

Measurement of azimuthal correlations of D^0 mesons with charged particles in pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV with ALICE at the LHC

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by

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23 March 2021



Dedicated to My Parents...

Acceptance Certificate

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Abstract

The ALICE (A Large Ion Collider Experiment) detector at the LHC is dedicated to the study the properties of the hot and dense QCD matter (Quark Gluon Plasma) produced in the nucleus-nucleus collisions at high energy. The heavy quarks (charm and beauty), having large masses, are produced in the hard-parton scattering in the early stages of the collisions. Therefore, they experience the whole evolution of the hot and dense medium, representing an important tool for its characterization. The study of angular correlations between D mesons and charged particles in Pb-Pb collisions give insight about the energy loss of charm quark and the medium-induced modification of its fragmentation into jets. Moreover, pp collisions help understanding the production mechanisms, fragmentation and hadronization of charm quarks and acts as a reference for p-Pb and Pb-Pb measurements. In this article, the measurement of azimuthal correlations between D^0 meson and charged particles for pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV are presented. The data are also compared with simulations results performed with different Monte Carlo event generators.

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Chapter 1

Introduction

"If I have seen further, it is by standing on the shoulders of Giants."

–Sir Isaac Newton

Universe is made up of matter and matter is made up of 118 elements [1] which have specific physical and chemical properties. These elements are assigned by its chemical symbol and arranged according to their atomic number, electronic configuration and chemical properties in a tabular form known as periodic table [2]. We also know from Dalton's atomic theory, all the matter is composed of atoms, which holds on to all the chemical properties of an element. According to Dalton's atomic theory, atoms are indivisible. In 1998, J.J. Thomson suggested that the atom is a positively charged solid sphere and electrons are embedded in it such a manner to make the atom neutral. In the year 1911, Ernest Rutherford discovered the nucleus from his famous gold-foil experiment. According to Rutherford's model the atom is consisting of a small tiny positively charged center called the nucleus and electrons are moving around the nucleus in a circular path. In 1917, Rutherford discovered the proton inside the nucleus and in the year 1920, he also suggested that a neutral particle may also present inside the nucleus. After the discovery of neutron by James Chadwick in the year 1932, it was confirmed that the nucleus was comprised of protons and neutrons. So, it was then believed that matter was made up of three subatomic particles, i.e., electron, proton and neutron, rather than 100s of chemical elements. However, most of the subatomic particles were discovered in "cosmic rays" during 1940-60. The deep inelastic scattering of electron and proton reveal the existence of quarks

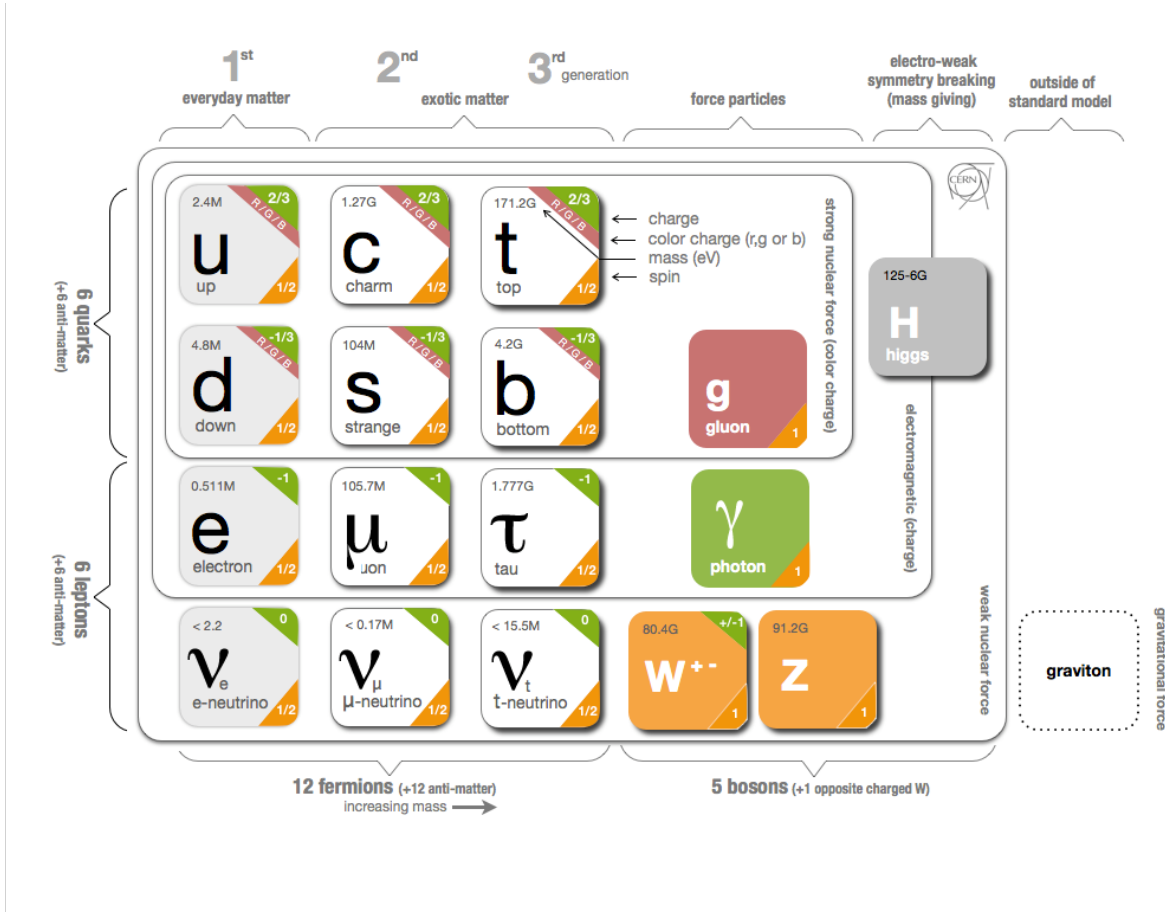


Figure 1.1: The fundamental particles in the standard model [3].

inside protons and neutrons. In addition to this, there gauge bosons which help in mediating the force between two particles in different interactions. In Fig. 1.1, the Standard Model (SM) elementary particles and their corresponding force carriers are tabulated.

1.1 The Standard Model

The Standard Model is the periodic table of particle physics.

Quarks: Six different flavor of quarks are found, up (u), down (d), charm (c), strange (s), top (t) and bottom (b). They all are spin 1/2 fermions and exist in three different colors, i.e., red, green and blue. Every quark has its corresponding anti-quark, which has the opposite charge. The quarks and anti-quarks are combined to form color neutral hadrons. Baryons are made up of three quarks, whereas mesons consist of a quark and an anti-quark. For example,

proton, being a baryon, consists of two up quarks and one down quark (uud), whereas J/ψ , being a meson, consists of one charm and an anti-charm quark ($c\bar{c}$). The quarks can interact among themselves via strong, weak and electromagnetic interactions.

Leptons: There are three leptons, i.e., electron (e), muon (μ) and tau (τ), with their corresponding neutrinos: ν_e, ν_μ, ν_τ . The leptons are electrically charged, whereas the neutrinos are neutral particles. Both the leptons and neutrinos have their respective anti-particles. The electron, muon and tau can interact via both electromagnetic and weak forces. But, the neutrinos can interact via weak force only.

Gauge bosons: The gauge bosons are the force carriers for strong, weak and electromagnetic interactions. The gluons ($m_g = 0$) are the force carrier in the strong interaction. $W^\pm$ ($m_{W^\pm} \sim 80.3$ GeV) and Z^0 ($m_{Z^0} \sim 91.1$ GeV) are the force carriers in weak interaction, whereas photon ($m_\gamma = 0$) is the force mediating particle in electromagnetic interaction. All the gauge bosons responsible for mediating the force have spin equal to 1.

Higgs bosons: The Higgs boson is the particle associated with the Higgs field, which is responsible for giving mass to all the elementary particles. The more strongly particle interacts with the Higgs field, the more massive the particle is. The Higgs boson of mass around 126 GeV was observed independently by the two experiments ATLAS and CMS at LHC in the year 2012, whose existence was initially proposed by Peter Higgs in 1964. In 2013, the Nobel Prize in Physics was awarded jointly to Peter Higgs and François Englert for the theoretical prediction of Higgs Boson.

1.2 Quantum Chromo-Dynamics (QCD)

The strong interaction between quarks and gluons can be described by the field theory of Quantum Chromo-Dynamics. QCD is based on the non-abelian gauge theory with the symmetry group $SU(3)$ of quantum field theory. QCD is very similar to the Quantum Electro-Dynamics

(QED) which describes the electromagnetic interaction between electrons and photons. However, in QCD the quarks have three basic color-charged states (red, blue, green) and associated with non-abelian gauge group SU(3), while in QED the electrons are associated with the abelian group U(1) for electric charge. Both the strong and electromagnetic interactions are mediated by a mass-less vector gauge bosons, called a gluon and photon, respectively. The crucial difference between QED and QCD is the color-charged gluons. The gluons are not only color-charged, but they also produce very strong color fields. So, the lagrangian density of a strong field consists of both quarks and gluons fields.

$$\mathcal{L}_{QCD} = \mathcal{L}_{gluon} + \mathcal{L}_{quark} \quad (1.1)$$

The gluon Lagrangian density is:

$$\mathcal{L}_{gluon} = -\frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} \quad (1.2)$$

with the gauge invariant gluon field strength tensor,

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - gf_{bc}^a A_\mu^b A_\nu^c \quad (1.3)$$

The quark Lagrangian density is:

$$\mathcal{L}_{quark} = \sum_f \bar{\psi}_f [i\gamma^\mu D_\mu - m_f] \psi_f, \quad (1.4)$$

where

$$D_\mu = \partial_\mu + ig \frac{\lambda_a}{2} A_\mu^a \quad (1.5)$$

Substituting 1.2 and 1.4 in 1.1, we get the final Lagrangian density for the strong interaction,

$$\mathcal{L}_{QCD} = -\frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} + \sum_f \bar{\psi}_f [i\gamma^\mu D_\mu - m_f] \psi_f \quad (1.6)$$

In the above equations, A_μ^a are the gluon fields of color and a varies from 1 to 8 and f_{bc}^a denotes the structure constant of SU(3) group. ψ_f is the quark field and f varies from 1 to 6 for the different types of flavors of quarks. D_μ represents the gauge covariant derivative, γ^μ are Dirac matrices which connect the spinor representation to the vector representation of the Lorentz group. λ_a , m_f , g are the Gell-Mann eight matrices, quark mass and strong coupling constant, respectively. So, the strong interaction leads to the interesting concept like quark confinement, asymptotic freedom and chiral symmetry restoration.

1.2.1 Asymptotic freedom

Asymptotic freedom plays a crucial role in QCD at shorter distances, less than about 0.2 fm. At this short distances, the strong coupling constant is so small that the quarks and gluons behave like free and this property is known as asymptotic freedom. To study this first we have to consider the electromagnetic interaction between electron and positron. The Coulomb interaction potential between electron and positron can be defined as

$$V(r) = -\frac{e^2}{4\pi r} \quad (1.7)$$

The Fourier transform of $V(Q^2)$ of $V(r)$ is

$$V(Q^2) = \int V(r)e^{iQ \cdot r} d^3r = -\frac{e^2}{Q^2}, \quad (1.8)$$

where Q is the momentum transfer in the center of mass frame [4]. In QED, virtual e^+e^- pairs are created due to the vacuum polarization effects. These virtual e^+e^- pairs screened the actual electromagnetic field and at short distances the screening effect is less. So, at large Q^2 , the perturbation calculation in QED becomes

$$V(Q^2) = -\frac{e^2(Q^2)}{Q^2} \frac{1}{1 - (e^2/12\pi^2)\ln(Q^2/4m^2)}, \quad (1.9)$$

where m is the mass of electron. At large Q^2 the effective coupling constant is

$$\alpha(Q^2) = \frac{e^2(Q^2)}{4\pi} = \frac{(e^2/4\pi)}{1 - (e^2/12\pi^2)\ln(Q^2/4m^2)} \quad (1.10)$$

This coupling constant $\alpha(Q^2)$ increases with the increase of Q^2 .

Similarly, in QCD, the vacuum polarization effect occurs. The vacuum polarization in QCD involves not only the gluon fragments into the $q\bar{q}$ pairs, but also the gluon turning into gluon pairs. This is not as simple as QED vacuum polarization, where only photon gives to virtual e^+e^- pairs. So, by applying the perturbation theory to the interaction between a quark and an anti-quark at large Q^2 we have the strong effective coupling constant (running coupling constant) is

$$\alpha_s(Q^2) = \frac{g_s^2(Q^2)}{4\pi} = \frac{4\pi}{[11 - (2/3)n_f][\ln(Q^2/\Lambda_{QCD}^2)]}, \quad (1.11)$$

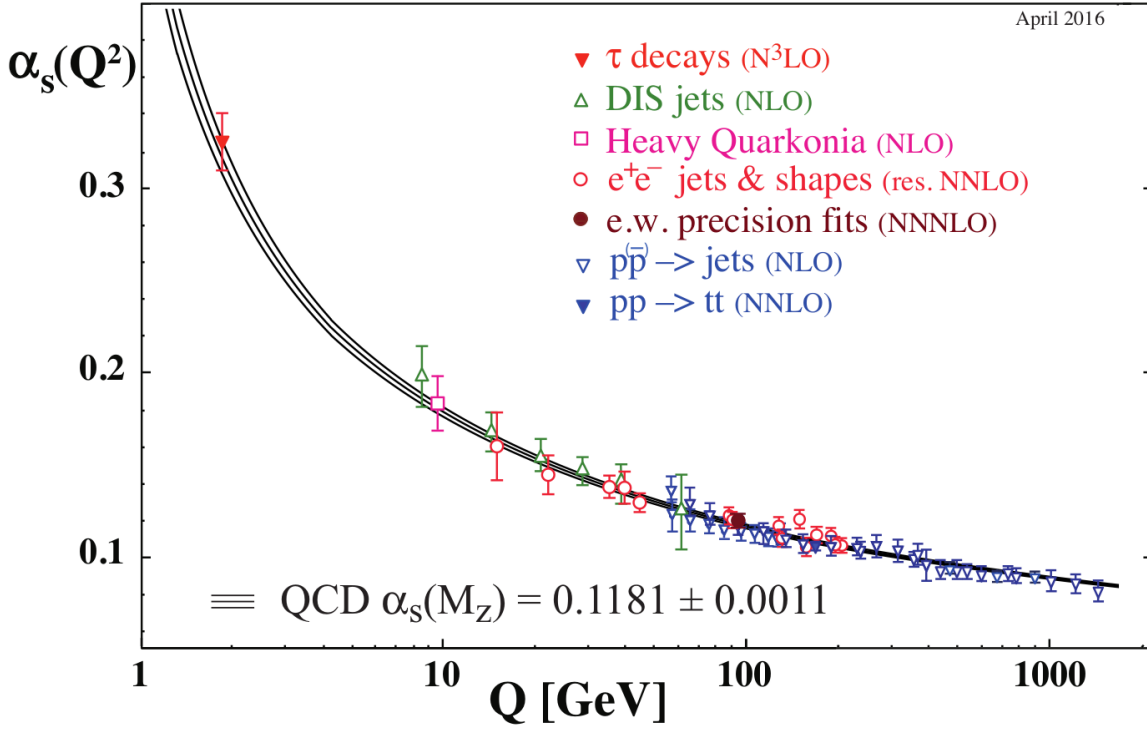


Figure 1.2: The running coupling constant, $\alpha_s(Q^2)$, as a function of momentum transfer Q in data and theoretical prediction using perturbative QCD [5].

where g_s is the QCD coupling constant, n_f is the number of quark flavors, Q^2 is the momentum transfer in strong interaction and Λ_{QCD} is the dimensional QCD scale parameter. Its value is around 250 MeV. The term $(11 - 2/3n_f)$ in Eq.1.11 is always positive, which means when Q^2 increases g_s^2 decreases and this is the basis of asymptotic freedom. The gluons have self coupling as they carry color charges. Due to this self-coupling, gluons have an anti-shielding effect which weakens the coupling as Q^2 increases. This behavior was first predicted by Gross and Wilczek (1973) and Politzer (1973) independently which earned them the Nobel prize in physics in 2004. The first experimental support for it came from detailed studies of deep inelastic lepton-nucleon scattering. The dependencies of α_s as a function of momentum transfer Q from different experiments is shown in Fig. 1.2.

So, it is clear from Fig. 1.2 that at large Q^2 , i.e., $Q^2 \rightarrow \infty$, $\alpha_s \rightarrow 0$, quarks and gluons behave as free particles. This nature of QCD is known as asymptotic freedom. Similarly, at

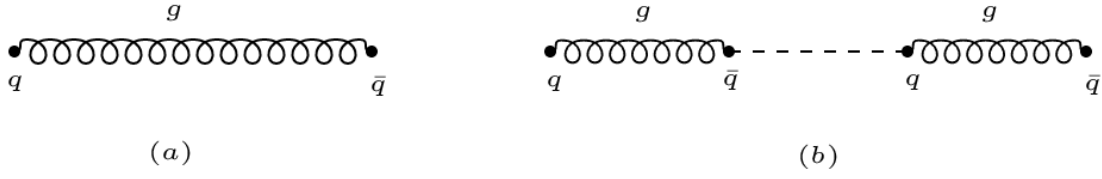


Figure 1.3: (a) quark and anti-quark connected by a stretched gluon string. (b) favorable situation to create a new quark-anti-quark pair involving two gluon strings

small Q^2 , i.e., $Q^2 = \Lambda^2$, $\alpha_s \rightarrow \infty$, the perturbation theory breaks down. And because of the large coupling strength at low Q^2 , quarks and gluons are confined in hadrons.

1.2.2 Confinement

As we discussed earlier in section 1.2.1, at low Q^2 , or large distance, perturbation theory fails. This large distance behavior is related to the confinement of quarks inside a hadron. The QCD vacuum is filled with massless and self interacting gluons. One can expect the quark-anti-quark potential takes the form $\frac{1}{r}$ like QED, but the quark-anti-quark potential is

$$V = -\frac{4}{3} \frac{\alpha_s}{r} + kr, \quad (1.12)$$

where the first term is associated with small r and second term is associated with the confinement at large r . As the second term is linear, if one wants to pull out a quark from a hadron, it simply produces another pair of $q\bar{q}$. It can be understood by visualizing a color string or tube of gluon-gluon interactions between $q\bar{q}$ inside a hadron. So, if we try to pull out the string, at some point, we have given so much energy that it eventually creates a more favorable situation for creating a new $q\bar{q}$ pair. So, now we have instead of one long string, there are two short strings as shown in Fig. 1.3. The value of the string constant is $k \sim 1 \text{ GeV/fm}$. This is why free quarks cannot be found outside a hadron.

1.3 QCD phase diagram and heavy-ion physics

It is believed that 13 billion years ago "Big Bang" occurred and the universe known to us was started to form. After a few micro second of the Big Bang, the universe was in extremely hot and dense state. As time elapsed, the hot and dense state of matter started to expand, going through different phase transitions and at the same time, the Universe started to cool down [6]. There was a phase, where the quarks and gluons are weakly bound and move freely, known as the quark-gluon plasma (QGP) phase. This phase occurred when the temperature (T) was above the critical temperature (T_c) as defined in Quantum Chromodynamics (QCD). When the temperature crosses the QCD critical temperature, a QCD phase transition occurs and quarks are confined to form hadrons like protons and neutrons. After few minutes of Big Bang protons and neutrons were combined together to form nuclei and the Universe still continues to expand till the thermal energy (due to temperature) is less than the binding energy of hydrogen atom. It took a very long time ($\sim 380,000$ years) to form the first hydrogen atom. This Big Bang event is a singular event and we cannot go back in time and study the formation of the early Universe. However, if a mini Bang can be created in the laboratory, then it can be studied well in a controlled manner. This condition can be achieved by increasing the density of the nucleus or by heating the nucleus. In the first method, the nucleus is compressed then the neighboring nucleons started to overlap with each other. As a result the wave function of the individual nucleon will be distorted. When the density increases to $\rho = 10\rho_0$ ($\rho_0 = 0.17$ nucleons/ fm^3) and the internuclear distance is comparable with the nucleon radius, then one can imagine that the nucleon would completely lose its identity and melt into a soup of quarks and gluons. The CBM experiment at GSI plans to study the properties of QGP by compressing the volume of the nucleus through the bombardment of two nuclei at low energy. In the second scenario the nuclear matter is heated upto a temperature beyond critical temperature ($T_c \sim 150$ MeV predicted by QCD). This can be achieved by colliding heavy nuclei at relativistic energy. The Relativistic Heavy Ion Collider (RHIC) experiment at BNL and Large Hadron Collider (LHC) experiments at CERN are studying the properties of QGP by colliding two heavy nuclei at relativistic energy.

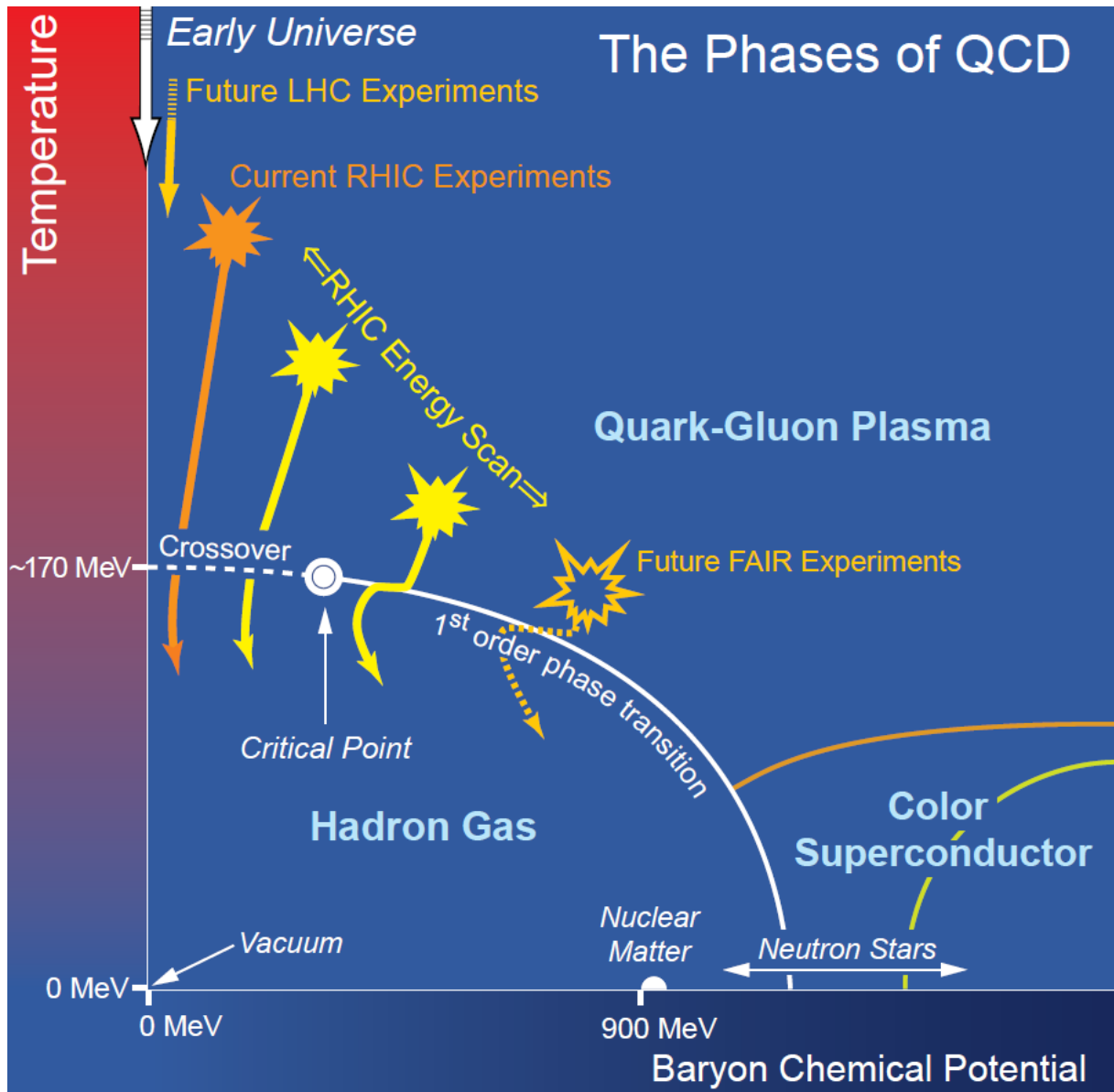


Figure 1.4: The schematic view of QCD phase diagram for nuclear matter [7].

To better understand the QCD vacuum, it is important to study the different phases and transitions between the phases of nuclear matter. Figure 1.4 shows the QCD phase diagram as a function of temperature (T) and baryon chemical potential (μ_B). μ_B is related to the net baryon density of the matter. The energy required to remove or add a baryon at fixed temperature and pressure is determined by μ_B . The ordinary nuclear matter with non-zero density at $T = 0$ is situated somewhere around 1 GeV in the μ_B axis of the $\mu_B - T$ phase diagram. The cold dense matter, neutron star found in nature, is situated somewhere between two to ten times the density of nuclear matter at zero temperature in the phase diagram. At high densities and low temperature, the quarks form *cooper pairs* and form a new condensate [8]. This phase is known as color superconductor phase. In this phase, chiral symmetry is broken and the first order phase transition occurs. At high temperature and high baryon chemical potential hadron gas phase exist. In this phase, nucleons interact with each other and form hadrons, resonances and pions. Further, when the temperature ($T \rightarrow \infty$) and density increase, we have a weakly coupled gas of quarks and gluons known as QGP. There is a smooth cross over between hadron gas phase and QGP phase occurred and is shown as dashed line in Fig. 1.4. The end point where the first order phase transition stops and the cross over starts is known as the critical point.

1.3.1 Lattice QCD

The de-confinement cannot be studied by pQCD. The phase transition from hadronic phase to QGP phase can be understood by the lattice QCD calculation at high temperature and density. The critical temperature (T_c) has been calculated for the case of 2-flavor (u, d considered as light quarks), 3-flavor (u, d, s considered as light quarks) and 2+1-flavor (u, d considered as light quarks and s considered as heavy quark) QCD and found to be 171 ± 4 MeV, 154 ± 8 MeV and 173 ± 8 MeV, respectively [9]. The scaled energy density, ϵ/T^4 , as a function of (T/T_c) is shown in Fig. 1.5. It is observed that there is an abrupt increase of degrees of freedom around T_c and saturates around $2T_c$ for all the flavors of QCD. This indicates a possible phase transition from hadronic state to the QGP state. Also, the equation of state by lattice QCD is always lie

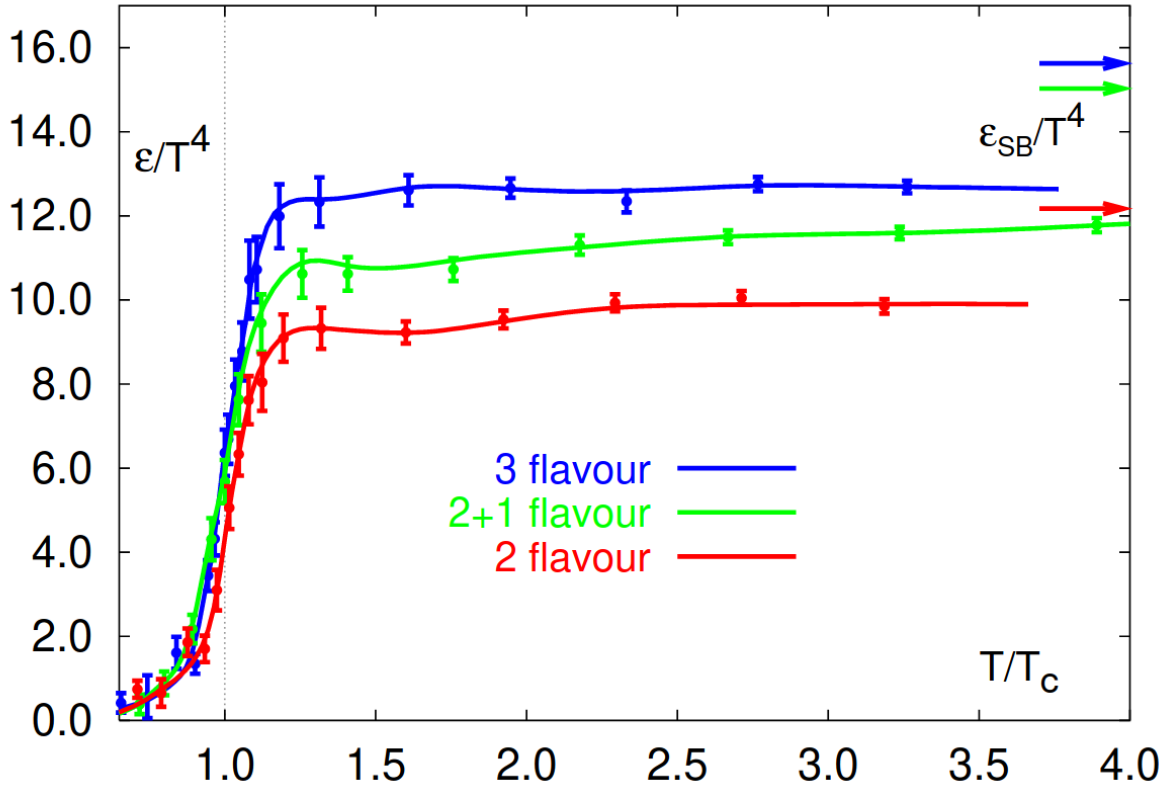


Figure 1.5: The energy density as function of temperature (lattice QCD calculation) [9].

below the Stefan-Boltzmann limit for all the three flavors of QCD shown as an arrow on the right side of Fig. 1.5

1.3.2 Space-time evolution of QCD matter in relativistic high-energy collision

At extreme temperature and density, ordinary matter undergoes a phase transition from a confined phase to a deconfined phase, where quarks and gluons are free from their parent hadrons and interact with each other. A similar kind of condition is formed after a few microseconds of formation of the early universe and we can recreate this condition with the help of ultra relativistic high-energy collision. At the LHC, with the highest energies and nearly zero baryon chemical potential, we can create the deconfined state of matter called the Quark-Gluon Plasma (QGP) and study its different properties. In relativistic heavy-ion collision experiments, two nuclei are accelerated with high velocities nearly the speed of light and collide with each

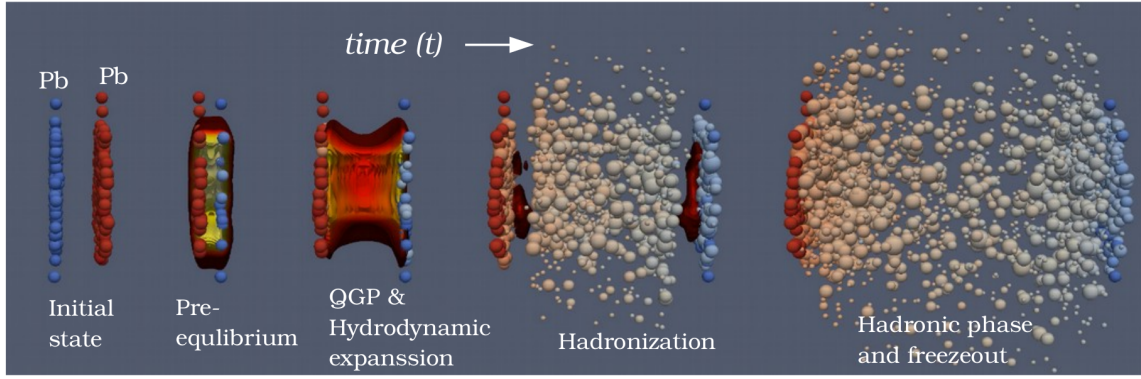


Figure 1.6: The stages of a relativistic heavy-ion collision, formation and expansion of QGP medium. Visualization originally created by Hannah Petersen and Jonah Bernhard [10].

other. The nuclei chosen are mostly spherical in nature and as they are travelled with relativistic velocities, they look like thin disc due to the Lorentz contraction along the beam direction (z -axis). At LHC, Pb nuclei is chosen for heavy-ion collision as it is most stable nuclei and also larger volume of fireball.

A pictorial representation of a heavy-ion collision and its evolution is shown in Fig. 1.6. A nuclear overlap region is created by colliding two nuclei and the region of overlap depends on the impact parameter (b). The impact parameter (b) is defined as the distance between the centers of the two colliding nuclei in the transverse plane. The involved nucleons in the nuclear overlap region are called as "participants" and those are outside this region are called as "spectators". So, for the central collision where $b \sim 0$ almost all the nucleons are participants.

Figure 1.7 is a schematic representation of space-time evolution in hadronic and heavy-ion collision systems. Critical temperature (T_c) and critical density are required for the formation of QGP. If such conditions are not satisfied during the collision then the matter undergoes a hydrodynamical evolution shown in left side of Fig. 1.7. After the impact of nucleons pre-hadronic phase arises, where the deconfinement of partons do not take place in spite of an enhancement of temperature and pressure. However, the recombination of nucleons into hadrons occur and can be detected after the hadron gas freeze-out.

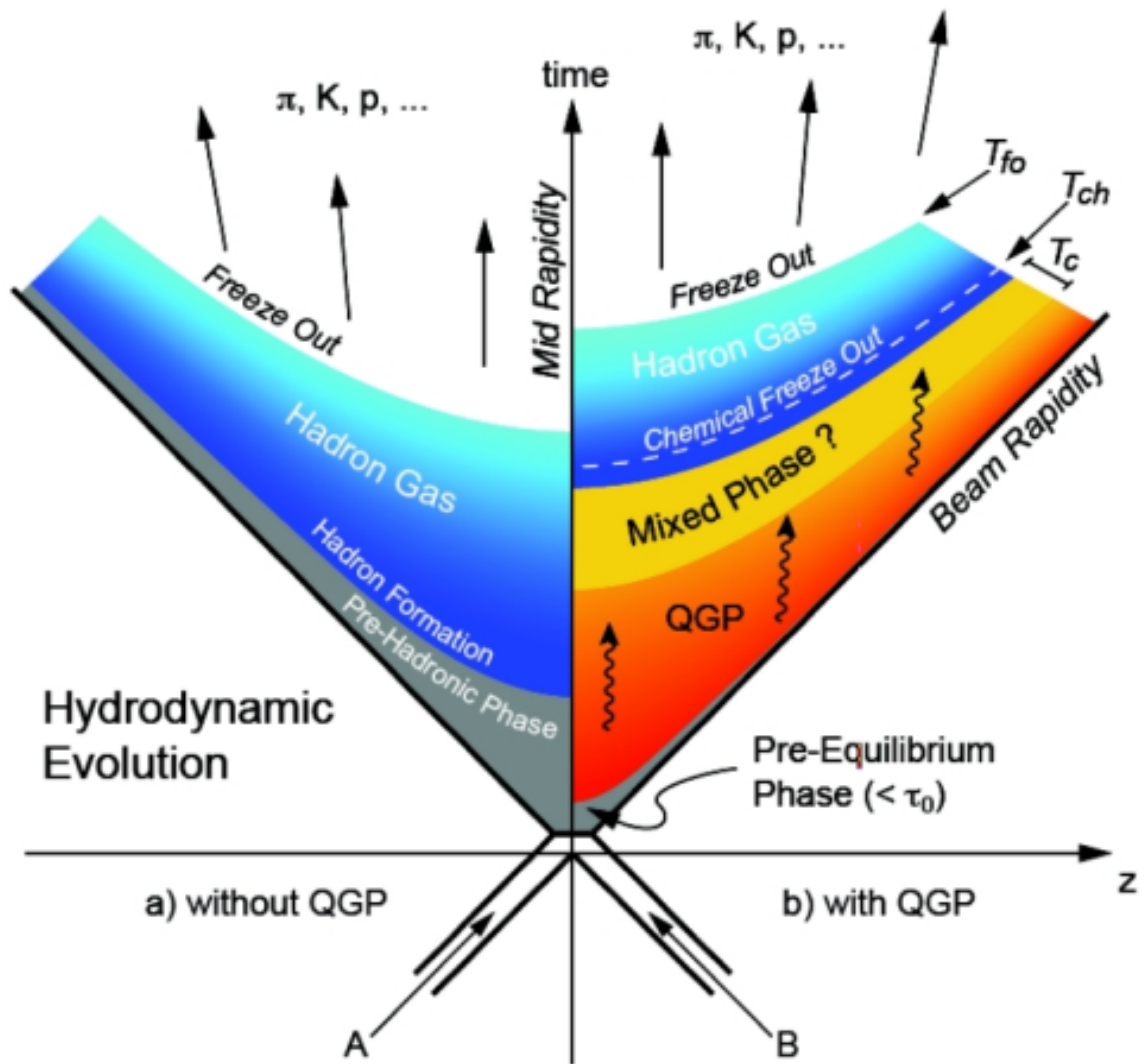


Figure 1.7: The schematic diagram of space-time evolution of relativistic heavy-ion collision and QGP [11].

The formation of QGP and transition to ordinary matter in the heavy-ion collision is demonstrated on the right side of Fig. 1.7. The different stages are as follows:

Pre-equilibrium:

The pre-equilibrium phase occurs just after the collision. In this state, multiple scattering of partons among each other leads to a large number of production of deconfined quarks and gluons. This stage produces high transverse momentum ($p_T \gg 1 \text{ GeV}/c$) particles and also both real and virtual photons; subsequently the virtual photons decay to lepton-antilepton pairs.

Thermalization:

The high density and temperature lead to the formation of QGP where the inelastic and elastic interaction between partons in QGP leads to thermalization. Due to the inner pressure, the system at thermal equilibrium starts to expand and the temperature starts to decrease. After the QGP state a possible mixed phase state occurs which shows first order phase transition signature.

Hadronization:

While the system is expanding and temperature reaches below critical temperature, the hadronization of quarks and gluons start to form new hadrons. The hadronization occurs mainly in two processes (a) fragmentation and (b) coalescence. The mechanism of fragmentation involves the high p_T partons fragment to form low p_T hadrons and dominates at higher energies. In the coalescence mechanism the low p_T partons combine to form high p_T hadrons and dominates at lower energies.

Freeze-out:

After some time inelastic collision between hadrons stopped which leads to the ceasing of formation of new hadrons. This is called *chemical freeze-out*. After the *chemical freeze-out*, the elastic scattering of hadrons with each other occurs. When the mean free path of the hadrons

becomes equivalent to the system size, the elastic scattering of hadrons stops. Then, the hadrons come out of the fireball and detected by the detector in the experiment. The stopping of elastic scattering of hadrons is called *kinetic freeze out* or *thermal freeze out*.

1.4 Experimental Probes to study QGP

1.4.1 Electromagnetic Probe

The photons and dileptons are considered as a great tool to characterize the dense and hot medium produced in the heavy-ion collisions. These are known as the electromagnetic probes as they interact via electromagnetically [12]. Their production cross-section is small and their mean free path is larger than the system size (~ 10 fm). Once they are produced they do not further interact with the medium [13]. So, they escape from the collision zone and carry accurate information about the circumstances of their production to the detector [14]. But the measurement of direct photons is a challenging process due to the large background coming from the electromagnetic decays of hadrons (mainly π^0 , η , ω) [15].

Direct photon:

The direct photon emitted from the fireball produced in the collision process can act as a tool for studying the properties of QGP. As the lifetime of QGP is very short, it hadronizes to hadrons and eventually, a large number of hadrons decay into photons. So, these decay photons are background and are needed to be removed to measure the direct photon. The background photons are removed by different techniques like invariant mass, mixed event method [12]. However, the measurement of the direct photon is critical. The direct photons are coming from several sources in nucleus-nucleus collisions. *Prompt photons:* These are produced from initial hard collisions by the reaction $a + b \rightarrow \gamma + X$. *Fragmentation photons:* These are coming from the fragmentation of initial hard scattered partons ($q \rightarrow q + \gamma$). *Pre-equilibrium photons:* These photons are emitted in the pre-equilibrium stages of the collision and difficult to distinguish from thermal photons. *Thermal Photons:* These are emitted from QGP phase as well as hadronic phase.

Therefore, the thermal photons are very important [13]. The thermal photons are mainly created through annihilation, Compton and bremsstrahlung processes. In the annihilation process, a quark and an anti-quark annihilated to form gluon and photon ($q + \bar{q} \rightarrow g + \gamma$), while in the Compton process a gluon can interact with a quark (anti-quark) to produce a photon and quark (anti-quark) ($g + q(\bar{q}) \rightarrow \gamma + q(\bar{q})$). This process is called as Compton process as the incident gluon plays the role analogous to the incident photon in the Compton scattering. The production rate and the momentum distribution of the photon depend on the momentum distributions of quarks, anti-quarks and gluons in the plasma and these are governed by the thermodynamical condition of the plasma. So, the photon produced in the QGP carries the information about the thermodynamical state of the medium at the time of their production [12].

Dilepton:

The dileptons are produced at every stage of heavy-ion collision like the photons. The q interact with $\bar{q}$ to produce a virtual photon (γ^*), which subsequently decays to lepton pairs ($q + \bar{q} \rightarrow \gamma^* \rightarrow l^+ + l^-$) in the QGP phase, whereas in the hadronic phase lepton pairs are produced from the decays of hadrons or from the interaction of charged hadrons with their anti-particles. The emission process of dileptons are classified in three different regions according to the mass (M) of dileptons. (i) $M < M_\Phi$ ($1.024 \text{ GeV}/c^2$), decays of vector mesons into lepton pairs are dominating sources, (ii) $M_\Phi \leq M \leq M_{J/\psi}$ ($3.1 \text{ GeV}/c^2$), thermal production of QGP dominates, (iii) $M \geq M_{J/\psi}$, dominated by charmed decay [12]. The first process is a very important process because it can provide the information about possible in medium modifications of hadronic properties at high density, especially of the ρ -meson [16, 17]. The lifetime of the fireball can be predicted by measuring the ρ and ω peak with the help of dileptons masses [18]. Dileptons are better suited to probe QGP than the direct photons because of additional information of invariant mass, which photons do not have.

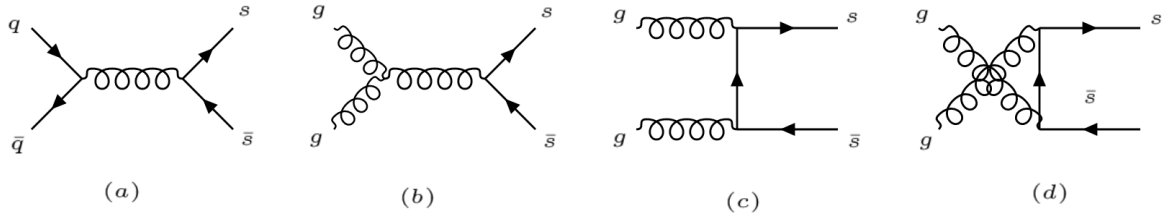


Figure 1.8: The Feynman diagrams of $s\bar{s}$ production in QGP. (a) $s\bar{s}$ formation by the $q\bar{q}$ annihilation process. (b)-(d) represent the production of $s\bar{s}$ through gluon fusion process [19].

1.4.2 Strangeness enhancement

Strangeness enhancement is one of the signatures of QGP in the heavy-ion collision and it was first theoretically proposed by Rafelski and Muller [19–21]. The enhancement of strange particles are important observables because at the initial stage, no strange (s) quarks are present as the colliding nuclei contain only u and d quarks. This indicates that strange quarks are produced thermally in the strong interaction process in the hot dense QCD medium and the enhancement shows in the final stage. It has been also originally proposed that the production of strange particles is enhanced in quark-gluon phase as compared to hadronic phase [22, 23]. This is because the gluon fusion ($gg \rightarrow s\bar{s}$) process is dominant in QGP medium and it is absent in hadronic phase and the cross-sections are very low for pp interactions. The $s\bar{s}$ can be produced through $q\bar{q}$ annihilation process and gluon fusion process in the QGP medium. The Feynman diagram representation of these two processes is shown in Fig. 1.8.

The production of strange quark and strange particles produced in a high density medium is shown pictorially in Fig. 1.9. For example, consider the zero temperature high density region. If the system melts to a soup of quarks, then it is made primarily by u and d quarks alone, as the nucleons are made by u and d quarks only. So, the Fermi energy (E_F) and the Fermi momentum (p_F) are nearly equal for this created soup, as the masses of u and d quarks are nearly zero. When the matter density increases the Fermi energy also increases. So, at matter density $\rho \sim 10\rho_0$, where ρ_0 is the nucleon density, the Fermi energy becomes $E_F \simeq 450$ MeV which is larger than the mass of $s\bar{s}$ pair. Hence, $s\bar{s}$ can be produced easily as compared to $u\bar{u}$ or $d\bar{d}$ pairs in the medium, which leads to the enhancement of strangeness production. After the formation of $s\bar{s}$

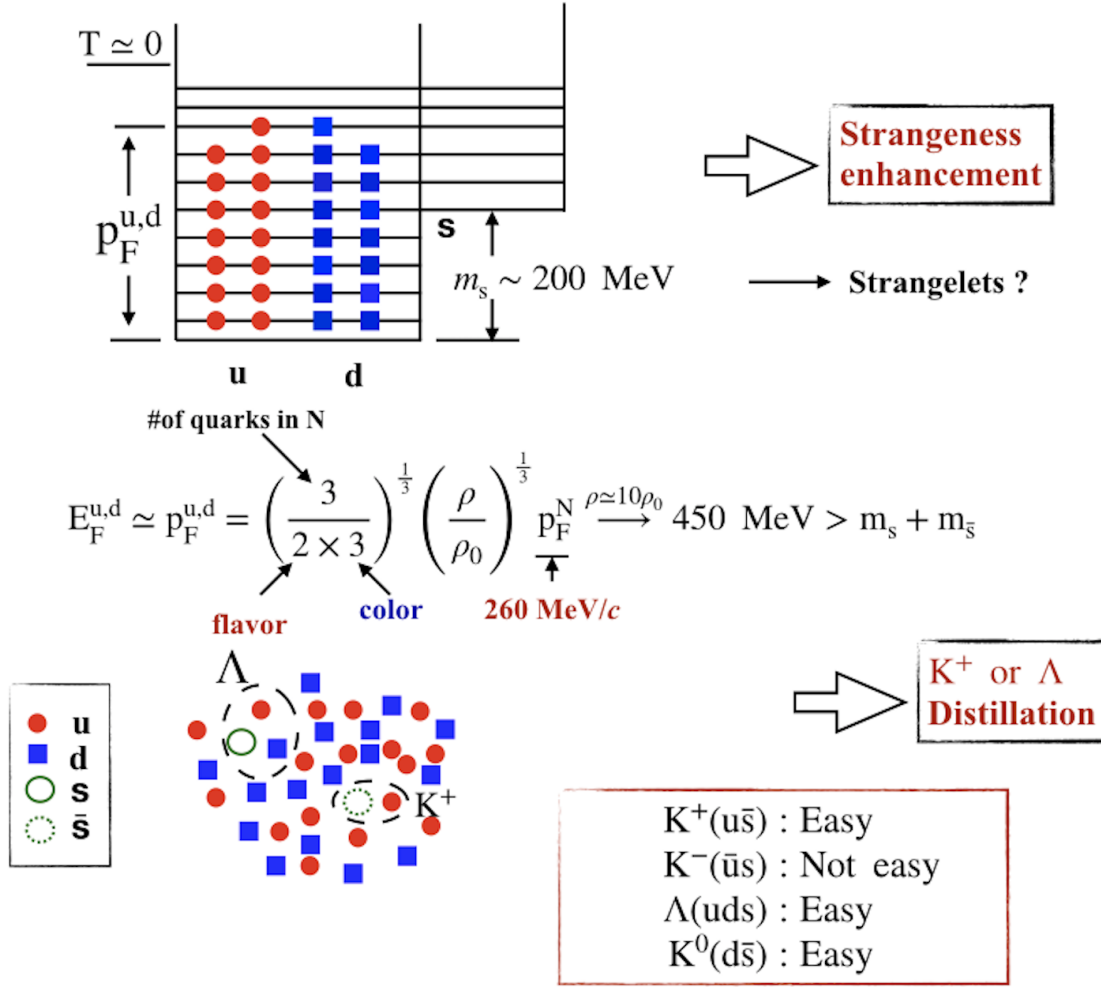


Figure 1.9: Pictorial representation of strangeness enhancement and distillation of K^+ (Λ or K^0) in high density quark matter. This pictorial representation originally created by Shoji Nagamiya [24].

in the soup of u and d quark, it is easy for a $\bar{s}$ to find a u or d quark to form K^+ ($u\bar{s}$) and K^0 ($d\bar{s}$). But it is not easy to find a $\bar{u}$ to combine with s to form K^- ($\bar{u}s$). Therefore, s quark combines with both u and d , which is plentifully available in the medium, to form Λ (uds) baryon [24].

The strangeness enhancement studied in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ in ALICE experiment [25] is compared with the results of Au–Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ [26–28] and Pb–Pb collisions at $\sqrt{s_{NN}} = 17.2 \text{ GeV}$ [29, 30] in STAR and NA57 experiments, respectively. (Although there is no advantage with Au–Au collision, but the RHIC accelerator was designed to provide Au-beams.) The comparison is shown in Fig. 1.10. The main observables

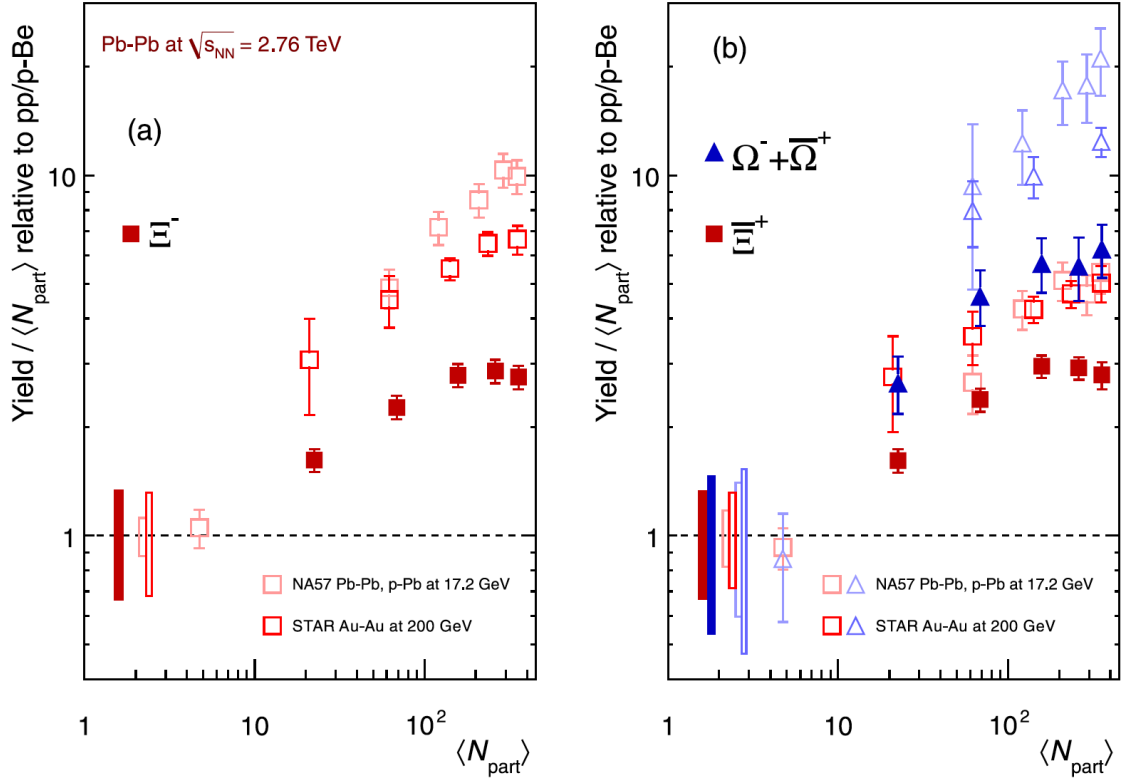


Figure 1.10: The strange hadron production as a function of the mean number of participants $\langle N_{part} \rangle$ in the ALICE at the LHC (solid symbols) compared to the RHIC and SPS results (open circle) [25].

to study the strangeness enhancement is the strangeness enhancement factor ($E(h)$) for a hadron (h) and is defined as:

$$E(h) = \frac{dN/dy(h)^{AA}}{N_{evt}^{AA} \langle N_{part}^{AA} \rangle} \frac{N_{evt}^{pp} \langle N_{part}^{pp} \rangle}{dN/dy(h)^{pp}}, \quad (1.13)$$

where $dN/dy(h)^{AA}$ and $dN/dy(h)^{pp}$ are the particle yields per unit rapidity in A-A and pp collisions, respectively. N_{evt}^{AA} and N_{evt}^{pp} are the number of events for A-A and pp collision systems. $\langle N_{part}^{pp} \rangle$ represents the mean number of participants. The enhancement of Ξ^- , Ξ^+ and $\Omega^+ + \Omega^-$ is shown in Fig. 1.10 (a) and (b), respectively. The solid symbols are the ALICE data points, whereas the open symbols are the NA57 and STAR data points. It is clearly evident from the Fig. 1.10 that more enhancement of strangeness is seen for particles containing more number of strange quarks at both low and high energies. It has also been observed that the enhancement of strangeness decreases with an increase in collision energy.

1.4.3 Quarkonium suppression

Quarkonia is the bound state of $c\bar{c}$ or $b\bar{b}$ quark pairs. The c and b quarks have large masses, so they are produced in the initial hard scattering process. J/ψ is known to be the most common form of charmonium ($c\bar{c}$) and was discovered by Ritcher and Ting separately in 1974. This is well known as the "November revolution" [31]. The *Debye screening* plays very important role in the suppression of J/ψ in high density medium. The phenomenon of screening of color charge due to quarks, anti-quarks and gluons in the presence of quark gluon plasma is commonly known as *Debye screening*. This phenomenon can be explained as follows: Let A and B are two persons. They went to a hotel together and they discussed with each other. So, their mutual interaction was strong. Next day they went to a conference and talked in presence of other people. Naturally their mutual interaction was weakened as it was screened by other people [32]. Similarly, if the J/ψ is placed in a QGP medium, *Debye screening* plays the role and weakens the interaction between c and $\bar{c}$. The string tension between c and $\bar{c}$ becomes zero in the QGP medium as the quarks and gluons are in the deconfined state. These two effects result the suppression of J/ψ production in the nucleus-nucleus collision as first suggested by Matsui and Satz in 1984 [33]. Let's briefly describe the mechanism of J/ψ suppression in the presence of QGP medium. Suppose J/ψ is a two body system of c and $\bar{c}$ quarks and the two quarks are placed at r distance apart. Then, the potential between them is

$$V(r) = kr - \frac{\alpha_{eff}}{r}, \quad (1.14)$$

where $\alpha_{eff} = q^2/4\pi$ and k is the string constant. The first term is due to the string tension between c and $\bar{c}$ and the second term is due to the Coulomb effect. Now the $c\bar{c}$ system is placed inside the QGP medium. The string constant(k) between c and $\bar{c}$ will vanish. Then only Coulomb interaction potential is present between the c and $\bar{c}$. This long range Coulomb interaction potential is now modified to short range Yukawa potential due to the screening effect. The Yukawa potential is

$$V(r) = \frac{qe^{-\frac{r}{\lambda_D}}}{4\pi r} \quad (1.15)$$

The Debye screening length(λ_D) is inversely proportional to the temperature. The $c\bar{c}$ pair confined within the Debye screening length. When the temperature is increased, the number of q and $\bar{q}$ increases, and the screening radius decreases as it is inversely proportional to temperature. If the screening radius becomes shorter than the hadron radius itself then q and $\bar{q}$ can no longer form the bound state to form a meson and therefore deconfined. In the $c\bar{c}$ case, it dissociates into a separate c and $\bar{c}$ in the plasma. After that the c and $\bar{c}$ are hadronized to form open charm mesons such as D ($c\bar{u}$ and $c\bar{d}$), $\bar{D}$ ($\bar{c}u$ and $\bar{c}d$), D_s ($c\bar{s}$) and $\bar{D}_s$ ($\bar{c}s$) by combining with light quark. As a result, the J/ψ is less in the final stage if the medium is QGP compared to the medium of no QGP. Therefore the suppression of production of J/ψ particle can be used as a signature for the presence of QGP [34].

