

Universidade de Lisboa Instituto Superior Técnico

Search for Direct Stau Pair Production at 8 TeV with the CMS Detector

Cristóvão Beirão da Cruz e Silva

Supervisor: Doctor João Manuel Coelho dos Santos Varela

Co-Supervisors:

Doctor André David Tinoco Mendes

Doctor Pedrame Bargassa

Thesis approved in public session to obtain the PhD Degree in
Physics

Jury final classification: Pass with Distinction

Jury

Chairperson: Chairman of the IST Scientific Board

Members of the Committee:

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“The story so far:

In the beginning the Universe was created.

This has made a lot of people very angry and been widely regarded as a bad move.”

— Douglas Adams, *The Restaurant at the End of the Universe*

Dedicated to my parents.

To my father, whom I miss every day

To my mother, for being very supportive,
specially in the stressful times of
preparing this thesis.

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Resumo

No Modelo Padrão da Física de Partículas, as massas das partículas são geradas através do mecanismo de Higgs que quebra a simetria electrofraca. O mecanismo de Higgs prevê a existência do bóson de Higgs. Resultados recentes de ambas as experiências ATLAS e CMS reportam a descoberta de uma nova partícula consistente com o bóson. Contudo, o sector de Higgs do Modelo Padrão sofre do chamado problema de hierarquia para o qual a supersimetria é uma possível solução. A supersimetria postula a existência de novas partículas, parceiras das partículas conhecidas, com o spin a diferir por meia unidade. A procura por estas novas partículas é, desta forma, um empreendimento importante na busca de uma compreensão mais profunda da teoria fundamental das partículas elementares.

Esta tese descreve a pesquisa pelo parceiro supersimétrico do leptão tau (stau). Os staus subsequentemente decaem para um leptão tau regular e um neutralino. A tese considera o estado final semi-hadronico, onde um dos taus decai para um electrão ou muão e o outro decai hadronicamente. O desafio desta tese prende-se com a identificação do leptão tau, sendo o fundo de taus falsos provenientes de eventos W+Jets de importância fulcral.

Resultados a partir dos dados recolhidos por CMS em 2012 a 8 TeV são apresentados, correspondendo a uma luminosidade de $19.7 fb^{-1}$. É requerido que os eventos tenham um par de sinal oposto de um electrão ou muão e um tau associado com energia transversa em falta e sem “b-jets”. O fundo principal, taus falsos, foi medido a partir dos dados. A análise emprega uma simulação com um modelo de espectro simplificado para gerar a simulação do sinal, permitindo assim que o resultado final seja apresentado da forma mais independente possível. Não foi encontrado nenhuma evidência significativa de sinal e limites foram estabelecidos na secção eficaz vezes o rácio de ramificação. Os resultados também foram interpretados sob o cenário de MSSM onde o stau é o NLSP e o neutralino o LSP.

Palavras-chave: física de altas energia, supersimetria, tau supersimétrico, CMS, LHC

Abstract

In the Standard Model (SM) of Particle Physics, the particle masses are generated through the Higgs mechanism through the breaking of the electroweak symmetry. The Higgs mechanism predicts the existence of the Higgs boson. Recent results from both the ATLAS and CMS experiments report the discovery of a new particle consistent with the Higgs boson. However, the Higgs sector of the SM suffers from the so-called hierarchy problem to which Supersymmetry is a possible solution. Supersymmetry postulates the existence of new particles, partners to the known particles, with spin differing by half a unit. The search for these new particles is, in this way, an important endeavour in the search for a deeper understanding of the fundamental theory of elementary particles.

This thesis describes a search for the supersymmetric partner of the tau lepton (stau). The staus subsequently decay to a regular tau lepton and a neutralino. The thesis considers the semi-hadronic final state, where one of the taus decay to an electron or muon and the other decays hadronically. The challenge in this analysis rests with the identification of the tau lepton, where the fake tau background from W+Jets events proved of particular importance.

Results from CMS proton-proton data recorded in 2012 at 8 TeV are presented, with an integrated luminosity of 19.7 fb^{-1} . The events were required to have an opposite sign pair of an electron or muon and a tau in association with missing transverse energy and no b-jets. The main background, fake taus, was measured from data. The analysis employs a simplified model spectra simulation to generate the signal simulation, allowing the final result to be presented in an as model independent way as possible. No significant evidence of signal was observed and limits were established on the cross section times branching ratio. The results were also interpreted under the MSSM scenario where the stau is the NLSP and the neutralino the LSP.

Keywords: high energy physics, supersymmetry, supersymmetric tau, CMS, LHC

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Glossary

Einstein summation convention A notational convention that implies the following equivalence:

$$a^\mu b_\mu = \sum_\mu a^\mu b_\mu$$

isolation parameter A quantity used to reject non-prompt or misidentified leptons. It is computed in a specified cone around the lepton momentum based on the charged hadrons, photons and neutral hadrons. In essence it is the energy originating from other particles within the cone and it is estimated with (from [1]):

$$I_{e,\mu} = \sum_{\text{charged}} p_T + \max \left(0, \sum_{\text{neutral}} p_T + \sum_{\gamma} p_T - 0.5 \sum_{\text{charged, pileup}} p_T \right)$$

$$I_{\tau} = \sum_{\text{charged}} p_T + \max \left(0, \sum_{\gamma} p_T - 0.46 \sum_{\text{charged, pileup}} p_T \right)$$

majorana fermion A Majorana fermion is a fermion that is its own antiparticle, hypothesized by Ettore Majorana in 1937.

pseudorapidity It is often used as a spatial coordinate of an object, analogous to the angle of the three-momentum of the object with the beam axis (θ). Pseudorapidity is often referred to with the symbol η . It is defined as:

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

p-value Used in frequentist statistics, it is a function of the observed sample results relative to a statistical model and measures how extreme the observation is.

ΔR Quadrature sum of the difference in azimuthal angle and the difference in pseudorapidity:

$$\Delta R^2 = \Delta \Phi^2 + \Delta \eta^2$$

relative isolation The isolation parameter normalised to the transverse momentum of the particle:

$$I_{\ell}^{rel} = \frac{I_{\ell}}{p_T(\ell)}$$

transverse momentum Component of the momentum perpendicular to the beam axis, often denoted with p_T .

turn-on curve Usually used in reference to the transverse momentum of an object in conjunction with trigger and reconstruction. It results from the fact that the trigger is performed on a simplified object and the reconstruction then smears the transverse momentum spectrum of the object (with respect to what the trigger sees). In consequence, the efficiency of the object as a function of the reconstructed transverse momentum is not a step function, as usually desired, but is smeared resulting in the so-called turn-on curve.

Acronyms

2HDM Two Higgs Doublet Model

ALICE A Large Ion Collider Experiment

ATLAS A Toroidal Large Hadron Collider Apparatus

CERN European Organization for Nuclear Research

CMS Compact Muon Solenoid

CR Control Region

CSV Combined Secondary Vertex

DAQ Data Acquisition

DQM Data Quality Monitoring

DY Drell-Yan

ECAL Electromagnetic Calorimeter

EWT Electroweak Theory

FOM Figure of Merit

HCAL Hadronic Calorimeter

HLT High-Level Trigger

HPS Hadron Plus Strips

ID Identification

L1 Level-1

LEP Large Electron-Positron Collider

LHC Large Hadron Collider

LHCb Large Hadron Collider beauty
LHCf Large Hadron Collider forward
LSP Lightest Supersymmetric Particle

MC Monte Carlo
MET Missing Transverse Energy
MoEDAL Monopole and Exotics Detector at the LHC
MSSM Minimal Supersymmetric Standard Model
MVA Multivariate Analysis

NLSP Next to Lightest Supersymmetric Particle
nvtx Number of Vertices

OS Opposite Sign

PDF Parton Distribution Function
PF Particle Flow
pMSSM Phenomenological Minimal Supersymmetric Standard Model
POG Physics Object Group
PS Proton Synchrotron
PU Pile-up
PV Primary Vertex

QCD Quantum Chromodynamics
QED Quantum Electrodynamics

SM Standard Model
SMS Simplified Model Spectra
SPS Super Proton Synchrotron
SR Signal Region
stau Supersymmetric Tau Partner
SUSY Supersymmetry

TOTEM Total Elastic and diffractive cross section Measurement

Chapter 1

Introduction

Physics can be described as the branch of science concerned with the nature and properties of energy and matter and their interactions. One of the fields of physics at the forefront of our current knowledge is particle physics. Particle physics deals with elementary particles and their interactions. The theoretical framework upon which particle physics is built is the so-called Standard Model (SM) of Elementary Particles and their interactions. Throughout the years, after many stringent tests, the SM has proven to be an extremely successful theory with unprecedented agreement with experimental data and also through the prediction of several new phenomena which have been successfully observed. An essential piece of the SM, which eluded experimental confirmation for many years, is the electroweak symmetry breaking, manifested through the so-called Higgs mechanism. The Higgs mechanism predicted the existence of a neutral scalar particle, the Higgs boson, which couples to all elementary particles, bestowing them their mass.

Studying particle physics is a challenging prospect since most of the particles under study are no longer readily found in nature. Ordinary matter is made up of up and down quarks and electrons, with the photon completing the picture of the readily available elementary particles. In order to study the other elementary particles, they must be produced. Typically existing for fleeting moments before decaying to stable elementary particles, requiring their existence to be inferred. These particles are created, for instance, through the collision of ordinary particles that have been accelerated, a practical application of the well-known mass-energy equivalence formalised by Einstein, $E = mc^2$. This is achieved through the use of particle accelerators, which

collide particles at the centre of large experimental detectors. The collisions of elementary particles are probabilistic in their nature and are governed by Quantum Mechanics. Consequently, the analysis of the data from the detector is, in its essence, a statistical analysis and many collisions must be performed in order to obtain meaningful results.

The European Organization for Nuclear Research (CERN) has a long history in the field of physics, operating particle accelerators since 1957, shortly after its inception in 1954, for research purposes. Examples of accelerators operated by CERN include the Super Proton Synchrotron (SPS), the Large Electron-Positron Collider (LEP) and more recently the Large Hadron Collider (LHC). The SPS was commissioned in 1976, having been converted into a $p\bar{p}$ collider in 1981. Two years later, the SPS was at the centre of the discovery of the W and Z bosons, the carriers of the weak interaction. The SPS is still in use today as the beam source for several experiments, including as an injector for the LHC. The LEP was in operation between 1989 and 2000 and was used to perform precision measurements for the electroweak theory. At its end of life, it was decommissioned to make space for the LHC.

The LHC accelerates protons (and lead-ions), with a designed centre of mass energy of 14 TeV. After a rocky start, in 2010 and 2011 LHC was operational at an energy of 7 TeV, having increased the energy to 8 TeV in 2012. After a long shutdown in 2013 and 2014, during which upgrades were performed, the LHC restarted taking data in 2015 at an energy of 13 TeV. One of the main goals in the conception of the LHC was to ascertain whether the Higgs boson exists or not, in this way completing the picture of the SM. The LHC has 4 main experiments, where the particle beams are made to collide. The experiments are: A Large Ion Collider Experiment (ALICE); A Toroidal Large Hadron Collider Apparatus (ATLAS); Compact Muon Solenoid (CMS); and Large Hadron Collider beauty (LHCb). ATLAS and CMS are so-called general purpose detectors as they strive to have a physics program as encompassing as possible. ALICE and LHCb are specialised detectors, targeted to specific objectives:

- ALICE is specialised in lead-ion collisions
- LHCb is focused on the study of physics of the bottom quark and the matter/antimatter asymmetry

Beyond the main experiments, there are several other smaller experiments, such as Large Hadron Collider forward (LHCf), Monopole and Exotics Detector at the LHC (MoEDAL) and Total

Elastic and diffractive cross section Measurement (TOTEM).

CMS is a 21.6 m long, 14.6 m wide, 14 000 t heavy detector that covers almost the full solid angle. A distinctive feature of the detector, and inspiration for its name, is the superconducting solenoid. The magnetic field from the solenoid bends the trajectories of the charged particles formed in the collisions, this allows the momentum of those particles to be measured. As many detectors in the High Energy Physics field, CMS has an onion-like structure with several layers of subdetectors, each targeting a specific type of particle or property of a particle. CMS is able to record the collision data at a rate of 40 MHz, the design frequency of the LHC. Subsequently the trigger system selects a subset of interesting events to be saved to storage and reconstructed for analysis, which reduces the rate to a few 100 Hz.

Searches for the Higgs boson have been under way for decades, with direct searches being performed with several particle accelerators, such as: at the SPS (in $p\bar{p}$ collisions), at the LEP (in e^-e^+ collisions), at the Tevatron (in $p\bar{p}$ collisions) and at the LHC (in pp collisions). Recently, in 2012, the LHC has discovered a new particle consistent with the Higgs boson. Further results in 2013 constrained this new particle to be even more Higgs-like. This discovery by the LHC falls in line with previous discoveries, a very amusing factoid, whereby the bosonic elementary particles have all been discovered in Europe and the fermionic elementary particles in the anglo-saxon countries [2]. With the discovery of the Higgs boson, the so-called hierarchy problem is brought to the forefront of Physics. Several theories have been proposed as solutions to this problem. Among these theories, the most popular one is known as Supersymmetry (SUSY), which establishes a new symmetry between bosons and fermions.

This thesis describes a search for the direct pair production of the Supersymmetric Tau Partner (stau) using the CMS detector. The search is sensitive to processes with a final state of missing transverse energy, one lepton (electron or muon) and one hadronically decaying tau lepton, with the results being interpreted under a SUSY perspective. The presence of stau pairs would lead to an excess of events with respect to the SM background. Results are given for 19.7 fb^{-1} of proton-proton collision data with a centre of mass energy of 8 TeV recorded in 2012.

The thesis is structured as follows. The standard model and its minimal supersymmetric extension are reviewed in Chapter 2. The experimental apparatuses, i.e. the CERN LHC and CMS, are described in Chapter 3. The software stack, including simulation and reconstructions algo-

rithms, has an essential role in complex physics analysis and is briefly discussed in Chapter 4. The base event selection criteria, the first step of the analysis software, is described in Chapter 5. Advanced selection criteria, targeted to the signal under study, are described in Chapter 6. A data-driven fake tau estimation method, crucial for the background estimation, is described in Chapter 7. The systematic uncertainties and their effects on the analysis are described in Chapter 8. Chapter 9 finishes the thesis, presenting the search results followed by conclusions and a short discussion of the results obtained.

Chapter 2

The Standard Model of Particle Physics and Supersymmetry

The concept that matter is made from a set of basic building blocks can be traced back to antiquity. For instance, ancient Greek philosophers set up the hypothesis that the universe consists of “ἄτομα” (*atoma*), indivisible elementary blocks of matter, from which the modern name of atom is derived. In modern physics, this concept of elementary blocks of matter is still present. In particular, in the Standard Model of particle physics it is manifested by the elementary particles which constitute all matter.

The Standard Model (SM) of particle physics is a theory describing the electromagnetic, weak and strong interactions of elementary particles. The theoretical and mathematical framework upon which the SM is built is quantum field theory, which combines special relativity and quantum mechanics. Furthermore, the SM is a gauge theory, respecting a group of symmetries. Under the SM, a group of particles, or vacuum itself, is determined by the lagrangian density. The equations of motion of the system can be derived from the lagrangian density, which is a function of the fields. From a theoretical perspective, the SM is an attractive theory because the description of the interactions arises naturally from symmetry principles. In particular that the lagrangian be invariant under certain local unitary transformations, the so-called gauge transformations.

The known particles, summarised in Fig. 2.1, constitute the particle content of the SM. Two

classes of particles can be identified:

- Fermions – named from the fact that they are characterised by Fermi-Dirac statistics. They have half integer spin and are the constituents of matter. The fermions are further subdivided into 3 families, or generations. Fermions are also subdivided into quarks and leptons.
- Bosons – named from the fact that they are characterised by Bose-Einstein statistics. They have integer spin and the exchange of bosons between fermions constitutes interactions between those fermions, i.e. they are the *force carriers*.

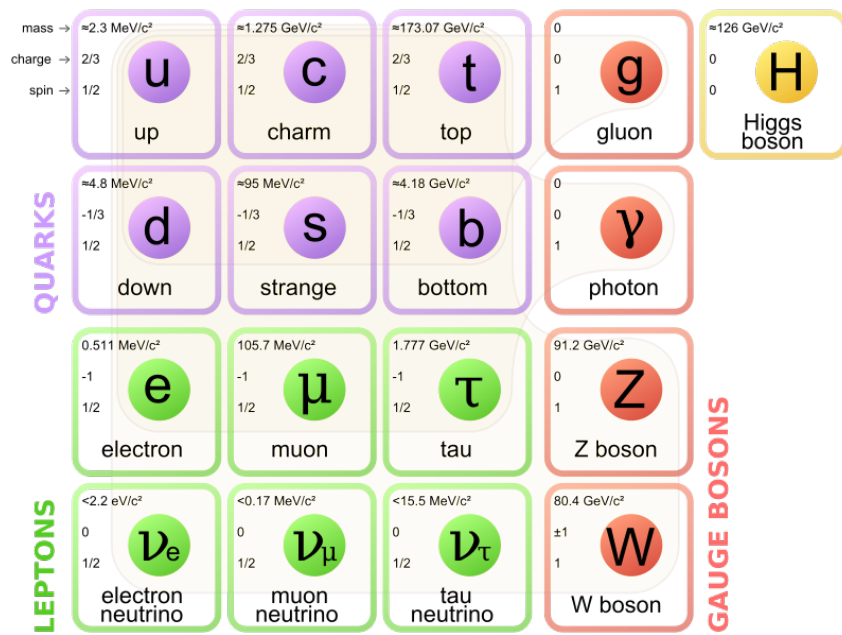


Figure 2.1: Particle content of the Standard Model, taken from [3]

There are four known forces in nature, the electromagnetic force, the weak force, the strong force and the gravitational force. The gravitational force is, so far, the only force not included within the framework of the SM. It is the weakest of all the forces, which is reflected in the fact that its effects are only observed when the objects being considered are massive, such as a planet, a sun or even a whole galaxy. This weakness of the gravitational force explains why very small objects, such as elementary particles, have vanishingly small gravitational interactions. Which is why, for the most part, it can be neglected in microscopic models such as the SM.

The electromagnetic force, is the most familiar of the forces. It is responsible for most of the phenomena observed during a person's daily life, ranging from our basic senses up to phenomena such as electricity, radio and even friction. Its name comes from the fact that it describes both

electric and magnetic phenomena. Quantum Electrodynamics (QED) is the field theory which describes the interactions of charged particles with photons. QED can be considered as the subset of the SM which accounts for only the electromagnetic force.

The weak force is responsible for radioactive decay, having an essential role in nuclear fission and nuclear fusion. It is unique among the forces since it allows for mixing of the different particle generations. The electromagnetic and weak forces are unified under a single force, called the electroweak force. The field theory describing the electroweak force is Electroweak Theory (EWT) and, like QED, EWT can be considered a subset of the SM.

The strong force is the strongest amongst the known forces, hence its name. It is a confining force, binding quarks together to form hadrons (2 quarks form mesons and 3 quarks form baryons) and binding protons and neutrons together to form the nucleus of atoms. The strong force has 3 associated charges which form a good analogy with the 3 primary colours when performing charge conservation calculations, hence it is also referred to as the colour force. The field theory describing the strong force is called Quantum Chromodynamics (QCD). Like EWT, QCD can be considered another subset of the SM and, up to current knowledge, it does not unify with the electroweak force.

With this minimal prescription of using EWT and QCD, most known phenomena can be described. However, EWT and QCD are not enough to account for all measured properties of the elementary particles since given the symmetries respected by this would-be theory, the particles would have no mass. This goes against experimental evidence, where only the photon has been measured, up to a very strict uncertainty, to be massless¹ [4]. The particle masses can be introduced in the theory by breaking the electroweak symmetry through the so-called Higgs mechanism. The Higgs mechanism predicts the existence of a neutral scalar boson, the Higgs boson. Until recently, experimental evidence consistent with the Higgs boson had not been seen. In the summer of 2012, results from the CERN LHC by both the CMS and ATLAS collaborations reported the discovery of a new boson [5, 6], with further measurements revealing its consistency with the Higgs boson [7–9].

The SM has revealed an unprecedented agreement between theory and experiment, in some

¹It should be noted that the gluon is expected to also be massless, although there are no experimental limits on its mass.

situations with a precision of 10 parts in a billion. Despite all of its successes, there are known deficiencies in the SM, for instance gravitation is not included. Several theories beyond the SM have been proposed to tackle its shortcomings. SUSY is one of these theories, introducing a new symmetry between bosons and fermions. SUSY tackles the so-called hierarchy problem, which will be elaborated on in section 2.2, and simultaneously provides convenient candidate particles for dark matter.

A full in depth treatment of the SM and SUSY will not be presented here. Only the most important and relevant aspects will be shown. A more detailed introduction may be found elsewhere [10–13].

2.1 The Standard Model of Particle Physics

2.1.1 Gauge Symmetries

In physics, the concept of a symmetry stems from the assumption that a certain quantity is not measurable. This is, given that a quantity is not measurable, the equations of motion should not depend on it and should be invariant under transformations of that quantity. Furthermore, through Noether’s theorem, it can be shown that each symmetry relates to a conservation law.

Some simple examples are the symmetries of space and time. The assumption that the origin of the coordinate system cannot be measured implies that the equations of motion should not depend upon the absolute space-time position. In fact, the equations of motion should be invariant under space translations, which through Noether’s theorem leads to the conservation of momentum. In a similar manner, the conservation of energy and of angular momentum can be obtained from the invariance under time translations and space rotations, respectively. These symmetries are geometrical in their nature and are easy to understand and visualise. The concept of a symmetry can be further generalised into, *internal* symmetries and *local* symmetries.

Internal symmetries are those whose transformation parameters do not affect the space-time point x . The simplest example of an internal symmetry is the phase of a wave function, known to be a non-measurable quantity. Consequently, the theory should be invariant under a change

of phase:

$$\Psi(x) \rightarrow e^{i\theta}\Psi(x) \quad (2.1)$$

This transformation leaves the space-time point invariant, so it is an internal symmetry. Through Noether's Theorem, invariance under a change of phase implies the conservation of the probability current.

The concept of a local gauge symmetry was introduced by Albert Einstein with the theory of General Relativity. Consider a space translation, as shown in Fig. 2.2. If A is the trajectory of a free particle in the (x, y, z) system, the transformed trajectory A' is also a possible trajectory of a free particle in the transformed (x', y', z') system. In other words, the dynamics of free particles are invariant under space translations by a constant vector. Since $\vec{a}$ does not depend on the space-time point x , this is a *global* transformation.

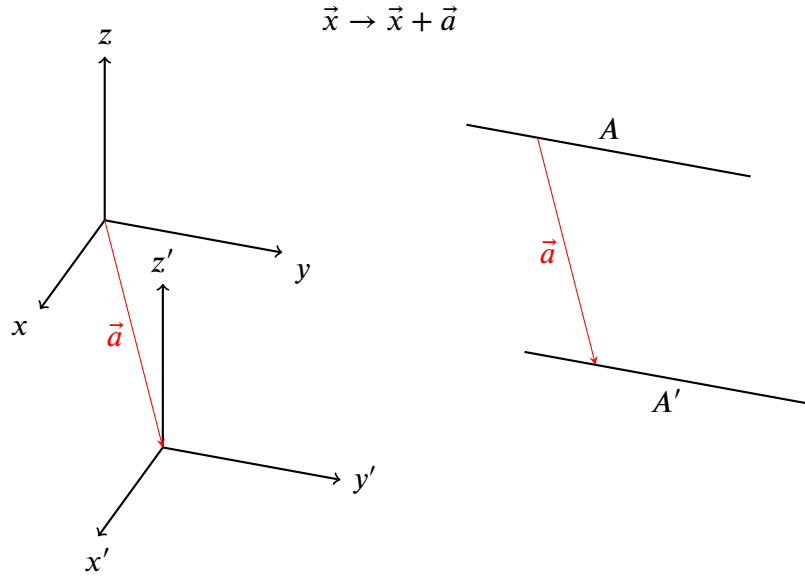


Figure 2.2: A space translation by a constant vector $\vec{a}$

By replacing $\vec{a}$ with an arbitrary $\vec{a}(x)$, the previous space translation transformation is turned into a local transformation, i.e. a transformation where the parameters are a function of the space-time point, shown schematically in Fig. 2.3. It is clear that a free particle would not follow the trajectory A'' . For A'' to be a trajectory, the particle must be subject to external forces. The theory that results from the determination of these forces, invariant under local transformations, is Classical General Relativity.

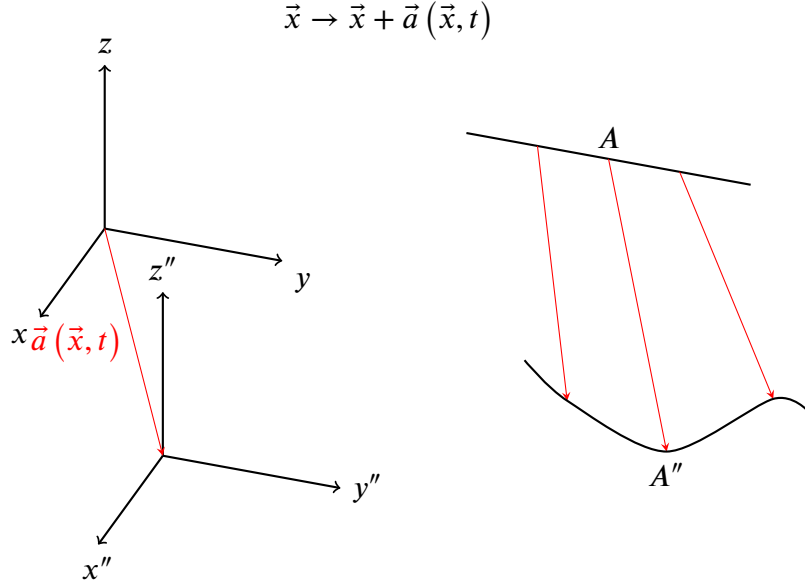


Figure 2.3: A space translation by a space-time dependent vector $\vec{a}(x)$

Returning to the example of the phase of a wave function, the lagrangian for a free half-spin fermion, the Dirac Lagrangian, is given by Eq. 2.2, where the Einstein summation convention is used, γ^μ are the four Dirac matrices, $\Psi = \Psi(x)$ is the Dirac spinor describing the (particle) field and m is the mass of the particle. The Dirac Lagrangian is invariant under internal transformations, for example the phase transformation, Eq. 2.1. The phase transformation can be made into a local transformation by replacing θ with $\theta(x)$, Eq. 2.3. However, the Dirac Lagrangian is not invariant under this transformation.

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

$$\Psi(x) \rightarrow e^{i\theta(x)} \Psi(x) \quad (2.3)$$

The Dirac Lagrangian is not invariant under local transformations because the derivative term in Eq. 2.2 gives rise to a term proportional to $\partial_\mu \theta(x)$. In order to restore gauge invariance, the equation must be modified, by replacing the derivative, ∂_μ , for the covariant derivative Eq. 2.4, where e is an arbitrary real constant and a new field, $A_\mu = A_\mu(x)$, is introduced which must undergo the transformation in Eq. 2.5 under a gauge transformation. D_μ is called the covariant derivative because it satisfies Eq. 2.6.

$$D_\mu = \partial_\mu + ieA_\mu \quad (2.4)$$

$$A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e} \partial_\mu \theta(x) \quad (2.5)$$

$$D_\mu \left[e^{i\theta(x)} \Psi(x) \right] = e^{i\theta(x)} D_\mu \Psi(x) \quad (2.6)$$

The gauge invariant Dirac Lagrangian is given by Eq. 2.7, which describes the interaction of a charged spinor field with an external electromagnetic field. Replacing the derivative operator by the covariant derivative turned the Dirac Lagrangian into the same equation but in the presence of an external electromagnetic field, represented by the field A_μ .

$$\begin{aligned} \mathcal{L} &= \bar{\Psi} \left(i\gamma^\mu D_\mu - m \right) \Psi \\ &= \bar{\Psi} \left(i\gamma^\mu \partial_\mu - e\gamma^\mu A_\mu - m \right) \Psi \end{aligned} \quad (2.7)$$

The complete picture can be obtained by including into Eq. 2.7 the lagrangian density corresponding to the degrees of freedom of the electromagnetic field itself. The form for these degrees of freedom is uniquely determined by the gauge invariance, in a similar manner to what was shown for the Dirac Lagrangian. Adding these terms to Eq. 2.7 results in:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) + \bar{\Psi}(x) \left(i\gamma^\mu D_\mu - m \right) \Psi(x) \quad (2.8)$$

with

$$F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x) \quad (2.9)$$

In summary, the starting theory, invariant under a group $U(1)$ of global phase transformations, was extended to have a local invariance, interpreted as a $U(1)$ symmetry at each point x . This extension, achieved through a purely geometrical requirement, implies the introduction of new interactions. Without it being introduced in the original theory, these “geometrical” interactions describe the well-known electromagnetic forces.

The transformations of the $U(1)$ group commute, consequently the $U(1)$ group is a so-called *Abelian* group. A useful generalisation is the extension of the previous formalism to non-Abelian groups. However, this is a non-trivial task, first discovered by trial and error, and goes beyond the scope of this thesis. Despite this, the results of such a generalisation are necessary to write the SM lagrangian.

2.1.2 Spontaneous Symmetry Breaking

Let $\phi(x)$ be a classical complex scalar field, the classical lagrangian density describing the dynamics is given by Eq. 2.10. This lagrangian is invariant under the group $U(1)$ of global transformations, Eq. 2.11.

$$\mathcal{L}_1 = (\partial_\mu \phi) (\partial^\mu \phi^*) - M^2 \phi \phi^* - \lambda (\phi \phi^*)^2 \quad (2.10)$$

$$\phi(x) \rightarrow e^{i\theta} \phi(x) \quad (2.11)$$

The second two terms of Eq. 2.10 correspond to the potential, Eq. 2.12. The ground state of the system corresponds to the minimum of $V(\phi)$. The minimum only exists if $\lambda > 0$ and the position of the minimum depends on the sign of M^2 , see Fig. 2.4.

$$V(\phi) = M^2 \phi \phi^* + \lambda (\phi \phi^*)^2 \quad (2.12)$$

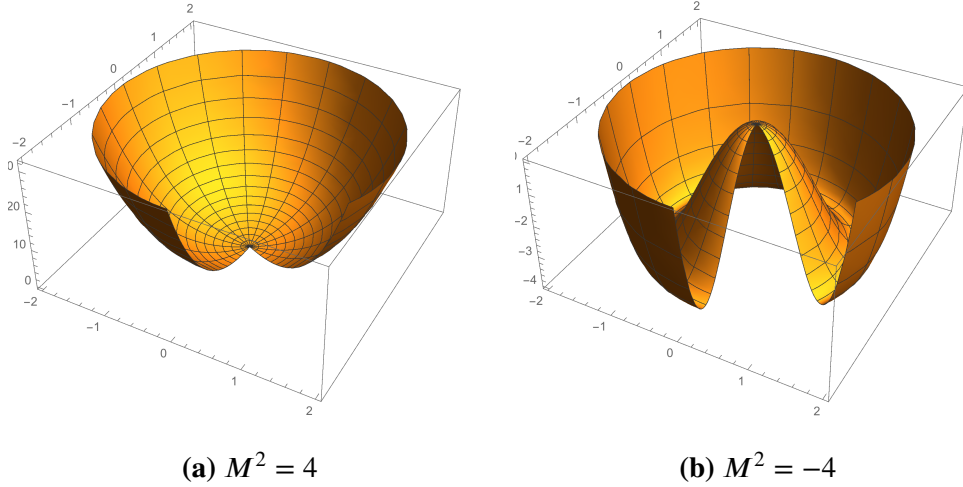


Figure 2.4: The potential $V(\phi)$, with $\lambda = 1$ and $|M^2| = 4$

For $M^2 > 0$, the minimum is at $\phi = 0$, a symmetric solution shown in Fig. 2.4a. For $M^2 < 0$ the solution is still symmetric but there is a circle of minima with radius $v = (-M^2/2\lambda)^{1/2}$, Fig. 2.4b. Each point on the circle of minima is a ground state with the same energy, i.e. the minima is degenerate and the ensemble of ground states is symmetric. Given the degeneracy of the ground state, a physical system at its minimal energy configuration must take one of the points on the circle. By “choosing” one of these points, the system is no longer in a symmetric situation and in this way the symmetry is spontaneously broken.

It can be useful to express the lagrangian around a given ground state, to this effect the field ϕ is translated. This transformation does not lead to a loss of generality since any point on the circle of minima can be obtained from any other given point by the transformation in Eq. 2.11. It is convenient to choose a point along the real axis in the ϕ -plane for the translation. Consequently, the field is written as Eq. 2.13. The lagrangian, Eq. 2.10, is then expressed as Eq. 2.14.

$$\phi(x) = \frac{1}{\sqrt{2}} [v + \psi(x) + i\chi(x)] \quad (2.13)$$

$$\begin{aligned} \mathcal{L}_1(\phi) \rightarrow \mathcal{L}_2(\psi, \chi) = & \frac{1}{2} (\partial_\mu \psi)^2 + \frac{1}{2} (\partial_\mu \chi)^2 - \frac{1}{2} (2\lambda v^2) \psi^2 \\ & - \lambda v \psi (\psi^2 + \chi^2) - \frac{1}{4} (\psi^2 + \chi^2)^2 \end{aligned} \quad (2.14)$$

The lagrangians $\mathcal{L}_1$ and $\mathcal{L}_2$ are completely equivalent and describe the dynamics of the same physical system. However, one can be more suitable to resolve certain classes of problems than the other. For instance, when using perturbation theory $\mathcal{L}_2$ is more likely to give sensible results, since $\mathcal{L}_1$ is described around an unstable point, a local maximum. The lagrangian $\mathcal{L}_2$ can be interpreted as describing a quantum system which consists of two interacting scalar particles, one with mass $m_\psi^2 = 2\lambda v^2$ (the third term in Eq. 2.14) and the other with $m_\chi = 0$, a so-called massless Goldstone boson.

In the presence of a gauge symmetry, spontaneous symmetry breaking leads to an interesting result. As in section 2.1.1, the lagrangian $\mathcal{L}_1$ is made gauge invariant by promoting the $U(1)$ symmetry to a gauge symmetry, with $\theta \rightarrow \theta(x)$, and replacing the derivative operator ∂_μ with the covariant derivative D_μ . As previously described, this implies the introduction of a massless vector field, A_μ , which can be called the “photon”. The photon kinetic energy term is also introduced, and Eq. 2.15 is obtained, which is invariant under the gauge transformation in Eq. 2.16.

$$\mathcal{L}_1 \rightarrow \mathcal{L}_1 = -\frac{1}{4} F_{\mu\nu}^2 + |(\partial_\mu + ieA_\mu)\phi|^2 - M^2 \phi\phi^* - \lambda(\phi\phi^*)^2 \quad (2.15)$$

$$\phi(x) \rightarrow e^{i\theta(x)}\phi(x); \quad A_\mu \rightarrow A_\mu - \frac{1}{e}\partial_\mu\theta(x) \quad (2.16)$$

Spontaneous symmetry breaking of the $U(1)$ symmetry only occurs if $\lambda > 0$ and $M^2 < 0$, as seen previously. In the currently described situation, it is more useful to perform the translation of the complex field using polar coordinates rather than Cartesian ones. The field is then written as Eq. 2.17. Taking advantage of gauge invariance, the vector field is written in an adequate

gauge Eq. 2.18, since this does not affect the equations of motion. With this notation, the gauge transformation Eq. 2.16 is simply a translation of the field ζ .

$$\phi(x) = \frac{1}{\sqrt{2}} [v + \rho(x)] e^{i\zeta(x)/v} \quad (2.17)$$

$$A_\mu(x) = B_\mu(x) - \frac{1}{e v} \partial_\mu \zeta(x) \quad (2.18)$$

$$\zeta(x) \rightarrow \zeta(x) + v\theta(x) \quad (2.19)$$

Replacing Eq. 2.17 and Eq. 2.18 into Eq. 2.15 the gauge invariant translated lagrangian is obtained.

$$\begin{aligned} \mathcal{L}_1 \rightarrow \mathcal{L}_2 = & -\frac{1}{4} B_{\mu\nu}^2 + \frac{e^2 v^2}{2} B_\mu^2 + \frac{1}{2} (\partial_\mu \rho)^2 - \frac{1}{2} (2\lambda v^2) \rho^2 \\ & - \frac{\lambda}{4} \rho^4 + \frac{1}{2} e^2 B_\mu^2 (2v\rho + \rho^2) \\ B_{\mu\nu} = & \partial_\mu B_\nu - \partial_\nu B_\mu \end{aligned} \quad (2.20)$$

The lagrangian $\mathcal{L}_2$ does not depend on $\zeta(x)$ and the formula describes two massive particles, a vector B_μ and a scalar ρ . This is the interesting result, alluded to earlier. In essence, the initially massless gauge vector boson acquired a mass from the introduction of the scalar symmetry breaking potential. Simultaneously, the would-be Goldstone boson, which originated from the symmetry breaking, no longer appears. The degrees of freedom of the Goldstone boson were used to make the transition from massless to massive vector bosons, i.e. the Goldstone bosons were “swallowed” by the massless vector bosons. As previously, this result can be extended to the non-Abelian case, but goes beyond the scope of this thesis.

2.1.3 Building the Standard Model

In order to build the SM, choosing the set of symmetries respected by the model is the first step. This is done by specifying the gauge group. Each generator of the group gives rise to a gauge boson, this was implicit in the previous sections but can be explicitly seen in the full treatment of non-Abelian gauge groups. From experimental results, it is known that the weak force has 3 associated bosons: the Z boson [14] and the $W^\pm$ bosons [15, 16]; and that the electromagnetic force has a single associated boson, the photon (γ). Given that the electromagnetic and weak

forces are unified under the electroweak force, its corresponding gauge group is the only non-trivial group with 4 generators; $U(1) \times SU(2)$. EWT is the theory describing only these two forces, subject to the mentioned gauge group. There are two quantum numbers originating from the generators of the gauge group. These quantum numbers are analogous to the well-known electric charge (Q). The first, the weak hypercharge quantum number (Y), corresponds to the generator of $U(1)$. The generators of $SU(2)$ do not commute among each other, consequently only one can be taken as a quantum number. It is customary to choose the third generator of $SU(2)$ as the weak isospin quantum number (T_3).

The inclusion of the strong force is more complex and will not be treated in full here. The simplest way to identify the associated gauge group would be to consider that for the model to be coherent, there must be 3 charge types associated to the strong force². Thus, the simplest group associated with the strong force is $SU(3)$. The $SU(3)$ group has 8 generators and as a result there are 8 bosons (gluons) associated to the strong force. Therefore, the gauge group of the SM is $U(1) \times SU(2) \times SU(3)$.

With this choice of the SM gauge group, the electric charge operator, Q , is defined by a linear combination of the weak hypercharge, Y , and the third component of the weak isospin, T_3 , summarised in Eq. 2.21 where the coefficient in front of Y is arbitrary and fixes the normalisation of the $U(1)$ generator relative to those of $SU(2)$.

$$Q = T_3 + \frac{1}{2}Y \quad (2.21)$$

The next step is to choose the fields of the elementary particles and assign them to representations of the gauge group. The number and the interaction properties of the bosons are completely specified by the gauge group. For the fermions, we could in principle choose any number and assign any representation. In practice, the choice is guided by observation, which, in fact, restricts the choice. The observed particles are summarised in Fig. 2.1. As can be seen in the figure, there are 12 fermions, 6 leptons and 6 quarks. The fermions are simultaneously subdivided into three generations (or families). Each generation consists of 2 leptons and 2 quarks, with each generation sequentially heavier than the previous. The three generations are in all other aspects the same; the two leptons are classified into one lepton with charge -1 and

²The requirement of 3 charge types is related to the cancellation of triangle anomalies, mentioned further on. The requirement results from the assumption of the electric charge of the quarks.

the other with charge 0; the two quarks are classified into one quark with charge $-1/3$ and the other with charge $+2/3$. There is no known reason why nature repeats the generations thrice. The simplest representation of the fermions that incorporates this repetition is to choose a specific representation for the first generation and repeat it for the others.

Given the experimental evidence that the charged W bosons only couple to the left-handed components of the particle fields, the left-handed fields are assigned to doublets of $SU(2)$. The right-handed components are assigned to singlets of $SU(2)$. This assignment determines the $SU(2)$ transformation properties of the fermion fields. It also fixes their Y charges, and therefore their $U(1)$ properties, using Eq. 2.21. Given the interaction of the quarks with the strong force, the quarks are assigned to triplets of $SU(3)$, whereas given that the leptons do not interact under the strong force they are assigned to singlets of $SU(3)$. Henceforth the symbol for a given particle will be used for its associated Dirac field.

