SEARCHES FOR SUPERSYMMETRY AT THE HIGH-LUMINOSITY LHC

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ABSTRACT

SEARCHES FOR SUPERSYMMETRY AT THE HIGH-LUMINOSITY LHC

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High Luminosity LHC (HL-LHC) project is an upgraded version of the LHC that enables to explore beyond the Standard Model theories and is expected to exceed the limits of currently conducted experiments. Supersymmetry is one of the commonly used and well-known beyond the Standard Model theories proposing a symmetry with brand-new particles and by doing so, bringing solutions to the unsolved zones that the Standard Model is not available to reach. In this thesis, by considering the high luminosity and the center of mass energy that are going to be achieved in scope of the HL-LHC project, single lepton and di-lepton final state channels are examined at $\sqrt{s}$=14 TeV. Three pile-up with two luminosity cases such as, for No pile-up and 50 pile-up, 300 fb^{-1} and for 140 pile-up 3000 fb^{-1} luminosity values are used. For the Standard Model background samples ($t\bar{t}$+jets, Boson+jets, Single t+jets and Di-boson) including with the signal sample (STC8, sTau-coannihilation) Pythia is used for simulation of them. Detector atmosphere is simulated via Delphes to insert the effects in all of the samples. In order to make an estimation in the most efficient cut flows for the Supersymmetry studies that are going to be conducted at HL-LHC and to develop a fundamental analysis technique, two different cut options for E_T^{miss} and

H_T are studied. Both of these variables are preferably used in most Supersymmetry searches and preferred to be studied for both of the final state channels in this thesis also. Besides these variables, the new topological variables, M_{T2}^W and $topness$ are also used in single lepton final state analysis. The positive impact in suppressing the background events by applying cuts starting from E_T^{miss} has been observed especially for the di-lepton channel yet the crucial gain is obtained by inserting the M_{T2}^W and $topness$ variables in single lepton channel. The discovery threshold has been exceeded for all of the options in scope of the expected single lepton final state, whereas more number of events are needed to increase the statics for the di-lepton final state in order to obtain a significance over 5σ for all of the cut options. The effectiveness of the topological variables in significance are almost the same at all pile-up scenarios. The highest significance value for single lepton is attained for No pile-up case, even if this case is accepted as an optimistic alternative, with a higher cut in E_T^{miss}. However for di-lepton case, 140 pile-up with lower H_T cut leads the maximum probability.

Keywords: Particle Physics, the Large Hadron Collider, the High Luminosity Large Hadron Collider, the Standard Model, The Supersymmetry, Single Lepton Channel, Di-lepton Channel, s-Tau Coannihilation, the CMS, the ATLAS, Pythia

ÖZ

YÜKSEK LÜMİNOSİTİLİ LHC DENEYLERİNDE SÜPERSİMETRİ ARAŞTIRMALARI

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Yüksek Lüminositili Büyük Hadron Çarpıştırıcısı'nın, Büyük Hadron Çarpıştırıcısı' nın geliştirilmiş bir versiyonu olarak Standart Model ötesi teorileri keşfetmesi ve halihazırda aktif olarak yürütülen deneylerin limitlerini aşması beklenmektedir. En bilinen ve çoğunlukla kullanılan Standart Model ötesi teorilerden olan Süpersimetri, yeni parçacıklar ile bir simetri önermekte ve bu öneri ile birlikte, Standart modelin ulaşmakta zorlandığı bölgelerde çözümsüz kalan problemlere çözüm getirmektedir. Bu tezde, geliştirilen deneylerde varılması amaçlanan yüksek lüminositi ve çarpışma enerjisi göz önünde bulundurularak, $\sqrt{s}$=14 TeV'de, tek ve çift lepton kanalları üç yığın durumu ve iki lüminositi değeri, 300 fb^{-1} yığınsız ve 50 yığın, 3000 fb^{-1} 140 yığın kapsamında incelenmiştir. Analizde kullanılan dört farklı Standart Model arkaplan örnekleri ($t\bar{t}$+jets, Boson+jets, Single t+jets and Di-boson) ve bir sinyal örneği (STC8, sTau-coannihilation), Pythia kullanılarak üretilmiş ve dedektör etkileri Delphes ile modellenmiştir. Yüksek Lümünositili Büyük Hadron Çarpıştırıcısı'nda yürütülen Süpersimetri çalışmalarında kullanılacak en verimli akış kesinti değerlerini belirlemek ve temel bir analiz tekniği geliştirmek amacıyla, birçok Süpersimetri ça-

lışmalarında kullanılan iki farklı değişken, E_T^{miss} ve H_T iki farklı kanal için, iki farklı kesinti değeri uygulanarak çalışılmıştır. Bu değişkenlerin haricinde, iki yeni topolojiksel değişken, M_{T2}^W ve $topness$, da tek lepton kanalı analizinde kullanılmıştır. Arkaplan olaylarını bastırmada olumlu bir etki E_T^{miss} değişkenine uygulanan kesinti ile, özellikle çift lepton kanalında gözlemlenmiştir ama kritik kazanım, M_{T2}^W ve $topness$ topolojiksel değişkenlerinin tek lepton kanalında kullanılması ile elde edilmiştir. Keşif eşik değeri tek lepton kanalında bulunan bütün opsiyonlar için aşılmıştır ama çift lepton kanalı için, bütün opsiyonlarda 5σ üzerine çıkmak ve istatistiği arttırmak için olay sayısının çoğaltılması gerekmektedir. Bütün yığın senaryolarında, iki farklı topolojiksel değişkenin sinyali öne çıkarmakta neredeyse aynı etkisinin olduğu gözlemlenmiştir. En yüksek olasılık değerinin tek lepton kanalı için, iyimser bir alternatif olmasına rağmen yığınsız durum içinde, E_T^{miss} değişkeni için yüksek bir kesintinin uygulandığı durumda elde edildiği görülmüştür. Çift lepton kanalı kapsamında ise, 140 yığın değeri ile daha düşük bir kesintinin uygulandığı H_T değişkeninin geçerli olduğu durumda maksimum keşif olasılığına ulaşılmıştır.

Anahtar Kelimeler: Parçacık Fiziği, Büyük Hadron Çarpıştırıcısı, Yüksek Lüminositili Büyük Hadron Çarpıştırıcısı, Standart Model, Süpersimetri, Tek Lepton Kanalı, Çift Lepton Kanalı, s-Tau Ortak İmhası, CMS, ATLAS, Pythia

To my family

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SM	Standard Model
SUSY	Supersymmetry
LHC	Large Hadron Collider
PU	Pile-Up
MSSM	Minimal Supersymmetric Standard Model
LSP	Lightest Supersymmetric Particle
GUT	Grand Unification Theory
EWSB	Electroweak Symmetry Breaking
SSB	Spontaneous Symmetry Breaking
DOF	Degrees of Freedom
STC	s-Tau Coannihilation
LS1	Long Shutdown 1
LEP	Large Electron Positron Collider
SPS	Super Proton Synchrothon
LINAC 2	Linear Acceleretor 2
PSB	Proton Synchrontron Booster
PS	Proton Synchrontron
SPS	Super Proton Synchrontron
CP	Charge Conjugation Parity
HL-LHC	High Luminosity Large Hadron Collider Project
EYETS	Extended Year-End Technical Stop
SLHA	SUSY Les Houches Accord
OOP	Object-Oriented Programming

CHAPTER 1

INTRODUCTION

From ancient times to today's world, questions about the universe, mostly related with the beginning of it, and the matter have always been in the humankind's minds. Hence, to answer all these question, numerous studies and searches about the building blocks of the matter have been investigating by different experimental and theoretical ways since several centuries.

Particle physics, as a branch of physics, introduces the most accepted current theory which describes the elementary particles and the interactions between them, the Standard Model (SM) of particle physics in order to answer questions about the universe and the matter. However even the SM, which is known as the most accepted theory in particle physics, it remains inadequate to suggest appropriate solutions for some problems which are introduced in Chapter 2.

At that point by being an extension of the SM of particle physics, Supersymmetry (SUSY) offers reasonable solutions to the problems that the SM can not solve. During Run I (2009 - 2013), The Large Hadron Collider (LHC) machine collected a huge volume of data and succeeded numerous achievements, including the discovery of the Higgs boson in July 2012 [1, 2]. Nevertheless, even if SUSY is the most promising tool, in experimental searches still there has been no sign about the existence of it. Due to the heavy masses of SUSY particles, the colliding energy of this run has not been enough to explore them. Thankfully, with the upgrade done during long shutdown (2013-2015) the LHC has reached $\sqrt{s} = 13$ TeV on June 2015 and this progress has brought back hope again. But with this hope, an obligation in finding and improving new procedures in SUSY analyses, especially in distinction of the signal from the background, has become inevitable since a center of mass energy at that magnitude also brings so many difficulties in analyses alongside itself, for sure.

In scope of the latest SUSY analyses, which still indicate that no signals have been observed so far, results make the High Luminosity Large Hadron Collider Project that much important most particularly for SUSY analyses itself and for the other beyond SM studies too. It is surely expected that this project is going to enlarge the limits of analyses strategies in which also comprises the pile-up (PU) effects in collisions. Among probing all of the compelling parameters in these searches, enhancing the knowledge in pile-up effects has a significance mark for sure, in order to eliminate the uncertainties in comprehension of many variable included analyses, that are probably going to be faced through the future of the experimental particle physics.

This research includes three pile-up with two luminosity cases such as, for No pile-up and 50 pile-up, 300 fb^{-1} and for 140 pile-up 3000 fb^{-1} luminosity values for single and di-lepton final state scenarios. Various selection cuts are applied during event selection. To develop a fundamental analysis technique, mainly two different kinds of limitations applied on corresponding kinematic variables, E_T^{miss} and H_T by aiming also indicating the most efficient method to get a higher signal statics. Compered to these common variables M_{T2}^W and $topness$, relatively new variables in SUSY searches, are also used in single lepton channel by aiming to fulfill the previously mentioned same missions.

In Chapter 2, since it is believed that as a theoretical background, the SM and SUSY are needed to be understood in order to be able to have an idea about this research, a very concise information about them is given with the shortcomings of the SM. After giving an information about the limits of the LHC and the importance of the Higgs boson discovery for the beyond the SM studies and naturally for this thesis also, the motivation of this research is highlighted.

In Chapter 3, the Large Hadron Collider (LHC) is introduced as the experimental setup of the analysis in this thesis and with four major experiments conducted in it. Before knowing the principal facts about the High Luminosity LHC project and also its projection on determination of analyses strategies in SUSY searches, some highlighted SM results and the status of SUSY, both from Run I results, are given.

In Chapter 4, signal and background samples are given with the tools used in the analysis of results and in production of these particular samples. The followed selection cuts applied on the variables are listed and signal selection rules are given. The importance of pile-up phenomenon is introduced. Inclusive variables with control plots are given in a way that mainly gathered according to pile-up and final state lepton numbers. Lastly, a comparison between single and di-lepton channels is presented by considering the impact of cuts and the variables.

CHAPTER 2

THEORY

In this chapter, the Standard Model of particle physics is introduced within the borders of questions which do not have appropriate answers suggested by the SM itself. Before giving information about the current limits of the LHC with the importance of the Higgs discovery, in essence information beyond the SM; SUSY is also mentioned with a simplified version of it, The Minimal Supersymmetric Standard Model (MSSM). Lastly the motivation of this research is emphasized at the end of Chapter 2.

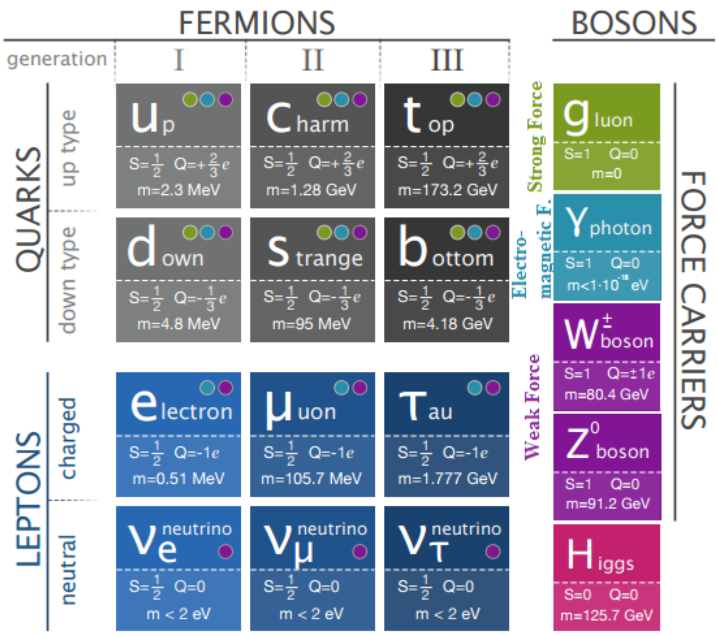
2.1 The Standard Model

The Standard Model is the most essential and valid theory in particle physics that gathers the known constituents (fundamental particles) of the universe and the interactions between them under a single roof. Once for all, with the discovery of the Higgs boson in July 2012 the missing part of the puzzle has been completed and as an answer to the question, "why particles have mass" has been hereby proven experimentally also [1, 2].

2.1.1 Particles and Interactions

The classification of particles in the SM has to be understood well in order to have a better comprehension in the foundation of particle physics. In detail, with their masses, charges, spins and names, fundamental particles in the SM can be seen in Table 2.1.

Table 2.1: Fundamental particles and forces (interactions) in the Standard Model, with their masses (m) [3], charges (Q), spins (s) and names. The associated interaction for each particle is indicated via circles on the right-top of the boxes. The Table is taken from [4].



Constitutively, particles in the SM are divided as fermions and bosons due to their spin numbers. As a result of Pauli exclusion principle, half integer spin numbers particles can not occupy the same state and fermions are known as the particles that provide this rule. However, for bosons this statement is not an exigence since they have integer spin numbers.

Also, as it can be seen from Table 2.1, the SM particles are gathering in 3 different generations where they show difference mainly in their masses. First generation particles are known as the lightest ones, whereas the masses increases as one goes through the higher generations. Hence, it can be said that the ordinary matter with which we are familiar consists of first generation particles since by having the lightest masses, they do not show decaying feature in the universe.

After giving a brief information about the fundamental particles, the fundamental forces in the SM is better to be introduced. As it is known, in the universe there are four fundamental forces; strong, electromagnetic, weak and gravitational force. These forces make particles affect each other with the corresponding gauge boson. Except the gravitational force, since the way of including this particular force into the SM is an unknown question for now, just the other three fundamental forces are included in the SM. For these three important interactions if it is needed to give concrete examples, it can be said that, while the strong force is responsible for holding the protons and the neutrons in the atomic nuclei, the electromagnetic force binds electrons to nuclei in atoms and weak force leads an energy production at the end of nuclear interactions, such as energy production in the sun [5]. Again from Table 2.1, the fundamental forces in the SM and Higgs field can be seen with their liable gauge bosons.

Since the SM is a gauge invariant quantum field theory (QFT), relatedly the forces in the universe except gravitational force are defined in QFT also [6]. In order of strenght, strong interaction is described by Quantum Chromodynamics (QCD) while Quantum Electrodynamics (QED) is the theory that determines the electromagnetic interaction. And QED is also joined with weak interactions by resulting a name as, electroweak force [7].

As a result of gauge invariance under SU(3) transformation group, strong interaction ensues. The particles named as quarks are mainly comprised in strong interactions. With six flavour of quarks, an additional quantum number arises in strong interactions, a conserved quantity defined as "color charge"; red (r), green (g) and blue (b). And the corresponding gauge boson in strong interaction is known as gluon. In the SM there are 6 quarks, multiplying each of them by 3, due to the color states now there are 18, plus their anti-particles, (having same features with each corresponding particle, except its "charge") 36 particles and plus 8 states for gluons as a result, it can be ended up with 44 particles interacting with strong interactions in the SM. By adding also 3 charged leptons with their 3 neutrinos plus the anti-particles of them and in addition, γ, $W^{\pm}$, Z^0 and Higgs boson; eventually it can be said that there are 61 particles in the SM.

Here a new particle physics phenomena is better to be described. On Table 2.2, coupling constant, α, is introduced. This unitless quantity helps to determine the cross-section measurement for the particle processes and also to determine how strength a force is in a particular interaction. In strong interaction, this constant, by representing the strength, is accepted as α=1. Coupling constant also has an influence on quark confinement and asymptotic freedom.

Table 2.2: Coupling Constants and their corresponding fundamental forces [7]

Coupling Constant α	Fundamental Forces
10^{-6}	Weak
10^{-2}	Electromagnetic
1	Strong

Gluons and quarks are not observed as free particles in nature. This phenomenon is known as confinement and accepted valid for larger distances, i.e. $> 10^{-15}$ m.

In contrast, in small distances, i.e. $< 10^{-15}$ m, "α" gets smaller and quarks and gluons act as if they are free, and this occurrence is named as asymptotic freedom in QCD. By defining confinement, another phenomena about quarks and gluons can be explained. In an appropriate provided distance, a quark (the same is valid for gluons also through by building mesons as force carriers) can be separated from its ancestor hadron in order to form another brand new quark pair.

Result of gauge invariance under transformation group U(1) gives rise to electromagnetic interaction. Here, mainly particles named as leptons are included in this interaction. The corresponding gauge boson is known as photon among the elementary particles in the SM.

As it is said before the last fundamental force involved in the SM is weak interaction. Weak interaction is a desinence of the gauge invariance under SU(2) transformation. In the SM, including neutrinos there are 6 leptons. With their anti-particles and the corresponding gauge bosons; $W^{\pm}$ and Z^0, the total number of elementary particles in the SM that mainly interact via weak interactions becomes equal to 15 [7].

2.2 Problems in the Standard Model

In science, the cases moving on the next steps without any reason to get motivated are not such an acceptable ways to proceed. From this fact, it can be said that in order to go beyond the SM, there should be some valid reasons for doing that. As it is mentioned before, even if the SM is known as the most general and acceptable theory in particle physics, it has some missing parts in it. These parts can be approached as problems in the SM.

2.2.1 Experimental and Observational Problems

The universe is not just consist of the matter that has been known as ordinary matter. By the observations that have been carrying on for decades, it is known that the current percentages in the total mass distribution of the universe are reported as in Figure 2.1.

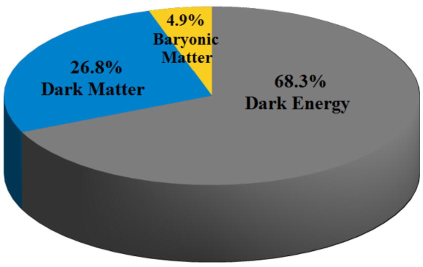


Figure 2.1: The percentages of the dark matter, dark energy and ordinary matter, due to the current results from the Planck Satellite [8]

As it is seen from Figure 2.1, the total percantage of the dark matter (a type of matter which generate extra mass and extra gravity that make galaxies to stay intact, apart from gravity generated by the known matter) and the dark energy (a type of energy contributes to the energy density and responsible from the universe's accelerated inflation) is much more than the ordinary (baryonic) matter, which means actually the mysterious part is still taking a big place in the particle physics even if a lot of questions has been answered by valid theories and the SM has been completed with the discovery of Higgs boson. Due to recent studies, the SM is not suggesting a candiate for dark matter and it has been also showed that lower limitation for the mass of the dark matter has been shaped as $\geq$ 10 keV [9]. With the fact that the dark matter has been formed right after the Big Bang, the particles refer it has to be stable or at least long-lived to exist at the present time. And this brings a neutral, stable and heavy particle relatively the ones in the SM. Hence, it can be said that it not possible to make an adequate explanation for the dark matter and the dark energy with our present knowledge rising from (upon on) the SM.

In theory, it is preferable that the Big Bang should have created equal amounts of matter and antimatter in the early universe. But due to the fact that, as a result of the annihilation, universe is not filled with just "light", there should be a matter-antimatter asymmetry in the early universe, which leads to a creation of remnants as the roots of matter density we know today. This asymmetry is known as baryon asymmetry and it is another physical concept that can not be explained with in the borders of the SM knowledge [10].

It is known that the ordinary matter in the universe consists of the 1^{st} family of the fermions in the SM. So a querier question about the reason for existance of the other generations, with a huge mass ratio difference between them also, rises up. Besides that, why the charge quantization of the charged particles in the SM is consisting of the way that it is today, is another question comes from the formation of the SM [11].

2.2.2 Theoretical Problems

In particle physics, the Grand Unification Theory (GUT) is a theory that gather the coupling constants of the fundamental forces in the SM at an one point, i.e. makes them equal in strength as one unified coupling constant. This tuning can be done at 10^{16} GeV scale, close to Planck scale i.e. 10^{19} GeV , at high energies. Theory and experiments have been carried on until today show that this is not possible in the SM unfortunately. But this does not mean that in a beyond the Standard Model theory, this impossibility would repeat itself.

Based on its strength, gravitation has the lightest coupling constant among the other fundamental forces. For example the large scale difference in representation of the coupling constants between the weak force and the gravitation is up to/around 10^{-32}. In addition, if the mass scale is examined for the Higss boson and the gauge bosons of corresponding interactions, it is clear that whereas bosons have a scale at 10^2 GeV, quadratic loop corrections to the Higgs boson are able to increase up to the order of 10^{19} GeV (see Equation 2.1), with an addition of the fact that gravitation can not be excluded at Planck scale anymore. And consequently there is again a huge incompatibility between the numbers as it is seen.

The previously mentioned quadratic loop corrections can be explained as follows.

In the SM, the bare mass of Higgs boson receives quantum loop corrections from all massive particles. For instance, a correction to the Higgs mass from an one-loop containing a fermion f, which couples the Higgs field, can be represented by the corresponding Feynman diagram in Figure 2.2.

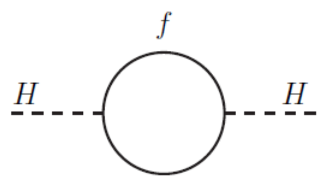


Figure 2.2: One-loop correction containing a fermion(f) to the Higgs mass [12]

This correction takes place when there is a cut-off scale which is responsible from the regulation of the loop integral. This scale can be assumed as ultraviolet cut-off since the SM becomes no longer valid there. In that case, the correction leads a mass difference between the physical and the bare mass of the Higgs boson as below:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + ... \tag{2.1}$$

From Equation 2.1, a quadratic sensitivity to the cut-off energy scale is apparently seen, Λ_{UV}^2 represents the ultraviolet momentum cut-off here and λ_f represents the Yukawa coupling for fermion. Due to the fact that, the Λ_{UV}^2 cut-off has the order of the Planck scale (10^{19} GeV) and according to the experimental results it has been concluded that the Higgs boson mass is equal to 125 GeV [2], the visible quadratic sensitivity to the cut-off energy scale is a problem here. This huge difference in the order of magnitude of the mentioned scales is since called as "hierarchy problem". However here, one can think that without fine-tuning, related with Equation 2.1, the Higgs boson mass should be close at the TeV scale as expected from the theory. But with fine-tuning, a compatibility between the theoretical value and the experimental value can be obtained, in where this time there is going to be another problem called as, naturalness problem.

2.3 Beyond the Standard Model: Supersymmetry

When it is thought about a beyond theory, as it is indicated before, it makes more sense to have valid reasons to do so. These reasons also bring creativity with themselves in the light of a huge motivation. In previous section, the problems in the SM have been mentioned and they are in enough number to make particle physicists be curious about investigating new theories that can suggest some solutions to the shortcomings of the SM. Supersymmetry (SUSY), as being an extension and beyond of the SM, is a spearheading candidate which can solve many of these problems.

For the theoretical background of SUSY, it can be said that the start was given in late sixties, early seventies. It was firstly proposed by Miyazawa and the idea was developed by strong theoretical contributions from many reputable scientists, Gervais and Sakita [13], Golfand and Likhtman [14], Akulov and Volkov [15], Wess and Zumino [16], Salam and Strathdee [17] as well as Haag, Lopuzansky and Sohnius [18, 19].

There is also an experimental history for SUSY that has to be mentioned. Even if for the SUSY particles, which are mentioned in details just after a couple of sentences, no signal has been discovered yet, the strong motivation to search for the discovery of them still continues. By considering the discovery conditions of the SUSY particles, the experiments have been tried to be carried out by developing brand new technologies in many experiments such as UA1 (SPPS machine at CERN), ALEPH - DELPHI - L3 - OPAL (LEP-CERN), CDF - D0 (Tevatron at Fermilab), H1 - ZEUS (HERA-DESY) as well as including CMS and ATLAS (LHC-CERN) until now (genereally, their features change due to their collision i.e. center of mass energy limits and type of the colliding particles) [20].

SUSY basically depends on a symmetry between two basic kinds of the particles in the SM, fermions and bosons. It introduces a mathematical mechanism that provide a symmetry such as:

$$Q|Fermion\rangle = |Boson\rangle \tag{2.2}$$

$$Q|Boson\rangle = |Fermion\rangle \tag{2.3}$$

where Q letter in Equations 2.2 and 2.3 is the operator that correspond to generator of SUSY.

SUSY carries out introducing a symmetry between fermions and boson in the SM by assigning a "superpartner" to each fundamental particles in the SM. These superpartners in SUSY are identical to their partners in the SM by having the same quantum numbers but except their spin numbers and, corresponds to the particle symbols of these superpartners, a "$\sim$" sign at the top of the partner particle symbols in the SM. To emphasize whether a superpartner introduced in SUSY is a fermion or boson, one can undertand this difference by paying attention to the names of the superpartners. In SUSY, superpartners are named due to some rules. In the light of these rules, by prepending a (s) to the fermion names in the SM for scalar superpartners in SUSY, e.g. (s)quark and (s)lepton, and by appending a suffix (ino) to the names of bosons in the SM e.g. Higgsino or gaugino, all these superpartners can be named.

It is said that SUSY is a symmetry between fermion and boson but if it is preferred to approach in more technical way, SUSY actually is a symmetry between the degrees of freedom of particles which include also spin. For example a spin 1/2 quark in the SM is associated to two scalar superpartners $\widetilde{q}_L$ and $\widetilde{q}_R$, for the corresponding the SM fermion where R and L indicate the chirality of them [21]. However in SUSY, the superpartners of these particles are scaler with zero chirality values. In addition, for another feature of the SUSY partners of these particles, it can be said that since no signal refer to any SUSY particles has been discovered yet, this shows superpartners in SUSY can not have the same masses with their partners in the SM. This non-symmetric mass difference is explained by symmetry breaking of SUSY. In Table 2.3, particles in the SM and their superpartners in SUSY can be seen with their spin numbers.

