Open charm and beauty measurements from small to large systems

Jonghan Park[1],* on behalf of the ALICE Collaboration

[1]Department of Physics, Inha University

Abstract. Heavy-flavor quarks (i.e. charm and beauty) are essential probes to investigate the properties of the quark-gluon plasma (QGP) created in ultra-relativistic heavy-ion collisions. The measurement of the nuclear modification factor (R_{AA}) gives insight into the in-medium parton energy loss in heavy-ion collisions. Furthermore, the measurements of heavy-flavor elliptic flow (v_2) provide crucial information about the degree of thermalization of heavy quarks in the QGP, the path-length dependence of heavy-quark in-medium energy loss, and possible recombination effects. The higher flow harmonics, such as the triangular flow (v_3), provide further constraints on the effect of fluctuations in the initial state of the system. The measurements in proton-proton (pp) collisions allow for testing perturbative quantum chromodynamics (pQCD) calculations and are needed as a baseline for investigating the medium effects in heavy-ion collisions. In this contribution, recent results of open charm and beauty production measured with the ALICE detector are discussed.

1 Introduction

The ALICE apparatus was designed to study the quark-gluon plasma (QGP), a state of matter in which colored-partons are deconfined. Due to their large mass, heavy quarks are mainly produced in initial hard-scattering processes, which occur before the QGP formation [1]. They interact with the medium during the full evolution of the system. Therefore, they are effective probes to investigate the properties of the QGP.

While traversing the medium, heavy quarks interact with the medium constituents and lose their energy via collisional [2] and radiative processes [3]. The medium effects in heavy-ion collisions are studied measuring the nuclear modification factor (R_{AA}). The R_{AA} is defined as the ratio between the p_T-differential yield in nucleus-nucleus collisions ($d^2N_{AA}/d\eta dp_T$) and the p_T-differential production cross section in pp collisions ($d^2\sigma_{pp}/d\eta dp_T$) scaled by the average nuclear thickness function $\langle T_{AA} \rangle$, which is a quantity proportional to the average number of binary nucleon-nucleon collisions. The measurement of heavy quark production in proton-proton (pp) collisions allows for testing pQCD calculations and provides the reference for measuring the R_{AA}.

Open charm and beauty hadron production is measured with the ALICE detector via the reconstruction of hadronic and semi-leptonic decay channels at midrapidity. The D mesons are measured via the $D^0 \to \pi^+K^-$, $D^+ \to \pi^+\pi^+K^-$, $D^{*+} \to D^0\pi^+$, $D_s^+ \to \pi^+\phi \to \pi^+K^+K^-$ decay channels, and their charge conjugate. The D meson yields are extracted from an invariant

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*e-mail: jonghan@cern.ch

mass analysis after applying topological and particle identification selections to enhance the signal-to-background ratio. Non-prompt D mesons are used to measure open-beauty hadron production. Exploiting machine-learning techniques based on Boosted Decision Trees, non-prompt D mesons are separated from the prompt D mesons [4]. Open heavy-flavor production is also measured by identifying the electrons from semi-electronic decays of charm and beauty hadrons. The production yield is extracted by subtracting the contamination of hadrons and of non-heavy flavor decay electrons from the inclusive sample. The production of beauty-hadron decay electrons is measured by determining statistically the fraction of beauty-decay electrons in the inclusive electron sample with an impact-parameter template fit method [5, 6].