The projection operators (left-handed: $\frac{1}{2}(1 - \gamma_5)$; right-handed: $\frac{1}{2}(1 + \gamma_5)$) are used to separate the right-handed from the left-handed fields. The fields in the lepton sector become:

$$\Psi_L^i(x) = \frac{1}{2}(1 - \gamma_5) \begin{pmatrix} \nu_i(x) \\ \ell_i^-(x) \end{pmatrix}; \quad i = 1, 2, 3 \quad (2.22)$$

$$R_i(x) \equiv \ell_{iR}^-(x) = \frac{1}{2}(1 + \gamma_5) \ell_i^-(x) \quad (2.23)$$

$$\nu_{iR}(x) = \frac{1}{2}(1 + \gamma_5) \nu_i(x) \quad (2.24)$$

Where i is the family index and the last equation is included, here only, for completeness, since there is no experimental evidence for right handed neutrinos. The fields ℓ_i^- are the charged lepton fields and ν_i the neutrino fields. R_i is the charged right-handed lepton field and the field Ψ_L^i is a doublet of $SU(2)$ of the left handed lepton fields, ν_{iR} is the would-be right-handed neutrino field. The transformation properties of these fields under local $SU(2)$ transformations are given by Eq. 2.25, where $\vec{\tau}$ are the three generators of the $SU(2)$ group. Since the leptons are singlets under $SU(3)$, they are not affected by local $SU(3)$ transformations, as a result their transformations are given by Eq. 2.26.

$$\Psi_L^i(x) \rightarrow e^{i\vec{\tau} \cdot \vec{\theta}(x)} \Psi_L^i(x); \quad R_i(x) \rightarrow R_i(x) \quad (2.25)$$

$$\Psi_L^i(x) \rightarrow \Psi_L^i(x); \quad R_i(x) \rightarrow R_i(x) \quad (2.26)$$

Given the Y normalisation set by Eq. 2.21, the $U(1)$ charge of the lepton fields is uniquely determined and, as a result, the transformation properties of the fields under local $U(1)$ transformations.

$$Y(\Psi_L^i) = -1; Y(R_i) = -2 \quad (2.27)$$

If a right-handed neutrino were to exist it would have $Y(\nu_{iR}) = 0$, which, in conjunction with it being a singlet under $SU(2)$ and $SU(3)$, would imply that it does not couple to any gauge boson. Thus it would be near impossible to detect since it would only interact with the Higgs boson.

In the quark sector, the fields are given by Eq. 2.28, Eq. 2.29 and Eq. 2.30, where i is the family index and an index for the colour is not explicitly written. The fields U^i are the up-type quarks fields and D^i the down-type quark fields. U_R^i and D_R^i are the right-handed fields for the up-type and down-type quark fields, respectively and Q_L^i is a doublet of $SU(2)$ of the left-handed quark fields.

$$Q_L^i(x) = \frac{1}{2} (1 - \gamma_5) \begin{pmatrix} U^i(x) \\ D^i(x) \end{pmatrix}; i = 1, 2, 3 \quad (2.28)$$

$$U_R^i(x) = \frac{1}{2} (1 + \gamma_5) U^i(x) \quad (2.29)$$

$$D_R^i(x) = \frac{1}{2} (1 + \gamma_5) D^i(x) \quad (2.30)$$

Under local $SU(2)$ transformations, the quark fields transform in a similar manner to the lepton fields, Eq. 2.31. However, under local $SU(3)$ transformations, the quark fields transform according to Eq. 2.32, with $t^C = \frac{1}{2} \lambda^C$ where $\vec{\lambda}$ are the eight generators of $SU(3)$ and C runs from 1 to 8.

$$Q_L^i(x) \rightarrow e^{i\vec{\tau} \cdot \vec{\theta}(x)} Q_L^i(x); U_R^i(x) \rightarrow U_R^i(x); D_R^i(x) \rightarrow D_R^i(x) \quad (2.31)$$

$$Q_L^i(x) \rightarrow e^{i\vec{t} \cdot \vec{\beta}(x)} Q_L^i(x); U_R^i(x) \rightarrow e^{i\vec{t} \cdot \vec{\beta}(x)} U_R^i(x); D_R^i(x) \rightarrow e^{i\vec{t} \cdot \vec{\beta}(x)} D_R^i(x) \quad (2.32)$$

The $U(1)$ charge of the quark fields, computed with Eq. 2.21, is:

$$Y(Q_L^i) = \frac{1}{3}; Y(U_R^i) = \frac{4}{3}; Y(D_R^i) = -\frac{2}{3} \quad (2.33)$$

For the choice of the Higgs scalar fields, the option with the minimal number of fields is taken. From experimental evidence, it is known that three of the four $U(1) \times SU(2)$ vector

gauge bosons must acquire a mass through the breaking of the electroweak symmetry. As seen in Section 2.1.2, in order to transition from a massless vector gauge boson to a massive one, a Goldstone boson must be “swallowed” by the vector gauge boson. Consequently, three Goldstone bosons are necessary. The minimal number of scalar fields necessary to accommodate the above is four, two charged and two neutral. The fields are chosen to be placed into a complex doublet under $SU(2)$.

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}; \quad \Phi(x) \rightarrow e^{i\vec{\tau} \cdot \vec{\theta}} \Phi(x) \quad (2.34)$$

The $U(1)$ charge of Φ is $Y(\Phi) = 1$.

The choice of fields and their representations are summarised in Table 2.1. The fields for right-handed particles have been replaced with the field for the corresponding left-handed antiparticles. For completeness, the gauge fields are also listed.

From this point onward, no more choices remain since all subsequent steps are uniquely determined by the previous choices, i.e. the gauge group, the particle fields and their representation under transformations of the gauge group. The most general renormalisable lagrangian, involving the fields in Eq. 2.22, Eq. 2.23, Eq. 2.28, Eq. 2.29, Eq. 2.30 and Eq. 2.34, invariant under gauge transformations of $U(1) \times SU(2) \times SU(3)$ is written. The result, Eq. 2.35, has been split into the several separate contributions, which will be elaborated on individually.

$$\mathcal{L} = \mathcal{L}_{\text{free+interaction}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} \quad (2.35)$$

$$\begin{aligned} \mathcal{L}_{\text{free+interaction}} = \sum_{i=1}^3 & \left[\bar{\Psi}_L^i i\gamma^\mu D_\mu \Psi_L^i + \bar{R}_i i\gamma^\mu D_\mu R_i + \bar{Q}_L^i i\gamma^\mu D_\mu Q_L^i \right. \\ & \left. + \bar{U}_R^i i\gamma^\mu D_\mu U_R^i + \bar{D}_R^i i\gamma^\mu D_\mu D_R^i \right] \end{aligned} \quad (2.36)$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \vec{W}_{\mu\nu} \cdot \vec{W}^{\mu\nu} - \frac{1}{4} \vec{G}_{\mu\nu} \cdot \vec{G}^{\mu\nu} \quad (2.37)$$

$$\mathcal{L}_{\text{Higgs}} = |D_\mu \Phi|^2 - V(\Phi) \quad (2.38)$$

$$\begin{aligned} -\mathcal{L}_{\text{Yukawa}} = \sum_{i=1}^3 & \left[G_i \left(\bar{\Psi}_L^i R_i \Phi + h.c. \right) \right] + \sum_{i=1}^3 \left[G_u^i \left(\bar{Q}_L^i U_R^i \tilde{\Phi} + h.c. \right) \right] \\ & + \sum_{i,j=1}^3 \left[\left(\bar{Q}_L^i G_d^{ij} D_R^j \Phi + h.c. \right) \right] \end{aligned} \quad (2.39)$$

Table 2.1: Field content of the Standard Model. The column representation indicates under which representations of the gauge group each field transforms, in the order $(SU(3), SU(2), U(1))$. Superscript C denotes an antiparticle; for the $U(1)$ group the value of the weak hypercharge is listed instead.

Gauge Fields – Spin 1				
Symbol	Associated Charge	Group	Coupling	Representation
B	Weak Hypercharge	$U(1)$	g'	$(\mathbf{1}, \mathbf{1}, 0)$
W^i	Weak Isospin	$SU(2)$	g_w	$(\mathbf{1}, \mathbf{3}, 0)$
G^i	Colour	$SU(3)$	g_s	$(\mathbf{8}, \mathbf{1}, 0)$
Fermion Fields – Spin $\frac{1}{2}$				
Symbol	Name		Representation	
Q_L^i	Left-handed quark		$\left(\mathbf{3}, \mathbf{2}, \frac{1}{3}\right)$	
$U_R^{i\,C}$	Left-handed antiquark (up)		$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{4}{3}\right)$	
$D_R^{i\,C}$	Left-handed antiquark (down)		$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3}\right)$	
Ψ_L^i	Left-handed lepton		$(\mathbf{1}, \mathbf{2}, -1)$	
$R_i^{\,C}$	Left-handed antilepton		$(\mathbf{1}, \mathbf{1}, 2)$	
Higgs Fields – Spin 0				
Symbol	Name		Representation	
Φ	Higgs boson		$(\mathbf{1}, \mathbf{2}, 1)$	

The “free+interaction” term, Eq. 2.36, corresponds to the gauge invariant Dirac Lagrangian. This term describes the free fermions and their interactions with the aforementioned gauge fields. The covariant derivatives are determined by the assumed transformation properties of the fields

and are given by:

$$D_\mu \Psi_L^i = \left(\partial_\mu - ig_w \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu + i \frac{g'}{2} B_\mu \right) \Psi_L^i \quad (2.40)$$

$$D_\mu R_i = \left(\partial_\mu + i g' B_\mu \right) R_i \quad (2.41)$$

$$D_\mu Q_L^i = \left(\partial_\mu - ig_s \vec{t} \cdot \vec{G}_\mu - ig_w \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - i \frac{g'}{6} B_\mu \right) Q_L^i \quad (2.42)$$

$$D_\mu U_R^i = \left(\partial_\mu - ig_s \vec{t} \cdot \vec{G}_\mu - i \frac{2}{3} g' B_\mu \right) U_R^i \quad (2.43)$$

$$D_\mu D_R^i = \left(\partial_\mu - ig_s \vec{t} \cdot \vec{G}_\mu + i \frac{g'}{3} B_\mu \right) D_R^i \quad (2.44)$$

The gauge term, Eq. 2.37, corresponds to the kinetic energy terms for the vector fields, which is fully constrained by the chosen gauge group. This term also describes the self-interactions of the W_ν and G_ν fields, which arise from the non-Abelian structure of the corresponding gauge groups, $SU(2)$ and $SU(3)$ respectively. The field strengths $B_{\mu\nu}$, $\vec{W}_{\mu\nu}$ and $\vec{G}_{\mu\nu}$ are given by:

$$B_{\mu\nu}(x) = \partial_\mu B_\nu(x) - \partial_\nu B_\mu(x) \quad (2.45)$$

$$\vec{W}_{\mu\nu}(x) = \partial_\mu \vec{W}_\nu(x) - \partial_\nu \vec{W}_\mu(x) + ig_w \left(\frac{\vec{W}_\mu(x) \vec{W}_\nu(x) - \vec{W}_\nu(x) \vec{W}_\mu(x)}{2} \right) \quad (2.46)$$

$$\vec{G}_{\mu\nu}(x) = \partial_\mu \vec{G}_\nu(x) - \partial_\nu \vec{G}_\mu(x) + ig_s \left(\vec{G}_\mu(x) \vec{G}_\nu(x) - \vec{G}_\nu(x) \vec{G}_\mu(x) \right) \quad (2.47)$$

The Higgs term, Eq. 2.38, introduces the Higgs potential into the SM lagrangian, describes the dynamics of the Higgs field and its interaction with the gauge bosons. The most general Higgs potential compatible with the transformation properties of the field Φ is given by Eq. 2.48. The covariant derivative, like for the fermion fields, is determined by the assumed transformation properties of the field and is given by Eq. 2.49.

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (2.48)$$

$$D_\mu \Phi = \left(\partial_\mu - ig_w \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - i \frac{g'}{2} B_\mu \right) \Phi \quad (2.49)$$

The last term in Eq. 2.35, Eq. 2.39, describes the coupling between the scalar Φ and the fermions, a so-called Yukawa coupling. In the absence of right handed neutrinos, this is the most general term. If right handed neutrinos exist, another Yukawa coupling term would be included, similar to the first term, with R_i replaced by ν_{iR} and Φ by $\tilde{\Phi}$ which is proportional to $\tau_2 \Phi^*$. Which, in conjunction with Eq. 2.24, shows that the SM can accommodate a right-handed

neutrino, but it would only couple to the Higgs field. The part of the Yukawa Lagrangian relating to the quarks requires a more in depth explanation. In general any basis in the quark family space can be chosen. There are two Yukawa terms, one for the up-type quarks, U_R^i , and the other for the down-type quarks, D_R^i . Given the non-conservation of the individual quark quantum numbers, there is no explicit pairing between the up-type and down-type quarks. As a result, in general it is not possible to simultaneously diagonalise both Yukawa terms, which requires at least one of the Yukawa terms to have non-diagonal terms which mix the families. By convention, the off-diagonal terms are attributed to the down-type quark space, as seen by the sum over two indexes in Eq. 2.39.

Of note in the SM lagrangian is that the $\vec{G}_\mu$, $\vec{W}_\mu$ and B_μ gauge bosons appear to be massless as well as all the fermions. With the lagrangian defined, the next step is to choose the μ^2 parameter of the Higgs potential to be negative, in this way triggering spontaneous symmetry breaking, as described in section 2.1.2. As a result, the minimum of the Higgs potential occurs at a distance of v from the origin, with $v^2 = -\mu^2/\lambda$. Translating the Higgs field by a constant along the real axis of the Φ -plane, Eq. 2.50, generates new terms in the lagrangian.

$$\Phi \rightarrow \Phi + \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.50)$$

The mass terms are among the most noteworthy of the generated new terms. The Higgs mass is taken from the coefficient of the quadratic part of $V(\Phi)$ after the translation of the field, the mass is given by Eq. 2.51. The fermion masses arise from the Yukawa term, for the leptons the mass is given by Eq. 2.52. The three arbitrary constants G_ℓ can be chosen such that the three observed masses of the leptons are obtained. The mass terms for the quarks must take into account the family mixing which results from the Yukawa term in the lagrangian, Eq. 2.39. For the up-type quarks, the masses are given by Eq. 2.53, which in semblance to the leptons can accommodate the three observed masses since there are three arbitrary constants G_u^q . For the down-type quarks a three-by-three mass matrix is obtained, Eq. 2.54.

$$m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda v^2} \quad (2.51)$$

$$m_\ell = \frac{1}{\sqrt{2}} G_\ell v \quad \text{with } \ell = e, \mu, \tau \quad (2.52)$$

$$m_q = G_u^q v \quad \text{with } q = u, c, t \quad (2.53)$$

$$m_q = G_d^{ij} v \quad (2.54)$$

It is usual to work in a space where the masses are diagonal, the basis of the down-type quarks must then be changed such that G_d^{ij} is diagonal. This can be done with a three-by-three unitary matrix, V , such that $V^\dagger G_d^{ij} V = \text{diag}$. The quark masses would then be given by $m_q = G_d^q v$, with $q = d, s, b$, which also accommodates for the three observed down-type quark masses with the three arbitrary constants G_d^q .

With this formulation, the matrix V encodes additional arbitrary constants. In general, a 3×3 complex matrix has 18 degrees of freedom (9 real and 9 imaginary), however the requirement to be unitary, $V V^\dagger = 1$, constrains 9 of the parameters. Invariance under phase transformations of the quark fields constrains a further 5 of the remaining 9 parameters. Consequently, the matrix V has 4 degrees of freedom, 3 of which can be identified as Euler rotation angles and the fourth as an arbitrary phase, it is traditionally written in the form:

$$V = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_3 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ -s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix} \quad (2.55)$$

with the shorthand notation $c_k = \cos \theta_k$, $s_k = \sin \theta_k$, $k = 1, 2, 3$. The phase, δ , is a natural source for CP, or T, violation, which a model with only two generations, or four quarks, does not allow. This matrix was first introduced by Kobayashi and Masukawa as an extension to the Cabibbo matrix, precisely because of the CP violation it allows. For this reason, this matrix is often called the Cabibbo–Kobayashi–Maskawa (CKM) matrix.

The mass terms for the gauge bosons arise from the $|D_\mu \Phi|^2$ term in the untranslated lagrangian, i.e. Eq. 2.35. Direct substitution of the covariant derivative and then performing the translation of the Higgs potential leads to the following quadratic term:

$$\frac{1}{8} v^2 \left[g_w^2 (W_\mu^1 W^{1\mu} + W_\mu^2 W^{2\mu}) + (g' B_\mu - g_w W_\mu^3)^2 \right] \quad (2.56)$$

By defining the charged vector bosons as in Eq. 2.57, their masses are obtained from Eq. 2.56 and given by Eq. 2.58. The neutral gauge bosons have a 2×2 non-diagonal mass matrix. After diagonalisation, the mass eigenstates become Eq. 2.59 and the mass eigenvalues are Eq. 2.60. As expected, one of the neutral bosons remains massless and is identified with the photon.

$$W_\mu^\pm = \frac{W_\mu^1 \mp i W_\mu^2}{\sqrt{2}} \quad (2.57)$$

$$m_W = \frac{v g_w}{2} \quad (2.58)$$

$$\begin{aligned} Z_\mu &= \cos \theta_W B_\mu - \sin \theta_W W_\mu^3 & \text{with } \tan \theta_W &= \frac{g'}{g_w} \\ A_\mu &= \cos \theta_W B_\mu + \sin \theta_W W_\mu^3 \end{aligned} \quad (2.59)$$

$$\begin{aligned} m_Z &= \frac{v\sqrt{g_w^2 + g'^2}}{2} = \frac{m_W}{\cos \theta_W} \\ m_A &= 0 \end{aligned} \quad (2.60)$$

The classical SM lagrangian, Eq. 2.35, contains nineteen arbitrary real parameters. They are:

- the three gauge coupling constants, g' , g_w , g_s
- the two parameters of the Higgs potential, λ and μ^2
- three Yukawa coupling constants for the three lepton families, G_ℓ with $\ell = e, \mu, \tau$
- six Yukawa coupling constants for the three quark families, G_u^q with $q = u, c, t$ and G_d^q with $q = d, s, b$
- four parameters of the CKM matrix, three angles and a phase
- the QCD theta angle, θ_{QCD}

2.1.4 Success and Shortcomings of the Standard Model

The SM, whose current formulation was finalised in the mid-1970s, has been an extremely worthy theory. It accurately describes most of the present-day data and has had an enormous success in predicting new phenomena. Predictions of the SM range from the prediction of the existence and properties of weak neutral currents, confirmed by Gargamelle in 1972 [17], to the prediction of the Higgs boson, for which a candidate has been discovered in 2012 [5, 6]. The precision tests of QED constitute one of the most impressive results of the SM, where an agreement between theory and experiment is found to within 10 parts in a billion (10^{-8}).

Another compelling prediction of the SM dates back to the discovery of the tau lepton (τ), where upon the discovery of the tau, the b and t quarks were predicted to exist [18]. The prediction results from the fact that a gauge theory, such as the SM, must be anomaly free. The charged particles in the SM contribute to the so-called triangle anomalies. Requiring the anomalies to cancel corresponds to requiring that the sum of the charges of all the particles in a family be null. Consequently, discovering the tau lepton, a new family, implied that the third family

quarks should exist in order to cancel the triangle anomaly. This same reasoning was used in the beginning of section 2.1.3 to justify the three colour charges of the quarks.

The success of the SM can be succinctly overviewed in the global electroweak fit of the SM [19]. The electroweak observable parameters are expressed as a function of the input parameters of the SM and their observed and predicted values are compared. With the discovery of the Higgs boson, all input parameters are known, which allows for a full assessment of the consistency of the SM. Fig. 2.5 summarises the results of the fit, with the pull values for each parameter. None of the pull values exceed 3σ , proving the consistency of the SM. The fit converges to $\chi^2 = 21.8$ with 14 degrees of freedom, resulting in a p -value of 0.08.

With all these results, it is safe to say that the SM is among the most stringently tested theories in physics and has mustered a staggering amount of experimental evidence in its favour.

Despite the unprecedented success of the SM, there are several known issues with the theory. For instance, measurements since 1998 have shown that neutrinos oscillate [20, 21], which requires them to also have mass. The SM can accommodate massive neutrinos, however there is no consensus on the mechanism to introduce the neutrino oscillations. The observed overabundance of matter over antimatter can not be explained within the framework of the SM. Even though the SM does have the mentioned complex phase in the CKM matrix which allows for CP violation, the effect is not large enough to explain the observed matter/anti-matter asymmetry observed in the universe.

Furthermore, the latest results from the Planck telescope experiment have revealed that ordinary matter accounts for only about 5 % of the mass-energy content of the universe, with dark matter accounting for slightly more than 26 % and dark energy making up the rest [22]. The SM has no candidate particle for dark matter, and an explanation for the nature of dark energy is still to be elucidated. Another fundamental flaw with the SM is the fact that gravity is not included within its framework.

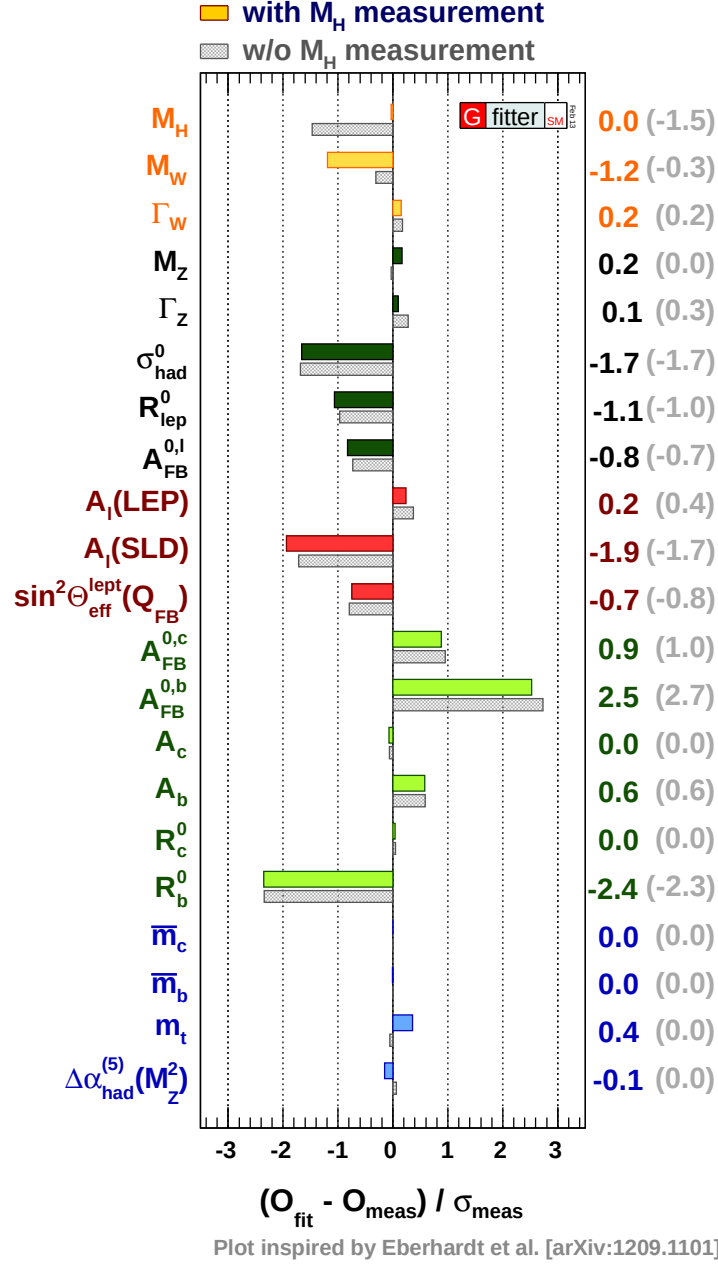


Figure 2.5: Differences between the SM prediction and the measured parameter, in units of the uncertainty for the fit including M_H (colour) and without M_H (grey). Figure taken from [19].

2.2 Supersymmetry

The shortcomings of the SM seem to indicate that the SM is an effective theory. Several theories have been proposed to address these shortcomings, such as Supersymmetry (SUSY), Technicolor and String Theories.

In a theory beyond the SM, where the Higgs mass is calculable, the radiative corrections

to the Higgs boson mass are quadratically divergent. These quadratic divergences must be cancelled by the bare mass of the Higgs for the theory to be renormalisable. If the theory is to be valid up to very high energy scales, the cancellation must be very precise which is, in general, considered a problem and requires fine-tuning. This problem is the so-called *hierarchy problem*. The quadratic growth of the Higgs boson mass beyond tree level is one of the motivations behind the introduction of SUSY.

To understand one of the main motivations for SUSY, consider a simplified theory with both a massive scalar, ϕ , and a fermion, ψ , in addition to a Higgs field, h , the lagrangian would be:

$$\mathcal{L} \sim -g_F \bar{\psi} \psi h - g_S h^2 \phi \quad (2.61)$$

In this theory, the one-loop contributions to the Higgs boson mass are illustrated in Fig. 2.6 and the terms that contribute to the mass of the Higgs are given in Eq. 2.62.

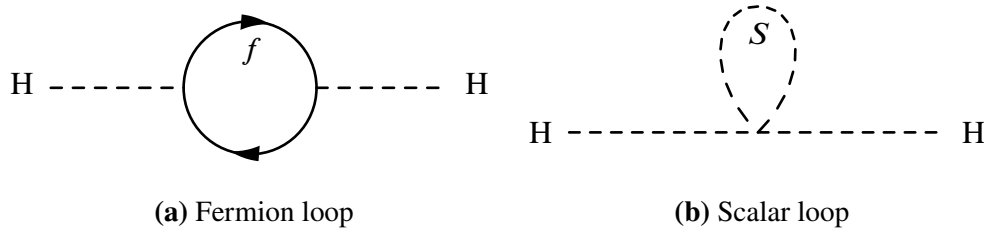


Figure 2.6: One-loop quantum corrections to the Higgs squared mass parameter, M_H^2 .

$$M_h^2 \sim M_{h0}^2 + \frac{g_F^2}{4\pi^2} (\Delta^2 + m_F^2) - \frac{g_S^2}{4\pi^2} (\Delta^2 + m_S^2) + \text{logarithmic divergences} + \text{uninteresting terms} \quad (2.62)$$

The minus sign between the fermion and scalar contributions is the result of Fermi statistics. If $g_S = g_F$, the terms that grow with Δ^2 would cancel, meaning there would be no quadratic divergence:

$$M_h^2 \sim M_{h0}^2 + \frac{g_F^2}{4\pi^2} (m_F^2 - m_S^2) \quad (2.63)$$

In this situation, the Higgs boson mass is given by Eq. 2.63 and is well behaved if the fermion and scalar masses are similar. Attempts to quantify “*similar*” have established that the difference should not be larger than about a TeV.

SUSY is introduced as a symmetry between particles of different spin. As a consequence, in a supersymmetric theory, the particle fields are combined into a superfield which contains fields

differing by half spin. With this construction, the fields in the superfield have the same coupling, i.e. $g_S = g_F$, by construction, in this way automatically mitigating the hierarchy problem. The simplest example of a superfield contains a complex scalar, S , and a two-component Majorana fermion, ψ . The allowed interactions are constrained by the Supersymmetry and the lagrangian of this simplest superfield is:

$$L = -\partial_\mu S^* \partial^\mu S - i\bar{\psi} \bar{\sigma}^\mu \partial_\mu \psi - \frac{1}{2}m(\psi\psi + \bar{\psi}\bar{\psi}) - cS\psi\psi - c^*S^*\bar{\psi}\bar{\psi} - |mS + cS^2|^2 \quad (2.64)$$

where σ is a 2×2 Pauli matrix and c is an arbitrary coupling constant. Since both the scalar and fermion share the same coupling constant, i.e. $g_S = g_F$, the cancellation of the quadratic divergences is automatic. It is also clear that both the scalar and fermion have the same mass. In summary, Supersymmetry extends the SM by associating to each particle another particle which differs by a unit of half-spin with all other properties being the same (mass and quantum numbers).

In this situation, Supersymmetry would have already been found since there should be a scalar with the same mass and quantum numbers as the electron for instance. In fact, in the spectrum of observed particles, none of them have a supersymmetric partner candidate. It follows that Supersymmetry, if it exists, must be a broken symmetry which induces a mixing among the eigenstates of the theory, thus a mass splitting between particles of the superfield.

2.2.1 Building the Minimal Supersymmetric Standard Model

To build the Minimal Supersymmetric Standard Model (MSSM), the same procedure as in section 2.1.3 is used. To keep the model as simple as possible, the minimal number of elements is added with respect to the SM. A supersymmetric theory is constructed by considering superfields instead of regular fields. In general, only two types of superfields need be considered, *Chiral Superfields* and *Vector Superfields*. A Chiral Superfield was specified in the previous example, it consists of a complex scalar field, S , and a two-component majorana fermion field, ψ . A Vector Superfield consists of a massless gauge field with field strength $F_{\mu\nu}^A$ and a two-component Majorana fermion field, λ_A .

The first step in the procedure is to select the gauge group. The MSSM respects the same

$U(1) \times SU(2) \times SU(3)$ gauge symmetries as the SM. The elementary particles must then be assigned a representation under the gauge group. The same representations as those used for the SM are used for the MSSM with the caveat that the fields must be placed into superfields. Since there are no candidates in the observed spectra for the supersymmetric partner particles, a new particle must be introduced as the superpartner for each of the known particles from the SM. In effect this doubles the particle content with respect to the SM. The particles are paired in superfields with the new postulated superpartners. The superfields are summarised in Table 2.2.

Table 2.2: Field content of the Minimal Supersymmetric Standard Model. The column representation indicates under which representations of the gauge group each field transforms, in the order $(SU(3), SU(2), U(1))$. Superscript C denotes an antiparticle, a tilde over a field is used to denote the corresponding supersymmetric partner field and for the $U(1)$ group the value of the weak hypercharge is listed.

Chiral Superfields		
Superfield	Representation	Field Composition
$\widehat{Q}_L^i$	$(\mathbf{3}, \mathbf{2}, \frac{1}{3})$	$Q_L^i, \widetilde{Q}_L^i$
$\widehat{U}_R^{iC}$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{4}{3})$	$U_R^{iC}, \widetilde{U}_R^{iC}$
$\widehat{D}_R^{iC}$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3})$	$D_R^{iC}, \widetilde{D}_R^{iC}$
$\widehat{\Psi}_L^i$	$(\mathbf{1}, \mathbf{2}, -1)$	$\Psi_L^i, \widetilde{\Psi}_L^i$
$\widehat{R}_i^C$	$(\mathbf{1}, \mathbf{1}, 2)$	$R_i^C, \widetilde{R}_i^C$
$\widehat{\Phi}_1$	$(\mathbf{1}, \mathbf{2}, 1)$	$\Phi_1, \widetilde{\Phi}_1$
$\widehat{\Phi}_2$	$(\mathbf{1}, \mathbf{2}, -1)$	$\Phi_2, \widetilde{\Phi}_2$
Vector Superfields		
Superfield	Representation	Field Composition
$\widehat{B}$	$(\mathbf{1}, \mathbf{1}, 0)$	$B, \widetilde{B}$
$\widehat{W}^i$	$(\mathbf{1}, \mathbf{3}, 0)$	$W^i, \widetilde{W}^i$
$\widehat{G}^i$	$(\mathbf{8}, \mathbf{1}, 0)$	$G^i, \widetilde{G}^i$

The second Higgs superfield in Table 2.2 requires further explanation. In the SM there is a single $SU(2)$ doublet scalar complex field, the Higgs field. In a supersymmetric theory, the

Higgs field acquires a fermion superpartner, an $SU(2)$ doublet of fermion fields. These extra fermion fields contribute to the triangle anomalies and would go uncancelled. The simplest way to cancel the anomalies is to add a second Higgs field with opposite $U(1)$ quantum numbers.

Similarly to what was done for the SM, once the superfields and their transformation properties are defined, the most general lagrangian is written. In a supersymmetric theory, there are further constraints on the allowed interactions between the ordinary particles and their superpartners. Mirroring the procedure for the SM, the result, Eq. 2.65 has been separated into its several separate contributions which will be elaborated on individually.

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{KE} + \mathcal{L}_{\text{interaction}} + \mathcal{L}_W + \mathcal{L}_{\text{soft}} \quad (2.65)$$

$$\begin{aligned} \mathcal{L}_{KE} = & \sum_i \left\{ (D_\mu S_i^*) (D^\mu S_i) + i\bar{\psi}_i \gamma^\mu D_\mu \psi_i \right\} \\ & + \sum_A \left\{ -\frac{1}{4} F_{\mu\nu}^A F^{\mu\nu A} + \frac{i}{2} \bar{\lambda}_A \gamma^\mu D_\mu \lambda_A \right\} \end{aligned} \quad (2.66)$$

$$\mathcal{L}_{\text{interaction}} = -\sqrt{2} \sum_{i,A} g_A [S_i^* T^A \bar{\psi}_i \lambda_A + h.c.] - \frac{1}{2} \sum_A \left(\sum_i g_A S_i^* T^A S_i \right)^2 \quad (2.67)$$

$$\mathcal{L}_W = - \sum_i \left| \frac{\partial W}{\partial z_i} \right|^2 - \frac{1}{2} \sum_{i,j} \left[\bar{\psi}_i \frac{\partial^2 W}{\partial z_i \partial z_j} \psi_j + h.c. \right] \quad (2.68)$$

The kinetic energy terms of the fields are accounted for in Eq. 2.66. The i sum is over the fermion fields of the SM, ψ_i , with their supersymmetric scalar partners, S_i and the 2 Higgs doublets with their fermion superpartners. The A sum is over the gauge fields and their associated supersymmetric fermion partners, called the gauginos. This kinetic energy term contains the equivalent terms from Eq. 2.37 and Eq. 2.36 of the SM.

The quartic interactions of the scalars and the interactions between the chiral superfields and the gauginos are completely specified by the gauge symmetries and the supersymmetry. These interaction terms are defined in Eq. 2.67, where g_A is the relevant gauge coupling constant. There are no arbitrary constants in this term of the MSSM lagrangian.

The next term in the MSSM lagrangian, Eq. 2.68, results from the so-called superpotential, W . It is a function of only the chiral superfields, z_i , and contains terms with 2 and 3 fields. The Yukawa couplings and scalar potentials are included in this term, Eq. 2.39 and part of Eq. 2.38 from the SM.

The most general superpotential is given by Eq. 2.69, where only a single family is considered. In general, the λ_i could be matrices, which would allow mixing among the 3 generations.

$$\begin{aligned}
W = & \epsilon_{ij} \mu \widehat{\Phi}_1^i \widehat{\Phi}_2^j + \epsilon_{ij} \left[\lambda_L \widehat{\Phi}_1^i \widehat{\Psi}_L^j \widehat{R}^C + \lambda_D \widehat{\Phi}_1^i \widehat{Q}_L^j \widehat{D}_R^C + \lambda_U \widehat{\Phi}_2^j \widehat{Q}_L^i \widehat{U}_R^C \right] \\
& + \epsilon_{ij} \left[\lambda_1 \widehat{\Psi}_L^i \widehat{\Psi}_L^j \widehat{R}^C + \lambda_2 \widehat{\Psi}_L^i \widehat{Q}_L^j \widehat{D}_R^C \right] + \lambda_3 \widehat{U}_R^C \widehat{D}_R^C \widehat{D}_R^C
\end{aligned} \tag{2.69}$$

The first term in the superpotential, $\mu \widehat{\Phi}_1 \widehat{\Phi}_2$, gives rise to the mass terms for the Higgs bosons. The terms proportional to λ_L , λ_D and λ_U give rise to the Yukawa coupling terms. The terms proportional to λ_1 , λ_2 and λ_3 are problematic since they give rise to lepton and baryon number violating terms which have very stringent experimental limits. Introducing a new symmetry, called R parity, that forbids these terms is the usual approach to this problem. R parity is defined as a multiplicative quantum number that assigns the value +1 to all the SM particles and -1 to their superpartners. For a particle of spin s , with baryon number B and lepton number L , it is given by:

$$R \equiv (-1)^{3(B-L)+2s} \tag{2.70}$$

The conservation of R parity implies that in an interaction the number of SUSY partners is conserved modulo 2. Consequently not only are SUSY particles produced in pairs but also a SUSY particle must decay to at least another SUSY particle and the Lightest Supersymmetric Particle (LSP) is stable. In SUSY formulations where the LSP is neutral, the LSP is a good candidate for dark matter since it is stable.

So far, the constructed MSSM lagrangian contains all of the SM particles as well as their supersymmetric partners, however the supersymmetry is unbroken and all particles remain massless. The mechanism by which supersymmetry is broken is not well understood. Consequently a set of assumed explicit “soft” mass terms for the scalar members of the chiral superfields and for the gaugino members of the vector superfields are introduced, Eq. 2.71 for a single family. The terms are called soft since they are chosen such that the quadratic divergences are not

reintroduced.

$$\begin{aligned}
-\mathcal{L}_{\text{soft}} = & m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - B\mu\epsilon_{ij} \left(H_1^i H_2^j + h.c. \right) + \tilde{M}_Q^2 \widetilde{Q}_L^* \widetilde{Q}_L \\
& + \tilde{M}_U^2 \widetilde{U}_R^* \widetilde{U}_R + \tilde{M}_D^2 \widetilde{D}_R^* \widetilde{D}_R + \tilde{M}_\psi^2 \widetilde{\Psi}_L^* \widetilde{\Psi}_L + \tilde{M}_R^2 \widetilde{R}^* \widetilde{R} \\
& + \frac{1}{2} \left[M_3 \widetilde{G}^i{}^C \widetilde{G}^i + M_2 \widetilde{W}^i{}^C \widetilde{W}^i + M_1 \widetilde{B}^C \widetilde{B} \right] + \frac{g}{\sqrt{2}M_W} \epsilon_{ij} \left[\frac{M_D}{\cos\beta} A_D H_1^i \widetilde{Q}_L^j \widetilde{D}_R^* \right. \\
& \left. + \frac{M_U}{\sin\beta} A_U H_2^j \widetilde{Q}_L^i \widetilde{U}_R^* + \frac{M_R}{\cos\beta} A_E H_1^i \widetilde{\Psi}_L^j \widetilde{R}^* + h.c. \right] \quad (2.71)
\end{aligned}$$

This lagrangian allows for arbitrary masses for the scalars and gauginos as well as arbitrary tri-linear and bi-linear couplings. In general, all of the terms in this lagrangian may be matrices involving the three families. The introduction of this lagrangian introduces over 100 new unknown parameters into the MSSM lagrangian. This is a consequence of introducing the most general terms to account for all possibilities since the supersymmetry breaking mechanism is not known. A full theory, with a mechanism for supersymmetry breaking, would significantly reduce the parameter space.

The inclusion of a second Higgs field in the MSSM results in a very rich phenomenology in the Higgs sector, similar to a general Two Higgs Doublet Model (2HDM). This sector will not be treated in full here, further information may be found elsewhere, such as in Refs. [12, 23]. The general picture does not change significantly with respect to the SM, apart from the introduction of a second Higgs field. This additional field adds more terms to the Higgs Potential. As in the SM case, for spontaneous symmetry breaking to occur, the potential must have a degenerate minima, which imposes constraints on the parameters of the Higgs potential.

In the MSSM, one of the Higgs fields couples to the down-type quark fields and the lepton fields, while the other Higgs field couples to the up-type quark fields. Before symmetry breaking, the two Higgs fields have 8 degrees of freedom. Three of the degrees of freedom are absorbed by the vector gauge fields when they acquire mass during symmetry breaking. The other 5 physical degrees of freedom give rise to additional bosons, two CP-even neutral Higgs bosons, h and H , one CP-odd neutral Higgs boson, A , and two charged Higgs bosons, $H^\pm$.

After electroweak symmetry breaking, new terms are generated, as in the SM case. The mass terms for the SM particles remain similar to the mass terms in the SM, with some corrections to account for the second Higgs field.

The mass terms for the supersymmetric partners result from the previously introduced soft mass terms, Eq. 2.71. For the fermions, with the exception of the neutrino, since there is a field for each helicity state, left-handed and right-handed, each will have its own SUSY partner which is a complex scalar. The tri-linear terms in Eq. 2.71 allow the complex scalar superpartner fields to mix when forming the mass eigenstates. This results in three 6×6 mass matrices, one for the up-type quark SUSY partners, one for the down-type quark SUSY partners and one for the charged lepton SUSY partners. The mass matrix for the leptons is similar to that of the up-type and down-type supersymmetric quarks (squarks).

The MSSM lagrangian contains 124 independent parameters, 18 of which correspond to the SM parameters and the rest which originate mostly from the soft breaking terms. Given this unwieldy amount of parameters, it is useful to introduce MSSM models that are restricted in their parameter space. An example of particular interest is the Phenomenological Minimal Supersymmetric Standard Model (pMSSM), since it makes a minimal number of assumptions, resulting in some degree of model independence. The pMSSM makes the following constraints with respect to a general MSSM model:

- R-parity is conserved – Implying that the LSP is stable
- There is no new CP-violation source, only those already present in the CKM matrix in the SM
- No flavour changing neutral currents at tree level
- For the first and second generation:
 - squarks and sleptons with the same quantum numbers are degenerate
 - tri-linear couplings are negligible

With this prescription, the pMSSM is governed by 19 parameters, in addition to those of the SM:

- gaugino masses – Bino mass (M_1), Wino mass (M_2) and gluino mass (M_3)
- Higgs sector parameters – pseudoscalar Higgs mass (m_A) and ratio of Higgs vacuum expectation values ($\tan \beta$)
- higgsino mass parameter – μ
- mass squared parameters for the degenerate first and second generation of squarks and sleptons – left-handed squark mass ($\tilde{M}_Q^2$), right-handed up-type squark mass ($\tilde{M}_U^2$), right-

handed down-type squark mass ($\tilde{M}_D^2$), left-handed slepton mass ($\tilde{M}_\psi^2$) and right-handed charged slepton mass ($\tilde{M}_R^2$)

- corresponding mass squared parameters for the third generation of squarks and sleptons
- third generation A parameters – top quark tri-linear coupling (A_t), bottom quark tri-linear coupling (A_b) and tau lepton tri-linear coupling (A_τ)

So far, no experimental evidence consistent with SUSY has been observed. Consequently, the results are expressed as limits, a summary of some of the results from the CMS collaboration can be found in Fig. 2.7. The results are taken from [24] which compiles the results from several CMS publications.

