

**Measurement of azimuthal correlations of D^+ mesons
with charged particles in pp collisions at $\sqrt{s} = 7$ TeV
and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE at
the LHC**

A thesis submitted in partial fulfilment of
the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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Under the guidance of
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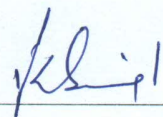
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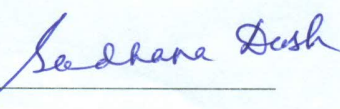


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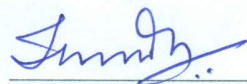
Thesis entitled **Measurement of azimuthal correlations of D^+ mesons with charged particles in pp collisions at $\sqrt{s} = 7$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE at the LHC** by **Jitendra Kumar** (Roll No. 09i12009) is approved for the degree of Doctor of Philosophy.

Examiners

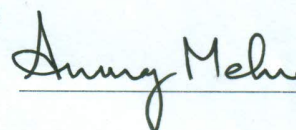
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Declaration of Academic Integrity

Hereby I declare that the thesis on "**Measurement of azimuthal correlations of D^+ mesons with charged particles in pp collisions at $\sqrt{s} = 7$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE at the LHC**" is solely my ideas in my own words and if any text passages or diagrams from books, papers, the Web or other sources have been taken or in any other way used, all references – including those found in electronic media – have been acknowledged and fully cited. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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*Dedicated to
My Family*

Abstract

ALICE (A Large Ion Collider Experiment) was designed for the study of heavy-ion collisions at the LHC. It is now established that in these collisions a state of matter consisting of deconfined quarks and gluons, Quark-Gluon Plasma (QGP), is formed. The QGP appears as the hottest and almost lowest-viscosity liquid ever observed. While the experiments at LHC and at RHIC have unravelled a lot of its properties, one still does not have a complete picture. One of the ways of exploring the properties of the QGP would be to perform Rutherford scattering experiments with well-defined probes. One can use hard scattering processes as sources of strongly-interacting probes. Then by comparing particle production rates in ion-ion collisions to that in proton-proton collisions, one can gain insight into the properties of the medium. There are several ways by which one can learn about medium properties, for example, measurement of two particle correlations distribution and their properties such as, yield I_{AA} , defined as the ratio of per correlation yields Y , measured in heavy-ion to that observed in pp collisions.

Two particle angular correlations have been extensively used to study the properties of the deconfined matter created in ultra relativistic collisions at RHIC and LHC. Building correlations with heavy-flavour particle having a mass greater than Λ_{QCD} has the advantage that their production is controlled by perturbative QCD and they are produced in the initial stages of the collision. Hence they experience the full evolution of the fire ball and are therefore ideal probes to determine the properties of the medium formed in heavy-ion collisions. Further, they provide insight into the energy loss mechanism of heavy quarks a topic of current interest. In this thesis work, we have measured the angular correlations between D^+ meson (trigger particles) and associated charged particles in pp and p-Pb collisions with the ALICE detector.

The measurements in pp collisions can provide insight into the production of heavy flavour particles and also provides a necessary reference for the heavy-ion measurements. To understand the complete picture of energy loss mechanism in heavy-ion collisions, one needs to understand cold nuclear matter (CNM) effects in the initial and final states of the collisions. Therefore, the study of D^+ meson angular correlations in p-Pb collisions may shed light on the underlying production mechanisms that give rise to the double-ridge structure observed in high multiplicity p-Pb collisions with di-hadron correlations (light-flavour sector).

The correlations distribution have been studied using D^+ meson as trigger particle in three p_T ranges from 3–5 GeV/ c , 5–8 GeV/ c and 8–16 GeV/ c and with associated charged particles having p_T greater than 0.3 GeV/ c , between 0.3 to 1.0 GeV/ c and finally with p_T greater than 1 GeV/ c . The similar correlation measurements using other D mesons (D^0 and D^{*+}) as trigger particles have also been performed by the ALICE collaboration and to improve the statistical precision on the results, average correlations from three (D^+ , D^0 and D^{*+}) measurements have been evaluated. The correlation properties of the averaged distributions have been then extracted and studied as a function of trigger p_T^D . Finally, correlation distributions are compared with simulations using different event generators and their tunes, e.g. PYTHIA, POWHEG+PYTHIA and EPOS.

This thesis work is first ever measurement of azimuthal correlations between D mesons and charged particles performed using minimum bias proton-proton collisions at $\sqrt{s} = 7$ TeV and proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV collected by ALICE experiment in 2010 and 2013 respectively.

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Chapter 1

Introduction

“It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are, If it doesn’t agree with experiment, it is wrong...”

— Richard Phillips Feynman

abstract: This chapter first describes the standard model and Quantum Chromodynamics (QCD). The physics of Quark Gluon Plasma (QGP) and recent results from different experiments at RHIC and LHC are discussed in the next sections. Finally, the importance of heavy-flavour physics and two particle correlations as a tool to study high-energy collision physics is also discussed in detail.

The universe is made up of fundamental constituents of matter and the **high energy particle physics** studies these fundamental constituents in a way; “how they interact with each other”. These constituents are governed by four fundamental forces viz. Weak force, Strong force, Electromagnetic force and Gravitational force having different ranges and strengths.

The Standard Model (SM) [1, 2] is a well tested theoretical framework which describes the properties of fundamental particles and their mutual interactions. The SM consists of twelve basic building blocks or the fundamental particles [3] called “fermions” which interact via well known fundamental forces. Except Gravitational, all three fundamental forces, i.e. Strong, Electromagnetic and Weak, are included into the SM. Each force has its own corresponding force carrier characterised as “gauge boson”, which is responsible for the interaction between particles and transfer of discrete amount of energy by exchange of carriers. The SM groups all the twelve “fermions” and five “gauge bosons” into four different categories named as, quarks, leptons, gauge bosons and the Higgs boson. Fermions are further classified into three stages of generations depending upon their masses and properties. The first generation includes the particles those are responsible for lightest

and most stable matter, whereas, heavier and less stable matter is incorporated by second and third generation of particles. This classification is also summarised in Figure 1.1.

- **Quarks:** The quarks are found in six different flavours: up (u), down (d), charm (c), strange (s), top (t) and bottom (b) and they exist in three primary colours: Red, Blue and Green. Each and every quark also has corresponding antiquark, which differs by opposite charge only. In nature, the quarks and gluons appear in colourless form therefore they only mix in such a way that they form colourless objects known as hadrons. For example, a combination of three coloured quarks (“baryons”, e.g. protons and neutrons) or a pair of quark-antiquark (“mesons”, e.g. J/ψ) can produce colourless particles. The up (u) and down (d) quarks lie in the first generation, charm (c) and strange (s) belongs to the second and top (t) and bottom (b) to the third generation.
- **Leptons:** The three leptons; electron (e), muon (μ) and tau (τ), are also arranged in three generations along their respective neutrinos (i.e. ν_e , ν_μ and ν_τ). Similar to quarks, all leptons and neutrinos also have corresponding antileptons and antineutrinos respectively.
- **Force carrier (gauge boson):** The strong interaction is the strongest of all four fundamental interactions and mediated by exchange of gluons (g , mass, $m=0$) whereas the electromagnetic interactions by photons (γ , $m=0$) and weak interactions by $W^\pm$ ($m \sim 80.38 \text{ GeV}^2$) and Z^0 ($m \sim 91.18 \text{ GeV}^2$) bosons. For example, the quarks and gluons that carry colour charge, a strong nuclear force is responsible to bind them together in neutrons and protons.
- **Higgs boson:** Higgs boson is also a gauge boson, which provides mass to all the particles incorporated in SM and it’s discovery in July, 2012 at the LHC has validated the SM [4].

Although SM is a well tested theoretical model which describes all the physics phenomena involving elementary particles at different energy scales and reproduces all the experimental physics results, but it fails to answer many open questions such as, weakness of gravitational force, massive neutrinos and their oscillations, matter-antimatter asymmetry etc.

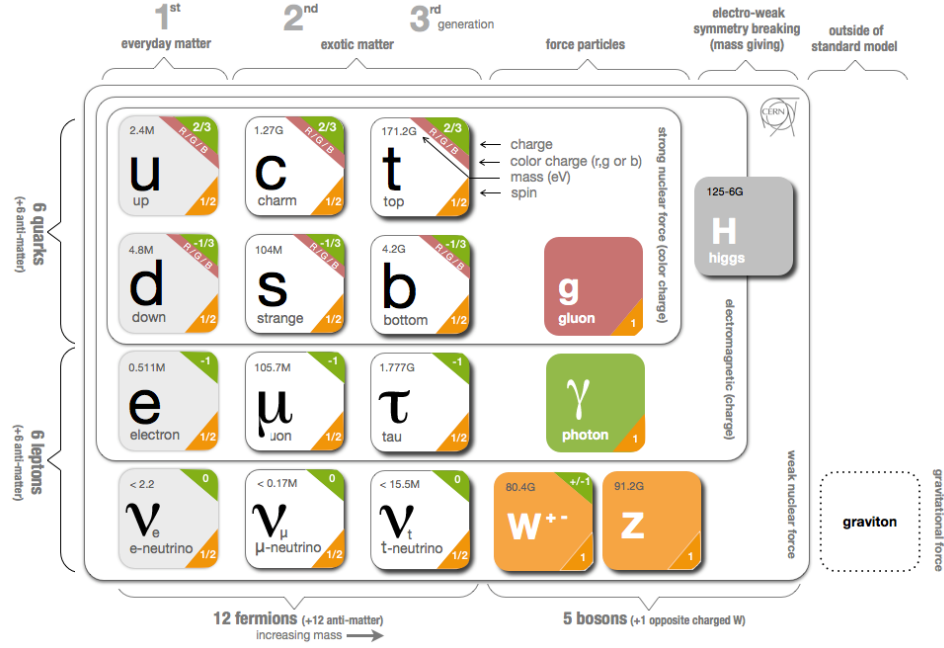


Fig. 1.1: Schematic view of fundamental particles in Standard Model. [source: \[3\]](#)

1.1 Quantum Chromodynamics (QCD)

QCD is one of the pillars of standard model and successfully describes physical processes involving large momentum transfer. It is a gauge theory of the strong interaction, which explains the properties of quarks, gluons and how they interact with each other. The strong force is an extremely short-range (order of ~ 1 fm) and is 100 times stronger in strength than the electromagnetic force. The force is described by a local, non-abelian $SU(3)$ gauge symmetry and the Lagrangian for the QCD is written as:

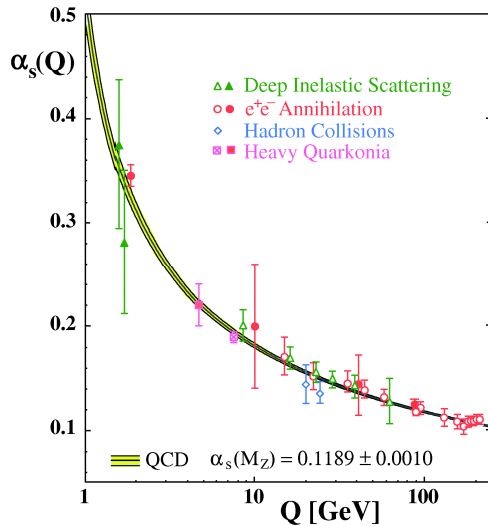
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^\alpha F_{\alpha}^{\mu\nu} + \sum_f \bar{\psi}_{\alpha,i,f} i\gamma^\mu [\delta_{ij}\partial_\mu - ig(A_\mu^\alpha t_\alpha)_{ij}] \psi_{\alpha,j,f} - \sum_f m_{\alpha,i,f} \bar{\psi}_{\alpha,i,f} \psi_{\alpha,i,f} \quad (1.1)$$

The definition of above Lagrangian $\mathcal{L}$ is based on the underlying symmetries for e.g. Poincare invariance, local colour gauge invariance and the flavour symmetries. One can say that it is constructed with Field content, Gauge invariance and the dynamics of gluons. The quark, anti-quark and gluons fields are represented by $\psi_{\alpha,i,f}(x)$, $\bar{\psi}_{\alpha,i,f}(x)$, and A_μ^α , respectively. The quark fields are Dirac spinors ($\alpha = 1, 2, 3, 4$ are functions of space-time) and transform under $SU(3)$ (with colour index i ; 1, 2 and 3 OR red, blue and green), the label f is an index for the flavour quantum number. The gluon fields A_μ^α are Lorentz vectors

and each generator t_a of the group is associated with one field. The Gauge invariance term $\bar{\psi}(iD_\mu - m)\psi$ ($D_\mu = \partial_\mu - igA_\mu^\alpha t_a$) is a fermion Lagrangian constructed from the quark fields, and is invariant under SU(3) transformation. The factor g is derived from the strong coupling constant $4\pi\alpha_s$. Finally, the term $F_{\mu\nu}$ is a kinematic term that explains the gluon dynamics, here gluon field strength tensor is defined by the commutator of two covariant derivatives. The main and more complicated difference between the QED and the QCD Lagrangian is that the gluon field tensor in QCD contains an additional term which represents the interaction between the colour-charged gluons. Gluons are not only colour-charged, but they also produce very strong colour fields. These interactions are responsible for many unique features of QCD, such as asymptotic freedom, colour confinement and chiral symmetry breaking.

Running coupling constant

The coupling strength of strong interaction is defined in terms of a running coupling constant α_s which is analogous to the fine structure constant α in QED. The α_s determines the strength of interaction between the quarks and the gluons. It is called a running coupling constant as its strength can be seen from the expression below and strongly depends on the square of momentum transfer. The theory possess some peculiar properties, such as; asymptotic freedom, colour confinement and chiral symmetry breaking.



$$\alpha(Q^2) \equiv \frac{g_s(Q^2)}{4\pi} = \frac{4\pi}{(11 - \frac{2}{3}n_f)\ln\frac{Q^2}{\Lambda_{\text{QCD}}^2}} \quad (1.2)$$

g_s = QCD coupling constant,
 n_f = number of quarks,

Q^2 = momentum transferred in strong interaction,
 Λ_{QCD} = QCD scale parameter, expected value is ≈ 250 MeV.

Fig. 1.2: Behaviour of QCD α_s as a function of the momentum transfer Q . source: [5]

- **Asymptotic freedom:** As the quarks or gluons within hadrons (such as baryons and mesons) come closer to each other, or at large momentum transfer ($Q^2 \rightarrow 0$, also running scale), the α_s becomes small (~ 0) as shown in Eq. 1.2. Therefore, the strength

of strong interaction diminishes at short distances and this strange behaviour of α_s has been precisely verified by various high-energy experiments as shown in Figure 1.2. In other words, the force between the constituents becomes weaker such that it asymptotically approaches zero for the confinement. This is actually opposite to QED α_{QED} , which becomes a strongly-coupled theory at very short distance scale and also explains that the quarks at short distance are contained in a “bag” and move freely inside the hadrons. On the other hand, at large distances same force becomes strong enough to bind the quarks within nucleus to prevent their isolation [6]. Because of asymptotic freedom feature in large momentum transfer region one can calculate the strong interaction physics in the perturbation theory which is an exact theory and has been tested by the experiments extensively [7]. The running coupling introduces a Λ_{QCD} dimensional scale parameter, which sets the scale at which α_s becomes large and the strong interaction physics becomes non-perturbative. In the Minimal subtraction scheme with 3 quark flavours, it’s value is around 250 MeV.

- **Quark confinement:** This is one of the prominent QCD feature at low-energy or momentum transfer which says that any strongly interacting system at temperature and density both equal to zero, must be a colour singlet at distance scale $> 1/\Lambda_{QCD}$. It explains the fact that the quarks can never be isolated because as the distance increases or the momentum transfer becomes small, the coupling constant diverges, which implies that the colour force of quarks does not drop off with increase in distance but increases significantly. As a consequence, isolated free quarks cannot exist in nature and on the other hand, the amount of energy required to separate an isolated quark becomes much higher than the pair production energy of quark-antiquark pair, which results in creation of new quark-antiquark pairs instead of it’s separation. These quarks (also known as “sea-quarks”) then combine to form hadrons and the phenomena therefore leads to the creation of particle spray, also known as “jet” in the relativistic high energy collisions¹. To fully understand this feature, one must calculate QCD at large distance scales where α_s becomes very strong but unfortunately these calculations are very difficult. QCD explains physical processes in the high momentum transfer limit, however it becomes non-linear at small momentum transfer or large distances making the coupling constant larger and thus preventing exact calculations. In such scenario, one uses either effective field theory which preserves the symmetries of original theory or Lattice QCD which discretizes space points as a calculation tool.

¹The energetic quarks and gluons produced in the high energy collisions can emit gluons while travelling away from the collision point and these gluons can split into even more gluons which results in a relatively narrow cascade, or jet, of particles [8]

- **Chiral symmetry restoration:** Chiral symmetry breaking is one of the main characteristics of QCD. Chiral symmetry is a continuous symmetry of QCD in the limit of vanishing quark masses. The symmetry is usually characterised by the chiral condensate of right- and left-handed components of quark fields $\langle \psi \bar{\psi} \rangle = \langle \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \rangle$. The QCD Lagrangian for massless quarks preserves helicity, as they travel at the speed of light, the chirality of quark is therefore independent of any observing Lorentz frame $\mathcal{L}_{QCD} = \mathcal{L}_{QCD}(\psi_L) + \mathcal{L}_{QCD}(\psi_R)$. So the QCD interaction does not couple the left and the right-handed quarks, but in the vacuum, quark mass is not negligible and their strong interaction is not damped, which results in the breaking of chiral symmetry and $\langle \psi \bar{\psi} \rangle \propto \Lambda_{QCD}^3 \neq 0$. The mass term in $\mathcal{L}_{QCD}$ explicitly breaks the chiral symmetry, resulting in a very strong polarization effect in the QCD vacuum and the empty space actually contains a soup of spontaneously appearing, interacting, and disappearing gluons. On the other hand, the masses of quarks are non-zero or finite but in comparison to hadronic scale (~ 1 GeV) the masses of the lightest quarks (up and down) are very small, such that the chiral symmetry can be considered as an approximate symmetry of the strong interactions (restoration of the chiral symmetry). The mass term $\mathcal{L}_{QCD}$ of heavier quarks (c, b or t) are more important and are responsible for the breaking of chiral symmetry.

1.1.1 Heavy-ion collisions and QCD phase diagram

The universe began with a primeval fireball, the so called “Big-Bang”, with extremely high energy densities and high temperature. The SM describes almost all physics phenomena and also reproduces experimental results but fails to address many other physical phenomenon as already discussed in the previous section. The QCD also fails to be a calculable tool at small momentum transfer scales or over large distances. On a global scale the mystery of missing energy and mass remain to be answered. The ultra-relativistic collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) produce matter which is similar to what existed in early stages of the evolution of our universe. More interesting fact is that this matter at RHIC as well as at LHC is also governed by strongly coupled physics. In hope of understanding some of the outstanding problems, one studies the deconfined matter where it is least understood, i.e. in the non perturbative regime and that of early universe. To understand the properties of this deconfined matter, study of the equation of state of nuclear matter at sufficiently large temperature and pressure is crucial. The heavy-ion collision physics program at RHIC and LHC are therefore of utmost importance as shown in Figure 1.3, representing the phase diagram of QCD matter as a function of control parameters, Temperature T and the baryonic-chemical potential μ

(net baryon number of the system). The baryonic-chemical potential is nothing but the energy required to increase the total number of baryons and anti-baryons by unity. The state of matter so called Quark-Gluon Plasma (QGP) occurs at very high temperature $T > T_c$, which can be interpreted in terms of basic quark and gluon like excitations, without confinement and with unbroken chiral symmetry in limit of massless quarks. The study of QGP is one of the main goals of heavy-ion program at the RHIC and at the LHC. At lower temperature, the intensity of the strong force increases and quarks and gluons are confined, which can be interpreted as a hadron gas. The chiral symmetry is restored in the transition from a hadron gas to QGP. There are two extreme scenarios by which one can go from normal nuclear matter to de-confined state of quarks and gluons.

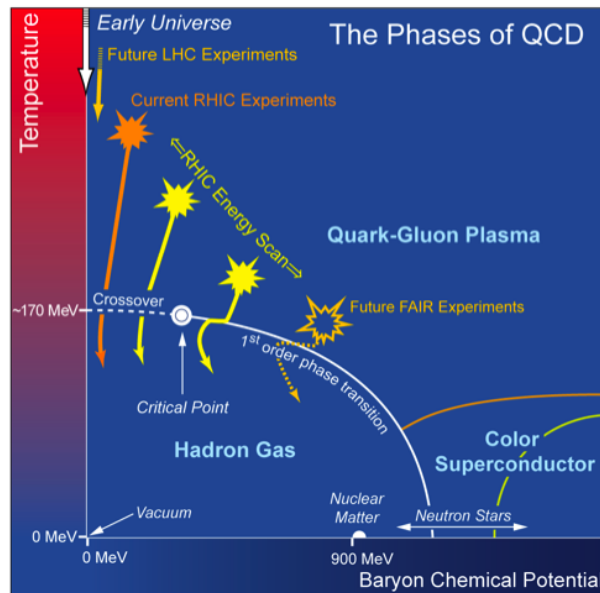


Fig. 1.3: QCD phase diagram depicting the variation of temperature with respect to baryonic-chemical potential.

- One extreme case is to increase the baryon density by fixing the temperature at $T = 0$. This state can be achieved at comparatively lower energies ($< 10 \text{ GeV}/A$) by colliding the nuclei resulting in complete stoppage of participating nucleons, and the baryon density is increased in the overlap region. As density increases, the nucleons tends to overlap, and beyond a critical point, the concept of individual nucleons goes away. In this case, quarks move freely in a comparatively larger volume ($\sim$ size of nucleus) and are no longer confined to a particular nucleon. This type of state is expected to be prevalent in neutron stars. The CBM [9] experiment at GSI plans to study the properties of QGP in this regime (as a function of Baryon Chemical potential).

- Another possible scenario is by increasing the temperature of system beyond a critical temperature predicted by QCD, i.e. $T_c \sim 154$ MeV, without changing the baryon density. This scenario was believed to be there when the universe was of the age of $\sim 10^{-6}$ sec. To attain a de-confined state of QGP, the two heavy nuclei are made to collide at relativistic energies. During the collision, nuclei pass through each other and slowing down of the participating nucleons results in energy loss which creates a hot and highly dense baryon free region around the central rapidity. The Large Hadron Collider (LHC) [10] at CERN (ALICE [11], CMS [12] and ATLAS [13]) and the Relativistic Heavy Ion Collider (RHIC) at BNL (STAR [14] and PHENIX [15] experiments), are investigating the properties of strongly interacting nuclear matter in this regime.

Finally, the transition region at high T and small μ is characterized as a cross-over region.

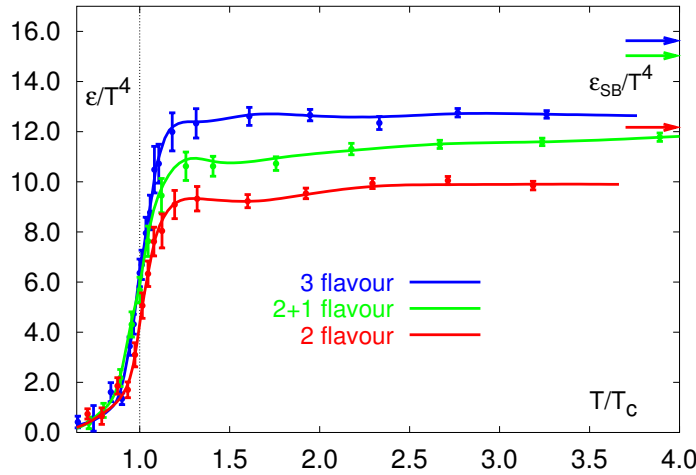


Fig. 1.4: Energy density (ϵ) as a function of Temperature (T) as per lattice QCD calculations.

1.1.2 Lattice QCD

The Lattice QCD is a well established non-perturbative approach which predicts that at extremely high energy densities and temperatures, there is a transition from normal hadronic degrees of freedom to Quark-Gluon Plasma (QGP). The equation of state from Lattice QCD calculations is depicted in Figure 1.4, showing the variation of Temperature (T) with the energy density (ϵ), which is scaled by T^4 . The term ϵ/T^4 stands for the number of degrees of freedom [16]. The remarkable increase of ϵ/T^4 around critical temperature $T = T_c$ (~ 154 GeV) is predicted. It explains that the number of degrees of freedom abruptly increases indicating the relevance of degrees of freedom for quarks and gluons and sat-

urates at higher temperature. For each flavour, the variation of temperature (T) versus energy density (ϵ) always lie under the Stefan-Boltzmann limit shown by arrows. The rapid increase by more than factor of 10 in degrees of freedom at temperature T_c points towards the possible phase transition from hadronic state to the QGP.

1.2 Relativistic heavy-ion collisions

Relativistic heavy ion collisions provide a distinctive environment to investigate the properties of primordial matter as well as explore a rich interplay between the strongly and weakly coupled physics – QGP [17]. In high energy heavy-ion collision experiments, two nuclei are accelerated to a very high velocities close to the speed of light and made to collide with each other.

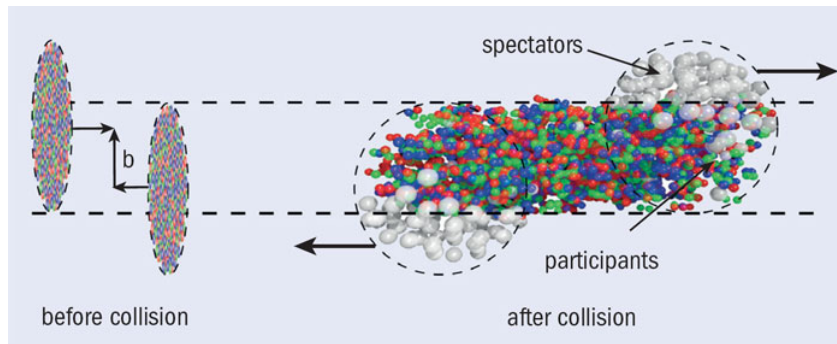


Fig. 1.5: Demonstration of heavy-ion collisions [source: \[18\]](#).

The colliding nuclei which are spherical in shape becomes Lorentz contracted in the direction of motion (beam direction or z -axis) and this Lorentz contraction allows one to represent these nuclei by thin disks. When two nuclei collide, “almond shaped” overlap region is formed depending upon the impact parameter. The nucleons that lie in the overlap region are called the **participants** and those which lie outside are called **spectators** as shown in Figure 1.5. The overlap region of heavy ions is defined by the key parameter “centrality”, which in another term depends on the impact parameters (b = distance between centres of two colliding nuclei). The head-on collisions are defined by the central collisions whereas peripheral collisions belongs to when both nuclei just graze each other. The most important requirement in creating the QGP in relativistic nucleus-nucleus collisions is to accomplish a very high energy density.

Figure 1.6 shows the space-time evolution of matter created in heavy-ion collisions by colliding the two lorentz contracted heavy ion nucleus in centre-of-mass frame. The pro-

jectile B comes from $z = -\infty$ and target nucleus A comes from $z = +\infty$, having speed close to the speed of light and undergo collision at $z = 0$ and time $t = 0$. The baryons lose energy and momentum and get slowed-down after the collision creating a baryon free overlap region. Energy lost in the collision is deposited in mid-rapidity region around $z = 0$. Experiments at RHIC and LHC have demonstrated that the enormous amount of deposited energy in the overlap region in a short duration of time is sufficiently high to create the QGP. The critical energy density calculated from the Lattice QCD calculations is $\sim 1 \text{ GeV}/\text{fm}^3$ for the formation of QGP phase in laboratory. In the initial step of collision just after the QGP formation, it may not be in thermal equilibrium instantly, but attain a mixed phase where partons and hadrons are present. As the time passes, the fireball expands and thermalizes, until the temperature decreases below the critical temperature of QCD. The energy is no longer sufficient to form a hadron. This is known as the “chemical freeze-out” when the chemical content of the hadron gas is fixed. As the hadron gas expands, the interaction between the hadrons vanishes and this is known as the “kinetic freeze-out”. Finally, at this point the particles steam out of the collision region, which is the existing state of universe, consisting of hadrons only.

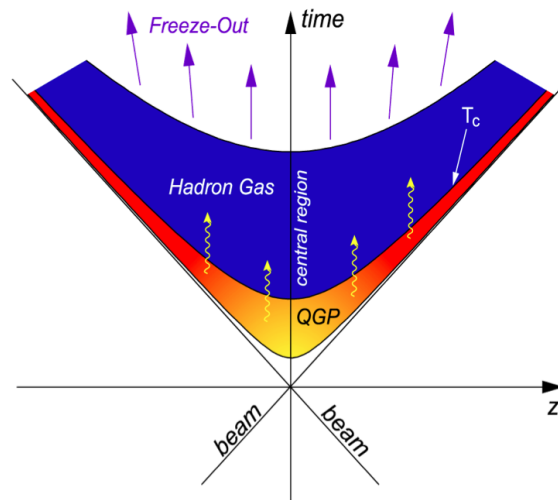


Fig. 1.6: Space time evolution.

The particles coming out of the fireball are then studied and detected by the surrounding detectors in high energy experiments to study the properties of QGP. The direct signatures of a QGP formation during the initial stages of collision are not possible. Heavy-ion collisions only provide an indirect evidence for QGP formation by detecting the produced particles. The main signatures which depicts the QGP formation are discussed in the next sections of this chapter.

1.2.1 Glauber model

The Glauber model is a phenomenological description of the nucleus-nucleus collisions, which is used to calculate geometric quantities. The model views the nucleus-nucleus collisions in terms of individual interactions of the constituent nucleons or independent nucleon-nucleon collisions.

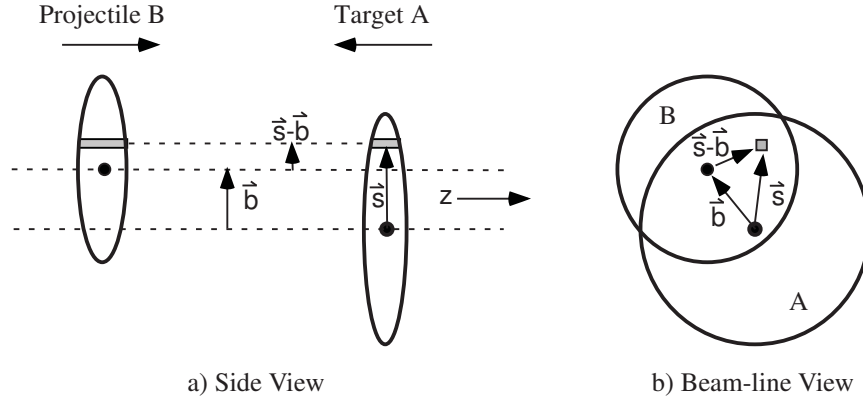


Fig. 1.7: Schematic representation of the Optical Glauber Model geometry, with (a) transverse, and (b) longitudinal views [source: \[19\]](#).

Figure 1.7 shows a schematic view (transverse and longitudinal) of a collision between two nucleus A (mass number) and B (mass number), described in terms of impact parameter (b). The probability of interaction between incoming nucleons of both nuclei can be defined as; $T_{AB}(b) \times \sigma_{inel}$, where σ_{inel} is the nucleon-nucleon inelastic cross section and $T_{AB}(b)$ is the thickness function and directly depends on the impact parameter. $T_{AB}(b)$ can be interpreted as an effective overlap area for which a nucleon of nuclei A can interact with another nucleon of nuclei B. The total inelastic cross section for the interaction of nuclei A and B can be expressed as;

$$\sigma_{inel}^{AB} = \int_0^\infty 2\pi b db \left\{ 1 - [1 - T_{AB}(b) \sigma_{inel}]^{AB} \right\} \quad (1.3)$$

One of the main fundamental features of this model is to measure the average number of nucleon-nucleon collisions $\langle N_{coll} \rangle$ as a function of impact parameter, defined as;

$$\langle N_{coll} \rangle = AB \cdot T_{AB}(b) \cdot \sigma_{inel} \quad (1.4)$$

→ Centrality

The geometrical quantities of the collision, for example, N_{part} , N_{spec} or N_{coll} as discussed above and the impact parameter are not directly measurable quantities in the experiments. Therefore, the alternate way to measure them is either via average charged-particle multiplicity N_{ch} or by measuring the energy deposited by the number of spectator nucleons [19, 20]. The quantity “centrality” of the collision is correlated to the particle multiplicity and directly related to the impact parameter (b). It is inferred by comparison of data with Monte Carlo simulation of the same collisions.

In ALICE experiment, the centrality can be measured either by the percentile of the hadronic cross section corresponding to a particle multiplicity (e.g., using VZERO detector in ALICE) or by the energy deposition of spectator nucleons or particles those are close to the beam direction (e.g., using zero-degree calorimeters: ZDC, E_{ZCD} in ALICE)². Figure 1.8 shows the distribution of total amplitudes in the VZERO detector and a fit based on NBD-Glauber model. The different centrality classes are indicated and a zoom of the most peripheral region is also shown in top-left of the same figure [20]. The estimation of the centrality in pp and p-Pb collisions system is rather complicated hence the violence of the collision is decided by the number of produced particles.

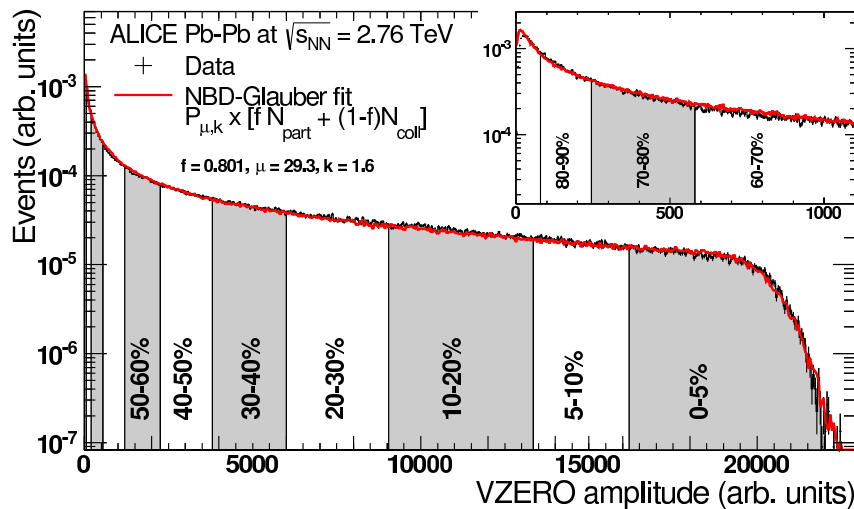


Fig. 1.8: [ALICE] The distribution of the VZERO amplitudes in Pb-Pb collision at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The distribution is fitted by the NBD-Glauber model, as shown by the red line. The different centrality classes corresponds to VZERO amplitudes are indicated in their percentiles. The zoom version on the top left indicates the centralities of most peripheral region.

²Energy deposited does not depend monotonically on the impact parameter b and this condition relatively hold better for central collisions (at small b values) only therefore, in case of peripheral collisions (at large b values), the E_{ZCD} usually combined with other observable in order to compensate the monotonic correlation

1.2.2 Experimental observables

In high energy experiments, the properties of the medium created in heavy-ion collisions can be studied by analysing the kinematic and chemical properties of the final state particles. The final state particles, such as; pions, kaons, protons, electrons, muons, neutrons and photons, reach to the detector and are detected by interactions with the detector medium. In this section, the recent experimental results from the RHIC to the LHC are discussed for some of the most important physics observables. These observables can be broadly classified into three different groups such as global, initial state and final state observables.

Initial State Probes

The initial state probes do not interact with the medium or QGP formation, therefore, their properties remain unchanged in the presence of medium (nucleus-nucleus collisions) or in the presence of cold matter (nucleus-nucleon collisions, discussed later in this chapter). The production of direct photons, leptons, and weak bosons do not interact via strong interaction and therefore, are considered as initial state probes.

→ Direct Photons

The direct photons are created via hard parton-parton scattering, mainly through $q\bar{q} \rightarrow \gamma g$, $g\bar{q} \rightarrow \gamma \bar{q}$, and $gq \rightarrow \gamma q$ processes in the early stage of the collisions. Since photons do not interact via strong interaction, their mean-free path is too large and hence they may not suffer any collision with other particles after they are produced. Therefore, photons pass through matter without interacting with the surrounding and carry information about the QGP, which can help us to discriminate the initial and final state effects [21]. The WA98 collaboration at CERN SPS reported the first direct photon measurement in the transverse momentum range, $1.5 < p_T < 4 \text{ GeV}/c$ in the most central Pb-Pb collisions (0-10%) at $\sqrt{s_{NN}} = 17.3 \text{ GeV}$ [22]. The direct photons in central collisions indicate a signal excess for $p_T > 1.5 \text{ GeV}/c$ while the peripheral collisions does not show any significant excess. The invariant direct photon multiplicity from central collisions is then compared to proton induced (pA) collisions as a function of transverse momentum. This comparison also exhibits an excess of direct photon production in the central collisions. The measurement finally concluded that, the excess in photon signal is either because of modification of the prompt photon production in nucleus-nucleus collisions or related to the contributions from pre-equilibrium or thermal photon emission.

The PHENIX collaboration at RHIC, the CMS, and ATLAS collaborations at CERN later also measured direct photons in heavy-ion collisions and found their results are rather consistent with NLO pQCD calculations³ [21]-[25]. The ALICE collaboration also measured direct photons production in the transverse momentum range, $0.9 < p_T < 14 \text{ GeV}/c$ at mid rapidity for different event centralities (central to peripheral) in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ [26]. Figure 1.9 shows that direct photons for $p_T > 5 \text{ GeV}/c$ are consistent with pQCD calculations. This supports that no such medium related effects are observed on the production of direct photons for transverse momentum region $p_T > 5 \text{ GeV}/c$. The low p_T region ($< 2 \text{ GeV}/c$), for mid-central and central collisions shows an excess above the prompt photon contributions. The results within uncertainties agree with models which assume QGP formation.

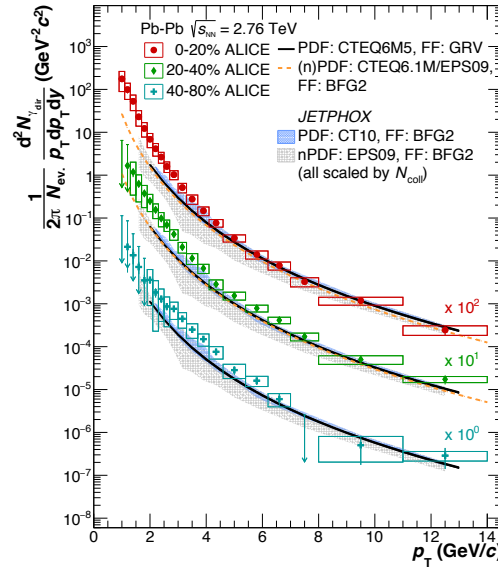


Fig. 1.9: [ALICE] Production of direct photons in different centralities of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ and comparison to different model predictions. In this figure centrality data points of 0-20% are scaled by factor of 100 and 20-40% are scaled by factor of 10 for better representation.

Bulk properties and collective phenomena

The general information about the collision such as multiplicity, the reaction plane, the volume and the initial energy density can be characterised as bulk properties and collective expansion of the medium. The measurement of charged particle pseudo-rapidity density for example depends on the parton density of the medium and therefore, can provide an estimation of the energy density. The spectra of particle momentum gives an

³pQCD calculations of the direct photons yield in pp collisions at same energy of heavy-ion collisions

insight into the collective and thermal properties of the medium, which basically contain low- p_T (soft) particles. Some of the other observables for e.g., strangeness enhancement, dynamical fluctuations and radial flow are explained in detail in this section.

→ Strangeness enhancement

Strangeness enhancement is one of the first proposed and important signature of QGP formation. One can get information about the temperature and collective flow of the system by studying the particle spectra. The feature of strangeness enhancement can be measured in terms of enhancement factor (E), which is defined as the ratio of strange particle yields (Y) normalized by average number of participating nucleons $\langle N_{\text{part}} \rangle$ in heavy ion collisions to that measured in pp collisions.

$$E = \frac{Y^{\text{AA}} / \langle N_{\text{part}}^{\text{AA}} \rangle}{Y^{\text{NN}} / \langle N_{\text{part}}^{\text{NN}} \rangle} \quad (1.5)$$

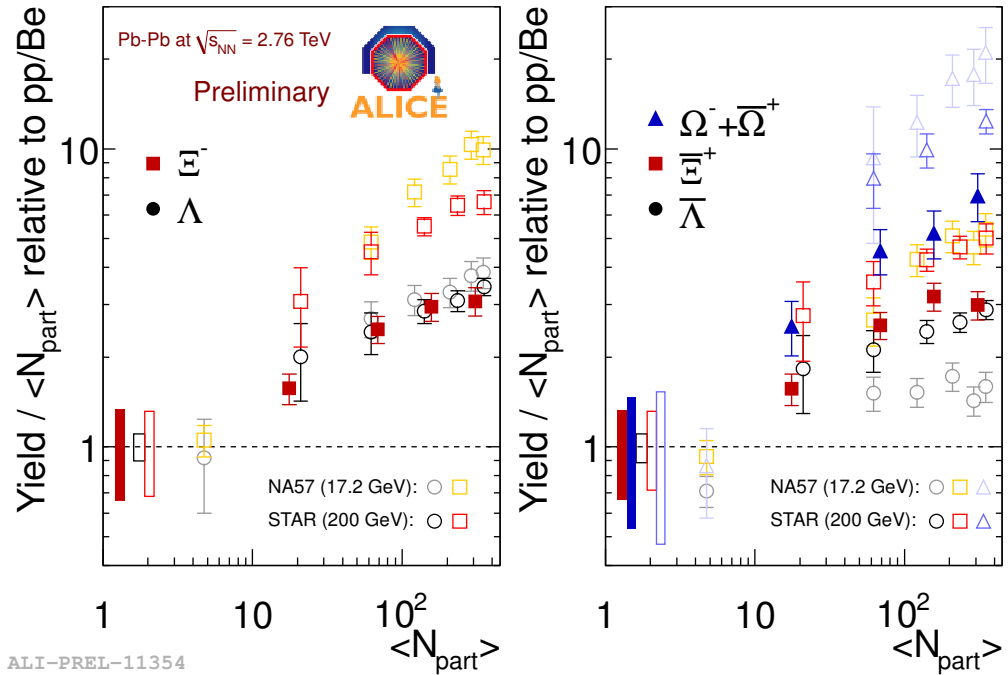


Fig. 1.10: [ALICE] Strangeness enhancement for multi-strange baryons, Λ , Ξ^- and $\Omega^- + \Omega^+$ in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and comparison to the previous measurements.

The strangeness enhancement has been studied at the RHIC and LHC, for example, ALICE collaboration studied the production of multi-strange baryons in Pb-Pb collisions and observed the strangeness enhancement with respect to pp collisions [27]. The results

are also compared to the previous measurements (e.g. STAR, NA57) and found that the strength of enhancement is larger than that measured by the STAR collaboration [28].

→ Dynamical fluctuations

The study of an event-by-event fluctuations provides a test bench to characterize the thermodynamic properties of the system, for example, fluctuations of any conserved quantity is predicted to be a signal of QGP and a phase transition. One can measure fluctuations using many physics observables such as, net-charge fluctuations, particle ratio fluctuations, temperature fluctuations and the Disoriented chiral condensates (DCC). The net charge fluctuations have been studied by calculating the particle ratio of total positive and negative charged particles on an event by event basis, i.e. $R = N_+/N_-$. The fluctuations via ratio instead of particles itself is considered to avoid the uncertainties arising from volume fluctuations. ALICE collaboration reported the net charge fluctuations dependence as a function of collision energy by measuring the observable $D (= \langle N_{ch} \rangle \langle \delta R^2 \rangle \approx 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle})$ [29], which is nothing but the charge fluctuations per unit entropy [30]. An approximate value of D for QGP by neglecting the interaction between the quarks is four times smaller than that of the Hadron Gas (HG). For example, the value of D for uncorrelated pion gas is estimated to be around 4 and can go down upto ≈ 3 , after taking the resonance yield into account. On the other hand, the D value for QGP is predicted in between 1.0 to 1.5, thus, its value can help us to differentiate the HG phase from the QGP one.

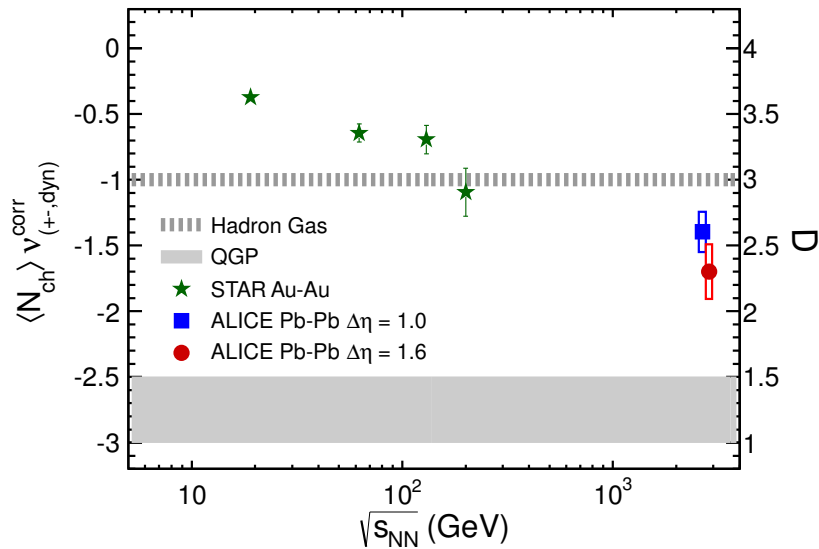


Fig. 1.11: [ALICE] Energy dependence of net-charge fluctuations measured in terms of $\langle N_{ch} \rangle v_{(+,-,dyn)}^{corr}$ (left axis) and D (right axis), for the most central Pb-Pb collisions.