In the ALICE experiment, the J/ψ suppression is seen in both Pb – Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV [35] and 5.02 TeV [36]. The main observables to study the J/ψ suppression is the nuclear modification factor (R_{AA}), which is defined as the ratio of J/ψ yield measured in Pb–Pb collision to the J/ψ yield in pp collision. Therefore, R_{AA} is expressed as:

$$R_{AA}^i = \frac{Y_{J/\psi}^i(\Delta p_T, \Delta y)}{\langle T_{AA}^i \rangle \sigma_{J/\psi}^{pp}(\Delta p_T, \Delta y)}, \quad (1.16)$$

where $Y_{J/\psi}^i(\Delta p_T, \Delta y)$ is the J/ψ yield measured in Pb–Pb collisions for centrality class i and $\langle T_{AA}^i \rangle$ is the nuclear overlap function calculated using Glauber Model [37] in centrality class i . $\sigma_{J/\psi}^{pp}(\Delta p_T, \Delta y)$ is the inclusive J/ψ cross section in pp collisions.

The R_{AA} of inclusive J/ψ in the range $2.5 < y < 4$ and $p_T \geq 0$ GeV/c measured at $\sqrt{s_{NN}} = 2.56$ TeV is shown in Fig. 1.11 as a function of charged particle multiplicity, $dN_{ch}/d\eta$ (left side) and the mean number of participants, $\langle N_{part} \rangle$ (right side). The centrality integrated R_{AA} of J/ψ is found to be $R_{AA}^{0\%-80\%} = 0.545 \pm 0.032(\text{stat}) \pm 0.083(\text{syst})$, which is showing a clear suppression of J/ψ . The measured R_{AA} is compared with the results obtained from the PHENIX experiment in both forward and mid rapidity in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [38][39][40] and shown in Fig. 1.11. The inclusive J/ψ R_{AA} measured in ALICE is a factor of 3 larger for $dN_{ch}/d\eta \geq 600$ ($N_{part} \geq 180$). It is also not showing any significant centrality dependence [35].

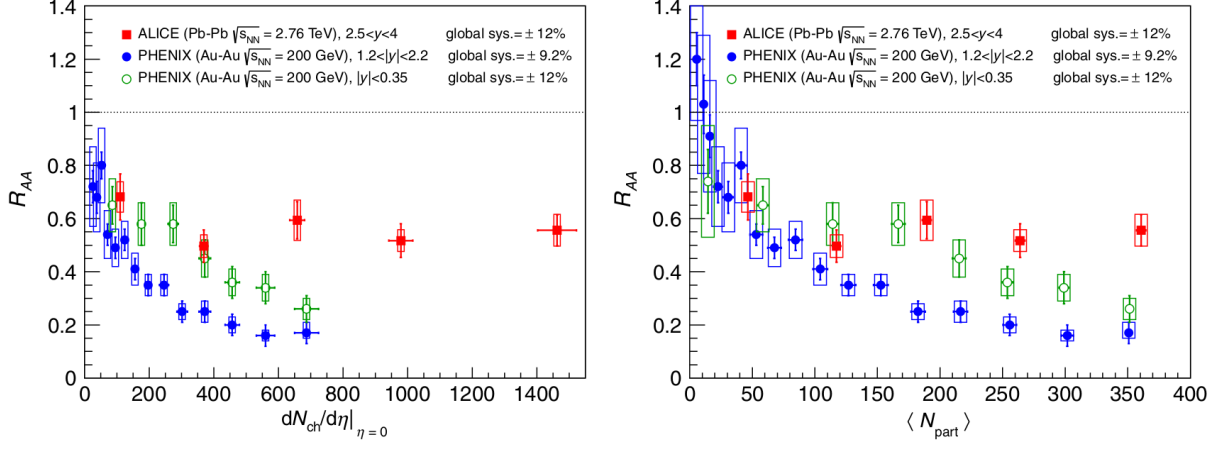


Figure 1.11: Nuclear modification factor (R_{AA}) of inclusive J/ψ as a function of $dN_{ch}/d\eta$ (Left panel) and N_{part} (Right panel) [35].

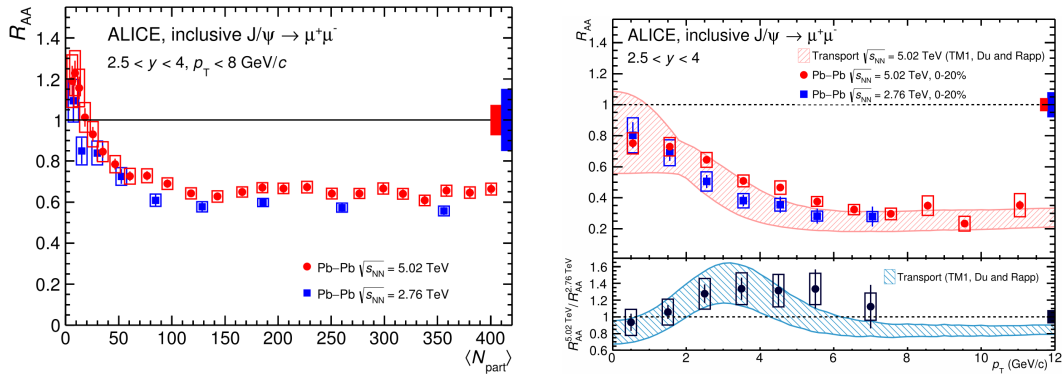


Figure 1.12: R_{AA} of J/ψ as a function of N_{part} at $\sqrt{s_{NN}} = 2.76$ TeV (left panel) and as a function of p_T at $\sqrt{s_{NN}} = 5.02$ TeV (right panel) in ALICE [36].

The comparison of centrality and p_T dependence of J/ψ R_{AA} in ALICE at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV is studied for the test of suppression and regeneration effect in the production of J/ψ . The color screening effect leads to the suppression of J/ψ , which is stronger in higher collision energy due to the higher QGP temperature. But, the $c\bar{c}$ production cross section also increases which leads to stronger recombination effects. These two effects are acting in the opposite way. So, by studying the J/ψ R_{AA} in different collision energies, we can get more information about the QGP evolution. The left panel of Fig. 1.12 shows the centrality dependence of R_{AA} for inclusive J/ψ measured in the range $2.5 < y < 4$, $p_T < 8$ GeV/c in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The centrality integrated R_{AA} of J/ψ is found to be $R_{AA}^{0\%-80\%} = 0.66 \pm 0.01(\text{stat}) \pm 0.05(\text{syst})$, which is higher than the R_{AA} measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The comparison of R_{AA} at $\sqrt{s_{NN}} = 2.76$ and $\sqrt{s_{NN}} = 5.02$ TeV is also shown in the left panel of Fig. 1.12 and it exhibits a systematic difference of about 15%, "even if the effect is within the total uncertainty of the measurements". The right panel of the Fig. 1.12 shows the comparison of p_T dependence of J/ψ R_{AA} in both collision energies $\sqrt{s_{NN}} = 2.76$ and $\sqrt{s_{NN}} = 5.02$ TeV in 0-20% centrality class and it exhibits an increase at low p_T . The ratio (r) of J/ψ R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV with respect to J/ψ R_{AA} at $\sqrt{s_{NN}} = 2.76$ TeV is calculated for the same centrality class and shown in the bottom panel of the right side of the Fig.1.12. The ratio is consistent for all the p_T region except for the region $2 < p_T < 6$ GeV/c, which is showing an increase in ratio. The data is compared with the theoretical transport model (TM1) [41, 42], where continuous dissociation and the regeneration of J/ψ is included in both the QGP and hadronic phase. It is inferred that the suppression mechanism is dominant at high p_T and regeneration mechanism dominant at low p_T for the production of J/ψ in QGP [36].

1.4.4 Jet quenching

The formation of heavy quarks and gluon scattering occurs in the early stage of the collision before the formation of QGP. These quarks and gluons, known as partons, travel through the medium and gets fragmented into collimated sprays of particles called "jets" [43]. These jets are formed back - to - back in hadron-hadron or e^+e^- collisions due to conservation of

momentum [34]. The high energy partons lose energy while travelling through the medium in heavy-ion collision. This causes the modification of jet structure. This mechanism is commonly known as "jet quenching". Theoretically, in 1982, J.D. Bjorken gave the idea of jet quenching by parton energy loss [44] through elastic parton scattering in the medium as a dominant process. But he was found to be incorrect. Later on Gyulassy and collaborators [45–47] suggested that the induced gluon bremsstrahlung mechanism is a more dominant one and fully evaluated by Baier, Dokshitzer, Mueller, Peign'e, and Schiff [48, 49]. Experimentally, jet quenching can be studied using the *two particle correlation* method.

Two particle correlation:

Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have studied the jet quenching via two particle correlations of high momentum hadrons and jet reconstruction method [43]. PHENIX experiment adopted the two particle angular correlation between high p_T charged particle and (π^0) to study the jet properties [50]. In this technique, the π^0 is considered as triggered particle and charged hadrons are considered as associated particles. So, the azimuthal angular difference becomes $\Delta\varphi = \varphi_{\text{trig}} - \varphi_{\text{assoc}}$. The angular distribution is plotted in the range $(-\pi/2, 3\pi/2)$ to demonstrate the features of back to back jets and this is shown in Fig. 1.13. The peak seen around 0 is known as near-side (NS) peak as both the trigger and associate particles are from the same jet, whereas the peak around π is known as away-side (AS) peak as the trigger and associate particles are from same and opposite side (recoiling) jet. Figure 1.13 shows the angular two particle correlation distribution of trigger particle momentum between $3.0 < p_T^{\pi^0} < 3.5$ GeV/c with associate particle p_T within 1.4 - 5.0 GeV/c. The jet fragmentation properties and parton intrinsic momentum were also extracted from this measurement. It was found to be consistent with the earlier results of jet measurements and also with the PYTHIA simulations. This measurement established that the two-particle correlation method is an indirect tool to study the jet properties.

The STAR experiment observed the jet quenching effect by studying the two particle correlation method in heavy-ion collision. To differentiate between the initial state effect and the final

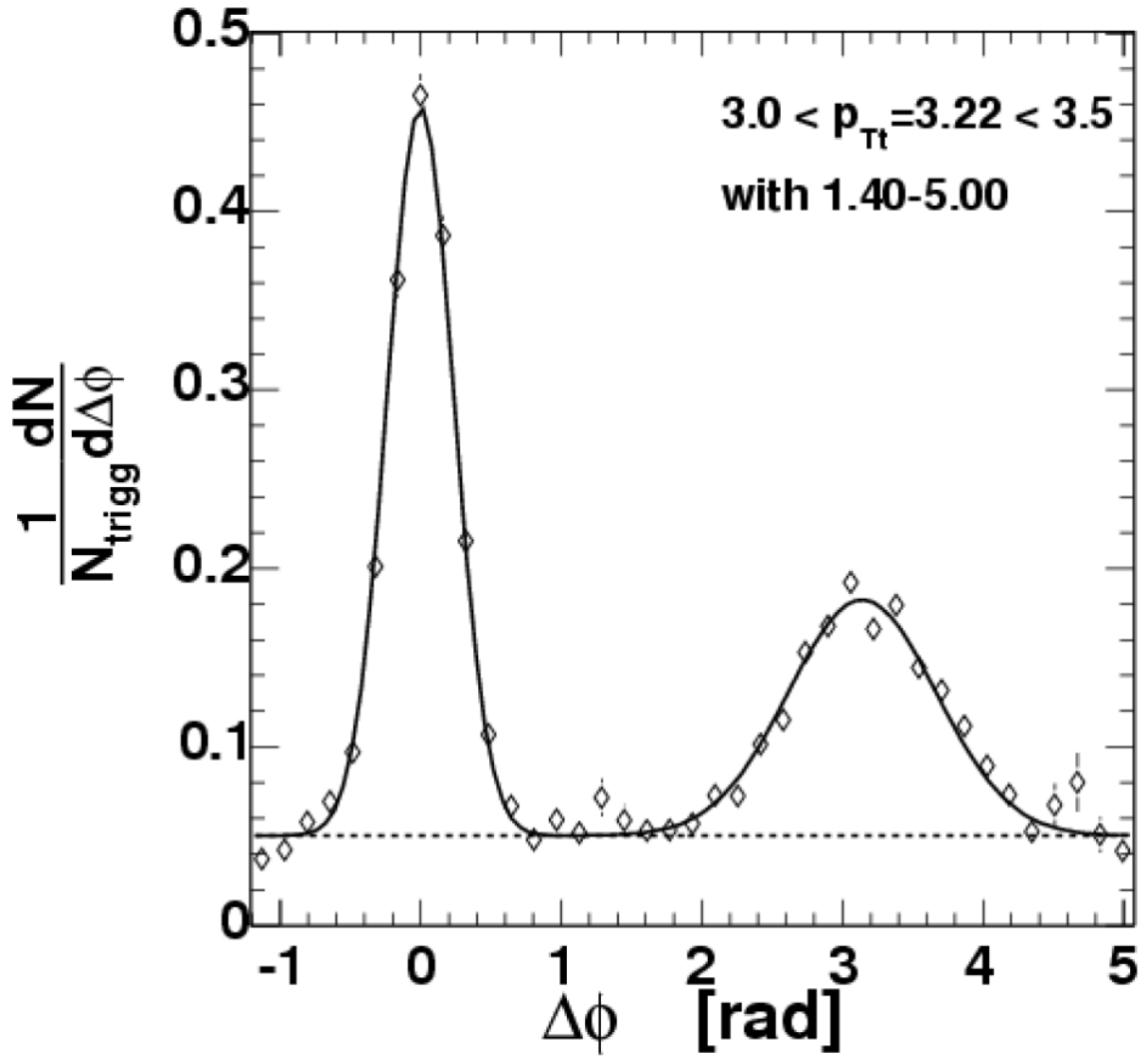


Figure 1.13: [PHENIX] Two particle azimuthal angular correlation distribution (Trigger particle: $3.0 < p_{\text{T}}^0 < 3.5$ GeV/c, Associate particle p_{T} : 1.4 - 5.0 GeV/c) [50] .

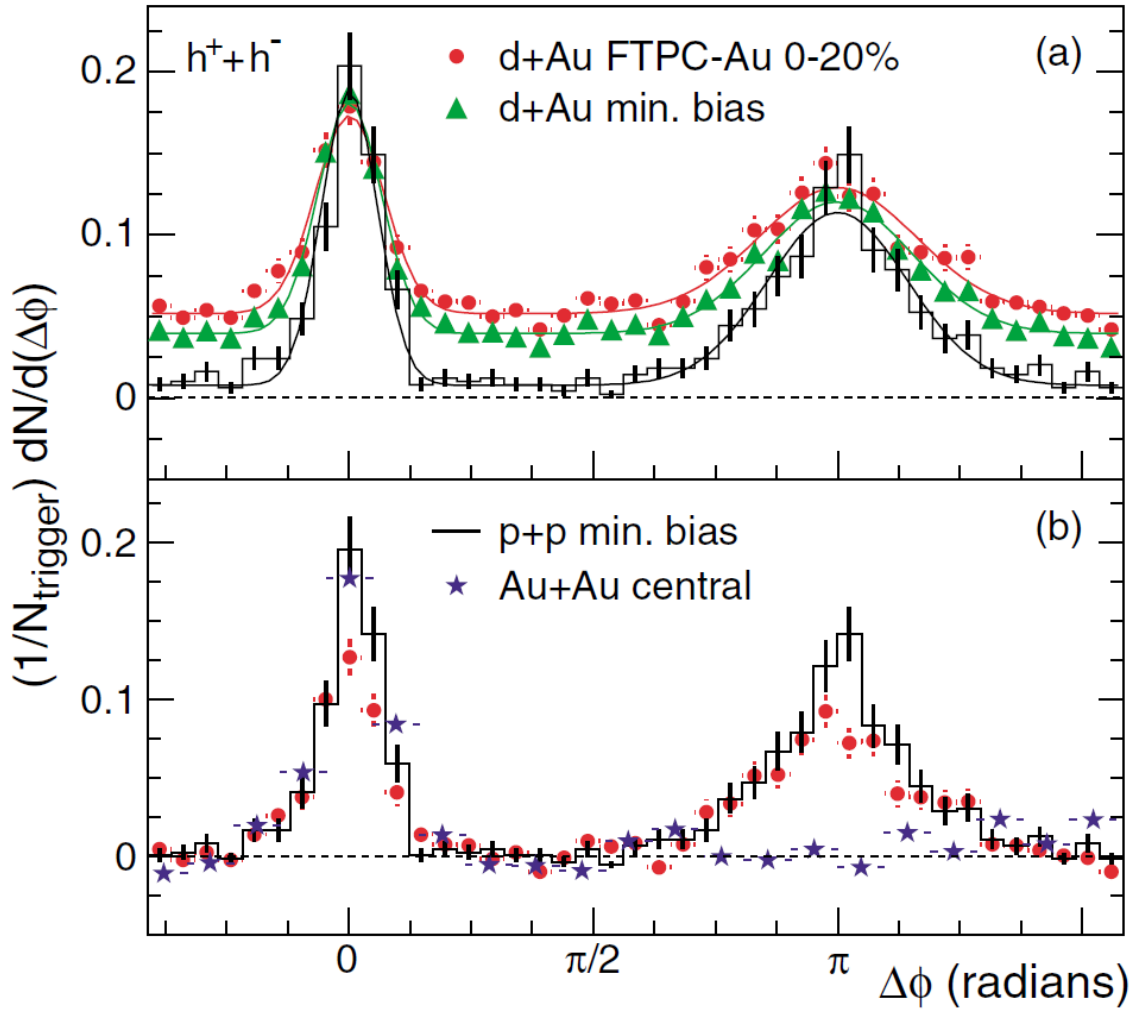


Figure 1.14: [STAR] Two particle azimuthal correlation distribution. (a) pp minimum bias, d–Au central and minimum bias systems, (b) pp minimum bias, d–Au central and Au–Au central collision systems [51].

state effect, the measurement was carried out for pp, Au–Au, and d–Au collisions at $\sqrt{s} = 200$ GeV [51]. Figure 1.14(a) represents the two particle azimuthal correlation distribution for p-p, d–Au central and d–Au minimum bias systems. All these three systems are showing similar trend in both near-side and away-side. The pedestal subtracted azimuthal angular correlation distribution for p-p and d–Au collision and both the pedestal and elliptic flow contribution subtracted azimuthal angular correlation distribution for Au–Au collision are shown in Fig. 1.14(b). It is seen that the near-side peak is same for all the three systems, but the away-side peak is suppressed compared to the p-p and d–Au systems. If the suppression is due to the initial state effect, then the suppression of away-side correlation in d–Au collision system would have been observed. But there is no evidence of suppression of away-side in d–Au system. As the suppression of away-side peak is observed only in Au–Au collisions, not in pp and d–Au collisions, this effect is attributed to the final-state interactions of partons with the dense medium produced in the Au–Au collisions. PHENIX experiment has also done this measurement in Au–Au collision systems for different p_T region of trigger and associated particles [52] and is shown in Fig. 1.15. A clear suppression of away-side is seen in Fig. 1.15 for the $p_T^{\text{trig}} > 4.0$ GeV/c and $p_T^{\text{assoc}} > 3.0$ GeV/c. Both the STAR and the PHENIX experiments of RHIC are showing suppression of away-side peak in the measurement of two particle azimuthal angular correlation in Au–Au collisions. ALICE experiment at LHC measured the particle-yield modification through azimuthal dihadron correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [53] to study the jet quenching. In this method the quantity I_{AA} is the main observable, which is defined as the ratio of correlation yield measured in heavy-ion collision with respect to pp collision. It can be expressed as,

$$I_{AA} = \frac{Y_{AA}^{\text{correl}}}{Y_{pp}^{\text{correl}}} \quad (1.17)$$

The value of I_{AA} should be unity in the absence of medium effects and it will deviate from unity in the presence of any medium effects.

The I_{AA} for NS and AS in most central collision (0%-5%) and peripheral collision (60% - 90%) with $8 < p_{t,\text{trig}} < 15$ GeV/c is shown in Fig. 1.16. The I_{AA} is 0.6 in the most central region for AS which indicates that there is an in-medium energy loss. The values of I_{AA} in peripheral

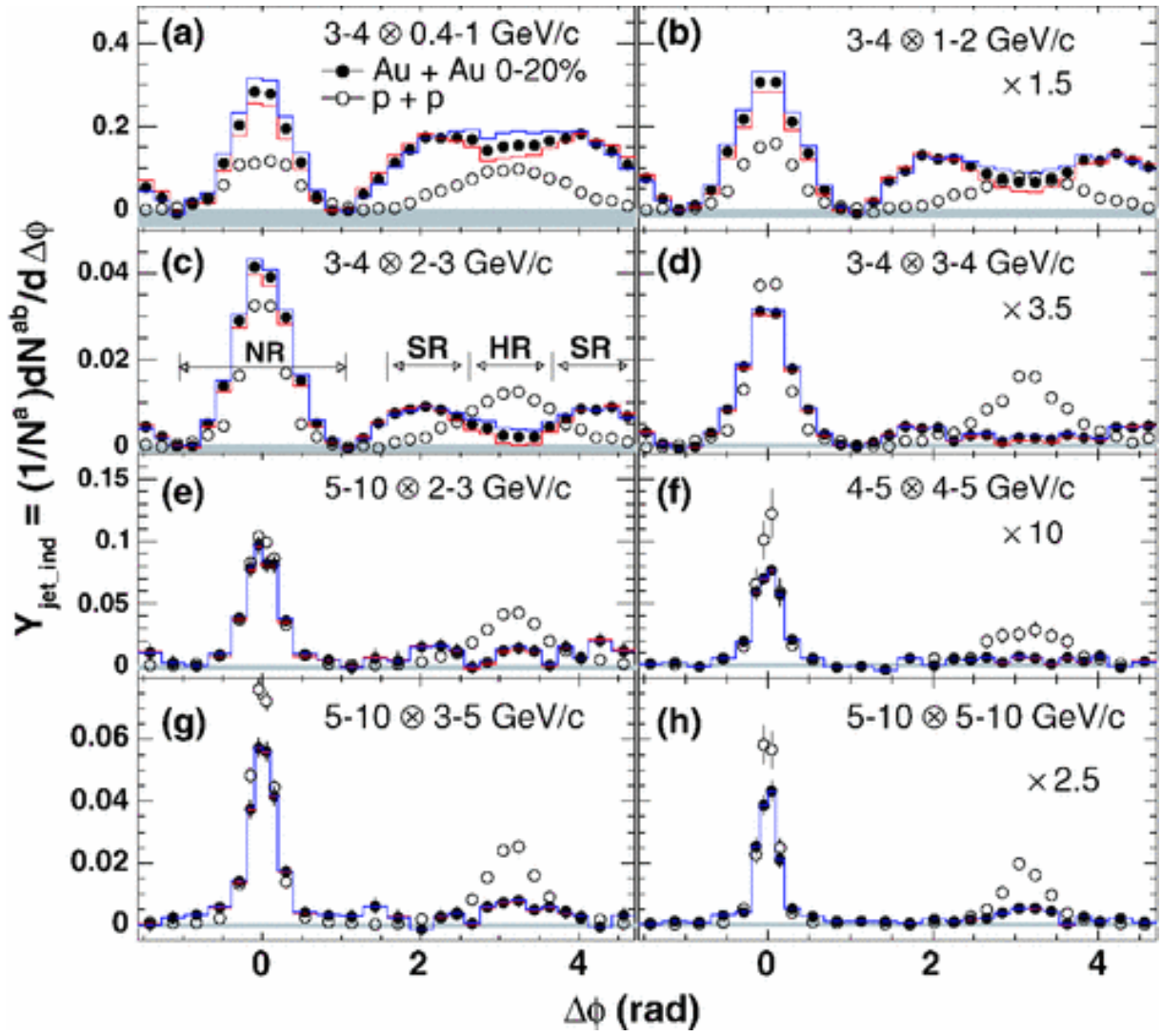


Figure 1.15: [PHENIX] Yield per trigger as a function of $\Delta\phi$ for different p_T region of trigger and associated particles in Au–Au (0% - 20% centrality) and in pp collision [52].

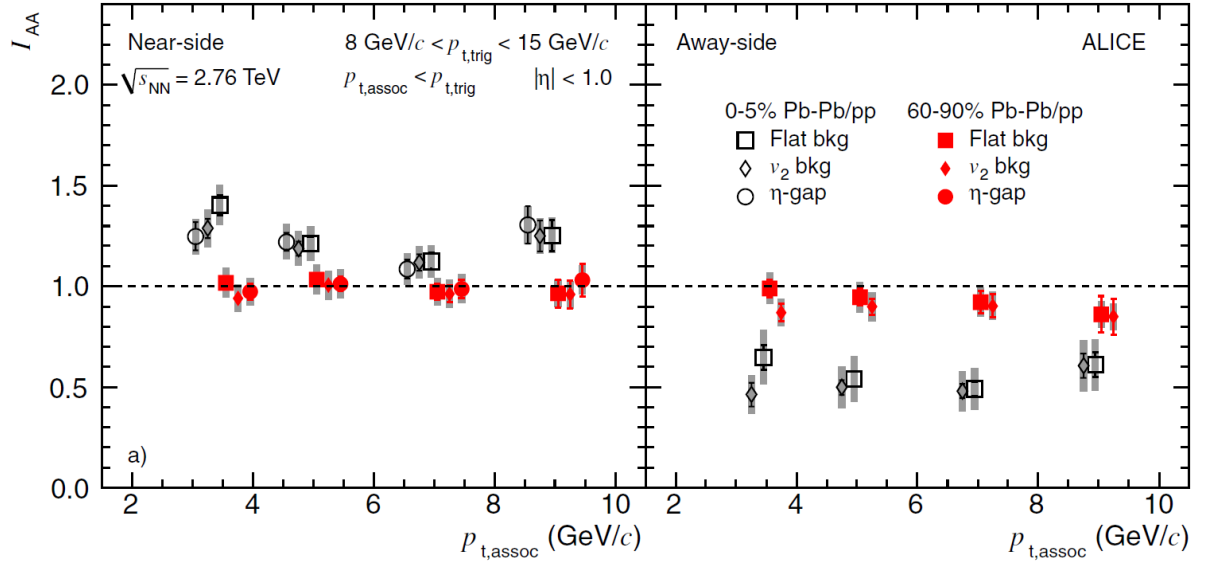


Figure 1.16: [ALICE] I_{AA} for most central collision (0%-5%) and peripheral collision (60% - 90%) with black open points and red solid points, respectively [53].

collision approaches to unity for both NS and AS, which again indicates that there is an absence of any medium. But for the first time, there is 20%-30% increase in NS of I_{AA} in the most central collisions. It could be due to a change of the fragmentation function or change of the quark/gluon jet ratio in the final state or bias on the parton p_T spectrum after energy loss due to selection of the trigger particle.

1.5 Organization of the thesis

In this thesis, a detailed measurement of azimuthal correlations of D^0 mesons with charged particles in pp collisions at $\sqrt{s} = 5$ and 13 TeV with ALICE detector is reported. This study is mainly motivated for two reasons. First one is that, this measurement in pp collisions allows to study the fragmentation and hadronization of charm quark as well as their production mechanism. The second motivation is that the heavy quarks like charm and bottom lose its energy while travelling through the medium. This energy loss will be reflected in the modification of the correlation distribution of final-state hadrons and other charged hadrons in Pb-Pb collisions. By doing this azimuthal correlation study one will be able to shed some light on the energy loss

by different partons. The correlation measurement in pp collisions will serve as a baseline for Pb–Pb collisions.

This thesis consists of six chapters. A brief review of SM, QCD and relativistic high-energy collision is discussed in Chapter 1. In particular, experimental probes to study QGP also describe in detail in this chapter. In Chapter 2, a literature review of angular correlation measurement between heavy flavor hadrons or their decay products in fixed-target experiments to collider experiments is described. The ALICE experimental set-up with a detailed explanation of the working principle of different sub-detectors is mentioned in Chapter 3. A detailed description and methodology of the analysis of measurement of azimuthal correlations of D^0 mesons with charged particles are explained in Chapter 4. In Chapter 5, different sources of systematic uncertainty are estimated. The final results and comparison with models are discussed in chapter 6. The summary and future perspective of this analysis are reported in Chapter 7.

Chapter 2

Literature Survey

"One never notices what has been done; one can only see what remains to be done"

– Marie Curie

In this chapter, a brief introduction about motivation of angular correlation measurement between heavy flavor hadrons or their decay products is described in Section 2.1. In Section 2.2, discovery of D^0 meson is mentioned. The $D\bar{D}$ azimuthal correlation and D - hadron azimuthal correlation in different experiment from fixed target to collider experiment are discussed in Section 2.3 and Section 2.4, respectively.

N.B. - In this chapter, I have used the notation for azimuthal angle as φ or ϕ according to the notation used in original experiment.

2.1 Introduction

In 1976, D mesons were discovered in the collision of e^+e^- at center of mass energies between 3.90 to 4.60 GeV [54]. Since then various techniques are being used to study the production mechanism of heavy quarks. One such method is the angular correlation measurement between heavy flavor hadrons or their decay products. The angular correlation measurement helps to differentiate between the Leading Order (LO) and Next to Leading Order (NLO) processes

responsible for heavy quark production at LHC energies. Both the LO and NLO processes give different angular distributions between the c and $\bar{c}$ quarks. As we know that the quarks are found in bound states, it is impossible to measure the angular correlations between the c and $\bar{c}$. So by taking their hadronic final state particles as observables one can measure the angular correlations. Since D mesons are the lightest charm hadrons, by studying the $D\bar{D}$ or D-hadron angular correlations, one can able to study the $c \rightarrow D$ fragmentation process and hadronization of heavy quarks. The angular distribution of $D\bar{D}$ should not differ much from the angular distribution of $c\bar{c}$ quarks due to the hard scattering process. But the D-hadron angular correlation method is much more indirect approach to study the $c\bar{c}$ correlations. But one can access the information of quark pairs by studying the near-side (NS) and away-side (AS) peak properties formed at $\Delta\varphi = 0$ and $\Delta\varphi = \pi$, respectively.

2.2 Discovery of D^0 meson

In 1976, the SLAC-LBL MARK I group first succeeded to discover the D mesons by studying the multihadronic states produced in e^+e^- annihilation at center of mass energies between 3.90 to 4.60 GeV [54]. This was observed by looking at the peaks in the invariant mass spectrum reconstructed by taking the charged pions and charged kaons. The invariant mass distributions of various combinations of $\pi^+\pi^-$, $\pi^\pm K^\mp$ and K^+K^- are shown in Fig. 2.1. In the raw invariant mass distributions, there are peaks observed near $1.74 \text{ GeV}/c^2$, $1.87 \text{ GeV}/c^2$, and $1.98 \text{ GeV}/c^2$ as shown in Fig. 2.1(a) to (c), respectively. The weighted invariant mass spectra are shown in Fig. 2.1(d) to (f).

It is evident from Fig. 2.1e that the peak around $1.87 \text{ GeV}/c^2$ is more favored one. The significance of this peak is more than 5 standard deviations. Similarly, the four prong decay case with different combinations, i.e., charged K with charged π , to produce neutral particle was considered. The weighted combinations of $(\pi^+\pi^-\pi^+\pi^-)$, $(K^\pm\pi^\mp\pi^\pm K^\mp)$, $(K^\pm K^\mp\pi^\pm\pi^\mp)$ invariant mass spectra are shown in Fig. 2.1g-i, respectively. There is a clear signal peak near $1.86 \text{ GeV}/c^2$ seen for $K3\pi$ system, which is shown in Fig. 2.1h and there is no evident of peak for the other two cases. The invariant mass spectra for both $K\pi$ and $K3\pi$ systems are fitted with

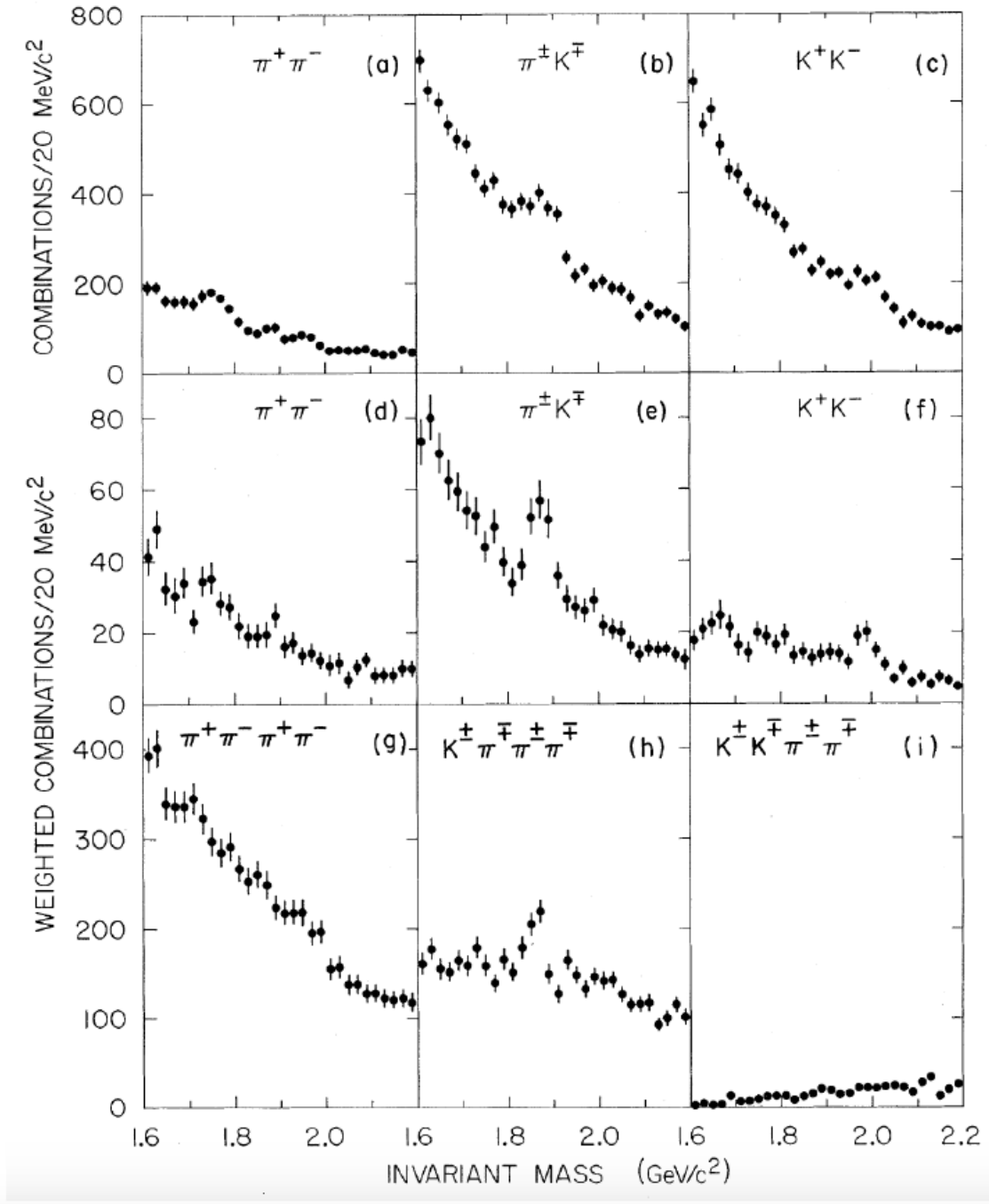


Figure 2.1: [SLAC] Invariant-mass spectra for neutral combinations of charged particles (a) $\pi^+\pi^-$, (b) $\pi^\pm K^\mp$, (c) K^+K^- ; Weighted invariant mass of (d) $\pi^+\pi^-$, (e) $\pi^\pm K^\mp$, (f) K^+K^- , (g) $\pi^+\pi^-\pi^+\pi^-$, (h) $K^\pm\pi^\mp\pi^\pm\pi^\mp$, (i) $K^\pm K^\mp\pi^\pm\pi^\mp$ [54].

Gaussian function for peak and linear and quadratic background functions to determine the mass and width. The masses for $K\pi$ signal peaks at $1.87 \text{ GeV}/c^2$, whereas for $K3\pi$ signal it peaks at $1.86 \text{ GeV}/c^2$. There is a $10 \text{ MeV}/c^2$ differences in masses observed between both $K\pi$ and $K3\pi$ systems. So, it is concluded that both the signals are none other than the same state. Thus, by observing the significant peak in invariant mass spectra of both $K^\pm\pi^\mp$ and $K^\pm K^\mp\pi^\pm\pi^\mp$, it was concluded that the decay products were coming from a particle of mass $1865 \pm 15 \text{ MeV}/c^2$ and decay width less than $40 \text{ MeV}/c^2$. Later on this particle was named as D^0 .

2.3 $D\bar{D}$ correlations

The NA16 experiment measured the $D\bar{D}$ correlations to study the charm pair correlations for the first time [55]. This experiment mainly studied three quantities: the rapidity difference between $D\bar{D}$ pair ($\Delta y = |y_D - y_{\bar{D}}|$), the effective mass (m) of $D\bar{D}$ and the transverse angle difference between $D\bar{D}$ ($\phi_T = \cos^{-1}(p_T^D \cdot p_T^{\bar{D}})$). p_T^D and $p_T^{\bar{D}}$ are the transverse momenta of the D and $\bar{D}$, respectively. The ϕ_T distribution of $D\bar{D}$ and the transverse angle difference between $D\bar{D}$ pairs of 22 events and $\psi\psi$ pairs are shown in Fig. 2.2(a) and (b), respectively. They have attempted to explain the ϕ_T distribution through $q\bar{q}$ and gg fusion processes. The $c\bar{c}$ creation process produces particles back-to-back. So, if there is any deviation from 180° observed in ϕ_T distribution, then this effect can be attributed to the intrinsic p_T in the fusion process or in the dressing-up process of charm and anti-charm quarks. The average p_T is found to be $0.9 \pm 0.1 \text{ GeV}/c$ for $D\bar{D}$ pairs and $0.9 \text{ GeV}/c$ for $\psi\psi$ pairs in the experiment. So, from this it can be concluded that the intrinsic p_T is coming from the initial state of the particle. The solid curve in the ϕ_T is predicted by taking $\langle p_T \rangle = 0.7 \text{ GeV}/c$.

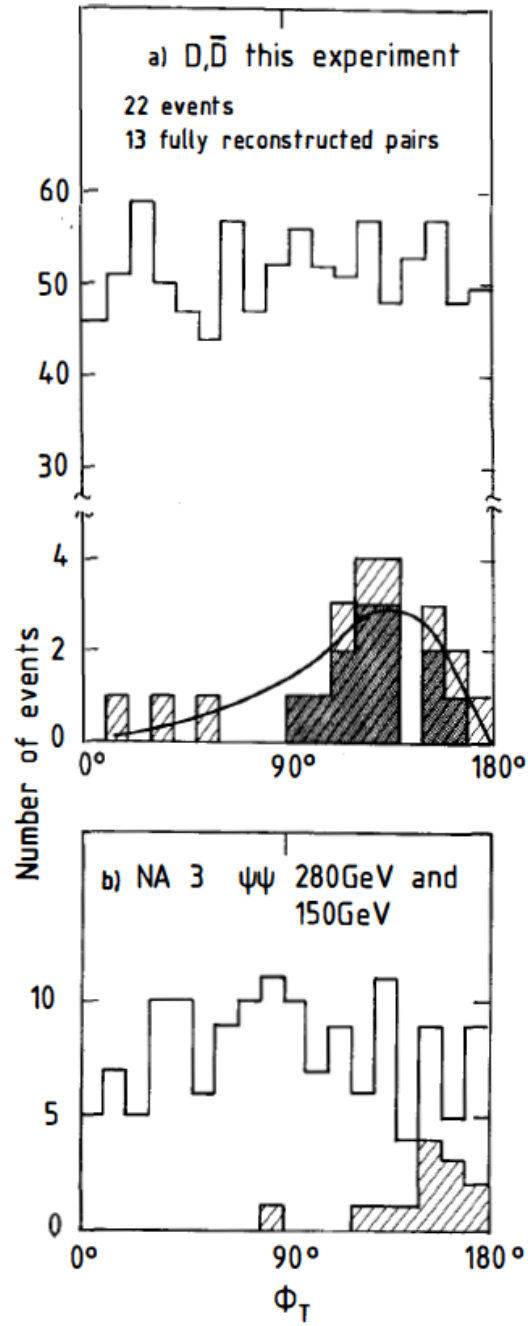


Figure 2.2: [NA16] The ϕ_T distribution of (a) $D\bar{D}$ pairs, (b) $\psi\psi$ pairs [55].

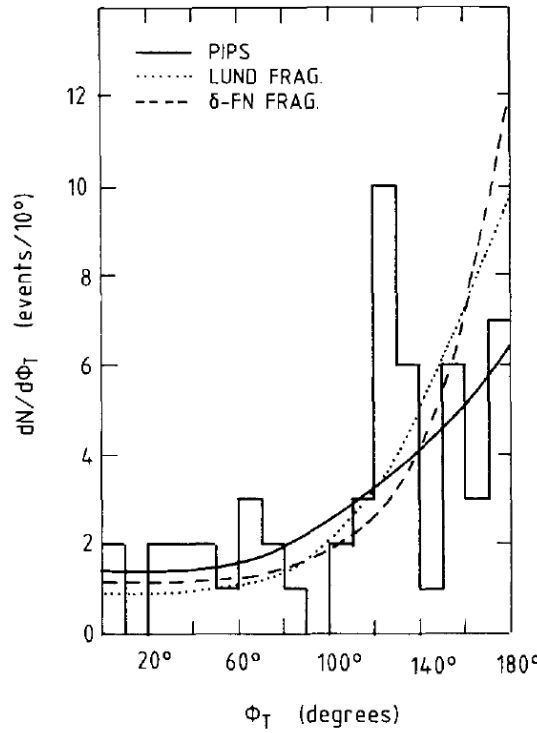


Figure 2.3: [NA27] ϕ_T distribution for 53 $D\bar{D}$ pairs [56].

2.3.1 NA27 Expt.

The $D\bar{D}$ correlation was studied in NA27 fixed target experiment in π^-p interaction with π^- beam of momentum 360 GeV/c. This experiment used the high resolution hydrogen little European bubble chamber (LEBC) and the European hybrid spectrometer (EHS) [56]. LEBC provides good detection of particles and EHS provides better momentum precision, electron identification and charged particle identification. Total 26500 π^-p interactions were collected, out of which only 53 charm pairs events were considered for the analysis. The angle between the D and $\bar{D}$ in the plane transverse to the beam direction, ϕ_T , is measured for all 53 charmed pairs of $D\bar{D}$ and its distribution is shown in Fig. 2.3. The average value of ϕ_T is found to be $(115 \pm 8)^\circ$ from the $D\bar{D}$ correlation.

The correlation distribution is compared with an empirical model, Peripheral Inelastic Phase Space model (PIPS) and also with QCD-fusion model with different fragmentation function. The solid curve in Fig. 2.3 is from the prediction of PIPS model and it describes the data qualitatively well except for the peak like structure at $\phi_T \sim 120^\circ$. The peak like structure at

$\phi_T \sim 120^\circ$ could be because of low statistics. The construction of a QCD-fusion model requires: (1) description of parton contents inside the proton, (2) calculation of the cross sections for the subprocesses and (3) some approximation for the $c \rightarrow D$ fragmentation process. Structure function used for the description of the parton content in the proton is determined by Duke and Owens [57][58]. The $q\bar{q}$ and gg fusion subprocesses are used for the calculation of D meson cross sections by taking the mass of the charm quark, $m_c = 1.25 \text{ GeV}/c^2$. The effect of the intrinsic transverse momentum (k_T) of the partons also included in the fusion model of the form $dN/dk_T^2 \propto e^{-k_T^2/\langle k_T^2 \rangle}$. The parameter $\langle k_T^2 \rangle = 0.64 \text{ (GeV}/c)^2$ is taken in the model. The hadronization process of charm quark considers the δ -function and Lund fragmentation functions. The δ -function is defined as $f(z) \sim \delta(z_{\max} - z)$, where $z = p_D/p_c$, p_D is the momentum component of the D along the direction of charm quark c and $z = z_{\max}$ corresponds to the condition $E_D = E_c$. In the Lund string model, the color field interaction has been taken into account, i.e., formation of c and $\bar{c}$ by breaking the color string [59]. In Fig. 2.3, the fusion model predictions are also shown. The dotted curve represents the fusion model with Lund fragmentation and dashed curve represents the fusion model with δ -function. Both the fusion models are poorly describing the experimental data and also failed to describe the curious peak like structure around $\phi_T = 120^\circ$. The Lund string and the δ -function fusion models are giving the value of $\langle \phi_T \rangle$ 126° and 129° , respectively. The same NA27 experiment also studied the $D\bar{D}$ in pp interactions at $400 \text{ GeV}/c$ beam momentum [60]. The ϕ_T distribution of $D\bar{D}$ pairs for 107 events is shown in Fig. 2.4. In Fig. 2.4, the histogram with dashed line corresponds to the raw ϕ_T distribution and histogram with solid line corresponds to the corrected ϕ_T distribution. The value of $\langle \phi_T \rangle$ is found to be $114 \pm 5^\circ$. The theoretical predications of fusion model with δ -function and Lund fragmentation are also shown in Fig. 2.4 with dashed curve and solid curve, respectively. Here also the fusion model is same as described in above with some changes in the parameters. Here, $\langle k_T^2 \rangle$ ranges from 0 to $0.64 \text{ (GeV}/c)^2$ and the charm quark mass varies from 1.2 to $1.4 \text{ GeV}/c^2$. The QCD fusion model with Lund fragmentation describes the data qualitatively well.

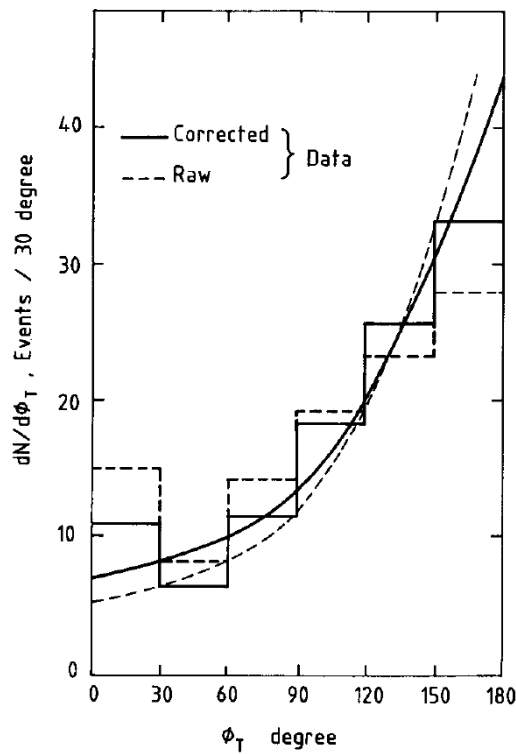


Figure 2.4: [NA27] ϕ_T distribution of 107 $D\bar{D}$ pairs. The histogram with dashed line represents the raw ϕ_T distribution, whereas the histogram with solid line represents the corrected ϕ_T distribution. The theoretical prediction from QCD fusion model with Lund fragmentation (solid curve) and with δ -function (dashed curve) [60].

2.3.2 WA75 Expt.

The WA75 hybrid emulsion experiment, situated at CERN Super Proton Synchrotron (SPS) [61] also carried out charm-pair correlations study. The results were obtained by analysing the data with 102 charm-pairs and 84 single charmed particles (D^0 , $\bar{D}^0$, D^+ , D^-) produced in the π - nucleus interactions with π beam of momentum 350 GeV/c. The azimuthal angle (φ) distribution of charmed-pair is shown in Fig. 2.5. The mean value of φ is found to be $\langle\varphi\rangle = (115 \pm 12)^\circ$ and it is in good agreement with NA27 results, $\langle\varphi\rangle = (115 \pm 8)^\circ$. From the results of both the experiments, it is seen that there is a peak near 180° . The φ distributions of different charmed pairs (D^+D^+), ($D^0, \bar{D}^0$), (D^-D^0) and ($D^+\bar{D}^0$) are shown in Fig. 2.5 b - e, respectively. All the φ distribution followed the similar trend and showed peak at 180° . From this experimental results, it is confirmed that the φ distribution is independent of charm pair species. The φ distribution in Fig. 2.5 (a) is compared with different theoretical models, the fusion model and the cluster model. In these theoretical models, the intrinsic parton momentum distribution is given by

$$\frac{dN}{dk_T^2} = \frac{\exp(-k_T^2/\langle k_T^2 \rangle)}{\langle k_T^2 \rangle} \quad (2.1)$$

The value of $\langle k_T \rangle (= 0.64 \text{ GeV}/c)$ was taken from lepton pair hadroproduction experiments.

The Fusion model [62]: In this model, the charm-anticharm quark pairs are produced through fragmentation process of colliding partons, gg or qq and then the charm-anticharm pair leads to the formation of charmed mesons like D, $\bar{D}$. The fragmentation functions are

(i) $D(z) = \text{const.} \times \{z[1 - 1/z - 0.15/(1 - z)^2]\}^{-1}$ from e^+e^- experiment [63],

(ii) $D(z) = \delta(1 - z)$, momentum of charmed meson is taken equal to that of charm quark.

Here $z = |p|/|P|$, $\bar{z} = |\bar{p}|/|\bar{P}|$ and $p(\bar{p})$ is the momentum of meson containing the charm(anticharm) quark, $P(\bar{P})$ is the momentum of charm (anticharmed) quark in the respective meson. The curve A and B in Figure 2.5 (a) is the theoretical model describing the φ distribution from the fusion model.

The Cluster model [64]: In this model hadronic cluster of fixed mass of $5 \text{ GeV}/c^2$ is produced by qq scattering and decays in its rest frame with a fragmentation function of the Boltzmann type. The curve C in Fig. 2.5 (a) represents the predictions of the cluster model.

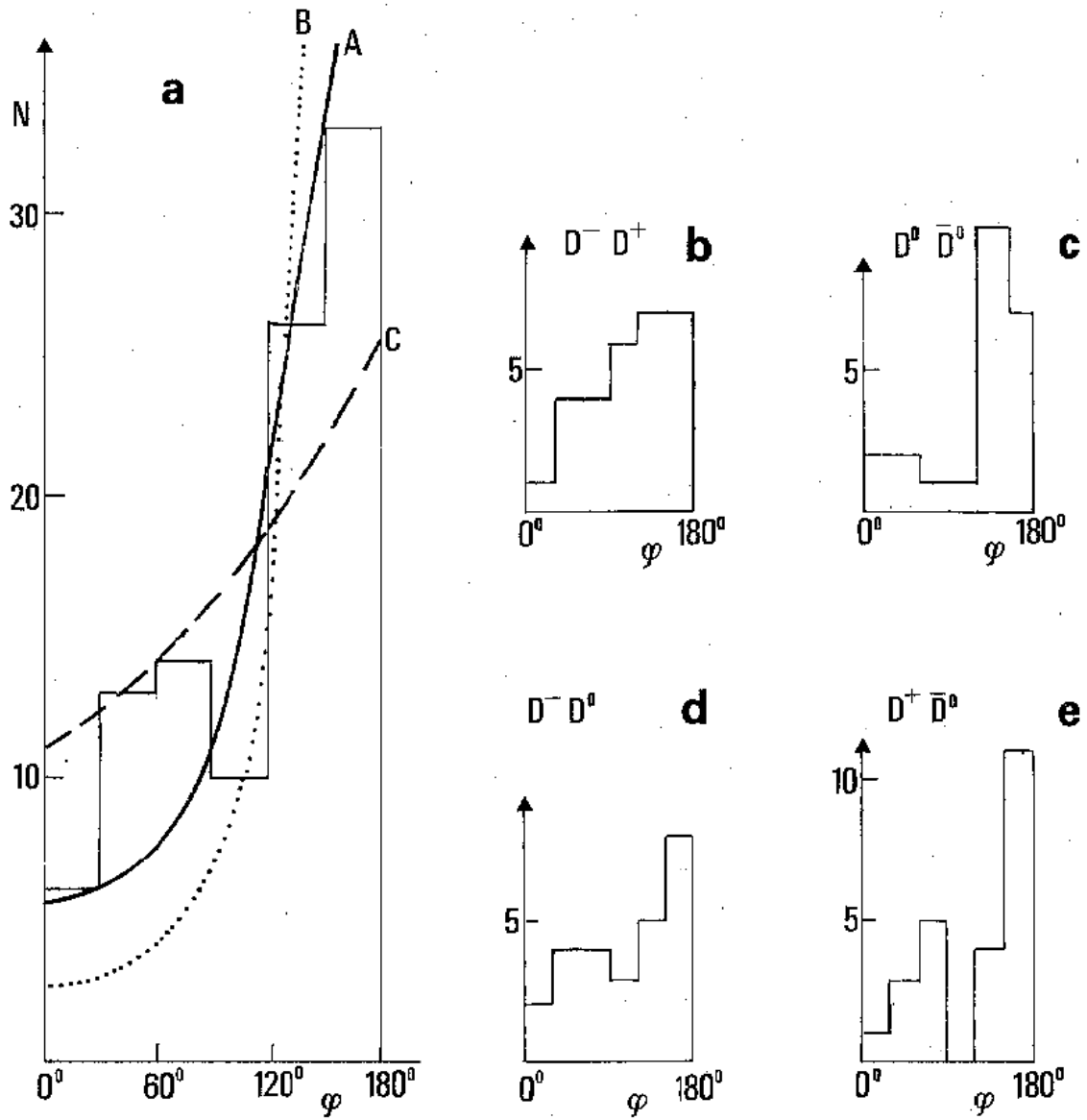


Figure 2.5: [WA75 Experiment] Distributions of azimuthal angles between the lines of flight of charmed pairs: (a) for all the pairs, (b)-(e) for the four different possible pairs [61].

It has been seen that the fusion model reproduced the experimental data quite well rather than the cluster model. The curve A reproduced the data more accurately from other model. The strong asymmetry of the φ distribution shows that effects due to Fermi motion of the nucleons, that are struck or to re-scattering inside the nuclei, could be small.

2.3.3 NA32 Expt.

The NA32 experiment at CERN, Geneva was a fixed target experiment with pion (96% pions and 4% kaons) as the beam of momentum 230 GeV/c and Cu of thickness 2.5 mm as target. The experiment has collected 542 events with two or more secondary vertices [65]. In this experiment, the correlation studies in the relative azimuthal angle (φ) of different combinations $D^0\bar{D}^0$, D^0D^- , $D^+\bar{D}^0$, D^+D^- , all $D\bar{D}$, $D_s^+\bar{D}$ and D_s^-D , $\Lambda_c^+\bar{D}$ and Λ_c^-D have been carried out. Figure 2.6 represents the φ distributions of different combinations of charmed particles. The distribution is normalized with number of events and corrected with acceptance.

The asymmetry seen in φ distribution is calculated as:

$$A = \frac{N(\varphi < 90^\circ) - N(\varphi > 90^\circ)}{N(\varphi < 90^\circ) + N(\varphi > 90^\circ)} \quad (2.2)$$

The average values of $\langle\varphi\rangle$, number of events and asymmetry A for different combinations of charmed particles are listed in Table 2.1. The φ distribution for all the combinations of D mesons are showing similar kind of asymmetry. The φ distribution of $\Lambda_c^+\bar{D}$ shows less asymmetry than all other combinations. An isotropic behavior is seen in the φ distribution of $D_s\bar{D}$ pairs. This indicates that the production mechanism of D_s is different from all other D mesons. The φ distribution of cc in Fig. 2.7 shows a behavior in between the isotropic and asymmetry. The φ distribution of $D_s\bar{D}$ pairs with different combination of leading D meson is shown in Fig. 2.8. All the combination of leading D mesons are showing asymmetry in the φ distribution. The asymmetry increases with the increase in number of leading D mesons and can be found in Table. 2.1. The φ distributions shown in Fig. 2.6(d-f) are compared with the cluster and fusion model. The dashed line represents the prediction from fusion model and the dotted line represents the prediction from cluster model. The cluster model describes the data roughly.

