

Contribution of various processes to charm quark production in p+p collisions at different energies

M.Sc. Thesis

By
TARUN KUMAR



DISCIPLINE OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY INDORE
JUNE -2020

Contribution of various processes to charm quark production in p+p collisions at different energies

A THESIS

*Submitted in partial fulfillment of the
requirements for the award of the degree
of
Master of Science*

by
TARUN KUMAR



**DISCIPLINE OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY INDORE
JUNE-2020**



INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Contribution of various processes to charm quark production in p+p collisions at different energies** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF SCIENCE** and submitted in the **DISCIPLINE OF PHYSICS, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from JULY-2019 to JUNE-2020 under the supervision of Dr. ANKHI ROY, Associate Professor.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Signature of the student with date
(TARUN KUMAR)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

24/06/2020

Signature of the Supervisor of
M.Sc. thesis #1 (with date)

(Dr. Ankhi Roy)

TARUN KUMAR has successfully given his/her M.Sc. Oral Examination held on **24 JUNE 2020**

Signature(s) of Supervisor(s) of MSc thesis
Date: 24/06/2020

Convener, DPGC
Date: 24/06/2020

Signature of PSPC Member #1
Date: 24/06/2020

Signature of PSPC Member #2
Date: 24/06/2020

Acknowledgements

I would first like to thank my thesis supervisor Dr. ANKHI ROY of the department of physics at IIT Indore. She consistently supported me for my work.

I must express my very profound gratitude to my mother for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis.

Abstract

There are six types of quarks and on the basis of mass variation we categorize them into light flavors and heavy flavors. We study charm quark in this thesis. We study the three different production mechanisms Flavor Creation, Flavor Excitation and Gluon Splitting which are Leading Order(LO) and Next to Leading Order(NLO). To understand the variation in contribution we consider three center of mass energies that are $\sqrt{s} = 200$ GeV, $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 14$ TeV. The contribution also affects the total cross section. We try to reproduce the experimental measurement from the theoretical understanding. We use Monte-Carlo LO based event generator that is PYTHIA8. It works on C++ programming language.

Contents

1	Introduction	11
1.1	Charm Quark	12
1.2	Motivation	13
2	Theory	15
2.1	Quantum Chromodynamics(QCD)	15
2.2	Perturbative QCD and Running Coupling Constant	16
2.3	The LO and NLO processes	16
2.3.1	Leading Order (LO)	18
2.3.2	Next To Leading Order (NLO)	18
2.4	Hadronisation	19
2.5	Cross section	20
3	Pythia : An Event Generator	21
3.1	Pythia - A Monte Carlo Generator	21
3.2	QCD processs	22
3.3	Event Generation In PYTHIA	22
3.3.1	The Hardest Process	23
3.3.2	Parton-Shower Evolution and MPI Generation	23
3.3.3	Hadronization	24
4	Kinematic Variables	26
4.1	Transverse Momentum	26
4.2	Rapidity and Pseudorapidity	27
4.2.1	Rapidity	27
4.2.2	Pseudorapidity	27

4.3	Invariant Mass	28
4.4	Azimuthal Correlation	29
5	Result	30
5.1	Cross section	30
5.2	Pseudorapidity	32
5.3	Transverse Momentum	33
5.4	Azimuthal Distribution	35
5.5	Azimuthal Correlation	37
6	Summary and Outlook	40

List of Figures

1.1	Classification of particles according to SM model.	12
1.2	Different measured charm production cross-section at different beam energies.[10]	14
2.1	The variation of running coupling constant with momentum transfer.	17
2.2	Leading Order (Flavor Creation).	18
2.3	Next to Leading Order (Flavor Excitation).	18
2.4	Next to Leading Order (Gluon splitting).	19
2.5	Charm pair fragmenting into decaying mesons.	19
3.1	Initial stage of event generation.	23
3.2	Parton-shower evolution of an event.	24
4.1	The different values of η corresponding to their respective polar angles.	28
5.1	Charm cross section by event generator with NLO accuracy and PYTHIA8	31
5.2	Pseudorapidity of muons and antimuons at $\sqrt{s} = 200$ GeV .	32
5.3	Pseudorapidity of muons and antimuons at $\sqrt{s} = 2.76$ TeV .	32
5.4	Pseudorapidity of muons and antimuons at $\sqrt{s} = 14$ TeV. .	33
5.5	Pair p_T of lepton pair at $\sqrt{s} = 200$ GeV.	34
5.6	Pair p_T of lepton pair at $\sqrt{s} = 2.76$ TeV.	34
5.7	Pair p_T of lepton pair at $\sqrt{s} = 14$ TeV.	35
5.8	Azimuthal Distribution of lepton pair at $\sqrt{s} = 200$ GeV. . .	36
5.9	Azimuthal Distribution of lepton pair at $\sqrt{s} = 2.76$ TeV. . .	36

5.10	Azimuthal Distribution of lepton pair at $\sqrt{s} = 14$ TeV. . . .	37
5.11	Azimuthal Correlation of lepton pair at $\sqrt{s} = 200$ GeV. . . .	38
5.12	Azimuthal Correlation of lepton pair at $\sqrt{s} = 2.76$ TeV. . .	38
5.13	Azimuthal Correlation of lepton pair at $\sqrt{s} = 14$ TeV. . . .	39

List of Tables

1.1	Open charm mesons	12
5.1	$\sigma_{c\bar{c}}$ [mb] by event generator with NLO accuracy and PYTHIA8	31
6.1	Contribution from different production mechanism in percentage	41

Chapter 1

Introduction

All matter surrounding us is formed by a complex composition of atoms with length scale of about angstrom. Atomic nuclei are made up of nucleons which are of the order in femtometer, i.e. protons and neutrons, and surrounded by electrons. Going to even smaller length scales, the constituents of the nucleons, these are the up and down quarks, which are bound by the strong interaction and belong to a group of six particles according to the Standard Model of particle physics. The Standard Model (SM) of particle physics combines our present knowledge on how matter is built from its constituents and how these constituents interact via three of the four fundamental forces: the electromagnetic, the strong and the weak interaction. Only gravity, the fourth of these forces, cannot yet be described in the corresponding framework. It may, however, be neglected for most of the scenarios in particle physics, as it is by many orders of magnitudes weaker than the other three interactions. Fig. 1.1 shows the classification of these elementary particles[1].

Of these particles, up, down and strange quarks have a mass in range of $\sim MeV/c^2$ and so we called them as light flavours, whereas charm, bottom and top quarks mass range is in $\sim GeV/c^2$ and therefore considered as heavy flavours.

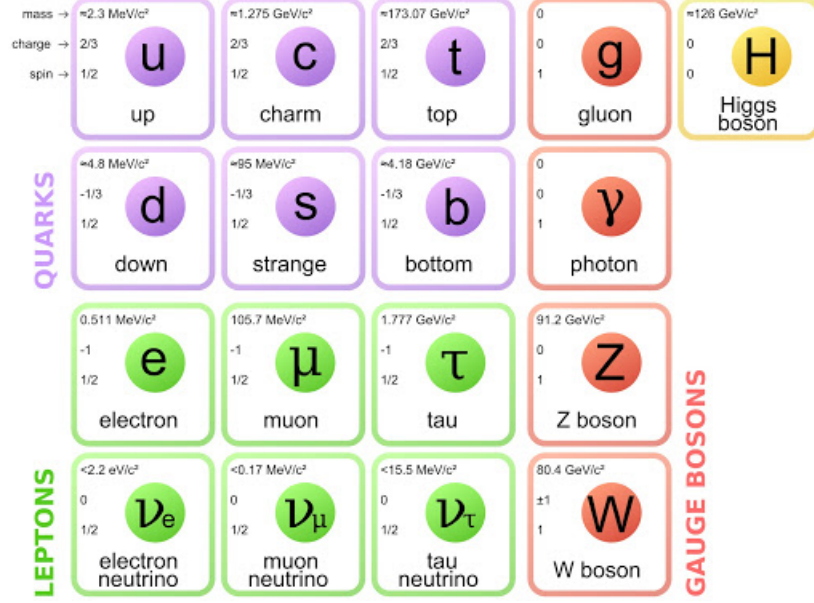


Figure 1.1: Classification of particles according to SM model.