Table 2.3: Fundamental particles in the Standard Model and their superpartners in Supersymmetry [22]

Quarks	Spin (1/2)	u	d	c	s	t	b
Squarks	Spin (0)	$\widetilde{u}$	$\widetilde{d}$	$\widetilde{c}$	$\widetilde{s}$	$\widetilde{t}$	$\widetilde{b}$

Leptons	Spin (1/2)	e	ν_e	μ	ν_μ	τ	ν_τ
Sleptons	Spin (0)	$\widetilde{e}$	$\widetilde{\nu_e}$	$\widetilde{\mu}$	$\widetilde{\nu}_\mu$	$\widetilde{\tau}$	$\widetilde{\nu}_\tau$

Gluon	Spin (1)	g
Gluino	Spin (1/2)	$\widetilde{g}$

Photon	Spin (1)	γ
Photino	Spin (1/2)	$\widetilde{\gamma}$

W boson	Spin (1)	$W^\pm$
Wino	Spin (1/2)	$\widetilde{W}^\pm$

Z boson	Spin (1)	Z^0
Zino	Spin (1/2)	$\widetilde{Z}^0$

Besides the superpartners introduced in Table 2.3, SUSY also requires additional Higgs bosons in order to prevent new divergences. With these new Higgs bosons, not surprisingly, the superpartners associated with them are also showing up in this extended beyond theory.

Table 2.4: New Higgs bosons presented in Supersymmetry and their superpartners [22]

Higgs bosons	Spin (0)	$\mathrm{H}^0, h^0, A^0, H^{\pm}$
Higgsinos	Spin (1/2)	$\widetilde{H}^{\pm}$, $\widetilde{H}^0_{1,2}$

In SUSY some other new particles, which are formed by the linearly combined Higgsinos and gauginos are also introduced. From Table 2.5, these mixtured particles can be seen [7, 22].

Table 2.5: Particles formed by Higgsinos and gauginos in Supersymmetry[22]

Charginos	Spin (1/2)	$\widetilde{\chi}^{\pm}_{1,2}$
Neutralinos	Spin (1/2)	$\widetilde{\chi}^0_{1,2,3,4}$

With all these idiocratical features, SUSY is a really strong candidate suggesting rational solutions to the some of the deficiencies in the SM as explained in Sections 2.3.1 and 2.3.2.

2.3.1 Solutions to Experimental and Observational Problems

Among the various beyond the Standard Model studies, SUSY is one of the leading approaches used to obtain a candidate for the dark matter. But how does SUSY achieve that?

It is known that in the SM, some quantum numbers are introduced including baryon and lepton numbers. These numbers are conserved in the particle interactions where they should be checked due the particle types involved in them. However due to their heavy masses, sparticles decay into the SM particles and intrinsically this ending brings a non-conservation in baryon and lepton quantum numbers in SUSY events. Also these events offer proton decays in a very short time period which does not match with the experimental values. By introducing a new parameter, R-parity, formed by some of the quantum numbers with the formula $R = (-1)^{3B+L+2S}$, a conservation is provided in SUSY events and a symmetry shows up with it. R-parity number equals to 1 for the SM particles and it is -1 for the SUSY particles. With this symmetry, the events that include unexpected proton decays in a very short time period can be excluded. These excluded events are the ones where baryon and lepton numbers are not conserved. As a consequence of this phenomenon, the production of SUSY particles in pairs becomes one of the outcomes. Besides that, by having an odd R-parity the lightest supersymmetric particle (LSP), since it can not decay into any other single SUSY particle and also a pair of the SM particles, it naturally becomes a dark matter candidate by being a stable sparticle [23, 24].

In the recent experimental results of astrophysics studies, it is found out that researches related with antimatter-matter relation, i.e. baryon asymmetry problem, can be solved by the light of dark matter studies. By introducing new explanations for the dark matter, it is already indicated that SUSY is one of the most promising beyond the SM extension among the others and hence in [25] a result explained as baryon and dark matter are generated from the same origin based on the precision measurement of the fluctuation of the cosmic background radiation, can be a spark to solve the baryon asymmetry problem. With this approach and the others like [26], baryon asymmetry is thought to be understood by brightening the dark matter problem via SUSY [27, 28].

The three generations of fermions and leptons in the SM have been observed in experiments so far but the reason or reasons lie/s beyond this generation problem is/are still mystery and impulsion for looking more deeply in theory. It is already said that in Supersymmetry part, SUSY proposes superpartners to the particles in the SM and hence it is expected from SUSY to be observed same number of generations for sparticles too. With the discovery of these sparticles by bringing an explanation to the generations in SUSY scientist hope to solve generation problem in the SM also. In addition, since all the particles in varied generations interact with the Higgs field differently, they have observable mass distinctions as can be seen from Table 2.1 such as for leptons; tau lepton is almost 3500 times heavier than the electron and for the quarks, the top quark is about 80.000 times heavier than the up quark which is really a huge number in particle physics word actually. But as the experimental and theoretical observations related with SUSY get more concrete, the probability to find a solution to generation and mass problem in the SM is expected to increase [30].

2.3.2 Solutions to Theoretical Problems

The GUT problem in the SM can be solved with a supersymmetric extension in the theory. The SM scale of GUT permits unpredicted proton decay events in theory even if experiments have showed that these are not possible. So an unification for the coupling constants becomes impossible. However it is already mentioned that in R-parity conserved SUSY theories unpredicted proton decay events are excluded and with higher mass scales in SUSY, an unification for the three fundamental interaction takes place in theory. From Figure 2.3, on the left the non-unification in the SM is showed whereas on the right the GUT is possible at nearly 10^{16} GeV through the changes in the energy dependence of the couplings for SUSY [31].

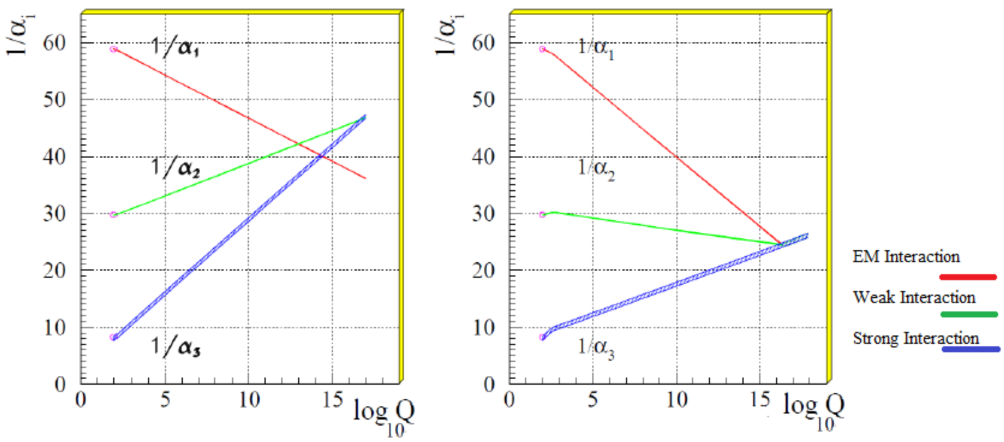


Figure 2.3: The GUT possibilities for both the Standard Model and Supersymmetry. In graphs, 1/a is representing the inverse coupling constant where $log(Q)$ is a function of energy. Figure is adapted from [32].

In Section 2.2.2, it is said since the method of covering it in the SM has not been figured it out yet, gravitation is not included in the SM. Particle physicists belive that a beyond the SM approach solves this problem and SUSY is one of them as expected.

By introducing sparticles, SUSY also requires a spin-2 massless particle named as graviton which has a superpartner named as gravitino. This theory has a specialized name as Supergravity and it also proposes the mediator (force) of graviton, known as gravity [33, 34, 21].

The last concept, which the SM remains incapable to explained it but SUSY suggests a solution, is hierarchy problem. As it is mentioned before, hierarchy problem is related with the huge difference in the order of magnitude of energy scales. Hence for a solution to solve that problem, it must be able to diminish that huge difference without bringing a naturalness problem with itself in contrast with the SM. By introducing a symmetry between fermionic and bosonic fields, SUSY makes the additional quantum loop correction represented in Figure 2.4 to Figure 2.2.

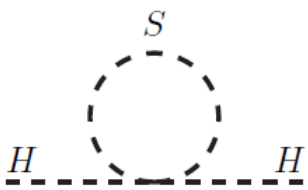


Figure 2.4: One-loop correction containing a scaler (s) to the Higgs mass [7]

With this approach now the Equation 2.1 has a new additional extended correction:

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda_{UV}^2 - .....] \tag{2.4}$$

If we compare Equation 2.1 and Equation 2.4, it can be seen that the index for λ is changed due to the change in particle interest such as a fermion is a scaler now, caused by the symmetry introduced in SUSY. Also with $\lambda_S = 2|\lambda_f|^2$, it is clear that a pair of scalers in SUSY corresponds to a fermion in the SM. Finally, by adding up both of the Equations, 2.1 and 2.4, the quadratic sensitivity in cut-off scale is removed naturally to annihilate the hierarchy problem.

In previous paragraphs, the solutions for the SM problems presented by the SUSY can also be presented in a more compact form indeed, as proposed by the Minimal

Supersymmetric Standard Model (MSSM) [36]. In particle physics, there are more than one SUSY models used by the particle physicists in order to explore new physics. MSSM is one of the widely used models among the other ones.

As it is expected, the numbers of particles and parameters increase by bringing an extension to the SM and by being able to minimize particle and parameter numbers as much as possible (i.e. from 105 parameters to 19 parameters), a more preferable MSSM model, phenomenological MSSM (pMSSM) is one the most prominent models [35]. Besides being able to decrease these numbers, pMSSM accepts $\tilde{\chi}^0$ (the LSP) instead of sneutrino as a dark matter candidate since the experimental results show that if the sneutrino was the dark matter, it must have been detected until now [37].

With solving hierarchy problem, introducing a dark matter candidate and graviton, providing the GUT and etc., MSSM creates an another crucial point which is known as the conservation of R-parity. In different searches and analysis for SUSY, R-parity can be accepted as conserved or not. As an example, R-parity is assumed to be conserved for the analysis involved in this thesis, since MSSM is taken into account for the theoretical foundation.

The fact that SUSY particles have not been discovered yet is leading a symmetry breaking at beyond of the current experimental limits. In other words, this can be also read as SUSY is not the exact symmetry; the superpartners do not have the same mass (due to a mass symmetry for instance) with the particles in the SM and this leads a symmetry breaking at beyond of the current limits. But before going through this breaking, it is better to talk about the most fundamental symmetry breaking in particle physics.

In order to explain the existence of massive gauge bosons which also can be seen from Table 2.1, a mechanism called Higgs Mechanism was proposed at the beginning of 60's. For the historical journey of this one of the most important milestones in particle physics world, [38] can be a good guide for whom may be curious about it.

Being able to explain the existence of massive gauge bosons, this mechanism is also able to brighten the foundation of the Electroweak Symmetry Breaking (EWSB).

It is known that the mathematical foundation of the SM is based on SU(3)xSU(2)xU(1) symmetry groups. In that group while SU(3) is corresponding to strong force symmetry group, SU(2)xU(1) is representing the combination of electromagnetic and weak forces. The fact that, SU(3)xSU(2)xU(1) is not able to explain the existence of massive gauge bosons, is actually the reason to break a symmetry, in other words this also means a breaking of the mass symmetry. This breaking of the mass symmetry occurs in SU(2)xU(1) part of the fundamental symmetry group spontaneously and hence it is named as Spontaneous Symmetry Breaking (SSB). After the realization of SSB, there is a change in the ingredient of the number of degrees of freedom (DOF) for the electroweak part of the symmetry group by keeping the actual (previous) number of DOF the same. The new ingredients are known as, two massive $W^{\pm}$ and Z^0 bosons, a scaler Higgs boson, a massless photon. Here as it seen, photon maintains its massless states hence the Higgs Field does not interact with it and keeps its symmetry during the EWSB and it does not couple to the field as expected [39].

A visualization of SSB is shown in Figure 2.5. A symmetry is provided as long as the Higgs potential is at its maximum value and the mass fields are zero, ε_{max}, i.e. $\phi_{1,2} = 0$ however when it starts to take different values than its maximum, i.e. $\phi_{1,2} \neq 0$, the symmetry is not provided anymore in where this process leads $W^{\pm}$ and Z^0 bosons to gain their masses. Last but not least, if one wants to build a cause effect relationship scheme shows that the dependence between Higgs Mechanism, EWSB and the existence of the massive gauge bosons then,

$$\text{Higgs Mechanism} \Rightarrow \text{EWSB} \Rightarrow \text{Existence of Massive Gauge Bosons}$$

might be a good representation.

Now it is appropriate to go back to symmetry breaking in the MSSM.

The Lagrangian of the MSSM is able to construct a basis to the particle mass spectrum of MSSM thanks to the expected symmetry breaking based on the fact there have not been any observed SUSY particles yet in current symmetry breaking limits defined in the SM. Hence, the symmetry breaking in the MSSM is provided by adding new terms (to the Lagrangian) which cover the cancellation of the quadratic divergence showed in Equation 2.1 and also extend the mass limits of the SM. This feature of new terms (conservation of the cancellation) leads to call the breaking as "soft" symmetry

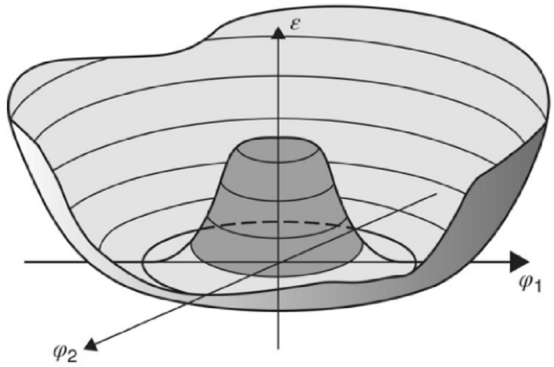


Figure 2.5: A visualisation of Spontaneous Symmetry Breaking. Figure is taken from [40].

breaking.

Although the conservation rule mentioned in previous part is still valid for the Higgs boson mass in scope of this soft symmetry breaking, it is not able to protect Higgs boson mass from a logarithmic contribution of top (t) mass and stop ($\widetilde{t}$) mass as it seen below equation:

$$(m_h^2) \simeq M_Z^2 cos^2(2\beta) + \frac{3m_t^4}{2\pi^2 \upsilon^2} ln(\frac{m_{\widetilde{t}}^2}{m_t^2}), \quad where \ m_{\widetilde{t}}^2 = \sqrt{m_{\widetilde{t}_1}^2 m_{\widetilde{t}_2}^2} \quad and$$

$$\beta = arctan(\tfrac{\upsilon_u}{\upsilon_d}), \quad where$$

$$\upsilon_{u,d} = vacuum\ expectation\ values\ of\ Higgs\ Boson\ giving\ mass\ to\ u\&d\ quarks \quad (2.5)$$

Frow the Equation 2.5, a mass contribution from t and $\widetilde{t}$ into the Higgs mass is obviously seen. This a reason for focusing on the decay mode $\widetilde{t} \rightarrow t\ \widetilde{\chi}_1^0$, in a harmony with the research carried on the thesis [39]. This mass dependency has been limited with the observation of Higgs boson mass in 2012 and in this scope, it can be said that the considered SUSY models in the studies are needed to provide this observation limits for sure. For instance, assuming this Higgs boson as the lightest Higgs boson is a way to ensure a non-conflicting case [41]. The mass limits, which are taken into account for this thesis, of $\widetilde{t}$ and $\widetilde{\chi}_1^0$ are mentioned in Figure 2.6 and in Section 3.2 with more details.

Even if the analysis conducted in this thesis is given explicitly in Chapter 4, before going through all the steps taken in it, actually it is better to explain "why this previously mentioned decay mode is crucial for this analysis" at this point. Among all the motivational reasons that encourage physicists to search for SUSY particles, proposing a dark matter candidate draws the most of attention without doubt. Hence, the decay modes include the single lepton and di-lepton final states, which propose $\widetilde{\chi}_1^0$ as the dark matter candidate, are studied in this thesis. For a more experiment based background, due to the current data taken from the Planck Satellite it is obvious that the numeric result on relic density measurements shows the relic density as $\Omega_{dm} = 0.1194 \pm 0.0022$ [42, 43]. Besides being the most precise measurement, theoretically it is also possible to reach this observed data by choosing $\widetilde{\chi}_1^0$ as a the dark matter candidate and a coannihilating superpartner (i.e. $\widetilde{\tau}$, as it is chosen for signal sample in this thesis and [39]), that is very close this particle in its mass range. This superpartner is needed to be attached to the decay channel since by doing so, it becomes solely probable to get the relic density in its experimentally observed range. The scenarios in which $\widetilde{\tau}$ comprised analyses are known as "s-tau coannihilation scenarios (STC)". There are more than one STC approach in SUSY analyses and in this thesis, STC8 benchmark point is preferred with $m_{\widetilde{\tau}}$ = 107 GeV and $m_{\widetilde{\chi}_1^0}$ =96 GeV (i.e. $\Delta m \simeq$ 11 GeV) [44, 43] to be studied as the "signal" sample since the aim is to see this SUSY signal at high luminosity collisions. In Figure 2.6, STC8 mass spectrum is shown. Here, another important point shows up; $\widetilde{t}$ mass. Because of the fact that at the LHC, the total cross-section for SUSY events are taken into account with a dependacy in lightest $m_{\widetilde{t}}$, this particle mass is automatically becoming a key factor in the analyses. In STC8 for instance, $m_{\widetilde{t}}$ almost pushes the limit of 1 TeV scale as it is clearly seen from Figure 2.6 [39, 43]. However if one consider the exclusion limits presented in Section 3.2, then the fact that these limits are valid for the simplified SUSY models, is needed to be kept in mind in order to make STC8 still in use for non-simplified SUSY studies [44].

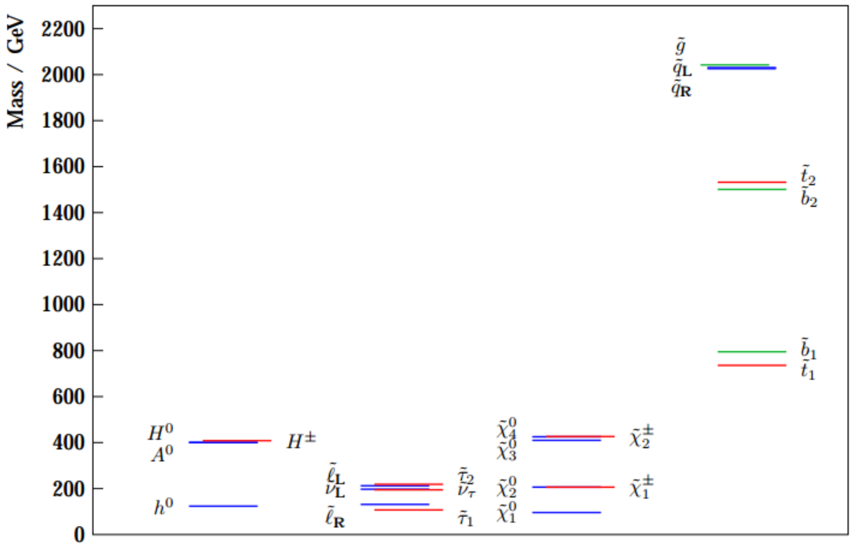


Figure 2.6: STC8 mass spectrum, $m_{\tilde{t}} = 736$ GeV. Figure is taken from [43].

2.4 Current Limits of the Large Hadron Collider (LHC), the Importance of the Higgs Discovery and Motivation of This Research

The limits for the searches done in experimental physics is bordered by the underlying theory and this is also valid for the experiments carried on particle physics as expected. Being in the scope of these limits, the instruments in particle physics experiments; colliders, detectors and etc., are designed by thinking also the future validation and discovery possibilities of the currently studied theories as much as possible. However, even if they are designed to be able to exceed obstacles, the results acquired at the end can not be promising and matched with the expected outcomes for each time. And the results of the SUSY searches have been faced with this case until now.

At this point the most important thing is the fact, considering the disappointing results as a motivation to build even more sophisticated and advanced machines. Also the scientist are sure about that there are plenty of new progresses which are waiting to be discovered and going to illuminate beyond the SM.

About SUSY, it is not that easy, even can be harder than expected, to search for it in the experiments because of the complexities that it brings itself as limitations of the experiments. These complications can be summarized as below:

- Introducing more massive superpartners (at TeV scales) and according to reasons presented in Section 2.3.1 and 2.3.2, the center of mass energy and production cross-sections are needed to be increased as much as possible. Taking two years data at center of mass energies 7-8 TeV and integrated luminosity $\simeq$ 30 fb^{-1} [45, 46, 47], the LHC has shown that these values were not enough to discover these particles or anything that refers to beyond the SM but the Higgs boson. After the Long Shutdown 1 (LS1), the LHC was been running since December 2018 again with the center of mass energy ($\sqrt{s}$) at 13 TeV even if it has been designed to be capable at $\sqrt{s}$ = 14 TeV too and for the integrated luminosity it has been expected (and concluded) to be around 150 fb^{-1} first, but it will be able to reach 300 fb^{-1} and even to 3000 fb^{-1} also. Due to these impressive values and also by considering the all information and discoveries done with past possibilities, it must be exciting to wait for exploring new hints refer beyond the SM. For more detailed information about the current and future limitations at the LHC, Chapter 3 is more appropriate to be reviewed.

- The long chains presented in sparticle decays make possible to come up to different type of SM particles (quarks/jets(hadronized quarks), leptons etc.), also the R-parity conservation mentioned in Section 2.3.1 requires the production of sparticles in pairs as it is said before. Besides, having SM particles with the LSP, since it is known as stable and a weakly interacting particle, all of these features are making the searches for SUSY hints difficult. Because of the weakly interacting feature of LSP, chasing LSP signatures at the detectors becomes a hard issue to deal with it. Hence, the searches for the LSP is depending on missing transverse energy (Section 4.4), like it is already done in the neutrino searches. So one must think and design very powerful microscops (detectors) which have high resolution in order not to lose sight of all these particles. This fact leads to detectors becoming huge in dimensions and costly in prices [21, 39, 48].

Everybody in particle physics world can confirm that the discovery of the Higgs boson has been a milestone for the particle physics searches done until now and also for the future studies that are going to be done in the next years. Obviously the experimental confirmation of the Higgs boson confused the minds about the expectations related with the SUSY at the beginning but later, it has been confirmed that the Higgs boson mass (at 125 GeV) is still supporting SUSY searches.

In accordance with the specifications made for the discovered Higgs boson, it is convenient to classify it as a candidate for the lightest Higgs particle, h^0 among the other ones proposed by the SUSY (the all Higgs particles in SUSY can be seen from Table 2.4). Hence besides the all yield brought by itself such as, completing the missing parts of the SM particle table, explaining the origin of mass and maybe the one of the most important, enhancing the reliability of the LHC (especially to encourage the investments for future studies), it would not be wrong to say that discovery of the Higgs boson has opened the new doors through the unknown world of the beyond studies [49, 50, 51, 52].

Under the light of previously mentioned journey of the SUSY, the motivation to look for any hint based on it is still surviving. Being the most reliable, common and valid approach, especially for the non-solved problems in the SM, it is not surprising that SUSY is accepted as a preferable beyond the SM theory. Also with the help of upgrades and improvements performed in the experimental instruments (colliders, detectors etc.) there is no need to avoid to look hopefully for some hints refer it.

In the last item placed at the constraints for the LHC part, it is pointed that there are a lot of different options for the possible sparticle decays. Here the thing is choosing the most appropriate one for the specified search and what you want to see at the final state i.e., the stabilized particles. It is also important to consider the excluded limits resulted by the previous and current studies carried on the experiments. Therefore, in this research, within a common approach taken into account in thesis [39], the single lepton channel is considered with up to 6 jets (2 of them are tagged as b-jets) and of course to catch a $\widetilde{\chi}^0$ as a dark matter candidate, the missing transverse energy is included as a kinematic variables. This channel is examined under the limitations of some specific and currently used topological items such as M_T, M_{T2}^W and $topness$ which are introduced in more details in [39], and with the commonly used selection values in order to eliminate the background event as much as possible. However our aim is to emphasize the future SUSY possibilities for the high luminocity LHC (the HL-LHC) programme especially for this specified channel rather than examining the effect of some specific and curently used topological values as it is done in the research [39]. In addition to that, pointing the most effective selection values according to the calculated various SUSY significances by using the physical restrictions promised to be achived at the HL-LHC is another aim of this research and hence, two different cut options for E_T^{miss} and H_T are also examined at No pile-up, 50 pile-up and 140 pile-up cases. Lasty, all these purposes for the analysis in this thesis are done for di-lepton channel (except the selection values applied on topological items, M_T, M_{T2}^W and and $topness$) since di-lepton selection is also known as one the most preferable and promising decay channels for the SUSY searches [44].

CHAPTER 3

EXPERIMENTAL SETUP AND ASSESSMENTS ON THE PAST STANDARD MODEL AND SUSY RESULTS

Following the theoretical background given in Chapter 2, one of the most powerful experimental configurations and the largest particle accelerator that can be engendered within the boundaries of today's technology, the Large Hadron Collider (LHC) is introduced in Chapter 3. As it is stated previously, in order not to miss any clue that delineates beyond SM searches, well designed powerful detectors are taking place in the LHC since the earliest days of this journey. By enhancing its technical abilities, the LHC is expanding its capabilities to explore the new realm of particle physics. Hence to hold a view related with the current and future scope of the LHC, in this chapter major experimental outcomes and principal results based on new physics searches from Run 1 assist us to proceed the last section which covers the High Luminosity LHC project, actually known as the future (upgraded) experimental setup for the research conducted in this thesis.