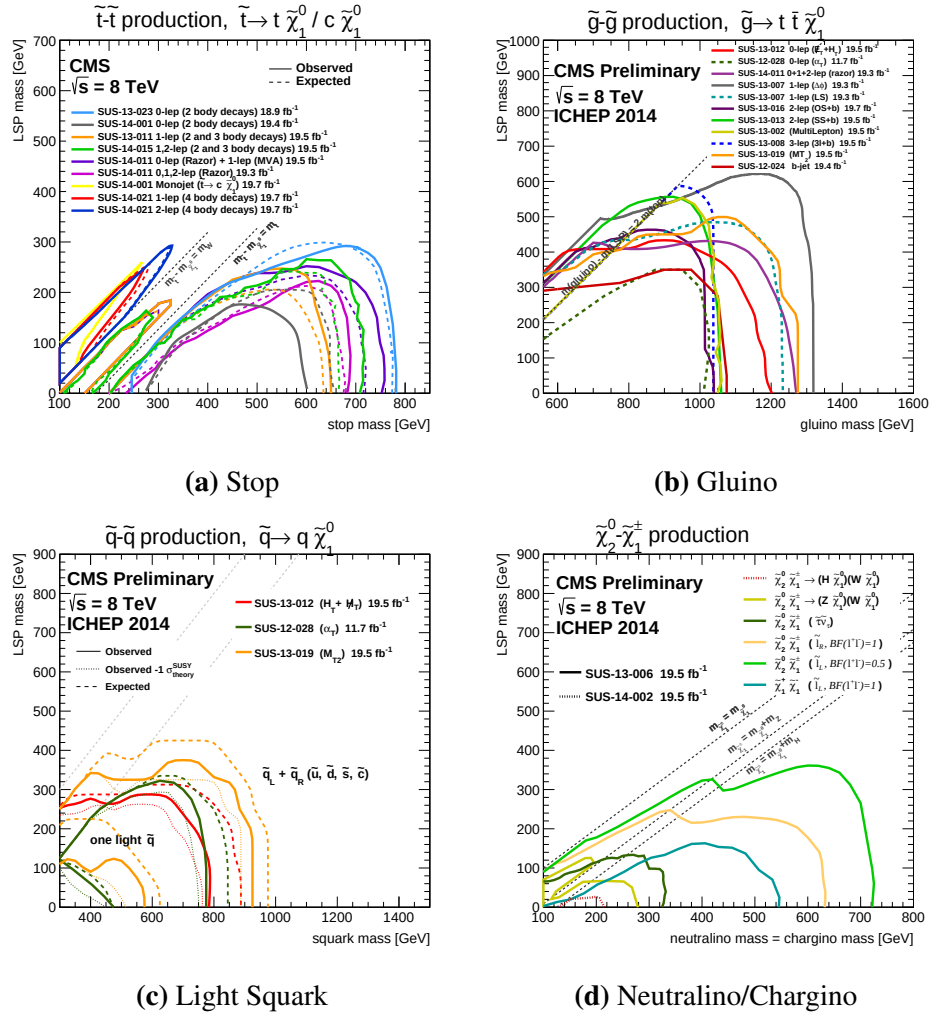


Figure 2.7: Selected SUSY results from the CMS collaboration. Figures taken from [24].

2.2.2 The case for Staus

The third generation of supersymmetric particles is normally viewed as the ideal candidate for discovering SUSY. It is generally expected that some of these supersymmetric partners will have lower masses than those of the first and second generations, making them more likely to be produced at an accelerator. This lends itself to the fact that the high masses of the third generation SM particles make the mass mixing effects in the SUSY sector more pronounced with respect to the first and second generations. To illustrate this effect, consider the mass matrix for the charged leptons. Since the cross-family effects can often be neglected it is simpler to consider each family on its own, effectively reducing the 6×6 mass matrix for the 3 families to a 2×2 mass matrix for each family. The mass matrix for the stau is represented in Eq. 2.72, the mass matrices for the charged leptons of the other families are the same only with the adequate variable substitutions. The off-diagonal terms in the mass matrices are proportional to the mass of the lepton and lead directly to the above-mentioned mass mixing effects.

$$M_{\tilde{\tau}}^2 = \begin{pmatrix} \tilde{M}_{\psi}^2 + m_{\tau}^2 + L_{\tau} & m_{\tau} X_{\tau}^* \\ m_{\tau} X_{\tau} & \tilde{M}_R^2 + m_{\tau}^2 + R_{\tau} \end{pmatrix} \quad (2.72)$$

With the following definitions:

$$X_{\tau} = A_{\tau} + \mu^* \tan \beta \quad (2.73)$$

$$L_{\tau} = \left(-\frac{1}{2} + \sin^2 \theta_W \right) m_Z^2 \cos 2\beta \quad (2.74)$$

$$R_{\tau} = -\sin^2 \theta_W m_Z^2 \cos 2\beta \quad (2.75)$$

The stau is often the lightest slepton within MSSM models, and frequently one of the lightest supersymmetric particles, [25–28] and given that the current LHC results disfavour light squarks and gluinos, the search for direct stau production becomes an interesting prospect. The non-observation of such events can also provide useful insights since it would allow to set limits on sectors of the MSSM which do not depend on the colour sector. Since the LSP is a natural candidate for dark matter, the observed relic dark matter density poses constraints on the properties of the LSP. Furthermore, the coannihilation processes involving the LSP and the heavier supersymmetric particles also affect the relic density [29]. In fact, a light stau, with a mass very close to the LSP, can participate in these coannihilation processes and might be a key ingredient for the observed relic dark matter density [29–32].

Recent results on the stau from the CMS collaboration can be found in [33]. Results from the ATLAS collaboration can be found in [34, 35]. The best current limit on the stau mass comes from the LEP experiments, with an upper limit on the mass close to 85 GeV [36–39].

Chapter 3

Experimental Apparatus

3.1 The Large Hadron Collider

The LHC is the largest and highest energy particle accelerator in the world. It has a circumference of 26.6 km and is installed in the tunnel built for LEP. The tunnel is located between 50 m and 175 m below the surface. The LHC consists of two synchrotron rings with counter rotating particle beams, generally protons but lead-ions are also used. It was designed for a centre of mass energy of 14 TeV in proton-proton collisions with a peak luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. An in depth description of the LHC is available in [40].

3.1.1 Beam Injection

A schematic of the CERN accelerator complex can be seen in Figure 3.1. Protons for the accelerators are produced by ionising hydrogen atoms, thus stripping them of their electrons. The protons subsequently undergo several acceleration steps prior to being delivered to the desired experiment. For instance, for the LHC, protons are ionised and accelerated to an energy of 50 MeV in the Linac2, which is a linear accelerator. The protons are then fed into a series of synchrotrons that sequentially increase the energy of the protons. The first is the Proton Synchrotron (PS) Booster, which increases the proton energy up to 1.4 GeV. The second step in the chain is the PS itself, after which the protons have achieved an energy of 25 GeV. The next accelerator

is the SPS, after which the protons are injected into the LHC at an energy of 450 GeV. Once within the LHC the protons are accelerated up to the operating energy and are then made to collide.

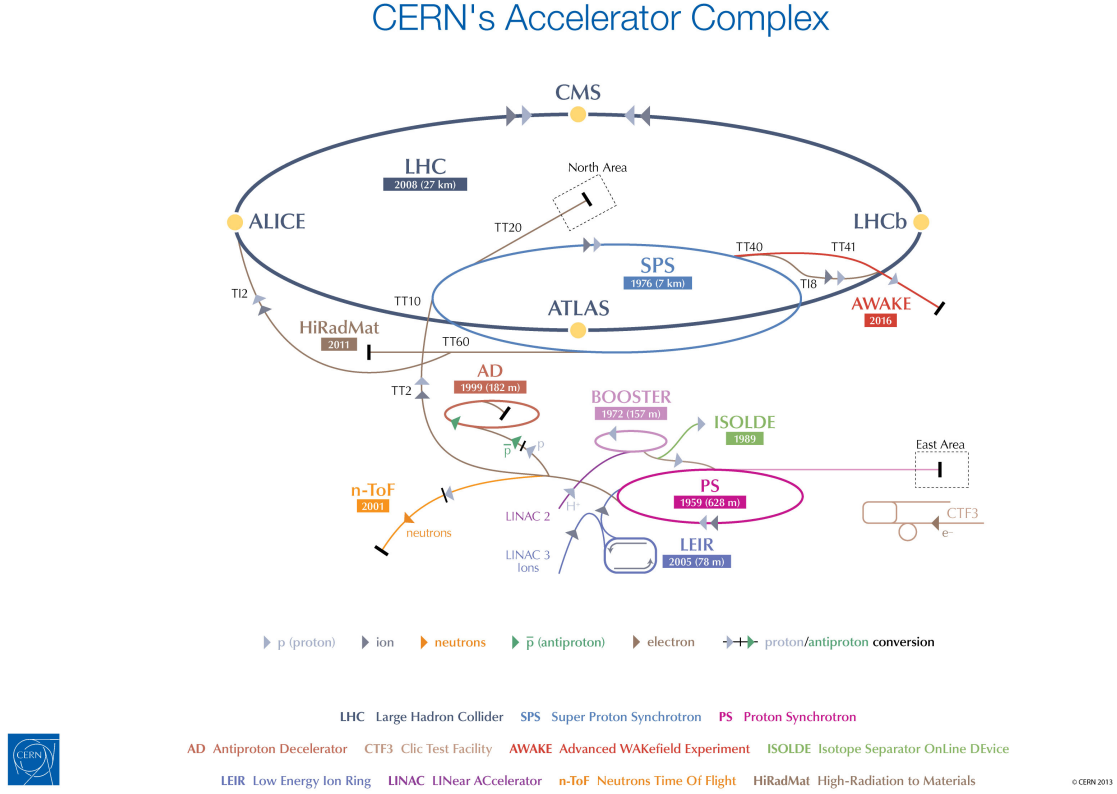


Figure 3.1: Schematic diagram of the CERN accelerator complex, not to scale. Taken from [41].

Within the LHC, the particle beams are not continuous but are grouped into bunches. The design parameters define that the bunches are separated by 25 ns, with each bunch containing 10^{11} protons. The bunch structure of the LHC beam is constrained by the filling scheme from the lower energy accelerators. In theory, the beams could contain 3564 bunches, however to allow for the ramp-up of the injection and kicker magnets and for the ejection kicker magnets (abort gap) as well as other engineering constraints, only 2808 of those bunches are filled when operating at the nominal bunch spacing. During the 2011 and 2012 data taking periods, the LHC operated with a bunch spacing of 50 ns and consequently only 1380 bunches were filled.

3.1.2 Magnets

The magnets employed by the LHC to bend the trajectory of the particle beams are superconducting niobium-titanium coils, cooled to 1.9 K with liquid helium. The dipoles are capable of producing a magnetic field of 8.33 T. The magnets are divided into several categories, depending on the configuration of the magnetic field, such as dipoles, quadrupoles, sextupoles and others. The dipoles steer the beams and keep them in a nearly circular orbit, 1232 of these magnets are used by the LHC. The quadrupoles focus the beams, 392 are located around the LHC ring. The other magnets are used to perform more finely tuned adjustments to the beams. A full list of all the magnets in the LHC, can be found in [42].

3.1.3 Luminosity

The quantity that measures the capability of a particle accelerator to produce interactions/events is called the luminosity, $\mathcal{L}$, and it is the proportionality factor between the rate of events and the cross section of those events, Eq. 3.1. The luminosity is a function of the beam parameters only and can be written as Eq. 3.2 for a Gaussian beam, where N_b is the beam intensity (number of protons in a bunch), n_b is the number of bunches, f_{Rev} is the revolution frequency, $\gamma_r = \sqrt{1 - \frac{v^2}{c^2}}$ is the relativistic gamma factor, ϵ_n is the normalised transverse beam emittance, β^* is the beta function ($\beta(s)$) at the collision point and F is a geometric luminosity reduction due to the crossing angle at the interaction point.

The beta function is the envelope around the trajectories of particles circulating in the lattice composed by the quadrupoles, thus it is a design parameter of the accelerator. The normalised beam emittance is an inherent property of the beam and characterises the quality of the beam. It is a measure of the average spread of the particles in position and momentum phase space. The width of the beam at a given point, s , in the orbit in the accelerator is given by Eq. 3.3. This makes it clear that the luminosity is inversely proportional to the beam size at the interaction

point.

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

$$\mathcal{L} = \frac{N_b^2 n_b f_{\text{Rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (3.2)$$

$$\sigma(s) = \sqrt{\epsilon_n \beta(s)} \quad (3.3)$$

A related concept is that of integrated luminosity, which is the luminosity integrated over a period of time, normally over a data taking period. The terms luminosity and integrated luminosity are sometimes used interchangeably and the same symbol is used for the two, care must be taken to not confuse the two.

Given the probabilistic nature of processes under the domain of particle physics, in order to study a certain process not only is it necessary for the process to occur and be recorded, but a statistically significant number of such events must be recorded. The cross section of a certain process quantifies the likelihood of that process to occur. Consequently, in general terms, in order to obtain a significant number of recorded events:

- Common processes, which have higher cross sections, require lower luminosities in order to be studied. However higher luminosities result in more recorded events which imply improved statistical accuracy
- Rare processes, which have lower cross section, require higher luminosities in order to be studied

High luminosities can be achieved through different ways, each with different trade-offs. For instance, high luminosities can be achieved through a high number of particles, N_b or n_b , or through a small beam size, ϵ_n or β^* . Consider β^* , the beta function can be shown to have an evolution according to Eq. 3.4 around the interaction point [43], where z is the distance from the interaction point along the beam direction. From Eq. 3.4 one can conclude that the smaller the beam size at the interaction point (i.e. the smaller the β^*), the larger the beam size at some distance from the interaction point. Thus, the smaller the beam size the larger the aperture of the injection quadrupoles must be (as well as the quadrupole dimensions themselves) and the larger the opening in the detector apparatus must be to allow the beam to enter the detector. Requiring a larger opening in the detector apparatus reduces the coverage of the detector and consequently also affects the performance of the detector. Thus, despite requiring the smallest

β^* possible to obtain the smallest beam width possible and consequently the largest luminosity possible, the choice of the β^* value is a compromise between the smallest value possible which still allows for reasonable dimensions of the injection quadrupoles and resulting an as small as possible opening at the ends of the detector apparatus.

$$\beta(z) = \beta^* + \frac{z^2}{\beta^*} \quad (3.4)$$

3.1.4 Pileup

A consequence of a high beam intensity (N_b) is that, in each bunch crossing, more than one proton-proton collision may occur. These “extra” interactions make the analysis of a process of interest challenging because they contribute extra particles to a particular bunch crossing and consequently to the measurement of the event. This effect of additional interactions is usually referred to as *in-time* Pile-up (PU), often referred to only as PU.

With the extremely small bunch spacing employed by the LHC, in particular with the 25 ns bunch spacing, the particles resulting from an interaction in a first bunch crossing do not have time to exit the detector before a second bunch crossing occurs. Consequently, it is possible for the detector to be measuring particles from different bunch crossings at a given instant in time. This leads to a distinct kind of PU than that described above. To distinguish between the two, the terms *in-time* PU and *out-of-time* PU are used.

A similar concept to that of PU is that of the underlying event. In a given interaction, two protons are made to collide, however the particles that actually collide are individual partons from each proton, the so-called hard interaction. The remaining partons from each proton go on to create showers of particles, normally close to the beam line, which constitute the so-called underlying event. These showers also contribute additional particles to the measurement (with respect to the hard interaction), just like for the PU. It should also be mentioned that in a single bunch crossing it is possible for several pairs of protons to collide, resulting in multiple interactions for each bunch crossing, further compounding the issues above.

3.2 Compact Muon Solenoid

The CMS detector is located at one of the four interaction points around the LHC and it is about 100 m beneath the surface at the foothills of the Jura mountains in Cessy, France. It is a general purpose detector and covers almost the full solid angle around the interaction point. It is 21.6 m long and has a diameter of 14.6 m and weighs 14 000 t. A diagram of the detector can be seen in Fig. 3.2.

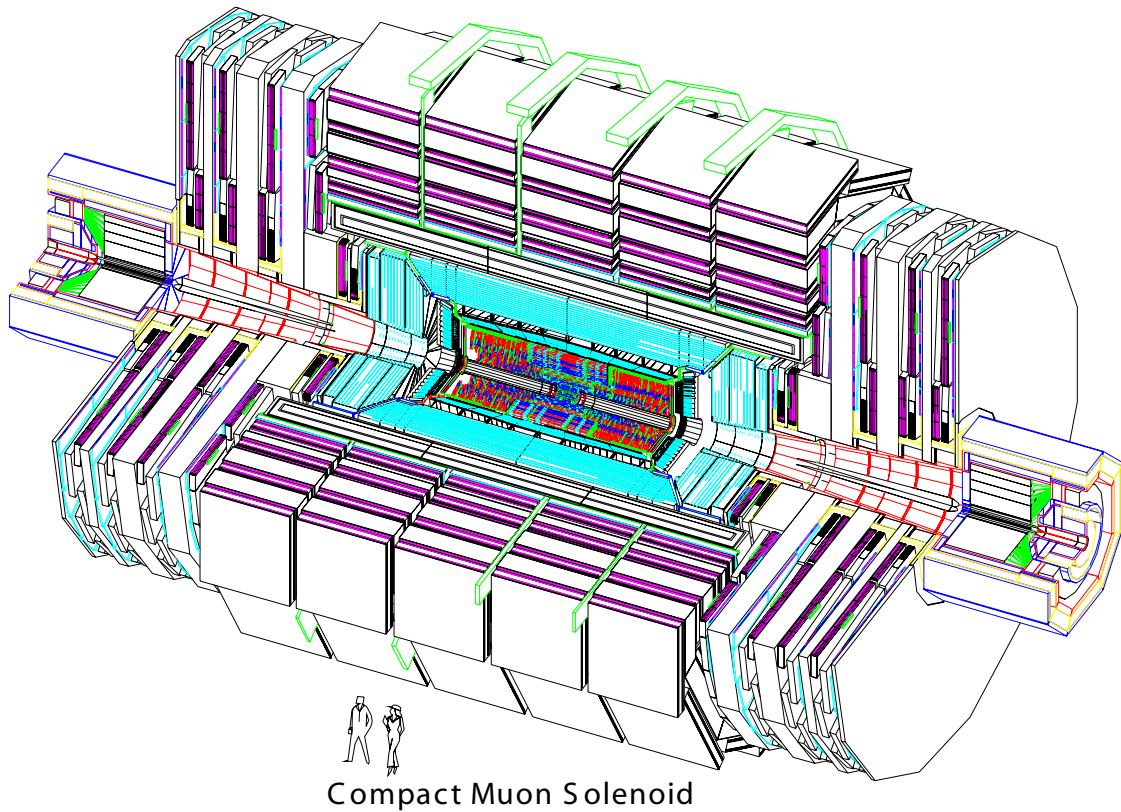


Figure 3.2: Schematic diagram of the CMS detector. Taken from [44].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal Electromagnetic Calorimeter (ECAL), and a brass and scintillator Hadronic Calorimeter (HCAL), each composed of a barrel and two end-cap sections. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in [45,

46]. The rapidity coverage of the CMS detector ranges between 2.4 and 5.2, depending upon the subdetector system considered.

3.2.1 Coordinate System

As is required, the CMS experiment uses a right-handed coordinate system. The origin of the coordinate system is defined as the nominal interaction point, with the x axis pointing to the centre of the LHC, the y axis perpendicular to the LHC plane pointing up and the z axis pointing in the anti-clockwise beam direction. The polar angle, θ , is measured from the positive z axis and the azimuthal angle, Φ , is measured from the positive x axis in the xy plane.

3.2.2 Tracker

The CMS tracker is designed to provide a measurement of the position of charged particles when they cross the silicon detectors within the volume of the tracker. These measurements allow to reconstruct the trajectory of the charged particles, further detailed in chapter 4. The reconstruction of the charged particle tracks has an essential role in the reconstruction of charged particles (electrons, muons, taus, hadrons and jets) as well as the determination of the interaction vertices. The tracks are also fundamental for the identification of b-jets, in particular through the evidence of a displaced vertex.

The functioning principle of silicon detectors relies on a reverse biased diode, creating a depletion zone with an electric field between the contacts of the diode. When a charged particle traverses the depletion zone, free electrons and holes are produced through ionisation. The electric field in the depletion zone causes the electrons and holes to travel in opposite directions, to the contacts of the diode, resulting in an electrical pulse that can be measured. By covering an area with several such detectors, it is possible to identify where a charged particle traversed.

The tracker is completely made of silicon detectors and is the largest silicon tracker ever built. Two types of silicon detectors compose the tracker, pixel detectors and strip detectors, used in each tracker subsystem: the Silicon Pixel Detector and the Silicon Strip Detector, respectively. Fig. 3.3 illustrates a schematic view of the CMS tracker in an r - z slice, with the different detector

subsystems identified. The nominal resolution of the tracker system on the momentum of a charged particle is typically 0.7 (5.0) % at 1 (1000) GeV in the central region and on the impact parameter is typically 10 μm for high momentum tracks. An in depth description of the tracker system and a description of its performance can be found in [46, 47].

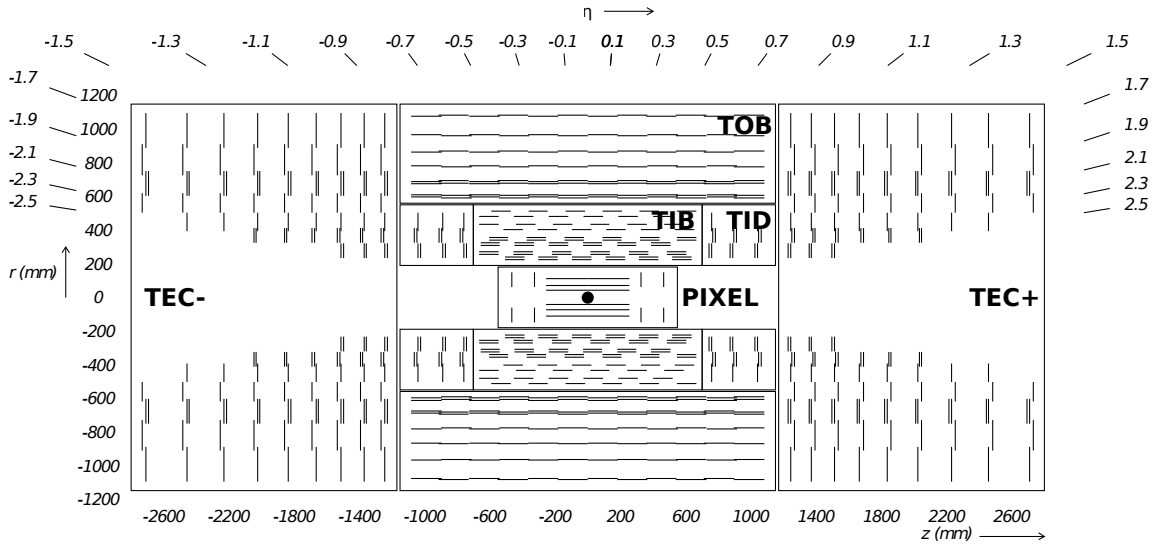


Figure 3.3: Schematic diagram of the CMS tracker in an r - z slice. Single lines represent layers of modules equipped with one sensor, double lines indicate layers with back-to-back modules. Taken from [47].

Silicon Pixel Detector

The silicon pixel detector has 66 million active elements over a surface area of about 1 m^2 . It covers a region from 4 cm to 15 cm in radius and 49 cm on each side of the interaction point. The detector consists of several layers, three in the barrel region and two on each side in the endcap region. The detector is designed to determine three very high precision three-dimensional points for each track. This is achieved through the use of active elements of n-in-n pixels with dimensions of $100\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$. The detector further exploits the presence of the 3.8 T magnetic field, for barrel and endcap, coupled with a geometric arrangement, for the endcap, to achieve sub-pixel resolution of the measurement of where a charged particle has passed through the sensor. Considering the particle flux at nominal luminosity, the pixel detectors are expected to have an average occupancy per LHC crossing of 0.01 %.

Silicon Strip Detector

The silicon strip detector has 9.3 million active elements over a surface area of about 198 m^2 . It covers a region from 25 cm to 110 cm in radius and 280 cm on each side of the interaction point. It is composed of three large subsystems: the Tracker Inner Barrel and Disks (TID/TID); the Tracker Outer Barrel (TOB); and the Tracker End Caps (TEC). The sensor elements are p-on-n type silicon microstrip sensors. The thickness of the sensors and dimensions of the strips vary, depending on which layer of the detector they are. Assuming the detectors are fully efficient, the silicon strip detector provides 8 to 14 high precision measurements of a track position, depending on the pseudorapidity of the track. The silicon strip detectors are expected to have an average occupancy per LHC crossing of 2 % to 3 % in the innermost layers and 1 % in the outermost layers, at nominal luminosity.

3.2.3 ECAL

The CMS ECAL detector provides 3 functions: measurement of the energy of electromagnetic radiation; basic identification for electromagnetic particles (electrons and photons); and triggering capabilities. A schematic diagram of the ECAL can be seen in Fig. 3.4. It is a hermetic homogeneous calorimeter made of 61200 lead-tungstate (PbWO_4) crystals in the barrel region and 7324 crystals in each of the two end caps. The lead-tungstate crystals serve as both the absorption and detection media of the ECAL. Lead-tungstate has a high density (8.28 g cm^{-3}), a short radiation length (0.89 cm) and a small Molière radius (2.2 cm). These characteristics permit the ECAL detector to have a high granularity and a compact size. The ECAL has been measured to have an efficiency above 99 % for objects with $E_T > 40 \text{ GeV}$ and to give an energy resolution for electrons from Z decays of 1.7 %. Further details of the CMS ECAL and its performance can be found in [48].

When the electrons and photons enter the lead-tungstate crystals, they give rise to an electromagnetic shower of particles. The shower ultimately results in a pulse of light which is measured by photodetectors at the outward facing ends of the crystals. In the barrel region, silicon avalanche photodiodes are used as the photodetectors, while vacuum phototriodes are used in the endcap region. In this way, during the measurement process, the photons and electrons are

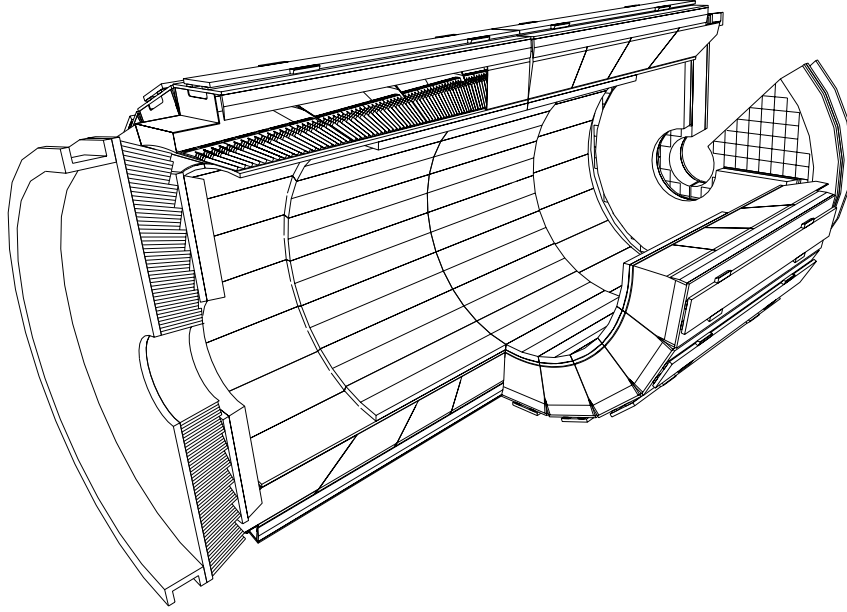


Figure 3.4: Schematic diagram of the CMS ECAL. Taken from [49].

absorbed by the detector.

The barrel part of the ECAL is subdivided into 360 crystals in Φ and 2×85 in η and covers the range $|\eta| < 1.497$. The crystals are mounted at a small angle with respect to the direction to the nominal interaction point in order to avoid particles passing through cracks in the detector. The crystal dimensions are roughly $22 \times 22 \text{ mm}^2$ at the front face and $26 \times 26 \text{ mm}^2$ at the rear face, with a length of 230 mm, corresponding to about 25.8 radiation lengths.

The end caps cover the range $1.497 < |\eta| < 3.0$, with the crystals arranged in a rectangular grid in (x, y) . To avoid cracks in the detector where particles could escape the crystals point at a focus 1300 mm beyond the nominal interaction point, thus being mounted at a small angle to the interaction point, similarly to the barrel region. The crystals have dimensions of $28.62 \times 28.62 \text{ mm}^2$ at the front face and $30 \times 30 \text{ mm}^2$ at the rear face, with a length of 220 mm, corresponding to about 24.7 radiation lengths.

Not that the ECAL crystals have dimensions compatible with the Molière radius of the material they are composed of, consequently the electromagnetic showers produced when a particle interacts in the crystals will leak into adjoining crystals. Consequently, the energy of the particles is measured as clusters of crystals and the clusters can further be used to reconstruct the position where the shower began, i.e. where the particle interacted.

The ECAL end caps are augmented with a lead-silicon-strip preshower, placed in front of the crystals, with the aim of identifying neutral pions in the endcap. It is a sampling calorimeter with two layers each composed of lead radiators to initiate an electromagnetic shower followed by silicon strip sensors to measure the energy deposit. The preshower helps the identification of electrons and improves the position determination of electrons and photons.

3.2.4 HCAL

The CMS HCAL aims to provide a measurement of the energy of hadronic radiation as well as triggering capabilities. With this purpose in mind, it has the task of measuring the energy of all particles remaining after the ECAL, with the exception of the muons. Similarly to the ECAL, the HCAL is split into a barrel detector (HB) and two endcap detectors (HE). The HCAL is further complemented by two sub-detectors: the forward hadron calorimeters (HF) placed at 11.2 m from the nominal interaction point, which have the purpose of extending the coverage of the calorimeter up to $|\eta| = 5.2$; and the outer hadron calorimeter (HO) placed outside the solenoid. A schematic view of a slice of the HCAL can be seen in Fig. 3.5.

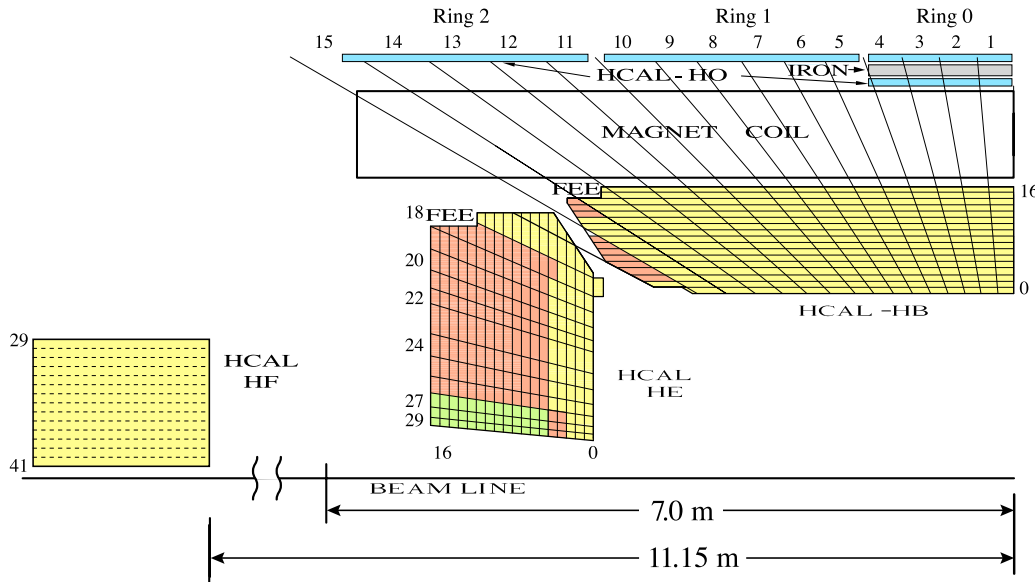


Figure 3.5: Schematic diagram of a quarter of the CMS HCAL in an r - z slice. Taken from [50].

HB and HE are sampling calorimeters with interleaved layers of brass as the absorber material and plastic scintillator as the active material. Brass was chosen as the absorber material given its reasonably small radiation length, its ease of machining and for being non-magnetic,

since it is located within the CMS solenoid. The plastic scintillator is an ideal choice for the active material since it allows to maximise the amount of absorber material before the solenoid. To catch possible energy leakage from the HB, layers of scintillators are placed outside the solenoid, constituting the HO. A more in depth description of the HCAL can be found in [46, 50].

The HB covers the range $|\eta| < 1.3$. It is built of 18 wedges, each covering 20° in the azimuthal angle, with each divided into four 5° sectors. Each half is split into 16 towers in η . The overall design gives an effective segmentation of 0.087×0.087 in the $\eta \times \Phi$ space. Its thickness corresponds to 5.8 hadronic interaction lengths at $\eta = 0$ and goes up to 10 at $|\eta| = 1.2$.

The HO catches the energy leakage from the HB and is placed in the inner layer of the return yoke. It has two scintillator layers in the innermost region (close to $\eta = 0$) and a single layer in the rest of the barrel region. This subdetector extends the coverage of the HCAL by effectively increasing the radiation lengths of the detector to over 10 hadronic radiation lengths. Geometrically, it is constrained by the muon system and closely follows its geometry, having 12 identical sectors in Φ . 95 % of all hadrons above 100 GeV deposit energy in the HO.

The HE covers the range $1.3 < |\eta| < 3.0$. It is made of brass disks, interleaved with scintillator wedges which cover 20° in the azimuthal angle. Each endcap is split into 14 towers in η . The outermost towers (smaller η) have a segmentation of 5° , while the innermost towers have a segmentation of 10° .

The HF covers the range $3.0 < |\eta| < 5.2$. One of the main purposes of this detector is the real time measurement of the luminosity delivered to CMS. The HF consists of a steel absorber structure of 5 mm thick plates alternating with quartz fibres as the active elements which generate a signal through the Cherenkov effect. The fibres are parallel to the beam direction and for the measurement the fibres channel the Cherenkov light to photomultipliers.

3.2.5 Superconducting Solenoid

The CMS superconducting solenoid is 12.5 m long and has a diameter of 6 m. It is designed to produce a 4 T magnetic field, storing 2.6 GJ of energy when at full current. The magnetic flux is returned through an iron return yoke, which envelopes the CMS detector. The return yoke weighs 10 000 t and is divided into 5 wheels and 2 end caps, with each endcap being divided into

3 disks. The yoke's purpose is to increase the homogeneity of the magnetic field in the tracker volume and reduce the stray field by returning the magnetic flux of the solenoid. The return yoke also serves as structural support for the whole CMS detector. The CMS Collaboration has decided to operate the superconducting solenoid at 3.8 T, instead of the nominal 4 T, until a more in depth understanding of the ageing of the solenoid has been obtained [51].

In order to accurately reconstruct the tracks of charged particles and in order for the simulated events to match the observed data as close as possible, a detailed map of the magnetic field is required. The field within the solenoid was mapped with specialised Hall effect sensors prior to the assembly of the CMS detector [52]. Further measurements during the assembly of the detector confirmed the validity of the previous measurements in the presence of the detectors within the solenoid. The field outside the solenoid, within the return yoke, is affected by the magnetic environment surrounding the CMS detector. Consequently, dedicated runs with cosmic muons were employed to map the magnetic field in this region [51]. In this way, the CMS magnetic field is mapped, in the central region to a precision better than 0.1 % and in the yoke to a precision of 3 % to 8 %.

3.2.6 Muon Chambers

The muon system in CMS has three main functions: muon identification; muon momentum measurement; and triggering. The muon system employs three types of gaseous particle detectors: drift tubes (DT); cathode strip chambers (CSC); and resistive plate chambers (RPC). The choice of which technologies were used is driven by the different radiation environments and the areas to be covered. In the barrel region, where the muon rates are low, DTs are used. In the endcap region, where the muon rates are high, CSCs are used. Both DTs and CSCs have the capability to trigger on the transverse momentum of the muons with good efficiency and high background rejection. However, due to the uncertainty on the background rates and the ability to measure the correct beam crossing time when the LHC reaches full luminosity a complementary system, consisting of RPCs was added to both the barrel and end caps. This addition stems from the fact that the RPCs provide a faster signal at the cost of a coarser resolution with respect to the DTs and CSCs. A schematic diagram of the CMS muon detectors and their layout can be seen in Fig. 3.6. The DTs and CSCs provide CMS with muon track segments for triggering with an

efficiency above 96 % and correctly identify the bunch crossing in over 99.5 % of the cases. An in depth analysis of the performance of the muon system as well as a more in depth description of the detector can be found in [53].

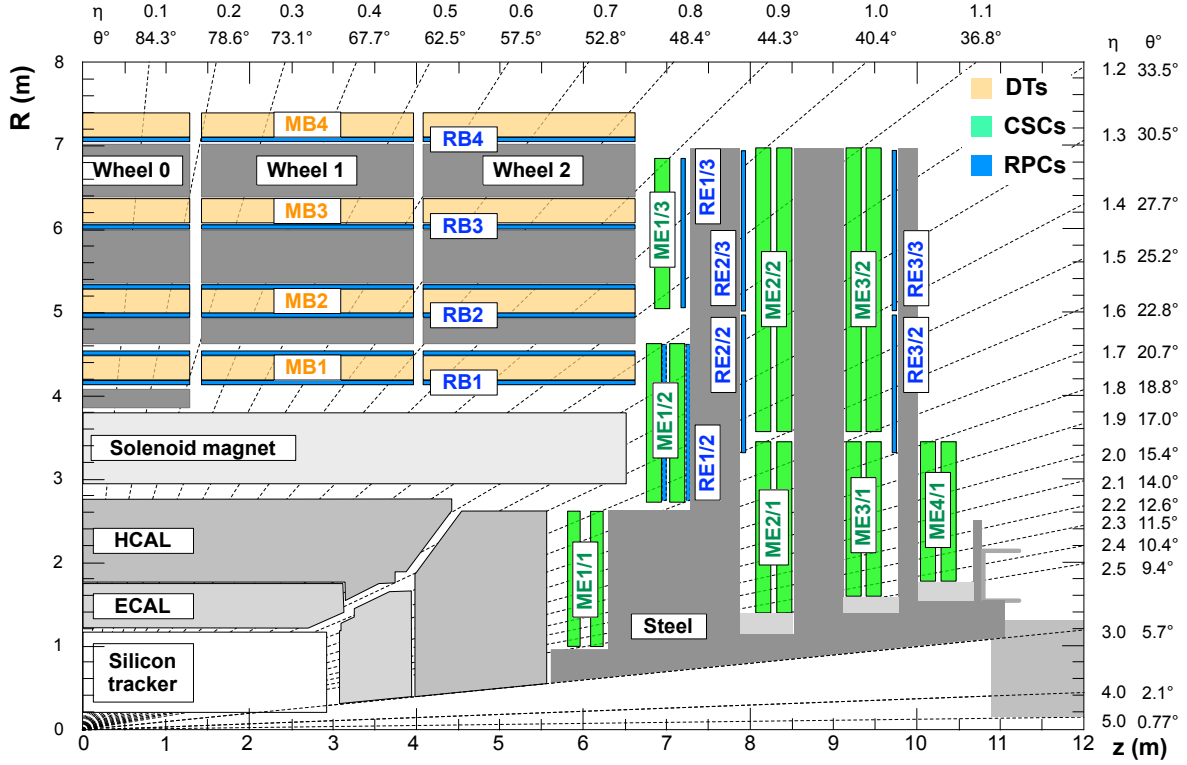


Figure 3.6: Schematic diagram of a quarter of the CMS detector in an r - z slice. The interaction point is at the lower left corner. The steel return yoke is shown in dark grey. The DTs are illustrated in light orange, the CSCs are illustrated in green and the RPCs are illustrated in blue. The different layers of the DTs are labelled MB, the CSC layers are labelled ME and the RPC layers are labelled RB and RE, depending on whether it is a barrel or endcap layer, respectively. Taken from [53].

