



St. Joseph's College (autonomous)

FINAL YEAR PROJECT

**“Study of jet clustering  
algorithms using simulated  
events of the top pair  
production at the Large  
Hadron Collider”**

*- Priyanka SN*

Supervised by  
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Indian Institute of Science



# Department of Physics

ST. JOSEPH'S COLLEGE (AUTONOMOUS)

## *Certificate*

This is to certify that the project entitled, “**Study of jet clustering algorithms using simulated events of top pair production at the Large Hadron Collider**” is a bonafide work carried out by **Miss. PRIYANKA SN**, student of **St. Joseph's College (autonomous)**, at **Indian Institute of Science** in partial fulfillment of the requirements for the degree of Masters in Physics in the year 2017-2018. This project report has been approved by as it satisfies the academic requirement of the project work prescribed for **MSc. in Physics**.

Dr.Sandiago  
Head of the Department  
Department of Physics

Place:

Date:



# Centre for High Energy Physics

INDIAN INSTITUTE OF SCIENCE

## *Certificate*

This is to certify that the project entitled, “**Study of jet clustering algorithms using simulated events of top pair production at the Large Hadron Collider**” is a bonafide work carried out by **Miss. PRIYANKA SN** , in partial fulfillment of the requirements for the degree of Masters in Physics in the year 2017-2018 at **St. Joseph’s College (autonomous)** is an authentic work carried out by her under my supervision and guidance.

To the best of my knowlwdge , the matter embodied in the project has not been submitted to any university/Institute for the award of any Degree.

Dr. Jyothsna Rani Komaragiri  
Centre for High Energy Physics  
Indian Institute of Science

Place:

Date:

## ACKNOWLEDGEMENT

The success and final outcome of this project required a lot of guidance and assistance from many people and I am extremely privileged to have got this all along the completion of my project. Dr. Jyothsna Rani Komaragiri took keen interest in guiding me by providing necessary information and her invaluable time. I respect and thank Dr. Jyothsna for providing me an opportunity and giving the support and guidance. My special thanks to Mr. Praveen Chandra Tiwari, 4th year Integrated Ph.D student at IISc for helping me implement all the executions through out the project. I am thankful to and fortunate enough to get constant encouragement, support and guidance from Dr. Arun Varma Thampan and Dr. Veena S Parvathy, teaching staff of St. Joseph's College (autonomous) who helped me in successfully completing the project work. Finally, I wish to thank my family and friends for their support and encouragement.

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# Declaration

I do hereby declare that review report of the proposed project entitled “Study of jet clustering algorithms using simulated events of top pair production at the Large hadron Collider” carried out in the final semester for the partial fulfillment of the requirements of the award of degree of Master of Science (M.Sc.) in Physics is prepared by me. To the best of my knowledge I didn’t breach any copyright act intentionally.

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Priyanka SN  
March 6th 2018

## **Abstract**

The top quark being the most massive amongst the quarks is an interesting subject to study. Also the recent discovery at LHC (2012) stating that the mass of Higgs-boson is of the same order as that of the top quark opens up the new realm of study. Jets are the way to study the top quarks. A simulation of 10000 events of proton-proton collision was generated using PYTHIA8 and jets were reconstructed by FASTJET3. This project aims to study the effect of various parameters which affect the jet multiplicity.

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# Chapter 1

## Introduction

### 1.1 Background & Motivation

Discovery of radioactivity was the stepping stone to the discovery of electrons, protons and later neutrons. Studies showed that electrostatic force could not be the reason for holding the nucleons together; therefore there had to be a different kind of force that held the nucleus - the Strong force and a different force that led to beta decay - the Weak force. The picture of indivisible atom was relevently replaced by the smaller entities : electrons, protons and neutrons. Added to this were the photons and neutrinos. Technological developments in 1960s enabled that high energy beams of particles could be produced in the laboratories. As a consequence, a wide range of controlled scattering experiments could be performed and the greater use of computers meant that sophisticated analysis techniques could be developed to handle the huge data that were being produced. This led to the detection of large number of unstable particles with shorter lifetimes.

The best theory of elementary particles we have at present is the standard model[1]. This aims to explain all the phenomena of particle physics, except those due to gravity, in terms of the properties and interactions of a small number of elementary (or fundamental) particles, which are now defined as being point-like, without internal structure.

**Fundamental particles** (also known as elementary particles) are the smallest building blocks of our universe. There are two types of fundamental particles:

1. Partilces that make up all matter, called **fermions**
2. Particles that carry force, called **bosons**

#### **Fermions**

All matter is made up of fermions, and these fermions come in two types: leptons and quarks.

#### **Leptons**

Leptons are fermions and are considered **solitary particles**. They don't form groups. Leptons come in 6 different varieties called **flavors**. The 6 flavors of leptons are :

1. Electron
2. Electron neutrino
3. Muon

4. Muon neutrino
5. Tau
6. Tau neutrino

Leptons carry a negative or neutral charge known as an **integer charge**. The electron, muon and the tau carry a negative (-1) charge and all the neutrinos carry a neutral (0) charge.

| Lepton               | Symbol     | Charge | Mass<br>[GeV/c <sup>2</sup> ] | Antiparticle     |
|----------------------|------------|--------|-------------------------------|------------------|
| Electron             | $e^-$      | -1     | 0.0005                        | $e^+$            |
| Electron<br>neutrino | $\nu_e$    | 0      | $< 10^{-9}$                   | $\bar{\nu}_e$    |
| Muon                 | $\mu^-$    | -1     | 0.106                         | $\mu^+$          |
| Muon<br>neutrino     | $\nu_\mu$  | 0      | $< 10^{-9}$                   | $\bar{\nu}_\mu$  |
| Tau                  | $\tau^-$   | -1     | 1.78                          | $\tau^+$         |
| Tau<br>neutrino      | $\nu_\tau$ | 0      | $< 10^{-9}$                   | $\bar{\nu}_\tau$ |

Figure 1.1: Lepton flavors

## Quarks

Quarks also come in 6 different flavors. The 6 flavors of quarks are:

1. Up
2. Down
3. Charm
4. Strange
5. Top
6. Bottom

The Up quark is the lightest of all and top quark is the massive one.

To further distinguish from leptons, quarks don't carry the same full charge that leptons do. They carry a positive or negative **fractional charge**. Up, Charm and the Top carry a  $\frac{2}{3}$  charge. Down, Strange and the Bottom carry  $\frac{-1}{3}$  charge. Quarks are never observed as single entities; they combine to form composite particles. Figure 1.2 summarizes the quarks, their charges and masses.

|          |                        |                         |                          |
|----------|------------------------|-------------------------|--------------------------|
| Mass →   | 2.4 MeV/c <sup>2</sup> | 1.27 GeV/c <sup>2</sup> | 173.1 GeV/c <sup>2</sup> |
| Charge → | 2/3                    | 2/3                     | 2/3                      |
|          | <b>u</b><br>up         | <b>c</b><br>charm       | <b>t</b><br>top          |
|          | 4.8 MeV/c <sup>2</sup> | 104 MeV/c <sup>2</sup>  | 4.2 GeV/c <sup>2</sup>   |
|          | -1/3                   | -1/3                    | -1/3                     |
|          | <b>d</b><br>down       | <b>s</b><br>strange     | <b>b</b><br>bottom       |

Figure 1.2: Quarks

### Matter and antimatter

For every type of matter particle, there also exists a corresponding **antimatter** particle, or **antiparticle**.

Antiparticles look and behave just like their corresponding matter particles, except for the charges. They have opposite charges. For instance an electron is electrically negative, but its antiparticle - positron is electrically positive. Gravity affects both of them similarly, because both the particle and antiparticle have same mass.

