Search for SUSY in Multilepton Final States

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Abstract

In this report the discovery of four different full SUSY models with different analyses at Larger Hadron Collider(LHC) and High Luminosity-Large Hadron Collider(HL-LHC) is discussed. The center of mass energy is $\sqrt{s} = 14$ TeV and the integrated luminosities are $\int \mathcal{L}\, \mathrm{dt} = 300 \mathrm{fb}^{-1}$ and $\int \mathcal{L}\, \mathrm{dt} = 3000 \mathrm{fb}^{-1}$, respectively for LHC and HL-LHC. Samples of 50 and 140 pileup were used in the analysis.

Contents

1 Theory

This chapter discusses the Standard Model theory of particle physics and its limitations to explain the motivation for Supersymmetry.

1.1 The Standard Model

The Standard Model in particle physics describes subatomic particles and their interactions. The SM includes ‘electromagnetic, weak and strong forces, but it excludes gravity since gravitational force has negligible effect with respect to the other three forces at the subatomic scale.

1.1.1 Elementary Particles in the SM

In the SM, the elementary particles are classified in accordance with their spin number and through which forces they interact with other elementary particles. The three generations of particles are as follows:

- 12 spin-½ fermions
  - 6 quarks
  - 6 leptons not interacting through strong force
- 12 spin-1 bosons
  - 8 massless gluons propagating the strong interaction
  - $W^{\pm}$ and Z^0 bosons propagating weak interaction
  - Photon propagating the electromagnetic interaction
- 1 spin-0 boson(the Higgs Boson)
  - Origin of particle mass
  - Yukawa interaction btw. particles and the Higgs field

The 12 fermions are also referred to as the matter particles and both quarks and leptons consist of three flavors of particles[6]. The first flavor consists of the lightest and stablest particles and all stable matter around the universe is made of particles of this flavor. The two other heavier generations of matter quickly decay into more stable particles; therefore they have not been observed as early as the elementary particles of first generation.
The standard model is now complete with the discovery of the Higgs boson in 2012 at LHC after its theoretical prediction in 1964 by Brout, Englert and Higgs. [3] Particles gain mass depending on the quantity of their interaction with the Higgs field; that is the lightest particles interact the least and the heaviest particles interact the most with the Higgs field.

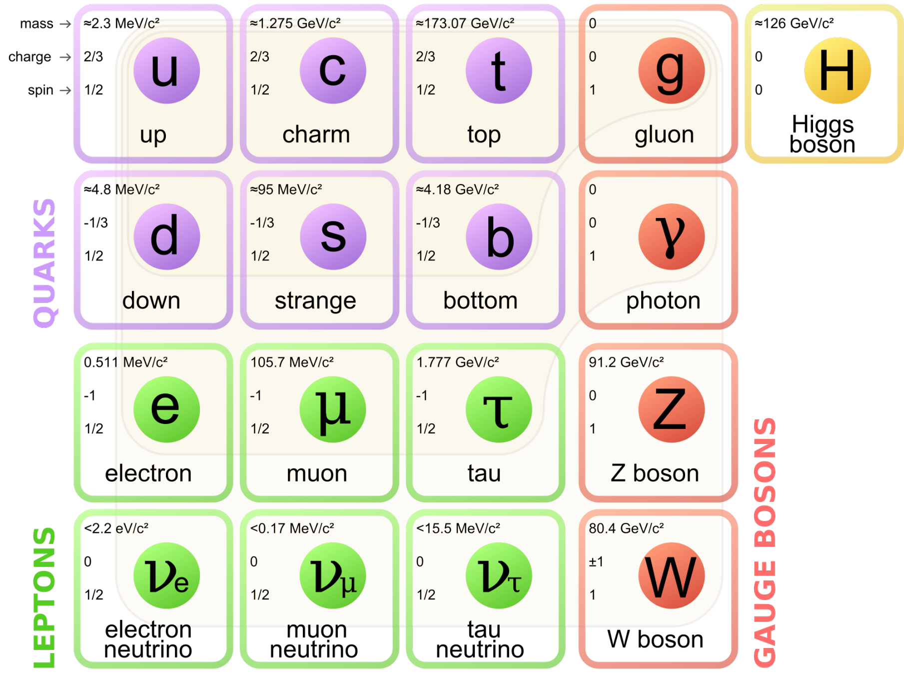


Figure 1: The SM elementary particles together with their mass, charge and spin[1]

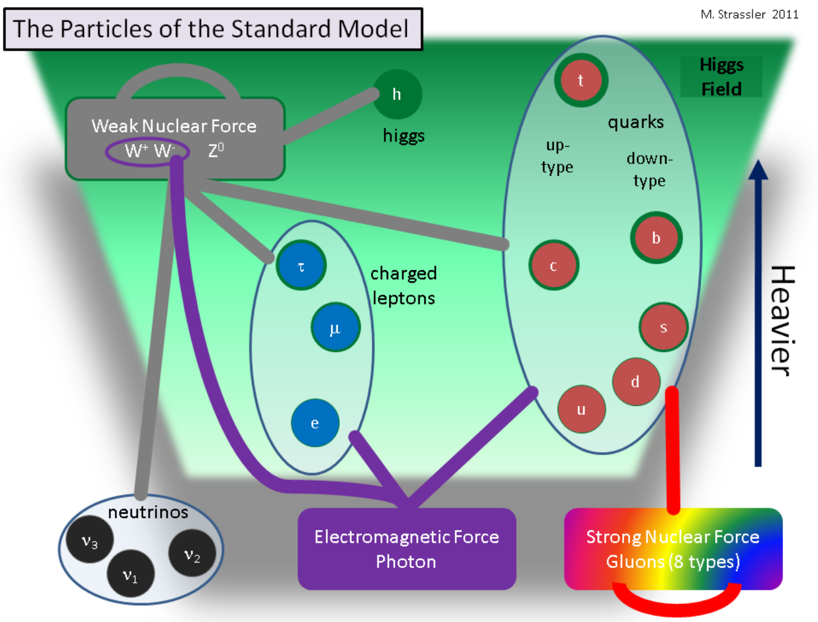


Figure 2: The interactions between elementary particles in SM[2]

1.1.2 Problems of the SM

Although the SM accounts for most of the observed phenomena in the universe, some theoretical concepts were introduced in an ad-hoc way and there are inconsistencies between some experiments and theoretical predictions. The most prominent experimental issues are [4]:

Neutrino Oscillations
: In the SM, neutrinos are massless particles; however, the discovered neutrino oscillations hint that neutrinos indeed have a mass.

Dark matter and dark energy
: The speeds of astrophysical objects are not declining with distance from the observed luminous material (as in the solar system). Furthermore, there is not enough evidence for astrophysical objects emitting no radiation, and are composed of ordinary matter.

Matter-antimatter symmetry
: The SM predicts equal amounts of matter and antimatter, but almost all the matter observed are made of matter. It should be easy to detect regions with antimatter prevalence, yet so far no evidence has been found.

Hierarchy Problem
: Inclusion of gravity inside SM is not possible and it cannot explain how the Higgs boson gain mass.

Unification of forces
: As in the figure below forces in SM do not unify, but it is possible in supersymmetry.

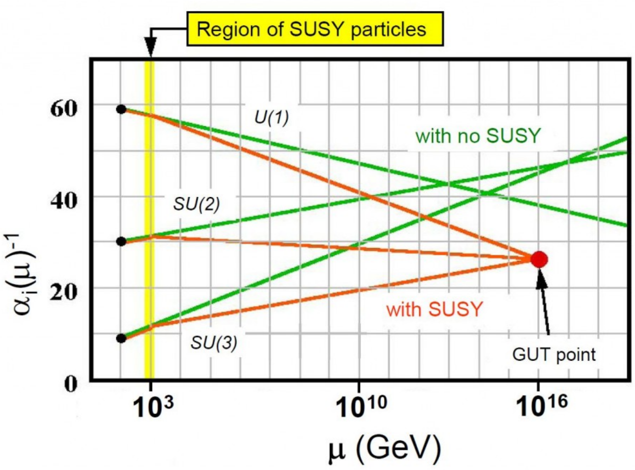


Figure 3: Running coupling constant in SM and SUSY [5]

1.2 Beyond the Standard Model

There are a large number of SM extensions, usually referred to as beyond the standard model(BSM) theories that aim to overcome the limitations of the SM. One of the most appealing extension theories is the Supersymmetry(SUSY).

1.2.1 SUSY

SUSY is the preferred BSM model since it addresses most of the SM issues and provides a symmetry(hence the name supersymmetry) which relates fermions and bosons as shown below:

$$\begin{aligned} Q|\text{BOSON} > &= |\text{FERMION} > \\ Q|\text{FERMION} > &= |\text{BOSON} > \end{aligned} \tag{1}$$

SUSY solves naturalness and gauge hierarchy problem of SM and unification of gauge couplings[6] as seen in Fig. 3. Also superpartners are introduced to ordinary SM particles and usually named by prefixing the SM model name with an "s", say selectron for the superpartner of the electron. The parameters of these SUSY particles are arranged in such a way that they cancel quadratic divergences in Higgs mass. Furthermore, in R-parity conserving models SUSY suggests the lightest neutralino[1] as the dark matter candidate solving another issue of the SM.