Table 1.1: Open charm mesons

Particle	Quark Content	Antiparticle	Rest mass(MeV/c^2)
D^+	$c\bar{d}$	D^-	1869.62 ± 0.20
D^0	$c\bar{u}$	$\bar{D}^0$	1864.84 ± 0.17
D_s^+	$c\bar{s}$	D_s^-	1968.47 ± 0.33
D^{*+}	$c\bar{d}$	D^{*-}	2010.27 ± 0.17
D^{*0}	$c\bar{u}$	$\bar{D}^{*0}$	2006.97 ± 0.19

1.1 Charm Quark

Our main focus is on charm quark, which is one of the heavy flavor quarks. Charm production has been experimentally observed and studied for almost 30 years, yet the understanding of this topic is far from complete. Charm quark has a very short lifetime which is nearly 1.1×10^{-12} seconds. Open charm is primarily studied through detection of charmed mesons, a bound state of a quark and an anti-quark. Mesons containing one charmed quark, are named as D-mesons[9]. Table 1.1 shows overall open charmed mesons. The hadrons produce also have a short lifetime same as charm quark so we can not analyse directly but we use its decay channels.

1.2 Motivation

In recent years, measurements of $c\bar{c}$ via the lepton pair continuum have been reported for various collisions systems at the Relativistic Heavy Ion Collider (RHIC) by the PHENIX and STAR Collaborations[2]. Till now these measurements have been limited to e^+e^- pairs at midrapidity. Now PHENIX add a new measurement of the $\mu^+\mu^-$ pair continuum at forward rapidity obtained in proton-proton (p+p) collisions at centre of mass energy ($\sqrt{s}$) that is beam energy = 200 GeV. Same work has been extended to higher energies 2.76 TeV and 14 TeV. These two energies selected keeping in mind of the recent data taken by LHC, CERN we study azimuthal correlation as we consider it to be a unique probe for studying heavy flavor production in p+p collisions. By using azimuthal correlation we can also disentangle the different production mechanisms and can analyse the contribution of Leading Order (LO) mainly with Flavor Creation (FC) and Next to Leading Order (NLO) that are Flavor Excitation (FE) and Gluon Splitting (GS) at different energies in p+p collisions.

We also determine the transverse momentum spectra to determine the cross section of the beam. Figure 1.2 shows the variation of cross section predicted by for the energies from different experiments. The charm cross section($\sigma_{c\bar{c}}$) by NLO event generator (FONLL) at $\sqrt{s} = 200$ GeV is $.301^{+1}_{-.210}\text{mb}$ [14] and at $\sqrt{s} = 2.76$ TeV is $4.8^{+3.6}_{-1.7} \pm 0.86\text{mb}$ [15]. For simulation we use PYTHIA8 that is a LO based event generator. Our objective is to reproduce the experimental measurement from the theoretical understanding. Ideally one should do the NLO based event generator like FONLL, POWHEG etc. However, Pythia is a user friendly and uses parton shower approach and also efficient to produce Leading Order (LO) contribution. So, we planned to start the work with Pythia and later on, reproduce the higher order contributions like (NLO..).

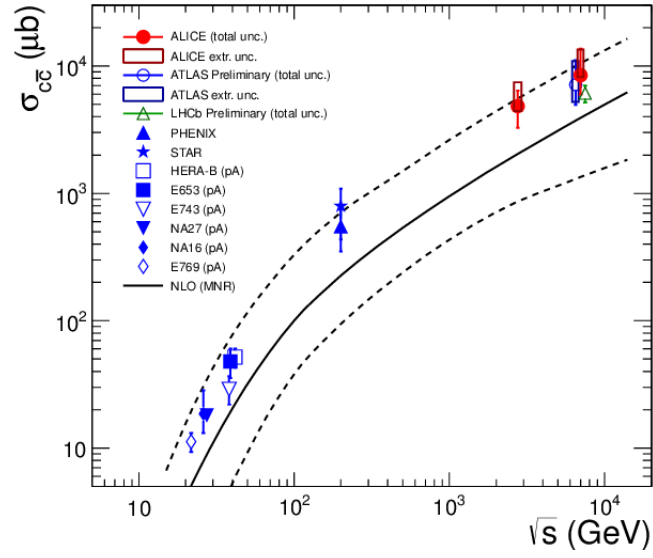


Figure 1.2: Different measured charm production cross-section at different beam energies.[10]

Chapter 2

Theory

2.1 Quantum Chromodynamics(QCD)

In modern physics we describe the fundamental forces in terms of fields, e.g. the electromagnetic field and the gravitational field. The spectacular success of Quantum Electrodynamics (QED) lead physicists to understand the importance of relativistic quantum field theory. In particular, it is realized that the fundamental forces seem to all belong to a special class of field theories, called “gauge” theories. The present belief is that QCD is also dictated by local gauge invariance. We start from the fact that the theory of strong interaction that is known as QCD. QCD is inspired by the success of QED, therefore there are lot of similarities. In QED, charged objects interact via the quanta of the electromagnetic field, the photons. Similarly, in QCD, colored objects interaction via quanta of the color field, the gluons. But we can differentiate by the fact that photons do not interact with each other while gluons go for self coupling.

QCD exhibits two main properties:

- **Color Confinement** : We know quark does not exist freely but in a pack that is known as hadrons. Due to a special potential a force acts between these quarks and avoids the separation. Therefore in order to increase the separation between quarks a high energy is required, when we increase the energy the force between quarks also increases and thus energy becomes so high and sufficient to produce a pair of

quark-antiquark and turning two hadrons from a single hadron.

- **Asymptotic Freedom :** At very small scale or at high energy the strong coupling also gets small and cause decrease in strength of interactions thus quarks to act like a free particle in hadrons. This property of the strong interaction is called asymptotic freedom[11].

2.2 Perturbative QCD and Running Coupling Constant

When the strong coupling constant (α_s) is less than unity at high momentum or short distance interactions, thus we apply perturbation theory techniques in QCD. There is a scale for energy that is λ_{QCD} , when the energy increases and comparable or greater than the λ_{QCD} then we apply perturbative QCD. The value of α_s is unity at beam energy equals to λ_{QCD} and value goes of decreasing on increasing the beam energy as shown in fig. 2.1.

The mathematical expression can be written as :

$$\alpha_s = \frac{12\pi}{(33 - 2n_f) \ln(\frac{Q^2}{\lambda_{QCD}^2})} \quad (2.1)$$

with $\lambda_{QCD} = 218 \pm 24$ MeV/c[12] being the scale parameter of QCD and n_f the number of quark flavours that is six.