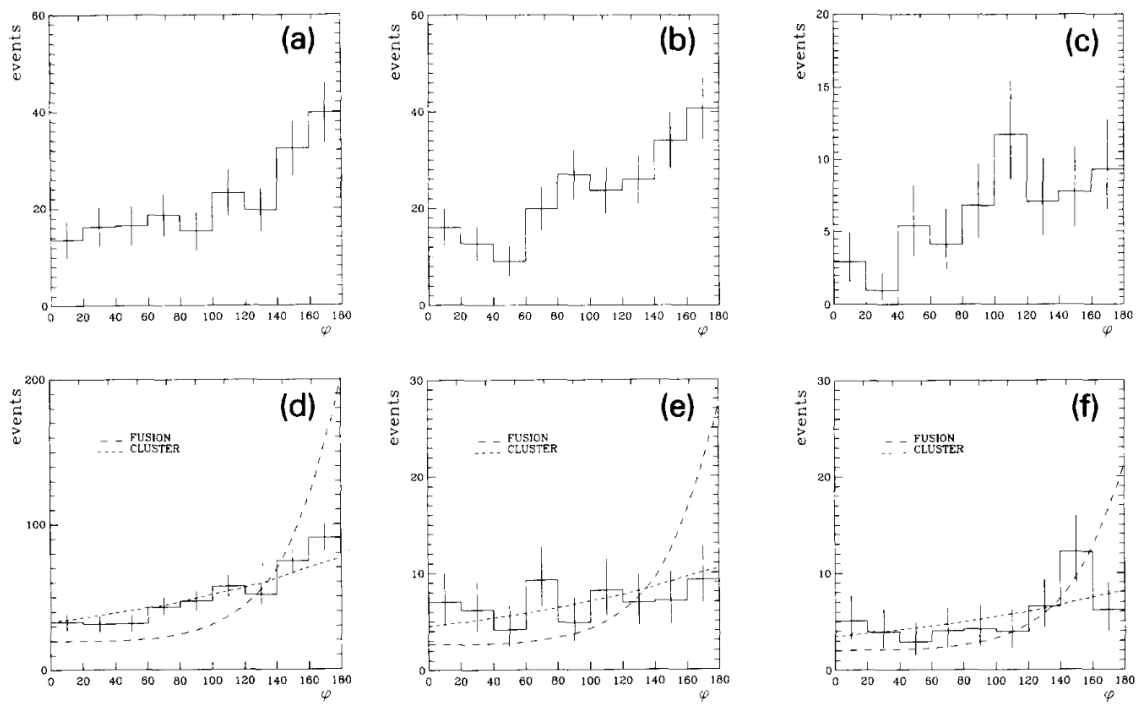


Figure 2.6: [NA32] The relative azimuthal angle φ (in degrees) distribution for different charmed pairs: (a) $D^0\bar{D}^0$, (b) D^0D^- and $D^+\bar{D}^0$, (c) D^+D^- , (d) all $D\bar{D}$, (e) $D_s^+\bar{D}$ and D_s^-D , (f) $\Lambda_c^+\bar{D}$ [65].

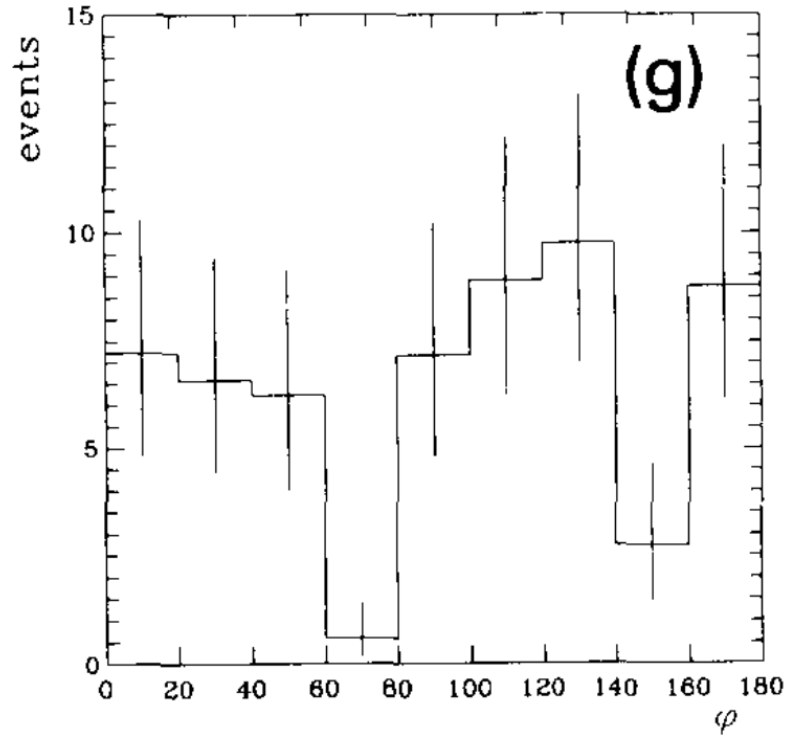


Figure 2.7: [NA32] The relative azimuthal angle φ (in degrees) distribution for cc [65].

Table 2.1: The number of events, average value of $\langle\varphi\rangle$ and asymmetry for different combinations of charmed pairs.

Combination of charmed	No. of Events	$\langle\varphi\rangle (^{\circ})$	A
$D^0\bar{D}^0$	195	107.6 ± 3.9	-0.27 ± 0.07
D^0D^- and $D^+\bar{D}^0$	209	110.0 ± 3.6	-0.35 ± 0.07
D^+D^-	56	111.4 ± 6.1	-0.46 ± 0.12
all $D\bar{D}$	460	109.2 ± 2.4	-0.33 ± 0.05
$D_s^+\bar{D}$ and D_s^-D	63	95.4 ± 6.8	-0.08 ± 0.13
$\Lambda_c^+\bar{D}$ and Λ_c^-D	49	104.5 ± 7.6	-0.18 ± 0.15
("cc")	58	99.0 ± 6.9	-0.24 ± 0.13
$\pi^- \rightarrow D\bar{D}$; both leading	115	112.4 ± 4.8	-0.44 ± 0.09
$\pi^- \rightarrow D\bar{D}$; one leading	241	108.4 ± 3.4	-0.31 ± 0.07
$\pi^- \rightarrow D\bar{D}$; none leading	90	105.7 ± 5.4	-0.22 ± 0.11

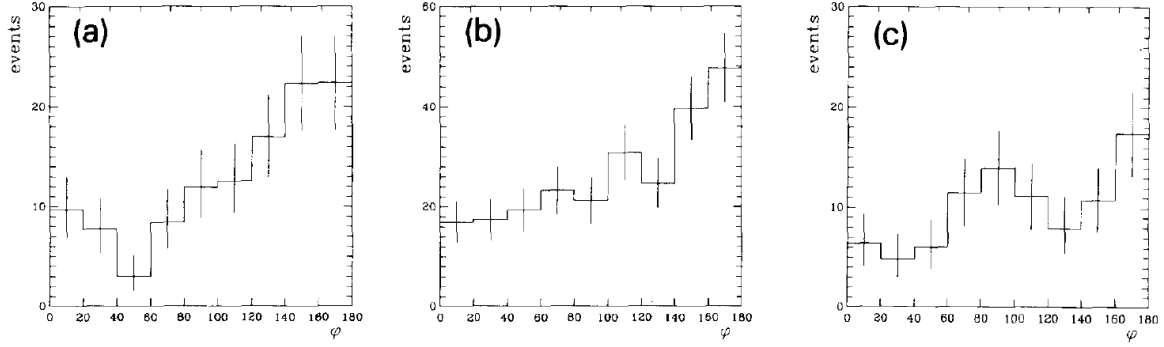


Figure 2.8: [NA32] The relative azimuthal angle φ (in degrees) distribution for various classes of $D\bar{D}$ pairs: (a) both leading, (b) one leading, (c) none leading [65].

The fusion model considers the charm quark fragmentation to charm hadron by the second order process $q\bar{q} \rightarrow c\bar{c}$ and $gg \rightarrow c\bar{c}$. The fusion model does not describe the data well and shows a large asymmetry. Nason et.al [66] have shown that the third order process $gg \rightarrow c\bar{c}g$ and $gq \rightarrow c\bar{c}q$, played a crucial role to describe the experimental hadronic production cross-section of the charm quark. That's why the higher order process may bring the asymmetry more close to the data [65].

2.3.4 E653 Expt.

The charm pair correlations had also been studied in the Fermilab experiment E653. In this experiment, a beam of protons with momentum 800 GeV/c struck a 1.47 cm thick nuclear emulsion target [67]. The results presented here are for the 35 charm pairs from the proton-emulsion interaction at $\sqrt{s} = 38.7$ GeV. The raw distribution of the opening angles projected onto a plane perpendicular to the beam, ϕ_T , of the charm pairs is shown in Fig. 2.9(a). Fig. 2.9 shows a peak around 180° as observed in the NA27 experiment due to the back-to-back nature of the production process at parton level. This peak at 180° deviates from the prediction of leading order calculation and it may have contribution from intrinsic transverse momenta of the initial state partons, hadronization of the charm quarks and higher order QCD corrections.

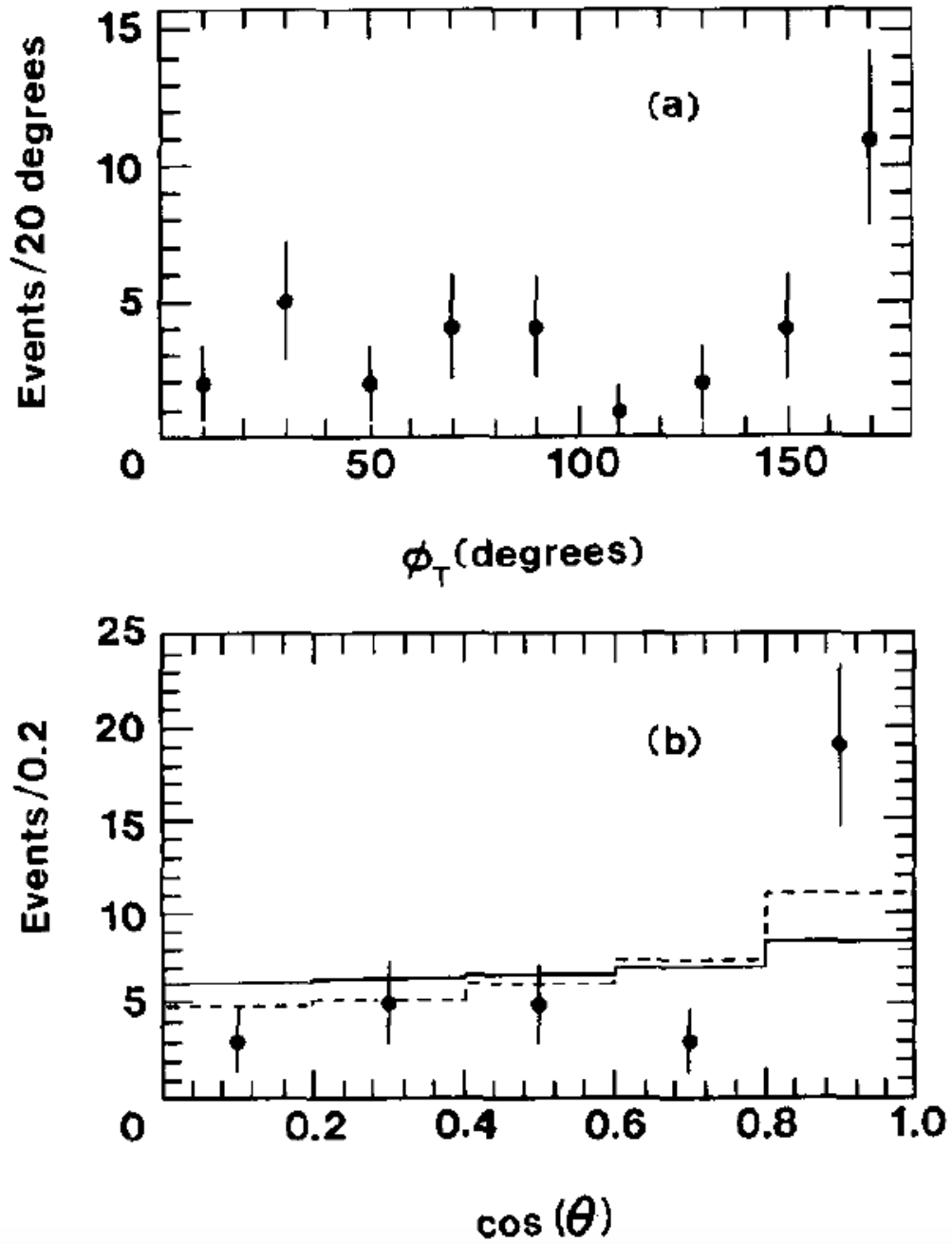


Figure 2.9: [E653] a) Raw ϕ_T distribution of charm pairs, b) Raw $\cos(\theta)$ distribution of charm pairs. Leading order QCD predictions for charm quark production by (solid line) $q\bar{q}$ annihilation and (dashed line) by gg fusion [67].

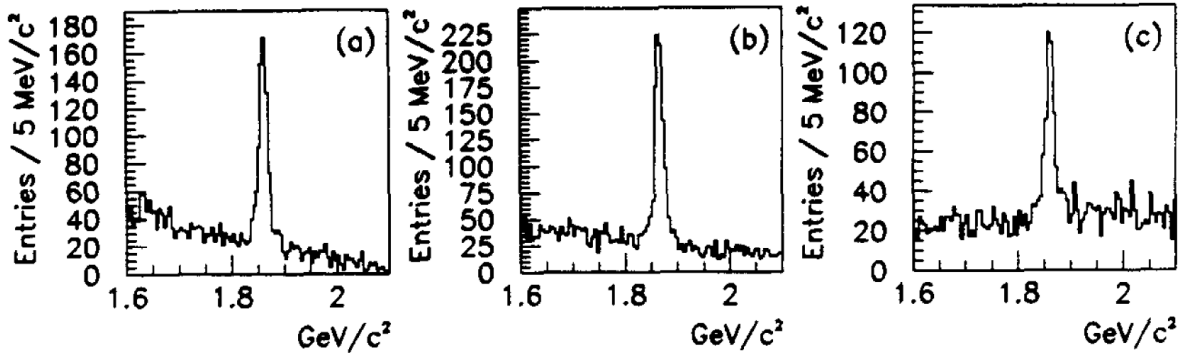


Figure 2.10: [WA92] The invariant mass distributions of D mesons and their charge conjugates:

(a) $D^0 \rightarrow K^-\pi^+$, (b) $D^+ \rightarrow K^-\pi^+\pi^+$, (c) $D^0 \rightarrow K^-\pi^-\pi^+\pi^+$ [68].

The raw $\cos(\theta)$ distribution for charm pairs are shown in Fig. 2.9(b), where θ is the smaller of the two charm particles polar angles in the charm pair center of mass. The leading order QCD predictions for the production of charm quark by $q\bar{q}$ annihilation and gg fusion process is shown in Fig. 2.9(b) by solid line and dashed line, respectively. It is evident from the figure that the gg fusion process is more convincing with data by giving a strong peak at $\cos(\theta) = 1$. It can be concluded from the results that the leading order QCD predictions cannot describe the ϕ_T distribution [67].

2.3.5 WA92 Expt.

WA92 experiment at CERN, Geneva is a fixed target experiment. The results mentioned here are the charmed particles pair produced in the collisions of 350 GeV/c π^- with a 2 mm thick Cu target [68]. The particle tracking is done using the Omega magnetic spectrometer. The invariant mass of the D mesons (D^0, D^+) and their charge conjugates have been reconstructed from their hadronic decay channels. The peak of the invariant mass is fitted with a gaussian distribution and is shown in Fig. 2.10. The detailed procedure for event reconstruction and background subtraction is described in reference [68]. The azimuthal angular distribution between the two D mesons ($\Delta\phi$) is evaluated and after background subtraction it is presented in Fig. 2.10. The $\Delta\phi$ distribution shown in Fig. 2.11(a) is compared with the theoretical NLO calculations and it has been observed that the c and $\bar{c}$ quarks produced more back to back than the

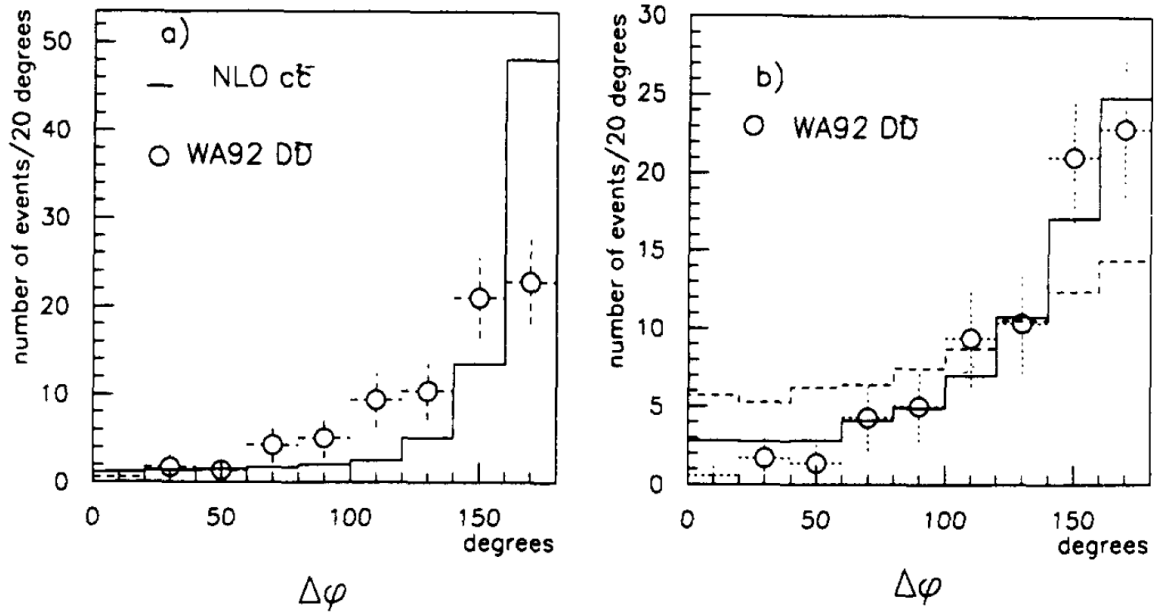


Figure 2.11: [WA92] The $D\bar{D}$ azimuthal correlations from WA92 experiment compared to (a) model with NLO perturbative QCD calculations, (b) model with NLO perturbative QCD calculations with $\langle p_T^2 \rangle = 0.3(\text{GeV}/c)^2$ (solid line) and $\langle p_T^2 \rangle = 1.0(\text{GeV}/c)^2$ (dotted line) [68].

experimental results. The simulation studies have also been done for the effect of charm quark fragmentation using Peterson's model. They have compared the $\Delta\phi$ distribution of generated $c\bar{c}$ pairs with the hadronized $c\bar{c}$ pairs ($D\bar{D}$) and shown in Fig. 2.12. From Fig. 2.12, it is clearly evident that the difference in $\Delta\phi$ distribution between the data and the NLO calculations cannot be attributed to hadronization process only. The experimental data are compared to a model [69] in which the incoming partons transverse momenta are randomly distributed as $dN/dp_T^2 \propto e^{-p_T^2/\langle p_T^2 \rangle}$ and added before performing the NLO pQCD calculations. The comparison with two different values of $\langle p_T^2 \rangle$ (0.3 and 1.0 $(\text{GeV}/c)^2$) is shown in Fig. 2.11(b). The dotted line represents the model with $\langle p_T^2 \rangle = 0.3 \text{ (GeV}/c)^2$ and solid line represents the model with $\langle p_T^2 \rangle = 1.0 \text{ (GeV}/c)^2$. The model with $\langle p_T^2 \rangle = 0.3 \text{ (GeV}/c)^2$ describes the experimental data qualitatively well. The $\Delta\phi$ distribution obtained from WA92 experiment is also compared with the results obtained from different experiments and shown in Fig. 2.13. The results from NA32, WA75 and E653 experiments are from charm hadroproduction process and are shown in Fig. 2.13 (a)-(c), respectively. From Fig. 2.13(a)-(c) it is evident that the model cannot describe the data with $\langle p_T^2 \rangle$ less than

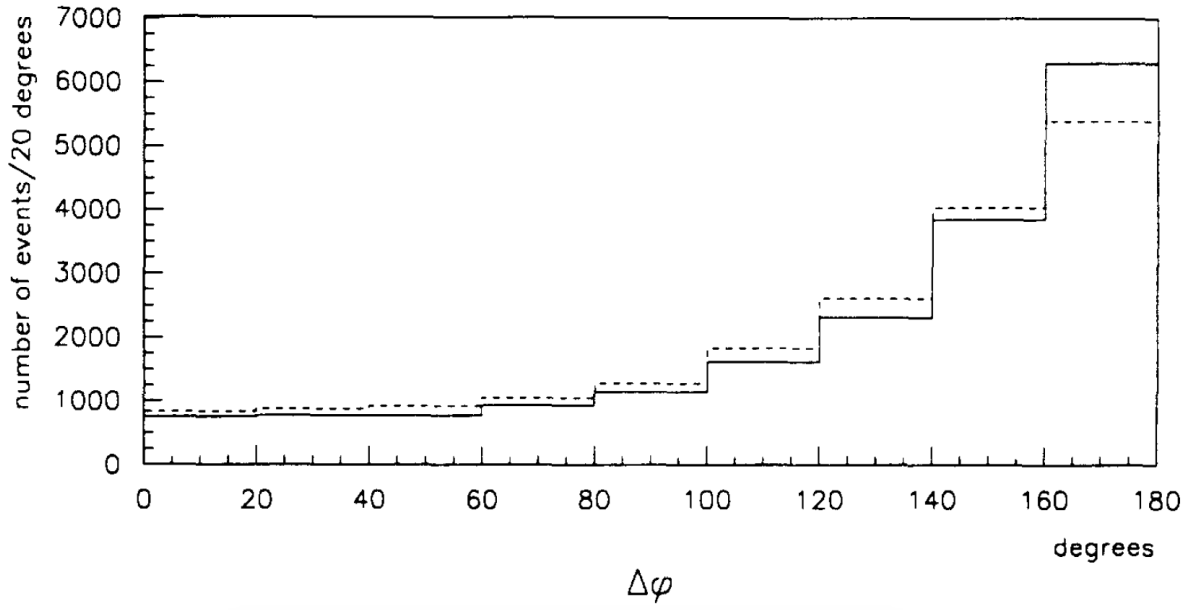


Figure 2.12: [WA92] The azimuthal correlations distribution of $c\bar{c}$ quark pairs (solid line histogram) and $D\bar{D}$ meson pairs (dotted line histogram) [68].

$1.0 \text{ (GeV}/c)^2$. But, in contrast to the results from charm photoproduction proces obtained from E687 experiment, shown in Fig. 2.13(d) can be explained by the model with $\langle p_T^2 \rangle$ less than $1.0 \text{ (GeV}/c)^2$. So, it is concluded that the results of WA92 are in a good agreement with the NLO QCD calculations if small non-perturbative effects are considered.

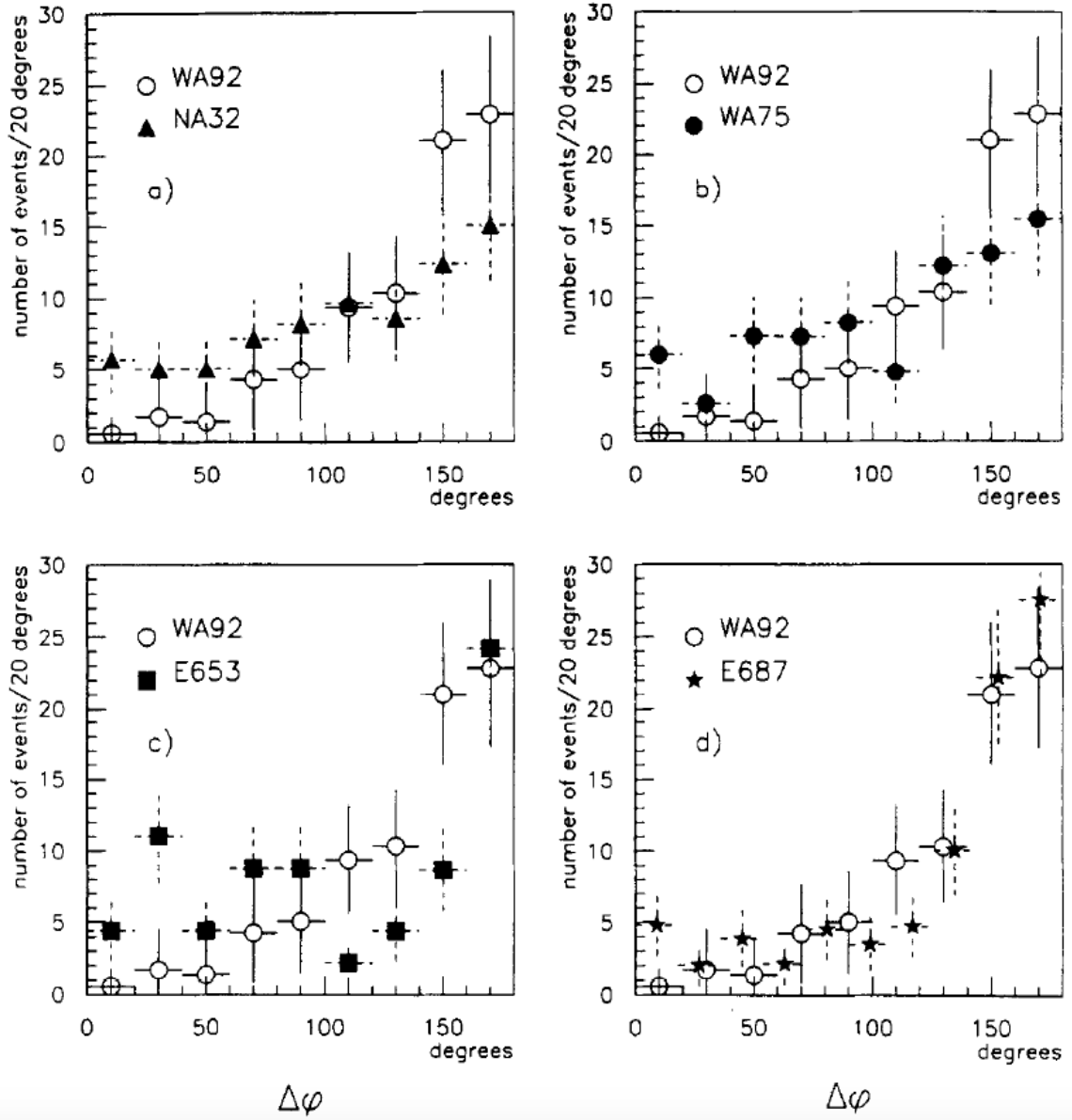


Figure 2.13: The $\Delta\phi$ distribution of $D\bar{D}$ from WA92 experiment compared to the experimental results of (a) NA32 (hadroproduction), (b) WA75 (hadroproduction), (c) E653 (hadroproduction), (d) E687 (photoproduction). All the distributions are normalized to WA92 results [68].

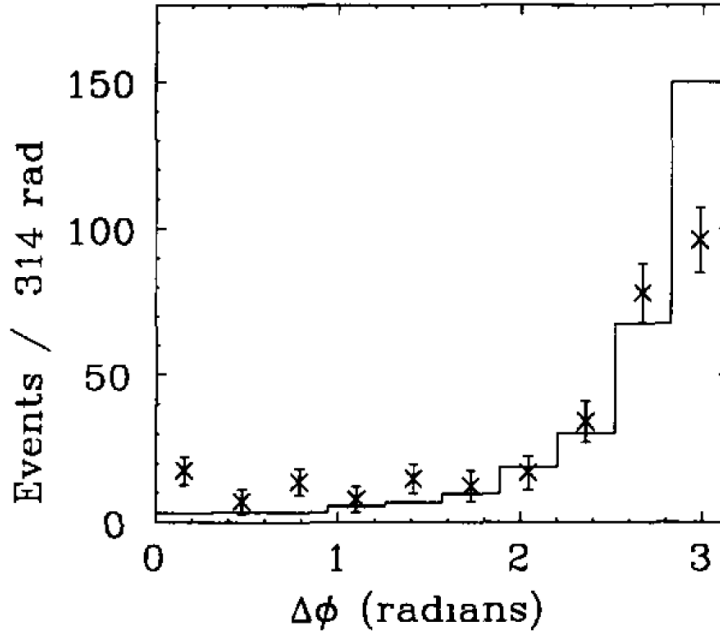


Figure 2.14: [E687] The star markers are the $\Delta\phi$ distribution of $D\bar{D}$ pairs and solid line corresponds to the Monte Carlo predictions [70].

2.3.6 E687 Expt.

The $D\bar{D}$ correlation has also been studied in high energy photoproduction E687 experiment at Fermilab [70]. The events considered for this analysis are coming from the data, where the average photon energy is approximately 200 GeV. In this experiment, $\Delta\phi$ is defined as the azimuthal angle between the D and $\bar{D}$ momentum vectors in the plane perpendicular to the photon direction. Figure 2.14 represents the $\Delta\phi$ distribution with its Monte Carlo predictions. The Monte Carlo prediction is based on the Lund fragmentation model. The Gaussian distribution with RMS 0.4 GeV/ c is considered for the intrinsic target gluon p_T in the Lund string model and quarks are dressed into hadrons. The tree level photon-gluon fusion process is taken into account for the production of charm quark in the Monte Carlo. Both the experimental data and model are peaking at $\Delta\phi = \pi$, which corresponds to the back-to-back $D\bar{D}$ production. The experimental result is smeared around $\Delta\phi = \pi$ and is flattened below $\Delta\phi = \pi$ compared to Monte Carlo prediction. The inconsistency in the data and the model could be due to the effects of intrinsic gluon p_T spreading and charm quark dressing [70].

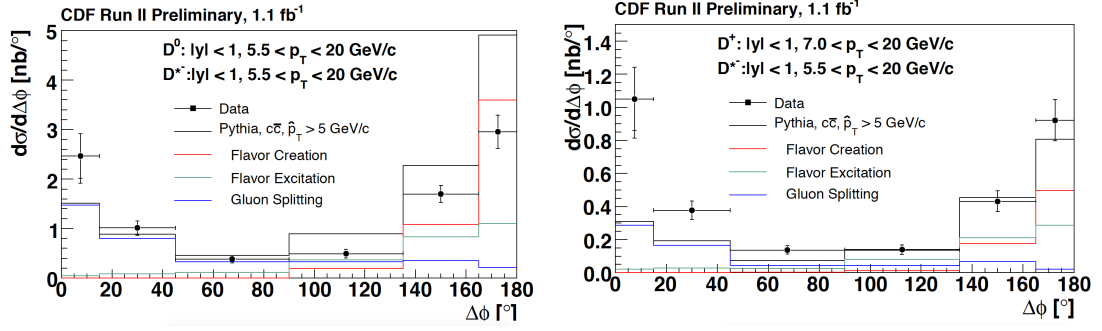


Figure 2.15: [CDF] The (D^0, D^{*-}) and (D^+, D^{*-}) pair cross section as a function of azimuthal angular difference between the two D mesons. The black line corresponds to PYTHIA simulations. The red line, green line and blue line correspond to the simulated events from flavor creation, flavor excitation and gluon splitting mechanisms, respectively [71].

2.3.7 Tevatron Expt.

The charm pair angular correlation measurement has been carried out in the $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in the CDF experiment at the Tevatron to study the $c\bar{c}$ production mechanism [71]. D mesons are reconstructed in central rapidity region, $|y^D| < 1.0$, for high p_T , $p_T^D \in [5.5, 20]$ GeV/c. The pair cross section of (D^0, D^{*-}) and (D^+, D^{*-}) as a function of azimuthal angular difference between the two D mesons is shown in Fig. 2.15. It is seen from the figure that the back-to-back production and collinear production have same size. The distribution is compared to the simulation results of PYTHIA with a leading order matrix elements with proton shower with Tune A. The data also compared to the sub-processes like flavor creation, gluon splitting and flavor excitation individually. The PYTHIA simulation is over estimating the back-to-back production ($\Delta\phi = 180^\circ$) and under estimating the collinear production ($\Delta\phi = 0^\circ$). The back-to-back production of $c\bar{c}$ is due to flavor creation process, while collinear production is due to gluon splitting process.

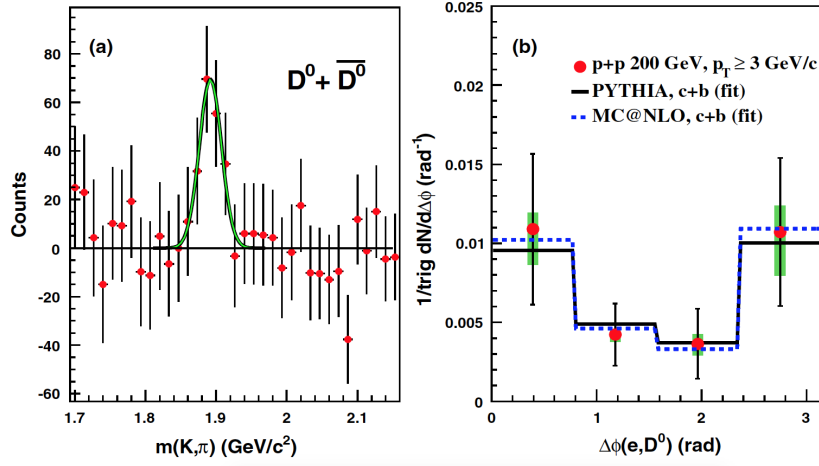


Figure 2.16: [STAR] (a) The background subtracted invariant mass distribution of $D^0 + \bar{D}^0$. (b) The azimuthal angular correlation distribution of nonphotonic electron and D^0 meson. The black solid line and dashed blue line represent the fit of the correlation function from PYTHIA simulations and MC@NLO simulation, respectively [72].

2.3.8 STAR Expt.

The azimuthal correlations between non-photonic electrons and D^0 , $(e_{\text{non}y} - D^0)$, is studied in pp collisions at 200 GeV in STAR experiment at RHIC [72]. The D^0 mesons and its charge conjugate were reconstructed from their hadronic decay channels, i.e., $D^0(\bar{D}^0) \rightarrow K^- \pi^+(K^+ \pi^-)$. The invariant mass distribution of D^0 is shown in Fig. 2.16(a). The events considered here are from the non-photonic electron trigger. The significance of the invariant mass is nearly 4.6. The azimuthal correlation distribution of $(e_{\text{non}y} - D^0)$, shown in Fig. 2.16(b), exhibits similar yields of both near-side and away side correlations peaks with large uncertainties. The results from the data are fitted with the correlation functions for charm and bottom production from PYTHIA and MC@NLO simulations having the relative B contribution as a free parameter. This analysis helps us to determine the charm and beauty contribution to the D meson production. It is observed that the near-side contribution is solely due to the B decays while the away side peak is related to both the charm pair production and B decays.

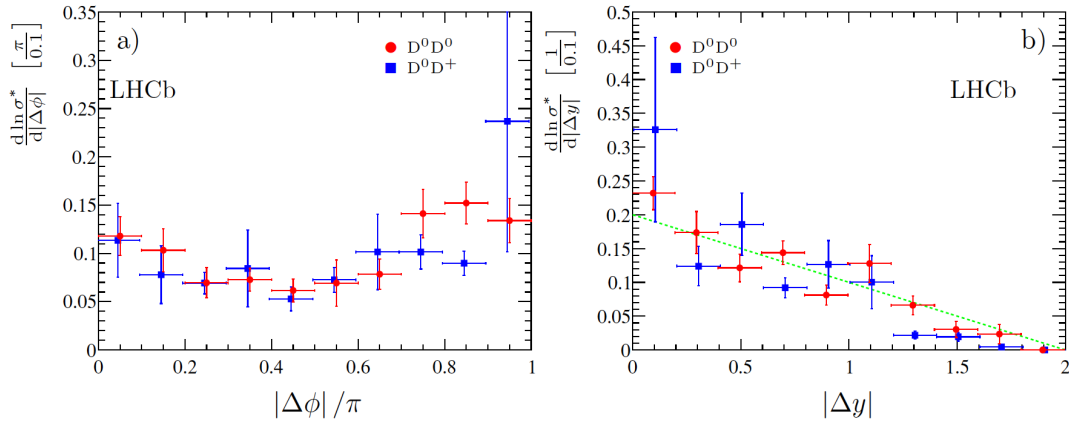


Figure 2.17: [LHCb] The correlation distribution of $D^0 D^0$ and $D^0 D^+$ events: (a) azimuthal angular correlation ($\Delta\phi$), (b) rapidity (Δy). The dashed line corresponds to the expected distribution for uncorrelated events [73].

2.3.9 LHCb Expt.

The LHCb experiment at LHC also studied the angular correlations between charm mesons in pp collisions at $\sqrt{s} = 7$ TeV [73]. While measuring the angular correlations, hadrons coming from cc and $c\bar{c}$ were considered for measurement of correlations in azimuthal angle and rapidity. The $\Delta\phi$ and Δy of DD correlation distributions are shown in Fig. 2.17. The $\Delta\phi$ distribution is showing a flat trend, while the Δy distribution is showing a triangular trend. No significant azimuthal correlation is observed. The flat trend of $\Delta\phi$ may be due to the uncorrelated D meson pairs formed in hard scattering process independently. The $\Delta\phi$ distribution for $D\bar{D}$ pairs are shown in Fig. 2.18. The $\Delta\phi$ distribution of $D\bar{D}$ pairs show an enhancement in small $|\Delta\phi|$ regions and is consistent with the $c\bar{c}$ production through gluon splitting model.

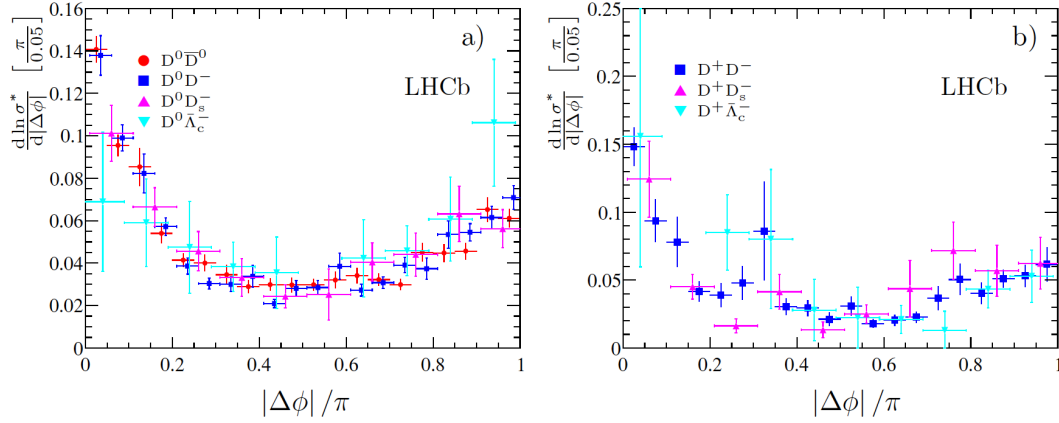
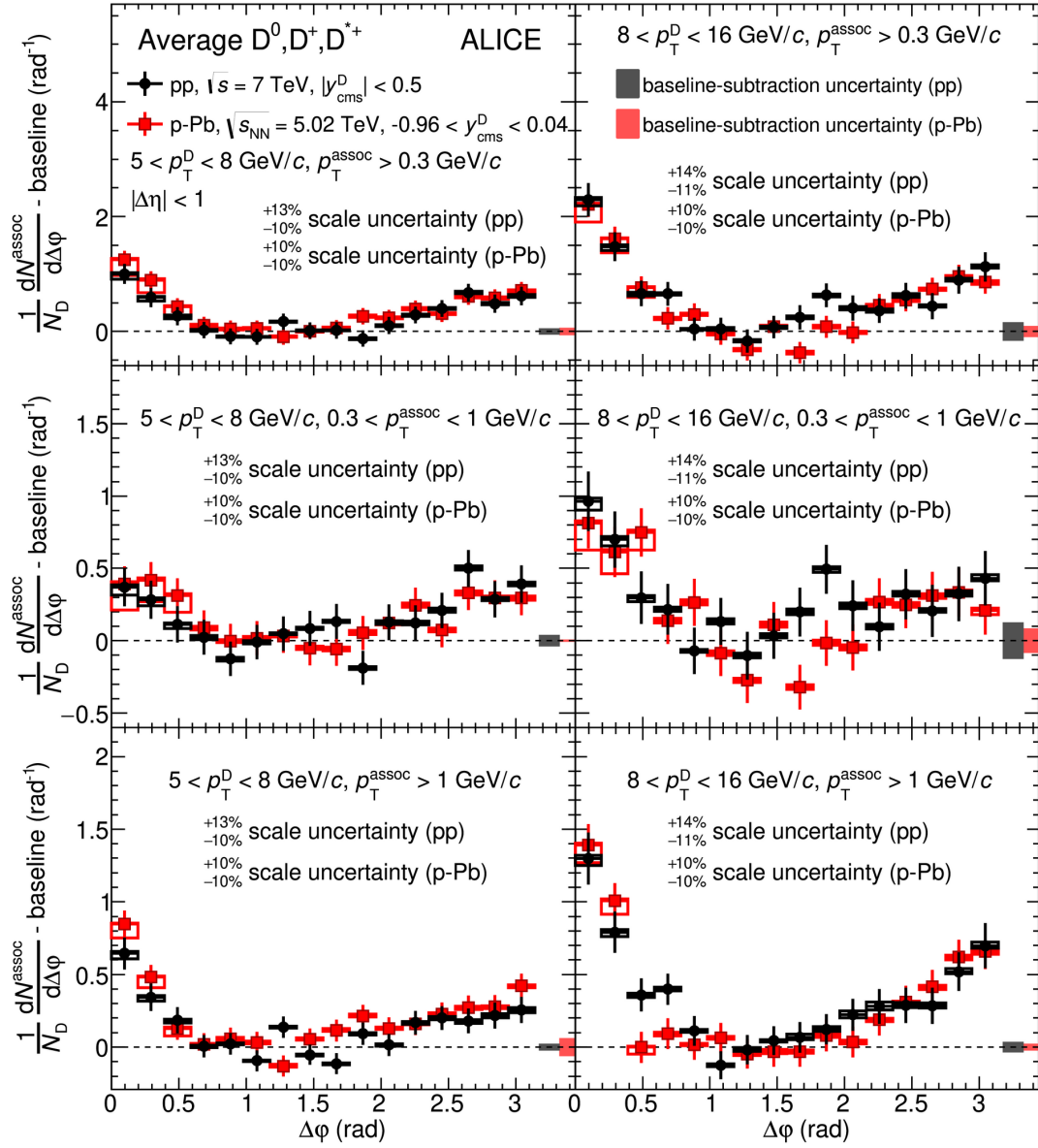


Figure 2.18: [LHCb] The azimuthal correlation ($\Delta\phi$) distribution for $D\bar{D}$ pairs: (a) $D^0\bar{D}^0$, $D^0\bar{D}^-$, $D^0\bar{D}_s^-$, $D^0\bar{\Lambda}_c^-$, (b) D^+D^- , $D^+D_s^-$, $D^+\bar{\Lambda}_c^-$ [73].

2.4 D-h correlations

The D-hadron azimuthal angular correlation has been studied in ALICE experiment at LHC for both pp and p-Pb collision systems at $\sqrt{s} = 7$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV, respectively [74]. The angular correlations have been studied in three different triggered D mesons p_T ranges with three different associated particles (charged hadrons) p_T ranges. The baseline subtracted $\Delta\phi$ correlation distributions in pp and p-Pb for different p_T ranges are shown in Fig. 2.19. The results shown here are the average results of three D mesons (D^0, D^+, D^{*+}). The left column shows the comparison of pp and p-Pb for the D mesons $5 < p_T < 8$ GeV/c, the right column is for $8 < p_T < 16$ GeV/c. The top row is for $p_T^{\text{assoc}} > 0.3$ GeV/c, middle $0.3 < p_T^{\text{assoc}} < 1.0$ GeV/c and bottom row is for $p_T^{\text{assoc}} > 1.0$ GeV/c. From Fig. 2.19, it is clearly evident that a clear near-side peak is visible with a wider small away side peak. The distribution from pp and p-Pb are same within the uncertainties. The correlation distributions are fitted with a double Gaussian and constant baseline function to find the peak properties like width and yields. The comparison of near-side peak yields and widths for both the systems as a function of D-meson p_T are shown in Fig. 2.20. The away side peak yields and widths are not reported due to the low statistics. The top row shows the near-side associated yields and bottom shows the near-side peak width. The left column is for $p_T^{\text{assoc}} > 0.3$ GeV/c, middle $0.3 < p_T^{\text{assoc}} < 1.0$ GeV/c and right is for $p_T^{\text{assoc}} > 1.0$ GeV/c. The near-side associated yields



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Figure 2.19: [ALICE] Comparison of azimuthal correlation distributions of D mesons with charged particles in pp collisions and p-Pb collisions after baseline subtraction for different kinematic ranges [74].

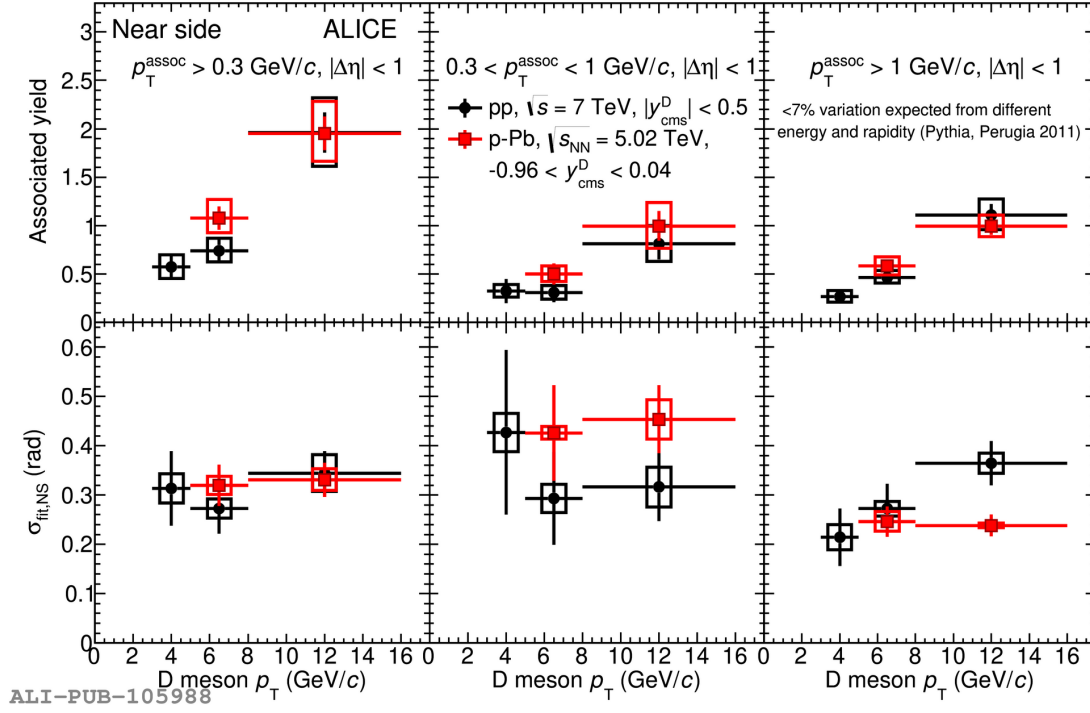


Figure 2.20: [ALICE] Comparison of near-side peak associated yield and width in pp collisions and p-Pb collisions after baseline subtraction for different kinematic range [74].

exhibit an increasing trend with increase in D-meson p_T in all the associated p_T ranges and the results are compatible for both the systems within the statistical uncertainties. The near-side width for $p_T^{\text{assoc}} > 0.3 \text{ GeV}/c$ seems to exhibit no D-meson p_T dependence. But nothing can be concluded for the time being with this statistical uncertainty. The baseline subtracted $\Delta\phi$ correlation distribution for pp at $\sqrt{s} = 7 \text{ TeV}$ compared with simulation performed with PYTHIA, POWHEG+PYTHIA and EPOS3 is shown in Fig. 2.21. In the near-side PYTHIA and POWHEG+PYTHIA are describing the data qualitatively well, while the EPOS3 model is giving a higher and wider distribution for near-side in all the D-meson and associated p_T ranges. The PYTHIA6 with perugia 0 and perugia 2010 tune are giving higher correlations values for away-side in $p_T^{\text{assoc}} > 1.0 \text{ GeV}/c$ for all the D-meson p_T ranges. The EPOS3 model is overestimating the correlations in away-side for D-meson $8 < p_T < 16 \text{ GeV}/c$ for all the associated p_T thresholds. The correlation pattern is described quite well by PYTHIA8 and POWHEG+PYTHIA in almost all the p_T ranges. The near-side yields, widths and baseline for pp collisions at $\sqrt{s} = 7 \text{ TeV}$ are also compared with the Monte Carlo models like PYTHIA,

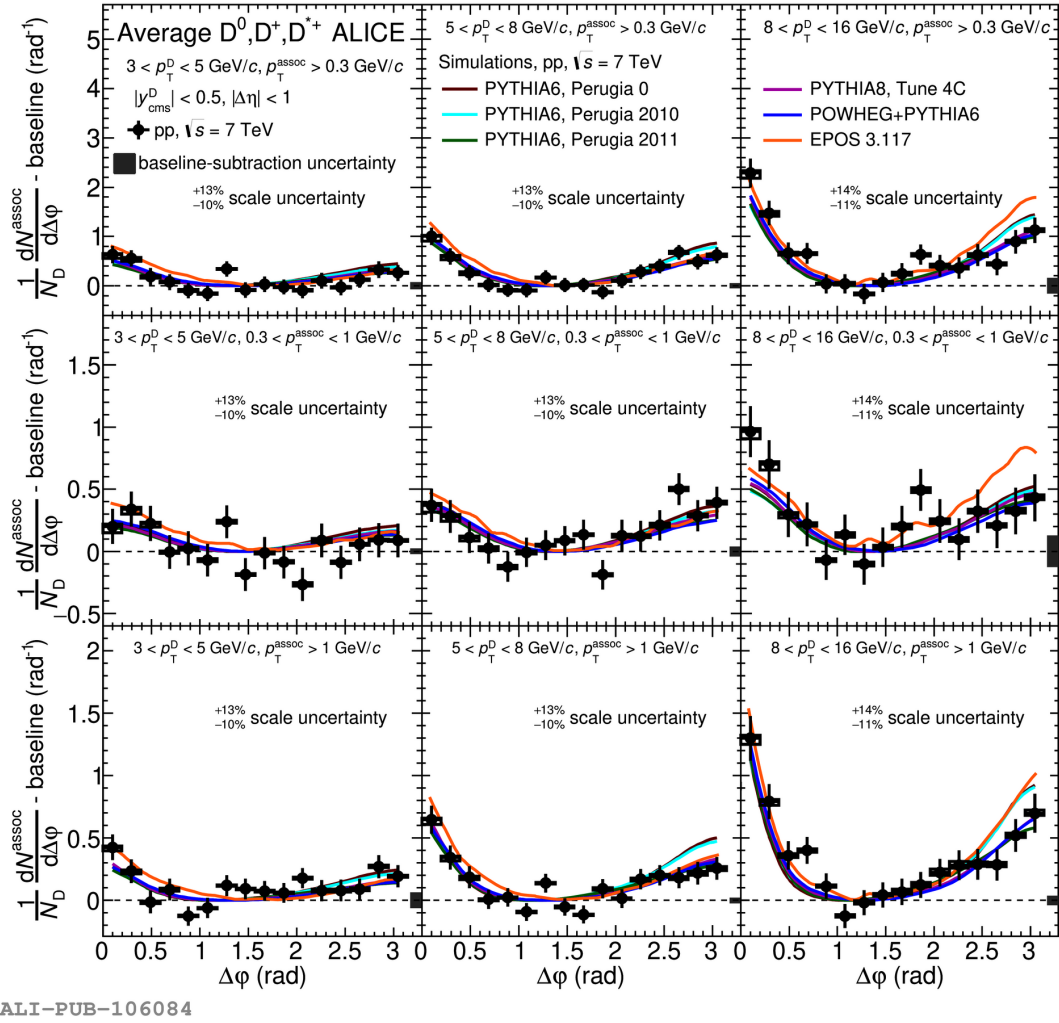
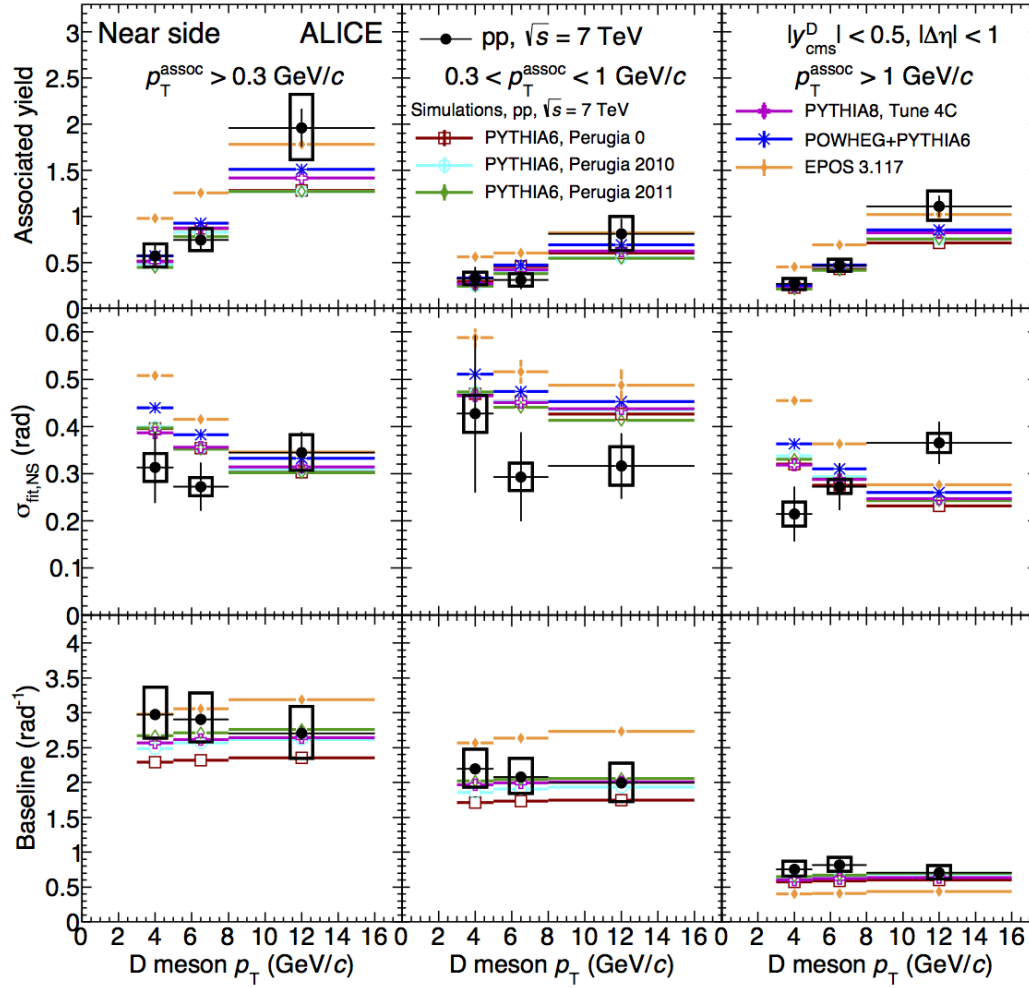


Figure 2.21: [ALICE] Comparison of $\Delta\phi$ correlation distributions in pp collisions and from Monte Carlo simulations with different event generators after the baseline subtraction [74].