3.1 The Large Hadron Collider

The story of the LHC actually started with a previously used (between the years 1989-2000) machine named as the Large Electron Positron Collider (LEP). During the years 1983-1984, with the discovery of $W^{\pm}$ and Z^0 bosons, Super Proton Synchrothon (SPS) proved its reliability in its own frame then scientists started to think about building a new machine that could be able to exceed the current borders in experimental particle physics and to collide particles with the maximum center of mass energy that could be reached until those years. Due the promising achievements acquired at SPS, by the middle of 80's scientist were also encouraged with the results and decided to start the construction for the new machine, LEP, as soon as possible. Since the idea was to accelerate the particles as fast as probable, the layout of the machine was designed in that motivation. In order to realize this purpose a $\sim$ 27 km (circumference) tunnel which has a variable depths between 50 to 170 m was built. The experiments conducted at LEP were again successful enough to reach a center of mass energy ($\sqrt{s}$), 209 GeV, were able to clarify some missing parts in the SM and also able to make precision measurement especially for the masses of $W^{\pm}$ and Z^0 bosons, yet it was not still adequate to go advance and look beyond the SM. At this point, scientist were agreed on the idea that increasing the mass of colliding particles was a good attempt, so instead of electron and positron, protons were decided to be accelerated in collisions. Again a new machine was needed to make possible this idea however before this, it was accepted that the circumference of tunnel built for the LEP was appropriate to be preferred for this brand new machine as well. In spite of this fact, different and more powerful machines were needed to be implemented inside of the tunnel expectedly. This newly built machine was placed as two diversified and separate rings that can make the particles (protons/heavy ions) accelerate in the opposite direction and make them collide head-to-head at four certain points of intersection. These point of intersections are actually named with the four heading experiments (detectors) conducted at CERN (i.e. at this superconducting hadron accelerator), in order of their sizes, A Toroidal LHC Apparatus (ATLAS), A Large Ion Collider Experiment (ALICE), Compact Muon Solenoid (CMS) and Large Hadron Collider beauty (LHCb). At first, scientists were thinking to turn the machine on in 2008 and with the planed schedule, the machine seemed to be ready to go into operation. However things did not go as planned and an electrical problem showed up in the magnet system which became actually a leading source for another problematic issues in the other components of the machine. Hopefully in an interval that can be counted as a short time period for scientific improvements, after almost one year, the machine now was ready to create the world's fastest protons/heavy ions to get the highest center of mass energy at the collisions.

Placed in the French-Switzerland border yet closer to Geneva, the Large Hadron Collider was started to be constructed in 2000 at CERN which is an acronym in French of "Conseil Européen pour la Recherche Nucléaire", means "The European Organisation for Nuclear Research". In this world's largest particle experimental complex, it is possible to collide both protons and heavy lead ions while for the first one the center of mass energy is $\sqrt{s} = 14$ TeV with a maximum peak luminosity = $10^{34}\ cm^{-2}s^{-1}$, for the second one per nucleon pair it is $\sqrt{s} = 5.5$ TeV with a maximum peak luminosity = $10^{27}\ cm^{-2}s^{-1}$, since it must be much harder to accelerate heavy lead ion as it is done for the protons, not surprisingly.

At the beginning, the purpose of constructing such an amazing machine was to verify the theory lies behind the SM by making precision measurements and especially to explore the Higgs Boson but aiming the searches for beyond of them also has been a part of this journey. The LHC machine can be seen from Figure 3.1 with its subsections and auxiliary facilities; the main detectors (experiments) and accelerators take part in it.

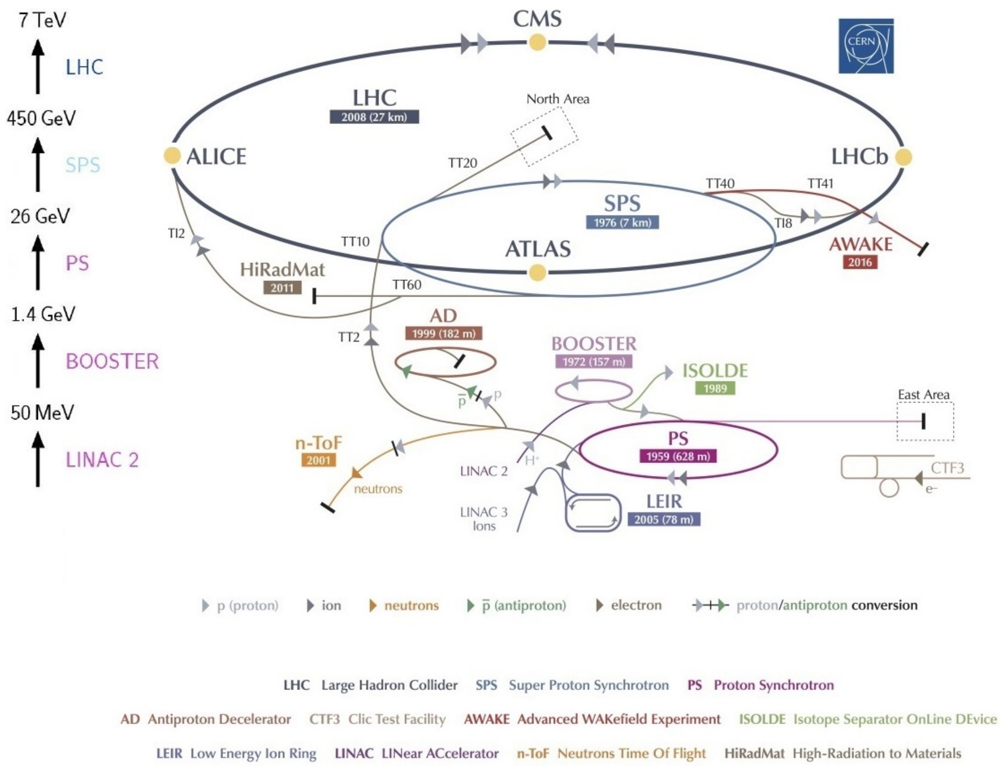


Figure 3.1: Schema of CERN experiment facilities including names of detectors and accelerators. Under the names of accelerators the activation year of them is indicated with their circumferences. Figure is adapted from [53].

Under the light of all previously mentioned purposes, the LHC is not able to accelerate particles (from here, just protons are assumed as the accelerated particles to make easier the expression) from the beginning of the acceleration process but it is capable to realize it gradually in order to reveal its potential in maximum level.

Proton beams are able to fill both of the LHC pipes in almost 4 minutes and 20 second by circulating inside of the ring 11245 times per second. Also in scope of the current energy limits that the LHC can achieve, each proton beam is able to reach 6.5 TeV in 20 minutes after the injection from SPS. Finally after reaching the desired energy, they collide at four intersection points as, 20 effective collisions every crossing times 31,6 millions crosses/sec, 600 million times collisions per second, i.e. they crush at the inside of four detectors with a center of mass energy, $\sqrt{s}$ = 13 TeV, as ensured for collision frequency of beams or bunches. At the end for a total time period of the turnaround of these steps, it is required almost 70 minutes to past indeed. But how is this process provided or what allow/allows the beam to act as it doees since we want particularly like the way it does actually. With a basic approach it is better to give an answer to these questions as follows: For both of the aims, keeping proton beams aligned and making them intersect (collide) at the detectors are provided by the versatile magnets, as it is expected if one thinks about today's accelerator technology [54, 55]. For a detailed information and a further reading about the design and types of magnets at the LHC, one can prefer to have a look at [56, 57].

It is underlined that design of a collider is an important (significant) factor in enhancing the performance of the experiments however the determination of the beam quality is quite essential though. Hence, besides the magnet technology and some other technical details (parameters) make the LHC such a great machine, there are some main beam parameters such as number of events, luminosity and cross-section that determine the beam quality and the performance of the experiment too, as a matter of course.

Number of events is one of the elements that needed to be considered. It is known that huge number of collisions are happening at the experiments in a very short time intervals but it is not possible to consider all of them for the searches, since each of them are serving to common or distinguished analyses for sure. Therefore, particle physicists are interested in specific collisions for the idiosyncratic analyses and they call these particular collisions, **event**.

In the determination of the total number of events for experimental particle physics measurements, it is required to introduce some other characteristic, crucial phenomena such as luminosity and cross-section.

Luminosity is approached in two ways; instantaneous, i.e. peak and integrated (total) luminosity.

Instantaneous luminosity (L) refers the largest/peak value for the number of protons that can be achieved to have per a specific interaction area at an instant time. The LHC is capable to get a peak luminosity, as indicated before, $10^{34}\ cm^{-2}s^{-1}$, yet in 2012 the machine was able to provide $7.7x10^{33}\ cm^{-2}s^{-1}$ for example. Instantaneous luminosity is expected to be decreased as time passes by since it is directly proportional to intensity of the beam which is a concept that is reduced by the actualized collisions and some deficiency caused by scattering, even if beams have long lifetime. But of course this is not a reason to quit yet a encouragement to reach the previously targeted luminosity limits. LHC does this by having a circulating beam with a current (0.58 A) and energy when it is in the operation. Also the huge number of protons kept in each bunch, intrinsically in both of the beams, help the LHC to collide particles in expected peak luminosities which can be calculated from the formula;

$$L = \frac{1}{4\pi} \frac{N_p^2 n_b f_{rev} \gamma}{\epsilon \beta^*} F \tag{3.1}$$

where N_p is the number of particles contained per bunch, n_b is the number of bunches which circulate with a frequency f_{rev}. And γ is the relativistic gamma factor, whereas ϵ refers to normalized transverse beam emittance with β^* which is known as the beta function at the collision point. F contributes to take into account the reduction caused by the beam crossing angle at the interaction point. If it is aimed to reach the number indicated before as, L = $10^{34}\ cm^{-2}s^{-1}$ with using the formula in Equation 3.1, it is better (needed) to use the values in [58], corresponding the parameters in Equation 3.1.

Even if it is possible to benefit from the huge number of protons, i.e. high luminosity in the collisions, there is another physical outcome named as **pile-up** and it can be counted as a challenge that affects the analysis techniques. Pile-up describes expected/occured number of interactions that take place per bunch of beam crossing and it is a confusable concept that likely to be understood as the additional interactions (vertices) originating from the soft or hard pp collision which has a special name as **underlying event** [59]. In an optimistic way, it is appropriate to dismiss effect of pile-up in the analysis with high luminosity. For example in this thesis since the SUSY search is taken into account for the HL-LHC project, it is unavoidable to consider pile-up events yet No pile-up case is also considered. In results section (Chapter 4), the detailed results for the study in this thesis with respect to preferred number of pile-up events are presented. In order to check the relation between pile-up events and the luminosity, Figure 3.2 can be seen as below:

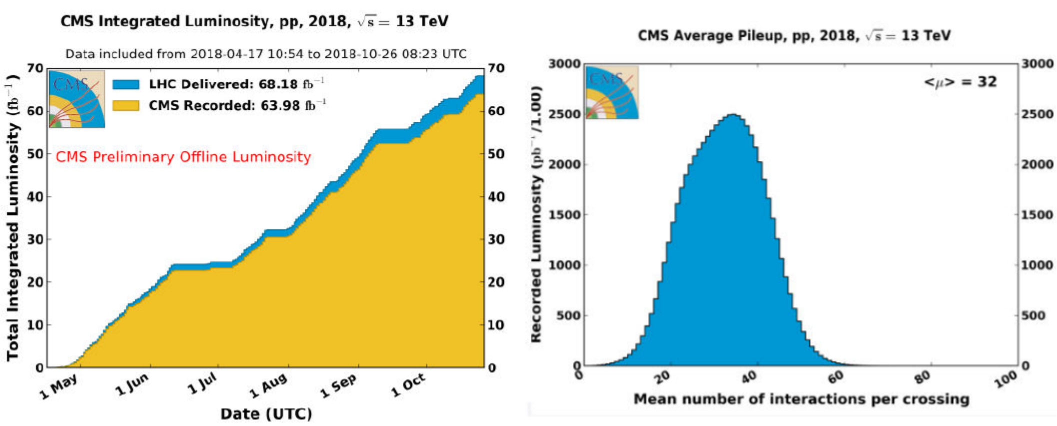


Figure 3.2: The integrated luminosity and pile-up data of the CMS for 2018, recorded at $\sqrt{s} = 13$ TeV. Figures are adapted from [60].

After explaining the peak luminosity, the **total/integrated luminosity** comes next. As it is clearly predictable from its name, integrated luminosity represents the total number of collisions, i.e. a numeric value that can be obtained by integration of the luminosity ensured by the collider over some time. Hence this relation can be expressed as;

$$\mathcal{L} = \int L(t)dt \tag{3.2}$$

For the numeric values of the integrated luminosity that have been recorded by the LHC, some examples can be given as $\mathcal{L}$ = 6.1 fb^{-1} at $\sqrt{s}$ = 7 TeV and 23.3 fb^{-1} at $\sqrt{s}$ = 8 TeV. Also from the plot in Figure 3.2, a detailed view on luminosity measurement of the CMS in 2018 can be seen. The numbers are also coinciding pretty much with the results obtained in the ATLAS experiment [61].

By bringing an explanation into peak and integrated luminosity, the total number of events in interest, i.e. desired process, produced at the largest collider (or any other) can now be formulated as;

$$N_{event} = \sigma_{event} \times \mathcal{L} \tag{3.3}$$

In Equation 3.3, there is an additional parameter, σ_{event}, named as **cross-section** which is in units of area since it refers to the cross-section area of the particular processes (events) in interest. This can be interpreted also as the production probability of aimed particles revealed from a collision of a pair of particles.

By all of these parameters, it is also possible to get **event rate** of the targeted processes by taking a simple time derivative of the number of events, $\frac{dN_{event}}{dt}$.

3.1.1 Major Experiments at the LHC

At CERN Accelerator Complex, as it is mentioned before, among the whole other perfectly designed and performed experiments there are four leading ones which are in operation for general or special purposes corresponding to desired physics searches. These experiments are performed by four main detectors, in scope of previously mentioned design/beam parameters of the LHC, including with the limits introduced by detectors themselves also.

In alphabetical order these four main experiments (detectors) are listed below:

ALICE (A Large Ion Collider Experiment) Placed 56 meters under the ground at Interaction Point 2 (IP2), ALICE detector is in charge of the studies related with quark-gluon plasma physics and the strong interaction as well. By having 26 m long, 16 m high, 16 m wide, this detector is designed to be capable for working at very high multiplicities too. A detailed info about ALICE can be found in [62].

ATLAS (A Toroidal LHC Apparatus) Being the largest particle detector that ever built, ATLAS was constructed inside of a previously used cavern from LEP era. However due to detector's huge size (46 m long, 25 m high, 25 m wide), the cavern (at IP1) was needed to be modifed first and then it would be possible to situate ATLAS 100 meters below the ground. Serving for multi-general purpose physics searches in range of the SM, ATLAS is in operation to look beyond it also, especially as SUSY searches. Outwardly placed toroidal magnets make design of ATLAS different among the other detectors. A detailed info about ATLAS can be found in [63].

CMS (Compact Muon Solenoid) CMS is one of the two (the other is ATLAS) multi-purpose detectors in the LHC. It is wisely to have two same purpose, yet diversified in technical desing, detectors in order to check and compare the results bilaterally. Hence it would not be wrong to say that even if the CMS is also operant for making precision measurements and validations in scope of the SM, it helps to particle physicists to look beyond the SM, like ATLAS does so. CMS is not as huge as ATLAS, since it has some differences in its technical design. As it is understood from its name, it is slightly designed more "compact" comparing to other ones. Having an onion-like shape, as it is observed for the other detectors too, CMS was constructed at IP5, the IP placed at the opposite side of the ATLAS detector. CMS is at almost 100 meters deep from the ground and its size (21 m long, 15 m high and 15 m wide) enougly covers all interaction regions in itself. A 4T superconducting magnet is able to inclose a wide part of the CMS, including the calorimeters. Especially this feature of the detector differs CMS among the other ones. Being highy capable in the particle detection in the limits set by the LHC, CMS played an influential role in the detection of Higgs boson in 2012. A detailed info about CMS can be found in [64].

LHCb (LHC Beauty) LHCb is specialized for the decays, i.e. events, of particles formed by b and anti b quark contributions. Being one of the four biggest experiments in the LHC, because of its specifications, the layout of the LHCb was not designed as generic as an accustomed detector. The dedication of search for matter and anti-matter asymmetry and violation in CP conservation (A symmetry that explains;

physics laws are invariant under any transformations in particle physics phenomena named as "**C**harge conjugation" and "**P**arity" [65].) make B meson decays (i.e. heavy flavour quark production) field of interest of this detector. Due to the fact that these type of rare decays happen very close (along) to beam line, the LHCb was enlarged (21 m long) as starting from the interaction point through the other direction. Like CMS and ATLAS, LHCb (10 m high, 13 m wide) is located 100 m below the ground but at a different interaction point (IP8). A detailed info about LHCb can be found in [66].

3.2 Highlighted the Standard Model Results and Recent SUSY Status

Considering the huge data ($\sim$ 75 petabytes [67]) collected even during Run 1, it was not inevitable to make influential number of searches and analyses up to now by aiming to understand the particle physics and make essential contributions to it. There have been a lot of studies conducted by all of the experiments at the LHC especially in Run 1 time and beyond any doubt, Higgs boson discovery has taken the most breathtaking moment during that interval. With a confirmation carried on five different decay channels, Table 3.1, scientists have been sure about the final state particles in all of these decay channels are referring the Higgs boson. Besides that, numerously precision measurements have been done in scope of the SM. As a recent instance, the decays of two kinds of B mesons B^0 and B_s^0 to μ^+ μ^- pair are observed at the same ratio predicted by the SM. This observation has been recognized by both the CMS and the LHCb experiments with an excess over 6σ for B_s^0 and 3σ statistical significance for B^0 decays at first [68] and then later, the largest particle detector ATLAS has also contributed to these rare observations, which they keep their unique emphasis depending on a suppressed condition in the SM and also on the likelihood of comprising some traces referring SUSY (or any new physics case), in particular with the branching ratio calculations [69].

Table 3.1: Primary Higgs boson (m_H = 125 GeV) decay channels with corresponding integrated luminosity and statistical significance numbers. Table is adapted from [70]

Channel	Luminosity (fb^{-1})	σ Observed (Experimental)
$H \rightarrow ZZ \rightarrow 4ll$	5.1 + 19.6	6.8 (6.7)
$H \rightarrow WW \rightarrow 2l2\nu$	4.9 + 19.5	4.3 (5.8)
$H \rightarrow \gamma\gamma$	5.1 + 19.6	5.7 (5.2)
$H \rightarrow bb$	5.0 + 18.9	2.1 (2.1)
$H \rightarrow \tau\tau$	4.9 + 19.4	3.2 (3.7)

Run 1 and the beginning of Run 2 were not a productive round for beyond the SM and dark matter searches. Unluckily, there have not been any signs which could have been evaluated under SUSY or new physics roof. Yet even so, it was a helpful period for sure to decide about where to illuminate in target of SUSY, new physics or how it is named, by excluding the parts not showing any beyond of what we know about the SM, the fundamental particles and their interactions.

Traveling through the journey of new physics discovery has been one of the leading motivations from the beginning of first run. On the other hand, having many parameters, many decay channels and so final states too, it is not surprising to see huge number of SUSY signature searches in the papers which all are actually raised thanks to the extreme labor performed by the scientist. After all, by contributing from numerous aspect, bringing fresh ideas in experimental searches of SUSY and excluding the limits in varied SUSY models, it would not be wrong to say during Run 1 and for now, all these studies are gathering at the same point at the end of the day: There have not been any observed clue for beyond the SM and SUSY or, new physics, YET. This "yet" word is important here to be strong enough to keep particle physicist motivated to look forward sedulously.

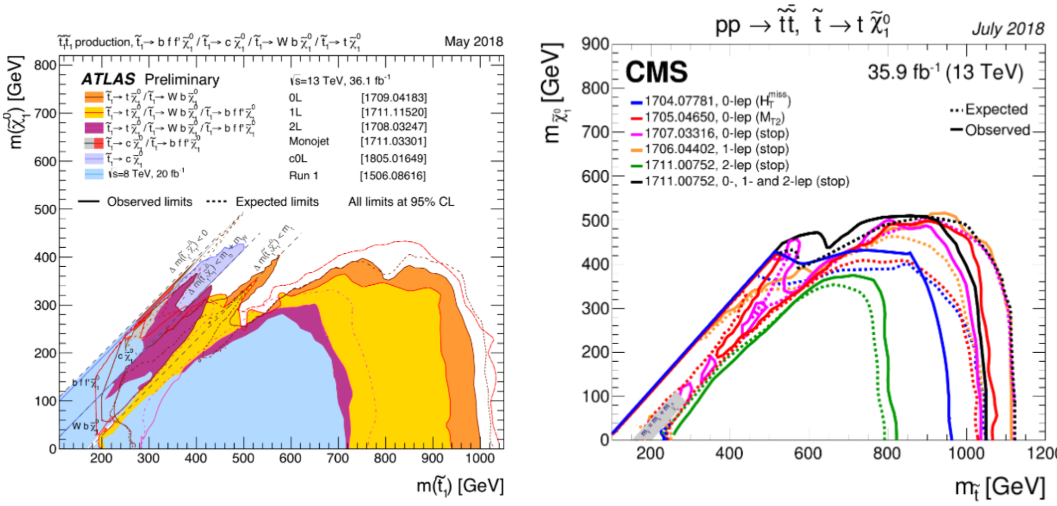


Figure 3.3: Left, at 95% confidence level, the excluded mass limits for direct $\tilde{t}$ pair production in different final states and various analyses at the ATLAS experiment at a center of mass energy $\sqrt{s}$ = 13 TeV. Figure is taken from [71]. Right, At 95% confidence level, the excluded mass limits for direct $\tilde{t}$ pair production in different final states and various analyses at the CMS experiment at a center of mass energy $\sqrt{s}$ = 13 TeV. Figure is taken from [72].

In addition to excluding the mass limits for superpartners included in various final states and models, studies have been conducted so far have provided us to look and focus properly for future studies. For instance in both plots placed in Figure 3.3 it is clear and highlighted that the regions cover very low values for $m_{\tilde{t}}$ and $m_{\tilde{\chi}_1^0}$ and regions with ˜ $m_{\tilde{t}}$ < 1 TeV mass are excluded in scope of the limits of simplified SUSY models due to the collected data at $\sqrt{s}$ = 13 TeV at both CMS and ATLAS experiments.

Here, the previously written motivation, the "yet" word takes the role again. The results reached up with data collected at $\sqrt{s}$ = 7, 8, 13 TeV have provided some promising results such as natural SUSY, which is known as a scenario ensuring the fine-tuning in a very slightly way, is still alive due to the fact that it does not require a light $m_{\tilde{t}}$ [73, 74]. This fact still matches with the excluded regions in Figure 3.3, since the regions present the exclusion limits such as; $m_{\tilde{\chi}_1^0}$ < 500 GeV and $m_{\tilde{t}} \leq 1$ TeV.

Moreover, the results collected up to now have not conflicted with the MSSM in a way that keeping its ability in suggesting solutions as it is mentioned already in Sections 2.3.1 and 2.3.2. Yet, some specific SUSY models such as constrained MSSM (cMSSM) can be excluded by considering the given limits, wherea phenomenological MSSM (pMSSM) still holds its preferability for future studies [75]. The description brought by MSSM for the Higgs boson stays valid in the frame of achieved results, also with the observed Higgs boson mass in 2012.

In the light of conclusive statements given above, it would not be risky to say that any hints refer to the any superpartners are needed to be searched at higher mass limits by based on less simplified SUSY models [75, 76, 77, 78, 79, 80, 81, 82]. This fact can be also approached as a motivation spot to choose and pursue "s-tau coannihilation 8" model for the study conducted in this thesis by knowing the fact that STC8 is a non-simplified SUSY model [44].

3.3 The High Luminosity Large Hadron Collider Project

The history of experimental particle physics has been filled with plenty of breathtaking moments for sure but it is not arguable that this would not be able to be achieved without any numerous improvements, upgrades or etc. in the instruments including with the LHC.

Among all of the experiments and project managed up to now, the High Luminosity Large Hadron Collider (HL-LHC) project has reached the peak point. Before going through the details of the HL-LHC project, it would be better to use a visualization, so Figure 3.4 can be taken as a reference to follow the previous and planned status of the LHC, from the beginning of its first operational stage to what will be aimed to be achieved at the end of 2030's.

In order to increase the resolution of the LHC camera, a high center of mass energy is needed with a high luminosity by considering the fact that the particles, which are foreseen to be discovered but have not been observed presently, have either heavier masses than the observed ones or they are not that much massive as they are thought but have lower cross-section values which make them pretty hard to be detectable in the current detector limits.

In previous sections it has been mentioned that the LHC is capable to reach 14 TeV as a center of mass energy yet, for the sake of the magnets (i.e. not to lead magnets get tired so much) and further, by considering the helium leak incident happen on September 2008, scientist are taking the process easy and for now they are operating the collider at 13 TeV. The HL-LHC project has been planned to use what the LHC can perform maximum and force all the technical limitations in it. So as it is seen from the timeline in Figure 3.4, the HL-LHC is going to start the run in 2026 just after finishing Phase 2 experiment upgrade. With an operational interval which is scheduled to take approximately 10 years, the HL-LHC will probe the particle physics world at 14 TeV center of mass energy with a high luminosity up to 3000 fb^{-1} as it is seen from Figure 3.4. The LHC was in EYETS time which had lasted till May, 2017 and this break is one of the steps that was needed to be taken before reaching the HL-LHC like all the other upcoming upgrades that will be carried out in current long shutdown which started in December 2018 and in all of the future technical shutdowns.

