Search for supersymmetry in the single lepton final state in 13 TeV pp collisions with the CMS experiment

Ece Asilar

Ausgeführt am Atominstitut der Technischen Universität Wien
in Verbindung mit dem Institut für Hochenergiephysik (HEPHY)
der Österreichischen Akademie der Wissenschaften

Doctor of Philosophy

August 2017

This thesis is dedicated to
someone
for some special reason

Acknowledgements

Robert Schöfbeck

Wolfgang Adam

Jochen

Office colleagues: Daniel Spitzbart, Navid k. Rad, Federico Ambrogy, Matheusz Zarucki, David Handle..

Other HEPHY people: Erica, Ilse, Johannes, WW, Suchita

LHC, and CMS

SUSY group convenors

To all POG

ACDVF People: Clauida ...

Guido van Rossum for python :)

Bram Moolenaar for vim :)

Social Life Friends, mom brother, Gökhan ...

Final but not least, FWF and DKPI

Abstract

FIXME Will be written at the end of the entire thesis.

Contents

Introduction **5**

1 Supersymmetry: as an extension of Standard Model **5**

1.1 Standard Model 5

1.1.1 Standard Model: Particle Content 5

1.1.2 Standard Model: from the quantum field theory window . . . 8

1.1.3 Standard Model: Experimental results 12

1.1.4 Shortcomings of the Standard Model 13

1.2 Supersymmetry as a solution 15

1.2.1 Algebra of Supersymmetry 17

1.2.2 Minimal Supersymmetric Standard Model 18

1.2.3 Simplified Models 21

1.2.4 Short History of SUSY searches at colliders 22

2 Experimental Setup **26**

2.1 The LargeHadron Collider at CERN 26

2.1.1 The CERN accelerator complex 27

2.1.2 The future of the LHC 28

2.2 The Compact Muon Solenoid experiment at the LHC 29

2.2.1 Superconducting Magnet 30

2.2.2 Tracker 31

2.2.3 Electromagnetic Calorimeter 32

2.2.4 Hadron Calorimeter 33

2.2.5 Muon System 34

2.2.6 Trigger and Data Acquisition Systems 35

2.2.7 Data Tiers of CMS 36

2.2.8 Luminosity measurement 37

2.2.9 Future of CMS 38

2.3 Event simulation 39

3 Object reconstruction and identification 40

3.1 Particle-Flow algorithm 40

3.2 Physics Object reconstruction 41

3.2.1 Primery vertices 41

3.2.2 Electrons 42

3.2.3 Muons 43

3.2.4 Jets 44

3.2.5 b tagged Jets 44

3.2.6 Missing transverse energy 45

4 Event Selection 47

4.1 SUSY signature 47

4.2 Samples 48

4.2.1 Data Samples 48

4.2.2 MC Samples 49

4.3 Baseline selection 50

5 Design of Search Regions 54

5.1 Signal Regions 55

5.1.1 Background and Signal composition in MB SR 55

5.2 Control Regions 56

5.2.1 Background composition in MB CR and SB SR/CR 56

5.2.2 Signal contamination in MB CR and SB SR/CR 58

6 Background Estimation 60

6.1 R_{CS} method 60

6.1.1 R_{CS} method in ttbar events 62

6.1.2 R_{CS} method in w jets events 67

6.2 QCD background estimation 71

6.3 Validation of the background estimation 72

7 Systematic Uncertainties 74

7.1 Systematic Uncertainties on background estimation 74

7.1.1 Theoratical Uncertainties 74

7.1.2 Experimental Uncertainties 75

7.2 Systematic Uncertainties on signal modelling 79

8 Results and Interpretation **82**
8.1 Results of background predition 82
8.2 Limit settings 84
8.3 Interpretation 86
8.4 Comparison to other results 87

9 Conclusion **90**

A Appendix **92**

Bibliography **96**

List of Figures

1.1 All fundamental particles of the standard model, the gauge and Higgs bosons are shown in the diagram. The electric charge, spin and mass (or limit for neutrinos) are given in the corners of the boxes [5]. . . 6
1.2 An overview of characteristics of the experimental tests of the SM is shown in the table. The information is mainly collected from "the Electroweak model and constraints on new physics" section in PDG2017 [5] . Additionally further information on g-2 measurements can be found from the paper published by Muon G-2 experiment [19]. . . . 12
1.3 The running couplings of U(1), SU(2), SU(3) is denoted by α_1, α_2, α_3 respectively. The figure represents the evolution of inverse of couplings with energy scale, for (a) non-supersymmetric SU(5) and (b) supersymmetric SU(5). The figure is taken from [29] pg. 282. 14
1.4 One-loop quantum corrections to the Higgs squared mass parameter m_H^2, due to (left) a Dirac fermion f, and (right) a scalar S [4] p.g. 3 . 15
1.5 Best exclusion limits on sparticle masses from searches for SUSY using SMS by ATLAS (top) and CMS (bottom) collaborations [39, 40]. In the upper plot, the green bars represent the 7-8 TeV results while the blue bars are summarizing the 13 TeV results. In the lower plot, the orange bars represent the 7-8 TeV results while the blue bars are summarizing the 13 TeV results. 23
1.6 Feynman Diagrams showing the gluiono pair prodution. SUSY particles are shown in blue. 24
1.7 left: Cross sections of gluino pair production for four different mass points are given as a function of the center of mass energy. right: Cross section of gluino pair production at 13 TeV center of mass energy is given as a function of gluino mass. [37] 24
1.8 Cross section of SM processes as a function of center of energy. [38] 25

4.1 Diagrams showing the simplified models T1tttt and T5qqqqWW. . . 47

8.1 left: right: 87

Abbreviations

ALICE A Large Ion Collider Experiment

ATLAS A Toroidal LHC Apparatus

BSM Beyond the Standard Model

CERN European Organization for Nuclear Research

CM Center of Mass

CMS Compact Muon Solenoid experiment

CMSSW CMS SoftWare framework

DAQ Data Acquisition

ECAL Electromagnetic Calorimeter

EWK Electroweak Theory

GUT Grand Unified Theory

HCAL Hadron Calorimeter

HF Hadron Calorimeter (Forward)

LHC Large Hadron Collider

LHCb the Large Hadron Collider Beauty Experiment

LINAC Linear particle Accelerator

PDG Particle Data Group

QED Quantum Electrodynamics

QFT Quantum Field Theory

SM Standard Model

SUSY Supersymmetry

Introduction

FIXME: To be written in a nicer way, at the end...

Organisation of the thesis:

¿ itemize the chapters

Chapter 1

Supersymmetry: as an extension of Standard Model

This chapter commences with a discussion of the Standard Model (SM) of particle physics. After presenting a brief theoretical overview, its success in explaining the majority of the experimental results will be explained. We will then discuss the missing aspects of the SM as a complete theory. The second part of this chapter is dedicated to the theory of supersymmetry (SUSY), as one of the possible theories beyond the SM (BSM). The SUSY discussion will include the framework of simplified model spectra (SMS): The results presented in this thesis are interpreted with in SMS.

1.1 Standard Model

The content of this chapter is based mainly on various textbooks on the standard model and quantum field theory [1–3].

1.1.1 Standard Model: Particle Content

The SM describes fundamental particles and their interactions. In this respect, the SM attempts to explain all physical phenomena with the exception of gravity, which has an insignificant effect on subatomic particles. There are three known fundamental interactions or forces in the SM: the electromagnetic, the weak and the strong forces. The interactions are mediated by force carrier particles called bosons. Bosons are quanta of gauge fields describing aforementioned interactions. The electromagnetic interactions are carried by the photon while Z^0 and $W^{\pm}$ bosons are responsible for the weak interactions. In the SM framework, these two seemingly different forces can be unified through the socalled electroweak theory. For the strong interactions, the force carrier bosons are called gluons and they are massless. Bosons are integer spin particles obeying the Bose-Einstein statistics.

The elementary particles that constitute the matter we know are called fermions. Obeying the Fermi-Dirac statistics, fermions are particles with half spin. Fermions incorporate quarks (with color charge) and leptons (without color charge). According to the SM, fermions can be categorized as three families or generations, which are very similar to each other in terms of characteristics of the particles. The first family represents the substance we see around us, the rest can be observed in the colliders or nuclear reactors or in the atmospheric showers.

Figure 1.1 shows the particle content of the standard model [1]. All are experimentally confirmed.