Figure 1.11 shows ALICE results on net charge fluctuations in pseudo-rapidity $|\eta|$ intervals, 1.0 and 1.6. Figure clearly shows a monotonic decrease in net charge fluctuations as one goes towards the higher beam energy, here, the lower energy data are taken from the STAR experiment at RHIC (measured with $|\eta| = 1.0$).

→ Azimuthal anisotropy

One can learn more about the heavy-ion collision dynamics by measuring the azimuthal distribution of partons in a perpendicular plane with respect to the beam direction. In non-central heavy-ion collisions (impact parameter, $b \neq 0$), the initial overlap region is anisotropic or spatially asymmetric. The lenticular shape is formed in the initial stage because of the partial overlap between colliding heavy-ion beams. The transverse (x-y) plane of the overlap region can be characterised into two axis, one is the minor axis (x axis), which is parallel to the direction of vector connecting the centre of two colliding nuclei and second is the major axis (y axis), perpendicular to the minor one as illustrated in Figure 1.12. The z axis by convention is the direction of colliding beam. The plane in x-z direction is defined as “reaction plane”.

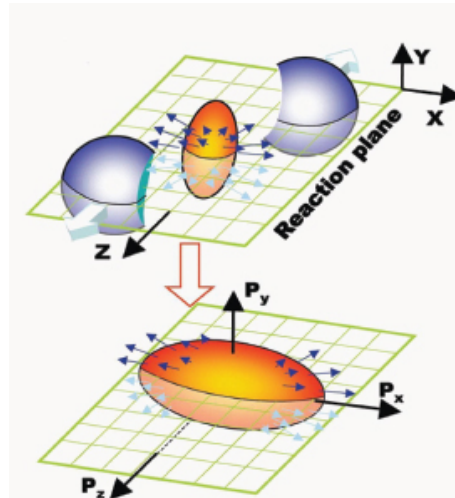


Fig. 1.12: Initial-state collision geometry in non-central heavy-ion collision.

It is predicted that the partons suffer multiple collisions inside the strongly interacting matter. Therefore, with almond shape geometry particles along minor axis are subjected to have more pressure gradient as compared to particles along major axis and the spatial asymmetry gets converted into an anisotropic momentum distributions. By studying the flow of particles in reaction plane, one can extract information about the EOS of matter produced in heavy-ion collisions. Therefore, measurement of azimuthal anisotropy is a powerful tool to study the production mechanism of hot and dense matter. The az-

imuthal anisotropy can be measured via Fourier coefficients of azimuthal distribution, also expressed as,

$$v_n = \left\langle \cos[n(\Delta\phi)] \right\rangle \quad (1.6)$$

Here, v_n is n^{th} order Fourier coefficient and $\Delta\phi = \phi - \psi_R$, is the difference between azimuthal angle ϕ of each particle and the reaction plane ψ_n of that event, for n^{th} harmonic. The first three components of flow are called as; directed, elliptic and triangular flow for $n = 1, 2$ and 3 respectively. It is observed that anisotropy is dominated by the second moment of azimuthal distribution called as elliptic flow, v_2 [31, 32]. Therefore, it is extensively used to address the initial geometry dynamics of partons in the transverse plane. It provides an evidence that the hot and dense matter created in heavy-ion collisions initially equilibrates and then it evolves according to hydrodynamic laws and finally formed matter behaves like a perfect liquid.

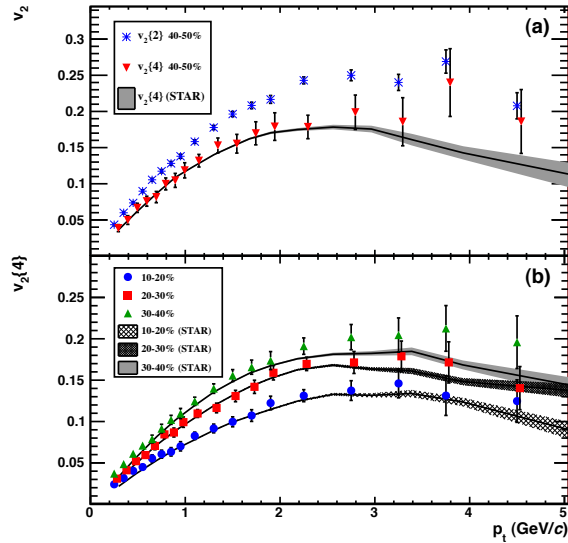


Fig. 1.13: [ALICE] Top plot a) $v_2(p_T)$ for the centrality bin 40–50% using 2- and 4- particle cumulant methods. Bottom plot b) represents comparison of ALICE $v_2\{4\}(p_T)$ results to the STAR measurements.

The elliptic flow v_2 , has been measured at RHIC and LHC [32]–[42]. Hydrodynamic model calculations, based on the relativistic hydrodynamics with EOS of matter and zero shear viscosity, fail to explain v_2 at lower energies but are in agreement with higher energy values measured by RHIC [43]. The pure hydrodynamic and other hybrid models that describe v_2 values measured at RHIC, accurately predict a higher values of about 10% to 30% for LHC energies. The v_2 measurement by ALICE collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is shown in Figure 1.13 [44]. Results show that the p_T differential values of v_2 are consistent with RHIC measurements [35] at low $p_T < 2$ –3 GeV/c, within uncer-

ainties. The overall increment of 30%, was predicted by a model and has been observed for integrated v_2 in comparison to RHIC values [35]. This suggests that a large fraction of this increment is due to an increase in mean p_T , $\langle p_T \rangle$. The ALICE collaboration also measured elliptic flow for identified particles [37]. A mass ordering in elliptic flow is observed for $p_T < 3$ GeV/ c range as shown in Figure 1.14, which could be due to interplay between elliptic and radial flow [45].

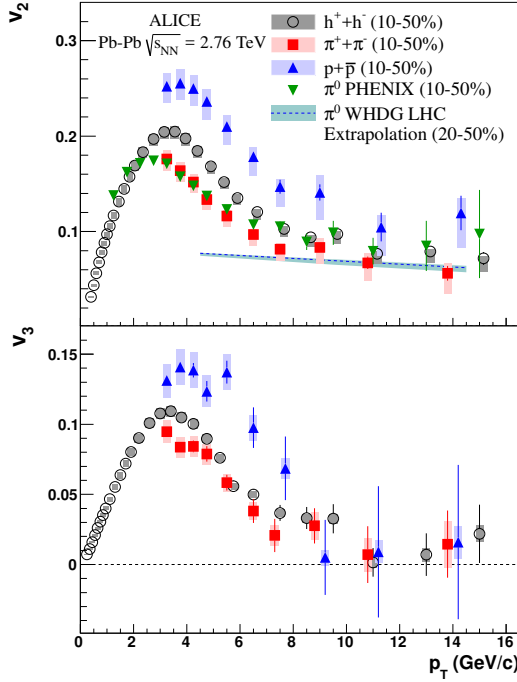


Fig. 1.14: [ALICE] v_2 (top) and v_3 (bottom) of identified particles (pion, proton) as a function of p_T in 10-50% centrality in Pb-Pb collisions.

Hard Probes

$\leadsto$ Nuclear modification factor R_{AA}

The nuclear modification factor R_{AA} is defined as the ratio of particle production measured in heavy-ion collisions to that measured in pp collisions, scaled by the equivalent average binary number of nucleon-nucleon collisions. The R_{AA} is one of the standard observable, which is sensitive to the interaction of partons in medium. It can be expressed as,

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{Y_{AA}}{Y_{pp}} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{\langle T_{coll} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \quad (1.7)$$

Here, dN_{AA}/dp_T , $\langle T_{coll} \rangle$ and $\langle N_{coll} \rangle$ are the p_T differential invariant yield, average nuclear overlap (thickness) function and the average number of binary collisions respectively, for a given centrality in heavy-ion collisions. The $\langle T_{coll} \rangle$ is proportional to $\langle N_{coll} \rangle$ and also con-

nects it to the inelastic nucleon-nucleon scattering cross section. The $\langle T_{\text{coll}} \rangle$ and $\langle N_{\text{coll}} \rangle$ can be estimated via Glauber model [46] by measuring convolution of ions nuclear density profiles in heavy-ion collisions. The R_{AA} equal to unity indicates absolute binary scaling between heavy-ion and nucleon-nucleon collisions; which means, in this case, one can consider heavy-ion collisions as an incoherent superposition of nucleon-nucleon (pp) interactions or in other words do not support any signature of medium effects (QGP). On the other hand, R_{AA} less than or greater than unity represents an existence of medium effects. The R_{AA} for the colour neutral particles (e.g. direct photons, W and Z bosons) is expected to be unity as they do not participate in strong interactions and has indeed been observed to be so.

It is predicted from QCD calculations that the energy loss for quarks is smaller than gluons because of the smaller colour coupling factor ($R_{AA}^g < R_{AA}^q$). Furthermore, it is also estimated that for $p_T < 10$ GeV/c region, where the masses of heavy quarks are not negligible compared to their momenta, the gluon radiations of heavy quarks are suppressed at small angle because of what is known as the “dead cone” effect [47]. This phenomena therefore, introduces a corresponding increase in R_{AA} of heavy quarks, resulting in a hierarchy, $R_{AA}^g < R_{AA}^{lq} < R_{AA}^c < R_{AA}^b$. Therefore, R_{AA} measurement is a unique tool to study parton energy loss mechanism and its dependence on colour charge and mass of the partons. Recent measurements at the RHIC and LHC support that the medium created in heavy-ion collisions affects hadron production [48, 49], resulting in a break-down of binary scaling, making R_{AA} not equal to one.

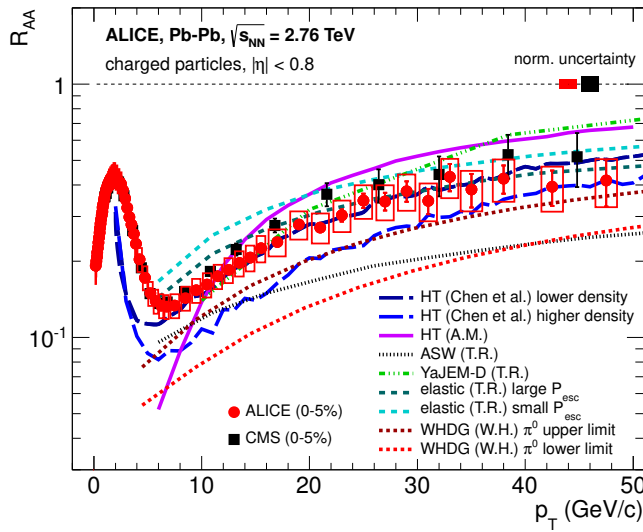


Fig. 1.15: [ALICE] Charged particle R_{AA} in the most central (0–5%) Pb–Pb collisions and the comparison to CMS results and different model calculations.

For example, R_{AA} of light-flavour hadrons at mid-rapidity in central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV is measured at RHIC [50]–[53] and a strong suppression by factor of ~ 4 –5 at high p_T region > 5 GeV/ c has been observed. The ALICE and CMS experiments at LHC have also measured R_{AA} of light flavours in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and observed even stronger suppression up to a factor of seven in p_T region 6–8 GeV/ c [54]–[56]. The ALICE collaboration also studied dependency of R_{AA} on event centrality [55]. The suppression in particle yield is larger in most central collisions (0–5%), which corresponds to $R_{AA} \approx 0.13$ for transverse momentum p_T , 6–7 GeV/ c as shown in Figure 1.15. The R_{AA} increases upto ≈ 0.4 for higher $p_T > 30$ GeV/ c . On the other hand, peripheral events (70–80%) show mild suppression of about $R_{AA} = 0.6$ –0.7 without having any strong dependence on p_T . The results are also compared to CMS and agrees well within uncertainties.

~ Two particle correlation measurements

In QCD hard scattering processes, fragmentation of high-energy quark or gluon produces a shower of partons, which in hadronization process is reflected as spray of hadrons, called “Jet”. In high energy collisions, parton pairs are produced with back to back topology due to the conservation of momenta and therefore, they manifest corresponding jets in back to back direction. The topology breaks when any of the radiated gluon carrying high momenta starts producing an additional spray of hadrons or jet, which also affects the features of back to back angular correlations. In case of heavy-ion collision, partons of jets lose their energy via gluon bremsstrahlung and multiple scattering phenomena while passing through the medium. The loss in the parton energy depends on their initial energy or in other words depends on the path length they travel in medium, which can even remove the demonstration of jets, known as “jet quenching”.

It was proposed that the study of high- p_T particles, in particular, angular correlations using high- p_T particles can provide information about jet production in hadron-hadron collisions [57, 58]. But later this was eclipsed by the jet reconstruction algorithms, that provide more quantitative details of hard scattering processes. The proposed method first adopted by PHENIX experiment [57, 58] measured angular correlations using high p_T pions (π^0) [59]. In general, correlation distributions are measured in $\Delta\varphi = (-\pi/2, 3\pi/2)$ range to demonstrate the features of back to back jets as shown in Figure 1.16. The $\Delta\varphi = (-\pi/2, \pi/2)$ range is defined as near-side (NS) correlation, represents π^0 trigger and associated particles from the same side jet, whereas the range $\Delta\varphi = (\pi/2, 3\pi/2)$ is defined as away-side (AS) correlations, represents trigger π^0 and associated particles from same and opposite side (recoiling) jet.

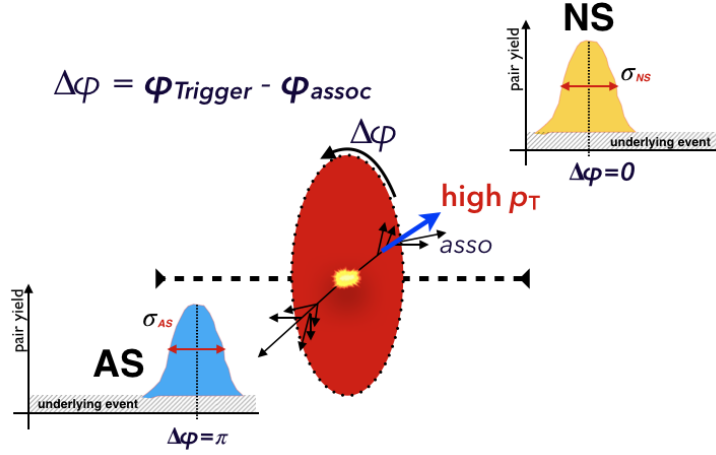


Fig. 1.16: [Dummy] The demonstration of two particle angular correlation in $\Delta\varphi = (-\pi/2, 3\pi/2)$ range.

Figure 1.17 shows angular correlations measured between high $p_T^{\pi^0}$ and other particles to demonstrate the expected jet-induced correlations [59]. Related jet kinematics were also extracted in this measurement and found consistent with previous jet measurements as well as with PYTHIA simulations. This measurement established that the two-particle correlation method is an indirect tool to study jet properties.

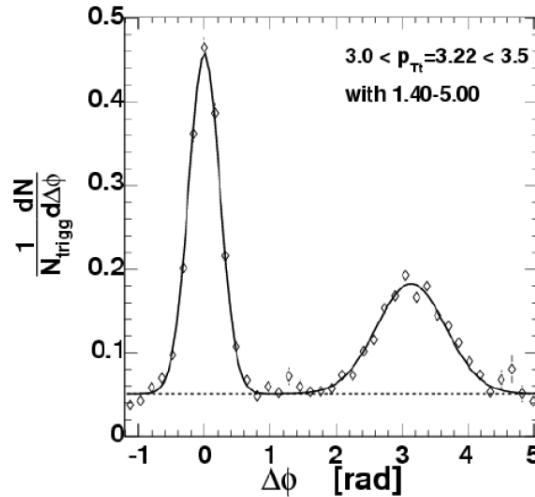


Fig. 1.17: [PHENIX] Per trigger angular correlations between trigger particle, $3 < p_T^{\pi^0} < 3.5$ GeV/c and associated particle, $1.4 < p_T^{assoc} < 5.0$ GeV/c for p+p collisions at $\sqrt{s} = 200$ GeV.

In heavy-ion collisions, two particle correlation measurements played an important role to understand the particle production processes and collective effects of medium. The prob-

ability of particle interaction with the medium increases with path length, hence the high- p_T hadrons are more sensitive to particles travelling outward from near-surface region of the collision zone, also known as “surface biased effect”. Therefore, from measurement of angular correlations using high- p_T particle in heavy-ion collisions, one can extract information about the interior of the medium as well as interaction of jets with medium. For example, a jet in opposite direction with respect to the jet containing a high- p_T particle, is expected to travel longer inside the medium. This increases the probability of interaction for opposite side jet with the medium and hence it loses relatively large amount of energy, which in turn leads to energy asymmetry in both jets (“di-jet asymmetry”). In two particle correlation measurements, generally correlation patterns and their properties are compared between heavy-ion collision and nucleon-nucleon collision. This comparison helps one to understand particle production processes and collective effects of the medium, e.g. an expected suppression in away-side correlations, which represents “jet quenching”(AS region). The quantity I_{AA} , defined as ratio of correlation yield in heavy-ion collision to that measured in pp collision, is used to address modification in NS and AS correlations. It can be expressed as,

$$I_{AA} = \frac{Y_{AA}^{correl}}{Y_{pp}^{correl}} \quad (1.8)$$

I_{AA} in the absence of medium effects is expected to be unity and in case of any medium effect it should deviate from unity, e.g. I_{AA} less than one provides a case for energy loss in the medium.

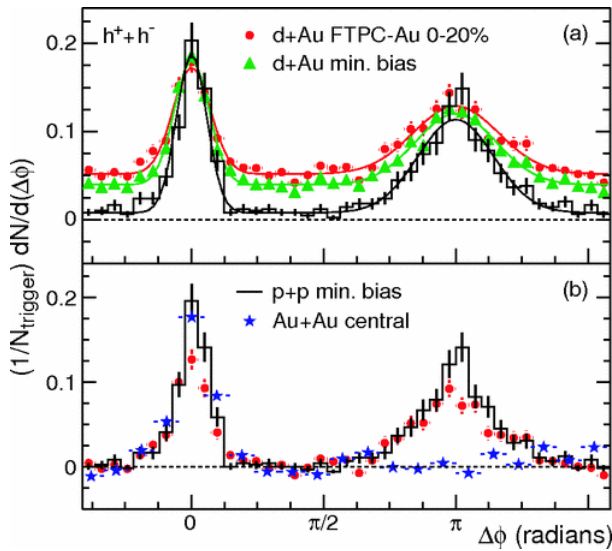


Fig. 1.18: [STAR] Comparison of the azimuthal distributions (a) for minimum bias and central d+Au collisions (red and green) and for p+p collisions. (b) for baseline subtracted central d+Au collisions to that measured in p+p and central Au+Au collisions.

The recent measurements of two particle correlations from RHIC to LHC energies established the method as a powerful tool to investigate the properties of matter created in high energy collisions [60]-[75]. The first evidence of jet quenching in heavy-ion collisions via two-particle correlation was measured by STAR collaboration in Au+Au and p+p collisions at $\sqrt{s} = 200$ GeV [60, 61]. It was observed that NS correlation peak in p+p and Au+Au collisions have similar patterns but AS peak in Au+Au collisions dramatically disappeared as shown in plot (b) of Figure 1.18. The role of initial state effects on this suppression was also studied by repeating the measurement in d+Au collisions as shown in plot (a) of Figure 1.18. Initial state effects introduce an enhancement in correlation baseline only, therefore, it was concluded that the suppression observed is due to the medium effect. PHENIX collaboration also measured di-hadron correlations in wide range of trigger and associated particle momenta in 0-20% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [62].

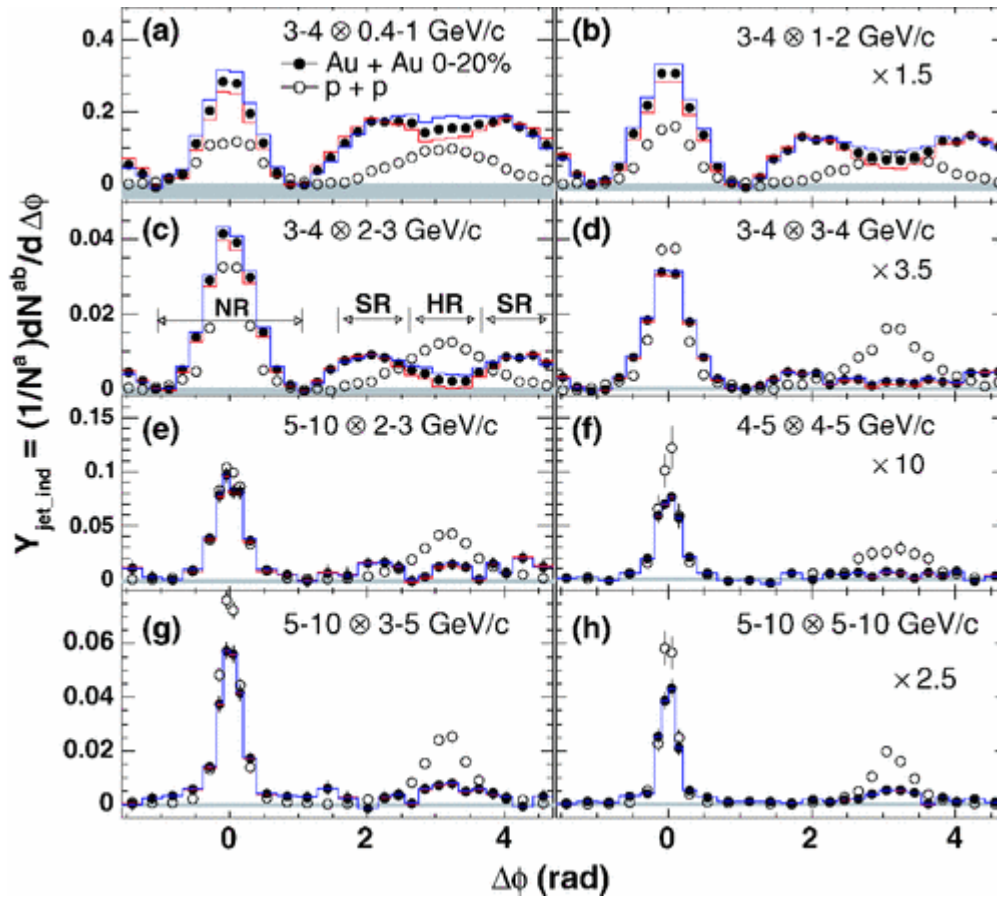


Fig. 1.19: [PHENIX] Comparison of per trigger azimuthal correlation distributions in central (0-20%) Au+Au collisions and p+p collisions at $\sqrt{s} = 200$ GeV for different p_T ranges of trigger and associated particles.

The PHENIX measurement confirmed the disappearance of AS correlation for trigger $p_T^{trigger} > 4 \text{ GeV}/c$ and associated $p_T^{assoc} > 3 \text{ GeV}/c$ as shown in Figure 1.19. These two measurements at RHIC, were the first that confirmed the evidence of jet-quenching mechanism via two particle correlations. In both measurements, NS correlation peak was also slightly affected, which on the other hand was interpreted as an indication of choosing higher p_T trigger particle to encounter better its surface bias property.

The higher beam energies in heavy ion collisions at LHC provide larger jet cross section, which allows one to study jet quenching phenomena in extended kinematic range with better precision. The ALICE collaboration measured the modification in particle yield via di-hadron correlation in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ [73]. The quantity I_{AA} is evaluated for NS and AS correlations for different centralities (most central = 0-5%, peripheral = 60-100%) in Pb–Pb collisions. In Figure 1.20 right hand side shows, away-side $I_{AA} \approx 0.6$ or in other words it represents that the yield of charged particles in opposite side jet is suppressed by $\sim 60\%$ for $p_T^{assoc} > 3 \text{ GeV}/c$ in central collisions. This measurement therefore, supported previous evidence for in-medium energy loss. Moreover, an enhancement of the order of 20% in near side I_{AA} is observed for the first time as shown in left plot of Figure 1.20. This enhancement could be due to several effects, such as, a change of fragmentation function, change of quark/gluon jet ratio due to medium coupling or bias on parton p_T spectrum after energy loss due to the selection of high p_T trigger particle. It should be noted that the suppression in away side I_{AA} measured at RHIC was 50% stronger than the one measured by ALICE (right plot of Figure 1.20), interestingly same difference is also observed in charged particle R_{AA} measurements.

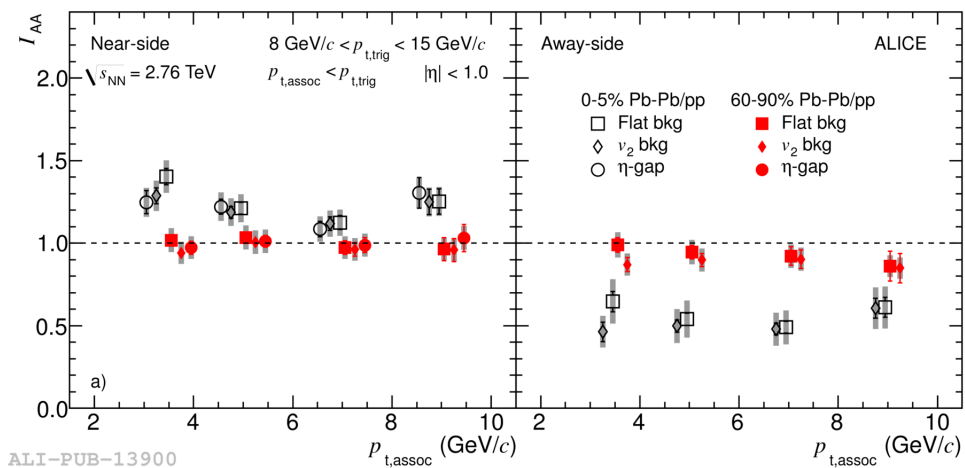


Fig. 1.20: [ALICE] Comparison of per trigger azimuthal correlation distributions in central (0-20%) Au+Au collisions and p+p collisions at $\sqrt{s} = 200 \text{ GeV}$ for different p_T ranges of trigger and associated particles.

1.2.3 Cold Nuclear Matter (CNM) effects

To get a complete picture of the energy loss mechanism in heavy-ion collisions, one needs to understand the cold nuclear matter (CNM) effects in initial and final states of the collision. The CNM effects are not related to the formation of QGP and exist in nuclei or nucleon-nucleus collisions. The nucleon-nucleus collisions, for example, d-Au collisions at RHIC and p-Pb collisions at the LHC are considered as small systems, due to relatively small region of overlap at the time of collision. Because of the asymmetric nature of collisions, nucleon-nucleus collisions data is expected to provide information about the QCD matter at high gluon density, giving insight into various phenomena such as parton shadowing or gluon saturation. The demonstration of different collision systems is shown in Figure 1.21. It must, however, be said that the recent studies of long-range correlations of charged hadrons [76]-[79] in p-Pb collisions at the LHC, nuclear modification factor of light flavour particles in d-Au collisions at the RHIC [80] and J/ψ and $\psi(2S)$ suppression in p-Pb (d-Au) collisions at both LHC and RHIC [81, 82] point towards the presence of final-state effects in these small systems too.

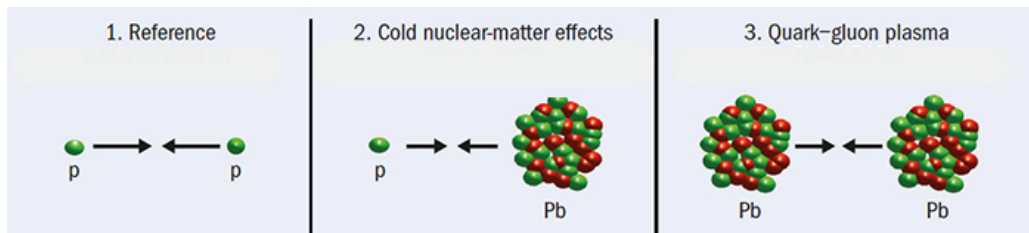


Fig. 1.21: Demonstration of different collision systems (pp in left, p-Pb in middle and Pb-Pb in right) source: [18].

≈ Nuclear shadowing

In the initial state, distributions of quarks and gluons in free nucleons are affected by high density nuclear environment, also known as parton-density shadowing. Therefore, the PDFs in the nuclei (bound nucleons) are modified as compared to that in a free nucleon. It further depend on the parton fractional momentum x and on the total number of nucleons or atomic mass number of the ions [83, 84]. The term “shadow” can be interpreted as that, the nucleons on the surface overshadow the nucleons present inside the nucleus. This is borne by the fact that the total cross section of hadron-nucleus is smaller with respect to the natural scaling of mass number times the hadron nucleon cross section ($\sigma_{hA} < A \cdot \sigma_{hN}$) [85]. Gluon saturation, is defined as a depletion in gluon density at low- x that may occur in the form of a color glass condensate (CGC). Model calculations based

on modifications of Parton Distribution Functions (PDFs) or Colour Glass Condensate (GCG) effective theory, provide a possible explanation for these effects [86]–[88]. On the contrary, “anti-shadowing” occurs also at medium x region that increases the PDFs and can enhance the particle production rate.

→ Cronin effect or k_T broadening

The Cronin effect [89, 90] refers to the enhancement of hadron production (mainly low p_T) in nucleon-nucleus collisions with respect to the scaled binary nucleon-nucleon collisions. The partonic scattering at the initial impact is believed to be one of the main source for Cronin effect [91]–[94]. The models based on this assumption can reproduce the production of inclusive hadron in d+Au collisions measured at RHIC. These models can also describe the suppression of charged hadrons observed in Au+Au collisions at RHIC [95]. Later, at RHIC, it was also observed that the Cronin effect depends on the type of particle, for example, for protons and anti-protons it was larger than that for pions [96]. Some recent studies also tried to explain the Cronin effect as a final state effect such as recombination and coherent multiple scattering [97]–[99]. Therefore, Cronin effect on particle production in nucleon-nucleus collision is important to understand as it can provide information on the dynamics of CNM effects.

The CNM effects in p-A collision system can be studied using several methods, for example, measurement of nuclear modification factor R_{pA} . The R_{pA} is similar to the quantity R_{AA} measured in heavy ion collisions. It is defined as,

$$R_{pA} = \frac{1}{A} \frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T} \quad (1.9)$$

Where $d\sigma/dp_T$ is the cross section measured in p-A and pp collision systems. The value of R_{pA} in the absence of CNM effects is expected to be unity. ALICE has measured nuclear modification factor for charged particle as a function of transverse momentum in p–Pb collisions and also compared it to the one measured in central (0–5%) and peripheral (70–80%) Pb–Pb collisions as shown in Figure 1.21 [100]. The measured R_{pPb} is found consistent with the unity for $p_T \geq 2$ GeV/c, which demonstrates that the strong suppression of R_{AA} observed for central Pb–Pb collisions was only due to the hot and dense matter created heavy ions collisions [101].

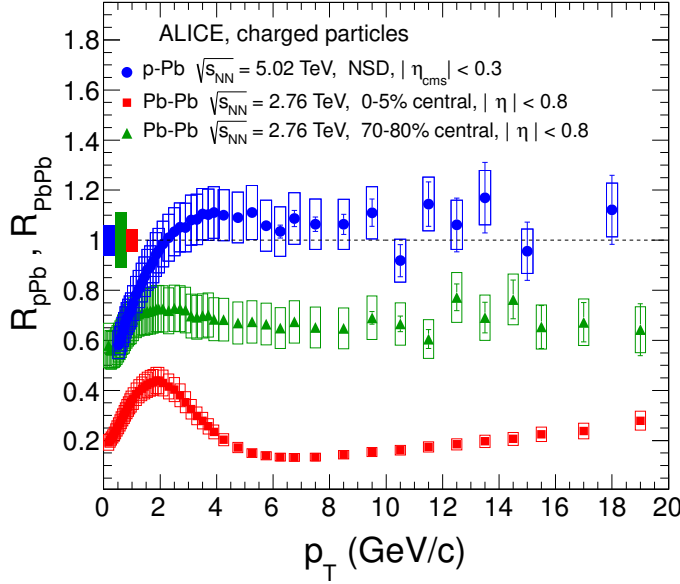


Fig. 1.22: [ALICE] The R_{pPb} of charged particles as a function of transverse momentum in p-Pb collisions and comparison to the R_{AA} measured in central and peripheral Pb-Pb collisions.

1.3 Study of heavy quarks via open heavy-flavour

The masses of heavy quarks ($m_c \approx 1.29$ GeV and $m_b \approx 4.19$ GeV) are much larger compared to light quarks ($m_u \approx 2.3$ MeV, $m_d \approx 4.8$ MeV and $m_s \approx 95$ MeV) and also to the QCD scale parameter Λ_{QCD} (~ 200 MeV/c). Therefore, the heavy quarks and their anti-quarks are predominantly produced in hard scattering processes (e.g. flavour creation, flavour excitation and gluon splitting [102]) during the early stages of collision and their production is governed by perturbative QCD. The special feature of heavy-quarks is that, even at zero momentum they introduce hard scale due to their large masses, therefore pQCD can be used to calculate their production cross sections over all momenta which is not the case for gluon and light quarks, where only at high p_T one can use pQCD. Experimentally, one can study the production of heavy-quarks via measurement of open heavy-flavour hadrons (e.g. B, D mesons or Λ_c) or their decay products (e.g. leptons from heavy flavour hadron decay). D mesons are the lightest open heavy flavour mesons, which contain a charm and light-flavour quark. The p_T -differential cross section for open heavy-flavour hadrons H_Q is defined by means of factorization theorem. This theorem is the convolution of three hard scattering cross sections; the parton distribution functions, the hard partonic scattering cross section and the fragmentation function.

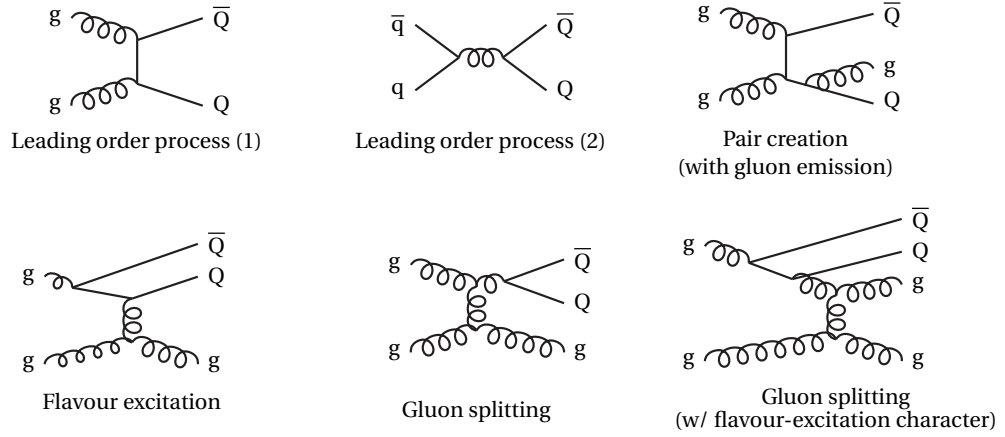


Fig. 1.23: Examples of heavy-flavour production mechanisms [102].

$$\begin{aligned}
 d\sigma^{pp \rightarrow H_Q X}(\sqrt{s}, m_Q, \mu_F^2, \mu_R^2) = & \sum_{i,j=q,\bar{q},g} f_i(x_1, \mu_F^2) \times f_j(x_2, \mu_F^2) \\
 & \times d\hat{\sigma}^{ij \rightarrow Q(\bar{Q})k}(\alpha_s(\mu_R^2), \mu_F^2, m_Q, x_1 x_2 s) \\
 & \times D_Q^{H_Q}(z, \mu_F^2)
 \end{aligned} \quad (1.10)$$

Here H_Q represents the heavy flavour hadron, m_Q is the mass of heavy flavour quark, μ_F^2 and μ_R^2 are the factorization and renormalization scales of QCD, respectively, x_1 and x_2 are the Bjorken x of two partons. The three convolution terms are defined as,

- $d\hat{\sigma}^{ij \rightarrow Q(\bar{Q})}$ is defined as partonic cross section which is estimated using pQCD calculations. This cross section includes the LO processes like quark-antiquark annihilation ($q\bar{q} \rightarrow Q\bar{Q}$) and gluon fusion ($g\bar{g} \rightarrow Q\bar{Q}$) and the NLO processes, for example, flavour excitation ($q\bar{Q} \rightarrow q\bar{Q}$) and gluon splitting ($g \rightarrow Q\bar{Q}$).
- $f_i(x_1, \mu_F^2)$ and $f_j(x_2, \mu_F^2)$ are the PDFs, that describe the partonic structure of colliding protons. It is defined as a probability of parton (i) inside the proton with momentum fraction $x_i = p_i/p$.
- $D_Q^{H_Q}(z, \mu_F^2)$ is the fragmentation function that parametrizes the probability for heavy quark Q fragmentation into a single heavy-flavour hadron H_Q with a momentum fraction $z = p_{H_Q}/p_Q$.

The study of heavy flavour production in nucleon-nucleon (e.g. pp) collision provides an important testing ground of pQCD. At the LHC energies, heavy-quark measurements in low p_T region can probe the parton PDFs at small Bjorken scale $x = \sim 10^{-4}$ because of

large momentum transfer Q^2 . The heavy quarks at LHC energies are mainly produced through gluon fusion processes ($g\bar{g} \rightarrow Q\bar{Q}$) and therefore, in addition they can provide information on gluon enhancement. Furthermore, the heavy-flavour measurements in heavy-ion collisions can provide information about the processes by which heavy quarks lose energy in QGP and could identify possible modifications to the charm parton shower and hadronization in the presence of a medium. In the next sections, the recent heavy-flavour measurements in heavy-ion collisions are discussed for different experimental observables. Finally, their measurement in p-Pb collision also discussed in the next section providing important understating of cold nuclear matter (CNM) effects in the initial and final states of collisions.

1.3.1 Heavy-flavour measurements in ALICE

~ D meson cross section in pp collision

The ALICE collaboration studied the charm production via D meson (D^0 , D^+ , D^{*+} and D_s) in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV [103]-[105]. The p_T -differential cross section of D mesons is measured and compared to theoretical calculations. Figure 1.24 shows the p_T -differential cross section for D^0 mesons measured in pp collisions at $\sqrt{s} = 7$ TeV, which indicates that the data is well described by pQCD calculations whereas the central predictions from FONLL(GM-VFNS) under(over) estimates the measurement.

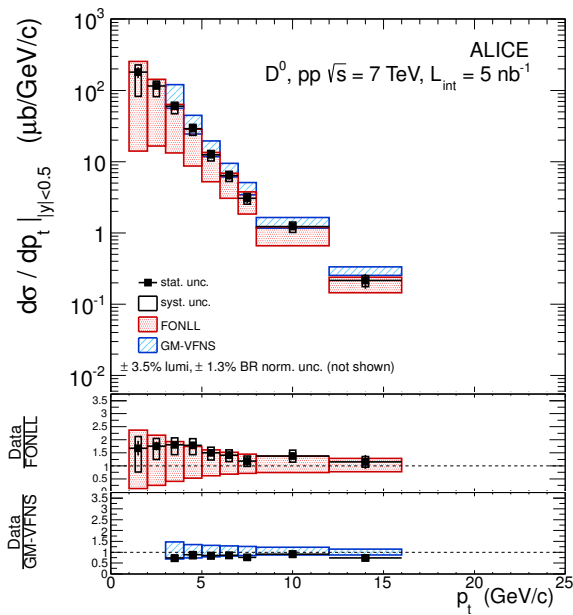


Fig. 1.24: [ALICE] p_T -differential inclusive cross section of D^0 meson in pp collisions at $\sqrt{s} = 7$ TeV and comparison to the theoretical calculations.

This measurement is also able to probe the gluon distributions at Brojken $x = \sim 10^{-4}$ in D^0 mesons at $p_T = 1.0$ GeV/ c but with current level of uncertainties one can not draw any conclusion about the small- x saturation effects.

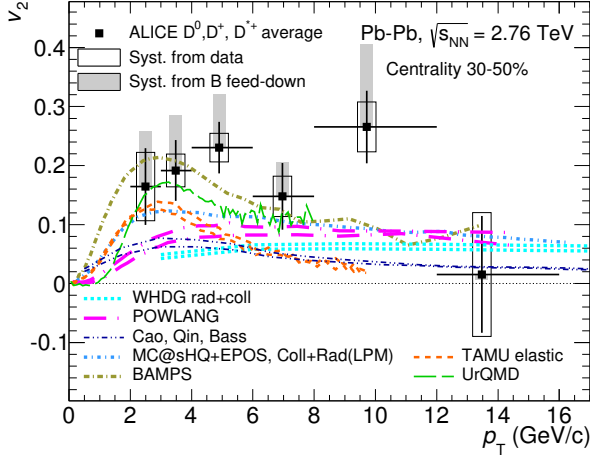


Fig. 1.25: [ALICE] D meson v_2 and comparison to model calculations in 30–50% centrality in Pb–Pb collisions.

→ Elliptic flow v_2

The elliptic flow in heavy-flavour sector provides further insight into the medium transport properties. In particular, the elliptic flow is expected to be sensitive to the degree of thermalization of heavy quarks. The non-zero elliptic flow indicates the signature of strong interaction of heavy quarks with the medium. Figure 1.25 shows D meson v_2 by ALICE collaboration, positive v_2 trend at 30% - 50% mid central Pb-Pb collisions in $2 < p_T^D < 6$ GeV/ c range is observed and values decreases toward more central collisions [106]. The measurement of elliptic flow v_2 and nuclear modification factor R_{AA} provides a more precise test for the underlying physics [107].

→ Nuclear modification factor R_{AA}

The R_{AA} measurements in heavy-flavour sector have been performed at RHIC by measuring the heavy-flavour hadrons R_{AA} indirectly from their inclusive decay electrons [108]–[110]. The measurement shows a suppression of similar order as observed for light flavour particles (e.g. pions). The ALICE and CMS collaborations measured the R_{AA} of J/ψ , over the transverse momentum range, down to zero p_T and $6.5 < p_T < 30$ GeV/ c in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [111, 112]. A suppression of factor 2-3 is observed by both ALICE and CMS collaborations. The R_{AA} for open heavy flavour hadrons, e.g. D-mesons, have been investigated at RHIC and LHC. Figure 1.26 shows R_{AA} of D^0 meson in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR collaboration [113].

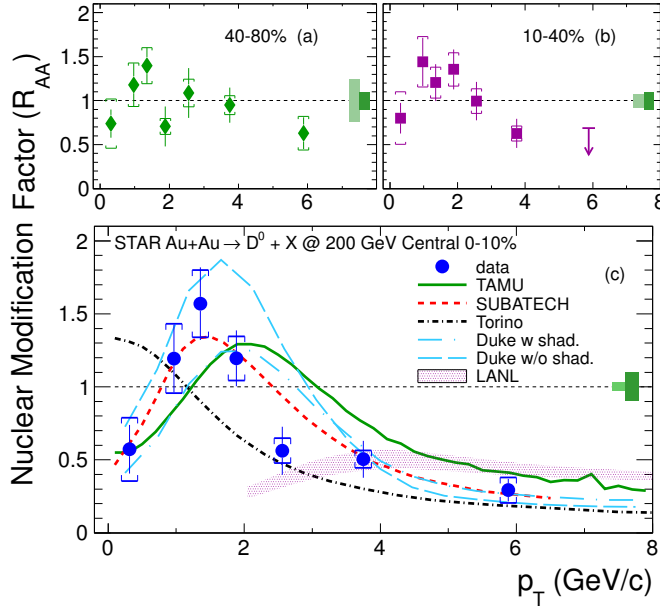


Fig. 1.26: [STAR] (a) R_{AA} for D^0 meson in peripheral 40–80%, (b) semi-central 10–40% and (c) most central 0–10% in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

A large suppression by factor of ~ 3 at $p_T^{D^0} > 2$ GeV/ c is measured whereas at $p_T^{D^0} \sim 1.5$ GeV/ c , a bump around unity is also observed which is consistent with model predictions.

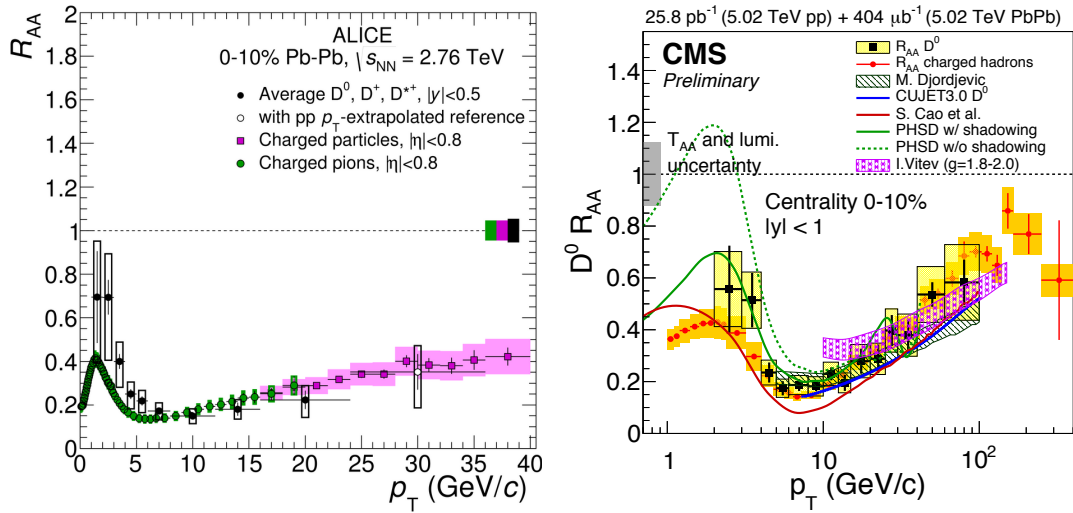


Fig. 1.27: [ALICE, CMS]: Nuclear modification factor R_{AA} of averaged D (D^0 , D^{*+} , D^0) meson (left) and D^0 meson (right) in central 0–10% Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV by the ALICE (left plot) and the CMS (right plot) collaborations.

