# Search for Supersymetry in Multilepton Final States at $\sqrt{s} = 14$ TeV

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**Abstract**

In this analysis, a search for Supersymmetry performed in multilepton final states for HL-LHC. Muon and lepton channels analyzed separately with 50 pileup and 140 pileup samples for Phase I and Phase II in 14 TeV center-of-mass energy. The Standard Model background and Supersymmetry signal samples are simulated with various requirements to differentiate signal from background.

# Contents

# 1. Introduction

Arche ($\acute{\alpha}\rho\chi\acute{\eta}$), the 'beginning' or 'origin' of the universe was the main question which occupying the intellect of the mankind since the days of Thales of Miletus (624–546 BC.). He brought the ancient knowledge of geometry from Egypt to Greece, which were used as a tool to understand the ways of Gods. Since then this wisdom forged by the hands of man who lived for it and today we are still not close to the end.

The Standard Model of particle physics (SM) is a theoretical tool to organize the matter that forms our universe. It describes the known matter with fundamental particles, six quarks and six leptons, and the relations between them with fundamental forces, strong, weak and electromagnetic interactions, with their mediating bosons. Masses of this particles are described by the interaction of particles with the Higgs field, whose quantum is called Higgs boson. Mankind build dedicated facilities all over the world to reach a higher understanding of the SM and its problems.

There are still many questions that the SM could not able to answer. Supersymmetry (SUSY) is one of the tools to solve the problems of the SM. Its an extension of the SM, which allows us to reach an extended symmetry between particles.

The Large Hadron Collider (LHC) is one of the facilities which build to understand physics of the SM and beyond the standard model (BSM), which operated by European Organization for Nuclear Research (CERN). It is a 26.7 km ring of superconducting hadron collider across the border between France and Switzerland. It is designed to collide two counter-rotating proton beams in four interaction point at center-of-mass energy of 14 TeV. The resulting particles are detect by seven different experiments. CMS is one of the biggest one of these experiments.

In this analysis, a search for SUSY is performed in a final state of multileptons for HL-LHC. Requirements are optimized in order to get highest significances in several different luminosity values for 50 and 140 pileup samples.

The analysis is structured as follows. In Section 1, SM and its problems briefly summarized through Section 1.1 to 1.2. In Section 1.3, SUSY has been shortly described as an extension to SM and in Section 4 multilepton analysis were studied and interpreted through results.

## 1.1. The Standard Model of particle physics

The SM of particle physics is the most successful model which describes known matter with strong, weak and electromagnetic interactions. Gravity is not included within SM, since its weaker than the other fundamental interactions, its neglected within the SM. The SM is based on a feature of the states of the particles which called the eigenvalues of the wave functions. According to the SM, particles are classified as 3 main group by their spin quantum numbers.

- Spin-1/2 fermions: They can be further divided into quarks and leptons. They do not interact by strong force.
- Spin-1 bosons: They are mediators of interactions. Eight massless gluon as mediator of strong force, which are combinations in doubles of three color charge. Three massive bosons $W^{\pm}$, $Z$ which are mediator of weak interaction and a massless photon as mediator of electromagnetic force.
- Spin-0 boson: Higgs boson, describes the origin of mass in SM through Yukawa interaction between particles and Higgs field.

Table 1.1.1: The quarks of the SM. Only top quark can be directly measured because it decays before it hadronizes [1].

| | Quark | | Charge [e] | Mass [GeV] |
|---|---|---|---|---|
| $1^{st}$ generation | down | d | -1/3 | $0.5 \times 10^{-2}$ |
| | up | u | 2/3 | $0.2 \times 10^{-2}$ |
| $2^{nd}$ generation | strange | s | -1/3 | $9.5 \times 10^{-2}$ |
| | charm | c | 2/3 | 1.275 |
| $3^{rd}$ generation | bottom | b | -1/3 | 4.18 |
| | top | t | 2/3 | 173 |

Table 1.1.2: The leptons of the SM. According to the model, neutrinos are massless, however resent observations revealed that neutrino flavors are oscillate which is only possible if they have mass [1, 2].

| | Lepton | | Charge [e] | Mass [GeV] |
|---|---|---|---|---|
| $1^{st}$ generation | electron | $e$ | -1 | $0.5 \times 10^{-3}$ |
| | $e$ neutrino | $\nu_e$ | 0 | |
| $2^{nd}$ generation | muon | $\mu$ | -1 | 0.11 |
| | $\mu$ neutrino | $\nu_\mu$ | 0 | |
| $3^{rd}$ generation | tau | $\tau$ | -1 | 1.78 |
| | $\tau$ neutrino | $\nu_\tau$ | 0 | |

Table 1.1.3: The gauge bosons of the SM. [1].

| Interaction | Boson | | Charge [e] | Mass [GeV] |
|---|---|---|---|---|
| Strong | 8 gluon | $g$ | 0 | 0 |
| Weak | W | $W^{\pm}$ | $\pm1$ | 80 |
| | Z | Z | 0 | 91 |
| Electromagnetic | photon | $\gamma$ | 0 | 0 |

The SM is driven as to be relativistic and renormalizable quantum field theory which invariant under local gauge group $SU(3) \otimes SU(2) \otimes U(1)$ where the gauge theory resulting $SU(3)$ is called quantum chromodynamics (QCD) and the quarks are form fundamental triplets (3) by color charge green, red, blue. Similarly gauge theory resulting $SU(2)$ is weak isospin group and all of them include a hypercharge from $U(1)$ symmetry [1].

## 1.2. Problems with the Standard Model

Although the SM describes the known matter beautifully its only explains 4% of the universe. Thus, in this section these deficiencies is discussed in experimental and theoretical content.

### Theoretical Arguments

**Gravity:** The SM doesn't include any information on inclusion of gravity in to the theory. There are several attempts for quantizing gravity, but graviton, quantum of gravity, is yet to be observed.

**Grand unification:** In order to understand the very beginning of the universe one needs to understand unification of fundamental forces, which is called Grand Unified Theory (GUT). Within SM we can unify electromagnetic and week forces. However, according to the experimental results it seems that its impossible to unify strong force with the other two. Also since there is no quantum theory of gravity, it remains unknown.

**The hierarchy problem:** The most challenging problem of the SM is the hierarchy problem. We are failing to understand the reason of the difference between masses of the lepton and quark generations. The SM is an effective theory, which means for relatively low energies it works perfectly. However, for high energies renormalization may diverge. The corrections comes for the Higgs mass diverges as well. This problem also related to fine-tuning and naturalness problems.

### Experimental Arguments

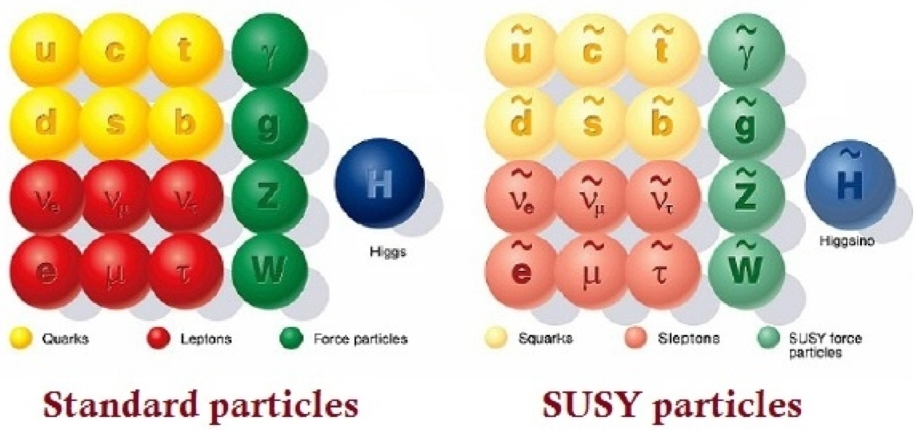
**Matter–Antimatter asymetry:** Obviously we do not observe antimatter as matter in the universe. However we know that matter and antimatter comes symmetric. This shows us that, at some point in the beginning of the universe, this fundamental symmetry should be broken. As mentioned in [3], in order to have such asymmetry one needs to violate baryon number conservation, CP invariance and thermodynamic equilibrium at the very beginning of the universe.

