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 effective probes of this 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 are expected to be sensitive to the energy density of the system through the mechanism of in-medium energy loss of heavy quarks. A sensitive observable to quantify the in-medium effects is the nuclear modification factor R_{AA} defined as:

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

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 study of the heavy-flavour particle elliptic flow should carry complementary information on the medium transport properties. It 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}.

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 consists of a thick front absorber, a beam shield, a dipole magnet,

Preprint submitted to Nuclear Physics A *October 9, 2012*

five tracking stations and two trigger stations behind an iron wall. In addition, for the analysis presented here, 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) are used.

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 latter was obtained from the analysis of the pp data sample at $\sqrt{s} = 2.76$ TeV collected in 2011. Details about the analysis strategy from the identification of muons from heavy-flavour decays until the conversion of yields into a cross section 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 selections. The events are classified according to their degree of centrality by means of the sum of the amplitudes of the signals in the VZERO detectors. The analyzed statistics, after selection cuts, corresponds to an integrated luminosity $L_{\mathrm{int}} = 2.7\ \mu\mathrm{b}^{-1}$.

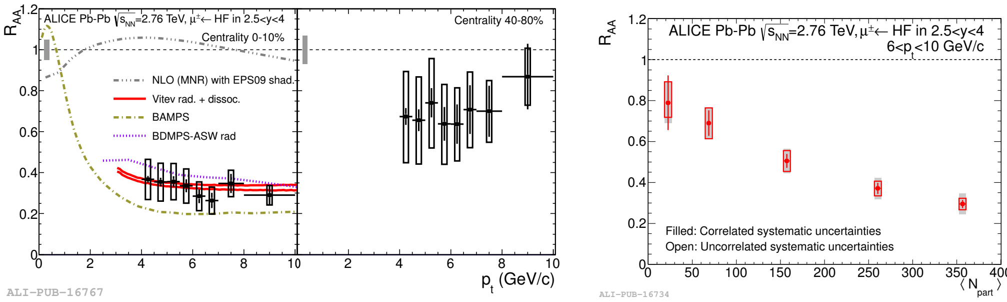

Figure 1: Left and middle: p_{T}-differential R_{AA} of muons from heavy flavour decays in 0–10% and 40%–80% centrality classes, respectively; statistical (bars), systematic (empty boxes) and normalization (filled boxes) uncertainties are shown. Data (0–10% centrality class) are compared to models including shadowing alone and in-medium energy loss. Right: R_{AA} of high p_{T} ($6 < p_{\mathrm{T}} < 10$ GeV/c) muons from heavy-flavour decays as a function of $\langle N_{\mathrm{part}} \rangle$.

Muons are identified by means of same track selection conditions as in pp collisions. Geometrical cuts on η and θ_{abs} (reconstructed angle at the end of the absorber) are applied. The track candidate in the tracking system has to be matched with the track 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 in order 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 cannot be evaluated as in pp collisions through Monte-Carlo simulations due to the presence of unknown nuclear effects, in particular medium-induced parton energy at forward rapidity. Therefore, this background component is estimated by extrapolating at 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 the front absorber. For a detailed description of the procedure we refer to [4] and references therein.

Figure 1 shows the p_T-differential R_{AA} in $4 < p_T < 10$ 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, 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 final state effects where in-medium energy loss would be dominant, initial state effects could influence the R_{AA} measurement. 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 relevant for heavy-flavour production, the main expected effect is the nuclear shadowing which reduces the PDF for partons with nucleon momentum smaller than 10^{-2}. This effect was estimated by means of perturbative calculations [5] and the EPS09NLO parameterization of the shadowing [6]. These calculations (grey-dotted-dashed curve) indicate that, in the p_T range of interest $4 < p_T < 10$ GeV/c, the 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 (BDMPS-APW [8]) and radiative 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 transport model predictions was also mentioned in [10]. The centrality dependence of the R_{AA} of muons from heavy-flavour decays in $6 < p_T < 10$ GeV/c, studied by means of $\langle N_{part} \rangle$ (average number of participation nucleons), is presented in Fig. 1 (right). In this region, the contribution of muons from beauty decays is dominant according to FONLL predictions for pp collisions at $\sqrt{s} = 2.76$ TeV [11, 4]. The R_{AA} of muons from heavy-flavour decays exhibits a strong suppression with increasing centrality, reaching a factor 3–4 in the most central collisions. This suppression is similar to that reported for D-mesons [10] and electrons from heavy flavour decays [12] measured at mid-rapidity in ALICE, and J/ψ from B decays measured in $|y| < 2.4$ and $6.5 < p_T < 30$ by the CMS Collaboration [13].

3. Inclusive muon elliptic flow

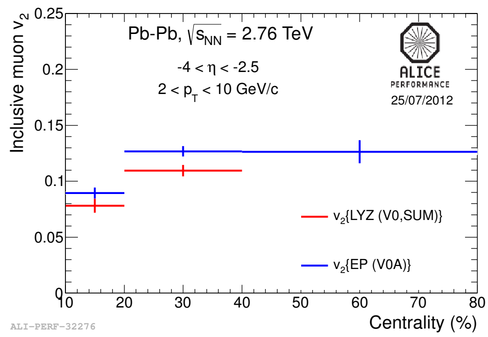

Figure 2: Inclusive muon v_2 as a function of centrality percentile from event plane and Lee-Yang zeros methods. Only statistical uncertainties are displayed.

A complementary analysis to the parton energy loss by means of the R_{AA} is provided by the nuclear collective 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 with muon trigger events. v_2 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:

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

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 harmonic of order n, is the estimated reaction plane. The resolution factor $1/\langle cosn\Delta\varphi_R\rangle$ 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 was determined by means of the azimuthal distribution of the VZERO-A amplitude only in order to avoid auto-correlation effects. 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 [14]. The Lee-Yang zeros method [15] which allows to extract v_2 directly from the genuine correlation between a large number of particles is also implemented. Such method is expected to provide the cleanest separation between flow and, non-flow effects and flow fluctuations. It uses the VZERO detector for the determination of the reference particle flow. Figure 2 displays the inclusive muon v_2 as a function of the centrality percentile in the region $2 < p_{\mathrm{T}} < 10$ 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 selections 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. Such behaviour demonstrates that the two methods exhibit different sensitivities to flow fluctuations and contribution from non-flow effects.

4. Conclusion

The production of muons from heavy-flavour decays has been measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV using the excellent capabilities of 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 $2 < p_{\mathrm{T}} < 4$ GeV/c. The forthcoming p–Pb run should allow to quantify initial state effects.

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