2 Results

The production of electrons from both inclusive heavy-flavor hadron decays [7] and beauty hadron decays was measured in pp collisions at $\sqrt{s}$ = 5.02 TeV at midrapidity. The fraction of the beauty hadron decay electrons to the one from inclusive heavy-flavor hadron decays in the transverse momentum (p_T) region $2 < p_T < 8$ GeV/c is shown in Fig. 1 (left). The result is described by the FONLL pQCD calculation [8–10] within the uncertainties. The measured values and the model prediction vary with p_T, indicating that the charm contribution is dominant at low p_T and the beauty contribution is increasing with p_T. The prompt and non-prompt D^0, D^+ and D_s^+ meson cross sections were measured in pp collisions at $\sqrt{s}$ = 5.02 TeV [4]. From the results of non-prompt D mesons, the total $b\bar{b}$ production cross section was computed. Figure 1 (right) shows $d\sigma_{b\bar{b}}/dy_{|y|=0}$ as a function of center-of-mass energy. The measurements are found to be compatible with FONLL [8–10] and NNLO [11] calculations. This result provides an important test for pQCD calculations in the beauty sector at the LHC.
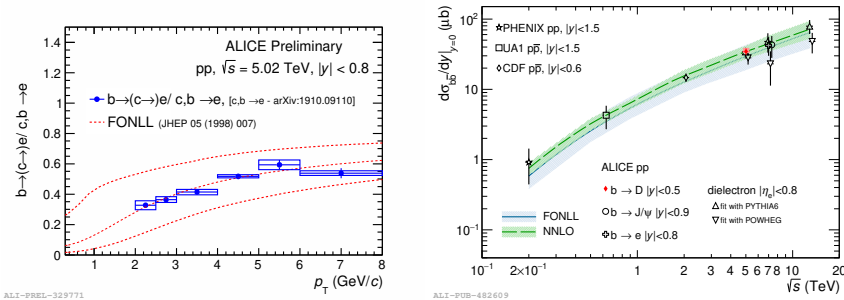

Figure 1. Left: Fraction of beauty-hadron decay electrons to heavy-flavor hadron decay electrons in pp collisions at $\sqrt{s}$=5.02 TeV. Right: Beauty production cross section per unit of rapidity at midrapidity as a function of $\sqrt{s}$ measured in pp and p$\bar{p}$ collisions by different experiments [4].

The production of electrons from inclusive heavy-flavor hadron decays [7] and beauty hadron decays is also measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, as well as the production of prompt and non-prompt D^0 mesons. Figure 2 (left) shows the R_{AA} comparison between inclusive heavy-flavor hadron decays and beauty hadron decays measured in 0–10% central Pb-Pb collisions. Both R_{AA} values are smaller than unity, suggesting that the heavy-flavor production is suppressed in Pb–Pb collisions with respect to pp collisions in the intermediate p_T region. The R_{AA} of beauty decay electrons tends to be higher than that of inclusive heavy-flavor hadron decay electrons at low p_T, though they are compatible within