**Neutrino oscillations:** The SM dictates that neutrinos are massless. However resent observations revealed that neutrinos are oscillate between their flavors which can only be possible by massive particles [2]. Also direct observation of these oscillations may open another door to CP violation with Kaon and B-meson systems.

**Dark matter and dark energy:** 95% of our universe is remain unknown. There are several observations reveals that there is a non-interacting matter with known matter and it changes the physics around galaxies and even in scale of universe [4]. However there is no possible candidate has been found by the SM.

## 1.3. The Minimal Supersymmetric Extension of the Standard Model

SUSY is known most elegant extension of SM. It based on an extended symmetry between fermions and bosons. In SUSY, for every fermion from the SM there is a boson super-partner and for each boson there is a fermion super-partner in SUSY. The Minimal Supersymmetric Extension of the Standard Model (MSSM) is supersymmetrization of the SM. The minimal means that it includes minimum amount of extra particles and couplings which consistent with phenomenology and constrained by resent experiments [5, 6].



The MSSM is extended Lie algebra of the SM. It basically introduces a new algebra, a coupling, between supersymmetric particles and SM particles. Although the results from LHC are all SM-like, which means there is no evidence of SUSY, its still the strongest candidate of BSM. Thus we keep looking for the next run of the machine at 14 TeV center-of-mass energy and higher luminosity. Since SUSY expected to reveal itself in the electroweak region, its surrounded by W and Z bosons and due to their high mass ranges its challenging task to differentiate SM background from SUSY.

The SM has so many lacking part that has to be explained. SUSY gives a explanation for almost all problems in SM. SUSY includes an additional symmetry called R-parity which includes baryon, lepton and spin quantum numbers [7].

$$R_P = (-1)^{3B+L+2S}$$

In R-parity violating scenario, it is possible to violate baryon number conservation as mentioned Sakharov's paper [3] and also within this scenario its possible to have a proton that decays. In R-parity conserving scenario we have lightest supersymmetric particle (LSP) as a dark matter candidate which is neutralino1,$\widetilde{\chi}_1^0$. It is possible to include quantum theory of Gravity in SUSY by gravitino. Also almost by chance SUSY introduces the unification of all forces in GUT scale. Moreover SUSY provides some loop corrections to the Higgs mass, which explains the hierarchy in SM.

# 2. The CMS Experiment

CMS experiment is one of the two multi-purpose experiment in LHC with A Toroidal LHC Apparatus (ATLAS) experiment. It build to investigate Higgs boson, the SM precision physics and search for BSM.

## 2.1. Working Principle and Structure

CMS is a cylindrical symmetric detector lies at LHC behind the French border. It build by basic onion principle. After proton-proton (pp) collision occurs at the vacuum chamber, daughter particles directly passes through tracker which detects particles trajectories and stores the information for other detector layers. Electromagnetic calorimeter (ECAL) is placed right after the tracker, this is the place intended to stop the electrons. Right behind the ECAL, hadronic calorimeter (HCAL) is placed which intend to detect and stop hadrons comes from hodronization of the quarks. Superconducting coil has been places after HCAL which applies 4T magnetic flux density on the particles to deflect their trajectories. After that muon chambers are placed to stop muons, since they can reach until the end of the detector muon chambers are build to stop them.

## 2.2. Analysis framework and Event Reconstruction

In a pp collision, CMS detects millions of particles showers in all direction. However, neither there is enough computing power to analyze all these outcomes nor enough space to store them. Thus, a trigger system inserted in to the server cloud of LHC. Trigger has multilayer structure to select events. It basically eliminates the unnecessary low energetic particles, the ones originated from inter nuclear reactions in the detector and the ones that chosen initially according to the specific analysis.

# 3. Simulations and Analysis

## 3.1. Monte Carlo Generators

Monte Carlo (MC) event generators are software libraries which simulates high energy physics (HEP) events [8]. It based on a random number generator principle, the generator basically choses random numbers by using a characteristic Gaussian curve choosen by the Lagrangian which comes from the theory. MC simulations are widely used as tool of phenomenology and calculating the estimations for the detectors either for calibration or detection.

#### Pythia

Pythia is a multi purpose event generator [9]. It can only able to calculate three level two-to-one and two-to-two hard processes in leading order (LO), next-to-leading order (NLO) corrections are approximated with parton shower algorithm.

#### Delphes

Delphes is a multipurpose fast simulation tool for detector physics [10]. It used to simulate tracking systems, calorimeters and muon systems with an embedded magnetic flux density. Most of the MC generators can be used as a interface in the framework. It generaly used for phenomenological purposes and simulating detector responses. A trigger level selection can also be included in to the simulation.

## 3.2. ROOT

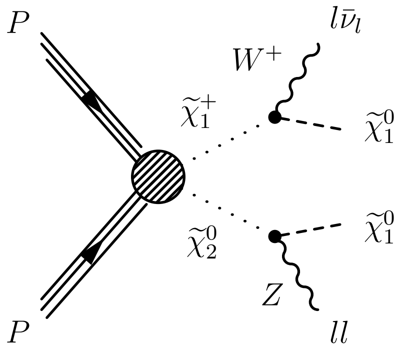
ROOT is a C++ based, open source tool to analyze large amounts of data or samples. In this analysis we used ROOT to analyze the scenarios generated by SUSY Les Houches Accord (SLHA) and Delphes. It used to draw histograms after specific requirements implemented to the samples. We stacked background, simulated by Delphes, and draw signal samples on them, by analyzing the number of events, calculated after the requirements that applied, we calculated the significance by using several algorithms.

# 4. Multilepton Analysis at the HL-LHC

In this analysis, we searched for SUSY by analyzing multilepton final states. Thus we mainly looked for the channels with W decaying to a lepton and missing energy which comes from LSP, for our SUSY models. In proceeding sections one will find the extended explanation of phase space that we are looking for, the details about models for specific channels and particles, the optimized requirement and optimization process, the significance calculation tools and results.

## 4.1. Analysis Motivation

Due to the high domination of Z and W in the SM, it suffers from tremendous amount of background in single and dilepton final states. The reason lies behind of our search is mainly suppressing these backgrounds. Thus we started with three-lepton final state which comes from chargino and neutralino decays.




The main reason of selecting this channel is significant signature on the mass regime below Z region. However, we couldn't been able to suppress the background with this phase space. Thus, we changed the topology, as in Section 4.3, to gluino associative production. With this environment by using less amount of requirements we have been able to suppress the background and get relatively high significances for various luminosity values. We first analyzed three and more muon final state events then in order to see full picture we looked for muon-electron cases.

## 4.2. Event Samples

For this analysis we used four main and one additional signal sample produces by SOFTSUSY, SUSYHIT, MADEVENT and PYTHIA which used in CMS Technical proposal for European Committee for Future Accelerators (ECFA) 2014. One can find the mass spectrum of these models in Figure 4.2.1. We also used STOC which stands for stop-coannihilation, however since it's not suitable for multilepton search we will not mention about it in our results.

Table 4.2.1: Selected NLO cross sections for the SUSY models [11].

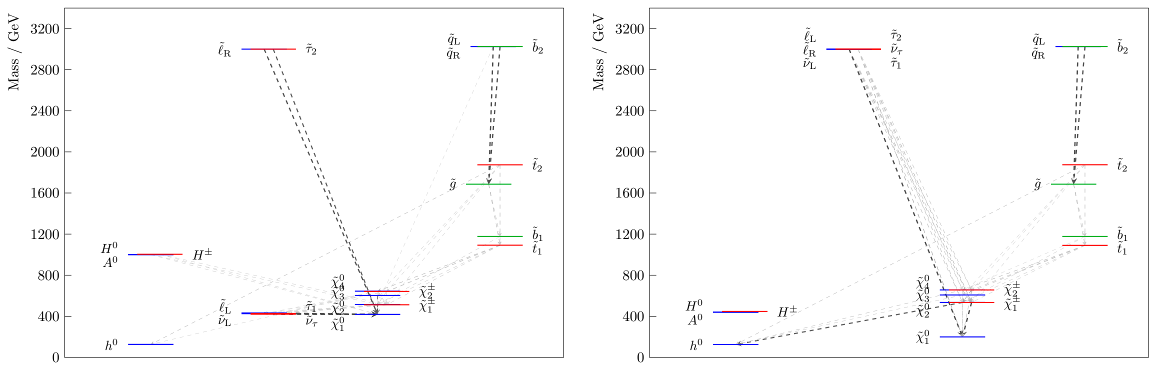
| [fb] | NM1 | NM2 | NM3 | STC | STOC |
|---|---|---|---|---|---|
| $\widetilde{g}\widetilde{g}$ | 5.4 | 5.4 | 5.4 | 0.007 | 0.53 |
| $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ | 29 | 22 | 460 | 1104 | 5.5 |

As background samples we used $t\bar{t}$, single top, diboson (VV+jets)[1], bosonjets (V+jets). These samples are produced by MadGraph and Pythia 6. Also the phase space is $H_T$ binned.