The D -meson R_{AA} has also been studied by ALICE and CMS collaborations [114, 115]. ALICE collaboration also measured the averaged D meson R_{AA} for $2 < p_T^D < 16$ GeV/ c

range in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and observed a strong suppression by factor of ~ 3 -4, for $p_T^D > 5$ GeV/ c as shown in left plot of Figure 1.27. The results are also compared with light flavour hadrons (pions) and no evidence of expected energy loss hierarchy has been found. This might be because of the fact that the final hadron spectra is affected by p_T distribution and fragmentation function of different partons. CMS collaboration recently measured D^0 meson R_{AA} for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [115]. A similar suppression by factor of ~ 4 -5 is observed in p_T range 6-10 GeV/ c as shown in right plot of Figure 1.27. The CMS results also show that a suppression factor reduces to 1.5 for higher $p_T^{D^0}$ region 60-100 GeV/ c .

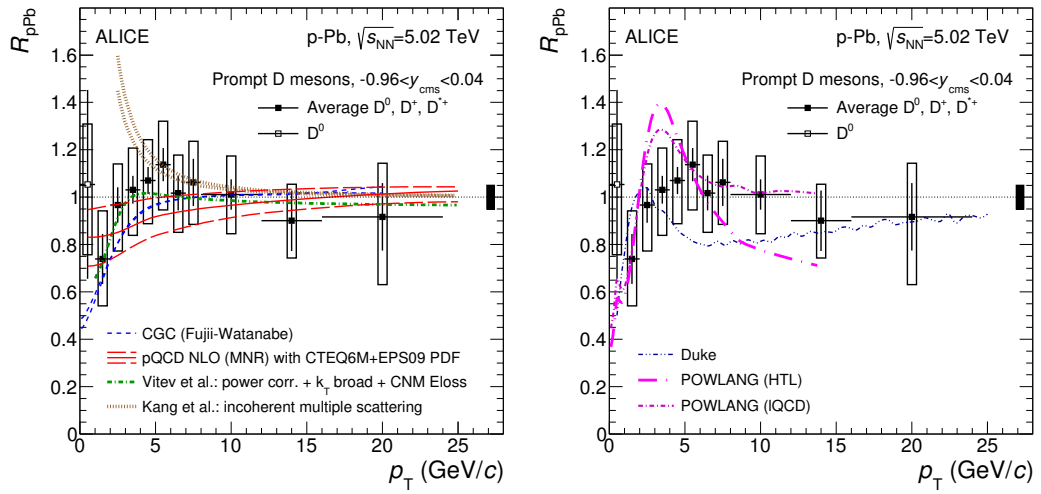


Fig. 1.28: [ALICE] Nuclear modification factor R_{pPb} of prompt D mesons in p_T range 1-24 GeV/ c in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV together with the R_{pPb} of prompt D^0 in p_T range 0-1 GeV/ c . The comparison with models those include only CNM effect is shown in the left plot and on the right, comparison with transport model is shown.

→ Nuclear modification factor R_{pPb}

The ALICE collaboration published results on nuclear modification factor R_{pPb} of D mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [116] and also as a function of charged particle multiplicity [117]. R_{pPb} averaged over all the D mesons (D^0 , D^+ and D^{*+}) has been measured in $1 < p_T < 24$ GeV/ c range and compared to various models that include initial-state effects. The R_{pPb} is found to be consistent to unity and also compatible with model calculations within uncertainties. Therefore, these results added an important reference to the previous D meson R_{AA} measurements, where suppression was observed which in turn establishes that it was only due to strong final-state effects induced by matter produced in heavy-ion collisions.

1.3.2 Correlation measurements in heavy-flavour sector

~ Proton-proton collisions

The correlation measurements using heavy-flavour quarks may provide further insight into heavy flavour production. In particular, they can provide information of heavy quark production from LO and NLO processes, as they involve different mechanisms for $c\bar{c}$ pair production. Therefore, angular correlation measurements allow to characterize the properties of different LO and NLO processes. For example, the events with $c\bar{c}$ pair production in back to back plane, as in LO processes, represent charmed fragmented jets (jet containing charm quark) in back to back directions. The study of charm-charm correlations or charm-associated particle correlations therefore, can provide information about the production mechanism of charm as well as the properties of events that contain heavy-flavour particles.

D mesons are the lightest charmed hadrons and also relatively easy to detect, therefore, they can be used in heavy-flavour correlation measurements (**also in this thesis**). The angular correlations using D mesons, for example; the $D\bar{D}$ correlation is expected to have direct signature of $c\bar{c}$ correlation and on the other hand correlation between D meson and associated particles can provide a way to characterize charm production and fragmentation processes. The NLO processes, in which a c or $\bar{c}$ quark radiates a hard gluon which further fragments in either of the jet direction will break the back-to-back topology of charmed jets. The angular correlations of $D\bar{D}$ and D-associated hadrons are therefore, promising probes to investigate NLO processes. The gluon splitting processes especially at high- p_T , can produce a collimated $c\bar{c}$ pair and because of same side direction it can introduce a unique broadening in the “AS correlations” in D-hadron correlation. Finally, in hard scattering processes e.g. “flavour excitation”, initial gluon splitting produces $c\bar{c}$ in hard interaction and the associated particles from quark fragmentation are produced with significantly different rapidity, this rather produces a flat $\Delta\varphi$ angular distributions between charmed hadrons and associated particles. The study of heavy-flavour correlations in pp collisions also provide necessary reference for heavy-ion measurements. In this thesis, we have measured the azimuthal correlations between D^+ mesons and charged particles in pp at $\sqrt{s} = 7$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the above mentioned objectives.

The angular correlation in heavy-flavour sector have already been investigated at RHIC and LHC, for example, correlation between heavy-flavour hadrons using cc and $c\bar{c}$ events in pp collisions at $\sqrt{s} = 7$ TeV are measured by LHCb collaboration [118].

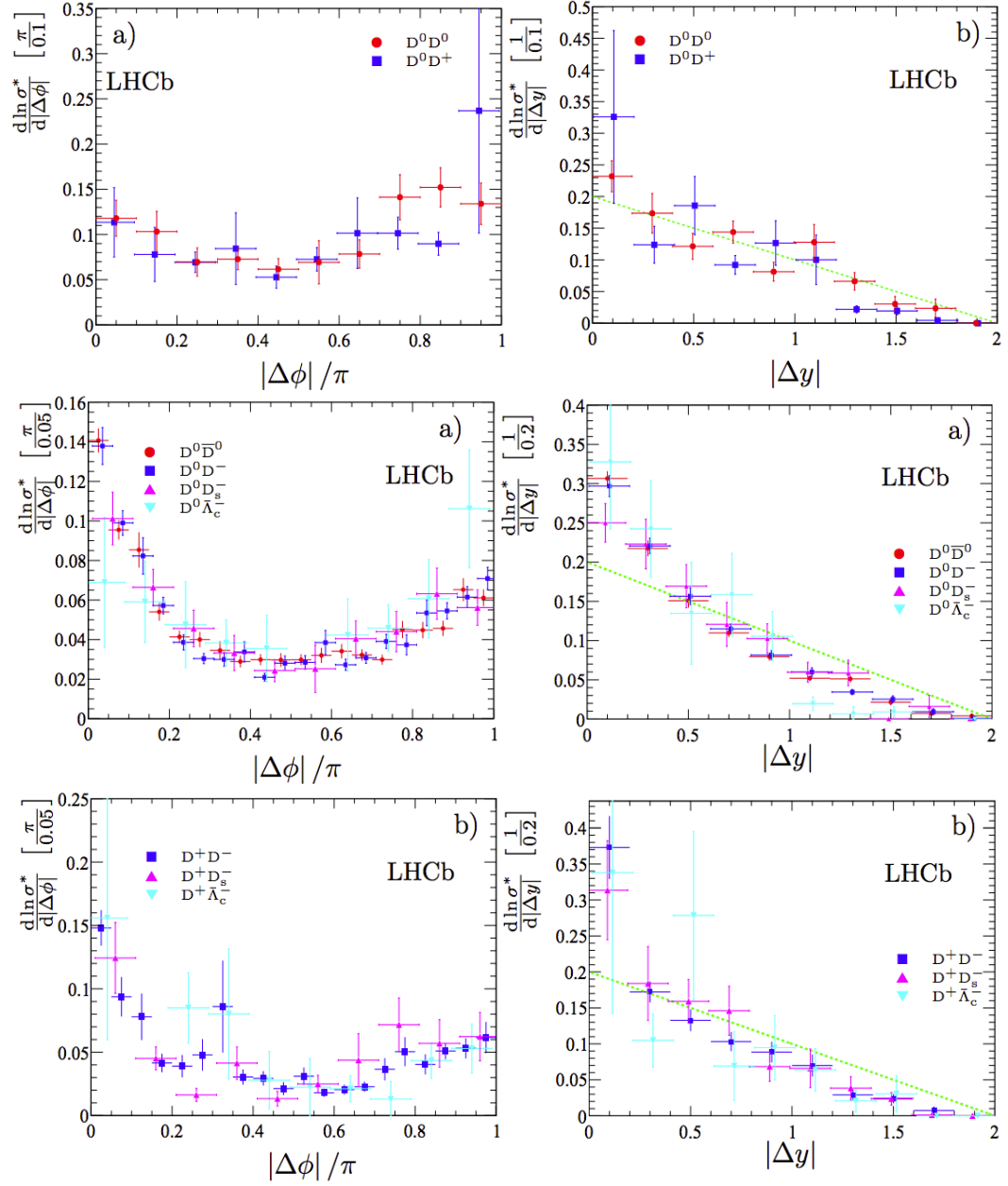


Fig. 1.29: [LHCb] Comparison of azimuthal correlation distributions ($\Delta\phi, \Delta\eta$) between heavy-flavour hadrons (D, Λ_c) in cc and $c\bar{c}$ events in pp collisions at $\sqrt{s} = 7$ TeV. The green dashed line shows in $\Delta\eta$ distribution from uncorrelated events.

Figure 1.29 shows correlations in azimuthal angle $\Delta\phi$ and rapidity $\Delta\eta$ plane between two open charmed hadrons (e.g. D, λ_c). The measurements show that the $\Delta\phi$ correlations in cc events are consistent with a flat distributions (top left plot of Figure 1.29) whereas a clear enhancement is observed in $c\bar{c}$ events at small $|\Delta\phi|$ (middle and bottom left plots of Figure 1.29). This enhancement is found to be consistent with the production of $c\bar{c}$ via gluon splitting processes [119]. The $\Delta\eta$ correlations also show similar enhancement at small $\Delta\eta$ values in $c\bar{c}$ events whereas distributions in cc events are triangular in shape. This shape is expected when rapidity distributions of charm hadrons are flat and do not have any correlation. In summary, LHCb measurements provided an important information about charm production mechanisms and properties of charm events. Furthermore, the angular correlation using electrons from heavy-flavour hadron decays (HFe) are also measured to estimate the contribution of electrons from beauty heavy-flavour hadron decays. The estimation of beauty contribution allows one to understand heavy-quark productions, e.g. dependency of quark masses on their energy loss and also provide necessary reference for energy loss measurements in heavy-ion collisions.

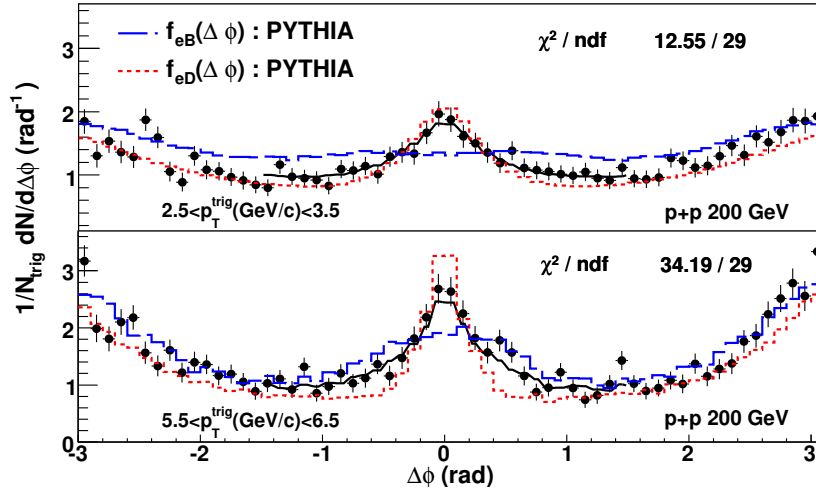


Fig. 1.30: [STAR] Per trigger azimuthal correlation between non-photonic electrons in p_T range, 2.5–3.5 GeV/ c (top) and 5.5–6.5 GeV/ c (bottom) with charged hadrons, the dotted and dashed curves represent the simulation expectations from D and B decays.

The STAR collaboration studied contribution of beauty in non-photonic electron production via heavy flavour correlations as shown in Figure 1.30 [120]. The beauty contribution of about 50% was observed at $p_T \leq 5$ GeV/ c , which indicates that at high p_T beauty production is suppressed in heavy ion collisions. The measurement also provided additional constraints to R_{AA} measurement of electron from B and D meson decays. ALICE collaboration has also measured beauty production via correlation measurements by using elec-

trons from semi-leptonic decay of beauty hadrons in pp collisions at $\sqrt{s} = 7$ TeV. Different correlation patterns for charm and beauty electrons are observed as shown in Figure 1.31 and was expected due to different decay kinematics of charm and beauty hadrons [121].

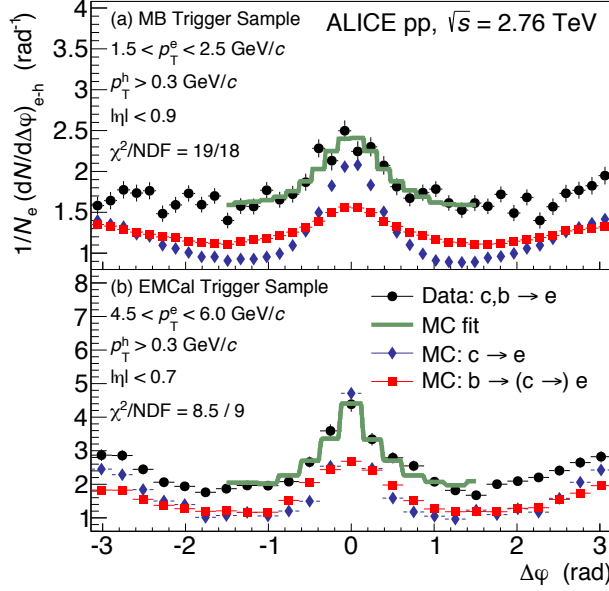


Fig. 1.31: [ALICE] Per trigger azimuthal correlation between heavy-flavour decay electrons in p_T range, 1.5–2.5 GeV/c (top) and 4.5–6.0 GeV/c (bottom) with charged hadrons, the diamonds and squares represent the simulation expectations from D and B decays.

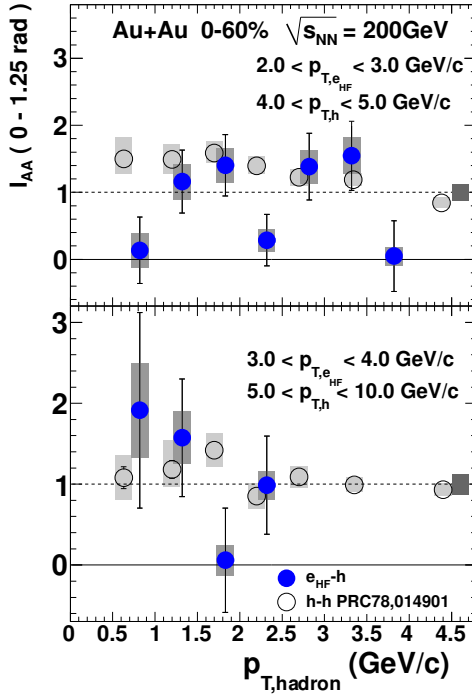


Fig. 1.32: [PHENIX] NS ($0 < \Delta\phi < 1.25$) correlation yield as a function of associated p_T for $2.0 < p_T^e < 3.0$ GeV/c (top panel) and $3.0 < p_T^e < 4.0$ GeV/c (bottom panel).

~ Heavy-ion collisions

Heavy flavour correlation measurements can also provide further insight into medium effects on heavy (charm and beauty) quarks. Similar to light flavour, comparison of azimuthal correlations in pp and Pb-Pb collisions can provide detailed information about the processes by which heavy quarks lose energy in QGP. One can spot possible modifications to the charm parton shower and hadronization in the presence of medium. The first attempt of heavy-flavour azimuthal correlation measurements between heavy-flavour decay electrons and charged hadrons in Au-Au collisions was made by PHENIX collaboration to address heavy-quark energy loss inside the medium [122]. Figure 1.32 shows NS correlation yield as a function of associated particle p_T^{assoc} . Results show that within large uncertainty I_{AA} is consistent with unity and are also consistent with light flavour (di-hadron) measurement [62]. AS correlation properties, where energy loss is observed by other measurement were not calculated because of insufficient statistics.

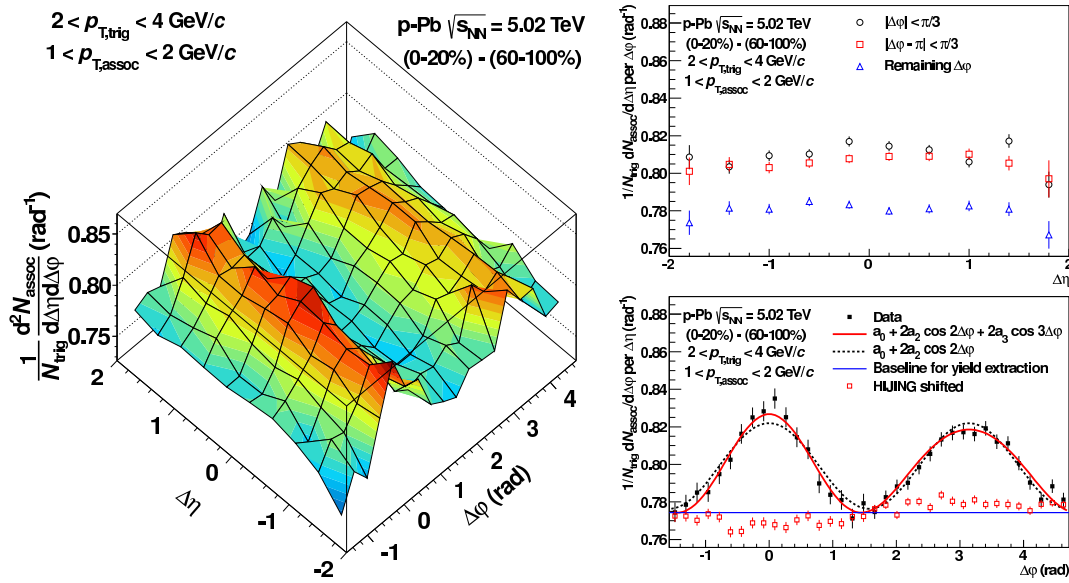


Fig. 1.33: [ALICE] Left panel: per trigger ($\Delta\phi$, $\Delta\eta$) azimuthal correlation between trigger charged particle $2 < p_T^{trig} < 4$ GeV/c and associated charged particle $1 < p_T^{assoc} < 2$ GeV/c in subtracted centrality class (0–20% - 0–60%) of p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Right panel: top plot shows $\Delta\eta$ projected correlation for different $\Delta\phi$ intervals and bottom plot shows near-side $\Delta\phi$ projected correlation in $0.8 < \Delta\eta < 1.8$, with comparison to the simulation using HIJING event generator.

~ Proton-lead collisions

The study of long-range heavy-flavour angular correlations (**one of the aim of current analysis in p-Pb collisions**) may shed light on underlying production mechanisms which give rise to the double-ridge structure observed in light-flavour di-hadron correlations with high multiplicity p-Pb collisions [123, 124]. In light flavour correlation measure-

ments, $(\Delta\varphi, \Delta\eta)$ the distributions are obtained for two different event centralities; central (0–20%) and peripheral (60%–100%) in p–Pb collisions. In order to quantify the differences in these two centrality classes (low and high multiplicity environment), correlation distributions are subtracted. The CMS collaboration reported first results on long-range correlation in p–Pb collisions, where double ridge structure in NS and AS correlations has been seen [124]. The ALICE collaboration later confirmed the similar structure in centrality subtracted (high to low) correlation distributions as shown in the left plot of Figure 1.33. The results confirm a distinct excess in correlation structure as previously reported by CMS collaboration. The two ridges in NS and AS correlation regions are observed and near-side ridge is qualitatively similar to CMS results. It has been suggested that this structure may be due to collectivity or gluon saturation effects [125, 126]. Therefore, the similar observation with heavy-flavour correlations may help to distinguish between collectivity or gluon saturation effects scenarios.

Chapter 2

A Large Ion Collider Experiment

“I have not failed. I’ve just found 10,000 ways that won’t work...”

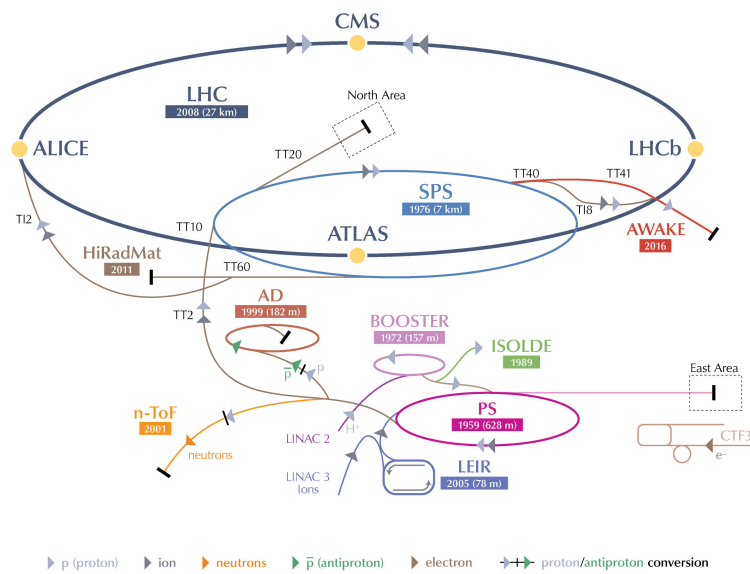
— Thomas Edison

abstract: This chapter describes the Large Hadron Collider (LHC) accelerator, details of A Large Ion Collider Experiment (ALICE) detector and its subsystems used in the analysis of azimuthal correlation between D^+ meson and charged particles in pp and p–Pb collisions.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [127, 131] straddling between Switzerland and France is the World’s largest and most powerful particle accelerator built and operated by the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. It consists of the double rings (counter-rotating beams) enclosed by superconducting magnets with a number of accelerating structures installed in a tunnel having a circumference of 26.7 kilometers, buried 50-175 meters underground. The LHC is designed to produce head-on collisions between two particles beams circulating in the opposite direction, either of protons up to the maximum centre of mass energy $\sqrt{s} = 14$ TeV or heavy ions (lead ions) up to $\sqrt{s}_{NN} = 5.5$ TeV [127]. In addition to the proton-proton and the lead-lead collisions, LHC is also capable of producing the head-on collision between protons and lead ions. The basic structure of the LHC accelerator is shown in Figure 2.1 [128] and example of its parameters for pp collision at centre of mass energy $\sqrt{s} = 13$ TeV are listed in Table 2.1 [129].

CERN's Accelerator Complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
 AD Antiproton Decelerator CTF3 Clic Test Facility AWAKE Advanced WAKEfield Experiment ISOLDE Isotope Separator OnLine DEvice
 LEIR Low Energy Ion Ring LINAC LInear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

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Fig. 2.1: Large Hadron Collider accelerator ring complex. [source:\[128\]](#).

Inside the LHC accelerator, two high-energy particle beams in separate beam pipes are circulated with speed nearly equal to that of light, in the opposite directions before they are made to collide. They are kept in an ultrahigh vacuum tube, and in circular orbit using a strong magnetic field maintained by the superconducting electromagnets. The protons or ions circulating in the two LHC rings are made to collide at four different points (pits), Presently, at pits 1, 2, 5 and 8, where four different major experiments namely, ATLAS, ALICE, CMS and LHCb have been built.

Quality	Number
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, protons	6.5 TeV
Nominal energy, ions	2.76 TeV/nucleon
Nominal energy, protons collisions	13 TeV
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11245
Number of collisions per second	1 billion

Tab. 2.1: Description of LHC parameters used in pp collisions at $\sqrt{s} = 13$ TeV. [source:\[127\], \[129\]](#).

Proton-Proton collisions: The beam of protons up to 50 MeV is produced by stripping off the orbiting electrons from the hydrogen atoms at the Linac-2 station and sent to the Proton Synchrotron Booster (PSB) for the initial stage acceleration up to 1.4 GeV. The beam is then fed to the Proton Synchrotron (PS) for next level of acceleration up to 25 GeV and injected into the Super Proton Synchrotron (SPS), where it is accelerated further up to 450 GeV. In the end, the beam is transferred to the LHC for the maximum acceleration up to

the energy of 7 TeV. So far at LHC, proton-proton (pp) collision data at the centre of mass energies of 0.9, 2.76, 5, 7, 8 and 13 TeV have been collected in past years.

Heavy-Ion collisions: The LHC collides the “Lead” ions produced by the Electron Cyclotron Resonance (ECR) source. These lead ions are transferred to Linac-3 station for the initial stage acceleration. ECR permits generation of multi-charged ions states using heat, magnetic field, and microwaves. ECR produces different charged ion states, and for lead, the maximum of 27+ charged ion states occur. The Pb^{27+} ions at Linac-3 are accelerated up to 4.2 MeV/nucleon and passed through a carbon foil to strip most of them to the Pb^{54+} ions. These Pb^{54+} ions are accumulated and accelerated up to an energy of 72 MeV/nucleon in the Low Energy Ion Ring (LEIR) and sent next to the PS. The Pb^{54+} ions are further accelerated by PS up to 5.9 GeV/nucleon and again made to pass through a second foil which fully ionizes them to Pb^{82+} ions. The Pb^{82+} ions are then transferred to the SPS to accelerate them up to 177 GeV/nucleon and finally injected into the LHC, where they can be accelerated up to their maximum energy of 2.76 TeV/nucleon. So far at LHC, heavy-ion (Pb-Pb) data have been collected for two centre of mass energies, namely, $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV.

Proton-lead collisions: The LHC also recorded data for proton-lead collisions at the centre of mass energy $\sqrt{s_{NN}} = 5.02$ TeV, where the beam of proton and lead are prepared in a same manners as described in the previous sections.

2.2 Physics Programme at the LHC

Two large experiments, the ATLAS (A Toroidal LHC ApparatuS) at Pit 1 and the CMS (Compact Muon Solenoid) at Pit 5, lie diametrically opposite in the LHC ring. They are the general purpose experiments, which concentrate on the physics predictions of the standard model and beyond it, such as signatures of supersymmetry (SUSY) and dark matter. In particular, one of the primary goals to prove the existence of the Higgs boson, which was declared to be found in July 2012 [132, 133]. Both ATLAS and CMS experiments have also a research program for the physics of heavy-ion collisions too. The LHCb (LHC-beauty) experiment at Pit 8 uses a forward detector and mainly focuses on the rare phenomena of Beauty decay (B Physics) and CP asymmetries. The significant contribution from LHCb collaboration, recently, has been the CP-violation measurement via the D^0 meson decay channels [134]. ALICE (A Large Ion Collider Experiment) at Pit 2 is specifically optimized for the study of heavy-ion collisions, primarily for the study of Quark-Gluon Plasma (QGP), a state of matter consisting of deconfined quarks and gluons. In addition

to heavy-ion, ALICE has also reached the physics program for proton-proton and proton-lead collisions, one of the recent outstanding results from ALICE collaboration has been the precision measurement of light nuclei-antinuclei mass difference [135]. The other significant results from ALICE collaboration has been the measurements of η/s value, di-jet asymmetry and collectivity in small systems, which provided insight into the QCD. The list of main operations so far at LHC, are summarised in Table 2.2.

Year	Programme highlights
2008, Sep	LHC delivered first beam but stopped after one week (19 th Sep) due to technical issue
2009, Nov	Restarted with lower energy beam
2009, Nov	First pp collisions data at $\sqrt{s} = 900$ GeV with $\mathcal{L}_{peak} = 5.2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 19.6 \mu\text{b}^{-1}$)
2009, Dec	First scientific results from LHC (from the ALICE detector)
2010, Mar	Data for pp collisions at $\sqrt{s} = 7$ TeV with $\mathcal{L}_{peak} = 1.7 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 0.5 \text{ pb}^{-1}$)
2010, Nov	Data for Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV with $\mathcal{L}_{peak} = 2.8 \times 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 9 \mu\text{b}^{-1}$)
2011, Mar	Data for pp collisions at $\sqrt{s} = 7$ TeV with $\mathcal{L}_{peak} = 9 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 4.9 \text{ pb}^{-1}$)
2011, July	Data for pp collisions at $\sqrt{s} = 2.76$ TeV with $\mathcal{L}_{peak} = 4.4 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 46 \text{ nb}^{-1}$)
2011, Nov	Data for Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV with $\mathcal{L}_{peak} = 4.6 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 146 \mu\text{b}^{-1}$)
2011, Dec	First new composite particle discovery, the χ_b (3P) bottomonium meson
2012, Apr	Data for pp collisions at $\sqrt{s} = 8$ TeV with $\mathcal{L}_{peak} = 0.2 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 9.7 \text{ pb}^{-1}$)
2012, Jul	Announcement of the discovery of a Higgs-like particle
2012, Dec	Data for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with $\mathcal{L}_{peak} = 5 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 0.89 \text{ nb}^{-1}$)
2013, Feb	Data for pp collisions at $\sqrt{s} = 2.76$ TeV with $\mathcal{L}_{peak} = 2.2 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mathcal{L}_{int} = 129 \text{ nb}^{-1}$)
2013, Feb	The last beams of the year and first LHC shut down for 2 years
2015, Mar	First injection tests for the Run 2 phase of LHC
2015, May	Data for pp collisions at $\sqrt{s} = 13$ TeV with $\mathcal{L}_{peak} = 5 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$
2015, Nov	Data for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with $\mathcal{L}_{int} = 225 \mu\text{b}^{-1}$
2016, Jun	The LHC achieves its designed luminosity value of $\mathcal{L} = 1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Tab. 2.2: Summary of main operations at the LHC and ALICE data taking. [source:\[128\]](#).

2.3 ALICE detector

ALICE is one of the four major experiments at LHC [136], which is specifically optimized for the study of heavy-ion collisions. The prime aim of ALICE is to examine in detail the behavior of nuclear matter at high densities and temperatures, where the formation of a new phase of matter, QGP is expected. The existence of QGP and its properties, understanding of confinement, and chiral-symmetry restoration phenomena are the key issues in QCD. The design of ALICE detector has been very well configured to handle the high multiplicity environment anticipated for heavy-ion (Pb-Pb) collisions (dN_{ch}/dy up to ~ 8000 at mid-rapidity). Therefore, ALICE has very high detector granularity. The ALICE detector can do tracking and particle identification from particle momentum ~ 100 MeV/ c to ~ 10 GeV/ c , which also allows the investigation of variety of other physics observables. ALICE has overall dimensions of $16 \times 16 \times 26$ m³ and a total weight of around 10k tons. The layout of the ALICE detector is shown in Figure 2.2. It is composed of seventeen detector systems that can be seen as the group of central barrel and forward-backward detectors based on their pseudorapidity (η) coverage.

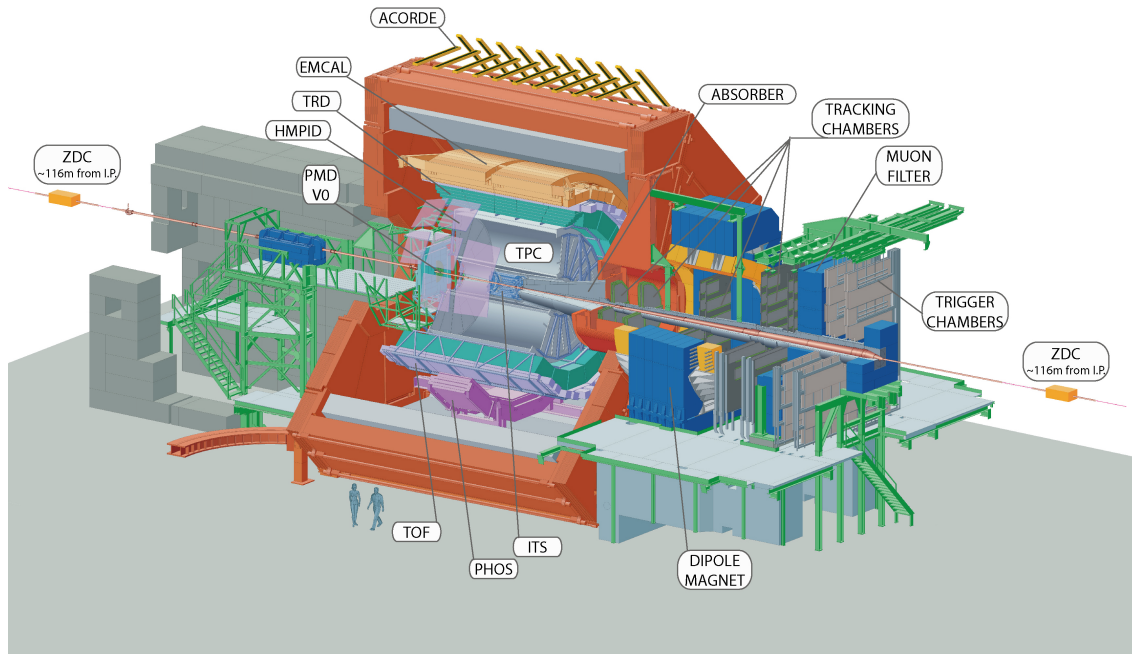


Fig. 2.2: The schematic view of the ALICE detector.

Central Barrel Detectors: The detectors in this region are mainly responsible for tracking and identification of charged particles and photons. They are embedded in magnetic field

$B \leq 0.5$ T, which is generated by the large L3 solenoid magnet. Main detectors in this region are:

- **Inner Tracking System (ITS):** High precision silicon detectors mainly focused on vertexing and the tracking of charged particles.
- **Time Projection Chamber (TPC):** Cylindrical shaped gas detector, which is primary detector for the tracking of charged particles supported by ITS. It is also used for identification of charged particles via energy loss (dE/dx) mechanism.
- **Time-of-Flight (TOF):** It consists of Resistive Plate Chambers (MPWC) with excellent intrinsic time resolution to provide high-precision time measurements. It is used for particle identification and capable of separating particles via ratios such as π/K ratio up to $2.2 \text{ GeV}/c$ and K/p ratio up to $4 \text{ GeV}/c$.
- **Transition Radiation Detector (TRD):** It provides electron identification at momentum in excess of $1 \text{ GeV}/c$, where the rejection of pions via TPC energy loss measurement is not sufficient.
- **High Momentum Particle Identification Detector (HMPID):** It is specialized to extend ALICE particle identification feature in higher momentum region (up to 3 GeV for the $\pi(K)$ and up to $5 \text{ GeV}/c$ for the protons), which is beyond the momentum range allowed by the energy loss measurements (ITS and TPC) and by the TOF.
- **Photon Spectrometer (PHOS):** It is a high resolution electromagnetic calorimeter based on leadtungstate crystals (PWO) and optimized for measuring photons in p_T range $0.5\text{-}10 \text{ GeV}/c$, neutral pions in p_T range $1\text{-}10 \text{ GeV}/c$, and η mesons in p_T range $2\text{-}10 \text{ GeV}/c$.
- **Electromagnetic Calorimeter (EmCal):** It is mainly used in the measurements of jet quenching.

Forward and Backward Detectors: In this region, detectors can be characterized into two categories; the first is muon spectrometer in the forward region for the study of muons and second contains general purpose detectors for event characterization and triggering.

- **Muon Spectrometer:** It is located in the forward region and consists of a complex arrangement of absorbers, dipole magnets, and fourteen planes of the tracking and triggering chambers.

- **Zero Degree Calorimeter (ZDC):** The primary role of ZDC is to measure the number of spectator nucleons (centrality measurement in heavy-ion interaction).
- **Photon Multiplicity Detector (PMD):** It is a gas proportional counter, measures event-by-event photon multiplicity and spatial (η , φ) distributions of photons.
- **Forward Multiplicity Detector (FMD):** It measures charged particle multiplicity in the forward pseudorapidity region. Along with the ITS detector at central rapidity, FMD can provide charged particle multiplicity in wider pseudorapidity coverage $-3.4 < \eta < 5.1$.
- **V0 Detector:** It consists of two arrays of scintillator counters (V0A and V0C). The V0 detectors are involved in fast triggering and centrality determination tasks.
- **T0 Detector:** It consists of two arrays of Cherenkov Counters. T0 measures the collision time and it also provides an early “wake-up” signal to the TRD.

The primary subsystems of ALICE detector used in current analysis of D^+ meson - charged particle azimuthal correlations are the ITS, TPC, and the TOF. Next sections elaborate the detailed description of their design and performances.

2.3.1 Inner Tracking System

The Inner Tracking System (ITS) shown in Figure 2.3 is installed around the beam pipe. The primary purpose of the ITS detector is to provide the precise measurement of collision vertex and tracking of charged particle. It consists of six cylindrical layers of silicon detectors within $z_{vtx} = \pm 10.6$ cm from the collision interaction point (i.e. $\pm 1\sigma$ of the luminous region). The layers are located from the innermost to outermost at radii 39 mm and 430 mm covering the pseudorapidity range from $|\eta| < 1.98$ to $|\eta| < 0.9$. Key tasks of the ITS is to provide:

- Precise determination of the distance of closest approach (DCA) with respect to the primary vertex to detect secondary vertices originate from the hyperons, and heavy flavour hadrons decay with a resolution better than 100 mm.
- Impact parameter and momentum resolution of the tracks reconstructed with the TPC.

- Excellent tracking performance, down to very low momenta (below 200 MeV/c) for high multiplicity environment created in heavy-ion collisions.

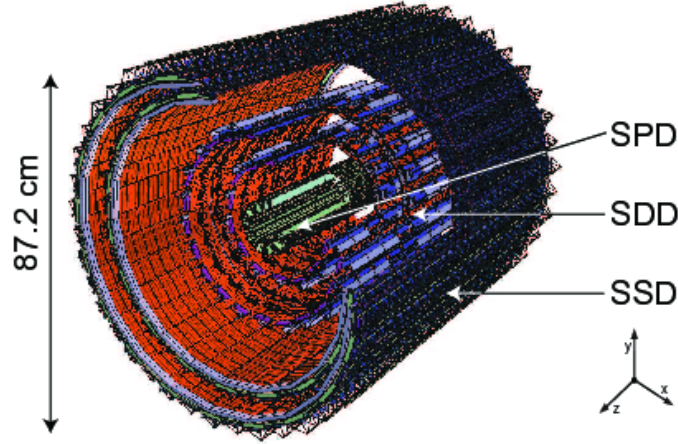


Fig. 2.3: Layout of the Inner Tracking System.

To achieve the high precision measurements of track DCA, energy loss dE/dx , and desired spatial resolution, the material budget of ITS has been kept quite low. This also minimizes the effects of multiple scattering, radiation levels and high granularity to ensure the low occupancy in central heavy ions collisions. The first two innermost layers of the ITS are made of Silicon Pixel Detectors (SPD), while the two intermediate layers are Silicon Drift Detectors (SDD) and the last two outermost layers, where the track density has comparatively less, are equipped with the double-sided Silicon Strip Detectors (SSD).

Silicon Pixel Detectors (SPD) The two innermost layers of ITS, with average radii of 3.9 cm (about 1 cm from the beam pipe) and 7.6 cm, are equipped with SPD. SPD plays a key role in the determination of primary and secondary vertex. It consists of high granularity pixels, a total of 9.8×10^6 with size $50(r\phi) \times 425(z) \mu m^2$ of each pixel. Considering this, one can achieve the excellent track spatial resolution of about $12(r\phi) \times 100(z) \mu m^2$ and track separation up to $50 \text{ tracks}/cm^2$ in the high track density environment (central Pb–Pb collisions). In addition to the tracking and vertexing capabilities, SPD can also provide a first level (L0) trigger signal, which is commonly used in the definition of minimum-bias events in all colliding systems.

Silicon Drift Detectors (SDD) The two intermediate layers, with average radii of 15.0 cm and 23.9 cm, are equipped with Silicon Drift Detectors, which covers a pseudorapidity range, $|\eta| < 0.9$ over full azimuthal angle. The key role of SDD is to provide a good track separation and dE/dx measurement for the particle identification.

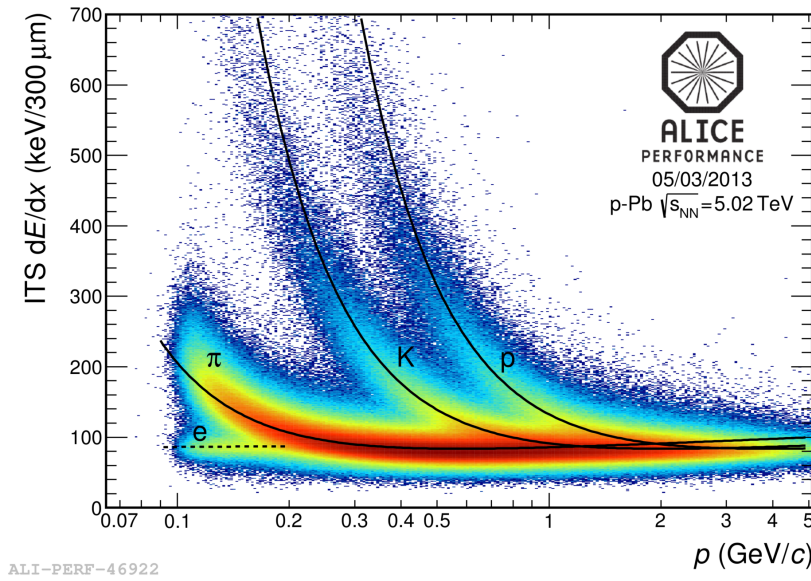


Fig. 2.4: The charged particle dE/dx distribution using ITS standalone track as a function of track momentum in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Silicon Strip Detectors (SSD) The two outermost layers, with average radii of 38.0 cm and 43.0 cm, are equipped with SSD, which covers a similar $|\eta| < 0.9$ range over full azimuthal angle. The main principle of SSD is the collection of e-h pairs created by charged tracks while passing through to SSD sensors. Its design provide two-dimensional position of charged track, allowing particle identification via dE/dx measurement. Figure 2.4 shows dE/dx distribution of the charged particles as a function of momentum using standalone ITS reconstructed tracks, where different bands of dE/dx distribution represent different particle species.

2.3.2 Time Projection System

TPC is the primary detector for charged particle tracking, which covers pseudorapidity range, $|\eta| < 0.9$, over full azimuthal angle. Together with other central barrel detectors (ITS, TRD, and TOF), TPC can provide charged particle momentum with a good two-track separation, particle identification and vertex determination. TPC can measure charged particle transverse momentum (p_T) from 100 MeV/c (with 1-2% resolution) to 100 GeV/c (5% resolution with ITS), which also enables the particle identification via dE/dx measurement in the intermediate p_T region. In addition to this, TPC can also provide statistical separation of the pions, kaons and protons yield at high p_T , exploiting the dE/dx relativistic rise, which is important for the studies of fluctuations in hadronic observables on an event-by-event basis.

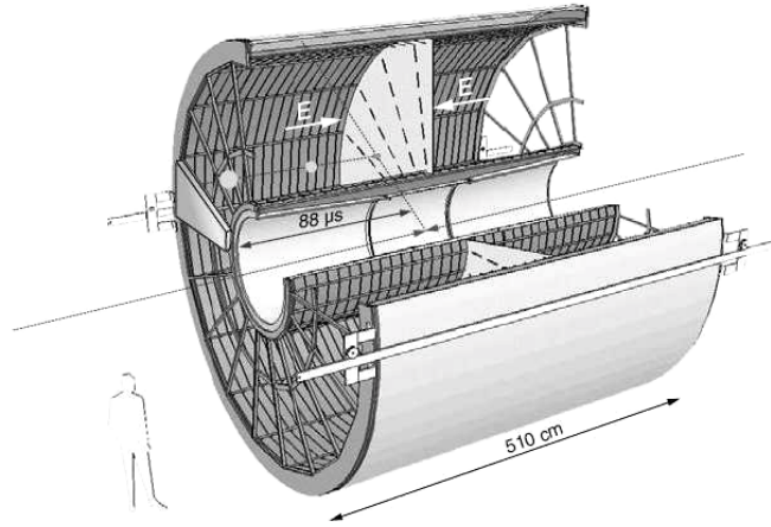


Fig. 2.5: Layout of the Time Projection Chamber.

