Dark Matter Production with Boosted W/Z Bosons at Large Hadron Calorimeter-LHC

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1.Abstract

Nature of dark matter is one of the most important questions for the universe. Until today, no one knows what kind of particles form the dark matter despite several evidences of its presence in the universe. This research describes how dark matter can be pair produced in the Large Hadron Collider (LHC). Methods and technics used to distinguish dark matter and ordinary matter are explained. An analysis of Monte Carlo simulation has been studied for dark matter mass of 100 GeV/c^2. The future work for this ongoing project will be based on testing data from the Compact Muon Solenoid at LHC using the results of the Monte Carlo simulation.

2. Introduction

What is dark matter? This question is one of the important questions about the universe that we do not have an answer for. The visible matter, as we know it, is 5 % of the constituents of the universe. Most of the matter in the universe, is composed of unknown matter called dark matter since no one has successfully seen it. We will address the first evidences of dark matter in space, talk about its history, and describe the methods we will be using to study it in the laboratory. The study will be done with the Compact Muon Solenoid (CMS) at the Large Hadron Collider (LHC). CMS is one of the detectors at of LHC, the particle accelerator located at the European Center for Nuclear Research (CERN).

The purpose of this paper is to describe the ongoing work in developing and analyzing Monte Carlo simulation about dark matter production in the CMS detector. Procedures and criteria to discriminate events produced will be discussed.

3. Materials and Methods

3.1 The Large Hadron Collider (LHC)

The LHC is the world's largest particle accelerator, built by the European Center for Nuclear Research (CERN). This facility was put in place to answer some open questions about the universe such as discovering the Higgs boson, the nature of dark matter, the nature of quark-gluon plasma, understanding why gravity is weaker than other fundamental forces, the imbalance between matter and antimatter in the universe, and other topics.

The LHC measures 27 km in circumference and resides 175 m deep underground. The LHC has superconducting magnets made in copper and niobium-titanium and these magnets are cooled down by 96 tons of liquid helium kept at temperature 1.9 K. Among those magnets, 1232 are dipole magnets which are used to bend the beam line into a circular path and 392 are quadrupole magnets which focus the beam line.

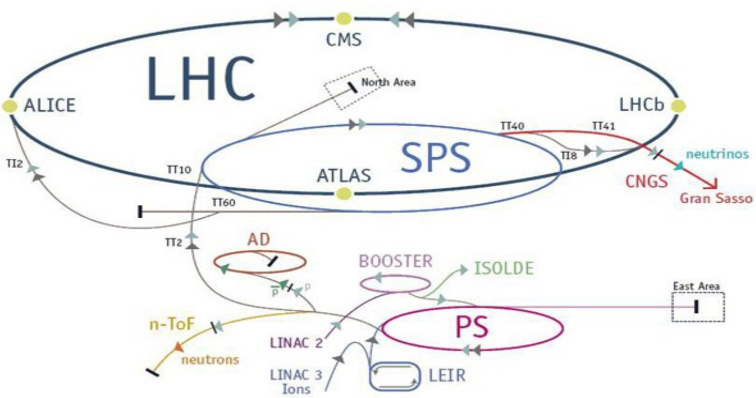

Figure 1: LHC acceleration process

The figure above describes the 5 steps by which the 8 TeV beams of protons is created.

1. The acceleration process starts with the introduction of hydrogen atoms in the source chamber of the linear particle accelerator (LINAC 2). In this chamber, the electrons are stripped off the atoms to obtain protons which are accelerated up to 50 MeV.
2. Step two of the acceleration continues in the Proton Synchrotron Booster where protons are squeezed together and repeatedly circulated until they gain an energy of 1.4 GeV.
3. For the third step, protons are transferred into the Proton Synchrotron. In this stage, the energy gain is no longer increasing the speed of protons, instead, it increases the mass of protons. The PS accelerates protons up to 26 GeV and they become 25 times heavier than at rest.

4. In the fourth step, The PS then moves protons to the Super Proton Synchrotron (SPS) which accelerates protons up to 450 GeV.
5. The last step is the introduction of the protons to the main ring where they are accelerated up to 8TeV and become 8000 times heavier than at rest.

Once the beams are in the vacuum pipes, they collide at 4 locations where the vacuum pipes crosses over. At the colliding locations, there are detectors designed to answer some of the questions mentioned above. Those detectors include CMS and ATLAS with primary mission of studying the origin of mass, the existence of extra dimension, and the nature of dark matter; ALICE is mainly studying quark-gluon plasma which is believed to have existed at the beginning of the universe, and LHCb mostly used to investigate the missing antimatter.

Since the opening of the LHC in 2008, there have been progress in the study of the universe. Scientists at CERN and all over the word, working in collaboration, have successfully created the quark-gluon plasma which has been studied in some details. The Higgs boson has also been discovered on July 4, 2012 and it is under detailed study. A new particle bottomonium state (Xb) has been observed in the LHC experiments. Other channels are also being investigated such as Dark Matter and Missing anti -matter.

2.2 The Compact Muon Solenoid (CMS) Detector

CMS, which was used for this study, is one of the detectors of the LHC. It is 25 m long, 15 m in diameters, and it weighs about 12,500 tons. The purpose of this detector was the search of the Higgs boson, extra dimensions, the nature of dark matter, and anything else that could explain the mysteries of the universe. In the LHC, two beams of protons are accelerated in opposite directions and collide at the center of the detectors. The radius of each beam is focused to 17μ before they collide at their interaction point. Each beam has 2,808 bunches with $1.15*10^{11}$ protons per bunch. Each second there is 31.6 million collisions, 40 Terabytes of data are produced and only 100 events of data recorded [1].

