PROCEEDINGS OF SCIENCE

# Studies of beauty suppression via nonprompt $D^0$ mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the CMS detector

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The transverse momentum spectra of $D^0$ mesons from b hadron decays are measured at midrapidity ($|y| < 1$) in pp and PbPb collisions at a nucleon–nucleon center of mass energy of 5.02 TeV with the CMS detector at the LHC. The $D^0$ mesons from b hadron decays are distinguished from prompt $D^0$ mesons by their decay topologies. In PbPb collisions, the $B \to D^0$ yield is found to be suppressed in the measured $p_T$ range from 2 to 100 GeV/$c$ as compared to pp collisions. The suppression is weaker than that of prompt $D^0$ mesons and charged hadrons for $p_T$ around 10 GeV/$c$. While theoretical calculations incorporating partonic energy loss in the quark-gluon plasma can successfully describe the measured $B \to D^0$ suppression at higher $p_T$, the data show an indication of larger suppression than the model predictions in the range of $2 < p_T < 5$ GeV/$c$.

*International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions*
*30 September - 5 October 2018*
*Aix-Les-Bains, Savoie, France*

*Speaker.





PoS(HardProbes2018)146

## 1. Introduction

Quantum chromodynamics (QCD) predicts the existence of a quark-gluon plasma (QGP) phase, consisting of deconfined quarks and gluons, at extremely high temperatures and/or densities. Experiments at the BNL RHIC and the CERN LHC indicate that a strongly coupled QGP is created in relativistic heavy ion collisions. Heavy quarks (charm and beauty) produced in heavy ion collisions are valuable probes for studying the properties of QGP. They are mostly produced in primary hard QCD scatterings at an early stage of the collision. During their propagation through the QGP, heavy quarks lose energy via radiative and collisional interactions with the medium constituents. Parton energy loss can be studied using the nuclear modification factor ($R_{AA}$), which is defined as the ratio of the particle yield in nucleus–nucleus (AA) to that in proton–proton (pp) collisions, normalized by the number of binary nucleon–nucleon collisions ($N_{\mathrm{coll}}$). Precise measurements of $R_{AA}$ for particles containing light, charm, and beauty quarks over a wide $p_T$ range can test the predicted flavor (parton mass) and energy dependence of the parton energy loss in the QGP. This can provide both important tests of QCD at extreme densities and temperatures, and constraints on theoretical models describing the system evolution in heavy ion collisions. In this report, we report a study of beauty production and in-medium energy loss performed by measuring nonprompt $D^0$ $p_T$ spectra in pp and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the CMS detector [1].

## 2. Analysis procedure

The $D^0$ and $\overline{D}^0$ mesons are reconstructed via the hadronic decay channel $D^0 \to K^-\pi^+$. Each $D^0$ daughter track is required to pass a high purity selection based on a multi-variate analysis of track quality variables. Tracks are required to have $|\eta| < 1.5$ and $p_T$ larger than 1 GeV/$c$ for the pp and PbPb minimum-bias data, and 2 and 8.5 GeV/$c$ for pp and PbPb $D^0$-triggered samples, respectively. For each pair of selected tracks, two $D^0$ candidates are created by assuming that one of the particles has the pion mass and the other has the kaon mass, and vice-versa. The $D^0$ candidates are required to have $|y| < 1$, where the track resolution is better. In order to reduce the combinatorial background and prompt $D^0$ contribution, the $D^0$ candidates are selected based on several geometrical criteria: a minimum probability that the two tracks come from a common decay vertex, a minimum distance between the decay vertex and the primary vertex (PV, the reconstructed collision point) divided by its uncertainty, and minimum distances of closest approach (DCA) to the PV for the pion and kaon tracks divided by their uncertainties. The selection is optimized for maximum statistical significance of the $B \to D^0$ (i.e., $D^0$ mesons from b hadron decays) yield.

The $B \to D^0$ decays are distinguished from prompt $D^0$ mesons by fitting the distribution of DCA between the $D^0$ path and the PV. The signal $D^0$ DCA distribution, including both the prompt and nonprompt components, is extracted by two methods. For $p_T$ bins in which there is abundant background ($D^0$ $p_T <$ 20 GeV/$c$ for PbPb), the $D^0$ meson yield in each $D^0$ DCA bin is obtained from an invariant mass fit with three components: a double-Gaussian function describing the signal, a broad Gaussian function describing $K$–$\pi$ swapped pairs, and a third-order polynomial component for the combinatorial background. Figure 1a shows an example of a three-component invariant mass fit for a selected $D^0$ DCA and $p_T$ bin. For the pp data and for $D^0$ candidates with $p_T >$ 20 GeV/$c$ from PbPb events, for which the background is low, a sideband subtraction method is used to

