Charm and beauty production in hadronic collisions via muon measurements at forward rapidity with ALICE

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Abstract. The latest results from the ALICE Collaboration on the measurements of open heavy flavours in the (di)muon channel at forward rapidity are presented. In the LHC Run 3, the new Muon Forward Tracker (MFT) adds vertex capabilities to the muon spectrometer, providing a unique way to discriminate muons from charm- and beauty-hadron decays. The analysis strategy is discussed and the status of the measurements in pp collisions at $\sqrt{s}$ = 13.6 TeV collected with the upgraded ALICE detector is reported.

1 Introduction

Heavy quarks (charm and beauty) are excellent probes to study the properties of the Quark-Gluon Plasma (QGP), a state of strongly-interacting matter at high temperature and energy density, formed in high-energy heavy-ion collisions. Indeed, due to their large masses, heavy quarks are produced in hard partonic scattering processes before the formation of the QGP, and they experience the full evolution of the hot and dense nuclear medium. Charm and beauty measurements in small collision systems, pp and p–Pb, serve as an important test of perturbative quantum chromodynamics (pQCD). They also represent the baseline to study the QGP and quantify hot-medium effects in heavy-ion collisions and provide the possibility to investigate cold nuclear matter effects. Measurements in these small collision systems gained additional interest with the observation, in high-multiplicity collisions, of final-state effects typically attributed to the QGP in Pb–Pb collisions. The origin of these effects in small collision systems is still under investigation.

Open heavy-flavour hadrons are measured with ALICE through the hadronic decay channels and with electrons from semielectronic decays of charm and/or beauty at midrapidity ($|y| < 0.8$), and in the semimuonic decay of charm and beauty hadrons at forward rapidity ($2.5 < y < 4.0$). A detailed description of the ALICE apparatus and its performance can be found in Refs. [1, 2]. In the following, a particular emphasis is placed on the recent measurements at forward rapidity using the muon spectrometer. These include the measurements of the muon azimuthal anisotropies in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV, and the charm and beauty production cross sections in pp collisions at $\sqrt{s}$ = 13 TeV via dimuons.

A major upgrade of the ALICE apparatus has been successfully carried out for the LHC Run3 [3]. ALICE is equipped with several new subdetectors and the readout of all existing subdetectors is upgraded due to the continuous readout. In particular, the new Muon Forward

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Tracker (MFT) provides vertexing to the muon spectrometer and allows us to distinguish muons from charm- and beauty-hadron decays in the single muon channel. The MFT analysis procedure is described and the status of the analysis of pp collisions at $\sqrt{s}$ = 13.6 TeV is presented.

2 Azimuthal anisotropies with muons in high-multiplicity p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV

The second-order Fourier coefficient of the inclusive muon azimuthal distribution (v_2) which quantifies the azimuthal anisotropy of produced muons, is studied as a function of transverse momentum $p_{\rm T}$ in high-multiplicity (0–20%) p–Pb collisions at both forward and backward rapidities using two-particle cumulants and forward-central two-particle correlations [4]. The results are obtained in a wide $p_{\rm T}$ interval, $0.5 < p_{\rm T} < 10$ GeV/c, where for $p_{\rm T} > 2$ GeV/c the contribution of muons from heavy-flavour hadron decays is dominant. Figure 1 (left) shows the $p_{\rm T}$-differential muon v_2 at forward rapidity after the subtraction of nonflow effects. The results from two-particle correlations and two-particle cumulants are consistent within uncertainties. A positive v_2 is measured with a significance reaching values of 4.6–12σ at intermediate $p_{\rm T}$ ($2 < p_{\rm T} < 6$ GeV/c). A comparison with the string-melting version of A MultiPhase Transport (AMPT) model [5, 6] and the colour glass condensate (CGC) predictions [7] is also displayed in Fig. 1 (middle and right). The anisotropies are generated from parton interactions in the early stage of the collisions in the CGC framework. The AMPT model addresses non-equilibrium dynamics and provides a microscopic evolution of parton interactions. The AMPT generates a positive v_2 for all particles and is in fair agreement with the measured inclusive muon v_2, suggesting that the v_2 is driven by the anisotropic parton escape mechanism. In the high-$p_{\rm T}$ region where the contribution of muons from heavy-flavour hadron decays dominates, both AMPT and CGC-based calculations describe the measured inclusive muon v_2. That indicates that possible contributions from initial-state effects are not excluded.