The CMS detector is built of 3 sub-detectors inside a magnetic field of 3.8 T solenoid and one sub-detector outside of the solenoid. The 3.8 T magnetic field bends charged particles and allows a precise measurement of the momentum of particles in the plane perpendicular to its direction. Particles that are produced after collision include photons, electrons, muons and others. The following figure shows the CMS by layers

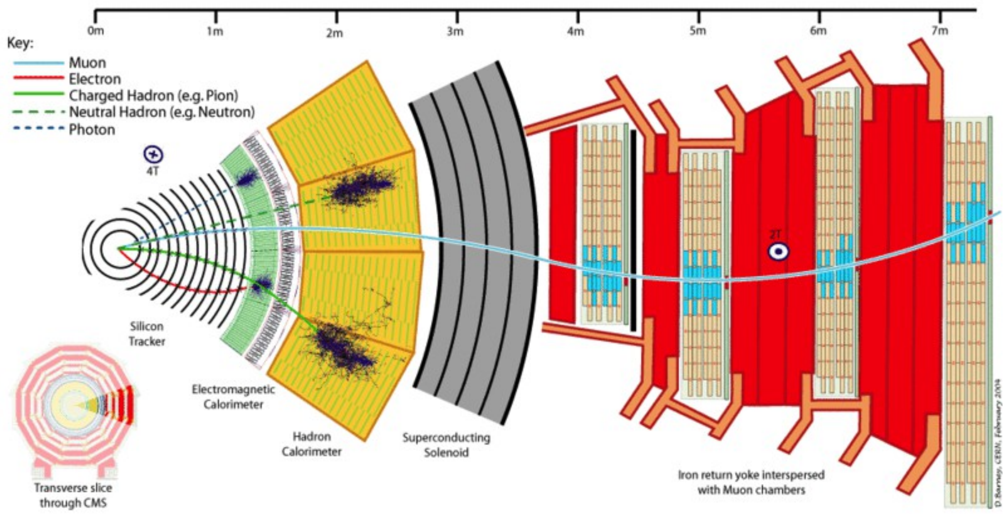

Figure 2: Sub-detectors of CMS

The five parts of the CMS detector are:

1. **The Tracker:** Made of silicon, the tracker is the inner most part of the detector. The role of this part of the detector is to measure with very high precision the momentum of charged particles produced after collision. The tracker measures the positions of particles with a precision of 10 µm then it reconstructs the tracks and records the path of charged particles moving in the 3.8 T magnetic field inside the detector. The Tracker consists of silicon pixels to deal with high intensity of particles emerging from collision and silicon micro strips to cover the Tracker. Note that the Tracker must be very close to the interaction point to detect short lived particles produced after collision.
2. **The Electromagnetic Calorimeter (ECAL):** The ECAL measures the energies and momentum of electrons and photons. The ECAL is made of crystals of lead tungstate ($PbWO_4$) which is

able to produce light when electrons and photons pass through it. The light intensity is proportional to the energy of the passing particle. The ECAL has two major parts, barrel and EndCaps. The EndCaps surface of the ECAL consist of sub detectors made from lead and silicon strip that are used to differentiate photons and pions.

3. **The hadronic Calorimeter(HCAL):** The HCAL was designated to measure the energies of hadrons, particles created during the collision of the quarks and gluons within the proton. The HCAL is a sampling calorimeter, namely so that particles interact in the dense material such as steel and they are detected in the scintillator. By absorbing the energy of particles, the scintillator material of HCAL emits a signal. The HCAL contains Hybrid Photodiodes which are used to amplify the signals and determine energies and type of the particles.
4. **The Magnet:** The magnet encloses the Tracker, ECAL, and HCAL. It is 13 m long, 6 m in diameter and it has an inductance of 14 H. The current through the coils of the solenoid is 18,160 A, giving a stored energy of 2.3 GJ [3]. This solenoid produces a magnetic field of 3.8T which bends the trajectories of charged particles in the detectors located inside the magnet.
5. **The muon detector and the iron return yoke:** The outermost part of the CMS detector is the muon detector used to find muons. Muons are able to go through long distance exciting and ionizing the material all the way in the sub-detectors. Therefore, the information from different detectors are put in place to identify the muons. The muon detector is made of the Drift Tubes (DT) to record the muons' position, Cathodes Strip Chambers (CSC) used in the end cap, and the Resistive Plate Chambers (RPC) to fast signal produced after a muon passes through the detector.

3.3 The Outer Hadron Calorimeter (HO)

The outer calorimeter is a part of CMS sub-detectors located outside of the solenoid coils. It is an extension of the HCAL outside of the solenoid and it is a tail catcher of HCAL. The HO takes an advantage of the solenoid which provides an absorption length of 1.4/ sinθ. This calorimeter is covering the region of HCAL with $| \eta | < 1.5$. The return yoke of the CMS detector has 5 rings labeled -2, -1, 0, +1,+2 and HO placed on each rings' first sensitive layer. All rings have one layer except the central, ring 0, which has 2 layers of HO because in this area particles encounter less material. The HO contains fibres from Y11 Kuraray wavelength shifting (WLS) which are inserts into scintillator tiles and used to gather the scintillator light. The WLS transport scintillator light to the photo detectors in the decoder box at the muon detector.

The importance of HO increases with the center of mass- energy of particles produced after collision. When measurements are taken without HO consideration, there is energy leakage particularly very significant at η equals zero. The measurements of the missing transverse energy (MET) are improved by taking HO into account. These measurements are very important because they could lead us to the discovery of supersymmetric particles.

3.4 Feynman Diagrams

Feynman diagrams are widely used in particles physics to represent interactions of particles. This section is included in this paper because any physics process has a simple representation using them. A Feynman diagram is composed by two types of lines: a straight line with an arrow and a wiggly line. In the Feynman diagram, two straight lines with arrow are connected only if they meet at one wiggly line and all pieces of the diagram must be connected. The most important part of the Feynman diagram is the endpoints of each line. Note that to read a Feynman diagram, one goes from left to right. The following schematic is an example of a Feynman diagram.

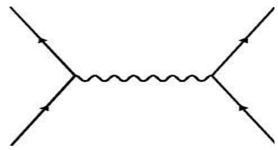

Figure 3: An example of a Feynman diagram

In the Feynman diagram, a straight line with an arrow represents a matter particle, a wiggly line represents a force particle, and a vertex represents an interaction. Feynman diagrams summarize theories like quantum electrodynamics (QED) which is the theory of interaction between matter and light. QED is often referred to as a theory of electrons, positrons, and photons. In this case, looking at the Feynman diagram, an arrow directed to the right represents an electron, an arrow directed to the left represents a positron, and the wiggly line stands for the photon. Electrons and positrons are matter particles called leptons while photons are force particle and they carry electromagnetic force between charged matter particles. In each Feynman diagram, there must be conservation of charges. That means that the total number of charges of particles going into an intersection, must be equal to the total number of charges particles going out of it. There is also conservation of momentum where the sum of momenta of particles interacting must be equal to the sum of momenta particles produced after the interaction.

