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Probing heavy quark dynamics in PbPb collisions with CMS

Gábor I. Veres* **on behalf of the CMS Collaboration**
Eötvös Loránd University, Budapest
E-mail: vg@ludens.elte.hu

Measurements of heavy flavor hadrons in PbPb collisions provide information about the heavy quark dynamics inside the quark-gluon plasma (QGP). Heavy quarks are sensitive to the transport properties of the medium and may interact with the QCD matter differently from light quarks. At low p_T, heavy quarks provide a direct window on the in-medium QCD force. At high p_T, the comparison of results for light and heavy particles provides insights into the expected flavor dependence of in-medium parton energy loss. Recently, the CMS collaboration established a comprehensive heavy flavor program in heavy ion collisions including the detection of charm and beauty mesons. Using the large statistics heavy ion data samples collected during the LHC Run 2, high precision open charm and beauty measurements are performed over a wide transverse momentum range. In this contribution, the first measurements of the radial distributions of D^0 mesons in jets in PbPb and pp collisions are presented, sensitive to the energy loss and diffusion of charm quarks in the QGP. Such effects for the bottom quarks are probed with the measurement of D_0 mesons from b-hadron decays in pp and PbPb collisions. In addition, the hadronisation of charm quarks and the importance of coalescence are constrained with the study of Λ_c baryons in pp and PbPb collisions. Finally, results on D_s and B_s production are reported and compared to D^0 and B^+ production, respectively, with implications on the importance of the recombination mechanism due to strangeness enhancement.

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*Speaker.

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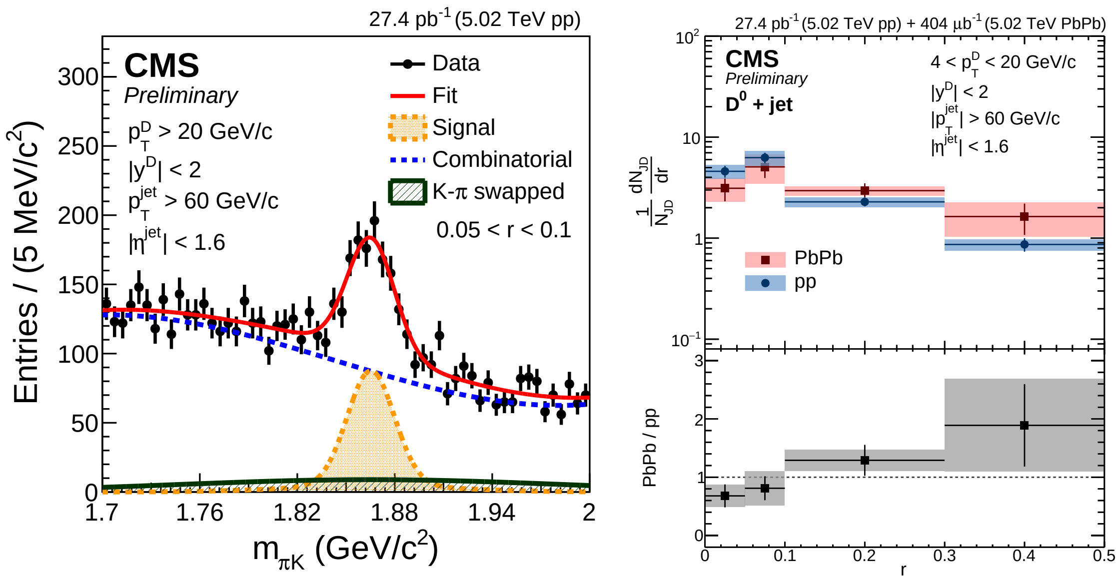

Figure 1: Left: Examples of D^0 candidate invariant mass distributions in the range $0.05 < r < 0.1$ in pp collisions at 5.02 TeV, where r is the angular distance between D^0 mesons and jets. Right: Distributions of D^0 mesons in jets as a function of the distance from the jet axis for $4 < p_T < 20$ GeV/c measured in pp (blue) and PbPb (red) collisions at 5.02 TeV. The ratio of the D^0 radial distributions of PbPb to pp are also presented in the lower panel [2].