3.2.7 Trigger

With the nominal LHC bunch spacing, it is expected to have a collision every 25 ns, corresponding to a rate of 40 MHz. The size of an event at CMS is $\mathcal{O}(1)$ MB, consequently storing all events would require to store 40 TB of data every second. Storing such an amount of data is clearly a gargantuan task. With this in mind, a reduction on the rate of events to be kept and

analysed must be performed, ideally by discarding the uninteresting events and keeping the interesting ones. This is the task of the trigger system, thus corresponding to the first step of the physics event selection and analysis. The interesting events are defined as those events where it is expected to find evidence of new physics or events where more precise measurements are desired, which correspond to events within specific ranges. In general, it is expected that new physics will be manifested by new particles, with higher masses, thus corresponding to events containing objects with higher transverse momentum. Consequently, the remaining events are considered uninteresting and are discarded.

In CMS the trigger system is split into two steps, the Level-1 (L1) trigger and the High-Level Trigger (HLT), with the L1 feeding directly into the HLT. The L1 trigger consists of custom designed, largely programmable, electronics, which are located on the detector and in its vicinity. The HLT trigger is a software system implemented in a computing farm. The HLT has the task of reducing the event rate from around 100 kHz, originating from the L1 trigger, to less than 1 kHz before storage. More in depth descriptions of the trigger systems can be found in [54–56].

L1

The L1 trigger only uses coarse data from the calorimeters and muon system, while the full granularity data is stored on the detector front-end electronics waiting for the L1 decision. The allowed L1 trigger latency, between a given bunch crossing and the distribution of the trigger decision to the detector front-end electronics, is $3.2\ \mu\text{s}$. The mismatch between the trigger latency ($3.2\ \mu\text{s}$) and the bunch crossing rate (25 ns) is managed through buffers on the front-end electronics, which hold the information until a decision by the L1 trigger has been reached. The L1 trigger is implemented pipelined logic to allow for the necessary throughput to reach a decision for each bunch crossing. The trigger decision is based on local, regional and global trigger components. A flow chart of the trigger architecture is displayed in Fig. 3.7.

The ECAL and HCAL cells are combined to form so-called trigger towers. Trigger primitives are generated by calculating the transverse energy of each tower. A regional calorimeter trigger then determines electron, photon and jet candidates and information relevant for muon and tau identification, on a regional level. The global calorimeter trigger calculates the total

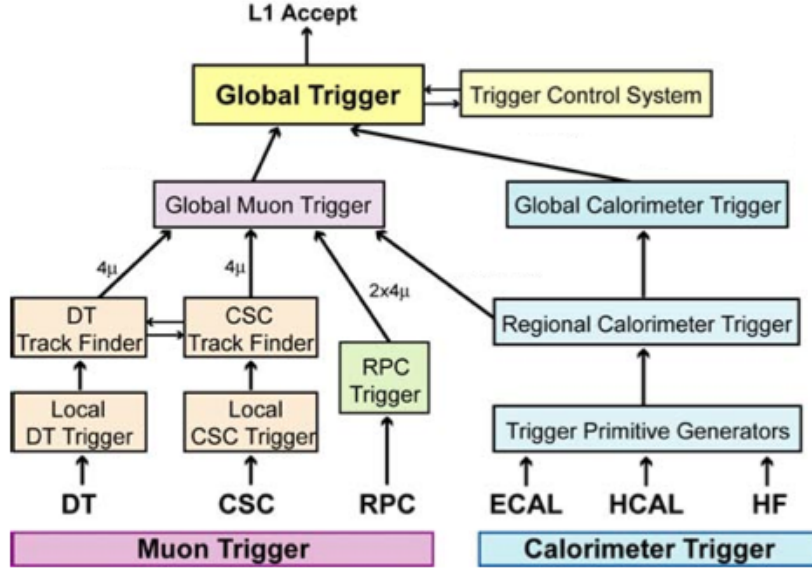


Figure 3.7: Flow chart of the CMS L1 trigger. Taken from [57].

transverse energy and the Missing Transverse Energy (MET), also providing information about the jets and the highest ranking trigger candidates.

All the types of muon detectors take part in the muon trigger. The DT chambers provide track segments in the ϕ projection and hit pattern in η , while the CSC determine three-dimensional track segments. The track finders in the DT and CSC calculate the transverse momentum, location and quality of a track segment. The RPCs use regional hit patterns to provide an independent measurement. The global muon trigger receives up to 4 candidate muons from each subsystem in conjunction with isolation information from the regional calorimeter trigger. The global muon trigger selects a maximum of four muon trigger candidates and determines their momentum, charge, position and quality.

The trigger objects identified by the global calorimeter trigger and the global muon trigger are forwarded to the global trigger. The global trigger makes the decision to accept or reject an event based on the results of algorithms which for example apply thresholds on the momentum of the objects or require a certain number of object to be present. The decision is then distributed back to the detectors so the full event information, with a size of $\mathcal{O}(1 \text{ MB})$, can be read out to the HLT trigger.

HLT

The HLT is implemented as a set of software filters that runs in a processor farm, thus being fully parallelized. The HLT processes all events accepted by the L1 trigger, i.e. it is seeded by the L1 trigger. The selection of events is optimised by rejecting events early, i.e. as soon as there is enough information to decide to not keep it. The reconstruction algorithms used are generally the same as those used for offline analysis, but to optimise for speed some features are sometimes only partially reconstructed. Such as only a restricted region of the detector is reconstructed or a limited set of information from the physics objects is retrieved. The HLT selection algorithms are organised in paths, an event is accepted by the HLT if it is accepted by any path.

3.2.8 DAQ

The CMS trigger and Data Acquisition (DAQ) system is designed to collect and analyse the detector information at the LHC frequency of 40 MHz. The DAQ system must not only sustain a rate of 100 kHz from the L1 trigger, at a total bandwidth of 100 GB s^{-1} from approximately 650 different sources (about 200 MB s^{-1} each), but it must also provide the computing power for the HLT to perform its task of further reducing the event rate to less than 1 kHz. Data is collected in so-called runs, during which the DAQ parameters do not change.

3.2.9 DQM

The Data Quality Monitoring (DQM) system continuously monitors the quality of the data. A sample of the recorded events are reconstructed, in particular calibration events, from which a large set of quantities are collected in histograms and compared between runs and reference values by both automated processes and through human intervention. If significant deviations are observed, the corresponding luminosity sections (lumisections) are marked as bad. CMS has defined a lumisection as a fixed period of time, set to 2^{18} LHC orbits, which roughly corresponds to 23.3 s. The information on the bad lumisections is combined with the detector status information to produce a curated list of certified runs and lumisections. In this way, only data that is known to be good is included in the physics analyses.

3.2.10 Luminosity and Pileup Measurement

In CMS two detectors are exploited to measure the luminosity, the forward hadronic calorimeter and the silicon pixel detector [58]. The forward hadronic calorimeter features a dedicated high rate acquisition system, the HF luminosity transmitter, which is independent from the central DAQ and provides a real-time luminosity measurement. It is capable of determining the luminosity with 1 % statistical uncertainty in 1 s, however it is subject to calibration drift and is non-linear with pileup. Thus, the preferred method for estimating the luminosity is using the silicon pixel detector.

The silicon pixel detector is characterized by a very low occupancy, below 0.1 %, and consequently is stable throughout data taking. The luminosity is estimated using the Pixel Cluster Counting method. The number of pixel clusters occurring on average in an event ($\langle n \rangle$), triggered by requiring only two bunches to cross at the interaction point, is used to estimate the luminosity, Eq. 3.5, where ν is the beam revolution frequency and σ_{vis} is the visible cross section. The visible cross section is measured in dedicated “Van der Meer” runs.

$$\mathcal{L} = \frac{\nu \langle n \rangle}{\sigma_{\text{vis}}} \quad (3.5)$$

The luminosity of each bunch crossing, Eq. 3.5, multiplied by the total inelastic cross section results in the number of interactions for the considered bunch crossing. Performing this procedure for all the bunch crossings in data results in the distribution of the number of interactions in data, also referred to as the PU distribution.

Chapter 4

Software Framework

CMS has put in place a common, generic event processing framework, which is also a model for data storage for the HLT, event reconstruction and analysis. The event processing code is written in C++ and the processing jobs are configured in Python. The job results are stored to disk with the ROOT framework. It is called the cmssw framework. An in depth description can be found in [59].

4.1 Simulation

An important part of any high energy physics analysis resides in the simulation of events, allowing to compare the experimental results with the theoretical predictions. In practical terms, a simulation provides simulated events which can be treated as if they were real events, through the reconstruction and analysis steps. The simulated events are generally produced through the Monte Carlo (MC) method, with repeated random sampling of the theoretical distributions; for this reason as a shorthand the simulations are often referred to only as MC. MC events are also used for studying and optimising the selection criteria prior to seeing the experimental results.

Simulation generally consists of three steps: the simulation of the proton–proton interaction; the propagation of the final state particles through the detector volume; and the response of the sensors to the particles. The PU is modelled by mixing simulated minimum-bias events on top of the simulated hard interaction before reconstruction of the event. Technically the simulation is

performed within the CMSSW framework, however some of the simulation softwares that perform the initial step of the simulation, called generators, are run as standalone programs and the output is subsequently fed into CMSSW.

4.1.1 Event Generation

The interaction of two colliding protons is simulated with event generators, typically using the MC method. There exist general purpose event generators, such as PYTHIA [60] and HERWIG [61], which simulate a variety of physical processes and also the parton shower and hadronisation. There are also specialised generators which focus on specific objectives and can be interfaced with other generators, such as the general purpose ones, in order to obtain the final physical states, i.e. the event after hadronisation process. An example of a specialised generator is TAUOLA [62], which simulates decays of only the τ lepton, with the specificity of including its polarisation.

MADGRAPH [63] is another commonly used generator, it is designed to generate matrix elements. The matrix element squared is an essential component for computing the cross section of a given physics process [64]. Once the matrix elements have been generated, MADGRAPH can evaluate the cross section or decay width of the associated process. Within the MADGRAPH framework, MADEVENT can subsequently be used to generate events. The generated events must then be processed with any program capable of simulating the parton shower and hadronisation, such as PYTHIA or HERWIG.

4.1.2 Detector Simulation

The evolution of the event through time and space after hadronisation as well as the interaction of the particles with matter constitute the detector simulation. Particles are propagated through the detector volumes and new particles are produced in the interactions with the detector material. The CMS detector simulation is performed with the GEANT4 [65] toolkit, which is written in C++ and integrated within CMSSW. The GEANT4 toolkit is the tool that effectively propagates the particles in time and space, through the detector volumes, and simulates the interaction of these particles with matter, which results in simulated energy deposits in the detector volumes.

The energy deposits in the detector volumes are converted to digitised signals using algorithms based on the observed detector behaviour. At this point, the digitised signals of the simulated event are similar to those of a real event and can be treated as any other event with the CMSSW event reconstruction and analysis chain.

4.1.3 Fast Simulation

The above described simulation approach is commonly referred to as FULLSIM, since it constitutes a full simulation of the whole physics and detector chain. It is a very time and resource intensive process. Another approach is the so-called fast simulation, FASTSIM, which performs about 100 times faster than the FULLSIM. In the FASTSIM approach, the events are generated with the event generators, like for the FULLSIM. The particles are then propagated through the detector volume. The material effects and the response of the detectors to the particles are obtained through parameterisation at the hit level. The results can then be treated as any other event with the CMSSW event reconstruction and analysis chain. A more in depth description of the CMS FASTSIM can be found in [66]. For this work, the FASTSIM approach is only used to process the signal samples, with FULLSIM being used to process all background samples.

4.1.4 Pileup Modelling

The PU interactions are modelled by mixing simulated minimum-bias events on top of the simulated hard-interaction events. Since the simulation efforts must start prior to all the data being collected, the distribution of the number of PU interactions in data is unknown. Therefore, the simulated events are generated with an assumed PU distribution and the events are re-weighted at the analysis time such that the PU distributions between data and simulation agree.

4.2 Event Reconstruction

Raw data from the CMS detector is, in essence, a collection of voltage readings from the various elements of the detector at the time of the event. However, to perform meaningful physical anal-

yses, it is preferable to work in terms of the particles that generated the observed signals. Thus, sets of algorithms, made to reconstruct the particles from the raw data, are implemented. These reconstructed particles form the so-called physics objects. The CMS Physics Object Groups (POGs) define a set of recommendations so that physics analysis can have a common set of definitions and parameters when using the above-mentioned physics objects, so-called working points.

4.2.1 Tracking

The tracking reconstruction has the purpose of reconstructing the trajectories of the charged particles from the energy deposits in the tracker detector. For the trajectories of muons, the energy deposits in the muon chambers, also referred to as the hits in the muon chambers, are also used. Given the presence of the magnetic field, aligned with the z axis, the trajectories of the charged particles are bent, in the transverse plane (the xy plane), and the charged particles, free from any other interactions, move along helices. With the reconstructed trajectories it is possible to measure the curvature of the trajectory. The curvature of the trajectory of the particle is an important measure since it relates directly with the momentum of the particle. The basic principle for this relation stems from equating the centripetal force with the magnetic force, Eq. 4.1, which results in an equation relating the momentum with the radius of the curvature of the trajectory of a particle, Eq. 4.2.

$$F_C \equiv m \frac{v^2}{r} = qvB \equiv F_B \quad (4.1)$$

$$p \equiv mv = qrB \quad (4.2)$$

Thus, exploiting the tracking with the magnetic field, which bends the particles in the transverse plane, permits to measure the momentum of the particles in the transverse plane, the so-called transverse momentum, p_T . Using simple trigonometry it is possible to relate the p_T with the total momentum using the angle θ of the trajectory, which is obtained from the tracking as well, Eq. 4.3.

$$p = \frac{p_T}{\sin \theta} \quad (4.3)$$

The large multiplicity of particles expected to be created in each event poses a challenge for the tracking algorithm. The hits associated to each track must be found and fitted in order

to obtain the track parameters. For this purpose CMS uses the so-called combinatorial track finder (CTF) algorithm. The CTF algorithm proceeds through three stages: track seeding; track finding; and track fitting. The track candidates are seeded from the hits in the pixel detector. The track finding stage is based on Kalman filters, where the trajectory is extrapolated to the next layer and compatible hits are associated to the track. The Kalman filter proceeds to update the track parameters with the new hit. In the final stage, the tracks are refitted with a Kalman filter and a second fitter (smoother) running from the exterior towards the beam line. More detailed descriptions can be found in [67, 68]. The muon tracking exploits the hits in the muon detector, where it is unlikely for particles that are not muons to reach. Conversely, the electron tracking has to handle not only the electron tracks, but tracks from all other charged particles, resulting in a much more challenging reconstruction environment. The CMS tracking is designed to provide an efficiency above 99 % for single muons with a transverse momentum above 1 GeV, for more details see [69].

4.2.2 Primary Vertices

The particle tracks, reconstructed as explained in the previous section, allow the reconstruction of the position of the interaction. In the presence of PU, a single event may contain multiple interaction points. In general, a single interaction per event is considered the Primary Vertex (PV). The vertex reconstruction can be separated into two steps, the clustering of the tracks in order to find the best partition of the tracks and the fitting of the set of tracks to the vertex. The tracks are clustered using the so-called Deterministic Annealing clustering of tracks [70]. The reconstructed vertex is required to have a z position within the nominal detector centre ($|z| < 24$ cm) and a radial position within the beam-spot ($|d_0| < 2$ cm). The reconstructed vertices are also required to have more than four degrees of freedom in the vertex fit. From the set of vertices passing these criteria, the vertex with the highest $\sum_{\text{tracks}} p_T^2$ is chosen as the PV. More details can be found in [71, 72]

4.2.3 Particle Flow

The Particle Flow (PF) algorithm reconstructs and identifies each individual particle in an event by using an optimised combination of information from the various elements of the CMS detector. One advantage of using the PF approach to the object identification is that it provides a consistent set of reconstructed particles for each event. The main ingredients for the PF algorithm, which are provided by the CMS detector, are an efficient and pure track reconstruction with a small material budget in front of the calorimeters, a good calorimeter granularity, a large magnetic field and a good separation between charged and neutral hadrons. A more detailed description of the PF algorithm can be found in [73, 74]. The algorithm can be described in the following simplified picture. Muons are identified in a first step, since they are the only measured objects reaching the muon chambers, and their tracks are removed from consideration for the subsequent steps. Tracks are extrapolated to the calorimeters and if they fall within the boundaries of one or several clusters, the clusters are associated to the track. This set constitutes the charged hadron candidates and the base objects are not considered for the remainder of the algorithm. A specific track reconstruction is used for the electrons, given the emission of Bremsstrahlung photons. A dedicated procedure properly associates the energy deposits from Bremsstrahlung photons with the electron track. Once all the tracks have been processed, the remaining deposits are considered photons, in the case of the ECAL, and neutral hadrons, in the case of the HCAL. Once each particle has had its energy deposits associated, its nature can be evaluated and the information from the subdetectors combined to determine its energy.

The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all Bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy. The four-momenta of individual particles can subsequently be used to cluster jets, to compute the MET, and to reconstruct the hadronic decays of the τ

lepton. The list of individual particles is also used to measure the isolation parameter of the particles.

4.2.4 Jets

Quarks and gluons fragment and hadronise almost immediately after being produced, leading to a collimated spray of energetic hadrons, called a jet. Consequently, jets are the experimental signature of quarks and gluons produced in a collision. Thus, jets are reconstructed by clustering the set of reconstructed particles into groups. Several algorithms have been devised for this purpose, of particular concern the algorithms should have as small sensitivity as possible to non-perturbative effects. Of note among the available algorithms, the anti- k_t algorithm has the property of defining jets with a circular boundary and little dependence on soft effects. The dimension of the jets determined by the anti- k_t algorithm is controlled by the R parameter. A more detailed description of the anti- k_t algorithm and of the other algorithms can be found in [75]. For this analysis, jets are reconstructed from all the PF candidates using the anti- k_t algorithm with $R = 0.5$ parameter. Charged hadron subtraction is applied to the jets in order to remove particle candidates which are associated to secondary vertices. The energy of the reconstructed jets is corrected in 3 steps: in a first step effects from pileup and the underlying event are subtracted from the jets, in a second step relative corrections are accounted for and in a third step absolute scale corrections are applied. For data, an extra residual correction is included in the absolute scale correction. The subtraction of the pileup contribution deserves particular attention as the same estimator is used to correct the isolation of the leptons. This estimator is computed using the FastJet algorithm [76]. The median of the energy density of the reconstructed jets (ρ) is used as an estimator for the contamination of the jet energy scale (or the lepton/photon isolation). An extra correction is applied for the simulated jets in order to reproduce the measured jet energy resolution.

4.2.5 b-Jet Identification

Several physics processes of interest are characterised by the presence of b quarks. Dedicated algorithms target the increased lifetime of hadrons containing a b quark, compared to other par-

ticles, to tag jets originating from b quarks. Each algorithm produces a numerical discriminator for each jet, which reflects the likelihood that the jet would originate from a bottom quark, by taking into account the properties of the charged particles within the jet. A working point in the efficiency versus purity space is selected by placing a cut on the discriminator.

One of the parameters used for b-jet identification is the track impact parameter (IP), which is calculated in 3D thanks to the great resolution of the CMS pixel detector. The resolution on the IP depends strongly on the track transverse momentum and pseudorapidity. The impact parameter significance is another observable, defined as the ratio of the IP to its uncertainty. A straightforward algorithm using this information is the Track Counting (TC) algorithm which ranks the tracks in a jet according to the IP significance, taking the IP significance of the second or third track as the discriminator. Further algorithms combine the IP from several tracks, such as the Jet Probability (JP) algorithm or the Jet B Probability (JBP) algorithm. JP estimates the likelihood that all tracks from a jet originate from the primary vertex. JBP estimates gives more weight to tracks with the highest IP significance, up to four.

The presence of a secondary vertex, as well as its properties, is used as a further discriminator for b-jets. These values include the distance and direction of the secondary vertex to the primary vertex, the multiplicity of secondary tracks and the invariant mass and energy of all tracks originating from the secondary vertex. The Simple Secondary Vertex (SSV) algorithm is one such discriminator, using the significance of the flight distance as the discriminating variable.

The Combined Secondary Vertex (CSV) algorithm is of particular interest since it is used for this analysis. It combines information from several of the discriminating variables, including the above described discriminating variables, being able to provide some discrimination even in the absence of a secondary vertex. Fig. 4.1 shows the efficiency vs mistag rates for the mentioned b-jet discriminators, for TC and SSV, two different tunes are shown, High Purity (HP) and High Efficiency (HE). Further information on b-jet identification can be found in [77].

4.2.6 Tau Jets

The tau lepton has two possible decay modes, either it decays to a lighter lepton and two neutrinos, the so-called leptonic decay mode, or it decays into one or more hadrons and a neutrino,

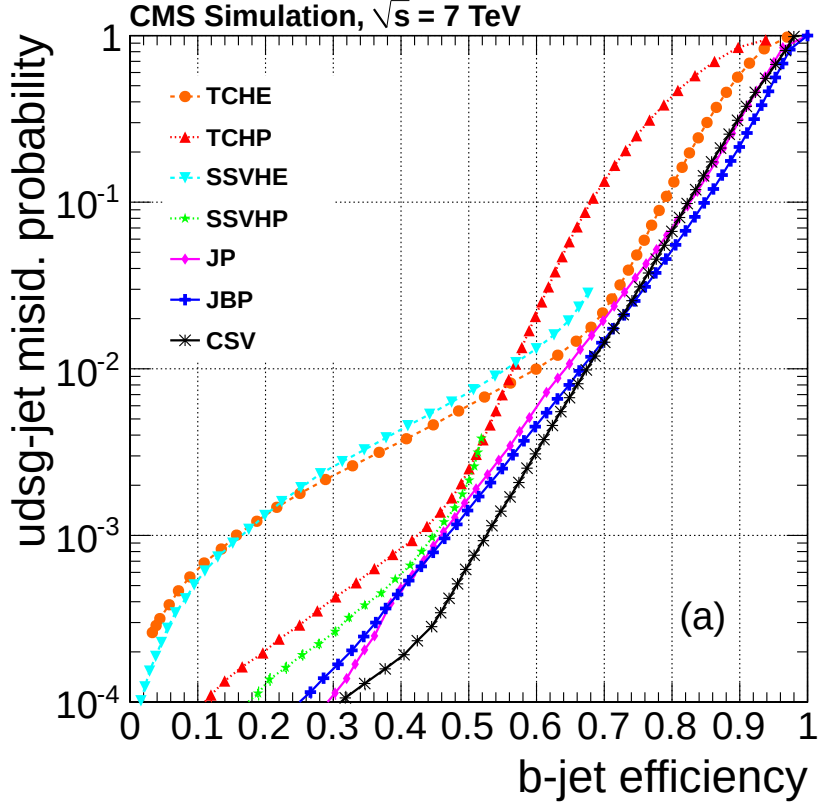


Figure 4.1: Performance curves for the b-jet discriminating algorithms obtained from simulation. Jets with $p_T > 60$ GeV in a sample of simulated multijet events are used to obtain the efficiency and misidentification probability values. Taken from [77].

the hadronic decay mode. In about two thirds of the cases tau leptons decay hadronically, typically into one or three charged mesons (predominantly $\pi^\pm$), accompanied by up to two neutral pions (π^0). The hadronically decaying taus are reconstructed as jets by the CMS reconstruction. Compared to other jets, the tau jets are characterised by having a low charged track multiplicity within the jet cone. These distinct features of the tau hadronic decays have been exploited for the identification of hadronically decaying tau leptons. The main hadronic tau decay modes are listed in Table 4.1.

The hadronically decaying tau identification is integrated within the PF framework. The algorithm currently employed by the CMS collaboration is the so-called Hadron Plus Strips (HPS) algorithm. The magnetic field, produced by the CMS solenoid broadens the signature of neutral pions (in the calorimeters) in the ϕ direction since it spreads the shape of the electromagnetic shower in this direction. The HPS algorithm starts with the collection of reconstructed jets and exploits the broadening effect by reconstructing the pions in a strip along ϕ . The reconstruction

Table 4.1: Hadronic decays of the τ lepton and the corresponding branching fractions. In the “decay mode” column, h represents an hadronic decay product, for example a pion (π) or a rho meson (ρ). The charge conjugate decays are not explicitly listed, but are in all aspects equal, apart from the change of sign.

decay mode	branching ratio (%)
$\tau^- \rightarrow h^- \nu_\tau$	11.5
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	26.0
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	10.8
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	9.8
$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$	4.8
other hadronic modes	1.7
Total	64.8

starts by centering a strip ($\Delta\eta = 0.05$ and $\Delta\phi = 0.20$) around the most energetic electromagnetic particle in the PF jet and iteratively adding the most energetic electromagnetic particle within the window to the strip, followed by recalculating the centre of the strip. The strips are subsequently combined with the remaining charged hadrons from the jet in order to reconstruct the tau decay topology. The different tau decay topologies correspond to the different tau decay modes, see Table 4.1. The decay topology affects the reconstruction of the four-momenta of the tau, all the charged hadrons are assumed to be pions and are required to be consistent with the intermediate meson decay resonances of the τ . In a final step, the reconstructed candidates are required to pass certain isolation criteria. The isolation criteria requires that there be no photons or charged hadrons within a $\Delta R = 0.5$ cone above a certain p_T threshold. Different p_T thresholds are used to define the different working points: loose, medium and tight. The loose working point is defined such that the tau misidentification probability (i.e. the probability of a jet being incorrectly identified as a tau) be 1 %. The subsequent working points reduce the misidentification probability by a factor of two. The τ identification efficiency for the loose, medium and tight working points is shown as a function of the τ p_T in Fig 4.2. More details on the HPS algorithm can be found in [78].

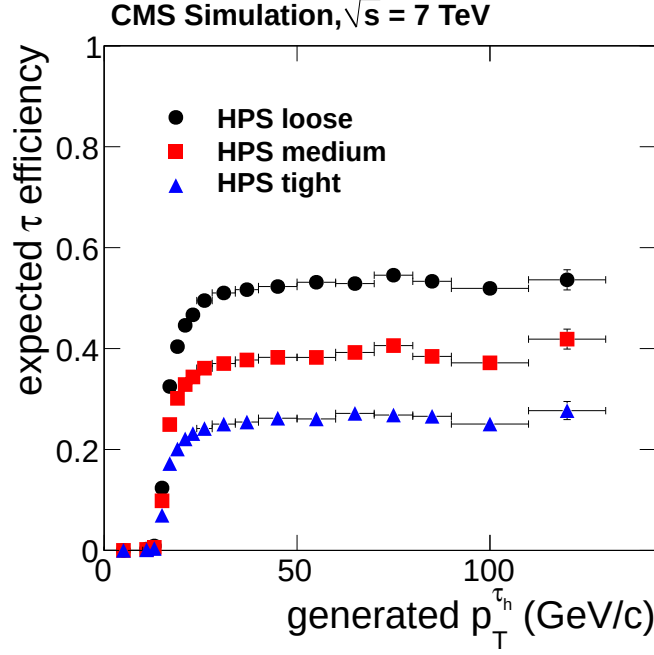


Figure 4.2: Efficiency of the tight, medium and loose working points of the HPS τ identification algorithm as a function of τ p_T . The efficiency was estimated using a sample of $Z \rightarrow \tau\tau$ events. Taken from [78].

4.2.7 Missing Transverse Energy

The CMS detector can detect nearly all particles that traverse its volume, the exceptions being neutrinos and other postulated weakly interacting particles. To infer the presence of these particles it is necessary to resort to the conservation of momentum. In a hadron collider, such as the LHC, the interacting particles are the partons of the individual protons and consequently the momentum of the initial state is not well defined. However, the momentum of the partons in the transverse plane is known to be vanishingly small and subsequently of the initial state as well. As a result, the sum of the transverse momentum of the detected particles is equal to the negative of the sum of the transverse momentum of the unobserved particles. Thus, the momentum imbalance of the measured particles in the transverse plane is used as an indicator for the presence of the unobserved particles. The magnitude of this quantity is called Missing Transverse Energy (MET) and is denoted by $\cancel{E}_T$.

The performance of the detector itself, of the particle reconstruction and even the particle misidentification affect the reconstruction of the MET. For instance, the mis-measurement of the energy of a single particle would result in $\cancel{E}_T > 0$ even if there were no neutrino or weakly

interacting particle in the event.

The MET is estimated from the imbalance of the transverse momentum of all the reconstructed PF candidates. This estimator is usually referred as raw MET and is defined as:

$$\vec{E}_T = - \sum_{i=1}^{N_{\text{PF}}} \vec{p}_{T,i} \quad (4.4)$$

Two types of corrections are applied to this estimator. The “Type-0” correction aims to mitigate the degradation of the $\vec{E}_T$ reconstruction due to the PU interactions by removing charged hadrons originating from the vertices of PU interactions. In addition to charged hadron subtraction, this correction removes an estimate of neutral PU contributions. The “Type-I” correction is a propagation of the jet energy corrections to $\vec{E}_T$, and acts by replacing the vector sum of transverse momenta of particles which can be clustered as jets with the vector sum of the transverse momenta of the jets to which the jet energy correction is applied.

The performance of the MET reconstruction algorithms is measured in events with a Z boson or an isolated photon. The large majority of these events contain no real source of MET. The transverse momentum of the boson is used as a reference for the sum of the transverse momentum of the remaining particles in the event. In this way, the MET resolution can be evaluated. Fig. 4.3 shows the MET resolution in the x-axis and in the y-axis as a function of the MET. Further details on the MET and the determination of its resolution may be found in [79].

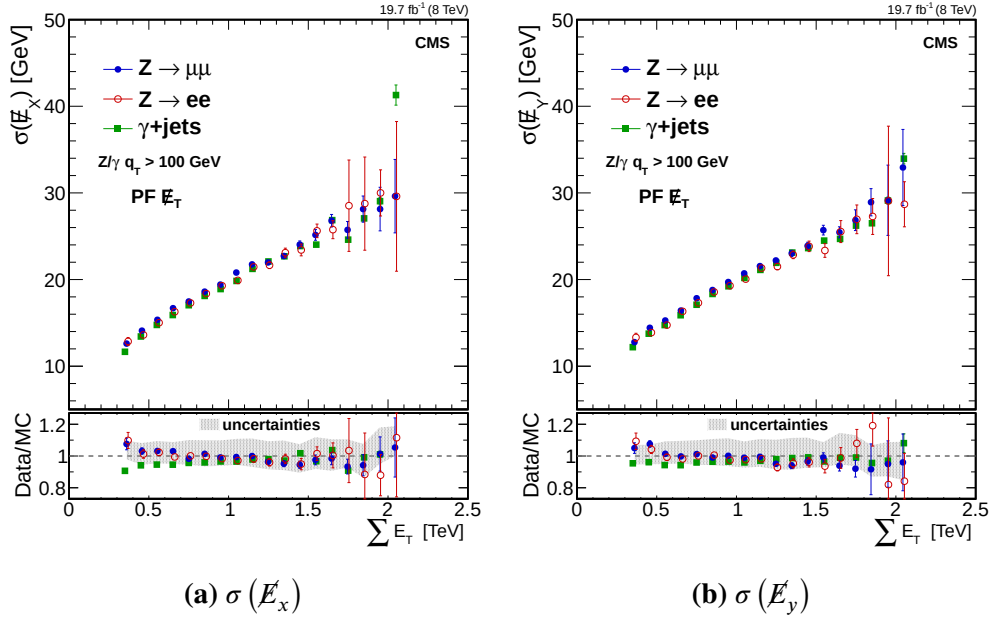


Figure 4.3: Resolution of the MET projection along the x -axis and along the y -axis as a function of MET in events with a Z boson or a photon. The upper frame shows the resolution in data and the lower frame shows the data/MC ratio. The grey error band represents the systematic uncertainties. Taken from [79].

Chapter 5

Base Event Selection

The work of this thesis focuses on the search for the production of staus in an R-parity conserving scenario, where the stau subsequently decays to the LSP and a τ lepton. As explained in section 2.2, given the conservation of R-parity it is expected that the staus will be pair produced. The LSP is assumed to be a neutral particle that exits the detector without being detected. In large parts of the pMSSM parameter space this LSP is the lightest neutralino, i.e. a mixed state of the super-symmetric partners of the neutral gauge bosons and the two neutral super-symmetric partners of the Higgs bosons. However the analysis does not require this constraint so other MSSM scenarios where the LSP is some other neutral particle are also probed. Figure 5.1 is a schematic Feynman diagram for the production of the stau at the LHC and subsequent decay as considered in this work.

The decay product of the stau is, in this scenario, a SM tau, which further undergoes the normal tau decay chains. The tau has two decay channels. The leptonic channel where it decays to a lighter lepton (e or μ) and two neutrinos, occurs in about 35 % of the cases. The hadronic channel where it decays to hadrons and at least one neutrino, occurs in about 65 % of the cases. The neutrinos leave the detector without being detected whereas the leptons and hadrons leave a signal and are reconstructed with a certain efficiency. As a result, there are three experimental channels for the stau pair production scenario: the di-leptonic channel, where both taus decay leptonically, the di-hadronic channel, where both taus decay hadronically, and the semi-leptonic (or semi-hadronic) channel, where one tau decays leptonically and the other hadronically, summarised in Table 5.1.

Table 5.1: Channels of the stau pair production scenario, with subsequent decay of the stau to a tau and the LSP. In the signature column ℓ is either an electron or a muon (e, μ) and τ_h is a hadronically decaying tau.

Channel	Signature	Branching Ratio
Di-leptonic	$2\ell + \cancel{E}_T$	$0.35 \times 0.35 = 0.1225$
Semi-leptonic	$\ell + \tau_h + \cancel{E}_T$	$2 \times (0.35 * 0.65) = 0.455$
Di-hadronic	$2\tau_h + \cancel{E}_T$	$0.65 \times 0.65 = 0.4225$

This analysis focuses on the semi-leptonic channel, which has the highest branching ratio and is expected to have a cleaner signature given the presence of a lepton. By construction, the analysis will look for an excess of events with significant MET in association with a lepton and an hadronically decaying tau.

5.1 Data and Simulation Samples

The data used in this analysis was recorded by the CMS detector during 2012 and corresponds to an integrated luminosity of 19.7 fb^{-1} . During this period, the LHC was producing proton collisions at a centre of mass energy of 8 TeV. The datasets chosen for this analysis correspond

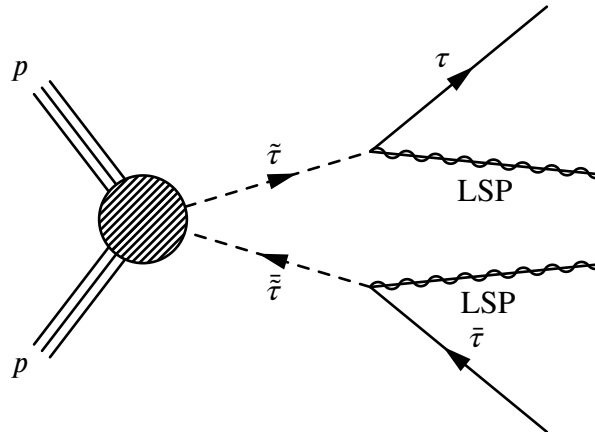


Figure 5.1: Feynman diagram of the production and subsequent decay of a stau pair. The underlying event from the proton collision is not shown to keep the simplicity of the diagram. The horizontal axis represents time and the vertical axis represents space.

to the set of events triggered on by at least one of the “TauPlusX” HLT triggers. These triggers consist of the set of triggers that require an hadronically decaying tau in association with an extra object, for example a lepton, jet or MET. Another possibility for this analysis would be the HLT single lepton triggers, which require a lepton (electron or muon) to be present in the event. However, these triggers have a higher threshold on the transverse momentum of the lepton than the “TauPlusX” triggers. Furthermore, a threshold on the transverse momentum of the tau, similar to that of the “TauPlusX” triggers would be required. Consequently, the single lepton triggers have a lower acceptance than the “TauPlusX” triggers for the signal for this analysis.

The simulated MC datasets used to describe the background processes relevant to this analysis and their respective cross sections are listed in Table 5.2. The background MC samples are generated with MADGRAPH, PYTHIA or POWHEG, and TAUOLA when applicable, and are part of the official CMS Summer 12 production.

In a Simplified Model Spectra (SMS) scenario, the SM is augmented with a specific set of particles and decays for those particles [80, 81]. The main free parameters of a SMS scenario are the masses of the new particles and branching ratios of their decays. These scenarios are extremely useful in setting limits in an as model independent manner as possible. Consequently, to generate the signal MC events an SMS scenario was used. This particular scenario contains a stau and a neutral stable particle (an LSP), with the stau decaying to the neutral particle and a tau. In order for the stau pairs to be produced, the scenario also contains the necessary coupling of the stau pair to the intermediary particles (i.e. the hatched area in Fig. 5.1).

The SMS signal MC samples were generated with PYTHIA and TAUOLA and simulation of the detector response was carried out with FASTSIM. The signal sample has mass points for $M_{\tilde{\tau}}$ between 50 GeV and 500 GeV, separated by 10 GeV, and M_{LSP} between 1 GeV and 480 GeV, separated by 10 GeV with the exception of the lowest M_{LSP} points with $M_{\text{LSP}} = 1$ GeV. The mass points also follow the constraint that $M_{\tilde{\tau}} > M_{\text{LSP}}$.

All data and MC samples were processed in a custom CMSSW module under CMSSW_5_3x. This module processes each event, keeping a reduced set of the event information, considered essential for the analysis, in a so-called nTuple. The nTuples were subsequently analysed with a custom framework, built upon the CMSSW framework. The code for this analysis is based upon code developed for the $H \rightarrow WW \rightarrow 2\ell 2\nu$ analysis and can be found at: <https://github>.

5.2 Online Selection

As previously mentioned, the custom analysis framework processes a specific dataset, a subset of the events recorded by CMS which have been triggered on by the TauPlusX HLT trigger. Only events with the presence of an hadronically decaying tau and a lighter lepton (electron or muon) are of interest for this analysis, see the expected signature of the semi-leptonic channel in Table 5.1. This corresponds to a subset of the TauPlusX triggers. Consequently, the analysis code requires the events to have been triggered on by at least one of this subset of TauPlusX triggers.

In the 2012 data taking period, there were 4 separate runs named 2012A, 2012B, 2012C and 2012D. During run 2012A the TauPlusX triggers of interest for this analysis correspond to:

- requiring the event to have an isolated muon with transverse momentum above 18 GeV within $|\eta| < 2.1$ and a loosely isolated tau with $p_T > 20$ GeV;
- or requiring the event to have an isolated electron with $p_T > 20$ GeV and a loosely isolated tau with $p_T > 20$ GeV.

For the subsequent runs (2012B, 2012C and 2012D), the parameters for these TauPlusX triggers were modified, thus corresponding to the following requirements:

- an isolated muon with $p_T > 17$ GeV within $|\eta| < 2.1$ and a loosely isolated tau with $p_T > 20$ GeV;
- or an electron with $p_T > 22$ GeV within $|\eta| < 2.1$ and a loosely isolated tau with $p_T > 20$ GeV.

In summary, all triggers require a reconstructed and loosely isolated tau with $p_T > 20$ GeV in association with a lepton, whose constraints change with the run period.

Table 5.2: List of the MC background samples considered. All samples are part of the official Summer 12 production.

Short Name	Process	Details	$\sigma \times \text{BR} [\text{pb}]$	Generator
Drell-Yan (DY)	$Z \rightarrow \ell\ell$ ($M_{\ell\ell} \in [10 ; 50] \text{ GeV}$)		8.60×10^2	MADGRAPH
		inclusive	3.53×10^3	MADGRAPH
	$Z \rightarrow \ell\ell$ ($M_{\ell\ell} > 50 \text{ GeV}$)	$Z \rightarrow \ell\ell + 1 \text{ Jet}$	6.72×10^2	MADGRAPH
		$Z \rightarrow \ell\ell + 2 \text{ Jets}$	2.17×10^2	MADGRAPH
		$Z \rightarrow \ell\ell + 3 \text{ Jets}$	6.12×10^1	MADGRAPH
		$Z \rightarrow \ell\ell + 4 \text{ Jets}$	2.76×10^1	MADGRAPH
	$Z + \gamma + \text{Jets}$		1.24×10^2	MADGRAPH
W + Jets	W + Jets	inclusive	3.67×10^4	MADGRAPH
		W + 1 Jet	6.53×10^3	MADGRAPH
		W + 2 Jets	2.13×10^3	MADGRAPH
		W + 3 Jets	6.24×10^2	MADGRAPH
		W + 4 Jets	2.57×10^2	MADGRAPH
	$W + \gamma + \text{Jets}$		4.62×10^2	MADGRAPH TAUOLA
QCD		Mu Enriched	1.35×10^5	PYTHIA
		$p_T \in [30, 80]$	4.62×10^6	PYTHIA
		$p_T \in [80, 170]$	1.83×10^5	PYTHIA
		$p_T \in [170, 250]$	4.59×10^3	PYTHIA
		$p_T \in [250, 350]$	5.57×10^2	PYTHIA
		$p_T > 350$	8.91×10^1	PYTHIA
$\gamma + \text{Jets}$		$p_T(\gamma) \in [15, 30]$	2.60×10^5	PYTHIA
		$p_T(\gamma) \in [30, 50]$	2.59×10^4	PYTHIA
		$p_T(\gamma) \in [50, 80]$	4.32×10^3	PYTHIA
		$p_T(\gamma) \in [80, 120]$	7.26×10^2	PYTHIA
		$p_T(\gamma) \in [120, 170]$	1.40×10^2	PYTHIA
		$p_T(\gamma) \in [170, 300]$	3.92×10^1	PYTHIA
		$p_T(\gamma) \in [300, 470]$	2.78	PYTHIA
		$p_T(\gamma) \in [470, 800]$	2.76×10^{-1}	PYTHIA
		$p_T(\gamma) \in [800, 1400]$	9.20×10^{-3}	PYTHIA
		$p_T(\gamma) \in [1400, 1800]$	5.86×10^{-5}	PYTHIA
$t\bar{t}$	$t\bar{t} + \text{Jets}$		2.47×10^2	MADGRAPH TAUOLA
	$t\bar{t} + W + \text{Jets}$		2.32×10^{-1}	MADGRAPH
	$t\bar{t} + Z + \text{Jets}$		2.06×10^{-1}	MADGRAPH
Single t	t – t-channel		5.49×10^1	POWHEG TAUOLA
	t – tW-channel		1.11×10^1	POWHEG TAUOLA
	t – s-channel		3.79	POWHEG TAUOLA
	$\bar{t}$ – t-channel		2.97×10^1	POWHEG TAUOLA
	$\bar{t}$ – tW-channel		1.11×10^1	POWHEG TAUOLA
	$\bar{t}$ – s-channel		1.76	POWHEG TAUOLA
VV/VVV	WWW + Jets		8.06×10^{-2}	MADGRAPH
	WWZ + Jets		5.80×10^{-2}	MADGRAPH
	WZZ + Jets		1.97×10^{-2}	MADGRAPH
	ZZZ + Jets		5.53×10^{-3}	MADGRAPH
	WW + Jets		5.82	MADGRAPH
	WZ + Jets		1.07	MADGRAPH
	ZZ + Jets		3.46×10^{-1}	MADGRAPH

5.3 Offline Selection

The event selection performed by the analysis software consists of a set of requirements placed upon the event, after the HLT trigger requirements. Specifically, the requirements are placed upon the objects within the event and the relations between the objects.

