutrino \( p_T \)s need to be subtracted.

- **B veto**
  By this criterion, we require that in the observed event no b-hadron was reconstructed. Excluding the events with b-hadrons helps us suppress the top quark background.

- **\( p_T \) difference of the leptons > 7 \text{ GeV}/c**
  This criterion ensures that there is a clear \( p_T \) difference between the leading and the subleading lepton. In the events of our interest we expect the subleading lepton to have significantly lower \( p_T \) because it is produced in the \( \tau \) decay, where some of the \( \tau \) leptons \( p_T \) is given to a neutrino and an antineutrino.

- **Leading lepton \( m_T > 50 \text{ GeV} \) and subleading lepton \( m_T < 40 \text{ GeV} \)**
  The missing transverse mass \( m_T \) can be calculated from (2.10), its strong angular dependence can be best seen in the equation for massless particles (2.11). Because the neutrinos in the decays of our interest are more likely to travel along the trajectory of the subleading lepton than along the trajectory of the leading lepton (same as in the the collinear approximation), we expect the difference of \( \phi \) coordinates of the neutrinos and the leading lepton to be closer to \( \pi \) than the \( \phi \) difference of the subleading lepton and the neutrinos. Considering the angular dependence of the \( m_T \), this criterion helps us select the events whose MET is correlated with the subleading lepton \( p_T \), this corresponds to the events of our interest.

- **\( |\phi_{MET} - \phi_{subleading}| < 0.7 \)**
  This criterion has a similar meaning as the previous one, it helps selecting the events whose MET is correlated with the subleading lepton \( p_T \)

- **Dilep mass > 30 GeV and < 150 GeV**
  Choosing the events by the invariant mass of the two leptons in the region relevant for the Higgs boson.
4.1.3 Misidentified Leptons - ”Fakes”

In our event selection, we assume that the leptons that pass our selection are isolated (they were not detected inside of a jet), because the "Number of electrons + number of muons = 2" criterion implicitly demands that the reconstructed leptons passed the isolation criteria. Two isolation criteria were used when creating our data samples. The isolation criterion based on the data from the inner detector demands:

\[
\frac{p_T^{cone20}}{p_T^{lepton}} < 0.20 \quad (4.1)
\]

Where \( p_T^{cone20} \) denotes the total \( p_T \) detected within a cone with a base radius of \( dR = \sqrt{d\eta^2 + d\phi^2} = 0.20 \) surrounding the detected lepton. The quantity \( p_T^{lepton} \) denotes the \( p_T \) of the detected lepton. Similar criterion applies to transverse energy based on the data from the calorimeters.

We need to take into account the imperfection of this selection. This isolation criterion is not 100% efficient and an actual lepton coming from a decay of a heavy hadron can sometimes pass our selection and fake an isolated lepton. We want to estimate this kind of background. For that, we have a data sample of the so-called "Fakes".

We assume that the shape of the kinematic distributions of the leptons coming from a hadronic decay is independent of the ratio in (4.1). The shapes of the kinematic distributions can thus be measured in real data based on the events with anti-isolated leptons (leptons passing the anti-isolation criterion - (4.1) with opposite inequality) and this distribution profile is assigned to the misidentified leptons passing our selection. However, we cannot assume that the distribution among our selected events will have the same normalization as the distribution within the events passing the anti-isolation criterion. Therefore, after performing the whole analysis, we normalize the ”Fakes” distribution so that we have the same amount of events in the simulations as in the data.
4.2 Results

In the following section, we are providing the invariant mass histograms of the events that passed our selection. We have defined the signal region to be the interval between 100 and 160 GeV, where the hypothetical peak corresponding to the Higgs boson was to be expected. In this signal region, the data were blinded in order for the experimentalist to not be biased towards choosing such selection criteria, which would highlight the sought for peak. The usual practice is that the data can only be unblinded, when the data and the background are in a good match in the sideband (outside of the signal region).

The data we were provided by the ATLAS collaboration are being analysed by the members of the collaboration in parallel and the status of the data during the completion of this thesis requires that the data should stay blinded. Therefore, in our histograms the data corresponding to the signal region cannot be plotted.

4.2.1 Invariant Mass Histograms

Invariant Mass According to MMC

The histogram shown in Figure 4.1 contains the invariant mass distribution of our selected events as calculated by the missing mass calculator (MMC). MMC is a more sophisticated and precise algorithm for the calculation of the invariant mass. It considers the most probable $\eta$ coordinate for the neutrinos (which is not always the same as the $\eta$ of the subleading lepton as claimed by the collinear approximation). More about the MMC method can be found in [6]. Invariant mass reconstructed by the MMC was already provided in our data samples.

![Invariant Mass According to MMC](image)

Figure 4.1: Invariant Mass According to MMC
In Figure 4.1, we can see generally a match of the data and the backgrounds within their error bars, with the exception of the last bin, where we observe more events in the data than in the simulations. The match of the data and the backgrounds depends heavily on the efficiency of the reconstruction algorithms and the trigger efficiency. Major correction of one of the reconstruction algorithms has been implemented by the reconstruction of the fakes. Further, more elaborate, corrections could be employed in order to achieve better match. However, for a basic analysis we find the match of the data and the backgrounds to be satisfying. The histogram further contains the simulations of our examined LFV Higgs boson decays, the data in the signal region being blinded do not allow us to make a statement about the precision of this simulation.