2.3 The LO and NLO processes

The α_s at high energies when it becomes less than one, it is possible to apply perturbative approach in observables. And also the cross section can be expressed as a series expanded in α_s . This approach is referred to as perturbative QCD (pQCD). The cross section $\sigma_{c\bar{c}}$ can be written as a sum of processes of increasing order in α_s :

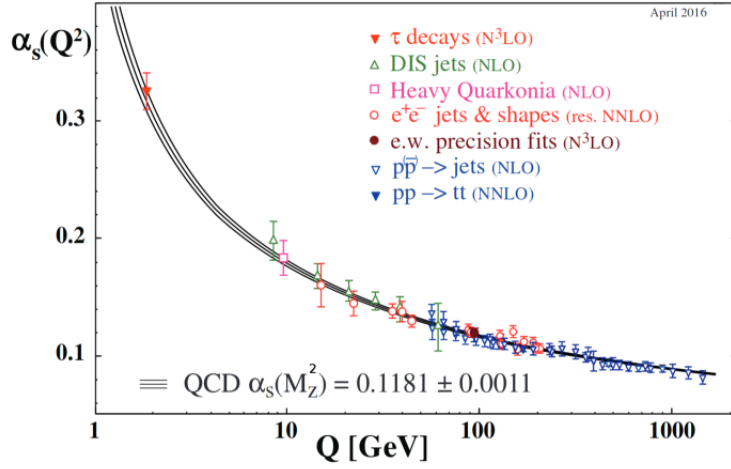


Figure 2.1: The variation of running coupling constant with momentum transfer.

$$\sigma_{c\bar{c}} = \alpha_s^2(\mu_R^2)\sigma_0 + \alpha_s^3(\mu_R^2)\sigma_1 + \dots$$

where μ_R is the hard scattering scale.

The leading-order (LO), or the first order represents by the function(α_s^2). The second order, or NLO results are denoted by the function(α_s^3) term. And higher orders, such as next to NLO (NNLO) with function(α_s^4), and so on.

In QCD, the higher level terms in power series of α_s do not give appropriate smaller corrections to the LO term. But, the NLO term is numerically comparable to the LO term, when beam energy ($\sqrt{s}$) is high. This can be understood from the fact that the cross section for the LO process $gg \rightarrow gg$ is nearly 100 times larger than for the $gg \rightarrow c\bar{c}$ process. Any of the final-state gluons in the $gg \rightarrow gg$ scattering can split into a $c\bar{c}$ pair, giving a higher order $c\bar{c}$ pair production process which has a proper cross section. The suppression of this splitting by scattering kinematics and the additional factor α_s compensate the cross section enhancement of the NLO contribution to the level of the LO. These events can then be subdivided into three classes, which we will call pair creation, flavour excitation and gluon splitting.

2.3.1 Leading Order (LO)

Leading Order covers Flavor creation (FC), that refers to the process which includes $2 \rightarrow 2$ processes of gluon fusion(fig. 2.2(a)) or $q\bar{q}$ annihilation(fig. 2.2(b)) diagrams plus higher order corrections to these processes[3].

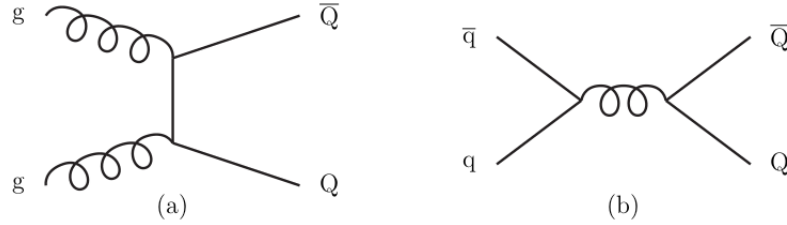


Figure 2.2: Leading Order (Flavor Creation).

2.3.2 Next To Leading Order (NLO)

NLO covers mainly flavor excitation and gluon splitting[3].

- **Flavor Excitation** : Scattering of a c-quark or $\bar{c}$ -antiquark out of the initial state into the final state by a gluons or by light quark. One of the produced c-quarks or $\bar{c}$ -antiquark interacts and gets kicked away at an angle as shown in fig. 2.3.

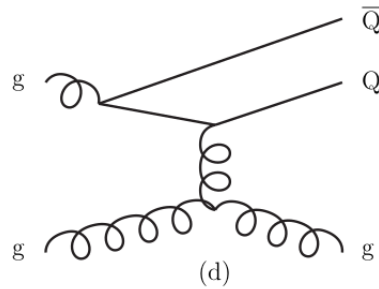


Figure 2.3: Next to Leading Order (Flavor Excitation).

- **Gluon Splitting** : It also can be considered as parton showering, $c\bar{c}$ pair created within a parton shower process ($g \rightarrow c\bar{c}$) in the initial or final state as shown in fig. 2.4.

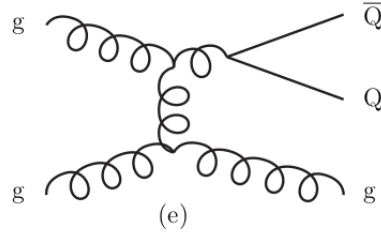


Figure 2.4: Next to Leading Order (Gluon splitting).

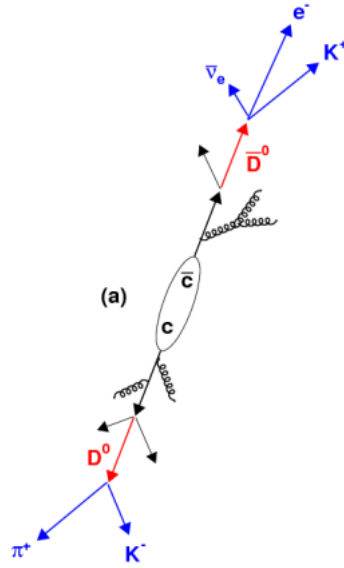


Figure 2.5: Charm pair fragmenting into decaying mesons.

2.4 Hadronisation

We collide proton with proton at a particular energy that can be centre of mass energy. After collisions charm quarks are also produced with its production mechanism (our focus is on FC, FE and GS), as their lifetime is very short and because of hadronization they assemble with other quarks to form mesons and also baryons.

D-mesons consist of single charm quark or antiquark (fig. 2.5) which also decay to dimuons pair and some other particles which we will not consider.

2.5 Cross section

In physics, when a collision of two particles takes place then the cross section is the measure of probability for a certain process. We can consider the example of Rutherford experiment in which alpha-particles are bombarded on gold foil. The cross section is the measure of probability that α -particles are deflected at certain angle. It is denoted by σ which is total cross section[16] and we define differential cross section as $\frac{d\sigma}{d\Omega}$, therefore

$$N_{events \text{ into solid angle } \Delta\Omega} = N_{incident} n x \frac{d\sigma}{d\Omega} \Delta\Omega \quad (2.2)$$

where

x = thickness of target (cm)

n = target atoms per unit volume

$N_{incident}$ = number of incident particles

Ω = solid angle

The value of cross section depends on the process. In section 2.3 we talk about the cross section for the LO process $gg \rightarrow gg$ is nearly 100 times larger than for the $gg \rightarrow c\bar{c}$ process. We work on three different production mechanisms and the cross section depends upon the different production mechanisms. These three production mechanisms are Flavor Creation, Flavor Excitation and Gluon Splitting. Also change in beam energy affects the value of cross section as shown in fig 1.2.

Chapter 3

Pythia : An Event Generator

3.1 Pythia - A Monte Carlo Generator

Event generators are software libraries that generate simulated high-energy particle physics events such as proton-proton collisions. They randomly generate events as those produced in particle accelerators, collider experiments or the early universe.

PYTHIA was originally written in FORTRAN 77, until the release of PYTHIA 8.1 which was rewritten in C++. Both the Fortran and C++ versions are being maintained because not all components were merged into the 8.1 version. However, the latest version already includes new features not available in the Fortran release. The following is a list of some of the features PYTHIA is capable of simulating:

- Hard and soft interactions
- Parton distributions
- Initial/final-state parton showers
- Multiple interactions
- Fragmentation and decay

3.2 QCD processs

There are mainly six QCD processes modeled in Pythia8, all are in LO approximation. Pythia8 contains various models of hard processes that provide approximations to the flavor creation, flavor excitation and gluon splitting mechanisms. They are made by combining hard process with parton shower. These three QCD mechanisms are represented in the following processes, shown with Pythia8 process number[5]:

- **code 114** : $q\bar{q} \rightarrow q\bar{q}$: FEX, if ISR gluon splits into a $c\bar{c}$ pair, one of c-quarks is boosted.
- **code 124** : $q\bar{q} \rightarrow c\bar{c}$: LO FC process, direct production of $c\bar{c}$ pair. It produces events with back-to-back topology.
- **code 115** : $q\bar{q} \rightarrow g\bar{g}$: GS, when one of the two final state gluons splits into a $c\bar{c}$ pair.
- **code 113** : $qg \rightarrow qg$: FE process, if ISR gluon splits into a $c\bar{c}$ pair, one of c-quarks is boosted via interaction with g.
- **code 123** : $g\bar{g} \rightarrow c\bar{c}$: LO FC process, direct production of $c\bar{c}$ pair. It produces events with back-to-back topology.
- **code 111** : $g\bar{g} \rightarrow g\bar{g}$: GS, final state gluon splits into a $c\bar{c}$ pair.