Table 4.2.2: Selected branching ratios of the SUSY models [11].

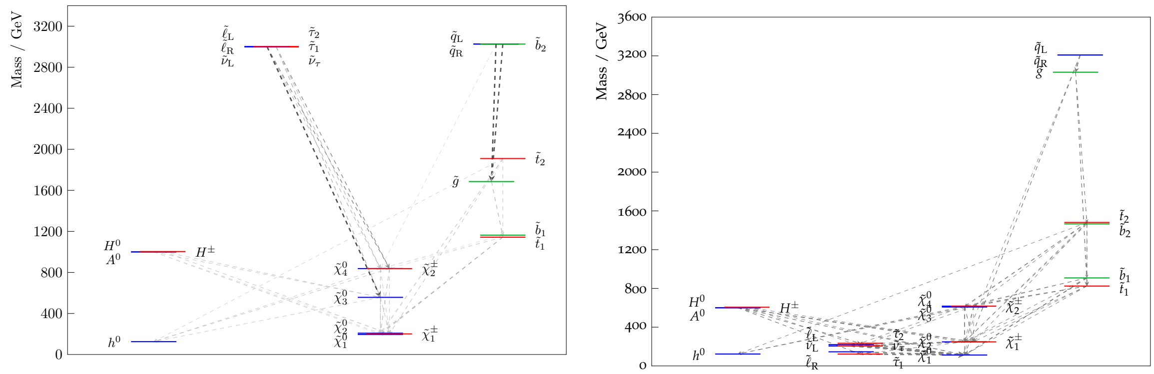
| % | NM1 | NM2 | NM3 | STC | STOC |
|---|---|---|---|---|---|
| $\widetilde{g} \rightarrow t\widetilde{t}_1$ | 60 | 60 | 60 | 26 | 50 |
| $\widetilde{g} \rightarrow t\widetilde{t}_2$ | - | - | - | 22 | - |
| $\widetilde{\chi}_1^+ \rightarrow \widetilde{\chi}_1^0 W^+$ | 1.7 | 100 | - | - | - |
| $\widetilde{\chi}_2^0 \rightarrow \widetilde{\chi}_1^0 Z$ | <1.7 | 12 | - | - | - |

From Table 4.2.1, one can see the selected cross sections of the models which we are focusing for this analysis. The "-" shows the ones which does not exist. Also in the Table 4.2.2 one can find the branching ratios that we are using for this analysis. Signal topology will be argued in Section 4.3.




(a) NM1 mass spectrum (b) NM2 mass spectrum

[1]Here V stands for either W or Z boson.

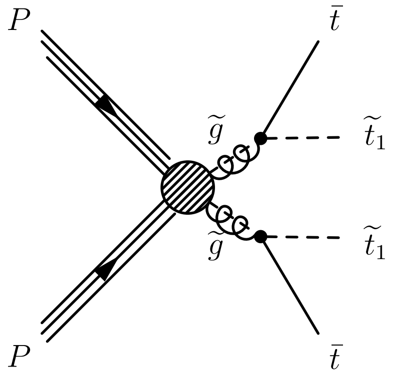


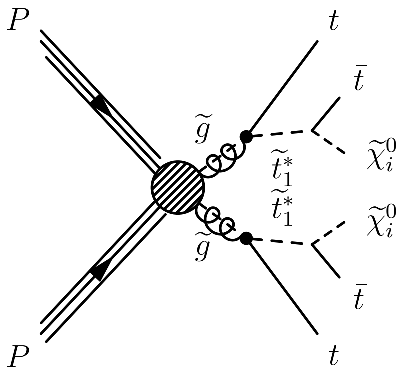

(c) NM3 mass spectrum (d) STC mass spectrum

Figure 4.2.1: Retrieved from [11]

## 4.3. Signal Topology of Multilepton Final States

We selected gluino associative production which mainly decays to $t\widetilde{t}_1^*$. Since top quark mainly decays to W and bottom quarks [12], one will end up with leptons, missing transverse energy and bottom quarks.




## 4.4. Event Selection

### Gluino Associative Production

For this channel we didn't need to require a complicated cut flow but we searched in several branches. First we require jets to have $P_T > 30$ GeV and $|\eta| < 4$. With the new developments in CMS we will be able to see higher rage of $\eta$[2] thus we enlarged our searched to higher $\eta$ values. We also cleaned jets from leptons, which $P_T > 10$ GeV, as $\Delta R > 0.4$[3]. Then since we need to end up with high energetic leptons at the final state we require the leading leptons to have $P_T^{1,2,3} > 25, 15, 10$ GeV and the others to have $P_T > 5$ GeV to avoid the inter nuclear originated leptons. Also we isolated the leptons

[2] $\eta = -\ln[\tan(\theta/2)]$
[3] $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

by $I_{rel} < 0.15$. We worked at medium B-jet tagging and the jets which has $P_T > 50$ GeV, $|\eta| < 1.8$ are tagged as B-jet.

With those pre-requirements we divided our search to several branch points. First we analyzed leptons and muons separately and require the lepton multiplicity is equal or greater than three. Then we analyzed bottom quark multiplicity separately. In first case since we need four bottom jets at final state, we required them to be equal or greater than four. In order to see the behavior of the signal at the lower B-jet multiplicity regions we selected two or three bottom jets. We realized that its possible to suppress the fake leptons which are coming from bottom quark decays by taking two or three b-jets. Then in order to suppress the background we required $E_T^{miss}$ to be greater than 300 and 500 for B-jet multiplicity equal or greater than four and two or three respectively.

| | Muon Selection | | Lepton Selection | |
|---|---|---|---|---|
| Lepton Multip. | $\geq 3$ | | $\geq 3$ | |
| BJet Multip. | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 |
| $E_T^{miss}$ [GeV] | $> 300$ | $> 500$ | $> 300$ | $> 500$ |

### Chargino & Neutralino Channel

Since this channel was not trivial to study we required a long cut flow. By using the same pre-requirements we analyzed muons which exactly equal to three since the channel requires a Z and W boson, the final state will be exactly three leptons. In order to eliminate background from low-mass Drell-Yan processes[4], $J/\psi$ and $\Upsilon$ decays we required $m_{l^+l^-} > 15$ GeV. In order to suppress the SM Z we eliminate Z band as $75 < m_{l^+l^-} < 105$ GeV. We required leptons $P_T > 20$ GeV and we required the leading jet transverse momentum to be greater than 120 GeV and 70 GeV respectively. B-Jets are vetoed in order to suppress the background from $t\bar{t}$. Also we required $H_T > 500$[5] GeV and $E_T^{miss} > 250$ GeV and we required the ratio between missing transverse energy and effective mass[6] to greater than 0.2.