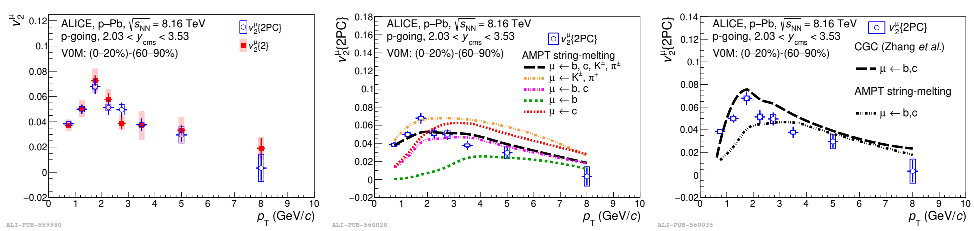

Figure 1. Left: inclusive muon v_2 measured at forward rapidity (p-going) in high-multiplicity p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV with two-particle cumulants (v_2^{μ}\{2PC\}) and two-particle correlations (v_2^{μ}\{2\}) . Vertical bars and boxes represent statistical and systematic uncertainties. Middle: comparison with AMPT calculations. Right: comparison with AMPT and CGC-based calculations.

3 Charm and beauty production cross section at forward rapidity in the dimuon channel

During the LHC Run 2, differential measurements of the heavy-flavour production cross sections have been performed at forward rapidity in the single muon channel without separating the charm and beauty contributions (see Ref. [8] and references therein). Recently, ALICE also measured, for the first time, the $p_{\rm T}$-integrated charm and beauty production cross sections at forward rapidity via the unlike-sign muon pair production in pp collisions at $\sqrt{s}$ = 13 TeV. The procedure consists in exploiting the high-mass region of the invariant mass distribution of $\mu^+\mu^-$ pairs ($m_{\mu^+\mu^-}$), namely the continuum region between the charmonium and bottomonium resonances ($4 < m_{\mu^+\mu^-} < 9$ GeV/c^2) which is dominated by the semimuonic decays of hadron pairs containing charm or beauty quarks. In this region, the combinatorial background (light-hadron decays) is found to be negligible. A simultaneous unbinned fit of the measured invariant mass and transverse momentum of $\mu^+\mu^-$ pairs ($p_{\mathrm{T},\,\mu^+\mu^-}$) up to $p_{\mathrm{T},\,\mu^+\mu^-}$ = 10 GeV/c with a cocktail of the different heavy-flavour components is performed to estimate the charm and beauty production cross sections. The templates are obtained from PYTHIA 8 Monte Carlo simulations. Figure 2 presents the measured charm and beauty production cross sections at forward rapidity in pp collisions at $\sqrt{s}$ = 13 TeV. The results at forward rapidity complement previous measurements by ALICE in the dielectron channel. The FONLL predictions [9] with CTEQ6 parton distribution functions are compatible with data within the experimental and theoretical uncertainties, although the measured charm (beauty) production cross section lies at the upper (lower) limit of the model calculations.

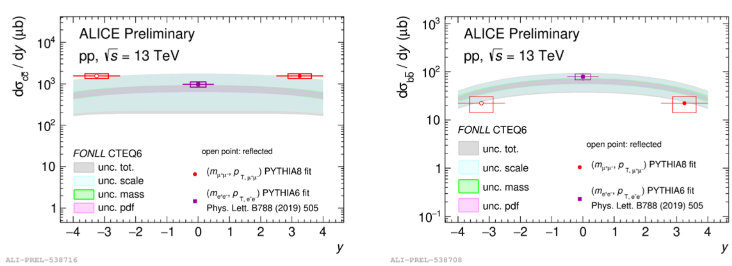

Figure 2. Charm (left) and beauty (right) production cross sections measured at forward rapidity via unlike-sign dimuons in pp collisions at $\sqrt{s}$ = 13 TeV. The vertical bars represent the statistical uncertainties and are smaller than the symbols, while the empty boxes correspond to the systematic uncertainties. The published results obtained at midrapidity in the dielectron channel are also reported. The production cross sections are compared with FONLL calculations.

