Nuclear modification factor and elliptic flow of muons from heavy-flavour decays in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

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Abstract. We report on the latest results from ALICE on the measurement of the nuclear modification factor and elliptic flow of muons from heavy-flavour decays at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. A strong suppression of muons from heavy-flavour decays is observed at high transverse momentum, $p_{\rm T}$, in the most central collisions compared to the binary-scaled expectation from pp events at the same energy, while a positive elliptic flow is observed at intermediate $p_{\rm T}$ in semi-central collisions. Comparisons with model predictions are presented.

1. Introduction

ALICE [1] is the dedicated heavy-ion experiment at the LHC, optimized to investigate the properties of strongly-interacting matter in extreme conditions of temperature and energy density where the formation of Quark Gluon Plasma (QGP) is expected. Heavy quarks (charm and beauty) are regarded as efficient probes of the properties of the QGP as they are created on a very short time scale in initial hard parton scattering processes and subsequently interact with the medium. Open heavy-flavour hadrons are expected to be sensitive to the energy density of the system through the in-medium energy loss of heavy quarks. In the high $p_{\rm T}$ region, the suppression of the heavy-flavour yields quantified by means of the nuclear modification factor, $R_{\rm AA}$, defined as the ratio of the yield measured in Pb–Pb collisions to that observed in pp collisions scaled by the number of binary nucleon-nucleon collisions, is used to study the heavy quark in-medium energy loss mechanisms. Due to the color charge effect, the radiative energy loss of gluons should be larger than that of quarks, and due to the dead-cone effect [2] heavy quark energy loss may be reduced with respect to that of light quarks. The heavy-flavour elliptic flow, the second order coefficient of the Fourier expansion of particle azimuthal distributions (v_2), should carry complementary information on the medium transport properties. It is expected to provide insights on the degree of thermalization of heavy quarks in the deconfined medium and on the path-length dependence of parton energy loss in the low and high $p_{\rm T}$ regions, respectively.

In the following, we focus on open heavy-flavour measurements at forward rapidity via single muons detected in the ALICE muon spectrometer (pseudo-rapidity coverage: $-4 < \eta < -2.5$) which consists of a thick front absorber, a beam shield, a dipole magnet, five tracking stations and two trigger stations behind an iron wall. Muons are identified by requiring that the track candidate in the tracking system is matched with the track reconstructed in the muon trigger system. This condition allows to reject most of the punch-through hadrons that are stopped in the iron wall. Then, acceptance cuts are applied. Furthermore, the correlation between the track momentum and the geometrical distance of closest approach to the primary vertex is used in order to remove fake tracks and tracks from beam-gas interactions. The remaining background after these selection cuts consists of muons from decays of primary light hadrons (π and K, mainly), called decay muons in the following. In addition to the muon spectrometer, for the analyses presented here, the VZERO detector comprising two of scintillator arrays, the two Zero Degree Calorimeters (ZDC), the Silicon Pixel Detector (SPD) and the Time Projection Chamber (TPC) are used. Collisions were classified according to their centrality, determined from the sum of the amplitudes of the signals in the VZERO detector and defined in terms of percentiles of the total hadronic Pb–Pb cross section.

2. Nuclear modification factor of muons from heavy-flavour decays

The study of in-medium effects with the $R_{\rm AA}$ observable requires the measurement of the pp reference. The latter was obtained from the analysis of the pp data sample at $\sqrt{s} = 2.76$ TeV collected in 2011 [3, 4]. The Pb–Pb data sample collected in 2010 with minimum bias trigger events is used to obtain the $p_{\rm T}$ distributions of muons from heavy-flavour decays for different centrality selections. The background contribution that needs to be subtracted is evaluated by

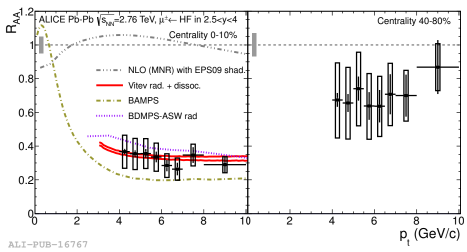

Figure 1. $p_{\rm T}$-differential $R_{\rm AA}$ of muons from heavy-flavour decays in 0–10% (left) and 40%–80% (right) centrality classes; statistical (bars), systematic (empty boxes) and normalization (filled boxes) uncertainties are shown. Data from the most central collisions are compared to models including shadowing alone and in-medium energy loss.

