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Supersymmetry Physics Studies for the CMS Detector Upgrade Program

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Abstract

In this project, searches for Supersymmetry with single lepton final state is studied at different center of mass energies, $\sqrt{s} = 8$, 13, 14 and 33 TeV. The Standard Model background and Supersymmetry signal samples are simulated and various event selection requirements are applied. Monte Carlo based event generetor Pythia, and together with ROOT analysis framework are used in the CMS Software (CMSSW).

Contents

1 Introduction

1.1 The Standard Model

As a branch of physics, Particle Physics is the subject that has shown how particularly matter is built and which is the beginning to explain where the origins (smallest constituents) of it all came from. In today's particle physics world, the all knowledge about the particles and the forces in the universe represented by the Standard Model, which scientists are all agree about, it is the best current theory of particle physics. The Standard Model basicly tries to describe what is known about elementary particles and interactions between them.

1.1.1 Classification of Particles and Fundamental Forces

In order to catch a good approach for the Standard Model, it is better to start with two main concepts of it; particles and forces. The Standard Model of particle physics refers to sum of our knowledge about all the particles, and the forces (besides not all of them).
If we start with particles, it can be said that by the end of 1942, it was believed, our universe was made of 4 particles:

Table 1: By the end of 1942, particles that believed the universe was made of. [1]

e^-	electron
p^+	proton
n	neutron
ν	neutrino

With the following years so many new particles (almost all of them are unstable) were discovered. Now in today's science world, all the matters and its physical interactions can be described in terms of two basic kinds of particles, which are named as bosons and fermions. While bosons are the particles that have integer spin numbers (s=0, 1, 2, etc.), fermions have half integer spin numbers (s=1/2, 3/2, etc.). There is another way to distinguish bosons and fermions by their collective properties under the interchange of two particles. If it is supposed that there are two identical particles in one closed system (i.e. a box), the probability of finding one particle in a given position and the other in another position, P(1,2), is expected to be equal to the probability of finding the particles interchanged in position, P(2,1), because of the fact that they are identical. And due to the quantum mechanics, the probabilities are given by square of wavefunction amplitudes:

$$P(1,2) = P(2,1) \Rightarrow |\Psi(1,2)|^2 = |\Psi(2,1)|^2 \tag{1}$$

Despite this mathematical expression, it does not mean that $\Psi(1,2) = \Psi(2,1)$. While it means actually;

$$\Psi(1,2) = e^{i\phi}\Psi(2,1) \tag{2}$$

where ϕ is some phase. If rotation is applied one more time to equation (2), it would give $\Psi(1,2) = e^{2i\phi}\Psi(2,1)$, implying that $e^{2i\phi} = \pm 1$. In other words,

$$\Psi(1,2) = +\Psi(2,1), boson$$
$$\Psi(1,2) = -\Psi(2,1), fermion \quad (3)$$

As it is seen mathematically, bosons are the particles whose wavefunctions maintain its sign under particle interchange, whereas fermions are the particles whose wavefunctions change sign under particle interchange. Finally the latest picture of the Standard Model, especially after the discovery of Higgs Boson at 125 GeV, can be seen from the figure 1. Belong the elementary particles, the theory itself is built to describe a par-

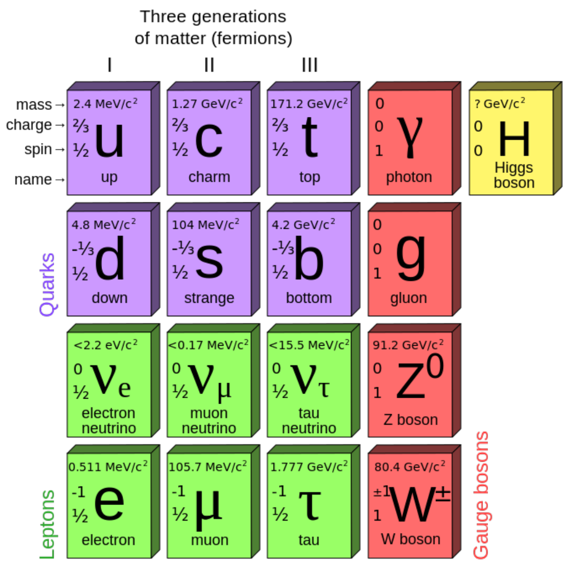

Figure 1: Elementary Particles in the Standard Model. [2]

ticular interaction among the fermions. Therefore, the mediators of the interactions among the fermions are generally referred as bosons. In addition to this, the quarks are the constructive particles of mesons and baryons are also known as hadrons can be seen from the figure 1. [1]

In a widely accepted way, for the fundamental forces the theoretical and experimental researches has been able to tell us, every interactions in the world are governed by some combination of four basic forces which are the results of their fields. In the order of their decreasing strengths these forces are known as; strong, electromagnetic, weak and gravitational forces. It is known that the Standard Model is combining electroweak theory (which is combination of electromagnetic and weak forces and developed by S. L. Glashow, S. Weinberg and A. Salam in 1960's) and theory of strong forces (appeared in 1970's) which is named Quantum Chromodynamics (QCD). However the Standard Model is not able to cover the gravitational force scale actually. Additionally, for some specific features of the forces, it can be said that while electromagnetic and gravitational forces have infinite range, strong and weak forces have finite range. Also strong and gravitational forces can be seen in every interactions in the nature, whereas electromagnetic force is seen between charged particles and weak force is seen between vector boson mediators [3]. And from table 2, the main forces in the universe and their associated boson with their gauge groups can be seen.

Table 2: Fundamental interactions with their associated bosons

Interaction	Mediating Bosons	Gauge Group
Electromagnetic and Weak	Z, $\gamma, W^{\pm}$	SU(2)$\times U(1)$
Strong	8 different gluons	SU(3)
Gravitational	graviton	?

1.1.2 Problems in the Standard Model and What Lies Beyond it

As it mentioned before, although the Standard Model is the most acceptable theory in particle physics, there are still some questions which has been shown in the experimental results and even the Standard Model is not able to give some answers to them. To make the problems more clear, basicly they can be arranged as in the below:

- Some new particles are needed to explain Dark Matter and Dark Energy which make up the majority as 95.1% of our universe. Because it is known that only 4.9% of the universe can be explained by ordinary matter in the Standard Model. [4]
- The Standard Model can not explain the asymmetry between matter and antimatter in our universe.
- As it can be seen from figure 2, unification of forces is not possible in the Standard Model.
- As it suggested by data of Cosmic Microwave Background (CMB) from Planck Telescope there must be an unknown matter content, which can be defined as dark matter, to explain the inflation of the universe. [5]
- What is the reason for the fact that there there are three generations of fermions and a huge mass ratio difference between them.

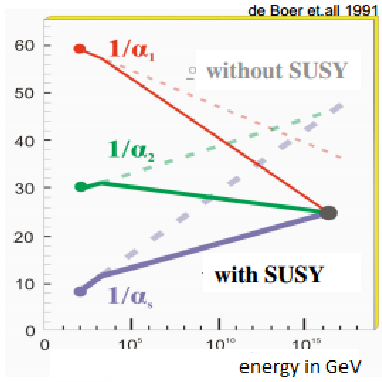

Figure 2: Unification of the coupling constants in the Standard Model and SUSY [6]

- Why the gravitational force is even in a much smaller scale than weak forces and what makes the Higgs-like boson particle gain mass is also waiting for the answer as also named as, Hierarchy problem. [7]

2 Supersymmetry(SUSY)

Supersymmetry is a well-known theory which is accepted by many physicists due the fact that it can introduce some solutions to the problems that are faced with in the Standard Model. SUSY is a theory, which provides the extension of the Lie algebra, that basicly combines fermion and boson fields.

$$\text{Q}|\ Boson\rangle \propto |\ Fermion\rangle \leftrightarrow Q\ |\ Fermion\rangle \propto |\ Boson\rangle \ (4)$$

One can search such a symmetry between these fields for the fact that bosons are the mediators of interaction. On the other hand, fermions are the constituents of matter which means theirs statistics is translated at the macroscopic level into the additive character of matter. Supersymmetry(SUSY) is also a theory that introduce superpartners to every known elementary particles, identical to them in all respects but except their spin numbers. This superpartners are named with a rule as presenting an (s) (for scalar superpartners) to the Standard Model particle name of that particle, e.g. (s)quark and (s)lepton and for the names of fermionic superpartners are constructed by appending the suffix ino, e.g. Higgsino or gaugino [7]. Also these superpartners are known as a solution to the Hierarchy problem by definition, since the superpartners to the Standard Model were chosen to cancel all quadratic divergences, thus they are putting a control on the Higgs mass [8]. Belong the superpartners, in many SUSY models (the models conserve R-parity such as Minimal Supersymmetric Standard Model) neutralino is accepted as a dark matter candidate. Neuralino and the other superpartners that introduced in SUSY can be seen from the figure below. In addition to this, SUSY includes the unification of the forces as bringing the energy scale differences nearly in a comman range as seen in figure 2.

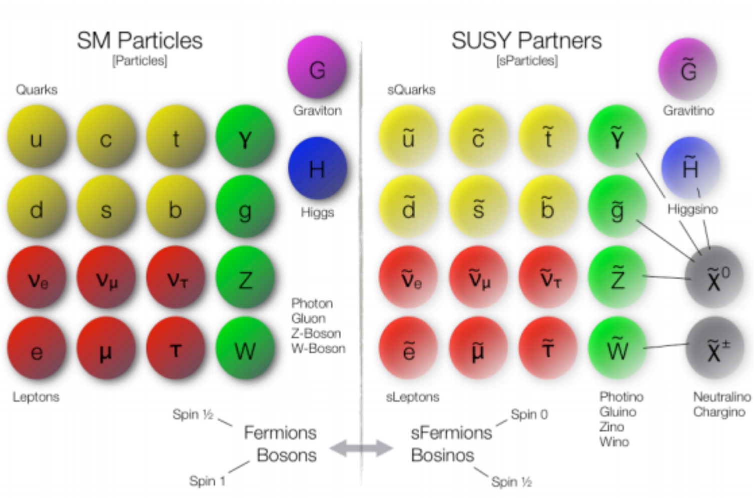

Figure 3: Particles in the SM and their superpartners in SUSY [9]

3 CMS Experiment

CMS detector is built to investigate a wide range of physical theories, including the search for the Higgs boson, extra dimensions, and particles that could formed dark matter i.e new physics.

