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Open heavy-flavour production from small to large collision systems with ALICE at the LHC

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Heavy quarks are effective probes of the hot and dense nuclear matter, the quark–gluon plasma, produced in ultra-relativistic heavy-ion collisions. Due to the short time scale characterising their production, heavy quarks experience the whole evolution of the system. In particular, measurements of heavy-flavour hadron production in Pb–Pb collisions at LHC energies give insight into the mechanisms of heavy-quark transport in the deconfined matter. In small hadronic systems, pp and p–Pb collisions, heavy-flavour measurements provide the baseline for observations of hot-medium effects in heavy-ion collisions, as well as tests of perturbative quantum chromodynamic calculations and measurements of cold-nuclear-matter effects. In this contribution, recent ALICE results on open heavy-flavour hadron production in pp, p–Pb and Pb–Pb collisions at various energies are discussed. New measurements are presented both for fully-reconstructed charmed hadrons and for single electrons from heavy-flavour hadron decays, also investigating the beauty-quark production via the measurement of D mesons and electrons from beauty-hadron decays.

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1. Introduction

Due to their large masses, charm and beauty quarks (heavy quarks) are mainly produced in hard-scattering processes between partons of the colliding nucleons. Therefore, their production can be described by perturbative quantum chromodynamic (pQCD) calculations down to zero transverse momentum (p_{T}). In ultra-relativistic heavy-ion collisions extreme temperatures are reached and lattice QCD calculations predict a phase transition of nuclear matter to a colour-deconfined medium, called quark–gluon plasma (QGP). Heavy quarks are produced in the initial stages of the nucleus–nucleus (Pb–Pb) collision, before the QGP formation, and experience the full evolution of the system while propagating through the medium and strongly interacting with the QGP constituents. In Pb–Pb collisions the measurement of hadrons containing heavy quarks provides crucial information on the in-medium parton energy loss. The comparison of heavy-flavour and light-flavour hadrons gives insight into the colour-charge and quark-mass dependence of energy loss. Moreover, the hadronisation mechanism of heavy quarks in the medium can be investigated comparing the production of different heavy-flavour hadron species, e.g., charmed baryons and mesons, or hadrons with and without strange-quark content [1]. Measurements of open heavy-flavour hadron production in proton-proton collisions are relevant tests of pQCD model calculations.

In ALICE, charmed hadrons are reconstructed at midrapidity ($|y| < 0.8$) via the hadronic decay channels: $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$, $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$, $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+ \to \mathrm{K}^-\pi^+\pi^+$, $\mathrm{D}_\mathrm{s}^+ \to \phi\pi^+ \to \mathrm{K}^-\mathrm{K}^+\pi^+$, $\Lambda_\mathrm{c}^+ \to \mathrm{pK}_\mathrm{s}^0$ and their charge conjugates. Particle candidates are built from pairs or triplets of tracks with the proper charge combination. Kinematic and geometrical selections on the displaced decay-vertex topology, together with particle identification, are applied to reduce the combinatorial background. The charmed-hadron raw yields are obtained from an invariant-mass analysis and the reconstruction efficiencies are estimated using Monte Carlo simulations [2]. In addition, heavy-flavour hadrons are studied through the measurement of electrons produced in their semi-leptonic decays. Electrons are identified at midrapidity using the information provided by ALICE central-barrel detectors [3]. The hadron contamination and electrons from non-heavy-flavour sources, mainly photon conversions and Dalitz decays of light neutral mesons, are subtracted from the measured inclusive yield, which is then corrected for the acceptance and selection efficiency [4]. Exclusive measurements of prompt charmed hadrons, originated from the hadronisation of charm quarks produced in the initial collision, and non-prompt ones, which are produced from beauty-hadron decays, are possible thanks to the longer proper mean-life of hadrons containing beauty quarks. This allows the ALICE experiment to assess beauty-quark production through the measurement of non-prompt D mesons and electrons from beauty-hadron decays.

2. Open heavy-flavour production in pp collisions

The production cross section of prompt [2] and non-prompt D mesons and of electrons from semi-leptonic heavy-flavour hadron decays [4] is measured at midrapidity in pp collisions at $\sqrt{s} = 5.02$ TeV. In the left panel of Fig. 1, prompt and new measurements of non-prompt D^+ mesons are compared, respectively, to FONLL [5] predictions and to FONLL with the $\mathrm{B} \to \mathrm{D} + \mathrm{X}$ decay kinematics described by the PYTHIA8 package [6]. In the right panel, the cross section of heavy-flavour decay electrons is compared to theoretical calculations. The measurements are well