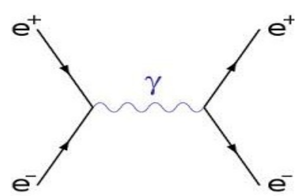

Figure 4. Feynman diagram of electron-positron interaction.

The diagram above can be interpreted as follow: an electron and a positron annihilate into a photon which in turn pair produces an electron and a positron. In that diagram, the photon is virtual because it cannot be directly seen.

The Z boson is also used in Feynman diagrams as a force carrier particle. It mediates the weak force. However, since the Z boson is massively heavy compared to the photon, it quickly decays into light particles such as electrons and muons. That makes the Z boson also a virtual particle. The following Feynman diagram shows how Z boson decays into muons.

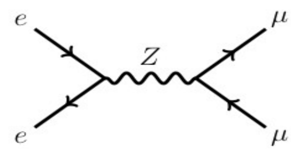

Figure 5: Feynman diagram involving Z boson

Since the Z boson decays before it reaches the detector, it is detected by resonance. To do that, the analysis of energy is considered from the energies of electron and positron before collision up to the energies of produced particles(muons, electrons, and positrons). Scanning over the energies in the process of collision, a bump in energies should be noticed. This bump identifies the presence of the Z boson in the process and its location in the mass plot allows to determine the mass of the Z boson. The Z boson can mediate the weak force between any leptons and any quarks.

Another type of force particle is the W boson which also mediates the weak force. Unlike photons and Z boson, W boson is electrically charged. That means there are W+ and W- both involved in radioactive decay of heavy nuclei into light nuclei. The W boson is also heavier than photons but slightly lighter than the Z boson. Therefore, like the Z boson, the W boson is a virtual particle because it lives a very short time before it decays into lighter particles.

In the Feynman diagram, W boson joins leptons and neutrinos but in a different way than other force particles we have seen above. The W boson joins any lepton to any neutrino.

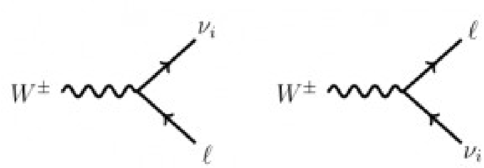

Figure 6: W boson decaying into leptons & anti-leptons

In the diagram above *l* stand for any charged lepton while υ_i represents any neutrino. For example, a W boson decaying into an electron and an electron -neutrino or W boson decaying into a tau and a tau-neutrino. Another special property of the W boson is that it can interact with other force particles (photons and Z boson) because it is electrically charged.

The following diagram show how the W boson is involved in neutron decay into a proton, electron and electron-neutrino.

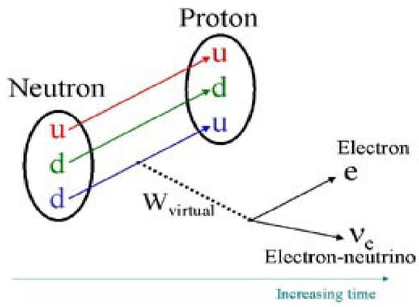

Figure 7: Neutron decay

3.5 ROOT

ROOT is an objet-oriented graphic framework designed and developed by scientists at CERN in order to help in data analysis of high energy physics. It uses an independent package CINT, a C++ interpreter, for the command lines and script processor. ROOT is mainly used for plotting and analyzing histograms and trees. All histograms in this study were plotted in ROOT.

3.6 Dark Matter

Dark matter is believed to form a huge part of the mass of the universe. Scientific studies of the universe has shown that only about 5% of the total constituents of the universe is visible matter. The remaining part of the universe is thought to be composed by dark matter (about 24%) and dark energy (about 71%). Dark matter don't emit or absorb x rays, light, or any other kind of electromagnetic radiation. It might be that dark matter emits electromagnetic radiation at a very low, undetectable le vel.

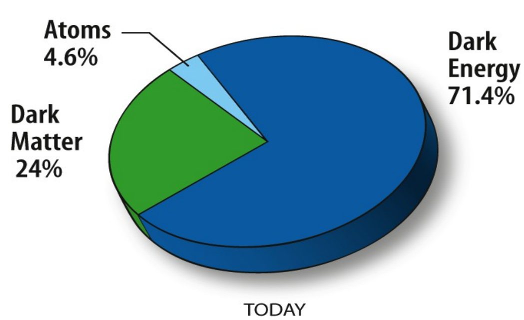

Figure 8: Components of the Universe

Even if no one has successfully seen dark matter, there are evidences of its existence. The main evidence of the dark matter is the gravitational force it exerts on visible matter in the universe. Other evidences of dark matter include:

- **Orbital velocities of stars in the milky way**: In 1932, Jan Oart realized a disagreement in determining the mass of huge astronomical objects in our galaxy using two different methods. The first method was using gravitational effects between the object being studied and the surrounding objects whereas the second method was the calculation of the total mass using the visible matter of the object such as gas, dust and stars. He found that there was a missing mass in the calculation from the second method.
- **Missing mass proved by orbital velocities of galaxy clusters:** The determination of the mass of coma cluster using the velocities of galaxies, showed that the mass of coma is 400 times greater than its expected mass (mass of visible galaxies). This experiment was conducted by Fritz Zwicky in 1933. He concluded that there must be an invisible matter that provides the mass and gravity which keeps the cluster together. Later in 1970's Vera Rubin made a series of quantitative measurements of mass for different clusters of galaxies and she reported the missing mass in each cluster.
- **Distribution of temperature of hot gases in galaxies**: some scientists who were not convinced by the idea of dark matter existence in the universe, decided to test the idea of undetected hot gas being mistakenly identified as dark matter. They took measurements using telescope such as Chandra X ray Observatory and they indeed found superheated gas in the galactic clusters. However, the mass of that hot gas was not enough to account for the estimated amount of dark matter in those galactic clusters. Results showed that dark matter that was 5 to 6 times more massive than the hot gas. Without the dark matter in the galactic clusters, there

would not be a reason that explains the gravity that prevents the hot gas from escaping.

- **Pattern of anisotropies in the cosmic microwave background**: Several experiments have observed angular fluctuations in the cosmic microwave background spectrum suggesting the presence of both baryonic matter and dark matter in the universe.
- **Gravitational lensing of background radiation**: Gravitational lensing is a phenomenon observed when a very distant luminous object such as a star is aligned with a huge object like a galaxy cluster that is between the observer and the source. The light coming from the luminous object is bent and converged by the gravitational field of the cluster as it moves toward the observer. From the obtained geometric shape, the mass/ light ratio of the cluster can be determined. This ratio is consistent with the presence of extra matter in the cluster. The greater the light is bent, the more massive the cluster is.