1. Introduction

The dynamics of heavy quarks inside the quark-gluon plasma created in ultra-relativistic heavy ion collisions is of particular interest for various reasons. The transport properties of the strongly interacting medium can be tested by studying phenomena related to heavy quarks, which are predicted and also observed to interact with the QCD matter differently compared to light quarks.

The second data taking period, Run 2, of the Large Hadron Collider (LHC) has provided a high integrated luminosity of PbPb collisions, enabling the LHC experiments to collect data sets with high statistics and to open up a detailed research program on charm and beauty mesons.

In the following contribution a few recent results from the CMS Collaboration [1] are presented. The radial distribution of D^0 mesons within jets is measured, sensitive to energy loss and diffusion of heavy flavor. The B_s meson production is also studied and employed as a test of recombination and strangeness enhancement in the hot and dense plasma. The high statistics data also allow us to perform measurements on the b-hadron decays to D^0 mesons to constrain the energy loss of b quarks in the medium, and an analysis of Λ_c baryon production, related to c quark hadronisation.

2. Radial profile of D^0 mesons in jets

The CMS Collaboration has analyzed the radial distribution of D^0 mesons in jets [2]. The D^0 mesons were reconstructed from the $D^0 \to K^{\pm}\pi^{\pm}$ decay. The D^0 yield was obtained from a fit to

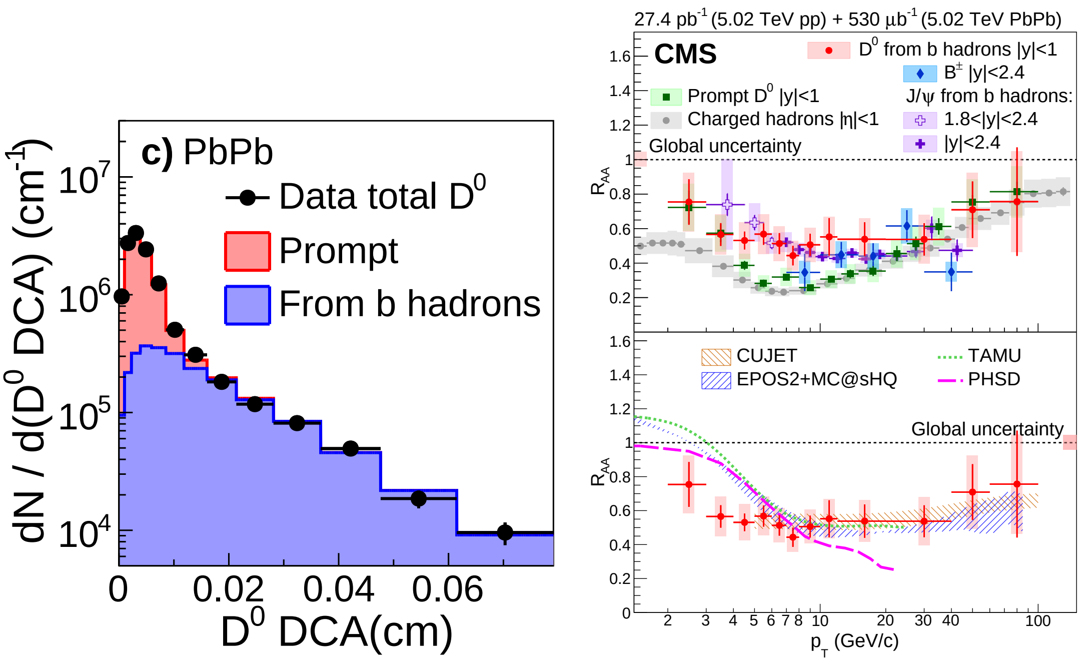

Figure 2: Left: signal DCA distribution obtained with the invariant mass fit for each DCA bin, and a prompt+nonprompt two-component fit to it, for D^0 p_T of 6-7 GeV/c in PbPb collisions. Right: the $B \to D^0$ nuclear modification factor R_{AA} for PbPb collisions at 5.02 TeV (red circles) compared to other particles (upper panel), and to various theoretical predictions (lower panel). The vertical bands around the data points and at unity represent the bin-by-bin and global systematic uncertainties, respectively [4].

the πK mass distribution as shown on the left panel of Fig. 1, and the number of jet-D^0 pairs was measured as a function of radial distance, r, from the jet axis.