5.3.1 Object Definition

The physics objects within each event are reconstructed using PF. In order to be considered, the objects are further required to satisfy some additional constraints so as to guarantee the quality of the objects and of the event overall. The experimental channel of this analysis is similar to that of the $H \rightarrow \tau\tau$ analysis [1], consequently as a starting point the object definition for that analysis was considered. The object definition was then further refined in order to reflect the particularities of this analysis.

Electrons

The electron POG defines two algorithms for the identification of electrons, the “triggering Multivariate Analysis (MVA)” electron Identification (ID) and the “non-triggering MVA” electron ID. Both are based on MVA techniques using a Boosted Decision Tree, with the first being tuned for events triggered on by the single lepton HLT triggers. The MVA combines multiple discriminating variables in order to maximise the sensitivity of the electron identification. Variables used include observables that compare measurements obtained from the ECAL and tracker, calorimetric observables such as the shape of the shower and energy fractions of the energy deposited in the HCAL and tracking observables such as the difference between the result from the Kalman filter fitted track and the track fitted with the specialised electron fitter. For a more detailed discussion, see [82]. For this analysis, since the single lepton triggers are not used, the “non-triggering MVA” electron ID was employed. The loose working point was chosen, as defined in [83], given the similarity between this analysis and the $H \rightarrow \tau\tau$ analysis.

The electrons are also required to have a transverse momentum above 25 GeV, this value is chosen in order to avoid the turn-on curve of the electron trigger efficiency, which is different

in the different run periods, and be fully efficient. The cut is set in such a way that only the plateau of the efficiency curve of the electrons, as a function of the electron p_T , is considered. It is also required that the electrons be within the central area of the tracker, which corresponds to a requirement that the electron's pseudorapidity be below 2.1 in absolute value. A further requirement is made on the pseudorapidity of the electrons in order to avoid that the electrons be located in the gaps of the ECAL between the barrel and the endcap, this corresponds to excluding electrons with $1.4442 < |\eta| < 1.5660$.

Additionally, the electrons are required to be isolated through the requirement to have a relative isolation of 0.1 in a $\Delta R < 0.3$ cone. Where ΔR is defined as the quadrature sum of the difference in azimuthal angle and the difference in pseudorapidity, Eq. 5.1. And relative isolation is defined as the isolation parameter normalised to the transverse momentum of the particle, Eq. 5.2, where isolation parameter is the sum of the energy of other particles in a cone around the particle of interest, Eq. 5.3. Two further requirements are made to ensure that the electron originates from the PV: $|dZ| < 0.1$ cm (the impact parameter from the PV along the beam axis) and $|d0| < 0.045$ cm (the impact parameter from the PV perpendicular to the beam axis). As a final set of requirements, the electron is required to have left a signal in all the layers of the inner tracker and to not have originated from the conversion of a photon. These last two requirements are made to increase the confidence that the electron has originated from the hard scattering process at the centre of the detector.

$$\Delta R^2 = \Delta\Phi^2 + \Delta\eta^2 \quad (5.1)$$

$$I_\ell^{rel} = \frac{I_\ell}{p_T(\ell)} \quad (5.2)$$

$$I_e = \sum_{\text{charged}} p_T + \max \left(0, \sum_{\text{neutral}} p_T + \sum_{\gamma} p_T - 0.5 \sum_{\text{charged, pileup}} p_T \right) \quad (5.3)$$

In summary, the electron object definition is:

- PF Electrons are used
- Loose non-triggering MVA ID
- $p_T > 25$ GeV
- $|\eta| < 2.1$
- $1.4442 < |\eta| < 1.5660$ excluded
- $RelIsolation_{\Delta R < 0.3} < 0.1$

- $|dZ| < 0.1 \text{ cm}$
- $|d0| < 0.045 \text{ cm}$
- No missing inner tracker hits
- No conversion

Muons

The standard CMS muon ID is used to identify the muons for this analysis. The tight working point of this discriminator is used. The working point corresponds to adding several requirements to the PF muons in order to increase the quality of the muons. The requirements are:

- $\frac{\chi^2}{\text{ndof}} < 10$ of the global muon track fit;
- at least one muon chamber hit included in the global muon track fit;
- the corresponding tracker track must be matched to muon segments in at least two muon stations;
 - a transverse impact parameter of the muon track with respect to the PV (d_{xy}) below 2 mm;
 - the longitudinal distance of the muon track with respect to the PV (d_z) below 5 mm;
 - at least 1 hit in the pixel detector;
 - at least 6 hits in the whole tracker.

More details on the muon ID can be found in [84, 85].

Further requirements for the muon object definition mirror the electron object definition, with some modifications to account for the performance differences between electrons and muons. The muons are required to have a transverse momentum above 20 GeV, a value chosen to avoid the turn-on curve of the muon trigger efficiency and be fully efficient. Like for the electrons, the cut is chosen such that only the plateau in the efficiency curve of the muons is considered. Similarly to the electrons, the muon pseudorapidity is required to be in the central region of the tracker, i.e. $\eta < 2.1$, and the muon relative isolation is also required to be 0.1 in a $\Delta R < 0.3$ cone.

To ensure that the muons originate from the PV, requirements on the impact parameters are made: $|dZ| < 0.2 \text{ cm}$ and $|d0| < 0.045 \text{ cm}$. No further requirements are made on the muons.

In summary, the muon object definition is:

- PF Muons are used
- Tight Muon ID
- $p_T > 20 \text{ GeV}$
- $|\eta| < 2.1$
- $RelIsolation_{\Delta R < 0.3} < 0.1$
- $|dZ| < 0.2$
- $|d0| < 0.045$

Taus

The base tau ID algorithm is the HPS algorithm, already described in section 4.2.6. The HPS algorithm tags the tau candidates with a discriminator indicating whether the tau decay mode was reconstructed, this is the byDecayModeFinding discriminator. Consequently, it is required that the tau be reconstructed as one of its decay modes by requiring the tau to be tagged with this discriminator. The above defined tau hadrons are still affected by a large multijet background. A handle to reduce this background is a set of isolation discriminators, since tau leptons are usually isolated from other particles in the event. For this analysis the tight isolation discriminator was chosen, which corresponds to requiring the isolation parameter of the tau in a $\Delta R < 0.5$ cone to be below 0.8 GeV. The corresponding discriminator is called byTightCombinedIsolationDeltaBetaCorr3Hits.

Electrons and muons have a high likelihood to be reconstructed as a tau, in the single hadron and hadron plus neutral pion decay topology, and have a high likelihood to pass the isolation requirements. Dedicated discriminators were developed to handle these cases. One to distinguish electrons from hadronic taus, using an MVA approach. Others to distinguish muons from hadronic taus, using both a cut based and an MVA approach. For the electrons a BDT discriminant is used, trained on observables that quantify the distribution of energy in the ECAL, observables sensitive to Bremsstrahlung and observables sensitive to the particle multiplicity as well as the parameters of the track. The medium working point of this discriminator is chosen for this analysis, named againstElectronMediumMVA5, which corresponds to an efficiency for hadronic taus above 70 % and an electron misidentification rate of 1.38×10^{-3} . For the muons,

this analysis uses the tight working point of the cut based discriminator, named againstMuonTight3. This corresponds to requiring the tau not to have track segments in two or more muon stations in a $\Delta R = 0.3$ cone, the tau not to have the sum of energies in the ECAL and HCAL below 0.2 of the momentum of the leading track and that there be no hits within a $\Delta R = 0.3$ cone in the two outermost muon stations. Further details on the HPS algorithm and the tau discriminators can be found in [86]. The used discriminators are in accordance with the tau POG recommendations.

The tau ID reconstruction has been commissioned for taus with transverse momentum above 20 GeV, so this requirement is enforced. Taus are also required to be within the tracker acceptance, through the requirement $\eta < 2.3$. Like for the lighter leptons, the tau is required to originate from the PV with the requirement $|dZ| < 0.5$ cm. A final requirement is that there be no electrons or muons within a $\Delta R < 0.5$ cone.

In summary, the tau object definition is:

- PF Taus are used
- Tau Discriminators:
 - byDecayModeFinding
 - byTightCombinedIsolationDeltaBetaCorr3Hits
 - againstElectronMediumMVA5
 - againstMuonTight3
- $p_T > 20$ GeV
- $|\eta| < 2.3$
- $|dZ| < 0.5$
- No electrons or muons in $\Delta R < 0.5$

Jets

Jets are, in general, not used in this analysis. However to help reject $t\bar{t}$ events, events which contain a b-jet are vetoed. In order to reject fake jets from spurious noise in the detector, the loose working point of the PF jet ID is used. The working point corresponds to requiring the jet to have a neutral hadron fraction below 99 %, a neutral electromagnetic fraction below 99 %, and a neutral lepton fraction below 99 %.

more than 1 constituent particle in the jet and a muon fraction below 80 %. For jets within $|\eta| < 2.4$, further requirements are a charged hadron fraction above 0 %, a charged multiplicity above 0 and a charged electromagnetic fraction below 99 %. Further details on the jet ID can be found in [87].

Jets are also required to not originate from PU, for this purpose the loose working point of the PU jet ID is used as a veto, the discriminator is named LooseFullPUJetID. The PU jet ID is a MVA approach combining information from the jet shape and from the track information within the jet in a BDT. More details on the PU jet ID can be found in [88]. All jets are required to have a transverse momentum above 30 GeV and are required to be within the tracker or calorimeter acceptance, i.e. a pseudorapidity below 4.7 in absolute value.

To identify which of the jets are candidate b-jets, the Combined Secondary Vertex (CSV) algorithm is used which is detailed in section 4.2.5. A medium working point is considered, i.e. requiring that the value returned from the CSV algorithm be above 0.679, corresponding to a misidentification probability of roughly 1 % for a jet with transverse momentum about 80 GeV.

In summary, the jet and b-jet object definition is:

- PF Jets are used
- Loose PF Jet ID
- Is not LooseFullPUJetID
- $p_T > 30 \text{ GeV}$
- $|\eta| < 4.7$
- If CSV > 0.679, the jet is considered a B-jet

5.3.2 Event Selection

In simple terms, the event selection is targeted to the expected signature and kinematic characterisation of the signal process. The efficiency of the requirements on the events is evaluated with the MC samples. For signal, a reference sample is considered, corresponding to the point where $M_{\tilde{\tau}} = 120 \text{ GeV}$ and $M_{\text{LSP}} = 20 \text{ GeV}$.

The presence of the LSP in the signal process is expected to correspond to an increase in

the MET of the events with respect to the SM background. Consequently, a requirement of $E_T > 30 \text{ GeV}$ is placed upon the events. This is expected to have a small impact on the signal process and a significant impact on some SM processes, effectively reducing the SM background. For the sum of SM background processes, this requirement has an efficiency of 28 % and for the reference signal sample an efficiency of 78 %.

Since the taus are pair produced, the taus have Opposite Sign (OS). To exploit this fact, the analysis requires the decay products to have OS, i.e. that the hadronic tau and the lepton (electron or muon) have OS. If an event has more than one OS pair, only the pair with the highest transverse momentum sum is considered. For the sum of SM background processes, this requirement has an efficiency of 60 % and for the reference signal sample an efficiency of 87 %.

To further help reduce the background SM processes, the events are required to satisfy another two selection criteria. The first, is targeted specifically to reduce the $t\bar{t}$ background process. The t quark decays almost exclusively to a b quark and a W boson. Vetoing events which contain a b -jet is then employed to reject these events. This cut also affects some other SM background processes while it has a smaller effect on the signal process. For the $t\bar{t}$ process, this requirement has an efficiency of 15 % (84 % for the sum of SM background processes) and for the reference signal sample an efficiency of 85 %.

The second cut is targeted to the $Z \rightarrow \ell\ell$ background process, although it has a strong effect on the multiboson (VV/VVV) processes as well. The cut vetoes events which have an extra lepton, muon or electron. In this way events with a reconstructed hadronic tau and two or more reconstructed leptons (muons or electrons) are rejected. For the $Z \rightarrow \ell\ell$ background process, this requirement has an efficiency of 87 % (95 % for the sum of SM background processes) and for the reference signal sample an efficiency of 100 %.

To increase the effectiveness of the extra lepton veto, the lepton object definition is slightly relaxed (i.e. loosened) with respect to that which was defined above for the lepton. In particular, the constraints on the: transverse momentum are lowered, pseudorapidity are increased, relative isolation are increased and impact parameter are increased.

The electron object definition for the veto is summarised as:

- PF Electrons are used
- Loose non-triggering MVA ID
- $p_T > 10 \text{ GeV}$
- $|\eta| < 2.4$
- $1.4442 < |\eta| < 1.5660$ excluded
- $RelIsolation_{\Delta R < 0.3} < 0.3$
- $|dZ| < 0.2$
- $|d0| < 0.045$
- No lost inner tracker hits
- No conversion

The muon object definition for the veto is summarised as:

- PF Muons are used
- Tight Muon ID
- $p_T > 10 \text{ GeV}$
- $|\eta| < 2.3$
- $RelIsolation_{\Delta R < 0.3} < 0.3$
- $|dZ| < 0.2$
- $|d0| < 0.2$

The base event selection is summarised as follows:

- $\cancel{E}_T > 30 \text{ GeV}$
- An OS pair of a tau and a lepton (electron or muon)
- Veto events with B-jets
- Veto events with extra leptons

5.4 Scale Factors

Despite all efforts to make the simulation and the experiment match, there are still some small differences between the two. Correcting for these differences is essential in order to obtain a correct estimate of the yields of the background processes from the MC simulation. To correct

for these differences the so-called scale factors are introduced. The scale factors are normally computed in a Control Region (CR), orthogonal to the Signal Region (SR), and are defined for the parameter of interest as the ratio between data and MC. In this analysis, the following scale factors are considered: scale factor for the Number of Vertices (nvtx) distribution, scale factor for the trigger efficiency, scale factors for the electron identification and isolation efficiency, scale factors for the muon identification and isolation efficiency and a scale factor for the hadronic tau identification efficiency. The scale factors effectively become a factor by which the weight of the MC events are multiplied. In this way, a scale factor below 1 corresponds to scaling down the corresponding event, while a scale factor above 1 corresponds to scaling up the corresponding event.

Number of Vertices

The MC simulation is produced with a specific nvtx distribution, not necessarily equal to that within data. In fact, the actual nvtx distribution for data can only be known after the relevant data has been collected, at which point most of the MC must already be ready for analysis. For this reason, an estimated distribution is used for the MC simulation and a first step is the PU re-weighting procedure. This procedure is comprised of the computation of the nvtx scale factor and its subsequent application to the MC simulation samples.

The observed nvtx distribution in data is retrieved, subsequently the nvtx distribution of the MC is retrieved and the ratio between the two defines the nvtx scale factor. Each distinct nvtx value has a different scale factor. Finally, the weight of each MC event is multiplied by the scale factor corresponding to the nvtx value of that event. This procedure is performed prior to any event selection, including triggers. Figure 5.2 shows the effect of the PU re-weighting procedure in this analysis at the preselection level.

Trigger

The efficiency of the TauPlusX triggers, used in this analysis, are not the same in data and in MC. These efficiencies have been independently measured for the $H \rightarrow \tau\tau$ analysis, [1, 83], and given the similarity with this analysis the results have been reused for this analysis. The

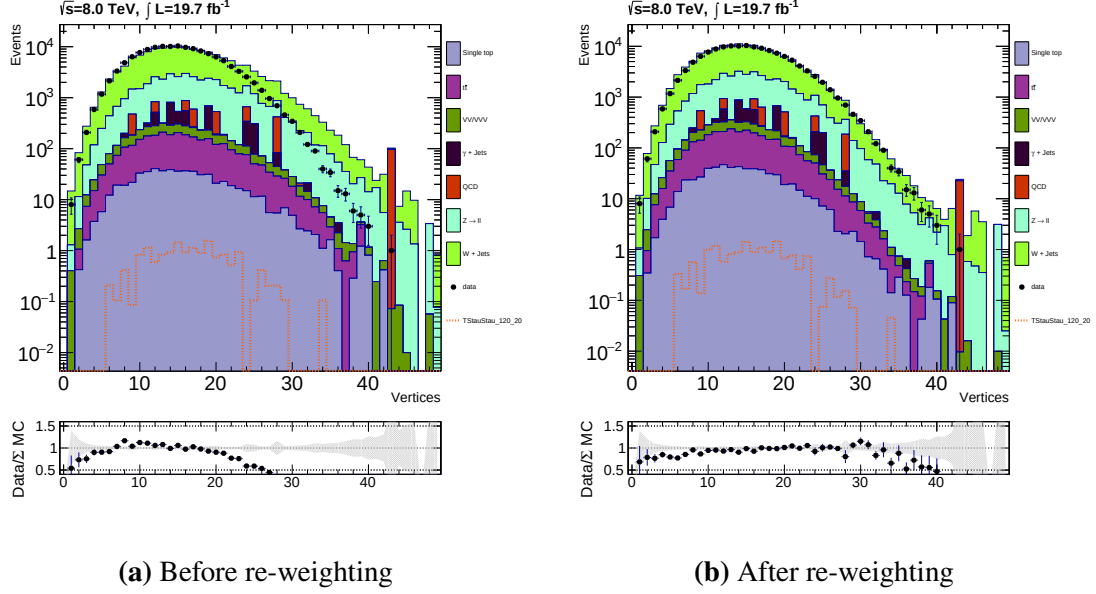


Figure 5.2: Effect of the nvtx scale factor on the nvtx distribution, before and after the re-weighting procedure. The considered MC processes are stacked and compared to data. Data corresponds to 19.7 fb^{-1} of certified CMS data and MC is scaled to the same luminosity value.

triggers have two legs, the hadronic tau and the lepton (electron or muon), the trigger efficiency is computed separately for each leg and the overall efficiency is given by the product of both efficiencies. For each leg, the efficiency curve is parameterised as a function of the object's transverse momentum by the cumulative distribution of a Crystal Ball function. The trigger scale factor is defined as the ratio between the trigger efficiency for data and the trigger efficiency for MC. The full parameterisation of the efficiency curves is described in [83].

Lepton Identification and Isolation

The identification and isolation efficiencies for the leptons also require scale factors to be applied. While the corresponding POGs define standard scale factors for these objects, for the $H \rightarrow \tau\tau$ analysis an updated set of values were computed. The scale factors are defined as a function of the object's transverse momentum and pseudorapidity. They are fully detailed in [83] and are repeated in Table 5.3 and Table 5.4 for reference.

Table 5.3: Scale Factors applied to the electrons, adapted from [83].

Bin	Identification	Isolation
$ \eta < 1.4479; p_T < 30 \text{ GeV}$	0.8999 ± 0.0018	0.9417 ± 0.0019
$ \eta > 1.4479; p_T < 30 \text{ GeV}$	0.7945 ± 0.0055	0.9471 ± 0.0037
$ \eta < 1.4479; p_T > 30 \text{ GeV}$	0.9486 ± 0.0003	0.9804 ± 0.0003
$ \eta > 1.4479; p_T > 30 \text{ GeV}$	0.8866 ± 0.0001	0.9900 ± 0.0002

Table 5.4: Scale Factors applied to the muons, adapted from [83].

Bin	Identification	Isolation
$ \eta < 0.8; p_T < 30 \text{ GeV}$	0.9818 ± 0.0005	0.9494 ± 0.0015
$0.8 < \eta < 1.2; p_T < 30 \text{ GeV}$	0.9829 ± 0.0009	0.9835 ± 0.0020
$ \eta > 1.2; p_T < 30 \text{ GeV}$	0.9869 ± 0.0007	0.9923 ± 0.0013
$ \eta < 0.8; p_T > 30 \text{ GeV}$	0.9852 ± 0.0001	0.9883 ± 0.0003
$0.8 < \eta < 1.2; p_T > 30 \text{ GeV}$	0.9852 ± 0.0002	0.9937 ± 0.0004
$ \eta > 1.2; p_T > 30 \text{ GeV}$	0.9884 ± 0.0001	0.9996 ± 0.0005

Tau Identification

The tau identification efficiency is very similar in data and MC, consequently a would-be scale factor would have a value close to 1. Thus, the regular procedure is to not apply a scale factor for the tau identification, nevertheless a systematic uncertainty which accounts for the difference is also included. However, for reconstructed taus that result from an electron faking a tau a scale factor is required. The scale factor is 1.6 ± 0.3 for taus with $|\eta| < 1.5$ and 1.1 ± 0.3 for taus with $|\eta| > 1.5$. A tau resulting from an electron faking a tau is defined as a tau with a generated electron within a cone of $\Delta R < 0.3$. The `againstElectronMediumMVA5` has the purpose of removing electrons faking taus, thus it is expected that no such events should remain after selection. In fact the number of events with electrons faking taus after applying the `againstElectronMediumMVA5` requirement is extremely low. In practice, this corresponds to a very small mistag rate which presents a challenge for measuring the scale factor. Since the number of taus surviving the requirement is so small, evaluating the scale factor is subject to large statistical

uncertainties. This explains why the scale factor presents the observed value and uncertainty. For the same reason, in this analysis, only a small number of events are affected by this scale factor.

5.5 Event Yields

The final yield at preselection level is summarised in Table 5.5 for data and for each of the MC samples as well as for the total expected yield. All MC samples have been weighted to the same luminosity as data and all the above-mentioned scale factors have been applied. The W + Jets process makes up for 73 % of the background SM events. Considering the W + Jets and $Z \rightarrow \ell\ell$ processes, in conjunction, accounts for 94 % of the background SM events. The other processes account for less than 2 % of the background SM events each. The Data/MC ratio at preselection is 0.9672 ± 0.0088 , which corresponds to a difference in the data and MC yield of about 3.7 sigma. However, the uncertainties in Table 5.5 are only statistical. Considering only the luminosity uncertainty (2.6 %) further increases the total uncertainty and accounts for the observed difference between data and MC. The overall agreement at preselection level is reasonable, as can be seen in Figure 5.3. The most striking disagreement between Data and MC at preselection level can be seen in the $p_T(\tau)$ variable, see Figure 5.3d. In this variable a trend is seen in the Data/MC ratio, i.e. MC has a slightly harder spectrum than Data. This disagreement is further noticed on variables that depend directly on the p_T of the τ particle, such as $M_T(\tau)$. This disagreement is mitigated by using the data driven background estimation, described in Chapter 7.

Table 5.5: Yields after preselection level for the considered MC background processes, for the total MC sum and for data. Data corresponds to 19.7 fb^{-1} of certified CMS data and MC is scaled to the same luminosity value. MC is corrected by the relevant scale factors. Only statistical uncertainties are listed.

Process	Yield
Single top	582 ± 15
$t\bar{t}$	2344 ± 40
VV/VVV	1477 ± 9
γ + Jets	2213 ± 671
QCD	2125 ± 815
$Z \rightarrow \ell\ell$	$30\,610 \pm 194$
W + Jets	$103\,232 \pm 630$
Total Expected	$142\,583 \pm 1245$
Data	$137\,902 \pm 371$

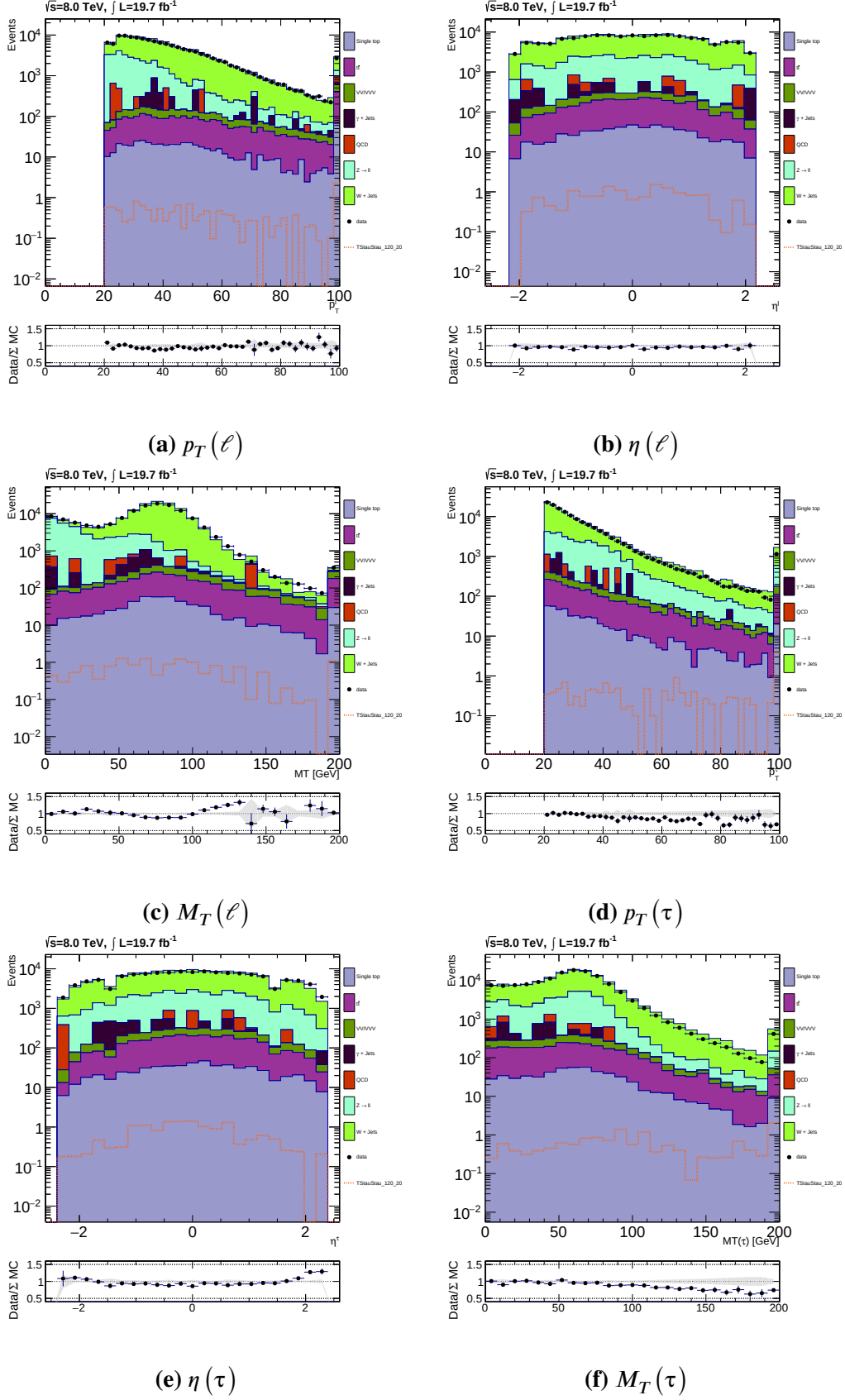


Figure 5.3: Variables after Preselection level, the considered MC processes are stacked and compared to data. Data corresponds to 19.7 fb^{-1} of certified CMS data and MC is scaled to the same luminosity value. All MC samples are corrected by the relevant scale factors.

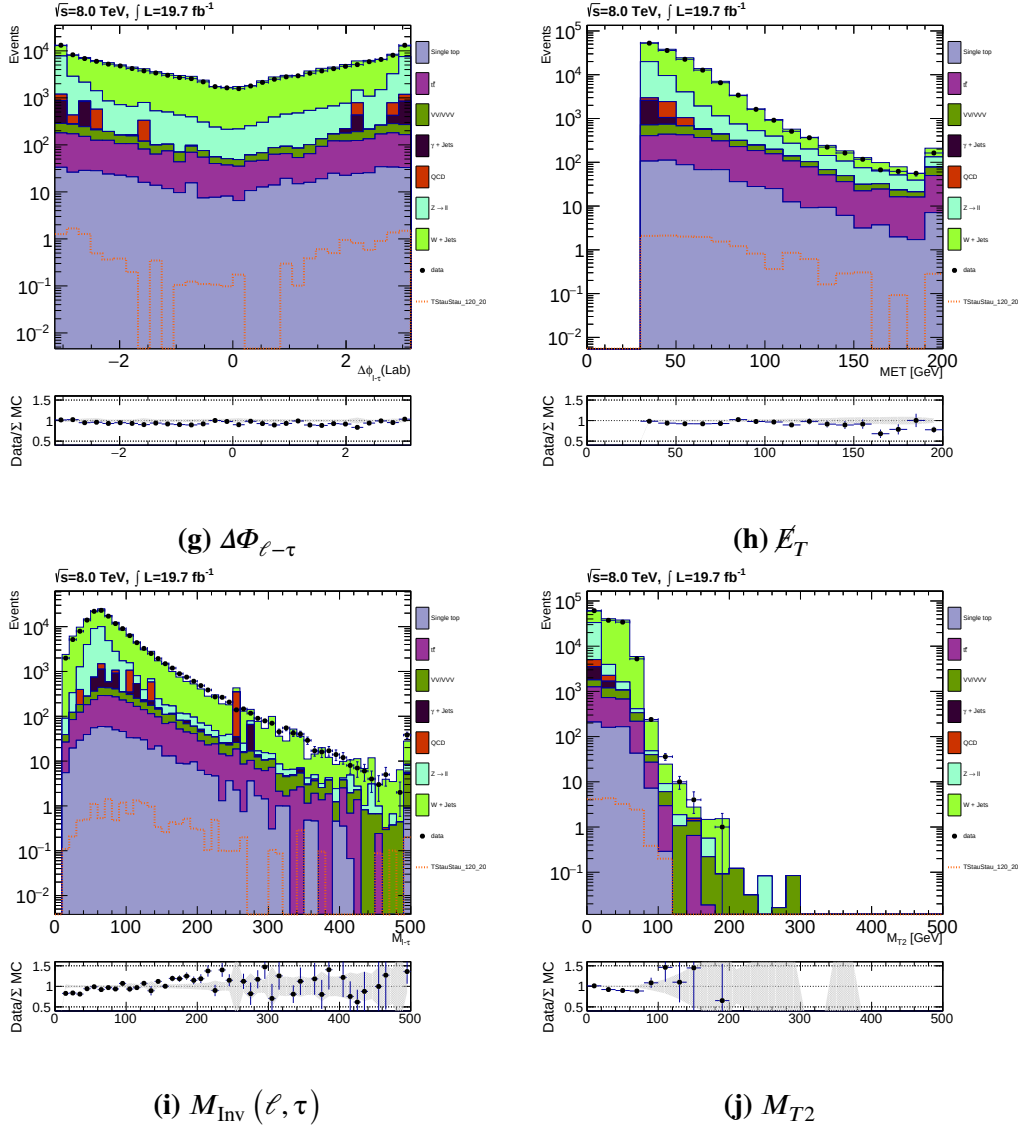


Figure 5.3: Variables after Preselection level, the considered MC processes are stacked and compared to data. Data corresponds to 19.7 fb^{-1} of certified CMS data and MC is scaled to the same luminosity value. All MC samples are corrected by the relevant scale factors. (continued)

Chapter 6

Signal Selection

The event preselection, defined in Chapter 5, sets the baseline for the analysis. However the contribution of the SM background processes is significant, see Table 5.5, and it is not the final step of the event selection.

For signal events, the parameter ΔM is defined as the difference between the mass of the stau and the mass of the LSP, i.e. $\Delta M = M_{\tilde{\tau}} - M_{\text{LSP}}$. The ΔM parameter is proportional to the energy available in the decay of the stau, thus strongly correlating with the properties of the decay products of the stau. For the signal process, the distributions of the discriminant variables are similar within points with the same ΔM .

As a first order approximation, the properties of signal events are considered only as a function of ΔM and the final event selection is made to depend upon this parameter. To this effect, a simulation sample for each ΔM value is defined by merging all the simulation samples of the signal points with the corresponding ΔM . For each ΔM sample the reference cross section is defined as the cross section of the signal point with $M_{\text{LSP}} = 50 \text{ GeV}$. With this definition, the expected signal yield for each ΔM value can be computed with the regular formula, Eq. 6.1, where $\mathcal{L}$ is the integrated luminosity, σ is the process cross section, N_{total} is the generated number of events for the sample and N_{selected} is the number of events that pass the selection criteria. In this chapter, the above values depend on the ΔM parameter, as a result, this dependence is explicitly defined in Eq. 6.1.

$$N_{\text{expected}} = \mathcal{L} \sigma_{\Delta M} \frac{N_{\text{selected}}}{N_{\text{total}}} \Big|_{\Delta M} \quad (6.1)$$

The definition of a sample per ΔM allows to perform the choice and optimisation of the selection cuts as a function of ΔM .

6.1 Cut Definition

In order to choose the cuts for each ΔM sample, an iterative cut selection procedure is applied. Prior to applying the iterative cut selection, a set of putative discriminant variables must be identified and taken as a basis for the cut selection. The list of considered discriminant variables is described in section 6.1.1 and the cut selection procedure is described below in section 6.1.2.

6.1.1 Discriminant Variables

The discriminant variables considered for the iterative cut selection procedure are summarised in Table 6.1. The range of cuts for each variable is also listed in the table. A more detailed description of each variable can be found below.

For the background SM processes there are two sources of MET: neutrinos, which go through the detector without being detected; mis-reconstruction, for instance if the reconstruction of the jet energy does not correctly account for the true energy of the jet. For the signal process, there is an additional source of MET, the LSP which also goes through the detector without being detected. In fact, there are two LSP particles for each event. As a result, it is expected that signal events will have a higher MET than background events. The different ΔM samples have different kinematics, thus affecting the properties of the LSP. Furthermore, the higher the ΔM the higher the MET is expected to be, see Fig. 6.1. Which justifies the choice of MET as a discriminant variable.

Similar to the MET, the transverse momentum of the lepton and of the hadronic tau depend on the ΔM . As mentioned in the introduction, the ΔM is proportional to the energy available in the decay of the stau. Thus, the higher the ΔM , the larger the phase space of the decay and

Table 6.1: Discriminant variables and the range of cuts considered for each

Variable	Short Description	Range
E_T	Missing transverse energy	[0 ; 300] GeV
$p_T(\ell)$	Transverse momentum of the lepton (electron or muon)	[0 ; 200] GeV
$p_T(\tau)$	Transverse momentum of the hadronic tau	[0 ; 200] GeV
$E_T + p_T(\ell)$	Sum of MET and the p_T of the lepton	[0 ; 300] GeV
$E_T + p_T(\tau)$	Sum of MET and the p_T of the hadronic tau	[0 ; 300] GeV
M_{Eff}	Sum of MET, $p_T(\ell)$ and $p_T(\tau)$	[0 ; 400] GeV
$ M_{\text{Inv}} - 61 $	Difference between the invariant mass of the tau and lepton with 61 GeV	[0 ; 300] GeV
$ M_{\text{SV Fit}} - 102 $	Difference between the “SV Fit” mass of the tau and lepton with 102 GeV	[0 ; 300] GeV
$M_T(\ell)$	Transverse mass of the lepton	[0 ; 300] GeV
$M_T(\tau)$	Transverse mass of the hadronic tau	[0 ; 300] GeV
$M_T(\tau) + M_T(\ell)$	Sum of the transverse mass of the lepton and the hadronic tau	[0 ; 400] GeV
M_{T2}	Stransverse mass	[0 ; 180] GeV
$\mathcal{Q}_x(\ell)$	First deconstructed M_T variable, of the lepton	[-2 ; 1]
$\mathcal{Q}_x(\tau)$	First deconstructed M_T variable, of the hadronic tau	[-2 ; 1]
$\cos \Phi_{\ell - \cancel{E}_T}$	Second deconstructed M_T variable, of the lepton	[-1 ; 1]

Table 6.1: Discriminant variables and the range of cuts considered for each (continued)

Variable	Short Description	Range
$\cos \Phi_{\tau-\cancel{E}_T}$	Second deconstructed M_T variable, of the hadronic tau	$[-1 ; 1]$
$\mathcal{Q}_x(\ell) + \cos \Phi_{\ell-\cancel{E}_T}$	Sum of the deconstructed M_T variables, of the lepton	$[-3 ; 2]$
$\mathcal{Q}_x(\tau) + \cos \Phi_{\tau-\cancel{E}_T}$	Sum of the deconstructed M_T variables, of the hadronic tau	$[-3 ; 2]$
$ \Delta\Phi_{\ell-\tau} $	Difference of the azimuthal angle between the lepton and the tau	$[0 ; \pi]$
$\Delta\Phi_{\ell\tau-\cancel{E}_T}$	Difference of the azimuthal angle between the MET and the system of the lepton and the tau	$[0 ; \pi]$
$\Delta R_{\ell-\tau}$	ΔR between the hadronic tau and the lepton	$[0 ; 5]$
$ \cos \theta_\tau $	Cosine of the angle between the tau and the beam-line	$[0 ; 1]$
$ \cos \theta_\ell $	Cosine of the angle between the lepton and the beam-line	$[0 ; 1]$

the higher the transverse momentum is expected to be, see Fig. 6.2. The transverse momentum variables are thus good candidates for discriminant variables, however it is expected that they will have a larger importance for the higher ΔM regions. Note that, for signal, the $p_T(\ell)$ distribution is slightly softer than the $p_T(\tau)$ distribution, which is likely associated with the extra neutrino in the leptonic decay of the tau when compared to the hadronic decay of the tau.

For the same reasons explained for the MET and transverse momentum variables, the sums $E_T + p_T(\ell)$, $E_T + p_T(\tau)$ and $M_{\text{Eff}} \equiv E_T + p_T(\ell) + p_T(\tau)$ are expected to increase as ΔM increases, see Fig. 6.3. As a result, they are good candidates for discriminant variables.