With the restart given for Run 2 in 2015 till long shutdown 2, the LHC has already been collected pp collision data with up to almost 150 fb^{-1} integrated luminosity also by satifying the design parameters such as hitting a peak luminosity = 10^{34} $cm^{-2}s^{-1}$ with a 25 ns bunch spacing. The early times of Run 2 has already caught some interesting moments such as; 750 GeV di-photon excess (even if at first this access was approached as a new particle but then later it turned out it was just a statistical fluctuation, that was an exciting instant indeed), recently discovered the rare B_s^0 decay into a muon pair for third time with 7.8σ [84, 85], and another fresh result announced by LHCb collaboration stating that an observation of five different Ω_c^0 states based on the analyses of the data collected both in Run 1 and Run 2 [86]. By starting the LS2 period for LHC, exciting news continue to come from the analysis of recently accumulated data such as, an observation of a rare mechanism of top quark production with a Z boson and a quark. As indicated in [87], based on the different interaction rules attained between quarks and Z bosons, this observation might be a hint for the beyond Standard Model theories and without doubt, this mechanism will be one of the favorite studies that is going to be investigated deeper in HL-LHC times. In addition

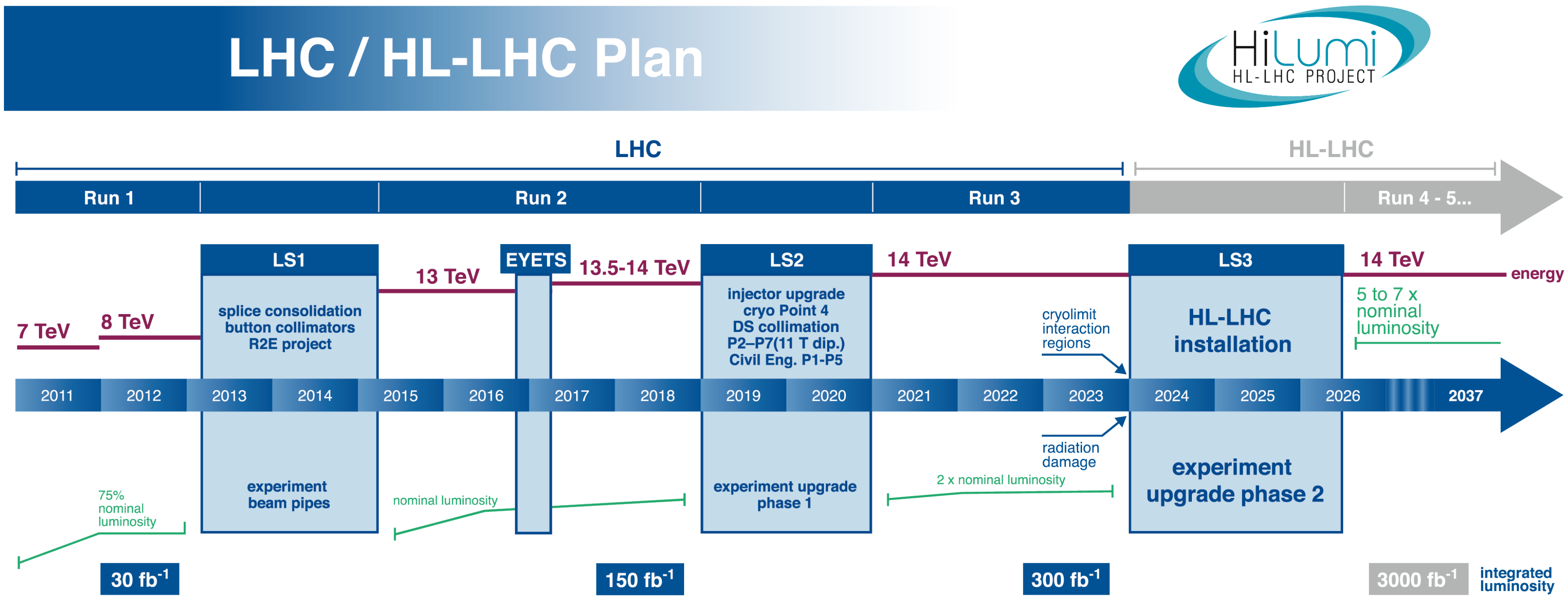


Figure 3.4: The schedule representing all significant time intervals for the LHC and the HL-LHC, including Run 1, 2, 3, 4, 5..., Extended year-end Technical Stop (EYETS), LS 1-2 and Phase 1-2 with corresponding center of mass energies and luminosity values. Figure is taken from [83].

to these, the experiments have not skipped to make precision measurements for sure and in this short period of time these obtained results during Run 2 are promising enough to encourage scientists to look further through the HL-LHC.

In a technical way, many changes have been done for the design of the detectors as well as for the LHC ring in the former shut down times in order to eliminate the deficiencies can be caused by being not technically adequate to overcome the enormous rate of data and these improvements will be held till the HL-LHC program ensured as functional. Although it is not suitable for the topic of this thesis to refer the entire technical upgrades performed up to now, one of the currently occurred modifications in the CMS detector can not be missed. The importance of this change is obvious from the fact that the action is actually called as "heart transplant" for the CMS. Besides that, if the pixel detector's crucial role among the other parts of the detectors themselves is considered in particle identification process, it would not be wrong to call it with the name it deserves. Engineers and physicists from different countries have participated and collaborated in this 5 years "heart transplant". Thanks to new pixel detector, with the restart which was given in May, 2017, now it is more feasible to get nearer to the track of the particles throughout their travels inside of the CMS, even much more closer than any other sub-detectors can ever do until now. Compared to the 68 million pixelated old detector, the brand new one includes 120 million pixels on it. This doubling in total number of pixels ensures a faster data taking and shorten the required time for data acquisition and so for data analyses too. Furthermore, the barrel and end-cap regions are thickened by increasing the number of layers such as 4 layers for the former, 3 layers for the latter one for each side of the border $\eta = 2$ covered with advanced electronics [88].

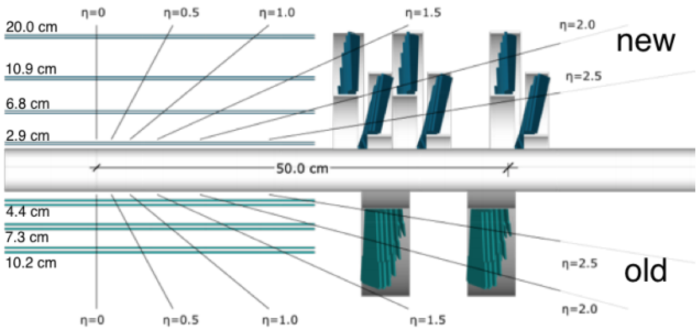


Figure 3.5: The side views of old and new pixels detectors in the CMS are given with the attained distances to make a better comparison between each other. η (see Section 4.4 values are also shown as one of the detector coordinate parameters to point out the significance of the enhancement in number and the revision in design of the pixels. Figure is taken from [89].

With the above mentioned upgrade and the all new improvements that will be brought into the LHC, scientists are aiming to catch up the high collision rates, i.e. the high luminosity, in order not to give a wisp of chance for increasing the ratio of missing particles that leave a trace on the sub-detectors. The innovated high technologically designed and produced instruments in these specialized experiments have been leading to open the new doors not only to particle physics but also to other fields of science and industry for example, biophysics, computer, electrical and electronics engineering, etc. And so, it is hard to imagine the profits that will be brought in technology and science through the studies and works done during the HL-LHC project, if one just thinks what have been accomplished by now.

3.3.1 The HL-LHC Projection on Determination of SUSY Search Strategies

While time is passing by taking steps to keep up with the HL-LHC term as quick as possible, a focused view on predictions of the HL-LHC project advantages in SUSY studies can be summarized as follows.

In order to understand SUSY in a wide ranged satisfying way and interpret its ingredients by being aware of what experimentally is going on, one must need to first figure the SM out both theoretically and experimentally. This rule is viable for the SUSY studies carried out in context of the HL-LHC too. Throughout the timeline shown in Figure 3.4, just after finishing experiment upgrade Phase 1, by reaching 300 fb^{-1} integrated luminosity and a peak luminosity as $2 \times 10^{34}\ cm^{-2}s^{-1}$ at the end, the number of measurements will be kept increased heavily year by year, for instance after Phase 2, it is aimed to be reached to $5 \times 10^{34}\ cm^{-2}s^{-1}$ for peak luminosity and 3000 fb^{-1} integrated luminosity in which these upgrades lead to give a rise in statistics of countless analyses topics and decay channels, i.e. the physics in interest. A rise in statistics stands for a reliability in studies and of course in the results that are going to be acquired at the end of the day. So it would not be inaccurate to explicate this as; with high statistics in the measurements it will be easier to sort out the SUSY signal from the SM background since physicists will be more sure about what they see or looking at referring the SM.

As a part of the future SM studies, Higgs boson will be again at the point of attention for sure. At the same time, examining almost the entire Higgs boson couplings and decays to the varied well-known particles will assist on exploring its couplings to the new particles, its correlation with SUSY and the more than one Higgs bosons foreseen by SUSY in a high resolution.

Based on the fact that particles come from Higgs boson decay are recognizable from their low energies and transverse momentums too, another convenience (for the new physics or the SUSY studies) that will be brought by focusing primarily (and simultaneously) on Higgs boson analyses at the HL-LHC can be favored as influential event selections ensured during the primary event selection procedure handled by maintaining the fundamental hardware trigger systems and advancing them. By adding such a purpose in the HL-LHC's "to do list" will assist on making physicist sure on Higgs physics like they have never been before and definitely expedite huntings for SUSY, new physics [83].

The fact that an increase in the center of mass energy certainly show up as a jump in the particle production cross-section is a key point for so many analyses as well as for SUSY searches too. Besides that, the rate of gluon and quark productions, which provide a convenient environment to generate SUSY particles, are synchronized to center of mass energy also. From Figure 3.6, the relation between superpartners and their corresponding pair production cross-sections can be examined. It is feasible to interpret Figure 3.6 such as the increase in the center of mass energy affects the stop/sbottom cross-section with multiplication of 10 by considering stop/sbottom mass as $\sim$ 1 TeV. This explication can be very motivating for SUSY searches if one compares the way of how the impact of increase in cross-section modifies the SM background events (i.e $t\bar{t}$+jets or W+jets) is accepted as it is resulted in 13 TeV, such as 2 or 3 times more than low center of mass energy (8 TeV) cross-section rates [48].

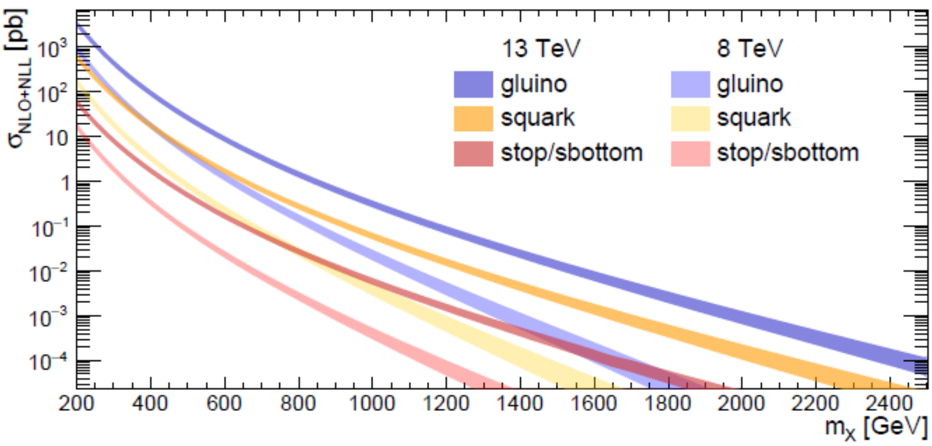


Figure 3.6: The relation between some well-known (gluinos, squarks and stops/sbottoms) superpartners and their matching pair production cross-sections at different center of mass energies as 8 and 13 TeV. Figure is taken from [48].

In experimental particle physics analyses there have been plenty of analysis methods preferred by physicists. Even if most of them are distinguished due to their specified unique ways, many of them also includes a lot of common elements. For SUSY searches, reconstructions of jets, identifications of leptons and photons and b-jet tagging are considered in determination of the best upgrade and analyses options with no doubt. Among them, missing transverse energy (E_T^{miss}) takes place as a crucial common element and it is favorably chosen to be a part of SUSY searches, as it is also used in the analysis of this thesis, Chapter 4. This kinematic parameter is heading on particularly the LSP searches. In accordance with the fact that in theory, a LSP candidate needs to be stable to not the decay any other particles and interact weakly with the ordinary matter push the analyses to include E_T^{miss}. Constituting the basis of SUSY signatures, E_T^{miss} is taking a huge place in identification of detector upgrade and maintenance works, besides in determination of SUSY search tactics. Additionally, if one thinks that SUSY can also be concealed in the tightened region formed by the SM background, and since E_T^{miss} exists also for the SM, some questions like, discovering SUSY is hard that can ever be thought and why being sensitive for E_T^{miss} is certainly important, why performing with a high luminosity is that important, will be more understandable.

With aiming the previously mentioned physics goals, it is needed to be maintained the particle reconstruction in an effective way such as eliminating the limitations and predicted damages can be faced during the HL-LHC program due to the high luminosity. Moreover collecting huge amount of data, operating with high luminosity, being capable to make precise measurements in particles' masses, cross-sections and any other physics phenomena (branching fractions, spin values etc.) and eliminating-suppressing the SM backgrounds are going to be main challenges for the future LHC, like most of them have been already putting the conditions in trouble and naturally limiting the horizon of what can be explored. However none of these mentioned complications hold the particle physicist away from proceeding on their persuasions for Supersymmetry both for now and in the future but encourage them to go further and look for beyond the SM insistently [48, 90, 91, 92, 93].

CHAPTER 4

SEARCHES FOR SUPERSYMMETRY AT THE HL-LHC

In this chapter, firstly by giving the event samples included in this analysis covering the Monte-Carlo simulation events generated via Pythia 6.4, the results obtained by using the specific analysis tools are given under two main final state decay channels (single and di-lepton final states) in which different types of cuts for some kinematic variables such as, H_T, E_T^{miss}, and topological variables as M_T, M_{T2}^W and $topness$ are applied with respect to suitable variable selection rules for both of the finale states.

In below sections, the reason lies behind following the particular cutflows is pointed out by considering the effect in eliminating background events and highlighting the signal events in more realistic and optimistic collision cases, i.e. events with and without pile-up situations. To do so, first more than one cut options for the variables, H_T, E_T^{miss}, in cutflows are examined for both of the channels like it is already done in most SUSY analysis and later three new topological variables are preferred only in signal lepton lepton channel, to see the most accurate path to move signal one step further from the background.

In order to understand the importance and the impact of the applied cuts for certain variables related with the elimination of the background events as efficient as possible for future planned the HL-LHC project in two certain final states, lastly the related tables showing the renaming number of events are presented with corresponding plots for both of the decay channels, with an addition of a comparison between each channel also.

4.1 Event Samples

According to research conducted in [94], the scenarios upper limited with the values for mass of $\tilde{t}$ as 1.5 TeV is helpful to cancel the large loop correction for the Higgs boson. In this manner, a $\tilde{t}$ accepted as the lightest superpartner for corresponding quark in the SM is expected to decay into more than one W boson, b quarks with two LSPs as a final state situation. Also it is known that $\tilde{g}$ associated $\tilde{t}$ pair production has the probability of W boson decaying leptonic as 40% with addition of the direct $\tilde{t}$ production with two of the W bosons decaying leptonic has a range of probability between 44% and 30% for electron-muon pair [39]. Hence in scope of the R-parity conserved SUSY theories, single lepton channel is in main interest for the final state with two LSPs and jets which (as indicated event selection) at least two of them are b quarks jets in order to reach the desired $\tilde{t}$ and $\tilde{g}$ sparticles.

In addition to this signle lepton final state channel, di-lepton channel is also probed in this thesis in a difference with [39]. By not specifically considering the charge combination, the included combinations of leptons for this di-lepton final state are; ee, $e\mu$ and $\mu\mu$. The other hadronic particles, neutrinos etc. are expected to come alongside or through with these leptons like they do in single lepton final state decays.

For a better understanding, some representative Feynman diagrams considered in studies [81, 82], which mainly focus on $\tilde{t}$ decay for simplified SUSY scenarios yet also valid for this thesis since related decays are in scope of this non-simplified signal model, are given for each channel in Figure 4.1 and Figure 4.2.

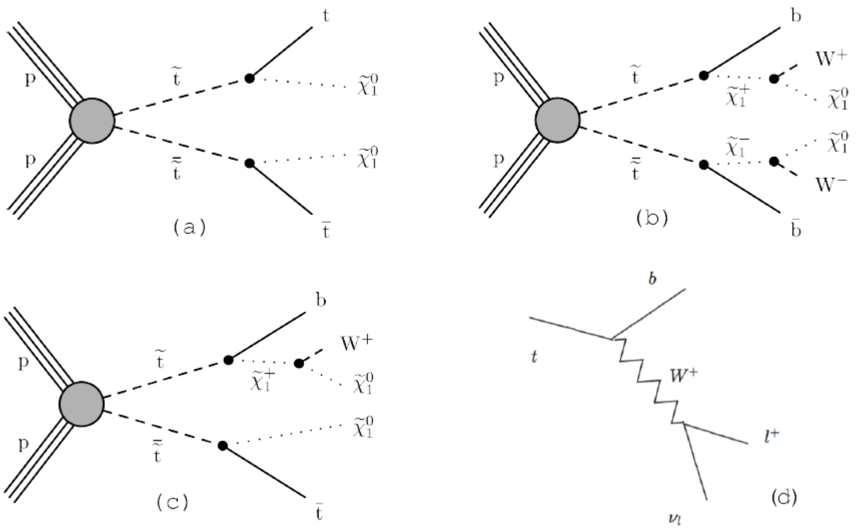


Figure 4.1: Corresponding Feynman diagrams for (a) $pp \to \tilde{t}\bar{\tilde{t}} \to t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0$, (b) $pp \to \tilde{t}_1\overline{\tilde{t}_1} \to b\ \tilde{\chi}_1^+\bar{b}\tilde{\chi}_1^- \to W^\pm\tilde{\chi}_1^0$ (c) $pp \to \tilde{t}\bar{\tilde{t}} \to b\ \tilde{\chi}_1^+\bar{t}\tilde{\chi}_1^0 \to W^+\tilde{\chi}_1^0$ and (d) $t \to bW^+ \to l^+\nu_l$. Figures are taken from [39, 81].

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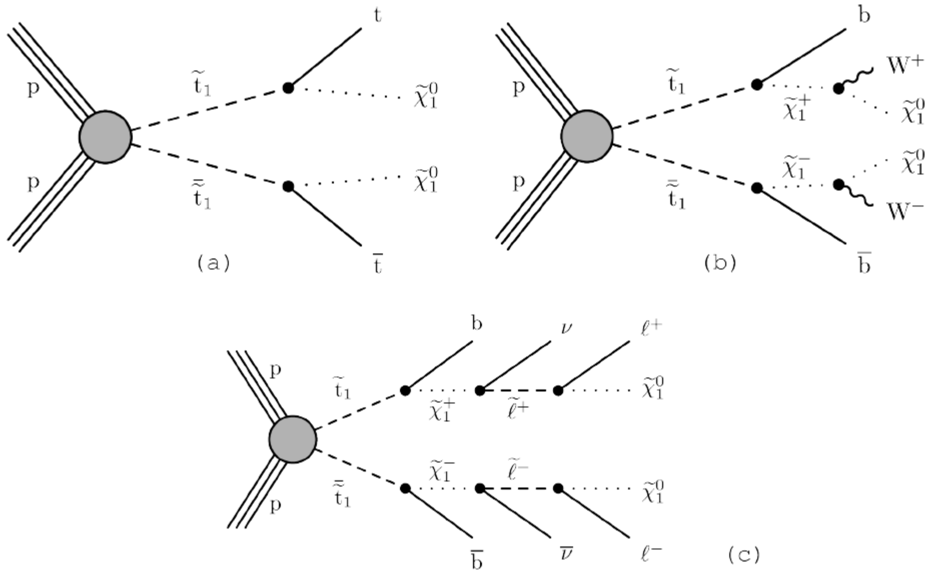

Figure 4.2: Corresponding Feynman diagrams for (a) $pp \to \tilde{t}_1\overline{\tilde{t}_1} \to t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0$, (b) $pp \to \tilde{t}_1\overline{\tilde{t}_1} \to b\ \tilde{\chi}_1^+\bar{b}\tilde{\chi}_1^- \to W^\pm\tilde{\chi}_1^0$ and (c) $pp \to \tilde{t}_1\overline{\tilde{t}_1} \to b\ \tilde{\chi}_1^+\bar{b}\tilde{\chi}_1^- \to \tilde{l}^\pm\nu\overline{\nu} \to l^\pm\chi_1^0$. Figures are taken from [82].

Decay	BR / % STC8
$\tilde{g} \to t\tilde{t}_1$	37.8
$\tilde{g} \to t\tilde{t}_2$	11.5
$\tilde{t}_1 \to t\tilde{\chi}_1^0$	13.2
$\tilde{t}_1 \to t\tilde{\chi}_2^0$	4.5
$\tilde{t}_1 \to t\tilde{\chi}_3^0$	22.4
$\tilde{t}_1 \to t\tilde{\chi}_4^0$	12.0
$\tilde{t}_1 \to b\tilde{\chi}_1^+$	10.8
$\tilde{t}_1 \to b\tilde{\chi}_2^+$	37.1
$\tilde{g} \to b\tilde{b}_1$	39.1
$\tilde{g} \to b\tilde{b}_2$	11.5
$\tilde{b}_1 \to b\tilde{\chi}_1^0$	58.2

Decay	BR / % STC8
$\tilde{\ell}_R \to l\tilde{\chi}_1^0$	100
$\tilde{\ell}_L \to l\tilde{\chi}_1^0$	95.3
$\tilde{\ell}_L \to l\tilde{\chi}_2^0$	1.7
$\tilde{\ell}_L \to \nu_l\tilde{\chi}_1^\pm$	3.0
$\tilde{\nu}_\ell \to \nu_\ell\tilde{\chi}_1^0$	100
$\tilde{\chi}_1^+ \to \tilde{\mu}_R^+\nu_\mu$	0.2
$\tilde{\chi}_1^+ \to \tilde{\tau}_1\nu_\tau$	67.9
$\tilde{\chi}_1^+ \to \tilde{\nu}_e e^+$	6.6
$\tilde{\chi}_1^+ \to \tilde{\nu}_\mu \mu^+$	6.6
$\tilde{\chi}_1^+ \to \tilde{\nu}_\tau \tau^+$	11.3
$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 W^+$	7.2
$\tilde{\chi}_2^+ \to \tilde{e}_L^+\nu_e$	4.6
$\tilde{\chi}_2^+ \to \tilde{\mu}_L^+\nu_\mu$	4.6

Decay	BR / % STC8
$\tilde{\tau}_1 \to \tau\tilde{\chi}_1^0$	100
$\tilde{\tau}_2 \to \tau\tilde{\chi}_1^0$	81.3
$\tilde{\tau}_2 \to \tau\tilde{\chi}_2^0$	3.4
$\tilde{\tau}_2 \to \nu_\tau\tilde{\chi}_1^\pm$	6.2
$\tilde{\tau}_2 \to \tilde{\tau}_1 Z$	9.1
$\tilde{\nu}_\tau \to \nu_\tau\tilde{\chi}_1^0$	94.2
$\tilde{\nu}\tau \to \tilde{\tau}_1 W$	5.8
$\tilde{\chi}_2^0 \to \tilde{e}_R^\pm e^\mp$	2.1
$\tilde{\chi}_2^0 \to \tilde{\mu}_R^\pm \mu^\mp$	2.1
$\tilde{\chi}_2^0 \to \tilde{\tau}_1^\pm \tau^\mp$	73.2
$\tilde{\chi}_2^0 \to \tilde{\nu}_e\nu_e$	5.7
$\tilde{\chi}_2^0 \to \tilde{\nu}_\mu\nu_\mu$	5.7
$\tilde{\chi}_2^0 \to \tilde{\nu}_\tau\nu_\tau$	9.5
$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$	1.2
$\tilde{\chi}_3^0 \to \tilde{\chi}_1^\pm W^\mp$	58.3
$\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 Z$	10.3

Decay	BR / % STC8
$\tilde{\chi}_2^+ \to \tilde{\tau}_2\nu_\tau$	5.1
$\tilde{\chi}_2^+ \to \tilde{\nu}_e e^+$	1.7
$\tilde{\chi}_2^+ \to \tilde{\nu}_\mu \mu^+$	1.7
$\tilde{\chi}_2^+ \to \tilde{\nu}_\tau \tau^+$	2.5
$\tilde{\chi}_2^+ \to \tilde{\chi}_1^0 W^+$	7.8
$\tilde{\chi}_2^+ \to \tilde{\chi}_2^0 W^+$	28.3
$\tilde{\chi}_2^+ \to \tilde{\chi}_1^+ Z$	25.0
$\tilde{\chi}_2^+ \to \tilde{\chi}_1^0 h^0$	18.8
$\tilde{b}_1 \to b\tilde{\chi}_2^0$	3.1
$\tilde{b}_1 \to b\tilde{\chi}_3^0$	10.7
$\tilde{b}_1 \to b\tilde{\chi}_4^0$	9.2
$\tilde{b}_1 \to t\tilde{\chi}_1^-$	5.1
$\tilde{b}_1 \to t\tilde{\chi}_2^-$	13.7

Decay	BR / % STC8
$\tilde{\chi}_3^0 \to \tilde{\chi}_2^0 Z$	23.2
$\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 h^0$	2.2
$\tilde{\chi}_3^0 \to \tilde{\chi}_2^0 h^0$	1.2
$\tilde{\chi}_4^0 \to \tilde{\tau}_2^\pm \tau^\mp$	3.2
$\tilde{\chi}_4^0 \to \tilde{\nu}_e\nu_e$	4.3
$\tilde{\chi}_4^0 \to \tilde{\nu}_\mu\nu_\mu$	4.3
$\tilde{\chi}_4^0 \to \tilde{\nu}_\tau\nu_\tau$	4.3
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^\pm W^\mp$	51.9
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 Z$	2.3
$\tilde{\chi}_4^0 \to \tilde{\chi}_2^0 Z$	2.0
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h^0$	6.7
$\tilde{\chi}_4^0 \to \tilde{\chi}_2^0 h^0$	15.8

Figure 4.3: Branching ratios for the proccesses involved in STC8 benchmark point. Branching ratios higher than 1% are in the list for gluino, $\tilde{t}$ and $\tilde{b}$. $\tilde{\ell}$ represents e and μ. Tables are taken from [44].

As it is seen from the diagrams, final states include various type of particles and they all have an importance on the determination of the numeric values of cut flow parameters seen in Section 4.3. For instance, based on the related researches, it is known that the probability of obtaining a decay as the $\tilde{t} \to t \to Wb$ is 100% [39] so it is not surprising to expect at least 2 b quarks for the channels in interest for this study.