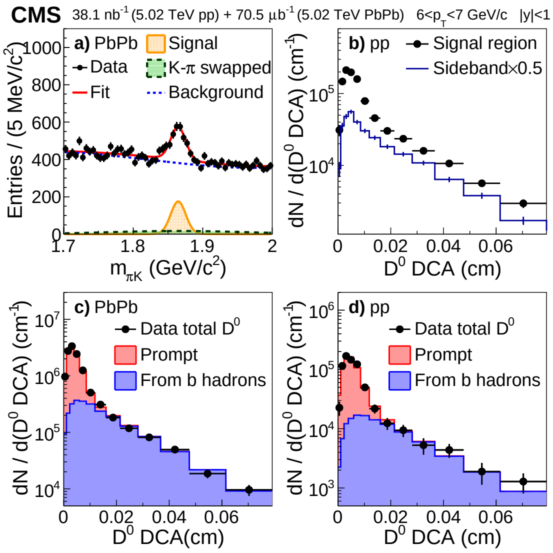


**Figure 1:** a) Example of a three-component invariant mass fit of a $D^0$ DCA bin for $p_T$ of 6–7 GeV/$c$ in PbPb collisions; b) DCA distributions for $D^0$ candidates in the signal invariant mass region and in the sidebands (scaled by the mass range ratio of 0.5) for $D^0$ $p_T$ of 6–7 GeV/$c$ in pp collisions; c) Signal DCA distribution obtained with the invariant mass fit for each DCA bin, and a prompt+nonprompt two-component fit to it, for $D^0$ $p_T$ of 6–7 GeV/$c$ in PbPb collisions; d) Signal DCA distribution obtained with the sideband subtraction, and a prompt+nonprompt two-component fit to it, for $D^0$ $p_T$ of 6–7 GeV/c in pp collisions [2].

obtain the signal $D^0$ DCA distribution. Figure 1b shows the DCA distributions for $D^0$ candidates in the signal invariant mass region ($|m_{\rm rec} - m_{\rm D^0}| < 0.025$ GeV/$c^2$) and for candidates in the sidebands ($0.05 < |m_{\rm rec} - m_{\rm D^0}| < 0.1$ GeV/$c^2$). The latter is scaled by the mass range ratio of 0.5, in order to estimate the background yield in the narrower signal region. Here $m_{\rm rec}$ is the reconstructed $K$–$\pi$ invariant mass and $m_{\rm D^0}$ is the nominal $D^0$ mass, 1.8648 GeV/$c^2$. The signal $D^0$ DCA distribution is calculated as the difference of the $D^0$ DCA distributions in the signal region and the sidebands.

In order to obtain the $B \to D^0$ yield, a two-component fit to the signal $D^0$ DCA distribution is carried out using prompt and nonprompt $D^0$ DCA templates obtained from Monte Carlo simulations, as shown in Fig. 1c and 1d. The prompt $D^0$ mesons have a narrow DCA distribution, with the width purely from the detector resolution, while the nonprompt $D^0$ DCA distribution is much wider because of the kink between the b hadron and $D^0$ meson directions.

## 3. Results

In Fig. 2, the $B \to D^0$ $p_T$-differential cross section in pp collisions and the invariant yield in PbPb collisions normalized with $T_{\rm AA} = N_{coll}/\sigma_{NN}^{inelastic}$ are presented. The plot also shows the nonprompt $D^0$ $p_T$ spectra found by decaying a $B$ meson $p_T$ spectrum from FONLL [3] pQCD calculation. The ratio of the measured pp spectrum over the FONLL prediction is shown in the bottom panel. The measured pp spectrum lies close to the upper limit of the FONLL prediction.

Figure 3 shows the $B \to D^0$ nuclear modification factor $R_{AA}$. It can be seen that the $B \to D^0$ $R_{AA}$ is below unity in the measured $p_T$ range from 2 to 100 GeV/$c$. In the upper panel, the $B \to D^0$ $R_{AA}$ is

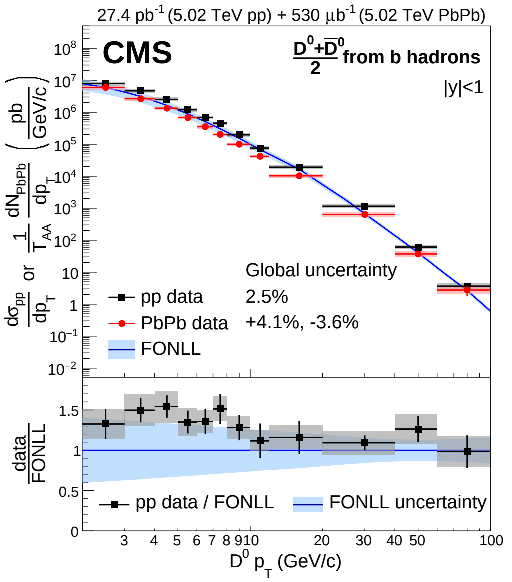


**Figure 2:** Upper panel: $B \to D^0$ $p_T$-differential cross section in pp collisions and invariant yield in PbPb collisions normalized with $T_{AA}$, at $\sqrt{s_{NN}} = 5.02$ TeV [2]. The vertical bands around the data points represent the bin-by-bin systematic uncertainties. Uncertainties are smaller than the symbols in most cases. The cross section in pp collisions is compared to FONLL [3] calculations. Lower panel: The data/FONLL ratio for the $B \to D^0$ $p_T$ spectra in pp collisions.