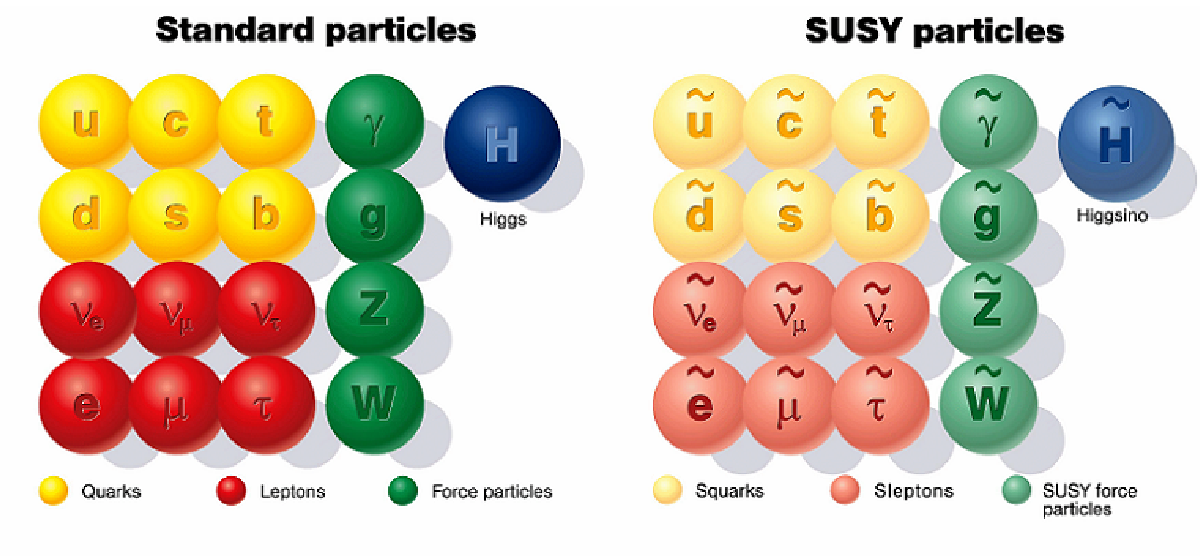


Figure 4: SM particles together with their counterparts in SUSY[7]

2 Experiment

2.1 CMS

The CMS is the name of the detector that is situated in the Large Hadron Collider(LHC) at CERN. As the other detectors CMS consists of layers of material to benefit from the different properties of particles to perform measurements on their momentum and energy. In order to measure the momentum of charged particles the CMS utilizes very strong magnets, so by inspecting the curve of the charged particle inside the magnetic field their momentum is measured indirectly. The magnet has to be really strong since there are particles with very high momentum; therefore a "Solenoid" is used and the niobium titanium coils carry a current of approximately 18000 A. The name "Solenoid" in Compact Muon Solenoid comes from this fact and the word "Compact" is dubbed after

[1]Lightest supersymmetric particle (LSP)

the fact that the tracker and calorimeter sections of the detector are fit within the coil resulting in a compact structure among detectors of similar weight.
The innermost layer inside the CMS layered structures is the tracking system consisting of silicon pixels and silicon strip detectors. Their role is to record the positions of charged particles penetrating through with accuracy, so that physicists can reconstruct their tracks.
The next two layers are calorimeters and their function is to measure the energy of the incoming electrons, photons and jets[2]. The first calorimeter layer is the electromagnetic calorimeter(ECAL) and it is designed with the intention to measure the energies of electrons and photons which interact electromagnetically. The second calorimeter is the hadronic calorimeter(HCAL) and its role is to measure the energy of the particles interacting by the strong force, the so called hadrons.
Muons are able to penetrate through all these layers and they are tracked in the outermost muon chamber detectors. There are also neutrinos that do not interact at all and their presence and track is inferred by summing the momenta of all the detected particles and using momentum conservation laws.

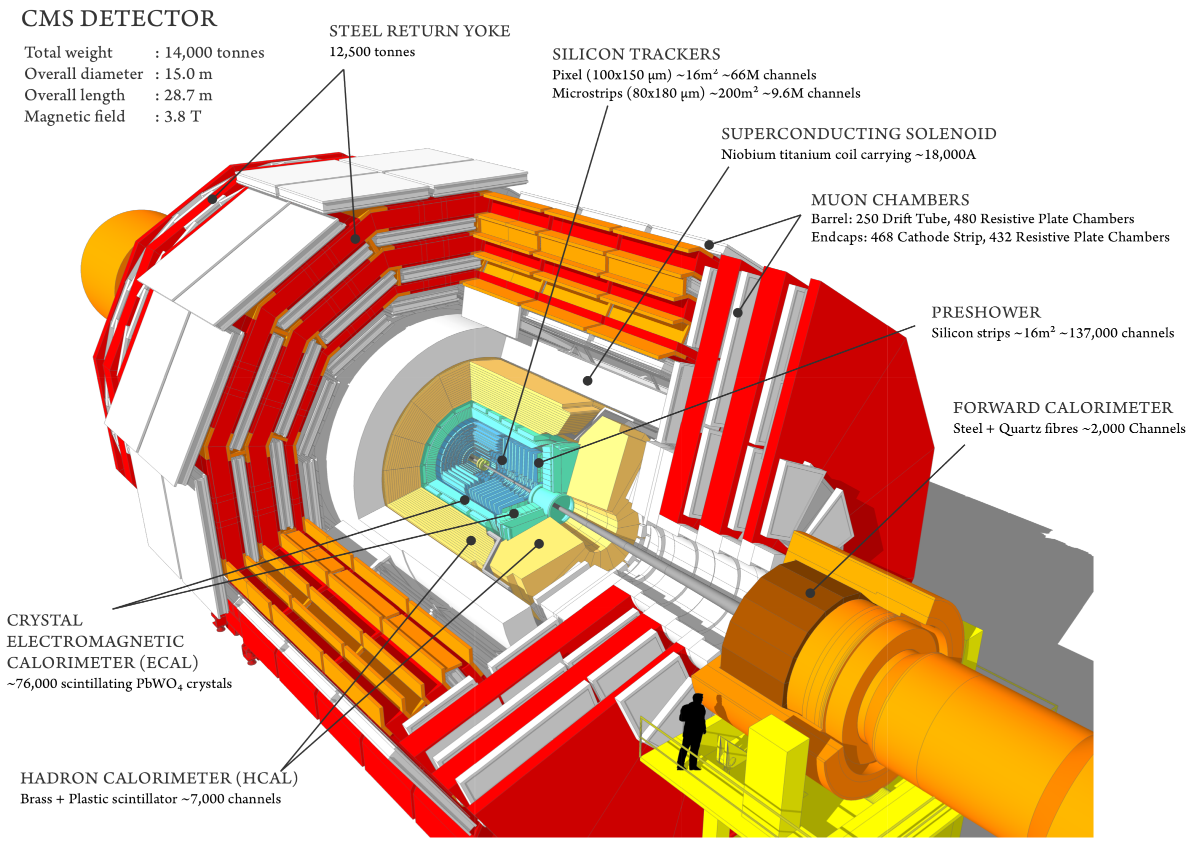


Figure 5: Sectional view of the CMS detector

[2]Particle shower produced by quarks are called jets.

2.2 Kinematics

In CMS experiments the origin of the coordinate system is at the nominal interaction point(IP), the z-axis points along the anticlockwise-beam direction, the x-axis points at the center of the LHC ring and y-axis is perpendicular to the LHC plane pointing away from the ground. The azimuthal angle ϕ is defined in the $x-y$ plane and measured from the x-axis, while the radial coordinate in the $x-y$ plane is referred to as r. The polar angle θ is measured from the positive z-axis as a matter of convention. The important kinematic variables are defined as follows:

Rapidity y

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \tag{2}$$

Pseudorapidity η [3]

$$\eta = -\ln[\tan(\theta/2)] \tag{3}$$

Transverse mass m_T

$$m_T = m_0^2 + p_x^2 + p_y^2 \tag{4}$$

Transverse momentum P_T

$$P_T^2 = P_x^2 + P_y^2 \tag{5}$$

3 Simulations

In our analysis the models are calculated using SuSpect 2.41/2.43 or SoftSusy 3.4.0 together with Susy-Hit 1.3b/3.4 and then the resulting SLHA files are fed as input to MadEvent, and then hadronized with Pythia 6.4. As a last step the resulting LHE files are processed with Delphes 3.0.10, the detector simulation package.

3.1 SUSY Spectrum Calculators

These packages calculate the supersymmetric mass and coupling spectrum, after some given or derived SUSY-breaking terms and a matching to known data on the SM parameters. In our case SuSpect 2.41/2.43 and SoftSusy 3.4.0 are spectrum calculators.[11] SuSpect is written in Fortran and can perform calculation of the SUSY and Higgs particle spectrum in the unconstrained Minimal Supersymmetric Standard Model(MSSM) together with constrained models with universal boundary conditions at high scales such as the gravity(mSUGRA), anomaly(AMSB) or gauge (GMSB) mediated breaking models. Spectrum calculations are also possible in the non-universal MSSM case with R-parity and CP conservation. The program also features renormalization group evolution between low and high energy scales, consistent implementation of radiatie electroweak symmetry breaking and calculation of physical masses with radiative corrections.[12]

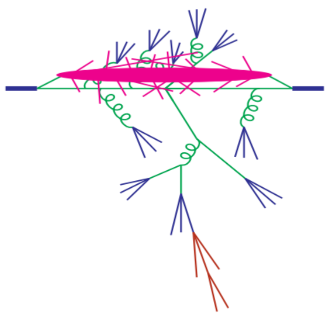
[3] In the relativistic limit rapidity and pseudorapidity are essentially the same.