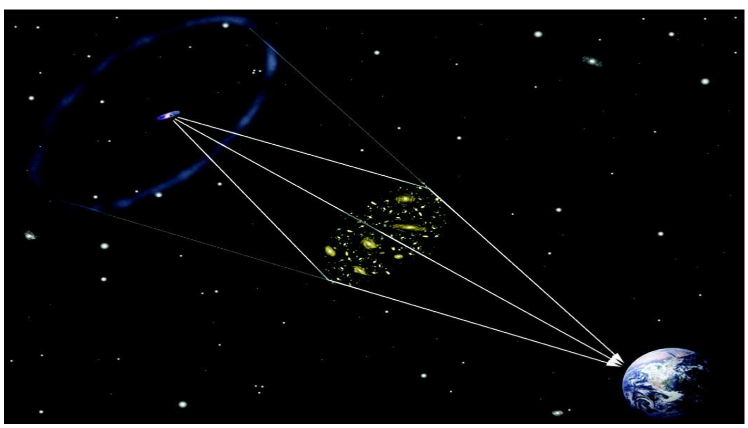

Figure 9: Gravitational lensing phenomenon.

Dark matter is theorized to be composed of subatomic particles yet to be discovered. There have been disputes of whether dark matter is composed of normal matter that we cannot see or exotic, unknown matter. The following ideas have been proposed:

- Some scientists thought that dark matter is formed by massive compact halo objects (MACHO's). MACHO's are massive objects located in the halo galaxies which evade being detected because they emit significantly very low luminosity. Those objects include white and brown dwarfs, neutron stars and black holes. However, experiments have shown that the total mass of the MACHO's is not enough to account for the estimated mass of dark matter.

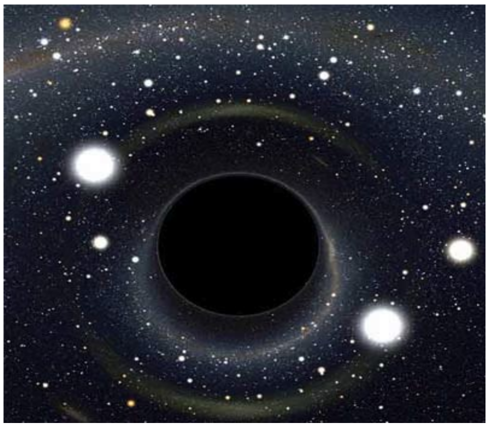

Figure 10: Black hole

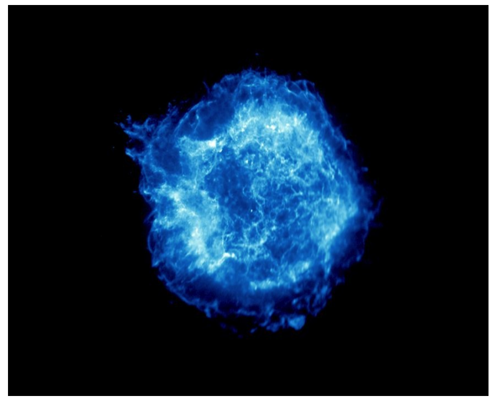

Figure11: Neutron star

- Another idea proposed to defy the existence of Dark matter was the modification of the newton's second law of motion. A physicist called Mordehai Milgron proposed a constant called MOND (modified newtonian dynamics) which he thought should be added to the famous newton's equation F= m*a when one is dealing with galactic motions. This constant was proposed to be used for motions with very low acceleration. This idea did not stand because dark matter existence could be proven using gravitational lensing phenomenon which does not involve newton's second law. Recently in 2004, there was a revision of MOND called TeVeS (Tensor _Vector _Scalar gravity) which included the gravitational lensing phenomenon. TeVeS called attention to experimentalists who showed that newton's second law still holds down to an acceleration of $5*10^{-14}$ m/s^2.
- Recently in 2011, a physicist at CERN Dragan Hajdukovic proposed a theory of the universe composed by matter and antimatter that are both electrically opposite and gravitationally opposite. He argued that the opposition in gravitational charges of matter and antimatter form

gravitation dipoles in space which are polarized by a gravitational field near a galaxy. this polarization strengthens the galaxy and keeps elements of the galaxy together.

- The most supported theory of the nature of dark matter is that dark matter is formed by particle which interact only by weak force and gravity. Those particles are usually referred to as weakly interacting massive particles (WIMPs). Particles scientists think that might be in dark matter are: axions which are small neutral particles much less massive than electrons believed to have existed after the big bang; neutralinos, particles similar to neutrinos but more massive and slower than neutrinos; and photinos which are similar to photons but 10 to 100 times more massive.

Up to day, the nature of dark matter is still an open question. No one knows what kind of particles are in the dark matter. Scientists all over the world are working hard to figure out the mysteries of dark matter. Different experiments are set up to test the proposed theories of dark matter and dark energy. One of the reasons that scientist are concerned with the nature of dark matter is that it can help determine the fate of universe. The universe was thought to be slowing down in its expansion until recent studies which surprised many scientists proving that the universe is instead expanding. This acceleration of the universe is caused by dark energy which is even more mysterious than dark matter.

3.7 Dark matter produced with boosted vector boson at LHC

After collision to two beams of protons, numerous particles are produced and they emerge in different directions in space. Unstable particles decay quickly into stable particles which are easy to detect. One of the theories about dark matter, suggests that particles that make up dark matter can be produced during quarks interaction in particle accelerators. One of the dark matter studies going on at the CMS is based on the following Feynman diagram

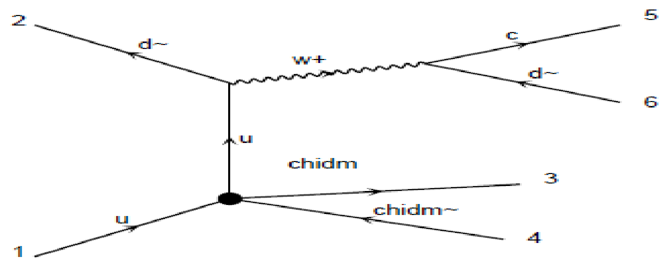

Figure 12: Feynman diagram showing dark matter production in the lab

In the figure above, an up quark from one proton beam interacts with the anti-down quark from another proton beam. In the process, a W+ boson is radiated and decays into a jet of quarks and a pair of dark matter and anti-dark matter is produced. Dark matter is hypothesized to have a mass ranging from 100 GeV/ c^2 to 1TeV/ c^2. This paper describes a part of study done for a dark matter mass of 100 GeV/ c^2.