uncertainties. At high p_T, they have very similar values. The observed trend is consistent with the expectation that the suppression of beauty hadrons is smaller than charm. Figure 2 (right) shows the R_{AA} ratio of non-prompt D^0 over prompt D^0 in the 0–10% centrality Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to several model predictions (MC@sHQ+EPOS2 [12], LGR [13, 14], TAMU [15], and CUJET3.1 [16]). The measured ratio, above unity, suggests that non-prompt D^0 mesons are less suppressed than prompt D^0 ones. This is a hint of the mass dependence of the in-medium parton energy loss. At very low p_T, the ratio decreases up to 3 GeV/c and increases from 3 GeV/c to 7 GeV/c. This behavior is mainly due to the formation of prompt D mesons via charm quark coalescence. Above 7 GeV/c, the ratio does not vary significantly with p_T within sum of statistical and systematic uncertainties.
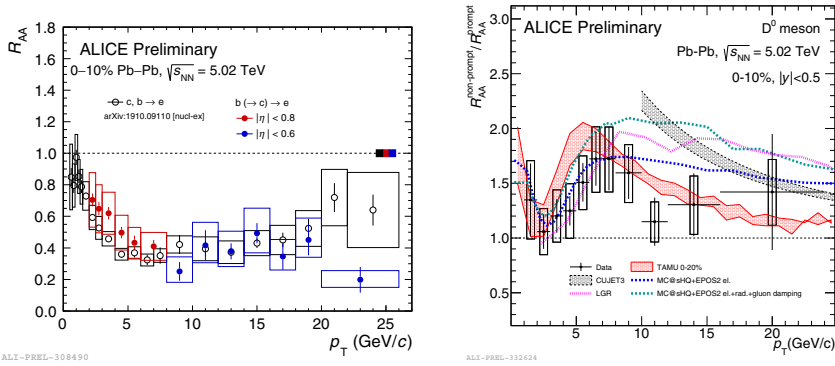
Figure 2. Left: Comparison of the R_{AA} of electrons from heavy-flavor hadron and beauty-hadron decays in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Right: Ratio of non-prompt D^0 to prompt D^0 R_{AA} in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to model predictions.
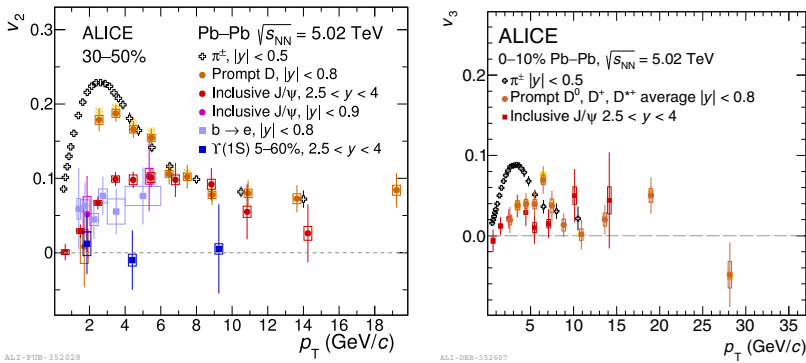
Figure 3. Anisotropic flow coefficient measurements as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Left: v_2 in 30–50% central collisions. Right: v_3 in 0–10% central collisions. [17]

The azimuthal anisotropy of particles provides further insight into the interaction of heavy quarks in the QGP. It can be quantified by the Fourier coefficients of the particle azimuthal distribution defined as $v_n = \langle \cos(n(\varphi - \Psi_n)) \rangle$, where φ is particle azimuthal angle and Ψ_n is n^{th}-order asymmetry plane formed by impact parameter vector and the beam axis using V0 detector. The elliptic flow v_2, which is the dominant coefficient in semi-central collisions, is

sensitive to the degree of thermalization of the heavy quarks at low p_T, while the path-length dependence of the in-medium parton energy loss becomes the main origin of a positive v_2 at high p_T. The triangular flow v_3 originates from event-by-event fluctuations in initial collision geometry. Figure 3 shows the v_2 (left) and v_3 (right) for several particle species. For v_2, the mass ordering hierarchy is seen for $p_\mathrm{T} < 3\,\mathrm{GeV}/c$ while the v_2 of prompt D and $\pi^\pm$ mesons are similar for $3 < p_\mathrm{T} < 6\,\mathrm{GeV}/c$. This supports the hypothesis that charm quarks hadronize via coalescence with light quarks from the medium. For $p_\mathrm{T} > 6\,\mathrm{GeV}/c$, all v_2 values converge to a similar value, except for $\Upsilon(1\mathrm{S})$. This suggests a similar path-length dependence of energy loss for different partons. A positive v_3 for non-strange D mesons is observed, as shown in Fig. 3 (right) indicating that the charm quarks are sensitive to the initial state event-by-event fluctuation of the created medium.

3 Summary and Outlook

In this contribution, recent results on open heavy-flavor production in pp and Pb–Pb collisions from ALICE Collaboration were presented. All the measurements are conducted utilizing Run 2 data. The results show that the pQCD calculations reasonably describe the open heavy-flavor data in pp collisions. The R_AA in central Pb–Pb collisions is lower than unity over a wide p_T interval, indicating that open heavy-flavor production is suppressed. The comparison between the R_AA of prompt and non-prompt D mesons as well as that between beauty-hadron decay electrons and the inclusive heavy-flavor hadron decay electrons suggest that the in-medium parton energy loss depends on the parton mass. The positive anisotropic flow indicates the participation of heavy quarks to the collective motion of the medium.

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