The measurement was done for pp and PbPb collisions at 5.02 TeV center-of-mass energy per nucleon pair for direct comparison. The results indicate a possible redistribution of the D^0 mesons in heavy ion collisions in the vicinity of the jet axis, compared to pp collisions, for low-momentum mesons (in the $4 < p_T^D < 20$ GeV/c range) as shown on the right panel of Fig. 1, while no such conclusion can be drawn from the data for $p_T^D > 20$ GeV/c. The results provide constraints on the parton energy loss in the QCD medium, and on the diffusion of heavy quarks. Theoretical calculations based on the SHERPA model provide a good description of the experimental data.

A related measurement of J/ψ meson production in pp collisions in jets was also completed by CMS recently [3]. Prompt and non-prompt J/ψ mesons were reconstructed separately. Prompt J/ψ mesons were observed to carry a smaller fraction of the jet momentum than predicted from models; the data show a qualitatively different trend compared to the PYTHIA8 event generator.

3. Beauty suppression: D^0 mesons from b-hadron decays

Decays of hadrons carrying a beauty quark have been identified in pp and PbPb collisions based on their decay topology and the distance of closest approach (DCA) to the primary vertex [4]. The yield of D^0 mesons was extracted from a fit to the πK mass peak in DCA bins in PbPb collisions, and from a simple subtraction of mass-sidebands in pp collisions. The DCA distribution

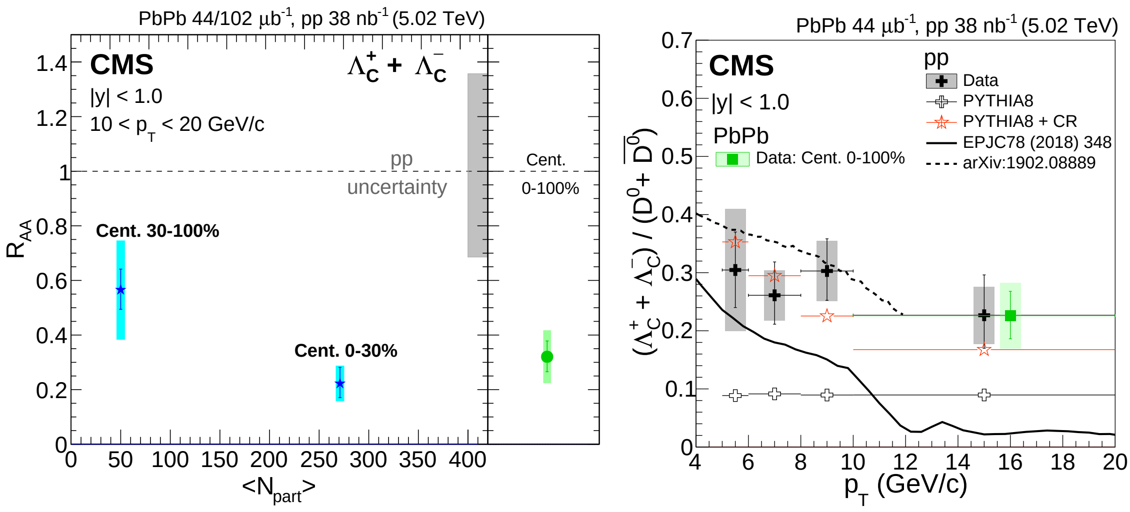

Figure 3: Left: the nuclear modification factor R_{AA} of charged Λ_c baryons versus $\langle N_{part} \rangle$. The box at unity indicates the total uncertainty in the pp differential cross section, which is common to all three R_{AA} values. Right: the Λ_c^+/D^0 production cross section ratio versus p_T from pp collisions as well as minimum bias PbPb collisions. The boxes and error bars represent the systematic and statistical uncertainties, respectively. The open crosses and open stars represent the predictions of PYTHIA 8 with the CUETP8M1 tune and with color reconnection, respectively. All predictions are for pp collisions [5].