## 4.5. Results

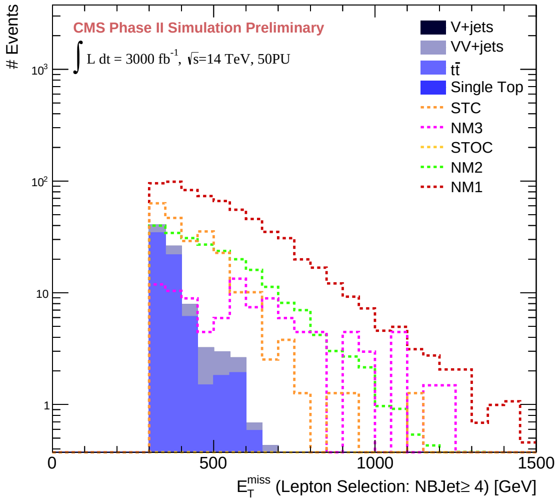
For chargino and neutralino case, since the cross section was relatively smaller than gluino associative production, we didn't have promising results. The search should include all leptons in order to increase the number of events and more effective B-tagging should apply in order to suppress the $t\bar{t}$ background.

[4]The Drell-Yan process occurs in high energy hadron scattering. A anti-quark annihilate by a quark and creates a virtual photon, $\gamma^*$, which creates a lepton and anti-lepton.

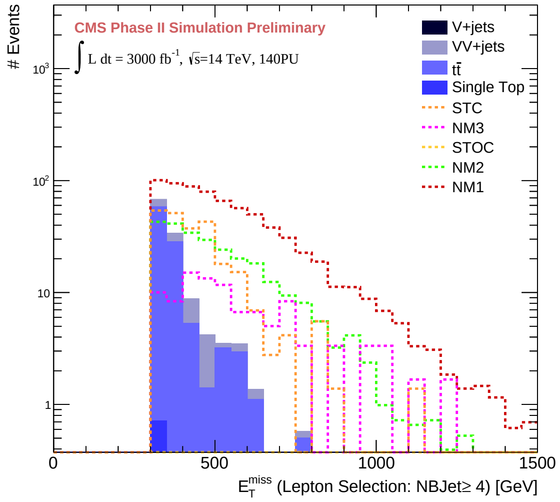
[5]$H_T$: scalar sum of all jet $P_T$.

[6]$M_{eff} = E_T^{miss} + H_T$

For gluino associative production we had promising results. We have been able to separate the signal from background with high significance. In Table A.1.1 and A.1.2 we able to suppress most of the background as expected by requiring the multilepton condition, we have been able to suppress V+jets and single top. Since SUSY particles are high energetic, $E_T^{miss}$ requirement didn't effect them as it effected the background.

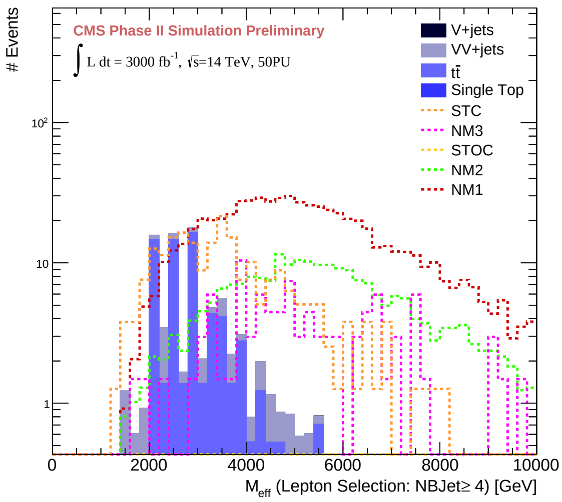



(a)

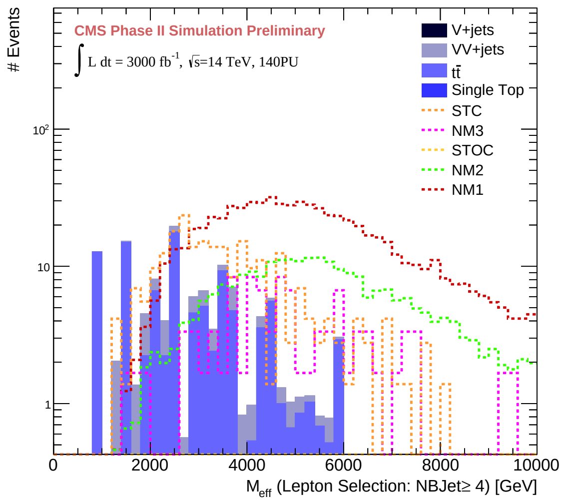



(b)

Effective mass is one of the most important search area for SUSY. Since SUSY particles are more energetic than the SM particles we see the peak of the signal shifted to right with respect to SM particles.




(c)




(d)

One can find the result tables and histograms at Appendix A.1 and A.2.

### Significance Calculation

For significance calculation we used two different tool. One is standard significance which is based on deviation of background.

$$Z = \frac{S}{\sqrt{b + \sigma_b^2}}$$

where S is the expected number of events from signal, b is the expected number of background events and $\sigma_b$ stands for variance of background. Since this equation diverges with small amount of background, as argued in [13], we used Asimov Significance.

$$Z_A = \left[ 2 \left( (s+b) \ln \left[ \frac{(s+b)(b+\sigma_b^2)}{b^2 + (s+b)\sigma_b^2} \right] - \frac{b^2}{\sigma_b^2} \ln \left[ 1 + \frac{\sigma_b^2 s}{b(b+\sigma_b^2)} \right] \right) \right]^{\frac{1}{2}}$$

In Figure 4.5.1, since standard significance divides the number of signal events with background it diverges with low values of background events. On the other, hand Asimov significance is tuned with the MC.

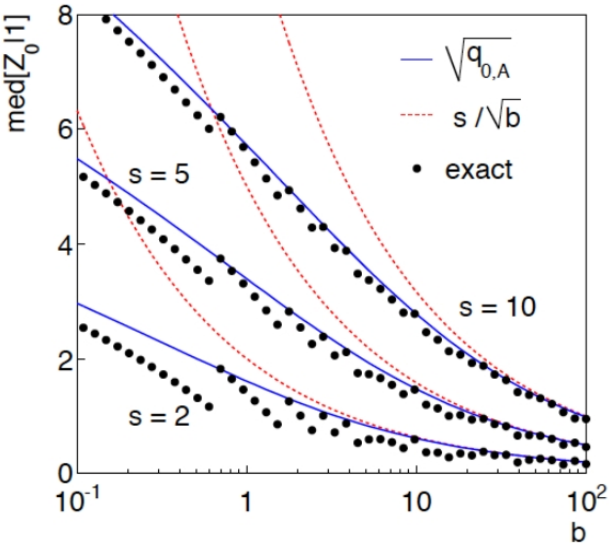



Figure 4.5.1: Here blue line represents Asimov significance, red line represents standard significance and dots are MC simulation values. Retrieved from [13].

| | | 140PU | | | | 50PU | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Phase II | | Phase I | | Phase II | | Phase I | |
| # BJet | | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 |
| # Bkg | | 123 | 76 | 12 | 7 | 84 | 35 | 7 | 3 |
| Asimov | NM1 | 13 | 6 | 9 | 3 | 15 | 9 | 11 | 4 |
| | NM2 | 6 | 2 | 4 | 1 | 7 | 3 | 5 | 1 |
| | NM3 | 3 | 1 | 2 | 0 | 4 | 1 | 2 | 0 |
| | STC | 6 | 3 | 4 | 1 | 7 | 5 | 5 | 2 |

By using these tools and the results mentioned previously we calculated the significances above. We accepted $5\sigma$ as discovery. In lepton selection, we can claim discovery for NM1 for all cases but for Phase I, 50 pileup, two or three bottom quark selection. Also NM2 and STC are slightly above the $5\sigma$. In Table A.1.4 we didn't calculated some certain channels, since the background is very low its impossible to differentiate signal from background in an experiment. Since with the muon selection we decreased the number of events too much its hard to claim discovery.

# 5. Conclusion

Supersymmetry explains so many things that we cant explain by the Standard Model of particle physics. By introducing an extended symmetry between fermions and bosons, SUSY solves most of the problems in the SM. Our search gives appealing results for the next run of LHC. With increased luminosity and center-of-mass energy its possible to find SUSY in HL-LHC.