The collision center of mass energies of the event samples in this analysis are 14 TeV and up until this time it is known that, this energy has not been reached yet, since based on its previous experiences, the LHC is taking into account all of the failure possibilities related with a hurried-up increase in center of mass energy. And this is the reason for preferring the use of simulated samples in this study. The mentioned samples are generated via diverse tools mentioned in Section 4.2.

4.1.1 Signal Samples

As it is mentioned in Section 3.2, s-Tau Coannihilation process refers the signal sample in this study. Specifically STC8 benchmark point is used due to its validity in suggestion a DM candidate by not contradicting with the theoretical background presented in Section 2.3.2. For a better manner of sense it would not be wrong to repeat the crucial numerical feature of this signal sample, STC8, such as in this thesis, this benchmark point is preferred with $\Delta(m_{\tilde{\tau}} m_{\tilde{\chi}_1^0}) \simeq 11$ GeV [44, 43]. STC8 mass spectrum is shown at Figure 2.6. Here, it is better to mention the branching ratios for selected signal in this study, STC8, which are given in Figure 4.3 by following decay order of the processes. To mention also about the production cross-section values of the spectrum for a better understanding, the values in Figure 4.4 helps us to estimate in what level the probability of observing SUSY signature is shaping at a center of mass energy equals to 14 TeV.

Process	LO (fb)	NLO (fb)	$K_{\mathrm{NLO/LO}}$	Process	LO (fb)	NLO (fb)	$K_{\mathrm{NLO/LO}}$
$\mathrm{pp} \to \tilde{g}\,\tilde{g}$	0.18	0.67	3.58	$\mathrm{pp} \to \tilde{\tau}_1\tilde{\tau}_1$	59.1	77.4	1.30
$\mathrm{pp} \to \tilde{q}\,\tilde{q}$	5.1	6	1.16	$\mathrm{pp} \to \tilde{\tau}_2\tilde{\tau}_2$	11.7	14.6	1.24
$\mathrm{pp} \to \tilde{q}\,\tilde{g}$	3	5.4	1.80	$\mathrm{pp} \to \tilde{\tau}_1\tilde{\tau}_2$	34.7	44.7	1.28
$\mathrm{pp} \to \tilde{q}\,\bar{\tilde{q}}$	16.4	25.4	1.54	$\mathrm{pp} \to \tilde{\nu}_\tau\tilde{\nu}_\tau$	20.4	25.9	1.26
$\mathrm{pp} \to \tilde{b}_1\tilde{b}_1$	22.8	38.3	1.67	$\mathrm{pp} \to \tilde{\tau}\tilde{\nu}_\tau$	73.9	93.6	1.26
$\mathrm{pp} \to \tilde{b}_2\tilde{b}_2$	0.2	0.37	1.90	$\mathrm{pp} \to \tilde{\chi}_1^0\tilde{\chi}_1^0$	0.34	0.42	1.25
$\mathrm{pp} \to \tilde{t}_1\tilde{t}_1$	37.7	62.7	1.66	$\mathrm{pp} \to \tilde{\chi}_i^0\tilde{\chi}_j^0$ (except $\tilde{\chi}_1^0\tilde{\chi}_1^0$)	15.8	19.6	1.24
$\mathrm{pp} \to \tilde{t}_2\tilde{t}_2$	0.16	0.31	1.94	$\mathrm{pp} \to \tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$	585	747	1.28
$\mathrm{pp} \to \tilde{\ell}_\mathrm{L}\tilde{\ell}_\mathrm{L}$	15.5	19.4	1.25	$\mathrm{pp} \to \tilde{\chi}_k^\pm\tilde{\chi}_m^\pm$ (except $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$)	17.3	20.2	1.17
$\mathrm{pp} \to \tilde{\ell}_\mathrm{R}\tilde{\ell}_\mathrm{R}$	32.4	41.8	1.29	$\mathrm{pp} \to \tilde{\chi}_1^0\tilde{\chi}_1^\pm$	10.0	12.9	1.29
$\mathrm{pp} \to \tilde{\nu}_\ell\tilde{\nu}_\ell$	19.4	24.6	1.26	$\mathrm{pp} \to \tilde{\chi}_1^0\tilde{\chi}_2^\pm$	1.07	1.36	1.27
$\mathrm{pp} \to \tilde{\ell}\tilde{\nu}_\ell$	63.3	79.6	1.26	$\mathrm{pp} \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm$	1170	1492	1.28
				$\mathrm{pp} \to \tilde{\chi}_2^0\tilde{\chi}_2^\pm$	3.51	4.33	1.23
				$\mathrm{pp} \to \tilde{\chi}_3^0\tilde{\chi}_1^\pm$	6.10	7.63	1.25
				$\mathrm{pp} \to \tilde{\chi}_3^0\tilde{\chi}_2^\pm$	22.0	27.0	1.25
				$\mathrm{pp} \to \tilde{\chi}_4^0\tilde{\chi}_1^\pm$	3.45	4.25	1.25
				$\mathrm{pp} \to \tilde{\chi}_4^0\tilde{\chi}_2^\pm$	24.4	29.8	1.25

Figure 4.4: Production cross-section values calculated for STC8 benchmark point. Values are listed according to leading and next-to leading order comparison. Table is taken from [44].

4.1.2 Background Samples

Background samples presented in this study are chosen as their level of contribution to previously indicated final states and they are listed without considering their level of contribution as; $t\bar{t}$+jets, Boson (W or Z)+jets, Single top+jets, and Di-boson. The Feynman diagrams for related backgrounds are shown in Figures 4.5 and 4.6. In similarity with the fact that, the SM events can be approached as a background event for itself, this is also valid for the SUSY. A non-simplified SUSY model is preferred in this thesis as it is chosen in [39], and by choosing this model, not only desired top squark decay are obtained but also the other decay options too. As an example, STC8 benchmark point has 13.2% possibility for the decay, $\tilde{t}\bar{\tilde{t}} \rightarrow t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0$ as it can be also seen from Figure 4.3 [44]. And the challenges here are coming from the pair production of $\tilde{b}$, $\tilde{g}$ and any quark superpartner production where all of them are counted as SUSY backgrounds in this study that ends up with the same final state particle [44].

In section 4.3, the selection rules are applied by concentrating in elimination of both the SM and SUSY backgrounds as much as possible.

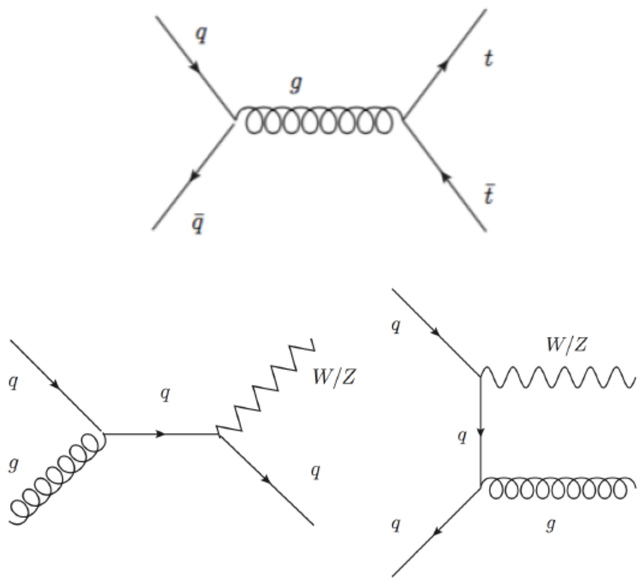

Figure 4.5: Feynman diagram for $t\bar{t}$+jets (top figure) and Feynman diagram for Boson (W or Z)+jets (left below figure; quark jets, right below figure; gluon jets. Figures are taken from [39].

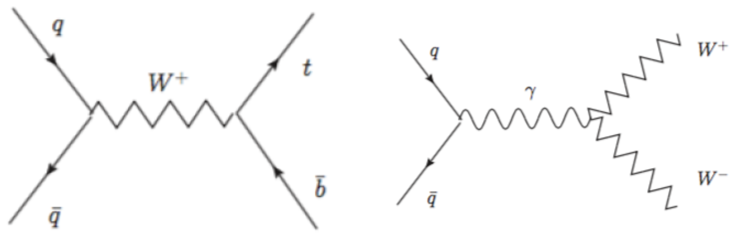

Figure 4.6: Feynman diagram for Single top+jets (right figure) and Feynman diagram for Di-boson (left figure). Figures are taken from [39].

4.2 Tools

The tools are used throughout this analysis are listed as MADGRAPH 5, Pyhthia event generator, Delphes fast simulation and ROOT data analysis framework. The detailed information about each tool is given below.

4.2.1 Pythia Event Generator

Pythia is a Monte Carlo technique based event simulation generator. Designed to be based on Monte Carlo, by preferring Pythia, users are able to obtain as many as randomness in the collisions and at the end of the simulations, where at some point this fact ensures the enhancements of reality in the resulted events with some information loss but in a most acceptable order [95]. To fulfill its missions in particle physics analyses Pythia has been developed in frame of what we know about particle physics up to now and we might know in the future [95]. This tool is used in this thesis to simulate signal and background events in a particular center of mass energy as 14 TeV and especially with particular integrated luminosity values (300 and 3000 fb^{-1}) which are kind of an upper limit that have not been reached in real collisions at CERN yet.

As a scientific method, the simulations are needed to be based in a theoretical background for sure. Hence, the same is valid for the simulations included in this study as expected. In a harmony with the study presented in thesis [39], for signal sample, SOFTSUSY 3.4.0 and the SUSY-HIT 1.3b/3.4 models are used to constitute theory base for relevant simulations in this study too. But here it is better to indicate that, one might choose not to draw values from models but set them by her/himself [95]. Also as it is already indicated before, since the SUSY particles have not been observed yet, the mass predictions are for these particles are not experimentally proven, however the importance of acquired results in exclusion of the mass limits can not be ignored. The indicated models in simulations use the SUSY Les Houches Accord (SLHA) data assigned to physical parameters of SUSY particals and these data are updated periodically by the excluded limit values announced and submitted at many conferences and meetings like Les Houches meetings.

Before going through the decay and hadronization processes in Pythia, the SLHA models and the SM background input files are operationalized via MADGRAPH 5, a framework is used to carry out the simulations of necessary phenomena in parton-level processes at computational base. At this point, here is the part that the input Les Houches Events (LHE) files of the Pythia for both the backgrounds and the signal are obtained to be subjected to decay and hadronization processes [95].

4.2.2 Delphes Fast Simulation

Delphes Fast Simulation framework allows the users to simulate detector atmosphere, effects and reaction of it in the simulated event analyses.

The detector framework, in similarity with a real particle detector, includes, from outside through the inside, a muon detector, ECAL and HCAL (electromagnetic and hadron calorimeters) and an inner tracker. In addition to fact that the volume of the detector is tunable including with the power of the magnetic field, the sub-parts of the simulated detector are positioned cylindrically symmetric around the beam axis [96]. For the samples used in this work, the version 3.0.9 is preferred to simulate detector environment.

Before going through the ROOT framework step of the analysis flowchart, the number of event generated and obtained at the end of previously mentioned phases in scope of Snowmass frame [44], are seen in Table 4.1 with respect to pile-up cases.

Table 4.1: Simulated event numbers

Samples	No PU	50 PU	140 PU	Total PU Event Number
$t\bar{t}$+jets	54964189	27398200	26900570	109262959
Boson (W or Z)+jets	252382070	55275245	53892678	361549993
Single top+jets	38159030	27185254	26673023	92017307
Di-boson	38527726	39710391	39738015	117976132
Total Background	384033015	149569090	147204286	680806391
STC8	1580000	1400000	1600000	4580000

4.2.3 ROOT Data Analyses Framework

Being an object-oriented program (OOP) construction based framework, ROOT is a user friendly analysis environment preferred by many high energy physicists. While C++ forms its basis, ROOT is also able to be extended with some other languages like Python. ROOT can be named as the last step needed to be taken before releasing the results of your work about which you finally attain some concrete outcomes like colorful histograms and statistical information appearing on them but this inference, one hundred percent sure, depends on the user's desire what to gain at the end of her/his studies.

OOP design of ROOT provides user the mostly all benefits that can be procured from any OOPs such as being able to approach the result systematically and in an analytical thinking way. Rather than dealing with the obstacles through the whole picture, OOP desing makes users to handle the problems through objects defined in the structure. An another nice thing that programmers are already used to it from OOPs, during the compilation process, ROOT also shows where the error is in your code which makes you not to search all of the lines, luckly [97].

In ROOT, while one can use the browser to look what is inside of the "*.root" extension files, this is also possible via the "terminal" screen (in Linux, an equivalent of command prompt in MS OS) by following the corresponding command rules defined in ROOT frameworld. For the analyses conducted in this work, the version 5.34 of ROOT is preferred.

4.3 Selection Cuts

By aiming to suppress the previously indicated background events known also as the ghost/undesirable contributors rather than the main interest's itself, i.e. a signature path for direct $\tilde{t}$ production in the single-lepton and di-lepton channel, the cuts that given in Table 4.2 are applied during the selection step of this analysis. The cut variables are commonly preferred in many SUSY analyses ([39, 44, 81, 82, 98, 99]) and they are chosen according to:

- Lepton cuts: To provide the desired final lepton state,
- Jet cuts: To enhance the long decay chains in SUSY events lead to signatures with multiple jets and eliminate $\tilde{b}$ pair production as a SUSY background,
- b-jet cuts: To eliminate $\tilde{b}$ and $\tilde{g}$ pair production,
- $\Delta\phi$: To suppress especially QCD background and other the Standard Model backgrounds

Table 4.2: Selection cuts

Variable	Limitation
Lepton P_t	> 25 GeV
Lepton $\|\eta\|$	$\leq$ 2.5
$\#$ of Lepton	= 1 & 2
Jet P_t	> 40 GeV
Jet $\|\eta\|$	$\leq$ 2.5
$\#$ of Jets	$\geq$ 4 for NoPU & 50PU, $\geq$ 6 for 140PU
b Jet P_t	> 30 GeV
b Jet $\|\eta\|$	$\leq$ 2.5
$\#$ of b Jets	$\geq$ 2
$\Delta\phi$	> 0.5 rad

Above mentioned selection cuts are called as particle flow and commonly preferred in most SUSY analyses in order to put the signal as much as further than the background events.

4.4 Variables

With the help of stating the corresponding cuts for the geometric variables known as η and $\Delta\phi$, it is more possible to suppress the SM background and isolate the signal events for this study as it is already followed in various analysis before. By adding up the prominent geometric and topological variables, E_T^{miss}, H_T, M_T, M_{T2}^W and $topness$ in corresponding cut flows for specific final state channels, suppression for background events turn out to be more efficient. To create a concrete comprehension, these variables can be shown in explicit forms as follows:

- **Geometric Variables**
  η (pseudorapidity) and $\Delta\phi$ are defined in scope of the detector parameters indeed. To illuminate η, Figure 3.6 can be seen. $\Delta\phi$ is explained as the azimuthal angle difference between the leading jets and H_T^{miss}. Here, H_T^{miss} is defined as,
  $H_T^{miss} = | - \sum\limits_{Jets}^{\longrightarrow} (P_t)|$.

- **Kinematic Variables**
  E_T^{miss} is an important parameter particularly in detection of LSP since it is known that the detection of neutrino superpartners would be possible through the construction of missing energy of neutrino next to a lepton. And it is formulated as $E_T^{Miss} = | - \sum\limits_{AllParticles}^{\longrightarrow} (P_t)|$.
  H_T is another commonly used kinematic variable which is formulated as
  $H_T = \sum\limits_{Jets} (P_t)$.

- **Topological Variables**
  In previous section, the topological variables are already mentioned and the detailed information about them are given in the study [39]. Besides the acknowledged parameters that are commonly used, the recently introduced used topological variables are known as, M_T, M_{T2}^W and $topness$. These variables are especially preferred for single lepton final state channel analyses whereas the commonly used kinematic variables are chosen to be parameters of cut flows in di-lepton final state analyses [100, 101].

  With a short description, M_T is known as the mass of a particle decay into one visible particle with a missing energy accompanied it. M_{T2}^W is in way more knotty than M_T and it is introduced as the minimum mass of the particle that can be composed by the whole corresponding transverse momentum and mass values of all on-shell particles. Since the W takes place here actually refers to W boson, the minimum mass of the particle can be thought as the t quark. By serving the same goal like M_{T2}^W, i.e. eliminating the $t\bar{t}$ background, $topness$ is preferred if there is missing lepton at the final state [39, 100, 101].

4.5 Signal Selection

The cuts are applied in this analysis continues with a goal of pushing down the background events as mush as possible. So by introducing with an addition to the commonly used variables, the newly introduced variables are also helping us to illuminate the signal event. Table 4.3 includes the cuts applied for signal selection. Signal selection cut variables are chosen according to [44]:

- E_T^{miss}: To enhance the probability of having leptonic finals states include neutrino and $\tilde{\chi}_1^0$ also to enhance signal of SUSY events lead to large missing transverse momentum in long decay chains,
- H_T: To eliminate hadronic energy of the background and enhance long decay chains in SUSY events lead to signatures with multiple jets,
- M_T: To eliminate backgrounds such as $t\bar{t}$, Di-boson and W boson which decay leptonic but one lepton is lost,
- M_{T2}^W: To eliminate backgrounds such as $t\bar{t}$ and Di-boson include more lost leptons which may refer to multi-leptonic final states,
- $Topness$: To define how well an event, in which M_{T2}^W variable might be also used for elimination of the background, can be reconstructed against/compared to the multi-leptonic final states

Table 4.3: Signal selection

Variable	Limitation
E_T^{miss}	> 500 GeV $\&$ 600 GeV
H_T	> 1000 GeV $\&$ 750 GeV
M_T	> 130 GeV
M_{T2}^W	> 200 GeV
$Topness$	> 8.5

4.6 Pile-up Events

An increase in luminosity brings some compelling conditions, which turn the researches to be conducted in much control, among its positive effects. By giving its description in Chapter 3, it is known that pile-up effect can be one of these conditions. If a close look is taken into Figure 3.5, it is expected to be reached huge values for integrated lumunosity such as 3000 fb^{-1} after experiment upgrade Phase 2, during Run 4, 5 and so on. Naturally, the expected improvement for lumunisity in future real world is simulated for this analysis with integrated lumunosity values as 300 fb^{-1} for No pile-up and 50 pile-up, 3000 fb^{-1} for 140 pile-up cases. 50 pile-up and 140 pile-up cases are preferred on purpose according to information in [91].

4.7 Results

All results represented in these upcoming sections are subjected to above mentioned steps which are needed to be taken during the simulated data production and data analysis processes.

Firstly, for an optimistic case, plots belong to No pile-up scenarios are given with respect to main variables introduced in Table 4.2. And then, 50 pile-up and 140 pile-up plots are following them for corresponding cuts follow too. Lepton-jet η and lepton-jet multiplicity plots are presented just for No pile-up case in order to avoid the repetition yet the same selection rules are surely valid in 50 and 140 pile-up cases.

The signal selection plots are introduced again for each pile-up cases. The tables just coming after the plots are showing the remaining number of events again for each pile-up cases. For the significance calculation in the tables, $S = Significance = s/\sqrt{b + (0.15 \times b)^2}$ is used in which s refers the remaining number of events for signal whereas b is taking place for the total remaining number of events for all background (BG) samples. Here 0.15 refers the uncertainty of the background events [80]. For di-lepton channel, the effect of variables M_T, M_{T2}^W and $topness$ in signal selection are not examined since as it is known, these variables are main of interest for single lepton channel analyses in manner of eliminating single-leptonic looking di-lepton final states and also for instance, M_{T2}^{W} has a cut-off mass around t mass for di-lepton final states. However, in single-leptonic eventst the scale is not that dramatic [44]. Even if the t mass is a consideration here, to explore its impact of limitations, M_{T2}^{W} cut is chosen to be higher than m_t.

4.7.1 No Pile-up, Single Lepton Channel

4.7.1.1 Selection Cuts Plots

In this section, selection cuts plots are presented in the first order to emphasize the interested channel which is single lepton channel with No pile-up case. For some variables, the applied cuts are given just after "the before cut" histograms. In this sense, the applied cut values are seen in a more recognizable way. The applied cut values are chosen with respect to current and common numbers among the other SUSY searches [44].

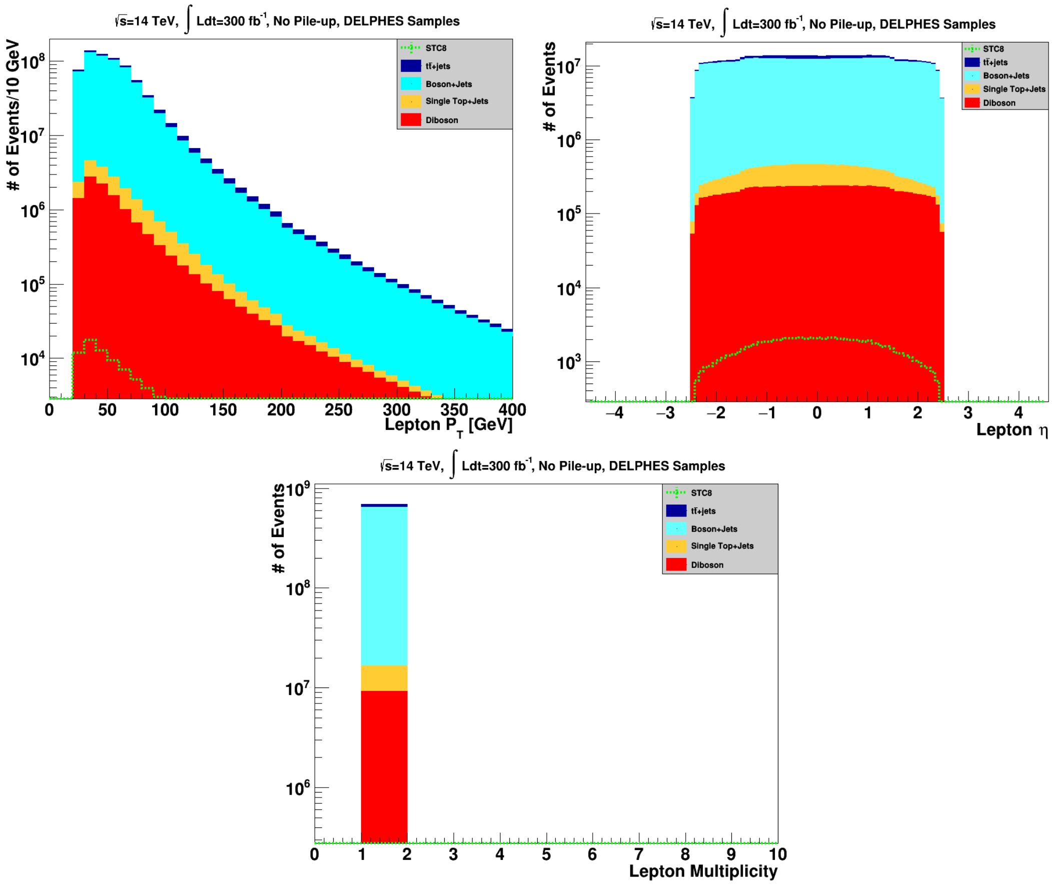

Figure 4.7: No Pile-up single lepton channel, lepton P_T, lepton η, lepton multiplicity plots

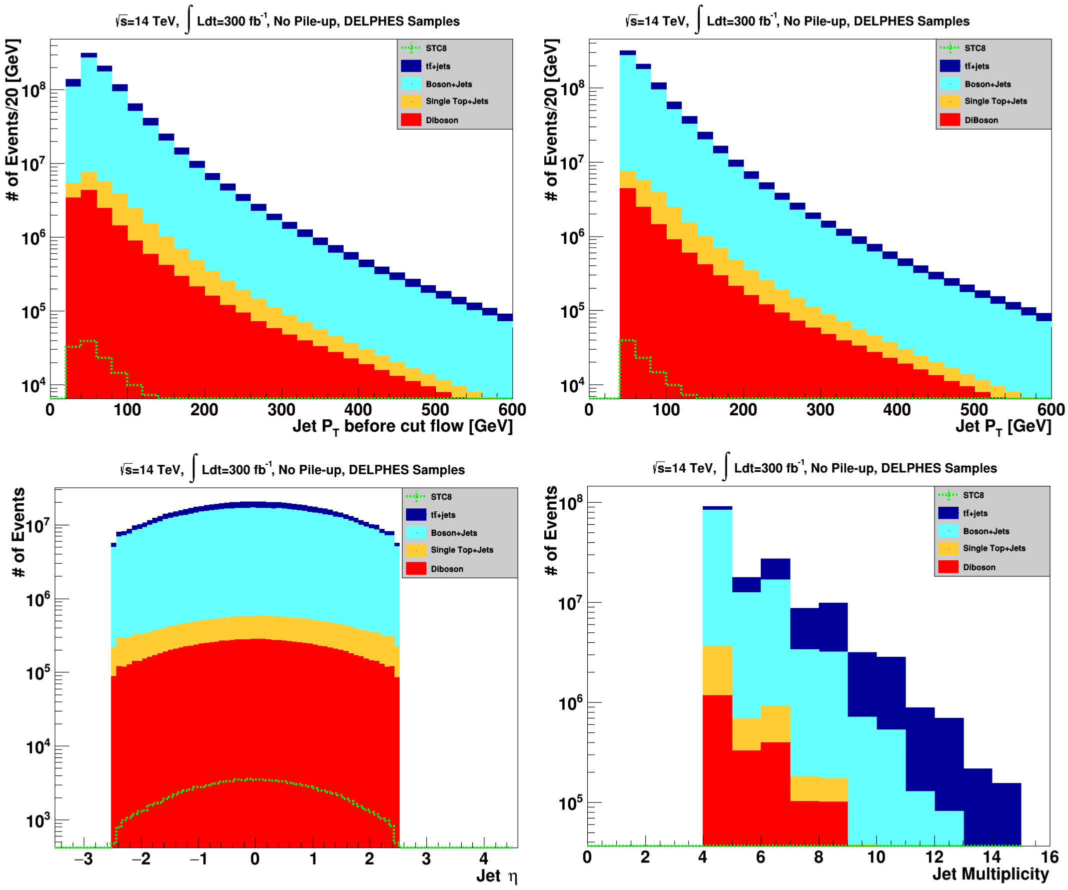

Figure 4.8: No pile-up single lepton channel, jet P_T, jet η and jet multiplicity plots

4.7.1.2 Signal Selection Plots

Signal selection process are applied by considering two different cut options in two common kinematic variables, E_T^{miss} and H_T. Firstly, it is preferred to keep the gap between these two variables close to each other such as $E_T^{miss} > 600$ GeV and $H_T >$ 750 GeV and then later, the gap is increased and the cut for H_T is increased dramatically to eliminate the background more. Yet it is observed that a little increase in the E_T^{miss} has a more impact rather than the H_T in eliminating backgrounds as it is see in Table 4.4. Topness and M_{T2}^W, which are relatively new topological variables are included to determine the effect of both of the variables in signal selection process.