of D^0 mesons can then be fitted with a sum of simulated templates for prompt and non-prompt D^0 mesons, as shown on the left panel of Fig. 2. The measured p_T distribution of D^0 mesons coming from decays of b-hadrons produced in pp collisions was compared to FONNL calculations, and it was found that the data is close to the upper limit of the uncertainty band on the theoretical results.

The nuclear modification factors can then be calculated by the scaled ratio of the non-prompt D^0 meson p_T distributions in PbPb and pp collisions. The comparison to other measurements show that the suppression of the non-prompt D^0 mesons is weaker than that of prompt D^0 mesons and that of charged hadrons in the moderate p_T range (around 10 GeV/c), as presented on the right panel of Fig. 2. Theoretical models give an accurate description of this suppression at high p_T, but underestimate it at low momenta. The possible reason for the latter may be a stronger than predicted b-quark energy loss, or alternatively, enhanced b-baryon production due to quark coalescence, leading to a deficit in the production of mesons carrying a b quark.

4. Λ_c^+(udc) baryon production in pp and PbPb collisions

Since baryon production is more sensitive to coalescence than meson production, it is also important to study strange and charmed baryons experimentally. For example, coalescence models predict that the $\Lambda_c^+(\mathrm{udc})/D^0$ ratio will be enhanced in heavy ion collisions with respect to pp.

The CMS Collaboration has used the decay channel $\Lambda_c^+ \rightarrow pK^-\pi^+$ to reconstruct the Λ_c^+ baryon in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV [5]. The measurement in heavy ion collisions was only performed for one p_T bin, $10 < p_T < 20$ GeV/c. The p_T distribution of Λ_c^+ in pp collisions was compared to PYTHIA8, which describes the shape of the experimental spectrum well, but slightly underestimates it. The nuclear modification factor for the Λ_c^+ baryon was measured in