To handle the large DY SM background, a discriminant variable targeted to this process is

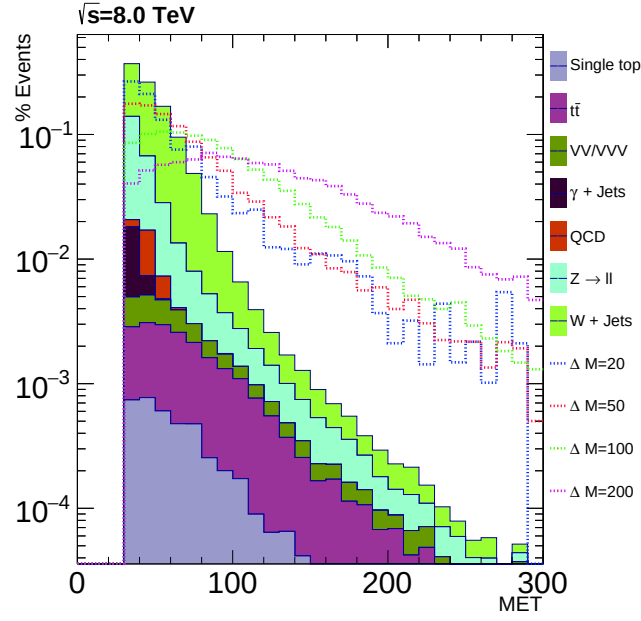


Figure 6.1: The $\cancel{E}_T$ discriminant variable after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

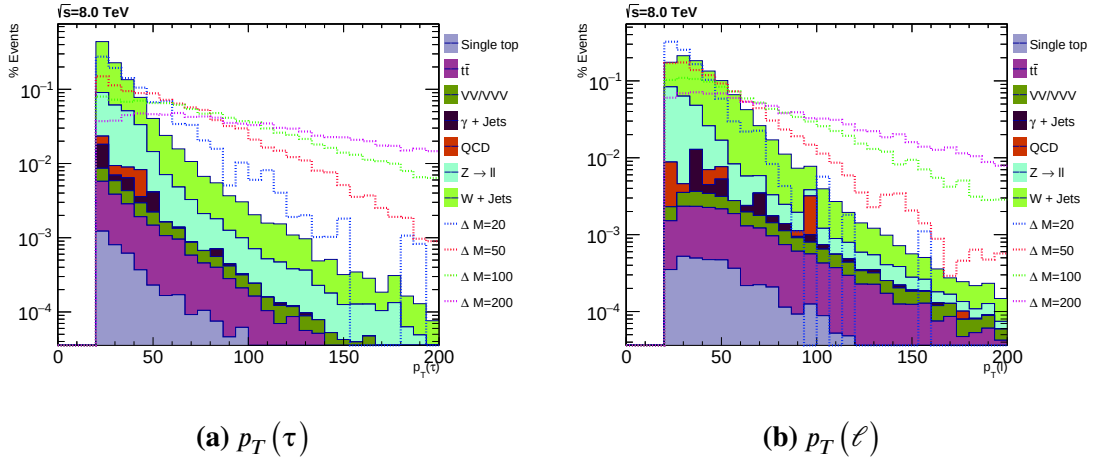


Figure 6.2: The $p_T(\tau)$ and $p_T(\ell)$ discriminant variables after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

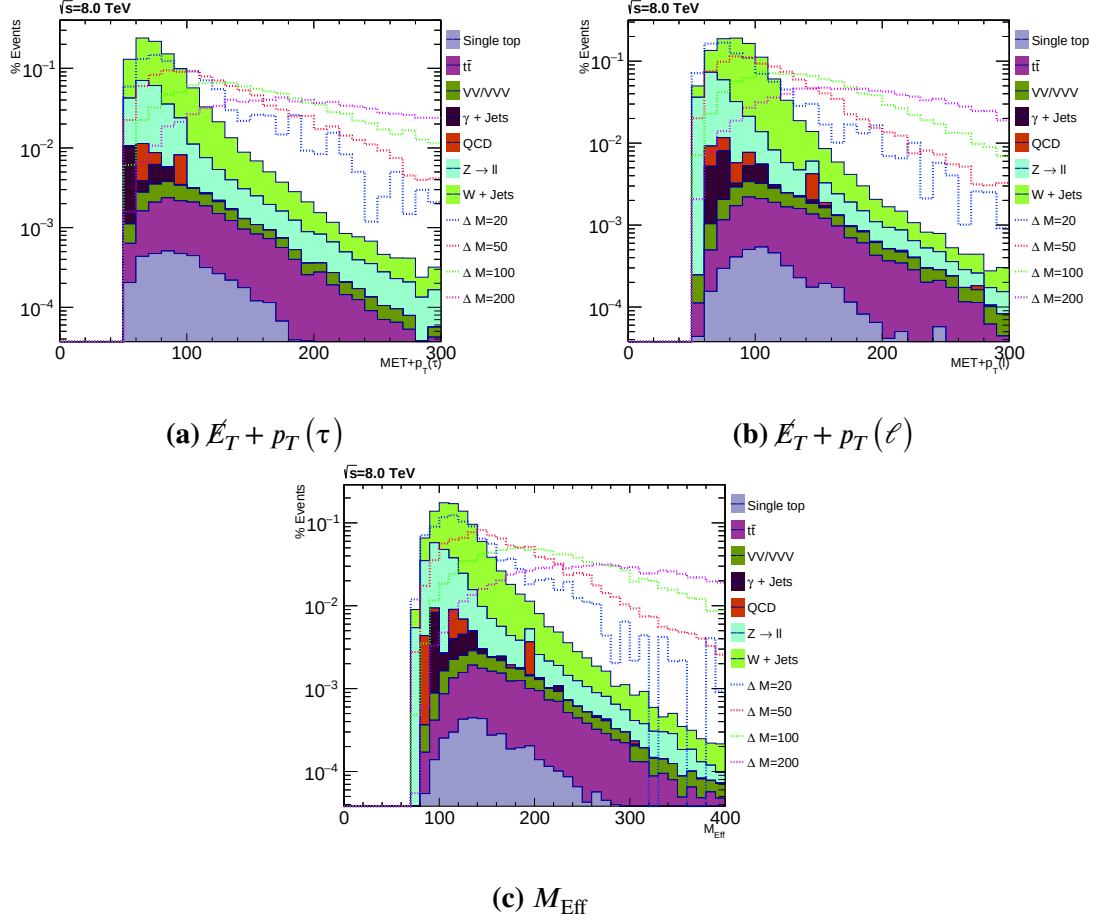


Figure 6.3: The $E_T + p_T(\tau)$, $E_T + p_T(\ell)$ and M_{Eff} discriminant variables after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

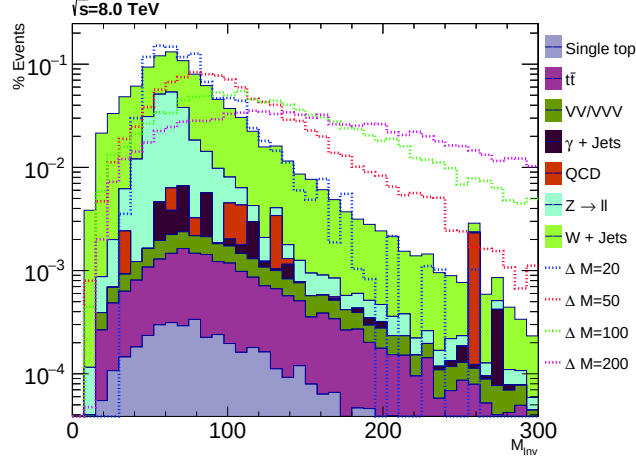


Figure 6.4: The M_{Inv} discriminant variable after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

introduced. In this process, since both taus originate from the Z boson, the invariant mass of the decay products is expected to reconstruct the mass of the Z boson. However, not all of the decay products are directly measured since the decay products include neutrinos, so only the visible decay products are considered. The base of the discriminant variable is the invariant mass of the reconstructed hadronic τ and the reconstructed lepton (electron or muon). Using the MC simulation of the DY process, it is verified that the peak of the invariant mass distribution is shifted down to 61 GeV, Fig. 6.5a. The same is not true for the signal process since they do not result from the same resonance, consequently a cut on the invariant mass distribution in a window around 61 GeV, the variable $|M_{\text{Inv}} - 61|$, can be effective in reducing the DY SM background for certain ΔM values and is used as a discriminant variable, see Fig. 6.4.

As an alternative to the invariant mass, the mass computed with the “SV Fit” algorithm can also be used. The algorithm is fully described in [89], it performs a maximum likelihood fit for each event to estimate the mass of a mother particle which decays to two taus, using the MET and the transverse momentum of the lepton and hadronic tau. The peak of the distribution for the DY SM background is observed to lie at 102 GeV, Fig. 6.5b, so the discriminant variable is defined in such a way to define a window around this value, i.e. $|M_{\text{SV Fit}} - 102|$, see Fig. 6.6.

The transverse mass variables, $M_T(x)$, are traditional variables used to determine the mass

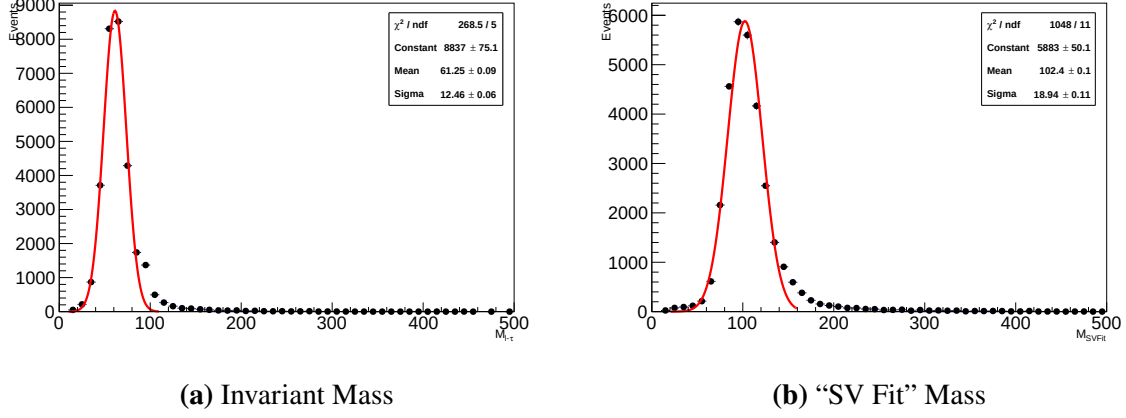


Figure 6.5: Mass distributions of the DY MC simulation. The peaks are fitted with a Gaussian and the fit parameters are listed in a box on the top right.

of a mother particle that decays to an invisible particle and a visible one. They are computed using the MET and an extra object, Eq. 6.2, the x value is used to reference which object, $\Phi_{x-\cancel{E}_T}$ is the azimuthal angle between the MET and the object and $E_T(x)$ is the transverse energy of that same object. For signal events, given the presence of further invisible particles, the $M_T(x)$ distributions are expected to be modified with respect to the SM expectation, see Fig. 6.7. The same applies to the $M_T(\ell) + M_T(\tau)$ discriminant variable.

$$M_T^2(x) = M_T^2(x, \cancel{E}_T) = 2E_T(x)\cancel{E}_T(1 - \cos \Phi_{x-\cancel{E}_T}) \quad (6.2)$$

The transverse mass variable, M_{T2} , is a variable specially introduced for SUSY searches [90, 91], Eq. 6.3. It is introduced in an analogous manner to the M_T variable, considering that a pair of particles are produced and each decay to an invisible particle and a visible particle. It further assumes the two invisible particles have the same mass. Similarly to the M_T variable, the endpoint of the M_{T2} variable sets a constraint on the mass of the original particle that is pair produced. However, the M_{T2} variable takes as input the mass of the invisible particle, therefore the constraint on the mass of the mother particle is a function of M_{LSP} . For this analysis, in the computation of M_{T2} , the M_{LSP} was considered to be zero. M_{T2} is expected to have a higher endpoint with signal events than with background events, being a good discriminator, see Fig. 6.8.

$$M_{T2}^2 = \min_{p_1^+ p_2^+ = p_1^-} \left[\max \{ M_T^2(p_T(\ell^-), p_1^-), M_T^2(p_T(\ell^+), p_2^-) \} \right] \quad (6.3)$$

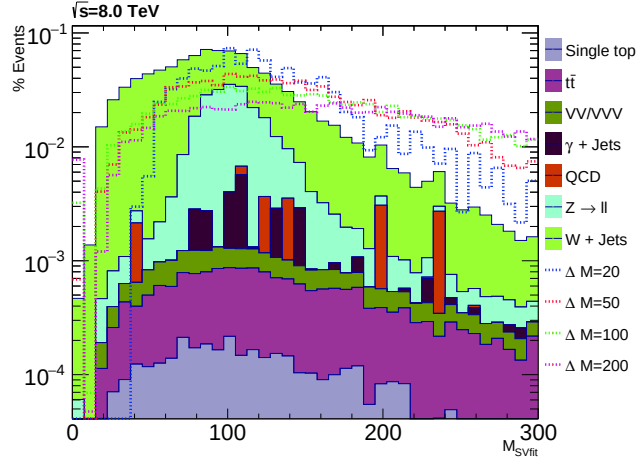


Figure 6.6: The $M_{SV \text{ Fit}}$ discriminant variable after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

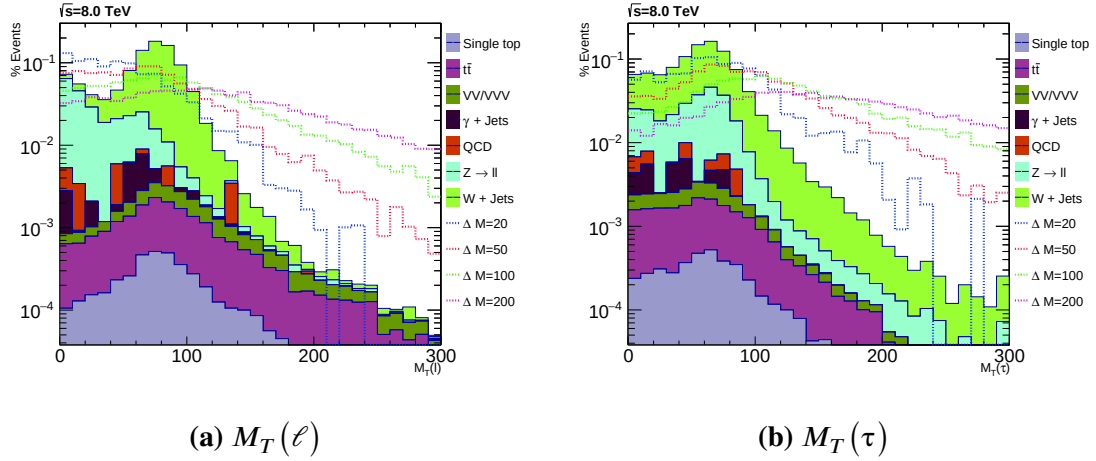


Figure 6.7: The $M_T(\ell)$ and $M_T(\tau)$ discriminant variables after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

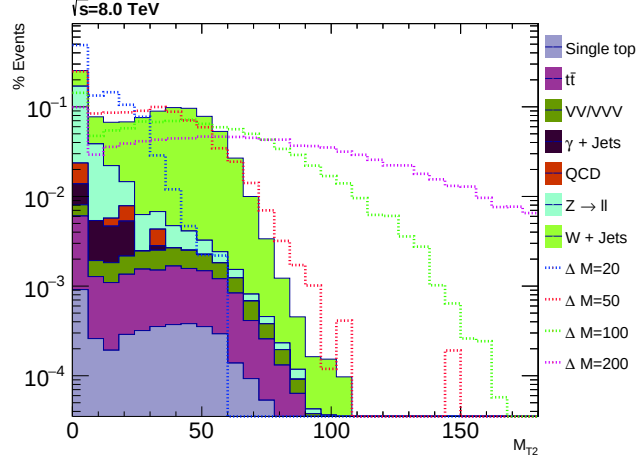


Figure 6.8: The M_{T2} discriminant variable after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

The deconstructed M_T variables are a set of variables introduced specifically targeted to the $\tilde{t}$ analysis, yet valuable for any analysis with undetected particles in the final state. They are fully detailed in [92]. In summary, the variables are obtained from the formula for the M_T variable, Eq. 6.4, where $\Phi_{x-\cancel{E}_T}$ is the azimuthal angle between the MET and the object under consideration and $E_T(x)$ is the transverse energy of that same object. The formula is rearranged in such a way that on one side there are only kinematical variables and on the other only topological ones, Eq. 6.5. Each side of the rearranged equation is now considered one of the deconstructed M_T variables, Eq. 6.6 and Eq. 6.7, in effect decorrelating the kinematical and topological components. From the formula it can be seen that the variable $\mathcal{Q}$ depends upon the M_T parameter, which in this approach is not known and must be assumed. The exact value to be used must be studied on a case by case basis, for this analysis, two possibilities are considered, $\mathcal{Q}_{80}(x)$ and $\mathcal{Q}_{100}(x)$, assuming $M_T = 80 \text{ GeV}$ and $M_T = 100 \text{ GeV}$ respectively. These values are recommended by the author of [92], the first value since it is the mass of the W, the second for being larger than $M(W)$ and for serving as a further check. The distribution of these variables can be

seen in Fig 6.9 for background and for 4 different ΔM signal points.

$$M_T^2(x) = 2E_T(x)\cancel{E}_T(1 - \cos \Phi_{x-\cancel{E}_T}) \quad (6.4)$$

$$1 - \frac{M_T^2}{2E_T(x)\cancel{E}_T} = \cos \Phi_{x-\cancel{E}_T} \quad (6.5)$$

$$\mathcal{Q}_{M_T}(x) \equiv 1 - \frac{M_T^2}{2E_T(x)\cancel{E}_T} \quad (6.6)$$

$$\cos \Phi_{x-\cancel{E}_T} \quad (6.7)$$

Considering the correlation plots of the deconstructed M_T variables for MC for the signal process and the main SM background processes, Fig. 6.10, it is observed that the two variables correlate differently for signal and background. Signal tends to cluster at the extremes of $\cos \Phi_{x-\cancel{E}_T}$ and at high values of $\mathcal{Q}_{M_T}(x)$, while the two main background processes cluster at one of the extremes of $\cos \Phi_{x-\cancel{E}_T}$ and at lower values of $\mathcal{Q}_{M_T}(x)$. Consequently, a cut on a variable like $\mathcal{Q}_{M_T}(x) + \cos \Phi_{x-\cancel{E}_T}$, which attempts to extract more information from the above correlation, is an interesting prospect for rejecting the background processes, see Fig. 6.11.

In the signal process, the $\tilde{\tau}$ particles are pair produced and as a result are mostly back to back, i.e. $\Delta\Phi_{\tilde{\tau}-\tilde{\tau}} \approx \pi$. For low ΔM values, the decay products from the $\tilde{\tau}$ decay do not change direction significantly from the $\tilde{\tau}$ direction and as a result the decay products continue in a mostly back to back direction, i.e. $\Delta\Phi_{\ell-\tau} \approx \pi$. For higher ΔM values, the decay products are more deflected from the original $\tilde{\tau}$ direction, resulting in a smearing of the values for $\Delta\Phi_{\ell-\tau}$. For the SM background processes, the $\Delta\Phi_{\ell-\tau}$ distribution is fixed according to the process. For example with $W + 1\text{Jet}$ events, where the W decays to a lepton and the jet fakes a tau, the lepton and the fake tau will be mostly back to back, i.e. $\Delta\Phi_{\ell-\tau} \approx \pi$, yet with $W + N\text{Jet}$ events, with $N > 1$, the lepton and the fake tau are no longer back to back, resulting in lower values for $\Delta\Phi_{\ell-\tau}$. These different behaviours for different ΔM values and different processes can be exploited to discriminate among the processes, in particular in conjunction with further discriminant variables. A similar reasoning can be made for the $\Delta\Phi_{\ell\tau-\cancel{E}_T}$ and $\Delta R_{\ell-\tau}$ discriminant variables. Fig 6.12 illustrates these discriminant variables.

The variables $\cos \theta_x$ have a one-to-one correspondence with $\eta(x) \equiv -\ln \left[\tan \left(\frac{\theta_x}{2} \right) \right]$. These variables are not expected to be significantly different between signal and background, however in combination with other discriminating variables, they can give a better discrimination

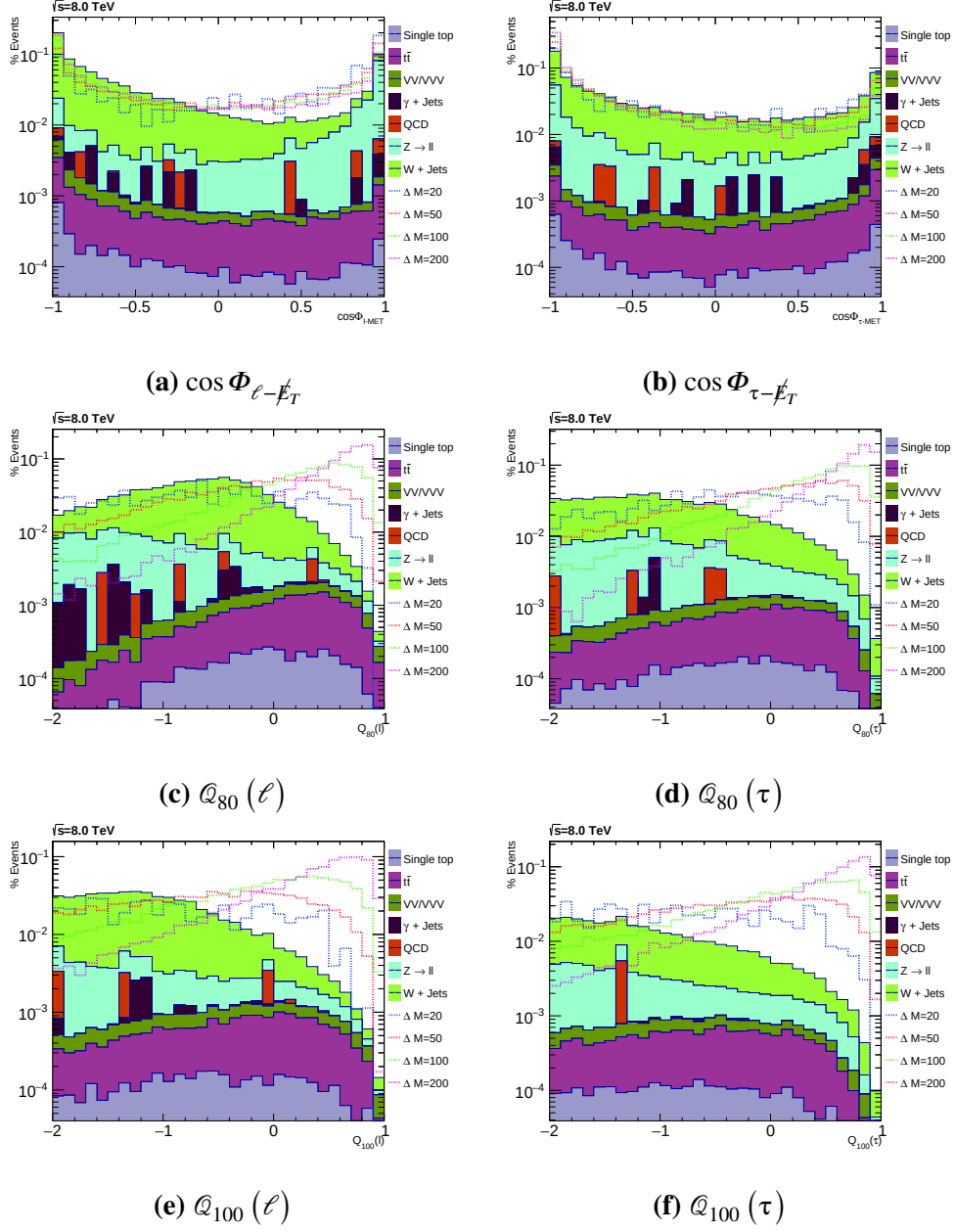


Figure 6.9: The deconstructed M_T discriminant variables after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

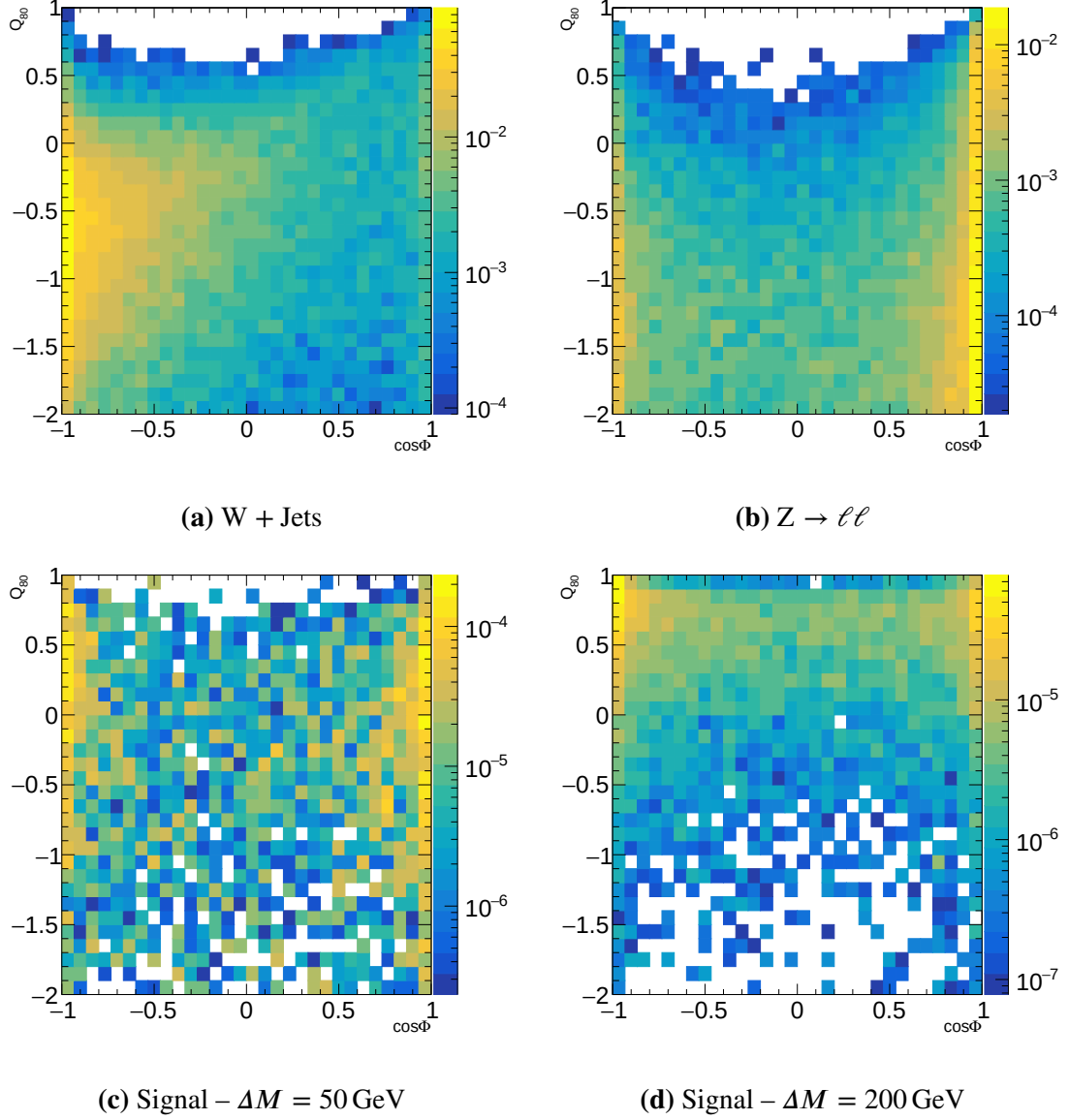


Figure 6.10: Correlation of the deconstructed M_T variables at preselection level for the main background processes and for signal, for two ΔM values. The considered deconstructed M_T variables are: $\mathcal{Q}_{80}(\ell)$ and $\cos \Phi_{\ell-\cancel{E}_T}$.

since the multi-dimensional correlation among the many variables is hard to visualise from first principles. Fig. 6.13 shows the distribution of these variables for signal and background.

Some of the discriminating variables in Table 6.1 are compound variables, obtained through the combination of several simpler variables. Figure 6.14 shows the distributions of some of the discriminant variables, those used in subsequent sections, in MC events compared to data at the preselection level.

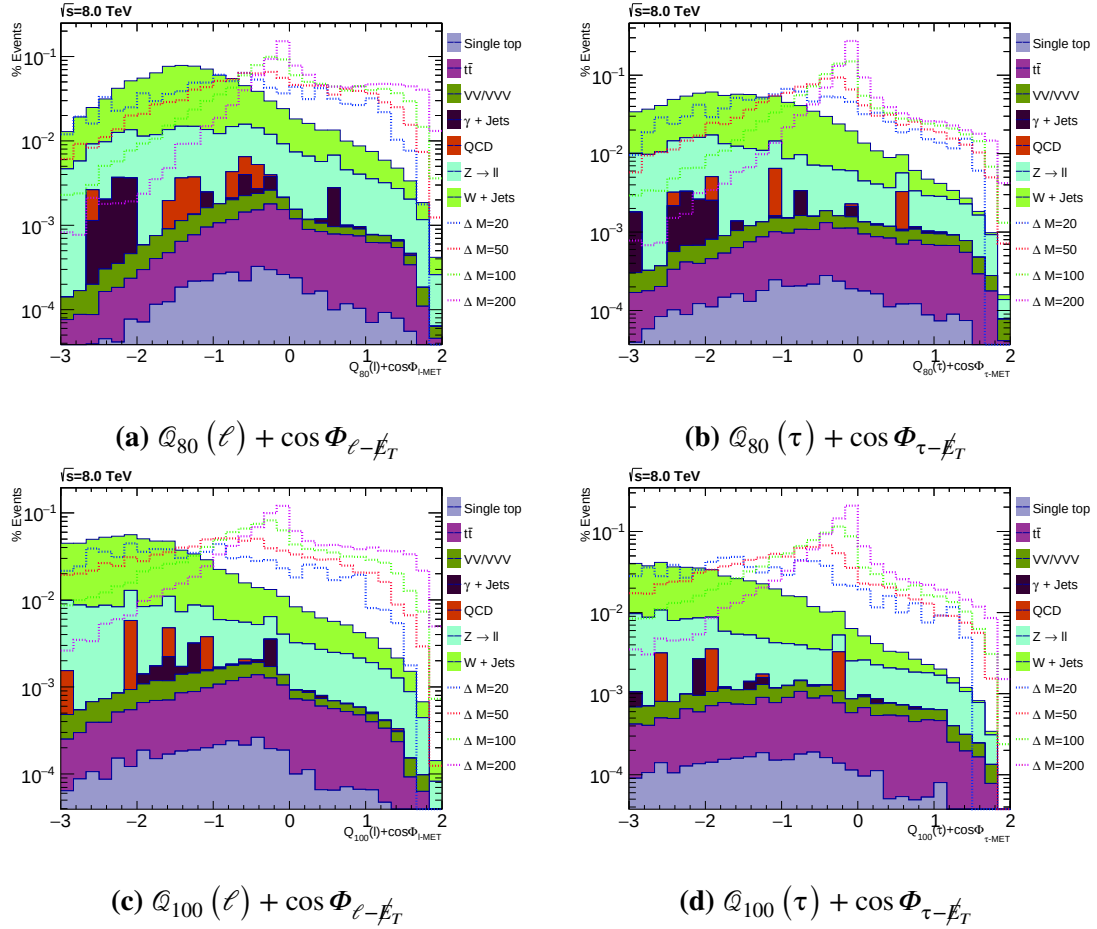


Figure 6.11: The correlated deconstructed M_T discriminant variables after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

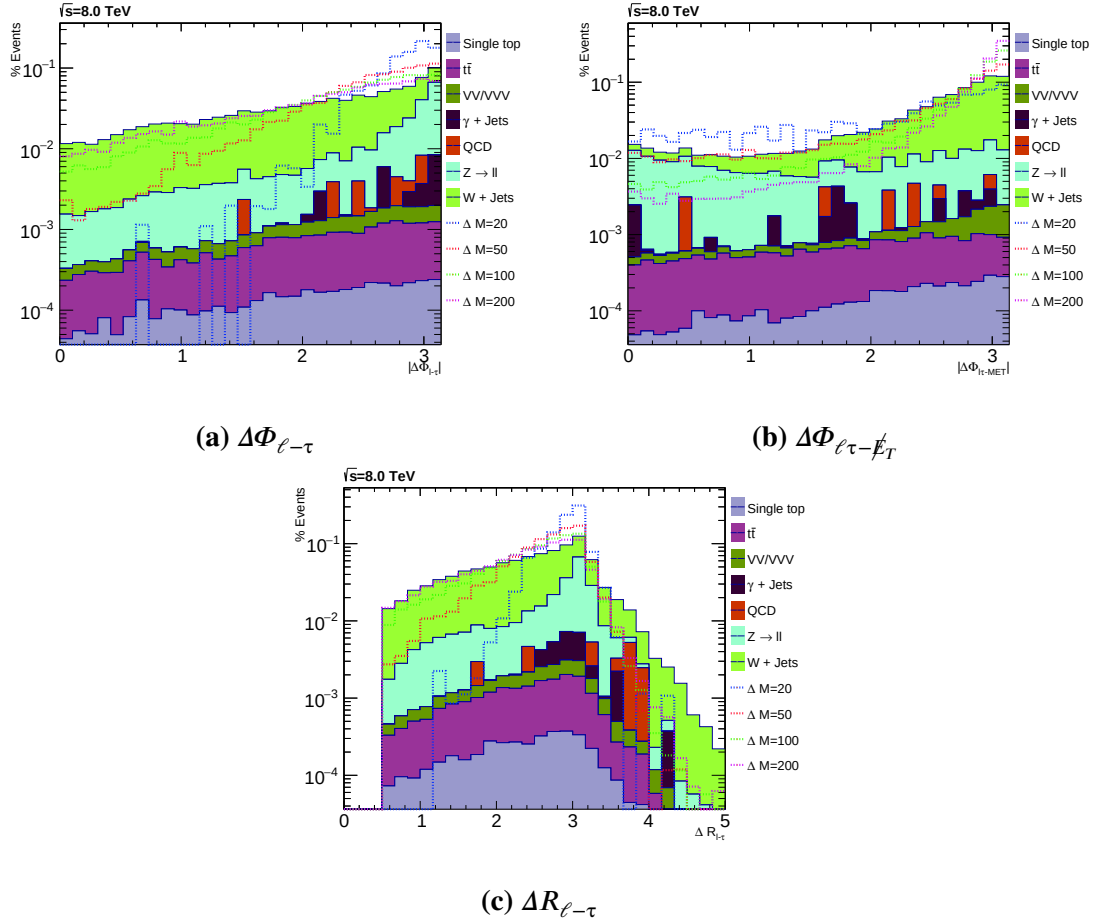


Figure 6.12: The $\Delta\Phi_{\ell-\tau}$, $\Delta\Phi_{\ell\tau-\cancel{E}_T}$ and $\Delta R_{\ell-\tau}$ discriminant variables after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

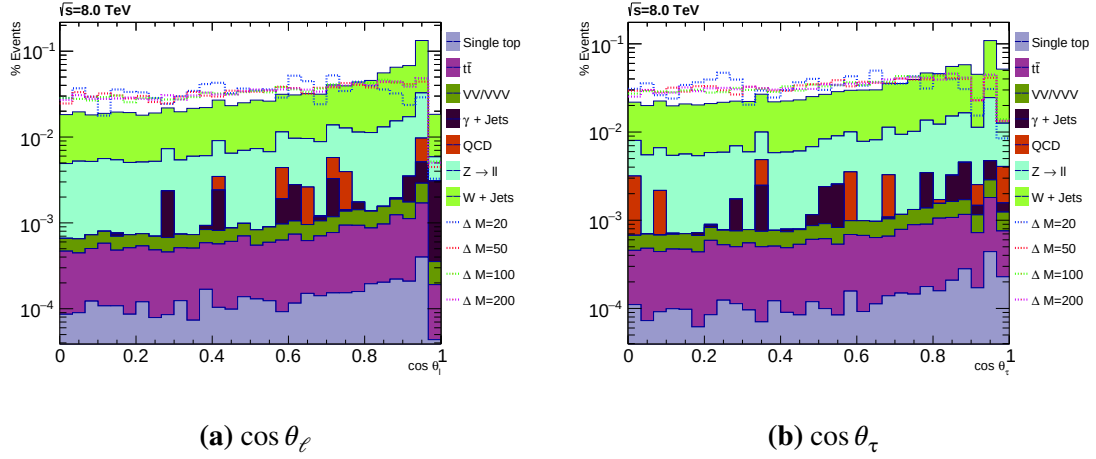


Figure 6.13: The $\cos \theta_\ell$ and $\cos \theta_\tau$ discriminant variables after preselection level for the MC sum and for 4 different ΔM signal points. The considered background MC processes are stacked and the sum is normalised to unity. Each signal sample is independently normalised to unity. All MC samples are corrected by the relevant scale factors.

6.1.2 Cut Selection Procedure

The cut selection procedure is performed for all the ΔM samples, but each ΔM sample is treated separately. The procedure starts by scanning for each variable, var , the values, X , within the variable's defined range. For each value, cuts of the type $var > X$ and $var < X$ are considered. For each cut, the signal and background yields are computed, n.b. for signal there is a yield for each ΔM sample. The yields are subsequently used to compute a Figure of Merit (FOM), n.b. once again there is a FOM for each ΔM sample. The FOM quantifies the expected significance of the selection after the statistical analysis. It is used instead of the statistical analysis since it is quicker and easier to perform and in this way it is used as a surrogate for the full statistical analysis. Once the scan is finalised, the variable, cut value and cut direction with the highest FOM is chosen as the optimal cut for that ΔM sample.

The FOM used for this analysis is summarised in Equation 6.8, where N_B is the expected background yield and N_S is the expected signal yield. This FOM is further detailed in [93]. This particular FOM was chosen for being the most performant one known by the author at the time.

$$\text{FOM} = 2 \times \left(\sqrt{N_S + N_B} - \sqrt{N_B} \right) \quad (6.8)$$

The above-described procedure is then iteratively repeated, with the care that for each ΔM

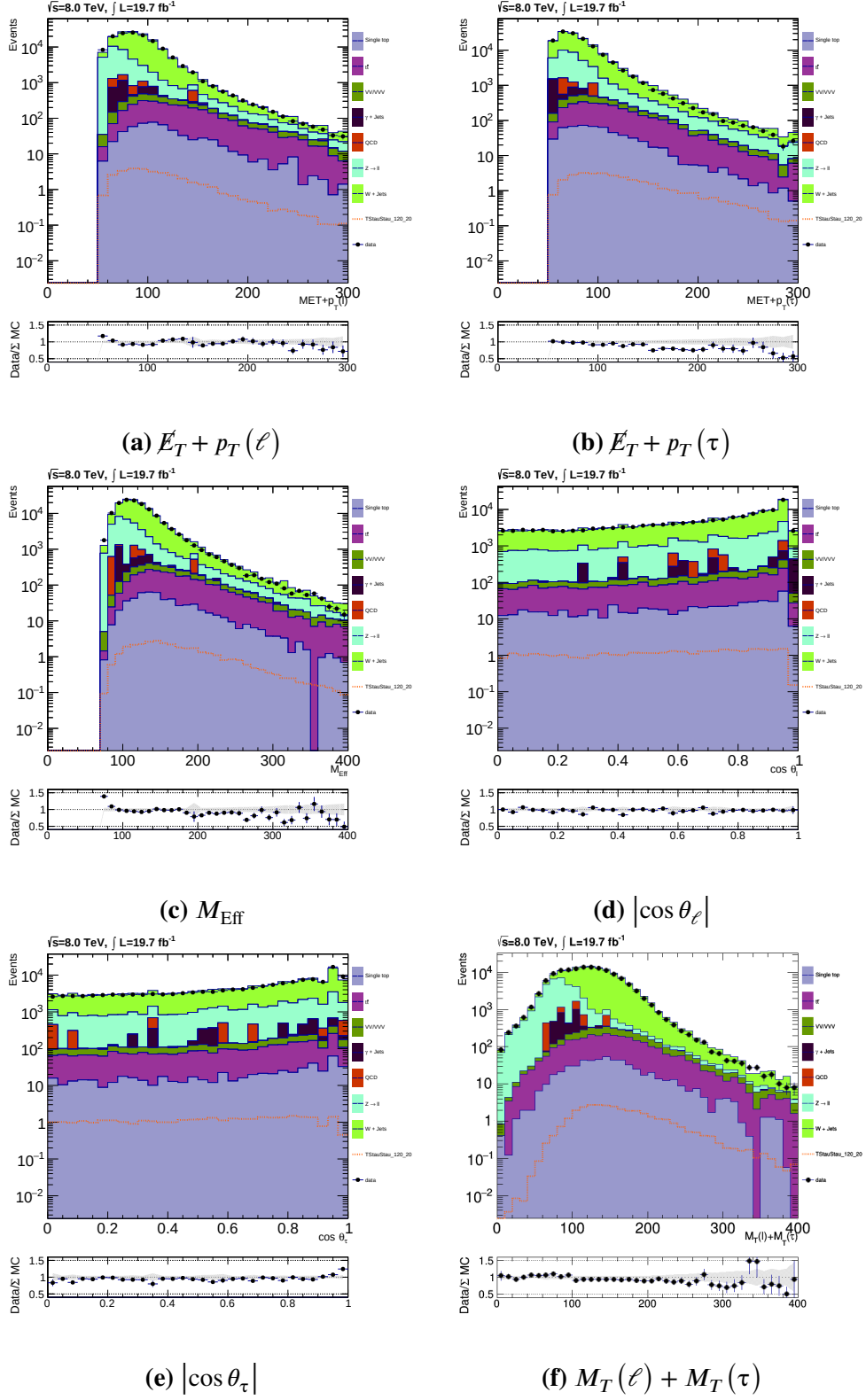


Figure 6.14: Compound variables after Preselection level, the considered MC processes are stacked and compared to data. Data corresponds to 19.7 fb^{-1} of certified CMS data and MC is scaled to the same luminosity value. All MC samples are corrected by the relevant scale factors.

sample a previously chosen cut is applied prior to performing any other scans and no further cuts on that variable be performed. The stopping condition of the procedure requires that cuts from one iteration to the next increase the FOM by more than the statistical uncertainty. It was also verified that in some situations the FOM would monotonically increase as the cut became tighter, resulting in the undesirable result that both the expected signal and background yields would become very small fractional values. To avoid this situation a further requirement was introduced whereby cuts which would lead to a signal yield below 3 events were disregarded. Once the iteration procedure is finalised, a full set of cuts for each ΔM region is obtained, in this way defining an optimal selection for each ΔM region.