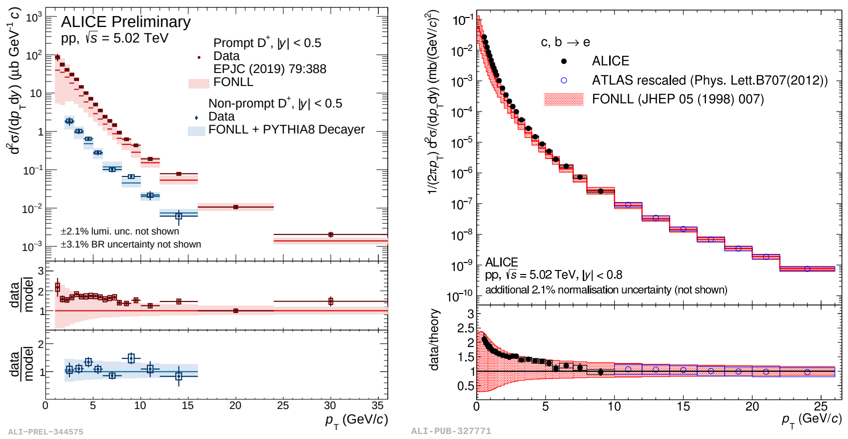

Figure 1: Left: prompt and non-prompt D^+-meson cross sections in pp collisions at $\sqrt{s} = 5.02$ TeV compared to FONLL predictions. Right: $e^{\pm}$ from heavy-flavour hadron decays compared to FONLL predictions.

described by pQCD calculations. The prompt D^+-meson measurement lies on the upper part of the FONLL prediction uncertainty band, while non-prompt D^+ mesons are in good agreement with the central predictions. A similar behaviour is observed for heavy-flavour decay electrons, where the cross section is on the upper edge of FONLL predictions for $p_T < 5$ GeV$/c$ and moves towards the central values at high p_T, where beauty-hadron decays are the dominant contribution.

3. D_s^+-meson abundance as a function of particle multiplicity

Figure 2 shows the yield ratio between D_s^+ and D^0 mesons measured by the ALICE experiment in p–Pb [7] and Pb–Pb [8] collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of the charged-particle multiplicity for different p_T intervals, together with new measurements in pp at $\sqrt{s} = 13$ TeV and in Pb–Pb collisions. The D_s^+/D^0 ratio in pp collisions does not show a dependence on the event multiplicity and it is in agreement with the expected value considering the charm-quark fragmentation fractions measured in e^+e^- collisions at LEP [9]. The measurement in minimum bias p–Pb collisions is compatible to what is observed in pp collisions at similar multiplicity values. An increase of the D_s^+/D^0 ratio with respect to pp and p–Pb is observed in Pb–Pb collisions at $p_T < 8$ GeV$/c$. This higher production of D_s^+ mesons in Pb–Pb is expected if charm quarks hadronise via coalescence with a quark of the QGP medium, where the production of $s\bar{s}$ pairs is enhanced [1].

4. Open heavy-flavour nuclear modification factor

The production of prompt charmed hadrons and electrons from heavy-flavour hadron decays [4] is measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and compared to pp collisions through the nuclear modification factor $R_{AA}\,(p_T) = (\mathrm{d}N_{AA}/\mathrm{d}p_T)/(\langle N_{coll}^{AA}\rangle \cdot \mathrm{d}N_{pp}/\mathrm{d}p_T)$; where $\mathrm{d}N_{AA}/\mathrm{d}p_T$ and $\mathrm{d}N_{pp}/\mathrm{d}p_T$ are the p_T-differential yields measured in nucleus–nucleus and pp collisions, respectively, and $\langle N_{coll}^{AA}\rangle$ is the average number of binary interactions in a nucleus–nucleus collision. In the left