3.3 Event Generation In PYTHIA

In PYTHIA, the event generation can be subdivided into three major steps: the generation of the hardest process, the propagation of initial-state and final-state radiation, i.e. the parton-shower evolution, and the fragmentation into hadrons.

The initial-state partons radiate and scatter inside the incoming projectiles which is denoted as Initial-State Radiation (ISR). These radiation is

nothing but partons (quarks and gluons) which moves in projectile according to its previous partonic interaction cross section. After some scattering, final yield is produced in form of stable particles.

3.3.1 The Hardest Process

The first step to generate events is by generating the hardest sub-process, which is the $2 \rightarrow 1$, $2 \rightarrow 2$ or $2 \rightarrow 3$ partonic process with the largest momentum transfer (Q^2) in the event figure 3.1. It determines the overall cross section and collision of the beam.

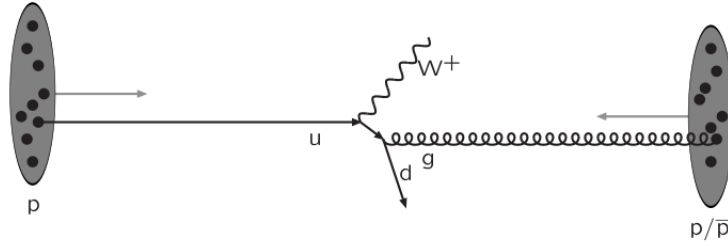
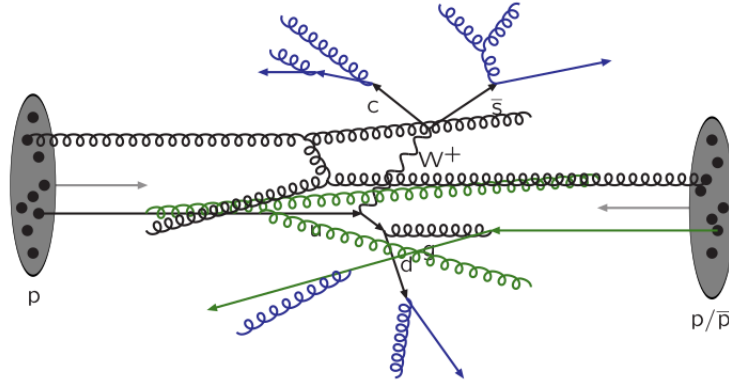


Figure 3.1: Initial stage of event generation.

3.3.2 Parton-Shower Evolution and MPI Generation

Partons (quarks and gluons) radiate gluons, taking it into consideration in an MC (Monte Carlo) event generator by a process called parton shower. The process is further divided into the radiation before and after the collision these are initial state radiation (ISR) and final state radiation (FSR). ISR and FSR are described as successive splittings of color carriers such as gluon splits in a pair of quark-antiquark or a quark can split into quark and a gluon. For the simulation of a complete FSR parton shower, one possible colour flow scenario is selected for the hardest process providing the initial condition for the shower.



Multiple parton-parton interactions . . .

Figure 3.2: Parton-shower evolution of an event.

3.3.3 Hadronization

The final step is Hadronization. It is a mechanism for transforming colored partons into colorless hadrons. The hadronization model in Pythia8 is based exclusively on the Lund string fragmentation model[13]. Since the non-perturbative QCD is not analytically solvable, results from hadron spectroscopy and lattice QCD calculations show that the color flux tube between $q\bar{q}$ pair can be well approximated by Cornell potential.

$$V(r) = -kr + \frac{4\alpha_s}{3r} \quad (3.1)$$

If the short-distance Coulomb term is neglected, the corresponding linear potential can be expressed as $V(r) = -k \times r$, where k is the string tension, is about 1 GeV/fm. When breaking the string, the $q\bar{q}$ pair is created on the spot, but it can QM (Quantum) tunnel to transverse momentum space. The flavour composition of the created $q\bar{q}$ pair is assumed to derive from a quantum mechanical tunneling process, which in turn implies a suppression of heavy quark production strongly suppressed in soft fragmentation processes the probability for up, down and strange is very high compared to charm such that charm and bottom production can be neglected in the

hadronization step. This implies that production of D and B hadrons in hadronization is negligible.

Chapter 4

Kinematic Variables

We introduce now a set of variables which will be used in the following sections. The center-of-mass of the partonic scattering is generally boosted with respect to the incoming hadrons' center-of-mass. Therefore, we classify the final state with variables that transform in a simple way under longitudinal boost: rapidity y , transverse momentum p_T and azimuthal angle ϕ . In terms of these variables, the 4-momentum of a particle of mass m is expressed as: $p^\mu = (E, p_x, p_y, p_z)$

4.1 Transverse Momentum

Three momentum can be divided into two components longitudinal and transverse momentum. Longitudinal momentum is in the direction of the beam and we consider it as the z direction (p_z). Transverse momentum is in perpendicular to the beam that is p_T . Therefore it is Lorentz invariant with respect to the collider.

It is defined as:

$$p_T = \sqrt{p_x^2 + p_y^2} \tag{4.1}$$

4.2 Rapidity and Pseudorapidity

4.2.1 Rapidity

Rapidity is one of the common variables used in accelerator physics. And mathematically it can be defined as the hyperbolic angle that differentiate two frame of reference in relative motion.

The variable rapidity "y" can be defined as

$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right) \quad (4.2)$$

where E is the energy of the particle and p_z is longitudinal momentum.

Rapidity is not Lorentz invariant, but it has a simple transformation property. It can be changed easily from one frame of reference to another frame of reference.

$$y = y' + y_{S'} \quad (4.3)$$

where

y = rapidity in system S

y' = rapidity in system S'

$y_{S'}$ = rapidity of S' measured in S

4.2.2 Pseudorapidity

Let us assume that a particle is emitted at an angle θ relative to the beam axis. Then its rapidity can be written as

$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right) \quad (4.4)$$

where $E = \sqrt{m^2 + p^2}$

we replace E by $\sqrt{m^2 + p^2}$ and p_z by $p \cos \theta$ in the equation then

$$y = \frac{1}{2} \ln \left(\frac{\sqrt{m^2 + p^2} + p \cos \theta}{\sqrt{m^2 + p^2} - p \cos \theta} \right) \quad (4.5)$$

At high energy $p \gg m$ and hence

$$y = \frac{1}{2} \ln \left(\frac{p + p \cos \theta}{p - p \cos \theta} \right) \quad (4.6)$$

$$= -\ln \left(\tan \left(\frac{\theta}{2} \right) \right) = \eta \quad (4.7)$$

$$(4.8)$$

And therefore, We define pseudorapidity as

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right) \quad (4.9)$$

And the value of η at different angles as shown in fig 4.1.