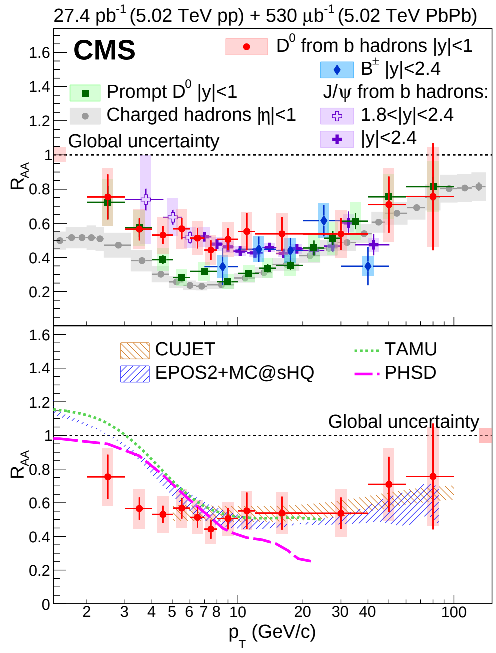


**Figure 3:** The $B \to D^0$ nuclear modification factor $R_{AA}$ for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (red circles) [2] compared to other particles [4, 5, 6, 7] (upper panel), and to various theoretical predictions [8, 9, 10, 11] (lower panel). The vertical bands around the data points and at unity represent the bin-by-bin and global systematic uncertainties, respectively.

compared with the $R_{AA}$ of $B$ mesons [4], nonprompt $J/\psi$ mesons from b hadron decays [5], prompt $D^0$ mesons [6], and charged hadrons [7]. The $B \to D^0$ $R_{AA}$ is consistent with the $B$ meson and nonprompt $J/\psi$ meson results, and extends the reach of b quark related $R_{AA}$ studies to a larger $p_T$ coverage at midrapidity. The $B \to D^0$ yield is less suppressed than prompt $D^0$ mesons and charged hadrons with $p_T$ around 10 GeV/$c$. This may reflect a dependence of the suppression effects on the quark mass, although a direct comparison requires a full modeling of the quark initial spectrum and hadronization, as well as of the decay kinematics.

In the lower panel of Fig. 3, the measured $B \to D^0$ $R_{AA}$ is compared with various theoretical predictions [8, 9, 10, 11]. At higher $p_T$, the CUJET, EPOS2+MC@sHQ and TAMU models all match the data well. However, at $p_T$ below 5 GeV/$c$, our measurements show a hint of stronger suppression than predicted by all available models. This could indicate a stronger energy loss of b quarks in QGP than predicted at low $p_T$, where collisional parton energy loss begins to dominate. It could also be due to other effects. For example, the fraction of b baryons out of all b hadrons may be enhanced at low $p_T$ in PbPb collisions, because b quarks can hadronize by coalescing with light quarks in the medium [12]. Given the much lower decay fractions of b baryons$\to D^0$ with respect to the $B^{\pm} \to D^0$ and $B^0 \to D^0$ cases, fewer b hadrons are seen in this analysis than expected by the models. This baryon enhancement effect is not accounted for by the models considered.

## 4. Summary

In summary, this report presents the $B \to D^0$ $p_T$ spectra in pp and PbPb collisions at 5.02 TeV with the CMS detector. The $D^0$ mesons from b hadron decays are distinguished from the prompt $D^0$ mesons by the DCA of the $D^0$ path relative to the PV. The measured spectrum in pp collisions is close to the upper limit of a FONLL calculation. In PbPb collisions, the $B \to D^0$ nuclear modification factor $R_{AA}$ is higher than for prompt $D^0$ mesons and charged hadrons around 10 GeV/$c$, which is in line with a quark mass ordering of suppression. Compared to theoretical predictions, the measured $R_{AA}$ is consistent with some models at higher $p_T$, but shows a hint of stronger suppression than all of the available models at low $p_T$. This could indicate a stronger energy loss of b quarks in the quark-gluon plasma than predicted at low $p_T$, or could reflect an enhanced b baryon production due to quark coalescence in PbPb collisions.

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