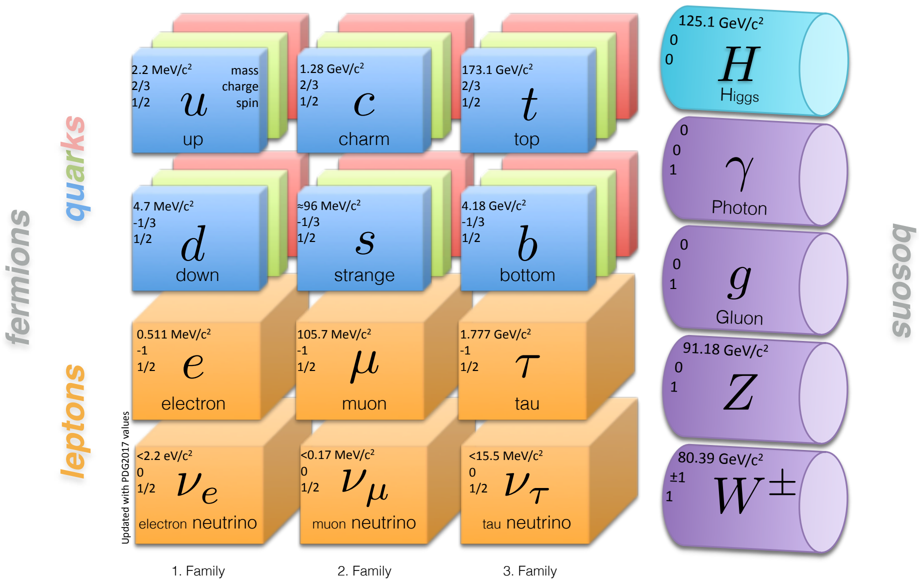

Figure 1.1: All fundamental particles of the standard model, the gauge and Higgs bosons are shown in the diagram. The electric charge, spin and mass (or limit for neutrinos) are given in the corners of the boxes [5].

The range of these forces is inversely proportional to their masses. Photon is massless so the range of electromagnetism is infinite while the range of weak force is constrained by the large mass of corresponding gauge bosons. This mechanism is more complicated in the strong force case; it will be discussed in the next paragraphs.

[1]In this thesis, the matter and anti-matter particles are considered as trivially coupled

The theory that aims to model strong force is called quantum chromodynamics (QCD). In Greek, the word $\chi\rho\hat{\omega}\mu\alpha$ chroma means color.

After observation of bound states such as $\Delta^{++}_{(uuu)}$, violating Pauli's exclusion principle, it is suggested that the quarks possess three color (red , blue, green) charges. The interaction between quarks occurs through gluons. The fact that gluons have color charge make them interact with themselves as well. Accordingly, QCD also admits bound states whose valence constituents are all gluons, the nonabelian gauge bosons of QCD. These additional mesons are one of the most important predictions of the SM and they are known as gluonia or glueballs. However, so far they have not been observed experimentally. For further reading, [17, 18] can be consulted. QCD has two important postulates.

Confinement: In nature we observe only color singlet (colorless) particles. The particles with color charges, i.e. quarks and gluons, immediately coalesce to form colorless bound states (hadrons) given an attempt to separate them. This is also known as hadronization. As a result of this phenomenon, despite the fact that gluons are massless, the range of the strong force is confined. Moreover, in experiments a shower of color-neutral particles [2] is observed instead of a single quark.

Asymptotic freedom: The interaction of quarks becomes asymptotically weaker as the energy increases or as the distance decreases. In other words, the strong coupling constant α_s increases with distance, but inside a meson or a baryon, they act as free particles. This asymptotic freedom helps to build an approximate model of QCD interactions [3]; otherwise QCD calculations are extremely complicated.

The interaction of charged particles with energies of the order of the $W^{\pm}$ boson mass can be described by quantum electrodynamics (QED). The symmetry group of the electromagnetic theory is a unitary transformation $U(1)_{EM}$; there is only a massless field associated to photon. The β-decay, where the neutron decays to a proton, electron and corresponding antineutrino through the W boson, explained by Enrico Fermi by an effective theory [7]. The theory was based on $SU(2)_L$ symmetry group. The subscript L stands for the left handed particles. Due to lack of right handed neutrinos in nature, only left handed fermions contribute to the weak interaction. In 1960s, Glashow-Salam-Weinberg proposed a unified theory of the QED and weak interactions [8–10]. After unification of electric and magnetic interactions by Maxwell, the unification of electromagnetic and weak interactions is an encouraging step towards the grand unified theories (GUT). In the formulation of the SM, initially all

[2] is called as jet

[3] perturbative QCD

the mass of particles are 0. Brout, Englert [11] and Higgs [12] solved the problem by implementing the electroweak symmetry breaking (EWSB), called BEH or only Higgs mechanism. This mechanism introduces an additonal scalar field, Higgs field. The SM Higgs boson is a Goldstone boson with mass given by $m_H = \sqrt{2\lambda}\nu$ [4]. The massive bosons of weak interaction also gain their mass through a non-zero vacuum expectation value (VEV) while for fermions direct Yukawa couplings to the Higgs boson provides their mass. Particles interact with the Higgs field at a different strength. Depending on the coupling between the Higgs field and the particle, its mass can be large or small. Photons, having zero rest mass, do not couple to Higgs field. In the absence of the Higgs field, all the particles would be massless.

The SM particle content and their interactions were briefly covered in this section. The chapter will continue with formulation of the SM.

1.1.2 Standard Model: from the quantum field theory window

In particle mechanics, a Lagrangian [5] is a function of the coordinates, and their time derivatives. In field theory technically a Lagrangian density is used and it is a function of the fields, ϕ_i and their position and time derivatives, $\partial_\mu \phi_i$. In relativistic theory, space and time coordinates are treated in the same way. The Lagrangian plays an important role in physics because the form of the Lagrangian is invariant under symmetries. Given a Lagrangian the equation of motion from the Euler-Lagrange equations can be derived by considering the least action principle, i.e requiring that the variation of action is zero [6]. Then, the Euler-Lagrange equation in a simple way can be written as follows:

$$\partial_\mu \frac{\partial L}{\partial(\partial_\mu \phi_i)} = \frac{\partial L}{\partial \phi_i} \tag{1.1}$$

The SM is a relativistic quantum field theory (QFT). Its Lagrangian is built on a global Poincare symmetry, which implies symmetry under translation, rotation and boost. According to Noether's theorem [30], each continuous symmetry is accompanied by a conservation law. The Poincaré symmetry points to conservation of energy, momentum, and angular momentum. The gauge group of the SM, which is a local symmetry, is described as:

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \tag{1.2}$$

[4] $\nu = (\sqrt{2}G_F)^{-\frac{1}{2}} \approx$246GeV, G_F is Fermi Coupling

[5] L=T-V, T is the kinetic energy of the particle in a potential V.

[6] $\delta S = 0$, where $S = \int L dt$.

where $SU(3)_C$,$SU(2)_L$ and $U(1)_Y$ are representing the gauge groups of the strong, weak and electromagnetic forces respectively. The subscript C refers color, L refers to left-handedness, and Y refers hypercharge. The conserved quantities, which correspond to the symmetry in the Equation 1.2, are color charge, weak isospin, electric charge, and weak hypercharge.

The rank of the group, i.e. the number of generators of the fields is at the same time the number of mediators, gauge bosons, of the corresponding vector field. For instance, the $SU(3)_C$ group has eight [7] generators thus it has eight vector fields which are called the gluon fields (G_μ). Following the same argument, the $SU(2)_L$ group has three vector fields, (W^1_μ, W^2_μ, and W^3_μ) and the $U(1)_Y$ group has only one vector field, (B_μ).

In addition, the EWSB, or in other words the Higgs mechanism, leads to an additional scalar field, which will be denoted as ϕ in upcoming equations. The SM Lagrangian resides two components: L_{QCD} and L_{EWK}. The first one is for strong interaction while the latter explains electroweak interaction.

- **Strong interaction**

As mentioned in the previous section, the theory that aims to model strong force is QCD. The QCD Lagrangian is given by:

$$L_{QCD} = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi + g_s \bar{\Psi} T_a G^a_\mu \gamma^\mu \Psi - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \tag{1.3}$$

where Ψ are the quark fields, γ^μ are the Dirac matrices, g_s is the strong coupling constant, T_a are Gell-Mann matrices and $G^a_{\mu\nu} \equiv \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f_{abc} G^b_\mu G^c_\nu$ [8]. When constructing the Lagrangian, a covariant derivative is introduced. This way, the terms stay invariant under gauge transformations. The covariant derivative for QCD is defined as: $D_\mu = \partial_\mu - i g_s T_a G^a_\mu$.