SoftSusy is a spectrum calculator able to perform in Next-to-Minimal Supersymmetric Standard Model(NMSSM), MSSM including flavor violation with or without R-parity consistent with input Standard Model fermion mass/mixings and electroweak/strong coupling data. It can calculate neutrino masses and mixing to 1 loop in the R-parity violating mode and as of the latest update it features 3 loop renormalization group equations and some 2-loop threshold corrections[13, 14, 15, 16, 17]. The program Susy-Hit is used for calculating supersymmetric particle decays within the framework of the MSSM in the preparation of our data samples. There are two Fortran codes HDECAY and SDECAY for the calculation of the decay widths and branching ratios of the MSSM Higgs bosons and the SUSY particles, respectively. Susy-Hit also calls a program for the calculation of the SUSY particle spectrum such as Suspect mentioned above. With the inclusion of all important higher order effects, MSSM particle spectrum and decay can be calculated with the highest level of precision presently[18].Prospino2 is used for the computation of next-to-leading order cross sections for the production of SUSY particles at hadron colliders such as LHC. Squark, gluino, stop, neutralino/chargino, and slepton pair productions are included in the version of Prospino2 used in our analysis[19]. The highest level of precision is achieved with the aid of Prospino2.

3.2 Monte Carlo Event Generators

Monte Carlo(MC) event generators are extensively used in high energy physics both by theorists and experimentalists. Especially experimentalists benefit from them to make predictions for collider experiments, determine the identity and significance of an observed resonance. As an example, the structure of a proton-proton collision at the Large Hadron Collider(LHC) is taken into account-this is the same with our case- and how an event generator describes this process is depicted. Most of the event generators divide this process into the following stages[10]:

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



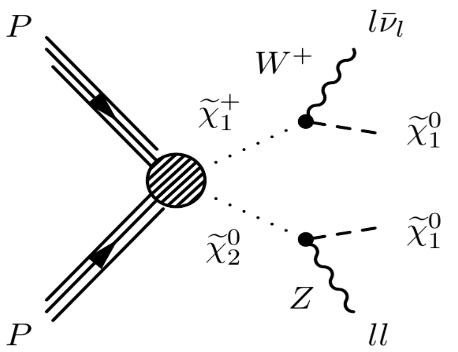
The MC generators, namely MadEvent and Pythia are used for signal samples, whereas the MC generators MadGraph and Pythia are used for background samples. In the current version MadEvent is a package derived from MadGraph allowing the generation of events at the parton, hadron and detector level. In the latest development of MadEvent it is aimed to speed up hadronization and detector simulation; therefore this program is released in a package containing the hadronization package Pythia 6.4.[20] This version of Pythia is used in our case to simulate the hadronization process in the preparation of sample for analysis.

3.3 Detector Simulations

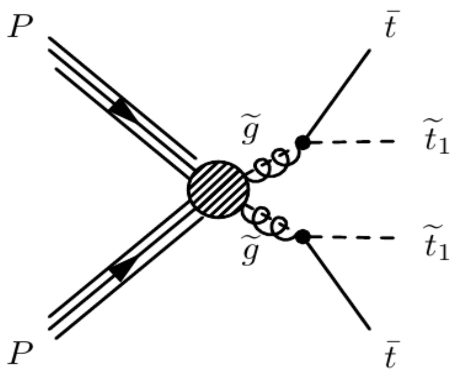
Detector simulations is used to predict the behavior of the detector when the particles hit the active regions of the detector. The detector simulation in our case is Delphes and it uses the output of the hadronization package Pythia to include the effects of a track propagation system in a magnetic field, electromagnetic and hadron calorimeters, and a muon identification system. The physics objects required for data analysis are reconstructed from the simulated detector response. The simulated detector response include tracks, calorimeter deposits and high level objets such as isolated electrons, jets, taus and missing energy. Delphes is a fast simulation package meaning that it is faster two to three orders of magnitude compared to the fully GEANT based simulations.[21]

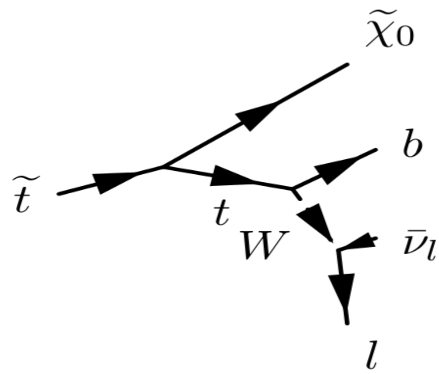
4 Analysis

4.1 Channel



We started the analysis by focusing on the chargino-neutralino channel. The cross section for this channel was pretty low; hence it was hard to distinguish the signal from the background and achieve a significance of 5 or[4] larger. The diagram on the left depict his channel. As can be inferred from the diagram there are no b-quark jets in this channel. In our latest analysis we focused on the gluino-gluino channel decaying as depicted in the following diagrams.





The decay products are leptons, jets together with b-quark jets and there is missing transverse energy owing to the presence of neutrinos and neutralinos. Compared to the previous one much better significance values were obtained in this channel.

[4]A significance of 5 or larger is discovery

4.2 Event Selection

Electrons		Jets	
1^{st} Leading Electron P_T	> 25 GeV	Jet P_T	> 30 GeV
2^{nd} Leading Electron P_T	> 15 GeV	Jet $\|\eta\|$	< 4.0
3^{rd} Leading Electron P_T	$>$ 10GeV	ΔR(Jets, Leptons*)	> 0.4
Leading 3 Electron I_{rel}	< 0.15	BJet P_T	> 50 GeV
Additional Electron P_T	> 5 GeV	BJet $\|\eta\|$	< 1.8
All Electron $\|\eta\|$	< 4.0	Bjet WP	medium

Remaining Selections	
# of e	$\geq$ 3
# of Jets	$\geq$ 2
# of B-tagged Jets	= 2 or 3
$\not{E}_T$	> 500 GeV

* $I_{rel} < 0.15$ $P_T > 10$ GeV $|\eta| < 4.0$

4.3 Plots

All of the following plots are before the $\not{E}_T$ cut, and the plots on the left hand side are for 50 PU, whereas the plots on the right hand side are for 140 PU.

4.3.1 $\int \mathcal{L}\ dt = 300\text{fb}^{-1}$

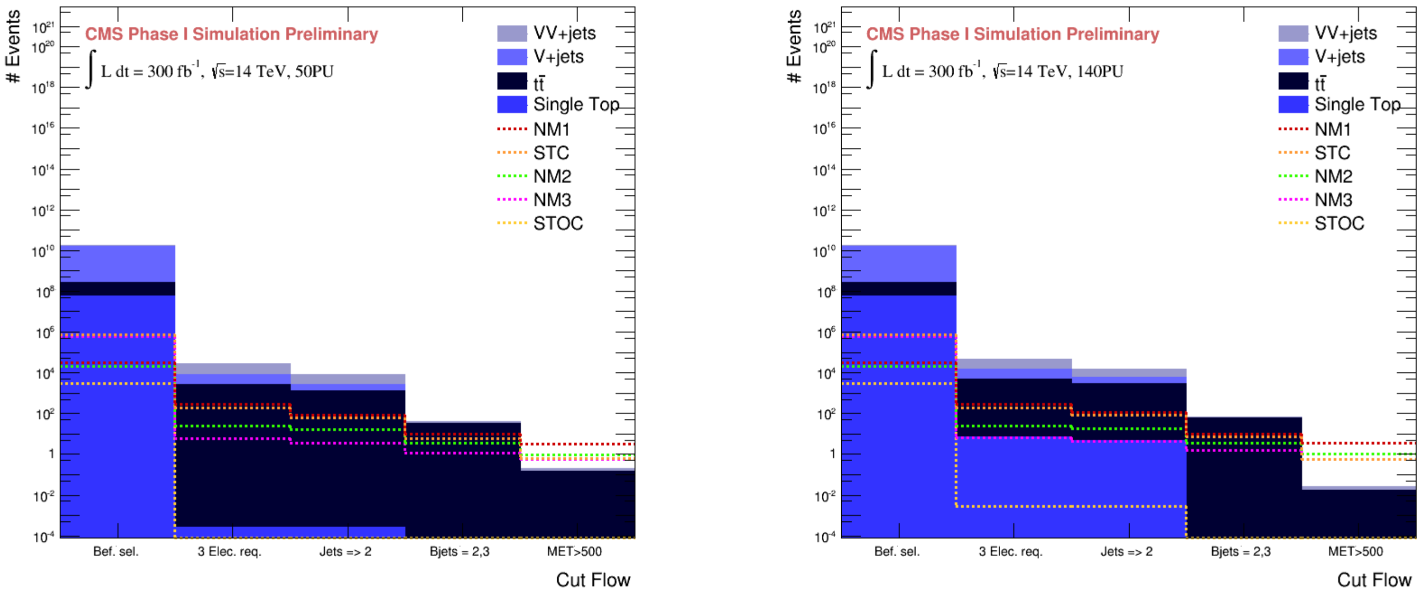
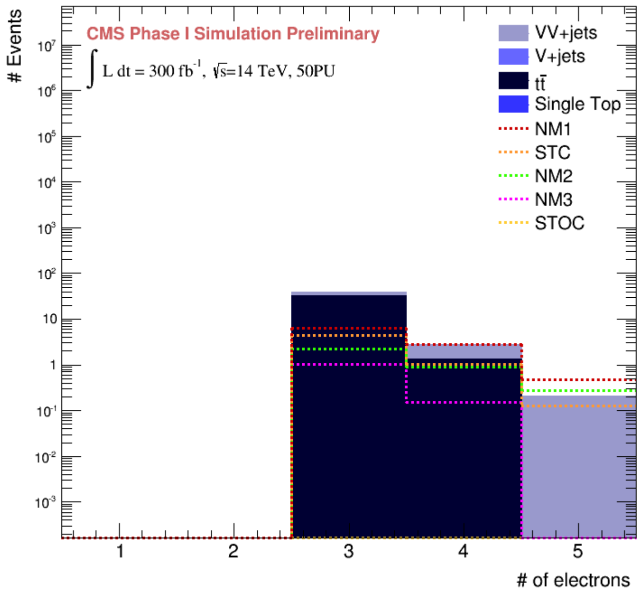
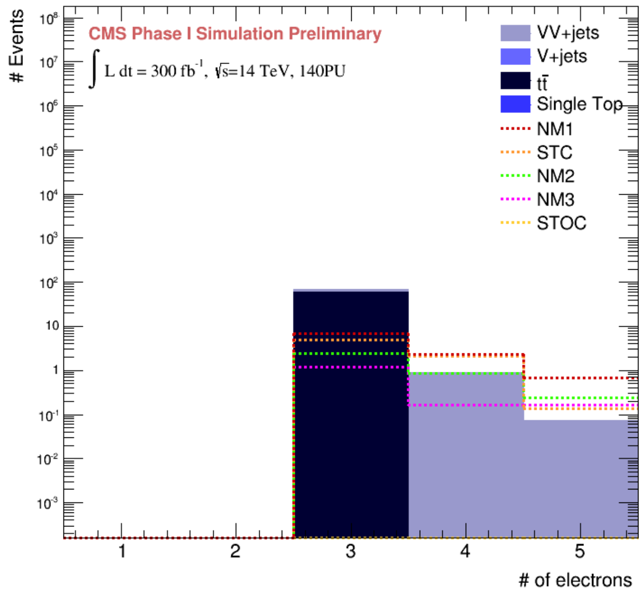