3.1 Working Principle and Structure

The CMS is designed with huge superconducting solenoid magnet in order to provide 4T magnetic field. The CMS detector has been expected to start at center-of-mass energy of 14 TeV at full LHC luminosity in 2015. In order to have a specific look to CMS working principle, it can be said that CMS is a particle detector that is designed to see a wide range of particles and phenomena produced in high-energy collisions at the LHC. According to information which is directly taken from the CMS detector web page [10], in the cylindrical onion shells shape of CMS, different layers of detector measure the different particles, and use this key data to build up a picture of events at the heart of the collision. And how does CMS work and detect particles? As a result of energy conservation, there must be some outgoing particles after the collision at the CMS. The particle that emerge from this collision and travel through outwards will first encounter the tracking system which is made of silicon pixels strip detectors. In this part the positions of passing charged particles are measured and this allows physicists to reconstruct their tracks. On the other hand, charged particles follow spiraling paths (due to their sign of charges) in the CMS magnetic field and the curvature of their paths reveal their momenta and charges also. After momenta measurement ot the particles, now the energies of the particles can be measured in the next layer of the detector called the calorimeters. Electrons, photons and jets which are the sprays of particles produced by quarks are stopped by the calorimeters, of course after their energy measurement. Therefore, the first calorimeter layer is designed to measure the energies of electrons and photons with great precision. Since these particles interact electromagnetically, it was appropriate to call this calorimeter as an electromagnetic calorimeter (ECAL). And the next part after ECAL is hadronic calorimeter HCAL which is the place to measure the energy of strong force interactions, hadrons. Although the CMS thick shell- structure there are still some particles that penetrate beyond the HCAL which is named as muons and weakly interacting fast moving particles named as neutrinos. Because of the fact that muons are charged particles their momenta can also be measured from the bending of paths in the CMS magnetic field. For neutrinos however there is no such an experiment due to their no-charge feature. [10]

3.2 Analysis framework and Event Reconstruction

In previous part it is said that CMS has an ability about conserving each event that happens during the collision. Therefore the CMS detector can record an anomalously large number of events especially when it is performing at its peak. Although this well-known performance of CMS, it is really hard to read every event and record them in the memory. Therefore, there is needed to a system that can select the potentially interesting events, such as those which will produce the Higgs particle, and reduce the rate to just a few hundred events per second, which can be read out and stored on computer disk for subsequent analysis. This system is named as trigger system. There should be also another branch at CMS that provide to separate for example two different event from each other. For this, detectors must have very good time resolution and the signals from the millions of electronic channels must be synchronized so that they can all be identified as being from the same event. After all these information, for supersymmtry and CMS relation it can be said that one of the main aim of the CMS experiment at the LHC is to search for SUSY particles (New Physics). What expected is that strongly interacting particles as gluinos and squarks can be found as the first SUSY particles that they might be seen at LHC. [10]

4 Simulations and Analysis

4.1 Monte Carlo Generators (MC Generators)

Monte Carlo (MC) event generators are software libraries that simulate high-energy particle physics events based on MC methods. This method helps us to solve the problems that can not be solved by analytical approaches. Monte Carlo (MC) method is applied in a way that, with making simulations as random number times and to reach the values which are the closer ones in the theory. Although in the detector studies event happened at that time are recorded, in MC generators, detector is replaced by event simulation programs. MC generators also make a contribution to detector's performance with determining the rates of event types. And related with this, MC can design detector simulations to determine the requirements of detector and their trigger systems. The background of events can be simulated in MC generators and this brings to experimentalists to predict analysis strategies before going through the experiment.

4.1.1 Pythia

Pythia is a most common a simulation program based on MC methods for particle collisions at very high energies in particle accelerators. Pythia helps to reconstruct complex multihadronic final states from a few-body hard processes. For the libraries that Pythia includes, it can be said that hard processes and models for initial & final state parton shower, multiple parton-parton interactions and particle decays can be obtained for physics studies. [11]

4.2 CMS Software (CMSSW)

CMSSW is built around a framework and an Event Data Model (EDM) so that physicists can perform their analysis. The primary goal of the Framework is to facilitate MC simulations, reconstruction and analysis software. According to information that taken from [12], " the CMSSW consists of one executable, called cmsRun, and many plug-in modules which are managed by the Framework. All the code needed in the event processing (calibration, reconstruction algorithms, etc.) is contained in the modules. The same executable is used for both detector and Monte Carlo data. The CMSSW executable, cmsRun, is configured at run time by the user's job-specific configuration file which actually tells to cmsRun that;

- Which data to use,
- Which modules to execute,
- Which parameter settings to use for each module,
- What is the order or the executions of modules,
- How the events are filtered within each path,

- How the paths are connected to the output files.

  Unlike other examples, cmsRun is extremely lightweight: only the required modules are dynamically loaded at the beginning of the job. The CMS Event Data Model (EDM) is centered around the concept of an Event. An Event is a C++ object container for all RAW and reconstructed data related to a particular collision. During processing, data are passed from one module to the next via the Event, and are accessed only through the Event. All objects in the Event may be individually or collectively stored in ROOT files, and are thus directly browsable in ROOT." [12] Finally, it is better to emphasize that for my project I mainly worked on the CMSSW 6.0.1 area which includes Pythia and ROOT in itself already. (Figure 4).

4.3 ROOT

An object oriented framework for large scale data analysis. ROOT is a C++ replacement (interpreter) of the popular PAW(Physics Analysis Workstation) program developed at CERN. From all over the world, users whether they have a CERN account or not, they can freeely use ROOT. In other words, ROOT is a liberal, informal development style that heavily relies on the diverse and deep talent of the user community [13]. For my project, I use ROOT after simulating the events for each center of mass energy with the Pythia, in order to plot my histograms, the graphical representations of data distribution. And as it was mentioned before, due the fact that ROOT is user friendly programming, I was able to handle all of the histogram features and also ROOT files via ROOT browser.

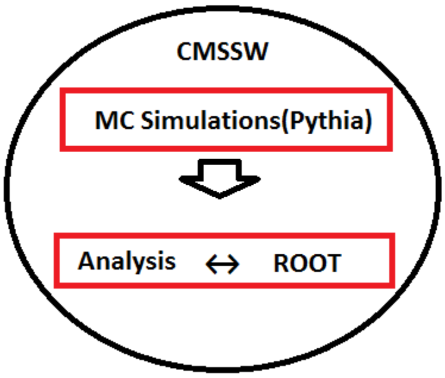

Figure 4: Workflow of my Project

5 Search for SUSY with Single Lepton Final State Analysis for the Upgrade Program

In order to explore superpartners (SUSY particles) there are more than one decay channels that can be investigated. Di-lepton decay channel, same sign lepton decay channel, opposite sign lepton decay channel and full- hadronic decay channel are some of them. In my project, I mainly concentrated on single lepton, either one muon or one electron, final state analysis, There are several reasons to investigate this channel specifically such as:

- It has an attractive signature of potential new physics,
- Final states with leptons are predicted in a wide range of BSM models,
- Leptons are able to provide clear signature in the dedector,
- Measurement of leptons at CMS more precise than that of jets,
- Single lepton final states has larger rates than di-lepton final state channels,
- It has a high branching ratio.
- Especially for the stop search, single lepton decay channels are more preferable, (Figure 5-6) [14]

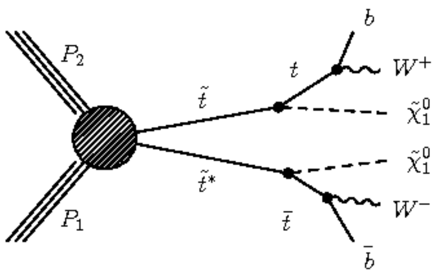

Figure 5: Diagram for stop pair production [14]

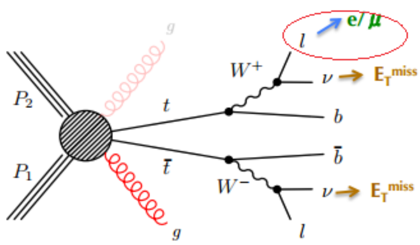

Figure 6: Diagram for $\tilde{t}$t-jets single lepton decay [14]

For the analysis that I have been done for my project, I considered several backgrounds in this search which are;

- $\tilde{t}$t-jets
- W-jets
- Z-jets
- QCD

But as it can be seen from the above diagrams, the main contribution for the SM background actually come from $\tilde{t}$t-jets and W-jets. Especially after applying the cut for event selection, the contribution come from Z-jets and QCD are negligable. I simulated these main backgrounds for several center of mass energies as $\sqrt{s} = 8$ TeV and for the upgrade program; $\sqrt{s} = 13$, 14 and 33 TeV. The simulated background and event numbers can be seen in table 3. In addition, the cross section values that obtained at the end of the MC level simulations are also in table 4.

Table 3: Event Numbers for Background Simulations

Background	Event Number
$\tilde{t}$t-jets	1000K
W-jets	2000K
Z-jets	1000K
QCD	1000K

Table 4: Cross sections for STC4 STC8 ttjets and wjets

Center of Mass Energies (TeV)	STC4 (pb)	STC8 (pb)	$\tilde{t}$tjets (pb)	wjets (pb)
8	2.08	0.89	129.1	20826
13	7.40	2.07	444.4	35000
14	8.52	2.34	530	40000
33	64.36	9.468	3390	103419

In general, for SUSY signal searches, there are four benchmark points which are considered in the analysis. These benchmark points are known as STC4, STC5, STC6 and STC8. Belong these benchmark points, I chose STC4 and STC8 as the benchmark points. The inclusive cross sections which respect to various center of mass energies can be seen in figure 7. And also the mass scales for STC4 and STC8 points are given in figure 8. and figure 9.