### Hadrons

Individual quarks combine to form composite particles called hadrons such that the hadrons have a net integer electric charge. Another property of hadrons is that they have no net color charge even though quarks themselves carry color charge.

There are two classes of hadrons:

1. Baryons : Any hadron which is made up of three quarks (qqq) is a baryon. Protons and neutrons are baryons. Protons contain 2 up quarks and a down quark, whereas neutrons contain two down quarks and an up quark.
2. Mesons : Mesons contain a quark and an antiquark (qqbar). One example of a meson is a pion, which is made up of an up quark and a down antiquark.

### Bosons

All interactions which affect the matter particles are due to an exchange of **force carrier particles**. What we normally think of as "forces" are actually the effects of force carrier particles on matter particles.

One important thing to know about force carriers is that a particular force carrier particle can only be absorbed or produced by a matter particle which is affected by

| Force           | Particles Affected | Strength   | Force carrier (Boson)              |
|-----------------|--------------------|------------|------------------------------------|
| Strong          | Quarks             | 1          | Gluon $g$                          |
| Electromagnetic | Charged particles  | $10^{-3}$  | Photon $\gamma$                    |
| Weak            | Quarks & leptons   | $10^{-8}$  | W boson $W^{\pm}$<br>Z boson $Z$   |
| Gravitational   | All masses         | $10^{-37}$ | Graviton<br>(yet to be discovered) |

Figure 1.3: The four known forces of nature. The relative strengths are approximate indicative values for two fundamental particles at a distance of 1fm (roughly the radius of a proton)

that particular force. For instance, electrons and protons have electric charge, so they can produce and absorb the electromagnetic force carrier, the photon. Neutrinos, on the other hand, have no electric charge, so they cannot absorb or produce photons.

Since we have 4 types of interactions namely strong, weak, electromagnetic and gravitational; we have a force carrier particle corresponding to each interaction.

1. **Gluons** - strong force carrier
2. **W and Z bosons** - weak force carrier
3. **Photons** - electromagnetic force carrier
4. **Graviton (predicted)** - gravity force carrier

## 1.2 Objective

Since it is possible to conduct a proton-proton collision, it is ideal to study the end products of such a collision. But it is not favourable to conduct an experiment at very high energies always. Therefore simulating the events is the solution. One such event generator is PYTHIA8 [3]. The main objective of this project is to generate the events using PYTHIA8 and cluster the product particles into jets using FASTJET3.

## 1.3 Benefits of Research

Formation of jets is one of the evidences for the existence of quarks. This project will help us understand the formation of jets and also verify the quark confinement theory. The top quark is highly unstable and hence decays. The number of jets obtained is the signature of decay mode through which the top quark decayed. Centre of Mass energy dependence will give the energy range at which the proton beams should be accelerated to get the better estimate of number of jets.



# Chapter 2

## Literature Survey

### 2.1 Literature Review and background work

To begin with, a study was made on elementary particles and their classification. Their representation, lifetimes and decay modes were understood. It was important to understand how the particle collisions take place. A small task was carried out to visualise the working regime, timescales and energies of the particles. The results are mentioned in next sections.

#### 2.1.1 Stability of particles

For a selected list of particles[5] with known mass and lifetimes, its momentum was varied as  $p = 1\text{GeV}/c$ ,  $p = 10\text{GeV}/c$  and  $p = 100\text{GeV}/c$ . The distance travelled by those particles before they decayed was calculated using the relativistic equation [4].

$$d = \gamma\beta c\tau \quad (2.1)$$

where  $\gamma = \frac{1}{\sqrt{1-\beta^2}}$  and  $\beta = \frac{v}{c}$ . So based on these calculations, with the detector kept fixed at a particular distance, it is possible to predict whether a particle would be stable enough to reach the detector.

Figure 2.1 shows the list of particles that were studied. It was also color coded according to the type of interactions the particles undergo.

**Conclusion:** As expected only the protons, neutrons and electrons were stable.

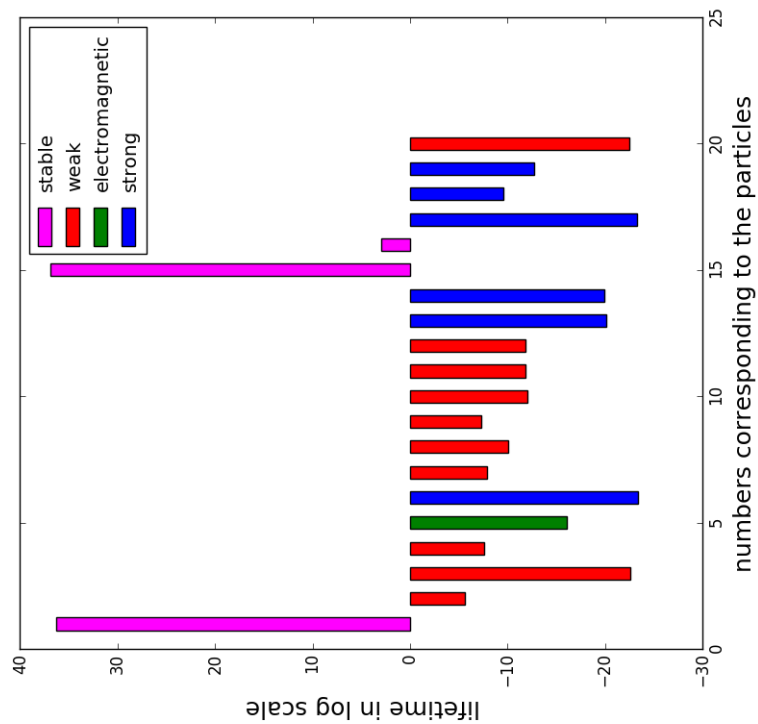


Figure 2.1: A plot depicting stability of particles, where the particles are numbered on the x-axis. The particle corresponding to each number is mentioned on to the right

### 2.1.2 Mass of the parent particle

Each pp collision produces a certain number of following particles:

1. Jets
2. Muons
3. Electrons
4. Photons
5. MET- the missing transverse energy

These particles further decay. A data set detected by the CMS detector, LHC was analysed. The data consisted of energy  $E$ ,  $p_x$ ,  $p_y$  and  $p_z$  - momentum in  $x$ ,  $y$  and  $z$  directions respectively for each particle in every collision event. Let us say, a certain collision produced 5 jets, 2 muons, 0 electrons and 1 photon. Then to know the mass of the particle that decayed to 2 muons, one should add the  $p_x$  for muon1 and muon2 to get total  $p_x$ . Similarly calculate  $p_y$ ,  $p_z$  and  $E$ . Using the relativistic equation calculate the mass. The value obtained is the invariant mass of the particle that decayed to give 2 muons.

$$m = \sqrt{E^2 - (p_x^2 + p_y^2 + p_z^2)} \quad (2.2)$$

So to calculate the mass of the particle that decayed to give the data under study, similar set of calculations was done and the peak in the plot below shows the invariant mass of the parent particle.

**Conclusion:** The mass obtained matched the theoretical value predicted for the muon mass and this confirms the formation of muons during proton-proton collision.

## 2.2 Inferences Drawn From Literature Review

The collider physics experiments are very useful in recreating the environment which will in turn create the particles that were produced moments after the Big Bang. The decay products obtained can be reconstructed back to know the parent particles.

