PROMPT $D^0$ MESON NUCLEAR MODIFICATION FACTOR AND
AZIMUTHAL ANISOTROPY IN HEAVY ION COLLISIONS WITH CMS

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The primary goal of heavy ion physics is to study the properties of the Quark Gluon Plasma (QGP), a state of matter comprising deconfined quarks and gluons. Heavy quarks (charm and bottom) are effective probes to study the properties of the QGP produced in heavy ion collisions. Because of their large masses, heavy quarks are primarily produced via initial hard scatterings in heavy ion collisions. They are expected to interact with the QGP differently than light quarks and gluons. The comparison between the nuclear modification factors of heavy flavor and light hadrons can provide insights into the expected flavor dependence of parton energy loss. The azimuthal anisotropy of heavy flavor hadrons can help quantify the interaction strength between the heavy quarks and the QGP medium at low transverse momentum ($p_T$), and provide unique information about the path length dependence of heavy quark energy loss at high $p_T$.

This dissertation presents the measurements of the prompt $D^0$ meson nuclear modification factor ($R_{AA}$) and azimuthal anisotropy coefficients $v_2$ and $v_3$ in PbPb collisions with the CMS detector at the CERN LHC. The $D^0$ meson production is found to be strongly suppressed in heavy ion collisions and the suppression has strong dependence on centrality and $p_T$. The suppression of $D^0$ mesons is consistent with that of light hadrons for $p_T > 5$ GeV/$c$, while a hint of smaller suppression is observed for $p_T < 5$ GeV/$c$. The $v_2$ values are found to be positive in the $p_T$ range of 1 to 40 GeV/$c$. The $v_3$ is measured for the first time and positive values are observed for $p_T < 6$ GeV/$c$. Compared to those of light hadrons, the $D^0$ meson $v_2$ and $v_3$ coefficients are found to be smaller for $p_T < 6$ GeV/$c$. Through the comparison with
theoretical calculations, the $v_2$ and $v_3$ results at low $p_T$ suggest that the charm quarks take part in the collective motion of the medium. The $R_{AA}$, $v_2$, and $v_3$ results provide new constraints on the models of the interactions between the charm quarks and the QGP medium, and the charm quark energy loss mechanisms.
1. Introduction

This chapter presents the theoretical basis of the experimental studies in this dissertation.

1.1 Standard Model

One of the major goals of physics is to explore the elementary particles and fundamental principles of the universe. A remarkable picture of the fundamental structure of matter is formed by the efforts of generations of physicists. It is found that a few elementary particles (six types of quarks, six types of leptons, four types of force carrier particles, and the Higgs particle) are the basic building blocks of everything in the known universe, and all known interactions can be categorized into four fundamental types of interactions (the gravitational interaction, the electromagnetic interaction, the strong interaction, and the weak interaction). The Standard Model of particle physics is currently the best understanding of how these elementary particles and three of the fundamental interactions (electromagnetic, strong, and weak) are related to each other [1–3]. In this section, some basic concepts of the Standard Model will be presented. A comprehensive review can be found in Ref. [4].

Figure 1.1 shows the elementary particles in the Standard Model. All particles can be categorized into two types: fermions (particles with half-integer spin) and bosons (particles with integer spin). All six types of quarks and six types of leptons are fermions and can be further grouped into three generations, each including two types of quarks and two types of leptons. The gluon is the force carrier of the strong interaction, the photon is the force carrier of the electromagnetic interaction, and the $W$ and $Z$ bosons are the force carriers of the weak interaction. The Higgs boson,
Figure 1.1.: The current elementary particles in Standard Model (taken from Wikipedia [5]).

which was discovered recently at the Large Hadron Collider (LHC) [6, 7], explains how most elementary particles acquire their mass [8].

Table 1.1 shows the fundamental interactions and some of their properties. Detailed discussion about the fundamental interactions can be found below.

The gravitational interaction acts on all particles having mass and is a long-range force. It is responsible for large-scale phenomena such as the falling apples, the motion of the Earth around the Sun, and the expansion of the universe, because these big bodies mostly contain zero net electric charges and the scale is out of the interaction ranges of weak and strong interactions. Unlike the other three interactions, the force
Table 1.1.: The fundamental interactions and some of their properties. The relative strength values are taken from Ref. [9] and reflect the relative magnitudes of the various forces as they act on a pair of protons in an atomic nucleus.

<table>
<thead>
<tr>
<th>Force carrier</th>
<th>Range (m)</th>
<th>Relative strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational</td>
<td>Not yet observed</td>
<td>∞</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Photon</td>
<td>∞</td>
</tr>
<tr>
<td>W^{±}, Z^0</td>
<td>10^{-18}</td>
<td>10^{24}</td>
</tr>
<tr>
<td>Strong</td>
<td>Gluon</td>
<td>10^{-15}</td>
</tr>
</tbody>
</table>

carrier of gravitational interaction has not been discovered and the Standard Model cannot describe it.

The electromagnetic interaction occurs between electrically charged particles and is a long-range force. It describes most of the phenomena of everyday experience such as friction, rainbows, lightning and all the electric devices, such as computers, microwave oven, television and computers. It is also the reason that the electrons are bounded around nuclei to form atoms.

The weak interaction is a short-range interaction, on the order of 10^{-18} m and affects all the quarks and leptons. It is the reason behind certain nuclear phenomena such as the β decay. It is the only interaction which can change the type (or flavor) of quarks and leptons. The heavier quarks rapidly change into up and down quarks through weak interaction and that is why up and down quarks are most common in the universe. Unlike the other three interactions, the weak interaction does not act as bounding force for any objects.

The strong interaction occurs among partons (quarks and gluons) and is a short-range interaction, on the order of 10^{-15} m. It is the reason why the positive charged protons along with neutrons can be bound together in the atomic nucleus, and the quarks can be bound together to form hadrons, such as protons and neutrons.
strong interaction is described by Quantum Chromodynamics (QCD) \[10,11\] in the Standard Model. In QCD, gluons interact with quarks and other gluons via the so-called color charge. The relation between color charge and strong interaction is analogous to that between electric charge and electromagnetic interaction, but the color charge comes in three types (red, green, and blue). There are two main properties in QCD: color confinement and asymptotic freedom. Color confinement is the phenomenon that observable particles are all color neutral, and color charged particles such as individual quark or gluon cannot be isolated \[12\]. As the energy scale increases or the distance between color charges decreases, the strong interaction between color charges decreases and this is called asymptotic freedom \[11,13,14\].

1.2 Quark Gluon Plasma

![Graph showing energy density and pressure normalized by $T^4$ vs temperature $T$ of equilibrant quark-gluon matter. Figure taken from Ref. [15].](image-url)

Figure 1.2.: Lattice QCD calculation of the energy density and pressure normalized by $T^4$ vs temperature $T$ of equilibrant quark-gluon matter. Figure taken from Ref. [15].
Lattice QCD calculations predict a color-deconfined state of quarks and gluons, which is defined as the Quark Gluon Plasma (QGP) [15–19]. Figure 1.2 shows the lattice QCD calculation of the energy density and pressure normalized by $T^4$ vs temperature $T$ [15]. A rapid rise in the energy density of matter around a critical temperature of $T_c \sim 185 – 195$ MeV corresponds to a transition to a state with deconfined quarks and gluons, the QGP. The formation of the QGP has been observed in experiments performed at the Relativistic Heavy Ion Collider (RHIC) [20–23] and at the LHC [24,25].

Figure 1.3.: An illustration of the QCD phase diagram from Ref. [26].

Figure 1.3 shows an illustration of the QCD phase diagram from Ref. [26]. There are three major states for the QCD system: hadron gas, the QGP state, and the color
superconductor. Because of color confinement, the quarks and gluons are defined in hadrons in normal environment, lying near the bottom right at cold temperatures and high baryon chemical potentials in Fig. 1.3. With an increase of temperature and/or density, the deconfinement of quarks and gluons occurs as a consequence of the asymptotic freedom and results in the formation of the QGP. The universe is also predicted to have been in the QGP state for a few milliseconds after the Big Bang. Another interesting state is the color superconductor in the large baryon chemical potential region at low temperature. In this region, as the normal electric charges behave to form superconductor, the quarks and gluons can form cooper pairs and stop from being scattered by the lattice.

1.3 Heavy Ion Collisions

Ultra-relativistic heavy ion collisions (referred as heavy ion collisions for short in later discussion) in the top left of Fig. 1.3 are used to create the QGP experimentally. In heavy ion collisions, the nuclei are accelerated close to the speed of light (> 0.999c) and thus are Lorentz contracted. When two nuclei collide with each other, the energy carried by the nuclei will be released in a small volume and a short time, and then the condition of high energy density and temperature can be fulfilled. The primary goal of heavy ion physics is to study the properties of the QGP, such as temperature, the equation of state, and the transport properties, in order to provide essential insights into the QCD and the early evolution of the universe.

In this section, the centrality of heavy ion collisions is first introduced, and then two key signatures of the QGP created in heavy ion collisions, parton energy loss and collective flow, will be discussed.

1.3.1 Centrality

The size of the proton is negligible in proton-proton collisions and the collision area can be taken as one point. However, for nucleus-nucleus (AA) collisions, such
as Lead-Lead (PbPb) nucleus collisions, the size of the nuclei cannot be ignored. Figure 1.4 shows a schematic view of a nucleus-nucleus collision, where the impact parameter $b$, the distance between the centers of the two colliding nuclei, is marked. One important concept is the centrality, which is used to evaluate the degree of the overlap of the two colliding nuclei. The centrality ranges 0–100%, where the centrality class of 0–10% corresponds to the 10% of collisions with the largest overlap of the two nuclei. Clearly, there is a direct relation between centrality and $b$. One PbPb collision can include a few to almost two thousand binary nucleon-nucleon collisions depending on the centrality. However, the collision geometry cannot be measured directly experimentally and only final-state observables are available. Fortunately, there is a direct correlation between the degree of the overlap of the collision and certain final-state observables, such as the number of final-state particles produced transverse to the beam direction, and the total energy deposited in very forward detectors. In the CMS experiment, the centrality is determined by the total energy deposited in both sides of the hadronic forward calorimeters (HF) discussed in Chapter 2 at pseudorapidities of $3 < \eta < 5$. The distribution of the total energy deposited of a large minimum bias collisions is measured, and is used to devid the data sample
into centrality classes, for example the top 10% most energy deposited corresponds to centrality class 0–10%. Figure 1.5 shows the distribution measured for PbPb collisions at 2.76 TeV [28]. The centrality can also be determined with other final-state observables, but the basic principle is the same.

![Distribution of the total transverse energy in the HF used to determine the centrality of the PbPb collisions at 2.76 TeV. The centrality boundaries for each 5% centrality interval are shown. Figure taken from Ref. [28].](image)

Figure 1.5.: Distribution of the total transverse energy in the HF used to determine the centrality of the PbPb collisions at 2.76 TeV. The centrality boundaries for each 5% centrality interval are shown. Figure taken from Ref. [28].

The geometric quantities of heavy ion collisions can be calculated using the Glauber model [27], where heavy ion collisions are described as a superposition of independent nucleon-nucleon collisions. The position of each nucleon in a nucleus is determined according to the Woods-Saxon distribution [29]. For the collisions between two nuclei A and B, the hard scattering cross section ($\sigma_{AB}^{hard}$), the nuclear overlap function ($T_{AB}$), the number of participant nucleons ($N_{part}$), the number of binary nucleon-
nucleon collisions ($N_{coll}$), and their relations can all be calculated (for more details see Ref. [27]).

### 1.3.2 Signature of the QGP

The QGP state produced in heavy ion collisions can just exist for a short time of a few fm/$c$ and cannot be directly observed. The properties of the QGP must be inferred from the final-state observables. This section will introduce two important signatures of the QGP: parton energy loss and collective flow.

**Parton Energy Loss**

Figure 1.6.: Cartoon of a hard scattering in pp (left) and PbPb (right) collisions. Figure taken from Ref. [30].

Figure 1.6 depicts the hard scatterings in pp and AA collisions [30]. Hard scatterings between two partons can create two or more partons with high transverse momentum ($p_T$). In PbPb collisions, where the QGP is produced, the out-going partons can lose significant amount of energy as they traverse the medium, primarily through gluon radiation [31, 33] and collisional energy loss [34, 35]. The spectra of
produced hadrons will shift toward lower $p_T$ region in AA collisions compared to pp collisions and hence appear suppressed at high $p_T$.

One observable to quantify the parton energy loss is the nuclear modification factor ($R_{AA}$) defined as the ratio of the yield in AA collision to that in pp collision scaled by the number of binary nucleon-nucleon collisions $N_{coll}$:

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{PbPb}}{dp_T} / \frac{dN_{pp}}{dp_T} = 1$$

The $R_{AA}$ can be measured differentially in $p_T$ or $\eta$, for a specific centrality class, or for a specific particle specie. $R_{AA} = 1$ means that the production is not modified relative to pp collisions. When $R_{AA} < 1$, the production is suppressed, which is the general expectation for hadrons with high $p_T$ as a consequence of the in-medium parton energy loss. For $R_{AA} > 1$, the production is enhanced. Apart from parton energy loss, initial-state effects [36–38] could also affect the production of particles in heavy ion collisions. To quantify the impact from the initial-state effects, studies have been performed in proton-nucleus (pA) collisions [39–42], and it is found that the initial-state effects don’t account for the suppression of high-$p_T$ particles in AA collisions. The $R_{AA}$ of high-$p_T$ particles is one of the key signatures of the QGP formation, and has been widely measured at RHIC [20–23] and LHC [24,25] to study the properties of the QGP produced in heavy ion collisions Figure 1.7 shows the $R_{AA}$ of charged particles in PbPb collisions at a center-of-mass energy $\sqrt{s_{NN}} = 5.02$TeV per nucleon pair as a function of $p_T$ for six centrality classes measured with the CMS detector [43]. Clearly, the production of charged particles is suppressed in PbPb collisions, and the supression has strong $p_T$ and centrality dependence.