[7] $3^2 - 1$

[8] f_{abc} are the structure constants

- **Electroweak interaction**

The electroweak Lagrangian, L_{EWK}, can be investigated in 4 pieces:

$$L_{EWK} = L_{Gauge} + L_{Fermion} + L_{Higgs} + L_{Yukawa} \tag{1.4}$$

The covariant derivative that leaves this Lagrangian invariant under transformations is described as: $D_\mu = \partial_\mu - igW^a_\mu \tau_a - ig' B_\mu Y_W$ where g and g' are the the gauge couplings of the $SU(2)_L$ and $U(1)_Y$ respectively. τ_a are the Pauli matrices. Y_W is the weak hypercharge defined as $2(Q - I_3)$. Q is the electric charge and I_3 is the third component of the weak isospin.

The first term in Equation 1.4 is defining the interaction between gauge bosons and it can be written as:

$$L_{Gauge} = -\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \tag{1.5}$$

where $W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g\epsilon^{abc} W^b_\mu W^c_\nu$, $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$.

The second term in Equation 1.4 stands for the fermion kinetic term:

$$L_{Fermion} = i\bar{\Psi}\gamma^\mu D_\mu \Psi \tag{1.6}$$

The third term is the Higgs Lagrangian, describing the Higgs field and its self-interaction:

$$L_{Higgs} = |D_\mu \phi|^2 - \lambda(|\phi|^2 - \frac{\nu^2}{2})^2 \tag{1.7}$$

where λ is the Higgs self-coupling strength. According to BEH mechanism, there is a scalar potential, which permeates the whole universe:

$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2 \tag{1.8}$$

, with the Higgs field Φ with weak hypercharge $Y = 1$, and a self-interacting SU(2) complex doublet in Equation 1.9 [9].

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ \phi^0 + ia^0 \end{pmatrix} \tag{1.9}$$

If the quadratic term is negative, the neutral element of the scalar doublet gains a non-zero vacuum expectation value (VEV) stimulating the spontaneous breaking of the SM gauge symmetry [5].

[9] ϕ^0:CP-even,a^0:CP-odd neutral component. ϕ^+:complex charged component

The final term in 1.4 is the Lagrangian of the Yukawa interaction between the Higgs field and the fermion fields (quarks and leptons). The L_{Yukawa} produces fermion masses through spontaneous symmetry breaking. It can be written in the most general way [31]:

$$L_{Yukawa} = -\epsilon^{ij}\phi_i l_{jI} y_{Ij}\bar{e}_j - \epsilon^{ij}\phi_i q_{\alpha jI} y'_{ij}\bar{d}^{\alpha}_j - \phi^{\dagger i} q_{\alpha iI} y''_{Ij}\bar{u}^{\alpha}_j + h.c \tag{1.10}$$

After SSB the neutral and charged current interactions between fermions and gauge bosons can be derived from the L_{EWK}. In order to extract the actual mass terms, a switch between basis with W^a ,B fields and a basis with mass eigenstates is required:

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} cos\theta_W & sin\theta_W \\ -sin\theta_W & cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^3 \end{pmatrix} \tag{1.11}$$

$$W^{\pm} = W^1 + iW^2 \tag{1.12}$$

The θ_W term is the EWK mixing angle or Weinberg angle. This quantity can be measured experimentally as well.

In this section, the formulation of the Lagrangian which explains the SM particle content disscussed in section 1.1.1 was briefly introduced. A more comprehensive and pedagogical formulation of the SM can be found in [5, 31]. The next section will continue with experimental status of the SM.

1.1.3 Standard Model: Experimental results

The entire SM particle content was discovered up to now. The fermionic substance was completed with the discovery of the top quark by the CDF and DØ experiments in 1995 [13, 14]. In 2012, a particle, at a mass of approximately 125 GeV, which has similar features to the Higgs boson predicted by SM was discovered by ATLAS and CMS experiments [15, 16]. Further studies with a much larger data set have provided precise measurements on its mass, production and decay rates. Results present consistency with the SM prediction, within errors. With this new discovery, the bosonic content of the SM is completed.

Testing the SM is not limited to collider experiments. In fact due to the technological constraints, probing the energies much larger than TeV scale is not possible with collider experiments; this much high energy can only be studied by cosmological experiments. In addition to cosmological and collider experiments, there are smaller scale Desktop experiments where particle properties can be further investigated with high precision in low energies (<GeV). In the Figure 1.2, an overview of the different

Experiment type	**Colliders**	**Smaller scale**	**Cosmology**
Energy	High/Low energy (≤13 TeV)	Low energy (≤ GeV)	Very high energy (>> TeV)
High precision	✓	✓	✗
Measurement	• Particle content • Electro weak unification	• Anomalous magnetic moments • Electric dipole moments • Mass measurements	• Dark matter • Dark energy
Consistency with the SM	Up to now, observations are consistent with the SM	g-2 was found to be 3 sigma away from the theoretical value	The SM does not have a dark matter candidate

Figure 1.2: An overview of characteristics of the experimental tests of the SM is shown in the table. The information is mainly collected from "the Electroweak model and constraints on new physics" section in PDG2017 [5] . Additionally further information on g-2 measurements can be found from the paper published by Muon G-2 experiment [19].

types of experiments probing the SM can be seen. In addition to this, an example list of different kinds of measurements is also added to the table. The colors are making an analogy to the degree of the consistency of the measurements with the SM. Taking into account not all the colors are green, the SM has several shortcomings not only from the experimental but also from theoretical perspective. These shortcomings are the topic of the next section.

1.1.4 Shortcomings of the Standard Model

As mentioned in the previous section, no evidence of new physics beyond the SM physics has been found at LHC. Moreover, up to now the SM has successfully explained the subatomic world physics. So, why are we searching for what is beyond the SM?

- **Experimental reasons**

Lacking explanation of Gravity: Certainly, the observation of gravitational waves is one of the two most exciting discoveries of our century. The announcement was done by LIGO and Virgo collaborations on 11 Feb 2016 [20]. The observed waveform satisfies the predictions of general relativity [21]. However, unless the gravitational field is quantized, it is impossible for the SM to include gravity.

No Dark Matter candidate: In 1933, Zwicky observed an unseen mass by applying the Virial theorem to the Coma cluster. He introduced this unseen mass as Dark matter (DM), originally in German called *dunkle Materie* [22]. The evidence of the DM got stronger with the observations made by V. Rubin and K. Ford on the velocity curve of more than twenty spiral galaxies [23]. Moreover, the observations of anisotropies in the cosmic microwave background (CMB) further supported the existence of DM. The data provided by Planck experiment, successor of COBE [25] and WMAP [24] experiments, is in good agreement with the ΛCDM (Lambda cold dark matter) model [26]. This model postulates a dark energy dominated (68%) flat universe, with 5% baryonic matter and 27% dark matter. Therefore, given the SM does not provide a viable cold dark matter candidate [10], in fact the SM fails to explain 95% of our universe.

Massless neutrinos: The observation of neutrino oscillations [27, 28] implies that at least two of the neutrinos should have non zero mass [11]. Neutrino masses

[10] In this context, Neutrinos are hot (relativistic) particles

[11] The oscillation frequencies are proportional to the mass difference of the neutrino flavors. Therefore, only upper bounds can be measured.

can be included as an input to fermion Yukawa couplings, otherwise massless. However, even this input does not explain the observed mass differences between the generations.

- **Theoretical reasons**

Addition to the solid experimental reasons, the SM has also theoretical insufficiencies, which are mostly aesthetic concerns of theorists.

Grand Unification: The unification of forces has started with the integration of electric and magnetic forces into one electromagnetic force. Then it was followed by the unification of electromagnetic and weak forces into the electroweak interaction. At this point, it is inevitable that one expects the merge of electroweak and strong interactions. In fact, the running couplings of electroweak and strong forces, as seen in the Figure 1.3, meet at around 10^{16} GeV. Finally, even the unification of gravity with other fundamental forces is strongly encouraged.