3.8 The backgrounds Reduction using Monte Carlo Simulations

To analyze data taken by the CMS detector, we did a Monte Carlo simulation to produce events very similar to the events produced at the point of interaction inside the CMS detector. We produce events that might contain dark matter which are called signal and events that we are not interested in and we call them the backgrounds in the process of interest. The goal of the Monte Carlo analysis is to model the background and study how we can get rid of it or at least reduce it a lot while keeping as many signal events as possible.

3.8.1 Quantum Chromodynamics (QCD) background and Jets

In this section, I introduce quantum chromodynamics which is our main background source and I talk about jets because we dealt with them in this analysis. QCD, similar to quantum electrodynamics and quantum field theory, is a theory of fundamental building blocks of matter and the interaction force between those blocks called quarks. In QCD theory, quarks are bound together by a strong force mediated by the exchange of particles called gluons. Similar to charged particles in QED, quark have color charge, compared to electric charge. There exist three type of color charge which are blue, red, and green. Note that the color of quarks does not have anything to do with the familiar color of objects. The color charges of quarks create force fields comparable to the electric field in QED. There exist eight force fields which are so strong and holds quarks and gluons together. Therefore, quarks can be only found in a family of quarks. The first family is a combination of three quarks with different color to form a colorless baryon and the second family is the formation of a meson by a combination of a quark and an antiquark. The color of the quark and the color of the antiquark neutralize each other to form a colorless meson.

The interaction of gluons with each other affects the QCD coupling. Quarks and gluons become free when distances between them decreases. The strong force is directly proportional to the distance separating quarks. When the distance between quarks and gluons is so small, those particles are able to move freely as colored partons. In scattering process, accelerated partons form narrowly collimated hadrons with a color confinement. A freely moving quark form a gluonic flux tube, which starts breaking and creating quark and anti-quark pairs when its length is about 1 fm. This process, called quark fragmentation, generates jets that have energy and momentum of the parent particles which can be measured experimentally. The same process of fragmentation applies to gluons. An analysis of jets provides a detailed study of properties of quarks and gluons. For example, A jet analysis helps to determine the spin, flavor and color charge, and interactions of quarks and gluons.

The following schematic shows the formation of a jet after a collision of two beams of protons

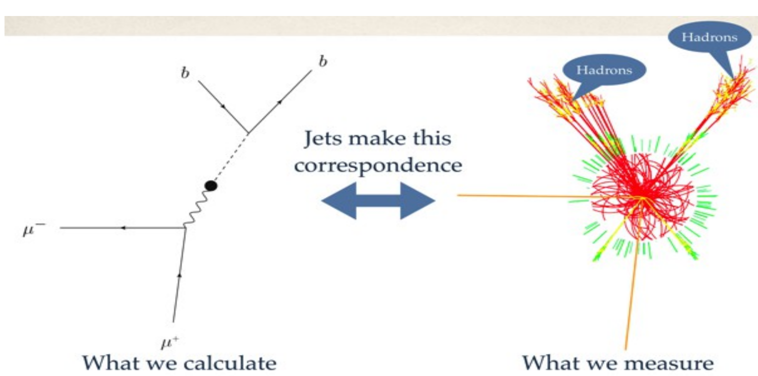

Figure 13: Jets formation

3.8.2 Backgrounds Reduction

After simulation is completed, our task is to reduce the backgrounds. This is done by applying two different types of cuts:

- Cuts based on kinematical variables of the jet and the Dark matter (MET)
- Cuts based on groomed jet substructure

There is a pre-selection that is done by keeping events that have at least one jet and a transverse momentum of ≥ 50 GeV/c. This pre-selection cut is made to get rid of the bulk of the background events.

A) The kinematical cuts follow the following variables:

- Leading Pt > 130 GeV/c: for this variable, we kept events for which the transverse momentum of the leading jet > 130 GeV/c, where the leading jet is the most energetic jet. This jet comes from the boosted W. his cut allows to take advantage of the jet sub-structure in further cuts.
- $|\eta| < 1.5$: as described before the variable eta represent a region covered by the outer calorimeter. Here we want to take advantage of the extension of HCAL by HO.

  The following figures shows eta in the CMS detector

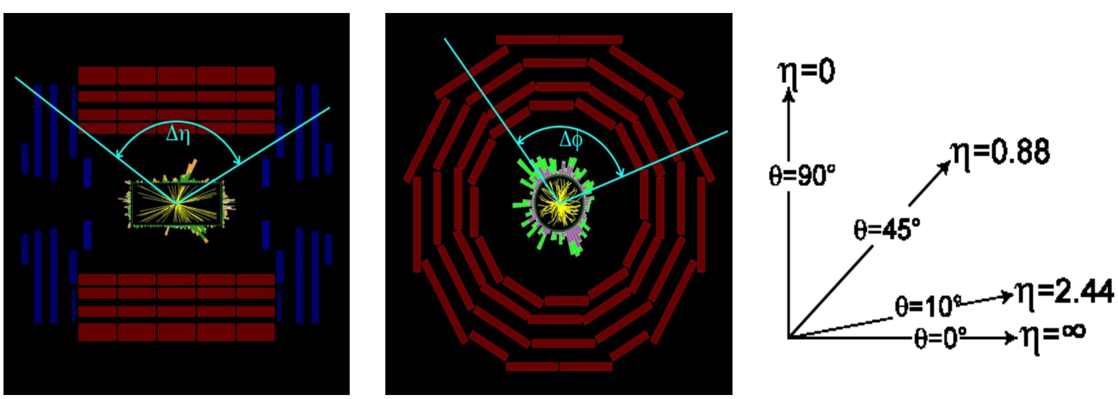

Figure 14: Representation of Eta

- Met-Pt > 150 GeV/c: The sum of momentum of particles produced after collision is smaller than the momentum of particles before collision. Since momentum is conserved after collision, there is a missing energy (Met). We assume the missing energy and momentum to be the energy and momentum of dark matter pair. Therefore, we assume the Met-pt to be of the same order magnitude to the W jet-pt. We chose a cut slightly higher in order to get rid of the QCD background.