This analysis held multilepton final state search for SUSY. Due to the domination of Z and W in the SM, multilepton search may give reasonable results to find SUSY. We searched for chargino and neutralino channels and gluino associative production. Although chargino and neutralino channel didn't give promising results due to relatively low cross section, we had promising results for gluino associative production. We see that there is no much difference between 50 pileup or 140 pileup cases but Phase I may not be enough to find SUSY, due to the low number of events but we have promising results for both Phase I and II.

This analysis can be extend for tau leptons to see the full picture. We also realized that missing transverse energy in 50 pileup samples has bug. By fixing the bug, it may possible to see better results for Phase I with 50 pileup samples.

# Appendix A Results

## A.1 Tables

Table A.1.1: Number of events for lepton Selection

| | 140PU | | | | 50PU | | | |
|---|---|---|---|---|---|---|---|---|
| | Phase II | | Phase I | | Phase II | | Phase I | |
| # Bjet | $\geq 4$ | 2or 3 | $\geq 4$ | 2or 3 | $\geq 4$ | 2or 3 | $\geq 4$ | 2or 3 |
| NM1 | 704 | 176 | 70 | 16 | 673 | 146 | 67 | 14 |
| NM2 | 260 | 40 | 26 | 4 | 234 | 38 | 23 | 3 |
| NM3 | 101 | 25 | 10 | 2 | 102 | 19 | 10 | 1 |
| STC | 240 | 73 | 24 | 7 | 228 | 74 | 22 | 7 |
| $t\bar{t}$ | 100 | 30 | 10 | 3 | 68 | 7 | 6 | 0 |
| Single top | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| V+jets | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| VV+jets | 23 | 46 | 2 | 4 | 16 | 28 | 1 | 3 |

Table A.1.2: Number of events for muon Selection

| | 140PU | | | | 50PU | | | |
|---|---|---|---|---|---|---|---|---|
| Lumi | Phase II | | Phase I | | Phase II | | Phase I | |
| Bjet | $\geq 4$ | 2or 3 | $\geq 4$ | 2or 3 | $\geq 4$ | 2or 3 | $\geq 4$ | 2or 3 |
| NM1 | 111 | 36 | 11 | 3 | 103 | 29 | 10 | 2 |
| NM2 | 35 | 7 | 3 | 0 | 33 | 6 | 3 | 0 |
| NM3 | 20 | 3 | 2 | 0 | 17 | 1 | 1 | 0 |
| STC | 42 | 22 | 4 | 2 | 42 | 15 | 4 | 1 |
| $t\bar{t}$ | 9 | 1 | 0 | 0 | 3 | 0 | 0 | 0 |
| Single top | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| V+jets | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| VV+jets | 7 | 14 | 0 | 1 | 3 | 10 | 0 | 1 |

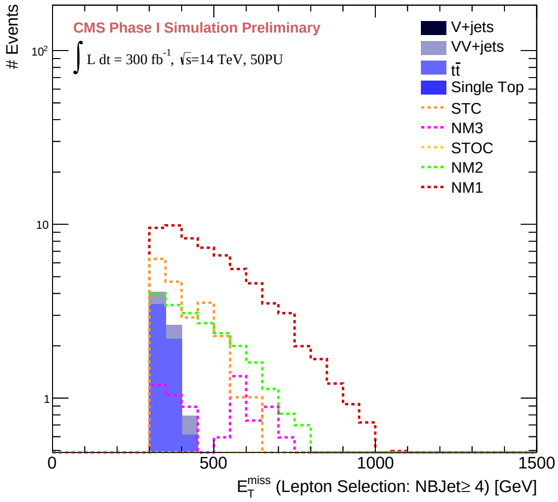
Table A.1.3: Calculated significances for lepton selection, Background uncertainty has taken as 20%

| | | 140PU | | | | 50PU | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Phase II | | Phase I | | Phase II | | Phase I | |
| | # BJet | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 |
| | # Bkg | 123 | 76 | 12 | 7 | 84 | 35 | 7 | 3 |
| Asimov | NM1 | 13 | 6 | 9 | 3 | 15 | 9 | 11 | 4 |
| | NM2 | 6 | 2 | 4 | 1 | 7 | 3 | 5 | 1 |
| | NM3 | 3 | 1 | 2 | 0 | 4 | 1 | 2 | 0 |
| | STC | 6 | 3 | 4 | 1 | 7 | 5 | 5 | 2 |
| Standard | NM1 | 26 | 10 | 16 | 5 | 35 | 15 | 22 | 7 |
| | NM2 | 9 | 2 | 6 | 1 | 12 | 4 | 7 | 1 |
| | NM3 | 3 | 1 | 2 | 0 | 5 | 2 | 3 | 0 |
| | STC | 8 | 4 | 5 | 2 | 11 | 8 | 7 | 3 |

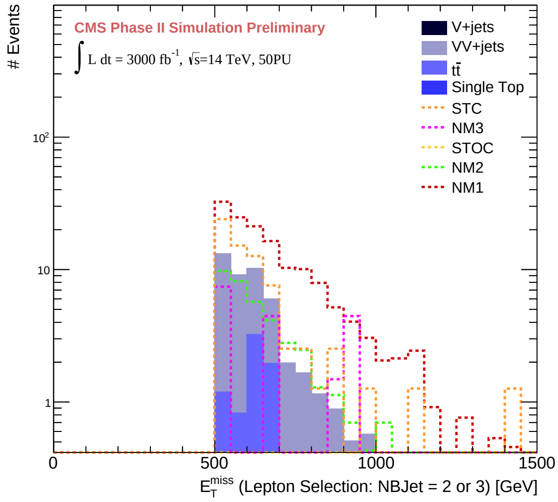
Table A.1.4: Calculated significances for muon selection, Background uncertainty has taken as 20%

| | | 140PU | | | | 50PU | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Phase II | | Phase I | | Phase II | | Phase I | |
| | # BJet | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 | $\geq 4$ | 2 or 3 |
| | # Bkg | 16 | 15 | 0 | 1 | 6 | 10 | 0 | 1 |
| Asimov | NM1 | 11 | 5 | – | 2 | 15 | 5 | – | 1 |
| | NM2 | 4 | 1 | – | 0 | 7 | 1 | – | 0 |
| | NM3 | 3 | 0 | – | 0 | 4 | 0 | – | 0 |
| | STC | 5 | 3 | – | 1 | 8 | 0 | – | 0 |
| Standard | NM1 | 21 | 7 | – | 2 | 37 | 7 | – | 1 |
| | NM2 | 6 | 1 | – | 0 | 12 | 1 | – | 0 |
| | NM3 | 3 | 0 | – | 0 | 6 | 0 | – | 0 |
| | STC | 8 | 4 | – | 1 | 15 | 1 | – | 0 |

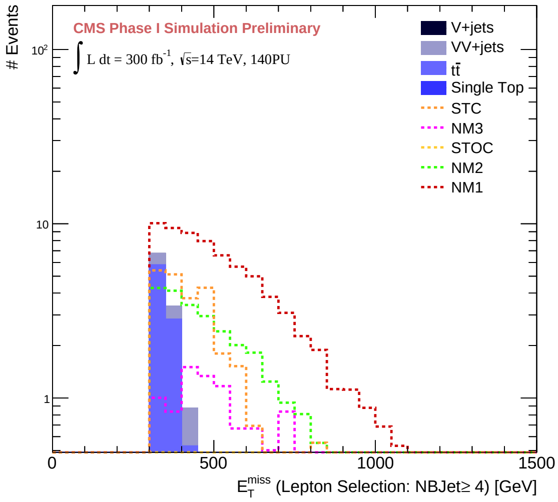
## A.2 Histograms



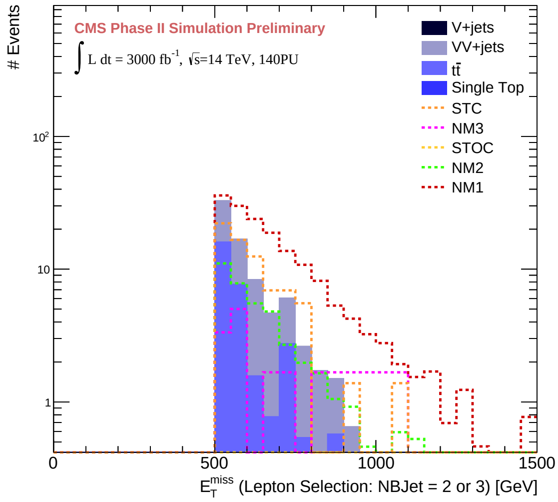

(a)