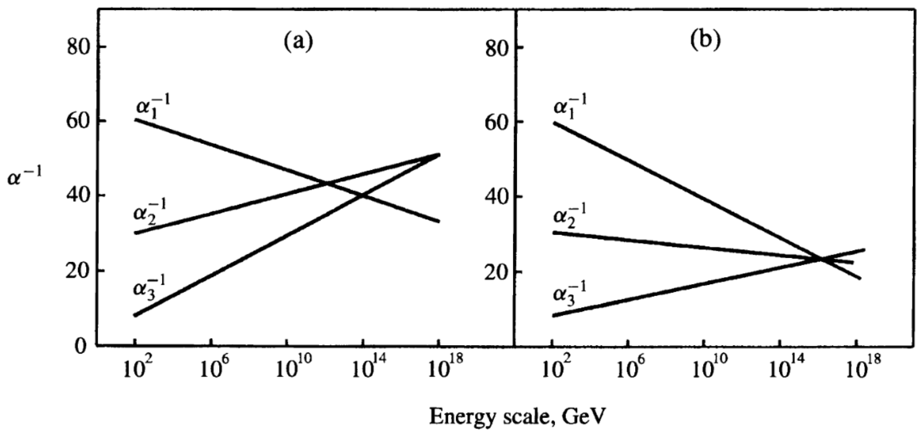

Figure 1.3: The running couplings of U(1), SU(2), SU(3) is denoted by α_1, α_2, α_3 respectively. The figure represents the evolution of inverse of couplings with energy scale, for (a) non-supersymmetric SU(5) and (b) supersymmetric SU(5). The figure is taken from [29] pg. 282.

Hierarchy problem: In the literature of particle physics, there are two kinds of hierarchy problems; the big and the little hierarchy problem. The first one is due to the huge difference between mass scale of weak forces (m_W) and gravity (Planck scale [12]). In fact, this is not a consistency problem but a naturalness problem. The latter,

[12]The Planck scale is the scale at which classical gravity theory is no longer valid but quantum gravity dominates. $M_P = 2.4\text{x}10^{18}$GeV

the little hierarchy problem, is a problem of how large m_H^2, in Eq.1.8, can get. It receives huge quantum corrections because Higgs boson,including itself, couples to all massive particles in the SM. This subject will be discussed carefully in the upcoming sections.

There are many Beyond the Standard Model (BSM) theories claiming to solve some of the aforementioned SM shortcomings. The candidate BSM theory must not belie the current observations; on the contrary it should predict them. Moreover, in order to be able to test the theory, it should also provide a phenomenological background. In a spectrum of BSM theories which satisfies these constraints, the Supersymmetric extensions of the SM are the most promising ones. This thesis focuses on a subgroup of these models, thus a relatively specified overview will be given in the following section.

Figure 1.4: One-loop quantum corrections to the Higgs squared mass parameter m_H^2, due to (left) a Dirac fermion f, and (right) a scalar S [4] p.g. 3

FIXME The rest of the document has not been crosschecked yet. FIXME

1.2 Supersymmetry as a solution

This chapter presents a brief summary of [4] in the context of this thesis search. When searching what is beyond the SM, a familiar concept, symmetry, helped again. A symmetry, which relates fermionic states to bosonic states, had already attracted physicists' attention in the first half of the twentieth century. It was in the 1970s; a theory of four-dimensional relativistic space-time (super)symmetry has emerged. This theory is known as Supersymmetry (SUSY). The supersymmetric transformation changes the spin angular momentum of the original SM fields by a factor of $\frac{1}{2}$ and this turns fermionic states into bosonic states, and vice versa. These additional partners are called superpartner. If these superpartners exist in TeV scale it can overcome several problems mentioned in section 1.1.4.
The existence of SUSY may lead to spectacular results that can be listed as follows:

Solving the hierarchy problem:
As mentioned in the previous section, Higgs boson couples to each massive SM fermion f through a Yukawa coupling λ_f. Therefore, the Higgs boson bare mass, the m^2 term in Equation 1.8, receives enormous quantum corrections. The one-loop radiative correction terms (see Figure 1.4 left) which are coming from Dirac fermions f are as follows:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + ... \tag{1.13}$$

where Λ_{UV} is an ultraviolet momentum cutoff, which is used to restrict the loop integral. The cutoff can be interpreted as the energy scale at which the new physics expected. Considering the top quark is the one with the largest mass among the SM fermions, the largest correction comes from it with $\lambda_f \approx 0.94$. If Λ_{UV} is of the order the Planck mass, then this correction to m_H^2 is around 30 orders of magnitude larger than the Higgs bare mass. In addition to the correction term given in Equation 1.13, a similar correction can be assumed from the heavy scalar particle S (see Figure 1.4 right) as:

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\Lambda_{UV}^2 + ... \tag{1.14}$$

where λ_S is the coupling strength between the scalar particle and the Higgs field. It should be noted that this time correction carries an opposite sign. In this way, the diverging terms can be eliminated if a scalar particle exist with $\lambda_S = \frac{1}{2}|\lambda_f|^2$.
SUSY overcomes the hierarchy problem by introducing the so-called superpartners, which possess the same quantum numbers with original fields except for the spin. As long as the masses of the superpartners are of the order O(TeV), SUSY can still be considered as natural. In order to achieve this, the SUSY breaking needs to be soft. This means that it remains a valid symmetry of the underlying laws of physics but is broken in the course of the evolution of the state of the universe.

Dark matter candidate:
The lower limit on the proton lifetime is set to 10^{30} years by experiments carried out in the water Cherenkov detector at Super Kamiokande in Japan [35]. This fact strongly suggests that the baryon number is conserved. Unlike the SM, in SUSY theories the baryon and lepton number conservations can be violated. In SUSY, to prevent proton decay, a new quantum number, called as R-parity is introduced:

$$R = (-1)^{3B+L+2S} \tag{1.15}$$

where B represents the baryon number, L is the lepton number, and S denotes the spin. All the SM particles have positive R-parity, while the superpartners have negative R-parity. Conservation of R-party entails that the SUSY particles can only be produced in pairs. Moreover, in SUSY, this conservation leads to a stable the lightest supersymmetric particle (LSP). LSP is neutral in terms of both electric and color charge. Thus it is one of the most viable cold dark matter candidates and it has great importance in this thesis. If it exists, it would appear as a high missing energy in the events observed by experiments. There are also R-party violating SUSY theories, but these are beyond the scope of this thesis.

Unification of gauge couplings:
Precise measurements of the running weak, strong and electromagnetic couplings performed at the Large Electron-Positron Collider (LEP) indicates that these couplings fail to unify at high energy (see Figure 1.3 a) [32, 33]. In [32], it is stated that the minimal supersymmetric standard model (MSSM) is the only possibility, without an intermediate mass scale. The MSSM can raise the scale of the unification by introducing a particle called the gluino, the spin half partner of the gluon. The gluino partially cancels the asymptotic freedom effect of the gluon itself [34]. The MSSM and its particle content will be explained in section 1.2.2.

Including gravity:
Even if it is not the subject of this thesis, it is worth mentioning that there is a SUSY model including gravity, namely supergravity. This model introduces a spin-2 massless gauge field, the graviton, which mediates gravity with its superpartner, the gravitino. Supergravity, like any other QFT of gravity, is also not renormalizable.

1.2.1 Algebra of Supersymmetry

As it is stated in the beginning of this chapter, a SUSY transformation turns a bosonic state into a fermionic state, and vice versa. SM particles and their superpartners constitute supermultiplets. For each of the chiral [13] SM fermions, there is a separate scalar partner and together they form chiral supermultiplets. The supersymmetric transformation operator Q can also be called as supercharge operator, can be read as:

$$Q\,|fermion\rangle = |boson\rangle \tag{1.16}$$

[13] left- and right- handed

$$Q\,|boson\rangle = |fermion\rangle\,. \tag{1.17}$$

In SUSY, the number of supercharges characterizes the theory. If there is only one supercharge then it is called a N=1 supersymmetry. If there are two supercharges then there is a N=2 supersymmetry and so on. For chiral fermions, generators Q and $Q^\dagger$ satisfy the commutation and anti-commutation relations:

$$\{Q, Q^\dagger\} = P^\mu\,,\ \{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0\,,\ [P^\mu, Q] = [P^\mu, Q^\dagger] = 0 \tag{1.18}$$

where $P^\mu = (H, \overrightarrow{p})$ stands for the spacetime momentum operator in which H is the Hamiltonian and $\overrightarrow{p}$ is the three-momentum operator. Similar to chiral supermultiplets, the SM gauge bosons together with their fermionic supersymmetric partners form gauge supermultiplets. The algebra in Equation 1.18 indicates that the partner and the superpartner states have the same mass. However, no scalar superpartners have been found yet, although it would be expected to detect low mass partners, like selectron, experimentally long ago. This indicates that the supersymmetry has to be broken and the superpartners have much larger mass.