Based on the histogram, we can see that the most dominant background process, which we did not manage to suppress, is the $Z \rightarrow \tau + \bar{\tau}$. We need to be careful when trying to suppress this background, because of its similarity to our signal events. When both of the $\tau$ leptons decay leptonically, it produces 4 neutrinos, our signal events produce 2. These two decays, only differing by two undetectable neutrinos, are therefore difficult to distinguish. On the other hand, we can see that our selection was quite successful with respect to suppressing the $Z \rightarrow e + \bar{e}$ background, which was aimed for by the ”Different flavour” criterion. Furthermore, considering the relatively low fraction of the $t$ quark background, we assume that the ”B veto” criterion was successful in suppressing this background.

**Invariant Mass in Collinear Approximation**

In Figure 4.2 we have plotted the histogram of the invariant mass calculated in the collinear approximation following (2.18).
We can see that the shape of the distribution of the invariant mass calculated in the collinear approximation ($m_{\text{coll}}$) slightly differs from the distribution shown in Figure 4.1. Generally, we can see a worse match of the data and the backgrounds in the sideband of Figure 4.2 compared to Figure 4.1. This can partially be due to the normalization of fakes being done based on the sideband of the invariant mass distribution according to the MMC. Some of the events from the signal region of the MMC distribution might have been assigned mass which lies the $m_{\text{coll}}$ sideband and vice versa. Therefore, when the normalization is not done based on all of the events from our analysis, the normalization factors for fakes might differ.

The peak corresponding to the simulations of the signal events in Figure 4.2 lies in the bin corresponding to $m_{\text{coll}}$ between 110 and 120 GeV. The mass of the Higgs boson, for which those simulations stood for, is known to be around 125 GeV, we consider this to be a clear indication of the insufficient precision of the collinear approximation.

### 4.2.2 Statistical Processing

The usual way to evaluate the significance of an excess observed in the data over simulation, is to evaluate the probability of the excess only being caused by a random fluctuation of the background. Our data are blinded in the signal region, therefore we cannot perform such analysis. We will however, describe the simplest way which could be used for such evaluation, in case our data in the signal region were accessible.

For the bin, where the excess would be the highest, we would subtract the number of background events from the number of events in the data. Let us denote this difference as $s$. The statistical significance $z$ of the excess can be calculated from the following equation:

$$z = \frac{s}{\sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2}}$$  \hspace{1cm} (4.2)

Where $\sigma_{\text{stat}}$ and $\sigma_{\text{sys}}$ stand for the statistical and systematic error of the background. In the case of the Poisson distribution (such as our case) $\sigma_{\text{stat}} = \sqrt{N}$, where $N$ is the number of events in the bin. The systematic error contains the uncertainties of the cross sections of the background processes as well as the uncertainties of simulations. The determination of the systematic error goes beyond the scope of this work.

The purpose of the statistical significance $z$ as defined in (4.2) is to tell, how many times was the observed excess greater than the error of the background. Based on the value of $z$, we can classify the statistical significance of the excess. In particle physics the most common thresholds of the significance are $z = 3$ and $z = 5$. We consider the excesses with $z \in (3, 5)$ to be an evidence of a new physical phenomena, whereas the excesses with $z > 5$ are considered to be a discovery of a new physical phenomena.
5. Summary

The aim of this thesis was to analyse potential LFV decays in the data gathered by the ATLAS experiment in CERN. Firstly, we have provided a brief theoretical introduction, necessary for the understanding of the analysis. The main part of the actual analysis was the event selection which comprised of an application of several selection criteria to the data samples with the aim to suppress the backgrounds while keeping the highest possible amount of the signal events. We have presented the outcome of our analysis in the form of the invariant mass histograms of the selected events.

Because the data in the signal region were blinded during the completion of this thesis, we cannot make a statement about whether we have observed the LFV decays or not. Instead of this conclusion, we can assess the results of the data selection with respect to the suppression of the backgrounds. Generally, we can say that the most of the backgrounds were suppressed to a satisfying measure, with the exception of the $Z \rightarrow \tau^+\tau^-$ decay which is difficult to distinguish from our signal events. Not being too restrictive with respect to the $Z \rightarrow \tau^+\tau^-$ background allowed us to keep the signal events in our analysis, as can be seen on the signal events simulations histograms in Figure 4.1 and Figure 4.2.

The match of the data and the backgrounds in the sideband in Figure 4.1 was within the respective error intervals in the majority of the sideband. However, in the last bin of the histogram, more events in the data than in the simulations were observed. We do not suppose this slight excess to be indicating any new physical phenomena. Instead, we take it as a sign that for a more detailed analysis, certain corrections to balance the inaccuracies of the reconstruction algorithms should be applied.

Figure 4.2 shows us that the collinear approximation method for the calculation of the invariant mass is less precise than the MMC. It can be seen from the position of the peak of the signal events simulations. This peak is expected to be placed in the bin next to the bin where the actual peak appeared. This is in contrast to Figure 4.1 where the peak appears in the expected bin.
Bibliography


## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Summary of the Standard Model</td>
<td>3</td>
</tr>
<tr>
<td>2.2</td>
<td>Scheme of the Decay $H \rightarrow \bar{\mu} + \tau \rightarrow \bar{\mu} + e + \nu_\tau + \bar{\nu}_e$ in the Laboratory Reference Frame</td>
<td>9</td>
</tr>
<tr>
<td>3.1</td>
<td>Scheme of the ATLAS Detector</td>
<td>13</td>
</tr>
<tr>
<td>4.1</td>
<td>Invariant Mass According to MMC</td>
<td>20</td>
</tr>
<tr>
<td>4.2</td>
<td>Invariant Mass in Collinear Approximation</td>
<td>21</td>
</tr>
</tbody>
</table>