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Figure 2.22: [ALICE] Comparison of near-side peak associated yield (top row), near-side peak width (middle row) and baseline (bottom row) values measured in pp collisions with the expectations from Monte-Carlo simulations with different event generators [74].

POWHEG+PYTHIA and EPOS3 and are shown in Fig. 2.22. The near-side associated yield is described quite well by EPOS3 in high p_T , i.e., $8 < p_T < 16$ GeV/c for all the associated p_T ranges. PYTHIA and POWHEG+PYTHIA are much more in agreement with near side associated yields obtained from data in the low and mid p_T ranges. The near-side width is not well described by all the above considered models. The baseline is showing no dependence of D-meson p_T and described well by all the models.

In this Thesis, we have measured the azimuthal correlation of D^0 mesons with charged particles in pp collisions at $\sqrt{s} = 5$ and 13 TeV with ALICE detector at LHC. We have extended this study for higher p_T bins due to more statistics. This study in pp collision will help us to understand mechanism of production of charm quark, fragmentation and harmonization to charm hadrons. It is also a baseline study for Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV. By comparing the results at different energies, we can study the collisional energy effect on correlation distribution and we can understand correlation peak properties in a better way.

Chapter 3

The ALICE experiment at the LHC

"It is tribute to how far we have come in theoretical physics that it now takes enormous machines and a great deal of money to perform experiments whose results we can not predict."

–Stephen Hawking

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is located between the Jura mountain and the Alps, and spreading the roots to both France and Switzerland. The circumference of the LHC ring is around 27 km and is located deep underground (150 m below the surface of the earth). The LHC is the world's largest and most powerful accelerator. It consists of two counter rotating vacuum pipes which are crossed with each other at four points, interaction points for the collisions. At the four points, 1, 2, 5 and 8, the four major experiments, called ATLAS (A Toroidal LHC Apparatus), ALICE (A Large Ion Collider Experiment), CMS (Compact Muon Solenoid) and LHCb (LHC-beauty), are built, respectively. Schematic diagram of LHC accelerator is shown in Figure 3.1. The LHC is capable of colliding not only proton-proton beams and lead-lead ion beams, but also proton-lead beams and the deformed nuclei such as xenon-xenon beams. It can collide upto 14 TeV center of mass energy for protons and 5.5 TeV for lead ions per nucleon pair. The parameters for pp collisions at $\sqrt{s} = 13$ TeV are shown in Table 3.1 [75].

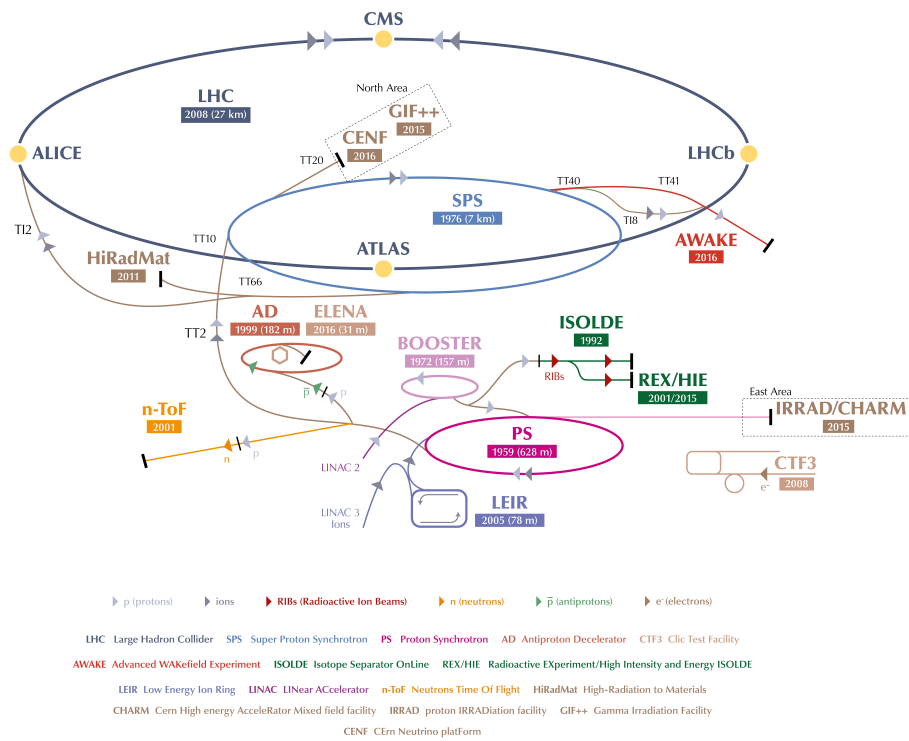


Figure 3.1: Schematic diagram of CERN LHC accelerator complex.

Table 3.1: LHC Machine parameter [76]

Parameter	Value
Circumference	26,659 meter
Dipole operating temperature	1.9 K (-271.3° C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy of protons	6.5 TeV
Nominal energy of ions	2.76 TeV/nucleon
Nominal energy of protons collisions	13 TeV
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.2×10^{11}
No. of bunches per Pb beam	592
No. of Pb ion per bunch	7.0×10^7
Number of turns per second	11245
Number of collisions per second	1 billion

3.1.1 Proton acceleration

The main source for proton in LHC is a bottle of compressed hydrogen gas. The hydrogen atom from the gas cylinder is injected to the fourth chamber of a CERN's Linear accelerator called LINAC-II, where the electrons are stripped off leaving behind the protons. As the protons are positively charged, they are accelerated by an electric field. After the first stage of acceleration inside LINAC-II the proton energy is increased up to 50 MeV and travelling with $1/3$ rd of the speed of light. After that, it enters into the circular Proton Synchrotron Booster (PSB) of 157 m circumference, where it repeatedly circulated to achieve the speed upto 91.6% of speed of light and then fed to the Proton Synchrotron (PS). The PS is 628 m in circumference. Here the protons are circulated for 1.2 sec and achieve 99.9% of the speed of light. As protons are getting closer to the limiting speed of light, the energy of each protons has become 25 GeV. Protons of energy 25 GeV are flown into the Super Proton Synchrotron (SPS), a huge ring of 7 km in circumference, where the energy of proton is increased upto 450 GeV. Then the beam of protons is split into two beams and allowed to pass through two beam pipes of the LHC of 26.7 km in circumference for final acceleration in opposite directions. Each proton beam has 2808 bunches of protons. The LHC accelerates the protons 11,000 times and each time the energy of the protons is boosted and finally each proton in the bunch achieves their maximum energy of 6.5 TeV. Once each beam achieves the maximum energy, they are allowed to collide at different interaction points.

3.1.2 Pb acceleration

The lead atoms have an atomic nuclei of 82 protons and neutrons in between 122 and 126. In the LHC, we are taking the lead isotope ${}_{82}\text{Pb}^{208}$, which contains 126 neutrons. A Pb sample of 2 cm long and 500 mg weight is taken and is heated to 500° C to form vaporised Pb atoms inside the Electron Cyclotron Resonance (ECR) source. At this stage an electric current is used to remove few electrons from lead atoms to form Pb^{27+} ions. Then the ions are passed through a linear accelerator called LINAC III, where they are accelerated upto 4.5 MeV per nucleon and after that again some of the electrons are stripped off to become Pb^{54+} ions. Next, these

Pb^{54+} ions are accelerated to 72 MeV per nucleon inside the Low Energy Ion Ring (LEIR) of circumference 78.54 m. Further the Pb^{54+} ions are injected to the PS, where they are accelerated to 5.9 GeV per nucleon and final stage of stripping off electrons is done to form the Pb^{82+} ions. This final Pb^{82+} ions passed through the SPS for further acceleration up to 177 GeV per nucleon and they are finally injected into the Large Hadron Collider in two opposite directions. In the LHC, the Pb ions beams are accelerated to 1.38 TeV per nucleon and are collided at a centre of mass energy 2.76 TeV at various interaction points [77].

3.1.3 Xe–Xe collisions

For the first time Xenon beam was accelerated and injected to the LHC on 12th October 2017 and collided at $\sqrt{s_{NN}} = 5.44$ TeV. The beam lasted for 6h [78]. The speciality of Xenon is that it is the 5th noble gas present in the periodic table having a proton number 54 and neutron number varies from 70 to 80 depending on the isotopes [79]. The Xenon nucleus used in the LHC has 54 protons and 75 neutrons. This Xenon nucleus is lighter than lead nucleus by $\sim 40\%$. Physicist thought that Xe–Xe collision may create a QGP-like medium, but a bit cooler and shorter lived compared to the one created in Pb–Pb collisions. Any differences observed in the measurements performed on data from the collisions of these two species should provide a valuable information on the production and nature of the QGP [80].

3.1.4 p–Pb collisions

LHC not only collides the beams made of two similar species, but also beams made of two different species. In 2012, LHC collided the proton and lead beam at $\sqrt{s_{NN}} = 5.02$ TeV energy for the first time [81]. The acceleration of protons and Pb ions is described earlier in section 3.1.1 and section 3.1.2, respectively. Again, the p–Pb collision is recorded at $\sqrt{s_{NN}} = 8.16$ TeV in the year 2015. To achieve the centre of mass energies 5.02 TeV and 8.16 TeV, the proton beam energy was set to 4 TeV and 6.5 TeV with the help of LHC magnets, respectively [82]. The purpose of p–Pb collisions is mainly to compare the results from different colliding species.

3.1.5 Physics at LHC

The main goal of LHC is to study the different aspects of physics like basic structure of matter, Quark Gluon Plasma in heavy ion, matter-antimatter asymmetry, cosmic ray particles from the outer space, supersymmetry, compositeness (substructure of subatomic particle), unification of all fundamental forces, search for extra dimensions, gravitons, black holes, dark matter, dark energy and Higgs boson [83]. The detectors ATLAS, CMS, ALICE and LHCb are installed at LHC exclusively for these physics studies. The ATLAS [84] and CMS [85] are general purpose particle physics detectors. Main aim is to study the basic building blocks of matter, fundamental forces of nature and testing the prediction of standard model. The ATLAS and CMS experiments at CERN announced independently the discovery of Higgs Boson of mass around 126 GeV on 4th July 2012. The Nobel Prize in Physics was awarded jointly to theorists François Englert and Peter Higgs on 8th October 2013 for the theoretical prediction of Higgs Boson. The LHCb [86] experiment was set up for the dedicated study of rare beauty (b) decays, CP violation and asymmetry between matter and anti-matter. An important milestone in the history of particle physics is the discovery of CP violation in charm particle decays by LHCb on 21st March 2019. The ALICE experiment was built for the dedicated study of heavy-ion physics, mainly to study the Quark-Gluon Plasma (QGP), a deconfined state of quarks and gluons. The recent important results from ALICE is the enhanced production of multi-strange hadrons in high multiplicity pp collisions at $\sqrt{s} = 7$ TeV [87], as similar to previously observed results in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

3.2 The ALICE experiment

The ALICE (A Large Ion Collider Experiment) detector at the LHC is designed to study the property of Quark-Gluon Plasma (QGP), a deconfined state of quarks and gluons, produced in the ultra-relativistic heavy-ion collisions. The ALICE detector is designed in such a way that it can perform in a high charged particles multiplicity environment to track and identify particles from low momentum (0.1 GeV/c) to very high momentum (100 GeV/c) and also reconstruct

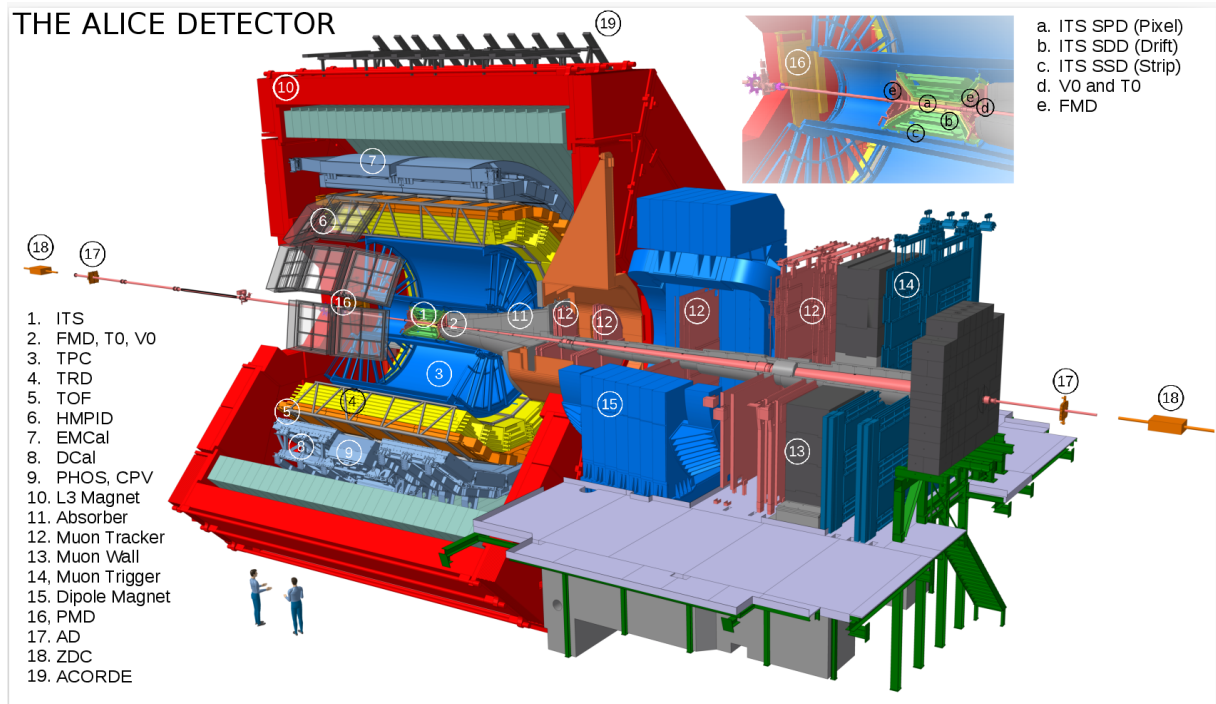


Figure 3.2: Schematic view of ALICE detector.

the short-lived particles like hyperons, D and B mesons. The ALICE detector is made up of several sub-detectors as shown in Figure 3.2. These detectors are categorised according to their positions as central barrel detectors, the forward detectors and the muon spectrometer. The details of these detectors are described in subsequent sections.

3.3 Central barrel detector

The central barrel detectors perform in the mid-rapidity ($|\eta| \leq 0.9$) region covering the full azimuthal range (0 to 2π). All the detectors located in the central barrel are placed inside the L3 solenoidal magnet, which creates a magnetic field up to 0.5 T. The detectors which are present in the central barrel are Inner Tracking System (ITS), Time Projection Chamber (TPC), Time Of Flight (TOF), A Cosmic Ray Detector (ACORDE), High Momentum Particle Identification Detector (HMPID), Transition Radiation Detector (TRD), Photon Spectrometer (PHOS) and Electromagnetic Calorimeter (EMCAL).

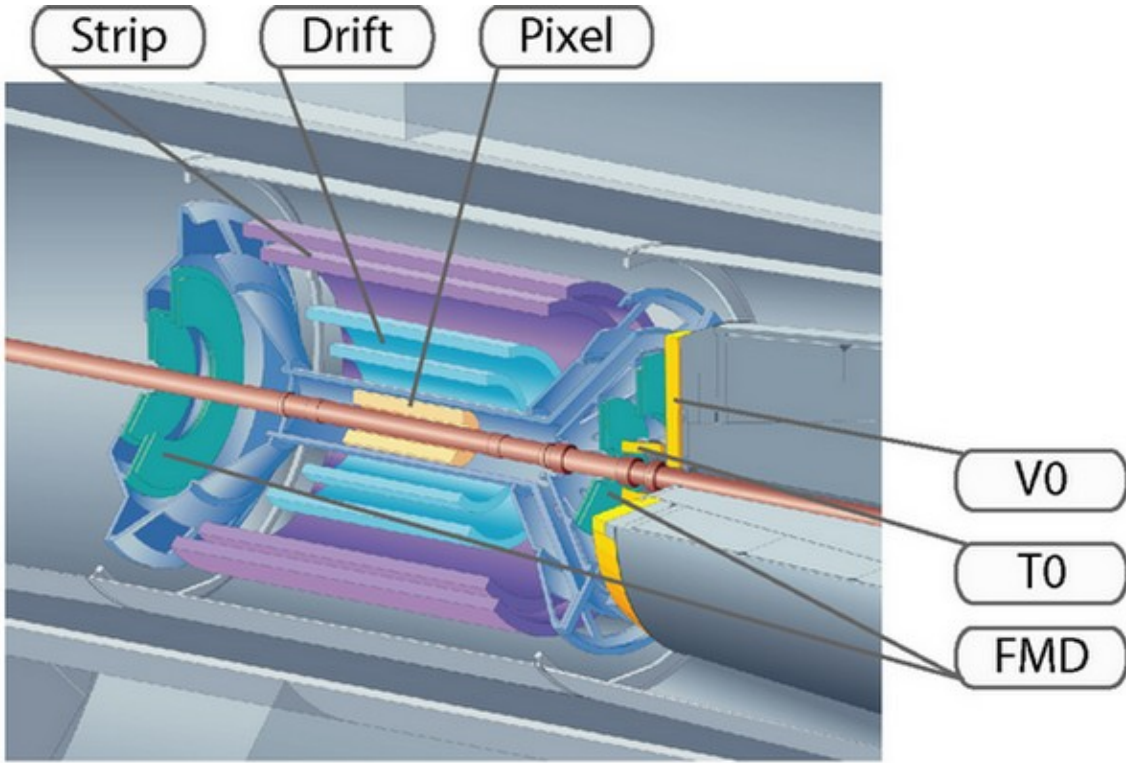


Figure 3.3: Schematic view of ITS [89].

3.3.1 Inner Tracking System (ITS)

The ITS [88] is made up of six cylindrical layers of silicon detectors covering a pseudorapidity range of $|\eta| < 0.9$. The beam pipe is surrounded by the ITS and the separation between the beam pipe and ITS ranges from 3.9 cm for the innermost layer up to 43 cm for the outermost layer of ITS. The fundamental objectives of ITS are to provide excellent tracking and identification of low momentum particles in high multiplicity environment, measurement of primary vertex position with a resolution better than $100 \mu\text{m}$ and estimation of secondary vertices originated from the hyperons decay, and heavy flavour hadrons decay with respect to the primary vertex by the distance of closest approach (DCA) method. From the six layers of ITS, the innermost two layers are made up of Silicon Pixel Detectors (SPD), the intermediate two layers are of Silicon Drift Detectors (SDD) and the outermost two layers are the double sided Silicon Strip Detectors (SSD). The schematic view of ITS with six layers is shown in Figure 3.3.

Silicon Pixel Detectors (SPD):

The SPD is the two innermost layers of ITS and located at a distance of 3.9 cm to 7.0 cm from the beam line. These two layers are equipped with hybrid silicon pixel detectors covering a range of $|\eta| < 1.95$. The primary objective of SPD is to determine the primary vertex and secondary vertex in a high multiplicity environment. The SPD also helps to achieve a track impact parameter resolution better than $50 \mu\text{m}$ for $p_T > 1.3 \text{ GeV}/c$.

Silicon Drift Detectors (SDD):

The two middle layers of ITS is composed of SDD, covering a pseudorapidity range of $|\eta| < 0.9$ and full azimuthal angle 2π . It is having radii of 15.0 cm and 23.9 cm. It helps in track separation and particle identification through dE/dx measurements.

Silicon Strip Detectors (SSD):

The two outermost layers of ITS are composed of SSD, covering a pseudorapidity range of $|\eta| < 0.9$ and also full azimuthal angle 2π , with radii of 38.0 cm and 43.0 cm. The SSD plays an essential role in connecting the tracks from the TPC to the ITS. The SSD also assists in particle identification by measuring the dE/dx .

3.3.2 Time Projection Chamber (TPC)

TPC [88] is the main tracking detector present in the central barrel of the ALICE detector system. It has a coverage of full azimuthal angle and pseudorapidity range of $|\eta| < 0.9$. TPC can help to provide the information about the charged particle momentum, particle identification and vertex determination together with other central barrel detectors (TOF, ITS and TRD). It can measure the transverse momentum (p_T) of charged particle from $0.1 \text{ GeV}/c$ to $100 \text{ GeV}/c$ with a resolution of 1-5%. The resolution of 5% at high p_T includes information from both the TPC and ITS. TPC can not only identify the charged particles in low momentum but also statistically differentiate pion, kaon and proton in high- p_T region.

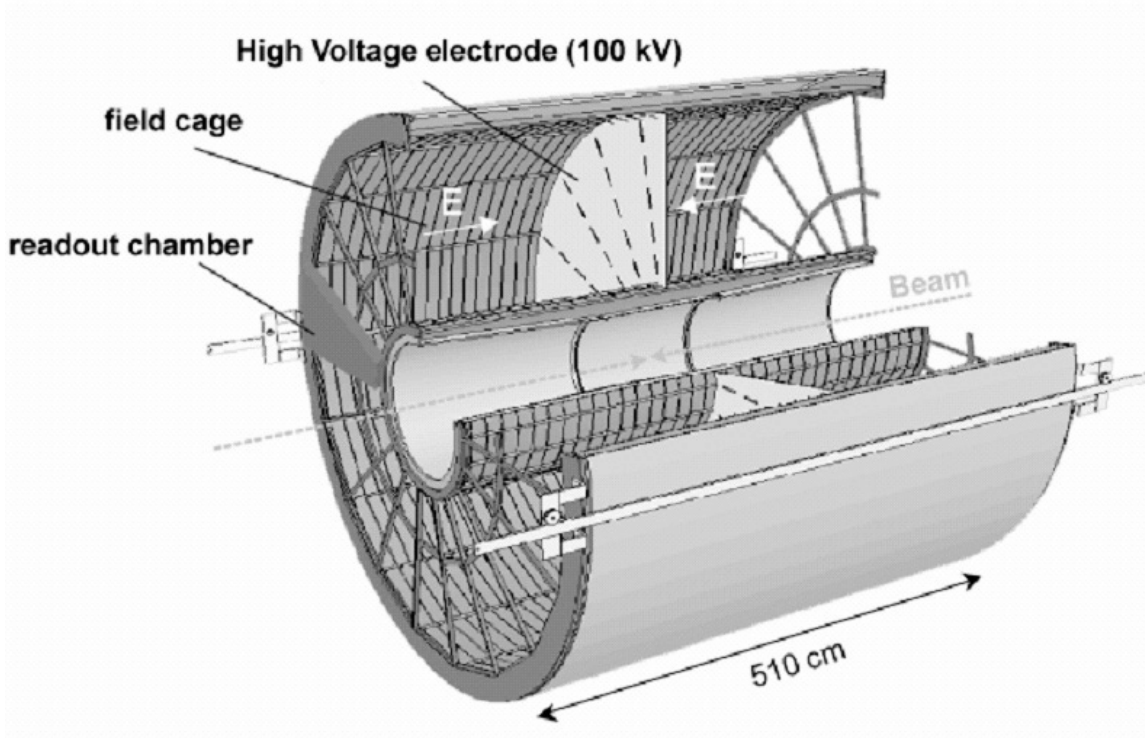


Figure 3.4: Layout of the ALICE TPC detector.

TPC is a cylindrical gas detector of total length of 510 cm along the beam direction and having an inner and outer radii of about 85 cm and 247 cm, respectively. The TPC layout is shown in Figure 3.4. The total volume of the detector is 90 m³ and filled with the mixture of Argon (Ar) and CO₂ in a proportion of 88:12 to have low material budget to reduce multiple scattering as well as formation of secondary particles. When a charged particle travels through TPC, it ionises the TPC gas resulting in the production of electrons. These electrons drift towards end plates from the creation point because of the presence of uniform electric field. Each end plates is divided into 18 trapezoidal sectors and installed with Multi-Wire-Proportional Counter (MWPC) with cathode-pad readout. Each sector is again divided into two chambers, Inner Read-Out Chamber (IROC) and an Outer Read-Out Chamber (OROC) with varying pad sizes from 0.3 cm² to 0.9 cm², respectively, to get a better dE/dx and position resolution.

The identification of the charged particle in TPC is done by measuring the specific energy loss (dE/dx) and the particles momentum simultaneously. The Bethe-Bloch formula describes the specific energy loss of charged particle traversing through the medium, which is used in the

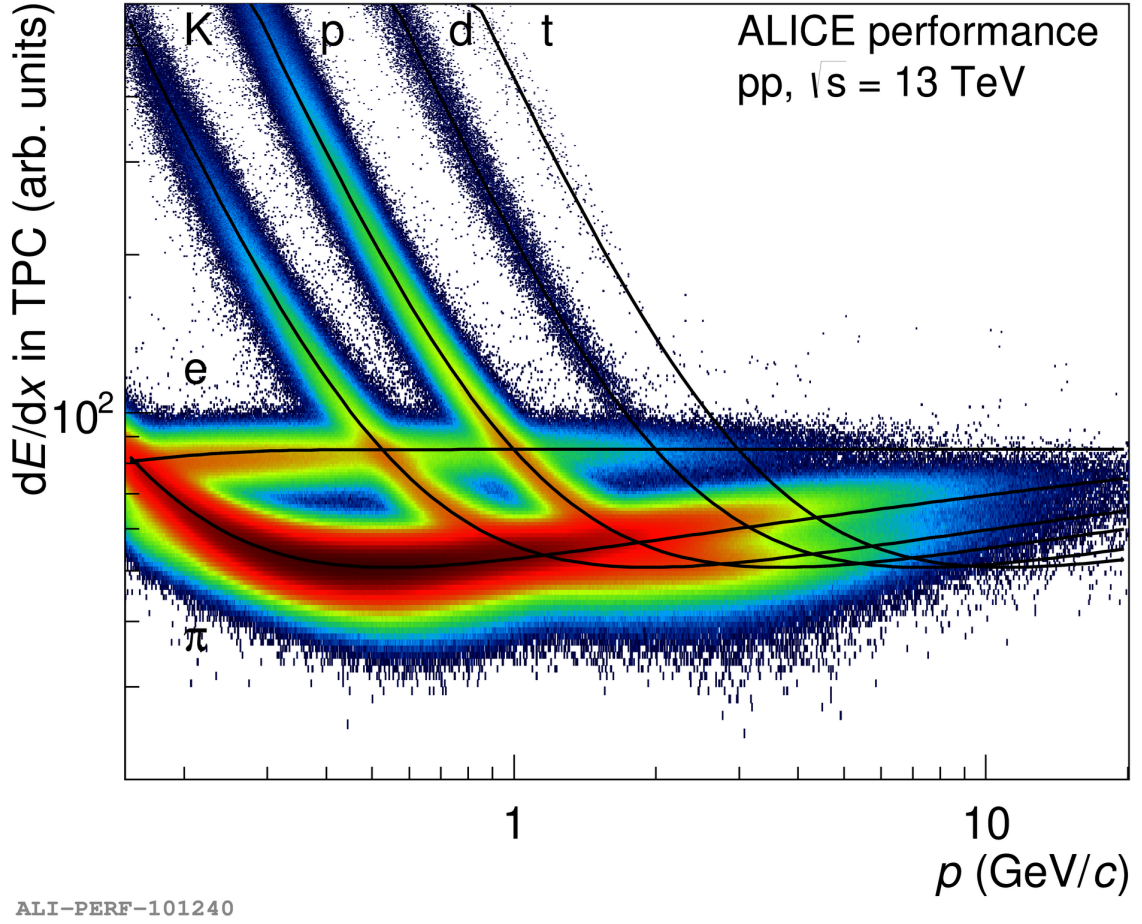


Figure 3.5: TPC- dE/dx as a function of charged particle momentum in pp collisions at $\sqrt{s} = 13$ TeV. The solid black lines correspond to Bethe-Bloch lines for various particle species.

particle identification in ALICE. The ALEPH collaboration proposed a function by which the formula is parametrized [90].

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln \left(P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right) \right) \quad (3.1)$$

In the above Equation (3.1), β , γ , P_{1-5} represents the particle velocity, Lorentz factor and the fitting parameters, respectively. TPC- dE/dx as a function of charged particle momentum is shown in Figure 3.5. The separations between the bands of different charged particle species like electrons, pions, kaons, protons, deuterium, tritium are clearly visible. The black solid lines correspond to the value of Bethe-Bloch parametrization for the above stated charged particles.

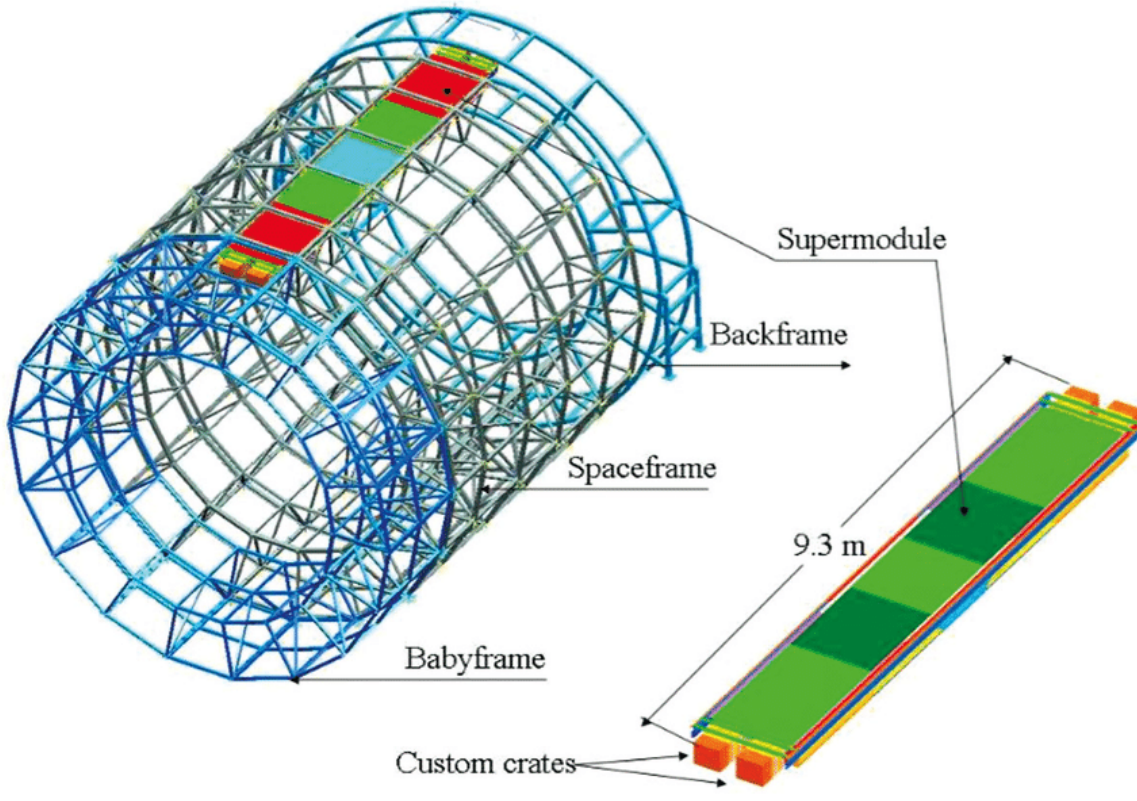


Figure 3.6: Layout of ALICE TOF [91].

TPC can provide dE/dx resolution up to 5.2% in pp collisions and 6.5% in most central collision (0-5%) in Pb–Pb collisions.

3.3.3 Time Of Flight (TOF)

TOF [88] has also a cylindrical layout of inner radius 370 cm and outer radius 399 cm from the beam line. The total barrel length of TOF is 745 cm. It covers the polar angle from 45° to 135° which correspond to the pseudorapidity $|\eta| < 0.9$. It has the full azimuthal coverage. It has 18 sectors in azimuthal plane and each sector is divided into 5 segments along the z-direction. The layout of TOF is shown in Figure 3.6. It is composed of 90 modules and 1593 Multigap Resistive Plate Chamber (MRPC) strips covering an area of 141 m^2 . Each strip contains 96 pickup pads which results into 152928 readout pads.

MRPC can work in an environment of high and uniform electric field. When a charged particle enters the gas volume, it produces avalanche immediately, which are collected by the readouts as signal with almost zero drift time. TOF can measure the charged particle velocity

($\beta = v/c$), where $v(L/t)$ can be estimated by measuring the time of flight " t " over the particle trajectory length " L ". The particle identification in TOF is done by measuring the particle mass and momentum. The momentum of the particle can be measured from other detectors and the mass is calculated by

$$m^2 = \frac{p^2}{c^2} \left(\frac{c^2 t^2}{L^2} - 1 \right) \quad (3.2)$$

Suppose, two charged particles are having same momentum and track length but different masses m_1 and m_2 , then they can be identified from the number of standard deviations shown in Equation (3.3).

$$n_\sigma = \frac{t_1 - t_2}{\delta t}, \quad (3.3)$$

where δt is the time resolution of the TOF detector and

$$t_1 - t_2 = \frac{L}{2c} \left(\frac{m_1^2 c^2 - m_2^2 c^2}{p^2} \right) \quad (3.4)$$

The main objective of the TOF is to identify particles in intermediate p_T range. Along with TPC, ITS, it can identify pions or kaons in p_T range 0.2-2.5 GeV/ c , protons in p_T range 0.4-4.5 GeV/ c and electrons in p_T range 0.1-0.7 GeV/ c . The TOF information allows better separation than 3σ for π/K and K/p ratio up to 2.5 GeV/ c and 4 GeV/ c , respectively. The velocity distribution of particle as a function of momentum of charged track is shown in Figure 3.7.

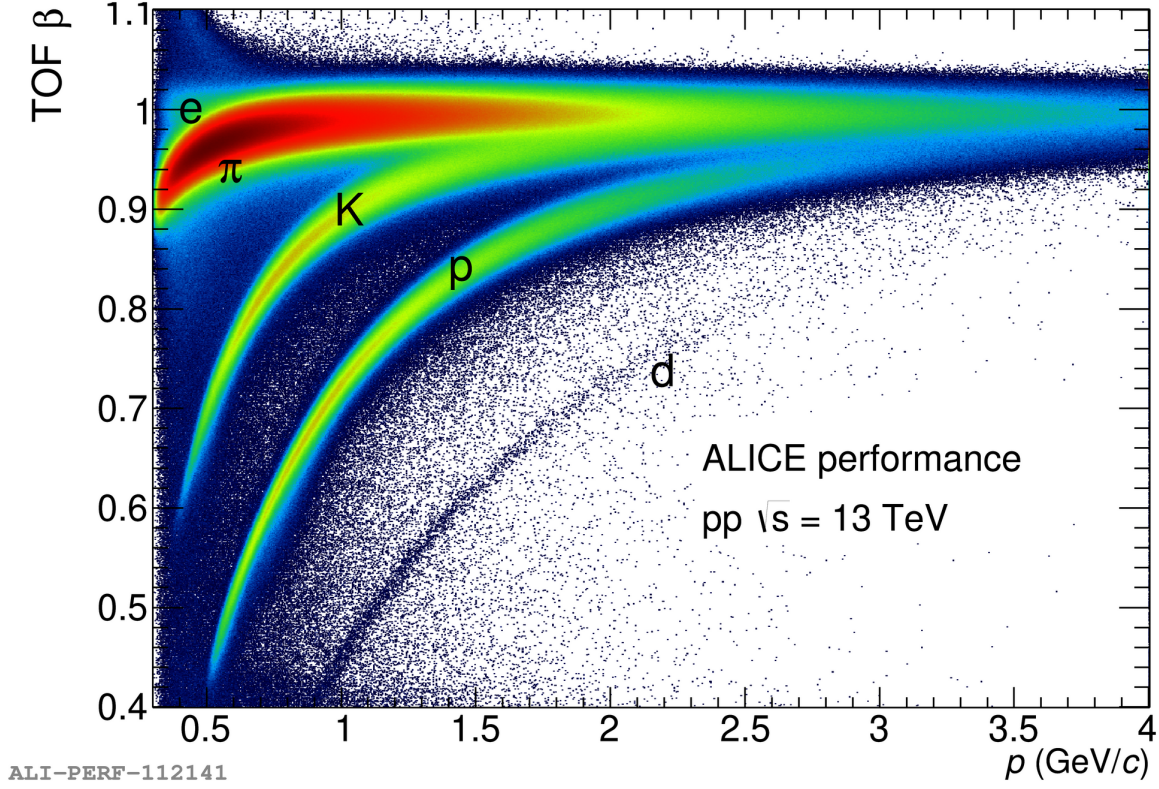


Figure 3.7: Particle velocity (β) measured by TOF as a function of charged track momentum.

3.3.4 A Cosmic Ray Detector (ACORDE)

ACORDE [88] is the cosmic ray detector of ALICE. It is made up of an array of 60 plastic scintillator counters and located on the upper surface of the L3 magnet at a radial distance of 850 cm from the interaction point. The pseudorapidity range is $|\eta| \leq 1.3$ and azimuthal coverage is $-60^\circ < \varphi < 60^\circ$. It has two purposes. First one is to provide a fast (L0) trigger signal for calibration, alignment and performance of several ALICE tracking detectors like ITS and TPC. Another purpose is to detect the atmospheric muons and multi muon events in combination with TPC, TRD and TOF.

3.3.5 High Momentum Particle Identification Detector (HMPID)

The HMPID [88] is a Ring Imaging Cherenkov (RHIC) detector located at a radial distance of 500 cm from the beam line, with a coverage of pseudorapidity range $|\eta| < 0.7$ and azimuthal range from 1.2° to 58.8° . The main objective of HMPID is to increase the parti-

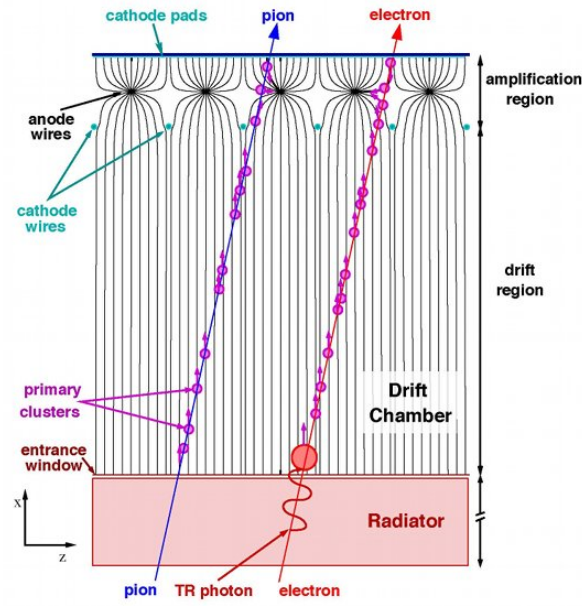


Figure 3.8: Schematic diagram of electron and pion passing through the TRD chamber [92].

cle identification capabilities of ALICE beyond the momentum range allowed by the energy loss measurements (ITS and TPC) and by TOF. It can identify high momentum pion, kaon and proton and discriminate π/K and $/p$ on a track-by-track basis up to $3 \text{ GeV}/c$ and $5 \text{ GeV}/c$, respectively.

3.3.6 Transition Radiation Detector (TRD)

TRD [88] is developed mainly for the identification of electron from pion at relatively high momentum ($p > 1 \text{ GeV}/c$). It is covering a pseudorapidity range of $|\eta| < 0.8$ and full azimuthal region. It is placed at a radial distance of 290 cm to 368 cm from the beam line. The 522 readout modules are arranged evenly in the six layers of TRD. The readout modules consist of a radiator, a drift chamber and multi-wire proportional chamber (MWPC) filled with Xe and CO_2 in a proportion of 85:15. The basic principle to distinguish electrons from charged particles is the emission of transition radiation by electrons in the radiator. The schematic diagram of electron and pion passing through the TRD chamber is shown in Figure 3.8.

3.3.7 Photon Spectrometer (PHOS)

The PHOS [88] is a high resolution electromagnetic calorimeter, covering a pseudorapidity range $|\eta| < 0.13$ and azimuthal range from 260° to 320° . It is located at a radial distance of 460 cm from the beam line. The main goal is to measure the photons coming out of the hot QCD matter created in Pb–Pb collisions and reconstruction of π^0 decaying to photons for the study of jet quenching and γ -jet correlations.

3.3.8 Electromagnetic Calorimeter (EMCAL)

The EMCAL [88] is a Pb-scintillator sampling calorimeter covering a 107° in azimuth and pseudorapidity range $|\eta| < 0.7$. The geometry is cylindrical and located at a radial distance of 450 cm from the beam line, opposite to the PHOS in azimuthal plane. The EMCAL enables the fast and efficient (L0, L1) trigger for hard jets, photons and electrons. It also enhances the ALICE capabilities to study the jet interactions in the medium produced in heavy-ion collisions, which helps to study the jet quenching effect.

3.4 Forward detectors

The forward detectors cover the wide rapidity range ($-3.4 \leq \eta \leq 5.1$). The forward detectors are: Photon Multiplicity Detector (PMD), Forward Multiplicity Detector (FMD), T0, V0 and Zero Degree Calorimeter (ZDC).

3.4.1 Photon Multiplicity Detector (PMD)

The PMD [88] is a particle shower detector, having a full azimuthal coverage and pseudorapidity range of $2.3 \leq \eta \leq 3.7$. It is located at a distance of 364 cm from the interaction point and perpendicular to the beam direction. It measures the multiplicity and spatial (η and φ) distribution of photons produced in the collision. It also helps in estimating the reaction plane to study the flow of charged particles.

3.4.2 Forward Multiplicity Detector (FMD)

The FMD [88] is a silicon semiconductor detector. It comprises of 5 rings of two types: inner and outer. The inner and outer type rings are subdivided into 20 and 40 sectors, respectively. The FMD comprises of FMD1, FMD2 and FMD3 detectors. The FMD1 has an inner type silicon sensor ring, both FMD2 and FMD3 have one inner type and one outer type silicon sensor rings. FMD is designed to measure the charged particle multiplicity distribution over a range $-3.4 < \eta < -1.7$ in backward and $1.7 < \eta < 5$ in forward region. It also helps to study the flow and jets by measuring the orientation of the collisions in the vertical plane.

3.4.3 T0

The T0 [88] is the trigger and fast timing detector. The T0 detector is composed of two arrays of cherenkov counter T0A and T0C. The T0A and T0C are placed in opposite directions from the interaction point at a distance of 360 cm and 70 cm, respectively. The T0A covers a pseudorapidity range of $4.5 < \eta < 5$, while T0C covers $2.9 < \eta < 3.3$. The main functions of T0 are to deliver an early wake-up signal to TRD, to provide the main signal to L0 and to give a precise start signal for time-of-flight (TOF). It also measures luminosity.

3.4.4 V0 :

The V0 [88] detector is made up of two arrays of scintillator named as V0A and V0C. V0A and V0C are placed on either side of the interaction point at a distance of 330 cm and 90 cm, respectively. V0A covers a pseudorapidity range $2.8 < \eta < 5.1$ and V0C covers the range $-3.7 < \eta < -1.7$. The V0 detector provides different kind of triggers, i.e., Minimum Bias trigger (MB), Multiplicity Trigger (MT), semi-Central Trigger (CT1) and Central Trigger (CT2), in AND mode operation with V0A and V0C. The main aim of V0 is to measure the charged particle multiplicity density and estimation of centrality in heavy-ion collisions.

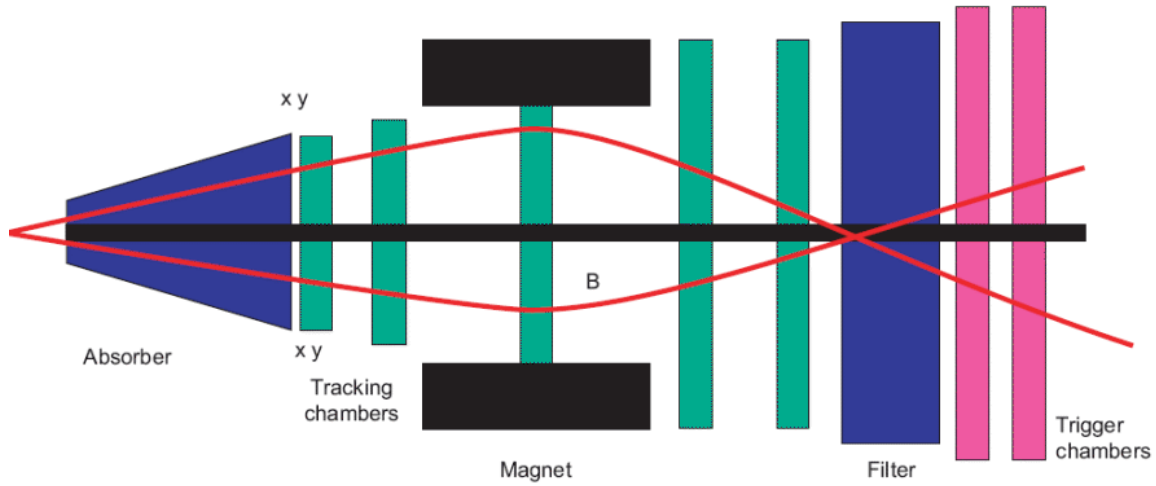


Figure 3.9: Cross-sectional view of Dimuon spectrometer.

3.4.5 Zero Degree Calorimeter (ZDC)

The two sets of ZDC [88] are installed on either side nearly zero degree polar angle, at a distance of 116 m from the interaction point. The ZDC measures the energy of the spectator (non-interacting) nucleons in a collision. Therefore, each ZDC contains two set of detectors ZN and ZP to measure the spectator neutrons and protons, respectively. The ZDC is used as centrality estimator and also used as a luminosity detector in heavy-ion collisions.

3.5 Muon Spectrometer

The muon spectrometer [88] covers a pseudorapidity range of $2.5 \leq \eta \leq 4$. The main components of muon spectrometer are shown in Figure 3.9.

The spectrometer consists of a front absorber, a tracking system, a large dipole magnet, a muon-filter wall and trigger chamber. The muons can only pass through the absorber and to restrain from multiple scattering and energy loss, the absorber is made of carbon and concrete. The muon tracking chamber consists of 10 cathode pads and arranged in 5 stations (2 pads per station). Two stations are placed before muon dipole magnet, one inside and two after the muon dipole magnet. After passing through the absorber the muons are detected in the muon chamber. The trajectory of high momentum muons are bent due to the presence of

magnetic field. Thereafter the muon passes through the filter and reaches to the muon trigger chamber, where muon trigger delivers the signal to ALICE Central Trigger Processor (CTP). It is optimized for the study of heavy quarkonia ($J/\psi, \psi', \Upsilon, \Upsilon', \Upsilon''$) via their di-muon decay channel in the forward rapidity region.

In this thesis I have used the data of ITS, TPC, TOF and VZERO detectors for my D^0 -hadron azimuthal correlation analysis in pp collisions at 5 TeV and 13 TeV.

Chapter 4

Analysis details and technique

"An experiment is a question which science poses to Nature and a measurement is the recording of Nature's answer."

–Max Planck

This chapter describes the techniques used in the measurement of D^0 - hadron azimuthal correlation in pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV. Section 4.1 describes the brief introduction of the analysis goal. The detailed analysis strategy starting from code used for the analysis, data set, event selection, D^0 signal extraction, correlation with charged hadrons and corrections for the correlations distribution are explained in Section 4.2.

4.1 Introduction

The study of heavy flavor hadrons are more important to investigate the properties of QGP. As heavy flavors are produced in the early stages of collision, they experience the full evolution of the fireball. They are subject to several modifications during the QGP phase, such as a progressive energy loss while travelling through the nuclear medium. So, their hadronization products carry the information of QGP effects. The study of two-particle azimuthal angular correlations in pp collisions allows to study the fragmentation and hadronization of charm quark as well as their production mechanism. D^0 - hadron azimuthal correlation in pp collision acts

as a reference for p-Pb and Pb-Pb results. To extend the study in p-Pb collision one can access cold nuclear matter effects and search for double ridge (i.e., long range ridge-like structures in near-side and away-side regions) as observed in hadron-hadron correlations.

A mutual relationship or connection between two or more things is known as correlation. The general technique for two-particle correlations are as follows: at first a charged particle with highest transverse momentum is selected in an event and called as "trigger" particle, then all other charged particles of the same event are called as "associated" particle with condition $p_T^{\text{assoc}} < p_T^{\text{trig}}$. For each associated particle the relative azimuthal angular difference ($\Delta\varphi = \varphi_{\text{trig}} - \varphi_{\text{assoc}}$) and relative pseudorapidity difference ($\Delta\eta = \eta_{\text{trig}} - \eta_{\text{assoc}}$) are calculated to build the correlation distribution. The correlation distribution gives two peaks, one around $\Delta\varphi = 0$, called the near-side peak and another around $\Delta\varphi = \pi$, called the away-side peak. The main aim of this method is to find and investigate the jets cone of both initial partons. The same analysis technique is used here with a small change. Here, the D^0 meson is taken as trigger particles and all other primary charged hadrons are taken as associated particles. The primary charged hadrons are the charged particles coming directly from the primary vertex, particles from the electromagnetic decays, strong decays and from heavy-flavor hadrons decays. As the trigger particles are D^0 mesons, the condition $p_T^{\text{assoc}} < p_T^{\text{trig}}$ is not so important in this analysis.

The angular correlation between D mesons and charged particles is studied in a region of $3 \leq p_T^D \leq 16$ GeV/c with an associated particle $p_T^{\text{assoc}} > 0.3$ GeV/c. One can not carry out this analysis in low p_T ($p_T^D < 3$ GeV/c) of D meson due to the large combinatorial backgrounds and also in high p_T ($p_T^D > 16$ GeV/c) due to limited statistics. In order to study the p_T dependence of trigger particle in correlation, the correlation distribution is evaluated in each p_T region of D mesons separately in an interval of 1 GeV/c. But to reduce the statistical fluctuations the D mesons p_T regions are merged and divided into 3 p_T regions : Low p_T ($3 < p_T^D < 5$ GeV/c), Mid p_T ($5 < p_T^D < 8$ GeV/c) and High p_T ($8 < p_T^D < 16$ GeV/c). Similarly, the study is done in different associated particle p_T region (> 0.3 GeV/c, $0.3 - 1.0$ GeV/c and > 1.0 GeV/c).

Table 4.1: D mesons properties

Particle symbol	D^0	D^+	D^{*+}
Quark content	$c\bar{u}$	$c\bar{d}$	$c\bar{d}$
Rest mass (GeV/c^2)	1.864	1.869	2.01
Charge	0	+1	+1
Spin	0	0	1
Parity	-ve	-ve	-ve
Mean Lifetime (fm)	1.2×10^{11}	3.1×10^{11}	2.07×10^3
Decay Channel	$D^0 \rightarrow K^- \pi^+$	$D^+ \rightarrow K^- \pi^+ \pi^+$	$D^{*+} \rightarrow D^0 + \pi^+ \rightarrow K^- \pi^+ \pi^+$
Branching Ratio	$3.89 \pm 0.04\%$	$8.98 \pm 0.28\%$	$67.7 \pm 0.5\%$

The analysis is done considering three D meson species (D^0 , D^+ , D^{*+}) in a similar way. The three D mesons properties and hadronic decay channels with branching ratio used in the analysis are given in Table 4.1.

4.2 Analysis Strategy

4.2.1 Data Set

The analysis is done in pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV. The ALICE experimental data and Monte-Carlo simulated data used in this analysis are listed in Table 4.2.

Table 4.2: Data set used for Analysis.

Energy ($\sqrt{s}$)	Data Set	Data Type (AOD), MB	Events Analysed (M)
5 TeV	LHC15n	pass2	~ 115
	LHC16i6a, LHC16h8b	PYTHIA	~ 3
13 TeV	LHC16d, 16e, 16g, 16h, 16j, 16k, 16l, 16o, 16p	pass1	~ 431
	LHC17c3a1, LHC17c3a2, LHC17h8a	PYTHIA	~ 32

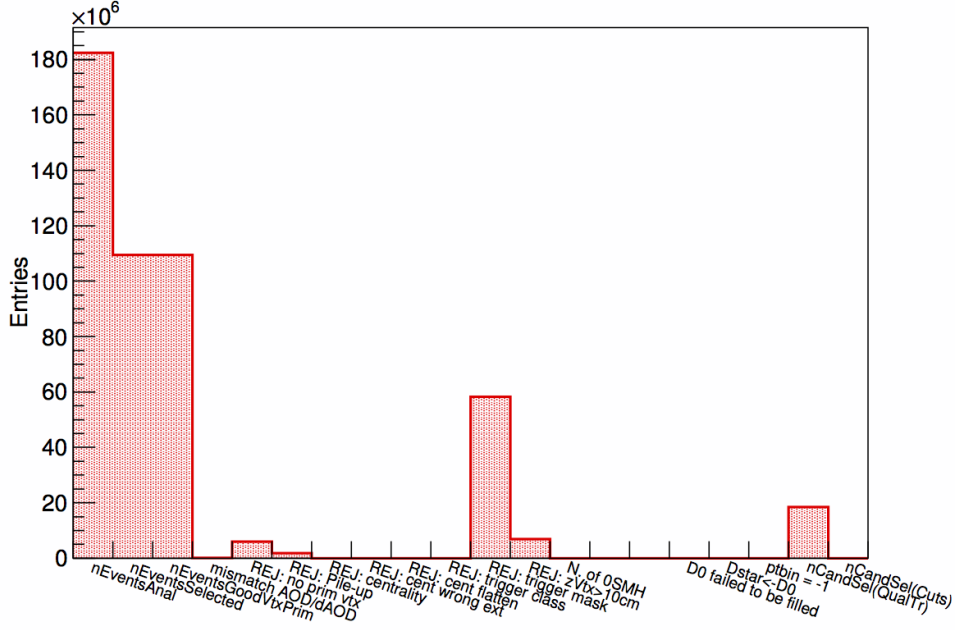


Figure 4.1: Event selection graph for pp collisions at $\sqrt{s} = 5$ TeV.

4.2.2 Event Selection

The trigger mask kINT7 is used for the event selection. The kINT7 trigger is configured by demanding a hit in the SPD detector and a hit in both the VZEROA and VZEROC detector. The event selections for pp collisions at $\sqrt{s} = 5$ and 13 TeV are shown in Fig. 4.1 and Fig. 4.2, respectively. From Fig. 4.1 (Fig. 4.2), it is seen that the total number of events processed: 180 M (1890 M) events, total number of events analyzed: 109 M (436.8 M) events and pileup rejection: 1.7M events.

