Beauty production in heavy-ion collisions with ALICE at the LHC*

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In this contribution, the final measurements of the centrality dependence of the nuclear modification factor ($R_{\text{AA}}$) of non-prompt $D^0$ in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV will be presented. These measurements provide important constraints to the mass dependence of in-medium energy loss and hadronisation of the beauty quark. The $p_T$-integrated non-prompt $D^0$ $R_{\text{AA}}$ will be presented for the first time and will be compared to the prompt $D^0$ one. This comparison will shed light on possible different shadowing effects between charm and beauty quarks. In addition, the first measurements of non-prompt $D^+_s$ production in central and semi-central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV will be discussed. The non-prompt $D^+_s$ measurements provide additional information on the hadronisation of beauty quarks and the production yield of $B^0_s$ mesons. Finally, the first measurement of non-prompt D-meson elliptic flow in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV will also be discussed. These measurements can constrain the degree of thermalisation of beauty quarks in the hot and dense QCD medium.

1. Introduction

Heavy quarks (charm and beauty) are produced in hard-scattering processes over short time scales compared to the quark–gluon plasma (QGP). They probe the whole system evolution interacting with the medium constituents. In particular, because of the larger mass, beauty quarks are expected to lose less energy \cite{1,2} and diffuse less than the charm quarks \cite{3,4}. Therefore, the comparison between charm and beauty nuclear modification factor ($R_{\text{AA}}$) and elliptic flow ($v_2$) provides insight into the quark mass-dependent of energy loss, heavy-quark diffusion properties.

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The D mesons from beauty-hadron decays (non-prompt D) are excellent probes for beauty properties currently. Existing data on the production of B mesons [5], and J/ψ from beauty decays [6, 7, 8] at midrapidity are limited by large uncertainties, while the broad correlation between the transverse momenta ($p_T$) of the lepton and the parent beauty hadron reduces the effectiveness of beauty-decay lepton measurements [9, 10].

In these proceedings, the measurement of open-beauty production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from ALICE at midrapidity is reported.

2. D-meson reconstruction

The non-prompt D mesons are reconstructed via their hadronic decay channels $D^0 \rightarrow K^-\pi^+$, and $D_s^+ \rightarrow \pi^+\phi \rightarrow \pi^+K^+K^-$. A multi-classification BDT algorithm [11], trained using variables sensitive to the decay topology and particle identification, is utilised to simultaneously increase the non-prompt ($b \rightarrow D$) fraction and suppress the combinatorial background. After extracting the yield via an invariant mass analysis, the $b \rightarrow D$ fraction is estimated by a $\chi^2$-minimisation approach based on variation of ML-based selections [11]. The measurement of the non-prompt $D^0\n2$ is performed with the scalar-product (SP) method [12]. In order to obtain non-prompt $D^0\n2(v_{2}^{\text{non-prompt}})$, a linear fit of $v_{2}^{\text{sum}}$ is performed as a function of $b \rightarrow D$ fraction, and extrapolates to $f_{\text{non-prompt}} = 1$, as described in [13].

3. Results

The left panel of Fig. 1 shows the $R_{AA}$ of non-prompt $D^0$ mesons [14] measured in the 0–10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The result is compared with the prompt $D^0$-meson $R_{AA}$ [15]. The non-prompt $D^0$-meson $R_{AA}$ is significantly higher than the prompt $D^0$ one for $p_T > 5$ GeV/c, indicating that non-prompt $D^0$ mesons are less suppressed than prompt $D^0$ mesons, and supporting the expectation that beauty quarks lose less energy than charm quarks because of their larger mass. An extrapolation of the measured spectrum is performed. The resulting non-prompt $D^0$-meson $R_{AA}$ for $p_T > 0$ is $1.00 \pm 0.10$ (stat.) $\pm 0.13$ (syst.) $^{+0.08}_{-0.09}$ (extr.) $\pm 0.02$ (norm.) [14] in the 0–10% centrality class, which is compatible with unity within uncertainties, and larger than the prompt one [15] within less than 1.5$\sigma$.

The non-prompt to prompt $D^0$-meson $R_{AA}$ ratio as a function of $p_T$ in the 0–10% central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is presented in the right panel of Fig. 1. The ratio can be described well by model predictions [16, 17, 18, 19, 20] that include collisional and radiative processes
Fig. 1. Left panel: the $R_{AA}$ of non-prompt $D^0$ mesons [14] in the centrality classes 0–10%, compared with the $R_{AA}$ of prompt $D^0$ mesons [15]. Right panel: non-prompt to prompt $D^0$-meson $R_{AA}$ ratio as a function of $p_T$ in the 0–10% central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to model predictions [16] (top), and to different modifications of LGR calculations [17, 18] (bottom).

In order to further understand the data pattern at low $p_T$ and the enhancement with respect to unity at high $p_T$ for the data, the ratio is compared with different LGR model [17, 18] calculations (bottom panel), highlighting the role of coalescence, shadowing, and mass dependence of energy loss. The LGR model suggests that the “valley” structure at low $p_T$ is mainly due to the formation of prompt D mesons via charm-quark coalescence (case iv), and the significant enhancement of the ratio at high $p_T$ is interpreted as the effect of the mass dependence of the in-medium energy loss (case i).

