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

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Abstract

Results from the ALICE experiment on the production of muons from heavy-flavour decays, at forward rapidity, in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV are reported. A particular emphasis is placed on the measurement of the nuclear modification factor as a function of transverse momentum and centrality, and on the comparison to model predictions. First results on the inclusive muon elliptic flow are presented.

1. Introduction

ALICE [1] is the dedicated heavy-ion experiment at the LHC, optimized to study the properties of strongly interacting matter in the extreme conditions of high temperature and energy density expected to be reached. Heavy quarks (charm and beauty), abundantly produced at the LHC, are regarded as valuable probes of the medium. Due to their large masses, they are created mainly in hard scattering processes in the early stage of the collision and subsequently interact with this medium. In particular, open heavy-flavour hadrons can probe the energy density of the system via their in-medium energy loss. A common observable to quantify the in-medium effects is the nuclear modification factor R_{AA}:

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \times \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}, \tag{1}$$

where $\langle T_{\mathrm{AA}} \rangle$ is the average nuclear overlap function in a given centrality class, $\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}$ is the p_{T}-differential yield in nucleus-nucleus (AA) collisions and $\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}$ is the p_{T}-differential cross section in pp collisions. According to QCD, the radiative energy loss of gluons should be larger than that of quarks, and due the dead-cone effect [2], heavy quark energy loss should be reduced with respect to that of light quarks. The elliptic flow of heavy-flavour particles, the second order coefficient of Fourier coefficient of the momentum azimuthal distribution in azimuthal angle, is expected to provide insights on the possible degree of thermalization of heavy quarks in the medium at low p_{T} and on the path length dependence of energy loss at high p_{T}.

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[1] A list of members of the ALICE Collaboration and acknowledgements can be found at the end of this issue.

Open heavy flavours are measured in ALICE at mid-rapidity through the semi-electronic and hadronic decay channels, and at forward rapidity through the semi-muonic decay channel. In the following, we focus on the measurement of open heavy-flavour production at forward rapidity via single muons detected in the ALICE muon spectrometer (pseudo-rapidity coverage: $-4 < \eta < -2.5$) which is comprised of a thick front absorber, a beam shield, a dipole magnet, five tracking stations and two trigger stations behind an iron wall. In addition, the analysis presented in this proceedings uses the VZERO detector made of two scintillator arrays VZERO-A ($2.8 < \eta < 5.1$) and VZERO-C ($-3.7 < \eta < -1.7$), the two Zero Degree Calorimeters (ZDC) and the Silicon Pixel Detector (SPD).

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

The study of in-medium effects with the R_{AA} observable, Eq. (1), requires the measurement of the production cross section in pp collisions. The reference heavy-flavour cross section in pp collisions is obtained from the analysis of muon triggered events in pp collisions at $\sqrt{s}$ = 2.76 TeV collected in 2011, corresponds to an integrated luminosity $\mathcal{L}_{\mathrm{int}}$=19 nb^{-1}. Details about this analysis, including the identification of muons from heavy-flavour decays and the cross section measurement can be found in [3, 4]. The Pb–Pb data sample collected in 2010 with minimum bias trigger events is used to obtain the p_{T} distributions of muons from heavy-flavour decays for different centrality classes. The event centrality is defined from the sum of signals in the VZERO detectors. The analyzed statistics, after selection cuts, corresponds to $\mathcal{L}_{\mathrm{int}}$=2.7 μb^{-1}.

Muons are identified with same track selection criteria as in pp collisions. Geometrical cuts on η and θ_{abs} (reconstructed angle at the end of the absorber) are applied. These muon candidates are required to match to tracks reconstructed in the muon trigger system, in order to reject most of punch-through hadrons that are stopped in the iron wall. Furthermore, the correlation between the track momentum and the distance of closest approach to primary vertex is used to remove fake tracks and tracks from beam-gas interactions. The remaining background after these selection cuts consists of muons from primary light hadron decays (π and K, mainly). This contribution can not be evaluated as in pp collisions through Monte-Carlo simulations, due to the presence of unknown nuclear effects, in particular medium-induced parton energy loss at forward rapidity. Therefore, this background component is estimated by extrapolating the π and K distributions measured in the central barrel [1] to the forward rapidity in both the pp and Pb–Pb collisions, and generating the decay muons through simulations of the decay kinematics and the front absorber. For a detailed description of the procedure we refer to [4] and references therein.

Fig. 1 shows the p_{T}-differential R_{AA} in $4 < p_{\mathrm{T}} < 10$ GeV/c in the 10% most central collisions (left) and in the $40-80\%$ centrality class (middle). A stronger suppression is observed in central collisions than in peripheral collisions (reaching a factor 3–4), with no significant p_{T} dependence within uncertainties. The R_{AA} measured in central collisions is compared to model predictions (Fig. 1, left). In addition to in-medium energy loss at final state, the nuclear modification factor R_{AA} is also influenced by various initial state effects. In particular, the nuclear modification of the Parton Distribution Functions (PDF) of the nucleons in nuclei could modify the initial hard scattering probability and consequently the heavy-flavour production yields. In the kinematic range covered by this analysis, the main initial state effects are nuclear shadowing which suppresses the partons with nucleon momentum fraction smaller than 10^{-2}. This effect has been estimated via perturbative calculations [5] and the EPS09NLO parameterization [6]. These calculations (grey-dotted-dashed curve) indicate that, in the p_{T} range $4 < p_{\mathrm{T}} < 10$ GeV/c, nuclear shadowing alone cannot explain the observed suppression at forward rapidity. The other predictions refer to the R_{AA} calculation with models implementing collisional (BAMPS [7]), radiative energy loss (BDMPS-ASW [8]) and radiative energy loss with in-medium hadronization [9]. They describe reasonably well the data within uncertainties. A similar agreement between the D-meson R_{AA} at mid-rapidity and energy loss predictions was also mentioned in [10].