B) They are also cuts made based on jet substructure information such as pruned jets (jets after discarding its soft parts):

- Pruned lead jet mass in the W/ Z range [65 – 105]: This cut is made to keep events that have W or Z bosons in the designated range of mass. The W and Z boson have masses about 80 GeV and 90 GeV respectively.
- Study of N-subjettiness: this cut is related to the multiplicity of the sub-jets. A jet can be formed by two, three, or more sub-jets. Since the W decays into 2 quarks we aim to have 2 sub-jets in the W.

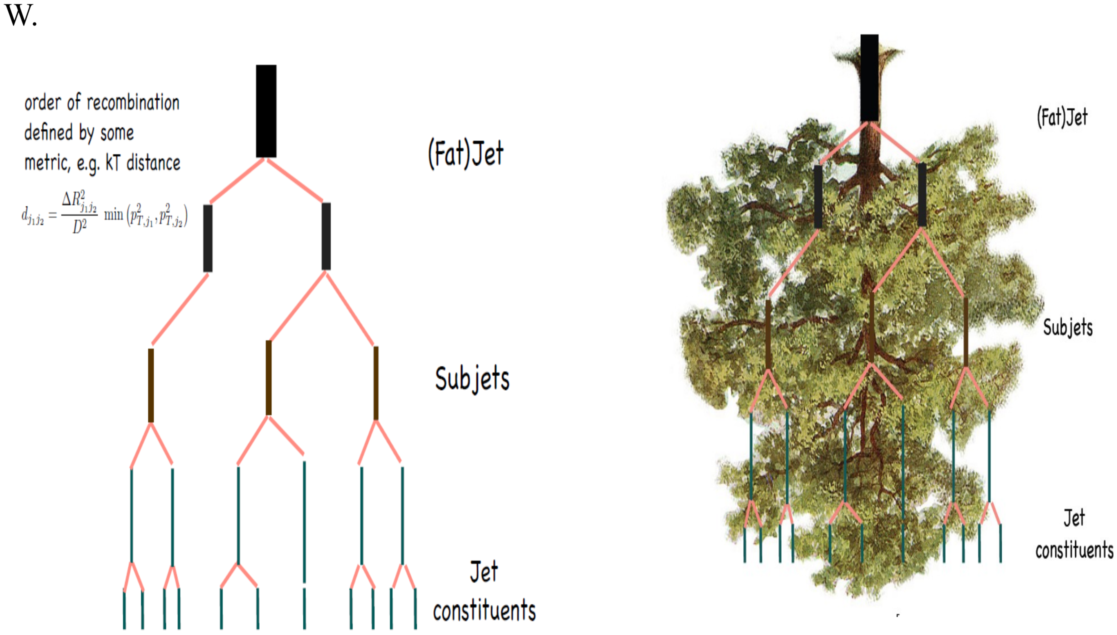

Figure 15: Comparison of a Jet and a Tree

The figure 16 shows steps followed to find sub-jets of a jet

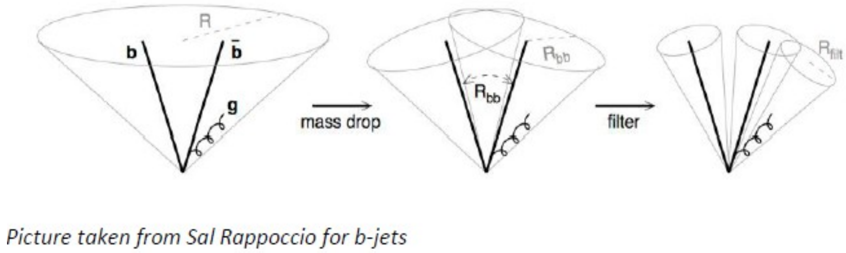

Figure 16: Jet cleaned to make sub-jets

Figure 15 shows the plots of Missing transverse energy (Met) and transverse momentum after cuts.