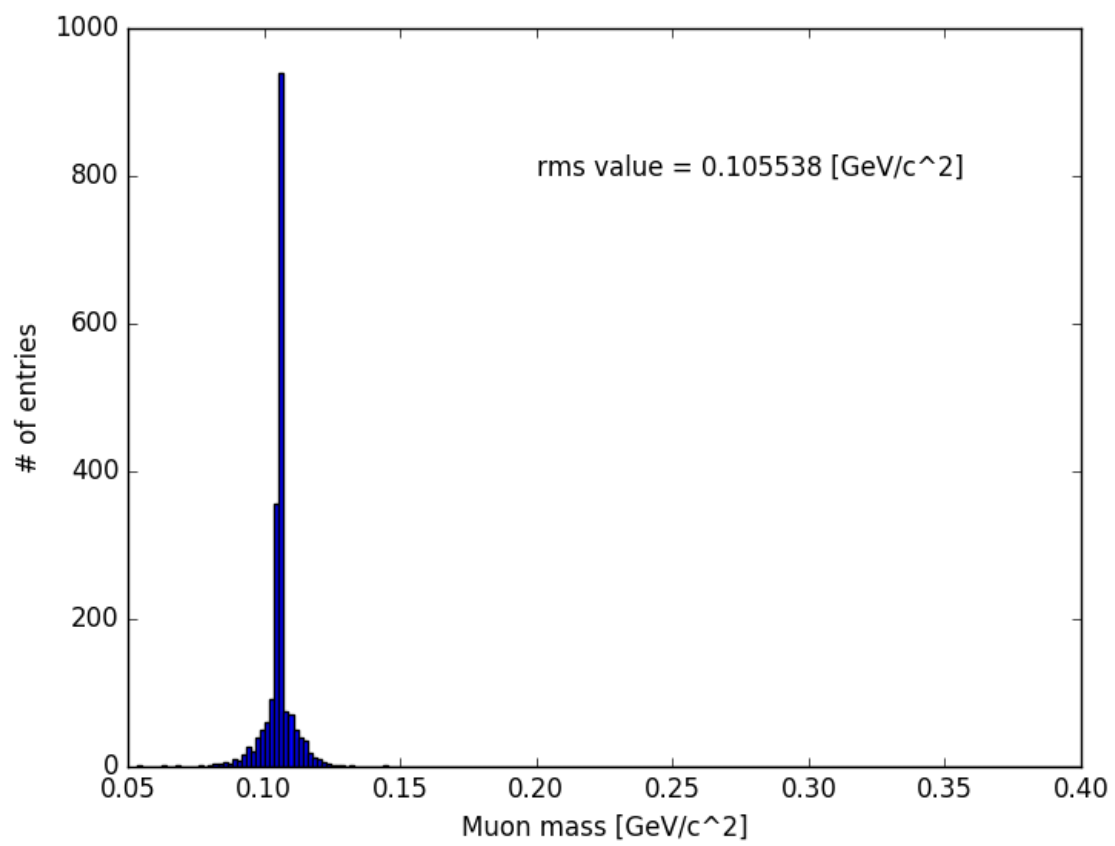


Figure 2.2: Invariant mass

# Chapter 3

## Problem Formulation and Proposed Work

### 3.1 Introduction

Experimental setups for carrying out scattering experiments are of two types :

1. Fixed target - A beam of particles strike the particles at rest.
2. Colliding beams - Two counter rotating beam particles strike each other head on.

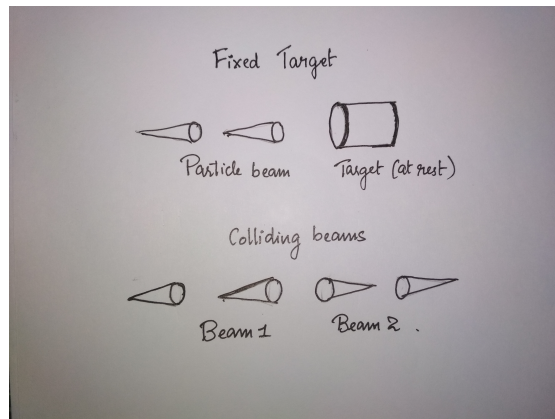


Figure 3.1: fixed target vs colliding beams

Two standard reference frames, corresponding to each of these setups are:

1. Lab frame - The coordinate system in which the beam particles are moving and the target is at rest.
2. Centre of Mass (CoM) frame - The coordinate system in which the net momentum is zero; the beam and the target particle move with equal and opposite momenta.

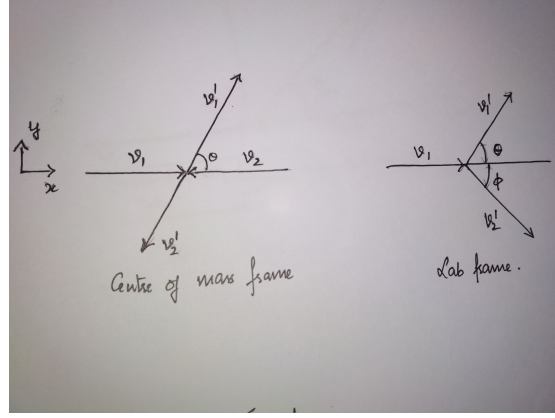


Figure 3.2: Schematic representation of Centre of Mass frame and lab frame

#### Variables Used :

1. Transverse Momentum  $p_T$  - It is the momentum along the transverse plane.

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (3.1)$$

2. Rapidity  $y$  - It is the measure of velocity.

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \quad (3.2)$$

3. Pseudorapidity  $\eta$  - We define the pseudorapidity as

$$\eta = -\ln \tan \frac{\theta}{2} \quad (3.3)$$

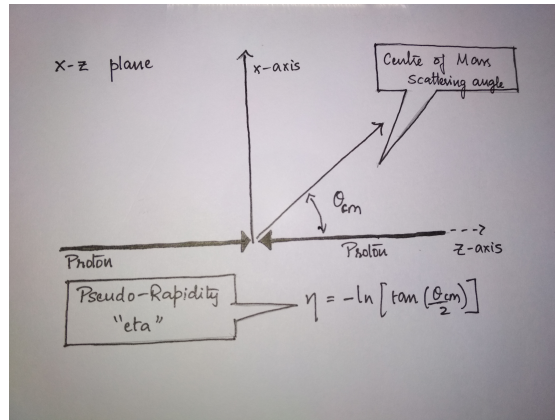


Figure 3.3: Pseudorapidity

4. Phi  $\phi$  - We take positive z-axis along the incident beam of proton direction.  $\phi$  is the azimuthal angle with respect to this direction.

## 3.2 Top quark pair production

As mentioned earlier, the **protons** fall under the class of particles called baryons. Baryons are the composite particles made up of 3 quarks. Proton consists of 2 up(u) quarks and 1 down(d) quark giving it the net electric charge of +e. Similarly antiproton consists of 2 up antiquarks and 1 down antiquark.

**Partons:** Quarks and gluons together are called as partons. A parton-parton interaction implies either of the quark, antiquark and the gluon interaction.

**Top quark:** Top quark or the t-quark is the most massive of all elementary particles with mass of  $173.1 \pm 0.6$  GeV. It has a spin  $\frac{1}{2}$  and experiences all 4 fundamental interactions: gravitation, electromagnetism, weak and strong interactions. Proton-proton collision and proton-antiproton collision are the major contributors to the top quark pair(ttbar)[6] production.