1.2.2 Minimal Supersymmetric Standard Model

The minimal supersymmetric extension of the standard model (MSSM) is the only irreducible representation of the SUSY algebra (the aforementioned N=1 supersymmetry case). In other words, this is the model with the least number of additional particles and degrees of freedom. All other representations can be reduced to combinations of chiral and gauge supermultiplets. The MSSSM chiral supermultiplets are shown in the Table 1.1 while the gauge multiplets are listed in the Table 1.2. As in the table, all superpartners are represented by a version containing a tilde (~) of the original SM particle symbols. The scalar counterparts, are indicated by adding an "s" as initials to the SM fermion names (e.g. selectron) while the fermionic gauge superpartners are represented by appending "ino" (e.g gluino). The subscripts L and R of the sleptons show only the helicity of their SM partners.

In MSSM, there are two Higgs chiral supermultiplets. They are the cure of the gauge anomaly, in other words, they leave the action invariant under the supersymmetry transformation. Moreover, by the construction of SUSY, the Higgs doublet with hypercharge $Y = \frac{1}{2}$ is only able to give masses to the up-type quarks while the one with hypercharge $Y = -\frac{1}{2}$ gives masses to the down-type quarks and charged fermions. Therefore, the $SU(2)_L$ complex scalar fields with hypercharge $Y = \frac{1}{2}$ and $Y = -\frac{1}{2}$ can be denoted by H_u and H_d respectively. The half spin superpartners are

Names		Spin 0	Spin $\frac{1}{2}$	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L\ \tilde{d}_L)$	$(u_L\ d_L)$	($\mathbf{3}$, $\mathbf{2}$, $\frac{1}{6}$)
(x3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	($\bar{\mathbf{3}}$, $\mathbf{1}$, -$\frac{2}{3}$)
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	($\bar{\mathbf{3}}$, $\mathbf{1}$, $\frac{1}{3}$)
sleptons, leptons	L	$(\tilde{\nu}\ \tilde{e}_L)$	$(\nu\ e_L)$	($\mathbf{1}$, $\mathbf{2}$, -$\frac{1}{2}$)
(x3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	($\mathbf{1}$, $\mathbf{1}$, 1)
Higgs, higgsinos	H_u	$(H_u^+\ H_u^0)$	$(\tilde{H}_u^+\ \tilde{H}_u^0)$	($\mathbf{1}$, $\mathbf{2}$, +$\frac{1}{2}$)
	H_d	$(H_d^0\ H_d^-)$	$(\tilde{H}_d^0\ \tilde{H}_d^-)$	($\mathbf{1}$, $\mathbf{2}$, -$\frac{1}{2}$)

Table 1.1: Chiral supermultiplets of the MSSM

Names	Spin $\frac{1}{2}$	Spin 1	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
gluino, gluon	$\tilde{g}$	g	($\mathbf{8}$, $\mathbf{1}$, 0)
winos, W bosons	$\tilde{W}^\pm\ \ \tilde{W}^0$	$W^\pm\ \ W^0$	($\mathbf{1}$, $\mathbf{3}$, 0)
bino, B boson	$\tilde{B}^0$	B^0	($\mathbf{1}$, $\mathbf{1}$, 0)

Table 1.2: Gauge supermultiplets of the MSSM

called higgsinos and represented as $\tilde{H}_u$ and $\tilde{H}_d$.
The gluino is a half spin color octet supersymmetric partner of the gluon. The superpartners of the electroweak gauge bosons are called winos and binos. The mixing of $\tilde{W}^0$ and $\tilde{B}^0$ are called zino ($\tilde{Z}^0$) and photino($\tilde{\gamma}$).
Due to the EWSB the higgsinos and electroweak gauginos mix with each other. The mixing between neutral higgsinos and the neutral gauginos results in four mass eigenstates called neutralinos and denoted by $\tilde{\chi}_i^0 (i = 1, 2, 3, 4)$. Whereas, the charged higgsinos and winos combine to form two mass eigenstates called charginos denoted by $\tilde{\chi}_i^\pm (i = 1, 2)$.
As mentioned when discussing the hierarchy problem, the breaking of SUSY needs to be soft. In the MSSM, SUSY breaking is introduced by including a new component (L_{soft}^{MSSM}) to the Lagrangian. The Lagrangian, then, can be read as:

$$L = L^{MSSM} + L_{soft}^{MSSM} \tag{1.19}$$

The Yukawa and gauge interactions are contained in the first term, L^{MSSM}, while the L_{soft}^{MSSM} is breaking the symmetry. In order not to cause ultraviolet divergences,

L_{soft}^{MSSM} includes only the terms with positive mass dimension. In this way, the correction terms of the Higgs mass contain only logarithmic divergences:

$$\Delta m_H^2 = -m_{soft}^2[\frac{\lambda}{16\pi^2} ln(\Lambda_{UV}/m_{soft}) + ...]. \tag{1.20}$$

In order to satisfy the natural requirement, $|\Delta m_H^2| < m_H^2|_{measured}$, m_{soft} needs to be of the order of TeV scale. This indicates that the new particles introduced by MSSM, if they exist, should be reachable at the LHC.

The L_{soft}^{MSSM} adds 105 new parameters to 19 parameters coming from pure SM. These 105 additional parameters are categorized as follows: 48 CP-violating phases in the gaugino/higgsino and squark/slepton sectors, and 21 squark/slepton masses with 36 mixing angles to define their mass eigenstates.

The too many parameters of the MSSM make the interpretation of the experimental results challenging, even almost impossible. Therefore, using universality assumptions at the Grand Unified Theory (GUT) scale, the number of free parameters is reduced to five parameters. This model, appropriately, is called as the constrained MSSM (cMSSM). Another approach would be to focus on a limited set of SUSY particle production and decay modes and allow other parameters to change freely. This effective theory approach is called simplified models spectra (SMS) [36] and in this thesis, results are interpreted in the context of SMS. Before introducing the simplified models, it is beneficial to give an overview of the MSSM particle decays. To stay in the scope of this thesis, only the R-parity conserving scenarios will be discussed. In these models, the cascade decays of SUSY particles always end with an LSP. In this search, the lightest neutralino, $\widetilde{\chi}_1^0$, is the LSP. An augmented version of the topic is presented in chapter 9 of [4].

Neutralino and chargino are mixtures of the higgsinos and gauginos that are the spin half partners of the Higgs and gauge bosons. A neutralino or chargino can decay into lepton+slepton or quark+squark pairs, given the condition that slepton and squark are light enough. A neutralino or chargino may also decay into a Higgs scalar or an electroweak gauge boson via lighter neutralino or chargino. Therefore, the possible two-body decay modes for neutralinos and charginos in the MSSM are:

$$\widetilde{\chi}_i^0 \rightarrow Z\widetilde{\chi}_j^0,\, W\widetilde{\chi}_j^{\pm},\, h^0\widetilde{\chi}_j^0,\, l\tilde{l},\, \nu\tilde{\nu} \tag{1.21}$$

$$\widetilde{\chi}_i^{\pm} \rightarrow W\widetilde{\chi}_j^0,\, Z\widetilde{\chi}^{\pm},\, h^0\widetilde{\chi}^{\pm},\, l\tilde{\nu},\, \nu\tilde{l} \tag{1.22}$$

Gluino decays via a squark exclusively, which can be either on- or off-shell. If the on-shell decays are allowed, then $\tilde{g} \rightarrow t\tilde{t}$ and $\tilde{g} \rightarrow b\tilde{b}$ are probably the dominating channels. Otherwise the squarks are off-shell and this favors the following decays: $\tilde{g} \to qq\widetilde{\chi}_i^0$ and $\tilde{g} \to qq'\widetilde{\chi}_i^{\pm}$.

1.2.3 Simplified Models

The simplified model spectra (SMS) involves only a part of the parameter space of MSSM. This simplification leaves a few phenomenologically relevant parameters to understand the SUSY models; the cross section, branching ratios, and masses. In this simplified framework, normally a limited number of decay channels are considered. In other words, the branching ratios are set to 100% or a linear combination of such models is used for mixed decays. In this way, results can also be reinterpreted within other (non-)SUSY theories.