For E_T^{miss} > 600 GeV and H_T > 750 GeV

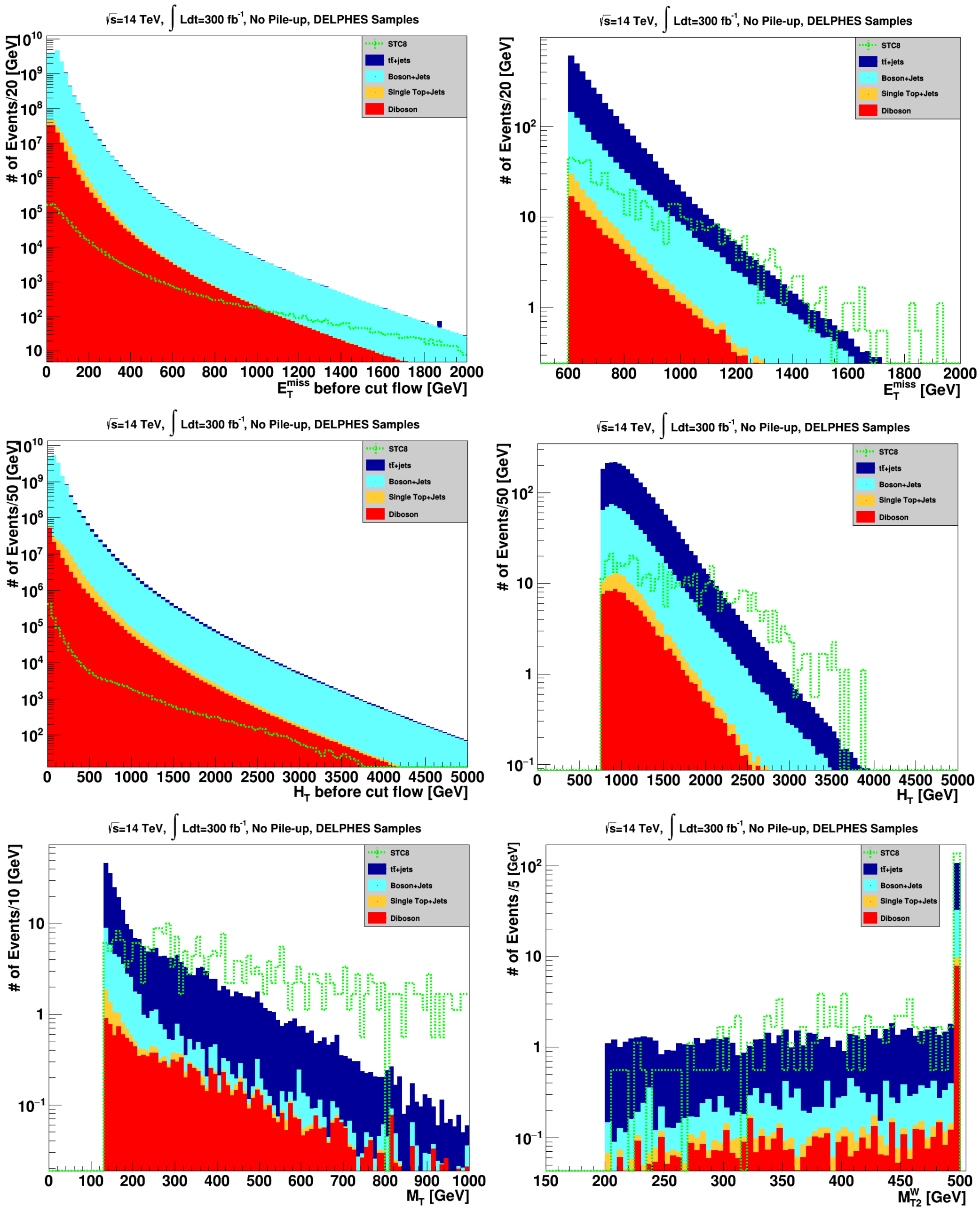

Figure 4.9: No pile-up single lepton channel, E_T^{miss}, H_T, M_T and M_{T2}^W plots for E_T^{miss} > 600 GeV and H_T > 750 GeV

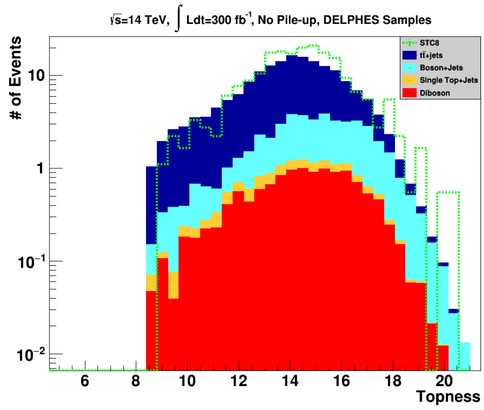

Figure 4.10: No pile-up single lepton channel, $topness$ plot for E_T^{miss} > 600 GeV and H_T > 750 GeV

For E_T^{miss} > 500 GeV and H_T > 1000 GeV

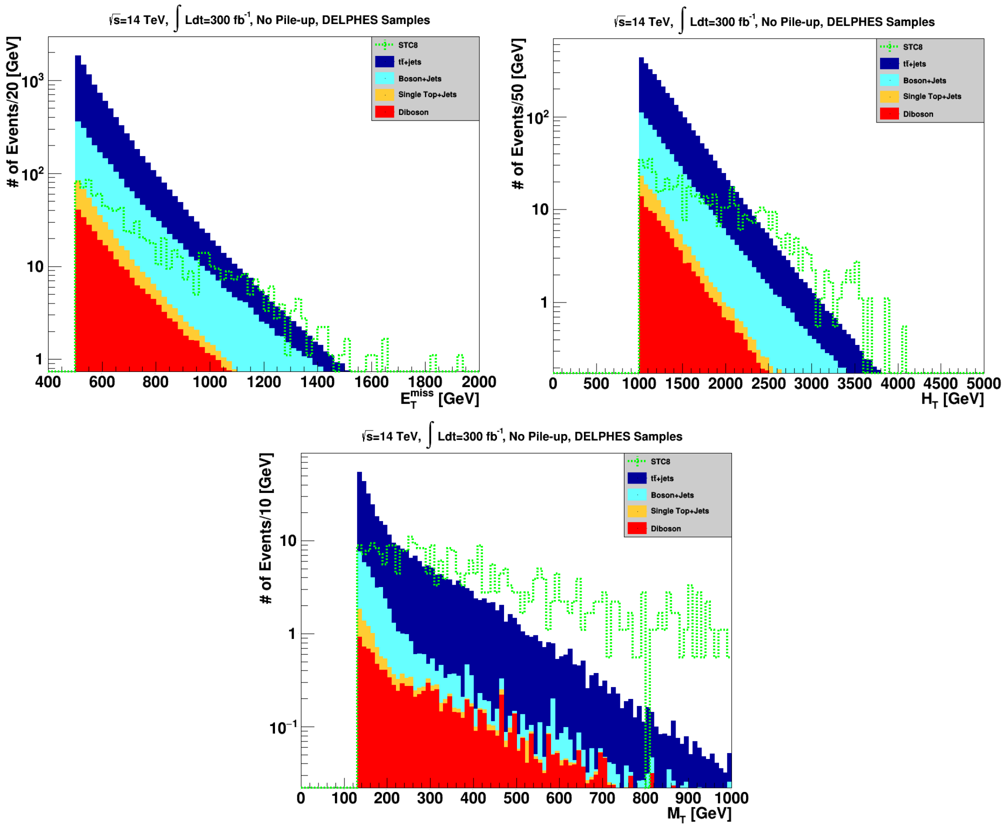

Figure 4.11: No pile-up single lepton channel, E_T^{miss}, H_T and M_T plots for E_T^{miss} > 500 and H_T > 1000 GeV

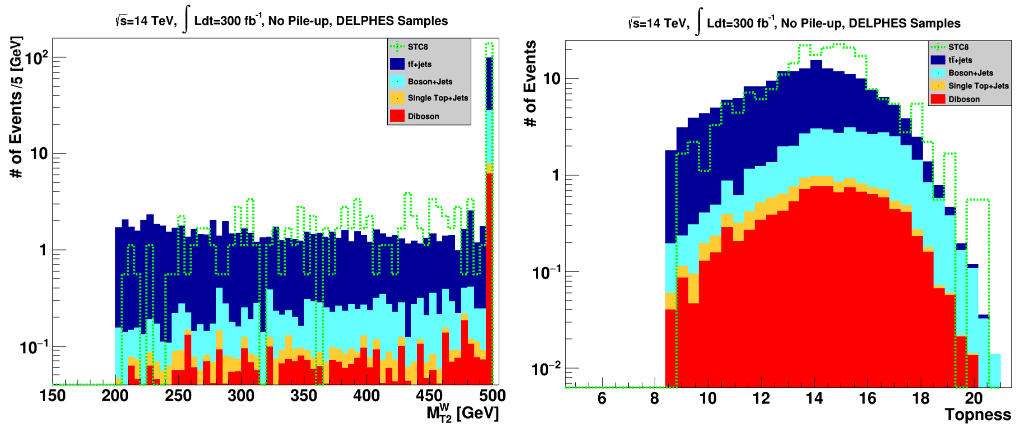

Figure 4.12: No pile-up single lepton channel, M^W_{T2} and $topness$ plots for $E_T^{miss} >$ 500 GeV and $H_T >$ 1000 GeV

Table 4.4: No pile-up single lepton final state, remaining number of events

Variable	$t\bar{t}$+jets	Boson+jets	Single t+jets	Di-boson	Total BG	STC8
Lepton Cuts	4.8×10^7	6×10^8	9×10^6	10^7	7×10^8	84216
Jet Cuts	2×10^7	1726610	883819	110134	22720563	5948
$E_T^{miss} >$ 600 GeV	2525	818	70	123	3536	547
$\Delta\phi >$ 0.5 rad	1997	772	54	114	2937	480
$H_T >$ 750 GeV	1848	670	50	103	2671	456
$M_T >$ 130 GeV	228	36	4	14	282	322
$M^W_{T2} >$ 200 GeV	134	32	3	13	**182**	**210**
$topness >$ 8.5	132	31	3	12	**178**	**209**
$S(M^W_{T2})$						6.89
$S(topness)$						6.97
$E_T^{miss} >$ 500 GeV	7362	1807	210	268	9647	900
$\Delta\phi >$ 0.5 rad	5848	1703	159	248	7958	791
$H_T >$ 1000 GeV	2354	641	59	97	3151	522
$M_T >$ 130 GeV	306	34	4	11	355	357
$M^W_{T2} >$ 200 GeV	146	30	3	9	**188**	**219**
$topness >$ 8.5	142	29	3	10	**184**	**220**
$S(M^W_{T2})$						6.98
$S(topness)$						7.15

4.7.2 No Pile-up, Di-Lepton Channel

4.7.2.1 Selection Cuts Plots

Selection cuts plots are presented with in the same variables for No pile-up single lepton case, with an exception for the difference of lepton multiplicity value, as expected.

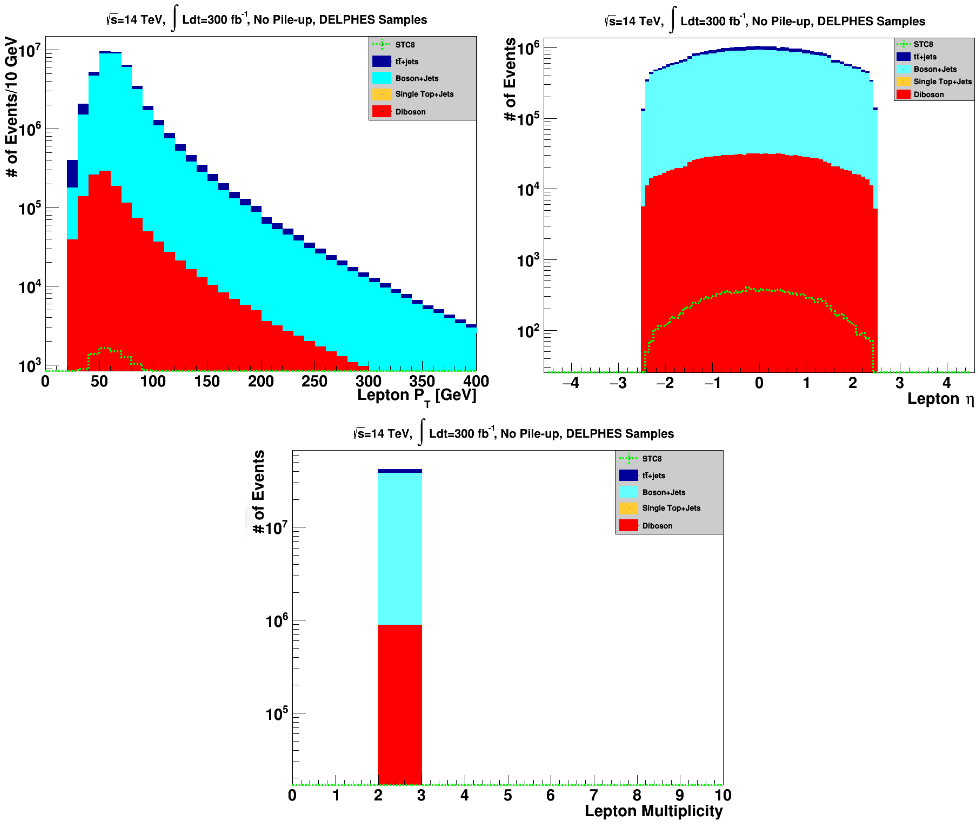

Figure 4.13: No pile-up di-lepton channel, lepton P_T, lepton η and lepton multiplicity plots

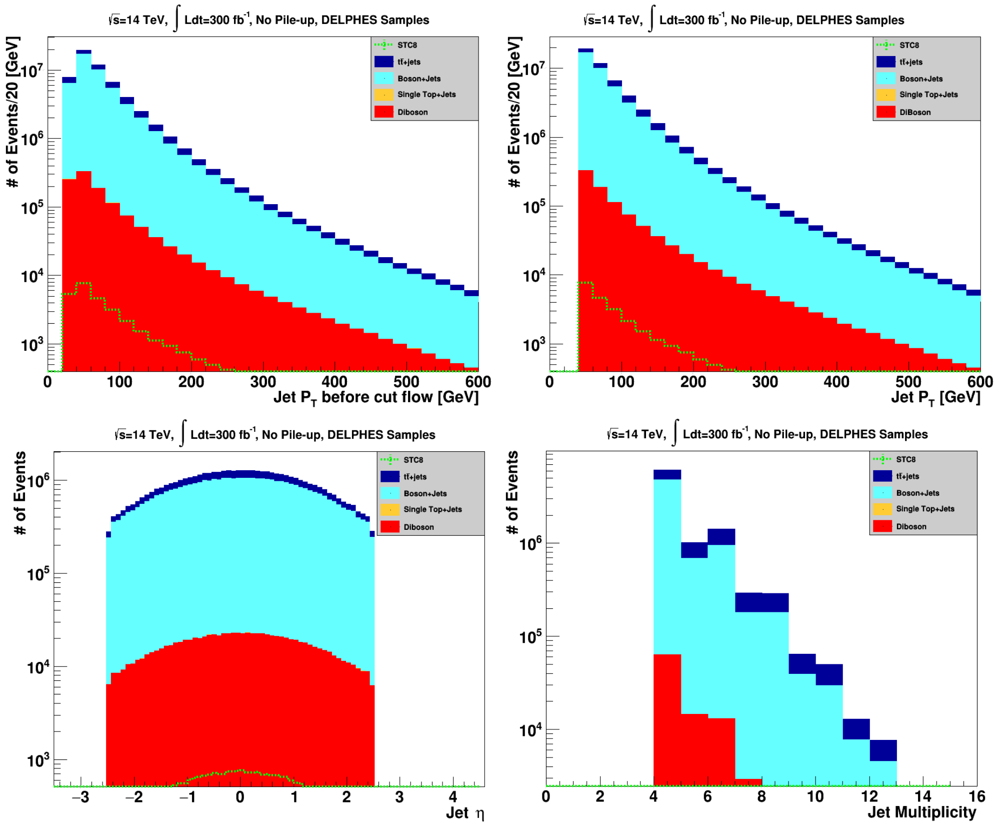

Figure 4.14: No pile-up di-lepton channel, jet P_T, jet η and jet multiplicity plots

4.7.2.2 Signal Selection Plots

Here with the same approach, signal selection process are applied by considering two different cut options in two common kinematic variables, E_T^{miss} and H_T. Yet since topness and M_{T2}^W are preferred to use specifically in single lepton channel, these variables are not included in signal selection process for di-lepton signal case. Since the lepton multiplicity differs here with leaving 2 leptons in the final state, the event left before the signal selection variables decrease strikingly as it presented in Table 4.5.

For E_T^{miss} > 600 GeV and H_T > 750 GeV

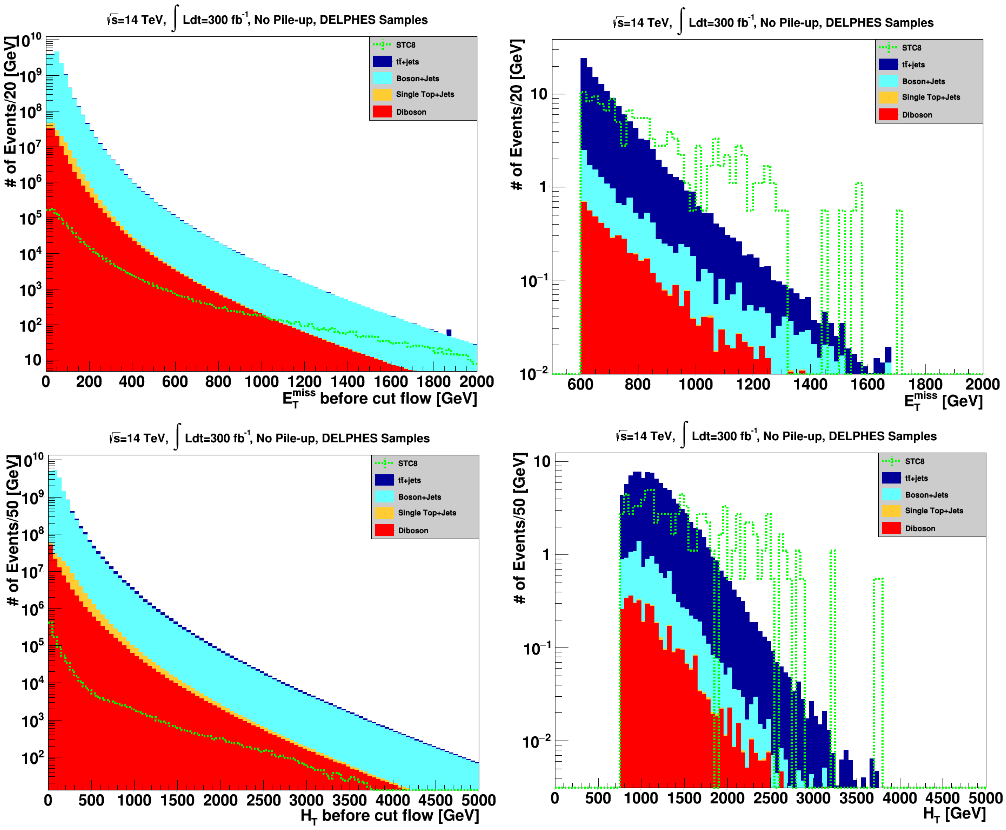

Figure 4.15: No pile-up di-lepton channel, E_T^{miss} and H_T plots for E_T^{miss} > 600 GeV and H_T > 750 GeV

For E_T^{miss} > 500 GeV and H_T > 1000 GeV

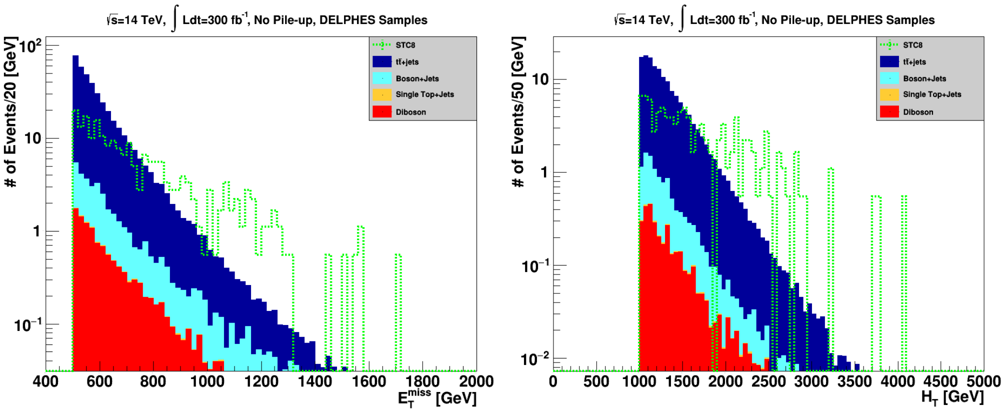

Figure 4.16: No pile-up di-lepton channel, E_T^{miss} and H_T plots for E_T^{miss} > 500 GeV and H_T > 1000 GeV

Table 4.5: No pile-up di-lepton final state, remaining number of events

Variable	$t\bar{t}$+jets	Boson+jets	Single t+jets	Di-boson	Total BG	STC8
Lepton Cuts	4×10^6	3.7×10^7	839	10^6	3.5×10^7	13390
Jet Cuts	10^6	118382	32	8778	1127192	1180
$E_T^{miss} > 600$ GeV	122	11	0	5	138	130
$\Delta\phi > 0.5$ rad	101	10	0	4	115	111
$H_T > 750$ GeV	92	9	0	3	**104**	**93**
S						4.99
$E_T^{miss} > 500$ GeV	357	24	0	11	392	216
$\Delta\phi > 0.5$ rad	292	23	0	10	325	117
$H_T > 1000$ GeV	138	8	0	3	**149**	**101**
S						3.97

4.7.3 50 Pile-up, Single Lepton Channel

4.7.3.1 Selection Cuts Plots

Selection cuts plots are presented for the single lepton channel with 50 pile-up case. In scope of the identical aim which is followed for No pile-up case, for some variables, the applied selection cuts are given just after "the before cut" histograms.

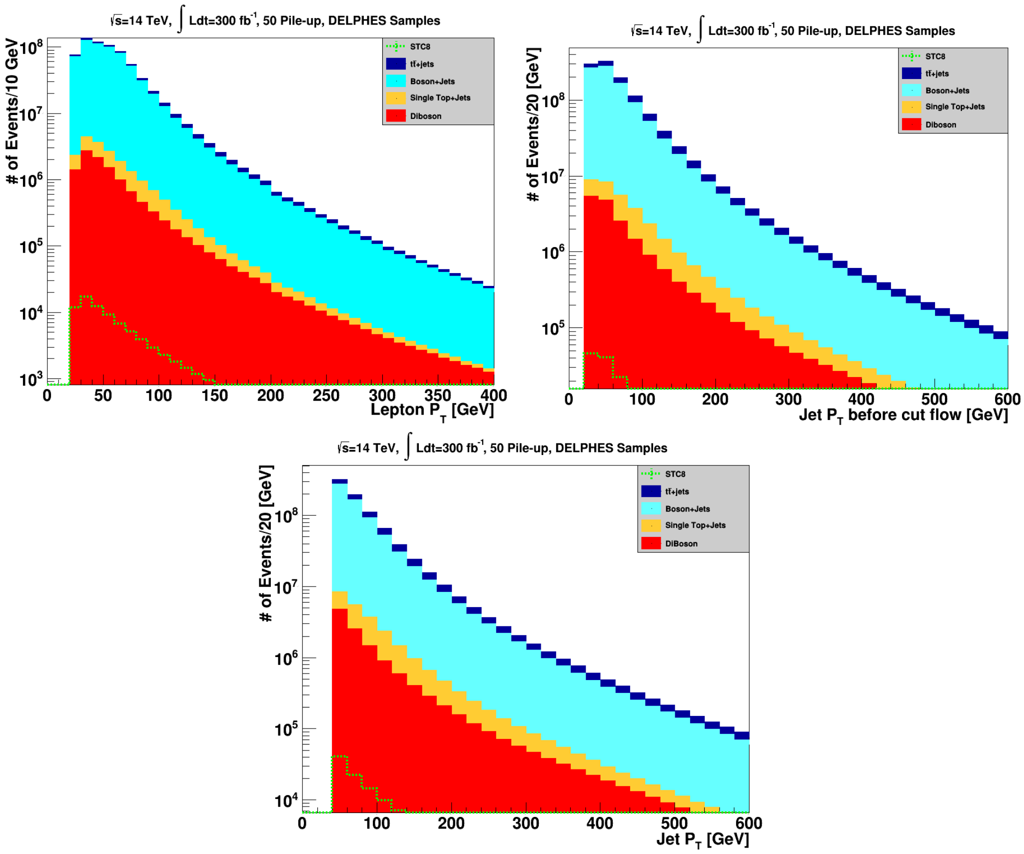

Figure 4.17: 50 pile-up single lepton channel, lepton P_T and jet P_T plots

4.7.3.2 Signal Selection Plots

In an analogy with No pile-up case, topness and M_{T2}^{W}, which are relatively new topological variables are included here too, in addition to commonly used kinematic variables in 50 pile-up case. From Table 4.6, it is obviously seen that, as a more realistic case, a dramatic rise in pile-up number does not have a crucial effect in significance calculation. Yet the remaining total number of events for background and as well as for the signal events increase noticeable as expected. Through the cut flow with the addition of the exclusive variables of this study, M_{T2}^{W} and $topness$, the elimination of the background events are concluded more effectively.