**Proton-proton collision:** When protons collide the gluons from each proton interact to form the top quarks. This is the dominant production mode at LHC, CERN. Figure 3.4 is a Feynman diagram representing the production

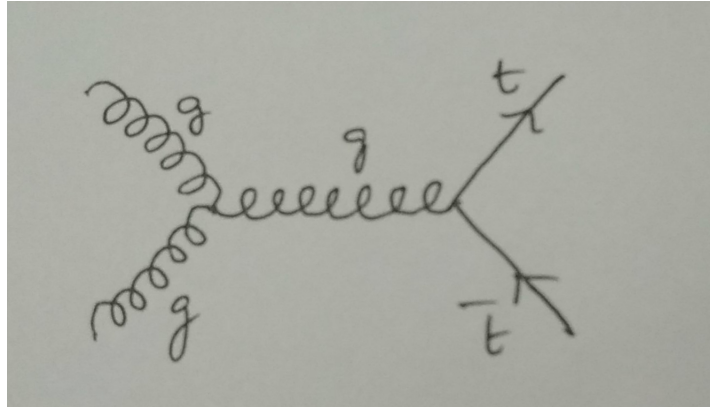


Figure 3.4: gluon-gluon to ttbar

**Proton-antiproton collision:** When proton and an antiproton collide, a quark from a proton and an antiquark from an antiproton annihilate to produce the ttbar pair. This is seen largely at Tevatron, FNAL. Refer to figure 3.5

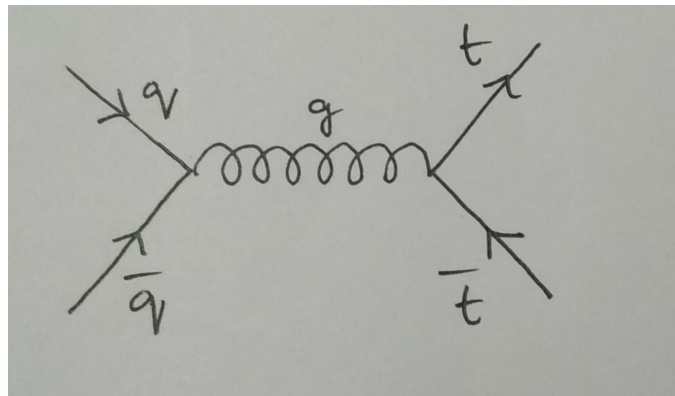


Figure 3.5: qqbar annihilate to form ttbar

The  $t\bar{t}$  being relatively massive, have a very short lifetime and hence they decay. The decay modes are :

1. Hadronic
2. Semileptonic
3. Dileptonic

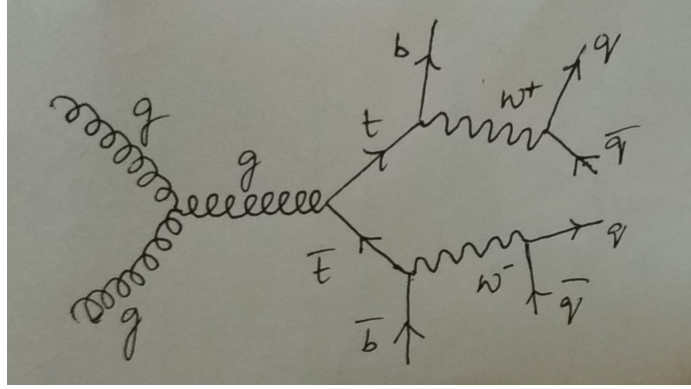


Figure 3.6:  $t\bar{t}$  decay

The figure 3.6 shows how the top quark pair decays. The top decays to b-quark and a  $W^+$  boson and the antitop decays to anti-b and  $W^-$  boson. Now it depends on how  $W^+$  and  $W^-$  further decay. If both the  $W^-$  bosons decay to quarks then the overall process is hadronic. If both the bosons decay to leptons, then it is termed as dileptonic. One of the lepton will be charged and the other will be its corresponding antineutrino. However, if only one of the bosons decay to leptons then it is a semileptonic process. Figure 3.7 summarizes the decay modes.

$$\begin{aligned}
 t\bar{t} &\rightarrow (bW^+)(\bar{b}W^-) \rightarrow (bq_1\bar{q}_2)(\bar{b}q_3\bar{q}_4) \quad [\text{Hadronic}] \\
 t\bar{t} &\rightarrow (bW^+)(\bar{b}W^-) \rightarrow (bq_1\bar{q}_2)(\bar{b}l^-\bar{\nu}_l) \quad [\text{Semileptonic}] \\
 t\bar{t} &\rightarrow (bW^+)(\bar{b}W^-) \rightarrow (bl^+\nu_l)(\bar{b}l^-\bar{\nu}_{l'}) \quad [\text{Dileptonic}]
 \end{aligned}$$

Figure 3.7:  $t\bar{t}$  decay modes

After the  $t\bar{t}$  decay, what we detect is the jets.

### What are jets?

It is the collimated spray of hadrons formed due to hadronization.

High energy collisions can cause the quarks within protons or newly creates  $q\bar{q}$  pairs to fly apart from each other with very high energies. Before they can be observed these quarks are converted into jets.

Based on the number of jets detected, one can say through which mode did the  $t\bar{t}$  decay. A schematic representation of jet formation is shown in figure 3.8.



### why do we observe jets?

Due to quark confinement quarks can't exist as free particles. So they hadronize to form jets.

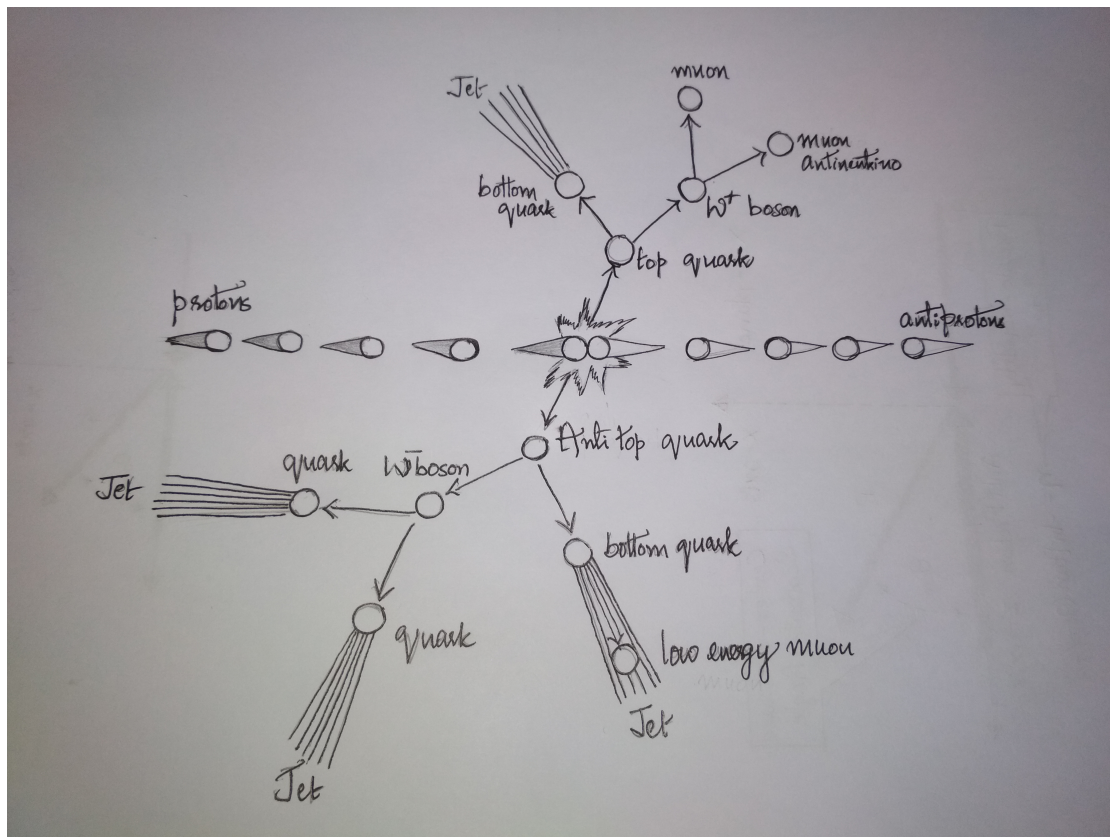


Figure 3.8: jet formation

# Chapter 4

## Methodology

### 4.1 Introduction

**Jet algorithm** - A jet algorithm maps the momenta of the final state particles into the momenta of a certain number of jets. There are two kinds namely Sequential clustering algorithm and Cone algorithm.