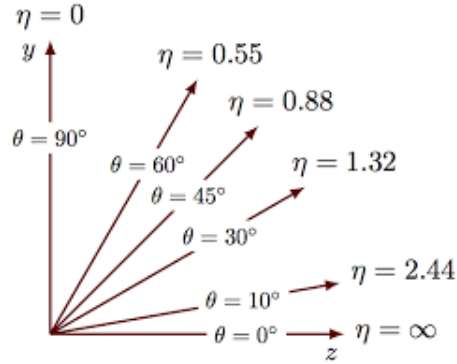


Figure 4.1: The different values of η corresponding to their respective polar angles.

4.3 Invariant Mass

In particle physics, the invariant mass m_0 is equal to the mass in the rest frame of the particle, and can be calculated by the particle's energy E and its momentum p as measured in any frame,

by the energy momentum relation:

$$m_0 = \sqrt{E^2 - p^2} \quad (4.10)$$

4.4 Azimuthal Correlation

Azimuthal correlation is defined as:

$$\Delta\phi = |\phi_1 - \phi_2| \quad (4.11)$$

Azimuthal angle or ϕ in spherical coordinate system exist in x-y plain. In particle physics the beam direction is considered in z-axis so ϕ exist in transverse plain and it shows the distribution of particles.

In high energy physics it can be a tool to disentangle different production mechanisms.

Chapter 5

Result

The observations in the thesis is done with three beam energies that are $\sqrt{s} = 200$ GeV, $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 14$ TeV. We have produced 3×10^9 events for 200 GeV, 2.76 TeV and 4×10^8 for 14 TeV.

Considering the process and generation of dimuons pair:

$$pp \rightarrow c\bar{c} \rightarrow \mu^+ \mu^- X \quad (5.1)$$

where X can be any hadron which we will not consider.

We are working on three different production mechanism that are FC, FE and GS. And these can be separated as their processes are different to each other. FC is a LO process, therefore it follows $2 \rightarrow 2$ and the mother particles can be gluons or quarks which are lighter than charm(fig. 2.2). FE and GS are NLO process which follows $2 \rightarrow 3$. For FE a c-quark which is produced by the decay of a gluon is scattered by other quark or gluon(fig. 2.3). And for GS a pair of charm and anticharm is produced from a gluon which is initially scattered by other gluon.

5.1 Cross section

We use PYTHIA8 event generator that focus only on LO. We have computed the value of cross section at beam energies $\sqrt{s} = 200$ GeV, $\sqrt{s} =$

Table 5.1: $\sigma_{c\bar{c}}$ [mb] by event generator with NLO accuracy and PYTHIA8

$\sqrt{s}$	Event generator with NLO accuracy	PYTHIA8
200 GeV	$.301^{+1}_{-.210}$	0.139
2.76 TeV	$4.8^{+3.6}_{-1.7} \pm 0.86$	5.080
14 TeV	—	31.343

2.76 TeV and $\sqrt{s} = 14$ TeV, and also the measured value by NLO event generator at respective energies.

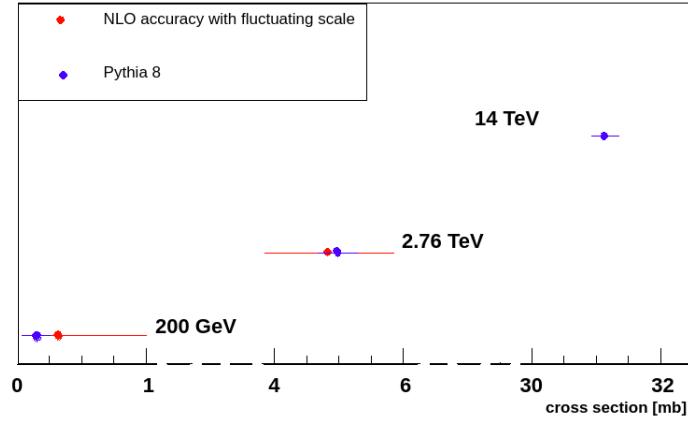


Figure 5.1: Charm cross section by event generator with NLO accuracy and PYTHIA8

As NLO also contributes in cross section therefore it may not match with the values of event generator with NLO accuracy.

Measurement at $\sqrt{s} = 14$ TeV is still incomplete, so we do not have the data point for charm cross section.

5.2 Pseudorapidity

The observation of pseudorapidity at $\sqrt{s} = 200$ GeV, $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 14$ TeV of muons and anti muons. The process should be unbiased towards this lepton pair.

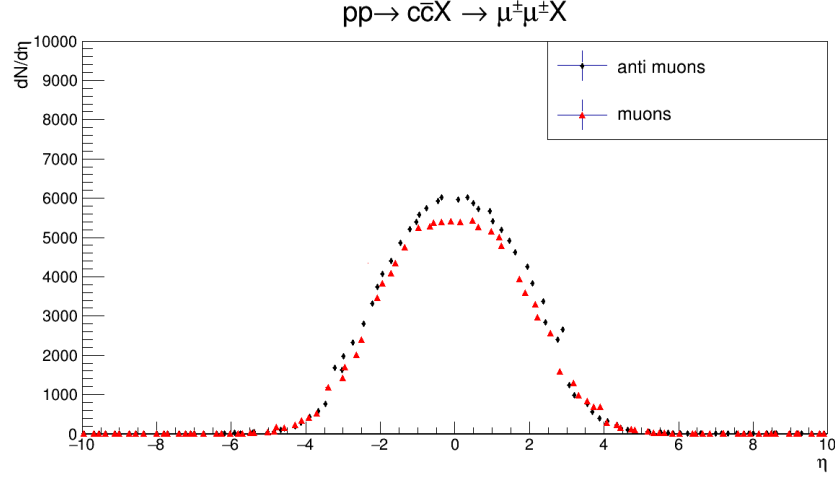


Figure 5.2: Pseudorapidity of muons and antimuons at $\sqrt{s} = 200$ GeV

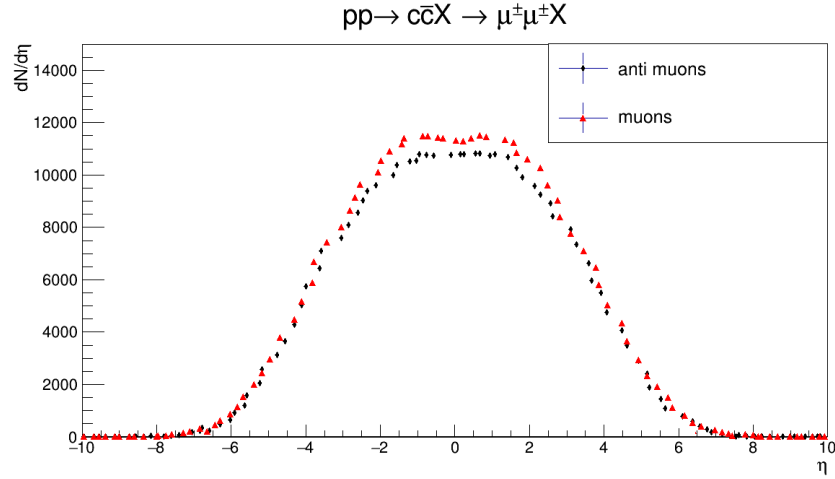


Figure 5.3: Pseudorapidity of muons and antimuons at $\sqrt{s} = 2.76$ TeV

But when we see the plots we see the process is biased towards a particular particle. This is because the probability of having lepton pair with different charges from charm is very high, but still there exists a probability to find lepton pair with same mass which affects the counts of muons and become biased towards a particular particle.