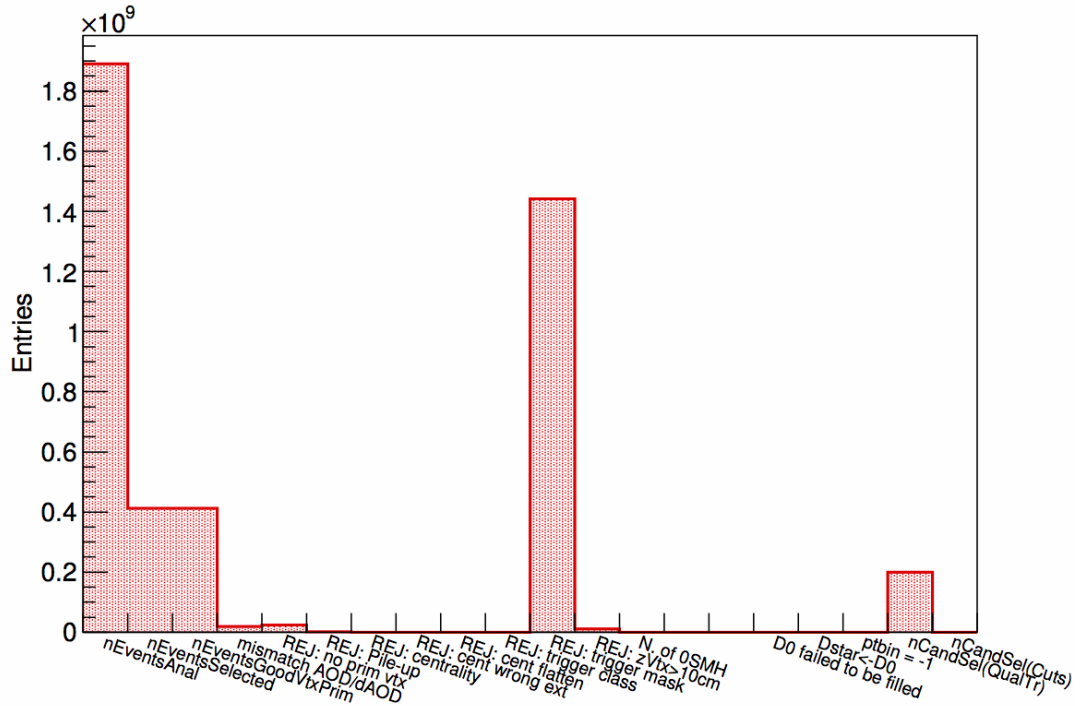


Figure 4.2: Event selection graph for pp collisions at $\sqrt{s} = 13$ TeV.

4.2.3 D^0 reconstruction, selection and signal extraction

The D^0 meson and its charge conjugate are fully reconstructed from their hadronic decay channels ($D^0 \rightarrow K^- \pi^+$; BR: $3.89 \pm 0.04\%$) at mid-rapidity. Schematic representation of D^0 meson hadronic decay channel is shown in Figure 4.3, where V_{prim} and V_{sec} represent the primary vertex and secondary vertex of prompt D^0 meson, respectively. Primary vertex is the point where the D^0 meson is produced, whereas the point where it decays to K^- and π^+ is called as secondary vertex. The decay length ($c\tau$) of D^0 is approximately equal to $122.6 \mu\text{m}$. The D^0 meson reconstruction is done in three steps: reconstruction of secondary vertex, topological selection and particle identification of the daughter tracks.

I) Secondary vertex reconstruction

At first negatively charged kaon and positively charged pion or their oppositely charged pair are selected from an event to reconstruct the secondary vertex by distance of closest approach

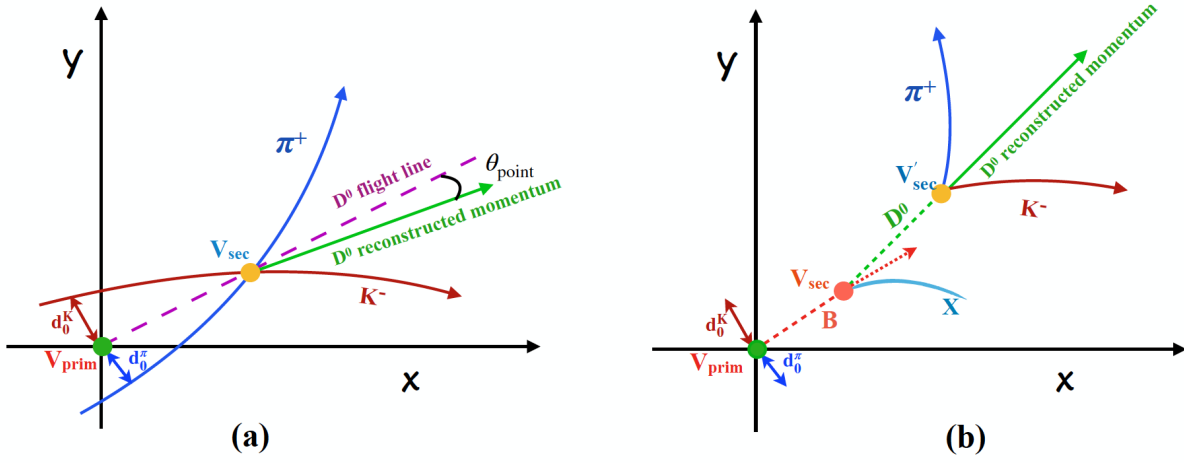


Figure 4.3: Schematic representation of decay of D^0 : (a) Prompt and (b) Feed-down.

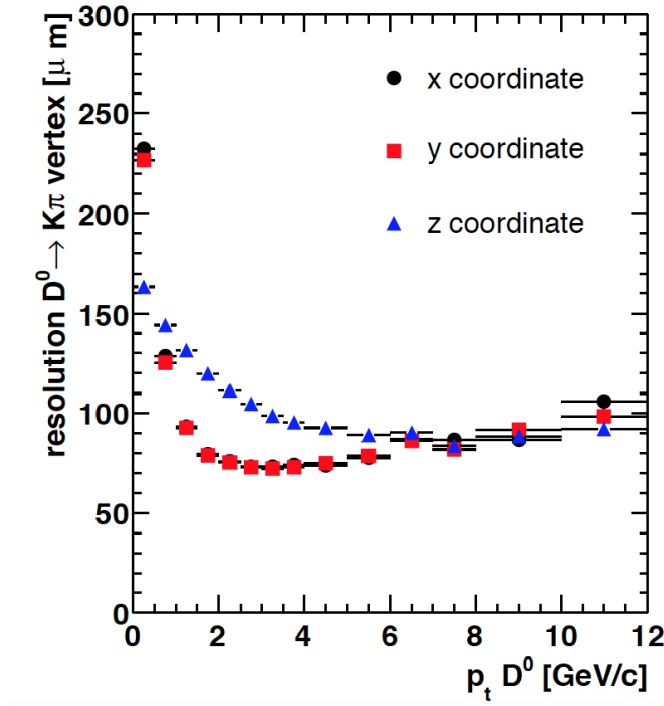


Figure 4.4: Resolution of secondary vertex ($D^0 \rightarrow K^- \pi^+$) as a function of p_T of D^0 [93].

(DCA). One can not determine the secondary vertex as a point because the selected tracks may be coming from two different decays or from the decay product of D^0 . So the secondary vertex point is lying in the line describing the distance of closest approach. The secondary vertex resolution of D^0 as a function of $p_T^{D^0}$ in x, y and z co-ordinates is shown in Figure 4.4.

Table 4.3: Topological selection cuts for reconstruction of D^0 in different p_T intervals.

Selection Cuts	p_T intervals (GeV/c)								
		3 – 4	4 – 5	5 – 6	6 – 7	7 – 8	8 – 10	10 – 12	12 – 16
$ \Delta M $ (GeV/ c^2)	<	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
DCA (μm)	<	300	300	300	300	300	300	300	300
$ \cos\theta^* $	<	0.8	0.8	0.8	0.8	0.8	0.9	0.9	1.0
$p_T^{K,\pi}$ (GeV/c)	>	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$ d_0^K $ (μm)	<	1000	1000	1000	1000	1000	1000	1000	1000
$ d_0^\pi $ (μm)	<	1000	1000	1000	1000	1000	1000	1000	1000
$d_0^K \times d_0^\pi$ (μm^2)	<	-12000	-8000	-8000	-8000	-7000	-5000	-5000	-10000
$\cos\theta_{\text{point}}$	>	0.9	0.85	0.85	0.85	0.85	0.85	0.85	0.85

The secondary vertex resolution at low p_T is of the order of $100 \mu\text{m}$ and it improves to $70 \mu\text{m}$ for high p_T . The resolution is bad at low p_T region due to multiple scattering of daughter particles. At very low p_T ($p_T < 1 \text{ GeV}/c$) the precision of resolution is better for z coordinate compared to x and y coordinates as the daughter tracks are back to back in transverse plane. However, the precision of resolution compromises at very high p_T region as the decay daughter tracks are more collinear along the direction of D^0 transverse momentum.

II) Topological selections

The D^0 can be reconstructed by event-by-event method analysis by combining negative tracks (K^-) particles with positive tracks (π^+) particles. This gives unwanted combinations which contribute to the background. To remove the background some selection criteria is implemented for the tracks. The topological selection cuts for reconstruction of D^0 in different p_T intervals in pp collision at $\sqrt{s} = 5 \text{ TeV}$ and 13 TeV are listed in Table 4.3 and Table 4.4, respectively and described below.

Table 4.4: Topological selection cuts construction of D^0 in different p_T intervals.

Selection Cuts	p_T intervals (GeV/c)							
		3 – 4	4 – 5	5 – 6	6 – 7	7 – 8	8 – 12	12 – 16
$ \Delta M $ (GeV/ c^2)	<	0.4	0.4	0.4	0.4	0.4	0.4	0.4
DCA (μm)	<	150	150	150	150	150	150	150
$ \cos\theta^* $	<	0.4	0.4	0.4	0.4	0.4	0.4	0.4
$p_T^{K,\pi}$ (GeV/c)	>	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$ d_0^K $ (μm)	<	900	700	700	700	700	900	800
$ d_0^\pi $ (μm)	<	900	800	700	1100	700	1100	800
$d_0^K \times d_0^\pi$ (μm^2)	<	-50000	-50000	-40000	-45000	-25000	-40000	-20000
$\cos\theta_{\text{point}}$	>	0.975	0.975	0.975	0.975	0.975	0.975	0.975

- ΔM : The mass difference between reconstructed invariant mass and PDG value of D^0 [5].
- DCA: The distance of closest approach (DCA), it is the minimum distance between the two daughter tracks (K^- and π^+) at the secondary vertex.
- $\cos\theta^*$: It is the cosine of decay angle (θ^*). It is the angle between the D^0 flight line in the lab frame and the momentum of the π^+ , after the decay, in the rest frame of D^0 . The distribution of $\cos\theta^*$ is flat for D^0 candidates and peaks at ± 1 for background candidates.
- $p_T^{K,\pi}$: Transverse momentum of daughter particles (K, π).
- $d_0^{K,\pi}$: It is the impact parameters of daughter tracks (K^- and π^+). This is defined as the shortest distance between the primary vertex and the extended part of the daughter tracks towards primary vertex in transverse plane.
- $d_0^K \times d_0^\pi$: It is the products of two daughter tracks impact parameters.
- $\cos\theta_{\text{point}}$: It is the cosine of pointing angle (θ_{point}). The pointing angle is the angle between the D^0 flight line (the line joining the primary and secondary vertex) and D^0 reconstructed

momentum. The distribution of $\cos \theta_{\text{point}}$ has peaks around ± 1 for D^0 candidates and flat for background candidates.

The values of these above mentioned parameters are chosen in such a way that the statistical significance "S" will be more. The significance is defined as:

$$S = \frac{S}{\sqrt{S+B}}, \quad (4.1)$$

where S represents the signal and B represents the background after the cuts.

III) Particle Identification of K^- and π^+

The particle identification selection is applied to the daughter tracks of D^0 . It is applied to check the compatibility with the pion or kaon hypotheses. The PID information is extracted both from TPC and TOF. From TPC the π/K is selected within the momentum range 0.6-0.8 GeV/c and from the TOF the tracks with momentum below 1.5 GeV/c are selected. For each track, compatibility with kaon and pion mass is calculated in both the detectors by measuring the difference in measured signal and expected signal. The D^0 candidate is accepted if the PID output for the two tracks is compatible with $K^\pm \pi^\pm$ hypothesis.

IV) Signal Extraction

The D^0 raw signal can be extracted from the invariant mass analysis of selected D^0 candidates. The invariant mass distribution for each p_T interval is fitted with Gaussian function for the signal and exponential function for combinatorial background. The invariant mass distributions of D^0 in pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV are shown in Fig. 4.5 and Fig. 4.6, respectively, for the p_T range $3 \leq p_T \leq 16$ GeV/c. The signal is extracted within 3σ range around the mean by subtracting the background (region below the red line) from the total fitted region (the blue line). The mean and σ are calculated from the fit.

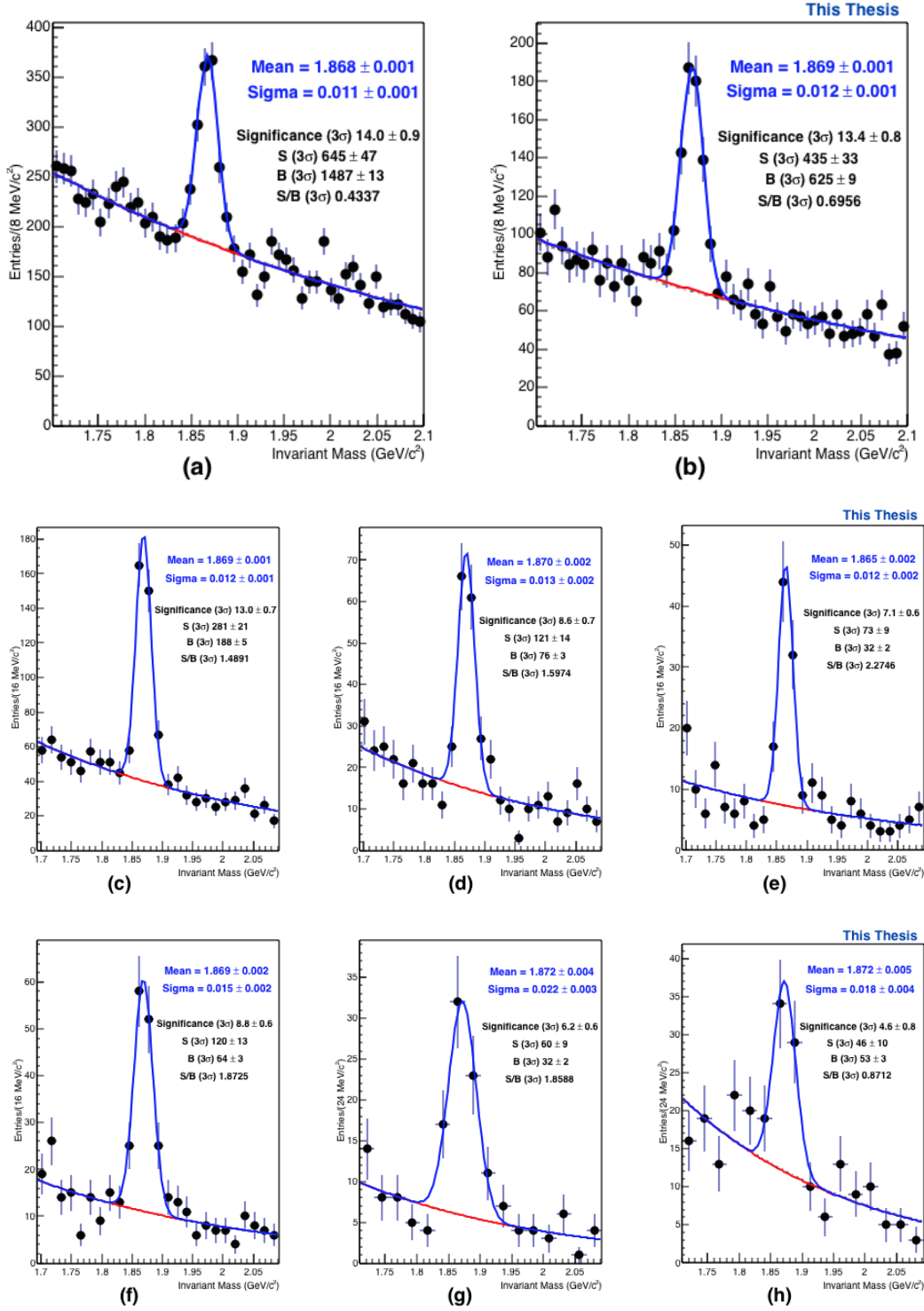


Figure 4.5: Invariant mass distributions of D^0 in pp collisions at $\sqrt{s} = 5$ TeV for different p_T region: (a) $3 \leq p_T < 4$ GeV/c, (b) $4 \leq p_T < 5$ GeV/c, (c) $5 \leq p_T < 6$ GeV/c, (d) $6 \leq p_T < 7$ GeV/c, (e) $7 \leq p_T < 8$ GeV/c, (f) $8 \leq p_T < 10$ GeV/c, (g) $10 \leq p_T < 12$ GeV/c, (h) $12 \leq p_T < 16$ GeV/c.

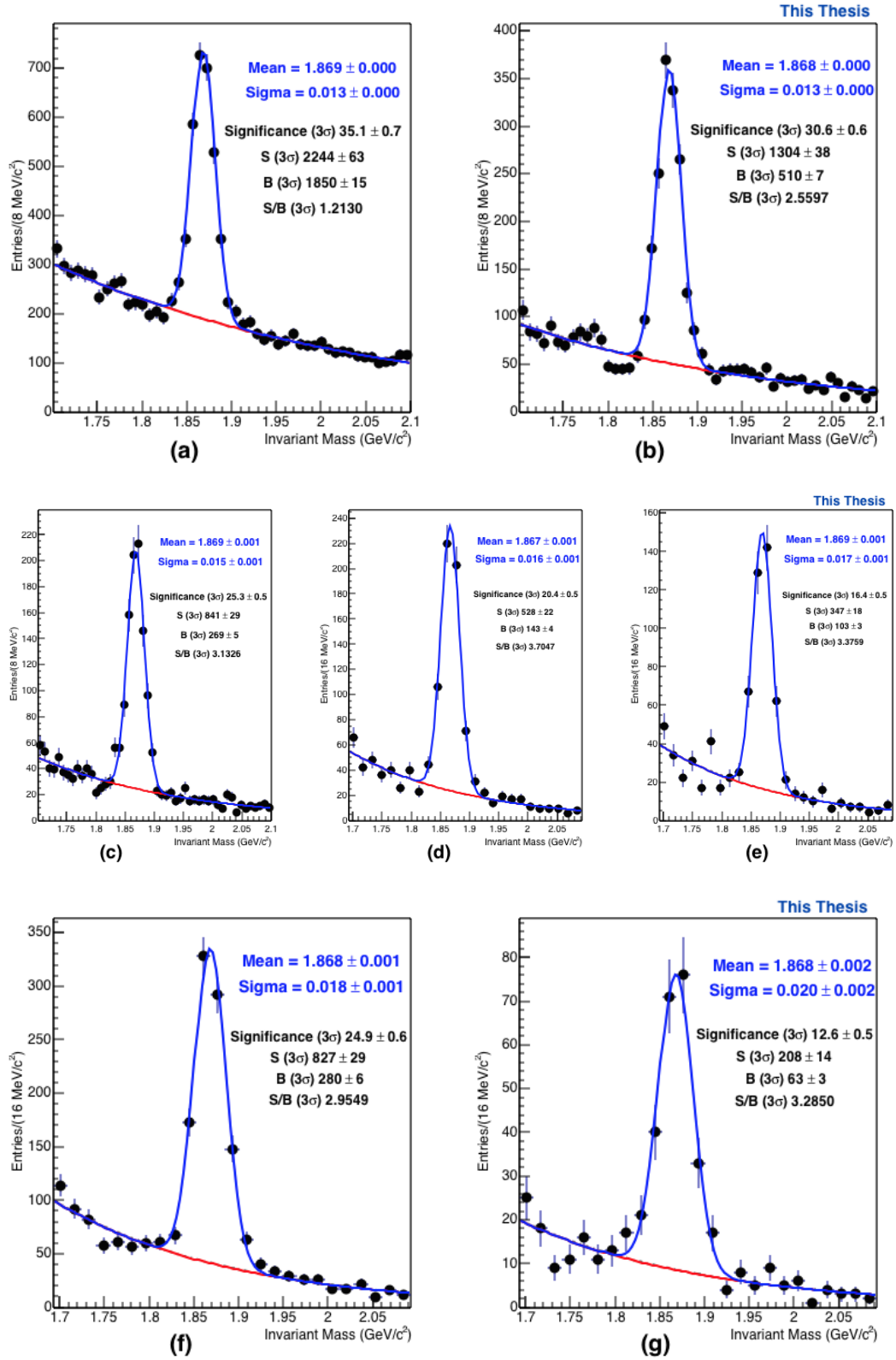


Figure 4.6: Invariant mass distributions of D^0 in pp collisions at $\sqrt{s} = 13$ TeV for different p_T region: (a) $3 \leq p_T < 4$ GeV/c, (b) $4 \leq p_T < 5$ GeV/c, (c) $5 \leq p_T < 6$ GeV/c, (d) $6 \leq p_T < 7$ GeV/c, (e) $7 \leq p_T < 8$ GeV/c, (f) $8 \leq p_T < 12$ GeV/c, (g) $12 \leq p_T < 16$ GeV/c.

4.2.4 Charged track selection

The charged track selection is to select the associated particles. The associated particles are mainly the charged particles coming from the primary vertex, particles from strong and electromagnetic decay of unstable particles, and particles from the decay of hadrons containing charm or beauty. The selection criteria for track quality are listed in Table 4.5.

Table 4.5: Track Quality cuts for charged tracks.

Track parameter	Value	Performance
$\chi^2/\text{TPC Cluster}$	4	Improves the quality of the track fit and significantly suppresses the fake high p_T tracks
DCA to VertexXY distance (cm)	1	DCA _{XY} : To assure that the tracks originate close to the primary vertex, which ensures the removal of secondary particle tracks
DCA to VertexZ distance (cm)	1	DCA _Z : Removes the tracks belonging to pileup vertices
Min. number of TPC crossed rows	70	Ensures quality of the track found in the track fitting procedure
Min. number of ITS clusters	3	Reduces the contamination of secondary particle tracks
Pseudorapidity coverage	0.8	To get optimal detector coverage and uniform track acceptance
Transverse momentum (GeV/c)	0.3	To remove the low p_T background tracks
TPC Refitting	ON	Refit of reconstructed tracks in global tracking to get high precision on the tracks
ITS Refitting	OFF	Refit of reconstructed tracks in global tracking to get high precision on the tracks

Tracks forming a D^0 candidate were rejected from the correlations study with the same D^0 candidate to avoid the auto-correlation. But these tracks are accepted for other D^0 candidates

in that event. The pions tracks (soft pion) coming from the decay of D^{*+} are also rejected by applying the invariant mass selection on $M(\pi) = M(D^{*+} \rightarrow D^0 + \pi \rightarrow K\pi\pi) - M(D^0 \rightarrow K\pi)$.

4.2.5 Correlation of D^0 candidates with associated tracks

Here, D^0 is the trigger particle and all other charged particles are the associated particles. For each pair, the relative azimuthal angle ($\Delta\varphi = \varphi_{trig} - \varphi_{assoc}$) and relative pseudorapidity ($\Delta\eta = \eta_{trig} - \eta_{assoc}$) is calculated to build the two-dimensional correlation distribution. The two-dimensional correlation distribution is plotted in the $\Delta\varphi$ range within $[-\pi/2, 3\pi/2]$ and $|\Delta\eta| < 1.0$ to obtain the good visibility of the correlation pattern. The maximum possible $\Delta\eta$ range covered is $|\Delta\eta| < 1.6$. But $|\Delta\eta|$ range is limited to $|\Delta\eta| < 1.0$ in the correlation distributions to avoid "wing effect", i.e., wings like structure appeared in the correlated correlation distributions at large $\Delta\eta$ and also to avoid high statistical fluctuations because of limited entries in that region of correlation distributions. When the correlation distribution is projected to $\Delta\varphi$ axis, one finds a correlation peak around $\Delta\varphi = 0$, called the near-side peak, and another correlation peak around $\Delta\varphi = \pi$, called the away-side peak. The near-side peak represents that both the trigger and associated particles are from same jet, whereas the away-side peak represents the trigger and associated particles are from opposite jets. For each transverse momentum interval the correlation distribution was evaluated both inside the invariant mass region of signal and sidebands. The signal region is defined as the invariant mass range inside $\pm 2\sigma$ from the center of the Gaussian peak in the invariant mass distributions while the sideband regions are defined as the two regions on the left and right side of the Gaussian peak between $\pm 4\sigma$ and $\pm 8\sigma$ from its center. The raw correlation distribution is shown in Fig. 4.7 and Fig. 4.8.

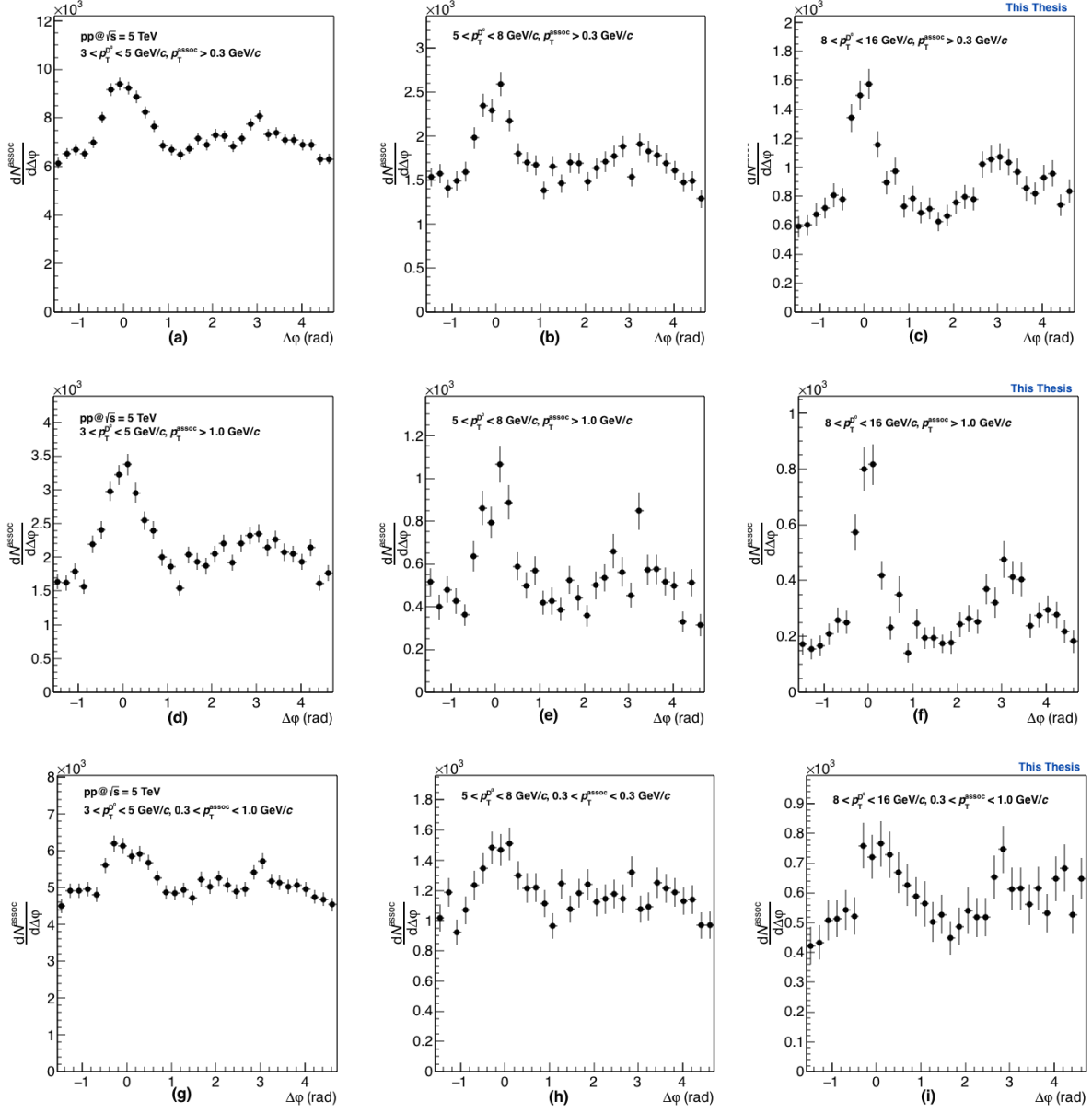


Figure 4.7: [pp, $\sqrt{s} = 5$ TeV] Raw $\Delta\phi$ correlation distribution of D^0 in pp collisions at $\sqrt{s} = 5$ TeV for different kinematic regions.

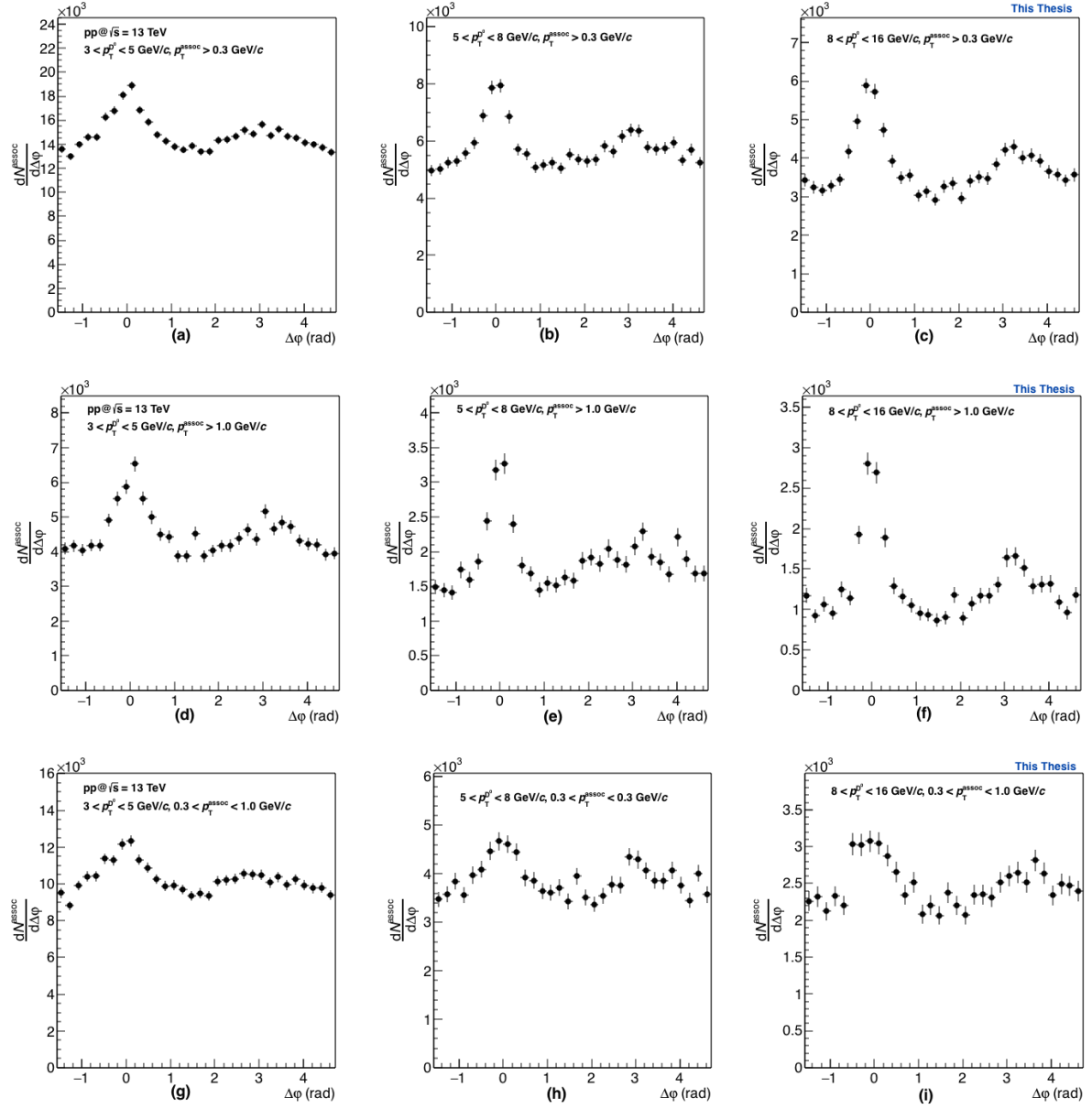


Figure 4.8: [pp, $\sqrt{s} = 13$ TeV] Raw $\Delta\phi$ correlation distribution of D^0 in pp collisions at $\sqrt{s} = 13$ TeV for different kinematic regions.

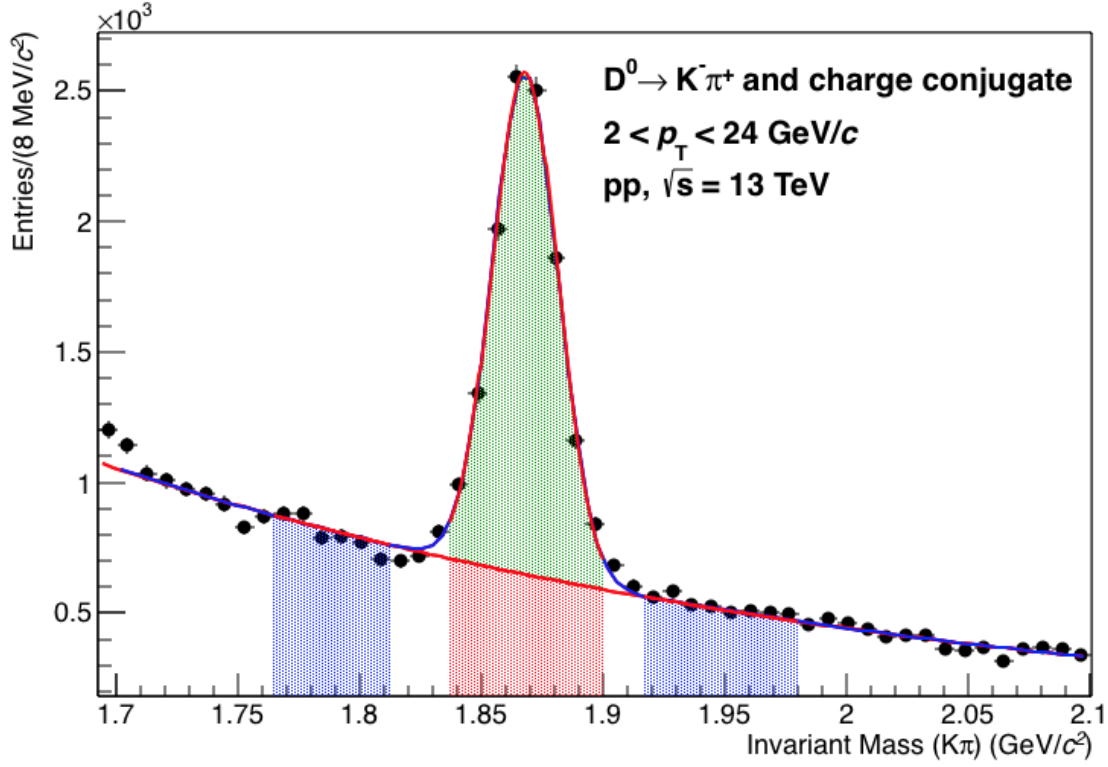


Figure 4.9: Invariant Mass plot of D^0 ($2 < p_T < 24 \text{ GeV}/c$).

4.2.6 Subtraction of the background correlations

The correlation distribution inside the signal region also contains the correlated tracks from the background candidates which passes through the D^0 selection cuts. This background correlation is removed by the sideband subtraction technique. In this technique, the signal with background region is defined within $\mu \pm 2\sigma$, the sidebands are defined from $\mu \pm 4\sigma$ to $\mu \pm 8\sigma$ either side of the signal region. The signal regions are shown in Fig. 4.9.

In this figure, the blue regions are the sidebands, green is the only signal region and red is the only background region. The sideband subtraction technique is described below in steps.

Step-I: The raw correlation distribution ($\Delta\eta, \Delta\phi$) of D^0 trigger particles for each p_T interval is calculated in the central region ($\mu \pm 2\sigma$) of the invariant mass peak. In this region both signal and background triggers are present.

$$C_{[S+B]}^{Central} = C_S^{Central} + C_B^{Central} \quad (4.2)$$

Step-II: The correlation distribution ($\Delta\eta, \Delta\phi$) is calculated for the sideband regions, which contains only background correlations. The D^0 candidates from the invariant mass range $(\mu - 8\sigma, \mu - 4\sigma)$, $(\mu + 4\sigma, \mu + 8\sigma)$ are defined as left and right sideband regions, respectively. The total left-right sideband correlation is:

$$C_B^{LR-Sideband} = C_B^{L-Sideband} + C_B^{R-Sideband} \quad (4.3)$$

Step-III: The sideband correlation distribution is normalized with respect to the background coming from the central region by a scaling factor. The scaling factor is calculated as:

$$f_s = \frac{Y_B^{L-Sideband} + Y_B^{R-Sideband}}{Y_B^{Central}}, \quad (4.4)$$

where f_s is the scaling factor. $Y_B^{L-Sideband}$, $Y_B^{R-Sideband}$, and $Y_B^{Central}$ are the yields from left sideband, right sideband and central regions calculated from the integral of background fit function, respectively.

Step-IV: Finally, the total scaled sideband correlation distribution is subtracted from the raw signal with background correlation distribution obtained in Step-I to get the signal correlation distribution.

$$C'_{[S+B]}^{Central} = C_{[S+B]}^{Central} - f_s \times C_B^{LR-Sideband} \quad (4.5)$$

This technique is used after the correlation distribution is fully corrected.

4.2.7 Correction for the correlations distribution

The correlation distribution is corrected to remove the detector effects, i.e., inhomogeneities and limited acceptance, efficiency for trigger and associated particles, the contribution coming from the hadron decays and from the secondary tracks.

I) Event Mixing correction

The angular correlation distribution is first corrected for non-physical effects. The distribution may be affected due to inhomogeneities in the trigger and track reconstructions as a function of $\Delta\varphi$ or $\Delta\eta$ or from limited detector acceptance. It has been seen that due to dead and inefficient area of detectors there is an excess correlation distribution in the near-side of the $\Delta\varphi$ distribution. This effect can be removed using mixed event technique. The analysis is being carried out on the same data sample used for the same event (SE) analysis. In the SE analysis, the D^0 trigger particle and the associated tracks (particles) are chosen from the same event of the collisions. But in the case of mixed event (ME) analysis, the trigger particles of one event is correlated with the associated particles of another event. The resulting distribution obtained from ME analysis contains no physical correlation because both the trigger and associated tracks are produced independently. This distribution manifested clearly the features related to the detector inhomogeneities and limited acceptance. The detector inhomogeneities and limited acceptance affect the SE and ME distributions in the same way. Because of this the SE distribution is corrected with the help of ME distribution to correct the detector effects. The correction is applied to each trigger particles p_T interval by dividing the bin by bin correlation distribution of same event by the mixed event. Then, the correlation distribution is normalized by the value at $(\Delta\varphi, \Delta\eta) = (0,0)$ of mixed event distribution.

The particular normalization factor is used because the trigger and associated particles experience the same effect at $(\Delta\varphi, \Delta\eta) = (0,0)$. In the mixed event analysis, the trigger and associated particles have similar multiplicity range and position of z-coordinate of the primary vertex. In the ME analysis, the events are classified in 9 pools. The pools are defined according to the multiplicity and z-vertex position. The multiplicity bins are categorized according to the number of SPD tracklets in the following ranges: [0,20], [20, 35], [35, $+\infty$] and the z-vertex position bins are defined as: [-10.0, -2.5] cm, [-2.5, 2.5] cm, [2.5, 10.0] cm. The mixed event distribution is constructed on both signal and sideband regions. Then, the event mixing correction is applied to both regions separately before the background subtraction of invariant

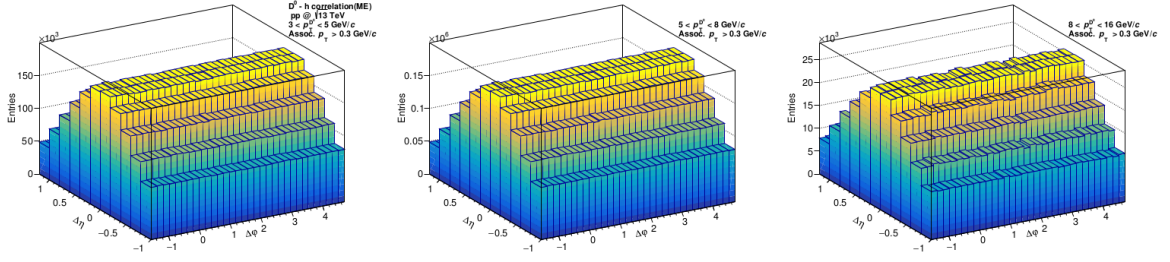


Figure 4.10: Mixed Event: $(\Delta\eta, \Delta\phi)$ correlations plots of D^0 meson in different kinematic ranges.

mass. The same event, $S_{SE}(\Delta\phi, \Delta\eta)$, and mixed event, $B_{ME}(\Delta\phi, \Delta\eta)$, correlations are defined as:

$$S_{SE}(\Delta\phi, \Delta\eta) = \frac{d^2 N^{SE}(\Delta\phi, \Delta\eta)}{d(\Delta\phi)d(\Delta\eta)} \quad (4.6)$$

$$B_{ME}(\Delta\phi, \Delta\eta) = \frac{d^2 N^{ME}(\Delta\phi, \Delta\eta)}{d(\Delta\phi)d(\Delta\eta)} \quad (4.7)$$

The event-mixing corrected correlation distribution is :

$$\frac{d^2 N^{corr}(\Delta\phi, \Delta\eta)}{d(\Delta\phi)d(\Delta\eta)} = \frac{S_{SE}(\Delta\phi, \Delta\eta)}{B_{ME}(\Delta\phi, \Delta\eta)} \times B_{ME}(0, 0), \quad (4.8)$$

where $B_{ME}(0, 0)$ is the normalization factor calculated from the ME distribution at $(\Delta\phi, \Delta\eta) = (0, 0)$.

In the ideal case, the mixed event distributions should look flat along $\Delta\phi$ due to no detector inhomogeneities and a triangular shape distribution along $\Delta\eta$ because of the finite acceptance of the detector. From Fig.4.10, it is clearly seen that there is a triangular shape distribution along $\Delta\eta$ but there is no particular structure found along $\Delta\phi$. From this one can say that there is no influence from the inefficient regions of the tracking detectors on the correlation distributions. The mixed event corrected (SE/ME) plots for both signal and sideband regions are shown in Fig. 4.11 and Fig. 4.12.

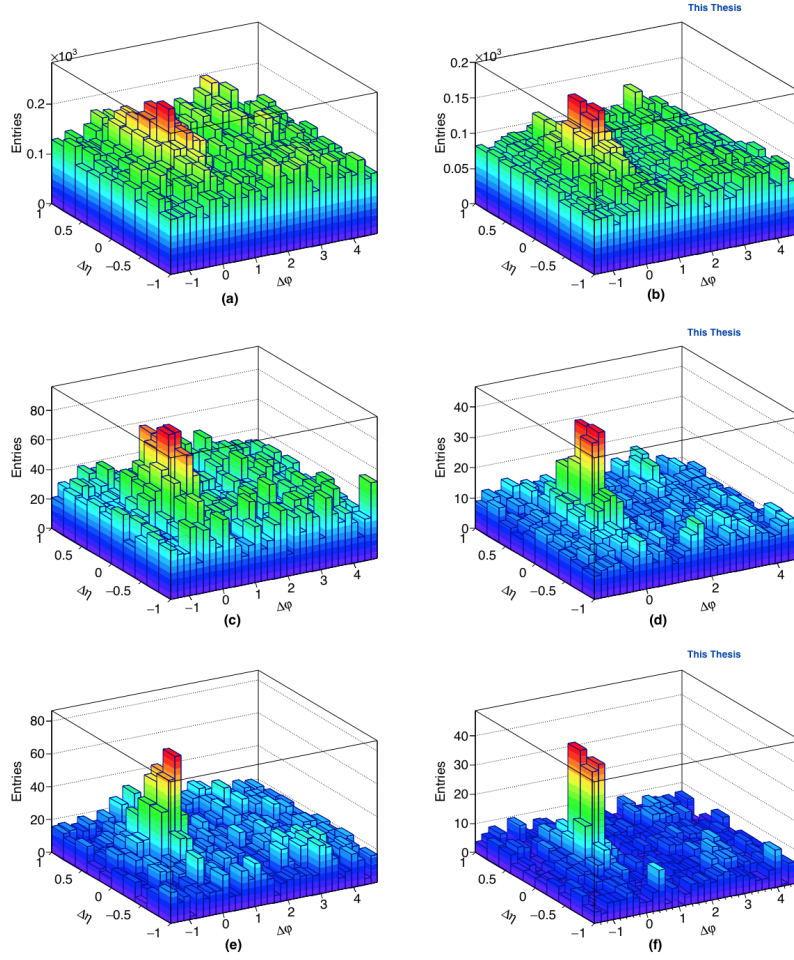


Figure 4.11: [pp, $\sqrt{s} = 5$ TeV] The ratio of SE and ME of D^0 -h ($\Delta\eta, \Delta\phi$) correlation distribution ($|\Delta\eta| < 1$) with $p_T^{\text{assoc}} > 0.3$ GeV/c with D^0 meson p_T ranges: (a) and (b) 3-5 GeV/c, (c) and (d) 5-8 GeV/c, (e) and (f) 8-16 GeV/c. Signal region - (a), (c) and (e); Sideband region - (b), (d) and (f).

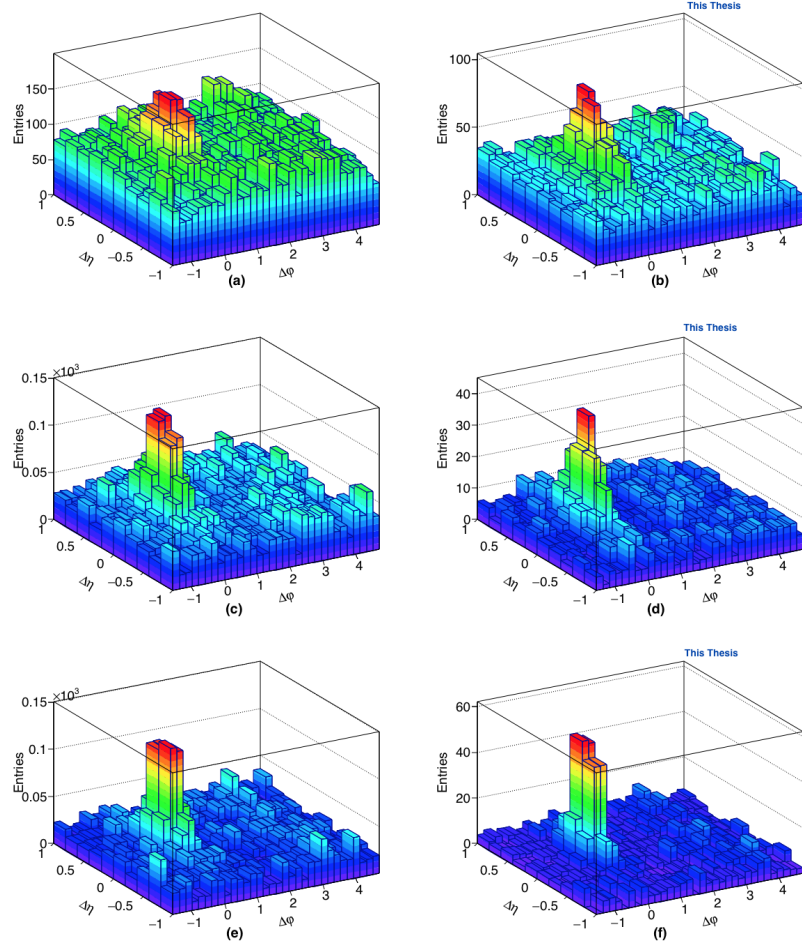


Figure 4.12: [pp, $\sqrt{s} = 13$ TeV] The ratio of SE and ME of D^0 -h ($\Delta\eta, \Delta\phi$) correlation distribution ($|\Delta\eta| < 1$) with $p_T^{\text{assoc}} > 0.3$ GeV/c with D^0 meson p_T ranges: (a) and (b) 3-5 GeV/c, (c) and (d) 5-8 GeV/c, (e) and (f) 8-16 GeV/c. Signal region - (a), (c) and (e); Sideband region - (b), (d) and (f).

II) Tracking efficiency correction

There are some tracks which are not constructed or not passed the quality selection due to a poor reconstruction present in the correlation distributions. The amount of lost tracks depends on the track reconstruction efficiency in the ITS and TPC. From the mixed event distributions it is clearly seen that the tracking has no dependence on η and φ variables. So the correlation distributions should be corrected. The tracking efficiency depends on the transverse momentum of the associated tracks. Therefore, the correction must be applied before integrating on the associated track p_T . The correction factor is applied to the two-dimensional distributions during the execution of the analysis. During the filling of signal and sideband regions, each correlation entry is weighted by the inverse of the associated tracks reconstruction efficiency.

Table 4.6: List of general purpose MC samples.

MC production	Anchored to data
LHC16h8b	LHC15n
LHC17f6	LHC16d
LHC17f9	LHC16e
LHC17d17	LHC16g
LHC17f5	LHC16h
LHC17e5	LHC16j
LHC17d20a1	LHC16k
LHC17d20a2	LHC16l
LHC17d16	LHC16
LHC17d18	LHC16p

The tracking efficiency is evaluated as the ratio of the number of particles after reconstruction and the number of particles generated at the beginning in the same acceptance for a defined "type" of particles and differentially in physical variables like p_T , η , φ , θ , and Z_{vx} . The efficiency map is calculated from a general purpose Monte Carlo simulation samples listed in Table 4.6.

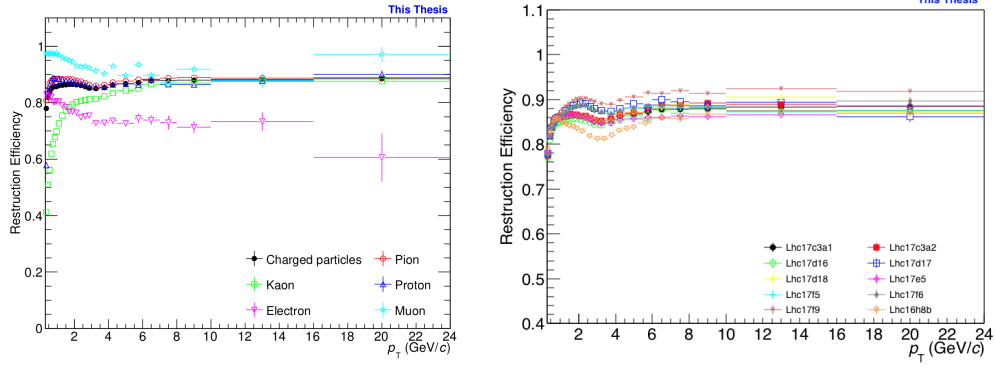


Figure 4.13: Left panel - Tracking efficiencies for different species as a function of p_T for LHC16k, Right panel - Tracking efficiencies for different period as a function of p_T (Right).

The three-dimensional efficiency maps are prepared using TH3D (p_T, η, Z_{0tx}) obtained from MC analysis after passing through several selection criteria listed in Table 4.5.

After preparing the 3D maps for each data period, the correlation spectra of each period is corrected with their corresponding efficiency maps. The tracking efficiencies as a function of p_T for different particle species like pion, kaon, proton, electron, and muon are shown in Fig. 4.13 (Left) for the MC production anchor to LHC16k data set. Figure 4.13 (Right) represents the p_T dependent tracking efficiency map for different period of data sets. From Fig. 4.13, it is seen that there is a p_T dependence below $p_T = 2$ GeV/c and almost constant above $p_T \geq 2$ GeV/c.

III) D^0 meson efficiency correction

The correlation distributions not only affected by tracking efficiency but also by the D^0 meson selection and reconstruction efficiencies. The p_T dependence of D^0 efficiency inside each p_T interval has an effect on the shape of the correlation distributions. But the average value of efficiency in each p_T interval has no influence because the correlation distribution is normalized by the number of D^0 trigger particles. The p_T dependence of selection and reconstruction efficiency for prompt and feed-down D^0 meson is shown in Fig. 4.14. The red color data points are for pp collisions at $\sqrt{s} = 5$ TeV and blue color points are for pp collisions at $\sqrt{s} = 13$ TeV. From the Fig. 4.14 it is clear that the D^0 efficiencies vary as a function of p_T and jumps between two adjacent p_T intervals. This occurs when two adjacent intervals have same D^0 selection cuts.

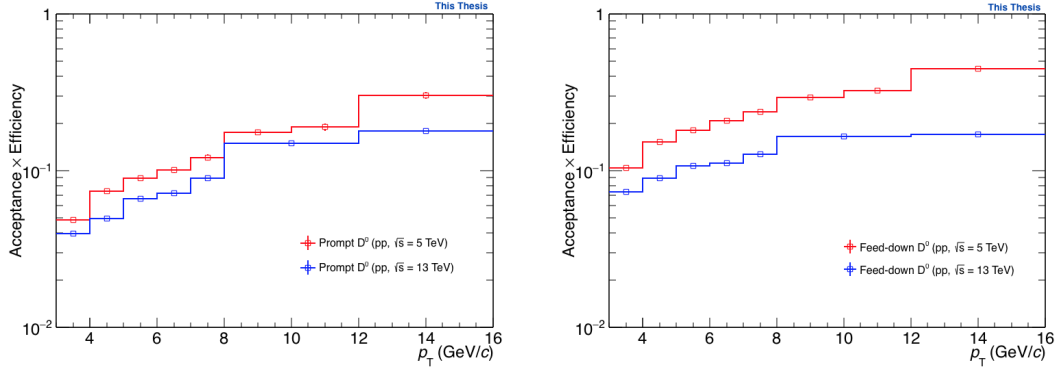


Figure 4.14: Acceptance and reconstruction efficiency of D^0 as a function of p_T : Left panel - Prompt, Right Panel - Feed-down. Red and Blue color points represent the pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively.

Because of the merging of two p_T bins, there is a bias in the uncorrected correlation distribution which needs to be removed. To remove the p_T bias the trigger efficiency is used. The correlation factor is applied during the execution of analysis like tracking efficiency. Each correlation entry in two-dimensional correlation distribution is weighted by the inverse of the reconstruction and selection efficiency of the triggered D^0 . The correlation factor is obtained from the efficiency map where the trigger is considered as a prompt D^0 meson. The final weight applied to each entry of correlation distributions are both tracking and D^0 meson efficiencies, i.e., $(\epsilon_{trig} \cdot \epsilon_{track})^{-1}$.

The D^0 efficiency map is calculated from HF enriched MC sample listed in Table 4.7 for this purpose.

Table 4.7: HF enriched MC sample.

MC production	Anchored to data
LHC16i6a	LHC15n
LHC17c3a1	LHC16k
LHC17c3a2	LHC16l
LHC17h8a	LHC16others

The trigger efficiency map is built considering only the $p_T^{D^0}$ and the event multiplicity, while the dependence on the D^0 rapidity is neglected. This is done to avoid large statistical fluctuations on the efficiency values due to the limited number of Monte Carlo sample. A significant dependence of D^0 efficiency is found on the multiplicity and it affects the correlation distributions within 5%.

The efficiency map is prepared by the formula, $map = N_1map_1 + N_2map_2 + N_3map_3$, where N_1, N_2 and N_3 are the number of events for LHC16k, LHC16l and LHC16others, respectively, and map_1, map_2 and map_3 are the respective efficiency maps. The prompt D^0 map is used to apply the trigger efficiency correction to the data distributions, while the feed-down D^0 was used for the evaluation of the feed-down contribution. The trigger efficiency modifies the normalization of correlation distributions. To recover the normalization to the number of trigger particles, it is necessary to properly scale the signal extracted from the invariant mass fits. For this each D^0 meson entry in the mass distributions is weighted by the inverse of its efficiency. After applying this one can calculate properly the number of trigger particles. This weight factor does not significantly modify the shape of the invariant mass distributions as compared to the raw invariant mass distributions.