Figure 6: Cut flow for 50 PU and 140 PU events


CMS Phase I Simulation Preliminary
∫ L dt = 300 fb^{-1}, √s=14 TeV, 50PU
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
Events
of electrons


CMS Phase I Simulation Preliminary
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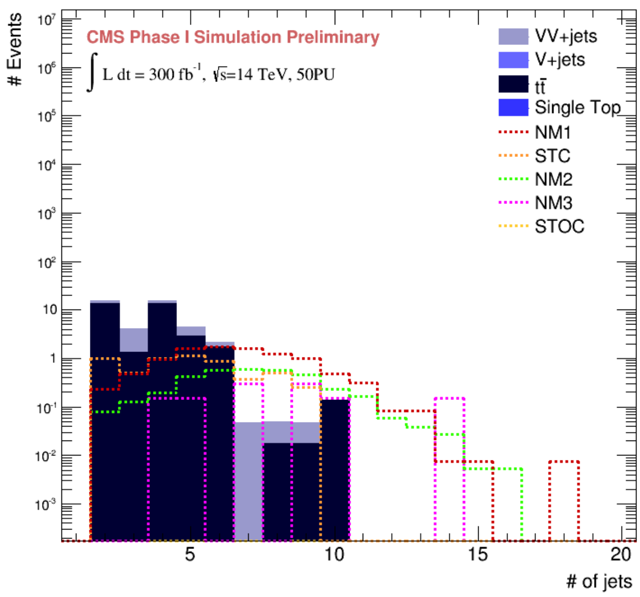
of electrons


CMS Phase I Simulation Preliminary
∫ L dt = 300 fb^{-1}, √s=14 TeV, 50PU
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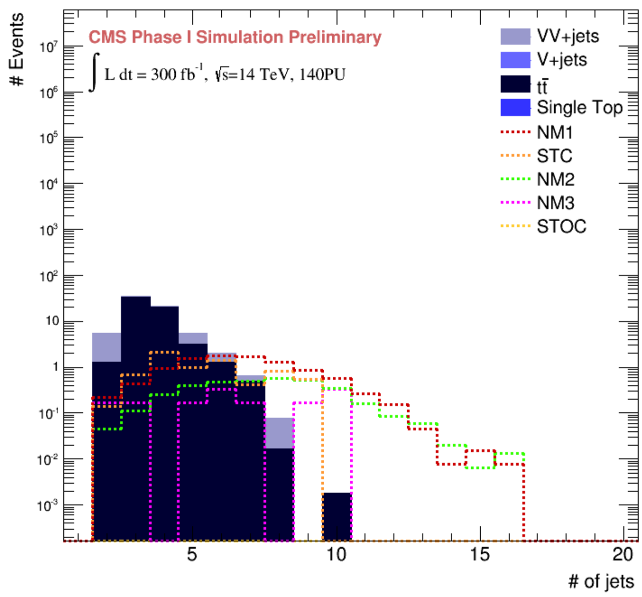
Events
of jets


CMS Phase I Simulation Preliminary
∫ L dt = 300 fb^{-1}, √s=14 TeV, 140PU
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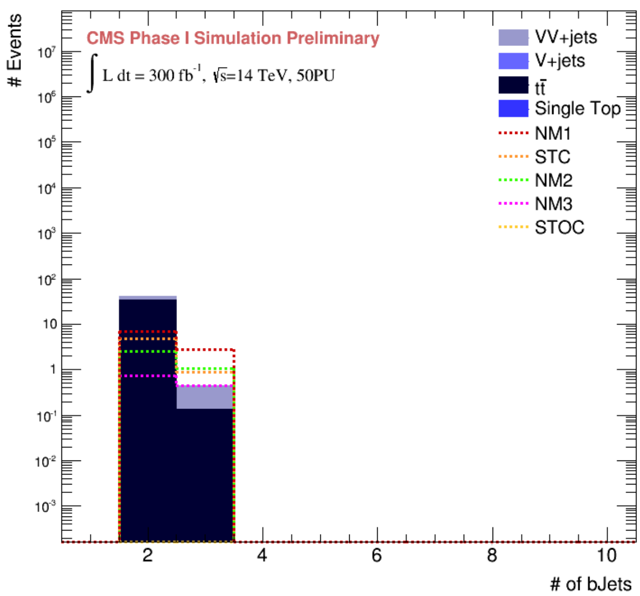
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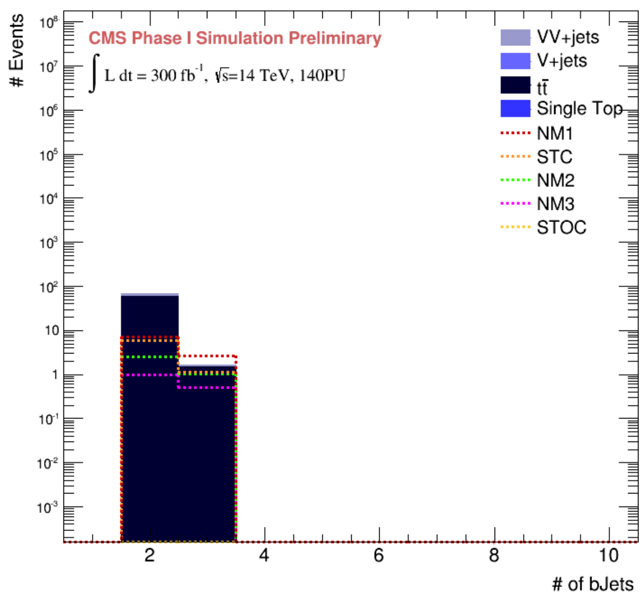
Events
of bJets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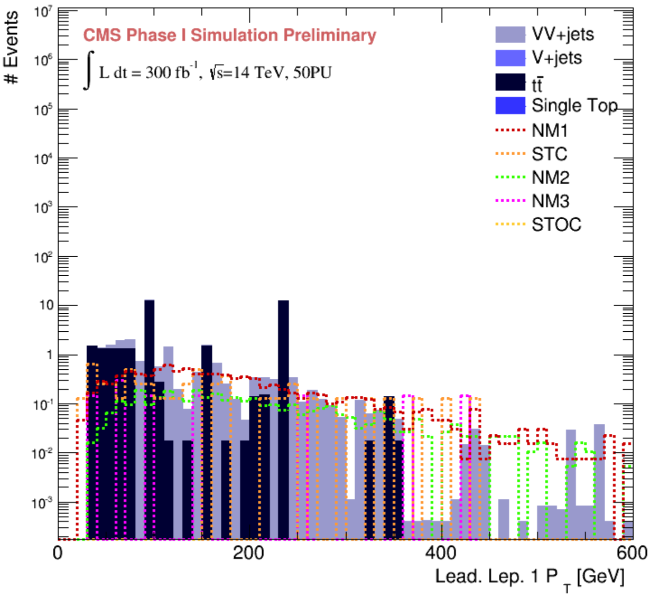
of bJets


CMS Phase I Simulation Preliminary
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VV+jets
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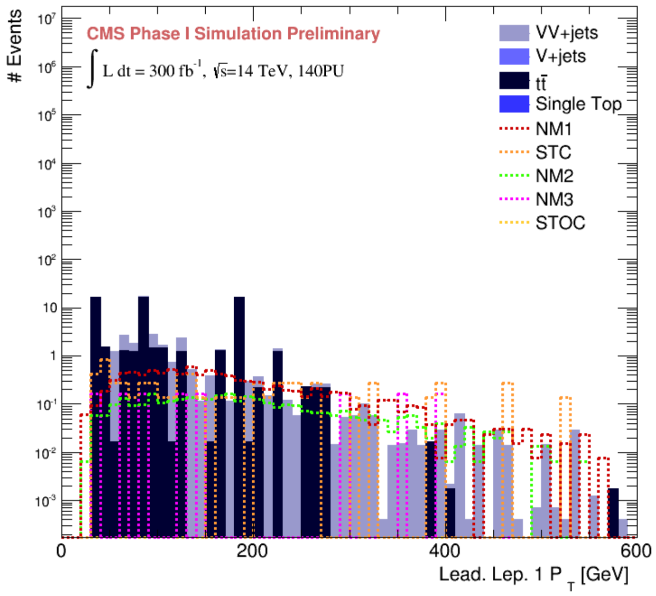
Events
Lead. Lep. 1 P_T [GeV]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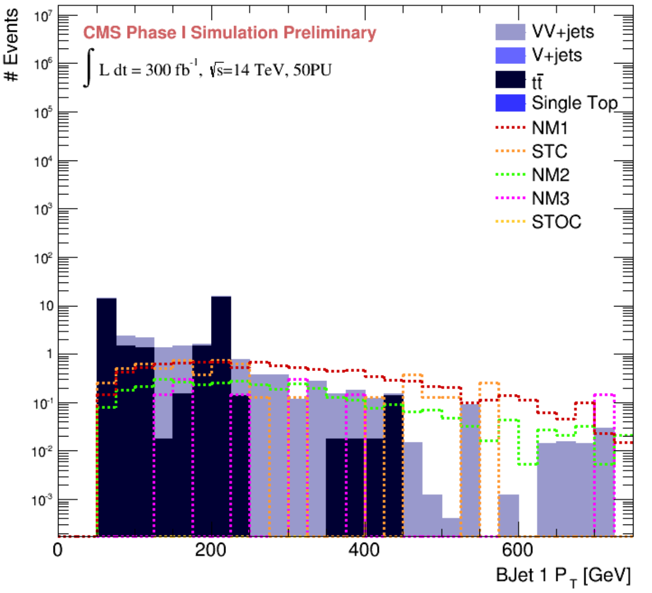
Events
Lead. Lep. 1 P_T [GeV]