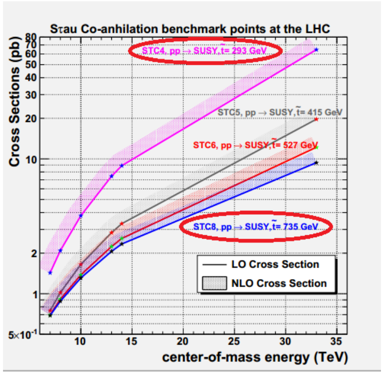

Figure 7: The inclusive cross sections of four investigated SUSY signal models [15]

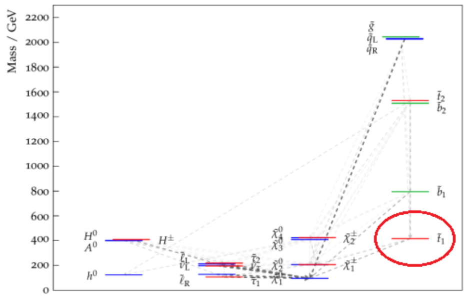

Figure 8: Mass scale in STC4 benchmark point used for SUSY search analysis [15]

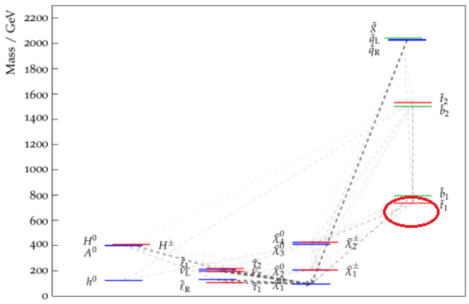

Figure 9: Mass scale in STC8 benchmark point used for SUSY search analysis [15]

The only difference between these mass scale plots for two benchmark points is the stop mass (300 GeV and 730 GeV, respectively). It is also better to indicate that all these benchmarks points are consistent with the Higgs mass $\simeq$ 125 GeV. In addition, the number of simulated events for SUSY signal in this analysis are in table 5. In order

Table 5: Event Numbers for SUSY Signal Simulations

Background	Event Number
STC4	500K
STC5	500K

to achieve more precise analysis, event selections are needed. The event selection requirements that I applied for the single lepton final state analysis are given in table 6.

Table 6: Event Selection Requirements

Description	Selection
Pt Lepton	> 20 GeV
Pt Jets	> 40 GeV
Jets η	< 2.3
Lepton η	< 2.1
Ht	> 1000 GeV
MET	> 500 GeV
MET (at 8 TeV)	> 250 GeV

For the scaling of the histograms,

$$(Luminosity \times Cross\ section)/(Number\ of\ Events) \tag{5}$$

formulation is applied with the given luminosity values:

Table 7: Luminosities for 8, 13, 14 & 33 TeV

Luminosities (1/fb)	Center of Mass Energies (TeV)
20	8
300	13
300	14
300	33

6 Results

For the last step of my analyses, I plotted histograms for different center of mass energies. In the plots below, it is possible to see different kind of kinematic variables such as; Jet Pt, Lepton Pt, HT, MET, Jet multiplicity, Jet η, Lepton η and Lepton multiplicity distributions as a result of single lepton selection. In order to understand the hadronic activity, HT distribution explained below, is plotted.

$$HT = \sum_{Jets}(P_t) \tag{6}$$

and as it was mentioned before, one of the supersymmetric particles in SUSY, which is assumed in many model as a candidate for the dark matter, neutralino can be estimated from the missing transverse energy MET which is,

$$MET = -\overset{\rightarrow}{\sum_{All\ Particles}}(P_t) \tag{7}$$

6.1 Results at $\sqrt{s}$ = 8 TeV

It is known that the CMS experiment collected data at $\sqrt{s} = 8$ TeV, in $\int$ Ldt = 20 /fb in 2012 already. Therefore in order to make a connection between the data and the expected results, it is better to investigate all these kinematical variables in $sqrts = 8$ 8 TeV are also plotted.