For E_T^{miss} > 600 GeV and H_T > 750 GeV

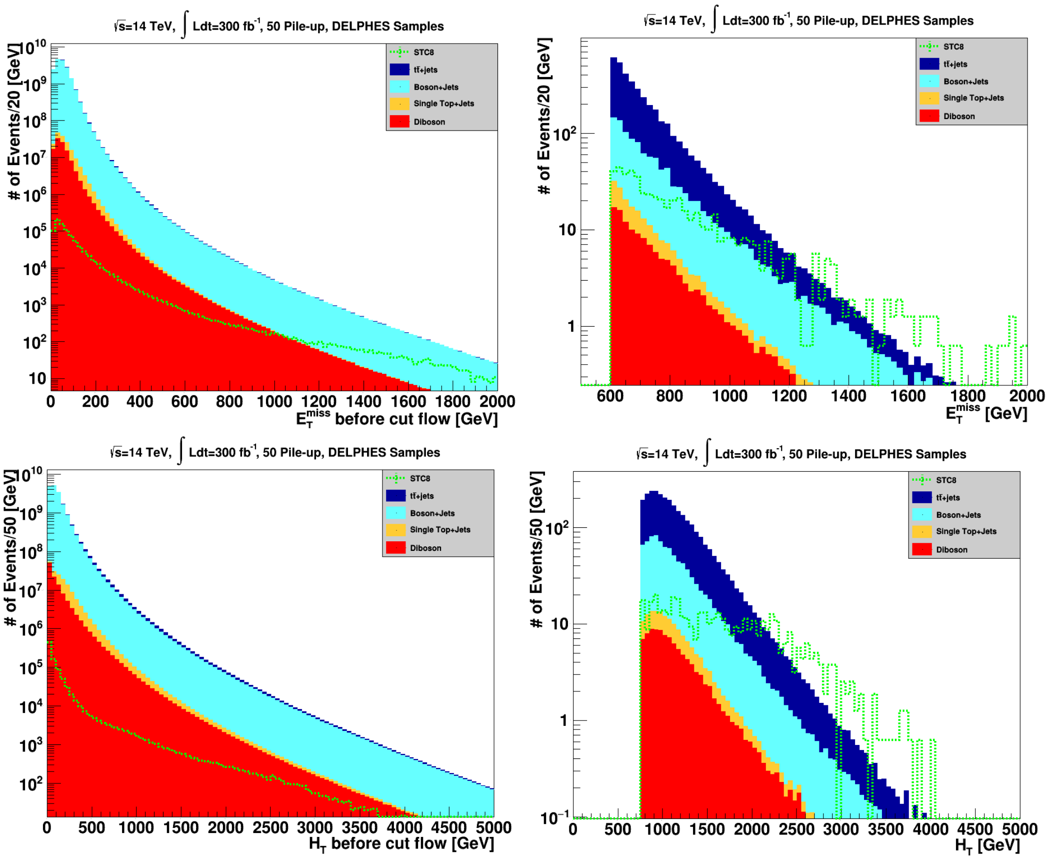

Figure 4.18: 50 pile-up single lepton channel, E_T^{miss} and H_T plots for E_T^{miss} > 600 GeV and H_T > 750 GeV

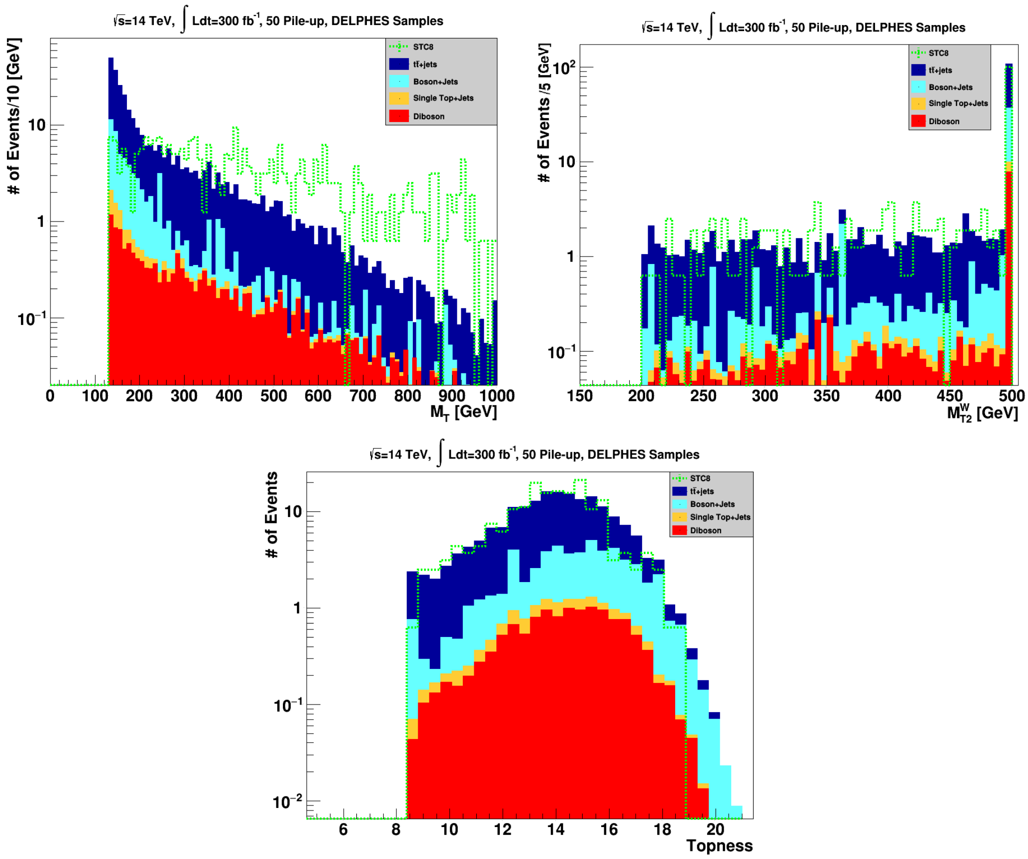

Figure 4.19: 50 pile-up single lepton channel, M_T, M_{T2}^W and $topness$ plots for E_T^{miss} > 600 GeV and H_T > 750 GeV

For E_T^{miss} > 500 GeV and H_T > 1000 GeV

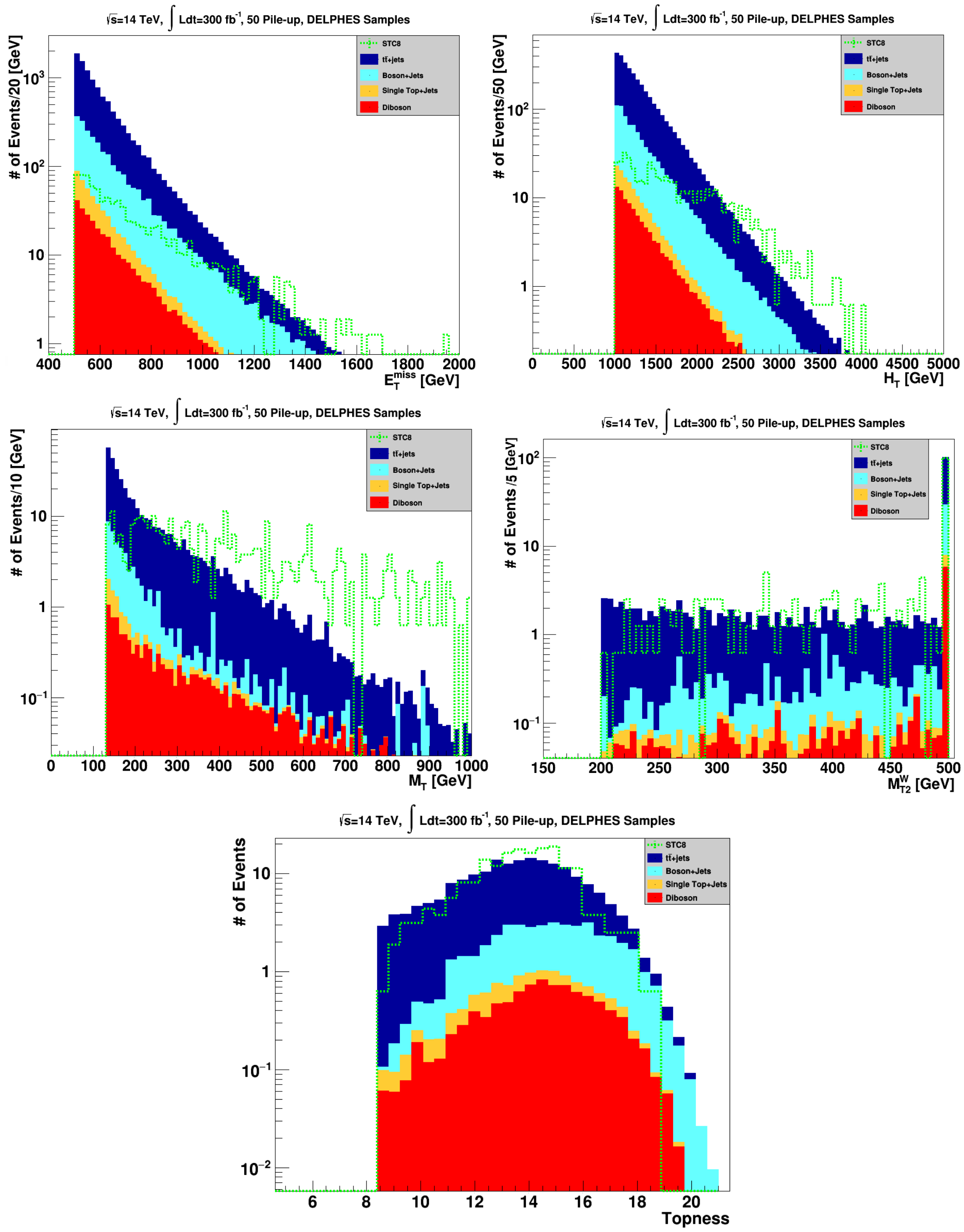

Figure 4.20: 50 pile-up single lepton channel, E_T^{miss}, H_T, M_T, M_{T2}^W and *topness* plots for E_T^{miss} > 500 GeV and H_T > 1000 GeV

Table 4.6: 50 pile-up single lepton final state, remaining number of events

Variable	$t\bar{t}$+jets	Boson+jets	Single t+jets	Di-boson	Total BG	STC8
Lepton Cuts	4.7×10^7	6×10^8	8.6×10^6	10^7	759×10^6	82144
Jet Cuts	2×10^7	2×10^6	861215	115994	23×10^6	6022
E_T^{miss} > 600 GeV	2678	860	79	127	3744	554
$\Delta\phi$ > 0.5 rad	2123	807	60	116	3106	482
H_T > 750 GeV	1950	736	56	105	2847	446
M_T > 130 GeV	230	47	5	15	297	317
M_{T2}^W > 200 GeV	135	41	4	13	**193**	**187**
$topness$ > 8.5	132	41	4	13	**190**	**186**
$S(M_{T2}^W)$						5.82
$S(topness)$						5.88
E_T^{miss} > 500 GeV	7697	1905	230	274	10106	907
$\Delta\phi$ > 0.5 rad	6128	1781	173	251	8333	799
H_T > 1000 GeV	2425	659	62	97	3243	519
M_T > 130 GeV	311	38	5	11	365	360
M_{T2}^W > 200 GeV	152	32	4	10	**198**	**191**
$topness$ > 8.5	147	32	4	10	**193**	**190**
$S(M_{T2}^W)$						5.8
$S(topness)$						5.92

4.7.4 50 Pile-up, Di-Lepton Channel

4.7.4.1 Selection Cuts Plots

In this section, selection cuts plots are presented with an exception for the difference of lepton multiplicity value again.

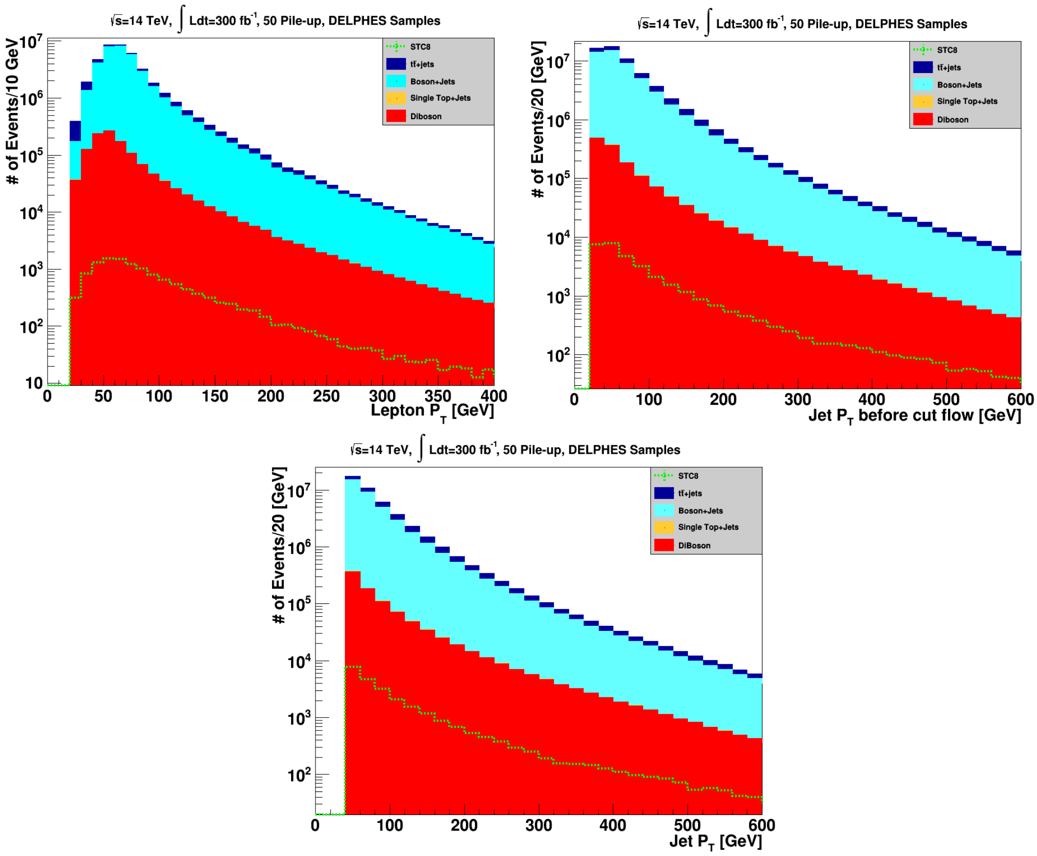

Figure 4.21: 50 pile-up di-lepton channel, lepton P_T and jet P_T plots

4.7.4.2 Signal Selection Plots

Signal selection process are applied by bypassing topness and M_{T2}^{W}. From Table 4.7, while an increase in total number of events is seen, the significance values do not change that much.

For E_T^{miss} > 600 GeV and H_T > 750 GeV

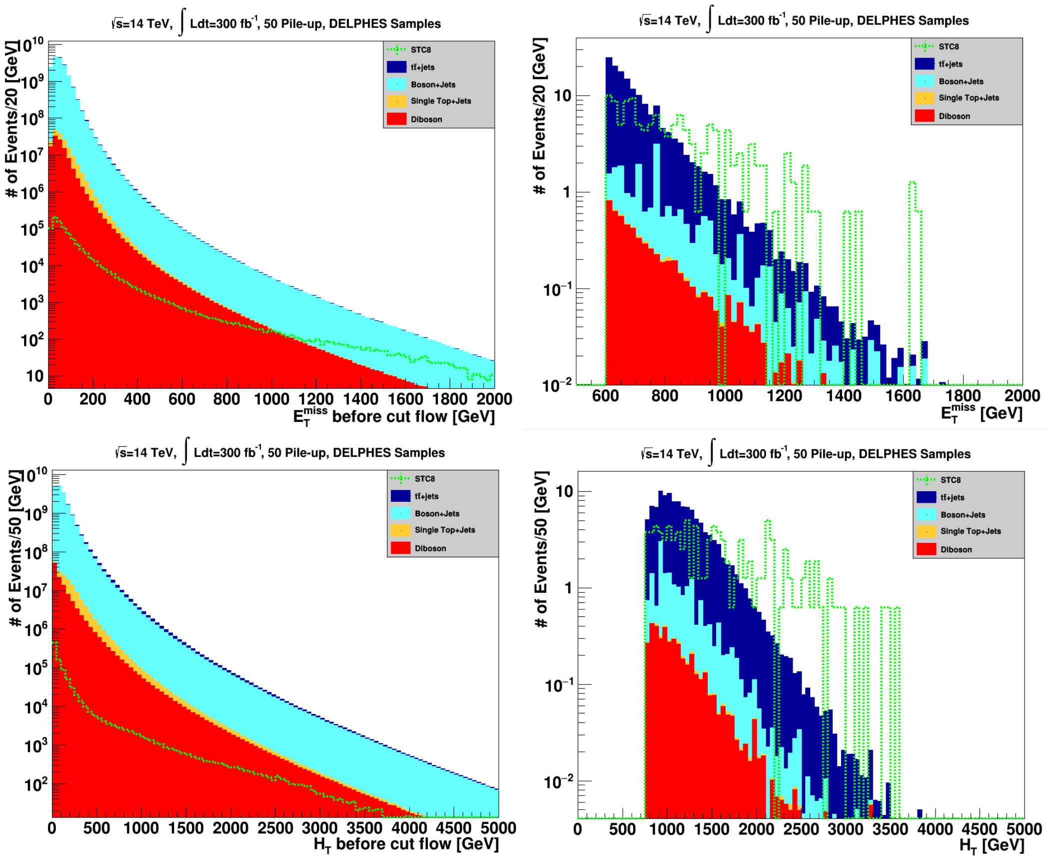

Figure 4.22: 50 pile-up di-lepton channel, E_T^{miss} and H_T plots for E_T^{miss} > 600 GeV and H_T > 750 GeV

For E_T^{miss} > 500 GeV and H_T > 1000 GeV

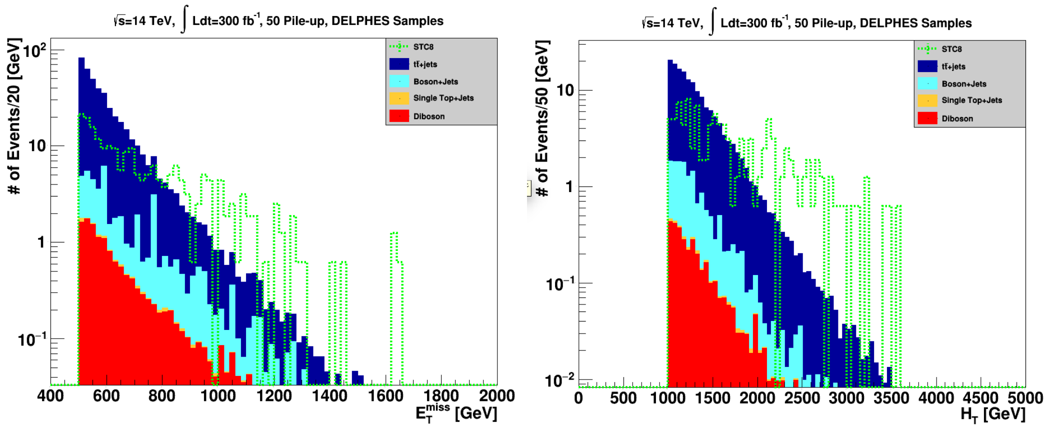

Figure 4.23: 50 pile-up di-lepton channel, E_T^{miss} and H_T plots for E_T^{miss} > 500 GeV and H_T > 1000 GeV

Table 4.7: 50 pile-up di-lepton final state, remaining number of events

Variable	$t\bar{t}$+jets	Boson+jets	Single t+jets	Di-boson	Total BG	STC8
Lepton Cuts	4×10^6	3.5×10^7	5885	10^6	4.5×10^7	12872
Jet Cuts	10^6	194419	168	9282	1203869	1208
E_T^{miss} > 500 GeV	134	15	0	6	155	128
$\Delta\phi$ > 0.5 rad	111	14	0	5	130	110
H_T > 1000 GeV	103	13	0	4	**120**	**99**
S						4.7
E_T^{miss} > 600 GeV	380	32	2	13	427	207
$\Delta\phi$ > 0.5 rad	311	30	1	12	354	177
H_T > 750 GeV	144	11	0	3	**158**	**109**
S						4.06

4.7.5 140 Pile-up, Single Lepton Channel

4.7.5.1 Selection Cuts Plots

For 140 pile-up case, selection cuts plots are presented for the single lepton channel. In scope of the identical aim which is followed for No pile-up and 50 pile-up case,for some variables, the applied selection cuts are given just after "the before cut" histograms.

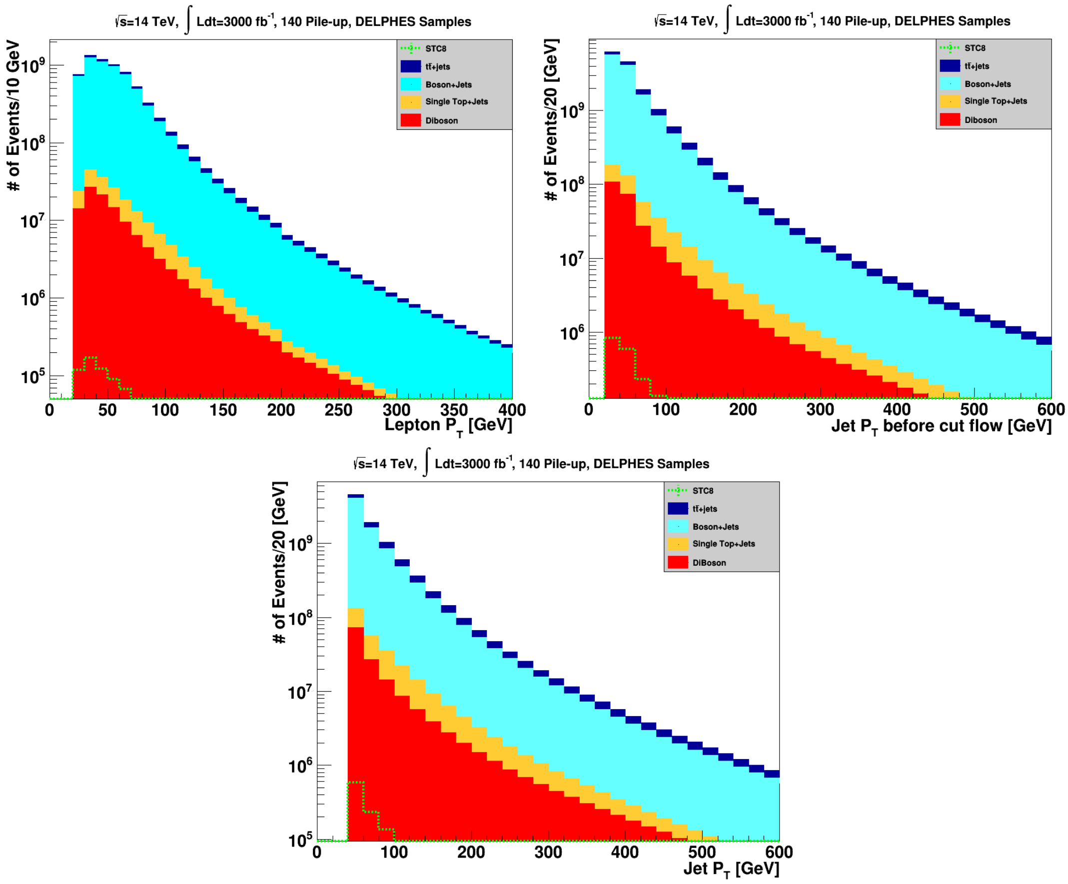

Figure 4.24: 140 pile-up single lepton channel, lepton P_T and jet P_T plots

4.7.5.2 Signal Selection Plots

From Table 4.8, it is obviously seen that, as a more future based realistic case in pile-up scenarios with a luminosity 3000 fb^{-1}, again a dramatic rise in pile-up number does not have a crucial effect in significance calculation while the rise in total number of events for background and as well as for the signal events is noticeable. Through the cut flow, with the addition of the exclusive variables of this study, M_{T2}^{W} and $topness$, the elimination of the background events are managed.