CMS Phase I Simulation Preliminary
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VV+jets
V+jets
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NM1
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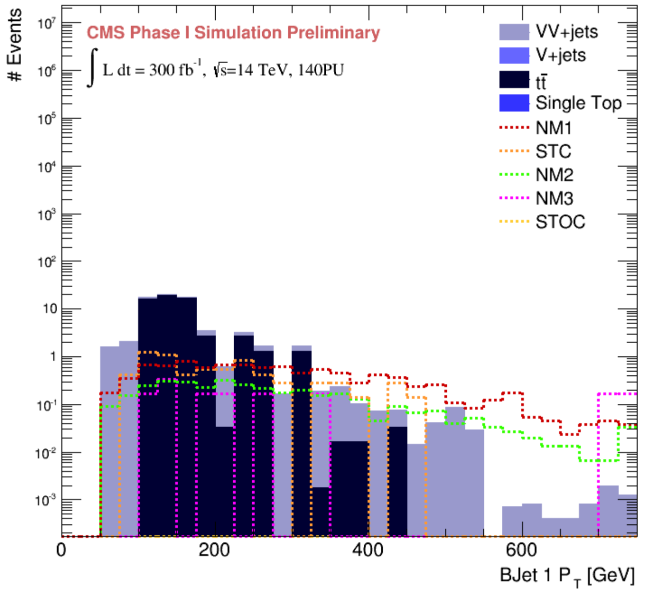
STOC
Events
BJet 1 P_T [GeV]


CMS Phase I Simulation Preliminary
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VV+jets
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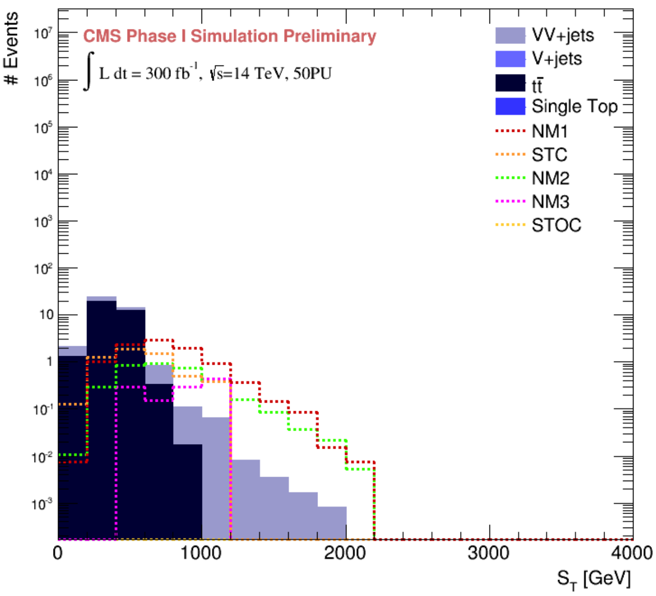
Events
BJet 1 P_T [GeV]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NM3
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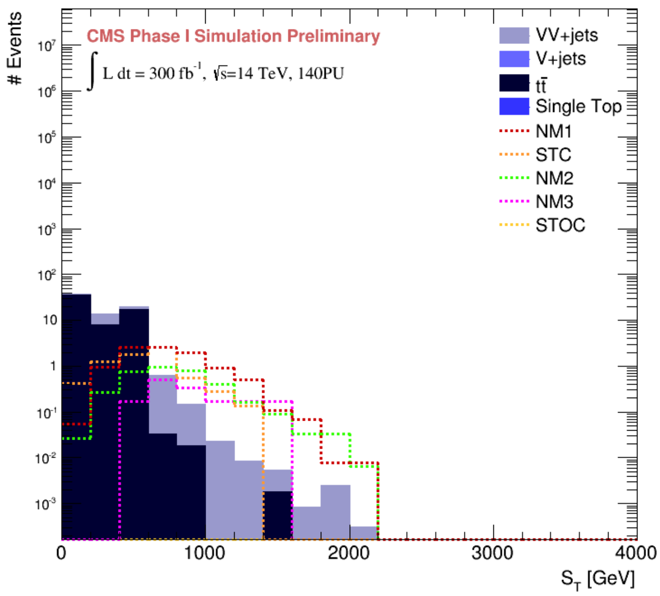
Events
S_T [GeV]


CMS Phase I Simulation Preliminary
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NM3
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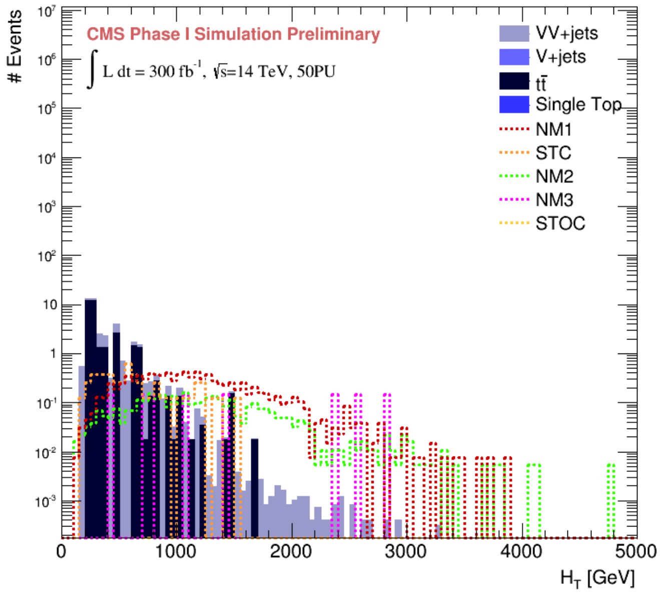
Events
S_T [GeV]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Events
VV+jets
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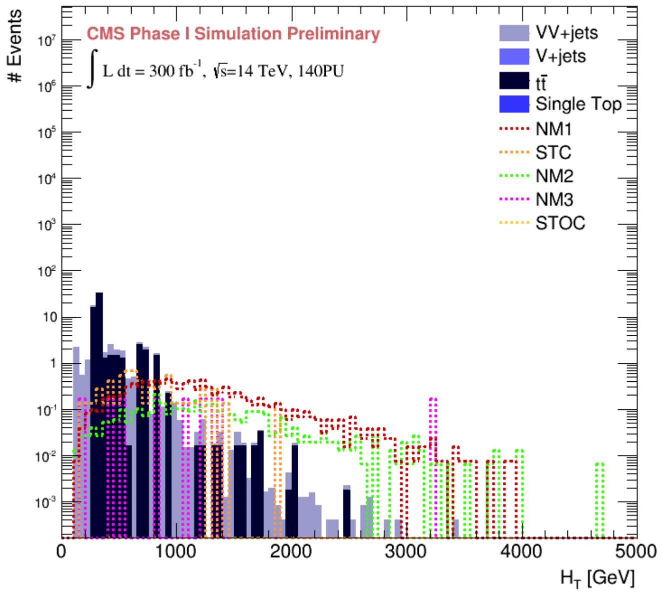
H_T [GeV]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VV+jets
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NM1
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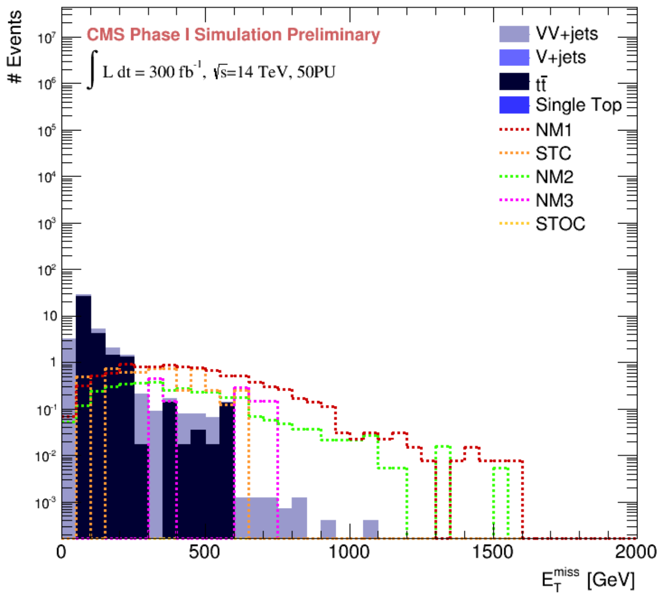
H_T [GeV]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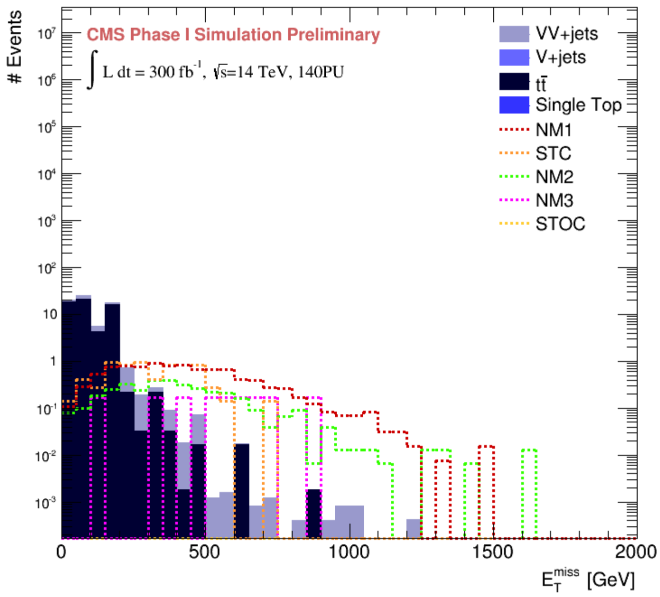
E_T^miss [GeV]


CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 140PU
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E_T^miss [GeV]

4.3.2 $\int \mathcal{L}\ \mathrm{dt} = 3000\mathrm{fb}^{-1}$

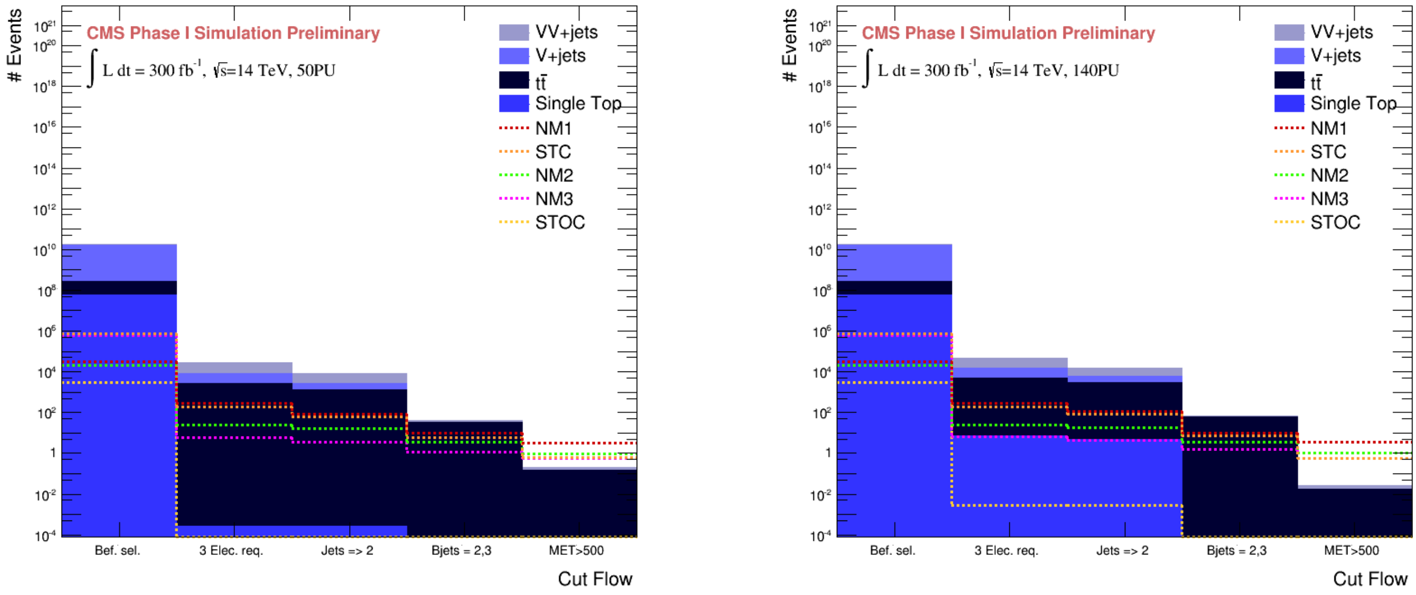
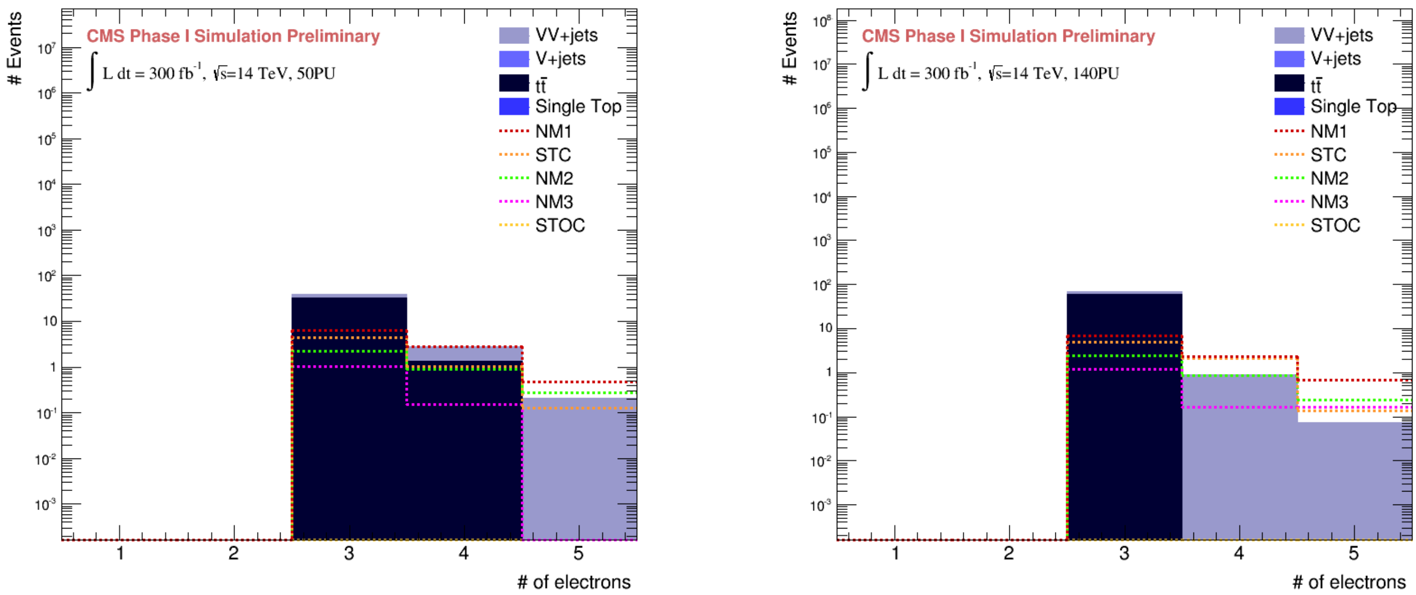
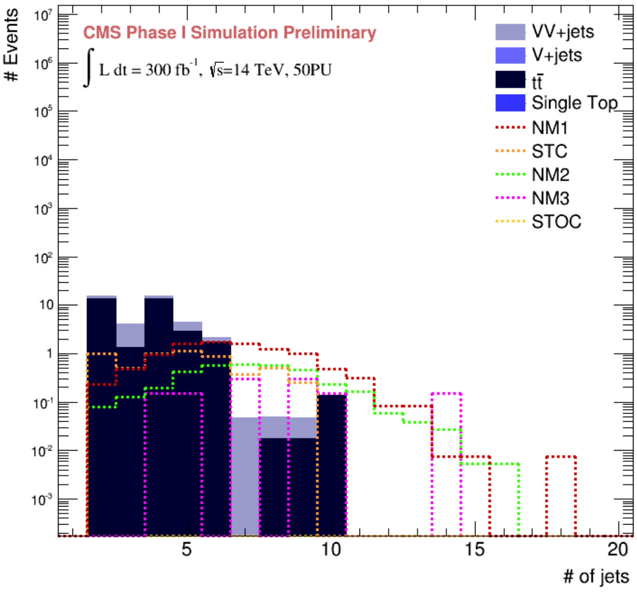


Figure 15: Cut flow for 50 PU and 140 PU events




CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 50PU
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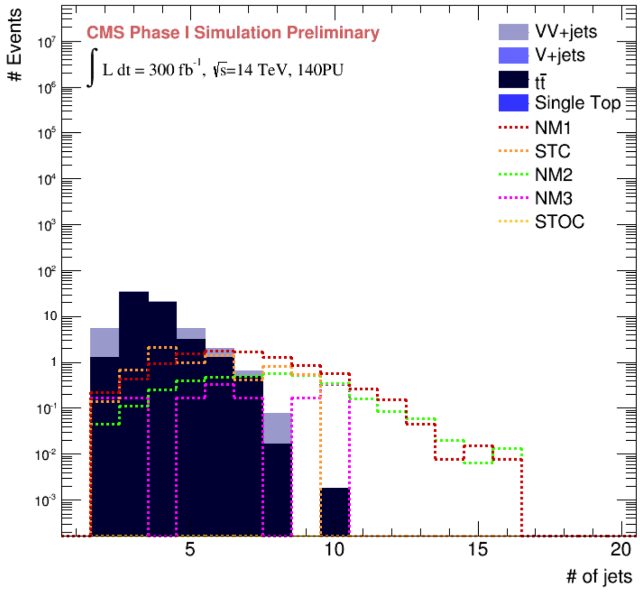
Events
of jets