Azimuthal Anisotropy

The collective motion of the emitted particles is an important signature of the QGP produced in heavy ion collisions, and suggests that the QGP is strongly coupled [45–46]. In this thesis, we will focus on the azimuthal anisotropy, which is an important type of the collective motion. In noncentral collisions, the reaction plane...
Figure 1.7.: The $R_{AA}$ of charged particles in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of $p_T$ for six centrality classes measured with the CMS detector [43].

for each event is defined as the plane formed by the beam direction and the impact parameter vector. As shown in Fig. 1.8, the overlap region of the two nuclei is spatially asymmetric like an almond shape if the nucleon density is continuous. However, in reality, the overlap region has a more irregular shape because the nucleon density is not continuous as showed in Fig. 1.9. The azimuthal anisotropy can be quantified by the Fourier coefficients $v_n$ in the azimuthal angle distribution of the hadron yield:

$$\frac{E}{d^3p} \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos \left[ n (\phi - \Psi_n) \right] \right),$$  \hspace{1cm} (1.2)

where $\phi$, $E$, $y$ and $p_T$ are the particle’s azimuthal angle, energy, rapidity, and transverse momentum, respectively. Here, $\Psi_n$ is the participant plane angle corresponding to the $n$th harmonic, defined as the azimuthal angle of the direction of the maximum particle density corresponding to the $n$th harmonic in the transverse plane [47]. The
Figure 1.8.: A schematic diagram of a noncentral AA collision viewed in the transverse plane, indicating the azimuthal angle $\phi$, the impact parameter $b$, and the reaction plane $\Psi_R$. Figure taken from Ref. [44].

$v_2$ and $v_3$ coefficients are commonly called elliptic flow and triangular flow, respectively. Figure 1.9 shows the decomposition of one initial condition into its first 4 harmonic deformations.

The azimuthal anisotropy originates from the initial geometry of the overlap region of the two colliding nuclei. Generally, two mechanisms account for the azimuthal anisotropy: at low and intermediate $p_T$ ($p_T$ lower than 5–8 GeV/$c$), the azimuthal anisotropy is from the collective expansion of the medium through the interactions among the medium constituents; at high $p_T$, the path length dependence of parton energy loss can give rise to positive azimuthal anisotropy [48,49].

However, neither the reaction plane or the participant planes can be measured directly experimentally. There are several experimental methods developed to eval-
Figure 1.9.: Decomposition of one initial condition into its first 4 harmonic deformations. Here, $\phi_n$ stands for the participant plane angle for the $n$th harmonic. Figure taken from Ref. [50].

uate the anisotropic flow based on the final-state particle distributions. One of the method is to reconstruct the event plane for each event. With the final state particles, the event plane can be built experimentally with the beam direction and the direction of the maximal flow determined from the azimuthal distributions of the final-state particles. Under reasonable assumptions, the event plane is expected to coincide with the participant plane [51]. The theoretical calculations also confirm that there is a strong event by event correlation between the the event plane and the participant plane [52–55]. More details about the event plane reconstruction with the CMS detector used in this thesis can be found in Refs. [44,56].

Figure 1.10 shows the measured $v_2$ utilizing event plane as a function of $p_T$ for different centrality classes [44] in PbPb collisions at 2.76 TeV. Significant $v_2$ values are observed, and the $v_2$ values have strong dependence on $p_T$ and centrality.

### 1.4 Open Heavy Flavor Study in Heavy Ion Collisions

Heavy quarks (charm and bottom) are effective probes to study the properties of the QGP medium produced in heavy ion collisions. They are primarily produced via initial hard scatterings in heavy ion collisions because of their large mass, and thus carry information about the early stages of the QGP [57,58]. Therefore, heavy quarks are cleaner probes to study the QGP than light quarks and gluons, which may be produced in different stages of the heavy ion collisions.
Figure 1.10.: The measured $v_2$ utilizing event plane as a function of $p_T$ for different centrality classes in PbPb collisions at 2.76 TeV. Figure taken from Ref. [44].

As the high-$p_T$ light partons, heavy quarks can lose energy via radiative and collisional interactions with the medium constituents when they traverse through the medium. Because the effective color charge of quarks is smaller than that of gluons, quarks are expected to lose less energy than gluons. Besides, the small-angle gluon radiation is expected to be smaller for heavy quarks than for light quarks and gluons, which is defined as the dead-cone effect [59–61]. The dead-cone effect is expected to be more obvious at low $p_T$, where the quark mass is not negligible. Thus, a hierarchy in the average radiative energy loss of gluons and quarks is expected at low $p_T$:

$$\langle \Delta E_{\text{gluon}} \rangle > \langle \Delta E_{\text{light}} \rangle > \langle \Delta E_{\text{charm}} \rangle > \langle \Delta E_{\text{bottom}} \rangle. \quad (1.3)$$

This energy loss hierarchy may be transferred to the $R_{AA}$, but many other factors may affect the $R_{AA}$ hierarchy of the gluons, light quarks and heavy quarks, such as the difference in the $p_T$ shapes of light hadrons and heavy flavor hadrons, and
also collisional energy loss \[62,63\]. Therefore, to get reliable predictions for the \(R_{AA}\) hierarchy, one has to rely on theoretical calculations taking all factors into account.

There is no collective motion associated with heavy quarks when they are produced. However, they can acquire collective flow through their interactions with the medium constituents. Therefore, the measurement of azimuthal anisotropy of the final-state heavy flavor hadrons can provide essential insights into the interactions between the heavy quarks and the medium and properties of the QGP. At low and intermediate \(p_T\), the heavy flavor hadron \(v_n\) coefficients are a good measure of the interaction strength between the heavy quarks and the medium. Comparing the \(v_n\) values of heavy flavor and light hadrons can quantify the extent to which heavy quarks flow with the medium. Besides, the measurement can help explore the coalescence mechanism for heavy flavor hadron production, where heavy quarks recombine with light quarks from the medium. The coalescence mechanism can lead to positive \(v_n\) of heavy flavor hadrons even if the heavy quarks don’t flow with the medium \[64,65\]. At high \(p_T\), the heavy flavor hadron \(v_n\) coefficients can help constrain the path length dependence of heavy quark energy loss \[48,49\], providing complementing information to the measurement of \(R_{AA}\).

In this thesis, the analyses on prompt \(D^0\) meson (including both the \(D^0\) and \(\bar{D}^0\) states) nuclear modification factor \[66,67\] and azimuthal anisotropy \[68\] in PbPb collisions with the CMS detector will be presented. The production of \(D^0\) mesons is found to be strongly suppressed in PbPb collisions, and significant azimuthal anisotropy coefficients \(v_2\) and \(v_3\) of \(D^0\) mesons are observed. Apart from these CMS measurements, similar measurements of D mesons are also performed with the STAR detector \[69,70\] and the ALICE detector \[71–74\]. Besides, the \(R_{pA}\) of D mesons from ALICE is consistent with unity within uncertainties and no clear initial-state effects are observed \[75\]. Thus, the suppression of \(D^0\) meson in PbPb collisions cannot be explained by initial-state effects, and is due to the interactions between charm quarks and the QGP medium.
2. The CMS Detector

The work in this thesis is performed using the data collected by the Compact Muon Solenoid (CMS) detector. The CMS detector is a general-purpose detector at the CERN Large Hadron Collider (LHC), which covers broad physics programs, such as the search for and study of the Higgs boson, the exploration of physics beyond the Standard Model, and also heavy ion physics.

Figure 2.1.: A schematic representation of the CMS detector with its various subsystems in retracted positions (CERN).
Figure 2.1 shows a schematic representation of the CMS detector with its various subsystems in retracted positions. The CMS detector is built around a 13-m long superconducting solenoid magnet with an inner diameter of 6 m, which can generate a magnetic field of 4 Tesla (about 100,000 times the magnetic field of the Earth). The actual strength is 3.8 Tesla during data taking. The strength of the magnetic field is to fulfill the desired momentum resolution. The CMS detector is mainly comprised of the inner tracking system, the superconduction magnet, the electromagnetic calorimeter, hadron calorimeter, the muon system, and forward detectors. This chapter presents certain details of the detector subsystems relevant to the analyses in this thesis. A complete description of the CMS detector can be found in Ref. [76].

The detector coordinate system has the origin centered at the nominal collision point inside the experiment, with the $z$ axis pointing along the counterclockwise beam direction, the $x$ axis pointing radially inward towards the center of the LHC ring, and the $y$ axis pointing vertically upward.

2.1 The Inner Tracking System

The CMS inner tracking system is designed to precisely and efficiently reconstruct the trajectories of charged particles and the secondary vertices. At the LHC design luminosity, around 1000 particles were expected to be produced within the tracker acceptance from more than 20 overlapping pp collisions per bunch crossing. Fortunately, this is similar to the number of particles produced in a PbPb collision at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV. Therefore, the CMS tracker also works well for heavy ion collisions.

The CMS tracker consists of two subdetectors, the pixel tracker and the silicon strip tracker. Figure 2.2 shows a schematic view of the CMS tracker in the $r-z$ plane. The pixel tracker (red lines in Fig. 2.2) resides closest to the beampipe, and consists of three concentric cylindrical barrel layers at midpseudorapidity at a distance of 4.4, 7.3, and 10.2 cm from the nominal collision point, and two disc-shaped endcap layers.
Figure 2.2.: Schematic view of the CMS tracker in the $r - z$ plane. The tracker is symmetric about the horizontal line $r = 0$, so only top half is shown in the Figure. The star, at the center of the tracker, stands for the nominal collision point. The green dashed lines divided the tracker into different parts. Figure taken from Ref. [77].

at forward and backward pseudorapidity. The silicon strip tracker (black and blue lines in Fig. 2.2) is comprised of 10 barrel layers (TIB and TOB) at midpseudorapidity extending outwards to a radius of 110 cm, and 3 smaller disc layers (TID) and 9 larger disc layers (TEC) at forward pseudorapidity. The data used in this thesis was taken before the pixel upgrade in the end of 2016, so the description here is for the pixel tracker before the upgrade. Details of the pixel tracker upgrade can be found in Ref. [78].

The inner tracker system is essential for the reconstruction of $D^0$ discussed in this thesis. The decay length of $D^0$ is 122.9 $\mu$m, so the flight distance is on similar order at low $p_T$ and can be on the order of 1 mm or even higher at high $p_T$. As mentioned in Chapter 3 the reconstruction of the secondary vertex using the two daughter tracks is a prerequisite for candidate selection in $D^0$ reconstruction. The quality of the secondary vertex reconstruction is determined by the reconstruction performance of particle trajectories, especially the accuracy of the position informa-
Figure 2.3.: High-purity track transverse (left) and longitudinal (right) impact parameter resolution as a function of $p_T$ for the CMS detector. The solid (open) symbols correspond to the half-width at 68% (90%) confidence level. Figures taken from Ref. [77].

Figure 2.4.: High-purity track $p_T$ resolution as a function of $p_T$ for the CMS detector. The solid (open) symbols correspond to the half-width at 68% (90%) confidence level. Figures taken from Ref. [77].
tion. The accuracy of the position information can be described by the resolution of track impact parameter. The impact parameter is defined as the minimal distance between the track helix and the primary vertex. Figure 2.3 shows the high-purity track transverse (left) and longitudinal (right) impact parameter resolution as a function of $p_T$. Another important property is the track $p_T$ resolution shown in Fig. 2.4. Benefitting from the 3.8-Tesla magnetic field, the $p_T$ resolution is typically 1–2% for tracks of $1 < p_T < 10$ GeV and $|\eta| < 1.5$. The impact parameter and $p_T$ resolutions in the Barrel region are better than those in the Endcap region, which is the reason that only tracks within $|\eta| < 1.5$ are used in $D^0$ reconstruction. Additional details of the performance of the CMS tracking system can be found in Ref. [77].

2.2 Hadron Forward Calorimeter

The hadron forward calorimeter (HF) is of particular importance to heavy ion collisions because the centrality can be determined with the HF detector, as discussed in Section 1.3.1 and the event plane can be reconstructed with the HF detector, as discussed in Refs. [44, 56].

The HF calorimeter provide azimuthal coverage in the pseudorapidity range $3.0 < |\eta| < 5.2$ and is required to withstand extremely high particle flux. The two halves of the HF calorimeter are located 11.2 m from the interaction region, one on each end. Left panel of Figure 2.5 shows the location of the HF detector on one end. For each pp collision, 760 GeV of total energy will be deposited into the HF on average, while only 100 GeV for all subdetectors within $|\eta| < 3.0$. The HF calorimeter uses 5 mm thick grooved steel as an absorber, with grooves approximately 1 mm wide and deep. Quartz fibers are used as the sensitive material and inserted into the grooves. Each HF calorimeter is comprised of 432 readout towers, containing long and short quartz fibers running parallel to the beam. The short fibers start at a depth of 22 cm from the front of the detector, while the long fibers run the entire depth of the HF calorimeter (165 cm). By reading out the two sets of fibers separately, the showers generated by
electrons and photons, which deposit a large fraction of their energy in the long-fiber calorimeter segment, can be distinguished from the showers generated by hadrons, which produce on average nearly equal signals in both calorimeter segments.

The HF calorimeter forms a hollow cylinder with an inner radius of 12.5 cm from the center of the beam line, and an outer radius of 130.0 cm. Azimuthally, each HF calorimeter consists of 18 modular wedges covering 20°. A diagram of the HF segmentation in the transverse plane is showed in the right panel of Fig. 2.5.

2.3 The Level-1 and High Level Trigger System

The collision rates of proton-proton and heavy ion collisions which the LHC provides can be on the order of 10 MHz or even higher. Recording all the collision events to disk will be prohibitively expensive, and processing all these events for analysis will take huge amount of computational resources. Therefore, the task of the trigger system at CMS is to reduce the rate of recording under 1 kHz by keeping the inter-
testing events for analyses and filtering out the uninteresting events. Therefore, the trigger system is an essential part at CMS and determines the data quality of analyses. A two-level trigger system, comprised of Level-1 (L1) Trigger [79] and High-Level Trigger (HLT) [80], is used at CMS. The L1 triggers are hardware-based, while the HLT triggers are software-based.

The L1 triggers consist of custom-built programmable electronics, which are largely integrated with the readout systems of subdetectors. The L1 triggers are designed to reduce the rate under 100 kHz. Within 4 \( \mu s \), the system must decide whether to drop an event or pass it to the HLT triggers. The L1 triggers are typically implemented using simple threshold algorithms written to field-programmable gate arrays (FPGAs), which allow for a fully customizable hardware circuit.

The HLT triggers select events in a similar way to that used in the offline processing, which can be time consuming. The large reduction factor of the L1 triggers allows much more processing time for the HLT triggers. For each event, objects such as tracks, muons, and jets can be reconstructed and selection criteria can be applied to select the events which may be interesting for offline data analysis. For example, the \( D^0 \) meson triggers discussed in Section 4.2.2 involve track reconstruction and \( D^0 \) candidate reconstruction. However, the offline reconstruction is usually too time consuming to perform at HLT especially for heavy ion collisions. Therefore, the HLT triggers usually use reconstruction simplified from the offline reconstruction. This can lead to differences in the HLT and offline reconstruction performances, such as efficiencies and resolutions, and further lead to some loss in trigger efficiency, which is the reason that the \( D^0 \) meson trigger efficiencies in PbPb collisions are around 90–95%.