(b)

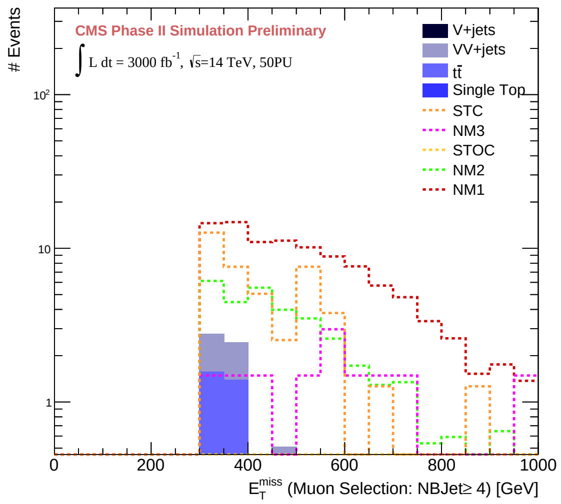



(c)

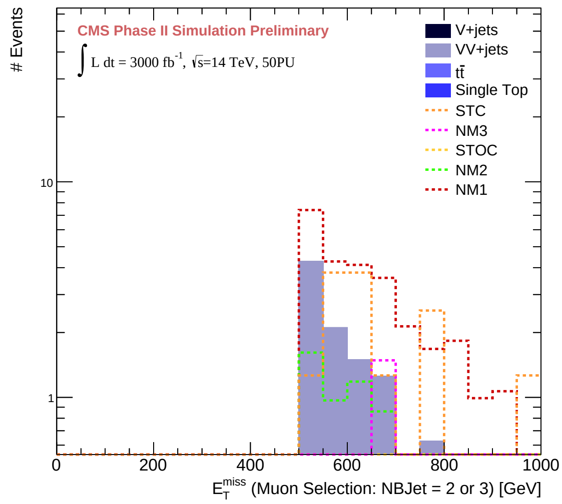



(d)

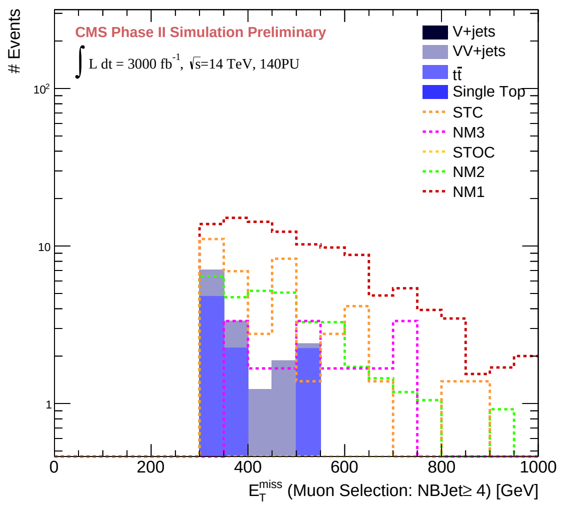
Figure A.2.1: Missing Transverse Energy for lepton selection.



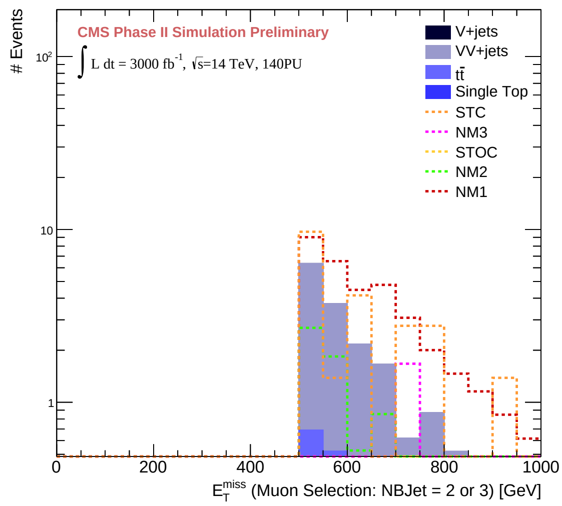

(a)




(b)

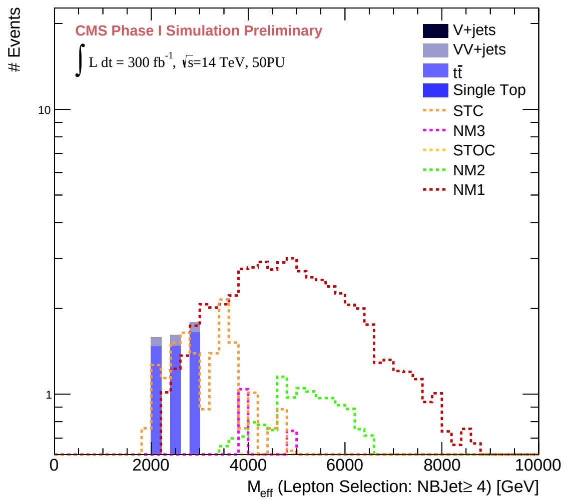



(c)

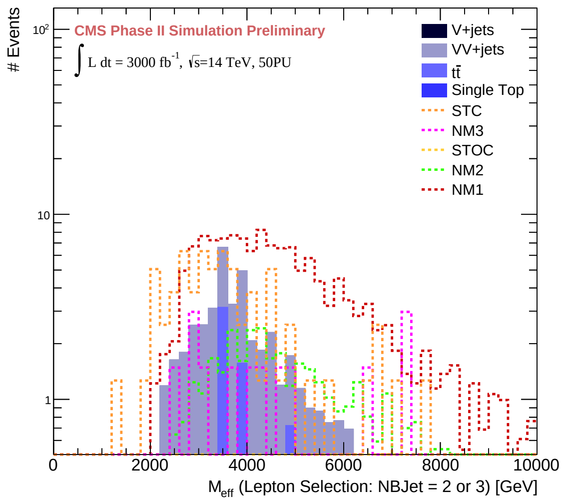



(d)

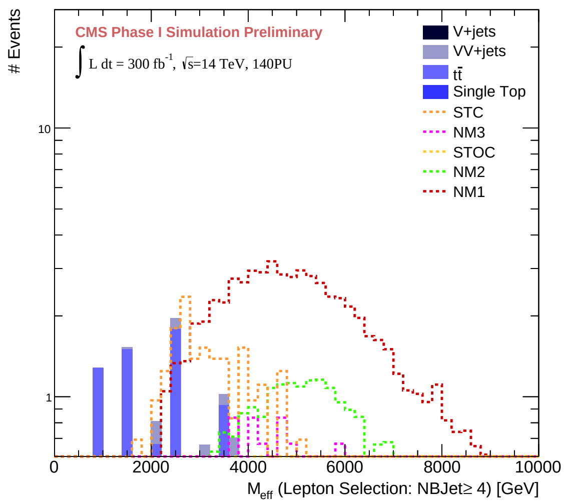
Figure A.2.2: Missing Transverse Energy for muon selection.