Design: TPC is a cylindrical shaped gas detector with an inner and outer radius of about 85 cm and 247 cm respectively. The overall length of TPC along the beam direction (z) is 510 cm. It covers pseudorapidity range $|\eta| < 0.9$, which matches with other surrounding detectors like ITS, TRD, and TOF. Figure 2.5 shows a schematic view of the TPC detector. TPC is designed with cylindrical field cage containing central high voltage (100 kV) electrode to fulfill the requirements of minimal material in the transverse direction of beam. The opposite axial potential degraders at both ends of TPC cylinder provides a highly uniform electrostatic field of 400 V in the full detector gas volume. The light counting gasses, 90% Ne and 10% CO_2 over 88 m^3 volume are used to keep low material budget and to reduce multiple scattering as well as secondary particle production.

Working principle: Whenever a charged particle enters into the TPC gas volume, it ionizes the filled gas along its path and produces ions and electrons. These generated electrons drift towards the end plates, where Multi-Wire-Proportional Counter (MWPC) is installed to measure the relative charged signal. The conventional MWPC with cathode pad readout chambers are mounted into eighteen trapezoidal sectors at each end plate of TPC. In total 570k readout pads in three different sizes varying from 0.3 cm^2 at the inner radius to 0.9 cm^2 at outer radius are used in trapezoidal sectors to keep low occupancy, which is necessary requirement for getting better dE/dx and position resolution.

Particle Identification: The particle identification mechanism of TPC is based on the specific energy loss (dE/dx), charge and momentum of the particle. The specific ionization

energy loss is described by the Bethe-Bloch formula, which is parameterized by a function proposed by ALEPH Collaboration [137].

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln \left(P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right) \right) \quad (2.1)$$

Here β is the particle velocity, γ is relativistic factor and P1-5 are the fit parameters. Figure 2.6 shows specific energy loss dE/dx , as a function of particle momentum. Results show a clear separation between different particle bands and solid lines represent the parameterization of Bethe-Bloch formula describing different particle species. TPC provides dE/dx resolution of about $\sim 5\%$ (6.5%) in pp collisions (0-5% most central Pb-Pb collisions).

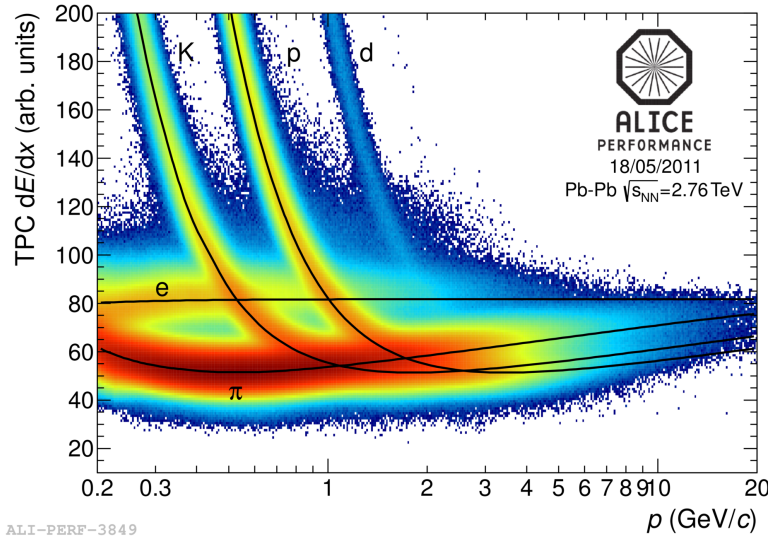


Fig. 2.6: Specific ionization energy loss (dE/dx) of particles in the TPC as a function of particle momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

2.3.3 Time of Flight

TOF detector provides particle identification in the extended p_T region. Together with the ITS and TPC, TOF can provide particle identification of 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. TOF has a global time resolution of about 80 ps, which allows to provide better separation than 3σ , for π/K ratio up to 2.5 GeV/c and K/p ratio up to 4 GeV/c.

Design: It is based on Multi-gap Resistive-Plate Chambers in a cylindrical configuration at the inner and outer radius of about 370 cm and 399 cm from the beam axis. The total length

of TOF detector is 7.45 meter and covers pseudorapidity range $|\eta| < 0.9$ over full azimuthal angle. TOF is composed of 18 sectors in azimuthal plane ($r\phi$) and each of these sectors are arranged into five segments oriented in z direction. The readout of TOF consists of about 152k sensitive pads of dimension $2.5 \times 3.5 \text{ cm}^2$ with time resolution of about 100 ps.

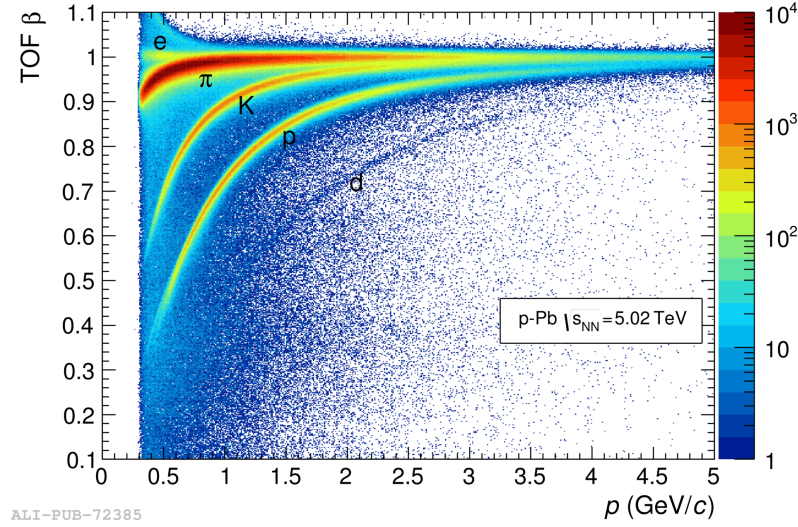


Fig. 2.7: Distribution of measured TOF β as a function of particle momentum in p–Pb collision.

Working Principle: The entry of charged particle creates ionization in the gas volume, which is amplified by the applied high electric field via electron avalanche process. The job of resistive plates is to stop this avalanche process in each gap and provide the total signal, which is the sum of signals from all gaps. TOF measures charged particle velocity $v = L/t$ based on the measurement of time of flight “t” of the charged particle over its known trajectory length “L”. The particle identification in TOF requires momentum and mass of charged particle. The measurement of particle momentum is possible via tracking from the other detectors, and the value of mass can be measured via momentum, $p = (t^2(t^2 - 1))$. The start time for TOF is provided by the T0 detector, which enables its PID measurement. If the signals from T0 detector are not available, then an average of particles arrival time with minimum of three particles is used as start time. Finally, in case of unavailability of both above methods, an average start time of the run is employed.

Particle Identification: The particle identification strategy in TOF is based on time difference between the measured and expected value, computed for each mass hypothesis from the track momentum (p) and length (L). Figure 2.7 shows measured velocity distribution of particles as a function of momentum which is measured by TPC in p–Pb collisions. The distribution is fitted with a Gaussian function whose width is the convolution of intrinsic

sic time resolution of TOF and resolution of event time. The bands of different particle species are well separated as discussed above.

2.3.4 Track and Vertex Reconstruction

Vertex Reconstruction

Reconstruction of the primary and secondary vertices with precision is the prerequisite to perform exclusive reconstruction of heavy flavour particles, which decays after few hundreds of μm due to their short lifetime. The precise measurement of primary vertex reconstruction allows measuring the displacement of decay vertex, which helps in improving their impact parameter resolution. It also provides a reference point for track reconstruction algorithm to construct the particle trajectories. At the time of data taking or at online level, a correct estimation of primary vertex position is mandatory to keep under control the beam position inside the interaction region and also essential to measure its spread along the x , y and z coordinates. Two innermost layers (SPD) of ITS detector are the most suitable system for reconstruction of primary vertex at online level. The initial estimation of interaction vertex position is measured as a space point at which the maximum number of tracklets, known as association of two clusters in the inner and outer layers of SPD, are covered. In ALICE, three different algorithms are mainly used to reconstruct the 3-dimensional primary vertex.

VertexerSPD3D: This algorithm can be characterized by the three steps called tracklet finding, tracklet selection, and vertex determination. In track finding step, the tracklets are constructed, requiring that they cross the fiducial region of cylindrical ITS. Then selection step of these tracklets is based on exploiting the distribution of intersection point of their pairs. Finally, in third step, 3-dimensional coordinates of the vertex are determined by finding a point of minimum distance among the tracklets. The vertex coordinates are then re-calculated by applying an additional selection on tracklets, based on their displacement from the first vertex estimation (removing tracklets farther than 1 mm). Algorithm steps are repeated once again with reduced fiducial region and tighter selections on tracklets. Finally, some additional demands on vertex position are imposed for final vertex position measurement, e.g. the point must be inside the beam pipe, having at least one tracklet contributor in the algorithm.

VertexerSPDz: This algorithm is typically used in case of very low multiplicity events, where quite often the VertexerSPD3D algorithm fails. This algorithm provides the z coordinate of primary vertex if other two coordinates are known with a minimum accuracy

of 200 μm . The tracklets in this algorithm are constructed by matching SPD points in the outer and inner layer within a small azimuthal window. The smaller azimuthal window is used to, reduce combinatorial background, avoid multiple scattering effects and select high momentum tracks (better approximated by straight lines). Initial attempt for the vertex determination on z position is made by computing a weighted average (z_{mean}) of z_i coordinates, which fall in the “Region of Interest” (ROI), defined as area nearby peak of z_i distribution. The calculation of z coordinate of the vertex is then re-iterated by re-centering ROI on previous z_{mean} position, until a symmetric region around z_{mean} is achieved. This process allows minimizing a bias caused by asymmetries in the tails of z_i distributions.

VertexerTracks algorithm: This algorithm provides higher precision on vertex determination in comparison to previous two algorithms, but it requires pre-reconstructed tracks. The reconstructed tracks are only used after qualifying criteria of having minimum number of clusters in their reconstruction process or the condition to fall inside cylindrical fiducial region with $r < 3$ cm and $|z| < 30$ cm. This algorithm can also be characterized by three steps: track selection, vertex finding and vertex fitting. The first step removes secondary and “fake” tracks, and in second step, vertex position is calculated as a point where the distance between accepted tracks is minimum. The second step is done in two iterations. In the first iteration, tangent to the tracks at nominal beam position is used, whereas in second iteration tracks are prolonged backward to the primary vertex found in first iteration. Finally, in the third step, tracks are extrapolated back to vertex position estimated in second step and a fitting algorithm obtains the best estimation of vertex position and its covariance matrix.

Track Reconstruction

The reconstruction of tracks is based on the Kalman filter algorithm [138], where tracks are locally parametrized as helices. The track parameters are updated at each point along its trajectory to encounter the path deviation of track due to its interaction with detector material.

Track reconstruction in the TPC: The searching of track path in TPC begins with a large radius and the seed for track searching process is obtained by using the information from two outermost TPC clusters and position of SPD vertex. A single charged track in TPC can produce a maximum of 159 clusters in the tangential pad rows of readout chamber. The condition of having at least 20 clusters and also a minimum of 50% of the expected clusters for a given track position are only accepted. The selected track is propagated towards inner radius of TPC using Kalman Filter algorithm. In simulation (ideal case of real

data), one can also calculate the track reconstruction efficiency, which is defined as ratio of reconstructed tracks to generated primary particles. Figure 2.8 shows charged track reconstruction efficiencies as a function of transverse momentum of the particle in pp and Pb-Pb collisions.

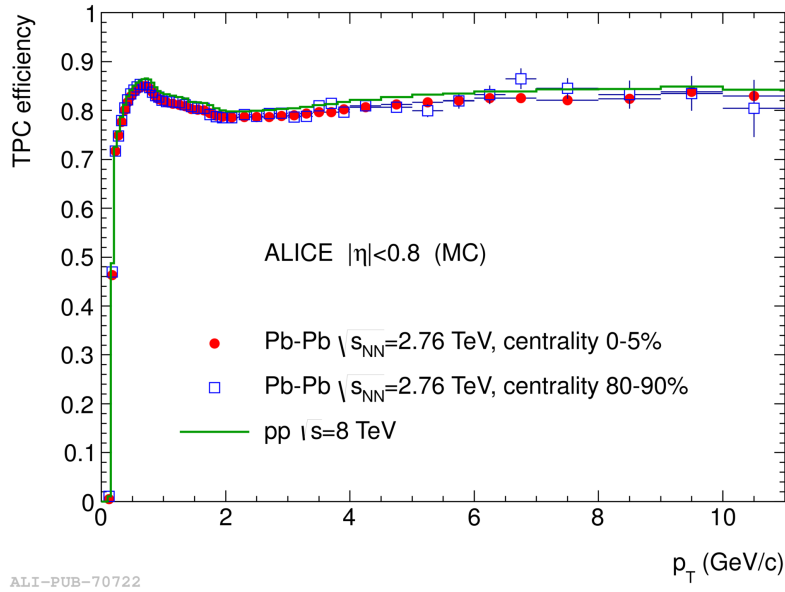


Fig. 2.8: [Simulation] TPC tracking efficiency for primary particles in pp and Pb-Pb collisions.

The drop in efficiency value at low p_T , around $0.5 \text{ GeV}/c$ is arising because of the energy loss and multiple scattering with detector material. Efficiency trend at larger p_T is governed by the loss of clusters; p_T dependent fraction of track trajectory projected on the dead zone between readout sectors.

Track reconstruction in the ITS: The matching of track is performed between reconstructed TPC track and reconstruction points in the outermost layers (SDD) of ITS, and this matching is used as a seed for ITS track finding process. The matched tracks are propagated down to innermost layers (SPD) of ITS within a proximity cut, which also takes into account the positions and errors. The track reconstruction in ITS is primarily performed in two steps. In first step, position of primary vertex is estimated using SPD pixels. This is used to guide the track finding and to maximize the efficiency of primary tracks. In the second step, vertex constraint is not used to allow track reconstruction with large displacements (e.g. tracks those originated from heavy flavour meson decays).

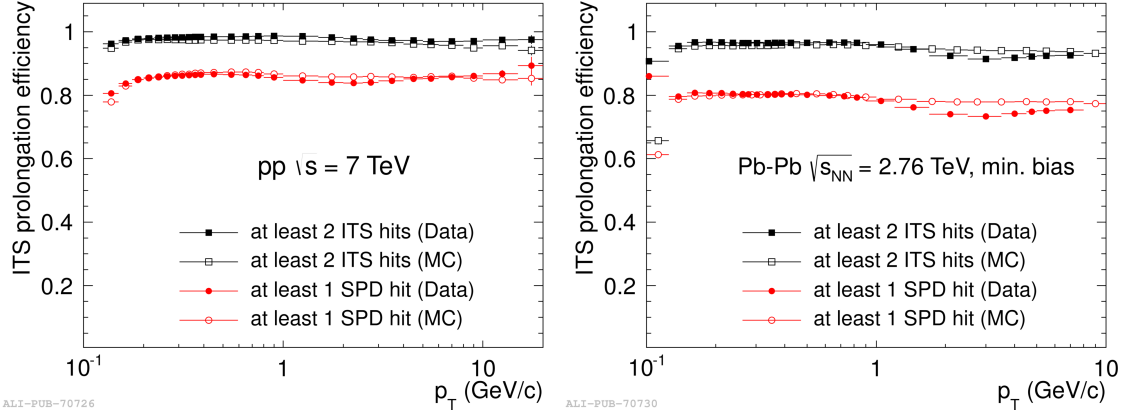


Fig. 2.9: ITS-TPC matching efficiency as a function of p_T for data and Monte Carlo simulation in pp collisions (left) and Pb-Pb collisions (right).

Figure 2.9 shows ITS-TPC matching efficiency as a function of track transverse momentum in pp and Pb-Pb collisions. The marker points (square and circle) show different efficiencies with various requirements of ITS/SPD hits in data and simulations. The matching efficiency is more than 95% with requirement of minimum two points in ITS and is about 85% when the requirement of at least one SPD point is imposed. The drop in the efficiency can be explained by presence of dead modules in SPD detector. Figure 2.9 also shows that the ITS-TPC matching efficiency in Pb-Pb collision is compatible with pp collision. The track reconstruction using standalone ITS is also measured with remaining clusters that were not used in combined ITS-TPC track reconstruction. The standalone ITS track reconstruction allows particle identification with very low momenta $80 \text{ MeV}/c$ using dE/dx measurements in SDD and SSD detectors.

Track back propagation: The reconstructed tracks from ITS are extrapolated from their point of closest approach to the preliminary interaction vertex and refitted using Kalman filter method in the outward direction. The length integral and time of flight of tracks are updated for the particle identification process. Once the track reaches to TRD detector, an attempt is made to match it with TRD tracklet. Similarly, tracks reaching TOF detector are matched to TOF clusters. Finally, tracks are propagated further for the matching with other detector signals e.g. EMCal, PHOS, and HMPID.

Inward fitting and vertex reconstruction with tracks: In the final stage of track reconstruction, all reconstructed tracks are refitted inward towards the TRD, TPC, and ITS without any constraint on SPD primary vertex. The position of interaction point is then recalculated with final reconstructed tracks, to improve the vertex reconstruction resolution using VertexerTracks algorithm.

2.4 Computing Facility at ALICE

ROOT: The development of the ROOT software started in 1994 in context of the past heavy-ion experiment, NA49 at CERN. It is the base platform where independent physics analysis applications are written. It has been entirely written in the C++ language containing built-in C++ interpreter and follows the Object Oriented Programming paradigm.

AliROOT and AliPhysics: The offline frameworks of ALICE, called AliROOT and AliPhysics based on ROOT, are used to reconstruct and analyze the data from real interactions as well as from Monte Carlo simulations. It can be executed on a local machine, a remote machine or cluster of machines with specific software enabled CAF (Cern Analysis Facility).

Grid Facility: The GRID computing facilities distributed over worldwide provides the excellent facility to analyze the huge amount of ALICE data in a reasonable time. The ALICE VO (Virtual Organization) sites spread over more than 80 different locations all around the world, shown in Figure 2.10.



Fig. 2.10: Snapshot of the ALICE-Grid sites worldwide. [source:\[139\]](#).

Chapter 3

Analysis Details and Methods

“Be less curious about people and more curious about ideas...”

— Marie Curie

abstract: This chapter describes methodology used in the measurement of angular correlation between D^+ mesons and charged particle in both pp and p–Pb collision systems. Section 1 includes a brief introduction to the analysis. In Section 2 and 3, details of pp and p–Pb collision data and the selection of collision events has been discussed. The detailed analysis procedure starting from the selection of trigger and associated charged particles to the background subtraction and various corrections are explained in Section 4.

3.1 Introduction

The analysis of azimuthal correlation between D^+ and charged particles follows the same methodology as is used in two-particle azimuthal correlation analysis. In two-particle correlation, azimuthal correlation pairs between a high p_T particle refer to “trigger” particle and other particles refer to “associated particle” from the same collision event are built. The correlation pairs are then accepted by requiring transverse momentum condition $p_T^{\text{assoc}} < p_T^{\text{trigger}}$. In this analysis, the trigger particle is defined as D^+ meson, which is reconstructed via its hadronic decay channel, $D^+ \rightarrow K^- \pi^+ \pi^+$ (Branching Ratio (BR) = 9.14 ± 0.19 %) and associated particles are defined as primary charged particles. As explained in the previous chapter, primary charged particles stand for charged hadrons produced directly from the primary vertex, including charged hadrons from the strong and electromagnetic decays and also from the decay of heavy-flavour hadrons. Since, a particle identity (D^+ meson) is defined as a trigger particle rather than a high p_T particle of an event, therefore, the condition of transverse momentum $p_T^{\text{assoc}} < p_T^{\text{trigger}}$ has not been used.

The angular correlation pairs are formed by selecting a trigger particle in the transverse momentum range $p_T^{D^+}$, 3–16 GeV/ c and associated particles with p_T^{assoc} threshold > 0.3 GeV/ c . The choice of trigger particles in transverse momentum range, $3 < p_T^{D^+} < 16$ GeV/ c is selected for two basic reasons, the first is to avoid large signal to background ratio of D^+ reconstruction in the low $p_T^{D^+}$ (< 3 GeV/ c) region and second is due to limited available statistics of D^+ candidates in the higher $p_T^{D^+}$ region (> 16 GeV/ c). The available statistics of run-2 LHC data recorded this year, with higher centre of mass energy $\sqrt{s} = 13$ TeV, will possibly allow exploring current measurement in the extended higher p_T trigger region as well as with better precision. In order to encounter the trigger p_T dependence, correlation pairs are separately evaluated in each of the trigger $p_T^{D^+}$ bin (1 GeV/ c interval) but to reduce the statistical fluctuations in results, correlation distributions are merged into three trigger $p_T^{D^+}$ regions, namely; low p_T (3–5 GeV/ c), mid p_T (5–8 GeV/ c) and high p_T (8–16 GeV/ c) region. Similarly, for associated particles, different p_T^{assoc} thresholds and range; > 0.3 GeV/ c , 0.3–1.0 GeV/ c and > 1.0 GeV/ c are used.

The analyses using other D meson candidates (e.g. D^0 , D^{*+}) as a trigger particle are also performed by the ALICE collaboration and consistent correlation results have been obtained. It was expected as all the three D mesons have similar particle properties. The fully corrected correlation distributions for all three mesons are obtained, and an average of the three individual results is finally computed to get better statistical precision on the results. This thesis work is the first ever measurement of the heavy-flavour correlation using D-mesons and charged particles. The analysis results are under process of paper publication from the ALICE collaboration [140] and will be discussed in the next chapter of analysis results.

Collision System	Type (AOD files)	Official Production #	Events analysed
proton-proton (pp) $\sqrt{s} = 7$ TeV	Data (Pass2, Min. bias)	LHC10b, 10c, 10d, 10e	~ 287 M ($M=10^6$)
	Monte Carlo (PYTHIA)	LHC10f7a, 10f6a, 10d4	~ 39 M
proton-lead (p-Pb) $\sqrt{s_{\text{NN}}} = 5.02$ TeV	Data (Pass2, Min. bias)	LHC13b, 13c	~ 90 M
	Monte Carlo (PYTHIA)	LHC13d3	~ 40 M

Tab. 3.1: Data set used for D^+ – charged particle azimuthal correlations in pp and p-Pb collisions.

3.2 Data Set

The measurement has been performed in pp collisions at centre of mass energy, $\sqrt{s} = 7$ TeV and in p-Pb collisions at centre of mass energy, $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The details of pp and

p–Pb collisions data, collected by the ALICE detector in year 2010 and 2013 are listed in Table 3.1. The Monte Carlo simulations used in various corrections, and validity checks are also listed in the same Table 3.1.

3.3 Event Selection

The physics events, selected by the minimum bias (MB) trigger is used for both pp and p–Pb analyses. The MB trigger is configured by demanding a hit in SPD detector or a hit in either of the VZERO-A or VZERO-C detector. This trigger configuration as the name implies is the least demanding of all the available triggers in ALICE framework and selects all inelastic proton-proton (or proton-lead) interactions. It allows one to separate beam-gas events over beam-beam events by using the timing information from the VZERO detectors. The selected events are then filtered out further by demanding only single good quality vertex, which itself is ensured by requiring minimum one track condition used in vertex reconstruction algorithm. All remaining MB events, basically with more than one reconstructed vertex called as pileup events are rejected from the analysis using a dedicated algorithm. Furthermore, events with longitudinal vertex position $|z_{vtx}| < 10$ cm relative to the nominal interaction point at $z = 0$ cm along the beam axis, are only considered. This selection is applied to insure the uniform track acceptance ($|\eta| < 0.8$) in the central barrel detectors of ALICE. e.g. ITS and TPC.

3.4 Analysis Method

In this section, stepwise detailed explanation of the analysis method, starting from selection procedure of a trigger particle and associated charged particles to the background subtraction and various analysis corrections, which finally adds up to obtain the fully corrected correlation distributions, is discussed.

3.4.1 Selection of trigger particle (D^+ meson)

The D^+ mesons and its charge conjugates used as a “trigger particle” are reconstructed via its hadronic decay channel, $D^+ \rightarrow K^- \pi^+ \pi^+$ (BR = 9.14 ± 0.19 %). To improve the signal to background ratio, we have exploited the fact that the decay of D^+ is through weak interaction and hence the signal (D^+ meson) extraction is based on reconstruction topologies of the secondary (decay) vertices, which are displaced from the primary vertex position.

Therefore, reconstruction of D^+ meson begins with the reconstruction of primary and secondary vertex. An invariant-mass analysis explained in the next section is then used to extract the D^+ trigger yield. Decay sketches of the prompt and feed-down D^+ meson are shown in Figure 3.1, where points a' and b' represents the position of primary and secondary vertex. The D^+ meson reconstruction strategy discussed in this subsection is categorised into three parts i.e. reconstruction of secondary vertex, topology selections and the particle identification.

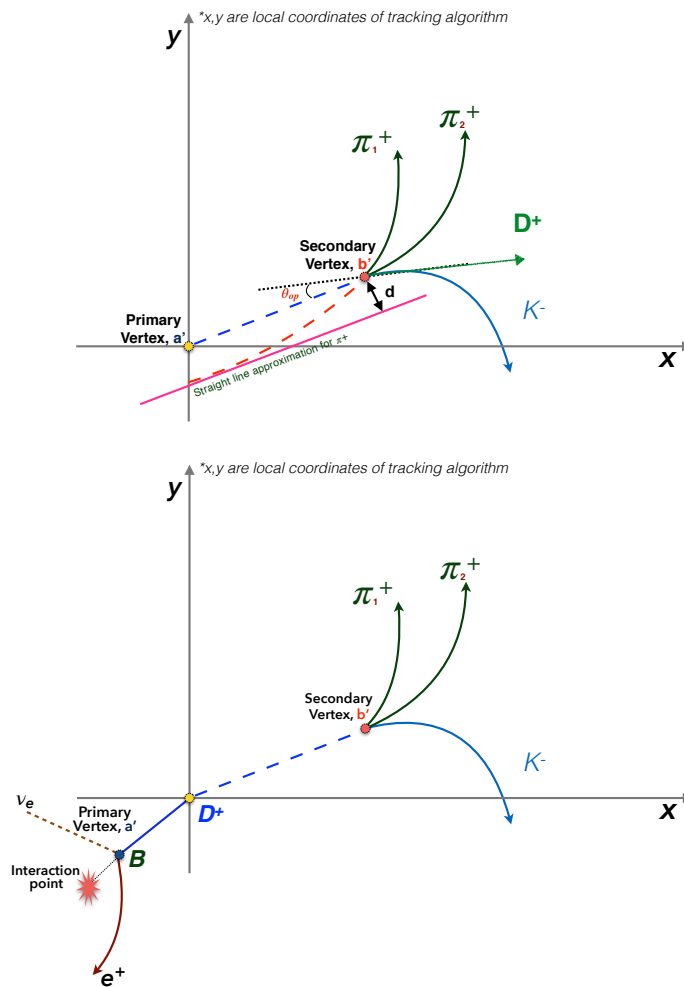


Fig. 3.1: Sketch of the prompt (top) and feed-down (beauty) D^+ meson decay.

A) Reconstruction of the secondary vertex

This is the first step for the reconstruction of D^+ meson and it starts by minimising the distance between decay tracks, i.e. two positively charged pion tracks and one negatively charged kaon track and in the same way the opposite sign charged tracks are used for the

anti-particle. The decay tracks are approximated as a straight line in the vicinity of primary vertex and then the secondary vertex is defined by finding the minimum segment between the decay tracks by keeping the spatial precisions of tracks.

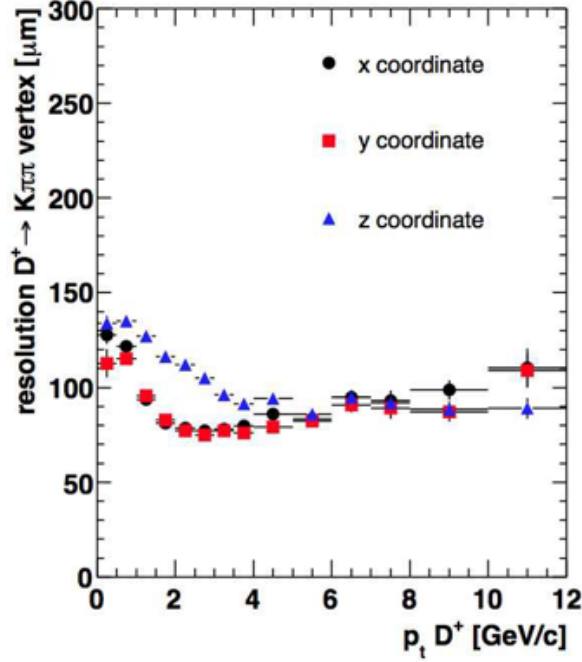


Fig. 3.2: D^+ secondary vertex resolution in x, y, and z coordinates in pp collisions. [source: \[141\]](#).

The measured resolution of the secondary vertex in x, y and z coordinates for pp collisions at $\sqrt{s} = 7$ TeV is shown in Figure 3.2 [141]. The resolution of about $120 \mu\text{m}$ is achieved in the low $p_T^{D^+}$ region and it improves up to $70 \mu\text{m}$ for the high $p_T^{D^+}$ region. In low $p_T^{D^+}$ region, the resolution is poor because the decay tracks are affected by multiple scattering effects, which is not the case at high $p_T^{D^+}$. However, in high $p_T^{D^+}$ region, the decay tracks are more collinear along the direction of D^+ momentum, resulting in low opening angle, which in turn affects the precision of secondary vertex resolution.

B) Topology selections

The reconstruction of D^+ mesons is initiated by grouping of three reconstructed charged tracks on behalf of actual decay tracks. This grouping generates a large amount of combinatorial background combinations which duplicates the D^+ candidates. Therefore, it is necessary to impose pre-selection criteria on the reconstructed charged tracks as well as on D^+ candidates. The kinematic and topological selections on the basis of geometrical properties are applied to the decay tracks and candidates, for example, considering the opposite charge of daughter kaons with respect to mother D^+ candidates and use large

proper decay length of D^+ candidate ($\sim 311.8 \mu\text{m}$). The main kinematic and topological selections used in the analysis are listed in Table 3.6 and are also explained below.

→ **Tracks quality:** The daughter charged tracks considered for D^+ candidates are reconstructed using ITS and TPC detectors in pseudorapidity region, $\eta < |0.8|$. Selection cuts, listed in the Table 3.2 are applied to improve their quality.

Track parameter	Value	Main role
$\chi^2/\text{TPC cluster}$	2	Improves the quality of the track fit and significantly suppressed the fake high- p_T tracks
DCA to VertexXY distance (cm)	0.25	DCA _{XY} : To assure that the tracks originate close to the primary vertex, which ensures the removal of secondary particle tracks. DCA _Z : Removes the tracks belonging pileup vertices.
DCA to VertexZ distance (cm)	1	
Min. number of TPC clusters	70	Ensures quality of the track found in the track fitting procedure
Min. number of ITS clusters	2	Reduces the contamination of secondary particle tracks
TPC refitting	ON	Refit procedure of the track reconstruction during the global tracking procedure to get high precision on tracks reconstruction
ITS-SPD hits	1	Minimum one hit in either of the two SPD layers to ensure the spatial measurement as close as possible to the primary and secondary decay vertices. This improves the impact parameter resolution of the daughter tracks and of the secondary vertex as well
Pseudorapidity coverage	0.8	To get optimal detector coverage and uniform tracks acceptance
Transverse momentum (GeV/c)	0.3	To remove the low p_T background tracks

Tab. 3.2: Selection criteria applied on decay tracks for the D^+ reconstruction.

→ **p_T distribution of daughters:** p_T distribution of decay tracks; kaons and pions are studied as a function of $p_T^{D^+}$ in PYTHIA6 Monte Carlo simulations. It is observed that the p_T of decay tracks for background D^+ mesons is softer than the signal D^+ mesons. Therefore a lower p_T cut listed in Table 3.6 is applied to reduce a large fraction of combinatorial background.

→ **Track impact parameter:** This selection is based on the impact parameter of decay charged tracks, which is described as the distance of closest approach between decay tracks and the primary vertex. This selection cut is not used in this analysis as the pres-

ence of third D^+ daughter track makes it difficult to apply. However, this cut is extremely useful for the reconstruction of two body decay candidates, for example, reconstruction of $D^0 \rightarrow K\pi$.

~ **Decay length (L):** It is defined as a distance between the primary and secondary vertex. In this analysis, L is measured three-dimensionally and as a function D^+ meson p_T . A lower threshold L value can reject a significant amount of background D^+ candidates but on the other hand same cut can introduce larger contamination of feed-down D^+ candidates, since the decay length for feed down D^+ candidates also includes the position of B-meson primary vertex which causes larger decay length. Therefore, an optimized cut on L value should be applied to get a proper rejection of background and feed-down D^+ candidates contribution.

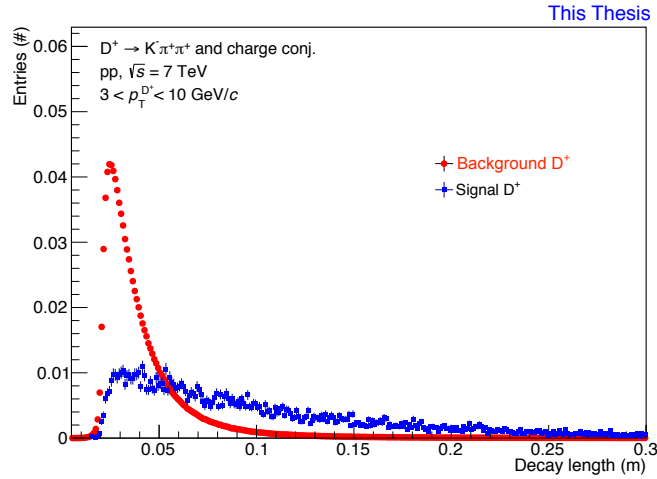


Fig. 3.3: Distributions of transverse decay length L for the signal and background D^+ candidates in $3 < p_T < 10 \text{ GeV}/c$.

Figure 3.3, shows the distributions of decay length L for signal candidates (Monte Carlo simulation) and background candidates (Data) for p_T region, $3 < p_T^{D^+} < 10 \text{ GeV}/c$ in pp collisions. The peak for background candidates in L distribution is located at $\sim 1.5 \text{ cm}$ and have negligible contribution for $L > 5 \text{ cm}$, whereas L distribution for signal candidates is characterized by the higher L values. As already discussed in the previous chapter, ITS provides better spatial resolution in transverse plane ($r\phi$) with respect to z plane, therefore, the resolution of vertex position is also found better in the transverse plane. The transverse decay length (L_{xy}) is therefore, used instead of three-dimensional L . In the analysis, a threshold on L_{xy}^{norm} (normalized to its uncertainty) is finally used as a selection criterion to reduce the contribution of background candidates.

→ **Pointing angle (θ_p)**: It is an angle between momentum direction and flight line of reconstructed D^+ candidate. The flight line is defined as the straight line between primary and secondary vertex of D^+ candidate. If the reconstructed secondary vertex does not correspond to signal candidate then a deviation from unity in the cosine of pointing angle $\cos(\theta_p)$ is expected. Pointing angle distributions for signal (Monte Carlo simulation) and background candidates (Data) for $3 < p_T^{D^+} < 10 \text{ GeV}/c$ are shown in the left plot of Figure 3.4.

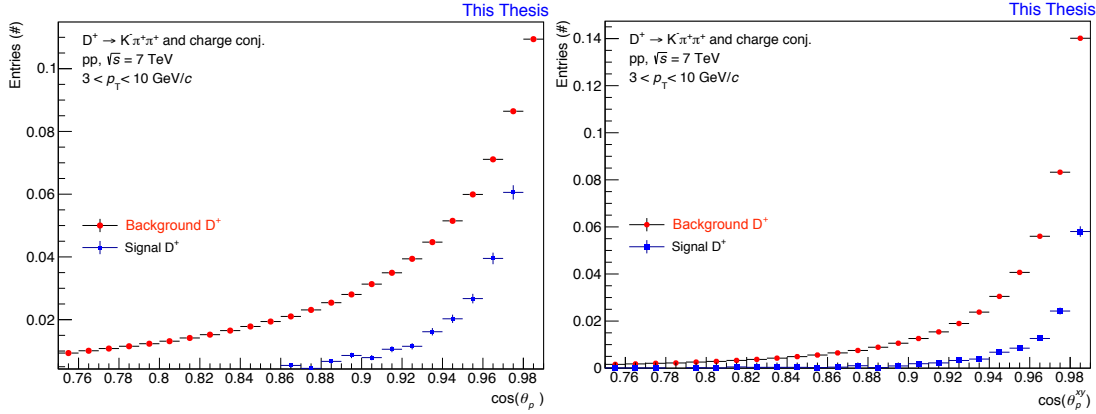


Fig. 3.4: The $\cos(\theta_p)$ (on the left) and $\cos(\theta_p^{xy})$ (on the right) for signal and background D^+ candidates in p_T region $3 < p_T < 10 \text{ GeV}/c$.

Because of the better resolution in transverse plane, transverse pointing angle is also used along with pointing angle to further reduce the contribution of background candidates. Both distributions shown in Figure 3.4 have different trends for signal and background candidates and are well separated at a certain value. This value of separation slightly varies depending on the p_T of D^+ , therefore, a mild $p_T^{D^+}$ dependent cut on both pointing angles are used to reject background candidates.

→ **Secondary decay vertex quality (σ_{vertex})**: The σ_{vertex} defined as $\sqrt{d_1^2 + d_2^2 + d_3^2}$, measures the dispersion of decay tracks around the secondary vertex. Here, d_{1-3} are the distances of minimum approach between the daughter tracks and secondary vertex. In principle, σ_{vertex} should be zero for signal D^+ candidates because decay tracks originates from the same secondary vertex. Figure 3.5 shows σ_{vertex} distributions for signal (Monte Carlo simulation) and background (Data) candidates for $3 < p_T^{D^+} < 10 \text{ GeV}/c$ in pp collisions. Both signal and background distributions have different peaks and trends therefore, an upper cut on σ_{vertex} is used to reduce background contributions.

→ **Fiducial acceptance of D^+ candidates**: η acceptance cut is used to select good quality decay tracks which introduces a limited acceptance of D^+ candidates, depending on transverse momentum. For example, at low $p_T^{D^+}$, decay tracks have larger dispersion along

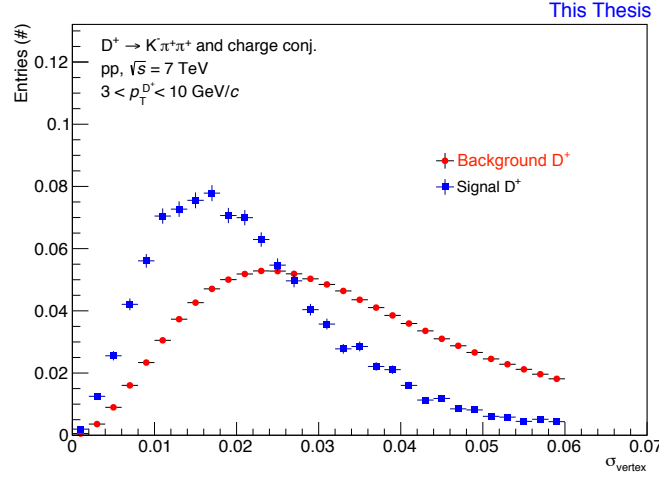


Fig. 3.5: The σ_{vertex} distributions for signal and background D^+ candidates in p_T region $3 < p_T < 10$ GeV/c.

the direction of D^+ candidates therefore, D^+ candidates are selected with a p_T dependent fiducial acceptance cut; e.g. $|y| < 0.5$ for $p_T^{D^+} < 4$ GeV/c and $|y| < 0.8$ for $p_T^{D^+} > 4$ GeV/c.

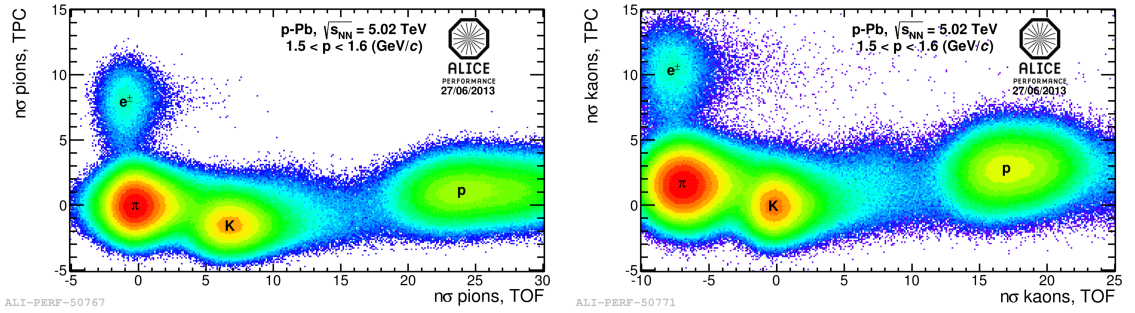


Fig. 3.6: The σ resolution parameters for pions in left plot and kaons in right plot for $1.5 < p_T < 1.6$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

C) Particle identification

Excellent PID capability of ALICE detector provides a powerful tool to reduce combinatorial background further. PID technique used to reduce combinatorial background is based on the identification of track triplets in which a negative track is compatible with kaon hypothesis and other two positive tracks are compatible with pion hypothesis. The identification of these decay track (kaon, pions) species is mainly based on specific energy loss (dE/dx) measurements in TPC detector. TOF detector is also used in conjunction with TPC to separate pions and kaons up to $p_T = 1.5(2)$ GeV/c. The daughter track distributions from specific energy loss in TPC and the time of flight in TOF provides σ resolution parameters; e.g. σ_{π}^{TPC} , σ_K^{TPC} , σ_{π}^{TOF} and σ_K^{TOF} .

Resolution	Transverse momentum (GeV/c)		
$\sigma_{\pi,K}^{Detector}$	$p_T < 1.0$	$1.6 < p_T < 0.8$	$p_T > 0.8$
$0 < \sigma_{\pi,K}^{TPC} < 1$	IDENTIFIED	IDENTIFIED	COMPATIBLE
$1 < \sigma_{\pi,K}^{TPC} < 2$	IDENTIFIED	COMPATIBLE	COMPATIBLE
$2 < \sigma_{\pi,K}^{TPC} < 3$	COMPATIBLE	COMPATIBLE	COMPATIBLE
$\sigma_{\pi,K}^{TPC} > 3$	REJECTED	REJECTED	REJECTED
$\sigma_{\pi,K}^{Detector}$	$p_T < 1.5$		$p_T > 1.5$
$0 < \sigma_{\pi,K}^{TOF} < 3$	IDENTIFIED		COMPATIBLE
$\sigma_{\pi,K}^{TOF} > 3$	REJECTED		REJECTED

Tab. 3.3: Selection criteria of $\sigma_{\pi,K}^{detector}$ for the daughter tracks and PID response categories.

- **REJECTED:** Very likely not to be π or K (outside dashed line)
- **COMPATIBLE:** with the π or K hypothesis (inside dashed line)
- **IDENTIFIED:** π or K in case of positive identification of the track (inside dashed line)

These parameters are calculated for each track triplet of D^+ meson candidates and suitable cuts on their values are used as a criterion for selection. Figure 3.6 shows distributions of σ^{TOF} as a function of σ^{TPC} for kaons on left plot and pions on right plot in p–Pb collisions. Signal track is identified in region around ($\sigma^{TPC} = 0$, $\sigma^{TOF} = 0$), whereas other dense regions represent other charged particles. The value of dE/dx and time of flight for each daughter track is compared to the expected value in the π and K hypothesis, which gives a PID response. This PID response is then characterized by σ^{TPC} and σ^{TOF} resolutions. The characterization cuts used on σ^{TPC} and σ^{TOF} , and corresponding category of PID response are listed in Table 3.3.

D) Correlation using reconstructed D^+ candidates

The reconstructed D^+ candidates for correlation study are analysed via an invariant mass analysis, basically to extract raw D^+ signal yield by fitting signal and background trends. The D^+ candidates are then selected in three different transverse momentum, $p_T^{D^+}$ ranges; low $p_T^{D^+}$ (3-5 GeV/c), mid $p_T^{D^+}$ (5-8 GeV/c) and high $p_T^{D^+}$ (8-16 GeV/c) in both pp and p–Pb collision analyses. In p–Pb analysis, trigger candidates in low $p_T^{D^+}$ range 3-5 GeV/c are not considered because of relatively large background correlations.