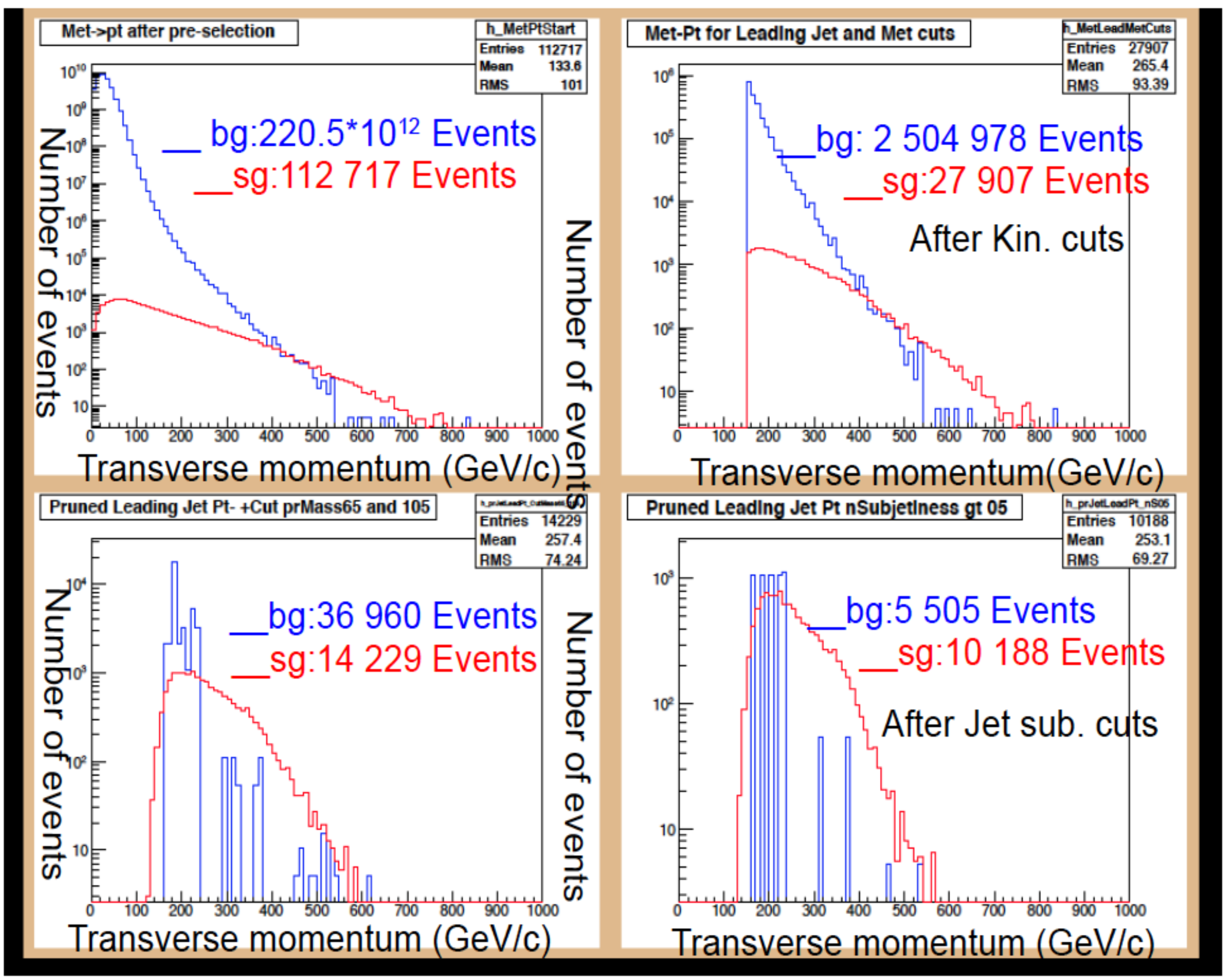

Figure 15: Plots of number of events of background and signal after kinematical cuts(top graphs) and after groomed jet substructure cuts(bottom graphs)

For the QCD background versus the signal histogram graphs shown above in figure 15:

Signal: 112 717 events at start → 27 907 events after kin. Cuts → 114 229 events after mass cut → 10 118 events after jet sub. Cut.

Background: $220.5*10^{12}$ events at start →2 504 978 events after kin. Cuts → 36 960events after mass cut → 5 505 events after jet sub. Cut.

Those histograms represent the QCD background (in blue) superposed with the signal(in red). At the top left we have Met before cuts and top right we have a graph of Met after kinematical cuts. At the bottom, we have Jet-pt with the mass-cut in the range of W/ Z on the groomed data and with the N-subjettiness added to all cuts.

4. Results

Table 1 above represents the signal and all the backgrounds before and after all cuts.

Sample Name	σ(pb)	# Events Before Cuts	# Events After Cuts	# For 20 fb^{-1}
$W^{+/-}$(J J) DM DM~	0.62	112740	10188	
Bg:$W^{+/-}$(J J)$\mathcal{V}\mathcal{V}\sim$	1.22	219202	1665	
Bg:QCD	192332	34.9×10^{9}	5499	
Bg:W+Jet	7669	1.4×10^{9}	82338	
Bg: ZJ$\mathcal{V}\mathcal{V}$	588	0.11×10^{9}	69153	
Sum_ Bg			158655	
Sqrt(Sum_Bg)			398.32	
Significance: Signal/sqrt(Sum_Bg)			25.58	8.5

Table 1: Summary of events produced and events left after reductions.

From the table above, the total number of background events left after cuts is 158655 while the number of signal events left is 10188. Since we are not interested in background events, we consider the total number of background events as error. We need to know the significance of our signal. To do that, we calculated the ratio between the total number of signal events left to the square root of total number of background events left. The calculated ratio is 25.58 σ. However, when doing Monte Carlo simulation, we produce more data than the actual data collected by the CMS detector during the whole run at 8TeV. Therefore, we have to calculate the significance for a sample of the size of our data which is a factor of 9 smaller. That brings our significance value to 8.5σ. In this case, a significance of 8.5 σ means that if we do see the signal the probability to happen by chance is very small. In other words, we can decide whether we have dark matter or not by comparing the data collected to the Monte Carlo simulations of the stacked background.

5. Future Work

This analysis will continue by plotting the real data from CMS detector on the top of the stacked histogram of backgrounds mentioned in the figure 16 below. One of the following outcome is expected:

- If there is a discrepancy between data and stacked backgrounds, it means that one might have a candidate for dark matter with mass of 100 GeV/c^2. A detailed study will begin in order to confirm the results.
- Otherwise, in the framework of weakly interacting massive particles (WIMPs), a new study will begin on dark matter with a mass of 200 GeV/$c^{2.}$

The following figure 16 is the stacked histogram of all backgrounds after all cuts were applied.

1. The background W1Jet, W2Jet and W3Jet in the figure are combined as W+Jet in the table
2. The Background ZJNUNU200to400 and ZJNUNU400toInf in the figure are combined under ZJNuNu in the table.
3. ZJNUNU200to400 meaning with a Met_pt in that range. The other Met_pt ranges have been