IV) Bias on B to D decay topologies

A Monte Carlo (MC) closure test was done on the D^0 sample to check the stability of the corrections applied to the correlation distributions. The correlation analysis is done both at kinematic and reconstruction levels with charm and beauty enriched MC samples for the MC closure test. At the kinematic level, only the acceptance cuts are applied to the D^0 mesons and associated particles. The identification of the D^0 mesons and hadrons and also rejection of the secondary particles in an event are made using the information from MC. At the reconstruction level, the analysis is done in similar procedure used in the data. Here, the event selection, acceptance cuts for D^0 mesons and the associated particles, topological cuts for D^0 mesons and PID selection for daughter particles of D^0 mesons are applied and the secondary particles are rejected by using the DCA selection. The event mixing correction is applied both at kinematic

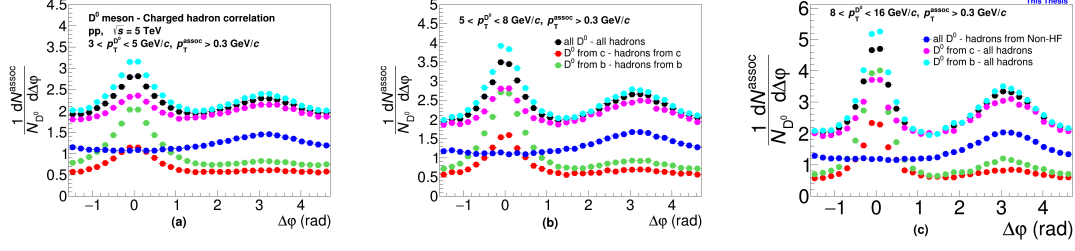


Figure 4.15: [pp, $\sqrt{s} = 5$ TeV] The D^0 - hadrons azimuthal correlation distribution obtained from MC at kinematic level for $p_T^{\text{assoc}} > 0.3 \text{ GeV}/c$. (a) $3 < p_T^{D^0} < 5 \text{ GeV}/c$, (b) $5 < p_T^{D^0} < 8 \text{ GeV}/c$, (c) $8 < p_T^{D^0} < 16 \text{ GeV}/c$.

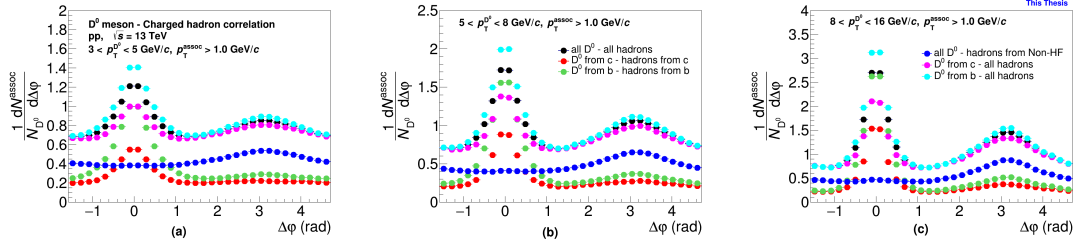


Figure 4.16: [pp, $\sqrt{s} = 13$ TeV] The D^0 - hadrons azimuthal correlation distribution obtained from MC at kinematic level for $p_T^{\text{assoc}} > 1.0 \text{ GeV}/c$. (a) $3 < p_T^{D^0} < 5 \text{ GeV}/c$, (b) $5 < p_T^{D^0} < 8 \text{ GeV}/c$, (c) $8 < p_T^{D^0} < 16 \text{ GeV}/c$

and reconstruction levels. The D^0 mesons efficiency and tracking efficiency corrections are used at only reconstruction levels. The $\Delta\phi$ correlation plots at kinematic level are shown in Fig. 4.15 and Fig. 4.16 for $p_T^{\text{assoc}} > 0.3 \text{ GeV}/c$ in pp collisions at $\sqrt{s} = 5 \text{ TeV}$ and for $p_T^{\text{assoc}} > 1.0 \text{ GeV}/c$ in pp collisions at $\sqrt{s} = 13 \text{ TeV}$, respectively. The $\Delta\phi$ correlation plots at reconstruction level are shown in Fig. 4.17 and Fig. 4.18 for $p_T^{\text{assoc}} > 0.3 \text{ GeV}/c$ in pp collisions at $\sqrt{s} = 5 \text{ TeV}$ and for $p_T^{\text{assoc}} > 1.0 \text{ GeV}/c$ in pp collisions at $\sqrt{s} = 13 \text{ TeV}$, respectively.

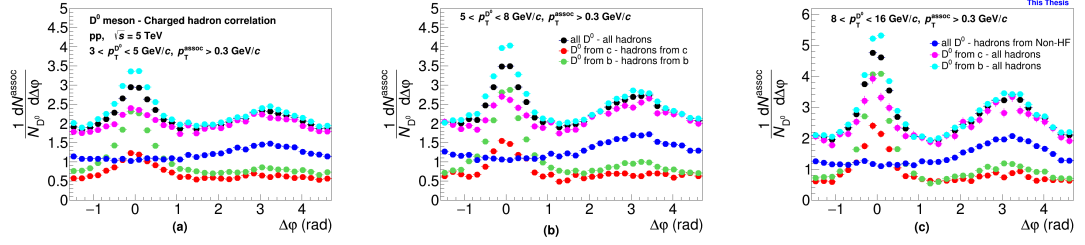


Figure 4.17: [pp, $\sqrt{s} = 5$ TeV] The D^0 - hadrons azimuthal correlation distribution obtained from MC at reconstruction level for $p_T^{\text{assoc}} > 0.3 \text{ GeV}/c$. (a) $3 < p_T^{D^0} < 5 \text{ GeV}/c$, (b) $5 < p_T^{D^0} < 8 \text{ GeV}/c$, (c) $8 < p_T^{D^0} < 16 \text{ GeV}/c$

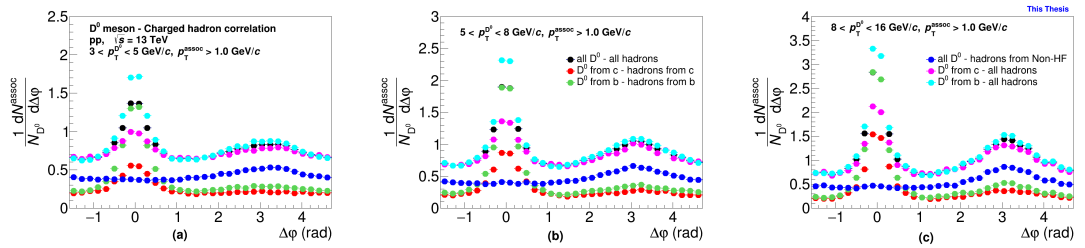


Figure 4.18: [pp, $\sqrt{s} = 13$ TeV] The D^0 - hadrons azimuthal correlation distribution obtained from MC at reconstruction level for $p_T^{\text{assoc}} > 1.0 \text{ GeV}/c$. (a) $3 < p_T^{D^0} < 5 \text{ GeV}/c$, (b) $5 < p_T^{D^0} < 8 \text{ GeV}/c$, (c) $8 < p_T^{D^0} < 16 \text{ GeV}/c$.

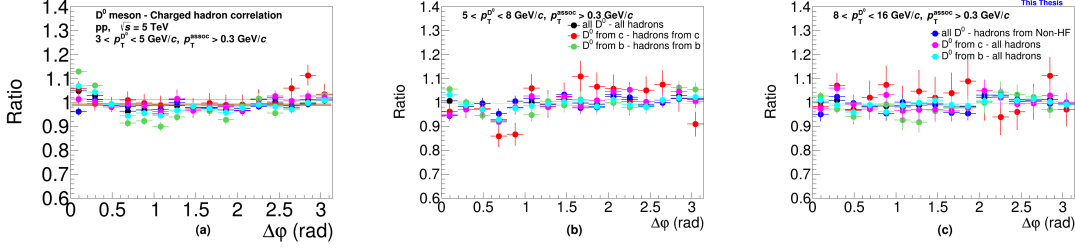


Figure 4.19: [pp, $\sqrt{s} = 5 \text{ TeV}$] Ratios of fully corrected azimuthal correlation distributions at reconstruction level and kinematic level for $p_T^{\text{assoc}} > 0.3 \text{ GeV/c}$. a) $3 < p_T^{D^0} < 5 \text{ GeV/c}$, (b) $5 < p_T^{D^0} < 8 \text{ GeV/c}$, (c) $8 < p_T^{D^0} < 16 \text{ GeV/c}$.

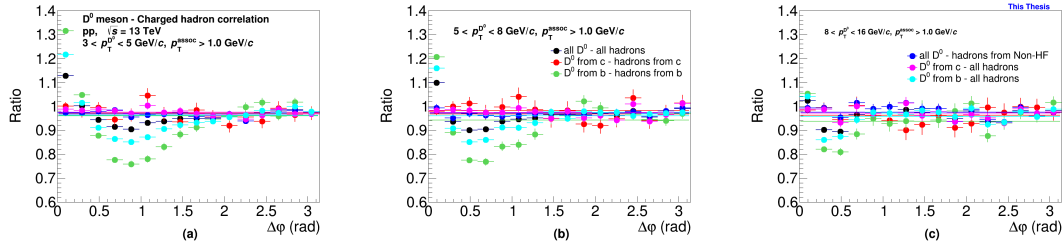


Figure 4.20: [pp, $\sqrt{s} = 13 \text{ TeV}$] Ratios of fully corrected azimuthal correlation distributions at reconstruction level and kinematic level for $p_T^{\text{assoc}} > 1.0 \text{ GeV/c}$. (a) $3 < p_T^{D^0} < 5 \text{ GeV/c}$, (b) $5 < p_T^{D^0} < 8 \text{ GeV/c}$, (c) $8 < p_T^{D^0} < 16 \text{ GeV/c}$.

The ratios of the correlation distributions at reconstruction and kinematic levels in pp collisions at $\sqrt{s} = 5 \text{ TeV}$ for $p_T^{\text{assoc}} > 0.3 \text{ GeV/c}$ and at $\sqrt{s} = 13 \text{ TeV}$ for $p_T^{\text{assoc}} > 1.0 \text{ GeV/c}$ are shown in Figure 4.19 and Fig. 4.20, respectively. In all these figures (Fig. 4.15 - Fig. 4.20), black points are the correlations between all D^0 mesons with all hadrons; red points are the correlations between both D^0 mesons and hadrons coming from c quark; green points are correlations between both D^0 mesons and hadrons coming from b quark; blue points are the correlations between all D^0 mesons with hadrons from light quarks (Non-heavy flavor decay); magenta points are the correlations between D^0 mesons coming from c quark with all hadrons; cyan points are the correlations between D^0 mesons coming from b quark with all hadrons.

It is evident from the ratio plots that they are compatible with one within the uncertainties. There is one exception that some structures in the near-side region is seen due to b-origin case. This similar kind of structure was already seen in pp 2010 and p-Pb 2013, p-Pb 2016 analysis,

and it was verified that they are induced by the topological selection cuts applied for the D^0 mesons. The presence of topological cuts for D^0 meson selection indirectly induced a bias on the topology of B to D decay topologies by favoring cases of small opening angle between the D^0 meson and other tracks from the B decay. This situation appears only at the reconstruction level, where the topological cut selections are applied. Therefore, the reconstruction/kinematic ratio plots show an excess at the near-side ($\Delta\varphi = 0$). These structures are prominent at low $p_T^{D^0}$, where the loose topological cuts are applied. However, this trend is disappeared at higher $p_T^{D^0}$ due to the tighter topological cuts. They are also more extensive in the higher p_T^{assoc} ranges, where the fraction of tracks coming from B-hadron decays dominates the overall correlation distributions.

The data correlation distribution needs to be corrected for this bias for the enhancement of b-origin correlation pairs at the center of the near-side region, which would influence the near-side peak features. The amount of the b-origin excess is evaluated from the reconstruction/kinematic ratio by considering the b – D^0 -all tracks case (dark green points). The excess quantity at the reconstruction level (affecting data) for each p_T range is quantified as a $\Delta\varphi = 0$ modulation **modul** for the few points on each side of the value or equivalently on the first five points of the reflected distributions, which start from $\Delta\varphi = 0$. This modulation factor is applied to the data correlation distributions for correction by taking into account that only the correlation entries from $B \rightarrow D$ are affected. At the same time, the $c \rightarrow D$ correlations need to be left unaltered. In particular, it has to be considered that, on data, $B \rightarrow D$ correlation pairs are only a fraction $(1 - f_{\text{prompt}})$ of the total and the amplitude of $(B) \rightarrow D|_{\text{amplit}}$ correlation pattern is greater than $(c) \rightarrow D|_{\text{amplit}}$ correlation pattern. Thus, we apply the following equation to get the corrected correlation plots.

$$C(\Delta\varphi)_{\text{corr}} = C(\Delta\varphi)_{\text{raw}} \times \left[\frac{c \rightarrow D|_{\text{amplit}}}{(B + c) \rightarrow D|_{\text{amplit}}} \times f_{\text{prompt}} + \frac{B \rightarrow D|_{\text{amplit}}}{(B + c) \rightarrow D|_{\text{amplit}}} \times (1 - f_{\text{prompt}}) \times \frac{1}{\text{modul}} \right] \quad (4.9)$$

Applying the **modul** factor to the beauty part of the data correlation distributions brings its value back to the generated level case effectively removing the bias. The correction's effect

is a shift of the data points in the near-side region (in general, downward in the first and second points, the upward in the others). In order to take into account for possible inaccuracies in the definition of the modulations or in their rescaling, a systematic uncertainty is applied on the corrected data points with value $|C(\Delta\varphi)_{\text{corr}} - C(\Delta\varphi)_{\text{raw}}|/\sqrt{12}$ on each side of the data points affected by the bias (symmetric uncertainty).

V) Secondary track contamination

The secondary particles are the particles coming from the strange hadron decay or from the interaction of particles with the detector material. The DCA cut ($\text{DCA}_z < 1.0$ cm, $\text{DCA}_{xy} < 0.25$ cm (1.0 cm)) applied to the associated track selection in pp collisions at $\sqrt{s} = 5$ TeV (13 TeV) is to remove the secondary particles. However, a small fraction of secondary tracks do survive after this cuts. To remove this residual contamination, the data correlation distribution needs to be corrected. The number of primary and secondary tracks are evaluated from Monte Carlo simulated data. After applying the selection cuts, the fraction of secondary tracks (f_{sec}) remained in the sample is calculated as a function of p_T^{assoc} for different D^0 p_T ranges, i.e., 3-5 GeV/c, 5-8 GeV/c and 8-16 GeV/c, and is shown in Fig. 4.21. In Fig. 4.21, the red and blue color points are for pp collisions at $\sqrt{s} = 5$ and 13 TeV, respectively. This Monte Carlo study suggests that the secondary contamination in the D^0 -hadron correlation is almost independent of D^0 meson $p_T^{\text{D}^0}$ and is less than 6%, but slightly decreases with track p_T^{assoc} . This implies that the purity, $p = 1 - f_{\text{sec}}$, is also independent of D^0 meson $p_T^{\text{D}^0}$, but increases slightly with track p_T^{assoc} . The purity values for different associated track p_T^{assoc} in pp collisions at $\sqrt{s} = 5$ TeV (13 TeV) are:

$$i) p_T^{\text{assoc}} > 0.3 \text{ GeV/c} : 0.972 (0.950)$$

$$ii) p_T^{\text{assoc}} > 1.0 \text{ GeV/c} : 0.979 (0.963)$$

$$iii) 0.3 < p_T^{\text{assoc}} < 1.0 \text{ GeV/c} : 0.969 (0.943)$$

The residual contamination from secondary tracks in the correlation distributions for $p_T^{\text{assoc}} > 0.3$ GeV/c is shown for pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV in Figure. 4.22

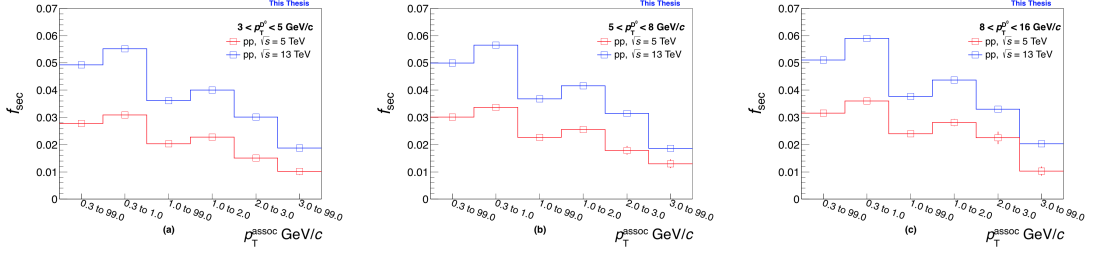


Figure 4.21: Fraction of secondary, f_{sec} , vs. p_T^{assoc} for different D^0 meson p_T ranges: a) 3-5 GeV/c, b) 5-8 GeV/c and c) 8-16 GeV/c.

and Fig. 4.23, respectively. It is clearly evident from Fig. 4.22 that the plot showing a flat trend along the $\Delta\varphi$ axis in pp collisions at $\sqrt{s} = 5$ TeV. But Fig. 4.23 is not flat along the $\Delta\varphi$ axis in pp collisions at $\sqrt{s} = 13$ TeV. The inhomogeneity is more than 1%. So, to remove this inhomogeneity the data correlation distribution is corrected by applying other approaches. The three possible approaches are the following:

- **Approach I:** The ratio, accepted primary tracks/all tracks, of $\Delta\varphi$ distribution is multiplied to the data $\Delta\varphi$ correlation distributions.
- **Approach II:** The ratio, accepted primary tracks/all tracks, of $\Delta\varphi$ distribution is fitted with a 9th order polynomial function and this function is used to correct the $\Delta\varphi$ correlation distributions in data.
- **Approach III:** The average of the ratio, accepted primary tracks/all tracks, of $\Delta\varphi$ distribution is moved by three points and this distribution is multiplied to the $\Delta\varphi$ correlation distributions in data.

The $\Delta\varphi$ distributions of fraction of primary tracks over all tracks for three different approaches are shown in Fig. 4.24. The blue markers, red line and red markers correspond to Approach I, Approach II and Approach III, respectively.

The $\Delta\varphi$ correlation distributions for different D^0 meson p_T ranges, i.e., 3-5, 5-8, 8-16 GeV/c, are studied by doing the purity correction in the standard approach and the three new approaches. The ratio plots of the three approaches with respect to the standard approach are

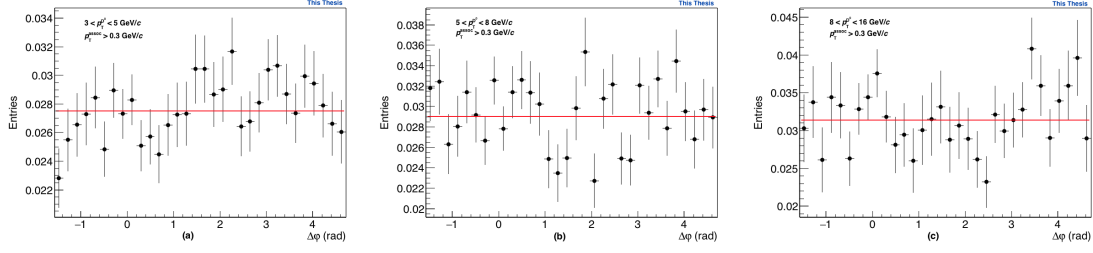


Figure 4.22: [pp, $\sqrt{s} = 5$ TeV] D^0 meson $\Delta\phi$ correlation distribution due to residual contamination from secondary tracks. p_T ranges: a) 3-5 GeV/c, b) 5-8 GeV/c, c) 8-16 GeV/c.

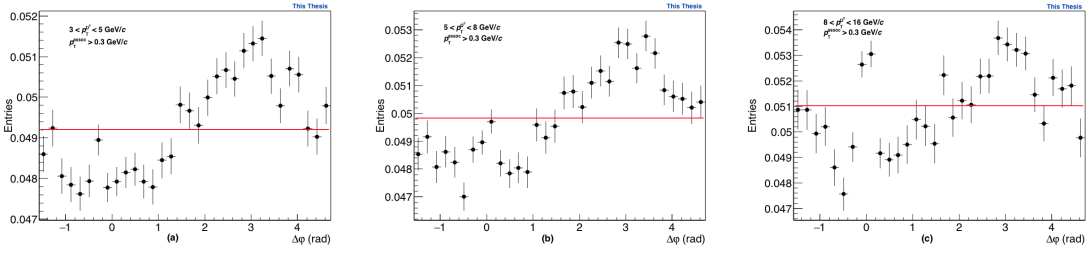


Figure 4.23: [pp, $\sqrt{s} = 13$ TeV] D^0 meson $\Delta\phi$ correlation distribution due to residual contamination from secondary tracks. p_T ranges: a) 3-5 GeV/c, b) 5-8 GeV/c, c) 8-16 GeV/c.

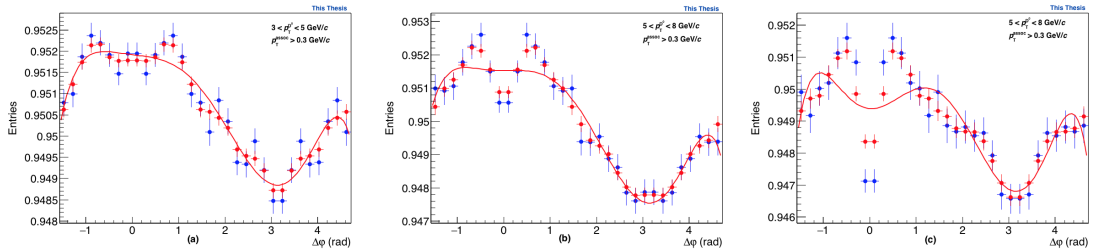


Figure 4.24: [pp, $\sqrt{s} = 13$ TeV] D^0 meson $\Delta\phi$ correlation distribution. Blue points - Approach I, Red points - Approach II, Red line - Approach III

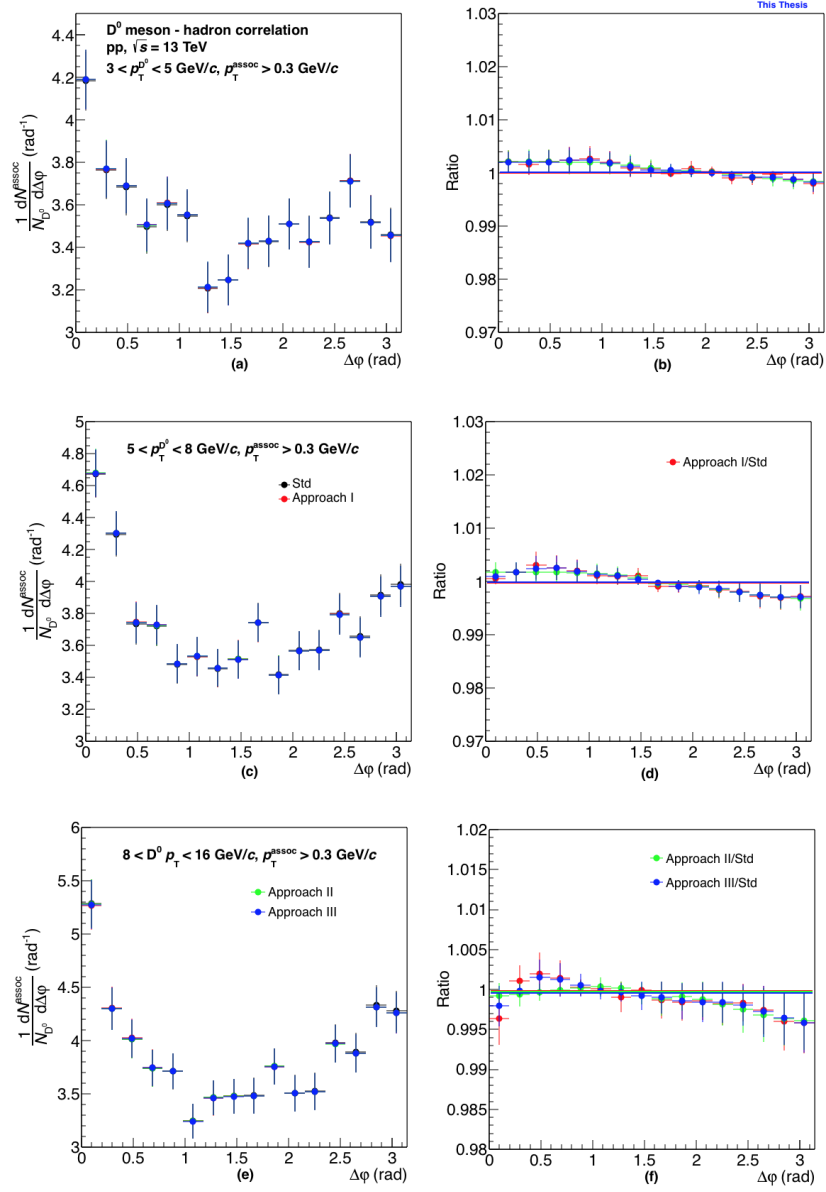


Figure 4.25: [pp, $\sqrt{s} = 13 \text{ TeV}$] $\Delta\varphi$ correlation for D^0 -meson p_T ranges: a) 3-5 GeV/c, c) 5-8 GeV/c and e) 8-16 GeV/c. b), d) and f) represents the ratios. Black marker - Standard Method, Red marker - Approach I, Green marker - Approach II, Blue marker - Approach III

also calculated and shown in Fig. 4.25. From this figure, it is observed that there is a maximum 1% uncertainty between the standard approach and the new approaches.

VI) Beauty feed-down

The raw D^0 -hadron correlation distributions contain both the contribution from prompt D^0 mesons and the feed-down D^0 mesons. The feed-down D^0 mesons are the mesons produced from B mesons decay from the b quark. The feed-down correlations are different from the prompt correlations as they are coming mainly from beauty jets and beauty hadron decays instead of charm jets and hadrons. It is not possible to distinguish between the prompt and feed-down D^0 mesons at reconstruction level due to similar selection criteria. The contribution from feed-down correlations is removed by using the MC template and f_{prompt} by Equation 4.10.

$$\tilde{C}_{promptD}(\Delta\varphi) = \frac{1}{f_{prompt}}(\tilde{C}_{inclusive}(\Delta\varphi) - (1 - f_{prompt})\tilde{C}_{feed-down}^{MCtempl}(\Delta\varphi)) \quad (4.10)$$

In the above equation,

- $\tilde{C}_{inclusive}(\Delta\varphi)$ is the azimuthal correlation per trigger before feed-down subtraction
- $\tilde{C}_{promptD}(\Delta\varphi)$ is the azimuthal correlation per trigger distribution after feed-down subtraction
- f_{prompt} is the relative fraction of prompt D^0 meson with respect to inclusive (prompt + feed-down) D^0 meson
- $\tilde{C}_{feed-down}^{MCtempl}(\Delta\varphi)$ is the template of the azimuthal correlation distribution of the feed-down component obtained from Monte Carlo simulation

f_{prompt} calculation: The f_{prompt} value is estimated using FONLL prediction and by using reconstruction efficiency of the prompt and feed-down D^0 candidates [94]. The f_{prompt} can be calculated as:

$$f_{prompt} = 1 - \left(\frac{N^{D^0+\bar{D}^0 \text{ from B raw}}}{N^{D^0+\bar{D}^0 \text{ raw}}} \right) \quad (4.11)$$

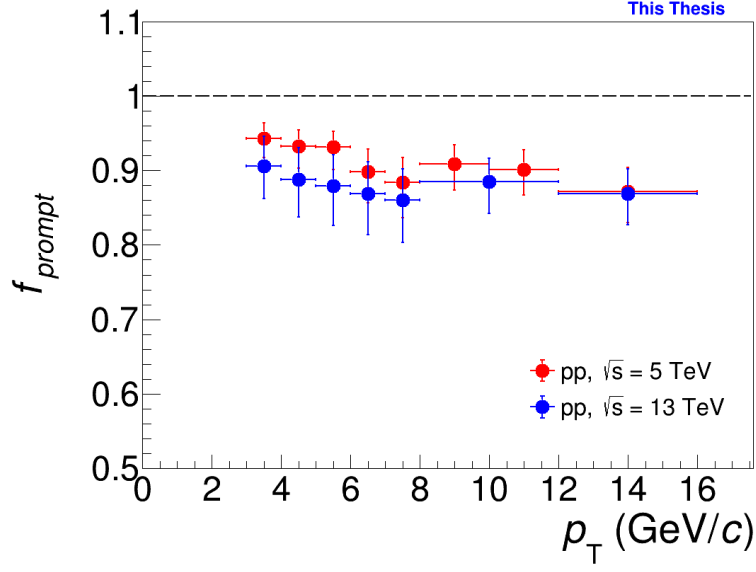


Figure 4.26: f_{prompt} as a function of p_T of D^0 estimated on the basis of FONLL predictions.

where

$$N^{D^0+\bar{D}^0 \text{ from B raw}} \Big|_{|y|<y_{fid}} = 2 \frac{d\sigma_{FONLL}^{D^0+\bar{D}^0 \text{ from B raw}}}{dp_T} \Big|_{|y|<0.5} \times \Delta y \times \Delta p_T \times (\text{Acc} \times \epsilon)_{\text{feed-down}} \times \text{BR} \times L_{\text{int}} \quad (4.12)$$

In the above equations 4.11 and 4.12, $(N^{D^0+\bar{D}^0} \text{ raw})$ represents the inclusive D^0 mesons yields calculated from invariant mass spectra of D^0 mesons in each p_T intervals. Δp_T is the width between the p_T intervals, BR is the branching ratio, L_{int} is the integrated luminosity, $(\text{Acc} \times \epsilon)_{\text{feed-down}}$ is the efficiency with acceptance of D^0 meson from B decay. The production cross-section of D^0 meson from B, $\left(\frac{d\sigma_{FONLL}^{D^0+\bar{D}^0 \text{ from B raw}}}{dp_T}\right)$, is calculated from the FONLL pQCD. The value of f_{prompt} as a function of p_T of D^0 is shown in Fig. 4.26.

Feed-down correlation templates: The feed-down correlation template, $\tilde{C}_{feed-down}^{MCtempl}$, is obtained by using PYTHIA6 event generators with perugia0 tune for all the $p_T^{D^0}$ and p_T^{assoc} ranges. The feed-down correlation distribution is also obtained by using different tunes of the event generators like PYTHIA6-perugia2010, PYTHIA6-perugia2011, PYTHIA8-4c for the systematic studies. The process of parton fragmentation into hadrons is the basic difference between these PYTHIA tunes, which can influence the shape of correlation distributions. The comparison of feed-down azimuthal correlation distributions based on different PYTHIA generators in

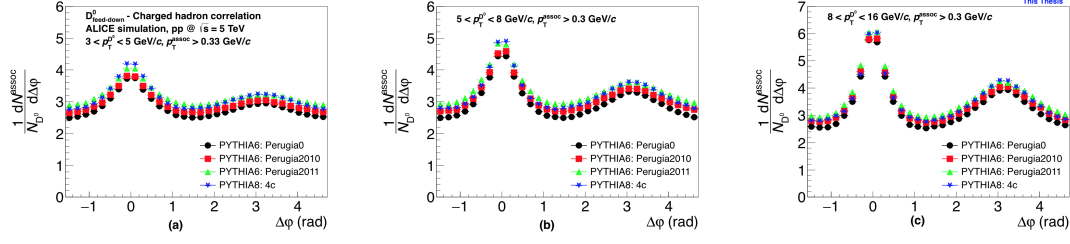


Figure 4.27: [pp, $\sqrt{s} = 5$ TeV] Comparison of the "feed-down" azimuthal correlation distributions with associated $p_T^{\text{assoc}} > 0.3$ GeV/c based on different PYTHIA generators and tunes in trigger p_T^{D0} ranges: (a) 3-5 GeV/c, (b) 5-8 GeV/c and (c) 8-16 GeV/c.

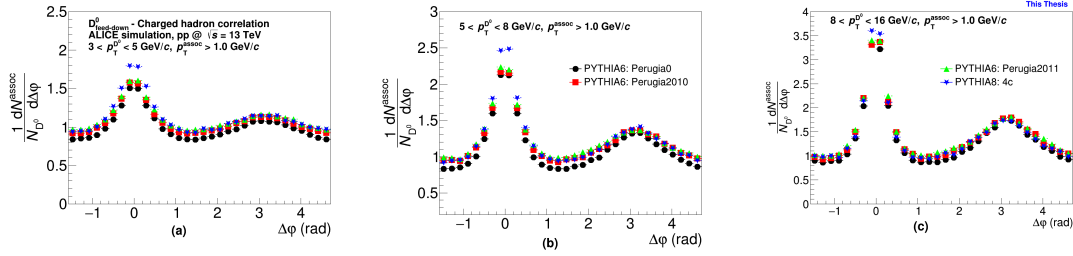


Figure 4.28: [pp, $\sqrt{s} = 13$ TeV] Comparison of the "feed-down" azimuthal correlation distributions with associated $p_T^{\text{assoc}} > 0.3$ GeV/c based on different PYTHIA generators and tunes in trigger p_T^{D0} ranges: (a) 3-5 GeV/c, (b) 5-8 GeV/c and (c) 8-16 GeV/c.

pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV are shown in Fig. 4.27 and Fig. 4.28, respectively. In Fig. 4.27 and Fig. 4.28, black, red, green and blue colour points represent the feed-down azimuthal correlation distributions based on MC simulations obtained from PYTHIA6-perugia0, PYTHIA6-perugia2010, PYTHIA6-perugia2011, and PYTHIA8-4c tune, respectively.

Chapter 5

Systematic Uncertainty

"Insanity is doing the same thing over and over again and expecting different results."

–Albert Einstein

Experiments are always associated with uncertainties. These uncertainties arise because of the limited number of measurements, the apparatus with which the measurements are being made and also the method. In a nutshell, measurements without uncertainties are highly unreliable. In this chapter, an attempt has been made to estimate the systematic uncertainties contributing to D^0 -hadron correlation from different sources.

5.1 Evaluation of the systematic uncertainties

In the D^0 -hadron correlation studies, various sources contribute to the systematic uncertainties. These sources are *i*) Signal (S) and Background (B) extraction, *ii*) Background correlation shape, *iii*) associated track efficiency, *iv*) D meson cuts stability, *v*) secondary particle contamination, *vi*) Feed-down subtraction, *vii*) bias on B to D decay topologies. Out of these, first five are the correlated systematic uncertainties and the last two are uncorrelated systematic uncertainties.

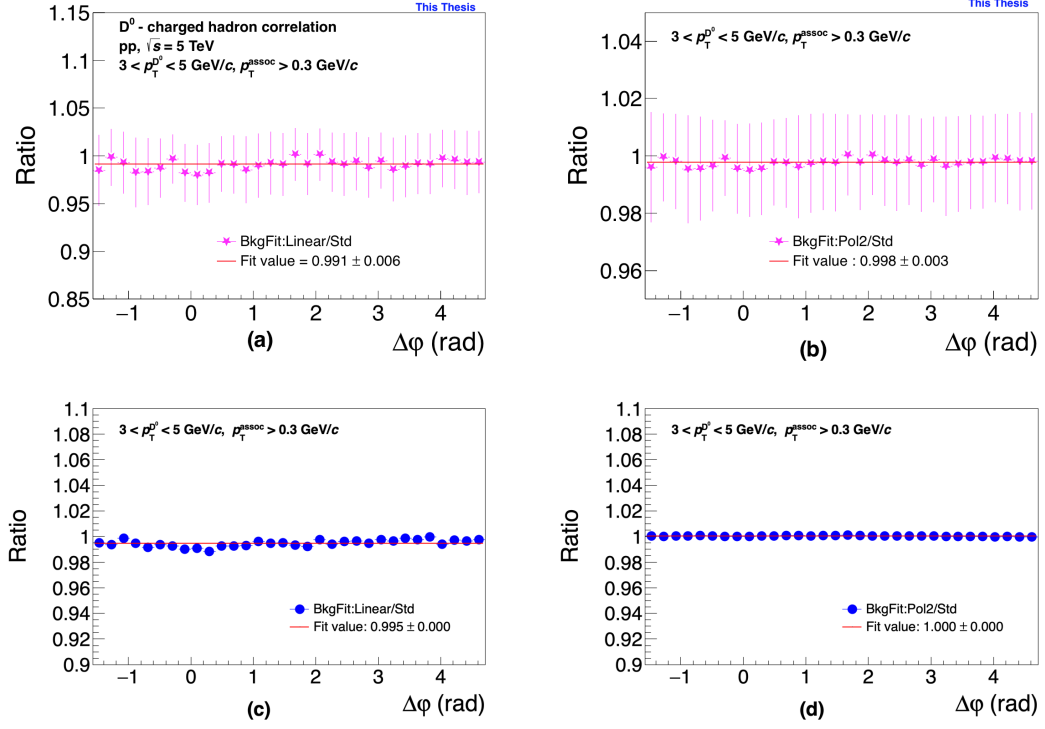
5.1.1 Signal (S) and Background (B) extraction

D^0 -hadron correlations are affected by the total yield of D^0 . And the D^0 yield depends on the methods by which signal (S) and background (B) of D^0 are being extracted from the invariant mass distribution of $K\pi$. This method contributes to one of the systematic uncertainties to the D^0 -hadron correlations and this is being estimated by changing the signal and background fitting functions and doing the rebinning. In the entire thesis, a standard method is being adopted for the D^0 yield extraction. In the standard method, the D^0 yield is extracted by integrating the Gaussian function fitted to the peak of the $K\pi$ invariant mass distribution from $1.7 \text{ GeV}/c^2$ to $2.1 \text{ GeV}/c^2$, and the background is estimated by integrating the background function. The systematic contribution to the correlation measurement is estimated by adopting the following yield extraction methods.

- *Method I:* Changing the exponential (Standard) background fit function to linear and polynomial
- *Method II:* Changing the Gaussian fitting function range for the extraction of yield
- *Method III:* Rebinning the invariant mass distribution of $K\pi$ before fitting
- *Method IV:* Extraction of S and B via integral of the fit functions or B via bin counting and S via integral of the Gaussian fitting function
- *Method V:* Considering the D^0 signal region within 1σ , 1.5σ and 3σ

The value of both the yields and sidebands normalization factors are affected in each p_T bin by changing the yield extraction methods. Apart from this different methods (*Method I-V*), all the rest of the procedures for the azimuthal correlation studies are same. The ratios of $\Delta\varphi$ correlation distributions of D^0 , $r_1(\Delta\varphi)$, are evaluated. This $r_1(\Delta\varphi)$ is defined as

$$r_1(\Delta\varphi) = \frac{\Delta\varphi \text{ correlations (different method)}}{\Delta\varphi \text{ correlations (standard method)}} \quad (5.1)$$

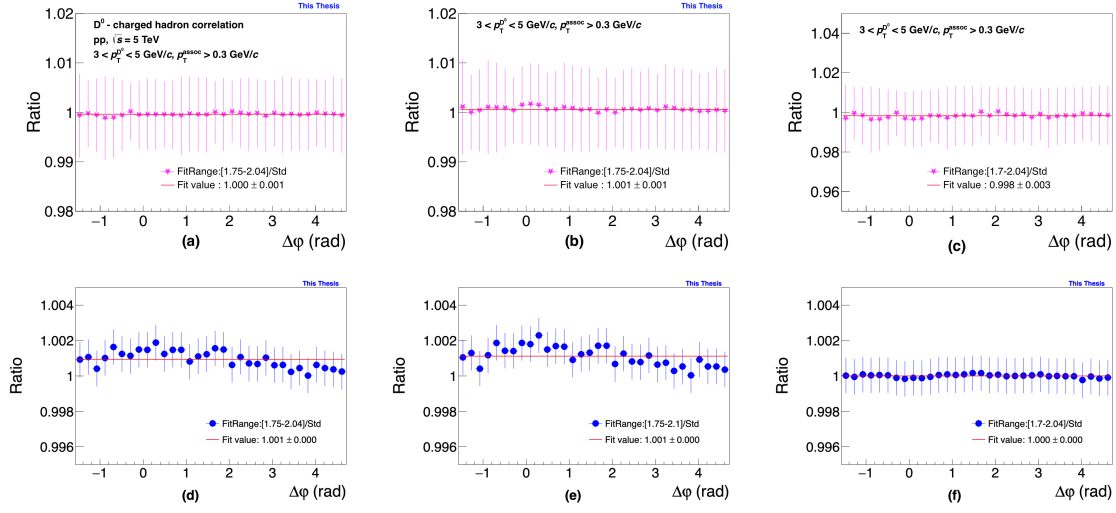
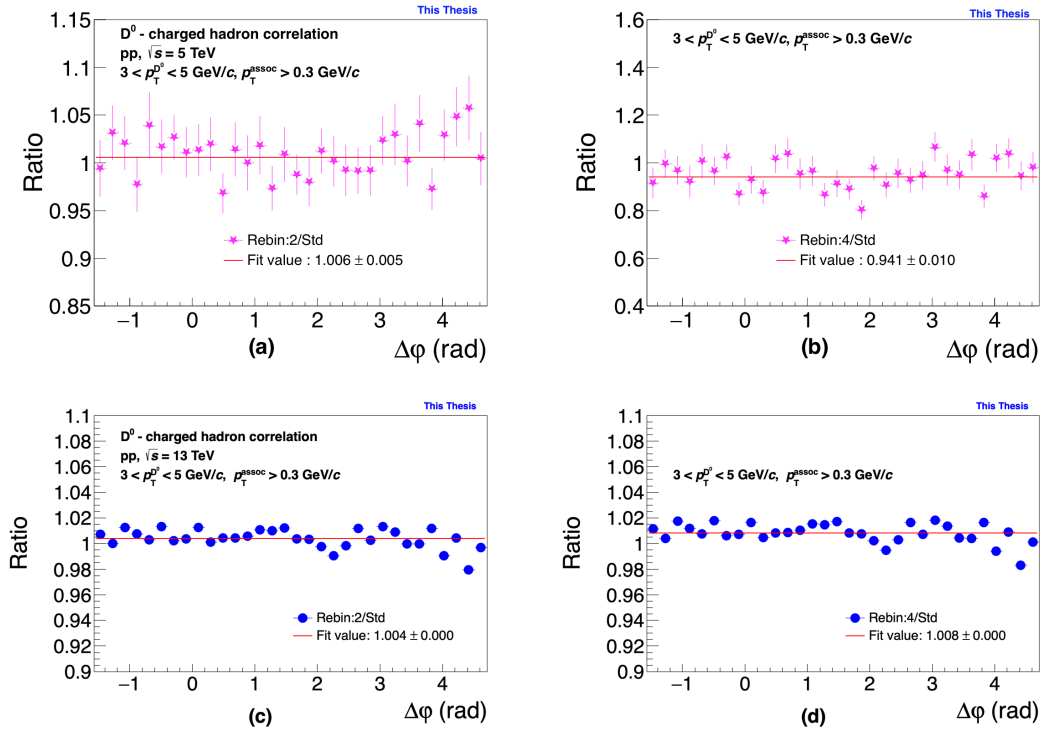
Figure 5.1: The $r_1(\Delta\phi)$ plots: *Method I*.

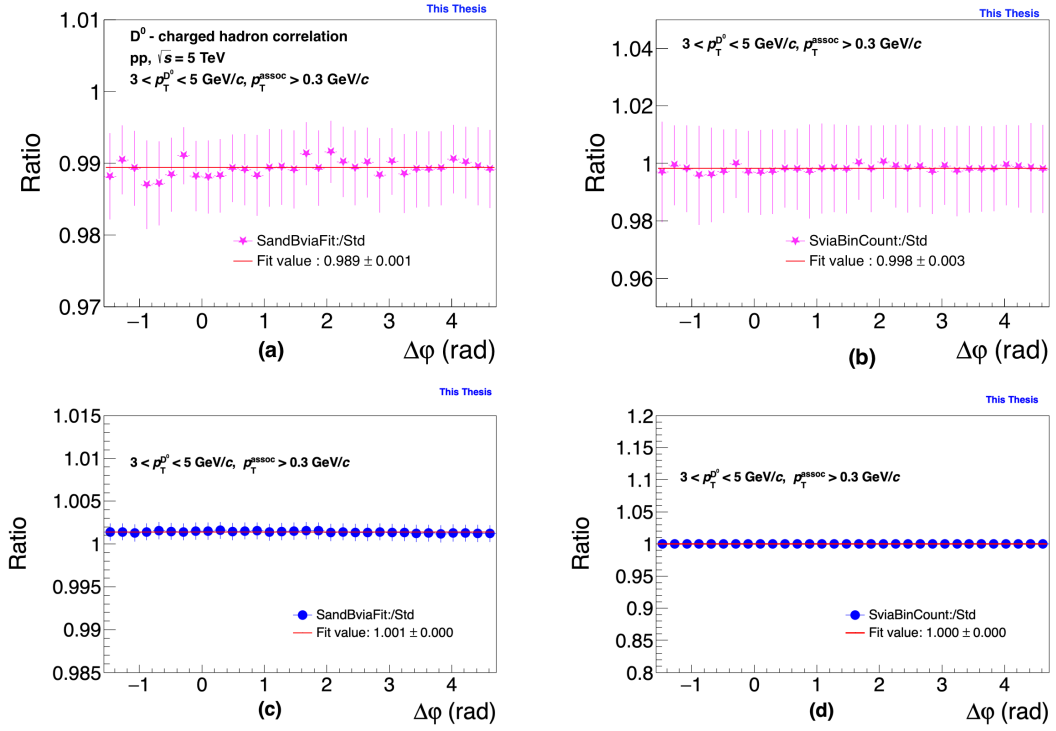
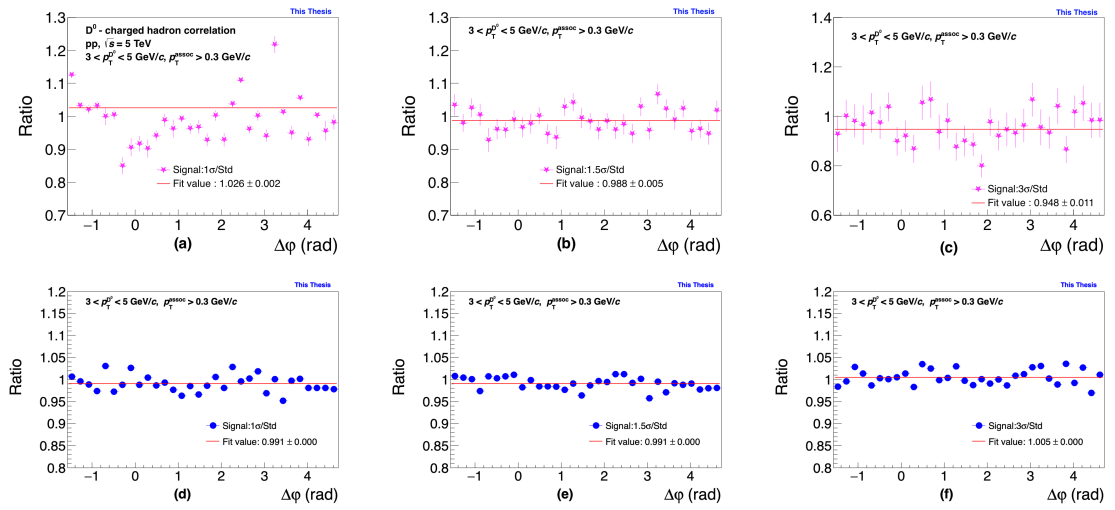
The $r_1(\Delta\phi)$ plots are obtained by implementing *Method I* and are shown in Fig. 5.1(a)-(b) and Fig. 5.1(c)-(d) for pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV, respectively. The $r_1(\Delta\phi)$ plots are fitted with a straight line with slope equals to zero as shown in the figure as red lines.

In *Method II*, the ranges of the Gaussian fitting function are $[1.75 - 2.04]$ GeV/ c^2 , $[1.75, 2.1]$ GeV/ c^2 and $[1.7, 2.04]$ GeV/ c^2 . The $r(\Delta\phi)$ plots are shown in Fig. 5.2(a)-(c) and 5.2(d)-(f) for pp collision at $\sqrt{s} = 5$ TeV and 13 TeV, respectively. Similarly, the $r_1(\Delta\phi)$ plots are obtained by implementing *Method III* are shown in Fig. 5.3(a)-(b) and Fig. 5.3(c)-(d) for pp collision at $\sqrt{s} = 5$ TeV and 13 TeV, respectively.

The $r_1(\Delta\phi)$ plots are obtained by implementing *Method IV* and again fitted to a straight line with slope equals to zero as shown in Fig. 5.4(a)-(b) and Fig. 5.4(c)-(d) for pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV, respectively.

The $r_1(\Delta\phi)$ plots are obtained by implementing *Method V*. These ratio plots are shown in Fig. 5.5(a)-(c) and Fig. 5.4(d)-(f) for pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV, respectively.

Figure 5.2: The $r_1(\Delta\varphi)$ plots: *Method II*.Figure 5.3: The $r_1(\Delta\varphi)$ plots: *Method III*.

Figure 5.4: The $r_1(\Delta\phi)$ plots:Method IV.Figure 5.5: The $r_1(\Delta\phi)$ plots:Method V.

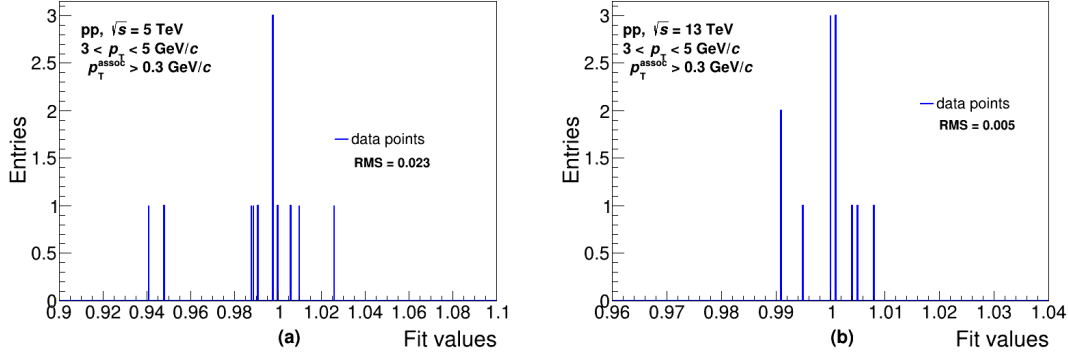


Figure 5.6: Parameter values obtained by changing the yield extraction procedure for pp collisions at a) $\sqrt{s} = 5$ TeV, b) $\sqrt{s} = 13$ TeV.

After implementing *Method I-V*, the $r_1(\Delta\varphi)$ plots are fitted to a straight line with slope equals to zero. All the straight line fit parameters are plotted in Fig. 5.6(a) and Fig. 5.6(b) for pp collision at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. The RMS values are found to be 0.023 and 0.004 for D^0 meson p_T range from 3 GeV/c to 5 GeV/c with $p_T^{\text{assoc}} > 0.3$ GeV/c. This indicates that the uncertainties due to signal and background extraction methods are less than 3% and 1% for pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV, respectively. The uncertainties for all the p_T ranges are calculated in similar way and listed in Table 5.2 and Table 5.3.

5.1.2 Background correlation shape

The systematic uncertainty contribution to the D^0 -hadron correlation study is due to the statistical fluctuations in the sidebands of the $K\pi$ invariant mass distribution and functions used to fit the background. To determine the uncertainty in the invariant mass regions, the sideband definition was varied with respect to the default ranges. The default range for the left sideband is from $\mu - 8\sigma$ to $\mu - 4\sigma$ and for the right sideband is from $\mu + 4\sigma$ to $\mu + 8\sigma$, where μ is the peak position of the $K\pi(D^0)$ invariant mass distribution. The sidebands ranges are modified to:

- $(\mu + 4\sigma)$ to $(\mu + 6\sigma)$
- $(\mu + 6\sigma)$ to $(\mu + 8\sigma)$
- $(\mu + 3\sigma)$ to $(\mu + 9\sigma)$

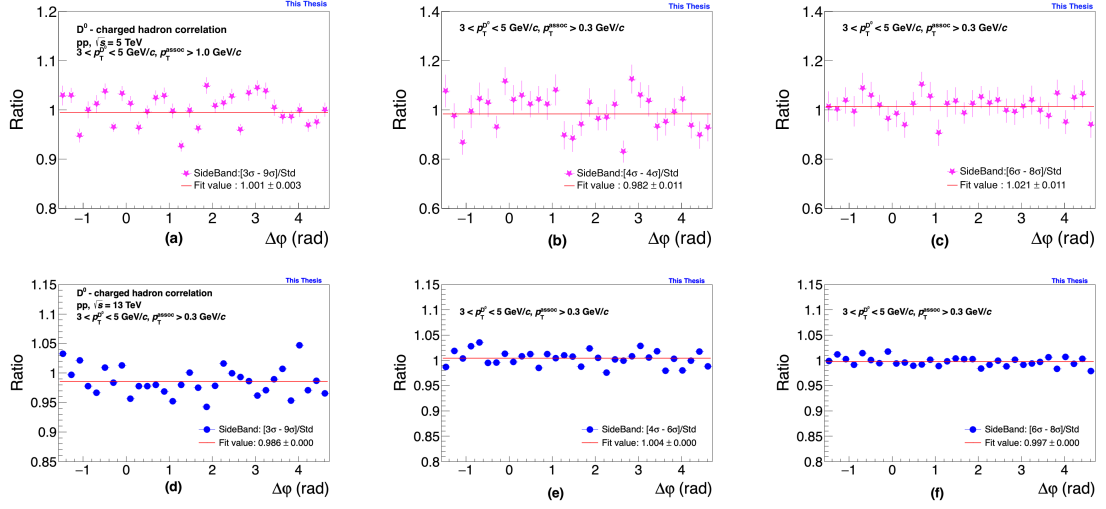


Figure 5.7: $r_2(\Delta\varphi)$ plots: (a)-(c) are for pp collisions at $\sqrt{s} = 5$ TeV and (d)-(f) are for pp collision at $\sqrt{s} = 13$ TeV.

Keeping the procedure same, the ratios of the $\Delta\varphi$ correlations of D^0 , $r_2(\Delta\varphi)$, are evaluated. This $r_2(\Delta\varphi)$ is defined as

$$r_2(\Delta\varphi) = \frac{\Delta\varphi \text{ correlations (different sideband range)}}{\Delta\varphi \text{ correlations (standard sideband range)}} \quad (5.2)$$

with the default ranges of the sidebands and with the modified ranges of the sidebands

The $r_2(\Delta\varphi)$ plots are extracted for each D^0 meson p_T bin and associated tracks p_T threshold for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV. The $r_2(\Delta\varphi)$ plots for D^0 p_T range from 3 GeV/c to 5 GeV/c with $p_T^{\text{assoc}} > 0.3$ GeV/c are shown in Fig. 5.7(a)-(c) and Fig. 5.7(d)-(f) for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. These $r_2(\Delta\varphi)$ plot show a flat trend along the $\Delta\varphi$ axis, which implies no effect on the correlation distribution due to the uncertainty on the background subtraction. But it affects the normalization factor.