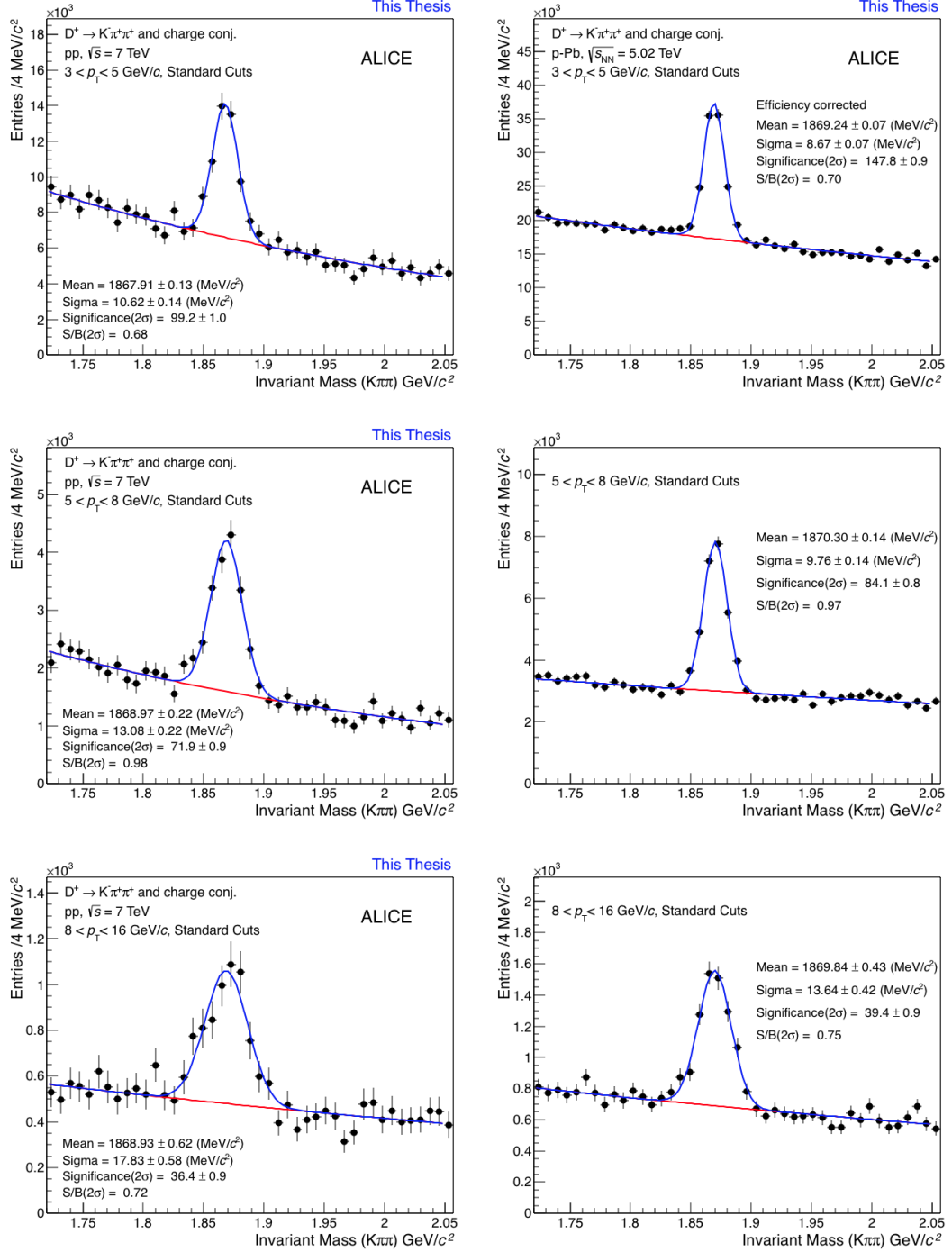


Fig. 3.7: The efficiency corrected D^+ invariant mass distributions in different $p_T^{D^+}$ regions; top panel for the low $p_T^{D^+}$ (3-5 GeV/c), middle panel for the mid $p_T^{D^+}$ (5-8 GeV/c) and bottom panel for the high $p_T^{D^+}$ (8-16 GeV/c) in pp collisions (left panel) and p-Pb collision (right panel).

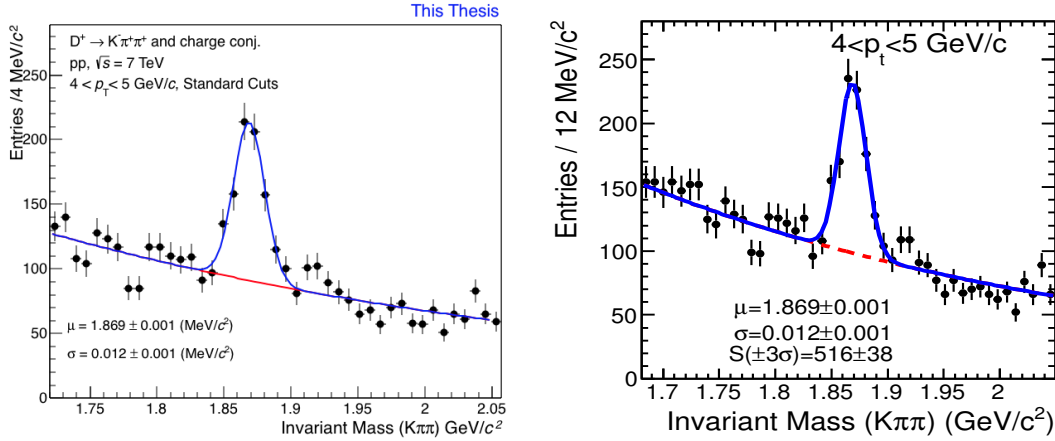


Fig. 3.8: Comparison of D^+ invariant mass distributions in p_T region 4-5 GeV/c measured by current analysis (left plot) with published results (right plot) in pp collisions at $\sqrt{s} = 7$ TeV.

Figure 3.7 shows efficiency corrected invariant mass distribution of D^+ meson candidates in all three $p_T^{D^+}$ regions of both pp and p-Pb collisions. The invariant mass distributions show clear D^+ invariant mass peak around the PDG value (1.86 ± 0.20 GeV/c²) in all $p_T^{D^+}$ regions and in both colliding systems.

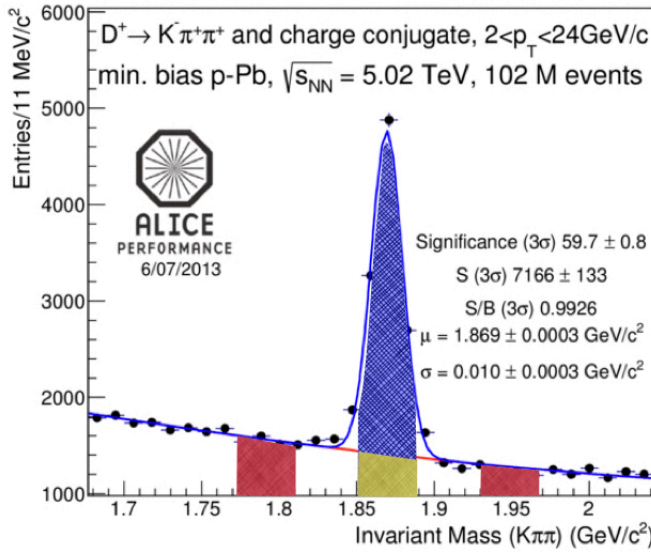


Fig. 3.9: [Dummy figure] Selection of the trigger particle in signal + background region (blue + yellow bands) and sidebands (red) region of the D^+ invariant mass distribution.

The ALICE collaboration has already published the results on D meson production in pp collision at $\sqrt{s} = 7$ TeV and p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV [103, 116, 117]. The D^+ reconstruction selection criteria used in the analysis is adopted directly from the published results. Figure 3.8 shows the comparison of D^+ invariant mass distributions obtained from the current analysis with published results for $p_T^{D^+}$ region 4-5 GeV/c in pp collisions and

as expected both distributions are in good agreement. The trigger particle (D^+ meson) for the correlations are finally considered in central (signal) region, defined as σ (mean) $\pm 2\mu$ (sigma) interval around the invariant mass peak, also indicated by blue+yellow bands in Figure 3.9. The selected trigger candidates in this region include background trigger candidates, those are present under the mass peak, indicated by yellow band. The trigger candidates from the yellow band introduce additional background correlations, which are removed by using “**sideband technique**” explained in the next section.

Track parameter	Value	Main role
$\chi^2/\text{TPC cluster}$	2	Improves the quality of the track fit and significantly suppressed the fake high- p_T tracks
DCA to VertexXY distance (cm)	0.25	DCA _{XY} : To assure that the tracks originate close to the primary vertex, which ensures the removal of secondary particles tracks. DCA _Z : Removes the tracks belonging pileup vertices.
DCA to VertexZ distance (cm)	1	
Min. number of TPC clusters	70	Ensures quality of the track found in the track fitting procedure.
Min. number of ITS clusters	2	Reduces the contamination of secondary particle tracks
ITS-SPD hits	1	Minimum one hit in either of the two SPD layers to ensure the spatial measurement as close as possible to the primary and secondary decay vertices, this improves the impact parameter resolution of the daughter tracks and of the secondary vertex as well.
Pseudorapidity coverage	0.8	To get optimal detector coverage and uniform tracks acceptance
Transverse momentum (GeV/c)	0.3	To remove the low p_T background tracks
Sigma to Vertex Requirement	OFF	Refit of reconstructed tracks in global tracking to get high precision on the tracks.
TPC Refitting	ON	
ITS Refitting	OFF	

Tab. 3.4: Standard set of charged track cuts (ITS-TPC track cuts 2010) used in both pp and p-Pb analyses.

3.4.2 Selection of charged particles (associated tracks)

In this analysis, charged hadron tracks measured by the ITS and the TPC detectors, corresponding to primary charged particles are used to build azimuthal correlations. The primary charged particles stand for all the prompt particles produced in the collision and all decay products (with decay length $c\tau < 10$ mm), except from the weak decays of strange particles (with $c\tau > 10$ mm). Details of charged hadron track selection are listed in Table 3.4. These selections are also adopted as a standard set of cuts, also defined as, “ITS-TPC track cuts 2010” in internal notation of ALICE collaboration. In these selection cuts mainly low-quality tracks are rejected to improve the track reconstruction probability and the contamination of secondary particles is also removed.

3.4.3 Construction of raw correlations

The correlation pairs between trigger D^+ particle and selected associated particles in specified p_T intervals are built in azimuthal $\Delta\varphi$ and pseudorapidity space $\Delta\eta$. Here $\Delta\varphi = \varphi_{trigg} - \varphi_{assoc}$ and $\Delta\eta = \eta_{trigg} - \eta_{assoc}$ refer to the difference in azimuthal angle and in rapidity between the trigger and associated charged particles from the same collision event. $\Delta\eta$ plane is mainly used to encounter the detector acceptance, which is corrected via “mixed event technique”, also discussed in the next section. In order to get better visualization of correlation patterns, the distributions are plotted in $\Delta\varphi$ range from $-\pi/2$ to $3\pi/2$ and $|\Delta\eta| < 1.0$. The limited range of $|\Delta\eta|$ is considered to avoid the “wing effect” and statistical fluctuations in both edges of $|\Delta\eta|$ plane. 1-D projection on $\Delta\varphi$ plane is finally considered to extract the correlation properties such as yield and width of distributions. The $\Delta\varphi$ range used in the analysis, can be characterized in two correlation regions: $(-\pi/2, \pi/2)$ range as “near-side (NS)” correlations and $(\pi/2, 3\pi/2)$ as “away-side (AS)” correlations and this notation have been used further in this thesis. NS correlations physically represent both trigger and associated particles from the same jet whereas AS correlations represent trigger and associated particles from the opposite side jet. The charged decay daughters of trigger particle (D^+ meson) are excluded from sample of associated particles to remove auto-correlation effect, which mainly affects NS correlation region.

The histogram bins, $\Delta\varphi = 32$ for $-\pi/2$ to $-3\pi/2$ range and $\Delta\eta$ bins = 18 for full range -1.6 to 1.6 are used, this is chosen on the basis of available statistics in pp and p-Pb data. Figure 3.10 shows an example of raw $\Delta\varphi$ azimuthal correlations using trigger D^+ candidates in the invariant mass region $\mu \pm 2\sigma$ (S+B), for all three different trigger $p_T^{D^+}$ regions and associated particle $p_T^{assoc} > 0.3$ GeV/c in p-Pb collisions. These raw correlations are not

background subtracted and also not corrected for any corrections; e.g. trigger or track efficiency. The uncorrected correlations structure in NS and AS regions are visible in all three distributions of different trigger $p_T^{D^+}$ regions.

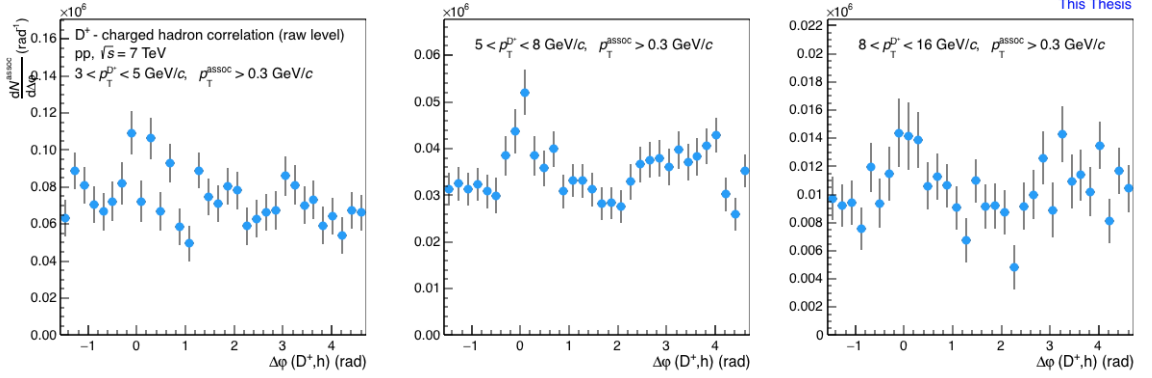


Fig. 3.10: $\Delta\phi$ raw azimuthal correlation for the trigger D^+ p_T region: low p_T 2-5 GeV/c (left plot), mid p_T 5-8 GeV/c (middle plot) and high p_T 8-16 GeV/c (right plot) and the associated particle p_T threshold > 0.3 GeV/c in p-Pb collision at centre of mass energy $\sqrt{s_{NN}} = 5.02$ TeV.

3.4.4 Subtraction of background correlations

In the construction of raw level correlations, trigger particles are considered from the central $\mu \pm 2\sigma$ region which also include background D mesons present under signal peak. Therefore, raw correlation has an additional contribution of the background correlations. This contribution of background correlations is removed via “**side-band technique**”. In this technique, a similar type of background correlations are estimated using background triggers (D^+ candidates) from side bands of the invariant mass distribution, indicated by red bands in Figure 3.9. These background correlations from left and right sidebands ($\mu \pm 4\sigma$ to $\mu \pm 8\sigma$) are combined together to get a total sideband (background) correlations of similar properties that present in central background correlations. Total sideband correlations are then scaled with respect to central background correlations and then subtracted from raw correlations to get raw signal correlations. Scaling factor is calculated by taking ratio of background trigger D^+ yields (via fit) in sidebands to central region. The stepwise detailed explanation of full background subtraction procedure with reference figures and notations is given below.

Step 1. Building raw correlations ($\Delta\phi, \Delta\eta$) using trigger particles from the central region of D^+ invariant mass distribution: $\mu \pm 2\sigma$ interval that also contains background triggers present under the mass peak or in other words, background correlation.

$$C_{[S+B]}^{Central} = C_S^{Central} + C_B^{Central} \quad (3.1)$$

Step 2. Estimation of background correlations ($\Delta\varphi, \Delta\eta$) using triggers from left and right side bands of the invariant mass distribution. Trigger D^+ candidates from the invariant mass intervals, $(\mu-8\sigma, \mu-4\sigma)$ and $(\mu+4\sigma, \mu+8\sigma)$ are used for the left and right side bands. The total background correlations using both side-band triggers can be defined as,

$$C_B^{LR-Sideband} = C_B^{L-Sideband} + C_B^{R-Sideband} \quad (3.2)$$

Step 3. Scaling of total side-bands background correlation with respect to the central one,

$$C_B^{LR-Sideband} = f_s \times C_B^{LR-Sideband} \quad (3.3)$$

Here, $f_s = (Y_B^{L-Sideband} + Y_B^{R-Sideband})/Y_B^{central}$ is a scaling factor for normalizing the amount of sideband background correlations with respect to the central background correlations. These yields (Y) of background triggers are calculated by taking integral from the exponential fit function in different intervals of invariant mass distribution.

Step 4. The total scaled side-bands background correlations calculated in Step 3 are then subtracted from the raw correlations those obtained in Step 1 to get the signal correlations only. Moreover, fully corrected correlation distributions are obtained only after applying all the appropriate corrections, discussed in the next sections.

$$C_{[S+B]}^{Central} = C_{[S+B]}^{Central} - C_B^{LR-Sideband} \quad (3.4)$$

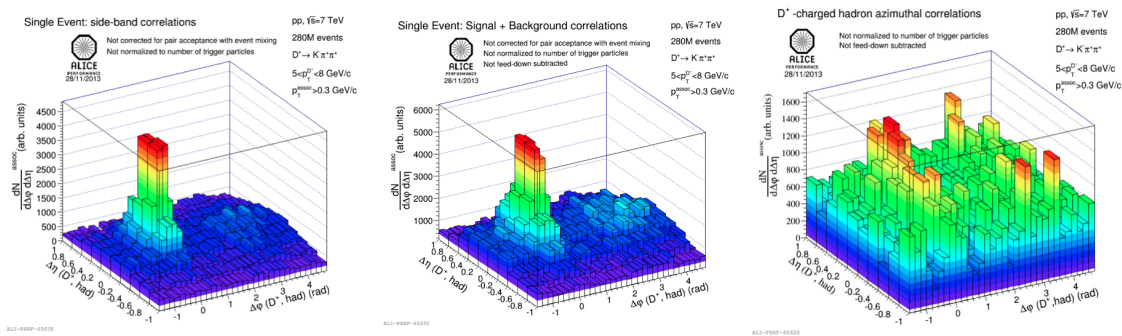


Fig. 3.11: 2D ($\Delta\varphi, \Delta\eta$) azimuthal correlations for trigger particles, $5 < p_T^{D^+} < 8 \text{ GeV}/c$ and associated particles, $p_T^{\text{assoc}} > 0.3 \text{ GeV}/c$ in pp collisions at $\sqrt{s} = 7 \text{ TeV}$; (left plot) scaled total correlation from the sidebands triggers, (middle plot) correlations from the central triggers region and (right plot) background subtracted correlations.

Figure 3.11 shows an example of the azimuthal correlations using triggers from S+B (step-1) and side-bands region (step-3) and the background subtracted correlation (step-4) for the case of trigger particles, $5 < p_T^{D^+} < 8 \text{ GeV}/c$ and associated particle $p_T^{\text{assoc}} > 0.3 \text{ GeV}/c$ in

pp collisions. The correlation peak in near side as well as some structures in away side are clearly visible for both regions and also after subtracting the background, though these plots are without any analysis corrections.

3.4.5 Corrections

The corrections for various defects, such as detector acceptance and inhomogeneities, data sample purity, efficiency of trigger and associated particles and the contribution of feed down (trigger D^+ meson, those are decay products of B meson) correlation are applied to get fully corrected correlation distributions. These corrections are individually explained in this section.

Mixed Event Correction: The structure in the angular correlation distribution, even for uncorrelated pairs originate from the limited detector acceptance and local inhomogeneities. This introduces a bias in correlation distributions, in particular, they can produce an additional contribution in NS correlations peak. Such defects are therefore, corrected via event-mixing technique. In this technique, correlations (uncorrelated pairs) in $\Delta\varphi$ and $\Delta\eta$ phase space are built by choosing trigger particle from one event and associated charged particles from another events. In an ideal case or case of proper detector homogeneity, mixed event correlation is expected to have a constant flat distribution along $\Delta\varphi$ plane and a smooth triangular shaped distribution along $\Delta\eta$ plane because of the limited detector acceptance as shown in Figure 3.12.

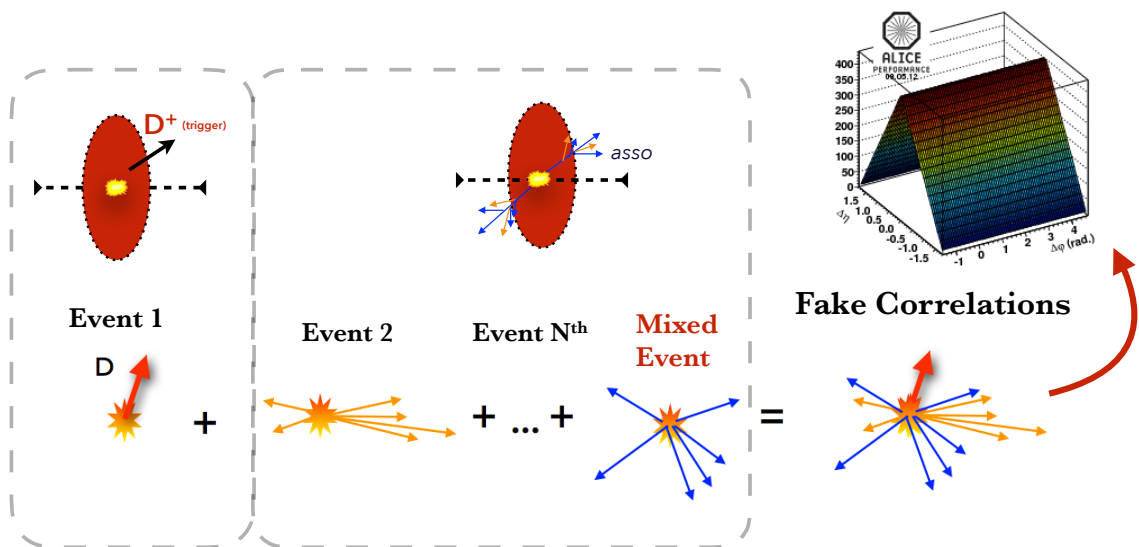


Fig. 3.12: [Dummy Figure] Demonstration of mixed event correlations.

For simplicity, a term “same-event” will be used further for correlations obtained using trigger and associated charged particles from same event and in same way term “mixed event” will be used for correlations obtained using trigger and associated particles from different events. The same-event correlations in central (S+B) and side-bands regions are corrected separately via mixed-event correlations before applying the background subtraction procedure. Furthermore, to quantify the defects dependency on event properties, total events based on their properties, e.g., z_{vtx} and charged particle multiplicity are characterized into different event pools. The event characterization in current analysis is limited because of available statistics therefore, wider range of event variables and reduced conditions of event mixing listed in Table 3.5 are employed. Correlation distributions are therefore, evaluated separately in different event pools for both same event and mixed event analyses. The correction of mixed event correlation also applied individually in each of the event pools. The corrected same event correlations from each event pool are finally added up to get total corrected correlations (SE/ME). The same procedure is applied for correlations in all $p_T^{D^+}$ and p_T^{assoc} ranges.

Collision system	Event multiplicity (#)	Z_{vtx} (cm)
pp at $\sqrt{s} = 7$ TeV	0, 20, 50, 105	-10., -2.5, 0, 2.5, 10.
p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV	0, 20, 50, 180	-10., -2.5, 0, 2.5, 10.
Minimum events to mix in each pool = 8		
Minimum tracks to mix in each pool = 500		

Tab. 3.5: Event variables and # of bins used for the mixed events correlations in both pp and p-Pb analyses.

Method: Event pools based on event properties are created via dedicated framework in ALICE software. Events preceding a D^+ meson candidates are stored in these pools. If any event pool satisfies the conditions mentioned in Table 3.5 is marked with status called “**pool ready**” and pools with “**ready**” status are then only used for mixed event correlations. This is important to get a proper quality statistics of mixed event correlation distributions in each pool. So each time whenever a trigger particle D^+ meson candidate found in existing event, mixed event correlations are obtained by using charged particles from other events those are stored in corresponding pool. Finally, mixed-event correlation distributions are normalized to $(\Delta\phi = 0, \Delta\eta = 0)$ and used as bin by bin weight in correlation distributions of same event.

Normalization procedure: Mixed event correlation distributions are generally normalized to the correlation entries at bin $\Delta\phi=0, \Delta\eta=0$, but in case of any detector inhomogeneities, this bin is expected to have highest influence with respect to the others bins. In the analysis, statistics of

trigger D^+ candidates are limited in selected $p_T^{D^+}$ region, therefore, mixed event distributions are also affected in terms of statistics and especially in case of high p_T region, i.e. $8 < p_T^{D^+} < 16$ GeV/c region or in high associated threshold $p_T^{\text{assoc}} > 1.0$ GeV/c. To consider this statistical fluctuations at $\Delta\varphi=0$ and $\Delta\eta=0$, an average of surrounding four bins is finally considered for normalization procedure.

Same-event $S(\Delta\varphi, \Delta\eta)$ and mixed-event $B_{ME}(\Delta\varphi, \Delta\eta)$ correlation functions are defined as;

$$S(\Delta\varphi, \Delta\eta) = \frac{d^2 N^{\text{same}}}{d\Delta\eta d\Delta\varphi} \quad \text{and} \quad B_{ME}(\Delta\varphi, \Delta\eta) = \frac{d^2 N^{\text{mix}}}{d\Delta\eta d\Delta\varphi} \quad (3.5)$$

Here, N^{same} and N^{mix} are the total number of correlation pairs measured in same event and mixed event analyses. The corrected same event correlation function from mixed-event correlation function is therefore, defined as;

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\varphi} = \frac{S(\Delta\varphi, \Delta\eta)}{\frac{1}{B_{ME}(0,0)} \times B_{ME}(\Delta\varphi, \Delta\eta)} \quad (3.6)$$

Here, $B_{ME}(0, 0)$ is normalization factor, calculated by taking average of correlation entries from four surrounding bins at $\Delta\varphi = 0$ and $\Delta\eta = 0$. The corrected same event correlations are also normalized to the number of trigger particles N_{trig} (same event), to study the per trigger correlation properties.

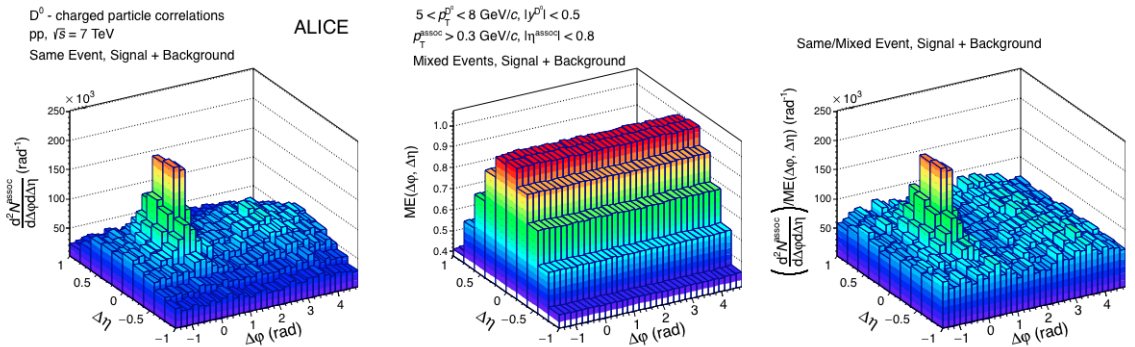


Fig. 3.13: Correlation $(\Delta\varphi, \Delta\eta)$ for the trigger (S+B) candidates, the left, mid and right plots represent the same, mixed and corrected same event correlation distributions respectively, using trigger particle $5 < p_T^{D^0} < 8$ GeV/c and charged particles with $p_T^{\text{assoc}} > 0.3$ GeV/c in pp collisions.

Figure 3.13 shows an example of correlation distributions from same event (left panel), mixed event (middle panel) and same event corrected by mixed event (right panel) using trigger particle $5 < p_T^{D^0} < 8$ GeV/c and associated particles $p_T^{\text{assoc}} > 0.3$ GeV/c in pp collisions.

sions. The correlation distribution are obtained using triggers from central (S+B) region of invariant mass distribution.

Charged track reconstruction efficiency: The sample of associated particles or charged hadron tracks used in the analyses are dependent to the track selection cuts, intrinsic property of the detectors (e.g. ITS and TPC) those are used in the track measurement and for the track reconstruction algorithm. These local dependencies can reduce the actual amount of associated charged particle tracks and therefore, can produce a bias in the correlation distributions. Thus, it is important to estimate total charged track reconstruction efficiency and corresponding correction should be applied into correlation distributions. The efficiency is measured as the ratio of particle yield at reconstructed level to generated level. PYTHIA6 generator with Perugia-0 tune is used as a standard simulation choice, which is also considered in other simulation level corrections.

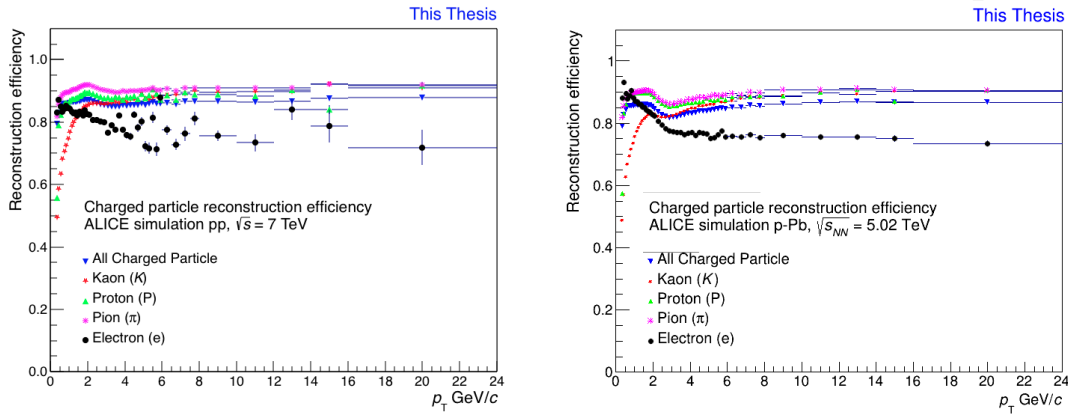


Fig. 3.14: [Simulation] p_T dependent charged tracking efficiency for different charged particle species and for all charged particles in pp collision at $\sqrt{s} = 7$ TeV (left) and p-Pb collisions at centre of mass energy $\sqrt{s_{NN}} = 5.02$ TeV (right).

In principle, charged track reconstruction efficiency can also have dependency on track and event parameters e.g. transverse momentum (p_T), rapidity (η), azimuth angle (ϕ), event multiplicity or Z_{vtx} , etc. Therefore, it is important to calculate it as a function of all dependent track variables, those are used in measurement. It is observed that the efficiency is almost independent to ϕ and η variables. On the other hand, shape of mixed event correlation plots also confirms that the efficiency is not dependent to ϕ and η . Figure 3.14 shows p_T dependent charged track reconstruction efficiency for all charged particles (black points) and also for individual charged particle species (different coloured points) in pp and p-Pb collisions. The efficiency for charged particles is almost flat for p_T region > 2 (3) GeV/c in pp (p-Pb) collisions. A small bump and drop like structures appear at low p_T region around 1.0–2 GeV/c and has been investigated extensively in an

earlier work. An averaged charged particle efficiency over full p_T^{assoc} range is measured about $\sim 85\%$ in both pp and p-Pb collisions.

Implementation: Track reconstruction efficiency is calculated three-dimensionally as a function of p_T , η and z_{vtx} and stored in a 3D-histogram. In the analysis and at online level, efficiency histogram is called and track by track efficiency value corresponds to the track variables p_T , η and z_{vtx} is extracted. The correlation pairs are then filled appropriately with efficiency weight, i.e. $1/\text{efficiency}$ value.

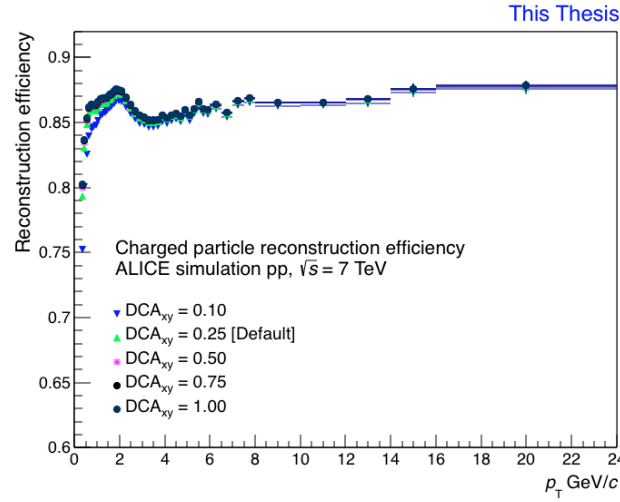


Fig. 3.15: [Simulation] p_T dependent charged tracking efficiency for different track DCA values in pp collision at $\sqrt{s} = 7$ TeV.

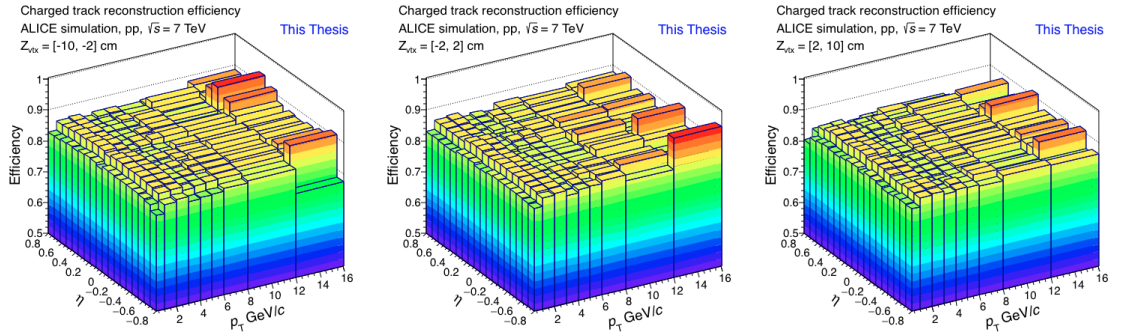


Fig. 3.16: [Simulation] 2-D charged tracking efficiency (p_T vs η) plot for the different z_{vtx} values; left plot for z_{vtx} range $[-10, -2]$ cm, middle plot for z_{vtx} range $[-2, +2]$ cm and right plot for z_{vtx} range $[+2, +10]$ cm in pp collisions at $\sqrt{s} = 7$ TeV.

Track DCA is an important parameter, which rejects contamination of the secondary particles. The effect of DCA cut on charged track efficiency is therefore studied and Figure 3.15 shows charged particle reconstruction efficiencies as a function of track DCA_{xy} values. The efficiencies for different DCA cuts show similar behaviour with the maximum devia-

tion of about 5% from standard DCA_{xy} value ($= 0.25$). The z_{vtx} dependencies on the efficiency is also studied by characterizing standard z_{vtx} range into three ranges; $[-10, -2]$ cm, $[-2, +2]$ cm and $[+2, +10]$ cm. The Figure 3.16 (middle) shows two-dimensional charged particle efficiency as a function of track p_T and η using central z_{vtx} range $[-2, +2]$ cm, efficiency is almost flat over full eta range and has small dependency for $p_T < 2$ GeV/c as already seen in the previous efficiency plots. Similar efficiency plots are also obtained for z_{vtx} $[-10, -2]$ cm (left plot) and z_{vtx} $[+2, +10]$ cm (right plot) and it is clear that all three 2D efficiency plots have similar trends and show mild dependency on the z_{vtx} .

Trigger reconstruction efficiency: Similar to charged track efficiency, correction for trigger reconstruction efficiency is also applied in a similar manner. Since statistics of trigger particles is limited in $p_T^{D^+}$ region, therefore, the dependency is calculated over $p_T^{D^+}$ and charged particle multiplicity only. η^{D^+} and z_{vtx} are excluded from efficiency calculation because of no strong dependency.

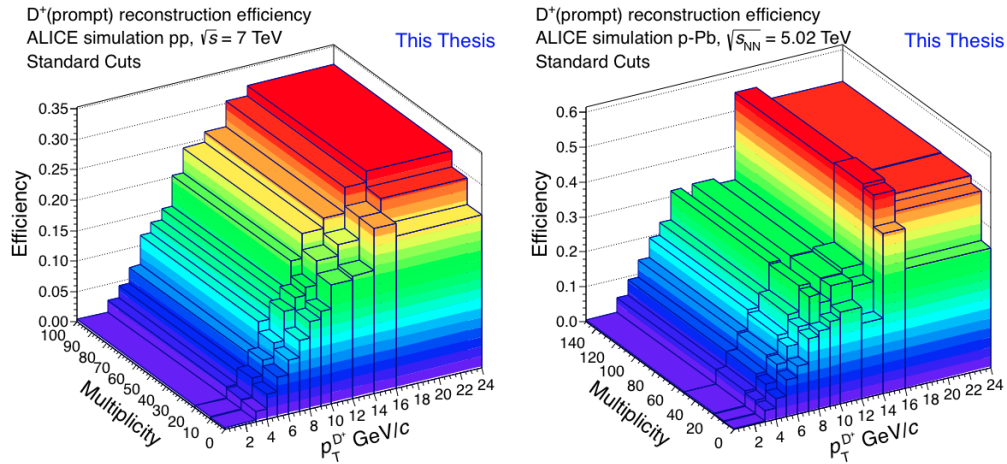


Fig. 3.17: [Simulation] D^+ meson efficiency (prompt) as a function of transverse momentum and event multiplicity in pp collisions at $\sqrt{s} = 7$ TeV (left) and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (right).

The correlation distributions are therefore corrected by using two-dimensional prompt trigger efficiency as a function of trigger $p_T^{D^+}$ and event multiplicity. Trigger efficiency is calculated in PYTHIA simulation by computing ratio of D^+ meson yield at reconstructed level to generated level. This efficiency is stored in 2-D histogram, and example plots of such in pp and p-Pb collisions are shown in Figure 3.17. The efficiency shows strong dependence on $p_T^{D^+}$ with a variation from $\sim 15\%$ at low $p_T^{D^+}$ to $\sim 40-50\%$ at high $p_T^{D^+}$ whereas it is almost flat (up to max $\sim 5\%$ variations) as a function of event multiplicity. The trigger $p_T^{D^+}$ bins are kept narrower at low p_T region to better encounter the dependency and broader at high p_T region to avoid the statistical fluctuations.

Implementation: Similar to charged reconstruction efficiency, trigger efficiency is also extracted from stored histogram for D^+ meson candidates. The inverse of the corresponding trigger (D^+) reconstruction efficiency is used as weight in correlation pairs. Invariant mass distribution is also corrected by trigger efficiency to measure efficiency corrected trigger yield. In the analysis, inverse of combined efficiency, basically product of both efficiencies; $eff_{total} = eff_{assoc} \times eff_{trigger}$ is applied as a total weight in correlation pairs.

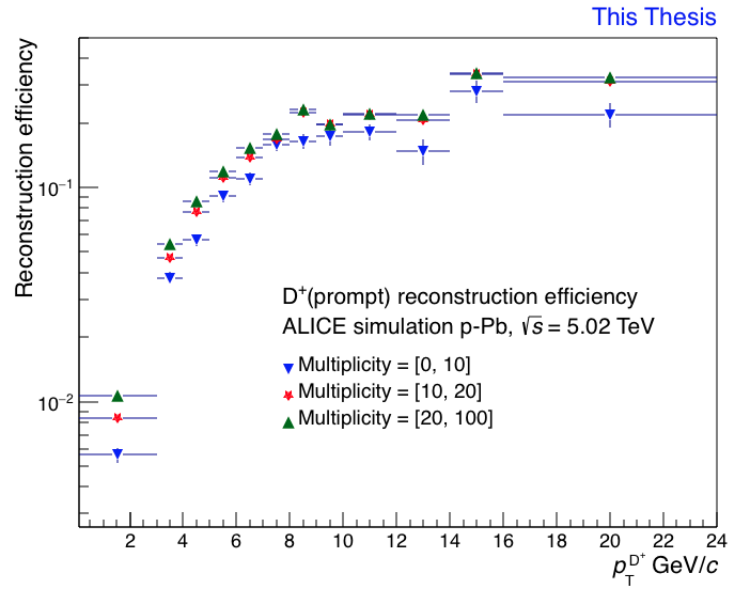


Fig. 3.18: [Simulation] D^+ meson efficiency (prompt) as a function of transverse momentum for different charged particle multiplicity in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Figure 3.18 shows the trigger efficiency as a function of the $p_T^{D^+}$ is consistent in three different event multiplicities.

Purity correction: As already discussed the secondary particles, for example, long-lived hadrons from strange particle decay and particles those are produced by interaction with the detector material should be removed from associated track sample. These particles are generally produced far from the interaction vertex, which results in their large track DCA values and therefore, a cut on track DCA can help to reject them. In principle, a tighter cut on DCA can remove all the contributions of secondary particles, but on the other hand, decay length of heavy flavour candidates (e.g. charmed hadrons) is also about few hundreds of microns (e.g. $c\tau \sim 300 \mu\text{m}$ for D^+). Therefore, a tighter cut on DCA also rejects decay particles of heavy flavour hadrons. The effect of DCA cut on associated charged tracks is therefore studied in detail and optimized DCA values, 0.25 cm in xy plane and 1.0 cm in z-plane are used. However, this DCA value does not fully remove the contribution of secondary particles, therefore, overall secondary particles contamination in correlation

distributions is estimated using PYTHIA simulations. The fraction of secondary particle correlations is obtained by computing ratio of $\Delta\varphi$ correlations obtained with all associated charged particles and with “secondary particles” only. This fraction is then used as “purity” factor to scale correlation distributions to encounter the contamination from secondary particles.

Beauty feed-down subtraction: The contribution of D^+ meson coming from B-meson is also present in D^+ trigger selections. The selection used in the reconstruction of D^+ meson candidates is optimized to maximise the signal to background ratio but this in parallel also enhances the fraction of feed-down (secondary) D^+ mesons, typically of the order of 5% at low $p_T^{D^+}$ and up to 20% at high $p_T^{D^+}$. The feed-down correlations are more sensitive to the properties of beauty jets and beauty hadron decays, which is in general different from those of charm jets and hadrons. The contribution of feed-down correlations are estimated in Monte Carlo simulation and stored as correlation templates then these templates and f_{prompt} factor are used to subtract the contribution of feed-down correlations. A detailed step wise explanation is given below:

Step 1. Final 1D $\Delta\varphi$ correlation: Feed down correction is applied in final one-dimensional $\Delta\varphi$ correlation results. $\Delta\varphi$ correlation can be defined as inclusive correlation, $C_{inclusive}(\Delta\varphi)$, as it is measured with both prompt and feed-down trigger candidates.

Step 2. f_{prompt} fraction: It is defined as relative fraction of prompt D^+ meson with respect to inclusive (prompt + feed-down) D^+ mesons and estimated using FONLL calculations and by using reconstruction efficiency of the prompt and feed-down D^+ candidates. The typical values of f_{prompt} is measured of about ~95% at $p_T^{D^+} \leq 5 \text{ GeV}/c$ and up to ~85% at $p_T^{D^+} > 5 \text{ GeV}/c$. The central f_{prompt} values are obtained using default parameters of FONLL predictions, but because of inbuilt uncertainty on the quark masses and QCD scales, FONLL calculations introduce an uncertainty in the f_{prompt} values. Therefore, uncertainty associated to f_{prompt} value is also evaluated by varying the parameters of FONLL calculations. Maximum and minimum variations are then considered as systematic values.

Step 3. Feed-down correlation templates: Feed-down correlation templates defined as $C_{MC-feed-down}(\Delta\varphi)$ are obtained using PYTHIA6 (Perugia0) event generator for all $p_T^{D^+}$ and p_T^{assoc} ranges. Templates are also obtained using other PYTHIA generators and tunes, for example, PYTHIA6 (tunes: Perugia2010 and Perugia2011), PYTHIA8 (4C tune). The effect of using other generators and tune based templates in feed-down subtraction procedure are also considered as systematic. Main difference among these different PYTHIA

tunes is mainly the variation of generator parameters, which mostly affects the process of parton fragmentation into the hadrons and hence can influence the shape of correlation distributions.

Step 4. Corrected results: Final corrected results can be expressed by the following expression:

$$C_{prompt}(\Delta\varphi) = \frac{1}{f_{prompt}} [p \times C_{inclusive}(\Delta\varphi) - (1 - f_{prompt})C_{MCfeed-down}(\Delta\varphi)] \quad (3.7)$$

The different correlation coefficients C and f_{prompt} are already discussed above. The constant p represents purity of the sample.

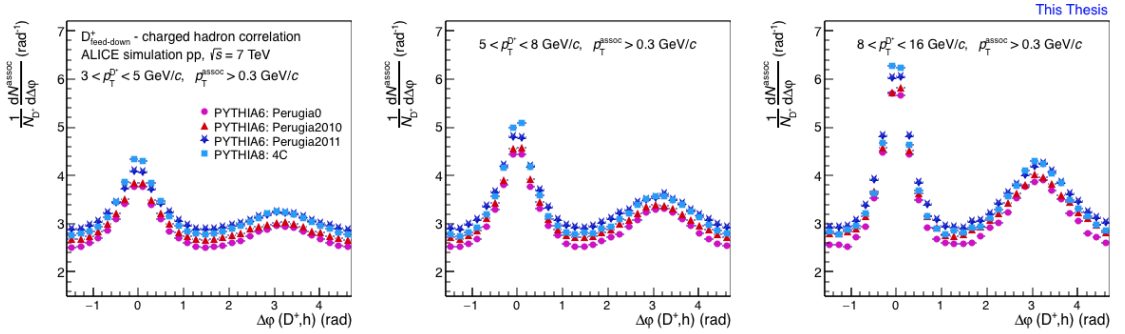


Fig. 3.19: [Simulation] Comparison of the “feed-down” azimuthal correlation distributions based on different PYTHIA generators and tunes in trigger $p_T^{D^+(b)}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range > 0.3 GeV/c in pp collisions.