**Sequential Clustering algorithm** : Identifies the pair of particles that are closest in some distance measure, recombine them, until some stopping criterion is applied.

**Cone algorithm** : It clusters together the particles within specific conical angular regions, such that the momentum sum of the particles contained in a given cone coincides with the cone axis. The strategy used to search for a stable cone and the procedure used to deal with cases where the same particle is found in multiple stable cone can be many.

The particles fed into to the fastjet algorithm are all treated as pseudojets. These pseudojets are then clustered based on the algorithm and the recombination selected.

The **Recombination Scheme** is the scheme through which the particle's 4-momenta are added. There are many ways. Simplest of them is the E-scheme which just adds the 4-vectors. Some other schemes are Et, Et2, pt and pt2.

#### 4.1.1 Sequential Recombination Algorithms:

There are two distance measures namely  $d_{ij}$  and  $d_{iB}$  where  $d_{ij}$  is the distance between two final state particles  $i$  and  $j$ .  $d_{iB}$  is the distance between the beam axis and the particle  $i$ . Based on how  $d_{ij}$  and  $d_{iB}$  are calculated, the sequential algorithms are divided into 3 types.

1. **kT jet algorithm** : For every particle pair  $i, j$  the  $d_{ij}$  and  $d_{iB}$  are calculated as given below.

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2) \frac{\Delta R_{ij}^2}{R^2} \quad (4.1)$$

with  $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ , where  $k_{ti}$ ,  $y_i$  and  $\phi_i$  are the transverse momentum, rapidity and azimuth of the particle  $i$  and  $R$  is the jet-radius parameter usually taken of order 1.

$$d_{iB} = k_{ti}^2 \quad (4.2)$$

Steps followed for clustering:

- (a) First find  $d_{ij}$  and  $d_{iB}$
  - (b) Find the minimum  $d_{min}$  of all the  $d_{ij}$ ,  $d_{iB}$ . If  $d_{ij}$  is minimum then merge the particles  $i$  and  $j$  into a single particle, summing their four-momenta (if the recombination scheme chosen is E-scheme); if  $d_{iB}$  is minimum then declare the particle  $i$  to be final jet and remove it from the list.
  - (c) Repeat from step 1 until no particles are left.
2. **Anti-kT jet algorithm** : In this algorithm  $d_{ij}$  and  $d_{iB}$  are given by

$$d_{ij} = \min(1/k_{ti}^2, 1/k_{tj}^2) \frac{\Delta R_{ij}^2}{R^2}, d_{iB} = 1/k_{ti}^2 \quad (4.3)$$

3. **Cambridge/Aachen jet algorithm** : In Cambridge/Aachen or C/A algorithm,  $d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$  and  $d_{iB} = 1$ .

In both anti-kT and C/A method steps used to cluster the jets is same as mentioned in steps for kT algorithm, except for the  $d_{ij}$  and  $d_{iB}$  which are calculated as mentioned in respective algorithms.

## 4.2 Strategy Implemented

The proton-proton collision was simulated using **PYTHIA8**, an event generating software. The data was then fed to **FASTJET3**[2] which clusters the jets based on the jet algorithms discussed earlier. With algorithms, recombination scheme, energy of the centre of mass (CoM), minimum transverse momentum  $pt_{min}$  and radius parameter  $Rparam$  available to be varied, a study was made on how the final number of jets vary with each variable being altered.

Also, as mentioned earlier the top quark pair can be produced in two ways i.e., a quark and an antiquark annihilation ( $q\bar{q} \rightarrow t\bar{t}$ ) and gluon-gluon interaction ( $gg \rightarrow t\bar{t}$ ).

The event generator enables the user to switch on the required mode of  $t\bar{t}$  production. Also, both the modes can be switched on simultaneously.

The plots were then generated using ROOTv5.34[7]

## 4.3 Results and analysis

How many jets should the jet algorithm reconstruct?

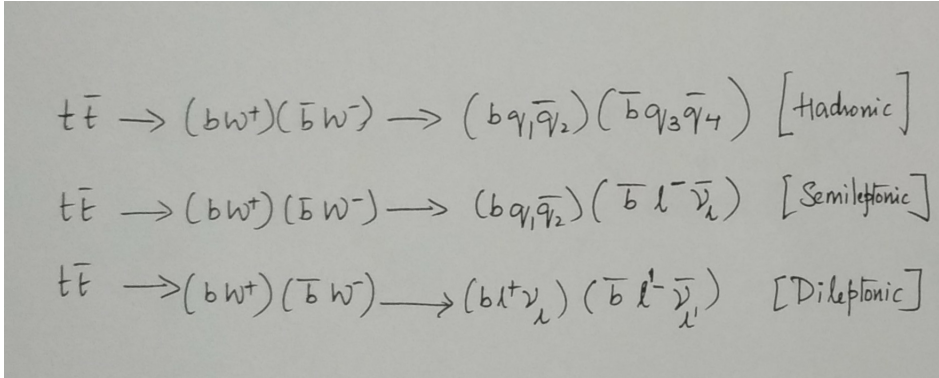


Figure 4.1: Jet multiplicity with various decay modes

Based on the decay modes of  $t\bar{t}$  shown in the figure above, theoretically one should get

1. Hadronic - 6 jets
2. Semileptonic - 4 jets
3. Dileptonic - 2 jets

**Jet multiplicity:** Jet multiplicity is the number of jets. It is important to know the number of jets because sometimes it is a part of event selection. For example, if you want to select a W boson decaying hadronically (into two quarks) then you generally look for events with two jets.

**pTMin:** It is the transverse momentum of the jet. In pp collision, transverse momentum is low. So theoretically jets reconstructed should correspond to low pTMin values.

**Rparam:** Rparam is the radius of the jet. Ideally Rparam should be large enough to cluster all the particles whose total pTMin matches sums up to the pTMin value selected. But it shouldn't be too large to capture the background events.