An example model ($\tilde{g} \to q\bar{q}\widetilde{\chi}_1^0$):

In this simplified model, gluino decays to two light quarks and a neutralino. Generally, the neutralino is considered to be the stable lightest supersymmetric particle or LSP. Hence, It is a strong candidate of Dark Matter. In this model conserning direct decay, the paramters include the mass of the gluino and neutralino ($m_{\tilde{g}}$, $m_{\widetilde{\chi}_1^0}$) and the production cross section of the gluino $\sigma(pp \to \tilde{g}\tilde{g} + X)$. The case where gluino decays to two light quarks and an intermediate chargino, with the latter decaying to a gauge boson and a neutralino can be read as:

$$\tilde{g} \to q\bar{q}\widetilde{\chi}_1^{\pm} \to q\bar{q}(W^{\pm}\widetilde{\chi}_1^0) \tag{1.23}$$

$$\tilde{g} \to q\bar{q}\widetilde{\chi}_2^0 \to q\bar{q}(Z^0\widetilde{\chi}_1^0). \tag{1.24}$$

In this case, the mass of the intermediate particle (chargino $\widetilde{\chi}_1^{\pm}$or a heavier neutralino $\widetilde{\chi}_2^0$) is also included in the parameters. In order to reduce the three-dimensional mass space, chargino mass is considered to be dependent to gluino and neutralino masses. The relation is given by: $m_{\widetilde{\chi}_1^{\pm}} = m\widetilde{\chi}_1^0 + r(m_{\tilde{g}} - m_{\widetilde{\chi}_1^0})$. The kinematics of the decay strongly related to the value of r. To further decrease the number of parameters, the branching ratio of these decays is set to 100%. The decay shown in the Equation 1.23 with a r=0.5, which indicates the mass of the chargino is at the midway, is used to interpret the results in this thesis.

A variety of SMS approaches has been investigated by the ATLAS and CMS collaborations at the LHC. In the following, a short history of SUSY searches at colliders will be discussed.

1.2.4 Short History of SUSY searches at colliders

Before the LHC, the first constraints on SUSY had already been set by UA1 experiment and the UA2 experiment at Super Proton Synchrotron. It was until 2000, SUSY searches continued up to 209 GeV at the electron-positron collider LEP. Until 2011, The CDF and D0 experiments at the Tevatron extended the limits in the context of cMSSM. In parallel between 1992 and 2007, the H1 and ZEUS experiments at HERA (The electron-proton collider) searched for the R-parity violating production of single SUSY particles. The LHC has started proton-proton collision at a center of mass energy of 7 TeV in 2010. Since then, ATLAS and CMS experiments have performed robust searches and provided strong limits in the context of SMS. The 2011 and 2012 runs of the LHC are called Run 1. During Run 1, 20 fb^{-1} data was collected at a center of mass energy 7 and 8 TeV. In 2012, with the discovery of Higgs boson, the SUSY models have been constrained further. Later, in the first stage of Run 2, approximately 36 fb^{-1} data has been collected at a center of mass energy 13 TeV. A summary of the both Run 1 and Run 2 results by ATLAS and CMS experiments is presented in Figure 1.5. Within the MSSM these results have already pushed the sparticle mass boundaries required to solve hierarchy/naturalness/fine-tunning problems. For instance, It was foreseen that the gluinos cannot be much heavier than 1 TeV and the higgsino mass should be around 200 GeV. Obviously, the latest results challenge these requirements. Nevertheless, there is still room for expanding the searches, for example, in the regions with compressed spectra where the analysis is not so trivial.

Expectations for gluino searches at 13 TeV:

LHC is a proton-proton collider. Consequently, high sensitivity is favored in the production of color charged particles: the gluino and squarks.

The gluino pair production diagrams are shown in Figure 1.6. The cross sections as a function of the center of mass energy and gluino mass are shown respectively in Figure 1.7 left and right. The cross section of gluino pair production increased significantly from 8 TeV to 13 TeV. However, the cross section of SM processes increased as well (see Figure 1.8). These figures indicate that at 13 TeV for 10^{10} SM events, 1 event including gluino pair production is expected. This sounds even harder than looking for a 4-leaf clover. Nevertheless, it is still achievable by designing an analysis strategy, with a robust background estimation and assigning the uncertainties carefully. An example of such a search will be presented in this thesis and in the section 8.4 a comparison of the latest results from gluino searches can be found.

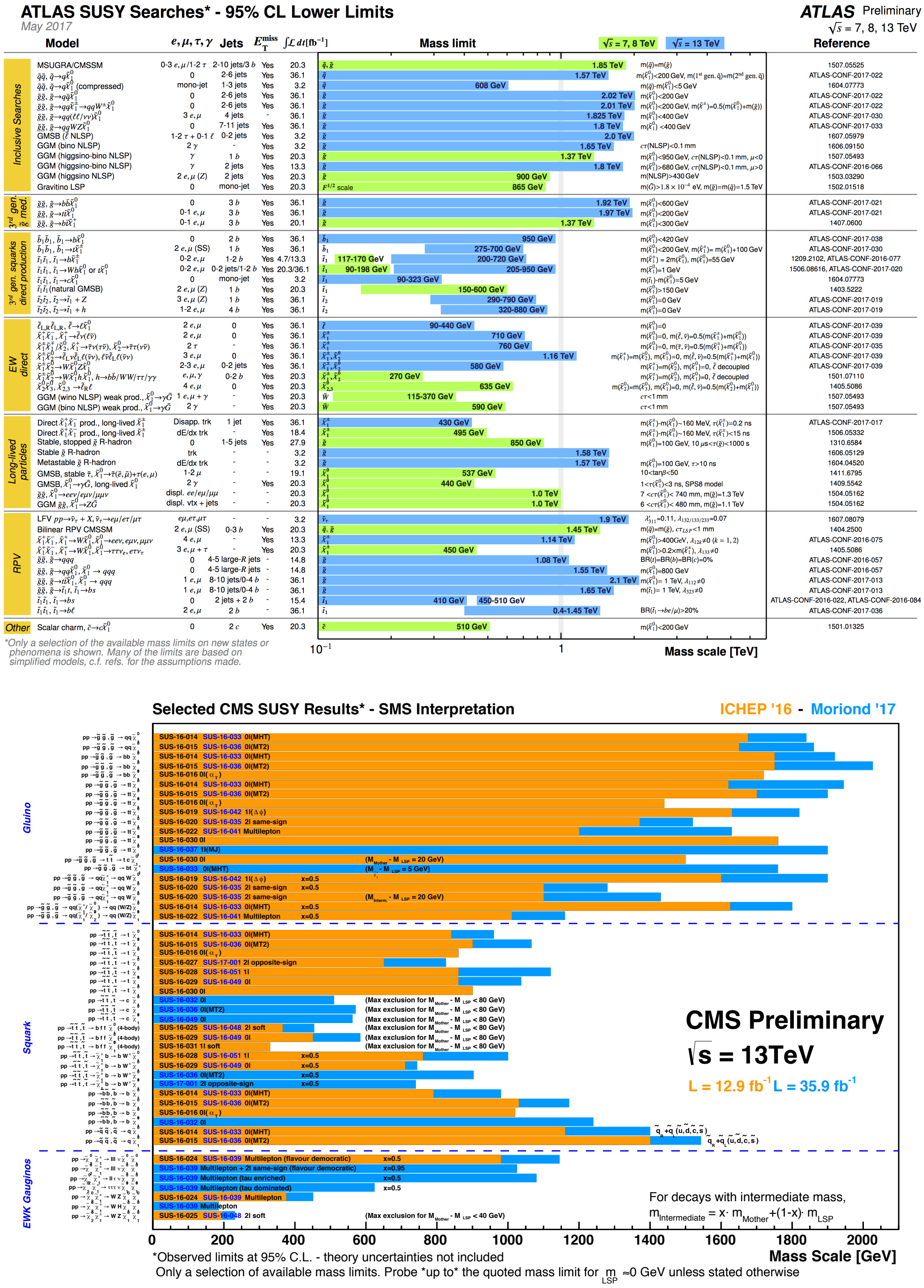

Figure 1.5: Best exclusion limits on sparticle masses from searches for SUSY using SMS by ATLAS (top) and CMS (bottom) collaborations [39, 40]. In the upper plot, the green bars represent the 7-8 TeV results while the blue bars are summarizing the 13 TeV results. In the lower plot, the orange bars represent the 7-8 TeV results while the blue bars are summarizing the 13 TeV results.

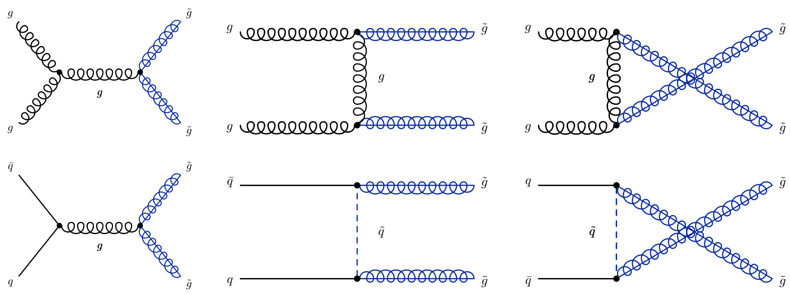

Figure 1.6: Feynman Diagrams showing the gluiono pair prodution. SUSY particles are shown in blue.