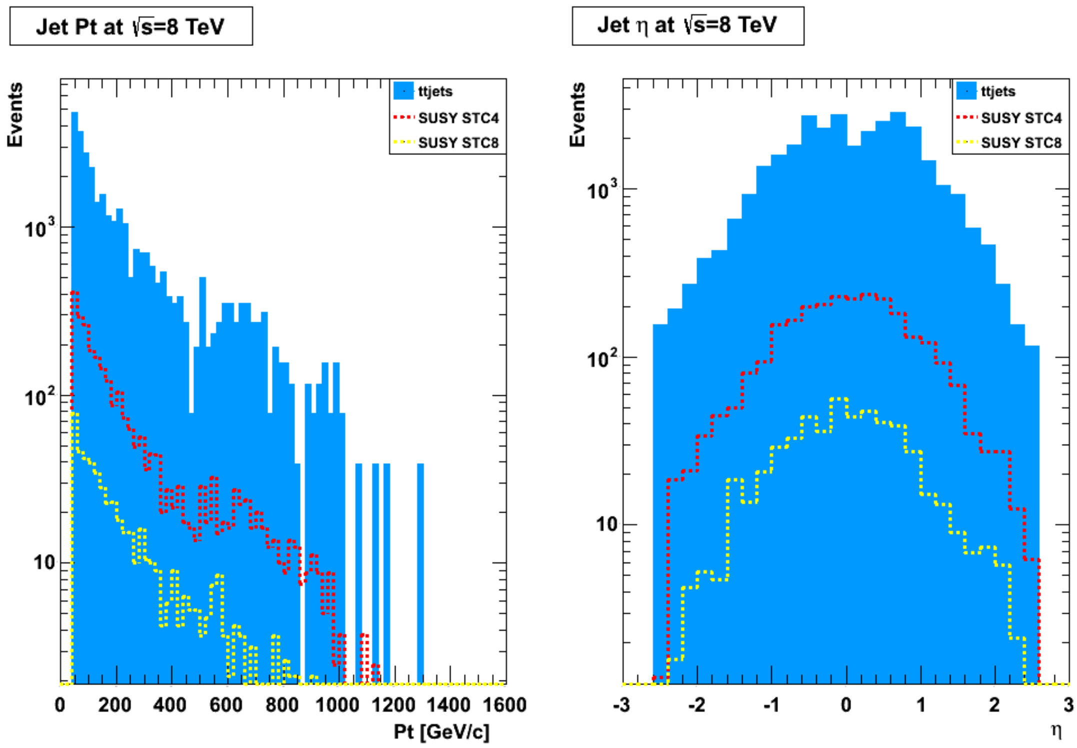

Figure 10: Jet Pt and Jet η distributions at $\sqrt{s} = 8$ TeV

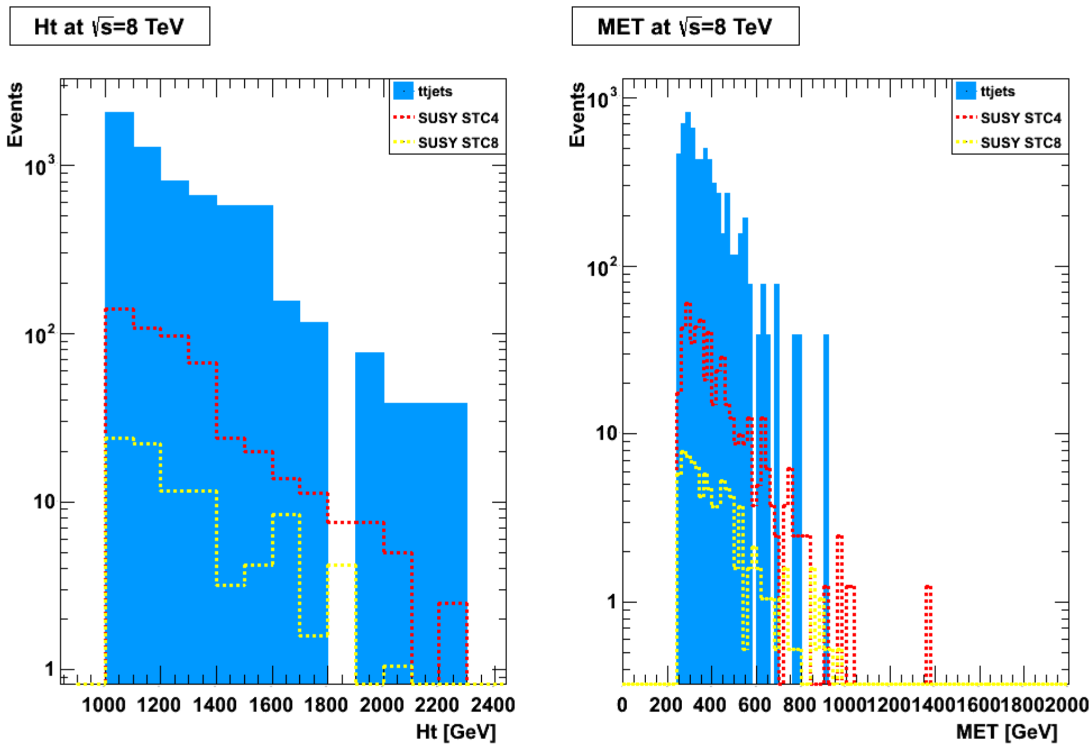

Figure 11: HT and MET distributions at $\sqrt{s} = 8$ TeV

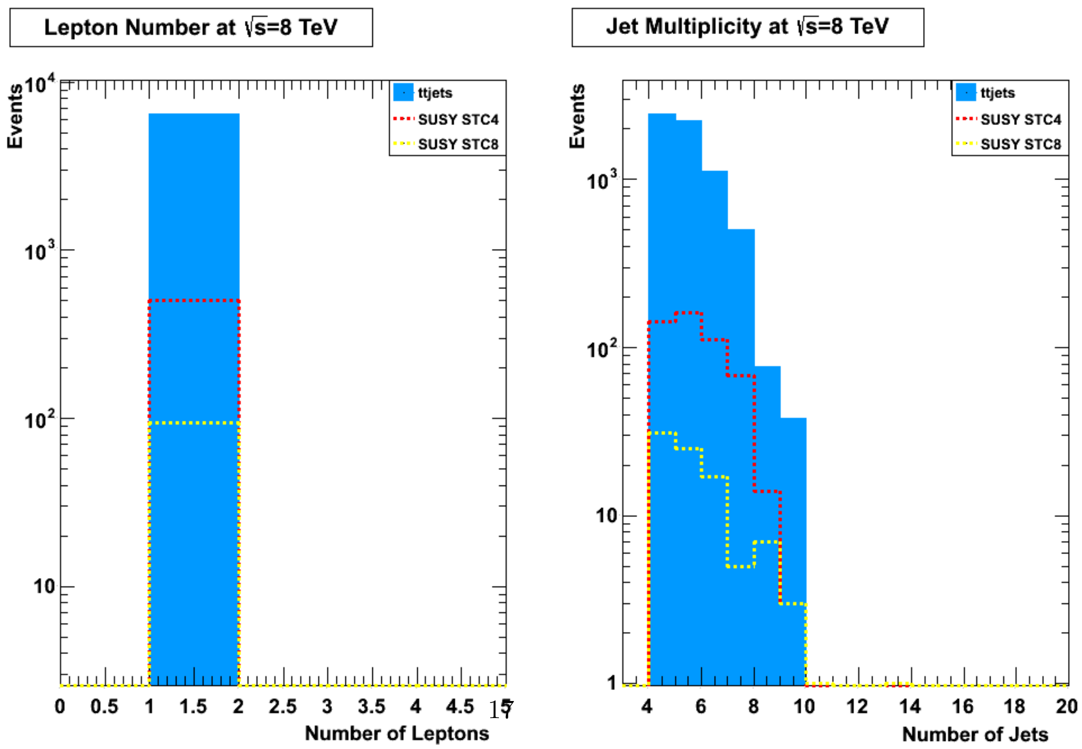

Figure 12: Lepton and Jet multiplicities at $\sqrt{s} = 8$ TeV

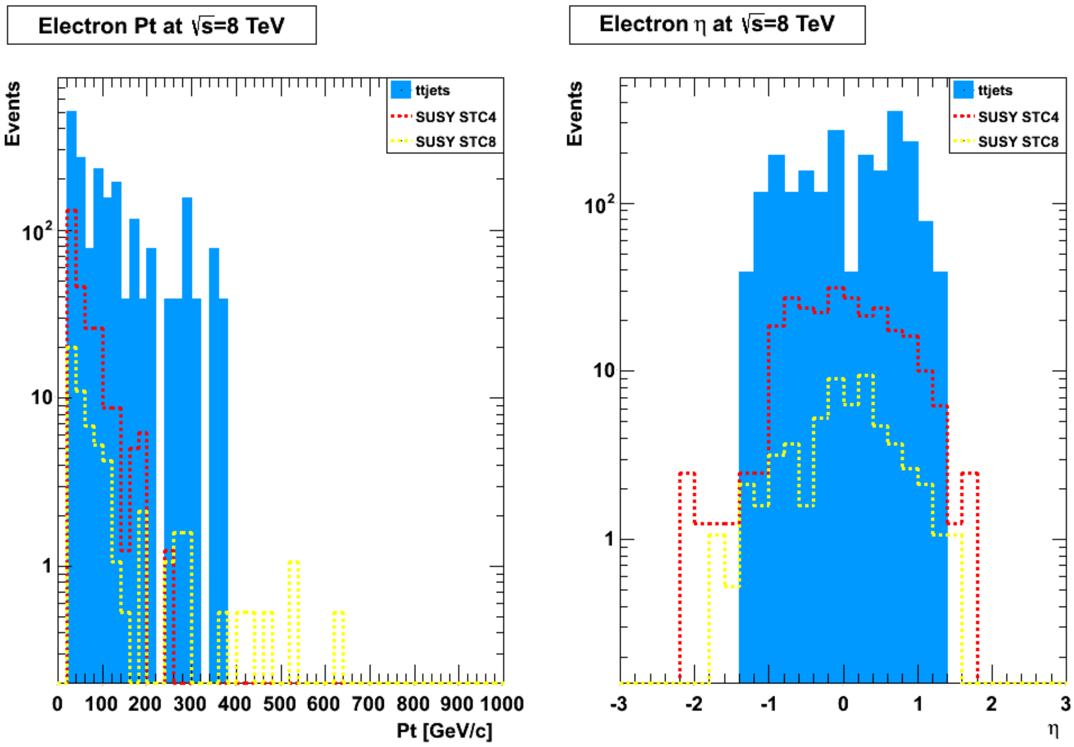

Figure 13: Electron Pt and Electron η distributions at $\sqrt{s} = 8$ TeV

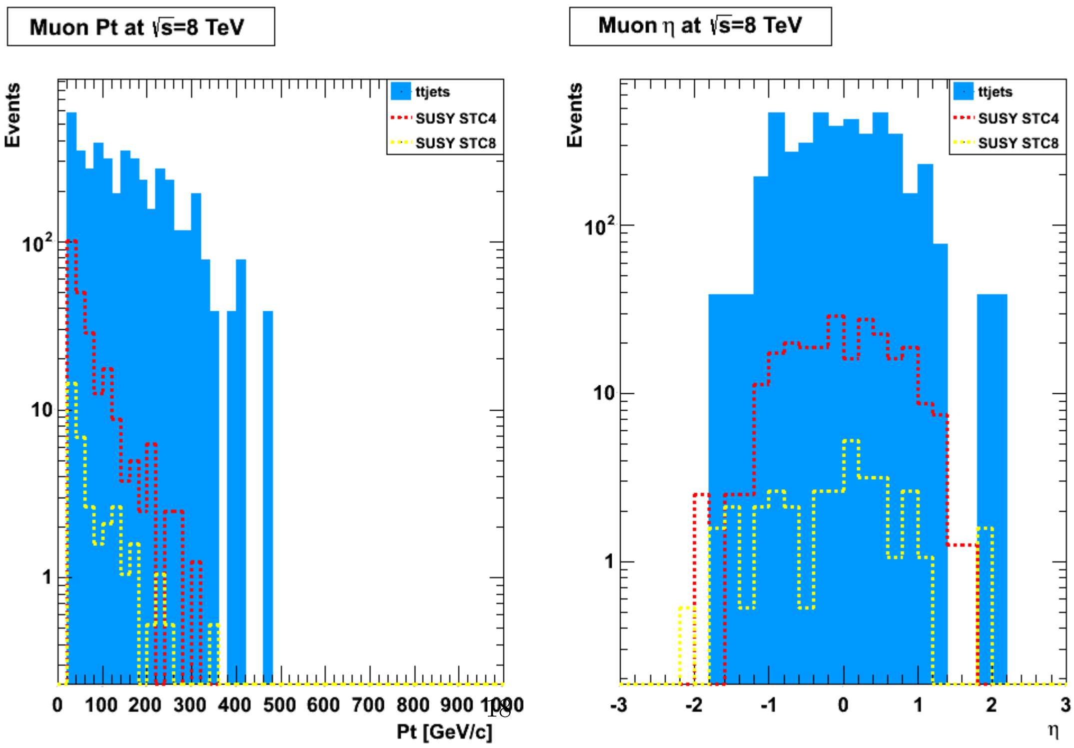

Figure 14: Muon Pt and Muon η distributions at $\sqrt{s} = 8$ TeV

6.2 Results at $\sqrt{s} = 13$ TeV

For the upgrade program studies, it is announced that LHC can possibly work firstly at $\sqrt{s} = 13$ TeV in 2015. For this reason below plots are also included in my analysis in $\int$ Ldt = 300 /fb.