One important concept for the trigger system is the prescale factor, which means only fraction of data from a specific L1 or HLT trigger will be further processed by a running counter or random selection. If the output rate of a specific L1 trigger is too high for HLT processing, applying a prescale factor of 3 to this L1 trigger means only 1/3 of events passing this L1 trigger will be passed to the HLT triggers.
2.4 The CMS Computing Model

It is difficult to fulfill the CMS computing and storage requirements at one single place for both technical and funding reasons. Therefore, a distributed system of computing services and resources, which is a global network of tiered computing facilities, has been constructed as the CMS computing environment. Figure 2.6 shows a schematic diagram of the CMS Computing System. A detailed description of the CMS Computing System can be found in Refs. [81].

Figure 2.6.: A schematic diagram of the CMS Computing System. Figures taken from Ref. [82].

The first tier of the system, known as Tier-0, is only one site, CERN. The Tier-0 facility accepts, stores, and archives raw collision data from the trigger system, performs an initial “prompt” reconstruction of the data, and distributes raw and reconstruction data among Tier-1 facilities.

The Tier-1 facilities archives (part of) the RAW and reconstruction data (secure second copy), performs additional reconstruction over the data with improved calibrations and algorithms, distributes reconstruction data used for analyses to Tier-2 facilities, and provides secure storage and redistribution for Monte Carlo simulations produced by the Tier-2 facilities.
The Tier-2 facilities keep part of the reconstruction data for physics analyses, provide computing resources (CPU and storage) for user usage, and produce Monte Carlo simulations, which are usually transferred to the Tier-1 facility for wider distribution. The Tier-2 activities are organized by the Tier-2 responsibles in collaboration with physics groups, regional associations, and local communities.
3. $D^0$ Reconstruction and Signal Extraction

In this thesis, the $D^0$ mesons are reconstructed through the hadronic decay channel $D^0 \rightarrow K^- \pi^+$ with a branching ratio of $3.93 \pm 0.04\%$ [83]. Figure 3.1 is the schematic view of the $D^0 \rightarrow K^- \pi^+$ decay channel and the variables marked will be defined and discussed below.

![Figure 3.1: Schematic view of the $D^0 \rightarrow K^- \pi^+$ decay channel.](image)

3.1 Reconstruction

The $D^0$ candidates are formed by combining pairs of oppositely charged tracks and requiring an invariant mass within a $\pm 200$ MeV/$c^2$ window of the nominal $D^0$ mass of 1864.83 MeV/$c^2$ [83]. Tracks are required to pass kinematic selections of $p_T > 0.7$ GeV/$c$ and $|\eta| < 1.5$, and must satisfy high-purity track quality criteria [77] to reduce the combinatorial background from misreconstructed tracks. For each pair of selected tracks, two $D^0$ candidates are considered. For the first candidate, the pion mass is attributed to the first track while the other track is assumed to have the kaon mass. The second candidate is defined by swapping the masses attributed to those
two tracks. For each candidate, a secondary vertex is reconstructed with a kinematic vertex fit [84]. Based on properties of these two-particle secondary vertices, several selections are applied in order to further reduce the combinatorial background. In particular, the selections are applied to:

- $d_0/\sigma(d_0)$: the 3D distance between the secondary vertex and the primary vertex divided by its uncertainty
- $\alpha$: the angle between total momentum vector of tracks and the vector from the primary vertex to the secondary vertex
- vertex probability: the $\chi^2$ probability of the secondary vertex fit
- DCA: the distance of the closest approach of $D^0$ candidates to the primary vertex

The selections on $d_0/\sigma(d_0)$, $\alpha$, and vertex probability are optimized in Section 3.2 and all applied in the measurements of $D^0$ meson nuclear clear modification factor analyses discussed in Chapter 4 and azimuthal anisotropy analysis discussed in Chapter 5, while the selection on DCA is only applied in the measurements of $D^0$ azimuthal anisotropy analysis to reduces the systematic uncertainties from nonprompt $D^0$ ($D^0$ from decays of b hadrons) contribution.

### 3.2 Selection Optimization

The goal of the optimization procedure is to maximize the statistical significance of the signal while keeping reasonably high signal efficiencies. The optimal cut minimizing background efficiency for aspecific signal efficiency is obtained by the TMVA (Toolkit for Multivariate Data Analysis with ROOT) [85]. Rectangular cut is chosen as the classification method in TMVA. Reconstructed candidates which can be matched to generated particles in MC are used as signal sample during training in TMVA, while the sideband of data sample is used as background sample. Sideband is
defined as $0.1 \text{ GeV}/c^2 < |M_{D^0} - M_{D^0}^{PDG}| < 0.15 \text{ GeV}/c^2$. The amount of background in the signal region is estimated by a linear interpolation using the sideband. The signal-to-background ratios are $p_T$ dependent, so the selections on $d_0/\sigma(d_0)$, $\alpha$, and vertex probability are optimized each $p_T$ bin.

The optimization is done for the measurements of $D^0$ meson $R_{AA}$ in PbPb collisions at 2.76 TeV, discussed in Section 4.1, and 5.02 TeV, discussed in Section 4.2 respectively. The selections on $d_0/\sigma(d_0)$, $\alpha$, and vertex probability applied in measurements of $D^0$ meson azimuthal anisotropy discussed in Chapter 5 are adopted from the optimized selections. The analyses actually don’t require the selections to be perfectly optimized as long as the $D^0$ signal significance after selection is not too bad. The plots shown below are from the optimization for the measurements of $D^0$ meson $R_{AA}$ in PbPb collisions at 2.76 TeV.

Figure 3.2.: Distributions of $D^0$ cut variables for background and signal candidates in the $p_T$ range 11.0–13.0 GeV/c.

Figure 3.2 shows the distributions of the selection variables of signal and background candidates in the $p_T$ range 11.0–13.0 GeV/c. The optimal selection values are defined as the one maximizing the statistical significance $s/\sqrt{s+b}$. Here, $s$ is the expected number of signal yield from the FONLL calculation, multiplied by the efficiency and acceptance from MC, and $b$ is the expected number of background in the signal region. The signal region is defined as $|M_{D^0} - M_{D^0}^{PDG}| < 2\sigma$, where $\sigma$ is
Figure 3.3.: Signal statistical significance versus signal efficiency in the $p_T$ range $11.0$–$13.0$ GeV/$c$.

<table>
<thead>
<tr>
<th>$p_T$(GeV/$c$)</th>
<th>$d_0/\sigma(d_0)$</th>
<th>$\alpha$</th>
<th>Vertex Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5–3.5</td>
<td>$&gt; 5.90$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.248$</td>
</tr>
<tr>
<td>3.5–4.5</td>
<td>$&gt; 5.81$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.200$</td>
</tr>
<tr>
<td>4.5–5.5</td>
<td>$&gt; 5.10$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.191$</td>
</tr>
<tr>
<td>5.5–7.0</td>
<td>$&gt; 4.62$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.148$</td>
</tr>
<tr>
<td>7.0–9.0</td>
<td>$&gt; 4.46$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.102$</td>
</tr>
<tr>
<td>9.0–11.0</td>
<td>$&gt; 4.39$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.080$</td>
</tr>
<tr>
<td>11.0–13.0</td>
<td>$&gt; 4.07$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.073$</td>
</tr>
<tr>
<td>13.0–16.0</td>
<td>$&gt; 3.88$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.060$</td>
</tr>
<tr>
<td>16.0–20.0</td>
<td>$&gt; 3.67$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.055$</td>
</tr>
<tr>
<td>20.0–28.0</td>
<td>$&gt; 3.25$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.054$</td>
</tr>
<tr>
<td>28.0–40.0</td>
<td>$&gt; 2.55$</td>
<td>$&lt; 0.12$</td>
<td>$&gt; 0.050$</td>
</tr>
</tbody>
</table>

Table 3.1.: Summary table of the selection criteria in different $p_T$ intervals.
the width of D candidates mass fitting in MC. Figure 3.3 presents the values of the signal significance versus the signal efficiency in the $p_T$ range 11.0–13.0 GeV/c. The final selection values are reported in Table 3.1.

### 3.3 Signal Extraction

The raw $D^0$ yield in each $p_T$ interval is extracted through a fit on the mass spectrum of $D^0$ candidates. The fit function consists of the following components:

- two Gaussian functions with same mean but different width and area to model the signal ($S(m_{inv})$).
- a third-order polynomial or an exponential function to model the combinatorial background ($B(m_{inv})$). In the $D^0 R_{AA}$ in PbPb collisions at 2.76 TeV analysis, a exponential function is used to model the combinatorial background in default fit, while a third order polynomial is used in default fit in the $D^0 R_{AA}$ and $v_n$ in PbPb collisions at 5.02 TeV analyses. When one is used in default fit, the other is used in the evaluation of systematic uncertainties.
- a single Gaussian function to describe the invariant mass shape of $D^0$ candidates with incorrect mass assignment from the exchange of pion and kaon designation ($SW(m_{inv})$).

The width of $SW(m_{inv})$ is fixed according to MC simulations. Also, the ratio of the yields of $SW(m_{inv})$ and $S(m_{inv})$ is fixed to the value extracted in simulations.

Two Gaussian functions are used to model the signal shape based on studies in MC simulation. As showed in Figure 3.4 and 3.5, two Gaussian functions can better describe the mass spectrum of MC truth $D^0$ candidates compared to a single Gaussian function. The MC truth $D^0$ candidates stand for the candidates which can be matched to generator level $D^0$ signal in simulation.

As discussed previously, two $D^0$ candidates are formed with each pair of tracks. It is the same for the two tracks from the real $D^0$ signal. One of the two candidates is real
Figure 3.4.: Fit to MC Truth $D^0$ mass spectrum with a single Gaussian in different $p_T$ intervals with PbPb simulation samples at 2.76 TeV discussed in Section 4.1.1.
Figure 3.5.: Fit to MC Truth $D^0$ mass spectrum with two Gaussian functions in different $p_T$ intervals for PbPb simulations at 2.76 TeV with PbPb simulation samples at 2.76 TeV discussed in Section 4.1.1.
$D^0$ signal while the other is background $D^0$ candidate with wrong mass assignment on tracks. The mass shape of the MC Truth incorrect mass assignment $D^0$ candidates are fitted with a single Gaussian function in Fig. 3.6 and it is found that a single Gaussian function can describe the mass shape of those candidates well. The MC Truth incorrect mass assignment $D^0$ candidates are the candidates formed by two tracks from real $D^0$ signal but with wrong mass assignment on two daughter tracks.

For combinatorial background, a third order polynomial or a exponential function is used because they can describe the mass shape of $D^0$ candidates in sideband regions in data.

Figure 3.7 shows the example fits to invariant mass distributions of the selected $D^0$ candidates in several $p_T$ intervals for the centrality class 0–100% in PbPb collisions at 2.76 TeV.
Figure 3.6.: Fit to the mass spectrum of MC Truth incorrect mass assignment $D^0$ candidates with a single Gaussian in different $p_T$ intervals with PbPb simulation samples at 2.76 TeV discussed in Section 4.1.1.
Figure 3.7.: Example fits to invariant mass distributions of $D^0$ candidates and their charge conjugates in selected $p_T$ intervals for centrality class 0–100% in PbPb collisions at 2.76 TeV. The curves show the fit functions as indicated in the legend.
4. Prompt $D^0$ Nuclear Modification Factor in PbPb Collisions

This chapter presents the details of the measurement of prompt $D^0$ nuclear modification factor in PbPb collisions at 2.76 TeV and 5.02 TeV.

4.1 Prompt $D^0$ Nuclear Modification Factor in PbPb Collisions at 2.76 TeV

This section presents the details of the measurement of prompt $D^0$ nuclear modification factor in PbPb collisions at 2.76 TeV.

4.1.1 Datasets and Monte Carlo Simulation

This analysis is based on the PbPb data at $\sqrt{s_{NN}} = 2.76$ TeV collected by the CMS experiment during the 2011 heavy ion run. The data collected by a minimum bias trigger is used. In order to suppress events due to noise, cosmic rays, double-firing triggers, and beam backgrounds, the minimum bias trigger is required to be in coincidence with bunches colliding in the interaction region. These coincident signals may come from either the beam scintillator counters (BSC, $3.23 < |\eta| < 4.65$) or in the steel/quartz-fiber Cherenkov forward hadron calorimeters (HF, $2.9 < |\eta| < 5.2$) from both ends of the detector, as described. The trigger has an acceptance of $(97 \pm 3)\%$ for hadronic inelastic PbPb collisions [86]. The number of events selected by the minimum bias trigger is around 30 million. The event selection used in this analysis is described in detail in previous publications (Refs. [87][90]). The collected events are cleaned for detector noise artifacts with the usage of a hadronic calorimeter (HCAL)
noise cleaning filter, and electromagnetic calorimeter (ECAL) spike removal. Events were sorted into different centrality classes.

Dedicated Monte Carlo (MC) simulations of $D^0$ mesons are used to determine the signal shape, and evaluate the reconstruction and selection efficiencies. Inclusive QCD events generated by the PYTHIA Monte Carlo generator Tune Z2 [91,92] are filtered for $D^0$ production and events passing the $D^0$ filter are embedded into a simulated PbPb background generated by the HYDJET Monte Carlo generator version 1.8 [93]. The parameters of this version of HYDJET are tuned to reproduce the particle multiplicity for different centralities. Around two hundred thousand PYTHIA+HYDJET events are generated for each $\hat{p}_T$ bin with boundaries of [0, 5, 10, 15, 30, 50, 80, 120, 170]. The $D^0$ filter requires that there is at least one $D^0$ with $p_T > 1.0$ GeV/$c$, and $|\eta| < 2.0$ in the PYTHIA event. In addition, the $D^0$ decay parameters are redefined such that all $D^0$ mesons decay through $D^0 \rightarrow K^- \pi^+$ channel, which is achieved with the EVTGEN package [94].

4.1.2 MC and Data Comparison

Differences between distributions of the selection variables of $D^0$ signal in data and MC simulation can introduce bias in efficiency correction. In this section, distributions of the $D^0$ selection variables are studied for $D^0$ signal in MC and data. In principle, only distributions of true $D^0$ signal are plotted in both cases, however this is impossible to ensure in data because of the small signal-to-background ratio. To get distributions of $D^0$ signal in data, sideband method is used to estimate the distributions of background $D^0$ candidates. Then the estimated distributions of background $D^0$ candidates are used to remove the background $D^0$ candidates in $D^0$ signal region to get the distributions of real $D^0$ signal.

The sideband is defined in symmetric windows outside of the true $D^0$ mass, $0.05$GeV/$c^2 < |M_{D^0} - M^{PDG}_{D^0}| < 0.07$GeV/$c^2$, while the signal region is defined around the $D^0$ signal peak, as $|M_{D^0} - M^{PDG}_{D^0}| < 0.03$GeV/$c^2$ ($D^0$ signal width is around 0.015
Distributions from simulation are scaled to the entries of data. Prompt and nonprompt $D^0$ candidates from simulations are scaled according to the fraction of prompt $D^0$, which is calculated in Section 4.1.4. For each comparison, the prompt $D^0$ contribution is plotted on the top of the nonprompt $D^0$ contribution to compare with distributions from data directly.

In data, the signal significance is quite small without $D^0$ candidate selections of decay length significance ($d_0/\sigma(d_0)$), the pointing angle ($\alpha$), and vertex probability. To get good $D^0$ signal, the candidates selections applied are:

- $d_0/\sigma(d_0) > 3.5$
- $\alpha < 0.12$
- vertex probability $> 0.05$

To show how sideband method works in details, the procedure of getting $d_0/\sigma(d_0)$ distribution of $D^0$ signal with $p_T > 7.0\text{GeV}/c$ in data is showed step by step as followed:

- Cuts on $\alpha$ and vertex probability are applied to increase signal-to-background ratio.
- Fit the mass spectrum as showed in Figure 4.1. With the integral of the background PDF of the fit function, get the number of background candidates in sideband and signal region (N1 and N2).
- Get the $d_0/\sigma(d_0)$ distributions in sideband and signal region, respectively (h1 and h2). So h1 is the $d_0/\sigma(d_0)$ of $D^0$ background candidates from sideband region and h2 is the $d_0/\sigma(d_0)$ of $D^0$ signal candidates and background candidates from signal region. Distributions of $N2/N1 \times h1$ and h2 are showed in the left plot of Figure 4.2.
- $d_0/\sigma(d_0)$ distribution of $D^0$ signal will be h2 - $N2/N1 \times h1$, showed in the right plot of Figure 4.2.
Figure 4.1.: Invariant mass distribution of $D^0$ candidates in data with $p_T > 7.0\text{GeV}/c$, $\alpha < 0.12$ and vertex probability > 0.05 cuts for centrality class 0-100%.

Figure 4.2.: (left) $d_0/\sigma(d_0)$ distributions in sideband scaled by N2/N1 (N2/N1 * h1) (red points) and signal region (h2) (black points). (right) $d_0/\sigma(d_0)$ distribution for $D^0$ signal in data with $p_T > 7.0\text{GeV}/c$, $\alpha < 0.12$ and vertex probability > 0.05 cuts (h2 - N2/N1 * h1).
Figure 4.3 shows the comparison for $D^0$ signals with $p_T > 7.0$GeV/c for centrality class 0-100%. When one variable is studied, the other selection criteria are applied. Red and blue histograms correspond to nonprompt and prompt $D^0$ components, respectively. The gray bands in ratio plots are uncertainties from uncertainties of nonprompt $D^0$ fraction. The plots show that, for $D^0$ candidate selection variables, MC and data distributions are in reasonable agreement, though with large statistical uncertainty.

Figure 4.3.: Comparison of variables for centrality class 0-100%. Distributions of rapidity (top left), $d_0/\sigma(d_0)$ (top right), $\alpha$ (mid-left), and vertex probability (mid-right) for $D^0$ signals from data and MC simulation with $p_T > 7.0$GeV/c.

The comparison is just done for $p_T > 7.0$GeV/c range and it is difficult to do the same study for lower $p_T$ range because of small signal-to-background ratio. The remnant discrepancies between distributions of the selection variables of $D^0$ signal in
data and MC simulation showed in Figure 4.3 are studied and considered as source of systematic uncertainties.

4.1.3 Acceptance and Efficiency Correction

The acceptance($\alpha$) $\times$ efficiency($\epsilon$) corrections are computed using the PYTHIA+HYDJET MC simulations and are calculated for prompt and nonprompt $D^0$ respectively. The efficiency correction is the product of the reconstruction efficiency ($\epsilon_{reco}$) and the selection efficiency ($\epsilon_{cuts}$). Different $p_T$ shapes between data and simulation may introduce bias to the correction factors. On the other hand, the generated prompt $D^0$ $p_T$ spectrum is weighted to the measured prompt $D^0$ spectrum as discussed below. To minimize this bias, the generated non-prompt $D^0$ spectrum is weighted to $R_{AA}$ scaled nonprompt $D^0$ spectrum from a fixed-order plus next-to-leading logarithmic (FONLL) [95,96] calculation for B hadron spectrum and PYTHIA+EVTGEN $B \rightarrow D^0$ decay kinetics, which is obtained in Section 4.1.4.

Corrections of acceptance and efficiency can be estimated as a whole by deviding the number of MC Truth $D^0$ candidates by the number of initially generated $D^0$. The formula used is the following:

$$\alpha \times \epsilon_{reco+cuts}(p_T, y) = \frac{N_{MC \, Truth \, Candidate} \left| p_T \geq 1.0 \mathrm{GeV}/c, \left| y \right| \leq 1.1, \text{all track quality cuts, all } D^0 \text{ cuts} \right|} {N_{gen} \left| y \right| < 1.0, p_T \geq 1.0 \mathrm{GeV}/c, \left| y \right| < 1.1, \text{all track quality cuts, all } D^0 \text{ cuts}}, \tag{4.1}$$

where $N_{MC \, Truth \, Candidate}$ and $N_{gen}$ are the numbers of reconstructed and generated $D^0$ respectively. It is important to note that in the numerator of Equation 4.1, reconstructed quantities are used for the $D^0$ $p_T$ and $y$ to correct the $p_T$ and $y$ resolutions, whereas in the denominator the generator level quantities are used.
\(\alpha \times \epsilon_{\text{reco}}\) includes effect from the detector acceptance and tracking and is calculated as the following:

\[
\alpha \times \epsilon_{\text{reco}}(p_T, y) = \frac{N_{\text{MC Truth Candidate}} |y| < 1.0, p_{\text{dau track}}^T \geq 1.0 \text{GeV}/c, |\eta_{\text{dau track}}| < 1.1, \text{all track quality cuts, no D}^0 \text{ cuts}}{N_{\text{gen}} |y| < 1.0}
\] (4.2)

\(\epsilon_{\text{cuts}}\) is the \(D^0\) topological cuts efficiency and calculated as the following:

\[
\epsilon_{\text{cuts}}(p_T, y) = \frac{N_{\text{MC Truth Candidate}} |y| < 1.0, p_{\text{dau track}}^T \geq 1.0 \text{GeV}/c, |\eta_{\text{dau track}}| < 1.1, \text{all track quality cuts, all D}^0 \text{ cuts}}{N_{\text{MC Truth Candidate}} |y| < 1.0, p_{\text{dau track}}^T \geq 1.0 \text{GeV}/c, |\eta_{\text{dau track}}| < 1.1, \text{all track quality cuts, no D}^0 \text{ cuts}}
\] (4.3)

Figure 4.4.: Prompt \(D^0\) spectrum from PbPb data (only with statistical error) fitted with power law function in 0-100% centrality.

To calculate the correction factors, the generated prompt \(D^0\) \(p_T\) spectrum is weighted to data prompt \(D^0\) spectrum in centrality 0-100% showed in Section 4.1.7.

There are three iterations (the last iteration is a stability check) to implement this:

- Iteration 1: The generated prompt \(D^0\) \(p_T\) spectrum is weighted to FONLL prompt \(D^0\) spectrum, which enables us to get the FONLL weighted prompt \(D^0\)
correction factors. The FONLL weighted prompt $D^0$ correction factors can be used to correct the $D^0$ raw spectrum to get data prompt $D^0$ spectrum.

- Iteration 2: The generated prompt $D^0 p_T$ spectrum is weighted to data prompt $D^0$ spectrum got in iteration 1 and we can get the data spectrum weighted correction factors. With this data weighted correction factor, we get new corrected data prompt $D^0$ spectrum.

- Iteration 3: The generated prompt $D^0 p_T$ spectrum is weighted to data prompt $D^0$ spectrum got in iteration 2. Then we can get new data spectrum weighted prompt $D^0$ correction factors and data prompt $D^0$ spectrum.

Figure 4.5.: MC prompt $D^0$ spectrum weighted to data prompt $D^0$ spectrum, data prompt $D^0$ spectrum (only with statistical error and FONLL prompt $D^0$ spectrum).

Figure 4.4 and Figure 4.5 show how the generated prompt $D^0 p_T$ spectrum is weighted to data prompt $D^0$ spectrum in iteration 2 and 3. Figure 4.4 shows prompt $D^0$ spectrum from PbPb data (only with statistical error) fitted with power law
function in 0-100% centrality. Then MC prompt $D^0$ spectrum is weighted to the fitted power law function. Figure 4.5 shows the weighted MC prompt $D^0$ spectrum, which agrees well with prompt $D^0$ spectrum from PbPb data. And the FONLL prompt $D^0$ spectrum is also plotted to show the shape difference.

Figure 4.6 shows prompt $D^0$ acceptance and efficiency from the 3 iterations in 0-100% centrality and the ratios to iteration 2. Difference between $\alpha \times \epsilon$ got from iteration 1 and iteration 2 is within 4.0%. And difference between $\alpha \times \epsilon$ got from iteration 2 and iteration 3 is within 0.1%, which is negligible compared with other systematics. And this small difference means the first two iterations are enough to get data spectrum weighted prompt $D^0$ correction factors. So in this analysis, correction factors from iteration 2 are used for prompt $D^0$.

Figure 4.6.: Prompt $D^0$ acceptance and efficiency from the 3 iterations in 0-100% centrality. The ratios to iteration 2 are also plotted.

Figure 4.7 shows the prompt and nonprompt $D^0 \alpha \times \epsilon_{\text{reco}}, \epsilon_{\text{cuts}}$ and $\alpha \times \epsilon_{\text{reco}+\text{cuts}}$, respectively, as a function of $p_T$ for $|y| < 1.0$ and centrality 0 – 100%. The $\alpha \times \epsilon_{\text{reco}}$
of prompt $D^0$ is higher than that of nonprompt $D^0$, which is the consequence of the fact that the heavy-ion tracking efficiency is higher for particles produced closer to the primary vertex. The tracks from prompt $D^0$ tend to be less displaced from the primary vertex than the tracks from nonprompt $D^0$. A corresponding effect is seen for $\epsilon_{\text{cuts}}$, where the values for prompt $D^0$ are smaller than nonprompt $D^0$ because the nonprompt $D^0$ is more displaced from the primary vertex. The efficiencies are evaluated in centrality classes corresponding to those used in the analysis and the centrality dependence of the efficiency is on the order of 10%.

Figure 4.7.: Prompt and nonprompt $D^0 \alpha \times \epsilon_{\text{reco}}$ (left), $\epsilon_{\text{cuts}}$ (middle) and $\alpha \times \epsilon_{\text{reco+cuts}}$ (right) as function of $p_T$ for $|y| < 1.0$ and centrality $0 - 100%$

4.1.4 B Feed-down Correction

The number of $D^0$ from mass spectrum fit in data is the total number prompt $D^0$ and nonprompt $D^0$. In order to obtain the prompt $D^0 p_T$ spectra, nonprompt $D^0$ needs to be subtracted from the inclusive $D^0$ spectra. In this analysis, the prompt $D^0$ fraction is calculated based on MC simulations and FONLL calculations, while the prompt $D^0$ fraction is extracted through template fits on DCA distributions in analysis with PbPb data at 5.02 TeV as discussed in Section 4.2. In this analysis, the basic idea is to calculate the expected number of nonprompt $D^0$ with FONLL calcula-
tion, nonprompt $D^0$ $R_{AA}$ and $(\alpha \times \epsilon_{\text{reco+cuts}})_{\text{nonprompt}} D^0$. The detail equations are as followed:

\[ f_{\text{prompt}} = 1 - \frac{N^\text{raw}_{\text{nonprompt}} D^0}{\frac{1}{2} N^\text{raw} D^0} \quad (4.4) \]

\[ N^\text{raw}_{\text{nonprompt} D^0} = T_{AA} \left( \frac{d\sigma_{pp}}{d^2p_T} \right)_{\text{FONLL}} \cdot R^\text{nonprompt} D^0 \cdot (\alpha \times \epsilon)_{\text{nonprompt} D^0} \cdot \Delta p_T \cdot Br \cdot N_{MB} \quad (4.5) \]

The ingredients entering Equation 4.4 and 4.5 are:

- $N^\text{raw}_{D^0}$: raw number of $D^0$ from mass spectrum fit in data;
- $\frac{1}{2}$ is because the number from mass spectrum fit is the total number of $D^0$ and its antiparticle;
- $N^\text{raw}_{\text{nonprompt} D^0}$: expected raw number of nonprompt $D^0$ from calculation;
- $T_{AA}$: the nuclear overlap function which varies with the centrality;
- $\left( \frac{d\sigma_{pp}}{d^2p_T} \right)_{\text{FONLL}}$: nonprompt $D^0$ spectrum from FONLL B hadron spectrum and PYTHIA+EVTGEN decay kinetics;
- $R^\text{nonprompt} D^0$: nonprompt $D^0$ $R_{AA}$ converted from nonprompt $J/\psi$ $R_{AA}$ and B-Jet $R_{AA}$, which will also be discussed in details later;
- $(\alpha \times \epsilon)_{\text{nonprompt} D^0}$: $(\alpha \times \epsilon)$ of nonprompt $D^0$;
- $N_{MB}$ is the number of minimum bias events sampled by the event selection;
- $Br$ is the branching fration of $D^0 \to K^- \pi^+$, which is 3.88 ± 0.05%.

In the 0–100% centrality range, the non-prompt $J/\psi$ results are taken from the preliminary results from HIN-12-014 PAS [97] and the b-jet results [98]. There is no measurements available in the $p_T$ range below 3 GeV/$c$ and the $R_{AA} = 1 \pm 1$ is assumed in this range. Based on the b-jet $R_{AA}$ measurements, $R_{AA} = 0.5 \pm 0.5$ is
used in the $p_T$ range above 30 GeV/$c$. The non-prompt $J/\psi R_{AA}$ values for centrality class 0–100% used in this study is summarized in left panel of Figure 4.8. For the centrality dependent results, the $R_{AA}$ between 6.5–30 GeV used in this study is shown in the right panel of Figure 4.8.

Figure 4.8.: (left) Non-prompt $J/\psi R_{AA}$ in the centrality interval 0–100% used in this study. (right) Non-prompt $J/\psi R_{AA}$ in the centrality interval 0–10%, 10–20%, 20–30%, 30–40%, 40–50% and 50–100% from the HIN-12-014 PAS [97].

In order to obtain the non-prompt $D^0$ and $J/\psi$ spectra from FONLL calculation, the first step is to calculate the B meson spectra from the FONLL web interface. The decay of B mesons is handled by EvtGen to obtain the non-prompt $D^0$ and $J/\psi$ spectra. In order to obtain the B meson $p_T$ spectra in different centrality bins, the correlation between B meson $p_T$ and daughter $J/\psi p_T$ is studied which is shown in left panel of Figure 4.9. Using this correlation matrix, the B meson $p_T$ spectra and $R_{AA}$ can be calculated form the non-prompt $J/\psi R_{AA}$. The results are shown in right panel Figure 4.9.

The correlation matrix of B meson $p_T$ and the daughter $D^0$ meson $p_T$ is shown in left panel of Figure 4.10. The B meson spectra obtained in the previous section
Figure 4.9.: (left) The correlation matrix between B meson $p_T$ and daughter $J/\psi$ $p_T$ obtained from pythia+evtGen. (right) The converted B meson $R_{AA}$ band.

is folded with the correlation matrix to produce the non-prompt $D^0$ spectra. Right panel of Figure 4.10 shows the results for 0–100%.

Figure 4.10.: (left) The correlation matrix between B meson $p_T$ and daughter $D^0$ $p_T$ obtained from pythia+evtGen. (right) The converted non-prompt $D^0$ $R_{AA}$ band.
Figure 4.11 shows the calculated prompt $D^0$ fraction (90 – 97%) in raw data yield for centrality class 0–100%.

Figure 4.11.: Calculated prompt $D^0$ fraction in raw data yield for centrality class 0–100%. The open boxes represent the uncertainties of prompt $D^0$ fraction.

4.1.5 pp Reference at 2.76 TeV

The pp reference used in the analysis is composed of a data-extrapolated reference and a calculation from FONLL. In the range $p_T < 16\text{GeV}/c$, results from the AL-ICE prompt $D^0$ measurements at 7 TeV \[99\] are rescaled to 2.76 TeV with FONLL calculation. The procedure in Ref. \[100\] is imitated. In the range $p_T > 16\text{GeV}/c$ where data run out of statistics, pure FONLL calculation is used as pp reference. For the FONLL calculation used in scaling data and as a pp reference, the CTEQ6.6 parton distribution functions were considered. The central values of the calculations are obtained considering $m_c=1.5$ GeV, while the renormalization and factorization scales $\mu_R=\mu_F= \sqrt{m^2 + p_T^2}$. The uncertainty band is evaluated by varying the perturbative parameters in the range $1.3 < m_c < 1.7 \text{ GeV}/c^2$ and $\mu_F$ and $\mu_R$ independently in the range $0.5 < \mu_F/m_T < 2$, $0.5 < \mu_R/m_T < 2$ with the constraint of
0.5 < \mu_F/\mu_R < 2. The pp reference used in this analysis is showed as filled and open triangles in Figure 4.12.

4.1.6 Systematic Uncertainties

Systematic uncertainties on the \( D^0 R_{AA} \) include the uncertainties on the \( D^0 \) cross section in PbPb collisions and the pp reference. The uncertainties on pp reference has been included when it is built as discussed in Section 4.1.5. Therefore, the uncertainties discussed here are from PbPb data. The sources of systematic uncertainties include the mass spectrum fit, efficiency correction, B feed-down correction, branching fraction, \( T_{AA} \), and \( N_{MB} \).

The systematic uncertainty on the tracking efficiency is 3.9% [101], thus the uncertainty on reconstruction efficiency from tracking efficiency is 7.8% for \( D^0 \). Besides, another 5.0% uncertainty is assigned based on MC closure study. Thus the total uncertainty on reconstruction efficiency is 9.3%.

The systematic uncertainty on the \( D^0 \) selection efficiency is evaluated as the ratio of each individual selection criteria (e.g. \( \alpha, d_0/\sigma(d_0) \), and vertex probability) between data and MC while other selections are applied. For example, the systematic uncertainty from the \( \alpha \) parameter is obtained by taking the ratio between data and MC of the \( \alpha \) distribution while the selections on \( d_0/\sigma(d_0) \) and vertex probability are applied. The uncertainty on the selection efficiency is found to be 14.1%, 5.2% and 11.4% for centrality ranges 0–30%, 30–100% and 0–100%, respectively.

In calculations of efficiency corrections, the generated prompt \( D^0 p_T \) spectrum is weighted to fitted function of data prompt \( D^0 \) spectrum. The shape of fitted function can change slightly if the statistical and systematic uncertainties are taken into account. To evaluate the uncertainty from the \( p_T \) shape, the prompt \( D^0 p_T \) distribution is applied a weight, which varies linearly from 1.3 to 0.7 (or from 0.7 to 1.3) over the \( p_T \) range analyzed to account for the maximum variations from the
statistical and systematic uncertainties. The uncertainty is evaluated by the relative differences on the efficiency corrections and found to be 1.0%.

The $D^0$ reconstruction efficiency decreases sharply as $d_0$ increases, thus the differences in $d_0$ distributions of $D^0$ signal between data and MC can introduce a bias in the efficiency corrections. This uncertainty is evaluated by calculating the ratio of $d_0$ cut efficiencies in data and MC and found to be 5.0%.

The systematic uncertainty on the mass spectrum fit is evaluated by varying PDFs used to fit both the signal and the background distributions. The background PDF is changed to a linear and a second order polynomial background function and the signal yields extracted are compared with the default yield to estimate the uncertainty from the background PDF. The uncertainty from the signal PDF is obtained by floating the widths of the two gaussians with a fixed ratio to model the $D^0$ signal, which can account for the possible differences in resolution between data and simulation. The total uncertainty on mass spectrum fit is found to be 5-25% depending on $p_T$ and centrality.

The systematic uncertainty on the B meson feed-down correction is evaluated by adding all individual uncertainties from Eq. (4.5) in quadrature. The total uncertainty on the prompt $D^0$ fraction is between 1-15% depending on the $p_T$ and centrality.

The total systematic uncertainty on the $D^0$ cross section in PbPb collisions is computed as the sum in quadrature of all the different contributions. The uncertainties for centrality 0-100% are summarized in Table 4.1. The systematic uncertainties for the centrality classes studied in this analysis are studied in the same way.

### 4.1.7 Results

The prompt $D^0$ cross section normalized by $T_{AA}$ in PbPb collisions is calculated as:

$$
\frac{1}{T_{AA}} \frac{dN_{PbPb}}{dp_T} \bigg|_{|y|<1} = \frac{1}{T_{AA}} \frac{1}{2 \Delta p_T} \frac{1}{N_{MB}} \frac{f_{\text{prompt}} N_{PbPb}}{B (\alpha \times \epsilon)_{\text{prompt}}} \bigg|_{|y|<1},
$$

(4.6)
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</thead>
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<tr>
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</tr>
<tr>
<td>Tracking efficiency</td>
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</tr>
<tr>
<td>$D^0$ selection efficiency</td>
<td>11.4%</td>
</tr>
<tr>
<td>$D^0$ decay length consistency</td>
<td>5.0%</td>
</tr>
<tr>
<td>MC $p_T$ shape</td>
<td>1.0%</td>
</tr>
<tr>
<td>Signal extraction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.0-13.0</td>
</tr>
<tr>
<td></td>
<td>7.0%</td>
</tr>
<tr>
<td></td>
<td>6.4%</td>
</tr>
<tr>
<td></td>
<td>18.2%</td>
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<tr>
<td></td>
<td>3.2%</td>
</tr>
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<td>$N_{MB}$</td>
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</tr>
<tr>
<td>Sum</td>
<td>6.6%</td>
</tr>
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</table>

Table 4.1.: Summary of relative systematics from data for centrality 0 – 100%.

where $T_{AA}$ is the nuclear overlap function which varies with the centrality $[102]$, $\Delta p_T$ is the width of the $p_T$ interval, $N_{MB}$ is the number of MB events sampled by the event selection, $B$ is the branching fraction of the $D^0 \rightarrow K^- \pi^+$ channel, $(\alpha \times \epsilon)_{\text{prompt}}$ is the prompt $D^0$ acceptance and efficiency, $f_{\text{prompt}}$ is the fraction of prompt $D^0$, and $N_{pp,Pb}$ is the raw yield of $D^0$ signal in each $p_T$ interval. The factor 1/2 accounts for the fact that $N_{pp}$ is the total yield of $D^0$ and $D^0$. Figure 4.12 shows the prompt $D^0$
Figure 4.12.: Cross section of prompt $D^0$ from PbPb data (red circles) for centrality class 0-100% and pp reference (filled and open triangles). For PbPb data, the errors represent statistical errors and the filled boxes represent systematic errors. For pp reference, the open boxes represent total uncertainties.

cross section normalized by $T_{AA}$ in PbPb collisions at 2.76 TeV for centrality class 0 – 100% (red circles). For comparison, the pp reference extracted as described in Section 4.1.5 is showed as filled and open triangles. This figure clearly shows that the $D^0$ cross section in PbPb data is significantly lower than that of the pp reference, indicating that prompt $D^0$ production in PbPb collisions is strongly suppressed.

Figure 4.13 shows the prompt $D^0$ $R^*_{AA}$ as a function of $p_T$ for centrality classes 0 – 100% (left) and 0 – 10% (right). To denote that the pp reference used in this analysis is not measured pp reference spectrum, the measured nuclear modification factor of prompt $D^0$ is named $R^*_{AA}$. The $R^*_{AA}$ indicates a trend toward less suppression in high $p_T$ range though the differences of the references should be taken into account.

The centrality dependence of prompt $D^0$ $R^*_{AA}$ is also studied in six $p_T$ intervals and four centrality bins. Figure 4.14 shows the prompt $D^0$ $R^*_{AA}$ as function of $p_T$ in
Figure 4.13.: Prompt $D^0 R_{AA}^*$ from PbPb data as function of $p_T$ for centrality classes 0-100% (left) and 0-10% (right). The error bars represent statistical errors and the filled boxes represent systematic errors from data only. The open boxes are the errors from pp reference. Systematic errors from $T_{AA}$, $N_{MB}$ and $D^0 \rightarrow K^- \pi^+$ branching fraction are represented by the gray boxes around unity.

centrality classes 0-10%, 10-30%, 30-50% and 50-100%. It is found that the suppression of prompt $D^0$ is larger in central collisions than in peripheral collisions.

In addition, the prompt $D^0 R_{AA}^*$ is compared with charged particle and nonprompt $J/\psi R_{AA}$. Figure 4.15 shows charged particle $R_{AA}$ ($7.2 < p_T < 9.6\text{GeV}/c$, $|\eta| < 1.0$) \cite{43}, prompt $D^0 R_{AA}^*$ ($8.0 < p_T < 16.0\text{GeV}/c$, $|\eta| < 1.0$) and nonprompt $J/\psi R_{AA}$ ($6.5 < p_T < 30.0\text{GeV}/c$, $|y| < 1.2$) \cite{97} as a function of $N_{\text{part}}$. It is interesting to notice that the prompt $D^0 R_{AA}^*$ falls between charged particle $R_{AA}$ and nonprompt $J/\psi R_{AA}$, but the uncertainties and the different kinetic ranges should be taken into account.

Figure 4.16 shows comparison of prompt $D^0 R_{AA}^*$ results of this analysis and $R_{AA}$ results from the ALICE collaboration \cite{103} for centrality class 0-20%. While the measurements from ALICE are within the rapidity range $|y| < 0.5$, and the
Figure 4.14.: Prompt $D^0 R_{AA}$ as function of $p_T$ for centrality classes 0-10% (top left), 10-30% (top right), 30-50% (bottom left), and 50-100% (bottom right). The error bars represent statistical errors and the filled boxes represent systematic errors from data only. The open boxes are the errors from pp reference. The systematic errors from $T_{AA}$, $N_{MB}$ and the $D^0 \to K^- \pi^+$ branching ratio are represented by the gray boxes around unity.

measurements from CMS are for the rapidity range $|y| < 1.0$, the two results are consistent within uncertainties.

From above results, it is clear that the production of $D^0$ mesons are significantly suppressed in semi-central to central PbPb collisions at 2.76 TeV, indicating strong
Figure 4.15.: Charged particle $R_{AA}$ (blue squares) \cite{43}, preliminary prompt $D^0$ $R_{AA}$ (black circles) and nonprompt $J/\psi$ $R_{AA}$ (green triangles) \cite{97} as function of $N_{\text{part}}$. The systematic errors of charged particle and nonprompt $J/\psi$ $R_{AA}$, showed as blue and green boxes respectively, include systematic uncertainties from integrated luminosity of the pp data sample and $T_{AA}$.

energy loss of charm quarks in the medium. The centrality dependence of the suppression is observed.
Figure 4.16.: Comparison of prompt $D^0 R_{AA}^*$ as measured by the CMS Collaboration (black circles) and $R_{AA}$ as measured by the ALICE Collaboration (blue squares) as function of $p_T$ for centrality class 0–20%. Measurements from ALICE are for rapidity $|y| < 0.5$, while measurements from CMS are for rapidity $|y| < 1.0$. 

$\sqrt{s_{NN}} = 2.76$ TeV

Prompt $D^0 R_{AA}^*$, CMS Preliminary $|y| < 1.0$, Cent. 0-20%

Syst. PbPb data

Err. pp reference

Filled markers: data-extrapolated reference

Open markers: FONLL reference

Prompt $D^0 R_{AA}^*$, Alice (JHEP 09 (2012) 112) $|y| < 0.5$, Cent. 0-20%

Syst.
4.2 Prompt $D^0$ Nuclear Modification Factor in PbPb Collisions at 5.02 TeV

This analysis has the following main differences compared with the analysis at 2.76 TeV: first, the pp reference in this analysis is measured $D^0$ cross section with pp data; second, dedicated HLT $D^0$ triggers are used during pp and PbPb data taking in 2015, thus this analysis reaches much higher $p_T$ than the analysis at 2.76 TeV; third, the prompt $D^0$ fraction is extracted in a data-driven way in this analysis, which is different from the method used in the analysis at 2.76 TeV. In the following sections, we will focus on these differences.

4.2.1 Datasets and Monte Carlo Simulation

This analysis is performed using the pp and PbPb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV collected in 2015. The total pp sample corresponds to an integrated luminosity of 25.8 pb$^{-1}$ while the PbPb sample to an integrated luminosity of 531 µb$^{-1}$. The data selected by minimum-bias and $D^0$ meson triggers is used. The detailed descriptions of the MB triggers can be found in Ref. [42] and detailed descriptions of $D^0$ triggers will be discussed later. The MB pp sample corresponds to about 2.5 billion events and the PbPb MB samples to about 300 million of events.

To reject events from background processes (beam-gas collisions and beam scraping events), events are required to pass a set of selection criteria in offline analysis as described in Ref. [42]. Both pp and PbPb events are to have at least one reconstructed primary, formed by two or more associated tracks and required to have a distance from the nominal interaction region of less than 15 cm along the beam axis. The PbPb collision events are also required to have at least three towers in each of the HF detectors with energy deposits of greater than 3 GeV per tower.

The Monte Carlo simulations are produced in the similar strategy as the ones used in the $D^0 R_{\text{AA}}$ analysis in PbPb collisions at 2.76 TeV discussed in Section 4.1.1.
4.2.2 $D^0$ Trigger

In order to enhance the statistics of high $p_T$ $D^0$ mesons, dedicated HLT $D^0$ triggers were designed for both pp and PbPb data taking. Since high $p_T$ $D^0$ mesons are usually associated with jets and high energy calorimeter towers in the HCAL, the HLT $D^0$ meson triggers are seeded by L1 jet triggers, which are gated with a “BPTX AND” requirement (both proton or lead beams are present, meaning a collision could happen) in order to lower the L1 rate. To cope with the large underlying event (UE) contribution in PbPb, the L1 jet triggers are constructed with jets with UE removed (denoted as “S1Jet”, stage 1 L1 trigger upgrade), using the average energy from a $\phi$ ring based algorithm. For events in which the desired L1-seed fired, a track reconstruction routine is performed at HLT, which is adopted from the offline track reconstruction.

After the tracks are reconstructed, $D^0$ candidates are built at HLT by associating pairs of tracks with opposite charges. To reduce the background contamination and the HLT rate, some topological selections is also applied at HLT, which are lower than the selections in offline analysis to account for the online and offline differences. The L1 triggers associated with each $D^0$ trigger paths are shown in Table 4.2.

The data collected by the minimum-bias triggers are used to evaluate the $D^0$ meson trigger efficiency. The trigger efficiencies for both pp and PbPb collisions are defined as following: the denominators are defined as the number of events with a leading $D^0$ (candidate with highest $p_T$) that fulfill the loose $D^0$ selection requirements, while the numerators are the number of events that fires the corresponding HLT $D^0$ trigger. Figure 4.17 shows the L1 and HLT trigger efficiency as a function of the $p_T$ of the leading $D^0$ candidate for pp data. The trigger efficiency reaches 100% at high $p_T$.

Samples recorded with different trigger paths are combined together for the analyses. In the left panel of Fig 4.18, the L1 trigger efficiency in PbPb are presented as a function of $p_T$. In Fig 4.19, the efficiencies of the $D^0$ mesons triggers in PbPb collisions are presented. In the left panel, the trigger efficiencies of the trigger paths
Table 4.2.: L1 jet trigger seeds for each $D^0$ meson trigger path during pp and PbPb data-taking period at 5.02 TeV

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<td>8</td>
<td>L1_SingleJet16_BptxAND</td>
<td></td>
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<tr>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
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<td>20</td>
<td>L1_MinimumBias</td>
<td></td>
</tr>
<tr>
<td>PbPb</td>
<td>40</td>
<td>L1_SingleS1Jet28_BptxAND</td>
<td></td>
</tr>
<tr>
<td>PbPb</td>
<td>60</td>
<td>L1_SingleS1Jet44_BptxAND</td>
<td>Unprescaled</td>
</tr>
</tbody>
</table>

Figure 4.17.: L1 (left) and HLT (right) trigger efficiency as a function of the leading $D^0$ candidate $p_T$ for pp data.

with thresholds at 20, 40, and 60 GeV/c are presented separately as a function of $p_T$. In Fig 4.19(right), the final turn on curve used for deriving the trigger efficiency correction is presented. The HLT trigger efficiency of the algorithm used in each $p_T$
Figure 4.18.: L1 trigger efficiency as a function of the leading $D^0$ candidate $p_T$ for PbPb data.

Figure 4.19.: (Left) Trigger efficiencies of the the trigger paths with thresholds at 20, 40, and 60 GeV/c as a function of $p_T$. (Right) Final turn on curves used for deriving the trigger efficiency correction fitted with a linear function.

interval was considered (See Table 4.3). The global turn on curve was fitted with a linear function, that is used to correct the final cross section. The systematic
Table 4.3.: Summary of HLT paths used in the pp and PbPb analysis in different $D^0$ $p_T$ intervals.

<table>
<thead>
<tr>
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</tr>
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</tr>
<tr>
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<tr>
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<td>$20 &lt; p_T &lt; 40$</td>
<td>20</td>
</tr>
<tr>
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<td>$40 &lt; p_T &lt; 60$</td>
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<tr>
<td>PbPb</td>
<td>$60 &lt; p_T &lt; 80$</td>
<td>60</td>
</tr>
</tbody>
</table>

uncertainty on the trigger efficiency (2%) is defined by the uncertainty on the zero polynomial coefficient of the fit.

4.2.3 B Feed-down Correction

The $D^0$ signal in data includes both prompt and nonprompt $D^0$. In order to obtain the prompt $D^0$ spectra, $D^0$ from B decays needs to be subtracted from the inclusive $D^0$ spectra. In this analysis, the prompt $D^0$ fraction is evaluated with a data-driven method, which performs a template fit on the distribution of DCA of $D^0$ signal to primary vertex with the DCA shapes of prompt and nonprompt $D^0$ from the PYTHIA+HYDJET simulations.

Figure 4.20 shows a cartoon of the nonprompt $D^0$ DCA. For prompt $D^0$, since they are directly from the primary vertex, the physics $D^0$ DCA is 0. Only detector resolution leads to finite values. For nonprompt $D^0$ from B feed down, as in shown
in Fig. 4.20, the B decay leads to finite physics $D^0$ DCA. Therefore, the DCA distributions of prompt and nonprompt $D^0$ are different. A template fit on the $D^0$C A distribution of $D^0$ signal in data with the DCA shapes of prompt and nonprompt $D^0$ from the simulations can help extract the prompt $D^0$ fraction. In each $p_T$ interval, the DCA distribution of $D^0$ signal in data is obtained through mass spectrum fit in bins of DCA or sideband substraction depending on the statistics. Figure 4.21 shows
Figure 4.22.: Fractions of prompt $D^0$ as a function of $p_T$ for pp collisions (left) and 0–100% centrality PbPb collisions (right) at 5.02 TeV.

examples of template fit on DCA distribution of $D^0$ signal for pp collisions (left) and 0–100% centrality PbPb collisions (right) at 5.02 TeV. Figure 4.22 shows the prompt $D^0$ fractions of as a function of $p_T$ for pp collisions (left) and 0–100% centrality PbPb collisions (right) at 5.02 TeV. The prompt $D^0$ fractions are found to be 75–95%.

Besides, to validate the data driven procedure for the prompt fraction estimation, the results obtained are cross checked with the estimation based on the FONLL+MC based calculations as discussed in Section 4.1.4. The results are found to be consistent within uncertainties.

4.2.4 Results

The prompt $D^0$ $p_T$-differential cross section in each $p_T$ interval in pp collisions is calculated as

$$
\left. \frac{d\sigma_{pp}}{dp_T} \right|_{|y|<1} = \frac{1}{2} \frac{1}{\Delta p_T} \frac{1}{E \cdot B} \frac{f_{\text{prompt} \cdot N_{pp}}}{(\alpha \times \epsilon)_{\text{prompt} \cdot \epsilon_{\text{trigger}}}} \right|_{|y|<1},
$$

(4.7)
Figure 4.23.: (left) The prompt \( D^0 \) \( p_T \)-differential cross section in pp collisions at \( \sqrt{s} = 5.02 \) TeV. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty, listed in the legend and not included in the point-to-point uncertainties, comprises the uncertainties in the integrated luminosity measurement and the \( D^0 \) meson \( \mathcal{B} \). Results are compared to FONLL and GM-VFNS calculations. (right) The prompt \( D^0 \) \( p_T \)-differential production yields divided by the nuclear overlap functions \( T_{AA} \) for PbPb collisions in the 0–100% (red) and 0–10% (blue) centrality ranges compared to the same pp cross sections shown in the left panel (black).

where \( \Delta p_T \) is the width of the \( p_T \) interval, \( \mathcal{L} \) is the integrated luminosity, \( \mathcal{B} \) is the branching fraction of the \( D^0 \to K^- \pi^+ \) channel, \( (\alpha \times \epsilon)_{\text{prompt}} \) is the prompt \( D^0 \) acceptance and efficiency, \( f_{\text{prompt}} \) is the fraction of prompt \( D^0 \), \( \epsilon_{\text{trigger}} \) is the \( D^0 \) trigger efficiency (for minimum bias trigger, it is 1), and \( N_{pp} \) is the raw yield of \( D^0 \) signal in each \( p_T \) interval. The factor \( 1/2 \) accounts for the fact that \( N_{pp} \) is the total yield of \( D^0 \) and \( \bar{D}^0 \). The measured prompt \( D^0 \) \( p_T \)-differential cross section in pp collisions at 5.02 TeV is presented in the left panel of Fig. 4.23. The calculations from FONLL and a
The prompt $D^0$ $p_T$-differential production yield in each $p_T$ interval in PbPb collisions normalized by $T_{AA}$ is calculated as:

$$\frac{1}{T_{AA}} \frac{dN_{PbPb}}{dp_T} \bigg|_{|y|<1} = \frac{1}{T_{AA}} \frac{1}{2\Delta p_T} \frac{1}{N_{MB} B} \left(\alpha \times \epsilon\right)_{\text{prompt}} \frac{f_{\text{prompt}} N_{PbPb}}{\epsilon_{\text{trigger}}} \bigg|_{|y|<1},$$

(4.8)

where $N_{MB}$ is the number of MB events used for the analysis and $T_{AA}$ is the nuclear overlap function [27]. The values of $T_{AA}$ are 5.61mb$^{-1}$ for inclusive PbPb collisions and 23.2mb$^{-1}$ for central events [42]. The other terms were defined in analogy with Eq. (4.7). The prompt $D^0$ $p_T$-differential production yields divided by the nuclear overlap functions $T_{AA}$ in PbPb collisions for centrality classes 0–100% and 0–10% are presented in the right panel of Fig. 4.23 and pp cross section shown in the left panel is plotted for comparison.

The $R_{AA}$ for the centrality class 0–100% is presented in the left panel of Fig. 4.24. It is found that the prompt $D^0$ production is suppressed by a factor of 3 to 4 in the $p_T$ range 6–8 GeV/c. The suppression factor decreases towards higher $p_T$ range. The $R_{AA}$ for the centrality class 0–10% is shown in the right panel of Fig. 4.24, which shows similar $p_T$ dependence to the $R_{AA}$ for the centrality class 0–100%.

The measured prompt $D^0 R_{AA}$ results are also compared to calculations of different models: M. Djordjevic [107] and CUJET 3.0 [108–110], which are two pQCD-based models including both collisional and radiative energy loss, I. Vitev [111,112], which is a pQCD-based model including radiative energy loss only, S. Cao et al. [113,114], which is a transport model based on a Langevin equation and includes both collisional and radiative energy loss, PHSD [115,116], which is a microscopic off-shell transport model based on a Boltzmann approach and includes collisional energy loss only, AdS/CFT [117], which is a model based on the anti-de Sitter/conformal field theory (AdS/CFT) correspondence and includes thermal fluctuations in the energy loss for heavy quarks. For AdS/CFT calculations, two settings of the diffusion co-
efficient of the heavy quark propagation through the medium (dependent on, and independent of the quark momentum) are provided. In the range of $p_T > 40$ GeV/$c$, the calculations from M. Djordjevic, CUJET 3.0 and I. Vitev are consistent with the measured results in both centrality ranges within the uncertainties, though the calculated central values tend to be lower than the experimental results. The calculations from S. Cao et al. can generally describe the measurement well in the centrality range 0–100%, while it overestimates the suppression for the central events. The calculations from AdS/CFT are consistent with the measured results in both centrality ranges. In the $p_T$ range of 10–40 GeV, all models describe well the measured results in both centrality ranges. For $p_T < 10$ GeV/$c$, the calculations from PHSD with shadowing are consistent with the measured results in the centrality range 0-100%, while the calculations from S. Cao et al. overestimate the suppression and the calculations from AdS/CFT lie at the lower bound of the experimental uncertainties for both centrality ranges.

The prompt $D^0$ $R_{AA}$ is compared to the measurements of the $R_{AA}$ of charged particles [42], $B^\pm$ mesons [118] and nonprompt $J/\psi$ meson [119] performed at the same energy and in the same centrality range 0–100% in the left panel of Fig. 4.25. For $p_T > 5$ GeV/$c$, the $D^0$ meson $R_{AA}$ is consistent with that of charged particles, while the $D^0$ meson $R_{AA}$ tends to be higher than that of charged particles for $p_T < 5$ GeV/$c$. The $B^\pm$ meson $R_{AA}$, which is measured in the $p_T$ range of 7–50 GeV/$c$ and the rapidity range of $|y| < 2.4$, is found to be consistent with the $D^0$ results within uncertainties. The nonprompt $J/\psi$ meson $R_{AA}$ is higher than the $D^0$ meson $R_{AA}$ in the measured $p_T$ range. Right panel of Fig. 4.25 shows the comparison between the $R_{AA}$ of $D^0$ meson and charged particles in the centrality range 0–10%, which shows similar trend as in the centrality range 0–100%.

In summary, the $p_T$-differential cross sections of prompt $D^0$ mesons in pp and PbPb collisions at 5.02 TeV, and the $R_{AA}$ in PbPb collisions at 5.02 TeV are measured in the $p_T$ range of 2–100 GeV/$c$ at midrapidity ($|y| < 1.0$) with the CMS detector. It is found that the production of prompt $D^0$ mesons is strongly suppressed in PbPb
Figure 4.24: $R_{AA}$ as a function of $p_T$ in the centrality range 0–100% (left) and 0–10% (right). The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty, represented as a grey box at $R_{AA} = 1$, comprises the uncertainties in the integrated luminosity measurement and $T_{AA}$ value. The $D^0$ $R_{AA}$ values are also compared to calculations from various theoretical models [107–117].

The $D^0$ $R_{AA}$ is found to be consistent with the charged particle $R_{AA}$ for $p_T > 5$ GeV/c, while tend to be higher for $p_T < 5$ GeV/c. The $D^0$ $R_{AA}$ is consistent with the $B^\pm$ $R_{AA}$, while lower than nonprompt $J/\psi$ $R_{AA}$. The $D^0$ meson $R_{AA}$ is also compared with calculations from different theoretical models and provides important inputs to the theoretical studies.
Figure 4.25.: (left) Nuclear modification factor $R_{AA}$ as a function of $p_T$ in the centrality range 0–100% (green squares) compared to the $R_{AA}$ of charged particles (red circles) [42], $B^\pm$ mesons (blue triangles) [118] and nonprompt $J/\psi$ meson (purple crosses and stars) [119] in the same centrality range at 5.02 TeV. (right) Nuclear modification factor $R_{AA}$ as a function of $p_T$ in the centrality range 0–10% (green squares) compared to the $R_{AA}$ of charged particles (red circles) [42] in the same centrality range.
5. Prompt \( D^0 \) Azimuthal Anisotropy in PbPb Collisions

This chapter presents the details of the measurement of the prompt \( D^0 \) azimuthal anisotropy in PbPb Collisions at 5.02 TeV.

5.1 Datasets and Monte Carlo Simulation

The data used in this analysis is the PbPb data at 5.02 TeV collected by the CMS detector in 2015. The data selected by a minimum bias trigger and a 30–100% centrality trigger is used. The minimum bias trigger was prescaled by a larger factor than the centrality trigger during data taking. The 30–100% centrality trigger is to enhance the statistics in centrality 30–50% analysis. The event selections applied in offline analysis is the same with the \( D^0 \) meson \( R_{AA} \) analysis at 5.02 TeV discussed in Section 4.2.1. The numbers of events used in this analysis for the centrality classes 0–10%, 10–30%, and 30–50% are 32 million, 64 million and 151 million, respectively.

The Monte Carlo samples used in the \( R_{AA} \) analysis at 5.02 TeV analysis discussed in Section 4.2.1 are used in this analysis.

5.2 \( D^0 \) Candidate Selection

As discussed in Section 3.1, apart from the selections on \( d_0/\sigma(d_0) \), \( \alpha \), and vertex probability, the selection DCA < 0.008 cm is applied in this analysis to suppress the nonprompt \( D^0 \) in data. Figure 5.1 shows the DCA < 0.008 cm selection efficiency for prompt and nonprompt \( D^0 \) after other analysis selections are applied. It shows the efficiency for prompt \( D^0 \) is 80–98% while the efficiency for nonprompt \( D^0 \) is 35–50%, which means the DCA < 0.008 cm selection can reduce the nonprompt \( D^0 \) fraction
by around 50%. This property is utilized in the evaluation of systematic uncertainty from nonprompt $D^0$ discuss in Section 5.4.

Figure 5.1: DCA < 0.008 cm selection efficiency for prompt and nonprompt $D^0$ after other analysis selections are applied.

5.3 Analysis Techniques

This section discusses the techniques used in this analysis to extract the $D^0$ $v_n$ coefficient.

5.3.1 EP and SP Method

With the event plane, the anisotropy coefficient $v_n$ can be measured with event plane method (EP method) and scalar product method (SP method).
The event plane angle $\Psi_n$ can be expressed with Q-vectors. The Q-vector of event plane is defined as:

$$Q_n = \sum_{k=1}^{M} \omega_k e^{in\phi_k},$$  \hspace{1cm} (5.1)$$

where $M$ represents the subevent multiplicity, $\phi_k$ is the azimuthal angle of the $k$th particle, and $\omega_k$ is a weighting factor.

The Q-vector of each $D^0$ candidate, $Q_{n,D^0}$, is defined as:

$$Q_{n,D^0} = e^{in\phi},$$  \hspace{1cm} (5.2)$$

where $\phi$ is the azimuthal angle of the $D^0$ candidate.

With the EP method, the $v_n$ is calculated with Q-vectors as:

$$v_n \{ \text{EP} \} \equiv \frac{\langle Q_{n,D^0} Q_{n,A}^* \rangle}{\sqrt{\langle Q_{n,A} Q_{n,B}^* \rangle \langle Q_{n,A} Q_{n,C}^* \rangle \langle Q_{n,B} Q_{n,C}^* \rangle}},$$  \hspace{1cm} (5.3)$$

where the denominator on the right is defined as the event plane resolution $R_n$.

With the SP method, the $v_n$ is calculated with Q-vectors as:

$$v_n \{ \text{SP} \} = \frac{\langle Q_{n,D^0} Q_{n,A}^* \rangle}{\sqrt{\langle Q_{n,A} Q_{n,B}^* \rangle \langle Q_{n,A} Q_{n,C}^* \rangle \langle Q_{n,B} Q_{n,C}^* \rangle}},$$  \hspace{1cm} (5.4)$$

In this analysis, the subscript $A$ and $B$ refer to event planes defined using calorimeter data, with the $HF_n^-$ planes covering the pseudorapidity range of $-5 < \eta < -3$ and $HF_n^+$ planes covering the range $3 < \eta < 5$, respectively. The subscript $C$ refers to event plane defined with tracker data with $-0.75 < \eta < 0.75$. The denominator of Eq. (5.4) and (5.3) effectively correct for the finite resolution of the $A$ event plane that results from finite particle multiplicities and detector effects. The averages $\langle Q_{n,A} Q_{n,B}^* \rangle$, $\langle Q_{n,A} Q_{n,C}^* \rangle$ and $\langle Q_{n,B} Q_{n,C}^* \rangle$ are taken over all events, while the average $\langle Q_n, D^0 Q_{n,A}^* \rangle$ is over all $D^0$ candidates in all events. The real part is taken for all averages of Q-vector products. To avoid the nonflow effects, the $\eta$ gap between $D^0$ candidates and the correlated event plane $A$ is required to be at least 3 units. Thus
HF\textsubscript{n} planes are used as event plane A and HF\textsuperscript{+}\textsubscript{n} planes are used as event plane B for \(D^0\) candidates from the positive \(\eta\) region, and vice versa.

Figure 5.2.: Ratios of RMS to mean values of elliptic and triangular flow for PbPb collisions at 2.76 TeV. The results assume the flow coefficients are proportional to the corresponding Glauber model eccentricities. This figure is copied from Ref. [120].

Luzum and Ollitrault have argued that it would be better to present experimental results using the SP method than using the EP method [120]. The argument is that that the results of the event plane method depend on the value of the event plane resolution, with

\[
v_n \{\text{EP}\} \xrightarrow{M_{\text{highres.}}} \langle v_n \rangle
\]

and

\[
v_n \{\text{EP}\} \xrightarrow{M_{\text{lowres.}}} \sqrt{\langle v_n^2 \rangle}.
\]

With the scalar product method one has

\[
v_n \{\text{SP}\} \equiv \sqrt{\langle v_n^2 \rangle}.
\]

Figure 5.2 copied from Ref. [120], illustrates how the mean and RMS values are expected to differ for PbPb collisions at 2.76 TeV. Thus in this analysis, the SP method is used as the default analysis method, while the \(\Delta\phi\) bins method, which is derived from the EP method, is used as a cross check.
5.3.2 Extraction of $D^0$ Signal $v_n$

After $v_n$ of each $D^0$ candidate is calculated with Eq. (5.4), to extract $v_n$ of $D^0$ signal ($v_n^S$), a simultaneous fit on mass spectrum and $v_n$ as function of invariant mass is performed. As discussed in Section 3.3, the mass spectrum fit function is composed of $B(m_{inv})$ for combinatorial background, $S(m_{inv})$ for $D^0$ signal, and $SW(m_{inv})$ for $D^0$ candidates with incorrect mass assignment. The average $v_n$ of all $D^0$ candidates as a function of invariant mass, $v_{n}^{S+B}(m_{inv})$, is fitted with

$$v_{n}^{S+B}(m_{inv}) = \alpha(m_{inv})v_n^S + (1 - \alpha(m_{inv}))v_n^B(m_{inv}),$$

(5.8)

where

$$\alpha(m_{inv}) = (S(m_{inv}) + SW(m_{inv}))/ (S(m_{inv}) + SW(m_{inv}) + B(m_{inv})).$$

(5.9)

Here, $v_n^B(m_{inv})$ is the $v_n$ of background $D^0$ candidates and is modeled as a linear function of invariant mass, while $\alpha(m_{inv})$ is the $D^0$ signal fraction as a function of invariant mass, which is from mass spectrum fit function. The K-$\pi$ swapped component is included in signal fraction because these candidates are from real $D^0$ and should have same $v_n$ value with real $D^0$ signal. The left panel of Fig. 5.3 shows an example of a simultaneous fit to the mass spectrum and $v_{2}^{S+B}(m_{inv})$ in the $p_T$ interval 4–5 GeV/$c$ for the centrality class 10–30%. The right panel of Fig. 5.3 shows an example of a simultaneous fit to the mass spectrum and $v_{3}^{S+B}(m_{inv})$ in the $p_T$ interval 5–6 GeV/$c$ for the centrality class 30–50%.

The $D^0$ signal in data is a mixture of prompt and nonprompt $D^0$, thus the measured $v_n^S$ above is also a combination of $v_n$ of prompt and nonprompt $D^0$, expressed as

$$v_n^S = f_{prompt}v_{n}^{prompt} + (1 - f_{prompt})v_{n}^{nonprompt}.$$  

(5.10)

In Eq. (5.10), $v_{n}^{prompt}$ and $v_{n}^{nonprompt}$ is the $v_n$ of prompt and nonprompt $D^0$ respectively, and $f_{prompt}$ is fraction of prompt $D^0$ in data. To extract the $v_n$ of prompt $D^0$, the $v_n$ of $D^0$ from data without the DCA < 0.008 cm selection is also measured.
besides the results with all analysis selections. With some calculations, $v_n^{\text{prompt}}$ can be expressed as

$$v_n^{\text{prompt}} = v_{n,1}^{S} + \frac{1 - f_{\text{prompt},1}}{f_{\text{prompt},1} - f_{\text{prompt},2}} (v_{n,1}^{S} - v_{n,2}^{S}),$$

where subscripts 1 and 2 refer to with and without DCA < 0.008 cm selection, respectively. The $v_n$ of $D^0$ from data with all analysis selections, $v_{n,1}^{S}$, is kept as central values in this analysis while the second term,

$$\frac{1 - f_{\text{prompt},1}}{f_{\text{prompt},1} - f_{\text{prompt},2}} (v_{n,1}^{S} - v_{n,2}^{S}),$$

is assigned as systematic uncertainty due to nonprompt $D^0$. The detail study on systematic uncertainty from remaining nonprompt $D^0$ is discussed in Section 5.4.
5.3.3 $\Delta \phi$ Bins Method

The azimuthal dependence of the particle yield can be written in terms of an harmonic expansion with [47]:

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{d\phi dE_T} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos [n(\phi - \Psi)]\right), \quad (5.12)$$

where $\phi$, $E$ and $p_T$ are the particle's azimuthal angle, energy, and transverse momentum, respectively. Therefore, another method to measure the $D^0 v_n$ is to divide the $D^0$ candidates into several $\Delta \phi$ bins and use the raw $D^0$ yield in each $\Delta \phi$ bin.

![Graphs showing $D^0$ mass spectrum fit in different $\Delta \phi$ bins for $v_2$ in $p_T$ interval 5.0–6.0 GeV/c and centrality 10–30%](image)

Figure 5.4.: $D^0$ mass spectrum fit in different $\Delta \phi$ bins for $v_2$ in $p_T$ interval 5.0–6.0 GeV/c and centrality 10–30%

Figure 5.4 shows an example of mass spectrum fit for $v_2$ in $p_T$ interval 5.0–6.0 GeV/c and centrality 10–30%. Then $v_n^{\text{obs}}$ can be extracted with a fit on the $d^2N/(d\phi d\Delta \phi)$ distribution using Eq. (5.13), where $N_0$ and $v_n^{\text{obs}}$ are free parameters.

$$N_0 + 2v_n^{\text{obs}} \cos(n\Delta \phi) \quad (5.13)$$
Figure 5.5: $d^2N/(dp_Td\Delta\phi)$ fit for $v_2$ in $p_T$ interval 5.0–6.0 GeV/c and centrality 10–30%.

The $D^0 v_n$ is $v_n^{\text{obs}}$ corrected by event plane resolution $R_n$, given as

$$v_n = \frac{v_n^{\text{obs}}}{R_n}. \quad (5.14)$$

Figure 5.5 shows $d^2N/(dp_Td\Delta\phi)$ fit for $v_2$ in $p_T$ interval 5.0–6.0 GeV/c and centrality 10–30%. The $v_n^{\text{obs}}$ values are shown in the figures.
5.4 Systematic Uncertainties

This section presents the studies of systematic uncertainties for both the SP method and the $\Delta\phi$ bins method. The systematic sources include remaining non-prompt $D^0$ as discussed in Section 5.3.2, the background mass PDF, the track selection, the $D^0$ meson yield correction (acceptance and efficiency) and the background $v_n$ PDF. Because the $D^0$ $v_n$ values are pretty close to zero, especially in the high $p_T$ range, absolute uncertainties are assigned in this analysis. The systematic uncertainty studies are discussed in detail below:

- Systematic uncertainty from the remaining nonprompt $D^0$

As discussed in Section 5.3.2, the second term of Equation 5.11,

$$\frac{1 - f_{\text{prompt},1}}{f_{\text{prompt},1} - f_{\text{prompt},2}} (v_{n,1}^{\text{sig}} - v_{n,2}^{\text{sig}}),$$

is taken as systematic uncertainties from non-prompt $D^0$, where subscript 1 and 2 refer to with and without DCA $< 0.008$ cm selection, respectively.

![Figure 5.6: Prompt $D^0$ fraction with (red) and without (blue) DCA $< 0.008$ cm selection for centrality classes 0-10%, 10-30%, and 30-50%.

In this analysis, the prompt $D^0$ fraction $f_{\text{prompt}}$ is evaluated from the template fit to the DCA distribution of $D^0$ signal in data as discussed in Section 4.2.3]
The discrimination between prompt and nonprompt $D^0$ mesons lies mainly in the large DCA region, thus the fit is performed on the entire range without the DCA < 0.008 cm selection, where both $f_{\text{prompt},1}$ and $f_{\text{prompt},2}$ are evaluated. Figure 5.6 shows the prompt $D^0$ fraction with (red) and without (blue) DCA < 0.008 cm selection. We can see the nonprompt $D^0$ fraction is suppressed by around 50% with the DCA selection. In the procedure of evaluating $\frac{1-f_{\text{prompt},1}}{f_{\text{prompt},1}-f_{\text{prompt},2}}$, the statistical and systematic uncertainties of $f_{\text{prompt},1}$ and $f_{\text{prompt},2}$ are considered. The uncertainties of $f_{\text{prompt},1}$ and $f_{\text{prompt},2}$ are strongly correlated, thus we take $f_{\text{prompt},1}$ and $f_{\text{prompt},2}$ minimum or maximum values at the same time.

Figure 5.7 shows the $D^0$ signal $v_2$ (upper) and $v_3$ (lower) with (red) and without (blue) DCA < 0.008 cm selection for centrality classes 0-10%, 10-30%, and 30-50%.
DCA selection are actually small. With the information in Figs. 5.6 and 5.7, we are able to calculate the

\[
\frac{1 - f_{\text{prompt},1}}{f_{\text{prompt},1} - f_{\text{prompt},2}} (v_{n,1}^{\text{sig}} - v_{n,2}^{\text{sig}}).
\]

One problem in this procedure is that the calculated \(v_{n,1}^{\text{sig}} - v_{n,2}^{\text{sig}}\) values not only include the effect from nonprompt \(D^{0}\) fraction change, but may also be affected by uncertainties form other sources, such as statistical fluctuations. In this case, the systematic uncertainty from nonprompt \(D^{0}\) may be overestimated. To minimize the effects from other uncertainties, the systematic uncertainty from nonprompt \(D^{0}\) is evaluated in wide \(p_{T}\) intervals 1-2 GeV/c, 2-8 GeV/c, and 8-40 GeV/c.

- **Systematic uncertainty from the background mass PDF**
  
The background mass PDF is varied to a 2nd order polynomial and an exponential function, then the extracted \(v_{n}\) values are compared with the default values.

- **Systematic uncertainty from the track selection**
  
The track selections applied in \(D^{0}\) reconstruction are varied and the effect on \(v_{n}\) results is studied.

- **Systematic uncertainty from the \(D^{0}\) meson yield correction**
  
  Both \(D^{0}\) yield correction factor (acceptance and efficiency) and \(v_{n}\) are functions of \(p_{T}\). In the \(v_{n}\) analysis, there may be systematic uncertainties from \(D^{0}\) correction factor. To evaluate the uncertainty from efficiency, each \(D^{0}\) candidate is corrected by the correction factor, then \(v_{n}\) values are extracted with the corrected distributions and compared with the default values.

- **Systematic uncertainty from the background \(v_{n}\) PDF**
  
The background \(v_{n}\) PDF is changed to a 2nd order polynomial in the \(v_{n}\) vs mass fit and the extracted \(v_{n}\) values are compared with the default values.
Tables 5.1 and 5.2 show summary of systematic uncertainties for $v_2$ and $v_3$, respectively.

<table>
<thead>
<tr>
<th>Centrality and Source</th>
<th>Invariant mass (SP) method</th>
<th>$\Delta \phi$ bins method</th>
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</thead>
<tbody>
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<td>1-2GeV/c</td>
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<tr>
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<td>Efficiency correction</td>
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<td>Track cuts variation</td>
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<tr>
<td>Bkg $v_n$ PDF</td>
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</tr>
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<td>Non-prompt $D^0$</td>
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<td>Centrality 10-30%</td>
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Table 5.1.: Summary of systematic uncertainties for $D^0 v_2$ in PbPb collisions at 5.02 TeV.

### 5.5 Cross Checks

In this section, some cross checks on the analysis are presented.
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<thead>
<tr>
<th>Centrality and Source</th>
<th>Invariant mass (SP) method</th>
<th>$\Delta\phi$ bins method</th>
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</thead>
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<tr>
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</tr>
</tbody>
</table>

Table 5.2.: Summary of systematic uncertainties for $D^0 v_3$ in PbPb collisions at 5.02 TeV.

5.5.1 $\eta$ Gap Study

As discussed in Section 5.3.1, the $\eta$ gap between $D^0$ candidates and correlated event plane A is required to be at least 3 units to avoid nonflow effects. However, there may be still residual nonflow effects. The evaluate the remaining nonflow effect, the $\eta$ gap between $D^0$ candidates and correlated event plane A is varied to see if there is clear trend on the $v_n$ values while the $\eta$ gap changes. This study was performed by
defining a number of new event planes covering different \( \eta \) ranges using the ECAL and HCAL detectors in addition for the HF detectors.

Figure 5.8 shows \( v_2 \) with different \( \eta \) gaps between \( D^0 \) candidates and correlated event plane A for centrality 0-10\% (left), 10-30\% (middle) and 30-50\% (right). No clear ordering on \( v_2 \) results with different \( \eta \) gaps are observed with current uncertainties, so no clear non-flow effects are observed and no systematic uncertainties from non-flow effects are assigned in the analysis. Figure 5.9 shows same plots for \( v_3 \) and no clear non-flow effects are observed.

Figure 5.8.: \( v_2 \) results with different \( \eta \) gaps between \( D^0 \) candidates and correlated event plane A for centrality 0-10\% (left), 10-30\% (middle) and 30-50\% (right). Lower panels show absolute differences from default.
Figure 5.9: $v_3$ results with different $\eta$ gaps between $D^0$ candidates and correlatd event plane A for centrality 0-10% (left), 10-30% (middle) and 30-50% (right). Lower panels show absolute differences from default.

5.5.2 Check on the Statistical Uncertainty of $v_n$ Results from Simultaneous Fit

This check is done to make sure that the statistical uncertainty of $D^0$ $v_n$ results from the simultaneous fit discussed in Section 5.3.2 is correct. The study is done by randomly dividing the data into 8 subsets and the $D^0$ $v_n$ are measured for each subset. Then the pull distributions of $v_n$ results in the 8 subsets are calculated and fitted with Gaussian function. If the $\sigma$ of the fitted Gaussian function is close to unity, the statistical errors of $v_n$ results are correct. Figure 5.10 show $v_2$ (lower) and $v_3$ (upper) from all data (solid points) and 8 randomly divided subsets (empty points). Figure 5.11 shows pull distributions for $v_2$ (left) and $v_3$ (right). The distributions are fitted with Gaussian functions (read lines). The $\sigma$ of fitted Gaussian functions, $1.04 \pm 0.06$ and $0.96 \pm 0.06$, are consistent with unity within one error bar. Thus,
no clear bias on the statistical errors of $D^0 v_n$ results from the simultaneous fit is observed.

Figure 5.10.: $v_2$ (upper) and $v_3$ (lower) from all data (solid points) and 8 randomly divided subsets (empty points) for centrality 0-10% (left), 10-30% (middle) and 30-50% (right).
Figure 5.11.: Pull distributions for $v_2$ (left) and $v_3$ (right) from the 8 subsets showed in Figure 5.10 and 5.11. The distributions are fitted with Gaussian functions (red lines).
5.6 Results

Figure 5.12 shows the prompt $D^0$ meson $v_2$ (upper) and $v_3$ (lower) coefficients at midrapidity ($|y| < 1.0$) for the centrality classes 0–10% (left), 10–30% (middle), and 30–50% (right), and compares them to those of charged particles (dominated by light flavor hadrons) at midpseudorapidity ($|\eta| < 1.0$) \cite{121}. The $D^0$ meson $v_2$ and $v_3$ coefficients increase with $p_T$ to significantly positive values in the low-$p_T$ region, and then decrease for higher $p_T$. For $p_T < 6$ GeV/$c$, the comparison between the measured results and theoretical calculations suggests a collective motion of charm quarks as discussed below. For $p_T > 6$ GeV/$c$, the $D^0$ meson $v_2$ values remain positive, suggesting a path length dependence of the charm quark energy loss; the $D^0$ meson $v_3$ precision is limited by the available data. Compared to those of charged particles, the $D^0$ meson $v_2$ and $v_3$ coefficients exhibit a similar $p_T$ dependence, while the magnitudes are smaller for $p_T < 6$ GeV/$c$ for the centrality classes 10–30% and 30–50%. Further study may determine whether it is a pure mass ordering or whether other effects, such as the degree of charm quark thermalization, coalescence, and the path length dependence of energy loss, are at play. For $p_T > 6$ GeV/$c$, the $D^0$ meson $v_2$ values are consistent with those of charged particles, suggesting that path length dependence of the charm quark energy loss is similar to that of light quarks. As has been observed for charged particles, the $D^0$ meson $v_2$ coefficient increases with decreasing centrality in the 0–50% centrality range, while the $v_3$ coefficient shows little centrality dependence. This is consistent with an increasing elliptical eccentricity with decreasing centrality \cite{44}, and an approximately constant triangularity stemming from geometry fluctuations \cite{56}.

Figure 5.12 also compares calculations from theoretical models \cite{108,116,122,124} to the prompt $D^0$ meson $v_2$ and $v_3$ experimental results. The calculations from LBT \cite{122}, CUNG 3.0 \cite{108}, and SUBATECH \cite{123} include collisional and radiative energy losses, while those from TAMU \cite{124} and PHSD \cite{116} include only collisional energy loss. Initial-state fluctuations \cite{125} are included in the calculations from LBT,
Figure 5.12.: Prompt $D^0$ meson $v_2$ (upper) and $v_3$ (lower) coefficients at midrapidity ($|y| < 1.0$) for the centrality classes 0–10% (left), 10–30% (middle), and 30–50% (right). The vertical bars represent statistical uncertainties, grey bands represent systematic uncertainties from nonprompt $D^0$ mesons and open boxes represent other systematic uncertainties. The measured $v_n$ coefficient of charged particles at midpseudorapidity ($|\eta| < 1.0$) \cite{121} and theoretical calculations for prompt $D$ meson $v_n$ coefficient \cite{108,116,122,124} are also plotted for comparison.

Thus calculations for $v_3$ coefficient are only available from these three models. For $p_T < 6$ GeV/$c$, LBT, SUBATECH, TAMU, and PHSD can qualitatively describe the shapes of the measured $v_2$, while the TAMU model underestimates the $v_2$ values. This may suggest that the heavy quark potential in the TAMU model needs to be tuned \cite{126} or that the addition of radiative energy loss is needed. The calculations from LBT and SUBATECH are in reasonable agreement with the $v_3$ results, while the PHSD calculations are systematically below the measured $v_3$ for centrality class 10–30%. In the calculations from LBT, SUBATECH, TAMU, and PHSD, the charm
quarks have acquired significant elliptic and triangular flow through interactions with the medium constituents, and the coalescence mechanism is also incorporated. Without including the interactions between charm quarks and the medium, the calculations from these models will be significantly lower than the data results as showed in Fig. 5.13. Thus, the fact that the calculated $v_n$ values are close or even lower than the measured results suggests that the charm quarks take part in the collective motion of the system. Whether and how well the $D^0$ anisotropy can be described by hydrodynamics and thermalization requires further investigation. For $p_T > 6$ GeV/c, PHSD and CUJET can generally describe the $v_2$ results. LBT and SUBATECH predict lower and higher $v_2$ values than in data, respectively, indicating that improvements of the energy loss mechanisms in the two models are necessary.

Figure 5.13.: The comparison of the $D^0$ meson $v_2$ (upper) and $v_3$ (lower) results and theoretical calculations removing the interactions between charm quarks and the medium for prompt $D$ meson $v_n$ coefficient $^{108,116,122,124}$. 
The $D^0$ meson $v_2$ results are also compared with results from ALICE in PbPb collisions at 2.76 TeV \cite{73} and 5.02 TeV \cite{74} in Fig. 5.14 which shows the results are consistent within uncertainties.

Figure 5.14.: The comparison of prompt $D^0$ meson $v_2$ from this analysis with results from ALICE in PbPb collisions at 2.76 TeV \cite{73} and 5.02 TeV \cite{74}.

Figure 5.15 shows $D^0$ meson $v_2$ and $v_3$ from the SP method and $\Delta\phi$ bins method for centrality 0-10%, 10-30% and 30-50%. The results from the two methods are consistent within uncertainties.

In summary, the measurements of prompt $D^0$ meson azimuthal anisotropy coefficients $v_2$ and $v_3$ using the SP method in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been presented. It is the first measurement of $D^0$ meson $v_3$ coefficient. The $v_2$ coefficient is found to be positive in the $p_T$ range of 1 to 40 GeV/c, and positive $v_3$ values are observed for $p_T < 6$ GeV/c. Centrality dependence is observed for $v_2$ coefficient, while $v_3$ coefficient shows little centrality dependence. Compared with those of charged particles, the measured $D^0$ meson $v_2$ and $v_3$ coefficients are found to be smaller for $p_T < 6$ GeV/c. The $v_2$ values for $p_T > 6$ GeV/c, which are consistent with those of charged particles, suggest that the path length dependence of charm quark energy loss is similar to that of light quarks. The comparison between the measured results and theoretical calculations suggests that the charm quarks take part in the
Figure 5.15.: $D^0$ meson $v_2$ (upper) and $v_3$ (lower) from SP method and $\Delta\phi$ bins method for centrality 0-10% (left), 10-30% (middle) and 30-50% (right).

collective motion of the system. The results provide new constraints on theories of the interactions between charm quarks and the QGP medium, and the charm quark energy loss mechanisms.
6. Summary

In summary, the measurements of prompt $D^0$ meson nuclear modification factor $R_{AA}$ and azimuthal anisotropy coefficients $v_2$ and $v_3$ in PbPb collisions with the CMS detector have been presented. It is the first measurement of the $D^0$ meson $v_3$.

The $R_{AA}$ results show that the production of prompt $D^0$ mesons are strongly suppressed in semi-central to central PbPb collisions. The suppression have strong dependences on centrality and $p_T$. The $D^0$ meson $R_{AA}$ is consistent with that of light hadrons for $p_T > 5$ GeV/$c$, while a hint that $D^0$ $R_{AA}$ is higher than light hadron $R_{AA}$ is observed for $p_T < 5$ GeV/$c$. The $D^0$ meson $R_{AA}$ is consistent with the $B^\pm$ meson $R_{AA}$ in the $p_T$ range of 7-50 GeV/$c$, but the uncertainties on the $B^\pm$ meson results are still large. Compared with that of nonprompt $J/\psi$ meson, the $D^0$ meson $R_{AA}$ is significantly lower for $p_T < 10$ GeV/$c$. These comparisons provide important information on differences of the energy loss of different flavors.

The prompt $D^0$ meson $v_2$ coefficient is found to be positive in the measured $p_T$ range of 1–40 GeV/$c$, and the $v_2$ is found to be positive for $p_T < 6$ GeV/$c$. Centrality dependence is observed for $v_2$ coefficient, while $v_3$ coefficient shows little centrality dependence. Compared with those of light hadrons, the prompt $D^0$ meson $v_2$ and $v_3$ values are found to be smaller for $p_T < 6$ GeV/$c$, while have a similar $p_T$ dependence. The $v_2$ values are consistent with those of charged particles for $p_T > 6$ GeV/$c$, suggesting that the path length dependence of charm quark energy loss is similar to that of light quarks. The comparison between the light hadron and $D^0$ results provide essential insights into the interaction strength between the charm quarks and the QGP medium. Through the comparison with theoretical calculations, the $v_2$ and $v_3$ results at low $p_T$ suggests that the charm quarks take part in the collective motion of the system.
These measurements show that the charm quarks strongly interact with the QGP medium. Comparison between the results of heavy flavor and light hadrons provide important inputs on the differences of interactions with the QGP of different flavors. The $D^0$ meson $R_{AA}$, $v_2$, and $v_3$ results provide important constraints on the models of the interactions between the charm quarks and the QGP medium, and the charm quark energy loss mechanisms. The work presented in this thesis allows us to set an important milestone in our understanding of the interactions between the charm quarks and the QGP medium.
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