The $R_{AA}$ of non-prompt $D^+_s$ mesons divided by that of prompt $D^+_s$ mesons [22] (left panel) and non-prompt $D^0$ mesons [14] (right panel) are shown in Fig. 2. In the 0–10% centrality class, a hint that both ratios are larger than unity in the $4 < p_T < 12$ GeV/c interval is presented, suggesting an enhancement of non-prompt $D^+_s$ in this interval. The trend can be explained by the interplay of mass dependence of energy loss and recombination in the QGP medium. The ratios are compatible with unity within uncertainties. The TAMU predictions [19] qualitatively describe the results for central collisions. For semicentral collisions the TAMU model overestimates the $R_{AA}$ ratio values.

Figure 3 shows the first measurement of non-prompt $D^0$ $v_2$ in 30–50% Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to the average $v_2$ of prompt D mesons [23] (left panel), and to model predictions [17, 24] (right panel). The non-prompt $D^0$ $v_2$ is found to be positive with 2.7 $\sigma$
Fig. 2. The $R_{AA}$ of non-prompt $D^{+}$ mesons $[21]$ divided by the one of prompt $D^{+}$ mesons $[22]$ (left panel) and non-prompt $D^{0}$ mesons $[14]$ (right panel) for the 0–10% and 30–50% centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The measurements are compared with TAMU model predictions $[19]$.

Fig. 3. The non-prompt $D^{0}$ $v_2$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 30–50% centrality class, compared to that of prompt average non-strange D mesons $[23]$ (left panel), and to the model predictions $[17, 24, 25, 19, 26, 27]$ (right panel).

The significance for the difference between non-prompt $D^{0}$ $v_2$ and that of prompt average non-strange D mesons is 3.2 $\sigma$ for $2 < p_T < 8$ GeV/c, indicating a different degree of participation to collective motion between charm and beauty quarks. Theoretical predictions $[17, 24, 25, 19, 26, 27]$ based on beauty-quark transport in
an hydrodynamical expanding medium can fairly describe the data within uncertainties. Future measurements with higher accuracy will provide important constraints to the models, and allow for accurate extraction of the spatial diffusion coefficient with beauty quarks.

4. Conclusion

In this contribution, the most recent results on the production and azimuthal anisotropy of non-prompt D mesons, measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, were presented. The non-prompt $D^0 R_{AA}$ provides an essential constraint on the mass dependence of energy loss in the medium. The non-prompt $D^{+} R_{AA}$ helps to further understand beauty-quark hadronisation in heavy-ion collisions. The first measurement of non-prompt $D^0$-meson $v_2$ indicates a different degree of participation in the collective motion between charm and beauty quarks. With the LHC Run3, the upgraded ITS and the increased integrated luminosity will allow for more precise beauty-hadron measurements at midrapidity with ALICE.

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REFERENCES

[1] B.-W. Zhang, E. Wang, and X.-N. Wang, “Heavy quark energy loss in nuclear medium”, Phys.Rev.Lett. 93 (2004) 072301, arXiv:nucl-th/0309040
[2] M. Djordjevic and M. Gyulassy, “Heavy quark radiative energy loss in QCD matter”, Nucl.Phys. A733 (2004) 265–298, arXiv:nucl-th/0310076
[3] G. D. Moore and D. Teaney, “How much do heavy quarks thermalize in a heavy ion collision?”, Phys. Rev. C 71 (2005) 064904, arXiv:hep-ph/0412348
[4] P. Petreczky and D. Teaney, “Heavy quark diffusion from the lattice”, Phys. Rev. D 73 (2006) 014508, arXiv:hep-ph/0507318.
[5] CMS Collaboration, A. M. Sirunyan et al., “Measurement of the $B^\pm$ Meson Nuclear Modification Factor in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Phys. Rev. Lett. 119 no. 15, (2017) 152301, arXiv:1705.04727 [hep-ex].
[6] CMS Collaboration, A. M. Sirunyan et al., “Measurement of prompt and nonprompt charmonium suppression in Pb–Pb collisions at 5.02 TeV”, *Eur. Phys. J. C* **78** no. 6, (2018) 509, arXiv:1712.08959 [nucl-ex].

[7] ALICE Collaboration, J. Adam et al., “Inclusive, prompt and non-prompt $J/\psi$ production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV”, *JHEP* **07** (2015) 051, arXiv:1504.07151 [nucl-ex].

[8] ATLAS Collaboration, M. Aaboud et al., “Prompt and non-prompt $J/\psi$ and $\psi(2S)$ suppression at high transverse momentum in 5.02 TeV Pb+Pb collisions with the ATLAS experiment”, *Eur. Phys. J. C* **78** no. 9, (2018) 762, arXiv:1805.04077 [nucl-ex].