cancelled by the cuts

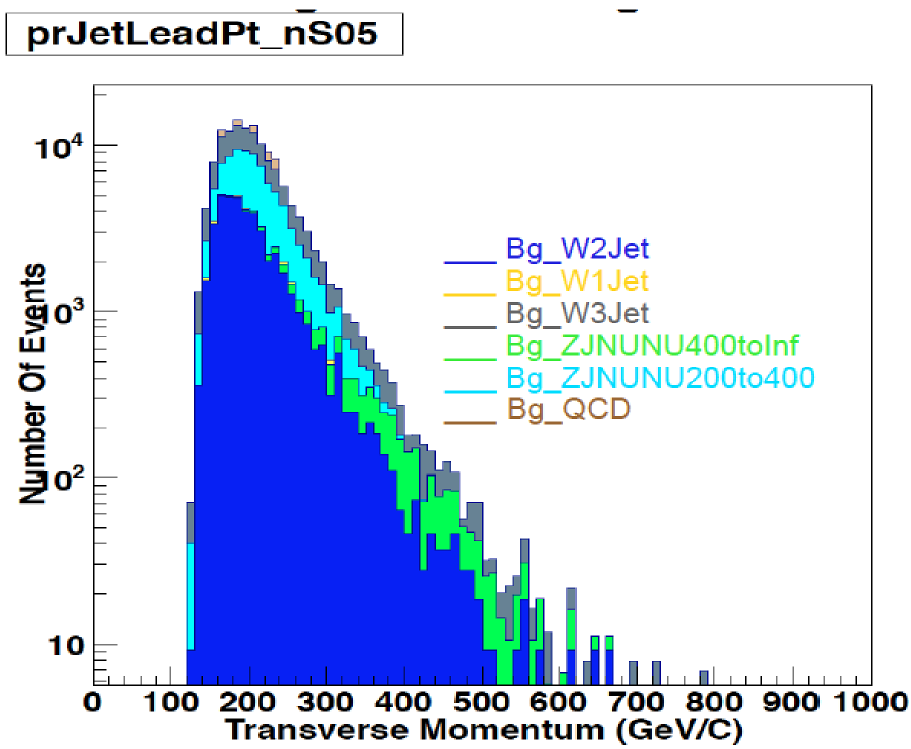

Figure 16: Stacked histogram of backgrounds events left after cuts

6. Conclusion

In this summer, a considerable amount of work was done regarding the analysis of Monte Carlo simulation. We were able to reduce backgrounds events from the range of billions to the range of thousands. The most significant reduction is the QCD background that went from 34.9 billion events to 5.5 thousands events. We have also been successful in keeping many signal events by starting with 112 thousands events and finish the cuts with 10 thousands events. The significance of 8.5δ shows that we are ready to use data from CMS and test dark matter on the proposed range.

7. Acknowledgement

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9.Appendix

9.1 Macro 1

The following code is for plotting graphs in figure 16.

```
{
// Nsanzineza Rene
//Tuesday July 30, 2013

TFile f1("HISTO_bgQCDLEFTSUM120to600_noQJETVOL_noQCD2CUT_MetPt150.root");
f1.cd();
f1.cd("demo");
TCanvas *c1 = new TCanvas("c1","PlotsofMet",900,700);
c1->Divide(2,2);
c1->cd(1);
h_MetPtStart->Draw();
c1->SetFillColor(42);
h_MetPtStart->SetLineColor(kBlue);

c1->cd(2);
h_MetLeadMetCuts->Draw();
h_MetLeadMetCuts->SetLineColor(kBlue);

c1->cd(3);
h_prJetLeadPt_CutMass65_105->Draw();
h_prJetLeadPt_CutMass65_105->SetLineColor(kBlue);

c1->cd(4);
h_prJetLeadPt_nS05->Draw();
h_prJetLeadPt_nS05->SetLineColor(kBlue);
//Open the second file

TFile f2("HISTO_wSUMDM_CutMass65_105_noQjetVol_noQCD2CUT_MetPt150.root");
f2.cd();
f2.cd("demo");
c1->cd();
c1->cd(1);
h_MetPtStart->Draw("Sames");
h_MetPtStart->SetLineColor(kRed);
gPad->SetLogy(1);
c1->Update();

c1->cd();
c1->cd(2);
h_MetLeadMetCuts->Draw("Sames");
h_MetLeadMetCuts->SetLineColor(kRed);
gPad->SetLogy(1);
c1->Update();

c1->cd();
c1->cd(3);
h_prJetLeadPt_CutMass65_105->Draw("Sames");
```

```
h_prJetLeadPt_CutMass65_105->SetLineColor(kRed);
gPad->SetLogy(1);
c1->Update();

c1->cd();
c1->cd(4);
h_prJetLeadPt_nS05->Draw("Sames");
h_prJetLeadPt_nS05->SetLineColor(kRed);
gPad->SetLogy(1);
c1->Update();
c1->Print("PlotsofMet.eps");
}
```

9.2 Macro 2

This macro plots the stacked histograms of the backgrounds in figure 15.

```
{
//Nsanzineza Rene
// Thursday July 25, 2013
// This macro produce a sctacked histogram  of six
//backgrounds for prJetLeadPt. It also plots all histograms non-stacked just for comparison


TFile f1("HISTO_bgW2JET_CUTMASS65_105_noQCD2CUT_noQjetVolCut_metPt150.root");
f1.cd();
f1.cd("demo");
THStack *hs = new THStack("hs"," stacked histograms prJetLeadPt_nS05");
TCanvas *c0 = new TCanvas("c0","prJetLeadPt_nS05",700,700);
h_prJetLeadPt_nS05-> SetFillColor(kBlue);
hs.Add(h_prJetLeadPt_nS05);


TFile f2("HISTO_bgZJNU_400toInf_CutMass65_105_noQCD2CUT_noQjetVolCut_MetPt150.root");
f2.cd();
f2.cd("demo");
h_prJetLeadPt_nS05-> SetFillColor(kGreen);
hs.Add(h_prJetLeadPt_nS05);


TFile f3("HISTO_bgW1JET_CUTMASS65_105_noQCD2CUT_noQjetVolCut_metPt150.root");
f3.cd();
f3.cd("demo");
h_prJetLeadPt_nS05-> SetFillColor(kYellow);
hs.Add(h_prJetLeadPt_nS05);


TFile
f4("HISTO_bgZJNUNU_200to400_CutMass65_105_noQjetVolCut_noQ2QCDCut_MetPt50.root");
f4.cd();
```

```
f4.cd("demo");
h_prJetLeadPt_nS05-> SetFillColor(7);
hs.Add(h_prJetLeadPt_nS05);

TFile f5(" HISTO_bgW3JET_CUTMASS65_105_noQCD2CUT_noQjetVOlCut_MetPt150.root");
f5.cd();
f5.cd("demo");
h_prJetLeadPt_nS05-> SetFillColor(36);
hs.Add(h_prJetLeadPt_nS05);

TFile f6("HISTO_bgQCD_170to300_MassCut65_105_noQJETVOL_noQCD2CUT_MetPt150.root");
f6.cd();
f6.cd("demo");
h_prJetLeadPt_nS05-> SetFillColor(42);
hs.Add(h_prJetLeadPt_nS05);
hs.Draw();
gPad->SetLogy(1);
hs->GetXaxis()->SetTitle("Transverse Momentum (GeV/C)");
 hs->GetYaxis()->SetTitle("Number Of Events");
 hs->GetXaxis()->CenterTitle();
 hs->GetYaxis()->CenterTitle();
TCanvas *c1 = new TCanvas("c1","NostackprJetLeadPt_nS05",700,700);
// post the stat box on the canvas
hs->SetTitle("prJetLeadPt_nS05");
hs->Draw("nostack");
c1->Print("bgNonstackedprJetLeadPt_nS05.eps");
c0->Print("bgEightprJetLeadPt_nS05.eps");
}
```