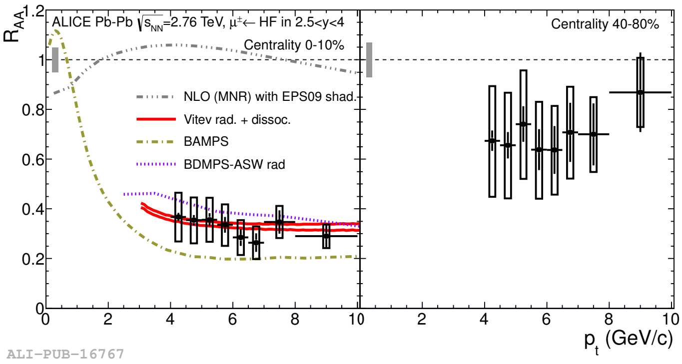

Figure 1: p_{T}-differential R_{AA} of muons from heavy-flavour decays in 0 – 10% (left) and 40 – 80% (right) centrality classes, respectively; statistical (bars), systematic (empty boxes) and normalization (filled boxes) uncertainties are shown; model predictions including shadowing alone and in-medium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

3. Inclusive muon elliptic flow

In this section, we report on the first measurement of the elliptic flow v_2 of inclusive muons at forward rapidity. The analysis is based on Pb–Pb data collected in 2011 by the muon trigger system. The v_2 coefficient is extracted by using the event plane and Lee-Yang zeros methods. In the event plane method, the azimuthal anisotropy is characterized by the Fourier coefficients calculated as:

$$v_n = \frac{\langle \cos n(\varphi - \Psi_n) \rangle}{\langle \cos n\Delta\varphi_R \rangle}, \tag{2}$$

where n is the order of the harmonic ($n = 2$ for elliptic flow component), φ is the muon azimuthal angle, and Ψ_n, the event plane for n-th order harmonic, is the estimated reaction plane. The average is done over particles and events. The resolution factor $1/\langle \cos n\Delta\varphi_R \rangle$ is an estimate of the error $\Delta\varphi_R = \Psi_n - \Psi_{\mathrm{RP}}$ on the reaction plane. In the present analysis, the event plane is measured in the VZERO-A to minimize auto-correlation effects (η gap of 5.3 between VZERO-A and muon spectrometer). The event plane resolution is determined with the three sub-event method with VZERO-A, VZERO-C (inner ring) and VZERO-C (outer ring) detectors. Alternatively, VZERO-A, VZERO-C and TPC (Time Projection Chamber) are also used as a second set of sub-events. More details on the implementation of the event plane method can be found in [11]. The Lee-Yang zeros method [12] which allows to extract v_2 directly from the genuine correlation between a large number of particles is also implemented. It uses the VZERO detector for the determination of the reference particle flow. Fig. 2 displays the inclusive muon v_2 as a function of the centrality percentile in the interval $2 < p_{\mathrm{T}} < 10$ GeV/c and $2.5 < y < 4$ from event plane and Lee-Yang zeros methods. A non-zero muon v_2 is measured in all centrality classes and the magnitude of v_2 increases as the centrality of the collision decreases. Moreover one can notice that as expected the Lee-Yang zeros method gives smaller v_2 values than the event plane method. Future improvements require the subtraction of the decay background contribution, in order to obtain the genuine elliptic flow from heavy flavour muons.

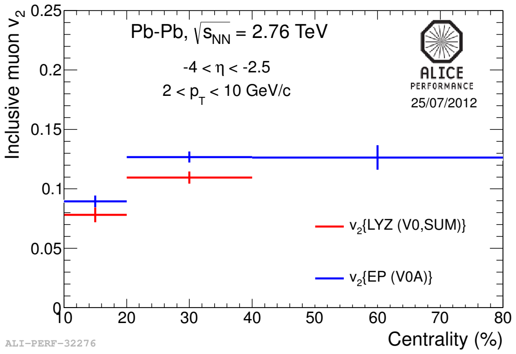

Figure 2: Inclusive muon v_2 as a function of centrality percentile from event plane and Lee-Yang zeros methods. Only statistical uncertainties are displayed.

4. Conclusions

The production of muons from heavy-flavour decays has been measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV with the ALICE muon spectrometer. The R_{AA} results give evidence for strong in-medium energy loss of heavy quarks at forward rapidity in central collisions. A non-zero v_2 of inclusive muons has been measured in the region $2 < p_{\mathrm{T}} < 10$ GeV/c. The forthcoming p–Pb run should allow to quantify initial state effects.

Acknowledgments

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