Hence, these $r_2(\Delta\varphi)$ plots are fitted with a constant term as shown in Fig. 5.7. All these constant parameters obtained from various sidebands ranges are plotted in Fig. 5.8(a) and Fig. 5.8(b) for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. The RMS values are found to be 0.016 and 0.007 for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. This indicates that the systematic uncertainties in D^0 meson p_T range from 3 GeV/c to 5 GeV/c with $p_T^{\text{assoc}} > 0.3$ GeV/c are found to be within 2% and 1% for pp collisions at $\sqrt{s} = 5$ TeV

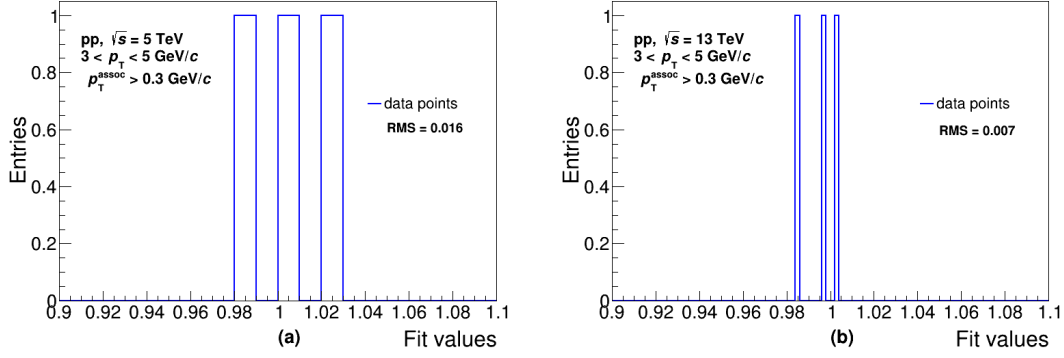


Figure 5.8: Parameter values obtained by changing the sideband definition for pp collisions: a) $\sqrt{s} = 5 \text{ TeV}$, b) $\sqrt{s} = 13 \text{ TeV}$.

and $\sqrt{s} = 13 \text{ TeV}$, respectively. The systematic uncertainties, which are coming from background correlation shape are calculated in the same manner for all other D^0 meson p_T ranges with different associated track p_T (p_T^{assoc}) and listed in Table 5.2 and Table 5.3 for pp collisions at $\sqrt{s} = 5 \text{ TeV}$ and $\sqrt{s} = 13 \text{ TeV}$, respectively.

5.1.3 Associated track efficiency

The uncertainty in the tracking efficiency is due to the associated charged particles selection criteria. This uncertainty can be evaluated by varying the associated track cuts selection. The variation of different cuts are:

- SetMinNClustersITS(0)
- SetRequireITSRefit(kFALSE)
- SetMinNCrossRowsTPC(90)
- SetMinRatioCrossedRowsOverFindableClustersTPC(0.9)

The variation of “SetMinRatioCrossedRowsOverFindableClustersTPC(0.9)” is not considered for pp collisions at $\sqrt{s} = 5 \text{ TeV}$. The tracking efficiency map as a function of associated track p_T for different associated track cuts and the ratio of all the maps to the standard one

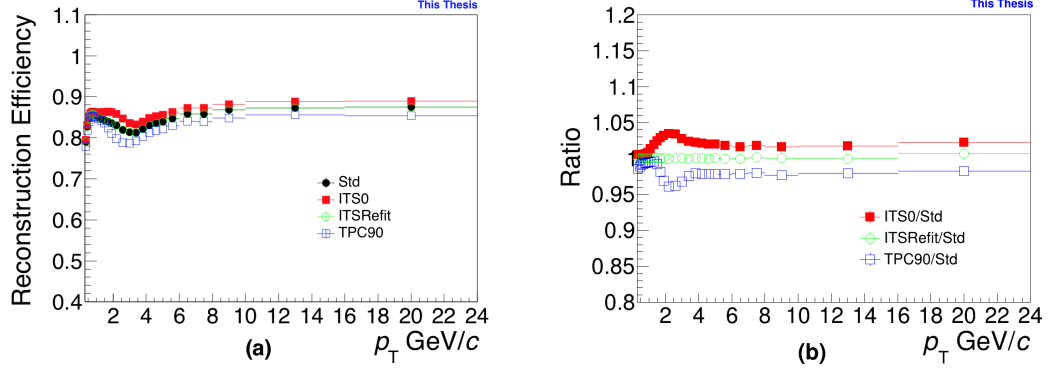


Figure 5.9: [pp, $\sqrt{s} = 5$ TeV] a) Associated track efficiency maps as a function of associated track p_T for different cut variation, b) ratio of efficiency maps with different cut variations with respect to the standard.

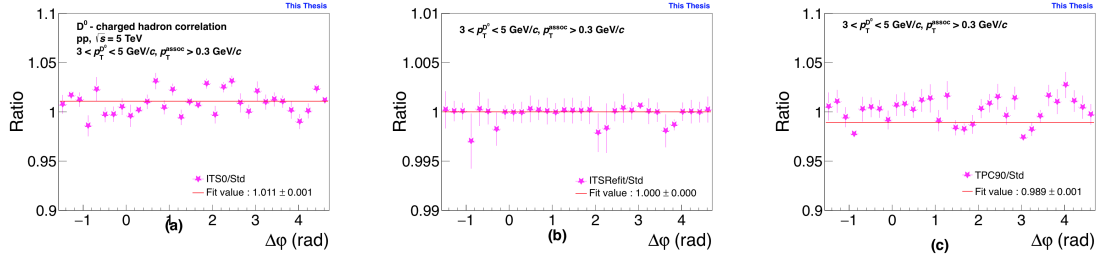


Figure 5.10: [pp, $\sqrt{s} = 5$ TeV] The ratios of D^0 - hadron correlation distributions with alternate approach to standard approach by varying the associate track cuts.

is shown in Fig. 5.9(a) and (b) for pp collisions at $\sqrt{s} = 5$ TeV. The different color markers represent the different cut variation in associated track cuts in Fig. 5.9. The ratio of $\Delta\phi$ correlation distributions with alternate approach to the standard approach are shown in Fig. 5.10(a)-(c) and Fig. 5.11(a)-(d) of D^0 meson p_T range from 3 GeV/c to 5 GeV/c for associated track $p_T^{\text{assoc}} > 0.3$ GeV/c for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively.

The ratio plots are fitted with a straight line with slope equals to zero as shown in Fig. 5.10 and Fig. 5.11. The RMS values of the fit parameters, shown in Fig. 5.12(a) and Fig. 5.12(b) for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively, are considered as the systematic uncertainties due to associated track efficiency.

The RMS values are found to be 0.009 and 0.022 for D^0 meson p_T range from 3 to 5 GeV/c with $p_T^{\text{assoc}} > 0.3$ GeV/c for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. This

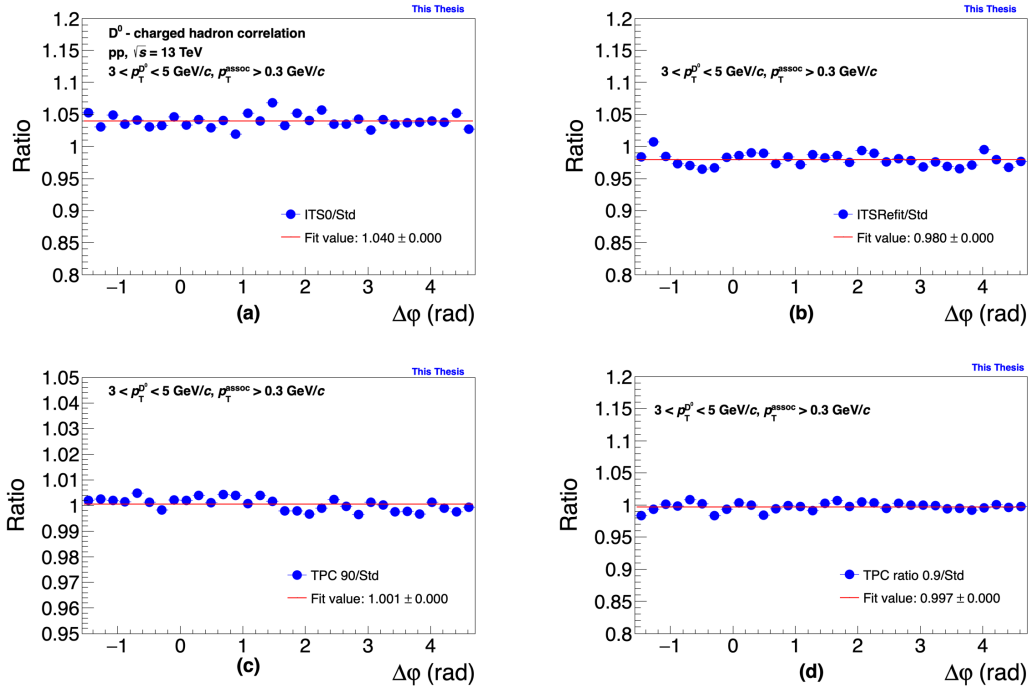


Figure 5.11: [pp, $\sqrt{s} = 13$ TeV] The ratios of D^0 - hadron correlation distributions with alternate approach to standard approach by varying the associate track cuts.

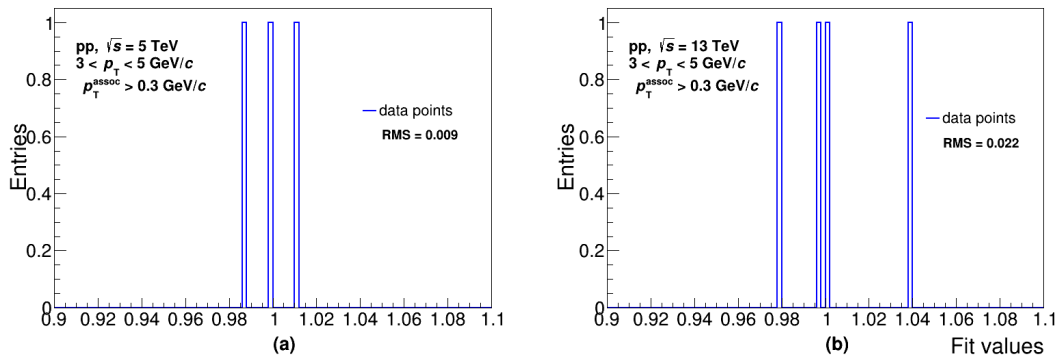


Figure 5.12: Parameter values obtained by changing associated track cuts for pp collisions: a) $\sqrt{s} = 5$ TeV, b) $\sqrt{s} = 13$ TeV.

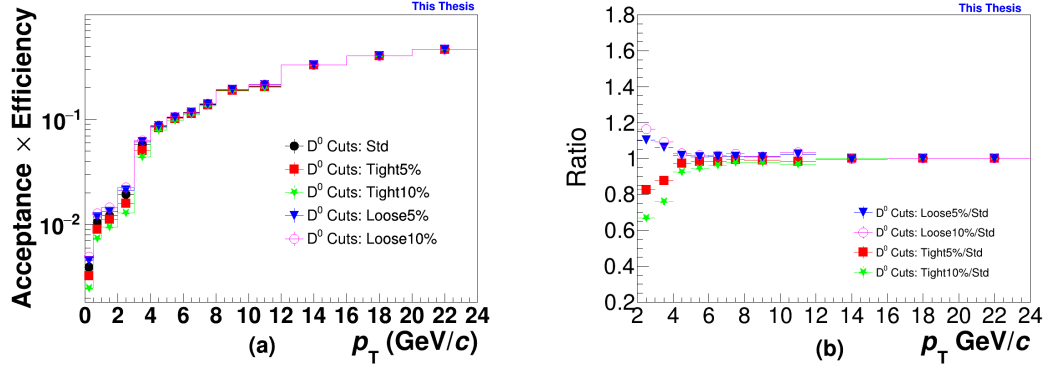


Figure 5.13: [pp, $\sqrt{s} = 5$ TeV] a) Comparison of Prompt D^0 efficiencies for different cut variations. b) Ratio of prompt D^0 efficiencies for different cut sets with respect to the standard cuts.

implies that the uncertainties due to different track cuts combinations are within 1% and 3% for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. Following the same procedure the systematic uncertainties for other D^0 meson p_T ranges and p_T^{assoc} ranges are calculated. The systematics uncertainties due to associated track cuts are listed in Table 5.2 and Table 5.3 for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively.

5.1.4 D^0 meson cuts stability

The systematic uncertainties can also arise from the D^0 meson topological cuts selection. One can minimize the uncertainty by varying the topological cuts like cosine of pointing theta angle ($\cos \theta_{\text{point}}$) and the product of daughter tracks impact parameters. The variation is carried out by varying the cuts loose or tight by 5%, 10% and 15%. 15% variation of cuts is not applied to pp collisions at $\sqrt{s} = 5$ TeV. The prompt and feed-down D^0 meson efficiency with different variation of cuts for pp collisions at $\sqrt{s} = 5$ TeV and their ratios with respect to the standard cuts are shown in Fig. 5.13 and Fig. 5.14, respectively. The rest of the procedure for the analysis is followed without any changes.

The ratio of $\Delta\varphi$ correlations distributions obtained using tighter cuts and loose cuts over the results with standard cuts for pp collisions at $\sqrt{s} = 5$ TeV are shown in Fig. 5.15(a)-(b) and Fig. 5.15(c)-(d), respectively. Similarly, for pp collisions at $\sqrt{s} = 13$ TeV, the ratio of

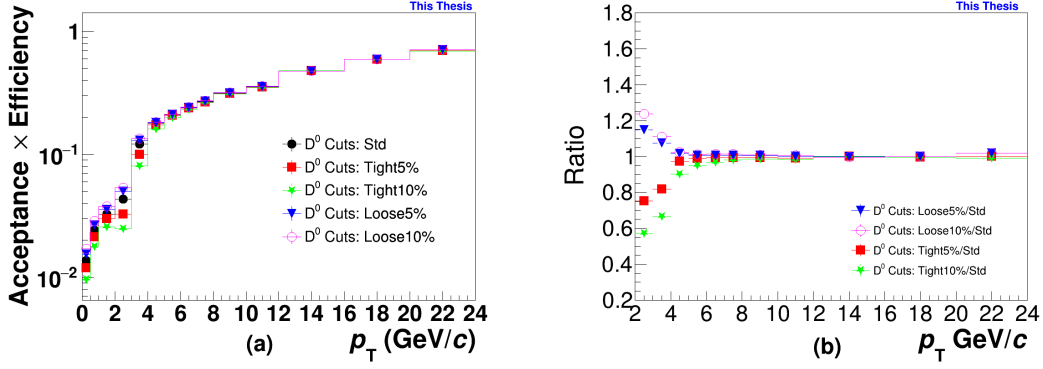


Figure 5.14: [pp, $\sqrt{s} = 5$ TeV] a) Comparison of feed-down D^0 efficiencies for different cut variations. b) Ratio of feed-down D^0 efficiencies for different different cut sets with respect to the standard one.

$\Delta\phi$ correlations distributions obtained using tighter cuts and loose cuts over the results with standard cuts are shown in Fig. 5.16(a)-(c) and Fig. 5.16(d)-(f), respectively. The ratio plots are shown for the D^0 meson p_T range from 3 to 5 GeV/c) with associated track $p_T^{\text{assoc}} > 0.3$ GeV/c.

The ratio plots are fitted with a constant term as shown in the respective figures to evaluate the systematic uncertainty. The red lines are the fitting lines with a constant term in the ratio plots. The RMS of the fit values obtained from the fitting of ratio plots are considered as the uncertainty. The fit parameters are plotted in Fig. 5.17(a) and Fig. 5.17(b) for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. The RMS values are found to be 0.023 and 0.006 in D^0 meson p_T range from 3 to 5 GeV/c with $p_T^{\text{assoc}} > 0.3$ GeV/c for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. So, the uncertainties due to D^0 meson selection cuts are 2.5% and 1% for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. The uncertainties are calculated for all other p_T ranges using the same method for both the systems and listed in Table 5.2 and Table 5.3.

5.1.5 Secondary particle contamination

In this section, the contribution of secondary track contamination to the systematic uncertainty on the D^0 -hadron correlation has been estimated. As described in section 4.2.7(V), the secondary track contamination is independent of D^0 meson p_T ($p_T^{D^0}$), but depends on the

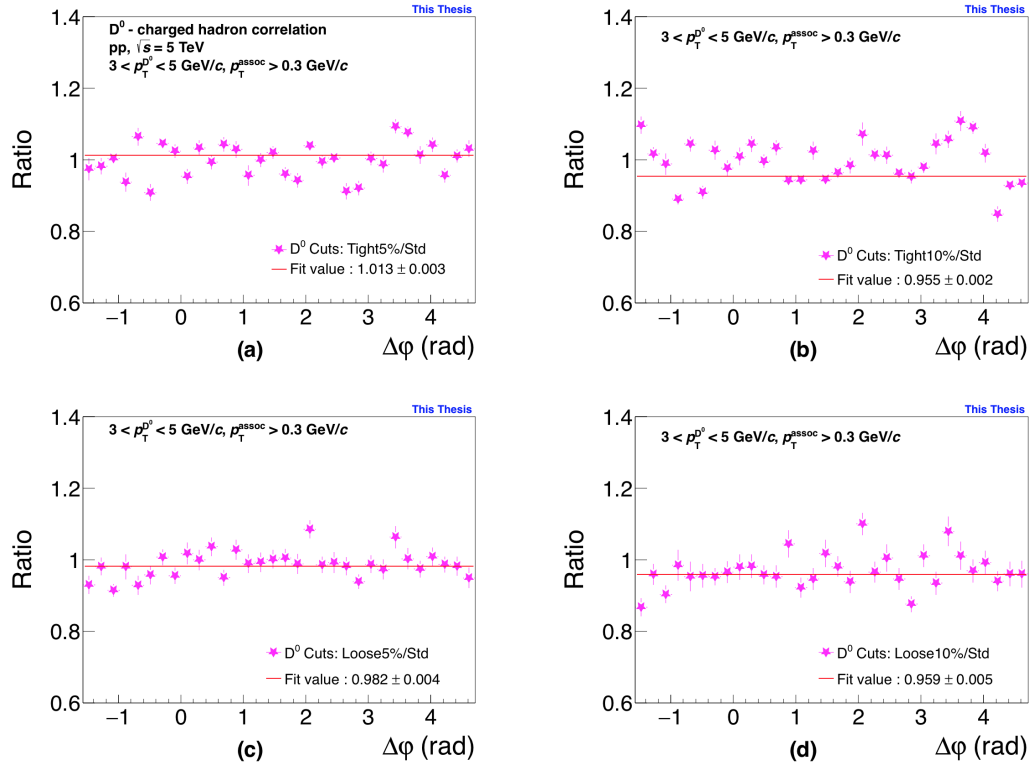


Figure 5.15: [pp, $\sqrt{s} = 5$ TeV] The ratios of D^0 - hadron correlation distributions with alternate approach to standard approach by varying the D^0 meson cuts.

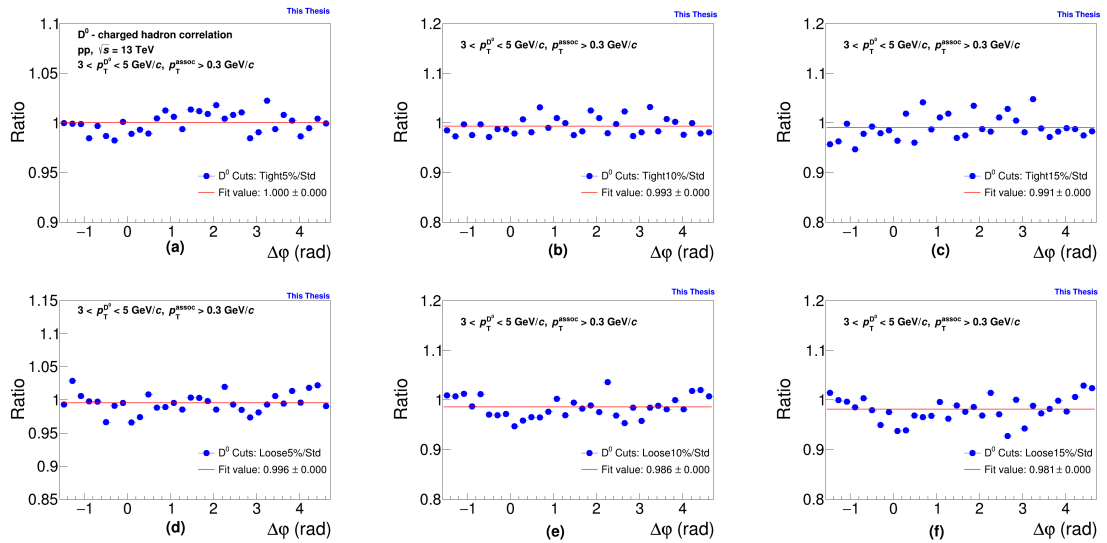


Figure 5.16: [pp, $\sqrt{s} = 13$ TeV] The ratios of D^0 - hadron correlation distributions with alternate approach to standard approach by varying the D^0 meson cuts.

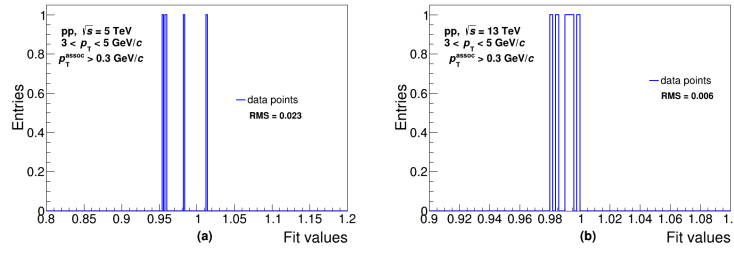


Figure 5.17: Parameter values obtained by changing D^0 meson selection cuts for pp collisions:

a) $\sqrt{s} = 5$ TeV, b) $\sqrt{s} = 13$ TeV.

associated track p_T (p_T^{assoc}). Hence, the fraction of secondary track contamination may change the correlation measurement. Therefore, one needs to find out the fraction of secondary contamination by varying the DCA_{xy} cut. The various DCA_{xy} cuts used to study the systematic contribution for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV are given in Table 5.1. By applying various DCA_{xy} cuts, the number of primary and secondary tracks are determined. Using this primary and secondary tracks information, the fraction of secondary contamination, f_{sec} , is estimated and the results are shown in Fig. 5.18(a) and 5.18(b) for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively.

Table 5.1: DCA_{xy} values used to study the systematic uncertainty.

Collision energy	DCA_{xy} (cm)					
$\sqrt{s} = 5$ TeV	0.25	0.1	0.50	1.0	2.4	999.0
	(std)					(No DCA_{xy})
$\sqrt{s} = 13$ TeV	0.25	0.1	0.50	1.0	2.4	999.0
				(std)		(No DCA_{xy})

The ratios of D^0 - hadron correlation plots obtained with respect to standard DCA_{xy} for different DCA_{xy} selections after purity correction are shown in Fig. 5.19 and Fig. 5.20. In Fig. 5.19, (a)-(c) the ratio plots are for pp collision at $\sqrt{s} = 5$ TeV and (d)-(f) are for the pp collisions at $\sqrt{s} = 13$ TeV. The ratio plots with $DCA_{xy} = 2.4$ cm and No DCA_{xy} cut are shown in Fig. 5.20(a)-(b) for pp collisions at $\sqrt{s} = 5$ TeV and in Fig. 5.20(c)-(d) for pp collision at $\sqrt{s}$

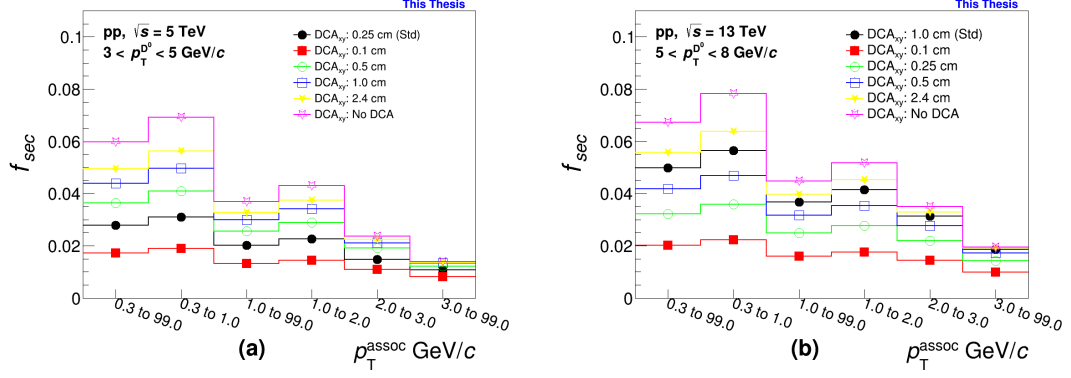


Figure 5.18: Fraction of secondary, f_{sec} , vs. p_T^{assoc} for different DCA_{xy} cuts. a) $p_T^{D^0}$ ranges 3 to 5 GeV/c at $\sqrt{s} = 5$ TeV, b) $p_T^{D^0}$ ranges from 5 to 8 GeV/c at $\sqrt{s} = 13$ TeV

= 13 TeV. The ratio plots shown here are for the D^0 meson p_T range from 3 to 5 GeV/c with associated track $p_T^{assoc} > 0.3$ GeV/c.

The ratio plots are fitted with a straight line with slope equal to zero as shown in Fig. 5.20. The extracted parameters for different values of DCA_{xy} are shown in Fig. 5.21. The RMS values of the the extracted parameters for different values of DCA_{xy} , shown in Fig. 5.21, indicate that the uncertainties due to the variation of DCA_{xy} values are within 3% and 4% for pp collision at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. The uncertainties at both the energies in different p_T ranges are calculated and listed in Table 5.2 and Table 5.3.

5.1.6 Feed-down subtraction

As mentioned earlier, the feed-down subtraction from the data distributions is performed by means of simulation templates of $B \rightarrow D - h$ correlation distributions from PYTHIA6 generator, with Perugia2011 tune, and considering the central value of f_{prompt} to extract the feed-down D meson contribution. In order to evaluate a systematic uncertainty due to the feed-down, the procedure is repeated for PYTHIA6+Perugia2011 templates, PYTHIA6+Perugia2010 and PYTHIA8. In each case, not only the central value of the measured f_{prompt} is considered to rescale the distributions, but also the maximum and minimum values of its total uncertainty are considered. Then, the envelope of nine different cases obtained by varying the templates and the f_{prompt} assumption are considered. The systematic uncertainty due to the feed-down is

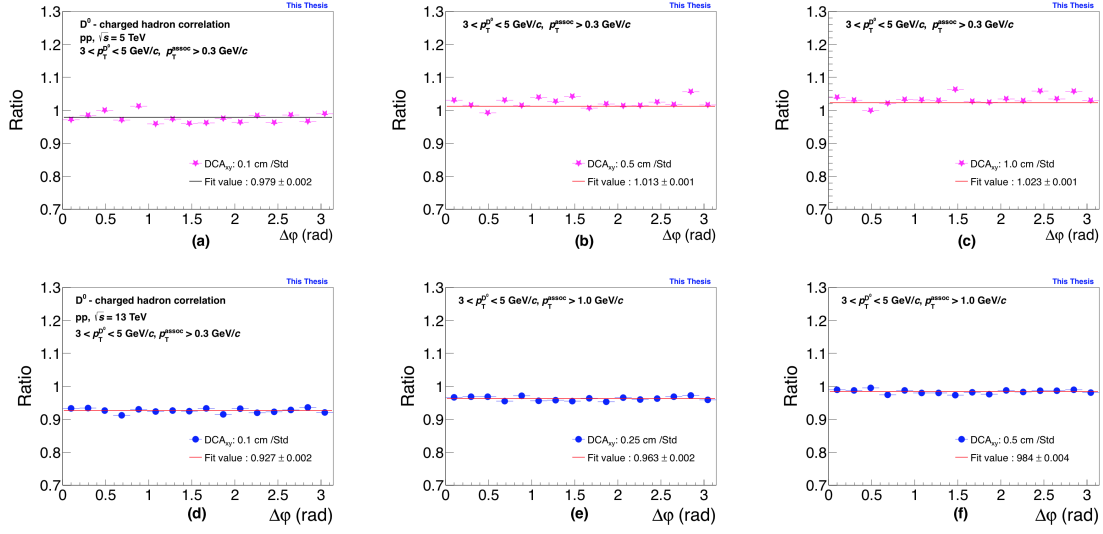


Figure 5.19: Ratios of purity corrected D^0 - hadron correlation plots obtained with different DCA_{xy} value. a)-c) for pp collision at $\sqrt{s} = 5$ TeV and d)-e) for pp collision at $\sqrt{s} = 13$ TeV.

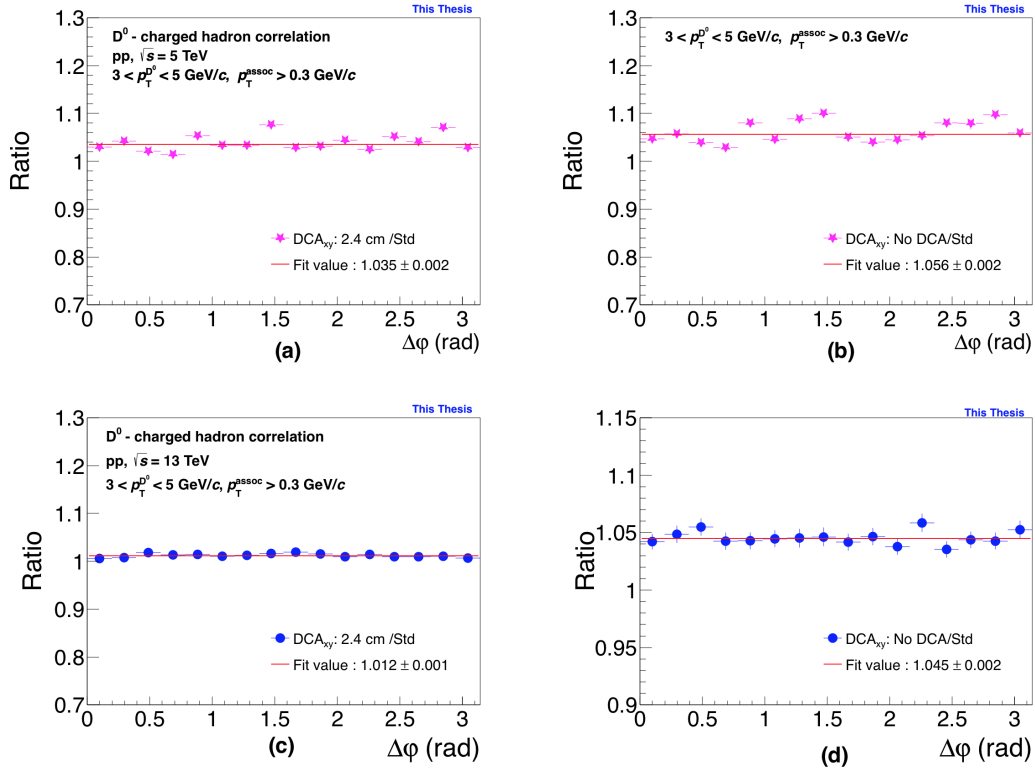


Figure 5.20: Ratios of purity corrected D^0 - hadron correlation plots obtained with $DCA_{xy} = 2.40$ cm and NoDCA cut. a)-b) for pp collision at $\sqrt{s} = 5$ TeV and c)-d) for pp collision at $\sqrt{s} = 13$ TeV.

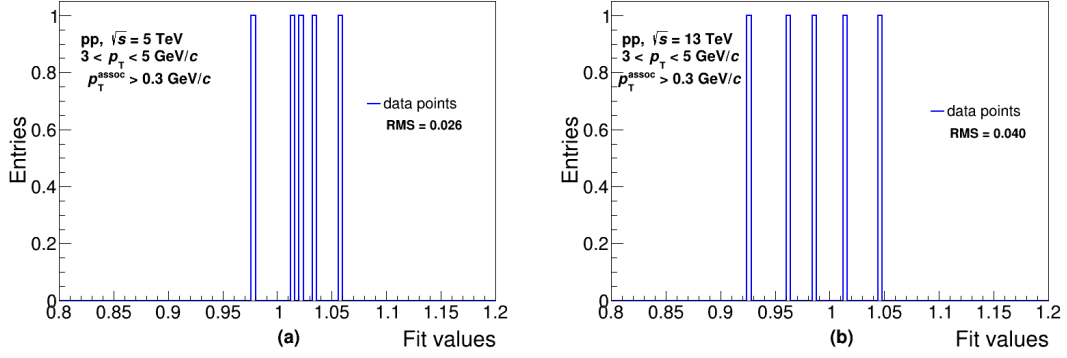


Figure 5.21: Parameter values obtained by changing DCA_{xy} cuts for pp collisions at a) $\sqrt{s} = 5$ TeV, b) $\sqrt{s} = 13$ TeV.

estimated by dividing $\sqrt{3}$ by the spread of the envelope. This uncertainty was assumed to be uncorrelated among different $\Delta\varphi$ points. The maximum uncertainties are found to be 3% and 5% for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively.

5.1.7 Uncertainty on correction for the bias on B to D decay topologies

The evaluation of this systematic uncertainty is already mentioned in 4.2.7 (IV). For each of the five data points close to the center of the near-side peak, which are affected by the bias, a bilateral and systematic uncertainty of amplitude $|C(\Delta\varphi)_{corr} - C(\Delta\varphi)_{raw}| / \sqrt{12}$ is assigned. It is assumed that if the correction is properly evaluated, the corrected data points are at the centre of the possible spread of the true unbiased results. In this case, the span of the possible true results (in case of underestimation/overestimation of the bias) goes from the uncorrected data points to its symmetric value, with respect to the corrected data point, on the other direction. If this distribution is uniform and constrained by these two values, the 1σ confidence region for the position of the true value of the unbiased points is in a bilateral $|C(\Delta\varphi)_{corr} - C(\Delta\varphi)_{raw}| / \sqrt{12}$ window, centred on the $C(\Delta\varphi)_{corr}$ points. This source of uncertainty is assumed to be uncorrelated among the $\Delta\varphi$ points. The largest value of uncertainty is less than 2% for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV.

5.1.8 Summary Table

The values of $\Delta\varphi$ -correlated uncertainties affecting the correlation distributions of D^0 meson for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV are listed in Table 5.2 and Table 5.3, respectively. The uncertainties included here are from S and B extraction, background correlation shape, associated track efficiency, D meson cuts stability and secondary particle contamination. The uncertainties from feed-down subtraction and bias on B to D decay topologies are excluded because they are uncorrelated among the $\Delta\varphi$ points.

Table 5.2: [pp, $\sqrt{s} = 5$ TeV] $\Delta\varphi$ -correlated uncertainties associated to the correlation distributions.

Sources	$p_T^{\text{assoc}} > 0.3$ GeV/c			$p_T^{\text{assoc}} > 1.0$ GeV/c			$0.3 < p_T^{\text{assoc}} < 1.0$ GeV/c		
$p_T^{D^0}$ (GeV/c)	3-5	5-8	8-16	3-5	5-8	8-16	3-5	5-8	8-16
Yield Extrac- tion	3.0%	3.0%	3.0%	4.0%	4.0%	4.0%	3.0%	3.0%	3.0%
Background subtraction	1.5%	1.0%	1.5%	2.0%	2.0%	8.0%	1.0%	1.5%	4.0%
Cut variation	2.5%	1.0%	3.0%	2.5%	1.5%	1.0%	6.0%	2.0%	3.5%
Tracking Effi- ciency	1.0%	1.0%	1.0%	2.0%	2.0%	2.0%	1.5%	1.5%	1.5%
Track Purity	3.0%	3.0%	3.0%	2.0%	2.0%	2.0%	3.0%	3.0%	3.0%

Table 5.3: [pp, $\sqrt{s} = 13$ TeV] $\Delta\varphi$ -correlated uncertainties associated to the correlation distributions.

Sources	$p_T^{\text{assoc}} > 0.3$ GeV/ c			$p_T^{\text{assoc}} > 1.0$ GeV/ c			$0.3 < p_T^{\text{assoc}} < 1.0$ GeV/ c		
$p_T^{D^0}$ (GeV/ c)	3-5	5-8	8-16	3-5	5-8	8-16	3-5	5-8	8-16
Yield Extrac- tion	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Background subtraction	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Cut variation	1.0%	2.0%	1.0%	1.0%	2.0%	1.0%	1.0%	2.0%	1.0%
Tracking Effi- ciency	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Track Purity	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	4.0%	4.0%	4.0%

Chapter 6

Results and Discussion

"Life is and will ever remain an equation incapable of solution, but it contains certain known factors."

–Nikola Tesla

6.1 Final correlation results

6.1.1 D^0 -h azimuthal correlation distributions

The final corrected correlation distributions, described in section 4.2.7, are plotted in the $\Delta\varphi$ range within $[-\pi/2, 3\pi/2]$ in different kinematic ranges. To reduce the statistical fluctuation the $\Delta\varphi$ correlation data points are reflected by folding the envelope of near-side centred at $\Delta\varphi = 0$ and away-side centred at $\Delta\varphi = \pi$, and plotted in the range of $[0, \pi]$. In doing so, the statistical uncertainty is reduced by a factor of $\frac{1}{\sqrt{2}}$. And while doing the folding it is assumed that the data points around the point of reflection are symmetrically distributed. The fully corrected azimuthal correlation distribution for the three p_T regions, i.e., $3 \leq p_T < 5$ GeV/c, $5 \leq p_T < 8$ GeV/c, $8 \leq p_T \leq 16$ GeV/c, with associated track p_T (p_T^{assoc}) threshold of 0.3 GeV/c, 1.0 GeV/c and from 0.3 to 1.0 GeV/c are shown in Figure 6.1 and Figure 6.2. From Fig. 6.2, it is clearly visible that the height of the correlation peak increases as we move from low p_T to high p_T

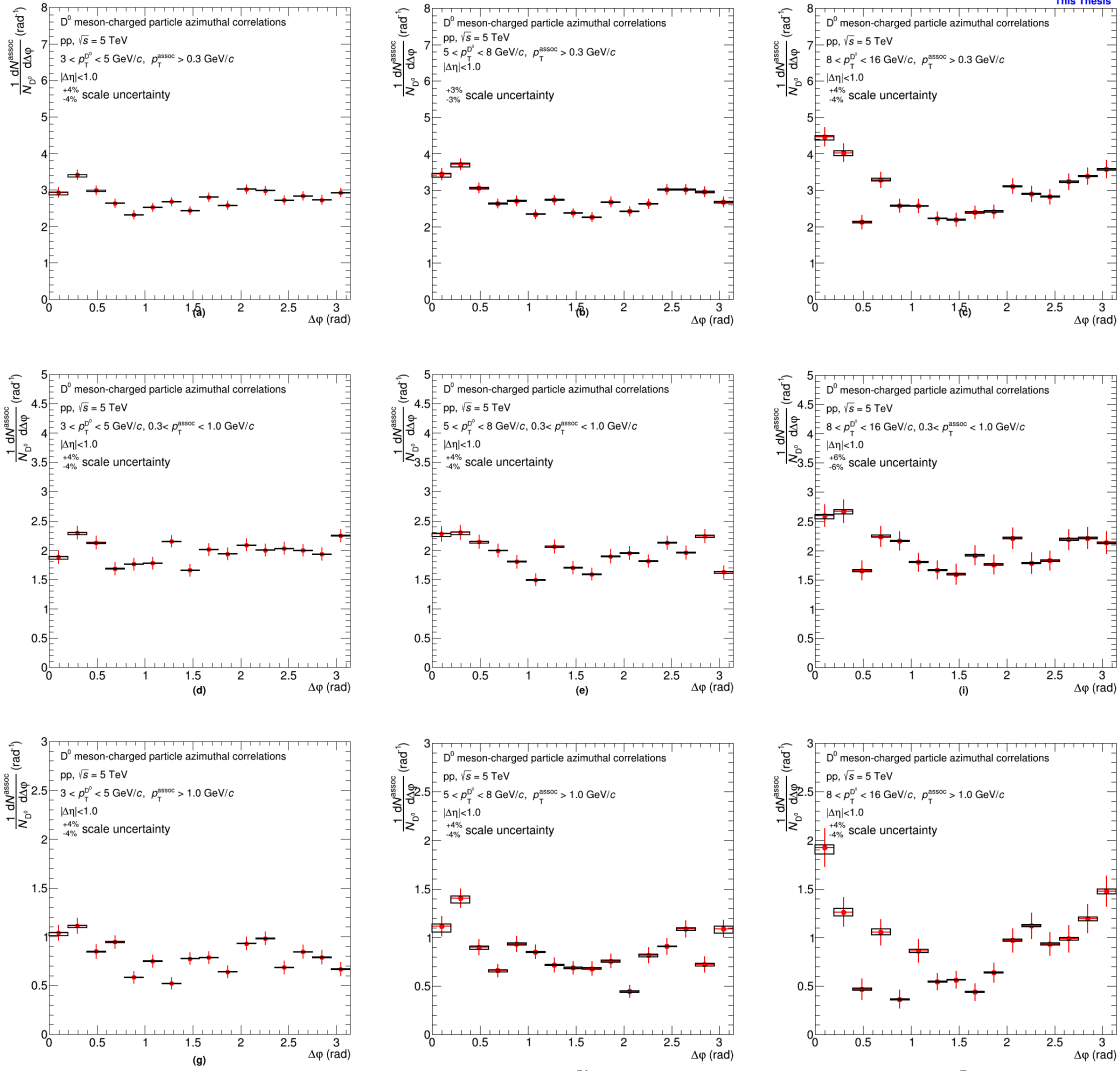


Figure 6.1: [pp, $\sqrt{s} = 5$ TeV] Fully corrected D^0 - hadron azimuthal correlation distribution for different D^0 meson p_T ranges.

of D^0 meson and also the baseline decreases with the increase of associated particle p_T (p_T^{assoc}) threshold.

6.1.2 Average of D^0 and D^{*+} results

The $\Delta\phi$ correlation plots for the D^{*+} meson is also obtained by doing the analysis in the similar manner as described for D^0 meson. In order to reduce the overall uncertainties, a weighted average of the azimuthal correlation distributions of the two D mesons, i.e., D^0 and

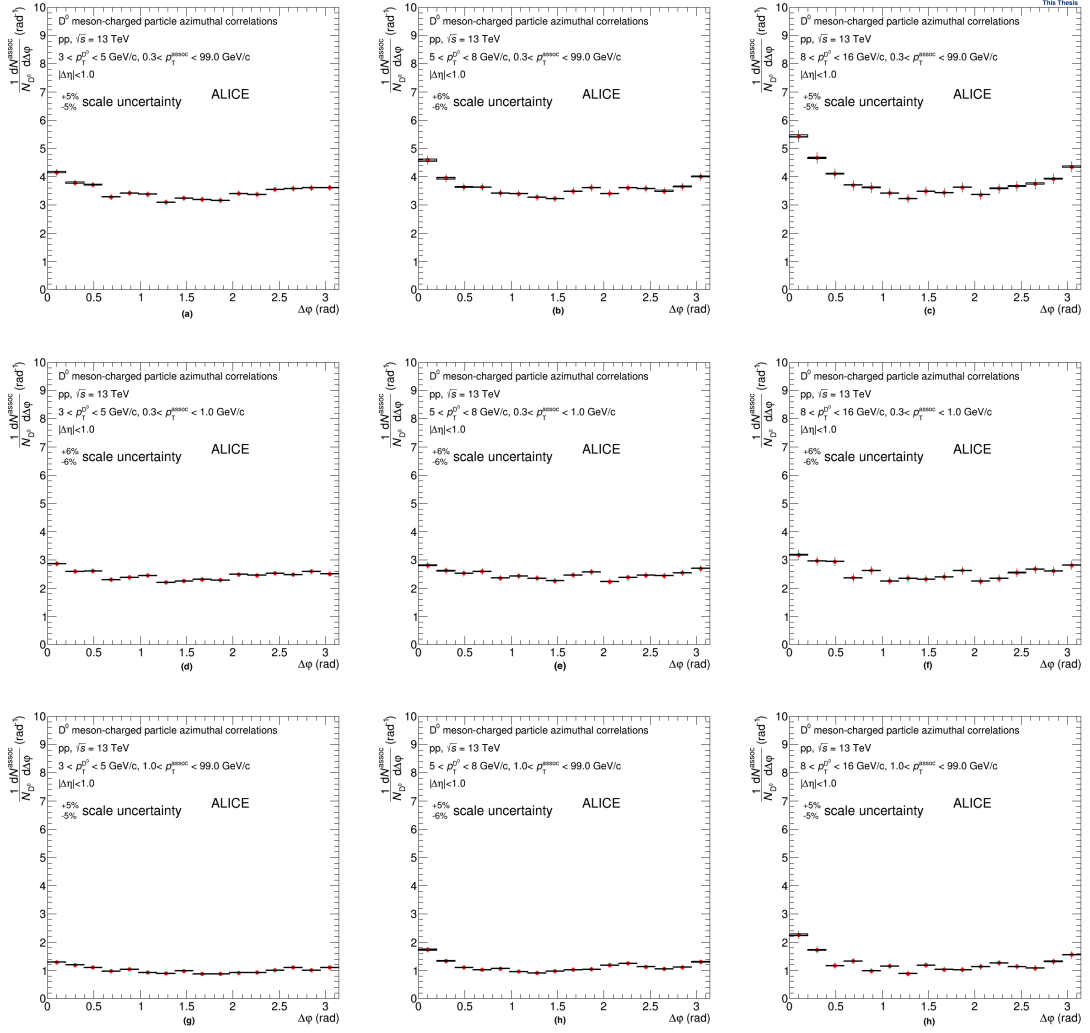


Figure 6.2: [pp, $\sqrt{s} = 13 \text{ TeV}$] Fully corrected D^0 - hadron azimuthal correlation distribution for different D^0 meson p_T ranges.

D^{*+} , are constructed using the Equation. 6.1 [95]. This weighted average is calculated only for pp collisions at $\sqrt{s} = 13$ TeV.

$$\left\langle \frac{1}{N_D} \frac{dN^{\text{assoc}}}{d\Delta\varphi} \right\rangle_D = \frac{\sum_{i=D^0, D^{*+}} w_i \frac{1}{N_D} \frac{dN^{\text{assoc}}}{d\Delta\varphi}}{\sum_{i=D^0, D^{*+}} w_i} \quad (6.1)$$

The weight factors used in Equation. 6.1 are calculated from the statistical uncertainty and the uncorrelated systematic uncertainty came from yield extraction and background correlation shape by using the Equation. 6.2.

$$w_i = \frac{1}{\sigma_{i,stat}^2 + \sigma_{i,uncorr.syst.}^2} \quad (6.2)$$

The correlated systematic uncertainty on the weighted average of $\Delta\varphi$ correlation distributions of D^0+D^{*+} is calculated as:

$$\sigma = \frac{\sum_{i=D^0, D^{*+}} w_i \sigma_{i,corr.syst}}{\sum_{i=D^0, D^{*+}} w_i} \quad (6.3)$$

The correlated systematic uncertainties are discussed in systematic chapter 5.

The average results of D^0 and D^{*+} azimuthal correlation distributions for D meson p_T ranges 3-5 GeV/c, 5-8 GeV/c and 8-16 GeV/c in different associated track p_T (p_T^{assoc}) threshold are shown in Fig. 6.3.

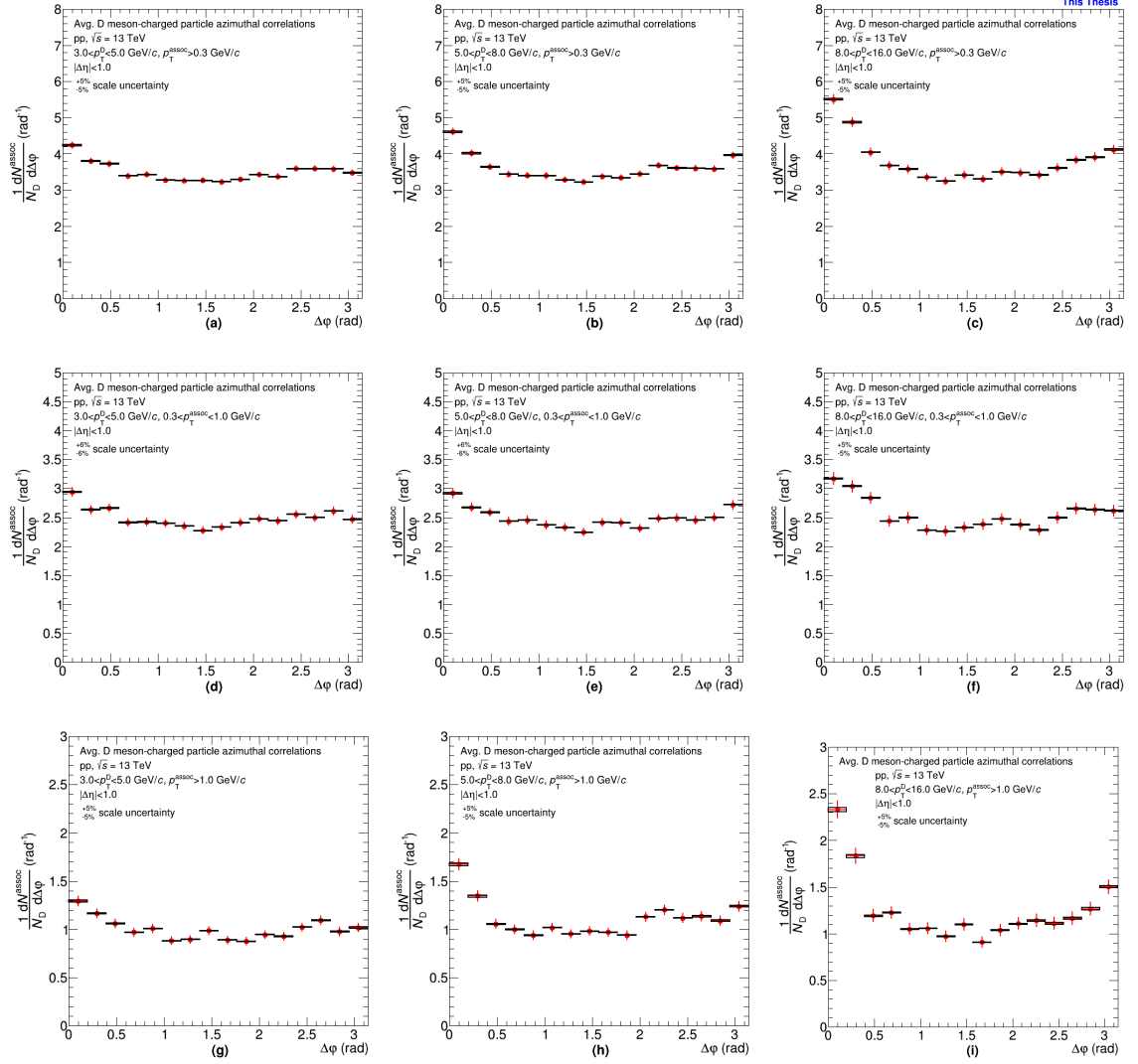


Figure 6.3: [$pp, \sqrt{s} = 13 \text{ TeV}$] Average of $D^0 + D^{*+}$ azimuthal correlations for different D meson p_T ranges.

6.1.3 Fit observable p_T trends and uncertainties

The D-hadron correlation distribution is fitted with a double Gaussian (centred at $\Delta\varphi = 0$ and $\Delta\varphi = \pi$) plus a constant term (baseline) to extract the physical parameters. The fitting function is given by Equation 6.4.

$$f(\Delta\varphi) = C + \frac{Y_{NS}}{\sqrt{2\pi\sigma_{NS}^2}} \times e^{-\frac{(\Delta\varphi - \mu_{NS})^2}{2\sigma_{NS}^2}} + \frac{Y_{AS}}{\sqrt{2\pi\sigma_{AS}^2}} \times e^{-\frac{(\Delta\varphi - \mu_{AS})^2}{2\sigma_{AS}^2}} \quad (6.4)$$

The $\Delta\varphi$ correlation distributions are fitted with double Gaussian function and a constant term, given by Equation 6.4, and shown in Fig.6.4(a) and (b) for pp collisions at $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV, respectively. The near-side and away-side yields and widths are found out from the fitting. Correlation baseline represents the *physical minimum* of $\Delta\varphi$ correlation distribution. The baseline is evaluated by considering the weighted average of the points in the transverse region from $\pi/4 < |\Delta\varphi| < \pi/2$.

The near-side observables (*yield and width*) give information on the multiplicity and angular spread of the particles from the fragmentation of the charm jet, whereas the away-side observables (*yield and width*) are related to the hadronization of the charm quark produced in the opposite direction [74]. The baseline value is a rough indicator of the underlying event multiplicity, though the baseline level has also contribution from charm and beauty pairs (especially in cases of NLO production for the heavy quarks). The evaluation of the systematic uncertainties of the yield and width of near-side as well as away-side is carried out as follows:

1. The fits are repeated by changing the range of the transverse region in which the baseline is evaluated.
2. In addition, $\Delta\varphi$ correlation points are shifted to the upper and lower bounds of their uncorrelated systematic boxes, and refitted.
3. The fits are also repeated by moving the baseline value from its default value (i.e., with the default transverse region) to default value $\pm$ statistical uncertainty.

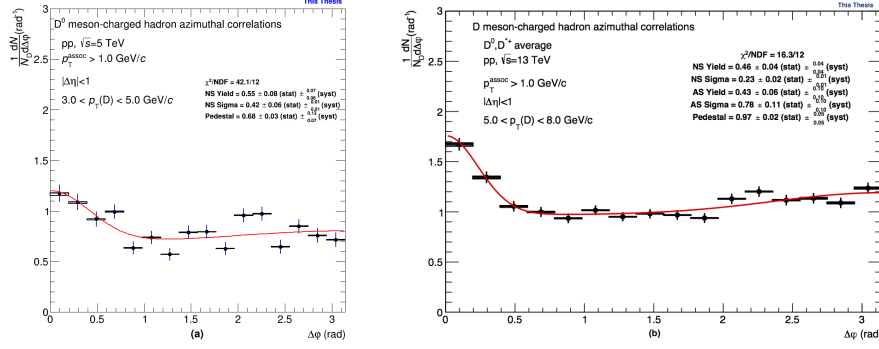


Figure 6.4: Fitting of a function expressed in Equation 6.4 to the $\Delta\phi$ correlation distributions: a) D^0 mesons for $3 \leq p_T^{D^0} < 5$ GeV/c for pp collisions at $\sqrt{s} = 5$ TeV, b) the weighted average of $D^0 + D^{*+}$ mesons for $5 \leq p_T^D < 8$ GeV/c for pp collisions at $\sqrt{s} = 13$ TeV.

The systematic uncertainty for the near-side and away-side widths can be calculated using Equation 6.5.

$$\sigma^{syst} = \sqrt{(\text{Max}(\Delta par^{BaselineShift}, \Delta par^{RMS OtherVariations}))^2 + (\sigma_{syst}^{corr})^2} \quad (6.5)$$

where $\Delta par^{BaselineShift}$ is the results from fits, obtained from point 3. $\Delta par^{RMS OtherVariations}$ is the RMS value obtained from point 1 and Point 2.

The near-side associated yield, width and baseline for different kinematic ranges are shown in Fig. 6.5, Fig. 6.6 and Fig. 6.7. The away-side correlation yield and width for pp collisions at $\sqrt{s} = 5$ TeV cannot be calculated due to the low statistics. It is evident from Fig. 6.5 that the near-side yield increases with the increase of D^0 meson p_T . The near-side width shown in Fig. 6.6, is constant within uncertainty, but there is a decrease in width with the increase of D^0 meson p_T as observed in Fig. 6.6(c). This may be due to more collimation of particles in the near-side jet as one increases the D^0 meson p_T . The base line is constant within the systematic uncertainty.