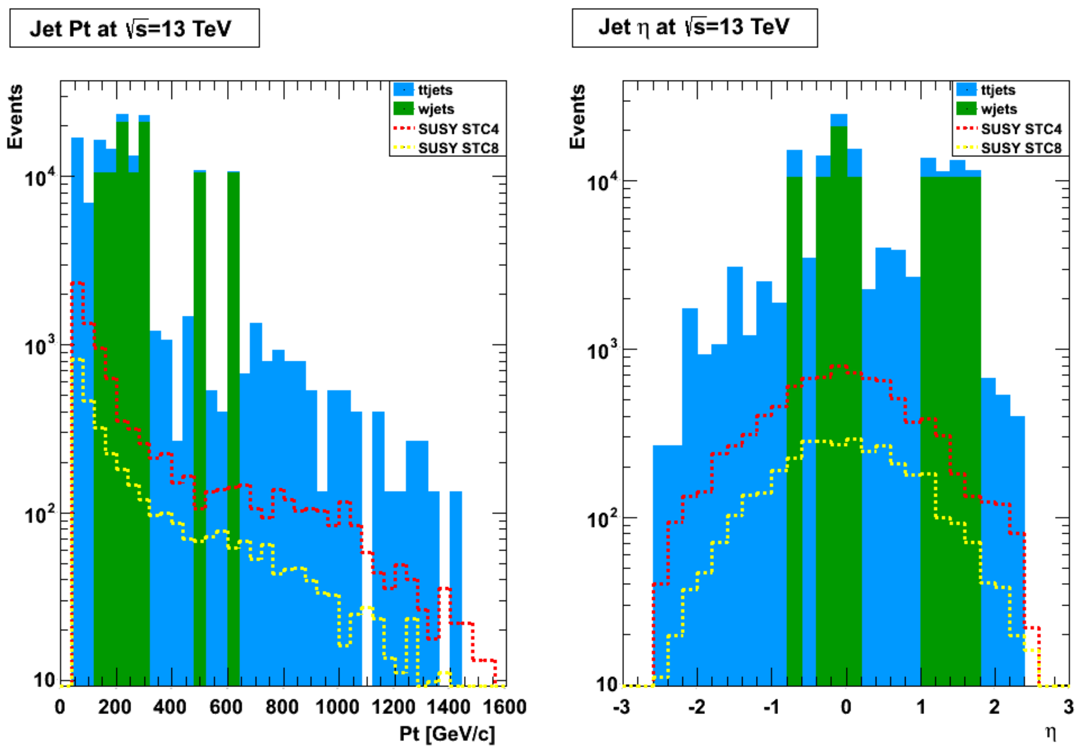

Figure 15: Jet Pt and Jet η distributions at $\sqrt{s} = 13$ TeV

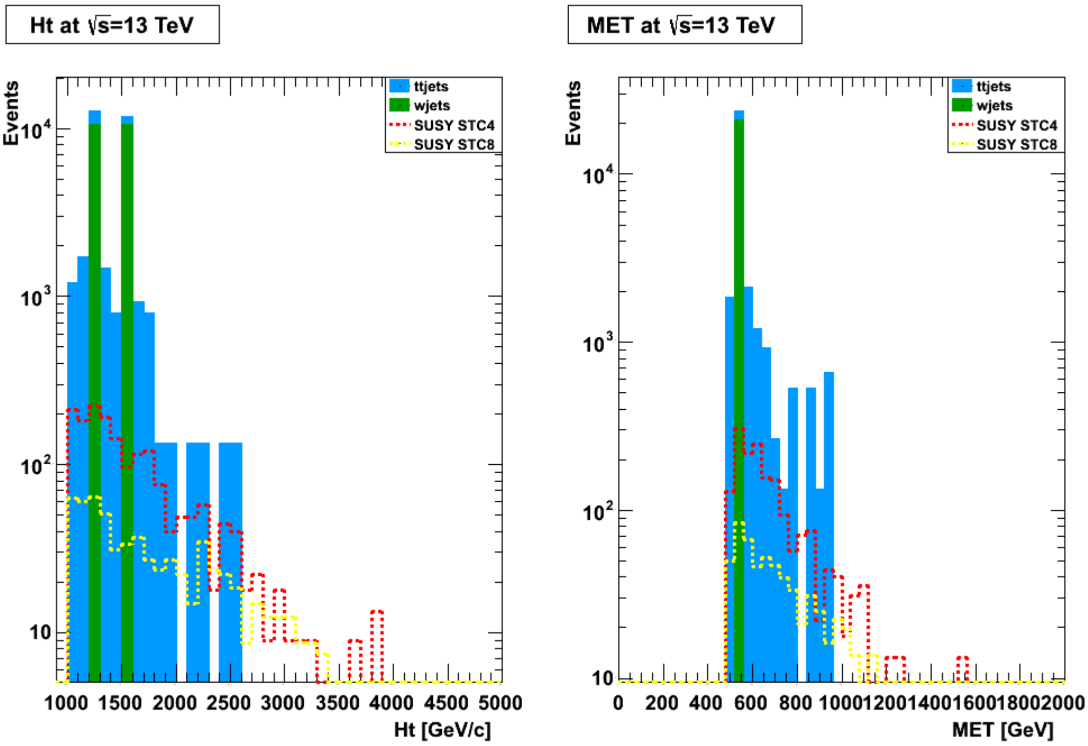

Figure 16: HT and MET distributions at $\sqrt{s} = 13$ TeV

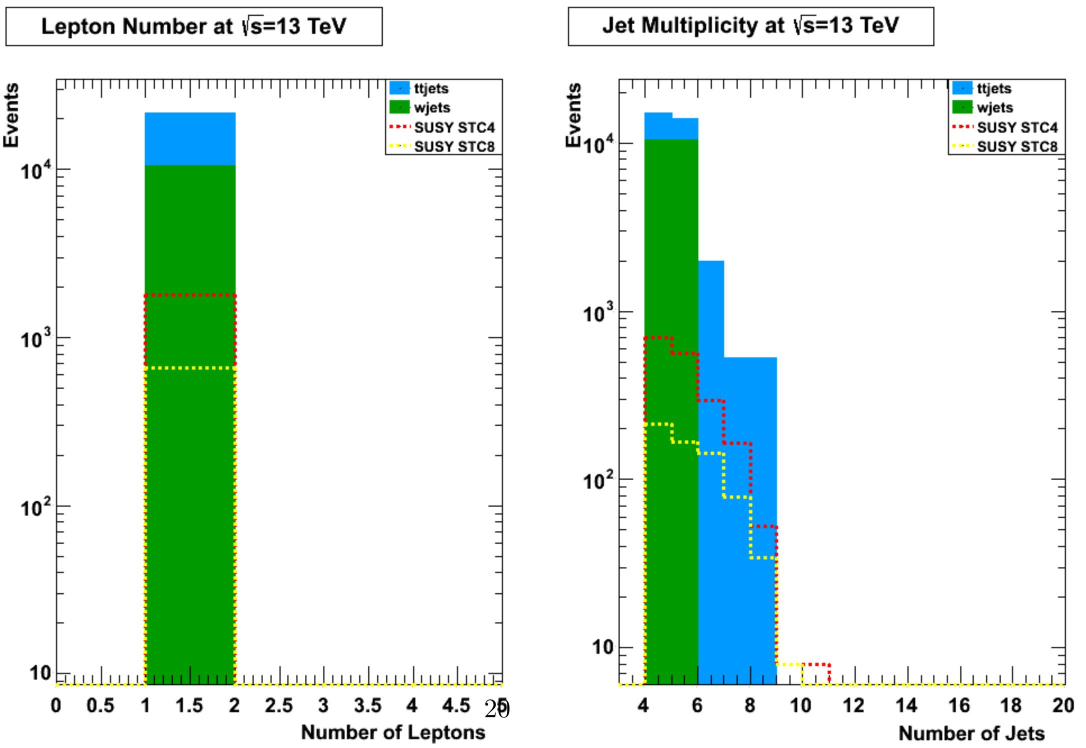

Figure 17: Lepton and Jet multiplicities at $\sqrt{s} = 13$ TeV

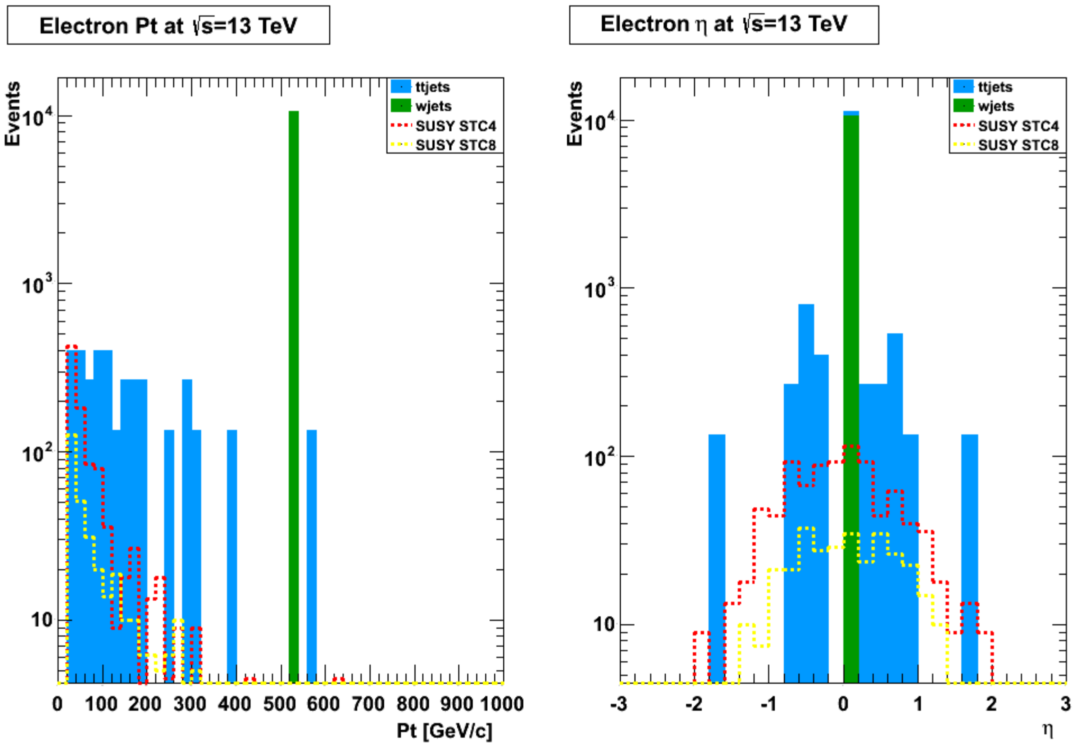

Figure 18: Electron Pt and Electron η distributions at $\sqrt{s} = 13$ TeV

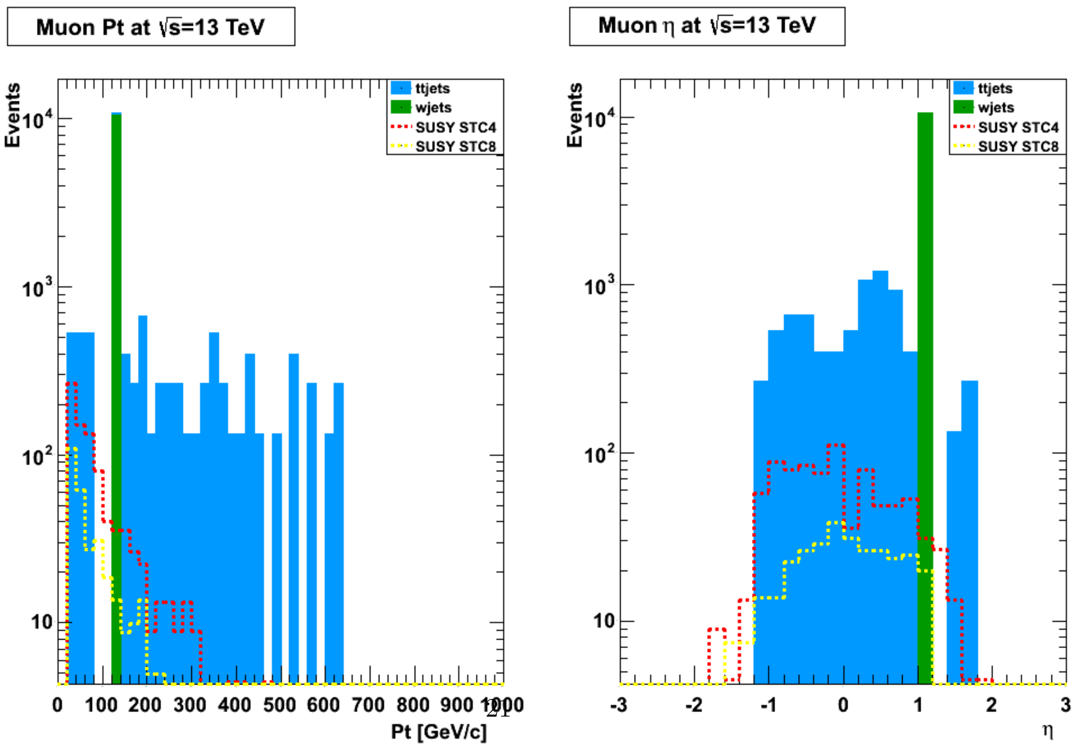

Figure 19: Muon Pt and Muon η distributions at $\sqrt{s} = 13$ TeV

6.3 Results at $\sqrt{s} = 14$ TeV

From the plots it can be seen that, whereas it was not possible to see any W-jets events at $\sqrt{s} = 8$ TeV, they has been able to be observed from $\sqrt{s} = 13$ TeV and also in the below kinematical distributions $\sqrt{s} = 14$ TeV, in $\int$ Ldt $= 300$ /fb