Figure 3.19 shows comparison of secondary (feed-down) correlations, based on different PYTHIA generators (and tunes) for all three $p_T^{D^+}$ ranges and associated charged particles with $p_T^{assoc} > 0.3$ GeV/c in pp collisions. Correlation baselines or the number of uncorrelated pairs in templates are slightly different among themselves. They are also slightly different in comparison to data points, therefore before performing feed-down subtraction, correlation baselines in all templates are shifted towards the data points to match them at the same level. Since the correlation distributions in Monte Carlo are not affected by statistical fluctuations, baselines are obtained by taking an average of two minimum points along $\Delta\varphi$. This shifting of baselines do not introduce any influence on feed-down subtraction method because the correlation from prompt and feed-down triggers have different correlation properties and also because correlation baseline differences are mainly due to underlying events.

Figure 3.20 shows an example of feed-down subtracted azimuthal correlation using standard PYTHIA templates and f_{prompt} values for trigger particle $5 < p_T^{D^+} < 8 \text{ GeV}/c$ (left) and $8 < p_T^{D^+} < 16 \text{ GeV}/c$ (right) and for associated particle $p_T^{\text{assoc}} > 0.5 \text{ GeV}/c$ in pp collisions. The comparison of correlation distributions before (black points) and after feed down subtraction (red points) is also shown in same figure, which shows that the feed-down subtraction affects final correlations of the order of $\sim 4\text{-}5\%$ only.

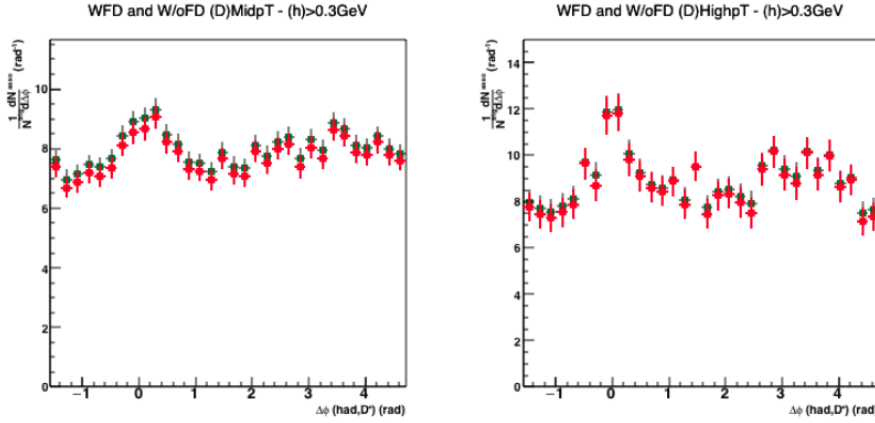


Fig. 3.20: Comparison of feed-down subtracted (red) with not subtracted (black points) azimuthal correlations for trigger particle in p_T range; 5-8 GeV/c (left), 8-16 GeV/c (right) and associated particle p_T threshold $> 0.3 \text{ GeV}/c$ using standard PYTHIA6+Perugia0 simulation template and standard f_{prompt} value.

3.4.6 Final results

The fully corrected azimuthal correlations are finally used to extract the correlation properties (e.g. NS and AS correlation widths and yields) by fitting the distributions with a function composed of two Gaussian functions (modelling the near and the away side peaks) and a constant term describing the correlation baseline. The mean value of a Gaussian function is fixed at $\Delta\varphi = 0$ and $\Delta\varphi = \pi$ and to accomplish the 2π periodicity of $\Delta\varphi$ variable, the function is “duplicated” with mean at $\Delta\varphi = 2\pi$ and $\Delta\varphi = -\pi$. The final corrected correlation distributions and their properties extracted using fits for all the trigger $p_T^{D^+}$ and associated particle p_T^{assoc} ranges are discussed in the next chapter.

$$f(\Delta\varphi) = C + \frac{Y_{NS}}{\sqrt{2\pi\sigma_{NS}^2}} \exp\left(-\frac{(\Delta\varphi - \mu_{NS|0})^2}{2\sigma_{NS}^2}\right) + \frac{Y_{AS}}{\sqrt{2\pi\sigma_{AS}^2}} \exp\left(-\frac{(\Delta\varphi - \mu_{AS|\pi})^2}{2\sigma_{AS}^2}\right) \quad (3.8)$$

Cut	System	Values	Properties
Invariant mass $M_{inv}^{D^+}$ (GeV/c ²)	pp	1.70 - 2.05	- Mass range around the PDG value (1.869 ± 0.190) - Default bin width = 0.012 - Side band regions for the background estimation
	p-Pb	1.70 - 2.05	
Daughter p_T^K, p_T^π (MeV/c ²)	pp	$K > 200$	- Reject low p_T background tracks - Kaons with opposite charge w.r.t. D^+ mother - Pions with same charge w.r.t. D^+ mother
	pp	$\pi > 400$	
	p-Pb	$K > 200$	
	p-Pb	$\pi > 350-400$	
Pointing angle $\cos(\theta_p)$	pp	< 0.990	- Cosine of pointing angle $\cos(\theta_p)$ - The value < 1 for D^+ mesons with $p_T > 0$ GeV/c
	p-Pb	< 0.990	
Pointing angle XY $\cos(\theta_p^{xy})$	pp	< 0.990	The pointing angle in the transverse plane
	p-Pb	0.950-0.990	
Impact parameter $d_0(r\phi)$ cm	pp	$K > 0$	- The lower limit rejects the primary particles - The upper limit removes highly displaced tracks
	pp	$\pi > 0$	
	p-Pb	$K > 0$	
	p-Pb	$\pi > 0$	
Distance of closest approach DCA(μ m)	pp	< 0.25	The lower limit rejects the secondary particles
	p-Pb	0.25-1.00	
Decay length L_{xy} (μ m)	pp	$> 0.2-10.0$	- Normalized decay length in the transverse (xy) plane - Normalized by the uncertainty
	p-Pb	$> 0.2-10.0$	
Distance of primary and secondary vertex dist 1-2 (μ m)	pp	$> 300-400$	Removes reconstructed background
	p-Pb	$> 300-400$	
Impact parameter square $d_0^2(r\phi)$ (cm ²)	pp	> 0	- On the basis of sign daughter tracks - For signal candidate the value should be negatively large and for background it is around 0.
	p-Pb	> 0	
Daughter p_T p_T^{max} (GeV/c ²)	pp	XXX	Reject fake tracks or reduce the combinatorial background
	p-Pb	XXX	

Tab. 3.6: Kinematic and topological selections criteria used for reconstruction of D^+ meson in pp collisions at $\sqrt{s} = 7$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Chapter 4

Systematics, Simulations and Results

“The problem is not to find the best or most efficient method to proceed to a discovery, but to find any method at all...”

— Richard Phillips Feynman

abstract: In this chapter, Section 1 elaborates the systematic uncertainty study associated to various sources. In Section 2, final corrected correlation results in both pp and p–Pb colliding systems are discussed. This section also discusses, the correlation results from averaged D (D^+ , D^0 and D^{*+}) and different comparisons, for example, correlations based on different triggers, correlation and their properties between pp and p–Pb systems. The detailed simulation studies based on different event generators (and their tunes) and also the comparison to final data results are discussed in the Section 3. The Section 4, finally concludes the current results and discusses possibilities about the future measurements.

4.1 Systematics studies

Stability of correlation distributions expected from systematic variation of various sources has been studied in both pp and p–Pb analyses. The contribution to systematic uncertainties from different sources are listed in Table 4.1. The full analysis procedure is repeated for each of source studies, and then systematic uncertainty is evaluated by comparing them with standard correlation distributions. The variation in systematics from all sources are classified into two classes of correlated and uncorrelated component. The uncertainties are therefore, calculated individually for both classes and then combined in quadrature to get an overall uncertainty. Finally, a total uncertainty is assigned to the corrected correlation data points.

As already discussed in the previous chapter, both pp and p–Pb analyses are performed for three $p_T^{D^+}$ ranges of trigger particle and three associated particle p_T^{assoc} regions. There-

fore, a total of nine final kinematic differential correlation distributions in each system is evaluated. “To save space” only a few of the systematic distribution plots will be illustrated e.g. a panel of correlation distributions in all three $p_T^{D^+}$ ranges of trigger particle in one system (either pp or p-Pb collisions) and for one particular range of associated particle p_T^{assoc} .

Source	Systematic variation (max uncertainty in pp (p-Pb))
Trigger efficiency	D^+ reconstruction using tight and loose selections $\rightarrow 10$ (10)%
Associated track efficiency	Track quality selections $\rightarrow +10\%$ (-5%) (4%)
Background subtraction	Sidebands region and background yields $\rightarrow 5\%$ (10%)
Secondary contamination	Different DCA cuts in xy and z plane and purity $\rightarrow 5\%$ (3.5%)
Beauty feed-down subtraction	Different simulation templates and f_{prompt} values $\rightarrow < 5\%$ (5%)
Trigger yield extraction	Signal region, yield extraction via fit/bin-counting, invariant mass range for fit, signal and background fit functions, bin width of invariant mass distribution. Total: $\rightarrow 10\%$ (10%)

Tab. 4.1: The list of different systematic sources considered in both pp and p-Pb analyses.

4.1.1 Trigger particle (D^+ meson) reconstruction efficiency

Standard selection criteria used in the reconstruction of D^+ mesons (trigger particle) in different trigger $p_T^{D^+}$ bins are optimised to maximise signal to background (S/B) ratio and significance. In final correlation, systematic uncertainty associated with trigger selection criteria is studied by varying kinematic and topological selections.

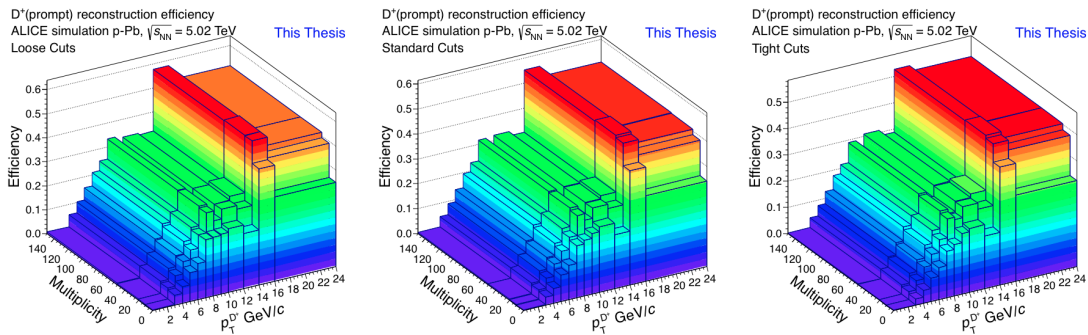


Fig. 4.1: [Simulation] D^+ (prompt) meson reconstruction efficiency as a function of $p_T^{D^+}$ and charged particle multiplicity in p-Pb collisions for different topological selections; loose (left plot), standard (middle plot) and tight (right plot).

A variation in the range of $\pm 5\%$ to $\pm 15\%$ depending on the sensitivity of selections is applied. It is applied mainly on the cosine of pointing angle, square of impact parameters and transverse decay length. The notation loose (tight) is used in this section which corresponds to the looser (tighter) selection.

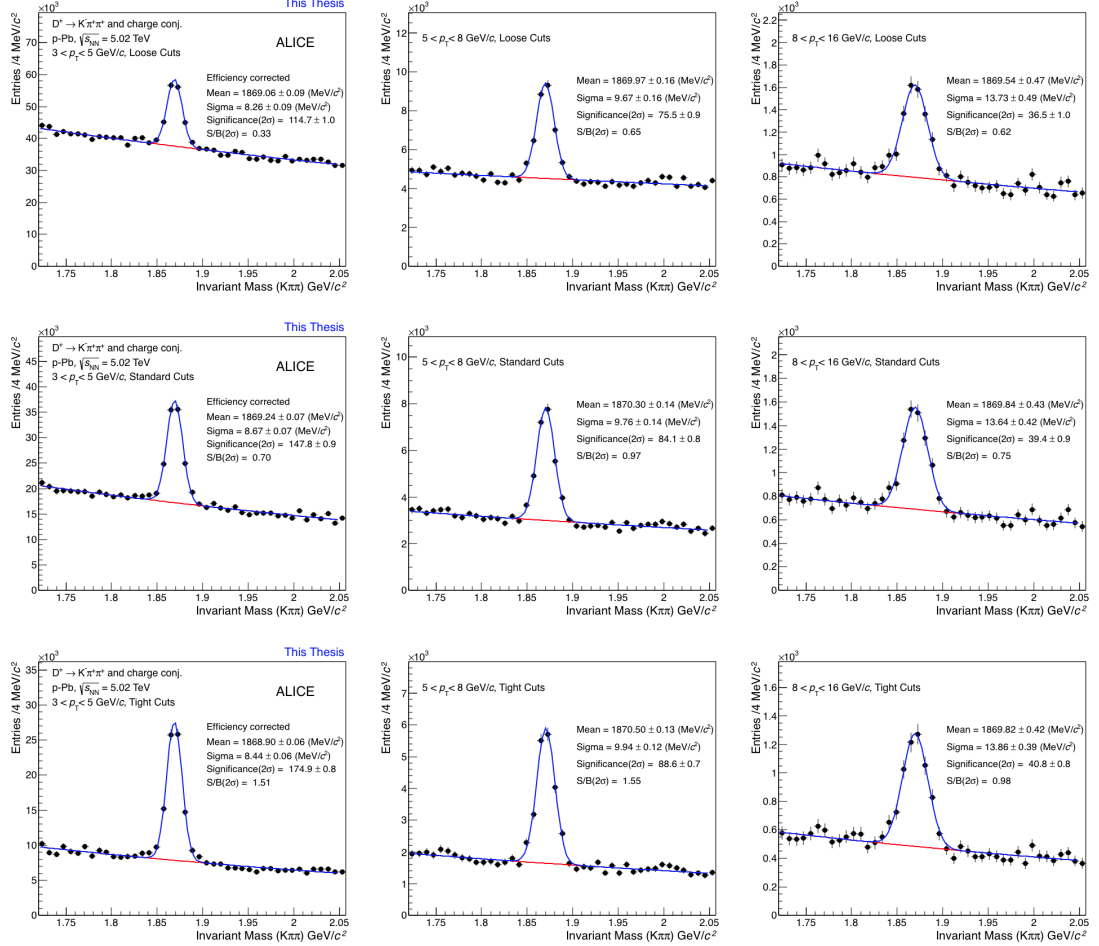


Fig. 4.2: Efficiency corrected invariant mass distribution of D^+ meson in all three p_T regions, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) for different topological cuts; loose selections (top panel), standard selections (middle panel) and tight selections (right panel) in p-Pb collisions.

In the analysis, correlation distributions and trigger yield are corrected with trigger efficiency. Therefore, the prompt D^+ meson reconstruction efficiency for all three (loose, standard, tight) selections was re-evaluated in Monte Carlo simulations and used online for trigger efficiency correction. Figure 4.1 shows prompt D^+ meson reconstruction efficiency as a function of $p_T^{D^+}$ and charged particle multiplicity in case of loose, standard and tighter selections. The reconstruction efficiency in all three cases shows a similar trend with a maximum variation of about $\sim 10\%$, mainly at low $p_T^{D^+}$ and low charged particle multiplicity. To obtain fully corrected correlation for all three cases, the standard analysis

procedure is repeated and individual efficiency corrected invariant mass distributions are used to extract the corresponding signal $N_{trigger}$ for the normalization of correlations.

Figure 4.2 shows efficiency corrected invariant mass distributions with loose (top panel), standard (middle panel) and tight (bottom panel) selections for all three standard $p_T^{D^+}$ regions in p–Pb collisions. The D^+ signal peak in all selections based on invariant mass distributions is clearly visible. The S/B ratio and significance increases from loose to tight selections whereas the number of trigger candidates decreases as expected. Fully corrected correlations are then evaluated and comparison of final correlations in p–Pb collisions are shown in the first three rows of Figure 4.3. The correlation distribution ratios of loose and tight selections with the standard one are also computed to evaluate systematic variations in correlation distribution. An example of correlation ratio for associated particles $> 0.3 \text{ GeV}/c$ are shown in the fourth row of Figure 4.3. Ratio plots show a maximum variation of about 10% in the low and mid $p_T^{D^+}$ trigger correlations and up to 15% in the high $p_T^{D^+}$ trigger correlations, where we have limited statistics. The corresponding study in pp collisions analysis suggests a similar maximum systematic variation of the order of 15%. Finally, the maximum value of the variations 10 (15)% is adopted as systematic uncertainties associated with trigger reconstruction in pp (p–Pb) analyses.

Track selection type	Set1 (Std)	Set2	Set3
Sigma to Vertex	kFALSE	kFALSE	kFALSE
Track refitting in ITS	kFALSE	kFALSE	*kTRUE
Track refitting in TPC	kTRUE	kTRUE	kTRUE
Min. number of ITS clusters	3	*0	3
Min. number of TPC clusters	70	70	70
χ^2 per TPC cluster	4	4	4
DCA to vertexZ	1.0	1.0	1.0
DCA to vertexXY	0.25	0.25	0.25
SPD hit requirement	No	No	*Yes

Tab. 4.2: Sets of different associated track selection used in systematic study. *Changes highlighted

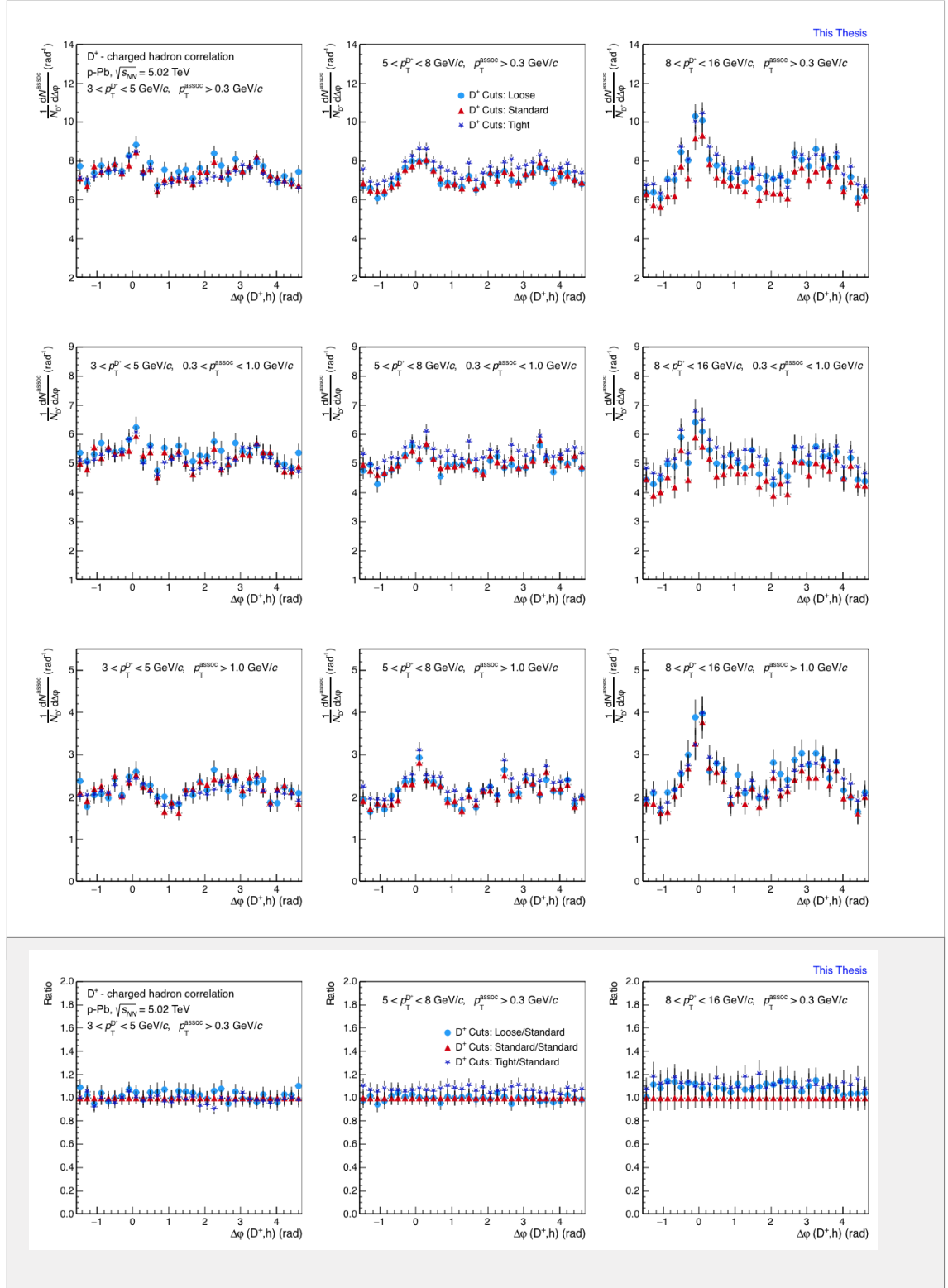


Fig. 4.3: Comparison of corrected azimuthal correlation distributions (1-3 rows) and ratios (4 row) based on different selections criteria of trigger particle (D^+ meson) in $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; > 0.3 GeV/c (first and fourth rows), 0.3-1.0 GeV/c (second row) and > 1.0 GeV/c (third row) in p-Pb collisions.

4.1.2 Charged (associated) track efficiency

Track selection criteria used on associated tracks to improve their quality is already discussed in the previous chapter. Systematic effects on the final correlations associated with the track selections are studied using two other selection sets. In the first set, a variation is applied by removing the requirement of the minimum clusters required in the ITS detector. This basically implies a least threshold on ITS cluster requirement (≥ 0), which allows all tracks which were eliminated by the requirement that ITS cluster should be greater than two are also considered. In other words provides all tracks from the TPC detector, also defined as TPC only track in ALICE notation. Then the second cut variation is set by adding an additional requirement of a hit in the SPD detector along with the demand of refitting ITS tracks. The considered track selections are summarised in Table 4.2. This variation in track selections also affects charged track reconstruction efficiency; therefore, efficiencies as a function of p_T , η and Z_{vtx} were also re-calculated for other two sets and employed in the analysis.

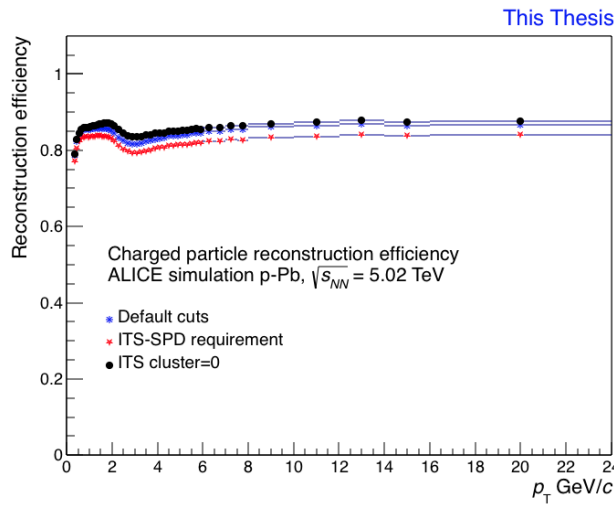


Fig. 4.4: [Simulation] Charged track reconstruction efficiency as a function of transverse momentum for different track selections in p-Pb collision.

Figure 4.4 shows comparison of charged particle reconstruction efficiencies as a function of p_T^{assoc} for all three sets of track selection in p-Pb collisions. The trend for different efficiencies are similar, and a maximum variation of about 3-5% with respect to standard efficiency is observed. A similar efficiency variation in pp analysis is also observed. The correlation distributions with different track selections are then corrected with their relative efficiencies.

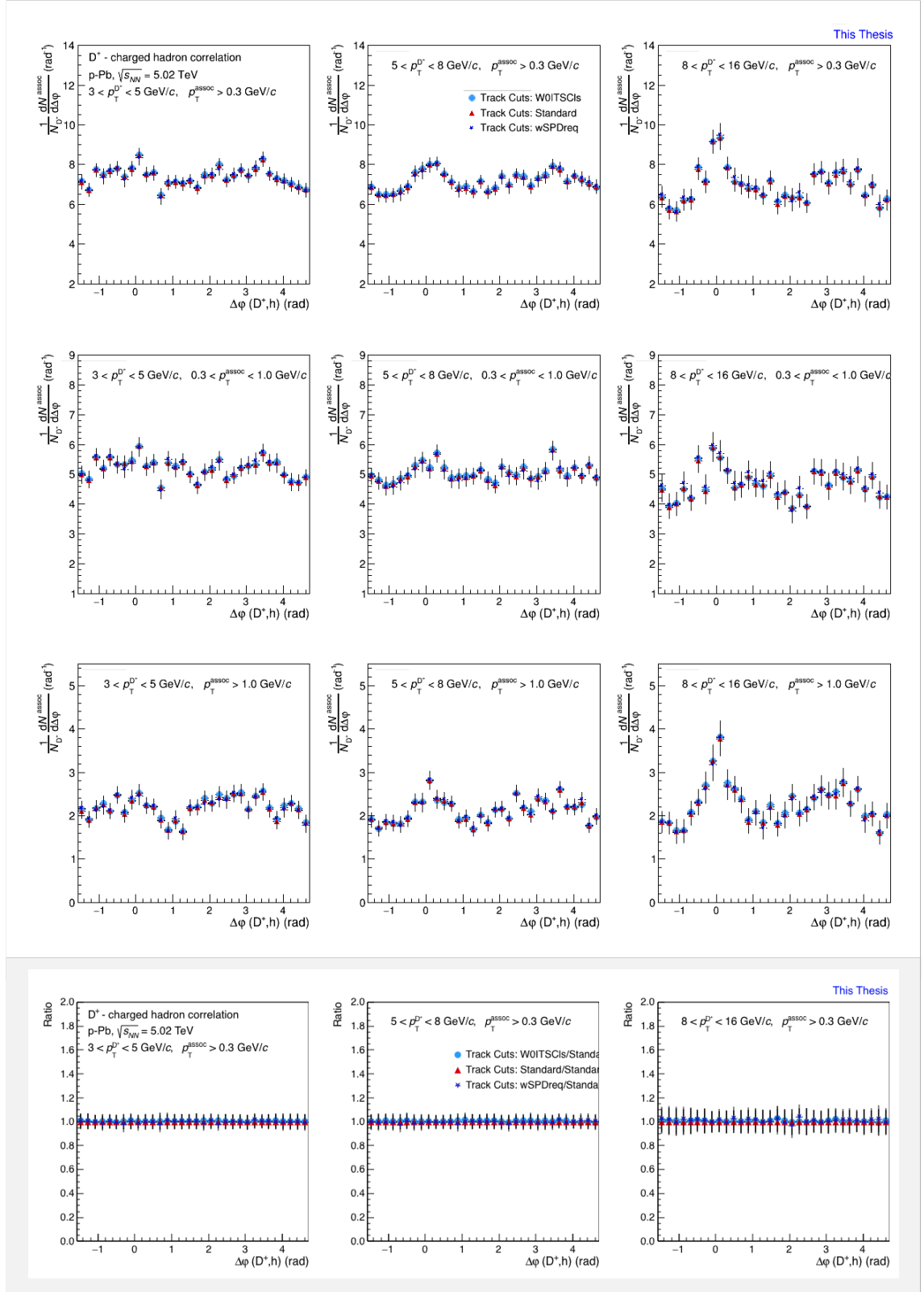


Fig. 4.5: Comparison of corrected azimuthal correlation distributions (1-3 rows) and ratios (4 row) based on different associated track selections in trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; > 0.3 GeV/c (first and fourth rows), 0.3-1.0 GeV/c (second row) and > 1.0 GeV/c (third row) in p-Pb collisions.

Figure 4.5 shows comparisons (1-3 rows) and ratio (4 row) of corrected azimuthal correlations obtained with different track selections for all standard $p_T^{D^+}$ ranges and p_T^{assoc} regions in p-Pb collisions. The correlation patterns are very similar with variation of the order of 2-5%. The study in pp analysis also shows a maximum variation of the order of 5%. Therefore, 5% is considered as systematic uncertainty associated with charged track selections in both pp and p-Pb colliding systems.

4.1.3 Secondary particles contamination

DCA cuts in the transverse (x-y) and z planes are used to remove contamination of the secondary particles from the sample of associated tracks. Systematic effect of DCA selections on the final correlation results is also studied, in which only variation in transverse DCA cut is considered and applied using different DCA_{xy} values 0.10 cm, (0.25cm standard), 0.50cm, 0.75cm and 1.00cm. The corresponding standard charged track reconstruction efficiencies are re-evaluated for all DCA values and online efficiency correction is applied. The purity of sample (or associated tracks) with respect to different DCA_{xy} cuts are estimated by calculating fraction of correlation using associated tracks as only secondary tracks with respect to all associated tracks and used to scale final correlations.

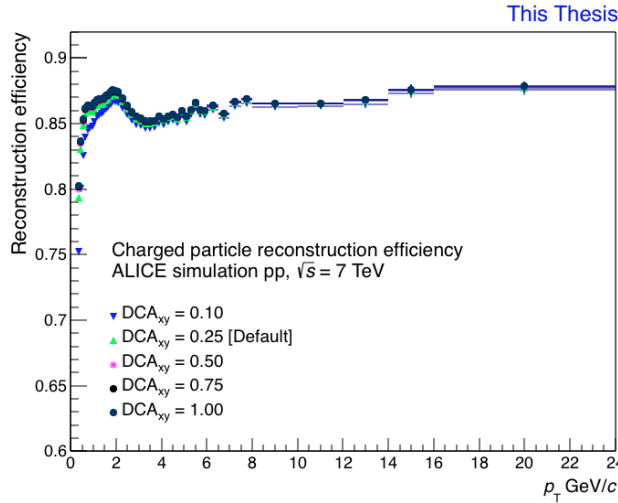


Fig. 4.6: [Simulation] Charged track reconstruction efficiency as a function of transverse momentum for different track DCA_{xy} values in pp collisions.

Figure 4.6 shows comparison of charged track efficiencies as a function of transverse momentum for different track DCA_{xy} in pp collisions. Efficiency trends are similar in all cases with a maximum variation of $\sim 2-3\%$ at low $p_T^{assoc} < 2 \text{ GeV}/c$ and less than 1% for the high $p_T^{assoc} > 2 \text{ GeV}/c$ region. The correlation distributions are then evaluated for all DCA_{xy} cuts and scaled with corresponding purities. Figure 4.7 shows correlation distributions

(top panel) and ratios (bottom panel) of corrected azimuthal correlation distributions using different DCA_{xy} cuts for all three trigger $p_T^{D^+}$ ranges and associated $p_T^{assoc} > 0.3 \text{ GeV}/c$ in pp collisions. A maximum variation of about 3.5 (5%) in pp (p-Pb) analysis is observed and considered as systematic uncertainty.

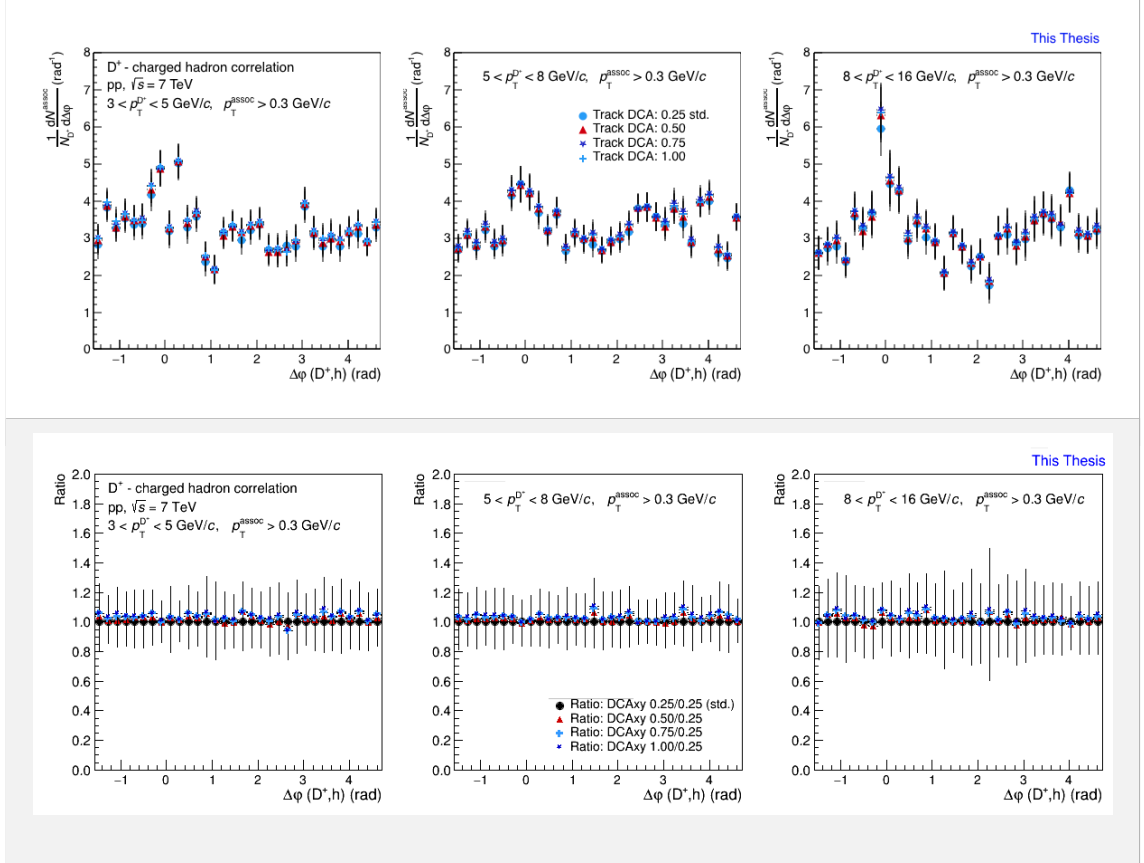


Fig. 4.7: Comparisons (top panel) and ratios (bottom panel) of corrected azimuthal correlation distributions based on different track DCA cuts in trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds $> 0.3 \text{ GeV}/c$ in p-Pb collisions.

4.1.4 Background subtraction vs. sideband range

The “sideband technique”, explained in the previous chapter is used to remove the contribution of background correlations. This technique basically estimates two quantities; the first is region or range of both left and right sidebands to obtain background correlations and the second is a scaling factor to scale total sideband background correlations with respect to central background correlations. In the ideal case of infinite statistics, shape of signal and background in the invariant mass distribution are smooth and therefore, it is

possible to calculate sideband background correlations and scale factor with precision. In current analysis, since statistics is limited, the influence of signal and background fluctuation is present in the invariant mass distribution. This affects fit performance, the definition of S+B, sideband correlations along with scale factor determination and as a result might also affect final correlations. These effects are, therefore, studied by changing definitions of sideband region and range in the invariant mass distribution. In the standard procedure, fit parameters mean (μ) and sigma (σ) of the invariant mass peak are extracted from S+B fit. Sidebands are then defined with 4σ width on the left ($\mu - 8\sigma, \mu - 4\sigma$) and on the right ($\mu + 4\sigma, \mu + 8\sigma$) side of mass peak. Systematic effect associated with this choice has been studied by choosing other two sideband definitions, one from (5σ to 9σ) and second from (4σ to 9σ).

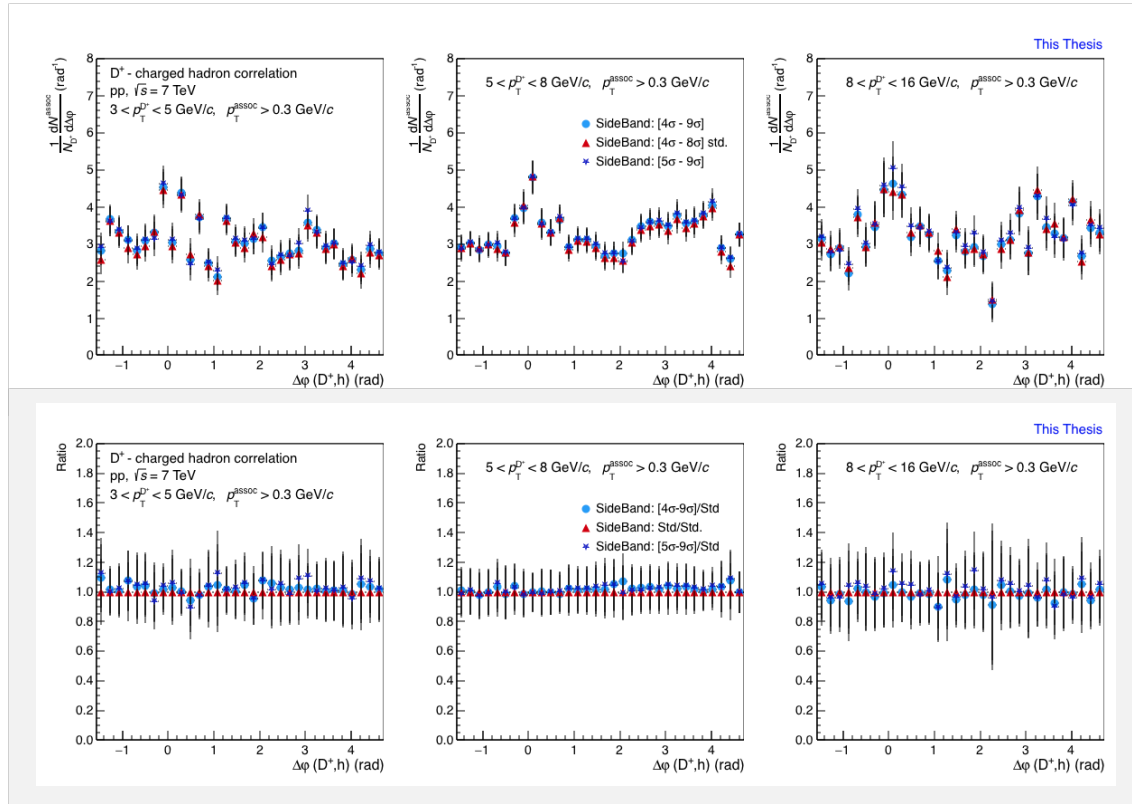


Fig. 4.8: Correlation distributions (top panel) and ratios (bottom panel) of corrected azimuthal correlation distributions based on different sideband definitions in trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated $p_T^{assoc} > 0.3$ GeV/c in pp collisions.

Figure 4.8 shows correlation distributions (top panel) and ratios (bottom panel) of final corrected azimuthal correlations using all three definitions of sidebands for all three trigger $p_T^{D^+}$ ranges and associated $p_T^{assoc} > 0.3$ GeV/c in pp collisions. The results show similar

correlation patterns with a maximum variation in range of about 5-10%, independent of p_T^{assoc} intervals. Similar uncertainties were evaluated for p-Pb data and also observed with other p_T^{assoc} region. Finally, a systematic uncertainty of 10% is considered from background subtraction procedure in both analyses.

4.1.5 Fit range of invariant mass distribution

The invariant mass distributions in all $p_T^{D^+}$ bins are fitted in mass range from 1.665 to 2.065 GeV/c^2 . The distributions are then fitted using signal and background functions in mass range from 1.70 to 2.05 GeV/c^2 . This interval was adopted to reduce the chances of fit failures because of statistical fluctuations in the higher mass region and large background in the lower mass region. Fit dependency on the mass range is, therefore, studied for systematics. Variations in the lower mass region up to 1.72 GeV/c^2 and higher mass region up to 2.02 GeV/c^2 are considered. These changes in mass range can affect the performance of fit and hence can also affect analysis procedure.

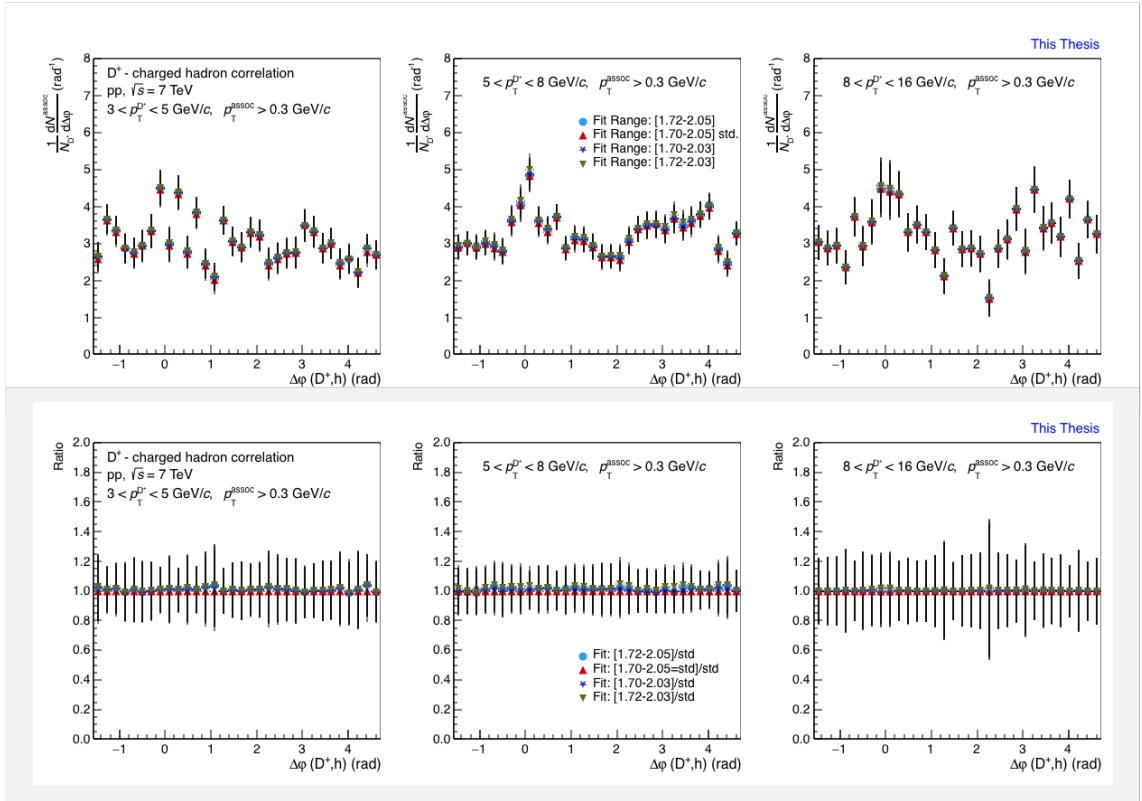


Fig. 4.9: Correlation distributions (top panel) and ratios (bottom panel) of corrected azimuthal correlation distributions based on fit range of invariant mass in trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated $p_T^{assoc} > 0.3 \text{ GeV}/c$ in pp collisions.

For example, a change in fit parameters μ and σ modifies the definition of sideband regions, full background subtractions procedure and also the number of triggers used in normalisation. Therefore, azimuthal correlations based on different fit ranges are studied in both analyses. Figure 4.9 shows correlation distributions and ratio of final correlation distributions for all three $p_T^{D^+}$ ranges and associated tracks $p_T^{assoc} > 0.3 \text{ GeV}/c$. The correlation ratios show that the maximum variation is below 5%. Similar values are observed for other associated thresholds and also in p–Pb analysis. Therefore, maximum variation, 5% is finally considered as a systematics in both pp and p–Pb analyses.

4.1.6 Trigger yield extraction methods

Gaussian and exponential functions as previously discussed, are adopted as a standard choice to fit signal and background trends in the invariant mass distributions. Then based on fit parameters signal ($\mu-2\sigma$, $\mu+2\sigma$) and sidebands region ($\mu\mp 8\sigma$, $\mu\mp\sigma$) are evaluated. The signal and background trigger yields are then extracted using two different approaches. In the first, integrals from both fit functions in central and sideband regions are considered and in the second, bin content in central and sidebands range are summed, also known as bin-counting (BC) method. The background trigger yields in central, and sideband regions are used to calculate background scaling factor $f_{scaling}$, defined by the ratio of background trigger yield in the central region to total sideband regions.

$$f_{scaling} = \frac{Y_{central}}{Y_{left} + Y_{right}} \quad (4.1)$$

The signal yield $N_{trigger}$ is also used to normalize correlation distributions. The quantities, $f_{scaling}$ and $N_{trigger}$ depend on the method used, for example, if the invariant mass distribution is not smooth or have statistical fluctuations, then value of $N_{trigger}$ via fit integral will be slightly different than that of measured via BC method. This variation in $N_{trigger}$ number introduces a shift in correlation baseline due to normalisation scaling, but correlation properties like NS or AS yield or shape parameters remain unchanged. Similarly, for the same reason, both methods also provide a different amount of background yields in central and sideband regions, and this changes $f_{scaling}$ factor or in other word changes the amount of background correlations used in subtraction procedure. Therefore, $f_{scaling}$ also introduces a shift in correlation baseline itself.

The standard choices highlighted in Table 4.3, are used to extract signal and background triggers. Statistics in the right sideband of the invariant mass distribution is limited as

Choice	Signal (S^c)	Central Bkg (B^c)	Sideband Bkg (B^{sb})
1	$(S + B^c)_{fit} - B_{fit}^c = S_{Fit}$	$B_{fit}^c = B_{Fit}$	B_{BC}^{sb}
2 (Std)	$(S + B^c)_{fit} - B_{BC}^c = S_{Fit}$	$B_{fit}^c + (S + B^c)_{BC} - (S + B^c)_{fit} = B_{BC}$	
3	$(S + B^c)_{BC} - B_{fit}^c = S_{BC}$	$B_{fit}^c = B_{Fit}$	
4	$(S + B^c)_{fit} - B_{fit}^c = S_{Fit}$	$B_{fit}^c = B_{Fit}$	B_{fit}^{sb}
5	$(S + B^c)_{fit} - B_{BC}^c = S_{Fit}$	$B_{fit}^c + (S + B^c)_{BC} - (S + B^c)_{fit} = B_{BC}$	
6	$(S + B^c)_{BC} - B_{fit}^c = S_{BC}$	$B_{fit}^c = B_{Fit}$	

Tab. 4.3: Yield extraction methods for signal and backgrounds in central and sidebands regions.

background decreases exponentially and even less in the higher $p_T^{D^+}$ bins. To avoid bias from poor fit quality, BC approach is finally adopted as a standard choice to calculate background trigger yields. Other possible choices of yield extraction are listed in Table 4.3 and used for a systematic study. In both yield extraction methods, first, fit on invariant mass distribution using signal and background fit functions is performed. Then based on fit parameters (μ, σ), yields are calculated in signal and background regions either by taking direct fit integral or counting entries via BC method. Figure 4.10 shows comparison of final azimuthal correlations using different yield extraction methods for all three standard trigger $p_T^{D^+}$ regions and associated p_T^{assoc} range 0.3-1.0 GeV/ c in pp collisions. The correlations results as expected are shifted with baseline only and does not affect its properties. Therefore, the systematics variation, in this case, is considered as uncertainty in baseline estimation.