## 1. Variation of mean number of jets with changing pTMin values

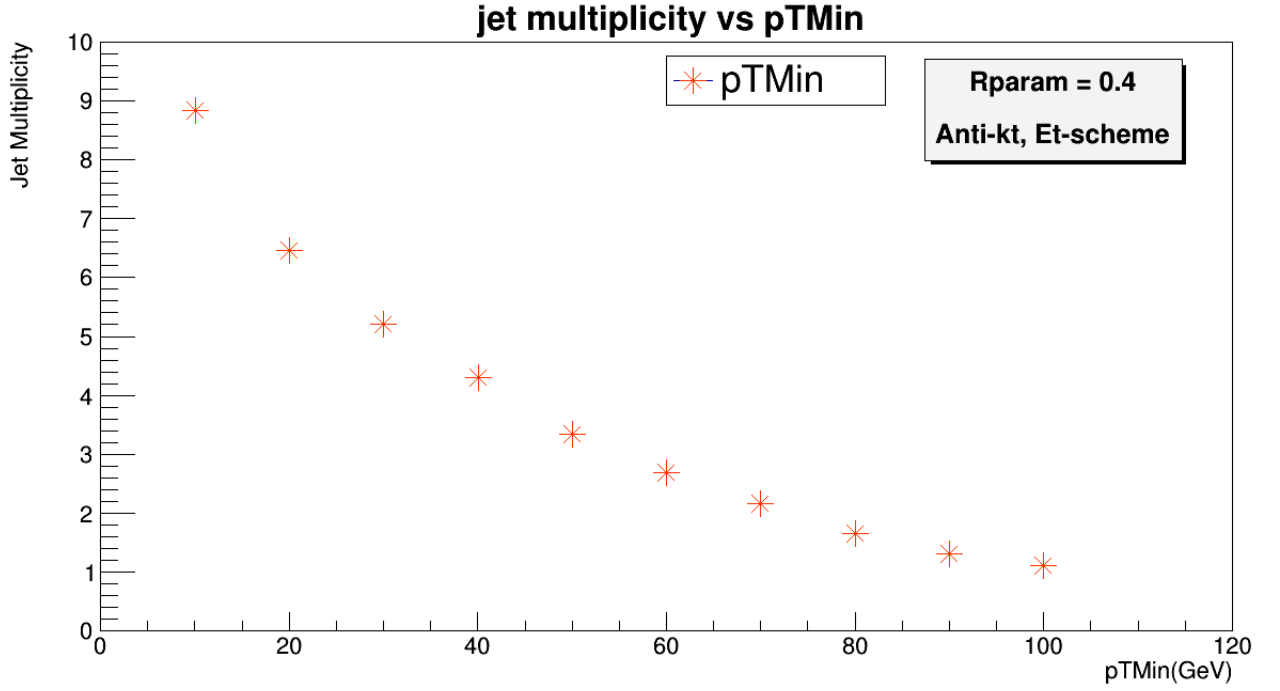


Figure 4.2: A plot of Jet multiplicity vs pTMin

Here keeping the  $R_{\text{param}} = 0.4$ , a variation of expected Jet multiplicity for hadronic decay was plotted against pTMin values ranging from 10 GeV to 100 GeV. For this study  $gg \rightarrow t\bar{t}b\bar{b}$  production mode and  $q\bar{q} \rightarrow t\bar{t}b\bar{b}$  production mode was kept on.

We know that the expected value of Jet multiplicity for a hadronic decay is 6. So with all other parameters set to above mentioned values, if the detector has to detect 6 jets then the pTMin should be approximately equal to 20 GeV.

However, standard jets obtained in  $t\bar{t}b\bar{b}$  events are at  $p_{T\text{Min}} = 30$  GeV.

## 2. Variation of number of jets with changing Radius parameter (Rparam) values

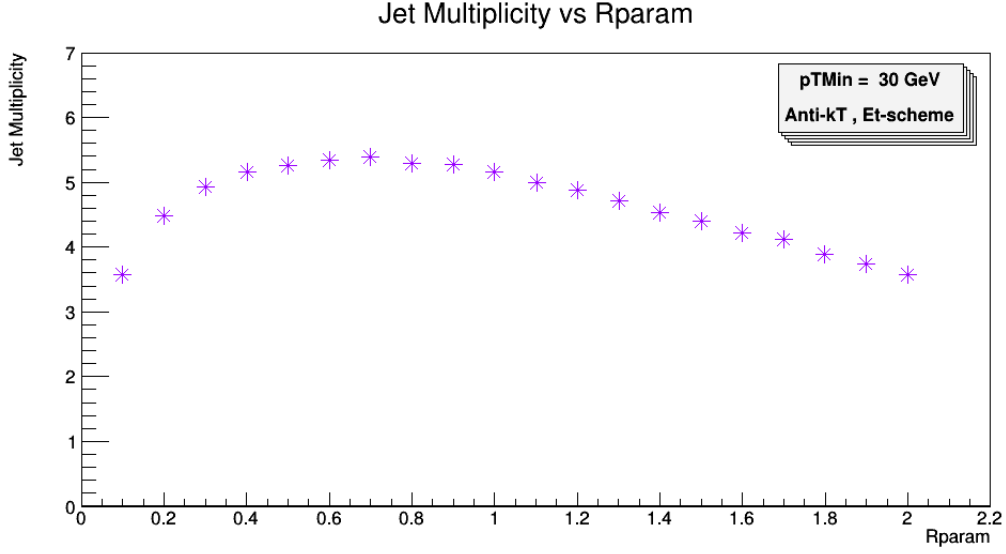


Figure 4.3: A plot of Jet multiplicity vs Rparam values

To study the effect of Rparam, pTMin was fixed to 30 GeV. With other settings remain as it is, Jet multiplicity was now plotted against Rparam values varying from 0.1 to 2. This study was made at 13TeV CoM.

Again for hadronic decay, to get 6 jets the Rparam value should lie between 0.5 to 0.8. This plot doesn't show a sharp peak.

The reason behind this are ISR and FSR. ISR-Initial State Radiation is the radiation emitted by the particles before the actual interaction. Similarly FSR-Final State Radiation is the radiation emitted by the scattered particles after interaction.

Throughout the study, ISR and FSR were not off. So they get added on while jet reconstruction.

### 3. How varying algorithms alter the results?

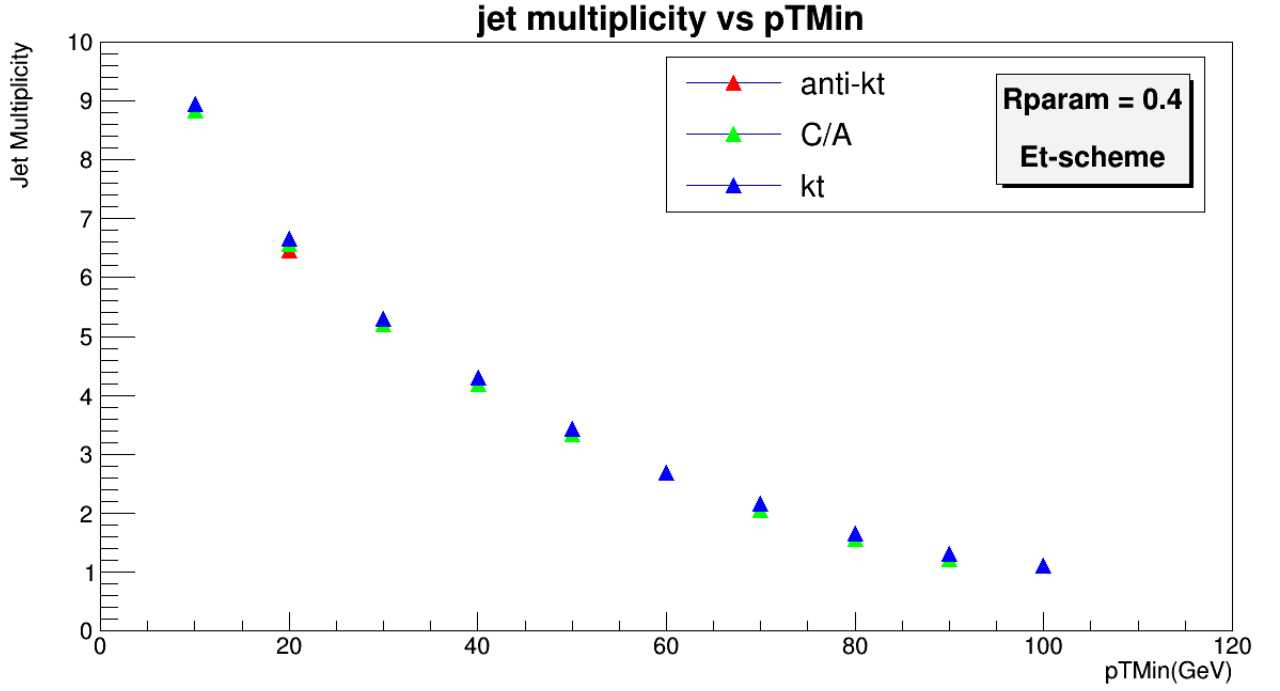


Figure 4.4: Algorithms varied were anti-kT, C/A and kT

Since we have different algorithms to cluster the jets, it is important to see how different algorithms affect the Jet multiplicity.