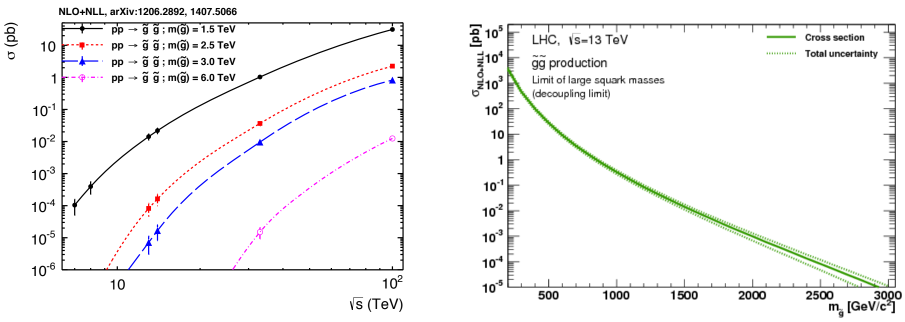

Figure 1.7: left: Cross sections of gluino pair production for four different mass points are given as a function of the center of mass energy. right: Cross section of gluino pair production at 13 TeV center of mass energy is given as a function of gluino mass. [37]

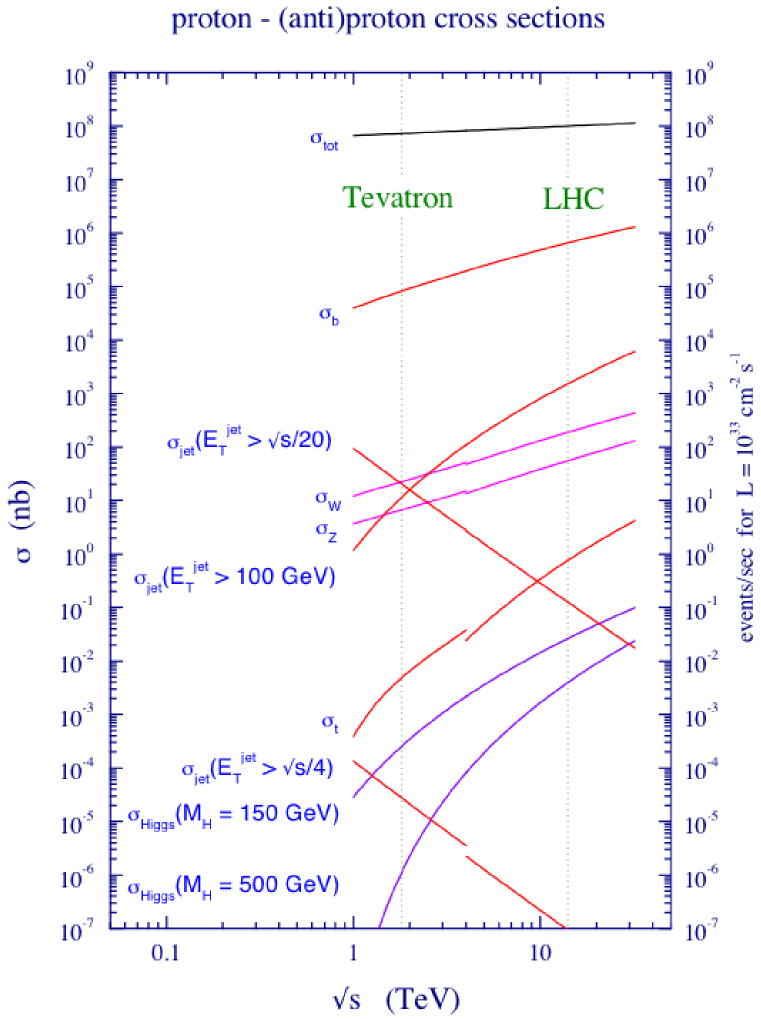

Figure 1.8: Cross section of SM processes as a function of center of energy. [38]

Chapter 2

Experimental Setup

2.1 The LargeHadron Collider at CERN

2.1.1 The CERN accelerator complex

2.1.2 The future of the LHC

2.2 The Compact Muon Solenoid experiment at the LHC

2.2.1 Superconducting Magnet

2.2.2 Tracker

2.2.3 Electromagnetic Calorimeter

2.2.4 Hadron Calorimeter

2.2.5 Muon System

2.2.6 Trigger and Data Acquisition Systems

2.2.7 Data Tiers of CMS

RAW , RECO , AOD ...

2.2.8 Luminosity measurement

Luminosity measurement measurement and the unceartinity on it are important measurement that will be touched shortly again in the systematics chapter

2.2.9 Future of CMS

upgrade plans.. pixel .. will help to motivate future of physics analysis

2.3 Event simulation

Describe madgrapgh , pythia .. will be short

Chapter 3

Object reconstruction and identification

3.1 Particle-Flow algorithm

3.2 Physics Object reconstruction

3.2.1 Primery vertices

3.2.2 Electrons

3.2.3 Muons

3.2.4 Jets

3.2.5 b tagged Jets

mention fake rate

3.2.6 Missing transverse energy

continue Missing transverse energy

Chapter 4

Event Selection

4.1 SUSY signature

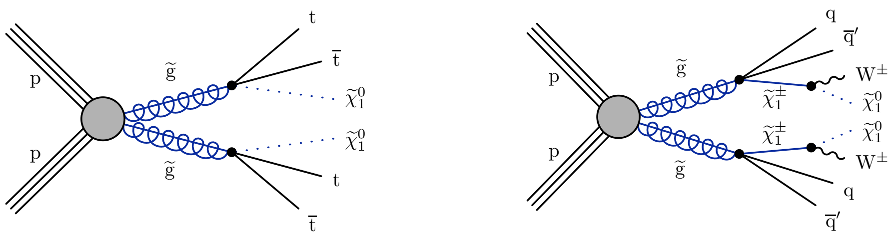

Figure 4.1: Diagrams showing the simplified models T1tttt and T5qqqqWW.

kinematic variables DeltaPhi , HT , LT ....
Put inclusive plots which then will support baseline selection

4.2 Samples

4.2.1 Data Samples

Shortly explain triggers

4.2.2 MC Samples

4.3 Baseline selection

plots ele channel

plots mu channel

Here introduce filters as well

Chapter 5

Design of Search Regions

Explain MB , SB...

Plots MB , SB...

5.1 Signal Regions

5.1.1 Background and Signal composition in MB SR

5.2 Control Regions

5.2.1 Background composition in MB CR and SB SR/CR

continue background composition

5.2.2 Signal contamination in MB CR and SB SR/CR

Tell that It is negligible

supporting plots : Tell that It is negligible

Chapter 6

Background Estimation

6.1 R_{CS} method

refer background compositions from the previous chapter

RCS stability plots ...

6.1.1 R_{CS} method in ttbar events

Maybe mention: Previously : SB was 1 bjet events -¿ you studied the extension now It is btagged region explain kappas

Explain dilepton correction on kappa tt

shortly tell systemtics, will be expalin in details ...

6.1.2 R_{CS} method in w jets events

continue ..

addition of diboson contributions to WJets ...

other contribution from MC

6.2 QCD background estimation

keep short you did nothing

6.3 Validation of the background estimation

plots, table

explanation

Chapter 7

Systematic Uncertainties

7.1 Systematic Uncertainties on background estimation

7.1.1 Theoratical Uncertainties

- σ(wjets)
- σ(ttbar)
- σ(others)

7.1.2 Experimental Uncertainties

- Dilepton control sample
  will be long plots

text of dilep

- JES
- Tagging of b-jets
- W polarization

- nISR reweighting
- Pileup
- QCD

7.2 Systematic Uncertainties on signal modelling

- Trigger
- Pileup
- Lepton efficiency

- Luminosity
- ISR
- Tagging of b-jets

- JES
- Factorization/renormalization scale
- Reconstruction of MET

Chapter 8

Results and Interpretation

8.1 Results of background predition

plots...