4 Charm and beauty production at forward rapidity via the semimuonic decay channel in pp collisions at $\sqrt{s}$ = 13.6 TeV

In the Run 3, the presence of the MFT, designed to add vertexing to the muon spectrometer enhances the capabilities of ALICE for measuring muons in the forward rapidity. This new subdetector improves the tracking performance of the muon spectrometer and adds the possibility to separate muons originating from charm- and beauty-hadron decays in the single muon channel. The inclusive muon p_{T} distribution obtained at forward rapidity with a fraction of the pp sample collected in 2022, presented in Fig. 3 (left), indicates that muons can be measured in a wide p_{T} range and study the region where muons from W-boson decays are clearly observed. This is very promising to study the charm/beauty production with high statistical precision in a broad p_{T} interval.

The analysis strategy to distinguish the different muon sources is based on the distance of closest approach to the primary vertex in the transverse plane ($\mathrm{DCA_{xy}}$) of global muon tracks (MFT tracks matched with tracks reconstructed in the muon tracking chambers and further matched with the muon identifier). Such study is performed exploiting the different decay lengths of beauty hadrons with respect to charm hadrons and other sources. Figure 3 (right) presents the typical $\mathrm{DCA_{xy}}$ distribution of the main muon sources estimated by means of simulations using PYTHIA 8 and the GEANT4 transport code. One notices that the signals and

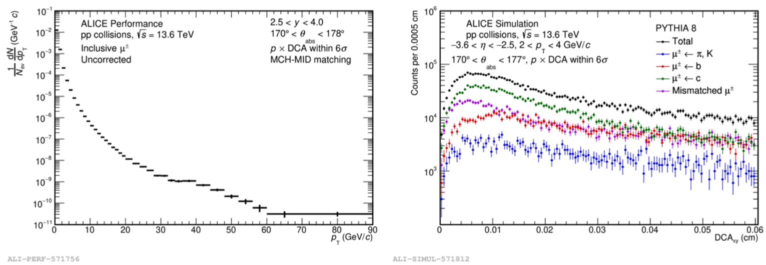

Figure 3. Left: inclusive muon p_T distribution measured in minimum bias collisions with a fraction of the sample of pp collisions at $\sqrt{s}$ = 13.6 TeV. Right: DCA distribution of the main muon sources obtained from a PYTHIA 8 simulation of pp collisions at $\sqrt{s}$ = 13.6 TeV.

the background exhibit different shapes, indicating that the separation of charm and beauty contributions can be achieved with the MFT. The performance for charm/beauty separation in pp collisions is first evaluated by means of dedicated Monte Carlo simulations. The DCA_{xy} distributions of the signals and background are parametrised with a variable-width Gaussian function. They further define the Monte Carlo templates which are combined after proper normalisation and employed to fit the total DCA_{xy}. The results indicate that the charm and beauty components can be measured separately in the semimuonic channel at forward rapidity in pp collisions at $\sqrt{s}$ = 13.6 TeV with the MFT coupled with the muon spectrometer. Such measurements can be achieved down to $p_T \simeq 0.5$ GeV/c and $p_T \simeq 1-2$ GeV/c for charm and beauty, respectively.

5 Conclusion

Measurements of azimuthal anistropies with muons in p–Pb collisions introduce new constraints in the interpretation of the collective behaviour in small systems and to model calculations. The p_T-integrated $c\bar{c}$ and $b\bar{b}$ production cross sections measured for the first time at forward rapidity via dimuons are in fair agreement with FONLL predictions. The MFT opens the path to new measurements such as charm and beauty production in the single muon channel. The performance study shows that the measurements can be performed differentially down to low p_T in pp collisions. High expectations are placed in the future charm/beauty analysis in Pb–Pb collisions at large rapidities, which will be unique at the LHC.

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