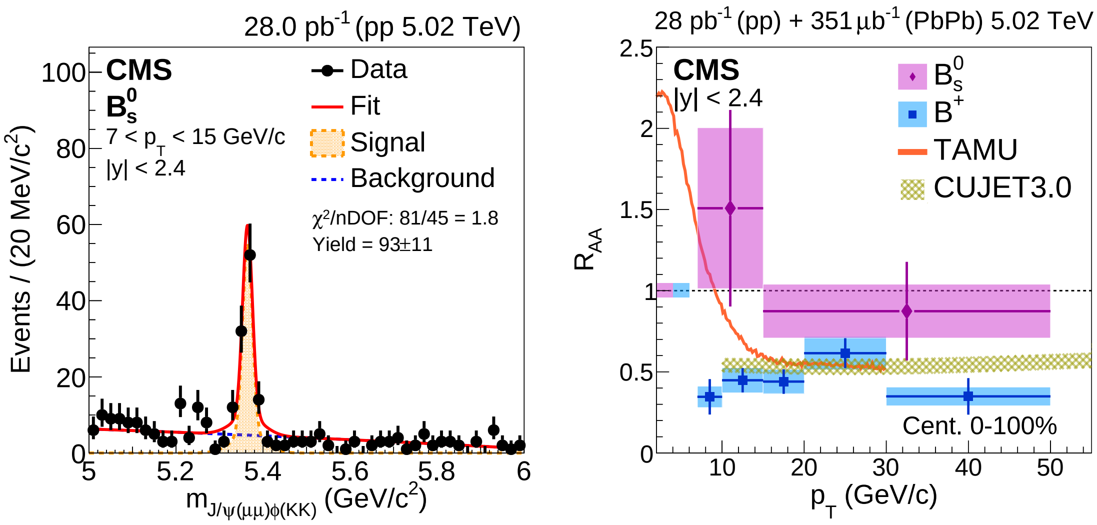

Figure 4: Left: invariant mass distributions of B_s^0 candidates in pp collisions measured in the range $|y| < 2.4$ and in the p_T range of 7-15 GeV/c. Right: the nuclear modification factor R_{AA} of B_s^0 measured in PbPb collisions at 5.02 TeV from 7 to 50 GeV/c. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The B^+ R_{AA} measurement is also shown for comparison. The global systematic uncertainty, represented by colored boxes at $R_{AA} = 1$, comprises the uncertainties in the integrated luminosity measurement and T_{AA} value. Two theoretical calculations are also shown for comparison: TAMU and CUJET3.0 [8].

central (0-30% centrality) and peripheral (30-100% centrality) PbPb collisions as well. The data indicate a possible suppression in PbPb collisions compared to pp, perhaps as a consequence of the interaction between the c quark and the quark-gluon plasma. The suppression is observed to be stronger in central collisions, as shown on the left panel of Fig. 3.

The Λ_c^+/D^0 ratio was also evaluated, and found to be consistent between pp and PbPb collisions, as opposed to the expectations from the coalescence phenomenon, as presented on the right panel of Fig. 3. It is also interesting to note that the p_T-dependence of the Λ_c^+/D^0 ratio in pp collisions is only described by the PYTHIA8 event generator if the color reconnection is included in the model. Calculations taking into account feed-down from heavier charmed hadrons [6] and a model based on coalescence and fragmentation [7] also gives a fair description of the pp data at low p_T, but the latter severely under-predicts the measured Λ_c^+/D^0 ratio at high p_T.

5. B_s meson production in pp and PbPb collisions

In order to test the properties of the deconfined medium created in heavy ion collisions, and to study the possible beauty-strangeness coalescence at low p_T, the production of B_s mesons was also measured at $\sqrt{s_{\rm NN}}$ =5.02 TeV in pp and PbPb collisions [8]. The decay channel $B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$ was used to reconstruct the B_s^0 meson, as shown on the left panel of Fig. 4.

The measured p_T distribution of B_s^0 mesons agrees very well with the predictions from FONLL in pp collisions. The nuclear modification factor of B_s^0 was measured in two p_T regions, and found to be 1.5 ± 0.6 (stat)$\pm$0.5 (syst) for $7 < p_T < 15$ GeV/c and 0.87 ± 0.30 (stat)$\pm$0.17 (syst) for $15 < p_T < 50$ GeV/c, as presented on the right panel of Fig. 4. On the other hand, previous measurements have shown that charged B^+ mesons are significantly suppressed in PbPb collisions compared to pp collisions, with nuclear modification factors around 0.5. One can then construct the ratio of the nuclear modification factors measured for the B_s^0 and B^+ mesons, which possibly indicates an enhancement at low p_T. The data is consistent with models of strangeness enhancement and a suppression as observed for B^+ mesons. The new data set collected in late 2018 and the heavy ion data taking periods of the High-Luminosity LHC will certainly be able to provide further tests on recombination, b-hadron production and the hadronisation of b quarks.

6. Summary

To summarize, the CMS Collaboration has a versatile heavy flavor program in heavy ion collisions, and besides quarkonium states, observables related to open charm and beauty are also studied. These measurements are often limited by statistics, therefore the third long data taking period of the LHC will improve the experimental uncertainties significantly.

A wealth of interesting results is already available from CMS on heavy flavor dynamics. The redistribution of the D^0 mesons within jets was observed for the first time in PbPb collisions. It was also found that J/ψ mesons in jets in pp collisions are much softer than model predictions. The measurement of D^0 mesons from b-hadron decays revealed a strong b-quark energy loss at low p_T. The Λ_c^+ baryons are suppressed in (central) PbPb collisions, and the coalescence model is not able to describe the results. The nuclear modification factor of B_s^0 mesons is consistent with unity, and the precision of the measured B_s^0/B^+ ratio, which is sensitive to coalescence, will greatly benefit from data taking at higher luminosities.

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