4.1.7 Invariant mass distributions vs. fit functions

The shape of background in the invariant mass distribution is fitted by an exponential function, and systematic variation is studied by using other fit functions e.g. second order polynomial (Poly2). The Poly2 function along with signal function (Gaussian+Poly2) is used to fit signal and background regions. This choice provides slightly different fit parameters (μ, σ) of signal peak hence changes the definitions of central and sideband correlations, $N_{trigger}$ and $f_{scaling}$. The correlation distributions are re-calculated and then compared to the standard results. Figure 4.11 shows comparison of fully corrected azimuthal correlation distributions based on two different background fit functions, for all three standard trigger $p_T^{D^+}$ ranges and associated $p_T^{assoc} > 0.3$ GeV/ c in pp collisions. A

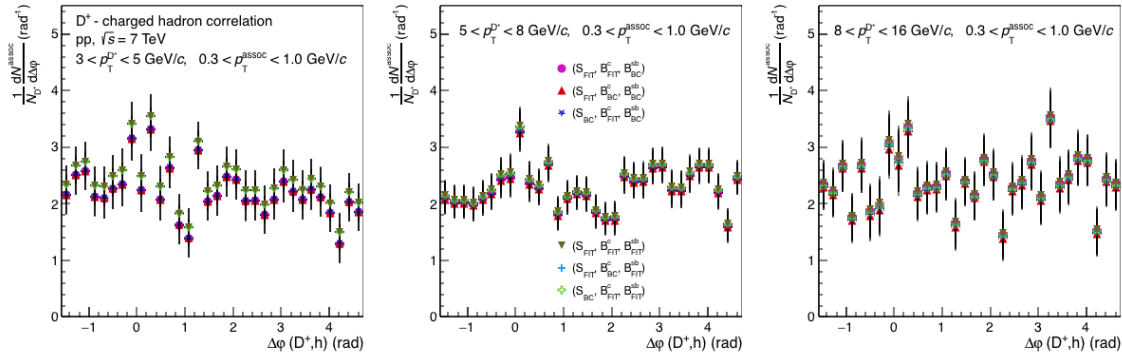


Fig. 4.10: Correlation distributions of the corrected azimuthal correlation distributions based on yield extraction methods in trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} range 0.3-1.0 GeV/c in pp collisions.

maximum variation of about 10% is found in correlation distributions for any associated p_T^{assoc} as also for p-Pb collisions. A 10% systematic uncertainty associated with our choice of background fit function is assigned to both pp and p-Pb analyses.

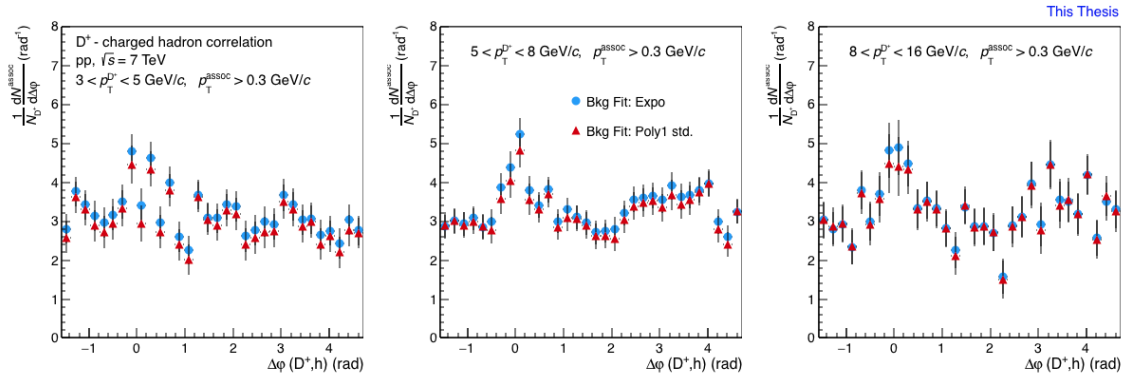


Fig. 4.11: Correlation distributions based on different background fit functions for trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} range 0.3-1.0 GeV/c in pp collisions.

4.1.8 Invariant mass distribution fit vs. bin width

The histograms of invariant mass distributions are filled using bin width of $2 \text{ MeV}/c^2$. This choice of small bin width introduces statistical fluctuations, especially in the higher p_T bins and affects the fit performance. Therefore, to reduce statistical fluctuations, mass bins are merged by factor of two ($4 \text{ MeV}/c^2$ standard). To calculate the influence associated with bin width choice on correlation estimation, signal and background fits are

repeated using higher bin width $6 \text{ MeV}/c^2$ and $8 \text{ MeV}/c^2$. The corresponding azimuthal correlations are re-calculated for all trigger $p_T^{D^+}$ ranges and associated p_T^{assoc} regions. Figure 4.12 shows comparison of final azimuthal correlations based on bin-width dependent invariant mass fits in all standard trigger $p_T^{D^+}$ ranges and associated $p_T > 0.3 \text{ GeV}/c$ in pp collisions. A maximum variation of about 5% is found for all correlation distributions in both colliding systems and considered as a systematic.

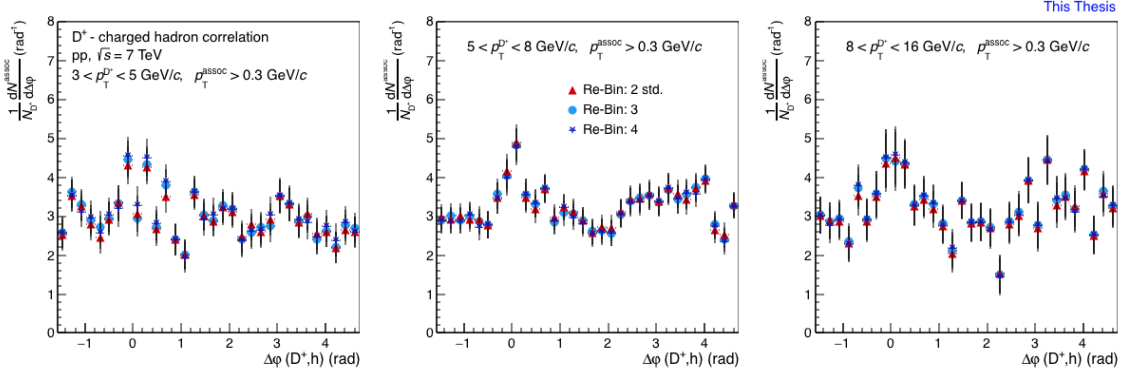


Fig. 4.12: Correlation distributions of corrected azimuthal correlation distributions based on different mass bin-width in trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} range 0.3-1.0 GeV/c in pp collisions.

4.1.9 Feed-down subtraction vs. templates and f_{prompt}

As already explained in the previous chapter, subtraction of feed-down ($b \rightarrow D$) trigger correlations was based on feed-down templates and f_{prompt} values. Therefore, systematic uncertainty associated with the choice of templates and f_{prompt} values is studied by considering different generators (and tunes) based correlation templates (shown in next section) and also by using a different range of f_{prompt} values. A maximum variation of the order of $\sim 8\%$, especially in NS region associated with feed-down subtraction process is observed in both colliding systems.

4.1.10 Extraction of correlation properties

The correlation properties e.g. NS yield, NS width and baseline are extracted in different ways as discussed in the previous chapter. The main source of this uncertainty is derived from extraction of correlation baseline itself, which is calculated under the assumption that, a variation of correlation in the transverse region does not contain any physical trend and is affected only by statistical fluctuations. Systematic uncertainty associated in extraction of correlation properties due to baseline definition is evaluated by extracting

Correlation Properties	Transverse momentum (GeV/c)			
	$5 < p_T^D < 8, p_T^{assoc} : 0.3-1.0$		$8 < p_T^D < 16, p_T^{assoc} > 1.0$	
	pp	p-Pb	pp	p-Pb
NS yield	$\pm 22\%$	$\pm 17\%$	$\pm 15\%$	$\pm 12\%$
NS width	$\pm 10\%$	$\pm 3\%$	$\pm 5\%$	$\pm 3\%$
Baseline	$\pm 13\%$	$\pm 12\%$	$\pm 15\%$	$\pm 11\%$

Tab. 4.4: Systematic uncertainties associated with correlation properties in pp and p-Pb collisions.

properties using a variation in the transverse region $\pm\pi/4$ of $\Delta\varphi$ correlation range. In addition to this, correlation fits are also repeated by moving correlation points up and down. The uncertainties in correlation properties for two p_T^D ranges and p_T^{assoc} regions are listed in Table 4.4.

4.2 Final correlation results

The final correlation distributions in all $p_T^{D^+}$ ranges and p_T^{assoc} regions are evaluated after applying all necessary corrections discussed in the previous chapter. To reduce statistical fluctuations on correlation points in standard $\Delta\varphi = (-\pi/2, 3\pi/2)$ range, points are reflected into reduced $\Delta\varphi = (0, \pi)$ range. The reflection is performed under the assumption that both NS and AS correlations contain similar statistics on both sides of their correlation peak. Since correlation points along $\Delta\varphi$ are reduced by a factor of two (from 32 bins to 16 bins), statistical uncertainty on reflected correlation points is reduced by the factor of $\frac{1}{\sqrt{2}}$. The reflection is performed by folding envelope of NS correlations centred at $\Delta\varphi = 0$ into forward half and AS correlations centred at $\Delta\varphi = \pi$ into backward half. Folding therefore, NS correlations region transforms from $\Delta\varphi = (-\pi/2 \rightarrow 0 \leftarrow \pi/2)$ to $(0 \leftrightarrow \pi/2)$ and AS correlations from $\Delta\varphi = (\pi/2 \rightarrow \pi \leftarrow 3\pi/2)$ to $(\pi/2 \leftrightarrow \pi)$. Figure 4.13 and Figure 4.14 show reflected distributions of fully corrected azimuthal correlations between D^+ meson and charged particles for all standard $p_T^{D^+}$ ranges and p_T^{assoc} regions in pp and p-Pb collisions. As already explained, the low $p_T^{D^+}$ region in p-Pb collisions is excluded from final results because of no clear correlation pattern. It is evident from the distributions that the height of near side correlation peak for both systems increases as trigger $p_T^{D^+}$ increases (without baseline). The correlation baseline, as expected decreases with increase in threshold

and range of associated particles p_T^{assoc} . Similar correlation measurements using other D mesons (D^0 and D^{*+}) as a trigger particle have also been performed in both pp and p-Pb collisions by the ALICE collaboration. The D^0 and D^{*+} mesons are reconstructed via hadronic decay channel $D^0 \rightarrow K^- \pi^+$ (with branching ratio, $BR = 3.88 \pm 0.05\%$) and $D^{*+} \rightarrow D^0 K \rightarrow \pi K K$ ($BR = 67.7 \pm 0.5\%$). The procedure of analysis in all three mesons is similar apart from meson dependent reconstruction and corrections. In D^0 correlation analysis, if trigger particle D^0 originates via $D^{*+} \rightarrow D^0(K\pi)$ then associated pions (soft pions) of this decay can produce an additional contribution in near side correlation peak. Therefore, soft pions are removed from associated particles in D^0 correlation analyses.

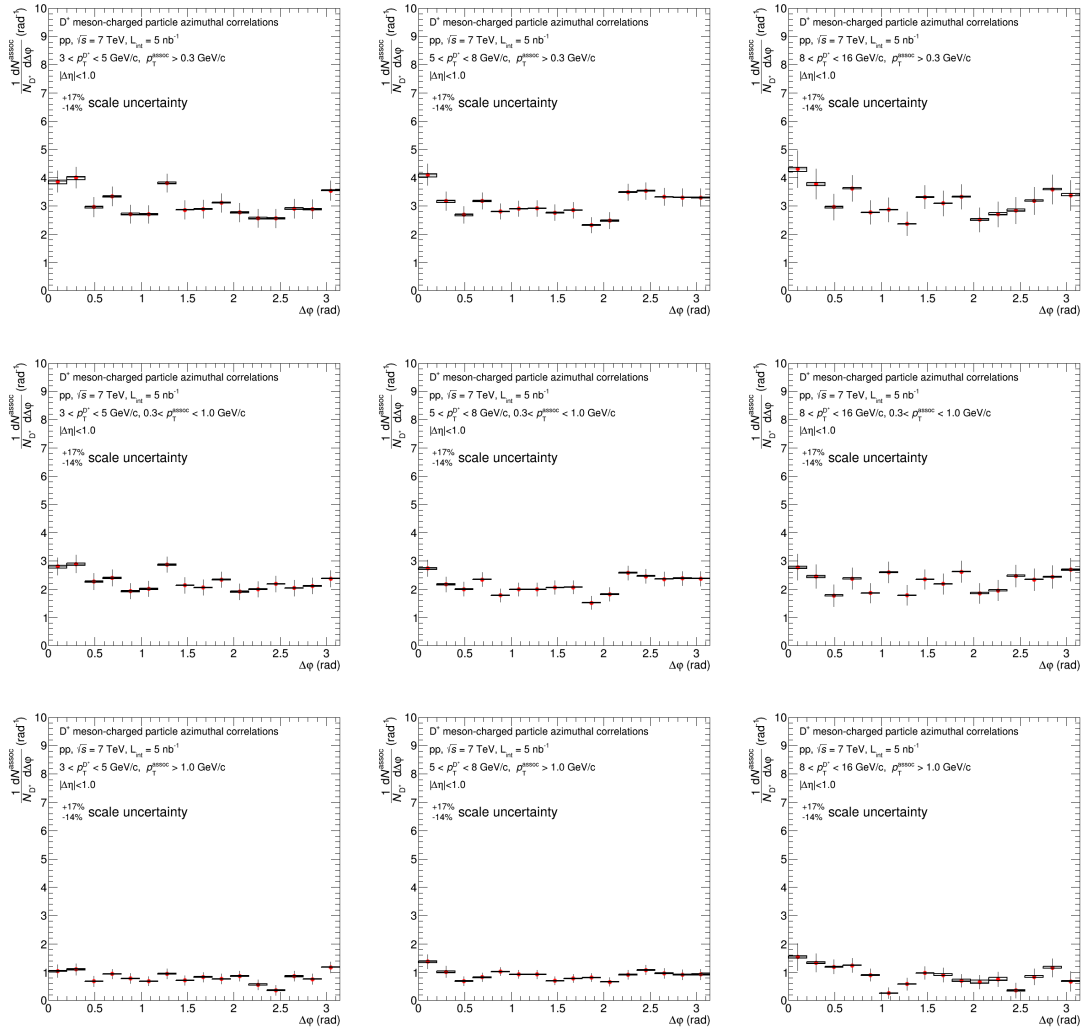


Fig. 4.13: Fully corrected azimuthal correlation distributions between D^+ meson and charged particles using trigger p_T^+ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) and associated p_T^{assoc} thresholds and range: $p_T > 0.3$ GeV/c (first row), 0.3-1.0 GeV/c (middle row) and > 1.0 GeV/c (bottom row) in pp collisions.

The comparisons of fully corrected correlation distributions obtained using all three trigger (D^+ , D^0 , D^{*+}) are shown in Figure 4.15 for pp collisions in top two panels and p–Pb collisions in bottom two panels.

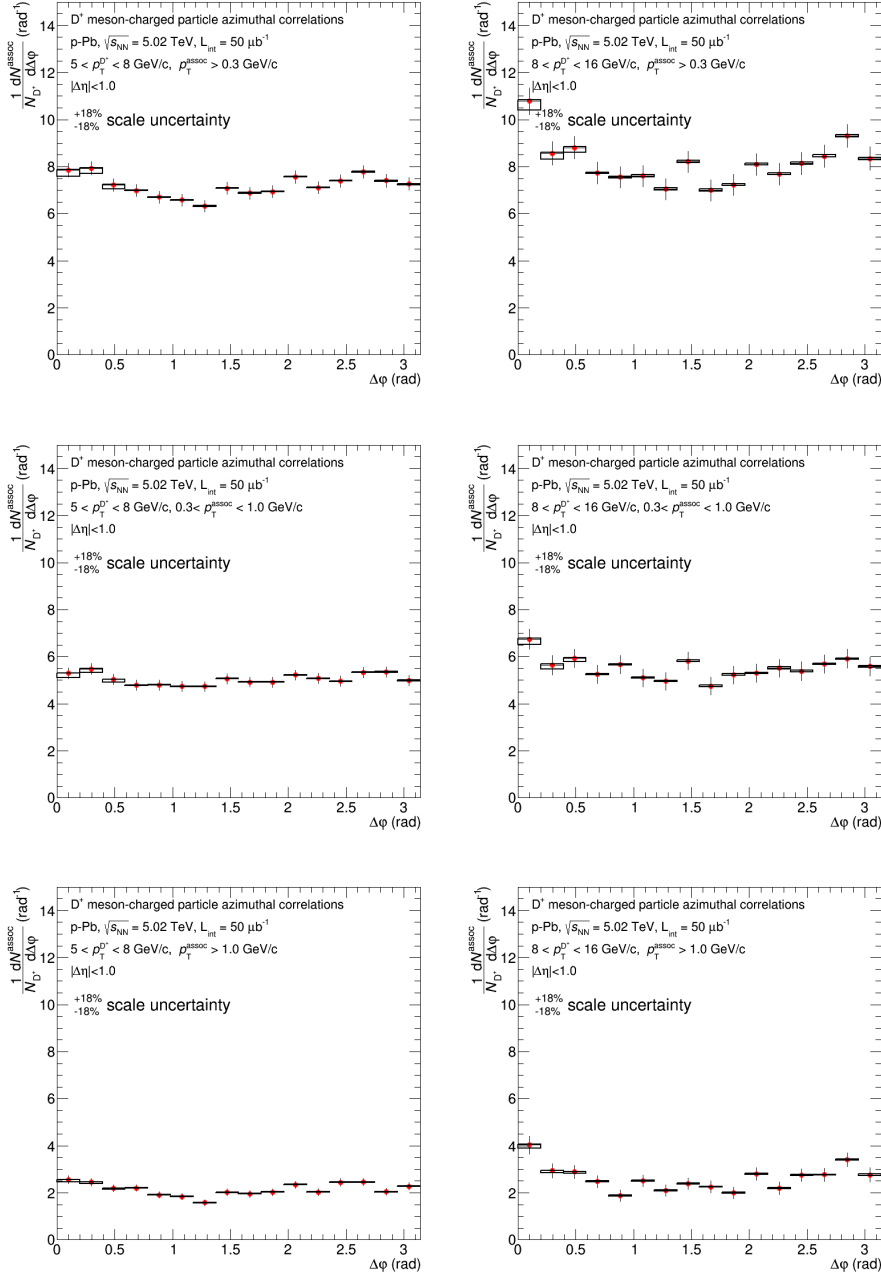


Fig. 4.14: Fully corrected azimuthal correlation distributions between D^+ meson and charged particles using trigger $p_T^{D^+}$ ranges, 5–8 GeV/c (left column) and 8–16 GeV/c (right column) and associated p_T^{assoc} thresholds and range: $p_T > 0.3$ GeV/c (first row), 0.3–1.0 GeV/c (middle row) and > 1.0 GeV/c (bottom row) in p–Pb collisions.

The results as expected shows similar correlation patterns and trends. All three distributions are also compatible within statistical uncertainty as well as within uncorrelated

systematic uncertainties, such as uncertainties on the signal, background normalization, and background shape among three D mesons.

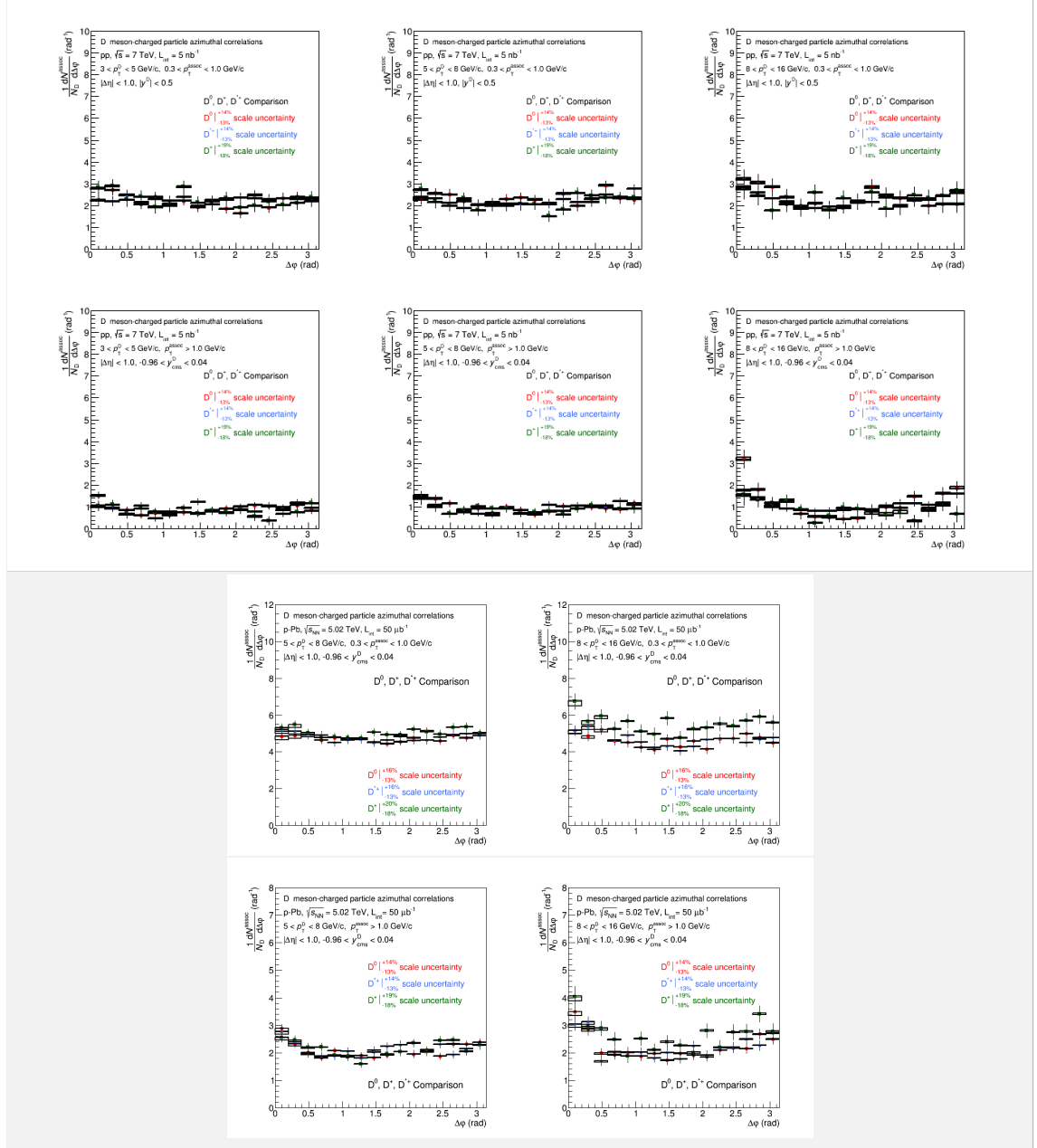


Fig. 4.15: Comparison of fully corrected azimuthal correlation distributions of different D meson (D^+ , D^0 , D^{*+}) in trigger p_T ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) in pp collisions (top two panels) and p-Pb collisions (bottom two panels).

To improve the statistical precision of correlation results, the average of background subtracted and fully corrected correlation distributions from three particle species are computed. The average of correlation is calculated by applying quadratic trigger weights as

$1/w_i^2$ ($w_i, i = D^+, D^0, D^{*+}$). Figure 4.16 shows averaged correlation distributions in pp and p-Pb collisions. The correlation trend and baseline show similar properties as observed in D^+ correlation distributions. The comparison of averaged correlation distribution in pp and p-Pb collisions is also estimated by subtracting correlation baseline, the baseline in turn is estimated using the method discussed in the previous chapter.

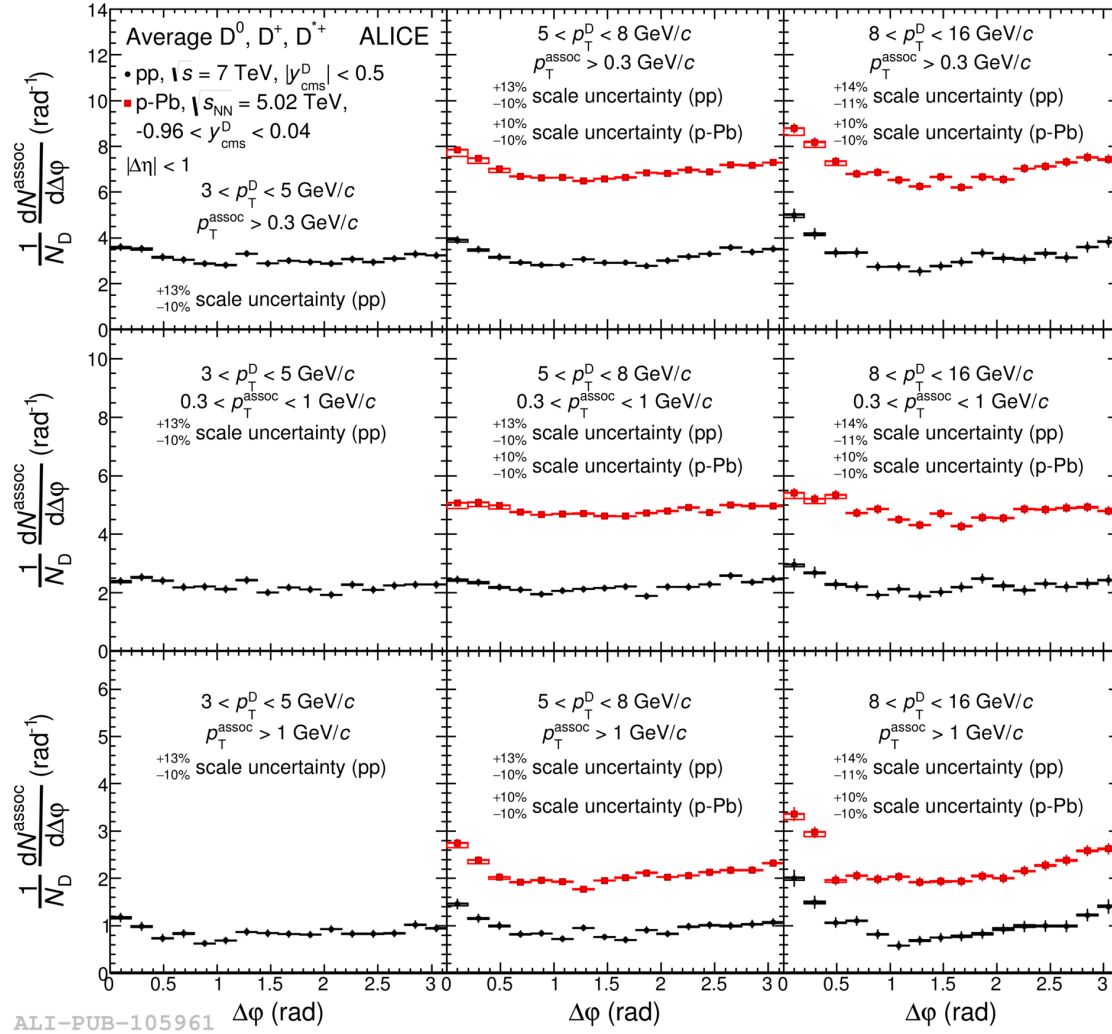
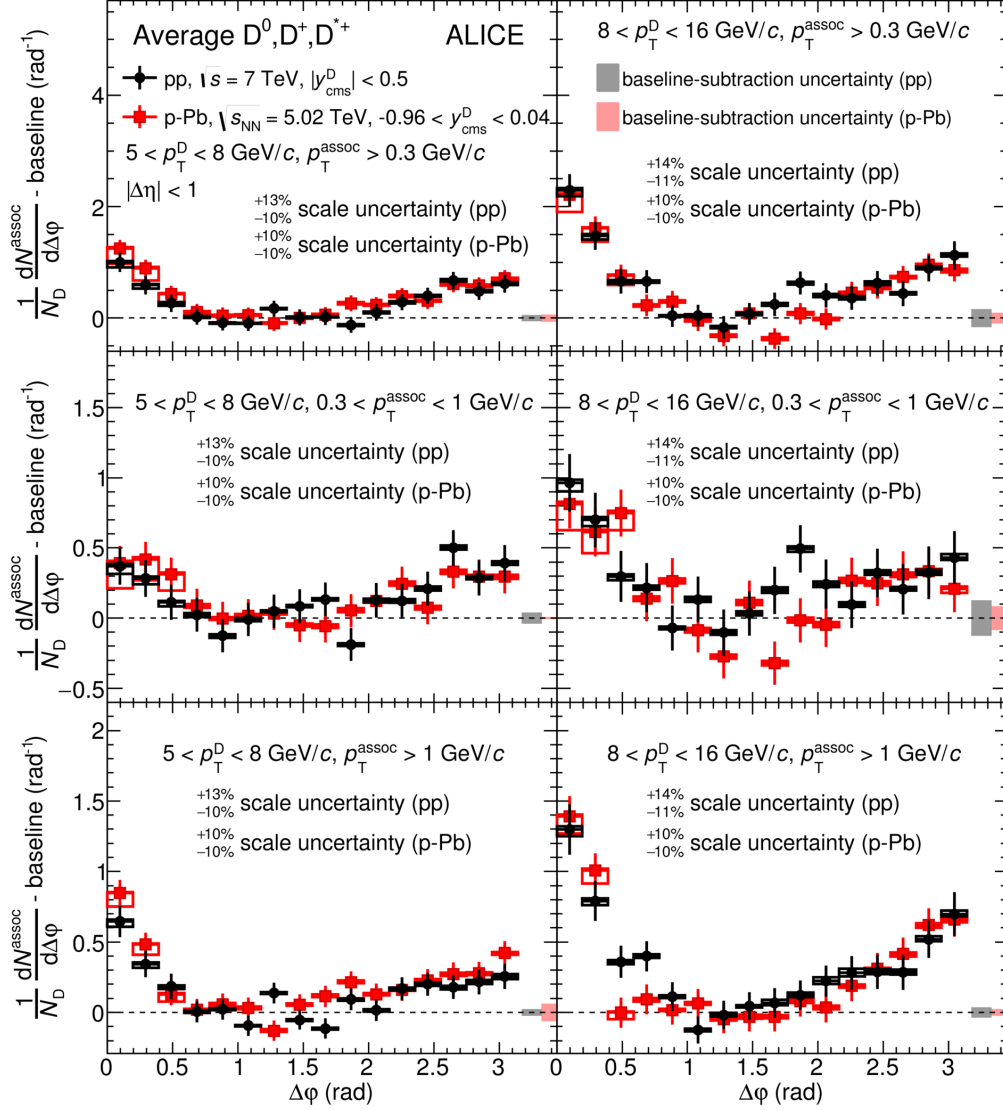


Fig. 4.16: Fully corrected azimuthal correlation distributions between averaged D meson and charged particles using trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) and associated p_T^{assoc} thresholds and range: $p_T > 0.3 \text{ GeV}/c$ (top row), $0.3-1.0 \text{ GeV}/c$ (middle row) and $> 1.0 \text{ GeV}/c$ (bottom row) in pp (black points) and p-Pb collisions (red points).

Figure 4.17 shows comparison of baseline subtracted averaged correlation distributions in pp and p-Pb collisions. The distributions are compatible within uncertainties. The correlation study with Monte Carlo simulation suggested a slight variation of the order of $\sim 7\%$ between both pp and p-Pb collision systems. This variation is small with respect to

current uncertainties in the final results. Therefore, it is not possible to precisely identify the predicted difference in current measurements.



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Fig. 4.17: Fully corrected and baseline subtracted azimuthal correlation distributions between averaged D meson and charged particles using trigger $p_T^{D^+}$ ranges, 5-8 GeV/c (left column) and 8-16 GeV/c (right column) and associated p_T^{assoc} thresholds and range: $p_T > 0.3 \text{ GeV}/c$ (top row), $0.3-1.0 \text{ GeV}/c$ (middle row) and $> 1.0 \text{ GeV}/c$ (bottom row) in pp (black points) and p-Pb collisions (red points).

The averaged correlation properties are then extracted using fit providing values of χ^2/NDF close to unity. For example, NS and AS correlation yields are calculated by fit integral and corresponding widths are measured by fit parameters. The AS correlation properties are not reported because of the poor statistical precision on fits. Figure 4.18 shows an example of correlation fits in pp and p-Pb collisions. The different fitting curves represent three

terms of the fit function. A similar fit response is also observed in other correlation distributions of p_T^D ranges and p_T^{assoc} regions. Figure 4.19 shows distributions of NS correlation yield (top panel) and width (bottom panel) as a function of p_T^D in pp and p–Pb collisions for $p_T^{assoc} > 0.3$ GeV/c (left panel), 0.3–1 GeV/c (middle panel) and > 1 GeV/c (right panel). The NS correlation yield exhibits an increasing trend with p_T^D and is compatible in both systems within statistical uncertainties.

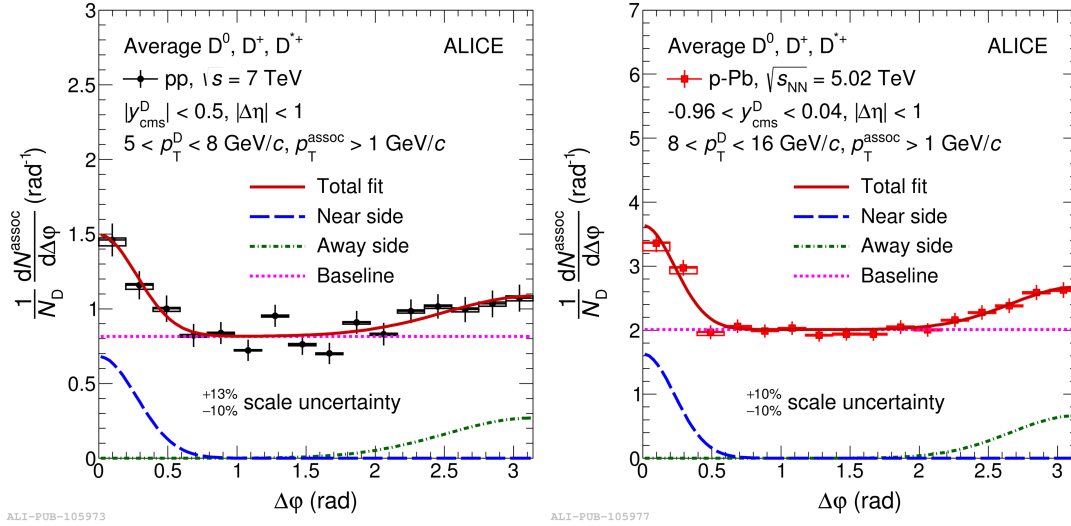


Fig. 4.18: Fit example of the averaged correlation distribution in pp (left) and p–Pb collisions (right).

The distributions for softer $p_T^{assoc} = 0.3$ –1 GeV/c and harder > 1 GeV/c ranges show consistent NS yield within uncertainties. On the other hand, NS correlation width shows no strong dependence on p_T^D in the case of $p_T^{assoc} > 0.3$ GeV/c (left panel), which has relatively better statistics but current level of uncertainty does not allow to quantify the actual dependency. A possible difference in NS width for pp and p–Pb collisions with current uncertainty values is also difficult to quantify. A v_2 -like modulation of the correlation baseline can introduce a bias in the extraction of correlation properties. Therefore, the effect in p–Pb analysis was studied by repeating correlation fit after subtracting the modulation from distribution. The modulation value $v_2 = 0.05$ for D mesons in all p_T^D region and $v_2 = 0.05$ (0.1) for associated charged particles with $p_T^{assoc} > 0.3$ (1) GeV/c are considered for subtraction. These v_2 values for charged particles are taken from previous studies [77] whereas for D mesons, we use the maximum value predicted in [142]. Using these assumptions, NS yield varies by an order of 10% in p_T^D range 5–8 GeV/c, whereas a variation in NS width and baseline are below 4% and 1%, respectively. With current statistics of p–Pb collision one can not argue about v_2 modulation like effects.

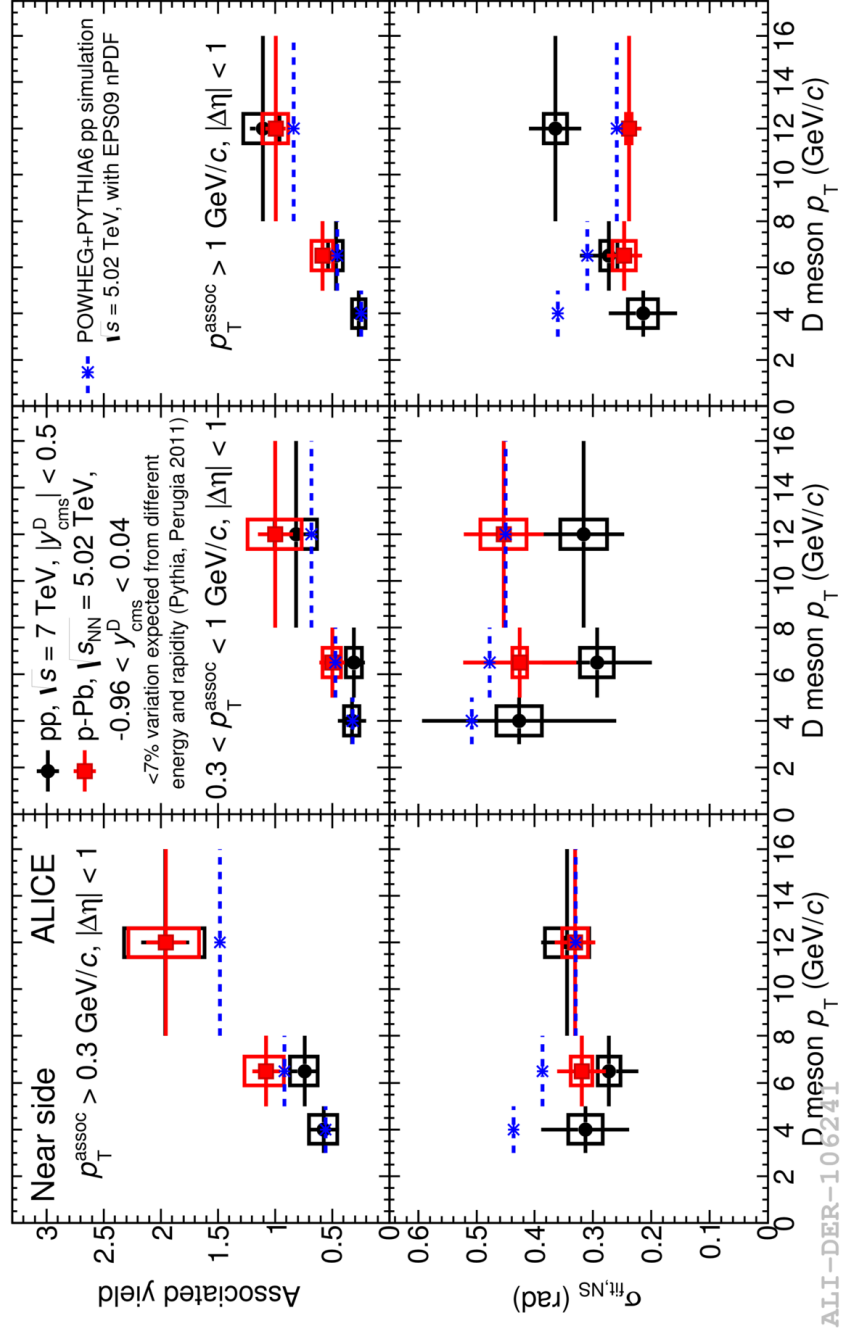


Fig. 4.19: Comparison of the correlation properties, NS yield (top panel) and NS width (bottom panel) as a function of p_T^D for associated p_T^D thresholds and range: $p_T > 0.3 \text{ GeV}/c$ (first column), $0.3-1.0 \text{ GeV}/c$ (middle column) and $> 1.0 \text{ GeV}/c$ (bottom column) in pp (black points) and p-Pb collisions (red points).

4.3 Simulation studies

The Monte-Carlo simulations with PYTHIA6 (Perugia0 tune) event generator for pp collisions at $\sqrt{s} = 7$ TeV and HIJING generator for p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are used in various analysis corrections. PYTHIA generator provides full topology of final state particles based on Born matrix element and parton shower for higher order radiation in strong and EM interaction and the hadronization (Lund strong and cluster model) [143].

The comparison of final azimuthal correlation distribution with simulation expectations is also evaluated using different generators and tunes, e.g. PYTHIA6 with Perugia0, Perugia2010 and Perugia2011 tunes [144], PYTHIA8 with 4C tune [143] and POWHEG coupled to PYTHIA6 (2011 tune) [145, 146] in both systems. In p–Pb collision, the difference in energy of proton and lead ions introduces a shift in rapidity ($\Delta y_{NN} = 0.465$) for current measurement of particle spectra, which is not the case for pp collisions. Therefore, the rapidity of the trigger and associated particles are shifted in p–Pb analysis. In order to make a fair comparison of correlation distributions between both systems, simulation in p–Pb collisions are obtained with a rapidity boost to reproduce rapidity shift of p–Pb collision reference frame.

In PYTHIA6 event generator, only Perugia tunes that consider different initial state and final state radiation are used. The main differences among these Perugia tunes are, for example, Perugia 2010 tune includes a modification of high- z fragmentation and that provides a different amount of final state radiation. Perugia 2011 tune includes tuning to first LHC data measurements, mainly multiplicity and underlying-event based studies. PYTHIA8 is a successor and C++ version of PYTHIA6 event generator, which is written in Fortran language. In addition to C++ version, it also includes improvements related to the Multi Particle Interaction (MPI) and colour reconnection contributions. POWHEG is an NLO-pQCD based generator and can be used with parton shower generators e.g. PYTHIA. It provides exclusive final-state particles with precision up to next-to-leading order processes. In the analysis, POWHEG+PYTHIA6 (Perugia 2011 tune) is considered and in case of p–Pb simulations, parton distribution functions (PDFs) are corrected for nuclear effects (CT10nlo with EPS09). In this section, simulated correlations using PYTHIA6 and PYTHIA8 generators and different comparisons based on generator tunes, collision systems and origin of trigger particle are shown. Correlation distributions are evaluated for all $p_T^{D^+}$ and p_T^{assoc} ranges in both systems and therefore, to avoid the display of similar correlation plots only a few of them are shown in this section. The simulation results for both pp and p–Pb collisions are obtained with high statistics. A total of ~1500 million

events are generated in all generators to avoid statistical fluctuations. Figure 4.20 shows correlation distributions of prompt D^+ ($c \rightarrow D^+$) azimuthal correlations, based on different PYTHIA generators and tunes in pp (top three rows) and p–Pb collisions (bottom row). The PYTHIA6: Perugia2011 and PYTHIA8:4C tunes show similar NS correlation in all $p_T^{D^+}$ ranges and associated p_T^{assoc} regions but produce different AS correlations, which is more pronounced in mid and high $p_T^{D^+}$ trigger correlations. This can be due to different mechanisms used by different generators and their tunes.

The correlation baseline in the simulation is extracted by “physical” minimum. The average of minimum points around NS and AS correlations is considered as “physical” minimum of distribution. This average value is then used to subtract the baseline from correlation distribution. Figure 4.21 shows, same comparisons as shown in Figure 4.20 after subtracting correlation baselines. In same way, correlation distributions of feed-down D^+ ($b \rightarrow D^+$) correlations before and after subtracting the baseline are shown in Figure 4.22 and Figure 4.23. This comparison shows that different PYTHIA6 tunes produce similar NS correlations but slightly different AS correlations whereas PYTHIA8 produces relatively higher NS and AS correlations in all $p_T^{D^+}$ ranges and p_T^{assoc} regions. Correlation distributions based on trigger origin (prompt or beauty) are also shown in Figure 4.24 for PYTHIA6:Perugia 2011 tune.