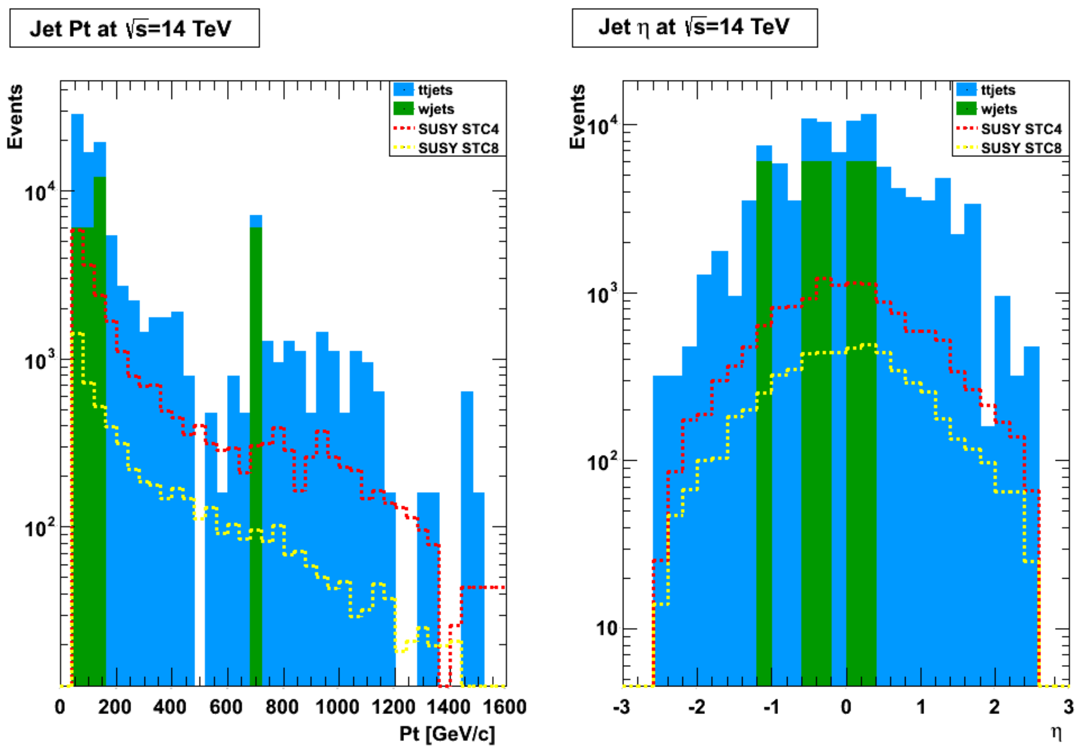

Figure 20: Jet Pt and Jet η distributions at $\sqrt{s} = 14$ TeV

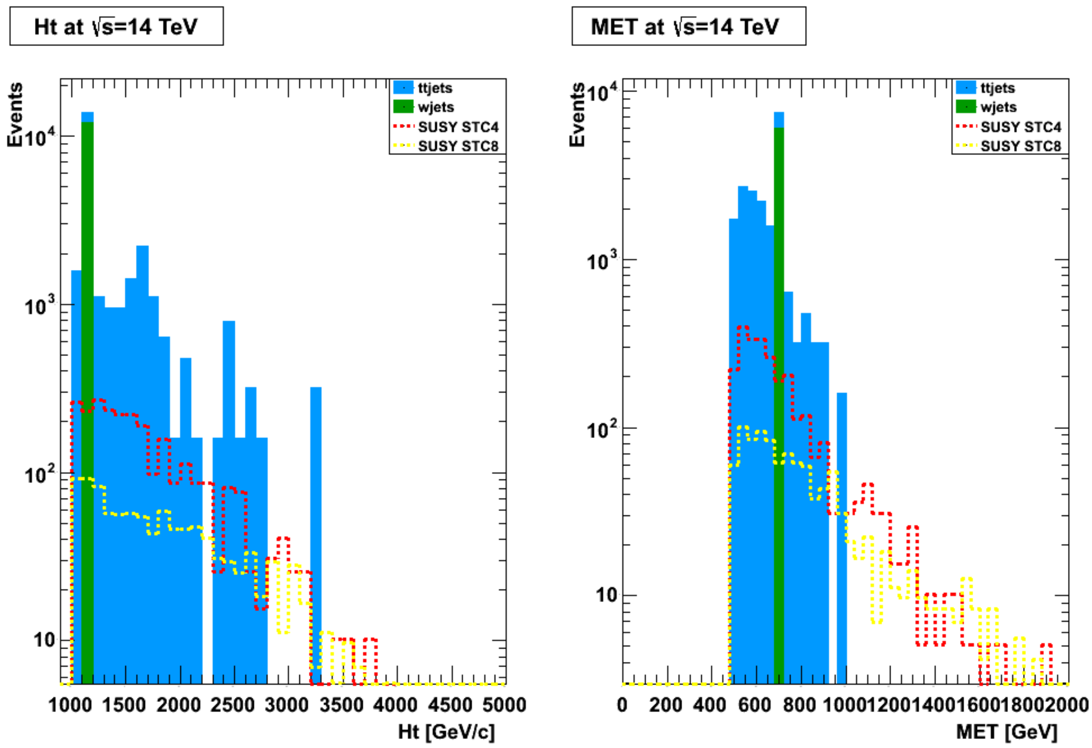

Figure 21: HT and MET distributions at $\sqrt{s} = 14$ TeV

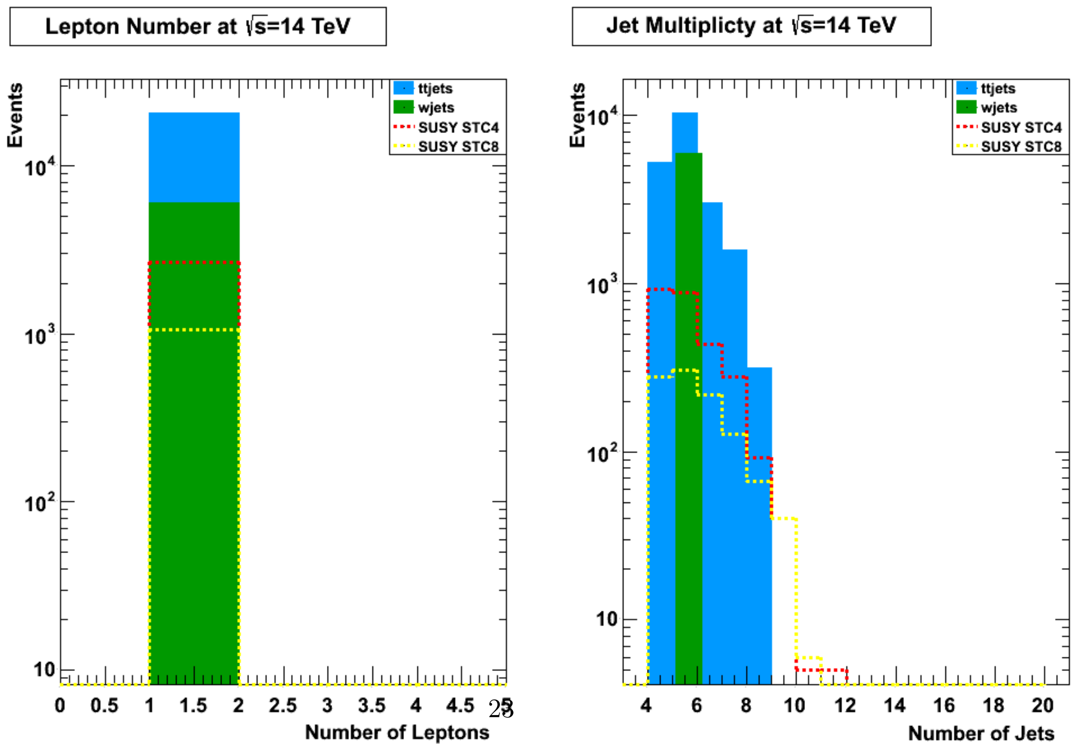

Figure 22: Lepton and Jet multiplicities at $\sqrt{s} = 14$ TeV

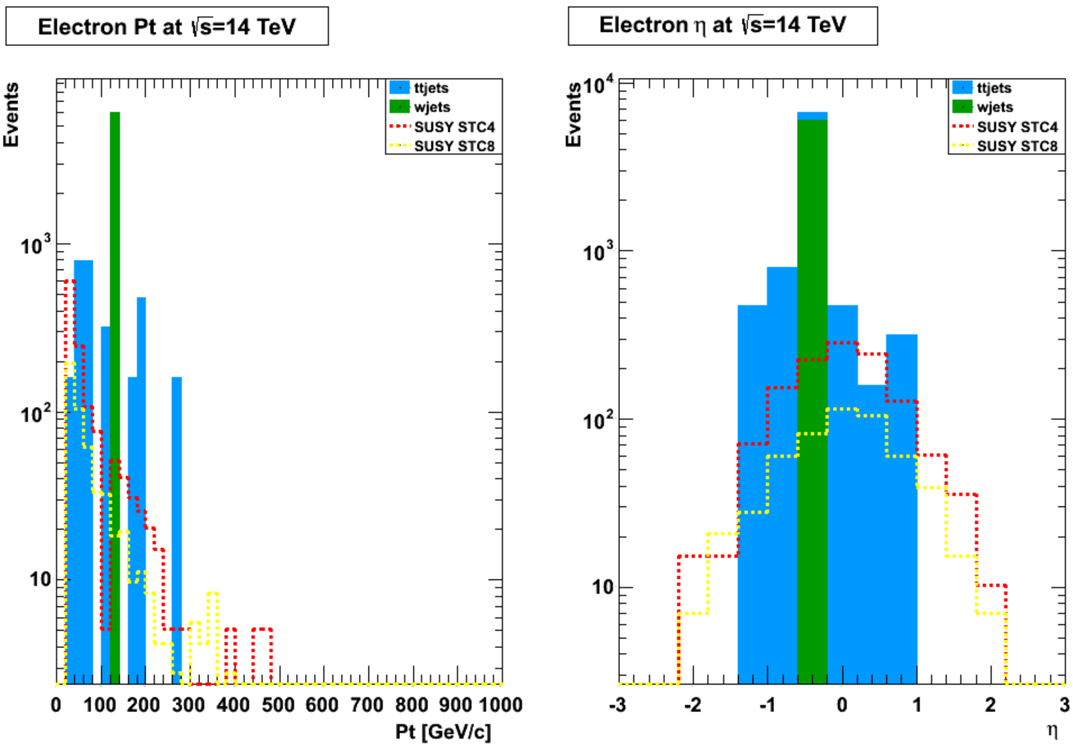

Figure 23: Electron Pt and Electron η distributions at $\sqrt{s} = 14$ TeV

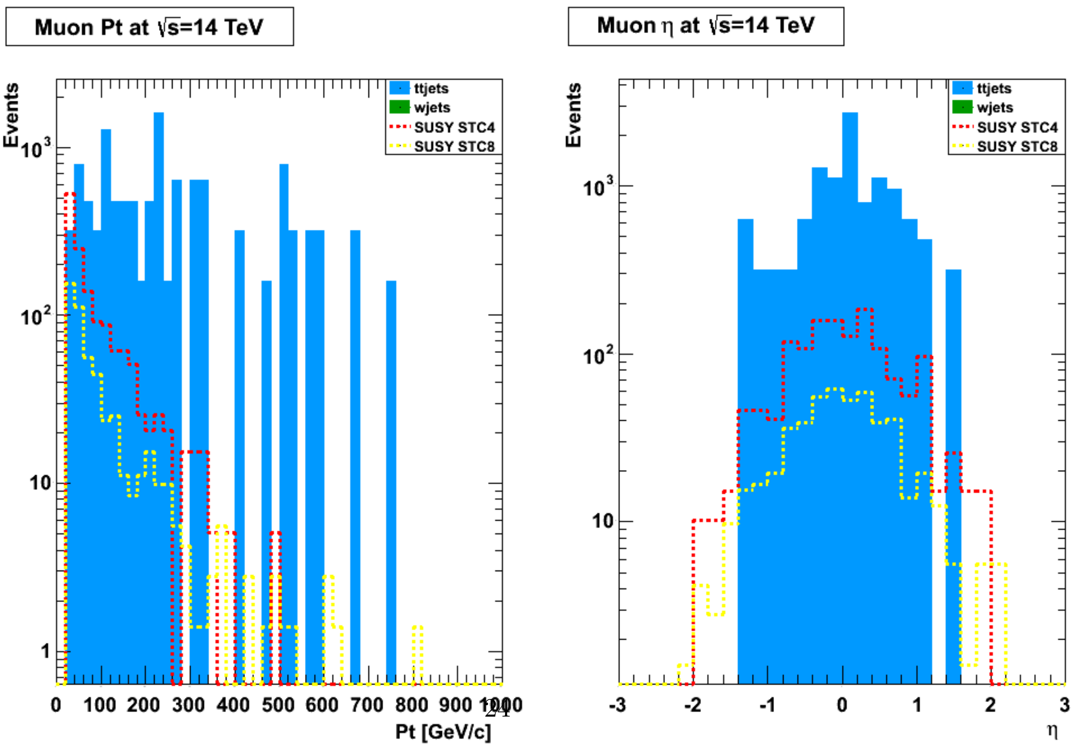

Figure 24: Muon Pt and Muon η distributions at $\sqrt{s} = 14$ TeV

6.4 Results at $\sqrt{s}$ = 33 TeV

In this section analysis were made in $\int$ Ldt = 300 /fb, basicly for the High Energy-LHC upgrade scenario at $\sqrt{s}$ = 33 TeV which actually shows that is needed to do a specific research and development for the LHC magnet. (Expected luminosity $\int$ Ldt = 3000 /fb)