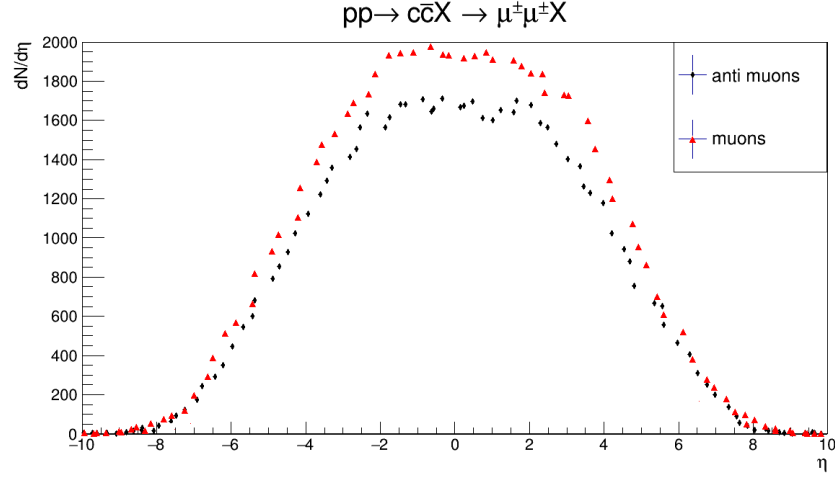


Figure 5.4: Pseudorapidity of muons and antimuons at $\sqrt{s} = 14$ TeV.

5.3 Transverse Momentum

The observation of transverse momentum at $\sqrt{s} = 200\text{GeV}$, $\sqrt{s} = 2.76\text{TeV}$ and $\sqrt{s} = 14\text{TeV}$ of muons and anti muons.

We have applied two cuts in the plots to have more accuracy:

- We have applied the cut for three momentum (p) of muons and antimuons to separate heavy flavors from the light flavors that is ($p > 3\text{GeV}$).
- We have applied second cut to disentangle pair of dimuons produced from open charm mesons that is pair mass of dimuons lie between 1.5 to 2.5 ($1.5\text{GeV} < m_{\mu\mu} < 2.5\text{GeV}$)

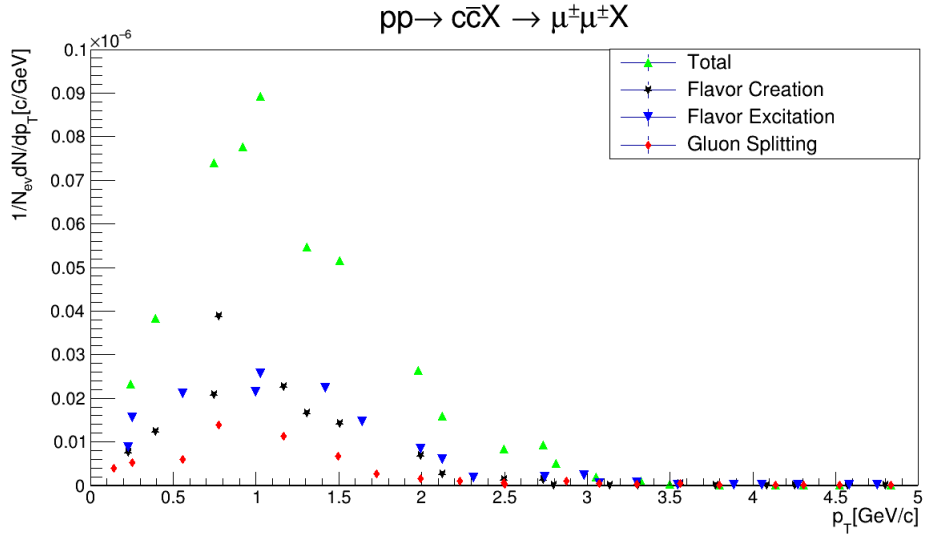


Figure 5.5: Pair p_T of lepton pair at $\sqrt{s} = 200$ GeV.

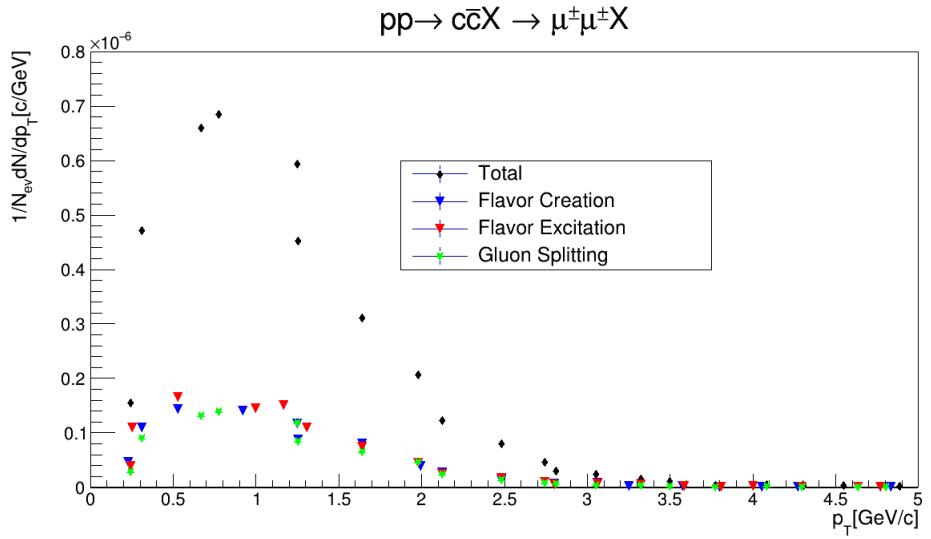


Figure 5.6: Pair p_T of lepton pair at $\sqrt{s} = 2.76$ TeV.

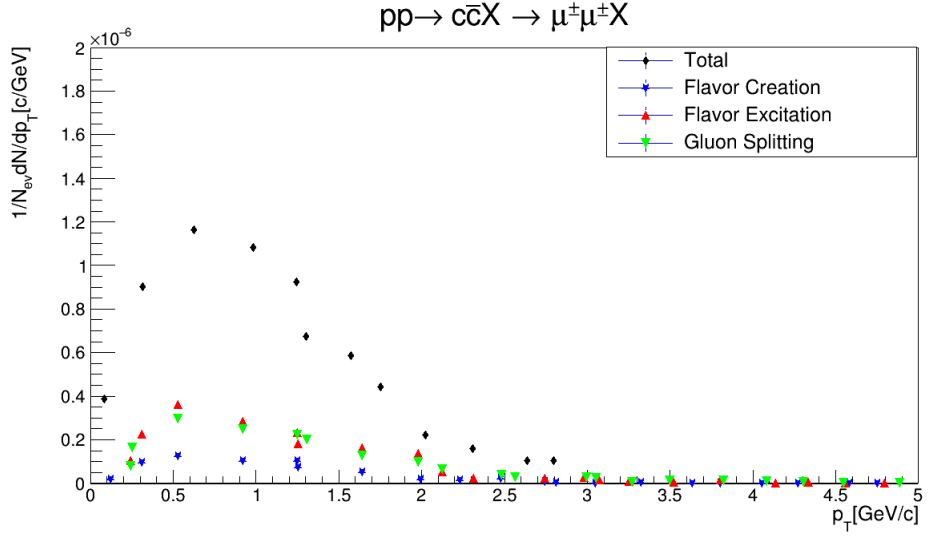


Figure 5.7: Pair p_T of lepton pair at $\sqrt{s} = 14$ TeV.

There are three production mechanisms Flavor Creation, Flavor Excitation and Gluon Splitting and the overall contribution has been separated in the plots. If we see the plots the contribution from these mechanisms vary with $\sqrt{s}$.

5.4 Azimuthal Distribution

The observation of ϕ distribution at $\sqrt{s} = 200\text{GeV}$, $\sqrt{s} = 2.76\text{TeV}$ and $\sqrt{s} = 14\text{TeV}$ of muons and anti muons.