For this variation, Rparam was fixed to 0.4 and Et-scheme was chosen. Both ttbar production modes were on. Decay mode was hadronic. The CoM energy was still equal to 13TeV.

From the figure it is clear that for a hadronic decay, all the 3 algorithms give approximately the same result. Hence it can be concluded that varying algorithms don't alter the result. Anti-kT algorithm gives slightly a better estimate.

#### 4. Energy variation

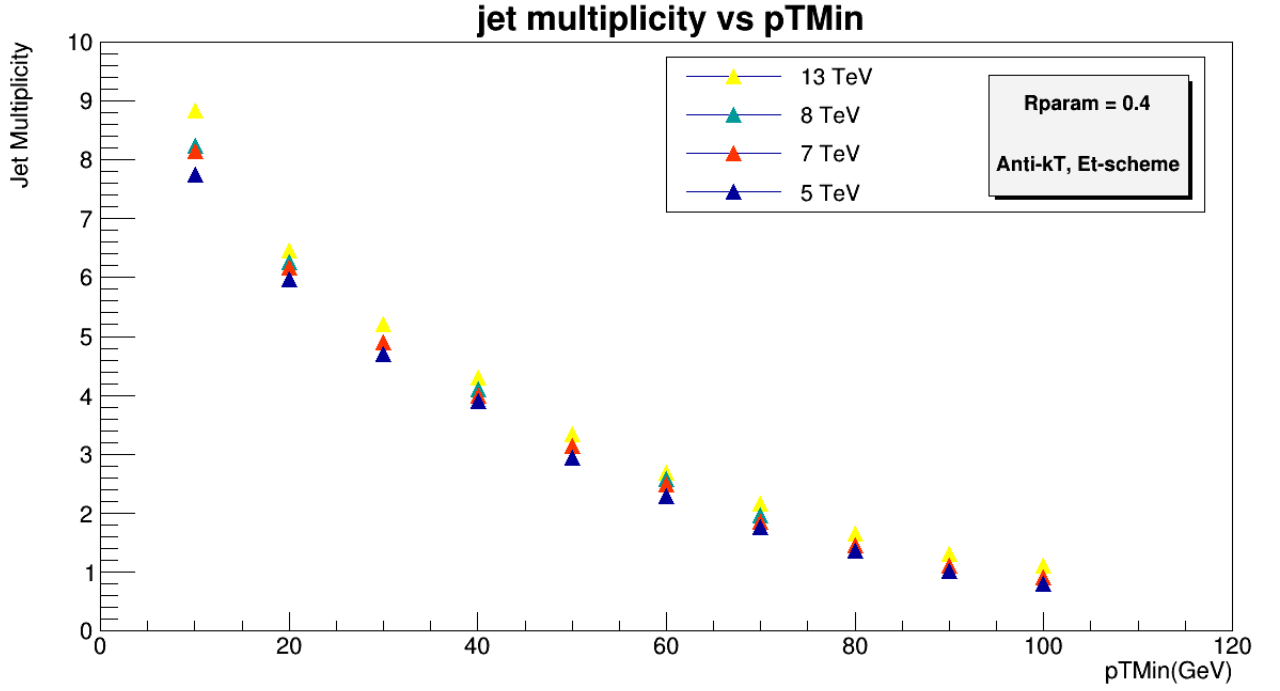


Figure 4.5: Variation in centre of mass (CoM) energy

The centre of mass (CoM) energy can be different, based on the initial energy. To obtain the above plot, the energy was varied as 5TeV, 7TeV, 8TeV and 13TeV.

The plot shows a slight variation in Jet multiplicity values with variation in pTMin. So it can be said that a small change in CoM energy will not have much impact on the results. However, it is expected to see a notable change if the energy values vary largely.



## 5. Do the recombination schemes affect the results?

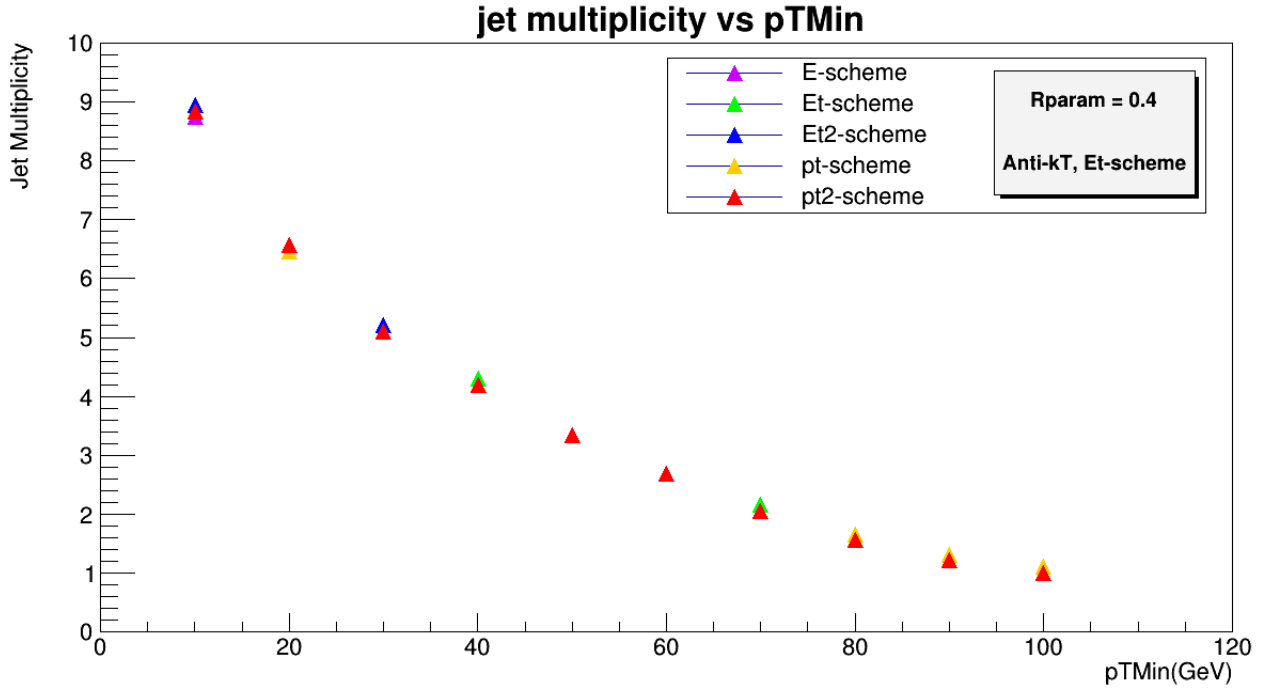


Figure 4.6: Change in mean jet multiplicity with changing recombination schemes

As mentioned earlier, there are different recombination schemes used to cluster the jets. In all the previous plots, the recombination applied was Et-scheme. When this scheme is varied to all other schemes it is seen that, there is a very little impact on the Jet multiplicity.

This variation was studied at 13TeV with both the  $t\bar{t}$  production modes on for hadronic decay.