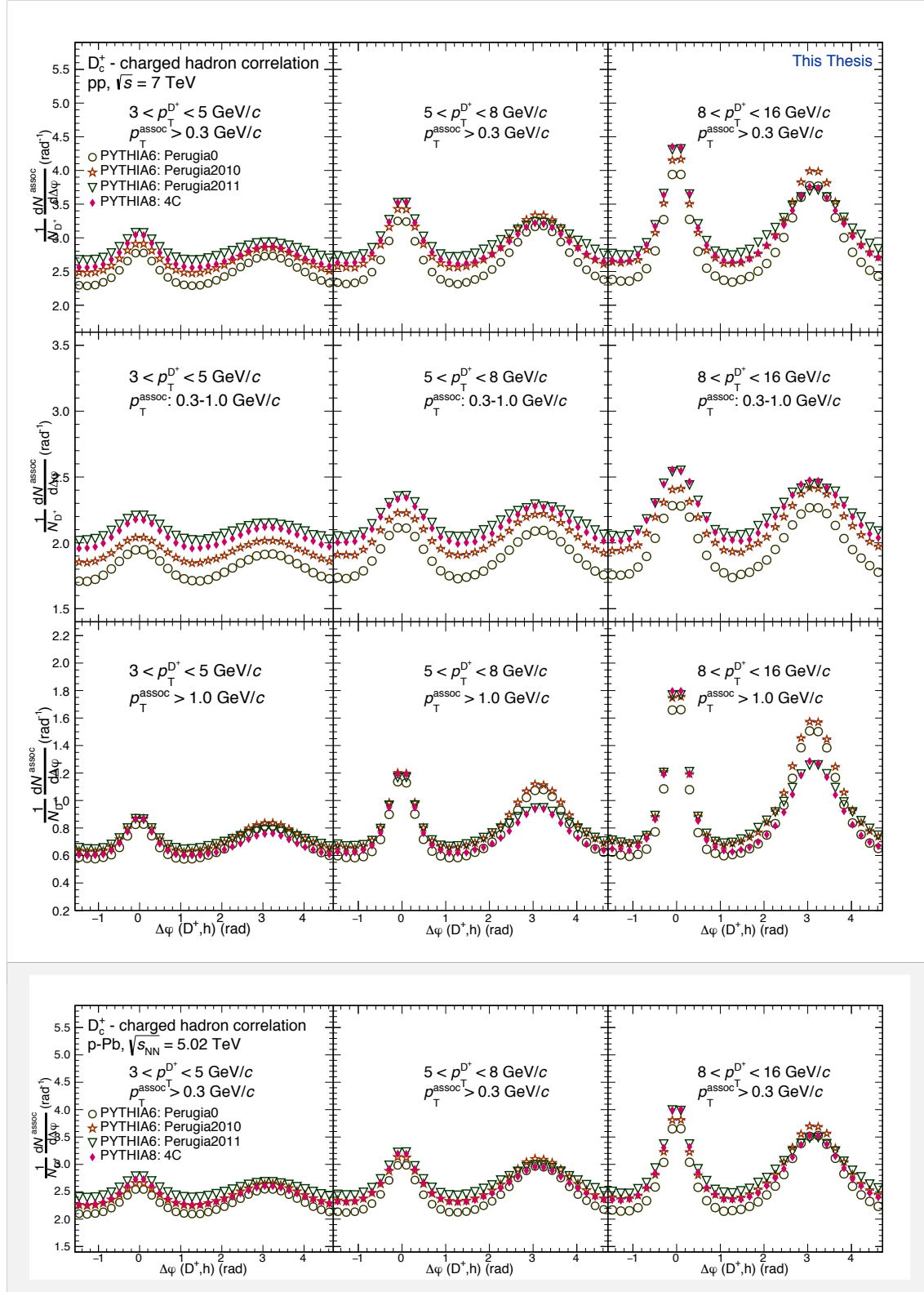


Fig. 4.20: [Simulation] Comparison of the “prompt” azimuthal correlation distributions based on different PYTHIA generators and tunes in trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; > 0.3 GeV/c (first and fourth rows), 0.3-1.0 GeV/c (second row) and > 1.0 GeV/c (third row) in pp collisions (first to third rows) p-Pb collisions (fourth row).

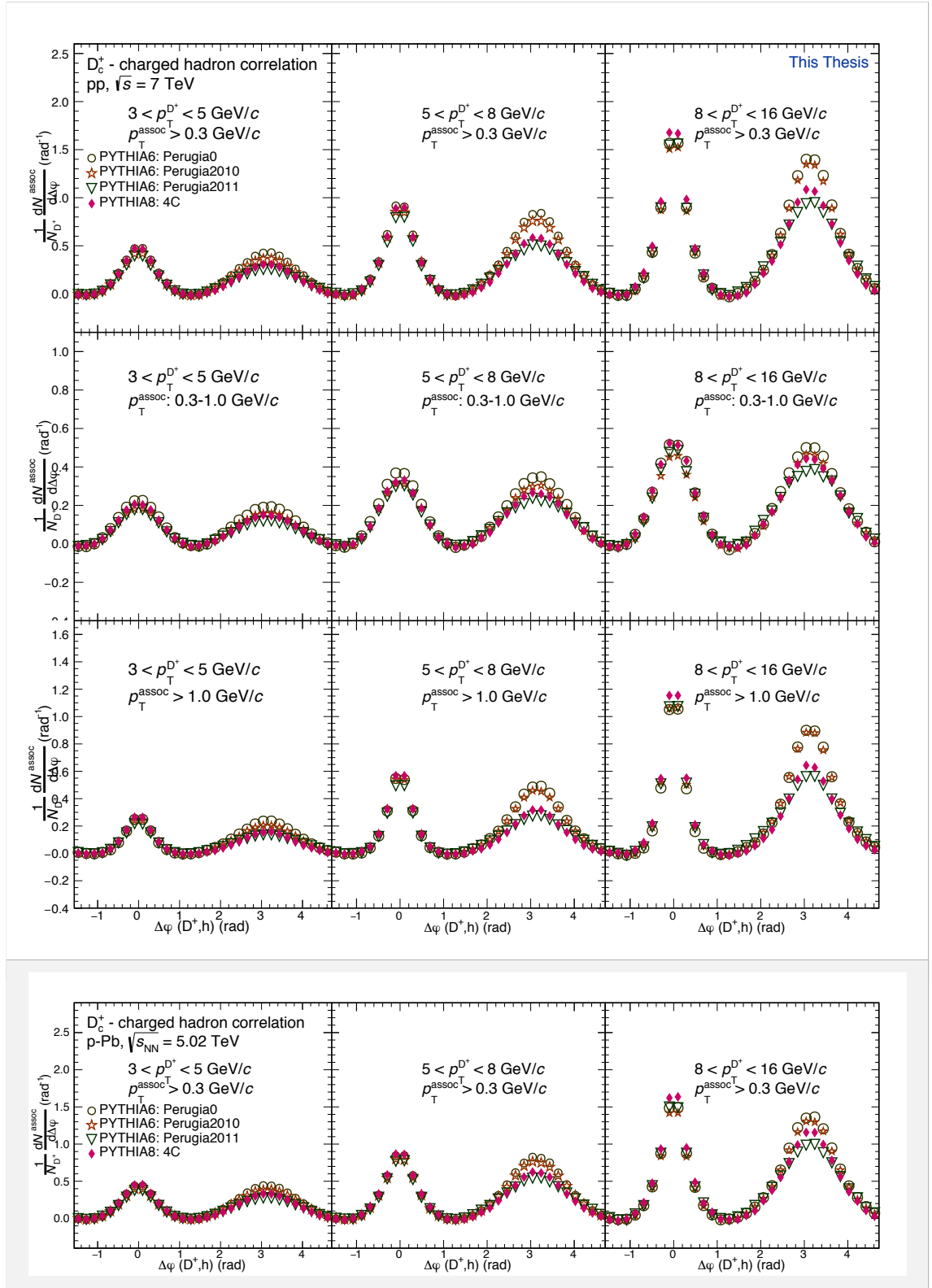


Fig. 4.21: [Simulation] Comparison of the baseline subtracted "prompt" azimuthal correlation distributions based on different PYTHIA generators and tunes in trigger $p_T^{D^+}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; $> 0.3 \text{ GeV}/c$ (first and fourth rows), $0.3-1.0 \text{ GeV}/c$ (second row) and $> 1.0 \text{ GeV}/c$ (third row) in pp collisions (first to third rows) p-Pb collisions (fourth row).

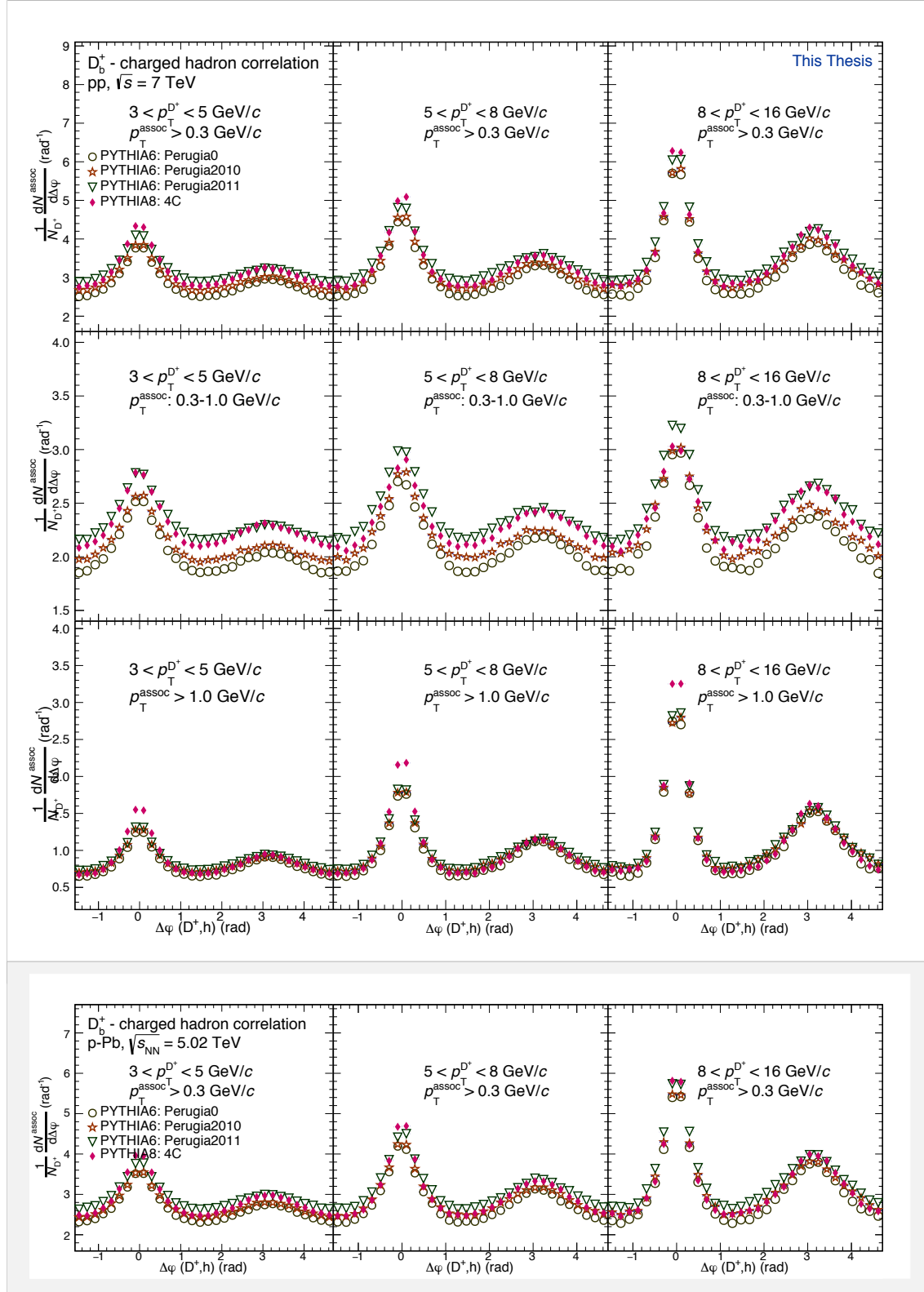


Fig. 4.22: [Simulation] Comparison of the “feed-down” azimuthal correlation distributions based on different PYTHIA generators and tunes in trigger $p_T^{D^+(b)}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; > 0.3 GeV/c (first and fourth rows), 0.3-1.0 GeV/c (second row) and > 1.0 GeV/c (third row) in pp collisions (first to third rows) p-Pb collisions (fourth row).

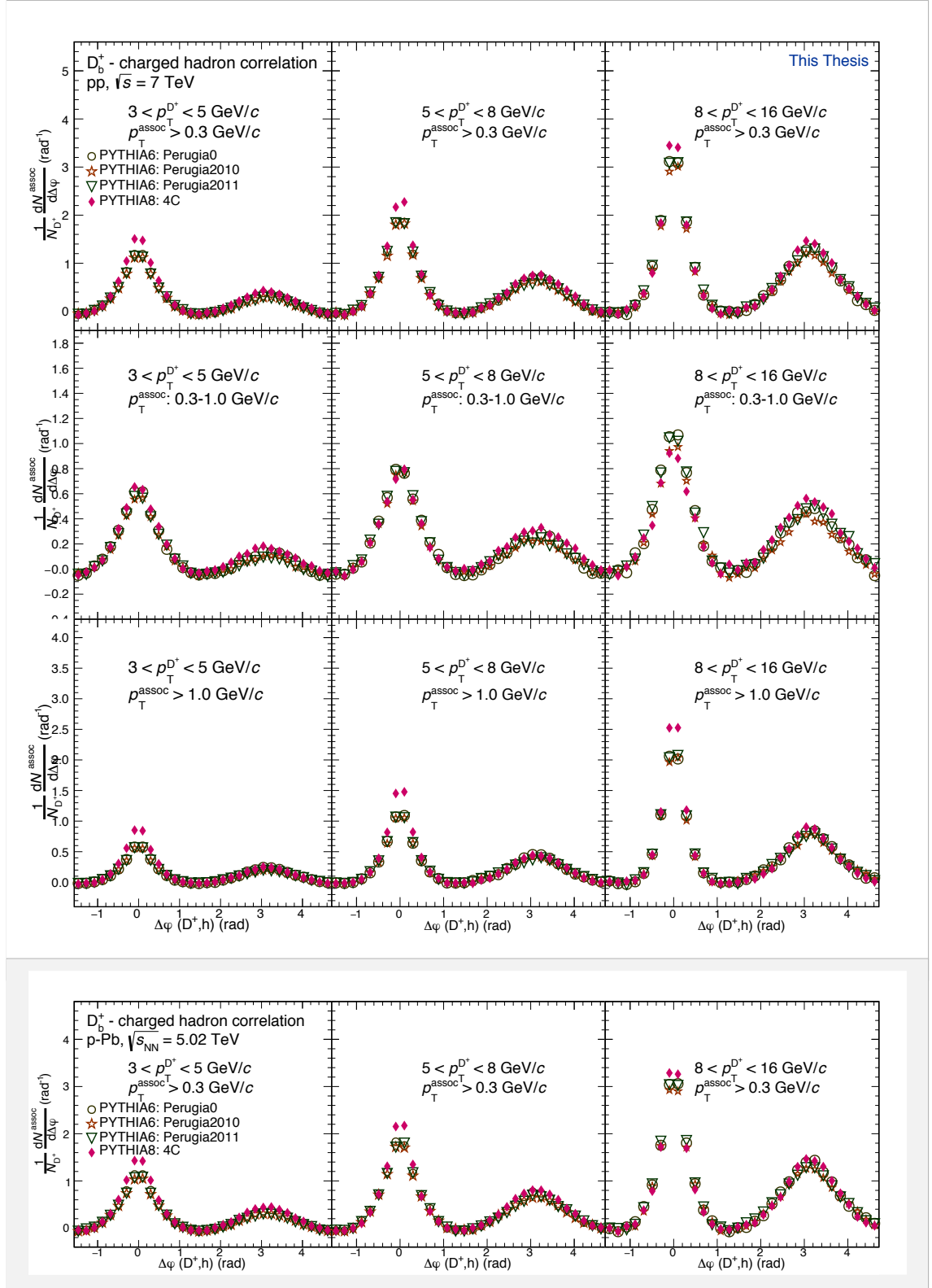


Fig. 4.23: [Simulation] Comparison of the baseline subtracted "feed-down" azimuthal correlation distributions based on different PYTHIA generators and tunes in trigger $p_T^{D^+(b)}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; > 0.3 GeV/c (first and fourth rows), 0.3-1.0 GeV/c (second row) and > 1.0 GeV/c (third row) in pp collisions (first to third rows) p-Pb collisions (fourth row).

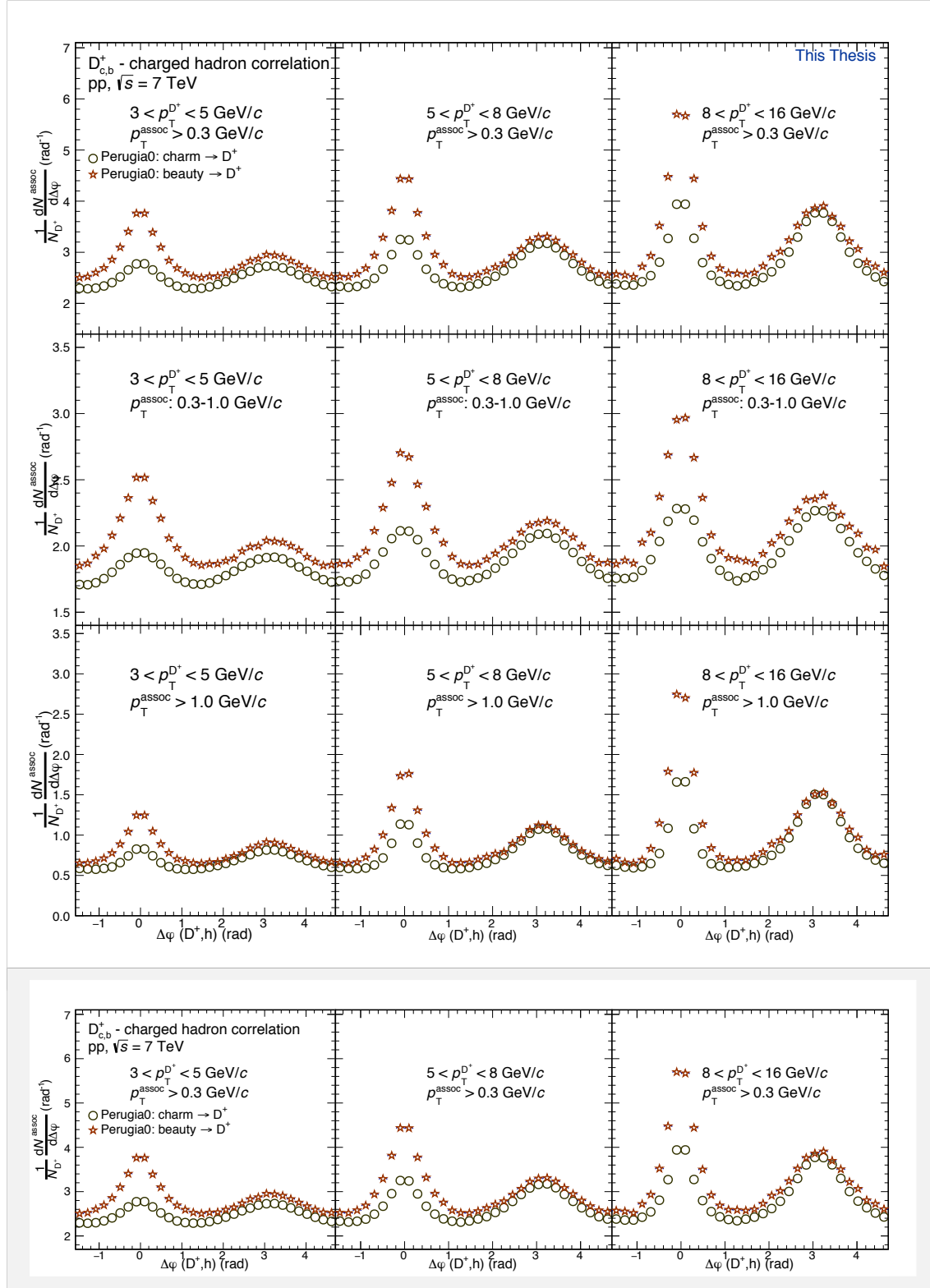


Fig. 4.24: [Simulation] Comparison of the prompt vs. “feed-down” azimuthal correlation distributions with PYTHIA:Perugia2010 tune in trigger $p_T^{D^{(*)}}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; > 0.3 GeV/c (first and fourth rows), 0.3-1.0 GeV/c (second row) and > 1.0 GeV/c (third row) in pp collisions (first to third rows) p-Pb collisions (fourth row).

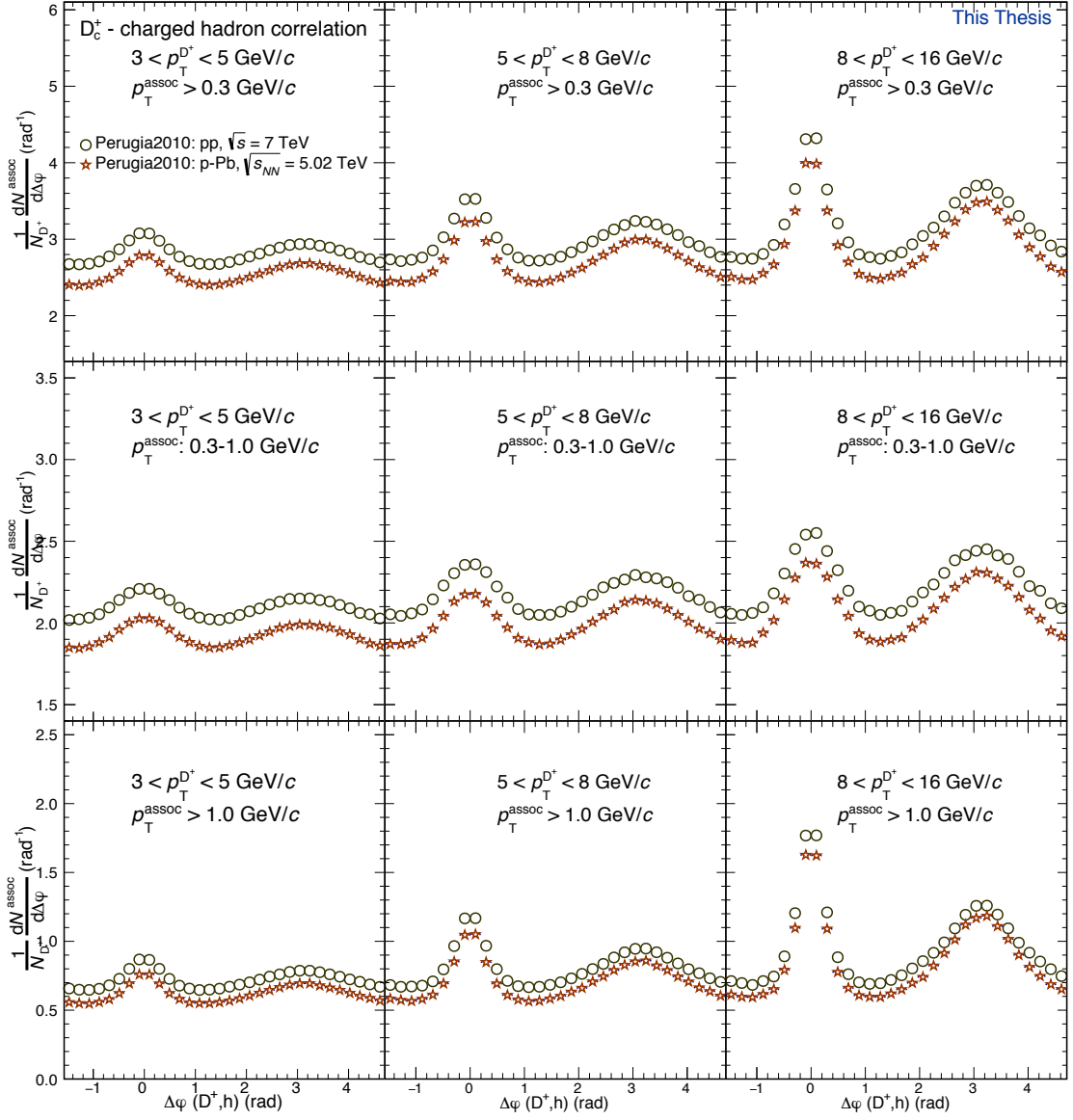


Fig. 4.25: [Simulation] Comparison of the “prompt” azimuthal correlation distributions in pp and p–Pb collisions using trigger $p_T^{D^+(b)}$ ranges, 3–5 GeV/c (left column), 5–8 GeV/c (middle column) and 8–16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; > 0.3 GeV/c (first row), 0.3–1.0 GeV/c (second row) and > 1.0 GeV/c (PYTHIA:Perugia2010 tune).

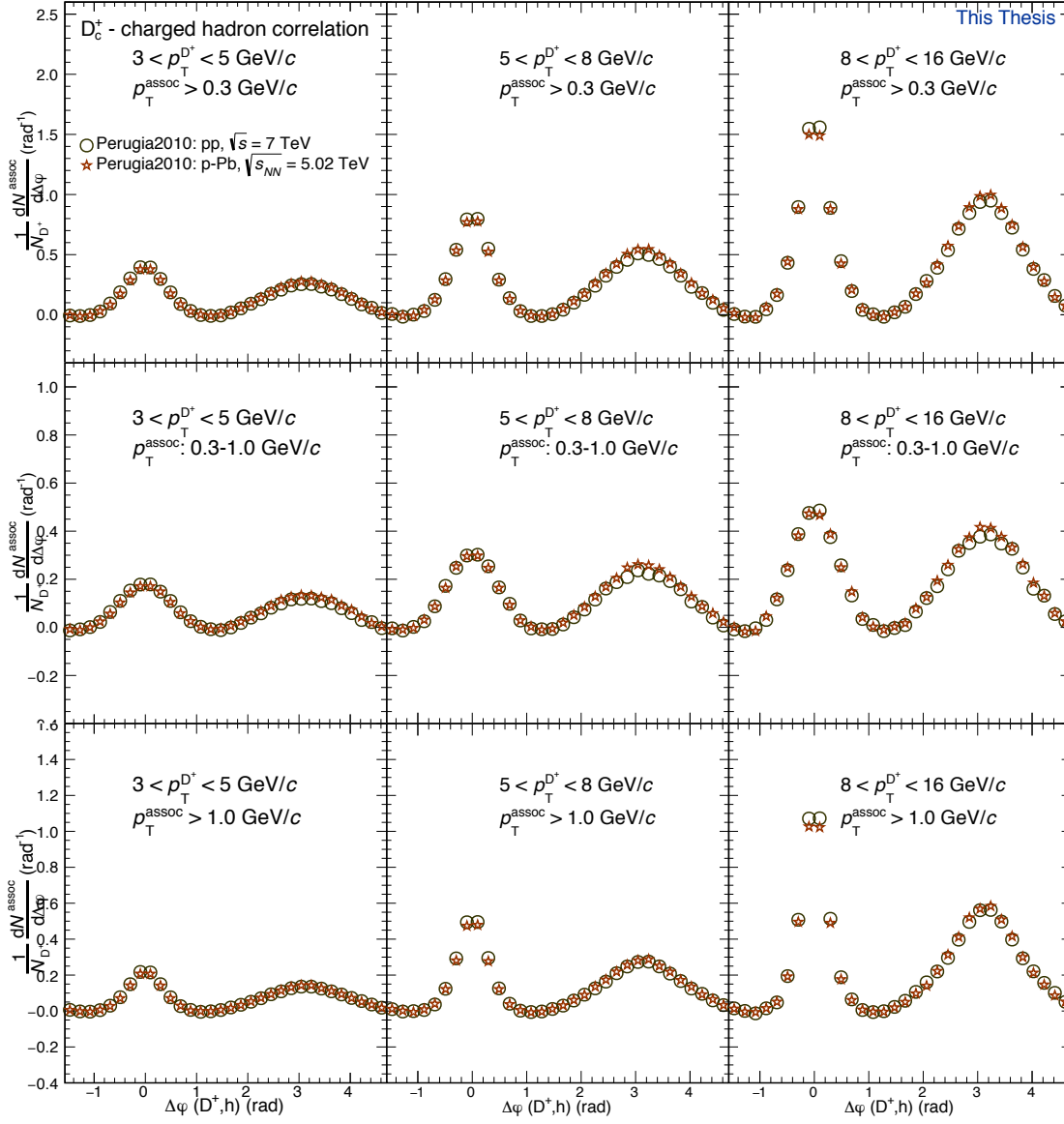


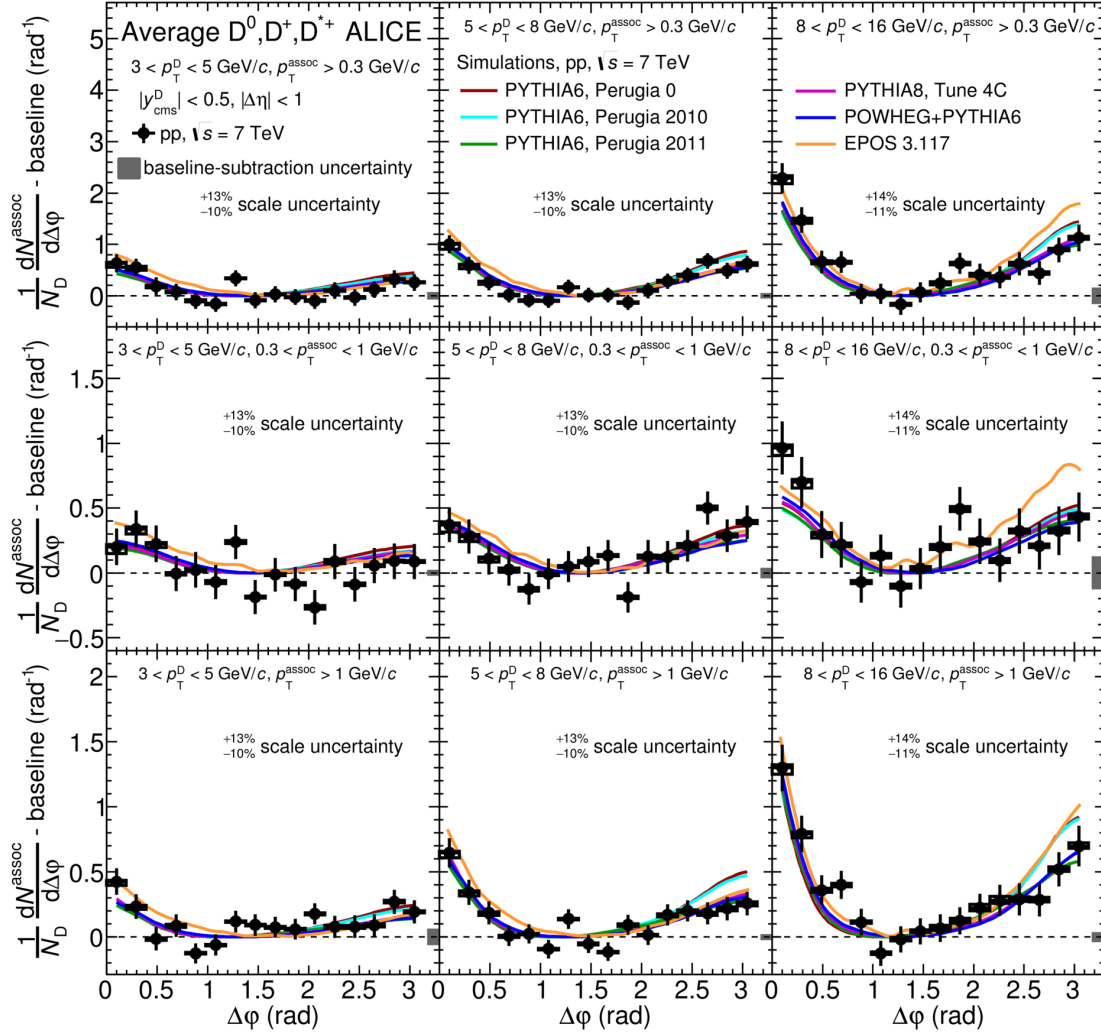
Fig. 4.26: [Simulation] Comparison of the baseline subtracted prompt azimuthal correlation distributions in pp and p-Pb collisions using trigger $p_T^{D^+(b)}$ ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) with associated p_T^{assoc} thresholds and range; $> 0.3 \text{ GeV}/c$ (first row), 0.3-1.0 GeV/c (second row) and $> 1.0 \text{ GeV}/c$ (PYTHIA:Perugia2010 tune).

The comparison indicates that feed-down correlation produces higher NS and AS peaks as well as higher baselines (upto a maximum of 8%) in all trigger and associated p_T bins. Finally, simulations are also compared between both pp and p–Pb collisions. Figure 4.25 shows the same using PYTHIA6:Perugia 2011 tune. The comparison shows that both systems produce similar AS and NS correlation patterns with a maximum variation of about 7% and as already discussed, it was expected because p–Pb simulations are measured with a different centre of mass energy and rapidity shifts.

4.3.1 Comparison of data with simulations

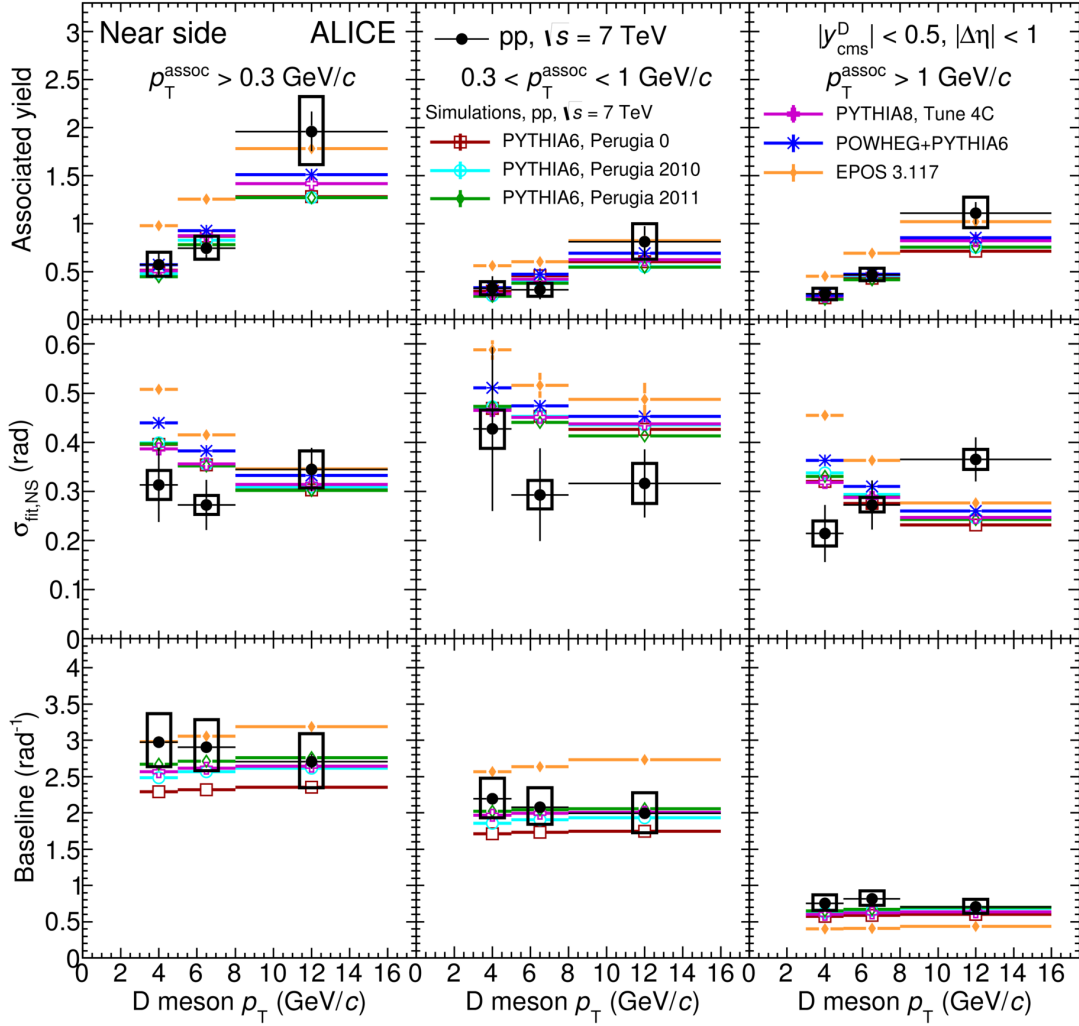
The final corrected correlation distributions and their properties are also compared with simulations based on different event generators and tunes. Figure 4.27 shows the comparison of final averaged azimuthal correlation distributions with simulations in pp collisions. Data are described by Monte Carlo within uncertainties over full $\Delta\varphi$ range, though data points in high p_T^D and $p_T^{assoc} > 0.3$ GeV/ c range show a hint of more pronounced trend in NS correlations peak with respect to simulations, but this increase is within 2σ . Since, statistical fluctuations are negligible in simulation, baseline and its uncertainty are estimated using the average of two lowest values of azimuthal correlation distribution. The correlation properties are then extracted and compared with data results. Figure 4.28 and 4.29 show comparison of NS yields (top panel), NS widths (middle panel) and baseline (bottom panel) with different simulations and data points in pp and p–Pb collisions. The NS correlation yield in different generators is lower in comparison to measured values for both systems. The factor of about 1.5 is observed in PYTHIA8 and POWHEG+PYTHIA simulations for $p_T^{D^+}$ 8-16 GeV/ c and $p_T^{assoc} > 0.3$ GeV/ c . The simulated NS width describes p–Pb data better than pp data points. The correlation baselines from simulations reproduce the data baseline within the uncertainties.

Plots are from next page onwards..



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Fig. 4.27: Comparison of final averaged azimuthal correlation distributions with different simulation expectations in trigger p_T^D ranges, 3-5 GeV/c (left column), 5-8 GeV/c (middle column) and 8-16 GeV/c (right column) and associated p_T^{assoc} thresholds and range: $p_T > 0.3$ GeV/c (first row), 0.3-1.0 GeV/c (middle row) and > 1.0 GeV/c (bottom row) in pp collisions (black points)



ALI-PUB-106020

Fig. 4.28: Comparison of correlation properties, NS yield (top panel), NS width (middle panel) and baseline (bottom panel) as a function of p_T^D for associated p_T^{assoc} : $p_T > 0.3$ GeV/c (first column), $0.3-1.0$ GeV/c (middle column) and > 1.0 GeV/c (bottom column) in pp (black points) and different simulations (other colours).

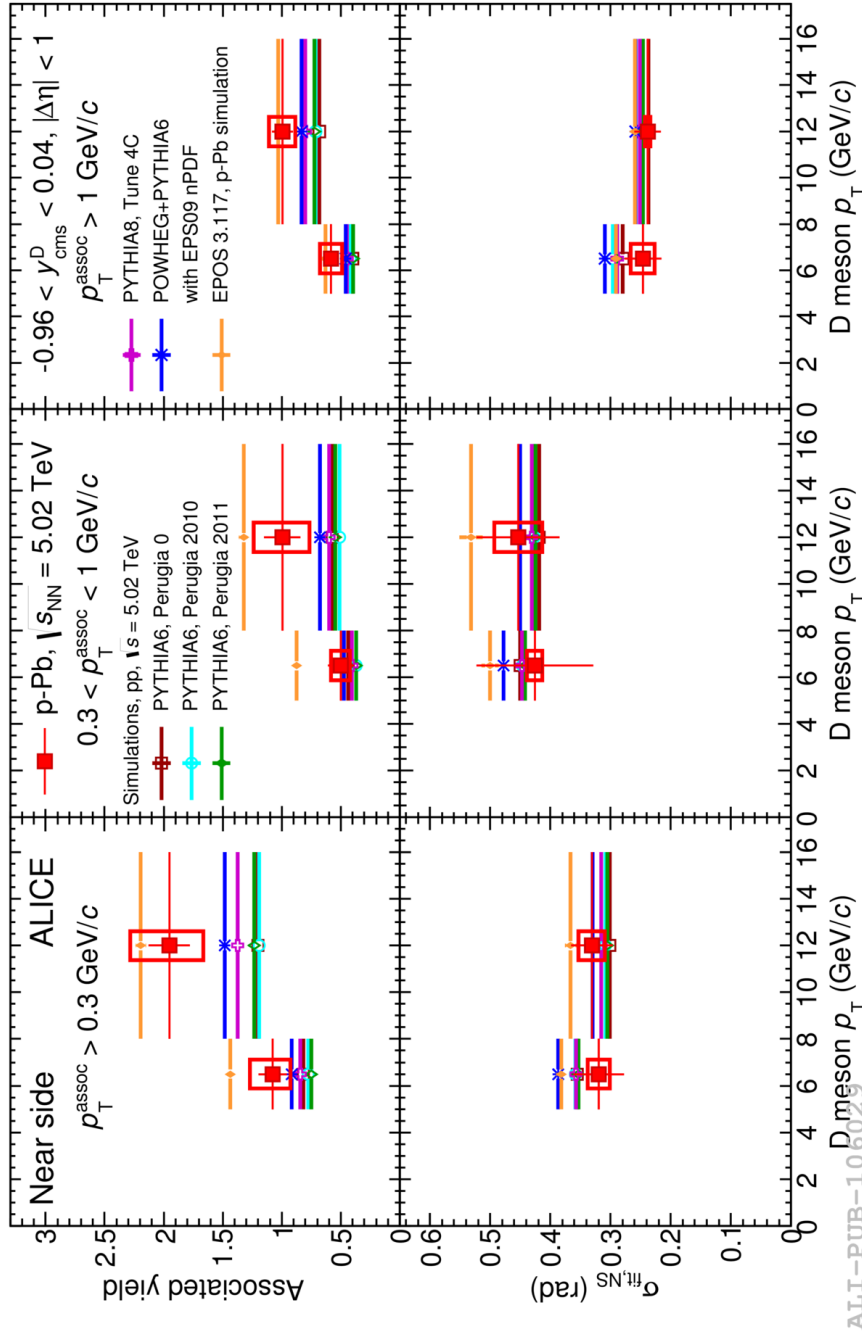


Fig. 4.29: Comparison of the correlation properties, NS yield (top panel) and NS width (bottom panel) as a function of p_T^D for associated p_T^{assoc} ; $p_T > 0.3 \text{ GeV}/c$ (left column), $0.3\text{--}1.0 \text{ GeV}/c$ (middle column) and $> 1.0 \text{ GeV}/c$ (right column) in p-Pb (red points) and different simulations (other colours).

4.4 Summary and future prospects

This thesis work presented first ever measurement of azimuthal correlations between averaged D meson and charged particles in pp and p–Pb collisions at the LHC. The correlation properties, e.g. NS correlation yield and width, which are sensitive to characteristics of jet containing the D meson and baseline which represent the underlying events are studied as a function of trigger p_T^D and differentially in p_T^{assoc} ranges. The analysis has been performed with trigger $p_T^{D^+}$ ranges, low: 3–5 GeV/ c , mid: 5–8 GeV/ c and high: 8–16 GeV/ c and associated charged particle p_T^{assoc} thresholds and range, > 0.3 GeV/ c , 0.3–10 GeV/ c , > 1.0 GeV/ c in both pp and p–Pb collisions. In p–Pb analysis, low p_T : 3–5 GeV/ c region is excluded because of no visible correlation pattern. The measurement using other D (D^0 , D^{*+}) mesons as a trigger particle in same kinematic ranges are also evaluated in both colliding systems by the ALICE collaboration. The correlation results from all three mesons in different p_T^D and p_T^{assoc} are found consistent within uncertainties, and therefore, the average correlation is evaluated to improve statistical precision on measurement. The final measured correlation distributions and their properties in both collision systems are found compatible within uncertainties. The simulation study based on PYTHIA generators suggested a maximum variation of the order of $\sim 7\%$ in correlations for both the systems. A variation was expected at least for two basic reasons, first because of the difference in centre of mass energy in both collisions and second is due to shifted rapidity in p–Pb collisions. The uncertainty on the current results does not allow to precise quantification of the expected variation. Given the current experimental uncertainties, comparison of azimuthal correlations between pp and p–Pb collisions do not reveal any evidence of CNM effects. The measured azimuthal distributions are also compared with simulations based on different Monte-Carlo generators and our results are consistent within uncertainties.

The comparison of D meson azimuthal correlation distribution between pp collisions and heavy-ion collision systems can provide information on the charm energy loss mechanisms in the medium, formed in heavy-ion collisions. The statistics collected during LHC run-1 data of heavy-ion collisions was not sufficient to perform this analysis in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In run-2 phase (2015 onwards), LHC recorded heavy-ion collision data for higher collision energy, Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV and with larger statistics (run-1 $\times 10$). The cross section for charm production at higher centre of mass energy, Pb–Pb collision ($\sqrt{s_{NN}} = 5.02$ TeV) is also predicted to increase by more than a factor of two with respect to the previous measurements in Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV. Therefore, run-2 data might allow measuring this analysis in heavy-ion (Pb–Pb) collisions, and in that case, the current pp and p–Pb measurements will provide crucial references.

The higher statistics of run-2, pp and p–Pb collisions data will also provide a better precision on the current measurements e.g. correlation patterns and properties will provide a more quantitative statement and constrain the comparison with appropriate simulations. Long-range correlations in rapidity are observed in high-multiplicity pp and p–Pb collisions at the LHC, which suggest the onset of collectivity in these small systems [76, 79]. Therefore, current measurements are important to study for similar effects in the heavy-flavour sector. The run-2 data of pp collisions at $\sqrt{s} = 13$ TeV and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV will also possibly allow exploring the long-range correlations as a function of charged particle multiplicity.

Analysis paper: Measurement of azimuthal correlations of D mesons and charged particles in pp collisions at $\sqrt{s} = 7$ TeV and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Status: Published: [arXiv:1605.06963](https://arxiv.org/abs/1605.06963)

Reference: [Eur. Phys. J. C 77 \(2017\), 245](#)

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