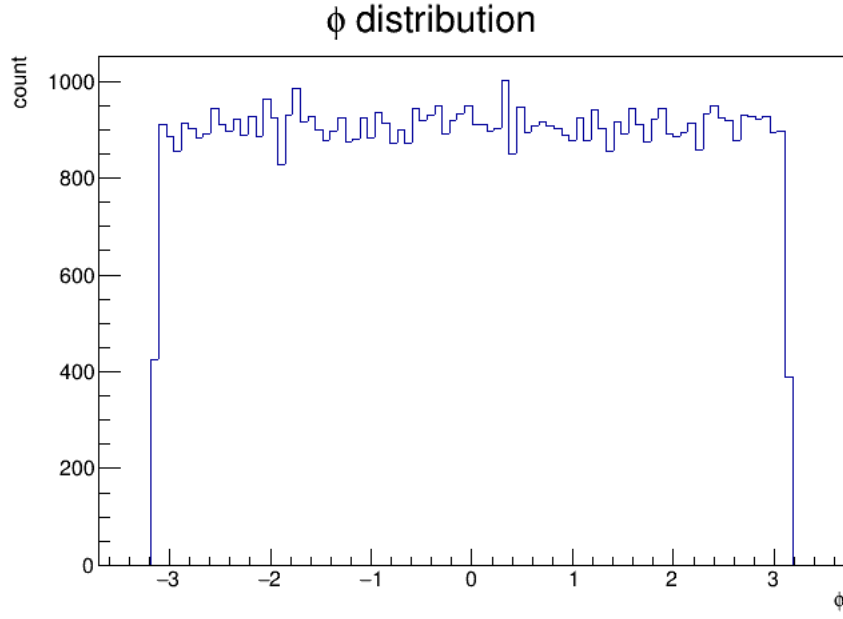


Figure 5.8: Azimuthal Distribution of lepton pair at $\sqrt{s} = 200$ GeV.

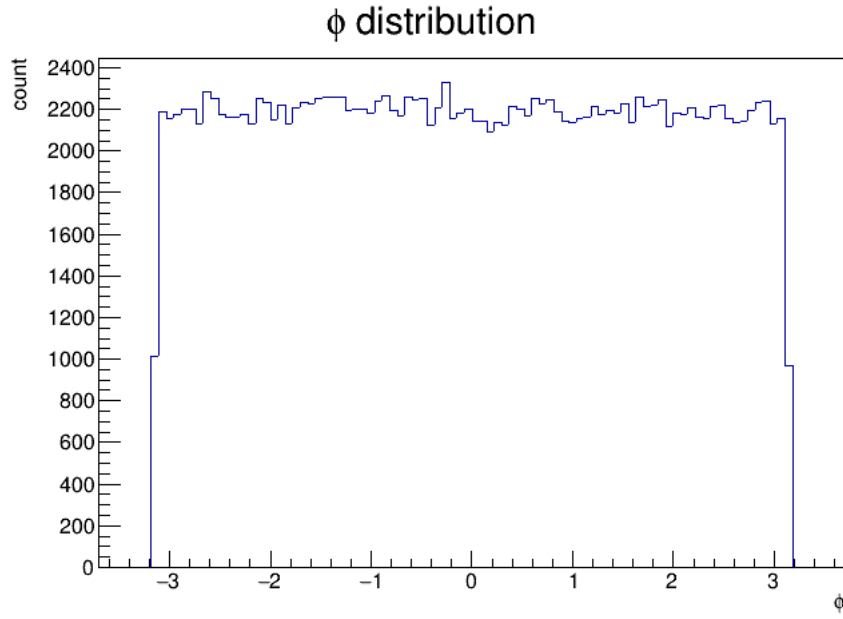


Figure 5.9: Azimuthal Distribution of lepton pair at $\sqrt{s} = 2.76$ TeV.

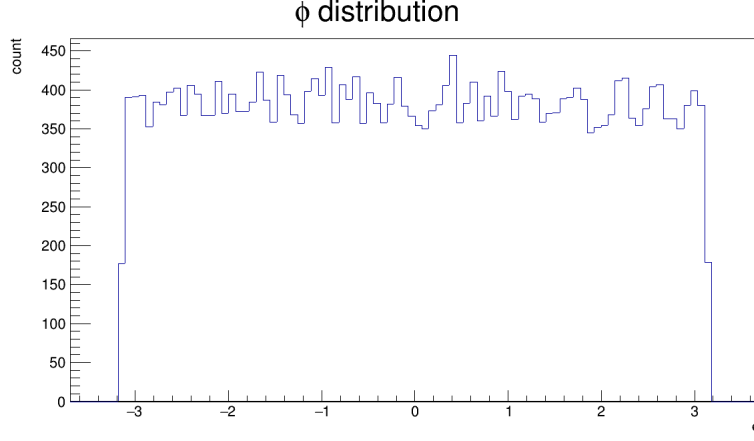


Figure 5.10: Azimuthal Distribution of lepton pair at $\sqrt{s} = 14$ TeV.

The overall distribution of muons and anti muons in transverse plane is uniform.

5.5 Azimuthal Correlation

The observation of $\Delta\phi$ at $\sqrt{s} = 200\text{GeV}$, $\sqrt{s} = 2.76\text{TeV}$ and $\sqrt{s} = 14\text{TeV}$ of muons and anti muons. We have applied two cuts in the plots to have more accuracy:

- We have applied the cut for three momentum (p) of muons and antimuons to separate heavy flavors from the light flavors that is ($p > 3\text{GeV}$).
- We have applied second cut to disentangle pair of dimuons produced from open charm mesons that is pair mass of dimuons lie between 1.5 to 2.5 ($1.5\text{GeV} < m_{\mu\mu} < 2.5\text{GeV}$)

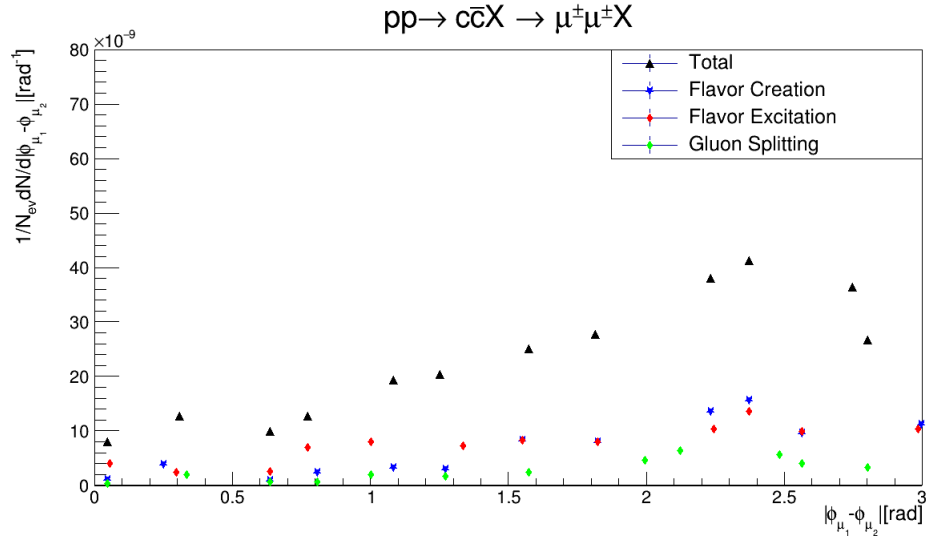


Figure 5.11: Azimuthal Correlation of lepton pair at $\sqrt{s} = 200$ GeV.