For E_T^{miss} > 600 GeV and H_T > 750 GeV

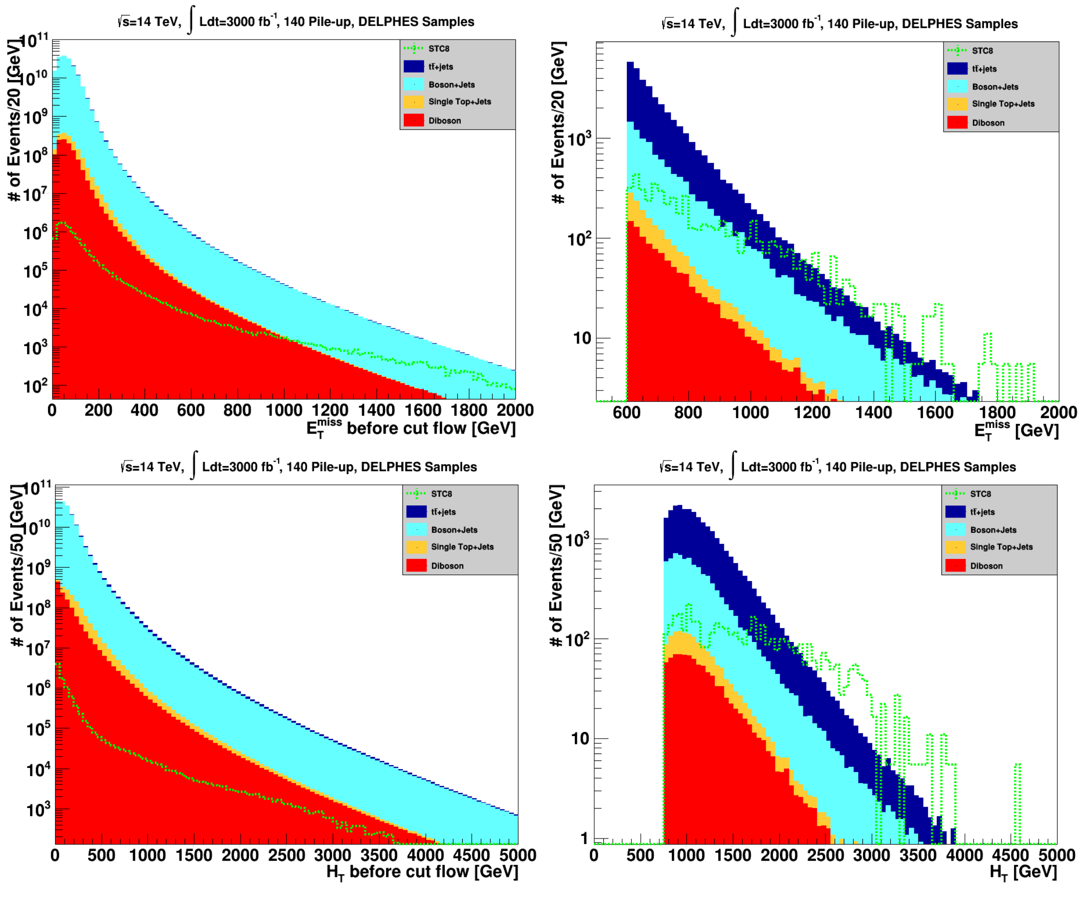

Figure 4.25: 140 pile-up single lepton channel, E_T^{miss} and H_T plots for $E_T^{miss} > 600$ GeV and $H_T > 750$ GeV

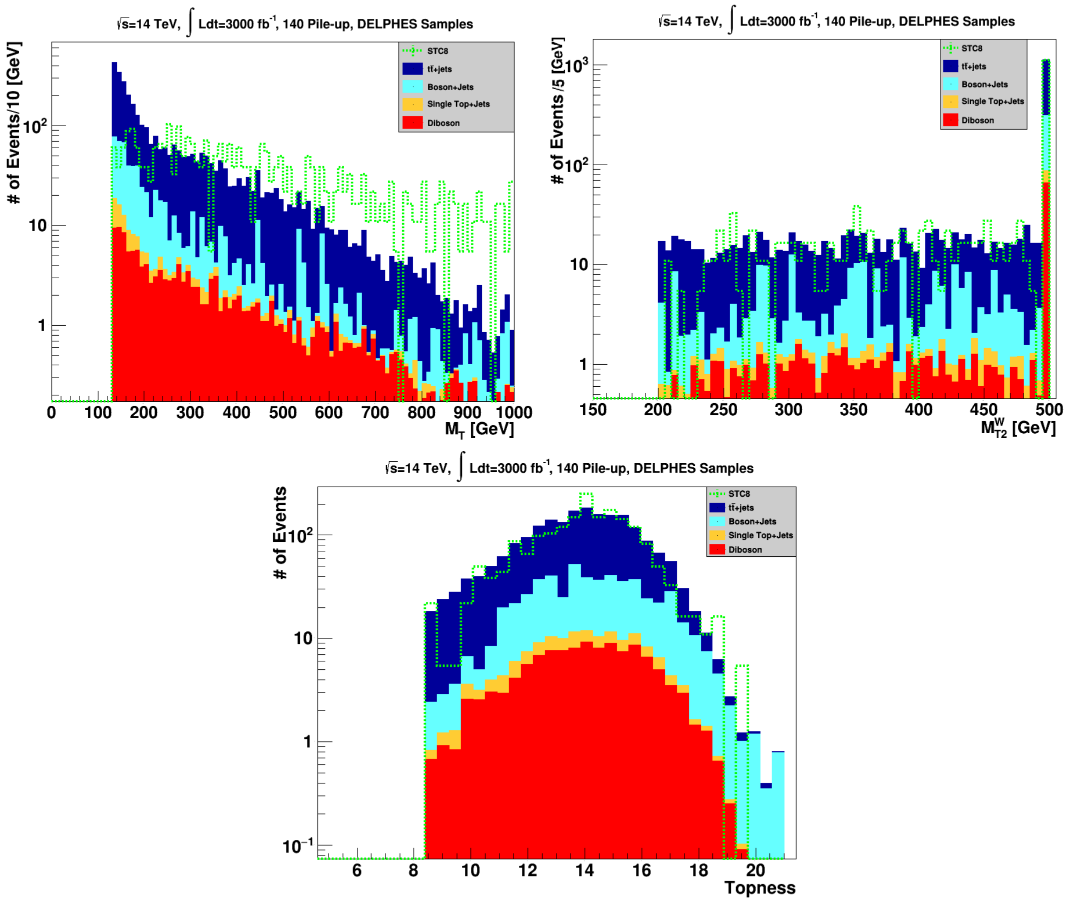

Figure 4.26: 140 pile-up single lepton channel, M_T, M_{T2}^W and $topness$ plots for E_T^{miss} > 600 GeV and H_T > 750 GeV

For E_T^{miss} > 500 GeV and H_T > 1000 GeV

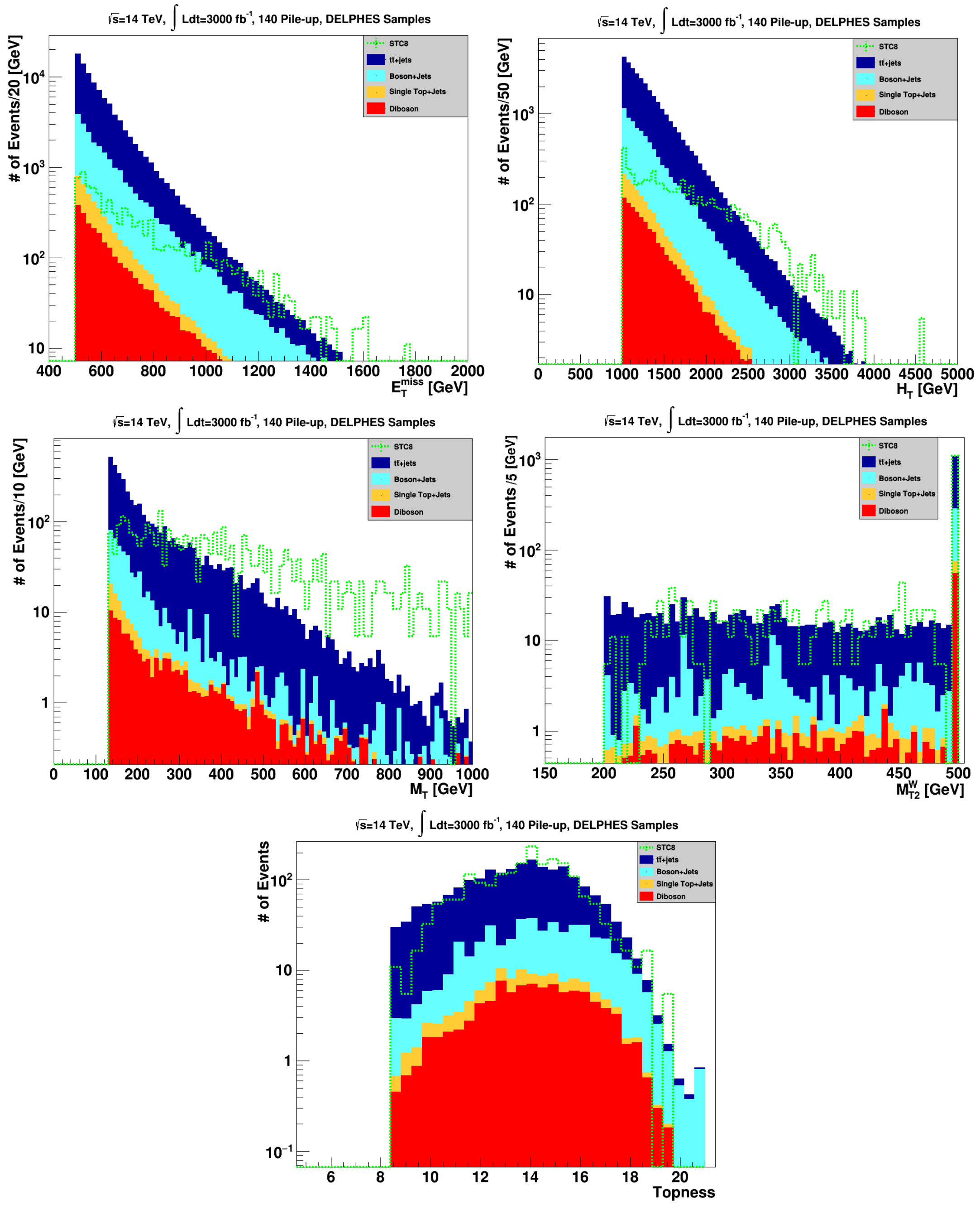

Figure 4.27: 140 pile-up single lepton channel, E_T^{miss}, H_T, M_T, M_{T2}^W and *topness* plots for E_T^{miss} > 500 GeV and H_T > 1000 GeV

Table 4.8: 140 pile-up single lepton final state, remaining number of events

Variable	$t\bar{t}$+jets	Boson+jets	Single t+jets	Di-boson	Total BG	STC8
Lepton Cuts	4.7×10^8	6×10^9	8.6×10^7	10^8	7×10^9	813843
Jet Cuts	10^8	2×10^7	6×10^6	950211	10^8	57094
E_T^{miss} > 600 GeV	24884	8103	751	1097	34835	5347
$\Delta\phi$ > 0.5 rad	19878	7563	584	1005	29030	4769
H_T > 750 GeV	18340	6883	550	922	26699	4430
M_T > 130 GeV	2570	482	48	141	3241	3213
M_{T2}^W > 200 GeV	1529	414	38	119	**2100**	**1870**
$topness$ > 8.5	1502	405	37	118	**2062**	**1871**
$S(M_{T2}^W)$						5.87
$S(topness)$						5.98
E_T^{miss} > 500 GeV	70715	18267	2169	2422	93573	8703
$\Delta\phi$ > 0.5 rad	56776	17020	1654	2211	77661	7808
H_T > 1000 GeV	23260	6505	634	914	31313	5053
M_T > 130 GeV	3341	409	51	117	3918	3563
M_{T2}^W > 200 GeV	1654	350	37	97	**2138**	**1964**
$topness$ > 8.5	1607	374	36	95	**2112**	**1958**
$S(M_{T2}^W)$						6.06
$S(topness)$						6.12

4.7.6 140 Pile-up, Di-Lepton Channel

4.7.6.1 Selection Cuts Plots

With an exception for the difference of lepton multiplicity value, selection cuts plots are presented for di-lepton case in 140 pile-up.

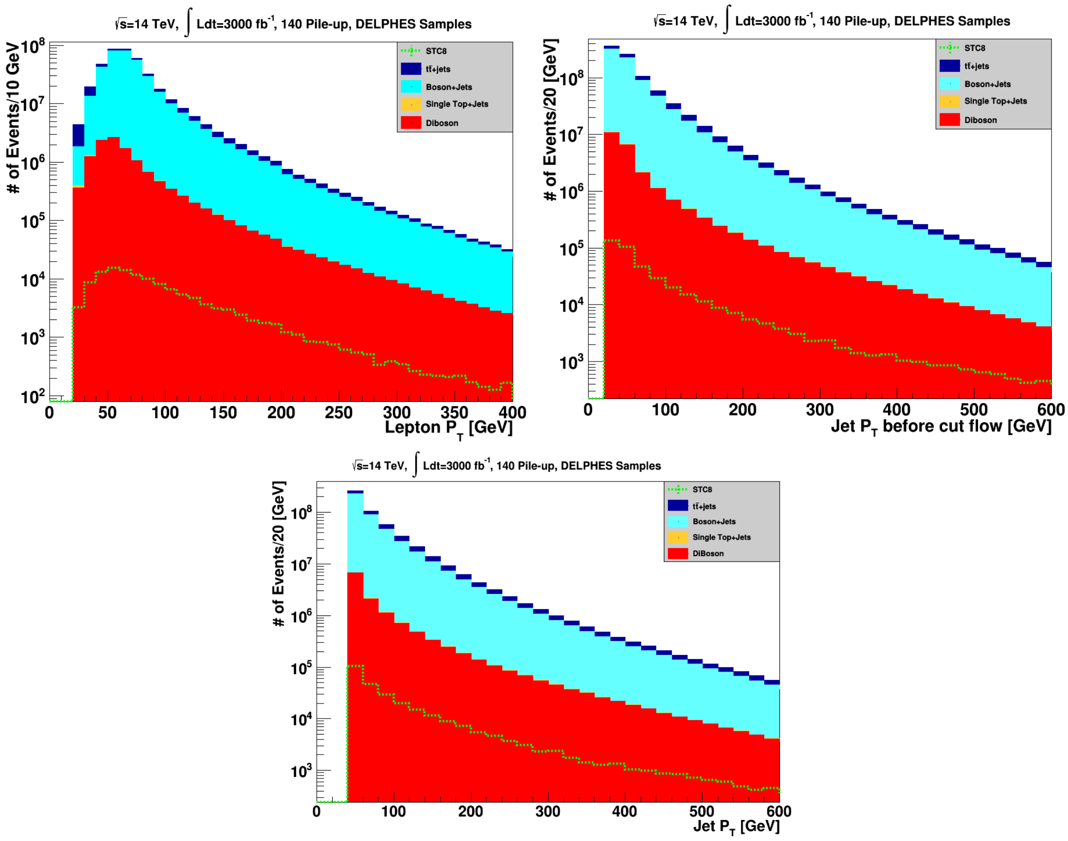

Figure 4.28: 140 pile-up di-lepton channel, lepton P_T and jet P_T plots

4.7.6.2 Signal Selection Plots

Without applying the topness and M_{T2}^{W} cuts, signal selection process are given below for 140 pile-up. From Table 4.9, while an increase in total number of events is seen, the significance values do not change that much. Yet an excess over 5 sigma is achieved for the case E_T^{miss} > 600 GeV and H_T > 750 GeV as seen from Table 4.10

For E_T^{miss} > 600 GeV and H_T > 750 GeV

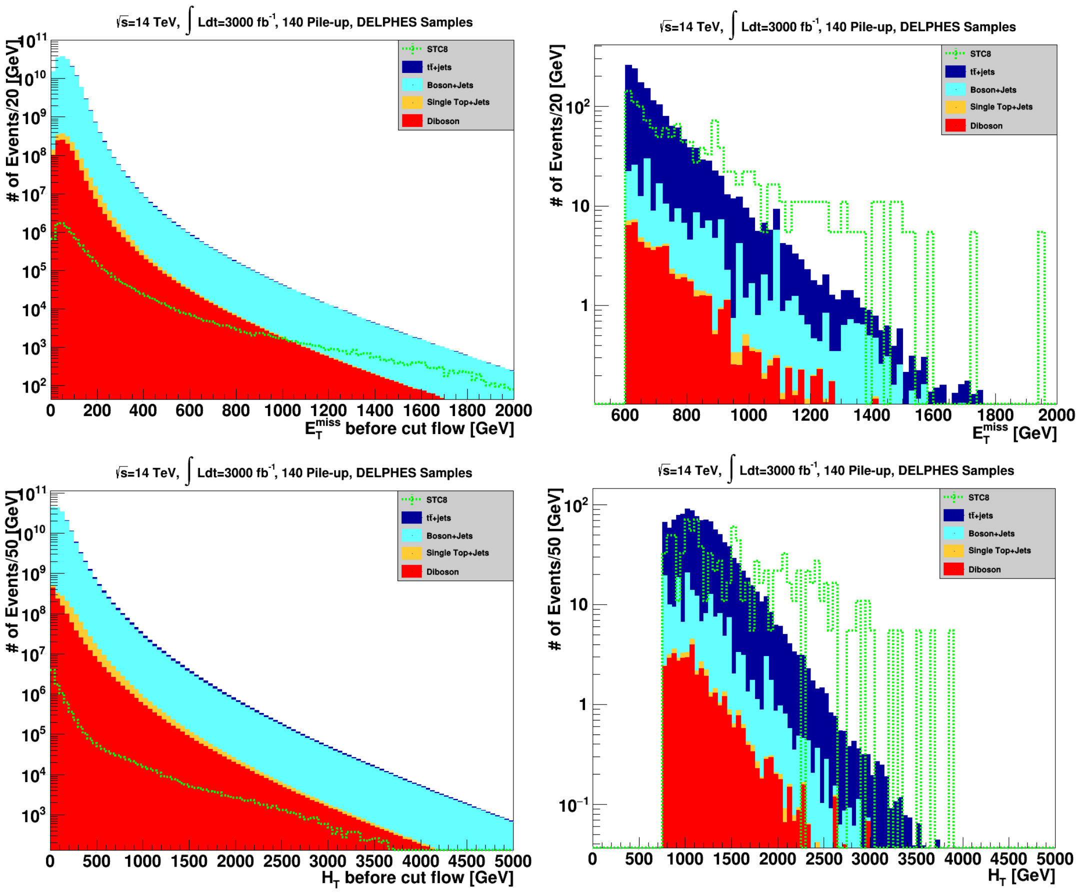

Figure 4.29: 140 pile-up di-lepton channel, E_T^{miss} and H_T plots for E_T^{miss} > 600 GeV and H_T > 750 GeV

For E_T^{miss} > 500 GeV and H_T > 1000 GeV

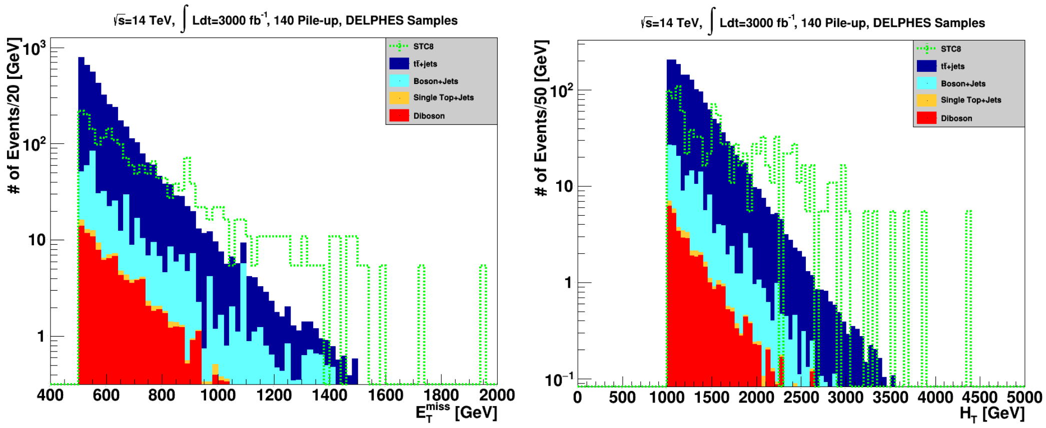

Figure 4.30: 140 pile-up di-lepton channel, E_T^{miss} and H_T plots for E_T^{miss} > 500 GeV and H_T > 1000 GeV

Table 4.9: 140 pile-up di-lepton final state, remaining number of events

Variable	$t\bar{t}$+jets	Boson+jets	Single t+jets	Di-boson	Total BG	STC8
Lepton Cuts	4×10^7	3×10^8	188875	10^7	3.5×10^8	129231
Jet Cuts	6×10^6	10^6	3568	67483	7×10^6	12599
$E_T^{miss} > 600$ GeV	1362	165	5	51	1583	1348
$\Delta\phi > 0.5$ rad	1124	157	4	47	1332	1190
$H_T > 750$ GeV	1018	151	4	38	**1211**	**1048**
S						5.67
$E_T^{miss} > 500$ GeV	3869	366	12	102	4349	2122
$\Delta\phi > 0.5$ rad	3170	344	11	94	3619	1877
$H_T > 1000$ GeV	1492	141	4	38	**1675**	**1129**
S						4.44

From the plots and the tables shared above it can be discerned that with the true cut values chosen to be applied in the variables, the observation probability of SUSY in the dedicated experiments still keeps its own potential and it is waiting to be released in the upgraded detectors. In Table 4.10, the significance values are given in scope of two final states examined in this study, single and di-lepton final states. From the table it can be clearly understood that the effectiveness of a relatively smaller cut in E_T^{miss} such as > 500 GeV and a cut in H_T as > 1000 GeV increase the probability of discovery of the signal at single lepton channel for both topological variables M_{T2}^W and $topness$. For di-lepton channel, the situation changes in a way that, a greater cut applied in E_T^{miss} such as > 600 GeV and a cut in H_T as > 750 have an impact to enhance significance value. As it is said before, since the topological variables are not in interest of the di-lepton channel, a comparison between them is not able to be conducted as expected. For the effect of topological variables in the signal lepton channel it would not be wrong to say that both of M_{T2}^W and $topness$ have similar contribution in suppressing the background as much as possible and by doing so, they take the signal one step further from the background samples. For di-lepton channel, it can be also said that the preferred cut variables have a more intense impact rather than the single lepton channel because of the fact that the lepton requirement is a big criterion here. In scope of this study, for signal lepton channel, suppressing the background events with a single lepton requirement might not be that much effective with the chosen cut values if one compare the probability of having a single lepton final state from the previously mentioned background events have more potential than the di-lepton final state based on the topology of the background as it is seen from the Figures 4.5 and 4.6. Luckily, the expected rise in the pile-up events for HL-LHC project has not an unexpected effect in significance values rather than it leads a plus push in the number of events for both backgrounds and the signal. Also by choosing more dramatic cuts for the signal selection variables, especially for the E_T^{miss} and H_T an increase in the significance values for high pile-up cases can be observed. If the dramatic suppression in the background events that obtained with the help of the variables E_T^{miss}, H_T, M_T, M_{T2}^W and $topness$ is considered, the likelihood of the usage of these specific variables in the HL-LHC can be more helpful than the expected yet to be more sure about inference, the statics i.e. the number of events generated in the simulations are needed to be augmented as much as feasible.

Table 4.10: Significance summary, $Significance = s/\sqrt{b + (0.15 \times b)^2}$

Event Selection	No Pile-up	50 Pile-up	140 Pile-up
Single lepton Final State	M_{T2}^{W} - $topness$	M_{T2}^{W} - $topness$	M_{T2}^{W} - $topness$
E_T^{miss} > 600 GeV and H_T > 750 GeV	6.89 - 6.97	5.82 - 5.88	5.87 - 5.98
E_T^{miss} > 500 GeV and H_T > 1000 GeV	6.98 - 7.15	5.8 - 5.92	6.06 - 6.12
Di-lepton Final State	No Topological Variable	No Topological Variable	No Topological Variable
E_T^{miss} > 600 GeV and H_T > 750 GeV	4.99	4.7	5.67
E_T^{miss} > 500 GeV and H_T > 1000 GeV	3.97	4.06	4.44

CHAPTER 5

CONCLUSION

Trying to find a sensible explanation to the questions about the formation of the universe or just the universe itself have been always coming alongside the human being. The help of developments gained in the technology by the time passes has been a plus for the experimental particle physics studies for sure. By fulfilling the particle table of the Standard Model, a well known theory that explains the known constituents of the universe and the interactions between them, and also with the discovery of Higgs boson, LHC has attracted a huge attention. However this has not been enough if one thinks that there are still some remaining unanswered questions. From theory side, Supersymmetry, which is one of the most common alternative theories among the other beyond the Standard Model studies, takes place by suggesting alternative solutions such as introducing a dark matter candidate, ensuring the GUT, bringing an explanation to flavor and mass hierarchy problem. Even if the SUSY particles, as known as the superpartners, still have not been observed and some of the mass limits are excluded in the current researches conducted by the CMS and ATLAS experiments, the hope stays alive at HL-LHC project especially for the R-parity conserved non-simplified SUSY theories, as it is preferred to be examined in this thesis. Single lepton and di-lepton final state channels are in the main focus of our analysis with the four Standard Model backgrounds, $t\bar{t}$+jets, Boson+jets, Single t+jets and Di-boson, and the signal sample STC8, corresponding to SUSY signal. Choosing the previously mentioned final states, it is expected to have single and di-lepton final states with multiple jets including b-jets, and also LSPs as a result of the decays and these particles are helping to decide about the selection cuts that are applied in order to suppress the Standard Model and even the SUSY background itself as explained in Chapter 4. In order to see the whether a dramatic cut applied in E_T^{miss} or in H_T is more crucial, two different options for these variables are studied for both of the final state channels. In addition, besides these two commonly used selection variables, for the single lepton final state, M_{T2}^{W} and $topness$ topological variables are also in the point of interest to decide on their preferabilities due the their effectiveness in the enhancing of significance values. All of these alternatives are simulated at $\sqrt{s} = 14$ TeV for No pile-up, 50 pile-up and 140 pile-up cases.

By having a look at the significance summary results given in Table 4.10, all of the conditions for single lepton final state channel at No pile-up, 50 pile-up and 140 pile-up scenarios have exceeded the discovery threshold, 5σ. Especially a lower cut in E_T^{miss} and a greater cut in H_T with $topness$ enhances the probability of discovery for signal sample among the background samples. Yet for di-lepton final state the case is not the same. Having a dramatic cut in E_T^{miss} with keeping H_T around > 750 GeV levels, increases the significance such as it goes beyond 5σ just for 140 pile-up case. This is actually not surprising if the ratio in background suppression of di-lepton channel is considered, it would be appropriate to say that the statistics are really needed to be augmented. For the preferabilities of topological variables it can be said that there is not a dramatic difference between two of them among their usage for three pile-up cases. Also by choosing more efficient and higher cuts for the signal selection variables, especially for the E_T^{miss} and H_T an increase in the significance values for high pile-up cases can be observed. Since statistics do have a momentous importance in experimental particle physics studies, by achieving the goals in future upgrade plan for the LHC in the path of turning it into the HL-LHC, it will be more certain to talk about what physicists are expecting to see as a result of the experiments since high luminosity means high statistics too. If the results for SUSY signal based on the real data will not change in future experiments in scope of STC8 limits, it would be better to look for the signal in new exclusion areas indicate higher masses such as $m_{\tilde{\tau}} >$ 107 GeV and $m_{\tilde{\chi}_1^0} >$ 96 GeV with a stop mass as $m_{\tilde{t}} >$ 740. For now, by depending on the simulation results presented in this thesis, of course also it would not be wrong to say, increasing statistics by enhancing the number of events generated in newly released versions of the analysis tools, in scope of the high luminosity -the aimed to be reached- values, helps a lot to see more concrete result at simulation level.

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