CMS Phase I Simulation Preliminary
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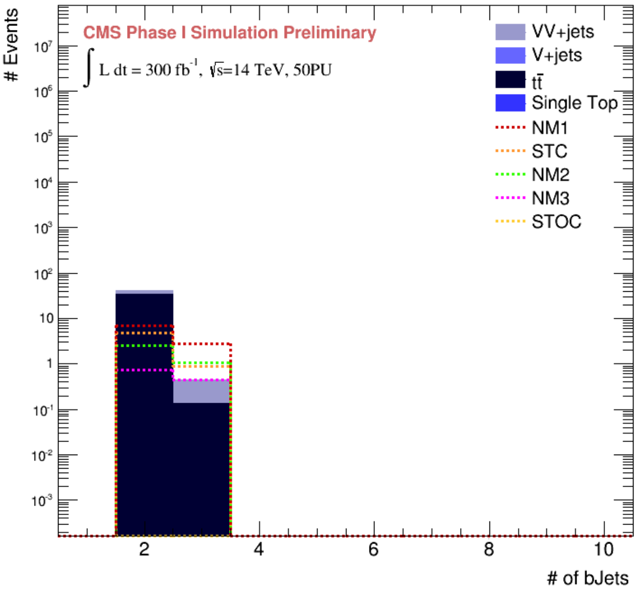
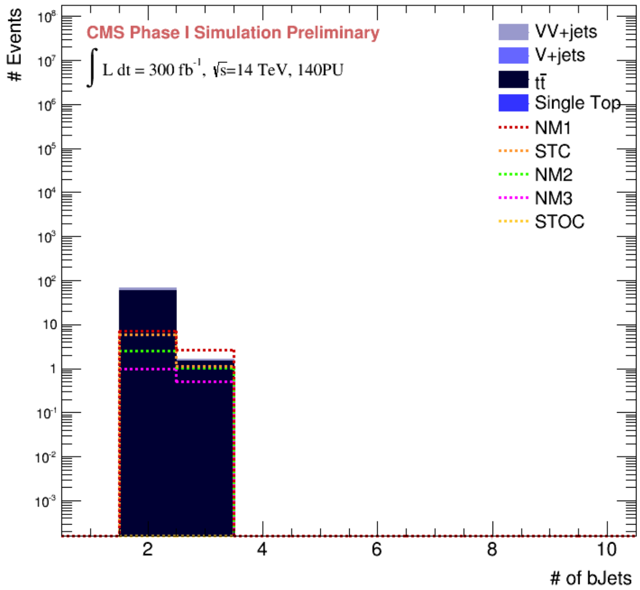
NM3
STOC
Events
of jets


CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 50PU
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
Events
of bJets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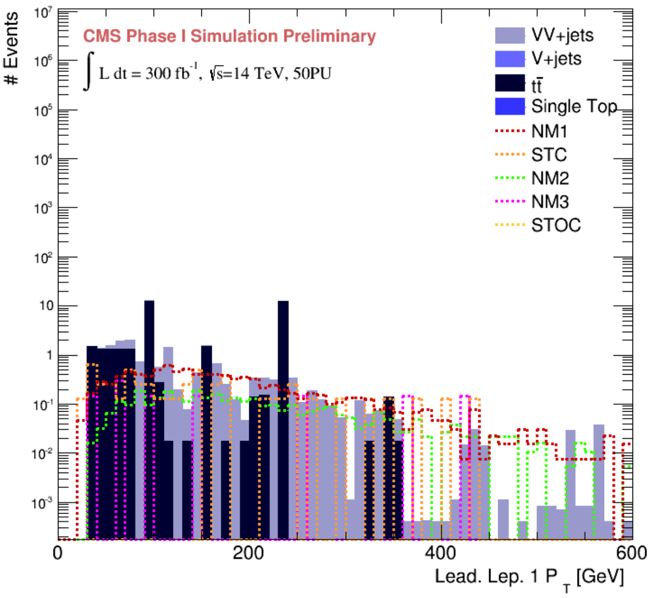
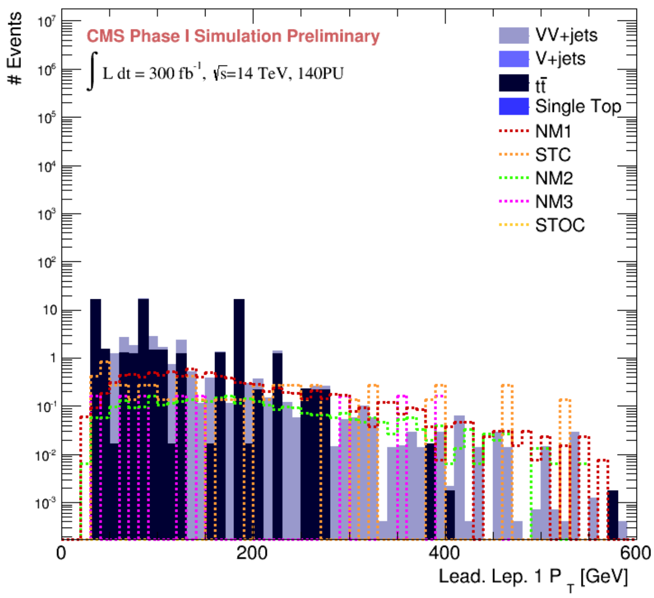
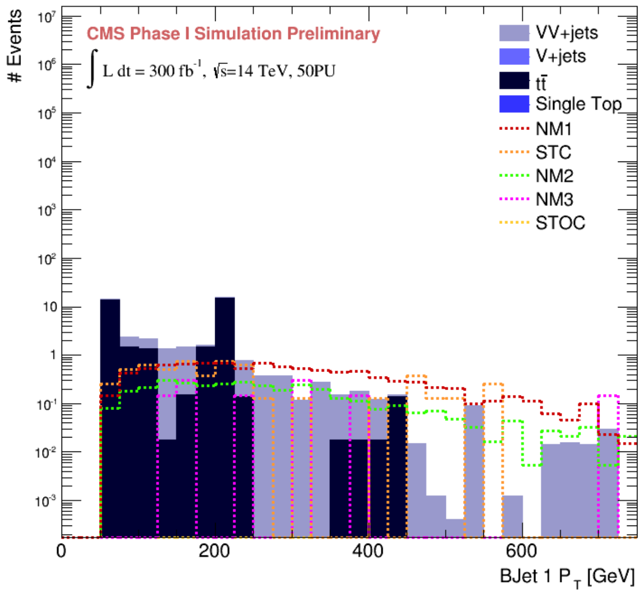
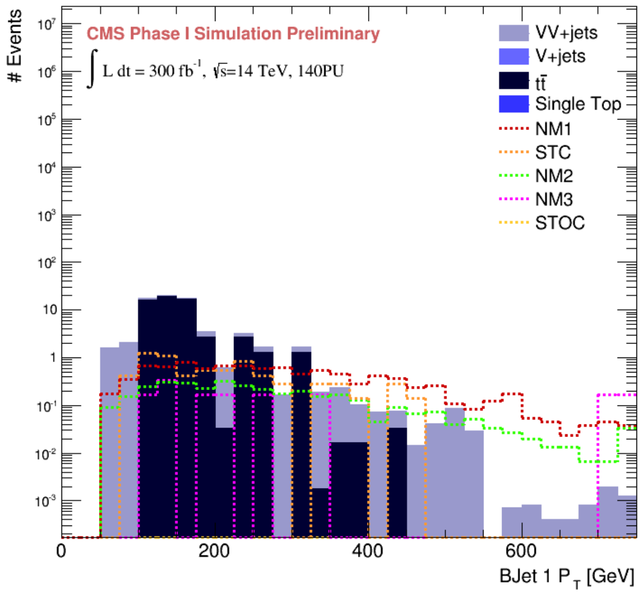
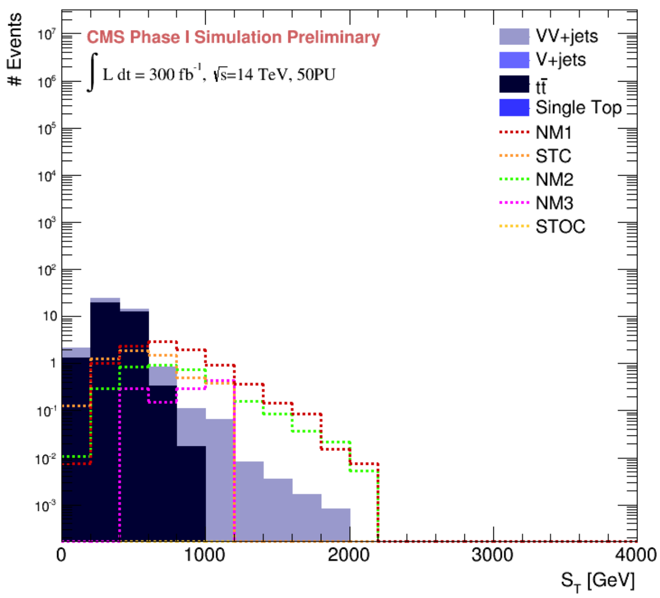
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
Events
of bJets