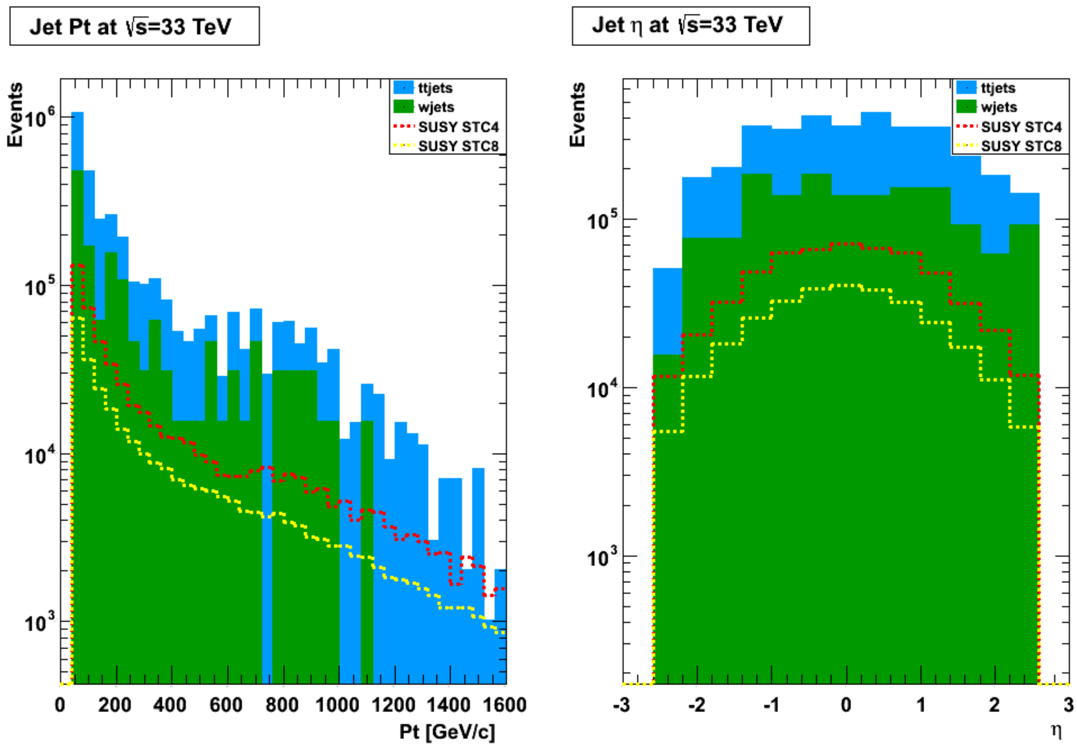

Figure 25: Jet Pt and Jet η distributions at $\sqrt{s}$ = 33 TeV

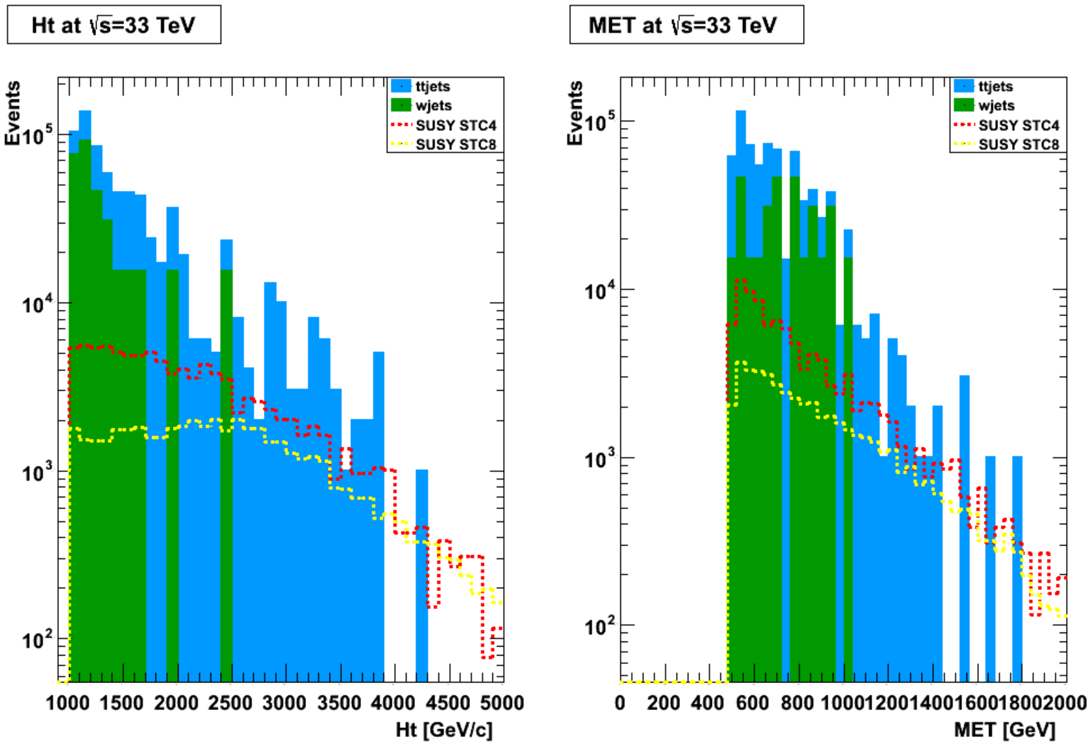

Figure 26: HT and MET distributions at $\sqrt{s} = 33$ TeV

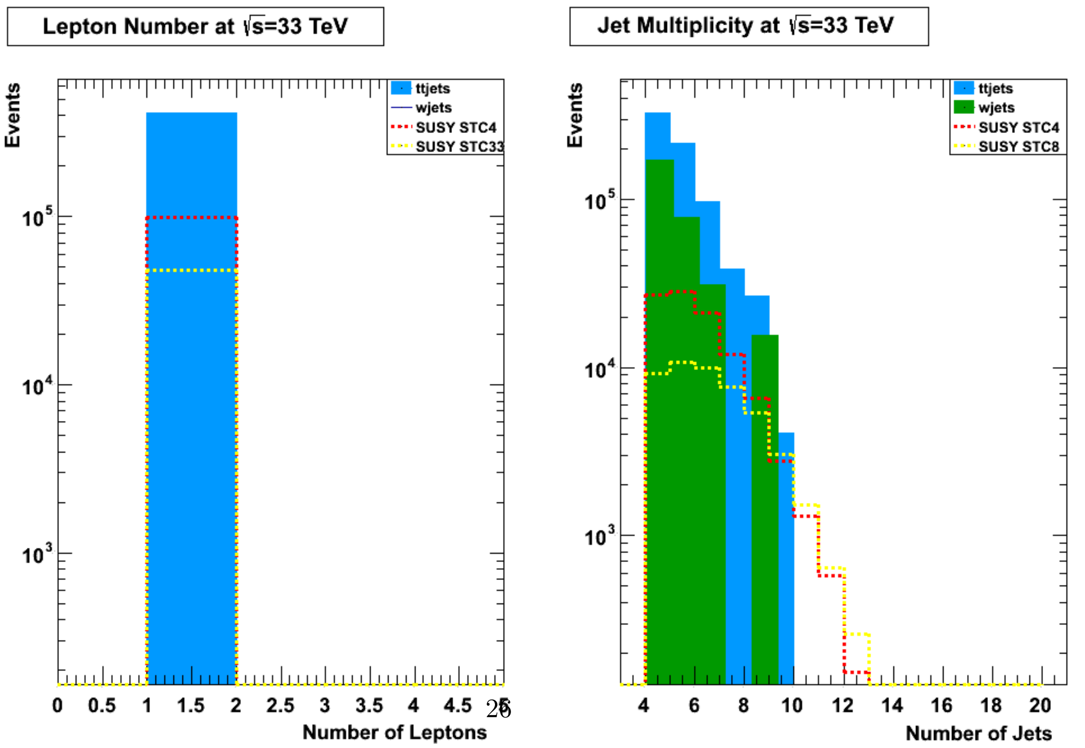

Figure 27: Lepton and Jet multiplicities at $\sqrt{s} = 33$ TeV

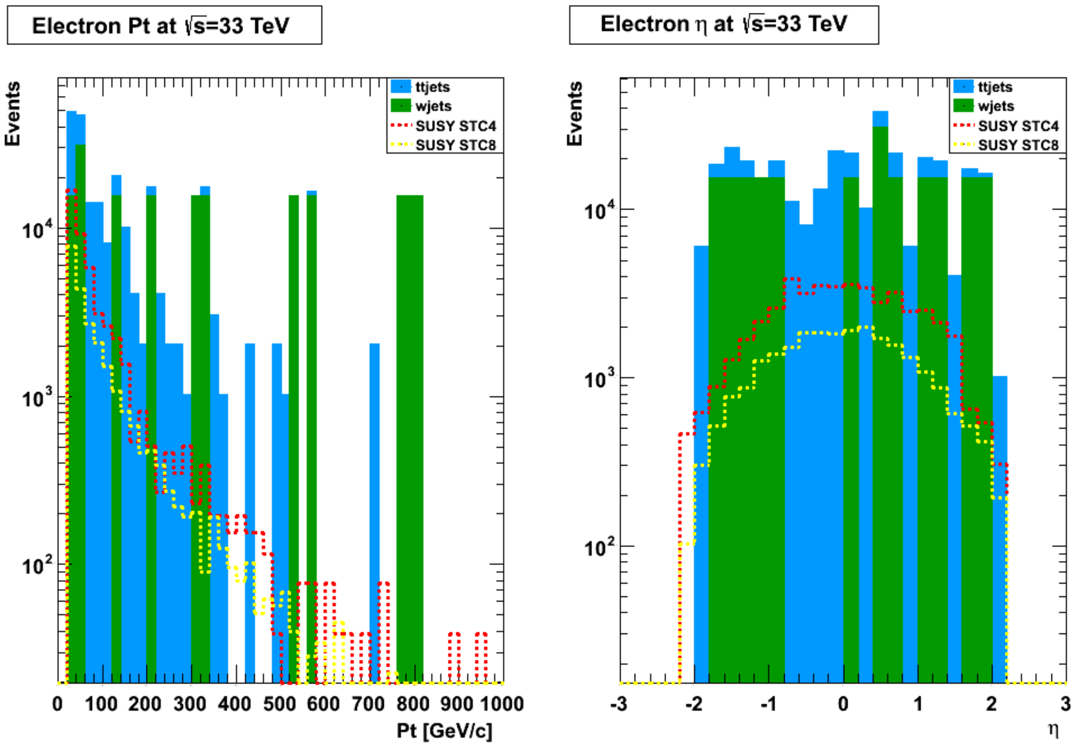

Figure 28: Electron Pt and Electron η distributions at $\sqrt{s} = 33$ TeV

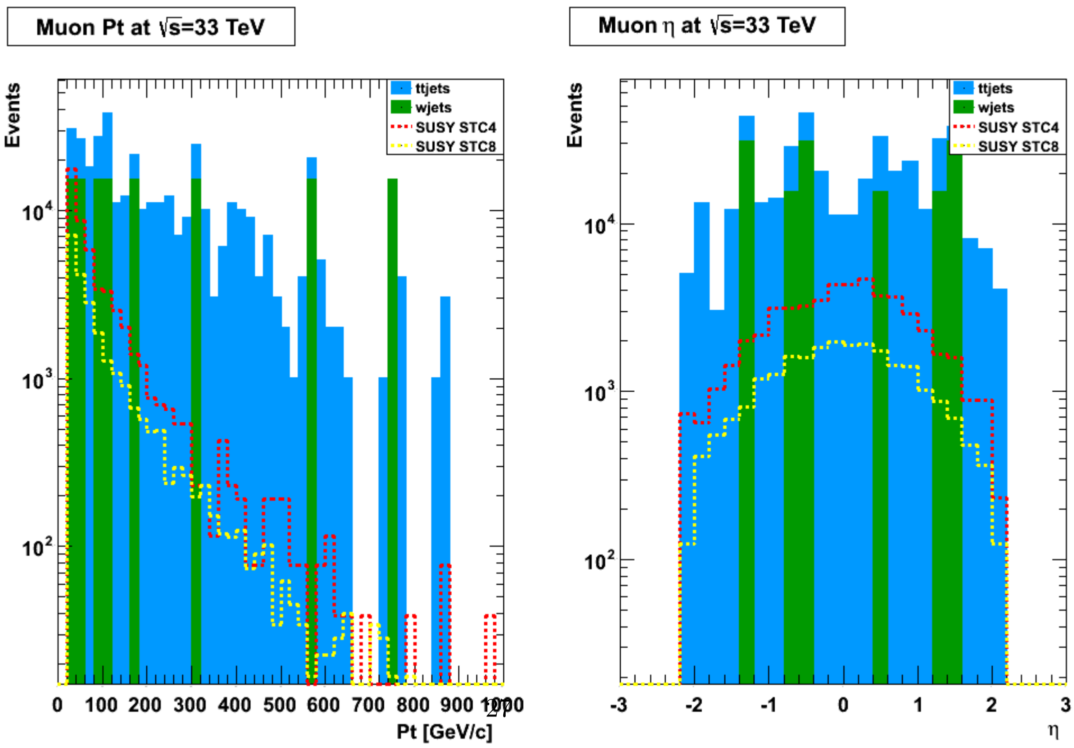

Figure 29: Muon Pt and Muon η distributions at $\sqrt{s} = 33$ TeV

7 Summary

In this study, I discuss the Supersymmetry search with single lepton final state for the CMS detector upgrade program. I tried to explain some basic concepts of SUSY and the CMS Detector. And I also introduced my workflow that I followed in this project which is in the order of simulations in Pythia and plotting histograms via ROOT in the CMS software frame. In my project, I studied various MC simulations for SUSY search with single lepton final state analysis at different center of mass energies. For background samples; I simulated tt-jets, W-jets, Z-jets and QCD and for SUSY signal samples; STC4 and STC8 benchmark points are simulated. Different kinematical variables, Jet Pt, Jet η, HT, MET, Lepton η, Lepton multiplicity, Lepton Pt and Jet multiplicity plots at $\sqrt{s} = 8$, 13, 14 and 33 TeV are presented. As a result, firstly it can be concluded that analysis needs to be improved for higher statistics of background and signal samples with optimization of the event selections. In addition, with the increase in the center of mass energy, it is seen that cross sections are also increased. Therefore, the possiblity to see W- jets background from $\sqrt{s} = 13$ TeV is observed. And for the High Energy- LHC upgrade scenario, it is concluded that all the Standard Model and SUSY signal points are more visible with higher number of events. As it is mentioned before, for this project I mainly concentrated on MC level analysis for single lepton final state. I plan to get the full event reconstruction and data analysis at the CMS detector in future.

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