8.2 Limit settings

explain cls

statistical tests

8.3 Interpretation

T5qqqqWW limit goes here

8.4 Comparison to other results

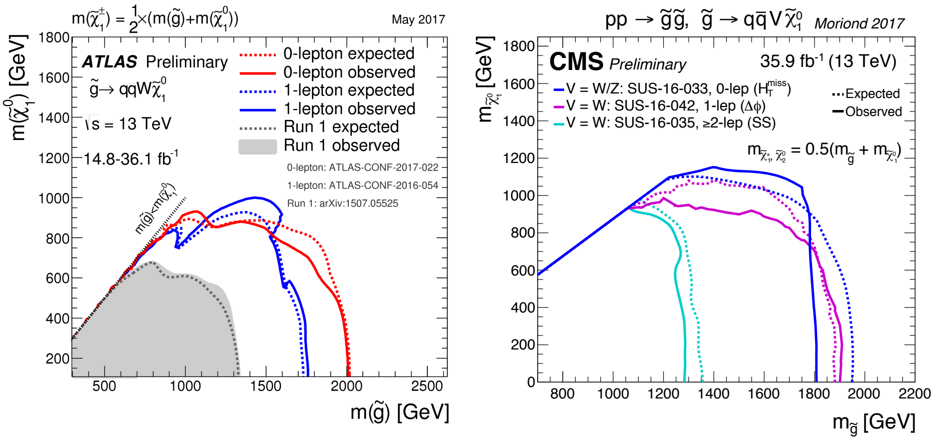

Figure 8.1: left: right:

with plots will take at least 2 pages

with plots will take at least 2 pages

Chapter 9

Conclusion

bitti

The End

Appendix A

Appendix

Bibliography

[1] F. Halzen and A. Martin, "Quarks and leptons: an introductory course in modern particle physics". Physics textbook. Wiley, 1984.

[2] D. Griffiths, "Introduction to Elementary Particles". Physics textbook. Weinheim, Germany: Wiley-VCH 454 p, 2014.

[3] B.R. Martin and G. Shaw, "Particle Physics". 4th Edition. ISBN: 978-1-118-91190-7

[4] S. P. Martin, A Supersymmetry primer, doi:10.1142/9789812839657_0001, arXiv:hep-ph/9709356. [Adv. Ser. Direct. High Energy Phys.18,1(1998)].

[5] C. Patrignani *et al.* [Particle Data Group], "Review of Particle Physics," Chin. Phys. C **40** (2016) no.10, 100001. doi:10.1088/1674-1137/40/10/100001

[6] Gell-Mann, M. Nuovo Cim (1956) 4(Suppl 2): 848. doi:10.1007/BF02748000

[7] E. Fermi, "An attempt of a theory of beta radiation. 1.", Z. Phys. **88** (1934) 161177.

[8] S. L. Glashow, Partial Symmetries of Weak Interactions, Nucl. Phys. **22** (1961) 579588, doi:10.1016/0029-5582(61)90469-2.

[9] A. Salam, Weak and Electromagnetic Interactions, Conf. Proc. C680519 (1968) 367377.

[10] S. Weinberg, A Model of Leptons, Phys. Rev. Lett. 19 (1967) 12641266, doi:10.1103/PhysRevLett.19.1264.

[11] F. Englert and R. Brout, Broken Symmetry and the Mass of Gauge Vector Mesons, Phys. Rev. Lett. 13(1964)321323,doi:10.1103/PhysRevLett.13.321.

[12] P. W. Higgs, Broken Symmetries and the Masses of Gauge Bosons, Phys. Rev. Lett. 13 (1964) 508509, doi:10.1103/PhysRevLett.13.508.

[13] CDF Collaboration, Observation of top quark production in p p collisions, Phys. Rev. Lett. 74(1995) 26262631, doi:10.1103/PhysRevLett.74.2626, arXiv:hep-ex/9503002.

[14] D0 Collaboration, Search for high mass top quark production in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV, Phys. Rev. Lett. 74 (1995) 24222426, doi:10.1103/PhysRevLett.74.2422, arXiv:hep-ex/9411001.

[15] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. **B716** (2012) 3061, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.

[16] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. **B716** (2012) 129, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.

[17] F. Brnner and A. Rebhan, "Nonchiral enhancement of scalar glueball decay in the Witten-Sakai-Sugimoto model," Phys. Rev. Lett. **115**, no. 13, 131601 (2015) doi:10.1103/PhysRevLett.115.131601 [arXiv:1504.05815 [hep-ph]].

[18] Y. K. Hsiao and C. Q. Geng, "Identifying Glueball at 3.02 GeV in Baryonic B Decays," Phys. Lett. B **727**, 168 (2013) doi:10.1016/j.physletb.2013.10.008 [arXiv:1302.3331 [hep-ph]].

[19] Bennett G et al. (Muon G-2 Collaboration) 2006 Phys.Rev. **D73** 072003 (Preprint hep-ex/0602035)

[20] Abbott, Benjamin P.; et al. (LIGO Scientific Collaboration and Virgo Collaboration) (2016). "Observation of Gravitational Waves from a Binary Black Hole Merger". Phys. Rev. Lett. **116** (6): 061102. Bibcode:2016PhRvL.116f1102A. PMID 26918975. arXiv:1602.03837 . doi:10.1103/PhysRevLett.116.061102.

[21] Castelvecchi, Davide (23 March 2016). "The black-hole collision that reshaped physics". Nature. 531 (7595): 428431. doi:10.1038/531428a.

[22] F. Zwicky. "On the Masses of Nebulae and of Clusters of Nebulae". Astrophys. J., 86:217 246, 1937. doi:10.1086/143864.

[23] 'V. C. Rubin, N. Thonnard, and W. K. Ford, Jr. "Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 /R = 4kpc/ to UGC 2885 /R = 122 kpc/".' Astrophys. J., 238:471, 1980. doi:10.1086/158003.

[24] G. Hinshaw *et al.* [WMAP Collaboration], "Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Data Processing, Sky Maps, and Basic Results," Astrophys. J. Suppl. **180**, 225 (2009) doi:10.1088/0067-0049/180/2/225 [arXiv:0803.0732 [astro-ph]].

[25] Boggess, N. W.; et al. (1992). "The COBE Mission: Its Design and Performance Two Years after the launch". The Astrophysical Journal. 397: 420. Bibcode:1992ApJ...397..420B. doi:10.1086/171797.

[26] P. A. R. Ade *et al.* [Planck Collaboration], "Planck 2015 results. XIII. Cosmological parameters," Astron. Astrophys. **594**, A13 (2016) doi:10.1051/0004-6361/201525830 [arXiv:1502.01589 [astro-ph.CO]].

[27] **Super-Kamiokande** Collaboration, Evidence for oscillation of atmospheric neutrinos, Phys. Rev. Lett. **81** (Aug, 1998) 15621567. doi: https://doi.org/10.1103/PhysRevLett.81.1562

[28] **OPERA** Collaboration, Observation of a first candidate event in the OPERA experiment in the CNGS beam, Physics Letters B 691 no. 3, (2010) 138 145. doi: https://doi.org/10.1016/j.physletb.2010.06.022

[29] D. H. Perkins, "Introduction to high energy physics". Cambridge University Press, 2000.

[30] Emmy Noether; Mort Tavel (translator) (1971). "Invariant Variation Problems". Transport Theory and Statistical Physics. 1 (3): 186207. arXiv:physics/0503066. doi:10.1080/00411457108231446.

[31] Give referance

[32] H. B. Kim and J. E. Kim, "Coupling constant unification and LEP data," J. Korean Phys. Soc. **27**, 129 (1994) [hep-ph/9302260].

[33] S. Schael *et al.* [ALEPH and DELPHI and L3 and OPAL and SLD Collaborations and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group], "Precision electroweak measurements on the Z resonance," Phys. Rept. **427**, 257 (2006) doi:10.1016/j.physrep.2005.12.006 [hep-ex/0509008].

[34] Wilczek, F., Raby, S., Dimopoulos, S. (1991, October). Unification of couplings. PHYSICS TODAY, 44(10), 25-33. doi: http://dx.doi.org/10.1063/1.881292

[35] B. Bajc, J. Hisano, T. Kuwahara and Y. Omura, “Threshold corrections to dimension-six proton decay operators in non-minimal SUSY SU (5) GUTs,” Nucl. Phys. B **910**, 1 (2016) doi:10.1016/j.nuclphysb.2016.06.017 [arXiv:1603.03568 [hep-ph]].

[36] S. Chatrchyan *et al.* [CMS Collaboration], “Interpretation of Searches for Supersymmetry with simplified Models,” Phys. Rev. D **88**, no. 5, 052017 (2013) doi:10.1103/PhysRevD.88.052017 [arXiv:1301.2175 [hep-ex]].

[37] C. Borschensky, M. Krmer, A. Kulesza, M. Mangano, S. Padhi, T. Plehn and X. Portell, “Squark and gluino production cross sections in pp collisions at $\sqrt{s}$ = 13, 14, 33 and 100 TeV,” Eur. Phys. J. C **74**, no. 12, 3174 (2014) doi:10.1140/epjc/s10052-014-3174-y [arXiv:1407.5066 [hep-ph]].

[38] WJS2012

[39] https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/index

[40] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS