D⁰ meson nuclear modification factor in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration

Abstract

D⁰ meson production has been measured in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the central rapidity, $|y| < 1$, and in the transverse momentum range between 2 and 100 GeV/c with the CMS detector at the LHC. The proton-proton dataset used for this analysis corresponds to an integrated luminosity of $25.8 \text{ pb}^{-1}$, while the PbPb dataset corresponds to $404 \mu\text{b}^{-1}$. The measured D⁰ spectrum in pp collisions is well described by perturbative QCD calculations. The nuclear modification factor $R_{AA}$, defined as the ratio between the corrected PbPb yield and the proton-proton cross-section scaled by the number of incoherent nucleon-nucleon collisions, was also measured. In the transverse momentum range $p_T = 6-10\text{ GeV/c}$, the D⁰ yield in the PbPb collisions is suppressed by a factor of 4-5 compared to the scaled proton-proton reference. At high $p_T$, the suppression is significantly reduced, approaching roughly a factor of 1.5 for particles with $p_T$ in the range 60-100 GeV/c. The measured D⁰ nuclear modification factor is compatible with the charged particle $R_{AA}$, within the experimental uncertainties.
1 Introduction

Heavy-quark production plays a crucial role in understanding the mechanisms of heavy-quark interaction with the medium created in heavy-ion collisions [1, 2]. Heavy quarks are primarily produced at early stages of heavy-ion collisions, and therefore carry information about the pre-thermalization properties of the quark gluon plasma [3]. Compared with light quarks and gluons, heavy quarks are expected to lose less energy due to smaller color charge and the dead cone effect [4]. Thus, the measurement of heavy-flavour spectra in heavy-ion collisions is considered a golden probe to investigate the mechanisms of in-medium energy loss of high momentum partons in the hot and deconfined medium created in ultra-relativistic heavy-ion collisions. In proton-proton (pp) collisions, the study of heavy-quark production allows one to test next-to-leading order QCD calculations at the LHC energies [5].

The LHC has provided a number of successful measurements addressing the modification of heavy flavor hadrons in a hot and dense medium. The CMS Collaboration has shown several significant heavy flavor results, including B hadron suppression through non-prompt J/ψ measurements in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [6], b jet nuclear modification factors both in PbPb collisions [7] and in pPb collisions [8], and B meson production in pPb collisions [9]. The nuclear modification factor of D mesons in PbPb collisions at 2.76 TeV was also studied as a function of the transverse momentum and the centrality by the ALICE and the CMS Collaboration [8, 10, 11]. These previous measurements indicate that there is significant suppression of heavy flavored objects in PbPb collisions at these energies and that initial state effects do not play a significant role.

In this note, the analysis of D$^0$ meson transverse momentum spectra in proton-proton and PbPb collisions at 5.02 TeV is presented in a wide transverse momentum range, from 2 to 100 GeV/c. D$^0$ mesons and charge conjugates are reconstructed in the central rapidity region, $|y| < 1$, of the CMS detector via the hadronic decay channel $D^0 \rightarrow K^- \pi^+$. The proton-proton D$^0$ differential cross section is presented as a function of $p_T$ and compared to FONLL calculations [5]. The nuclear modification factor $R_{AA}$ will also be presented for two selection of collision centrality, 0-100% and 0-10%, and compared to the $R_{AA}$ of inclusive charged particles at the same energy and centrality selection and to predictions from different theoretical calculations.

2 CMS detector

A detailed description of the CMS experiment can be found in Ref. [12]. The silicon tracker, located in the 3.8 T magnetic field of the superconducting solenoid, is used to measure charged particles within the pseudorapidity range $|\eta| < 2.5$. It provides an impact parameter resolution of $\approx 15 \, \mu m$ and a $p_T$ resolution of about 1.5% for particles with $p_T = 100$ GeV/c. Also located inside the solenoid are an electromagnetic calorimeter (ECAL) and a hadron calorimeter (HCAL). The ECAL consists of more than 75,000 lead tungstate crystals, arranged in a quasi-projective geometry and partitioned into a barrel region ($|\eta| < 1.48$) and two endcaps extending out to $|\eta| = 3.0$. The HCAL consists of sampling calorimeters composed of brass and scintillator plates, covering $|\eta| < 3.0$ in the same barrel-indict structure as the ECAL. Iron hadron-forward (HF) calorimeters, with quartz fibers read out by photomultipliers, extend the calorimeter coverage out to $|\eta| = 5.2$. Calorimeter cells are grouped in projective towers of pseudorapidity ($\eta$) and azimuthal angle ($\phi$) granularity given by $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$ at midrapidity. Segmentation becomes coarser at larger rapidities. An efficient muon system with detection planes made of drift tubes, cathode strip chambers, and resistive plate chambers, is deployed for the
2 Event selection

This analysis is performed using the 2015 pp and PbPb data collected at $\sqrt{s_{NN}} = 5.02$ TeV. The pp sample corresponds to an integrated luminosity of 25.8 pb$^{-1}$, while the PbPb sample corresponds to an integrated luminosity of 404 µb$^{-1}$. Both the pp and PbPb data were selected using events with a minimum bias trigger and a transverse momentum larger than 8 GeV/c. Once tracks are reconstructed, $D^0$ candidates are formed by associating pairs of tracks with opposite sign. To reduce the background contamination, a very loose selection on the $D^0$ decay topology is also applied.

Three HLT $D^0$ triggers were used in the pp and the PbPb analyses, with $D^0 p_T$ thresholds of 15, 30, 50 and 20, 40, 60 GeV/c, respectively. The highest threshold triggers in both pp and PbPb collisions always selected events unprescaled, while the triggers with lower thresholds had to be prescaled to cope with the large instantaneous luminosity of the LHC. The efficiencies of these trigger algorithms are evaluated offline by counting the fraction of events with good $D^0$ candidates passing the HLT $D^0$ triggers within a sample of events selected by a combination of minimum-bias and jet triggers.

Minimum-bias events were selected online using the information from the hadronic forward calorimeters (HF) and the beam pickup monitors (BPTX). Offline, events selected for analysis are required to have at least one reconstructed primary vertex, formed by at least two tracks, with a distance from the center of the nominal interaction region of less than 15 cm along the beam axis. In PbPb collisions, the offline analysis also requires a coincidence of at least one of the HF calorimeter towers (with more than 3 GeV of total energy) from each side of the interaction point. The event centrality in PbPb collisions is determined from the event-by-event total energy deposition in both HF calorimeters.

4 MC efficiency

Dedicated pp and PbPb $D^0$ MC samples are made to estimate the acceptance and selection efficiencies, to study the background components, and to evaluate systematic uncertainties. Inclusive QCD events are generated with PYTHIA using Tune CUETP8M1 [14, 15] and PYTHIA 8.202 TeV. Only events with at least one $D^0$ with $p_T > 10$ GeV/c and $|\eta| < 2.0$ were kept. For PbPb MC samples, selected PYTHIA events were embedded in generated HIJING PbPb events (version 1.8, tune “Drum”) [16]. Around forty thousand events were collected for each PYTHIA $p_T$ interval with boundaries of [0, 5, 10, 15, 30, 50, 80, 120, 170] GeV/c in both pp and PbPb samples.
state radiation (FSR) is simulated using PHOTOS [18]. The samples produced are inclusive D^0 samples, prompt D^0, and non-prompt D^0 (D^0 from B-hadron decay) samples.

5 D^0 reconstruction

D^0 candidates are reconstructed by combining pairs of oppositely charged particles and requiring an invariant mass within 0.2 GeV/c^2 of the nominal D^0 mass, as given by the particle data group (PDG) [19]. The tracks used in the D^0 reconstruction must fulfill kinematic and quality selections, with different track selections applied in the analysis of minimum-bias and D^0-triggered events, due to the specific selection criteria applied in HLT tracking sequences. In particular, in the high p_T PbPb analysis, a single track selection of p_{T\text{min}} = 8.5 GeV/c was applied in the offline analysis to account for the p_{T\text{min}} = 8 GeV/c track seed selection applied at HLT. For each pair of selected tracks, two D^0 candidates are created by assuming one of the particles has the mass of the pion while the other has the mass of the kaon, and vice-versa. Several topological cuts are applied in order to reduce the combinatorial background. In particular, the D^0 candidates are selected based on:

- two-dimensional (2D) decay length (d_0/\sigma(d_0)) normalised to its error,
- pointing angle, defined as the angle between the total momentum vector of the tracks with the vector connecting the primary and the secondary vertex,
- CL(\chi^2), defined as the \chi^2 confidence level of the D^0 vertex fit.

6 Signal extraction

The D^0-meson yields in each p_T interval are extracted by fitting the invariant mass distributions with a binned maximum-likelihood function. Two examples of D^0 candidate invariant mass distribution are shown in Fig. 1 for pp (left) and PbPb (right) collisions. The combinatorial background, generated by randomly combining pairs of tracks not originating from a D^0 meson decay, is modeled by a third order polynomial. The signal shape is modeled by two Gaussians with same mean but different widths. An additional Gaussian function is used to describe the invariant mass shape of D^0 candidates with incorrect mass assignment from the exchange of pion and kaon designation. The widths of the Gaussian functions that describe the D^0 signal shape and the shape of the D^0 candidates with swapped mass assignment are fixed according to MC simulations. Also the ratio between the yields of the signal and of the D^0 candidates with swapped mass assignment is fixed to the value extracted in simulations.

7 Systematic uncertainties

Systematic uncertainties on the cross-section arise from the signal extraction procedure, trigger and reconstruction efficiencies, branching fractions, and luminosity determination. The systematic uncertainty due to the selection of the D^0-meson candidate (varying in the range 0.5–3.6% for pp and 2.7–3.5% for PbPb depending on the D^0 p_T) is evaluated by considering the ratio of the selection efficiencies estimated in data and in MC. The uncertainty due to the signal extraction procedure (1.6–8.2% for pp and 1.3–9.4% for PbPb) is evaluated by varying the probability distribution functions used to fit the signal and the background distributions. The uncertainty due to the D^0 trigger efficiency is evaluated as the statistical uncertainty on the zeroth-order coefficient of the linear function used to model the efficiency turn on curve. The systematic uncertainty of the hadron tracking efficiency (4.0% for pp and 5.0% for PbPb) is esti-
estimated from a comparison of two-body and four-body D⁰ decays in data and simulated samples (using the method described in [20]). The systematic uncertainty on the prompt D⁰ fraction is estimated as the spread of prompt fraction values obtained with different methods. The first method, used for the determination of central values of the measurement, determines the D⁰ prompt fraction by fitting the distribution of the D⁰ decay length in the transverse plane with a prompt and non-prompt shape from Monte Carlo simulations. The second method uses an analogous fit procedure on the decay length normalised by its uncertainty. In the last method, the prompt fraction is obtained by using FONLL [5] predictions for prompt and non-prompt production convoluted with the acceptance and selection efficiency of prompt and non-prompt D⁰ candidates. The uncertainty related to the MC \( p_T \)-shape was evaluated by reweighting the MC D⁰ \( p_T \) distribution according to the \( p_T \)-shape obtained from D⁰ FONLL calculations. The total systematic uncertainty of the cross-section measurement in each transverse momentum interval is computed as the quadratic sum of the individual uncertainties. The global uncertainty on the proton-proton luminosity measurement is 12%. A global systematic uncertainty of 2% was assigned in the PbPb analysis to account for the uncertainty on the MB selection efficiency (0.99 ± 0.02). The uncertainty on the branching ratio of the D⁰ decay channel considered is 1.3% [19].

8 Results

8.1 \( p_T \)-differential cross section in pp at 5.02 TeV

The \( p_T \)-differential cross section in pp collisions is defined as:

\[
\left. \frac{d\sigma}{dp_T} \right|_{|y|<1.0} = \frac{1}{2} \frac{f_{\text{prompt}}}{\Delta p_T} \frac{N^{D^0}}{|y|<1.0} \left( \text{Acc} \times \epsilon \right)_{\text{prompt}} \cdot \text{BR} \cdot \alpha_{\text{prescale}} \cdot \epsilon_{\text{trigger}} \cdot \mathcal{L} .
\]

where \( \Delta p_T \) is the width of the \( p_T \) interval, BR is the branching ratio of the decay chain, \( \mathcal{L}=25.8/\text{pb} \) is the integrated luminosity, \( \left( \text{Acc} \times \epsilon \right)_{\text{prompt}} \) represents the acceptance times efficiency correction and \( N^{D^0}_{|y|<1.0} \) are the yields extracted in each \( p_T \) interval. The factor 1/2 accounts for the

Figure 1: Examples of D⁰ candidate invariant mass distribution in pp (left) and PbPb collisions (right) at 5.02 TeV.
fact that the yields were measured for particles and antiparticles, but the cross section is given for particles only. The factor \( f_{prompt} \) is the fraction of prompt \( D^0 \) that was estimated in data as described in the previous section. The raw yields \( N_{[y]<1.0}^{D^0} \) are corrected in order to account for the average prescale factor \( \alpha_{\text{prescale}} \) and the efficiency \( \epsilon_{\text{trigger}} \) of the trigger that was used to select events in that specific \( p_T \) interval. In Fig. 2, the \( p_T \)-differential cross section of \( D^0 \) mesons at central rapidity (\( |y| < 1 \)) is presented for \( pp \) collisions at \( \sqrt{s} = 5.02 \) TeV. Statistical uncertainties are plotted as vertical bars while the boxes around the data points represent the total systematic uncertainties. The FONLL [5] prediction at the same energy is superimposed. The ratio of the data to the FONLL prediction is also shown. The CMS measurement lies in the upper bound of the FONLL prediction.

\[
\frac{1}{T_{AA}} \frac{dN_{D^0}^{p}}{dp_T} \bigg|_{|y|<1.0} = \frac{1}{T_{AA}} \frac{1}{2} f_{prompt} \frac{N_{D^0}^{p}}{|y|<1.0} \Delta p_T (\text{Acc} \times \epsilon) \cdot \text{BR} \cdot N_{\text{events}} \cdot \alpha_{\text{prescale}} \cdot \epsilon_{\text{trigger}}.
\]

(2)

where \( N_{\text{events}} \) are the number of MB events analysed. The nuclear modification factor \( R_{AA} \) is then defined as:

\[
R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN_{D^0}^{p}}{dp_T} / \frac{d\sigma_{pp}^{D^0}}{dp_T}.
\]

(3)

where \( T_{AA} \) is the nuclear overlap function (\( T_{AA}=5.58/\text{mb} \) for inclusive PbPb collisions and \( T_{AA}=23.2/\text{mb} \) for events in the centrality interval 0-10%) [31]. In Fig. 3 (left), the nuclear modification factor in the centrality range 0-100% is shown as a function of \( p_T \). The \( R_{AA} \) shows a suppression of a factor 4 to 5 at \( p_T \) of 6-7 GeV/c. At higher \( p_T \), the suppression decreases to a

Figure 2: \( p_T \)-differential cross section of prompt \( D^0 \) mesons in \( pp \) collisions at \( \sqrt{s} = 5.02 \) TeV compared to the FONLL predictions [5].

8.2 Nuclear modification factors in PbPb collisions

The \( dN/dp_T \) in PbPb collisions is defined as:

\[
\frac{1}{T_{AA}} \frac{dN_{D^0}^{p}}{dp_T} \bigg|_{|y|<1.0} = \frac{1}{T_{AA}} \frac{1}{2} f_{prompt} \frac{N_{D^0}^{p}}{|y|<1.0} \Delta p_T (\text{Acc} \times \epsilon) \cdot \text{BR} \cdot N_{\text{events}} \cdot \alpha_{\text{prescale}} \cdot \epsilon_{\text{trigger}}.
\]
value of about 1.5 in $p_T$ range 60-100 GeV/c. In the same plot, the inclusive charged particle $R_{AA}$ result is superimposed for an equivalent event selection [21]. Within the current uncertainties, the two results are consistent. In the right panel of Fig. 3, the same result is presented for the centrality range 0-10%. In this centrality range, the $D^0$ nuclear modification factor remains compatible with the inclusive charged hadron $R_{AA}$. The results are also compared to various theoretical calculations [22–30].

9 Conclusions

In this note, measurements of the prompt $D^0$ production cross section and nuclear modification factor $R_{AA}$ in pp and PbPb collisions in the central rapidity region ($|y| < 1$) at $\sqrt{s_{NN}} = 5.02$ TeV from CMS are presented. The $R_{AA}$ of prompt $D^0$ mesons is measured as a function of the $D^0$ transverse momentum from 2 to 100 GeV/c in two centrality ranges. The $D^0$ $R_{AA}$ is found to be strongly suppressed in PbPb collisions when compared to the measured pp reference scaled by the number of binary nucleon-nucleon collisions. These measurements are consistent with the nuclear modification factors of charged hadrons in the corresponding centrality ranges.
References


[6] CMS Collaboration, “Prompt and non-prompt $J/\psi R_{AA}$ with 150 $\mu b^{-1}$ integrated PbPb luminosity at $\sqrt{s_{NN}} = 2.76$ TeV”, *CMS PAS HIN-12-014* (2012).