The associated yield and width of near-side, and away-side for pp collisions at $\sqrt{s} = 13$ TeV for different kinematic ranges are shown in Fig. 6.8, 6.9, 6.10, 6.11, 6.12, respectively. It is evident from Fig. 6.8 and Fig. 6.9 that the near-side yield increases with the increase of D meson p_T , whereas the near-side width is constant within the uncertainty. The away-side

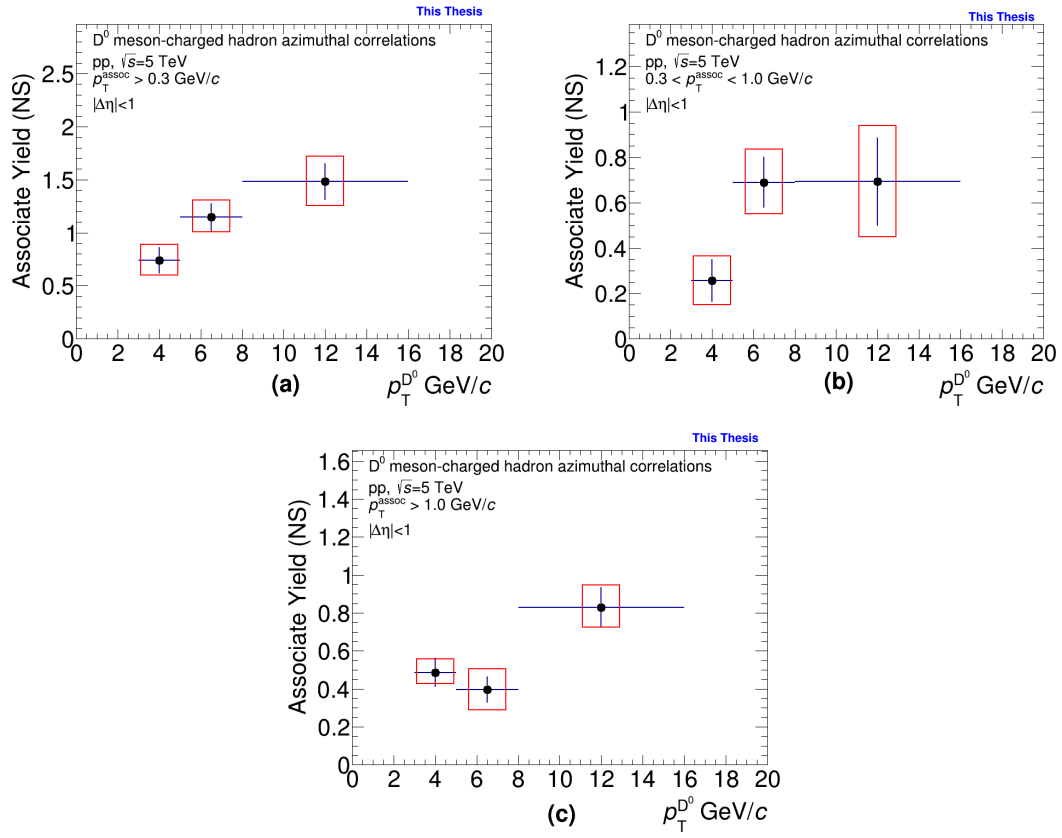


Figure 6.5: [pp, $\sqrt{s} = 5$ TeV] Near-side yield as a function of $p_T^{D^0}$ for kinematic ranges: a) $p_T^{assoc} > 0.3$ GeV/c, b) $0.3 < p_T^{assoc} < 1.0$ GeV/c, c) $p_T^{assoc} > 1.0$ GeV/c.

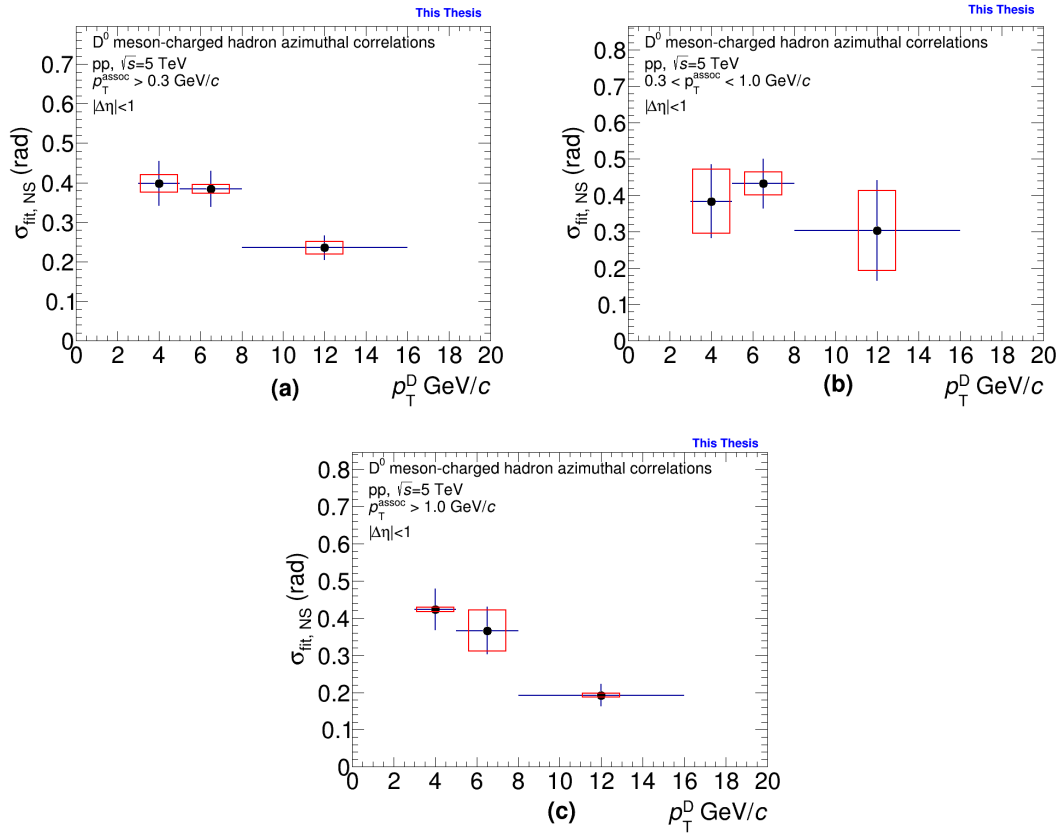


Figure 6.6: [pp, $\sqrt{s} = 5$ TeV] Near-side width as a function of $p_T^{D^0}$ for kinematic ranges: a) $p_T^{\text{assoc}} > 0.3$ GeV/c, b) $0.3 < p_T^{\text{assoc}} < 1.0$ GeV/c, c) $p_T^{\text{assoc}} > 1.0$ GeV/c.

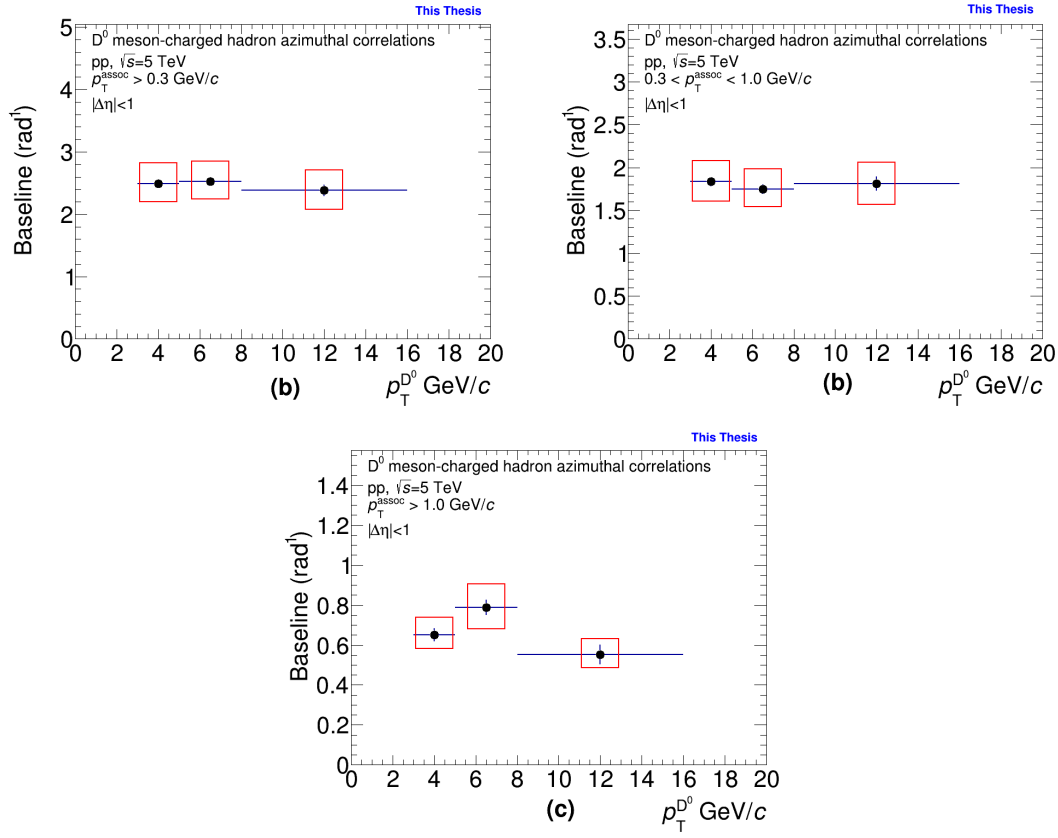


Figure 6.7: [pp, $\sqrt{s} = 5$ TeV] Baseline fit as a function $p_T^{D^0}$ for kinematic ranges: a) $p_T^{\text{assoc}} > 0.3$ GeV/c, b) $0.3 < p_T^{\text{assoc}} < 1.0$ GeV/c, c) $p_T^{\text{assoc}} > 1.0$ GeV/c.

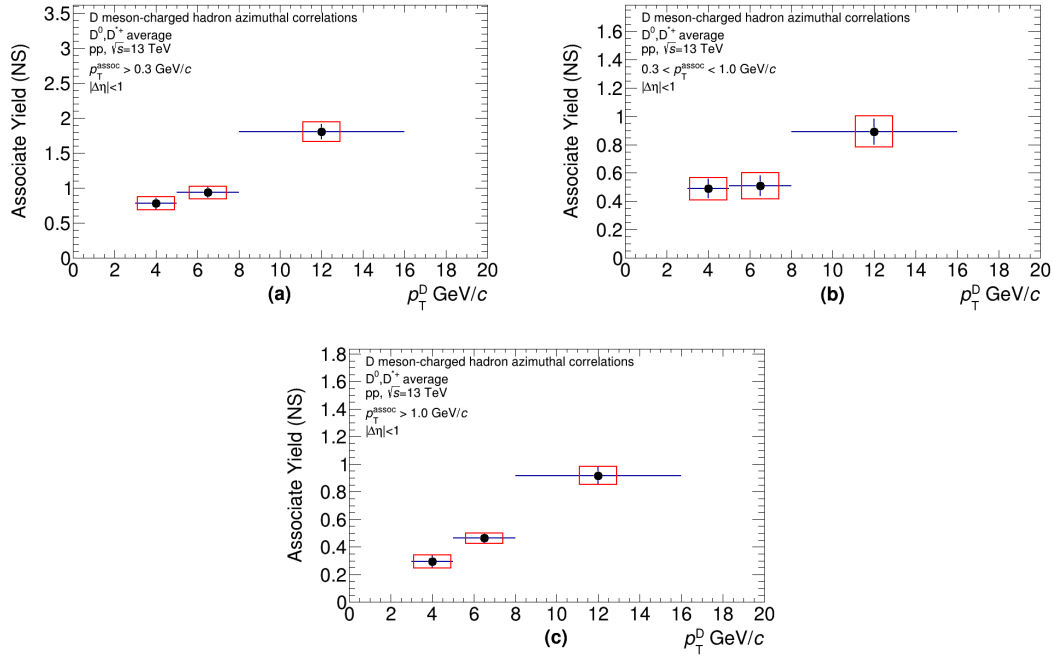


Figure 6.8: [pp, $\sqrt{s} = 13$ TeV] Near-side yield as a function of p_T^D for kinematic ranges: a) $p_T^{\text{assoc}} > 0.3$ GeV/c, b) $0.3 < p_T^{\text{assoc}} < 1.0$ GeV/c, c) $p_T^{\text{assoc}} > 1.0$ GeV/c.

associated yield shows an increasing trend and away-side width shows a decreasing trend with the increase of D meson p_T . The height of the baseline of the average correlation distributions for pp collisions at $\sqrt{s} = 13$ TeV, shown in Fig. 6.12, is constant for all the D meson p_T . The height of the baseline decreases with the increase of associated track p_T (p_T^{assoc}).

The systematic uncertainties of the considered observables from the variation of fit procedure (which is not the full uncertainty) for each kinematic ranges are shown in Figure 6.13, 6.14, 6.15, 6.16, 6.17, respectively.

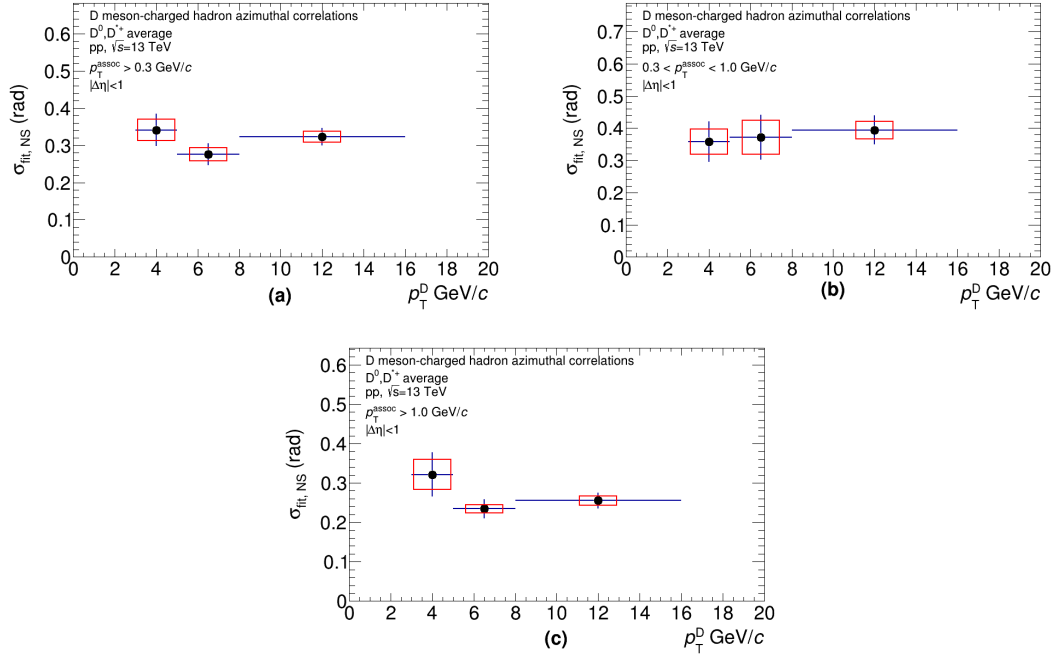


Figure 6.9: [pp, $\sqrt{s} = 13$ TeV] Near-side width as a function of p_T^D for kinematic ranges: a) $p_T^{\text{assoc}} > 0.3$ GeV/c, b) $0.3 < p_T^{\text{assoc}} < 1.0$ GeV/c, c) $p_T^{\text{assoc}} > 1.0$ GeV/c.

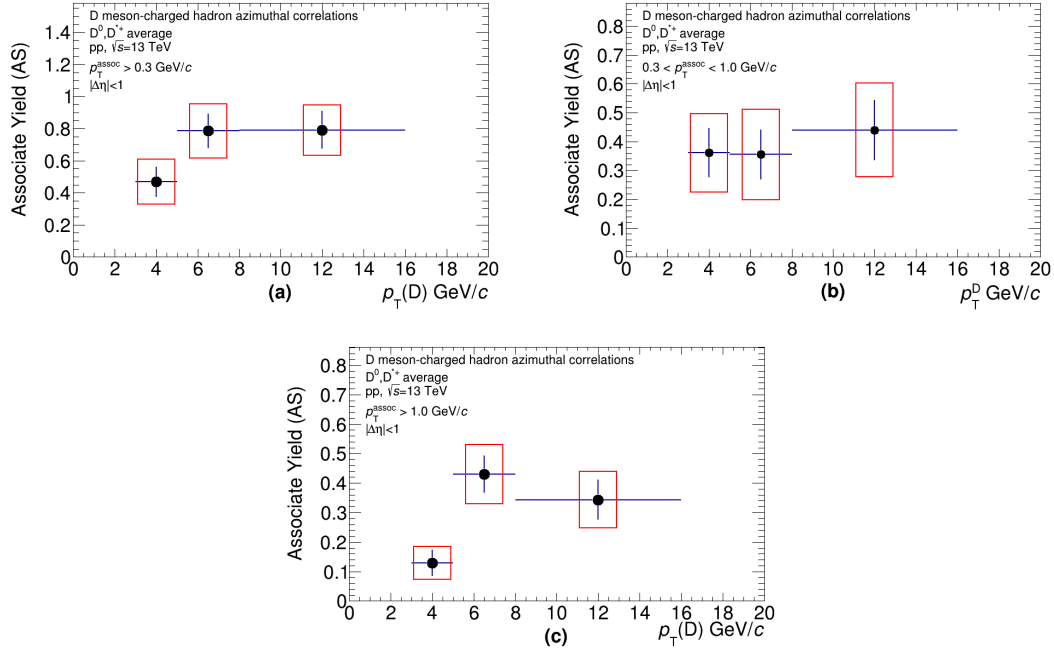


Figure 6.10: [pp, $\sqrt{s} = 13$ TeV] Away-side yield as a function of p_T^D for kinematic ranges: a) $p_T^{\text{assoc}} > 0.3$ GeV/c, b) $0.3 < p_T^{\text{assoc}} < 1.0$ GeV/c, c) $p_T^{\text{assoc}} > 1.0$ GeV/c.

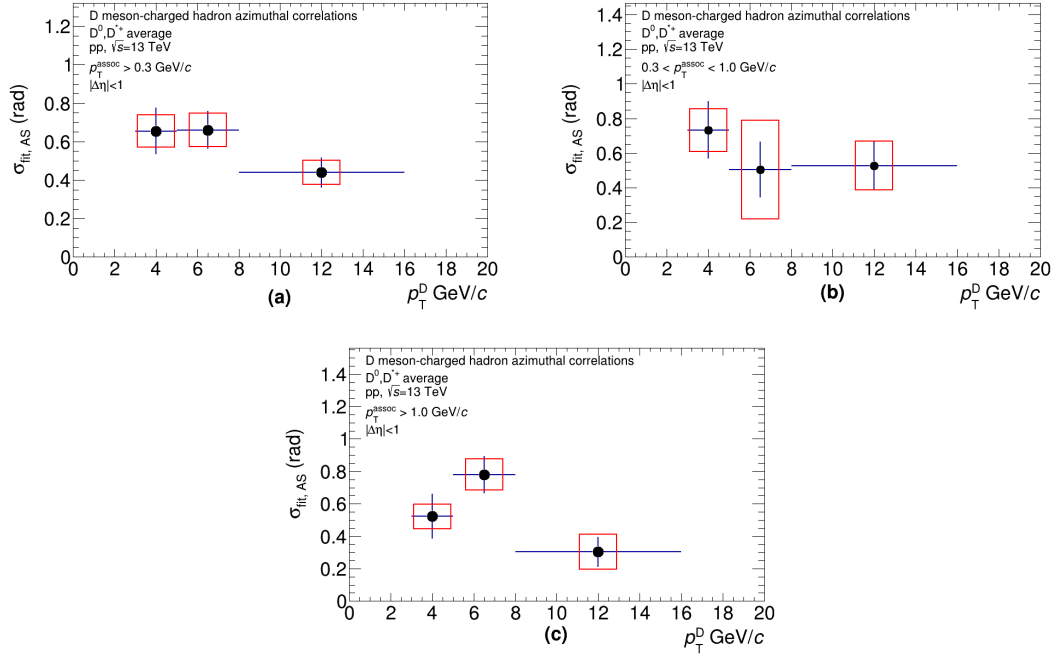


Figure 6.11: [pp , $\sqrt{s} = 13$ TeV] Away-side width as a function of p_T^D for kinematic ranges: a) $p_T^{assoc} > 0.3$ GeV/c, b) $0.3 < p_T^{assoc} < 1.0$ GeV/c, c) $p_T^{assoc} > 1.0$ GeV/c.

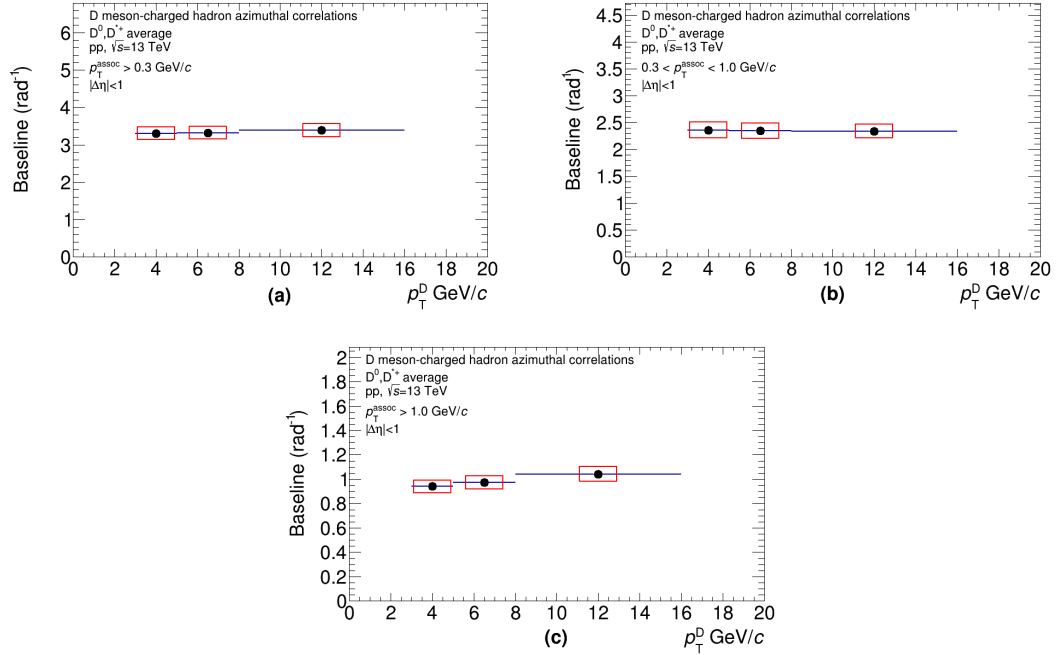


Figure 6.12: [pp , $\sqrt{s} = 13$ TeV] Baseline fit as a function p_T^D for kinematic ranges: a) $p_T^{assoc} > 0.3$ GeV/c, b) $0.3 < p_T^{assoc} < 1.0$ GeV/c, c) $p_T^{assoc} > 1.0$ GeV/c.

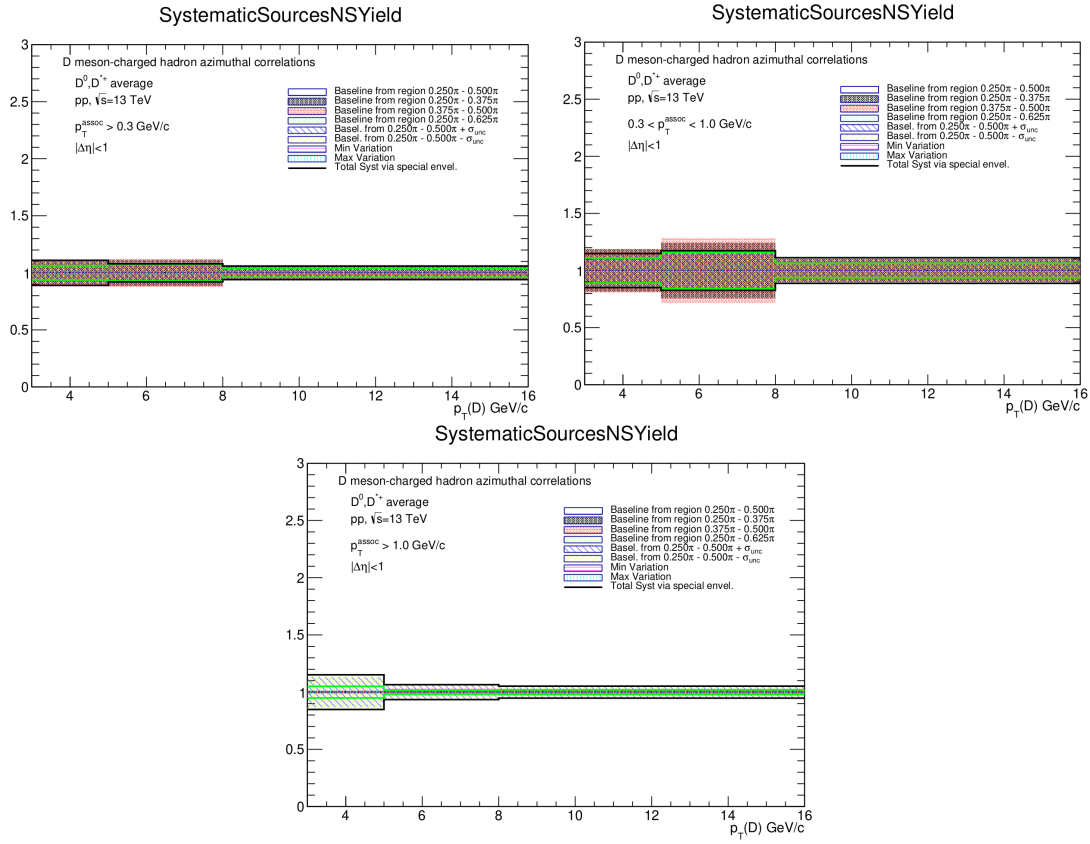


Figure 6.13: [$pp, \sqrt{s} = 13$ TeV] Systematic uncertainties of near-side yield coming from variation of fit procedure for different kinematic ranges in pp collision at $\sqrt{s} = 13$ TeV.

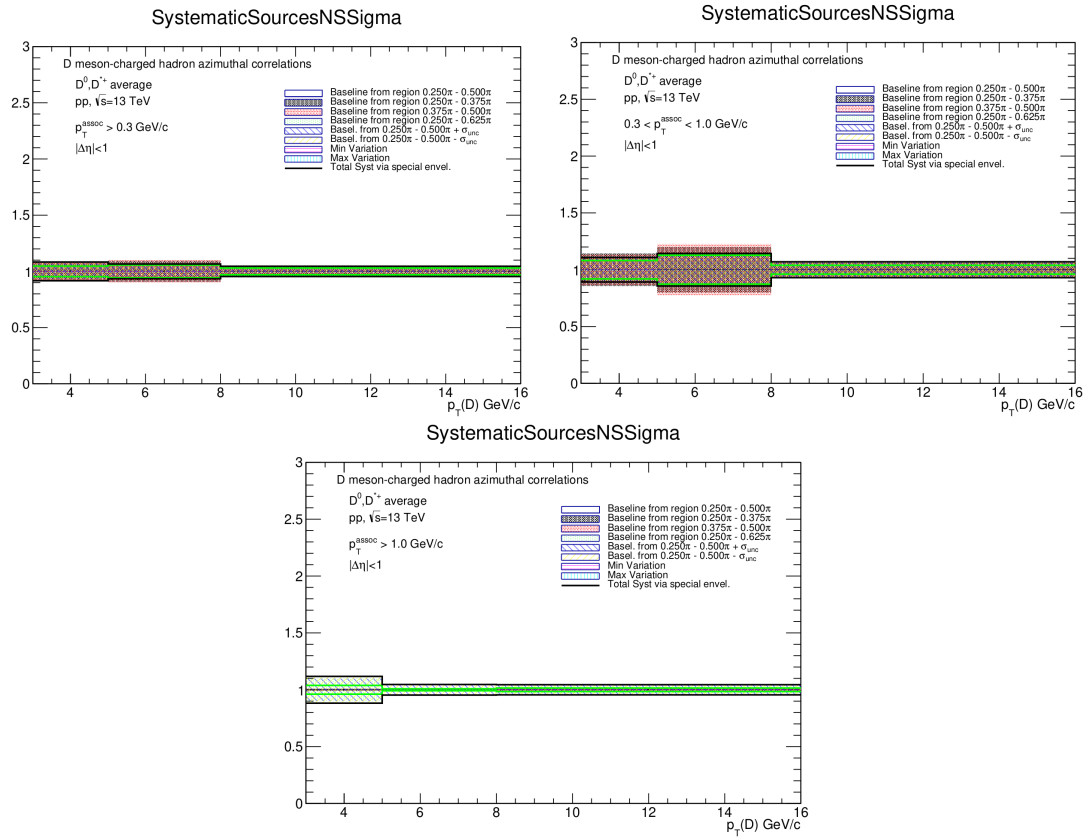


Figure 6.14: [$pp, \sqrt{s} = 13$ TeV] Systematic uncertainties of near-side sigma width from variation of fit procedure for different kinematic ranges in pp collision at $\sqrt{s} = 13$ TeV.

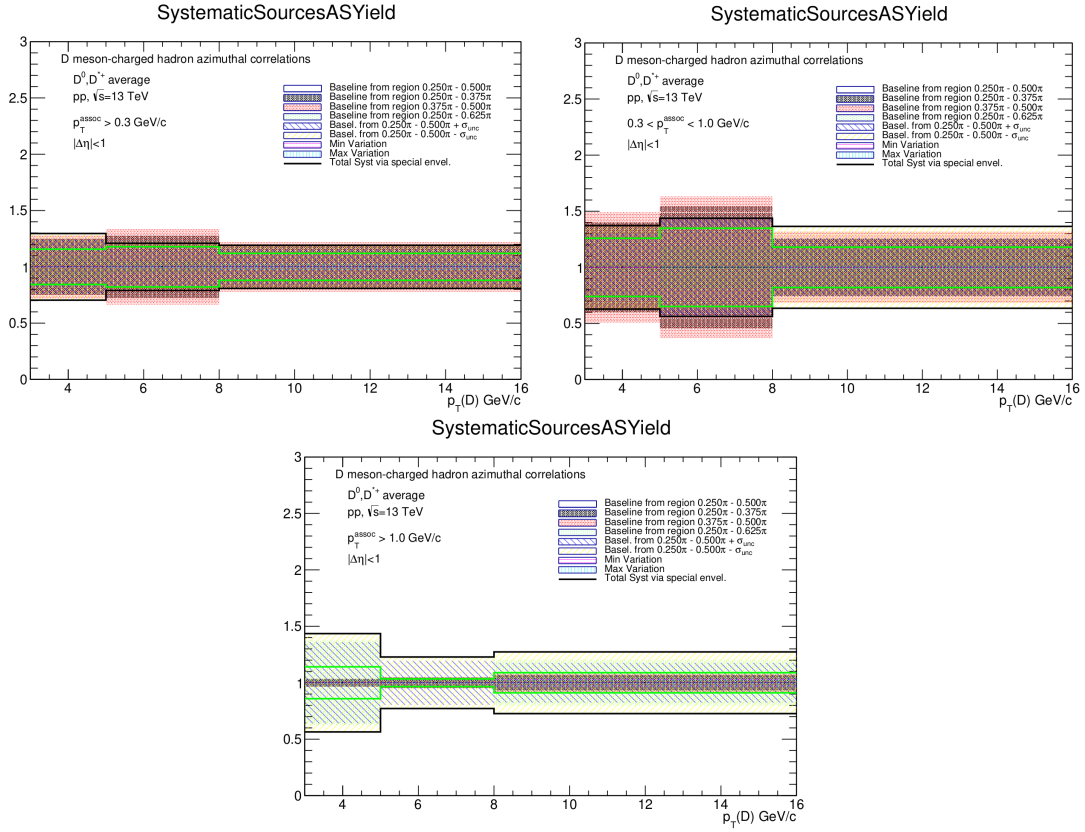


Figure 6.15: [$pp, \sqrt{s} = 13$ TeV] Systematic uncertainties of away-side yield coming from variation of fit procedure for different kinematic ranges in pp collision at $\sqrt{s} = 13$ TeV.

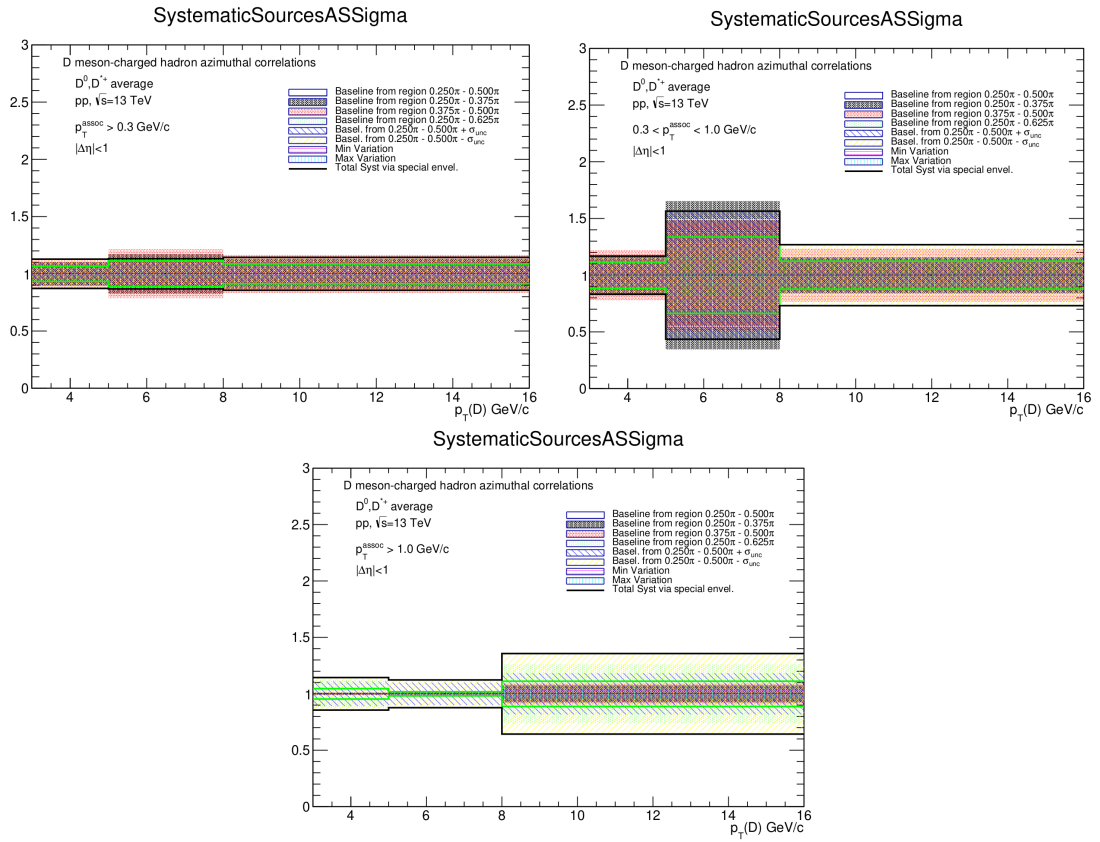


Figure 6.16: [pp, $\sqrt{s} = 13$ TeV] Systematic uncertainties of away-side sigma width from variation of fit procedure for different kinematic ranges in pp collisions at $\sqrt{s} = 13$ TeV.

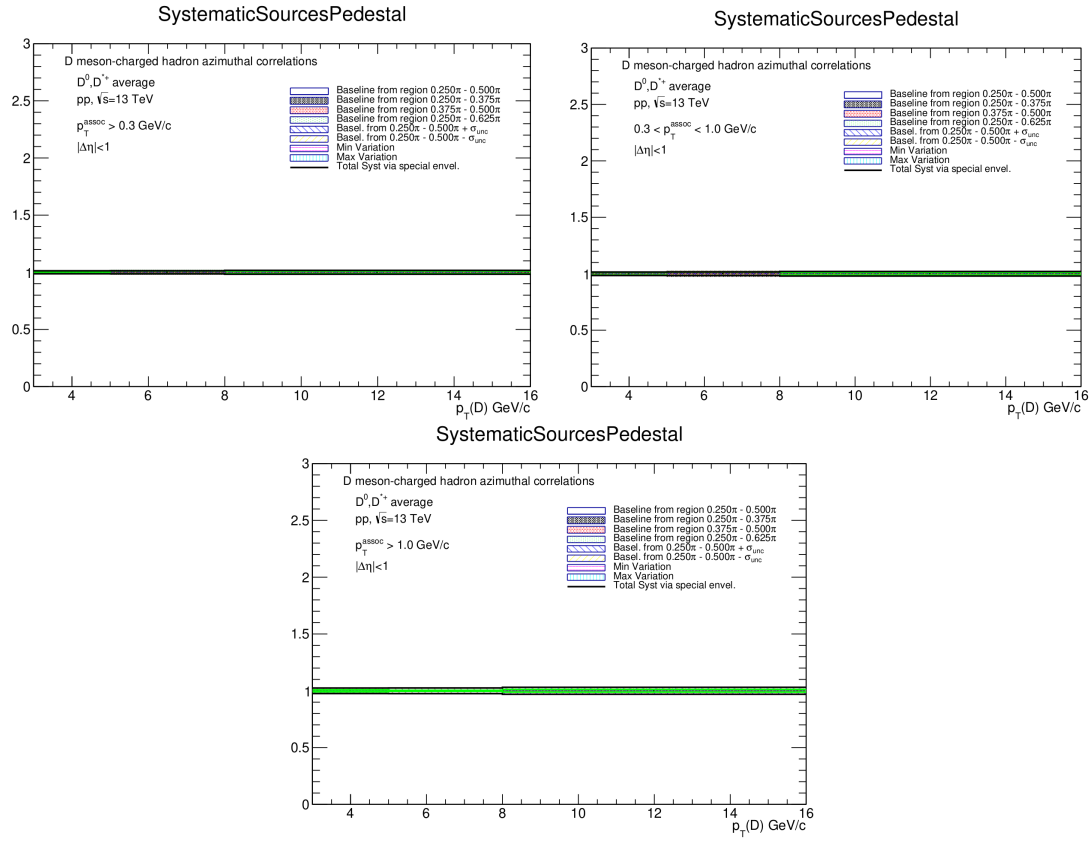


Figure 6.17: [pp, $\sqrt{s} = 13$ TeV] Systematic uncertainties of baseline height coming from variation of fit procedure for different kinematic ranges in pp collisions at $\sqrt{s} = 13$ TeV.

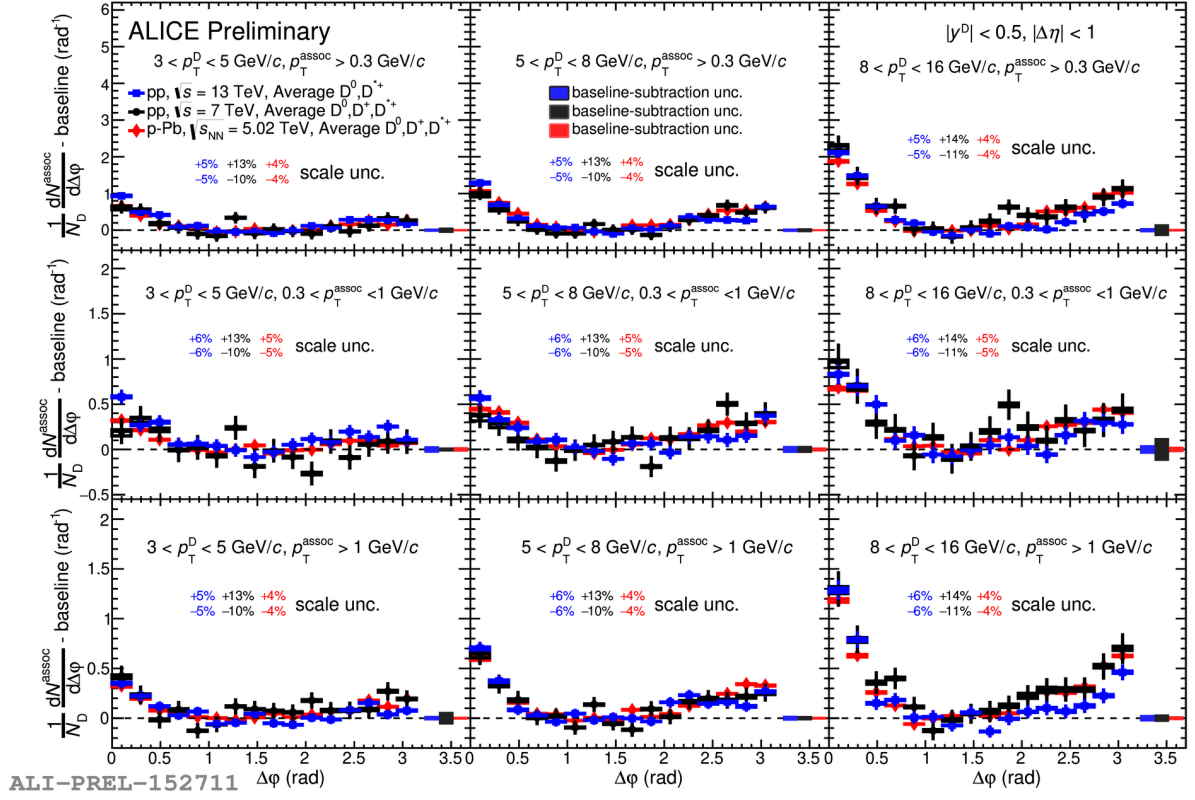


Figure 6.18: Comparison of $\Delta\phi$ correlation distributions of D mesons with charged particles in pp and p-Pb collisions after baseline subtraction, for different kinematic ranges.

6.1.4 Comparison of results among pp 7 TeV, 13 TeV and pPb 5.02

In Fig.6.18 comparison of $\Delta\phi$ correlation distributions of D mesons with charged particles in pp collisions (7 TeV [74], 13 TeV) and p-Pb collisions (5.02 TeV [74]) after baseline subtraction for different kinematic ranges are shown. The blue points, black points, and red points represent correlation distributions obtained from pp collisions at 13 TeV and 7 TeV, and p-Pb collisions at 5.02 TeV, respectively. The distributions are showing similar trend and compatible within uncertainties for all the kinematic ranges.

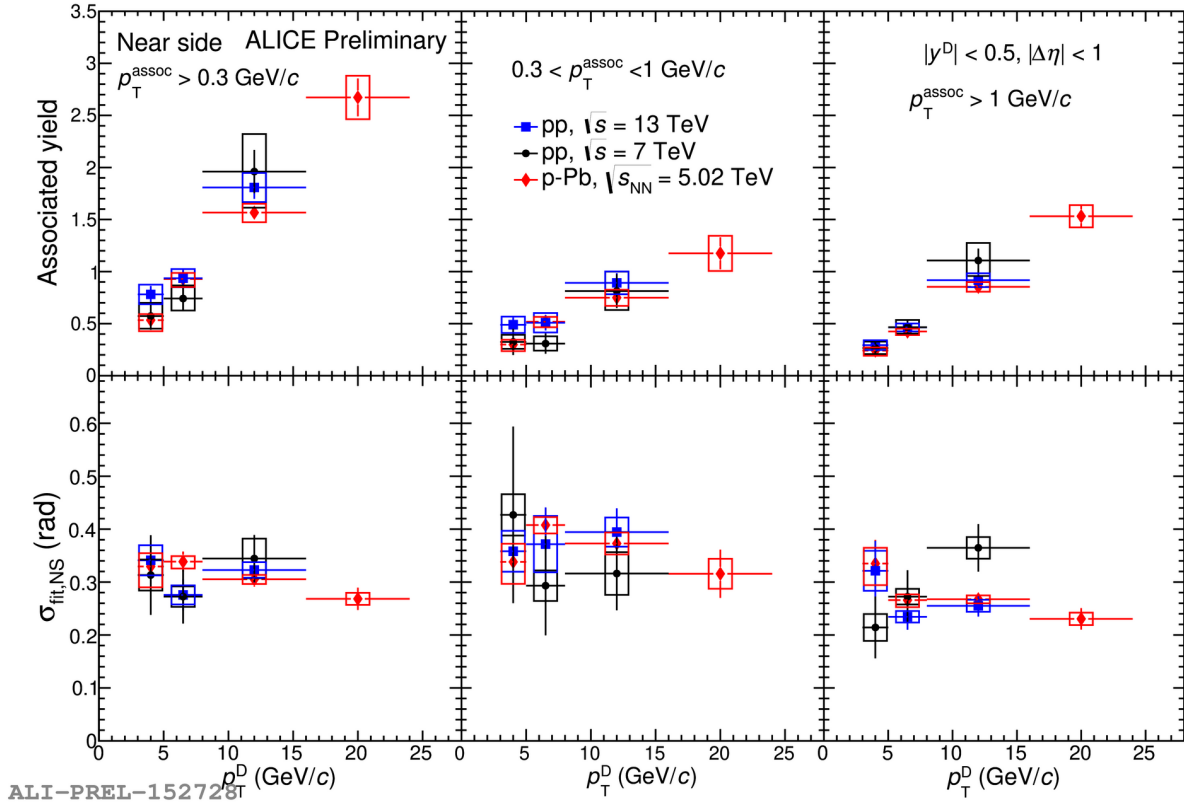


Figure 6.19: Comparison of near-side peak associated yield and near-side peak width in pp and p–Pb collisions for different kinematic ranges.

The comparison of near-side associate yield and width in pp collisions (7 TeV, 13 TeV) and p–Pb collisions (5.02 TeV) are shown in Fig. 6.19. In this plot, blue points represent the results for pp collisions at 13 TeV, black points are for pp collisions at 7 TeV and red points are for p–Pb collisions at 5.02 TeV for all kinematic ranges. The near-side associated yield increases with the increase of D meson p_T and the width is constant within the uncertainty. The distributions look compatible among the systems within uncertainties for all the kinematic ranges.

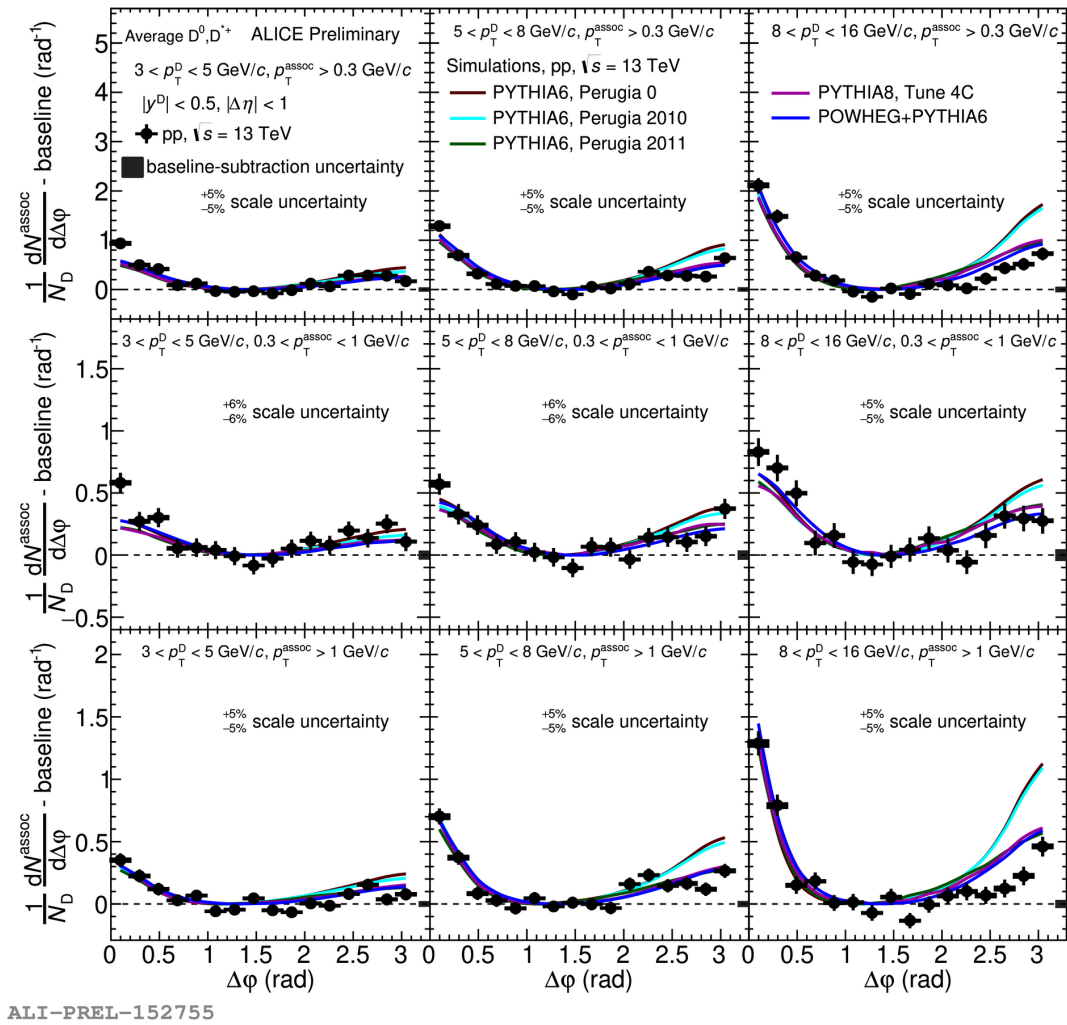


Figure 6.20: Comparison of $\Delta\varphi$ correlations distributions in pp collision with expectations from Monte Carlo simulations performed with different event generators after the baseline subtraction.

6.1.5 Comparison with models

In Fig.6.20, the $\Delta\varphi$ correlations distributions after the baseline subtraction measured in pp collisions at 13 TeV are compared with results from different Monte Carlo event generators. The models reproduce the data well on the near-side. On the away-side, POWHEG+PYTHIA6 and PYTHIA8 [96] are closer to the data than PYTHIA6 [97]. In Fig.6.20, PYTHIA6 is overestimating the away-side due to its only Leading Order (LO) contributions.

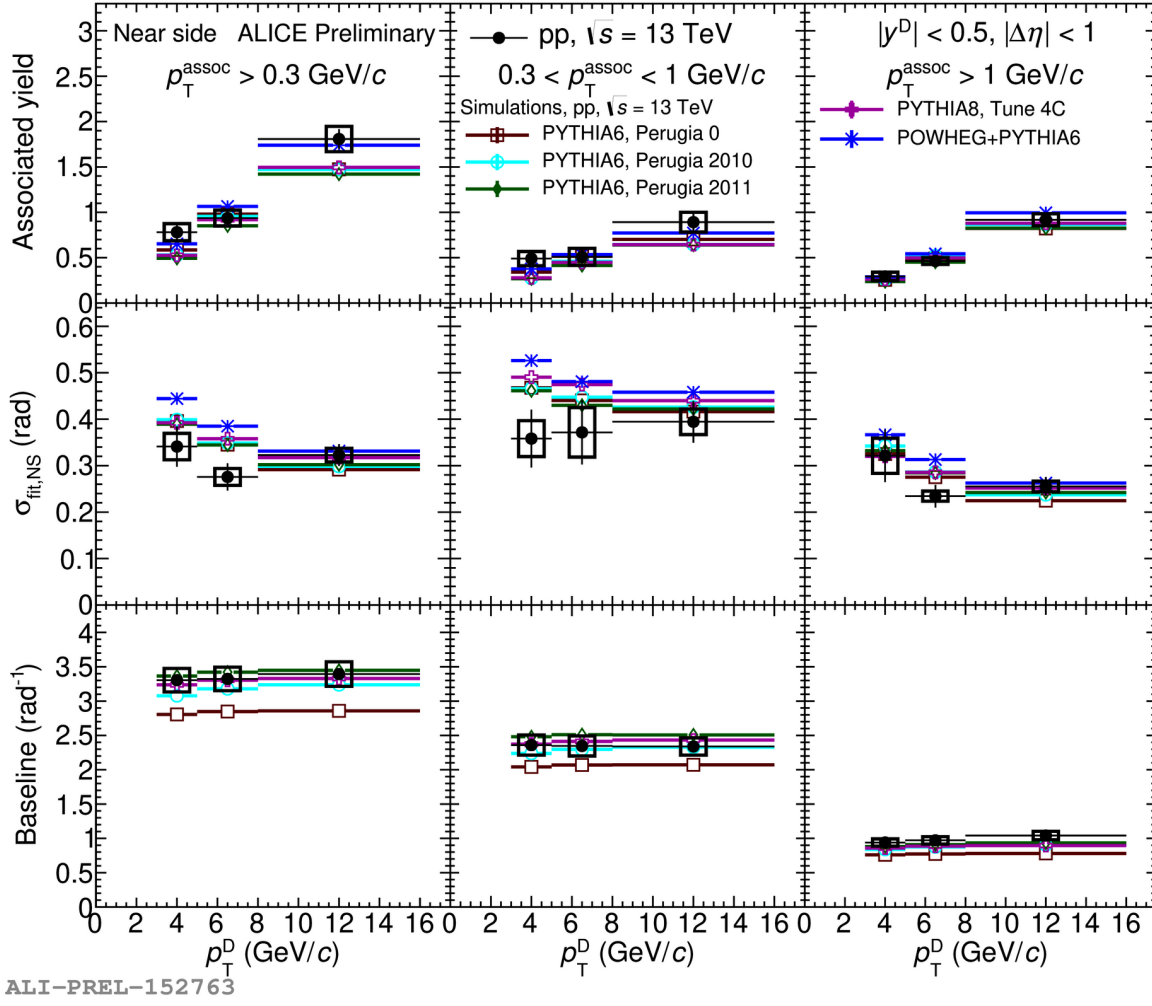


Figure 6.21: Comparison of near-side peak associated yield (top row), near-side peak width (middle row) and baseline (bottom row) values measured in pp collisions with the expectations from different Monte Carlo event generators.

In Fig. 6.21, the near-side yield, width and baseline are compared with the expectations from Monte Carlo simulations using different event generators. The baseline is decreasing with the increase of associated track p_T threshold. The results are compatible within uncertainties for all the kinematic ranges.

Chapter 7

Summary

"The greatest value of a picture is when it forces us to notice what we never expected to see."

–John Tukey

In this Thesis, measurements of azimuthal correlation of D^0 meson with charged particles in pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV have been carried out. The measurement is done in three D^0 meson p_T ranges, i.e. $3 \leq p_T^{D^0} < 5$ GeV/c, $5 \leq p_T^{D^0} < 8$ GeV/c, $8 \leq p_T^{D^0} < 16$ GeV/c, with different associated particles p_T threshold, i.e. $p_T^{\text{assoc}} > 0.3$ GeV/c, $0.3 \leq p_T^{\text{assoc}} \leq 1.0$ GeV/c and $p_T^{\text{assoc}} > 1.0$ GeV/c. The near-side observables like near-side associated yield and width, which give the information about the multiplicity and angular spread of particles from the fragmentation of charm jet, are calculated both for pp collisions at $\sqrt{s} = 5$ TeV and 13 TeV. The away-side observables are more related to the harmonization of charm quark produced in the opposite direction. The away-side associated yield and width are also calculated only for pp collisions at $\sqrt{s} = 13$ TeV and not calculated for pp collisions at $\sqrt{s} = 5$ TeV due to large statistical fluctuation. The baseline has been estimated for both the collision systems and it gives the information about underlying event multiplicity. The study of azimuthal correlation of D^{*+} meson with charged particles in pp collisions at $\sqrt{s} = 13$ TeV has also been carried out in ALICE experiment. In order to reduce the overall uncertainties, a weighted average of the azimuthal correlation distributions of the two D mesons (D^0 , D^{*+}) has been calculated. The final average correlation distribution obtained for pp collisions at $\sqrt{s} = 13$ TeV are compared

with the results of pp collisions at 7 TeV and p–Pb collisions at 5.02 TeV. The distributions are showing similar trend and compatible within uncertainties for all the kinematic ranges. The $\Delta\varphi$ correlations distributions after the baseline subtraction measured in pp collisions at 13 TeV are compared with the expectations from different Monte Carlo event generators. The models agree with the data well on the near-side.

7.1 Future prospects

The azimuthal correlation measurement in high multiplicity pp collisions at $\sqrt{s} = 13$ TeV as a function of multiplicity can allow us to explore the long-range correlations. The LHC Run 3 data set will allow us to perform this study with better precision and in different event multiplicity classes due to higher luminosity and the improved performance on the D-mesons reconstruction. The upgraded ITS detector based on CMOS monolithic active pixel sensor (MAPS) will help us to measure the heavy-flavor hadrons with better precision to nearly zero p_T . This measurement in Pb–Pb collisions can help us to study the path-length dependence of heavy-quark energy loss and disentangle the contributions from collisional and radiative energy loss mechanisms.

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