Figure 6.15 shows the first step of the above mentioned procedure for a single discriminant variable, $M_T(\ell) + M_T(\tau)$, for the $\Delta M = 100$ GeV sample for cuts of the type $M_T(\ell) + M_T(\tau) > X$. According to Figure 6.15c, the cut with the highest FOM is $M_T(\ell) + M_T(\tau) > 270$ GeV, considering the statistical uncertainty, all of the cuts in the range $M_T(\ell) + M_T(\tau) > [240 ; 320]$ GeV are compatible. Starting from the cut $M_T(\ell) + M_T(\tau) > 320$ GeV the signal yield goes below 3, Figure 6.15b. As a result, the cuts with the cut value above 310 GeV are not considered. At this level of the cut selection and according to the prescription, the cut $M_T(\ell) + M_T(\tau) > 270$ GeV is chosen as the optimal cut.

Note that in the above procedure the definition of a cut for a given ΔM region depends on all previous cuts for that same region since the previous cuts are applied prior to scanning for the new FOM maximum. Consequently, the order in which the cuts are selected is well defined and guided by the FOM maximisation procedure.

Directly applying the above described procedure on all considered discriminating variables results in the set of cuts described in Table 6.2. Note that for $\Delta M = 10$ no cuts were selected. This results from the fact that the trigger and preselection efficiencies for this signal region are so low that after preselection the expected signal yield is already below 3 events. For $\Delta M > 240$ no cuts were selected either, which is due to the very low cross sections of this region. This results in an expected signal yield below 3 events prior to any additional cuts, similar to the $\Delta M = 10$ region. It can also be seen that for several of the ΔM samples the procedure had to stop since the signal yield was reaching 3 events.

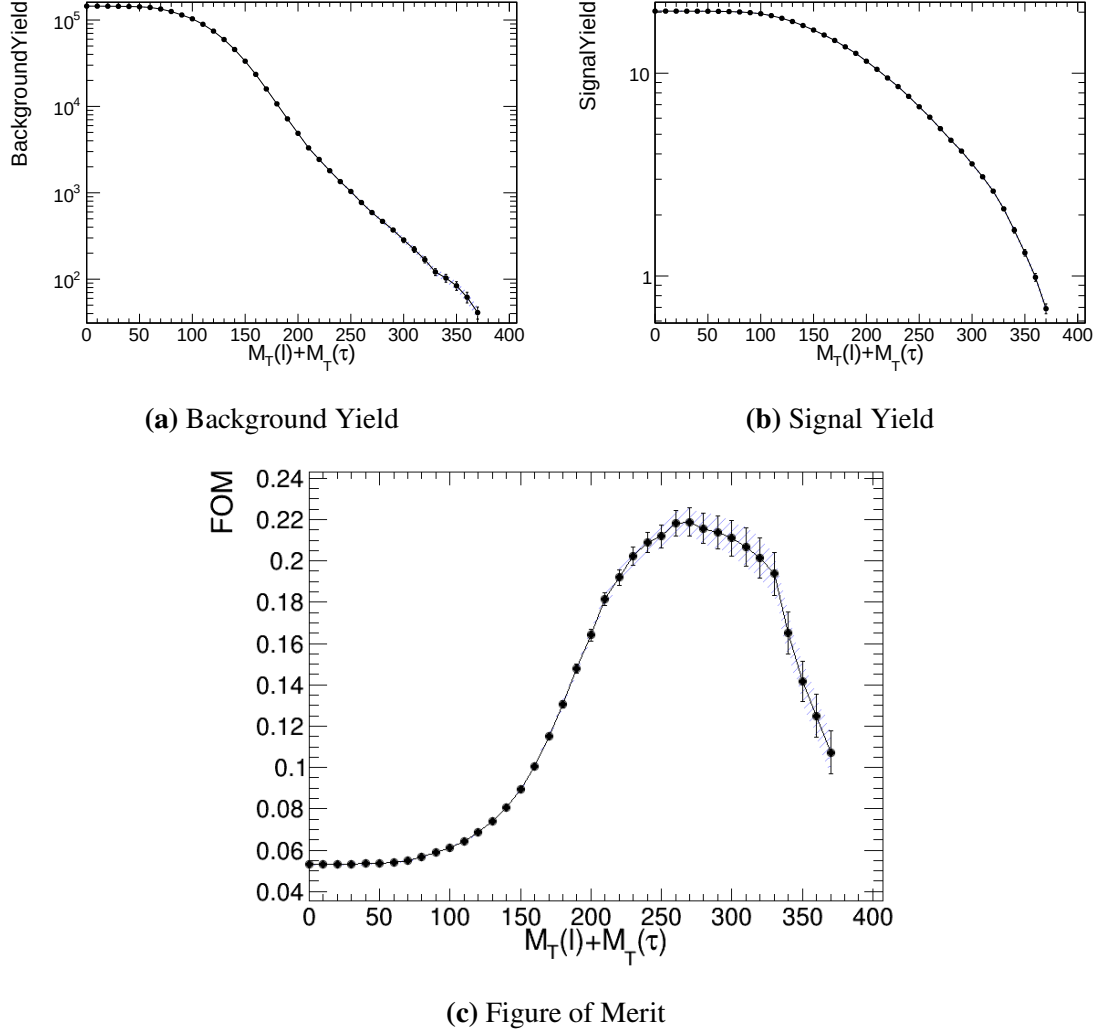


Figure 6.15: First step of the cut selection prescription for the variable $M_T(\ell) + M_T(\tau)$ and $\Delta M = 100$ GeV. For a given value on the x-axis, the value read off the y-axis is the yield (or FOM) after applying a cut with the given value. The signal and background yields are computed from MC simulation scaled to the luminosity of 19.7 fb^{-1} . The background yield is given by the sum of the yields of the individual background processes. The signal yield is computed with the prescription given at the beginning of Chapter 6. The FOM is computed according to Eq. 6.8.

6.1.3 Cut Simplification

It is clear from Table 6.2 that applying the full cut selection as described, i.e. a different selection for each ΔM value, is very complex with several different sets of cuts, all using different discriminant variables. Applying such a large set of cuts is also both time and resource intensive. With the intent of keeping a minimal set of cuts, but sacrificing as little as possible in the performance of the analysis, a slightly modified cut selection procedure is used, however with-

Table 6.2: Direct application of the iterative cut selection procedure. All dimension-full cuts are in units of GeV. The signal and background yields are computed from MC simulation scaled to the luminosity of 19.7 fb^{-1} . The background yield is given by the sum of the yields of the individual background processes. The signal yield is computed with the prescription given at the beginning of Chapter 6. The FOM is computed according to Eq. 6.8. The cuts are successively applied, starting with Cut 1.

ΔM	Cut 1	Cut 2	Cut 3	Cut 4	Cut 5	N_S	N_B	FOM
10	–	–	–	–	–	–	–	–
20	$\Delta\phi_{l-\tau} > 2.33$	$MET + p_T(\tau) > 100$	$ M_{Inv} - 61 < 70$	$M_{T2} < 40$	–	3.030 ± 0.169	3841 ± 87	0.04887 ± 0.00278
30	$Q_{80}(\tau) > -0.3$	$\Delta\phi_{l-\tau} > 2.43$	$ M_{Inv} - 61 < 50$	$\Delta\alpha_{l-\tau} > 1.22$	$MET + p_T(\tau) > 120$	3.124 ± 0.154	605 ± 29	0.12676 ± 0.00698
40	$Q_{100}(\tau) > -0.7$	$\Delta\phi_{l-\tau} > 2.33$	$ M_{Inv} - 61 < 120$	$\cos\theta_{\tau} < 0.9$	–	9.182 ± 0.233	2950 ± 80	0.16890 ± 0.00486
50	$MET + p_T(\tau) > 130$	$\Delta\phi_{l-\tau} > 2.23$	$\cos\theta_{\tau} < 0.9$	–	–	11.157 ± 0.227	2761 ± 75	0.21210 ± 0.00519
60	$Q_{100}(\tau) > 0$	$\Delta\phi_{l-\tau} > 1.92$	$\cos\theta_{\tau} < 0.9$	–	–	9.782 ± 0.197	1965 ± 63	0.22040 ± 0.00569
70	$M_T(l) + M_T(\tau) > 230$	$Q_{80}(\tau) + \cos\Phi(\tau) > -0.33$	$\Delta\alpha_{l-\tau} > 1.11$	–	–	7.078 ± 0.154	959 ± 41	0.22808 ± 0.00694
80	$M_T(l) + M_T(\tau) > 240$	$\cos\theta_l < 0.9$	–	–	–	7.578 ± 0.135	1156 ± 45	0.22250 ± 0.00590
90	$M_T(l) + M_T(\tau) > 270$	$\cos\theta_l < 0.9$	–	–	–	5.871 ± 0.106	538 ± 28	0.25228 ± 0.00805
100	$M_T(l) + M_T(\tau) > 300$	$M_T(\tau) > 60$	$\cos\theta_l < 0.9$	–	–	4.546 ± 0.083	230 ± 19	0.29803 ± 0.01337
110	$M_T(l) + M_T(\tau) > 300$	$M_T(\tau) > 70$	–	–	–	4.625 ± 0.075	281 ± 21	0.27463 ± 0.01151
120	$M_T(l) + M_T(\tau) > 330$	$M_T(\tau) > 80$	–	–	–	3.684 ± 0.068	144 ± 14	0.30466 ± 0.01625
130	$M_T(l) + M_T(\tau) > 330$	$M_T(\tau) > 80$	–	–	–	3.476 ± 0.054	144 ± 14	0.28764 ± 0.01507
140	$M_T(l) + M_T(\tau) > 330$	$M_T(\tau) > 80$	–	–	–	3.406 ± 0.047	144 ± 14	0.28188 ± 0.01464
150	$M_T(l) + M_T(\tau) > 330$	$M_T(\tau) > 80$	$Q_{100}(l) > 0$	–	–	3.080 ± 0.044	111 ± 11	0.29028 ± 0.01586
160	$M_T(l) + M_T(\tau) > 330$	$M_T(\tau) > 80$	–	–	–	3.076 ± 0.041	144 ± 14	0.25463 ± 0.01320
170	$M_T(l) + M_T(\tau) > 330$	$M_T(\tau) > 50$	–	–	–	3.022 ± 0.036	161 ± 14	0.23633 ± 0.01112
180	$M_T(l) + M_T(\tau) > 310$	$M_T(\tau) > 60$	–	–	–	3.026 ± 0.035	237 ± 19	0.19589 ± 0.00832
190	$M_T(l) + M_T(\tau) > 300$	–	–	–	–	3.069 ± 0.033	365 ± 22	0.16029 ± 0.00526
200	$M_T(l) + M_T(\tau) > 280$	–	–	–	–	3.023 ± 0.031	547 ± 29	0.12906 ± 0.00366
210	$M_T(l) + M_T(\tau) > 250$	$Q_{100}(l) > -0.5$	–	–	–	3.006 ± 0.028	940 ± 40	0.09790 ± 0.00229
220	$M_T(l) + M_T(\tau) > 240$	–	–	–	–	3.012 ± 0.028	1429 ± 51	0.07963 ± 0.00162
230	$M_T(l) + M_T(\tau) > 210$	–	–	–	–	3.004 ± 0.027	3389 ± 86	0.05159 ± 0.00080
240	$Q_{80}(\tau) > -1.6$	$Q_{80}(\tau) + \cos\Phi(\tau) > -2.33$	$M_T(l) + M_T(\tau) > 50$	–	–	3.000 ± 0.025	75824 ± 844	0.01090 ± 0.00011
250	–	–	–	–	–	–	–	–
260	–	–	–	–	–	–	–	–
270	–	–	–	–	–	–	–	–
280	–	–	–	–	–	–	–	–
290	–	–	–	–	–	–	–	–
300	–	–	–	–	–	–	–	–
310	–	–	–	–	–	–	–	–
320-330	–	–	–	–	–	–	–	–
340-350	–	–	–	–	–	–	–	–
360-370	–	–	–	–	–	–	–	–
380-390	–	–	–	–	–	–	–	–
400-410	–	–	–	–	–	–	–	–
420-440	–	–	–	–	–	–	–	–
>440	–	–	–	–	–	–	–	–

out being as automated as the previously described procedure. The modified procedure involves at each iteration step comparing the evolution of the FOM for each ΔM sample and its neighbouring ΔM samples and choosing a cut in common for as many neighbouring ΔM samples as possible, always taking care that the FOM is not significantly different from the maximum FOM

for those samples. An effort was also made to involve subset of discriminant variables as small as possible while still maintaining reasonable performance.

In this modified procedure the $\Delta M = 10$ GeV sample was purposefully given the same cuts as the $\Delta M = 20$ GeV sample. For the $\Delta M = 240$ GeV sample, for the first iteration the constraint of a signal yield of 3 events was changed to 4 events. All samples with $\Delta M > 240$ GeV were given the same cuts as the $\Delta M = 240$ GeV sample.

In this way 5 distinct sets of cuts were defined, summarised in Table 6.3. The table also defines the labels used to identify each set of cuts. The signal yields and FOM for each ΔM sample is summarised in Table 6.4.

Table 6.3: Simplified set of cuts per ΔM region. The units for the dimension-full cuts are in GeV. The background yields are computed from MC simulation scaled to the luminosity of 19.7 fb^{-1} . The background yield is given by the sum of the yields of the individual background processes.

Label	ΔM Range [GeV]	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	N_B
C1	[10 ; 60]	$E_T + p_T(\tau) > 130$	$\Delta\Phi_{\ell-\tau} > 2$	$\cos \theta_\tau < 0.9$	$ M_{\text{inv}} - 61 < 120$	$M_{T2} < 35$	1243 ± 44
C2	[70 ; 110]	$M_T(\ell) + M_T(\tau) > 260$	$\cos \theta_\ell < 0.9$	$M_T(\tau) > 60$	$E_T + p_T(\ell) > 140$	–	458 ± 28
C3	[120 ; 170]	$M_T(\ell) + M_T(\tau) > 285$	$M_T(\tau) > 60$	$M_T(\ell) > 90$	$E_T + p_T(\tau) > 160$	–	126 ± 12
C4	[180 ; 230]	$M_T(\ell) + M_T(\tau) > 210$	$M_{\text{Eff}} > 240$	$E_T > 80$	$M_T(\tau) > 80$	–	580 ± 32
C5	≥ 240	$M_{\text{Eff}} > 110$	$E_T + p_T(\tau) > 70$	$M_T(\ell) + M_T(\tau) > 50$	–	–	$72\,604 \pm 841$

Table 6.4: Signal yield and FOM for each ΔM sample after the modified cut selection procedure. The signal yield is computed from MC simulation scaled to the luminosity of 19.7 fb^{-1} . It is computed with the prescription given at the beginning of Chapter 6. The FOM is computed according to Eq. 6.8.

ΔM	Cuts	N_S	FOM
10	C1	0.22 ± 0.06	0.0063 ± 0.0018
20	C1	1.62 ± 0.12	0.0460 ± 0.0036
30	C1	4.26 ± 0.18	0.1208 ± 0.0055
40	C1	6.15 ± 0.19	0.1743 ± 0.0062
50	C1	7.07 ± 0.18	0.2003 ± 0.0062
60	C1	5.48 ± 0.15	0.1832 ± 0.0062
70	C2	4.50 ± 0.13	0.2297 ± 0.0100
80	C2	4.82 ± 0.10	0.2461 ± 0.0096
90	C2	5.70 ± 0.10	0.2655 ± 0.0094
100	C2	6.26 ± 0.10	0.2914 ± 0.0099
110	C2	5.90 ± 0.08	0.2747 ± 0.0092
120	C3	3.51 ± 0.07	0.3103 ± 0.0159
130	C3	3.22 ± 0.05	0.2841 ± 0.0142
140	C3	3.13 ± 0.04	0.2767 ± 0.0137
150	C3	3.08 ± 0.04	0.2724 ± 0.0135
160	C3	2.81 ± 0.04	0.2488 ± 0.0123
170	C3	2.71 ± 0.03	0.2395 ± 0.0118
180	C4	3.00 ± 0.03	0.1612 ± 0.0066
190	C4	3.00 ± 0.03	0.1371 ± 0.0046
200	C4	2.77 ± 0.03	0.1150 ± 0.0033
210	C4	2.53 ± 0.03	0.1047 ± 0.0030
220	C4	2.39 ± 0.02	0.0993 ± 0.0029
230	C4	2.20 ± 0.02	0.0914 ± 0.0026
240	C5	3.00 ± 0.02	0.0111 ± 0.0001

6.1.4 Signal Region Definition

Since the FOM is used as a surrogate for the full statistical analysis, it is important to verify if the selected set of cuts is indeed the most performant set of cuts for the desired signal space. To this effect, the expected upper limit for each $(M_{\tilde{\tau}}, M_{\text{LSP}})$ mass point is computed using the asymptotic CL_s method¹ [94, 95] for all sets of cuts. Figure 6.16a shows for each $(M_{\tilde{\tau}}, M_{\text{LSP}})$ mass point which set of cuts has the best (i.e lowest) expected upper limit, the colour refers to the numbering of the label of the set of cuts.

Figure 6.16a shows that the sets of cuts $C4$ and $C5$ are the best in a limited region. Furthermore, the improvement of $C4$ and $C5$ with respect to the second best cut is small. Consequently, $C4$ and $C5$ are discarded and Figure 6.16b shows where each set of cuts, from the reduced set $C1$, $C2$ and $C3$, has the best performance.

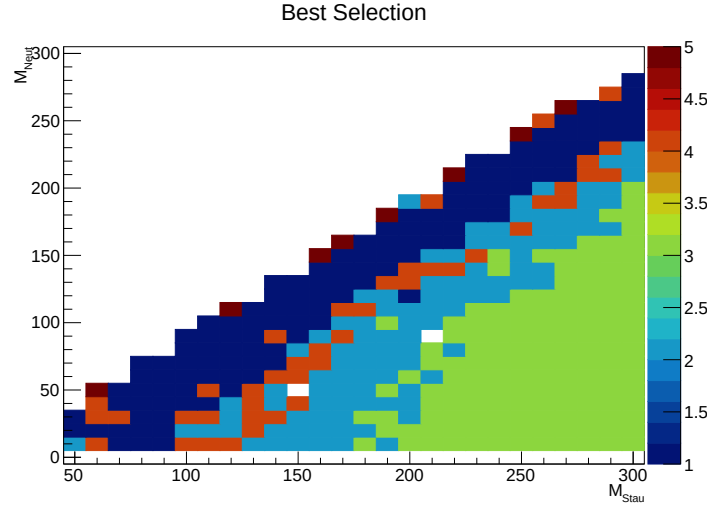
The three sets of cuts, $C1$, $C2$ and $C3$, have very clearly defined regions where each performs best. Using Figure 6.16b as a guide, three non-exclusive SRs are defined, each to be used for different ΔM regions:

- SR1 – $C1$; $\Delta M \in [10 ; 70] \text{ GeV}$
- SR2 – $C2$; $\Delta M \in [80 ; 160] \text{ GeV}$
- SR3 – $C3$; $\Delta M \geq 170 \text{ GeV}$

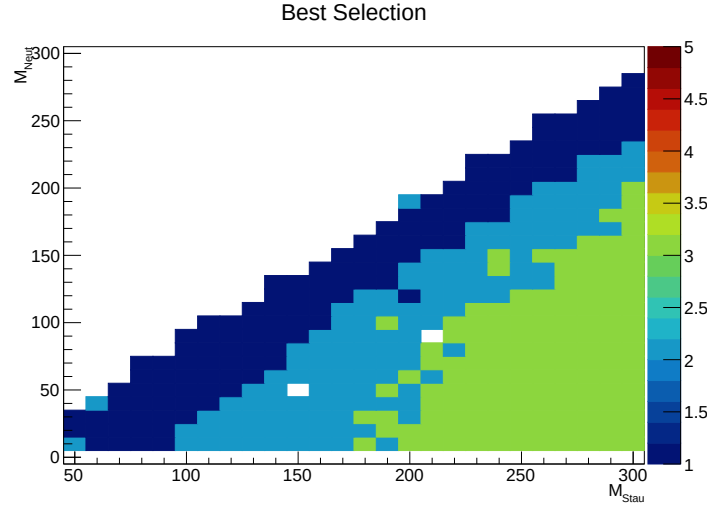
6.2 Event Yields per Signal Region

For each SR, the observed data yields and the expected background yields, using only MC, as well as some reference expected signal yields are summarised in Table 6.5. The defined sets of cuts are clearly effective in reducing the DY background process, bringing it to the same order of magnitude, or lower, as the $t\bar{t}$ process. Despite being significantly reduced, the $W + \text{Jets}$ background process continues with a significant yield, constituting the dominant background process. It makes up at least 50 % of the background events. Data and the expected SM back-

¹To compute the expected upper limit, the combine tool is used and only statistical uncertainties and the luminosity systematic uncertainty are considered. The tool is further described in Chapter 9 , where it is used for the final result



(a) All sets of cuts



(b) Reduced set of cuts

Figure 6.16: Best set of cuts per mass point. For each mass point the expected upper limit on the signal cross section is computed with the asymptotic CL_s method, considering only the statistical uncertainty. The signal and background yields are computed from MC simulation scaled to the luminosity of 19.7 fb^{-1} . The background yield is given by the sum of the yields of the individual background processes. All MC samples are corrected by the relevant scale factors. The colour refers to the numbering of the label of the set of cuts

ground are mostly in agreement, with SR1 showing the largest disagreement. The disagreement is largely driven by the disagreement seen in the $p_T(\tau)$ variable, see Figure 5.3d.

Table 6.5: Yields per SR. Data corresponds to 19.7 fb^{-1} of certified CMS data and MC is scaled to the same luminosity value; the signal MC are normalised to $\sigma = 1 \text{ pb}$. For SR1, the signal point $M_{\tilde{\tau}} = 50 \text{ GeV}$; $M_{\text{LSP}} = 10 \text{ GeV}$ is shown, for SR2, the signal point $M_{\tilde{\tau}} = 100 \text{ GeV}$; $M_{\text{LSP}} = 10 \text{ GeV}$ is shown and for SR3, the signal point $M_{\tilde{\tau}} = 180 \text{ GeV}$; $M_{\text{LSP}} = 10 \text{ GeV}$ is shown. All MC samples are corrected by the relevant scale factors.

Process	SR1	SR2	SR3
Single top	33.35 ± 3.81	15.96 ± 2.59	4.61 ± 1.33
$t \bar{t}$	224.42 ± 12.42	59.22 ± 6.35	24.09 ± 4.03
VV/VVV	66.58 ± 1.90	40.25 ± 1.44	20.94 ± 1.03
γ + Jets	0	0.42 ± 0.34	0.24 ± 0.21
QCD	0	0.22 ± 0.20	0.20 ± 0.20
$Z \rightarrow \ell\ell$	230.32 ± 16.30	39.70 ± 6.71	4.61 ± 1.23
W + Jets	688.46 ± 38.49	302.82 ± 26.25	71.85 ± 11.27
Total Expected	1243.13 ± 43.81	458.59 ± 27.99	126.54 ± 12.15
Signal	5.32 ± 3.07	47.11 ± 10.48	122.50 ± 15.00
Data	1107 ± 33	421 ± 20	131 ± 11

Chapter 7

Data Driven Background Estimation

The slight mismodelling of the $p_T(\tau)$, see Figure 5.3d, prompts for a more robust method to estimate the SM background rather than relying only on MC. The $W + \text{Jets}$ process accounts for roughly two thirds, see Table 5.5 (at preselection) and Table 6.5 (at each of the SRs), of the SM background. Most of the $W + \text{Jets}$ events passing preselection are expected to contain a so-called fake tau. Thus, it is expected that a large fraction of the SM background originates from fake taus. A fake tau is defined as some object, not a tau, which given the detector efficiency and event PU is reconstructed as an hadronic tau. Since the tau reconstruction uses the HPS algorithm, the majority of the fake taus are expected to result from jets. In contrast to fake taus, a prompt tau is defined as a tau object which is reconstructed as an actual tau.

To better understand the nature of the SM background, a preliminary analysis was performed on the SM MC background samples. The analysis uses the same event preselection as described in Chapter 5. The taus are classified based on the information of the generated event. The matching between the two is performed in a cone with $\Delta R = 0.3$, i.e. a reconstructed tau is classified according to which particles from the generated event are within a $0.3 \Delta R$ cone. A prompt tau has a generated tau within the cone and a fake tau does not. Figure 7.1 summarises the results from this analysis. The figure shows that events with fake taus do indeed have a higher presence in the background composition, however there is a significant contribution from prompt taus as well. The above-defined tau classification, fake and prompt, is used for the remainder of this chapter.

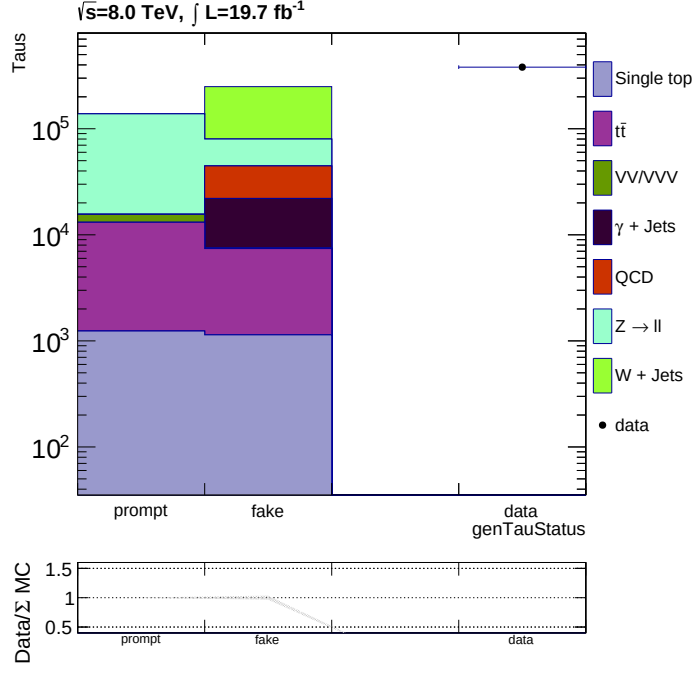


Figure 7.1: Tau provenance at preselection, obtained from the preliminary analysis. Taus are classified according to whether they have a generated tau within a cone of $\Delta R = 0.3$ (prompt) or not (fake).

Events with fake taus are thus targeted with a data driven estimation method. The method used is the fakeable object method [96], originally developed for fake electrons and muons. Here, the method has been adapted for τ objects. This method is further detailed in section 7.2. With the fakeable object method, the two main components required to predict the background originating from fake taus are the tau fake rate (f) and the tau prompt rate (p), section 7.1 details how f and p are estimated.

7.1 Fake Rate and Prompt Rate Estimation

For the fakeable object method, the fake rate is defined as the probability of a loosely identified fake object to qualify the criteria (defined for the main analysis) of the object to be selected. In this analysis, this translates to the probability of a loosely identified fake tau to pass the tight tau identification, with all other tau object definition requirements as defined in section 5.3.1. Consequently, the fake rate, f , would be defined as the ratio of the yield of tightly identified fake

taus, $N_{\text{Fake Tau}}^{\text{Tight}}$, with the yield of loosely identified fake taus, $N_{\text{Fake Tau}}^{\text{Loose}}$ ¹:

$$f = \frac{N_{\text{Fake Tau}}^{\text{Tight}}}{N_{\text{Fake Tau}}^{\text{Loose}}} \quad (7.1)$$

As a data driven estimation method, the fake tau yields with the tight and loose selections ($N_{\text{Fake Tau}}^{\text{Tight}}$ and $N_{\text{Fake Tau}}^{\text{Loose}}$) are taken from data in an appropriate CR. Unfortunately, in data it is not possible to tag the tau objects with whether they are fake or prompt, the information is only available in MC. Consequently, the chosen CR must be enriched in fake taus. The CR must also have a low signal contamination so as not to be affected by the signal to be measured. However, in data there is a contribution of prompt taus as well as a resonance from the DY process which alter the above ratio, even in the CR. With this in mind, the yields of prompt taus and the DY yield are estimated from MC in that same CR and are subtracted from the data yield prior to the computation of the fake rate:

$$f = \frac{N^{\text{Tight}}(\text{Data}) - \left(N^{\text{Tight}}(Z \rightarrow \ell\ell) + N_{\text{Prompt Tau}}^{\text{Tight}}(\text{Other MC}) \right)}{N^{\text{Loose}}(\text{Data}) - \left(N^{\text{Loose}}(Z \rightarrow \ell\ell) + N_{\text{Prompt Tau}}^{\text{Loose}}(\text{Other MC}) \right)} \quad (7.2)$$

The prompt rate is defined in a similar manner to the fake rate, but instead of fake taus, it uses prompt taus:

$$p = \frac{N_{\text{Prompt Tau}}^{\text{Tight}}}{N_{\text{Prompt Tau}}^{\text{Loose}}} \quad (7.3)$$

For this analysis, the prompt rate is computed in MC, with the $Z \rightarrow \ell\ell$ sample, using the same control region as for the fake rate, Eq. 7.4. In MC the hadronic taus are easily tagged as prompt or fake, allowing Equation 7.3 to be applied directly, using the definition introduced above. This was also exploited for the fake rate, where the prompt contribution was subtracted from data.

$$p = \frac{N_{\text{Prompt Tau}}^{\text{Tight}}(Z \rightarrow \ell\ell)}{N_{\text{Prompt Tau}}^{\text{Loose}}(Z \rightarrow \ell\ell)} \quad (7.4)$$

Control Region

Among the control regions studied, the one observed to bestow the best performance is defined by inverting the MET cut and removing the b-jet veto when compared to the preselection. In

¹The nomenclature used in this subsection uses $N_Y^X(Z)$, where the Y and Z components are optional. It stands for the yield of events with ($Y = \{\text{prompt, fake}\}$) taus passing the requirement X (of the sample Z).

essence, being defined by the set of cuts:

- $E_T < 30 \text{ GeV}$
- An OS pair of a tau and a lepton (electron or muon)
- Veto events with extra leptons

Furthermore, a closure test, using only W+Jets MC was performed, since it is expected that in the W + Jets process nearly all events passing preselection will contain a fake tau. The full fake rate estimation method was applied to the W + Jets sample as if it were data and the estimated events with fake taus were compared with the events expected from W + Jets MC after preselection. At preselection level, the ratio of estimated fake tau events with events expected from W + Jets MC was observed to be consistent with 1 for each discriminant variable, see Figure 7.2, furthermore the overall ratio was 0.952 ± 0.010 , only statistical uncertainty. Other tested CRs result in ratios of the order of 1.2. The positive result of this closure test in MC, with respect to other considered CRs, lends confidence to the selected CR. The small bias in the overall ratio of the closure test should be considered as a systematic uncertainty on the estimated fake tau events.

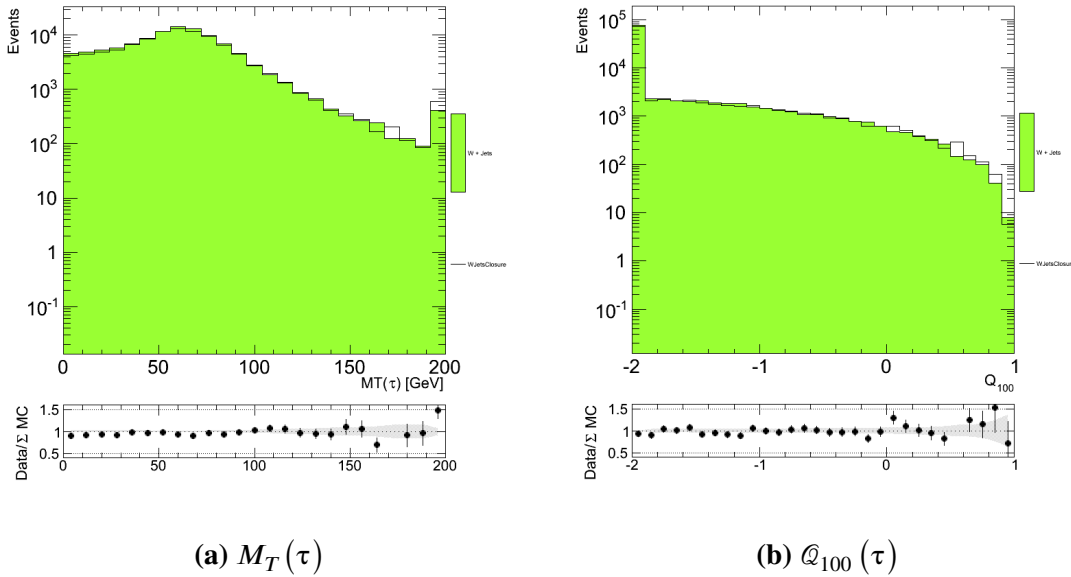


Figure 7.2: Data-driven fake tau estimation closure test on W + Jets MC.

In this CR, the computed fake rate is 0.497 ± 0.004 . The fake rate is also computed in bins of $\eta(\tau)$, see Figure 7.3, and a dependence of f on $\eta(\tau)$ is clearly visible. Considering the $\eta(\tau)$ dependent fake rate, the f for events with $\eta(\tau) = 0$ is given by Eq. 7.5.

$$f = 0.494 \pm 0.020, \text{ for } \eta(\tau) = 0 \quad (7.5)$$

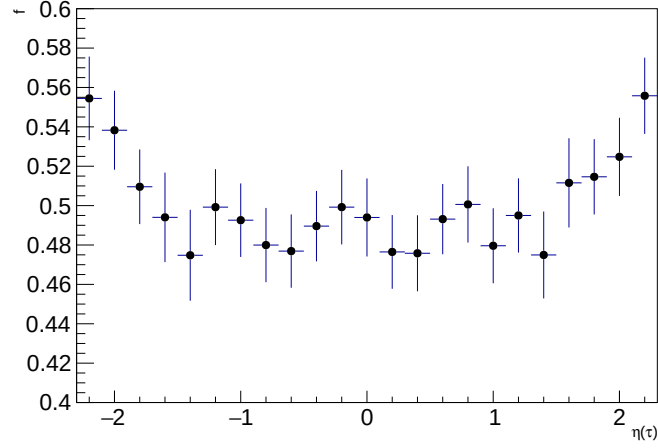


Figure 7.3: Tau Fake Rate, f , as a function of $\eta(\tau)$. The fake rate is evaluated on data in bins of $\eta(\tau)$ using Eq. 7.2. Data corresponds to 19.7 fb^{-1} of certified CMS data and MC is scaled to the same luminosity value. All MC samples are corrected by the relevant scale factors.

In this CR the prompt rate is summarised in Eq. 7.6. Analogously to the fake rate, the prompt rate is computed in bins of $\eta(\tau)$, Figure 7.4. No significant dependence of p on $\eta(\tau)$ is seen.

$$f = 0.786 \pm 0.005 \quad (7.6)$$

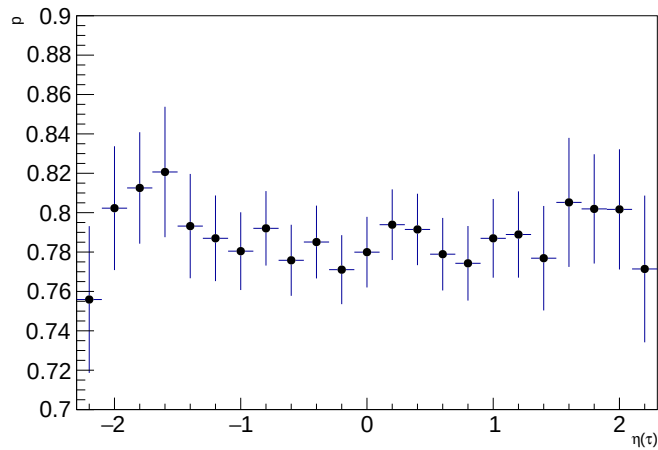


Figure 7.4: Tau Prompt Rate, p , as a function of $\eta(\tau)$. The prompt rate is evaluated on the $Z \rightarrow \ell\ell$ MC sample in bins of $\eta(\tau)$ using Eq. 7.2. The MC samples are corrected by the relevant scale factors.

7.2 Fake Tau Estimation

The fakeable object method is used to estimate the fake tau component in this analysis. As previously mentioned, the method requires the tau identification to be loosened to the loose tau ID instead of the tight tau ID, i.e. using the `byLooseCombinedIsolationDeltaBetaCorr3Hits` discriminator instead of the `byTightCombinedIsolationDeltaBetaCorr3Hits` discriminator. According to the fakeable object method, the estimated fake tau contribution in a certain SR is given by Equation 7.7, where $N_{\text{Fake Taus}}$ is the estimated fake tau backgrounds, N_{NonTight} is the yield of data events with taus that pass the loose tau identification but do not pass the tight tau identification and N_{Tight} is the yield of data events that pass the tight tau identification. This method can be applied for any given set of cuts, allowing to obtain a data driven prediction of the fake tau contribution for any of the SR defined in Chapter 6. Equation 7.7 can also be applied to individual bins in a distribution, allowing to use the $\eta(\tau)$ dependent f for instance.

$$N_{\text{Fake Taus}} = \frac{p \times f}{p - f} N_{\text{NonTight}} - \frac{f \times (1 - p)}{p - f} N_{\text{Tight}} \quad (7.7)$$

Using constant f and p , as measured in Section 7.1, and applying the fakeable object method (Eq. 7.7) at preselection, a data-driven estimation of the fake tau background for any distribution is obtained. Figure 7.5, shows the distribution of $p_T(\tau)$ and $\eta(\tau)$. The trend of disagreement between data and the background processes as a function of $p_T(\tau)$, which was previously observed (see Fig. 5.3d), is no longer present. However, a disagreement is observed as a function of $\eta(\tau)$, an artefact of using a constant f . Doing the data driven estimate in bins of $\eta(\tau)$, by using $p = 0.786 \pm 0.005$ and taking f from Figure 7.3 mitigates this disagreement, see the following section for results. The $\eta(\tau)$ dependent fake rate is used in all subsequent sections.

7.3 Event Yields per Signal Region

With the data driven fake tau estimate in place, the background yield at any selection level is given by the data driven fake tau estimate added to the sum of the prompt component of the MC processes. At preselection, the data/background ratio is 1.069 ± 0.005 , and Table 7.1 summarises the predicted background yields as well as observed data. As expected, the $W + \text{Jets}$ MC component is left with a negligible contribution, with the other processes accounting for

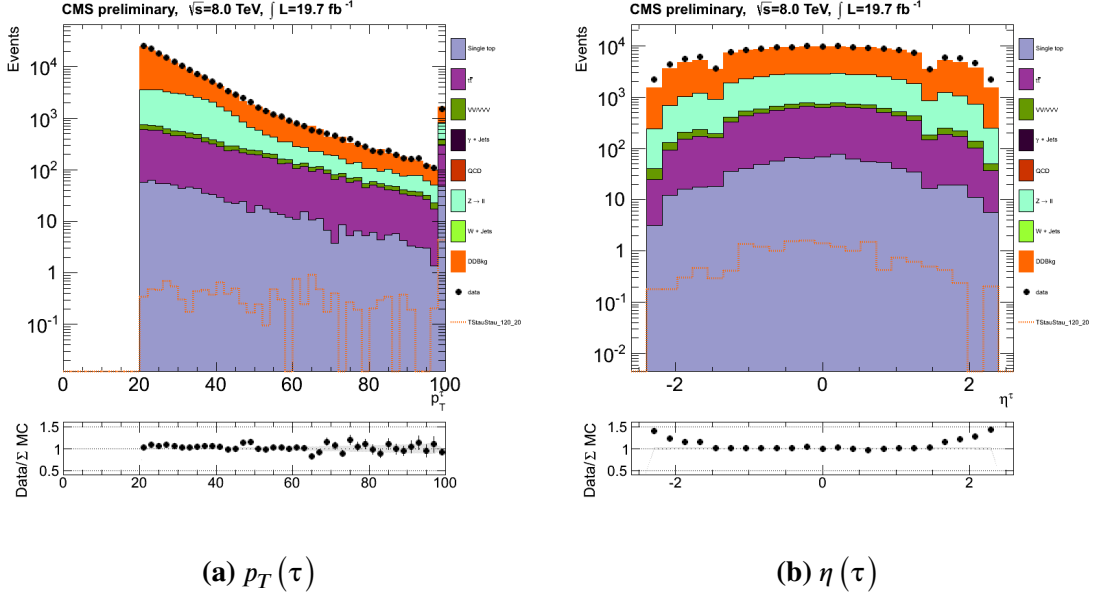


Figure 7.5: $p_T(\tau)$ and $\eta(\tau)$ at Preselection using a flat fake rate for the fake tau estimate

the majority of the background, apart from the fake tau component. Fig. 7.6 shows some of the selection variables at preselection, using the data driven fake tau estimate, which improves the data/background agreement.

To evaluate the effect of the data driven background estimation, compare Table 7.1 with Table 5.5 and Fig. 7.6 with Fig. 5.3. The undesirable observation of the disagreement as a function of $p_T(\tau)$ is no longer present and the overall agreement between data and the estimated background is significantly improved.

The data driven fake tau method is applied to the three signal regions to obtain the expected background yield, see Table 7.2. An immediate observation from this table is that there is no observed excess in data.

Table 7.1: Yields after preselection for the fake tau component, using the data driven method, for the considered MC background processes, for the total fake tau and MC sum and for data. Data corresponds to 19.7 fb^{-1} of certified CMS data and MC is scaled to the same luminosity value. For MC, only events with prompt taus are considered. The MC samples are corrected by the relevant scale factors.