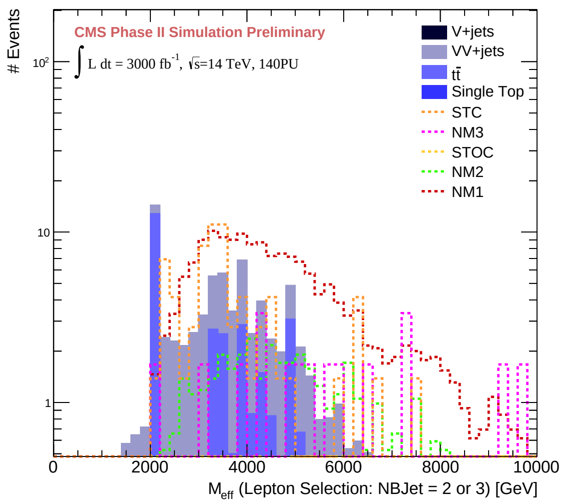

(a)




(b)

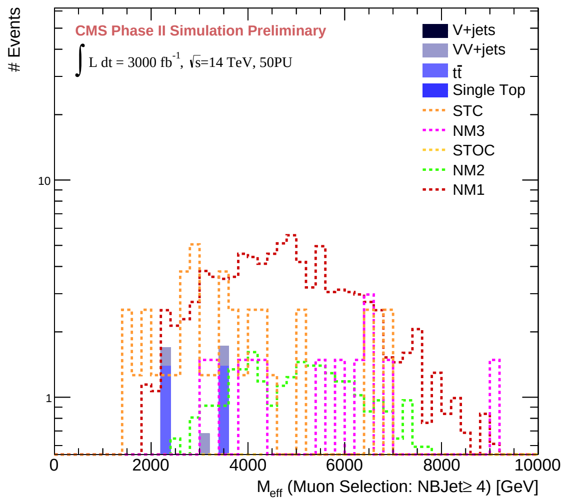



(c)

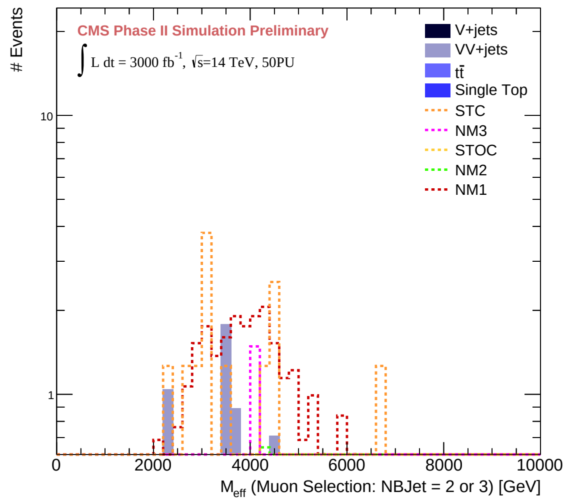



(d)

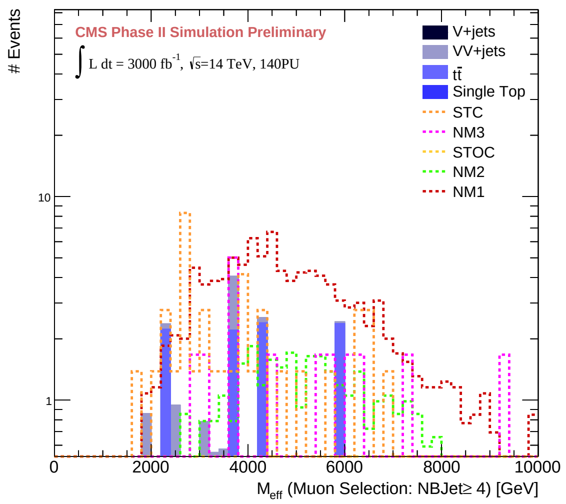
Figure A.2.3: Effective Mass for lepton selection.



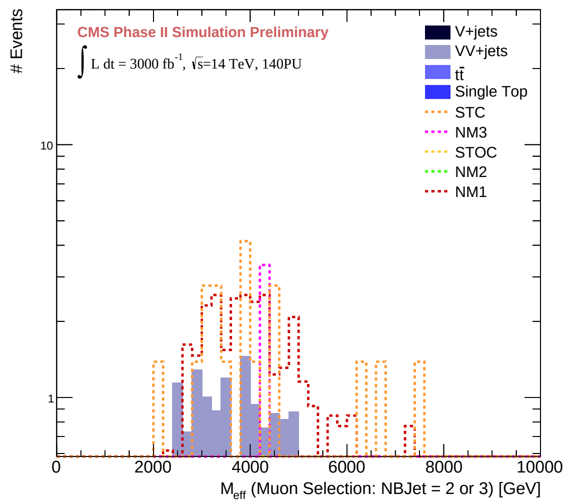

(a)




(b)

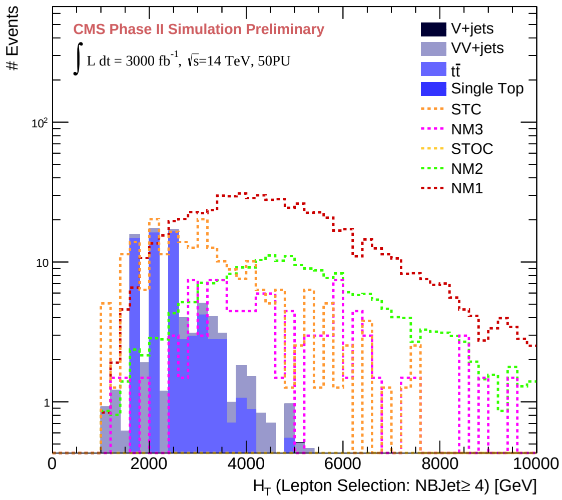



(c)

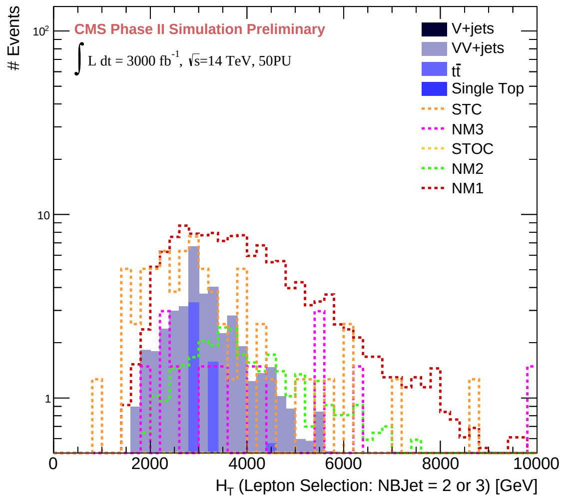



(d)

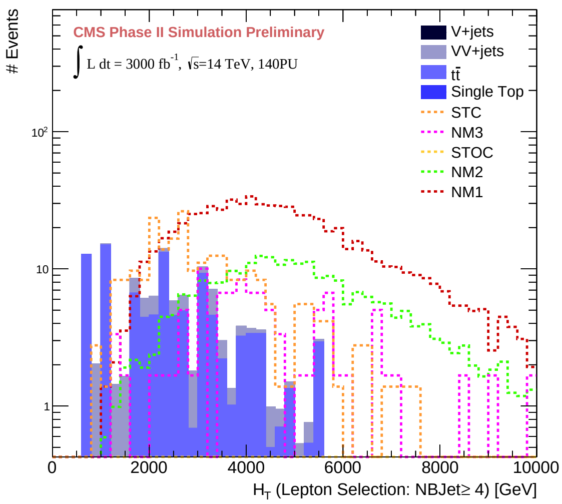
Figure A.2.4: Effective Mass for muon selection.



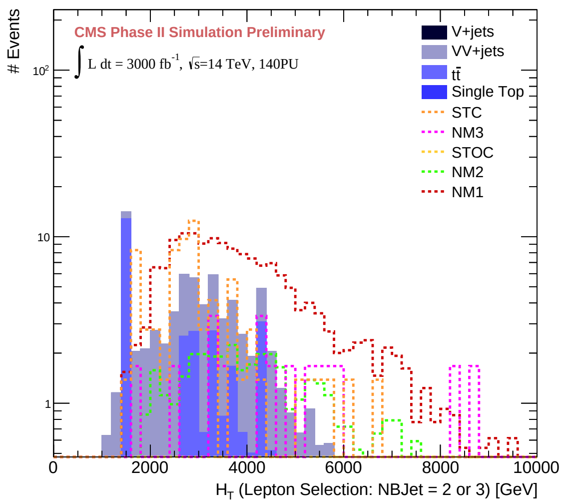

(a)




(b)




(c)




(d)

Figure A.2.5: $H_T$ for lepton selection.