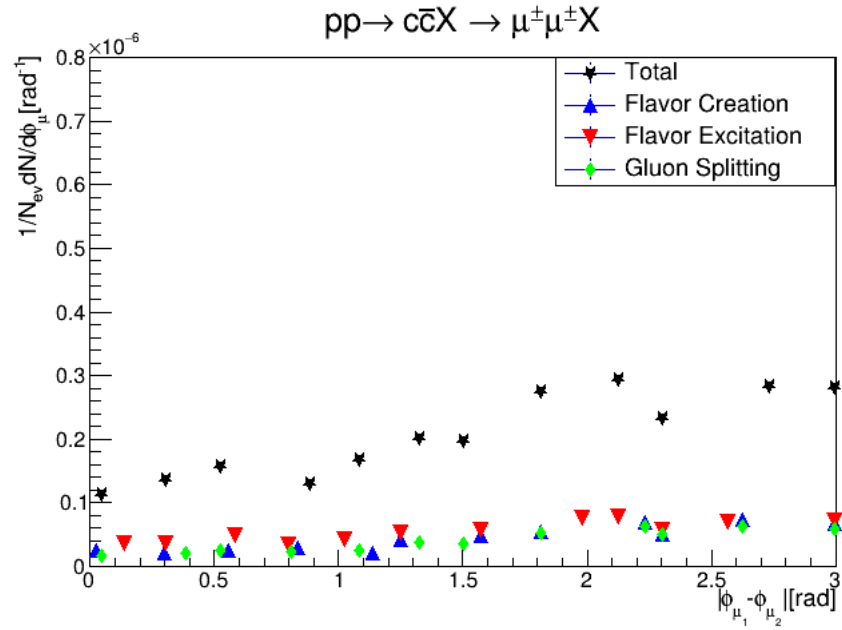


Figure 5.12: Azimuthal Correlation of lepton pair at $\sqrt{s} = 2.76$ TeV.

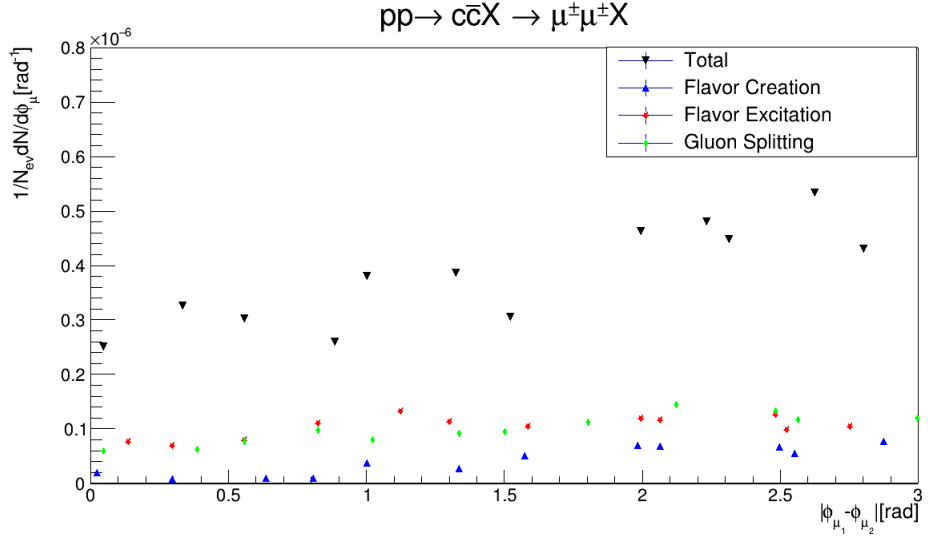


Figure 5.13: Azimuthal Correlation of lepton pair at $\sqrt{s} = 14$ TeV.

There are three production mechanisms Flavor Creation, Flavor Excitation and Gluon Splitting and the overall contribution has been separated in the plots. If we see the plots the contribution from these mechanisms vary with $\sqrt{s}$.

Chapter 6

Summary and Outlook

In this thesis we have done simulation using PYTHIA8 event generator where we do p+p collisions. We are focused on three different beam energies $\sqrt{s} = 200$ GeV, $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 14$ TeV. As we are working on three different production mechanism FC, FE and GS that contribute in LO and NLO. And we consider a tool that is azimuthal correlation to distangle these production mechanism. These production mechanism also contribute in charm cross section($\sigma_{c\bar{c}}$).

In table 5.1 the data for $\sigma_{c\bar{c}}$ is from an event generator with NLO accuracy and the data we observed from PYTHIA8. We know PYTHIA8 is based on LO process, therefore in case of $\sigma_{c\bar{c}}$ it shows only LO contribution and the $\sigma_{c\bar{c}}$ does not match the value with NLO accuracy. The fluctuation in data with NLO accuracy is much higher as shown in the table. And at $\sqrt{s} = 14$ TeV the work has not done and thus we do not have NLO accuracy data point. Also PYTHIA8 works fine for a certain beam enaegy range. To get a better accuracy in values of $\sigma_{c\bar{c}}$ we need NLO based event generator such as POWHEG, FONLL.

Although PYTHIA8 is a LO based event generator but it works on parton shower approach. So we can simulate the contribution from these production mechanism. And we can also analyse them how they vary with different beam energies. In table 6.1 we can see that the contribution from NLO goes on increasing on increasieing the beam energy and opposite case for LO term which gives us conclusion about strong running coupling constant.

Table 6.1: Contribution from different production mechanism in percentage

$\sqrt{s}$	Flavor Creation	Flavor Excitation	Gluon Splitting	Total
200 GeV	31.99	36.53	17.41	85.93
2.76 TeV	21.66	26.24	23.58	71.48
14 TeV	11.80	27.28	27.22	66.30

Table 6.1 provide overall information about the different production mechanism. Here we can see the contribution percentage in production of dimuons from Flavor Creation goes on decreasing and it is opposite for Gluon Splitting. We know at very high beam energy the value of coupling constant becomes very small as shown in figure 2.1. The running coupling constant can be expanded into LO, NLO, NNLO and so on. On increasing $\sqrt{s}$ the contribution from the higher order terms start increasing and also they start contributing to the beam cross section and we see cross section σ start increasing with $\sqrt{s}$. In table 6.1 we see that on increasing the beam energy not only the NLO processes start dominating but contribution from higher order terms start increasing as total contribution from three production mechanisms is decreasing.

Bibliography

[1] SM model of particles. <https://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/>

[2] Measurements of dimuons pairs from open heavy flavor and Drell-Yan in p+p collisions at centre of mass energy = 200 GeV. <https://arxiv.org/abs/1805.02448>

[3] Emanuel Norrbin and Torbjorn Sjostrand. Production and hadronization of heavy quarks. <https://cds.cern.ch/record/437604/files/0005110.pdf>

[4] C. Y. Wong. Introduction to high-energy heavy ion collisions. 1995. ISBN 9789810202637.

[5] Pythia 8 online manual.
<http://home.thep.lu.se/~torbjorn/pythia81html/Welcome.html>

[6] Torbjorn Sjostrand, Stephen Mrenna and Peter Skands. Pythia 6.4 manual. <https://doi.org/10.1088/1126-6708/2006/05/026>

[7] David J. Griffiths. Introduction to elementary particles.

[8] User's Guide - ROOT - CERN. <https://root.cern.ch/guides/users-guide>

[9] Charm Quark. https://en.wikipedia.org/wiki/Charm_quark

[10] Charm cross section. <https://cds.cern.ch/record/1490903/plots>

[11] Lacture on asymptotic freedom QCD.
<https://www.nikhef.nl/~h24/qcdcourse/section-6.pdf>

[12] Coupling Constant. https://en.wikipedia.org/wiki/Coupling_constant and <https://facultystaff.richmond.edu/~ggilfoyl/research/CrossSectionIntro.pdf>

[13] Lund string fragmentation model.
https://particle.wiki/wiki/Lund_string_model

[14] MEASUREMENT OF THE OPEN CHARM CROSS-SECTION IN 200 GEV HEAVY-ION COLLISIONS AT STAR. arXiv:0805.4228.

[15] Measurement of charm production at central rapidity in proton-proton collisions at centre of mass energy = 2.76 TeV. ArXiv:1205.4007

[16] Cross section. [https://en.wikipedia.org/wiki/Cross_section_\(physics\)](https://en.wikipedia.org/wiki/Cross_section_(physics))