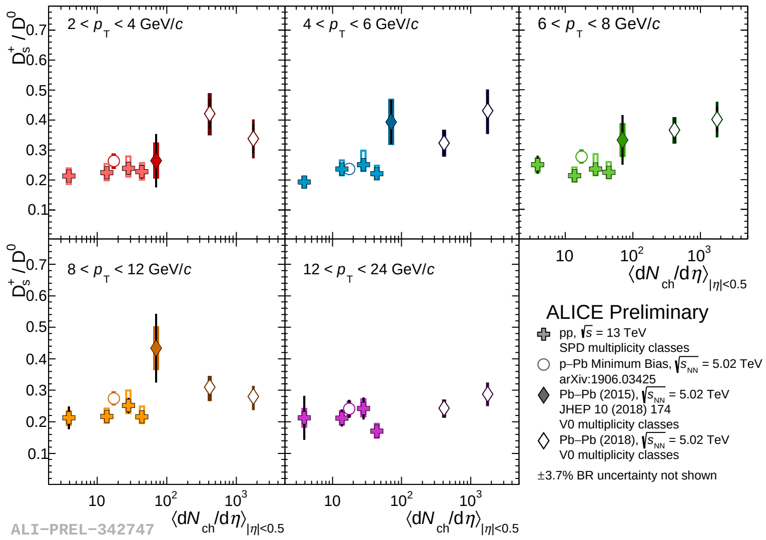

Figure 2: D_s^+/D^0 ratio measured in pp, p–Pb and Pb–Pb collisions as a function of the charged-particle multiplicity and for different p_T intervals.

panel of Fig. 3, the measured R_{AA} of strange and non-strange D mesons, Λ_c^+ and charged particles [10] in central Pb–Pb collisions are reported. A strong suppression of the charmed and light-flavour

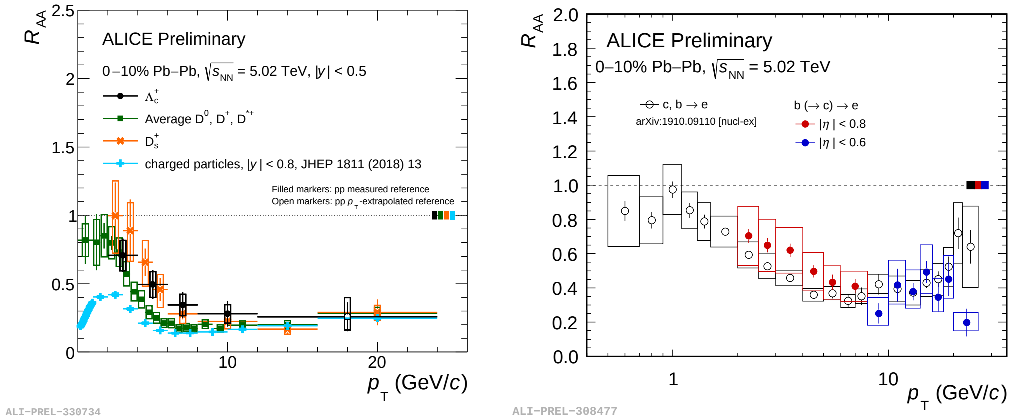

Figure 3: Left: R_{AA} comparison between Λ_c^+, non-strange D mesons, D_s^+ and charged particles in the 0–10% centrality class. Right: R_{AA} comparison of $e^{\pm}$ from heavy-flavour hadron and beauty-hadron decays.

hadron R_{AA} is observed, as expected in the presence of the QGP due to in-medium energy loss. The R_{AA} of non-strange D mesons is higher than that of charged particles below 4 GeV/c, while they are compatible at higher p_T. This behaviour can be explained by the mass and colour-charge dependence of energy loss. However, also other factors play a role, such as the different initial p_T distributions and fragmentation functions of charm and light quarks and the different effects of hadronisation via recombination and radial flow [8]. Finally, there is an indication of a smaller suppression of D_s^+ mesons and Λ_c^+ baryons than non-strange D mesons at $p_T < 8$ GeV/c . In the right panel of Fig. 3, the R_{AA} of electrons from semi-leptonic beauty-hadron decays in central Pb–Pb collisions is compared to that of inclusive heavy-flavour decay electrons. The R_{AA} of electrons coming from beauty hadrons is above the inclusive one in all the $p_{\rm T}$ intervals below 10 GeV/c, even if compatible within uncertainties, pointing to a possible mass dependence of heavy-quark energy loss, where beauty quarks lose less energy in the medium than charm quarks.

5. Conclusions

The ALICE collaboration has measured the production of charmed hadrons and electrons from heavy-flavour hadron decays in different collision systems and at different centre-of-mass energies. In addition, the production of beauty quarks has been investigated with the measurement of non-prompt D mesons and electrons from beauty-hadron decays.

In pp collisions, the measured D-meson and heavy-flavour electron cross sections are compatible with pQCD calculations. In Pb–Pb collisions, the indication of a higher $\mathrm{D_s^+}/\mathrm{D^0}$ ratio than in pp, at low $p_{\rm T}$, is in agreement with the charm-quark hadronisation via quark recombination in the QGP. The D-meson $R_{\rm AA}$ is higher than that of charged particles at $p_{\rm T} < 4$ GeV/c, suggesting a colour-charge and quark-mass dependence of the energy loss. Furthermore, an indication of a smaller energy loss of beauty quarks than charm quarks is observed through the measurement of electrons from beauty-hadron decays.

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