Process	Yield
Single top	318 ± 12
$t \bar{t}$	1647 ± 34
VV/VVV	1426 ± 9
$Z \rightarrow \ell \ell$	$26\,205 \pm 179$
W + Jets	30 ± 8
Fake Taus	$99\,354 \pm 478$
Total Expected	$128\,980 \pm 512$
Data	$137\,902 \pm 371$

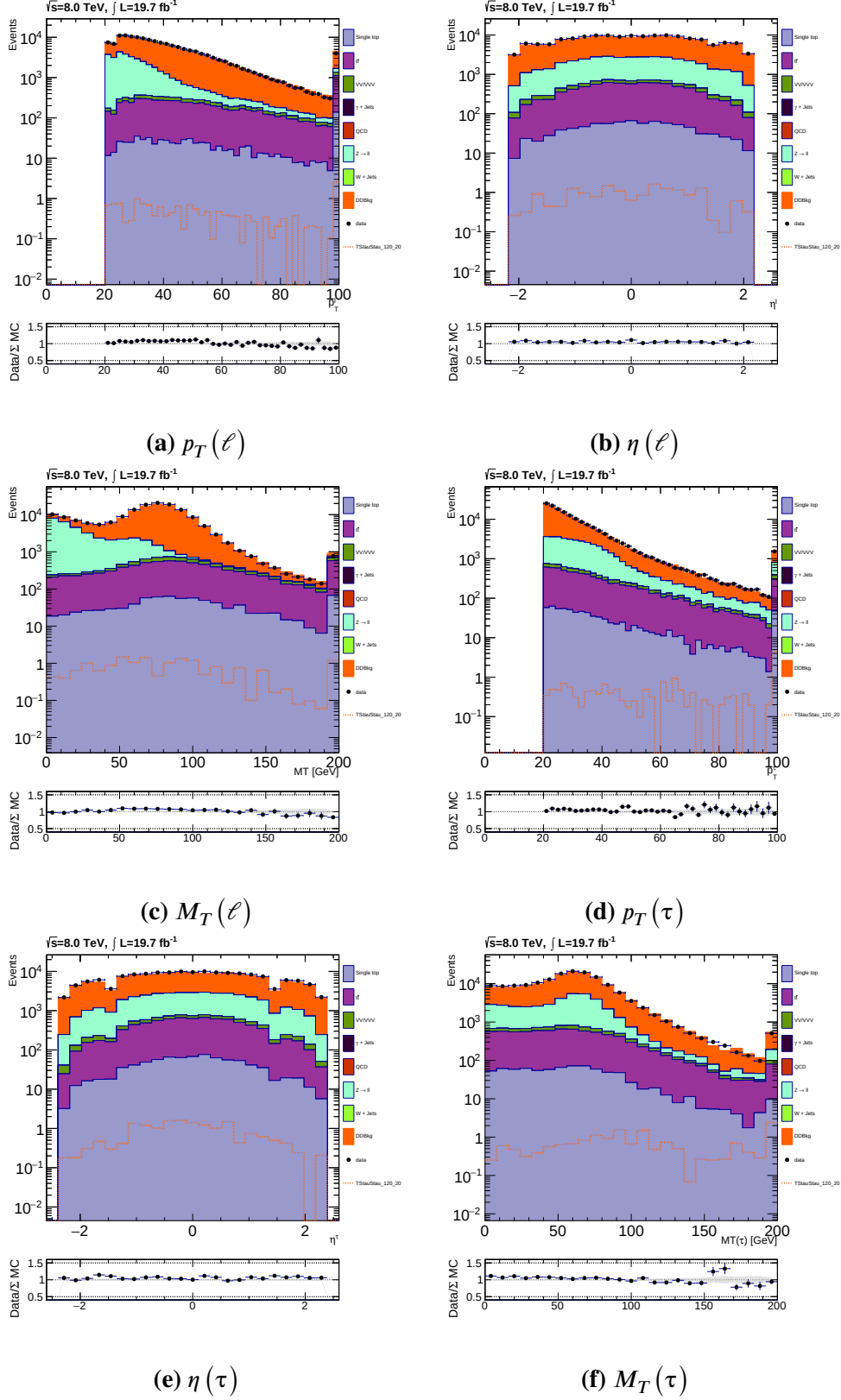


Figure 7.6: Variables after Preselection, the considered background processes are stacked and compared to data. Data corresponds to 19.7 fb^{-1} of certified CMS data and background consists of MC scaled to the same luminosity value for the prompt taus and the above-mentioned data-driven procedure for the fake taus. All MC samples are corrected by the relevant scale factors.

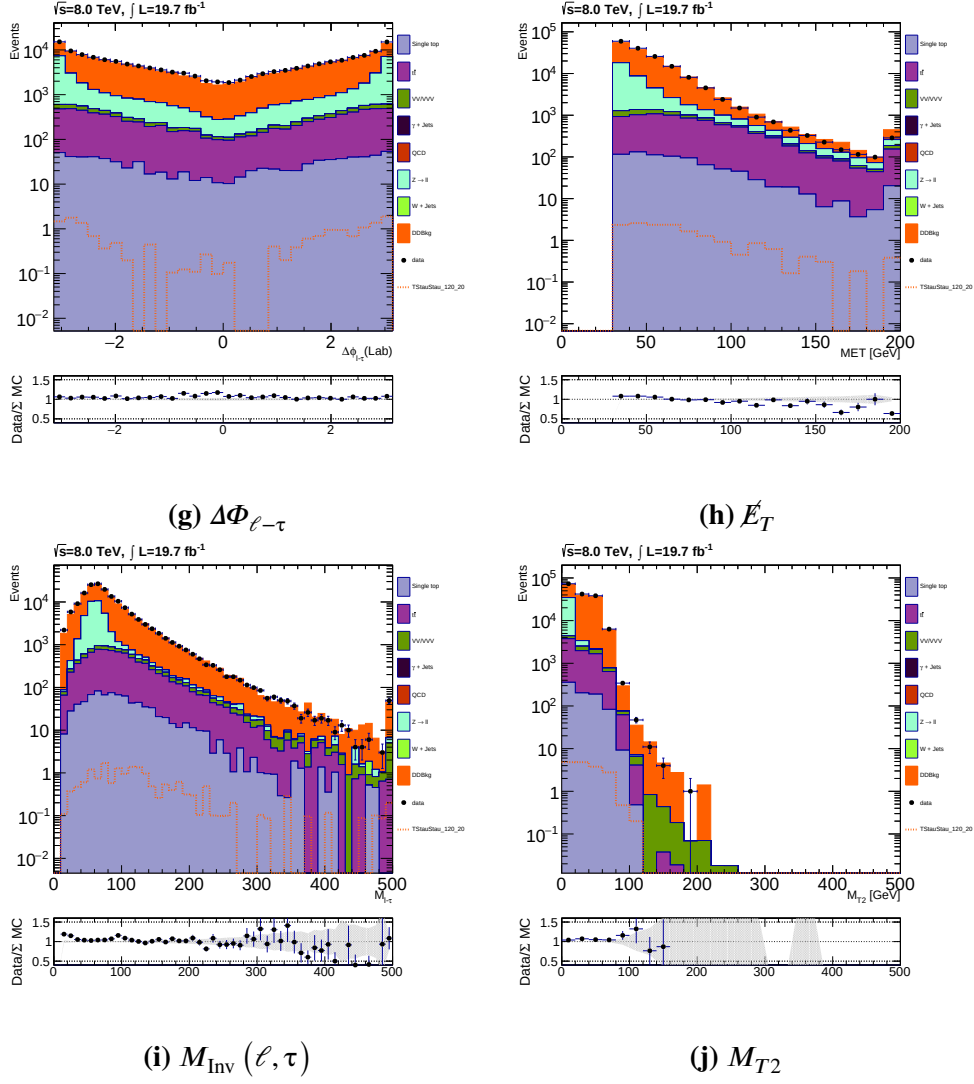


Figure 7.6: Variables after Preselection, the considered background processes are stacked and compared to data. Data corresponds to 19.7 fb^{-1} of certified CMS data and background consists of MC scaled to the same luminosity value for the prompt taus and the above-mentioned data-driven procedure for the fake taus. All MC samples are corrected by the relevant scale factors. (continued)

Table 7.2: Yields per Signal Region considering the data driven fake tau contribution. The signal yields are normalised to $\sigma = 1$ pb. For SR1, the signal point $M_{\tilde{\tau}} = 50$ GeV; $M_{\text{LSP}} = 10$ GeV is shown, for SR2, the signal point $M_{\tilde{\tau}} = 100$ GeV; $M_{\text{LSP}} = 10$ GeV is shown and for SR3, the signal point $M_{\tilde{\tau}} = 180$ GeV; $M_{\text{LSP}} = 10$ GeV is shown. For background MC, only events with prompt taus are considered. All MC samples are corrected by the relevant scale factors.

Process	SR1	SR2	SR3
Single top	23.89 ± 3.25	11.86 ± 2.20	3.96 ± 1.24
$t\bar{t}$	182.89 ± 11.20	48.80 ± 5.73	19.76 ± 3.62
VV/VVV	63.32 ± 1.83	33.49 ± 1.30	17.72 ± 0.94
$Z \rightarrow \ell\ell$	200.50 ± 16.05	31.24 ± 6.54	0.49 ± 0.26
W + Jets	1.60 ± 1.60	–	–
Fake Taus	643.16 ± 38.55	328.03 ± 26.58	94.77 ± 14.54
Total Expected	1115.37 ± 43.42	453.42 ± 28.08	136.70 ± 15.07
Signal	5.32 ± 3.07	47.11 ± 10.48	122.50 ± 15.00
Data	1107 ± 33	421 ± 20	131 ± 11

Chapter 8

Systematic Uncertainties

Estimating the uncertainty of a measurement is an essential part of performing the said measurement. In general, uncertainties can originate from several sources, such as from the measurement process itself up to effects of the environment. Uncertainties are split into two types, statistical uncertainties and systematic uncertainties. Statistical uncertainties result from the statistical nature of the measurement process and are essentially stochastic in their nature. Systematic uncertainties result from an effect that consistently affects the result of repeated measurements which may or may not be known *a-priori*. In previous chapters all quoted values have been accompanied by their corresponding statistical uncertainties.

For this analysis, several sources of systematic uncertainty are considered, in particular those arising from the data driven background estimation method and those related to the simulation of the MC events and the performance of the detector. The effects of the systematic uncertainties on the yields are estimated by taking the difference between the nominal value of the yield and that obtained by varying the source of the systematic uncertainty. Several ancillary measurements are used to calibrate or compute the background and signal yields. The associated uncertainties constitute the systematic uncertainties for the analysis.

The following sections describe each of the considered systematic uncertainties and their effects on the yields. The effect of each systematic uncertainty may change depending on the considered SR. When relevant, the effect of the systematic uncertainty is reported for each signal region separately. The effect of a systematic uncertainty on the yield can be asymmetric. When

the systematic uncertainty is asymmetric, both the up and down variations are reported, with the up variation above the down variation. Note that, given the data driven background estimation, the MC is only used to estimate the prompt component of the SM background. Thus, the uncertainties quoted for the MC SM background processes are only on the prompt subset of those processes.

8.1 Luminosity

The luminosity is estimated according to the latest recommendations for data acquired in 2012 [97], using the pixel cluster counting method. The MC events are then weighted by the luminosity estimate so that the MC yield matches the expectation for the given luminosity.

Since the luminosity is a scale applied to MC, the uncertainty on the luminosity translates directly to the uncertainty on the final yield, for all yields estimated from MC. As a result, the luminosity systematic uncertainty affects both signal and the background estimated from MC in the same amount. Note that it does not affect the data driven background estimation. The uncertainty on the luminosity for the considered data when using the pixel cluster counting method is 2.6 % [98].

8.2 Cross Section

The cross section quantifies the likelihood of an event to occur and is computed within the framework of a model. The cross section is then used to normalise the expected yield from MC events.

For the background processes, the cross sections are computed within the SM. The SM has 19 free parameters, 18 of which are measured experimentally and placed into the model in order to compute the cross sections. The uncertainties on these measured parameters are systematic uncertainties for the computation of the cross sections. The uncertainties on the cross sections are taken from the reference standard model cross sections for CMS at 8 TeV, [99]. The final effect on the yields of each process is summarised in Table 8.1.

Table 8.1: Effects of the cross section systematic uncertainties on the expected yield of each of the different MC background samples. The systematic uncertainties result from the uncertainty on the 18 experimentally measured input parameters to the SM.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Single top	2.7	2.7	2.7
$t\bar{t}$	2.5	2.5	2.5
VV/VVV	3.5	3.4	3.4
$Z \rightarrow \ell\ell$	5.5	5.1	2.7
W + Jets	<1.0	–	–

The signal MC samples are not normalised to a given cross section when setting an upper limit on the cross section. Consequently, there is no systematic uncertainty associated with the signal cross section in this situation. For setting an exclusion limit, the signal MC must be normalised to a reference cross section. The reference cross sections and associated systematic uncertainties [100] are computed using PROSPINO2 [101]. The uncertainty on the signal cross sections differ from signal point to signal point and vary between 2 % and 5 %.

8.3 Pile-up

The simulated MC samples are generated with a given distribution for nvtx. For the analysis, the actual nvtx distribution is measured in data. The measured distribution is used to re-weight the MC events, such that MC and data have the same distribution. The statistical uncertainty on the measured distribution is a systematic uncertainty for the re-weighting procedure. The effect of this uncertainty on the final yields is summarised in Table 8.2. For signal, the effect changes from point to point and ranges between 0.2 % and 3 %.

Table 8.2: Effect of the pile Up systematic uncertainty on the different MC samples and for each SR.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Single top	-1.8 +2.0	+5.4 -4.8	+9.4 -8.4
$t\bar{t}$	< 0.1	+1.6 -1.2	+1.3 +0.06
VV/VVV	+0.8 -0.6	+1.0 -0.9	+0.9 -0.8
$Z \rightarrow \ell\ell$	-1.8 +1.8	-3.2 +2.6	-2.2 +1.4
W + Jets	+5.4 -7.2	—	—

8.4 PDF

For the simulated MC events, the initial state for the event is chosen according to a Parton Distribution Function (PDF). The PDFs are measured quantities and have associated uncertainties. Furthermore, there is a choice of which set of PDFs to use.

To account for the uncertainty on the PDF and for the choice of the chosen PDF, the PDF4LHC prescription is used [102, 103]. To estimate the effect of this uncertainty, three sets of PDFs are taken into account, CT10 MSTW2008 and NNPDF23, as well as their uncertainties. For each event, the weight from each PDF set is used as well as all the uncertainty variations. The largest deviation is the considered PDF systematic uncertainty. The effect of this uncertainty is summarised in Table 8.3. For signal, the effect changes from point to point and ranges between 0.5 % and 20 %.

8.5 Jet Energy Scale and Jet Energy Resolution

Charged hadrons and photons constitute about 85 % of the average energy of a jet. The charged hadron fraction is accurately measured with the tracker, where the tracks give a measurement of the energy of the particles. The photons are measured in the ECAL. The neutral and charged hadrons are measured by the HCAL, which is a sampling detector so only a fraction of the deposited energy is measured. Furthermore, to reach the HCAL the hadrons must pass through the

Table 8.3: Effect of the PDF systematic uncertainty on the different MC samples and for each SR.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Single top	+12.1 -13.9	+42.6 -47.5	+18.9 -18.4
$t\bar{t}$	+9.5 -9.8	+11.1 -11.3	+10.1 -11.2
VV/VVV	+10.2 -8.9	+13.7 -11.3	+17.7 -14.6
$Z \rightarrow \ell\ell$	+7.8 -6.8	+6.9 -7.1	+9.4 -12.1
W + Jets	+31.8 -28.2	—	—

ECAL, also leaving some energy depositions in it. In order to accurately reconstruct the energy of a jet, all this information must be correctly taken into account and the non-linearity of the detector response must be calibrated. To complicate this process, there are the PU interactions, which provide additional background particles and energy.

To correct for all these effects and reconstruct the jet energy, the set of so-called Jet Energy Corrections (JEC) are applied to the jets. The JEC are a set of sequential corrections to be applied to the jets, as a function of the jet properties, and are essentially a scaling of the jet's four-momentum, i.e. they are setting the Jet Energy Scale (JES). Each step of the JEC corrects for a specific effect. Naturally, the corrections are estimated from several measurements, which have their associated uncertainties, which reflect on the final energy scale of the jets, constituting the JES uncertainty. The final JES uncertainty is below 3 % for all considered jets.

In addition to effects that affect the absolute scale of the jets, some can also affect the resolution on the transverse momentum of the jets. These effects are also estimated and are introduced as a systematic uncertainty on the jets, the Jet Energy Resolution (JER) uncertainty. The total JER uncertainty varies between 2 % and 4 % in the tracker region and goes up to 10 % in the end caps and HF. An in depth description of the JEC procedure and all associated uncertainties can be found in [104]. The effect of these uncertainties on this analysis are summarised in Table 8.4 and 8.5. The effect of these uncertainties on signal are typically very low, below 1 %, for some signal points the effect goes up to 6 %.

Table 8.4: Effect of the jet energy scale systematic uncertainty on the different MC samples and for each SR.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Single top	+0.6 -1.1	+4.1 -7.7	+0 -11.3
$t\bar{t}$	-0.9 +0.4	+4.0 -8.9	+0.2 -4.3
VV/VVV	+3.2 -2.0	+4.0 -4.3	+6.4 -6.9
$Z \rightarrow \ell\ell$	+1.2 -4.6	+0.4 -2.7	+0 -0
W + Jets	+54.9 -0	—	—

Table 8.5: Effect of the jet energy resolution systematic uncertainty on the different MC samples and for each SR.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Single top	+0.4 +3.3	+0 +1.4	+0 +5.8
$t\bar{t}$	+0.2 +2.8	+3.1 -5.2	-1.2 -4.9
VV/VVV	+1.5 +0.2	+1.8 -2.3	+3.8 -0.6
$Z \rightarrow \ell\ell$	+2.9 -3.9	+2.0 -1.4	+0 -26.0
W + Jets	+0 -0	—	—

8.6 Lepton Energy Scale

The uncertainty in the strength of the magnetic field, the position of the individual tracking sensors and of the position of the hits in each sensor translate into an uncertainty of the tracks reconstructed with those hits. This uncertainty corresponds to an uncertainty of the momentum of the associated particle, effectively it is an uncertainty on the energy scale of the particle, i.e. a scaling factor applied to the momentum. Details on the measurement of this uncertainty for electrons and muons can be found in [82, 85]. For muons the uncertainty is 1 %, for electrons in the barrel region the uncertainty is 2 % and for electrons in the endcap regions the uncertainty is 5 %. Consequently, in order to evaluate the effect of this uncertainty, the scale of the objects is varied by the corresponding uncertainty. The effect of this uncertainty is summarised

in Table 8.6. For signal, the effect of this uncertainty is typically 1-2 %, with few signal points varying as much as 13 %. The higher variations tend to correlate with lower ΔM samples.

Table 8.6: Effect of the lepton energy scale systematic uncertainty on the different MC samples and for each SR.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Single top	-1.0 +3.8	+3.9 -5.3	+11.7 -10.0
$t\bar{t}$	+1.8 -0.7	+6.8 -7.6	+9.4 -3.3
VV/VVV	+0.0 -0.2	+2.3 -3.4	+6.6 -3.8
$Z \rightarrow \ell\ell$	+2.1 +0.5	-0.7 +0.4	+14.9 -0
W + Jets	+54.9 -0	—	—

8.7 Tau Energy Scale

Similarly to the jets, the τ energy measured by the detector needs to be corrected in order to obtain the true energy of the τ . The scaling is estimated from measurements, consequently it is affected by uncertainties which become systematic uncertainties for the analysis. An in depth description can be found in [86]. A conservative approach for this systematic uncertainty is taken by varying the momentum of the taus by 3 %. The effect of this uncertainty is summarised in Table 8.7. For signal, the effect of this uncertainty is typically 3-4 %, with few signal points varying as much as 11 %. The higher variations tend to correlate with lower ΔM samples.

8.8 Unclustered MET Energy Scale

The MET has two main components, the clustered and the unclustered one. The clustered component corresponds to the jets, since the jets result from the clustering of individual reconstructed objects. The uncertainty on the energy reconstruction of these objects is already accounted for with the JES and JER systematic uncertainties and is correctly propagated through the MET. However, the unclustered component of the MET, also had its energy reconstructed, thus is also

Table 8.7: Effect of the tau energy scale systematic uncertainty on the different MC samples and for each SR.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Single top	-2.6 +0.0	+3.9 -1.5	+11.7 -11.3
$t\bar{t}$	+2.8 -2.1	+5.2 -14.8	+6.6 -18.6
VV/VVV	+1.7 -2.0	+4.6 -6.2	+5.2 -7.5
$Z \rightarrow \ell\ell$	+4.1 -6.0	+1.7 -7.3	+0 -0
W + Jets	+0 -0	—	—

affected by an uncertainty. To correctly account for this uncertainty, the MET is separated into its two components and the unclustered component has its energy varied by 10 % [105]. The effect of this uncertainty is summarised in Table 8.8. For signal, the effect is typically below 6 %, with a few low ΔM signal point having values as large as 15 %.

Table 8.8: Effect of the unclustered MET energy scale systematic uncertainty on the different MC samples and for each SR.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Single top	+8.5 -7.1	+18.4 -31.8	+34.8 -18.4
$t\bar{t}$	+5.4 -2.7	+22.9 -14.5	+32.2 -25.4
VV/VVV	+10.6 -6.4	+10.0 -11.2	+23.6 -16.2
$Z \rightarrow \ell\ell$	-9.8 +13.4	-17.3 +13.7	+34.6 -26.0
W + Jets	+54.9 -0	—	—

8.9 Lepton ID and Isolation

The scale factors that correct for the different efficiency in data and MC of the ID and isolation requirements are affected by uncertainties, listed in Table 5.3 and Table 5.4. The effect of this systematic uncertainty is estimated by varying the scale factors by their associated uncertainties.

These systematic uncertainties have an effect of 0.1 % or lower for all MC samples, signal and background.

8.10 Tau ID

The tau ID is not required to be corrected by a scale factor. However, this evaluation was based upon measurements, with associated uncertainties. Consequently, to account for this uncertainty, the weight of the events is varied by 6 %. Since all events have a tau, and the variation of the event weights is a constant number, this systematic uncertainty affects both signal and background MC by the same fixed amount of 6 %.

8.11 Data Driven Method

The fake and prompt rates, measured in Chapter 7, used to estimate the fake tau background contribution have a non-negligible statistical uncertainty. The statistical uncertainty on the rates is a source of systematic uncertainty for the data driven background estimation, see Eq. 7.5 and Eq. 7.6 as an example for an event with $\eta(\tau) = 0$. To estimate the effect of this uncertainty, the fake and prompt rates are independently varied by their statistical uncertainties. The effects of these uncertainties on the yields of the fake component of each SR are summarised in Table 8.9.

Table 8.9: Effect of the data driven systematic uncertainties on the estimated fake tau background for each SR.

Process	SR1 [%]	SR2 [%]	SR3 [%]
Fake Rate	+11.1 -9.8	+11.4 -9.9	+11.4 -10.0
Prompt Rate	+0.6 -0.6	+0.2 -0.2	+0.3 -0.3

The bias seen in the closure test of the fake tau estimation method should also be present as a source of systematic uncertainty, an effect of about 5 %. However, the uncertainty from the fake rate has double the value. In order to be economical and conservative, only the uncertainties from the fake rate and the prompt rate were considered since they provide the needed coverage.

Chapter 9

Conclusion

9.1 Final Results

The observed data and predicted SM background yields in each of the three SR are consistent with each other, see Table 7.2. Thus, no excess of events is observed, as is expected if events where the stau is produced were to be present. With no hint of discovery, a logical next step is to set limits on the cross section of the signal process, in order to extract as much information as possible. Since an SMS scenario was used to generate the signal events, the limit obtained when using these signal samples is on the $\sigma \times \text{BR}$ of any process consistent with the particles introduced in the SMS scenario. For this analysis, this corresponds to a limit on the $\sigma \times \text{BR}$ of any process with stau-like particles which are pair produced and decay to a τ and an undetected particle.

For the purpose of defining confidence intervals on the $\sigma \times \text{BR}$, the modified frequentist approach (CL_s) [94, 106] is employed and a simple “cut and count” analysis is performed. The expected event yield for each mass point is parameterised as Equation 9.1, where s (b) is the expected signal (background) yield for that mass point and is assumed to depend on some nuisance parameters $\vec{\theta}$. The signal yield is normalised to a cross section of 1 pb such that the limit on the *signal strength modifier* (μ) can be interpreted as a limit on $\sigma \times \text{BR}$.

$$v(\mu, \vec{\theta}) = \mu s(\vec{\theta}) + b(\vec{\theta}) \quad (9.1)$$

The probability to observe n events with given an expected yield of ν , is given by:

$$Poisson(n, \nu) = \frac{\nu^n}{n!} \exp(-\nu) \quad (9.2)$$

With this parameterisation of the expected event yield, each source of systematic uncertainty is associated with a nuisance parameter. The nuisance parameters are constrained by auxiliary measurements, see Chapter 8, that restrict their values with certain confidence intervals. Uncertainties which correspond to a scaling of the signal and background yields, such as the luminosity uncertainty and efficiency uncertainties, are modelled as a nuisance parameter with a Log-normal distribution, Equation 9.3. Where k is defined as $k = 1 + \epsilon$, with ϵ being the relative scale of the uncertainty.

$$\rho(\theta|\hat{\theta}) = \frac{1}{\sqrt{2\pi \ln k}} \exp\left(-\frac{(\ln \theta/\hat{\theta})^2}{2(\ln k)^2}\right) \frac{1}{\theta} \quad (9.3)$$

Uncertainties that result from counting a number of events (i.e. that are statistical in origin), such as an uncertainty related to the number of events in a CR, are modelled as a nuisance parameter with a gamma distribution, Equation 9.4. Where N is the observed yield in the CR and n is the expected yield extrapolated with $n = N \cdot \alpha$.

$$\rho(n|N) = \frac{1}{\alpha} \frac{\left(\frac{n}{\alpha}\right)^N}{N!} \exp\left(-\frac{n}{\alpha}\right) \quad (9.4)$$

The likelihood of observing n events (data), considering all of the above, is modelled as:

$$L(\text{data}|\mu, \vec{\theta}) = Poisson(n, \nu(\mu, \vec{\theta})) \cdot p(\hat{\theta}, \vec{\theta}) \quad (9.5)$$

$$= \frac{(\mu s(\vec{\theta}) + b(\vec{\theta}))^n}{n!} e^{-(\mu s(\vec{\theta}) + b(\vec{\theta}))} \cdot p(\hat{\theta}, \vec{\theta}) \quad (9.6)$$

Given L , a test statistic constructed with the profile likelihood ratio is defined as Equation 9.7. Where $\vec{\theta}_\mu$ is the set of nuisance parameters which maximise the likelihood function for a fixed value of μ and $\hat{\mu}$ and $\hat{\vec{\theta}}$ are the values for the signal strength and nuisance parameters that result in the global maximum of the likelihood function. The constraint $\hat{\mu} \leq \mu$ forces the test statistic to give one sided confidence intervals while the constraint $\hat{\mu} \geq 0$ has a physical origin, which is requiring the signal cross-section to be non-negative.

$$q_\mu = -2 \ln \frac{L(\text{data}|\mu, \vec{\theta}_\mu)}{L(\text{data}|\hat{\mu}, \hat{\vec{\theta}})}, \text{ constrained by } 0 \leq \hat{\mu} \leq \mu \quad (9.7)$$

To establish arbitrary confidence intervals on μ the sampling distribution of q_μ , $f(q_\mu|\mu's + b)$, is needed as a function of μ' . The construction of the sampling distribution can be done by generating pseudo-data with Monte Carlo techniques or, as an alternative approach, based on an asymptotic formula for q_μ [95] which is valid in the large sample limit. Given an observed test statistic, q_μ^{obs} , the size and the power of the test are defined as:

$$p_\mu = P(q_\mu > q_\mu^{obs} | \mu s + b) = \int_{q_\mu^{obs}}^{\infty} f(q_\mu | \mu s + b) dq_\mu \quad (9.8)$$

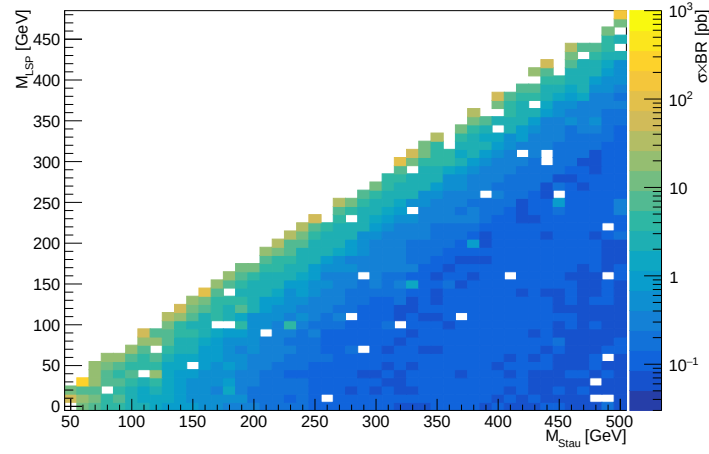
$$1 - p_b = P(q_\mu > q_\mu^{obs} | b) = \int_{q_\mu^{obs}}^{\infty} f(q_\mu | b) dq_\mu \quad (9.9)$$

The two values are combined to obtain the CL_s value for a given μ , Equation 9.10. The signal strength modifier, μ , is said to be excluded at a confidence level $1 - \alpha$ if CL_s is equal to α .

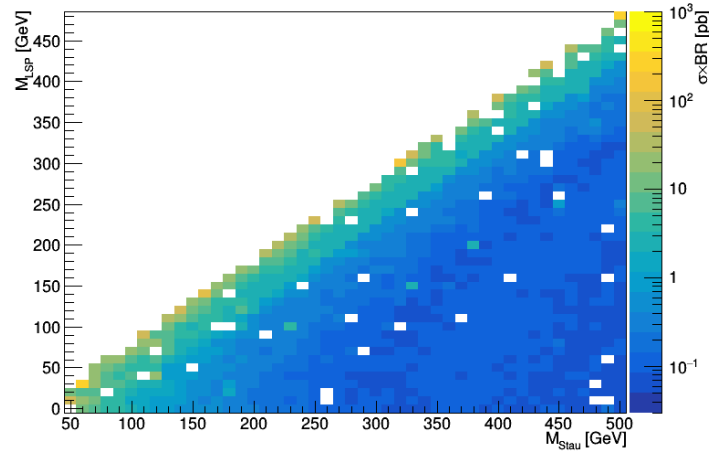
$$CL_s(\mu) = \frac{p_\mu}{1 - p_b} \quad (9.10)$$

The CL_s method, as well as other statistical methods, is implemented in the ‘‘Higgs Combination Tool’’ [107], *combine* for short, developed for the 2012 Higgs boson discovery, which is the tool that was used for this work. For each signal mass point the expected signal yield, expected background yields and observed data are obtained and passed to *combine* for further processing, accompanied by all the systematic uncertainties, n.b. the background yields and observed data are the same for all signal mass points within the same SR which is characterised by a range of ΔM .

The result from processing with the *combine* tool is the CL_s upper limit on the $\sigma \times BR$ at the 95 % confidence level for each signal point. The results were collated and are shown in Figure 9.1. The expected upper limit on the $\sigma \times BR$ is obtained by considering only the expected background yield and is the result expected in the absence of signal. The observed upper limit on the $\sigma \times BR$ is obtained by taking into account the observed data yield. Given that the expected background yield and observed data yield are consistent in the three SR, it is not surprising that the expected and observed upper limits on the $\sigma \times BR$ are compatible with each other as well. Since the properties of the signal events are expected to depend primarily on the ΔM (as a first order effect), it is also expected that the upper limit will also only depend on this parameter. This effect is clearly seen as bands of similar value travelling from bottom left to top right, where an upper limit of $\mathcal{O}(10)$ is seen for low ΔM signal points and the limit decreases as ΔM increases.



(a) Expected Limit



(b) Observed Limit

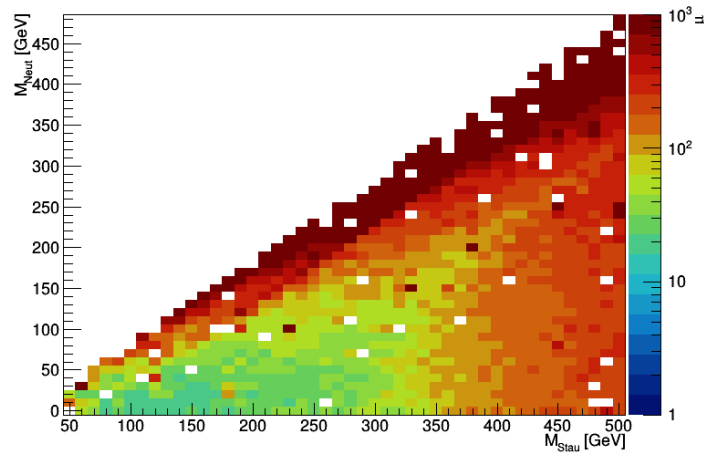
Figure 9.1: Expected and observed upper limit on $\sigma \times \text{BR}$ as a function of $M_{\tilde{\tau}}$ and M_{LSP} . The upper limit is computed with the CL_s method at 95 % confidence level. The expected limit is the expected result in the absence of signal. The observed limit is the observed upper limit on $\sigma \times \text{BR}$.

A few of the signal points have no limit set, several factors contributed to this fact. The first of which is the limited statistics of the simulated MC signal events, which combined with the selection cuts lead to some of the points not having any events passing the full selection. Other issues are linked to the *combine* tool, although not a problem with the tool itself, the algorithm was not able to converge to a value in a reasonable amount of time. In these situations, no value for the upper limit is reported.

It is also interesting to interpret the above limits within the pMSSM in the situation where

the stau is the Next to Lightest Supersymmetric Particle (NLSP) and the neutralino the LSP. If the stau is the NLSP, it can only decay to the LSP, consequently the branching ratio, BR, is equal to 1. In this interpretation the data is modelled with the formula: $N = B + \mu' S$, where N is the expected yield, B is the predicted background yield and S the predicted signal yield, correctly normalised to the theoretical cross section of stau pair production. The upper limits on $\sigma \times \text{BR}$ are thus reinterpreted into upper limits on the signal strength, μ' . This makes it evident whether the stau, as the NLSP, can be excluded for any of the signal points.

In order to reinterpret the upper limits on $\sigma \times \text{BR}$ into upper limits on μ , the reference CMS cross sections [100] for slepton pair production are taken, which depend solely on the stau mass and do not depend on the assumed SUSY parameters. For each signal point, the upper limit on $\sigma \times \text{BR}$ is then divided by the corresponding reference cross section, resulting in an upper limit on the signal strength for each signal point, Figure 9.2. It is expected that, in this plot, any point that has been excluded by these results will have a signal strength below 1. This interpretation should be taken with care since it is not as model independent as the upper limits on $\sigma \times \text{BR}$. In this interpretation there is the implicit assumption that $\text{BR} = 1$ and that there is no intermediate new particle whose mass is below $2M_{\tilde{\tau}}$.



(a) Observed

Figure 9.2: Observed upper limit on the signal strength, μ , as a function of $M_{\tilde{\tau}}$ and M_{Neut} . The limit is calculated from the upper limit on the $\sigma \times \text{BR}$ by taking the cross section of stau production assuming the stau is the NLSP. Points that are excluded with the current dataset, under this assumption, are expected to have a signal strength below 1.

From Figure 9.2 it can be seen that, with the current analysis and processed data, it is not possible to exclude any of the signal points. The points with the best (i.e. lowest) upper limit on the signal strength have a value $\mathcal{O}(10)$ and are located at low M_{Neut} and with $M_{\tilde{\tau}}$ between 70 GeV and 250 GeV.

The main result of this work is summarised in Figure 9.1 where limits on the $\sigma \times \text{BR}$ of any process with stau-like particles which are pair produced and decay to a τ and an undetected particle are set.

9.2 Achievements

Although the work here presented is of the sole responsibility of the author, this work was performed in coordination with the Institute for Research in Fundamental Sciences (IPM) group of Tehran, where a sustained effort was made to have a common object identification and base event selection. This effort resulted in the base selection in the publication [33].

Taking into account Figure 9.2 it is clear that within the considered parameter space of pMSSM, no signal points are excluded. However, it should be noted that at the time of the writing of this thesis no published results from CMS on the stau production were available. Thus, the results from Figure 9.1 are considered the main result from this work, whereby limits, as model independent as possible, are set on the $\sigma \times \text{BR}$ of any process with stau-like particles which are pair produced and decay to a τ and an undetected particle.

The work for this thesis successfully implemented a new data-driven background estimation method for fake taus and was among one of the first analysis in CMS to employ the Deconstructed M_T variables, despite not being represented in the final set of selected analysis cuts. This work also successfully implemented an analysis with different selection cuts for different ΔM regions, thus resulting in a more efficient and targeted selection across the $M_{\bar{\tau}}, M_{\text{LSP}}$ plane. Furthermore, the selection was optimised using a FOM procedure, a quantitative procedure with repeatable results, thus not depending upon qualitative observations.

The results of this work should be compared to the recent results from CMS in publication [33]. In general, the results of publication [33] show lower upper limits on the cross section of stau pair production; however it should be noted that the results of this publication use only the hadronic final state for the stau pair production scenario. The hadronic final state is favoured by an extremely low $W + \text{Jets}$ contribution to the background, resulting in better limits on the cross section. Thus, the final result is marginally improved with the introduction of the semi-hadronic channels, explaining why the semi-hadronic final state was not considered for the final publication [33]. A direct comparison between the work of this thesis and that of the paper is thus not possible, since the results for the semi-hadronic channel are not shown for the stau pair production scenario. However, this work is expected to lead to better results in a direct comparison with the same final state of [33] since a ΔM dependent selection and a robust data-

driven background estimation were employed.

It should also be noted that the code for this analysis is embedded within an analysis framework (the $2\ell 2\nu$ framework), the framework provides a common nTuple production code and object wrapper functions. However, the full analysis code had to be written from scratch, although the process is simplified by the framework. This process was valuable and useful since it helped provide a firm grasp on the knowledge of how to set up an analysis and provided a view on the inner workings of CMSSW which is many times lost when working with a production ready analysis where the work focuses on improving the already existing code.

9.3 Future Work

Given the time constraints for the elaboration of this work, not all aspects of the thesis were explored to their full extent, leaving possible avenues for future work. A first consideration is the signal MC simulation. For this analysis a sample with 10 000 events per signal mass point was used, however this proved to be close to the threshold of usability, see Figure 9.1 and Figure 9.2 where significant statistical fluctuations are evident. A new sample with increased statistics per mass point would prove useful. If the time dedicated to the simulation of events can not be increased, this could be reasonably achieved by reducing the range of the signal mass points where samples are generated. For instance the mass points with $M_{\tilde{\tau}} > 300 \text{ GeV}$ could most likely be excluded since their cross sections are so low, allowing the remaining mass points to have increased statistics.

As another example, it was observed that the di-hadronic channel, while more challenging given the pure hadronic final state, offers a significant improvement on the expected limits, see [33]. This is a result of the significantly reduced $W + \text{Jets}$ background:

- in the semi-leptonic channel, the $W + \text{Jets}$ background has proven to be very resilient to the analysis cuts. The W decays into a real lepton (electron or muon) and a jet fakes a tau
- in the di-hadronic channel, for $W + \text{Jets}$ to pass the event selection two hadronic taus must be reconstructed. The W decays to a τ in only $\sim 10 \%$ of the cases of which only 65% decay hadronically, in which situation a jet must fake a tau. In all remaining situations,

W + Jets events can only pass the selection criteria if two jets fake a tau. In this way, the W + Jets background is significantly reduced with respect to the semi-leptonic channel

Consequently, the inclusion of the di-hadronic channel in this analysis is expected to bring a significant improvement to the final results.

The Deconstructed M_T and the $M_{SV \text{ Fit}}$ variables were not present in the final set of analysis cuts. However, it was expected that these variables would be among the most powerful to discriminate signal from some of the backgrounds. The $M_{SV \text{ Fit}}$ variable has a few parameters to tune its performance, which were not able to be fully explored. For the Deconstructed M_T variables, a more in depth study of the correlations between the two variables and with $\cancel{E}_T$ and M_T is needed to better exploit these variables. For instance, consider Figure 6.10 a non-linear cut on the $(\cos \Phi_{\ell-\cancel{E}_T}, \mathcal{Q}_{80}(\ell))$ plane should perform better than a cut on the $\mathcal{Q}_{80}(\ell) + \cos \Phi_{\ell-\cancel{E}_T}$ variable.

During the initial part of the project, the author had the opportunity to work with MVA in the context of the Higgs analysis. MVAs excel at exploiting differences in correlations of variables between signal and background. Employing an MVA technique for this analysis would most likely provide a significant improvement to the final result.

As a final remark, most of this work was developed during the long shutdown of the LHC and used the latest data available from the CMS collaboration, i.e. the 8 TeV data from 2012. The LHC has since started operation at a new energy and is well on track to recording an even larger integrated luminosity, updating the analysis to run on the new data is another path for future development of this work.

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