extrapolating to forward rapidity the π and K distributions measured in pp and Pb–Pb collisions in the ALICE central barrel [1], and generating the decay muons through simulations of the decay kinematics and interaction with the front absorber [4]. Figure 1 shows the $p_{\rm T}$-differential $R_{\rm AA}$, in $4 < p_{\rm T} < 10$ GeV/c, in the 10% most central collisions (left) and in the 40%–80% centrality class (right). A stronger suppression is observed in central collisions compared to peripheral collisions, with no significant $p_{\rm T}$ dependence within uncertainties. The suppression reaches a factor 3–4 in the 10% most central collisions. The $R_{\rm AA}$ measured in central collisions is compared to model predictions (Fig. 1, left). In addition to final state effects where in-medium energy loss would be dominant, initial state effects could influence the $R_{\rm AA}$ measurement. In the kinematic range relevant for heavy-flavour production, the main expected effect is nuclear shadowing. This effect was estimated by means of perturbative QCD calculations [5] and the EPS09 NLO parameterization of nuclear PDFs [6]. These calculations, shown as grey-dotted-dashed curve in the left panel of Fig. 1, indicate that, in the range $4 < p_{\rm T} < 10$ GeV/c, nuclear shadowing alone cannot explain the observed suppression at forward rapidity. The other predictions shown in Fig. 1 refer to the $R_{\rm AA}$ calculations with models implementing radiative energy loss (BDMPS-APW [8]), radiative and dissociation energy loss with in-medium hadronization [9], and a partonic transport model (BAMPS), which includes collisional energy loss and accounts effectively for radiative processes by scaling the binary cross section with a correction factor tuned at RHIC energies [7]. They describe the data reasonably well within uncertainties. The measured suppression at forward rapidity is similar to that reported for D mesons [10] and electrons from heavy flavour decays [11] measured at mid-rapidity with ALICE.

3. Elliptic flow of muons from heavy-flavour decays

We report on the first measurement of the elliptic flow of muons from heavy-flavour decays at forward rapidity ($2.5 < y < 4$) and high p_T ($p_T > 3$ GeV/c) in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The analysis uses the 2011 Pb–Pb data sample and is based on central and semi-central trigger events. Various analysis techniques which exhibit different sensitivity to non-flow effects and flow fluctuations have been exploited. In the following, we discuss results obtained with the scalar product [12], 2- and 4-particle Q-cumulants [13], and Lee-Yang zeros with sum and product generating functions [14]. The reference particle flow is determined from TPC standalone tracks. In order to determine the elliptic flow of muons from heavy-flavour decays ($v_2^{\mu\leftarrow HF}$), one needs to subtract background contribution from that of the inclusive muons. This is done according to:

$$v_2^{\mu\leftarrow HF} = \frac{v_2^{\mu} - f^{\mu\leftarrow K\pi} \cdot v_2^{\mu\leftarrow K\pi}}{1 - f^{\mu\leftarrow K\pi}}, \quad (1)$$

where v_2^{μ} is the measured inclusive muon elliptic flow and $v_2^{\mu\leftarrow K\pi}$ is the elliptic flow of decay muons. $f^{\mu\leftarrow K\pi}$ is decay muon fraction that contributes to the inclusive muon yield. The v_2 of decay muons is estimated by extrapolating to forward rapidity the elliptic flow of charged hadrons measured in $|\eta| < 2.5$ by the ATLAS collaboration [15] and performing fast detector simulations in order to obtain the decay muon v_2. The extrapolation is done in various p_T intervals with a 2^{nd} oder polynomial. Several other functions (polynomials up to 3^{rd} order, gaussian) are used to evaluate the systematic uncertainty, and they give the maximum $\sim 4\%$ uncertainty in the final results. The fraction of decay muons varies between 5–15%, depending

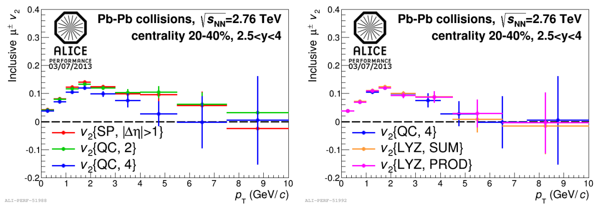

Figure 2. p_T-differential inclusive muon v_2 from various flow methods. Only statistical uncertainties are displayed.

on p_T and centrality [4]. Figure 2 presents the p_T-differential inclusive muon v_2 from 2- and multi-particle correlation flow methods in the centrality class 20–40%. Scalar product and 2-particle Q-cumulants give compatible results within uncertainties (Fig. 2, left). A similar behaviour is also observed when comparing results with 4-particle Q-cumulants and Lee-Yang zeros, indicating that non-flow contributions are negligible at 4^{th} order (Fig. 2, right). There is a systematic decrease of the v_2 magnitude with 4-particle Q-cumulants as compared to 2-particle Q-cumulants and scalar product, which might be attributed to initial flow fluctuations as already reported for charged hadrons measured with ALICE at mid-rapidity [16]. Figure 3 (left) displays the v_2 of muons from heavy-flavour decays in $3 < p_T < 10$ GeV/c as a function of the collision centrality, obtained via 2-particle Q-cumulants. A positive v_2 is measured in semi-central collisions (20–40% centrality class) with a significance larger than 3σ, and the