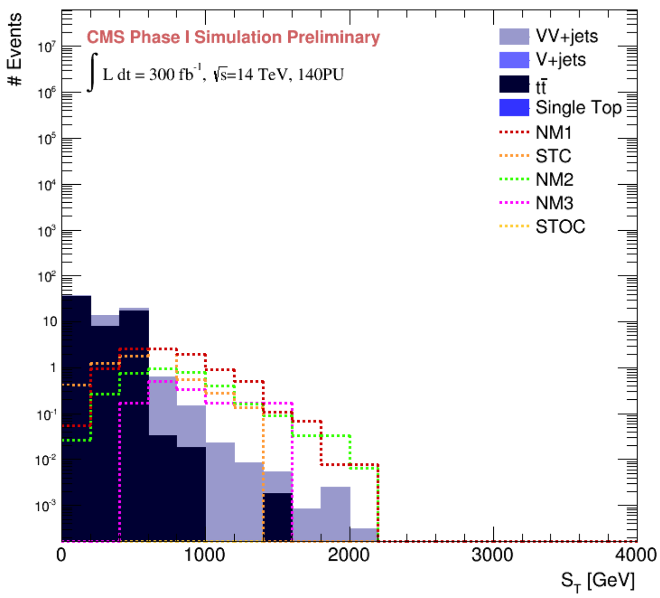

CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 50PU
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
Events
Lead. Lep. 1 P T [GeV]

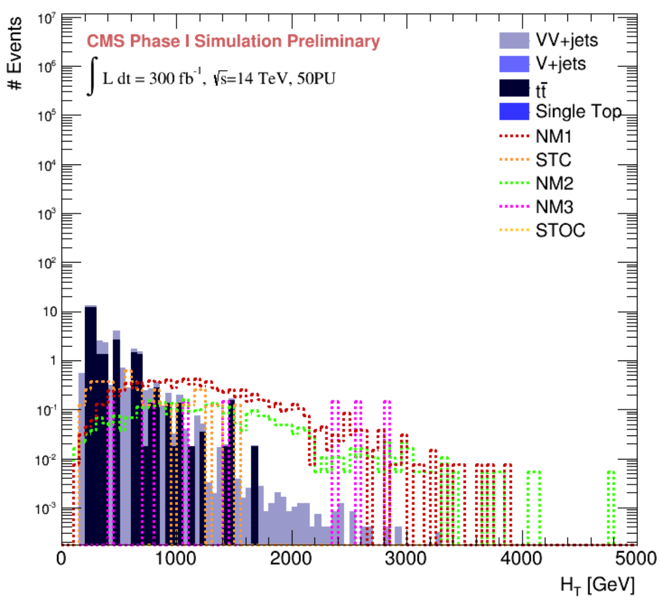

CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 140PU
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
Events
Lead. Lep. 1 P T [GeV]

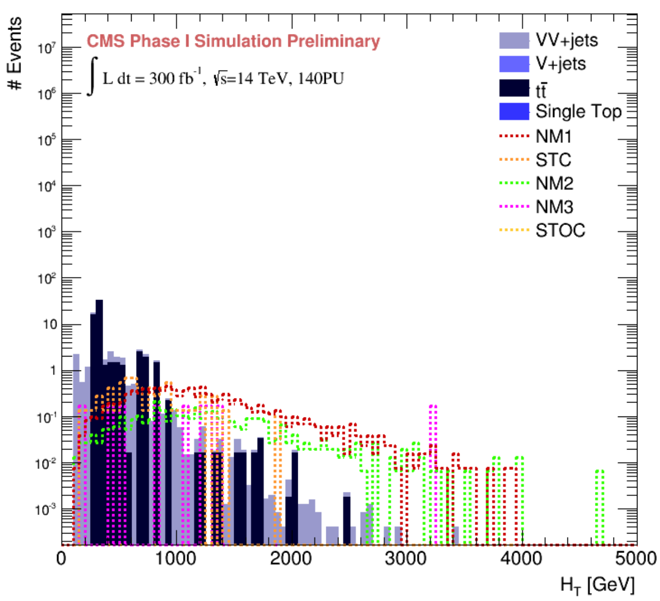

CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 50PU
Events
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
BJet 1 P_T [GeV]

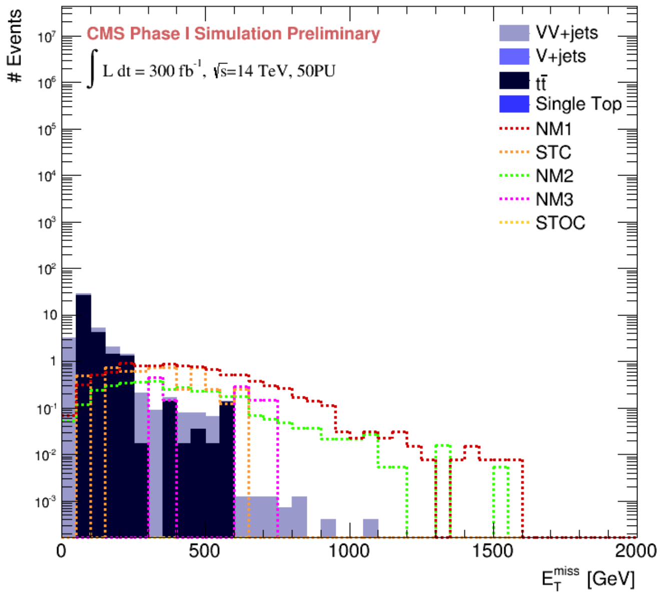

CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 140PU
Events
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
BJet 1 P_T [GeV]

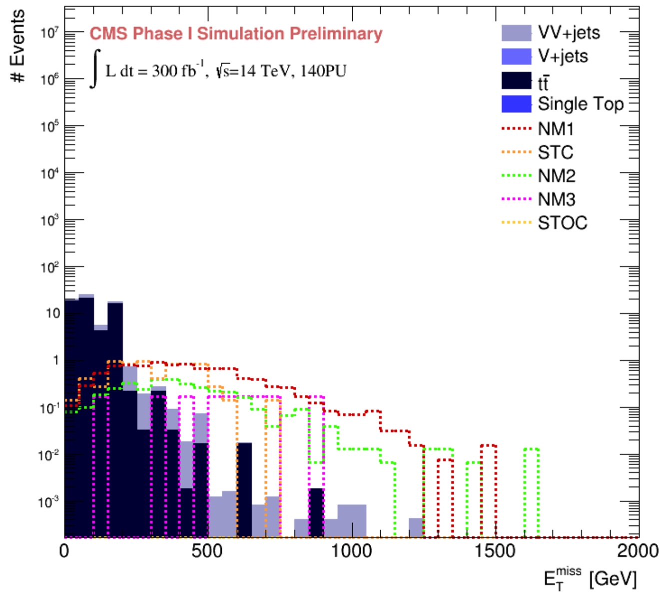

CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 50PU
Events
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
S_T [GeV]


CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 140PU
Events
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
S_T [GeV]


CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 50PU
Events
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
H_T [GeV]


CMS Phase I Simulation Preliminary
∫ L dt = 300 fb⁻¹, √s=14 TeV, 140PU
Events
VV+jets
V+jets
tt̄
Single Top
NM1
STC
NM2
NM3
STOC
H_T [GeV]





4.4 Significance Calculation

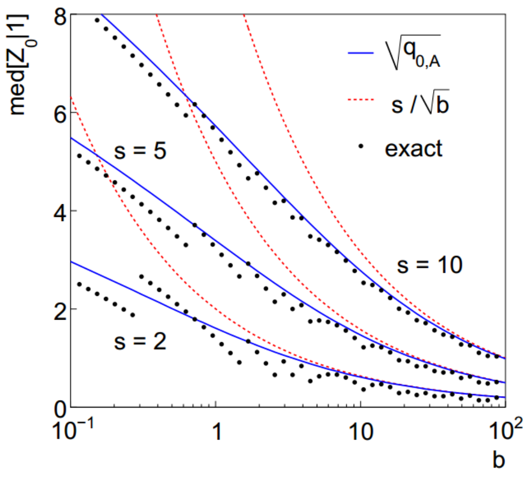
In calculation of significance the standard significance formula and Asimov significance formula is used. The standard significance formula is as follows:

$$\frac{s}{\sqrt{b+\sigma_b^2}} \tag{6}$$

And the Asimov significance is as follows:

$$Z_A = \left[2\left((s+b)\ln\left[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right] - \frac{b^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right]\right)\right]^{1/2} \tag{7}$$

Where s is the number of signal events, b is the number of background events and σ_b is the product of uncertainty and the number of background events. The motivation to use the Asimov significance is due to the fact that the standard significance diverges when the background is really close to zero and this is not the case with the Asimov significance.[22]



Pileup	Total Background	NM1	NM2	NM3	STC
50PU	1	3.3	1.0	0.6	0.6
140PU	1	3.4	1.0	1.0	0.6

Table 1: Remaining event counts after all the cuts

			NM1	NM2	NM3	STC
50 PU	Standard	Phase I	3.24	0.98	0.59	0.59
		Phase II	22.32	6.53	4.01	4.29
	Asimov	Phase I	2.35	0.86	0.54	0.54
		Phase II	10.18	4.30	2.95	3.11
140 PU	Standard	Phase I	3.33	0.98	0.98	0.59
		Phase II	-	10.00	9.81	5.39
	Asimov	Phase I	2.41	0.86	0.86	0.54
		Phase II	12.14	5.49	5.42	3.50

Table 2: Significance for various SUSY models

4.5 Conclusion

As can be seen from the Tb. 2 discovery can be claimed for NM1, NM2 and NM3 models at 3000 fb^{-1} of integrated luminosity and for 140 PU events. Only NM1 is discovered for 50 PU events at 300 fb^{-1} of integrated luminosity. Discovery is not possible at 300 fb^{-1} of integrated luminosity for 50 PU or 140 PU events. The gluino-gluino channel had a really small cross section and due to this fact the analysis with b-jet veto did not yield good results since the cross section of this event is really low. Furthermore, the channel with 4 or more b-quark jets were problematic and all the background was eliminated after the b-quark jets cut. The current objectives are to improve the analysis, achieve discovery in the gluino-gluino channel and study the b-quark jet tagging in detail.

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