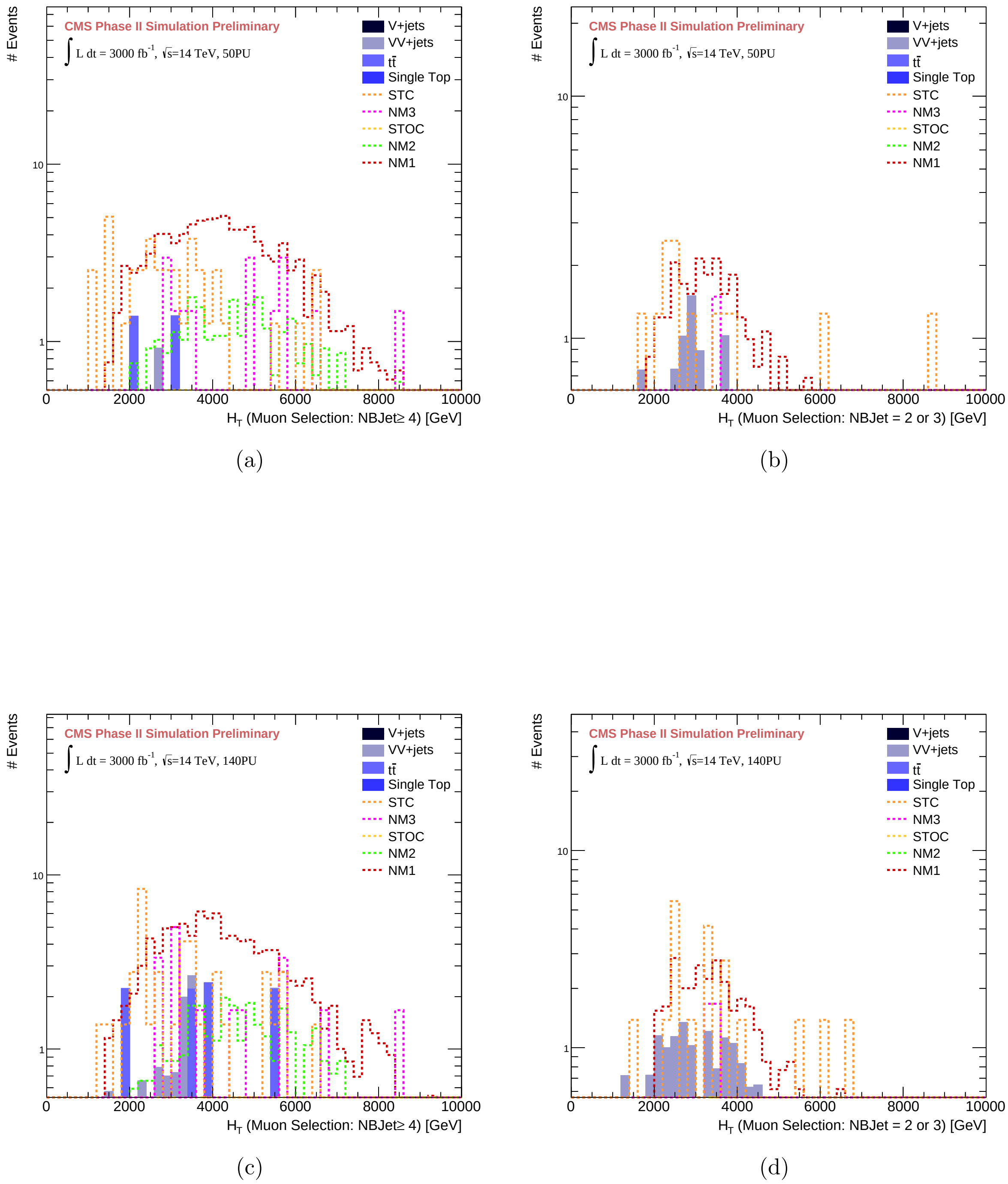



Figure A.2.6: $H_T$ for muon selection.

# Appendix B Acronyms

**ATLAS** A Toroidal LHC Apparatus

**BSM** beyond the standard model

**CERN** European Organization for Nuclear Research

**CMS** Compact Muon Solenoid

**ECAL** Electromagnetic calorimeter

**ECFA** European Committee for Future Accelerators

**GUT** Grand Unified Theory

**HCAL** hadronic calorimeter

**LHC** Large Hadron Collider

**LO** leading order

**LSP** lightest supersymmetric particle

**HL-LHC** High-Luminosity-LHC

**HEP** high energy physics

**MC** Monte Carlo

**MSSM** Minimal Supersymmetric Extension of the Standard Model

**NLO** next-to-leading order

**PDG** Particle Data Group

**pp** proton-proton

**SM** Standard Model of particle physics

**SUSY** Supersymmetry

**SLHA** SUSY Les Houches Accord

**QCD** quantum chromodynamics

## References


[1] Griffiths, D.(2008).Introduction to Elementary Particles, $2^{nd}$ Edition: Wiley-VCH.

[2] Waltham, C. (2004). Neutrino Oscillations for Dummies. Am.J.Phys., 72, 742-752. Retrieved from arXiv:physics/0303116v1 [physics.ed-ph]

[3] Sakharov, A. D. (1966). Violation of CP invariance, C asymmetry and baryon asymmetry of the universe. Pisma Zh. Eksp. Teor. Fiz., 5(1), 32-35.

[4] Duda, G. & Garrett, K. (2011). Dark Matter: A Primer. Adv. Astron. Retrieved from arXiv:1006.2483v2 [hep-ph]

[5] Bilal, A. (2001, Jan. 10). Introduction to Supersymmetry. Retrieved from arXiv:hep-th/0101055v1

[6] Martin, S. (2011, September). A Supersymmetry Primer. Retrieved from arXiv:hep-ph/9709356v6

[7] Dreiner, H. (1997, July 24). An Introduction to Explicit R-Parity Violation. Retrieved from arXiv:hep-ph/9707435v2

[8] Seymour, M., & Marx, M. (2013, April). Monte Carlo Event Generators. Retrieved from arXiv:1304.6677v1 [hep-ph]

[9] Sjostrand, T., Mrenna, S., & Skands, P. (2006). PYTHIA 6.4 Physics and Manual. Retrieved from arXiv:hep-ph/0603175v2

[10] Ovyn, S., Lemaitre, V., & Rouby, X. (2010, April 8). Delphes, a framework for fast simulation of a generic collider experiment. Retrieved from arXiv:0903.2225v3 [hep-ph]

[11] Melzer-Pellman, I. (2014, September 3). Full models for discovery stories. Retrieved from SUSY Analyses Twiki page

[12] Liss, T. (2011, December). THE TOP QUARK. Retrieved from Particle Data Group (PDG)

[13] Cowan, G., Cranmer, K., Vitells, E., & Gross, O. (2013). Asymptotic formulae for likelihood-based tests of new physics. Eur.Phys.J., C71(1554,2011). Retrieved from arXiv:1007.1727v3

[14] Skands, P., Allanach, B., Baer, H., Balazs, C. et all.(2004, November). SUSY Les Houches Accord: Interfacing SUSY Spectrum Calculators, Decay Packages, and Event Generators. JHEP 0407:036,2004 Retrieved from arXiv:hep-ph/0311123v4

[15] The ATLAS Collaboration. (2014, July). Search for Supersymmetry at the high luminosity LHC with the ATLAS experiment. CERN: Geneva. Retrieved from ATL-PHYS-PUB-2014-010

[16] Beringer, J. et al.(2012) W Boson, PR D86, 010001 Retrieved from Particle Data Group (PDG)

[17] The CMS Collaboration. (2014, April 23). Search for anomalous production of events with three or more leptons in pp collisions at $\sqrt{s}$=8 TeV. Retrieved from CMS-PAS-SUS-13-002

[18] The CMS Collaboration. (2013, May 29). Search for supersymmetry in pp collisions at $\sqrt{s} = 8$ TeV in events with three leptons and at least one b-tagged jet. CERN: Geneva Retrieved from CMS-PAS-SUS-13-008

[19] Gershtein Y., Luty M., Narain M., Wang L. -T., Whiteson D., Agashe K., Apanasevich L., Artoni G., Avetisyan A., Baer H. et al..(2013, Nov. 1) New Particles Working Group Report of the Snowmass 2013 Community Summer Study. Retrieved from arXiv:1311.0299v1 [hep-ex]