## 6. Jet Multiplicity in different production modes

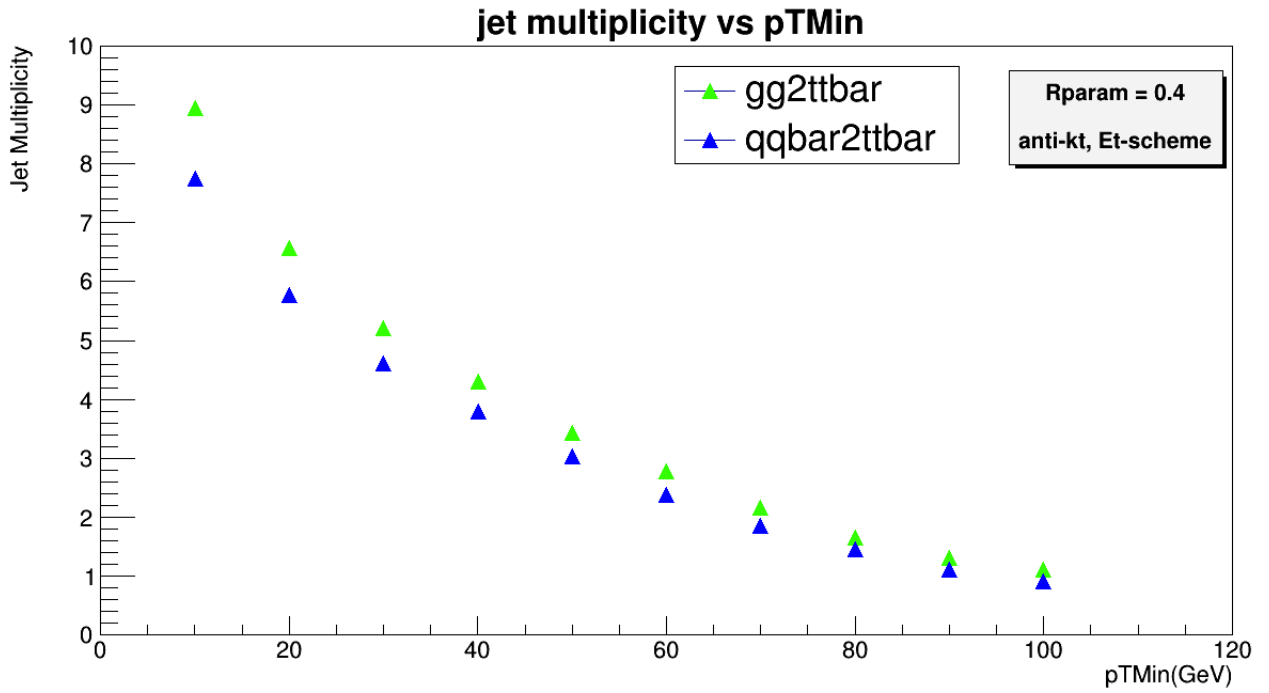


Figure 4.7: A plot showing how the jet multiplicity varies with variation in pTMin in two different production modes

All this while both ttbar production modes were on. Now one of them was switched off ( $gg \rightarrow ttbar$ / $qqbar \rightarrow ttbar$ ) and the variation in jet multiplicity was again plotted for the other mode ( $qqbar \rightarrow ttbar$ / $gg \rightarrow ttbar$ ).

There is a significant amount of change observed at lower pTMin values which become not so significant at higher pTMin values.

## 7. Cross section values at various CoM energies

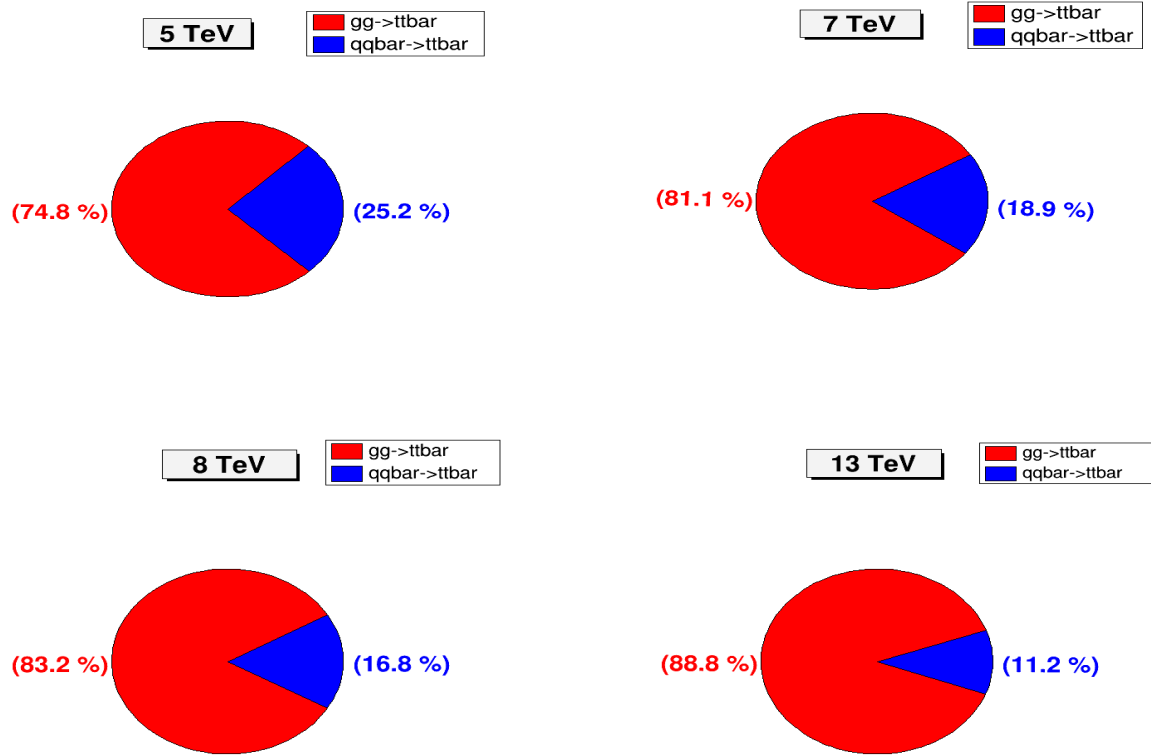


Figure 4.8: Figure showing that in pp collisions  $gg \rightarrow t\bar{t}$  production mode dominates

As centre of mass energy increases cross section for  $gg \rightarrow t\bar{t}$  production mode increases in proton-proton collisions i.e., at LHC. If proton and antiproton beams were collided then a similar study would have yielded  $q\bar{q} \rightarrow t\bar{t}$  as dominant production mode. This is evident from the experimental results at Tevatron, Fermilab.

## 4.4 Summary

The results of the variations studied are summarized below.

1. Ideal pTMin value is 20 GeV.
2. Radius of the jet (Rparam) should lie between 0.5 to 0.8.
3. Anti-kT algorithm is a preferable choice.
4. At low CoM energy a slight variation can be neglected.
5. All recombination schemes give the same results.
6. While working at relatively low pTMin values, Jet multiplicity can help you determine the ttbar production mode.
7. With increase in CoM energy, cross section for  $gg \rightarrow t\bar{t}$  production increases significantly.

## 4.5 Conclusion

Top quark pair production is the sensitive probe to new physics. Accuracy in measurements are extremely important as any deviation from theoretical model would suggest new particles or new interactions. So studying the effect of various parameters on Jet multiplicity before hand makes the problem look relatively simple. In this project effect of pTMin was studied. So all the plots obtained act as calibration curves where in you can determine the pTMin required for expected number of jets at certain other parameters fixed. A similar study can be conducted by varying the Rparam values.

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