[9] ALICE Collaboration, J. Adam et al., “Measurement of electrons from beauty-hadron decays in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV”, *JHEP* **07** (2017) 052, arXiv:1609.03898 [nucl-ex].

[10] ATLAS Collaboration, G. Aad et al., “Measurement of the nuclear modification factor for muons from charm and bottom hadrons in Pb+Pb collisions at 5.02 TeV with the ATLAS detector”, *Phys. Lett. B* **829** (2022) 137077, arXiv:2109.00411 [nucl-ex].

[11] ALICE Collaboration, S. Acharya et al., “Measurement of beauty and charm production in pp collisions at $\sqrt{s} = 5.02$ TeV via non-prompt and prompt D mesons”, *JHEP* **05** (2021) 220, arXiv:2102.13601 [nucl-ex].

[12] S. A. Voloshin, A. M. Poskanzer, and R. Snellings, “Collective phenomena in non-central nuclear collisions”, *Landolt-Bornstein* **23** (2010) 293–333, arXiv:0809.2949 [nucl-ex].

[13] CMS Collaboration, A. M. Sirunyan et al., “Studies of charm and beauty hadron long-range correlations in pp and pPb collisions at LHC energies”, *Phys. Lett. B* **813** (2021) 136036, arXiv:2009.07065 [hep-ex].

[14] ALICE Collaboration, S. Acharya et al., “Measurement of beauty production via non-prompt $D^0$ mesons in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”, arXiv:2202.00815 [nucl-ex].

[15] ALICE Collaboration, S. Acharya et al., “Prompt $D^0$, $D^+$, and $D^{*+}$ production in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV”, *JHEP* **01** (2022) 174, arXiv:2110.09420 [nucl-ex].

[16] M. Nahrgang, J. Aichelin, P. B. Gossiaux, and K. Werner, “Influence of hadronic bound states above $T_c$ on heavy-quark observables in Pb + Pb collisions at the CERN Large Hadron Collider”, *Phys. Rev. C* **89** no. 1, (2014) 014905, arXiv:1305.6544 [hep-ph].

[17] S. Li, W. Xiong, and R. Wan, “Relativistic Langevin dynamics: charm versus beauty”, *Eur. Phys. J. C* **80** no. 12, (2020) 1113, arXiv:2012.02489 [hep-ph].

[18] S. Li and J. Liao, “Data-driven extraction of heavy quark diffusion in quark-gluon plasma”, *Eur. Phys. J. C* **80** no. 7, (2020) 671, arXiv:1912.08965 [hep-ph].
[19] M. He, R. J. Fries, and R. Rapp, “Heavy Flavor at the Large Hadron Collider in a Strong Coupling Approach”, *Phys. Lett. B* 735 (2014) 445–450, arXiv:1401.3817 [nucl-th].

[20] S. Shi, J. Liao, and M. Gyulassy, “Global constraints from RHIC and LHC on transport properties of QCD fluids in CUJET/CIBJET framework”, *Chin. Phys. C* 43 no. 4, (2019) 044101, arXiv:1808.05461 [hep-ph].

[21] **ALICE** Collaboration, “Measurement of beauty-strange meson production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV via non-prompt $D_s^+$ mesons”, arXiv:2204.10386 [nucl-ex].

[22] **ALICE** Collaboration, S. Acharya *et al.*, “Measurement of prompt $D^+_s$-meson production and azimuthal anisotropy in Pb–Pb collisions at $\sqrt{s_{NN}}=5.02$TeV”, *Phys. Lett. B* 827 (2022) 136986, arXiv:2110.10006 [nucl-ex].

[23] **ALICE** Collaboration, S. Acharya *et al.*, “Transverse-momentum and event-shape dependence of D-meson flow harmonics in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Lett. B* 813 (2021) 136054, arXiv:2005.11131 [nucl-ex].

[24] S.-Q. Li, W.-J. Xing, X.-Y. Wu, S. Cao, and G.-Y. Qin, “Scaling behaviors of heavy flavor meson suppression and flow in different nuclear collision systems at the LHC”, *Eur. Phys. J. C* 81 no. 11, (2021) 1035, arXiv:2108.06648 [hep-ph].

[25] S.-Q. Li, W.-J. Xing, F.-L. Liu, S. Cao, and G.-Y. Qin, “Heavy flavor quenching and flow: the roles of initial condition, pre-equilibrium evolution, and in-medium interaction”, *Chin. Phys. C* 44 no. 11, (2020) 114101, arXiv:2005.03330 [nucl-th].

[26] W. Ke, Y. Xu, and S. A. Bass, “Linearized Boltzmann-Langevin model for heavy quark transport in hot and dense QCD matter”, *Phys. Rev. C* 98 no. 6, (2018) 064901, arXiv:1806.08848 [nucl-th].

[27] W. Ke, Y. Xu, and S. A. Bass, “Modified Boltzmann approach for modeling the splitting vertices induced by the hot QCD medium in the deep Landau-Pomeranchuk-Migdal region”, *Phys. Rev. C* 100 no. 6, (2019) 064911, arXiv:1810.08177 [nucl-th].