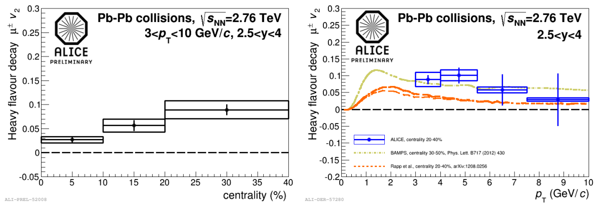

Figure 3. Left: v_2 of muons from heavy-flavour decays in $3 < p_T < 10$ GeV/c as a function of the collision centrality. Right: p_T-differential v_2 of muons from heavy-flavour decays in the 20–40% centrality class compared to model predictions (see text). Statistical (bars) and systematic (empty boxes) uncertainties are shown. The results are obtained via 2-particle Q-cumulants.

magnitude of v_2 decreases as the collision centrality increases. The p_T-differential v_2 of muons from heavy-flavour decays in the 20–40% centrality is compared to transport model predictions, BAMPS [7] and Rapp *et al* [17] (two orange lines show the band of uncertainty), in Fig. 3 (right). The data are well reproduced by the BAMPS calculations within uncertainties, while they are underestimated by the Rapp *et al* predictions obtained with a heavy-flavour transport model based on collisional processes where the interactions of heavy quarks with the medium proceed via resonance formation. Finally, it is worth noticing that the measured v_2 is comparable in magnitude with that measured at mid-rapidity for electrons from heavy-flavour decays [18].

4. Conclusion

The production and propagation of muons from heavy-flavour decays has been measured at forward rapidity in Pb–Pb collisions with ALICE. The R_{AA} results provide evidence for strong in-medium energy loss of heavy quarks in central collisions. We have presented the first measurement of the v_2 of muons from heavy-flavour decays at forward rapidity, which is found positive in the region $3 < p_T < 10$ GeV/c for semi-central collisions.

Acknowledgments

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References

[1] Aamodt K *et al* [ALICE Collaboration] 2008 *JINST* **3** S08002
[2] Dokshitzer Y L and Kharzeev D E 2001 *Phys. Lett.* B **519** 199 (*Preprint* hep-ph/0106202)
[3] Abelev B *et al* [ALICE Collaboration] 2012 *Phys. Lett.* B **708** 265 (*Preprint* arXiv:1201.3791)
[4] Abelev B *et al* [ALICE Collaboration] 2012 *Phys. Rev. Lett.* **109** 112301 (*Preprint* arXiv:1205.6443)
[5] Mangano M L *et al* 1992 *Nucl. Phys.* B **373** 295
[6] Eskola K *et al* 2012 *JHEP* **0904** 065 (*Preprint* arXiv:0902.4154)
[7] Uphoff J, Fochler O, Xu Z, and Greiner C 2012 *Phys. Lett.* B **717** 430 (*Preprint* arXiv:1205.4945)
[8] Armesto N *et al* 2005 *Phys. Rev.* D **71** 054027 (*Preprint* hep-ph/0501225)
[9] Sharma R *et al* 2009 *Phys. Rev.* C **80** 054902 (*Preprint* arXiv:0904.0032)
[10] Abelev B *et al* [ALICE Collaboration] 2012 *JHEP* **1209** 112 (*Preprint* arXiv:1203.2160)
[11] Thomas D for the ALICE Collaboration 2014 these proceedings.
[12] Adler C *et al* [STAR Collaboration] 2002 *Phys. Rev.* C **66** 034904 (*Preprint* nucl-ex/0206001)
[13] Bilandzic A, Snellings R, and Voloshin S 2011 *Phys. Rev.* C **83** 044913 (*Preprint* arXiv:1010.0233)
[14] Bhalerao R S *et al* 2003 *Nucl. Phys.* A **727** 373 (*Preprint* nucl-th/0310016)
[15] Aad G *et al* [ATLAS Collaboration] 2012 *Phys. Lett.* B **707** (2012) 330 (*Preprint* arXiv:1108.6018)
[16] Aamodt K *et al* [ALICE Collaboration] 2010 *Phys. Rev. Lett.* **105** 252302 (*Preprint* arXiv:1011.3914)
[17] He M, Fries R J, and Rapp R 2012 *Phys. Rev.* C **86** 014903 (*Preprint* arXiv:1106.6006)
[18] Dubla A for the ALICE Collaboration 2014 these proceedings