Open heavy-flavour results from ALICE

Diego Stocco for the ALICE Collaboration
SUBATECH (Ecole des Mines, CNRS-IN2P3, Université de Nantes), Nantes, France
E-mail: diego.stocco@subatech.in2p3.fr

Abstract. The ALICE Collaboration has measured heavy-flavour production in a wide rapidity range and in several decay channels in pp, Pb–Pb and, recently, in p–Pb collisions. An overview of some recent results is presented in this paper, with a particular emphasis on the first measurements in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. A selection of the new results in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV is discussed as well.

1. Introduction

The ALICE experiment [1] studies the properties of the strongly interacting matter at the extreme energy densities reached in ultra-relativistic heavy-ion collisions at the LHC. The measurement of open charm and open beauty production plays an important role in the investigation, shedding light on the mechanisms of parton energy loss and hadronization in the hot and dense medium formed in high-energy nucleus-nucleus collisions. In particular, it allows one to test theoretical models predicting that the energy loss increases with the colour charge of the parton and decreases with its mass [2]. Heavy-flavour measurements in nucleon–nucleon and nucleon–nucleus collisions are mandatory for this study: the former sets the reference, while the latter allows to disentangle the initial-state effects (such as the modification of the Parton Distribution Functions in nuclei [3], the saturation of the gluon distribution at low Bjorken-x values and transverse momentum broadening of partons [4]), from the ones due to the interaction with the high energy density medium.

The excellent performance of the ALICE detector allows heavy-flavour measurements in several decay channels and in a wide rapidity range. At forward rapidity, open heavy-flavour production is studied inclusively in the semi-muonic decay channel. At mid-rapidity, D mesons are reconstructed via their hadronic decays and, in addition, electrons from semi-leptonic decays of charm and beauty hadrons are measured. After a description of the experimental apparatus and the strategy used for the measurements (Section 2), the most recent results in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV (Section 3) and the very first results in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV (Section 4) will be discussed. The pp results are not treated in this paper, but an interesting recent study on D meson production as a function of charged particle multiplicity is discussed elsewhere in these proceedings [5].

2. Heavy-flavour measurements with ALICE

ALICE [1] consists of a central barrel, a Muon Spectrometer and a set of detectors at large rapidities for global event characterisation and trigger. The central barrel ($|\eta| < 0.9$) is equipped with a solenoidal magnet providing a magnetic field up to 0.5 T, which allows the measurement of charged particles down to low p_T. The tracking is performed by combining the information from the Time Projection Chamber (TPC) and the Inner Tracking System (ITS). The latter is made of six layers of silicon detectors providing a resolution on the distance between the track and the primary vertex (impact parameter) of better than 65 μm for $p_T > 1$ GeV/c [6]. Charged particles are identified via their specific energy loss in the TPC and their time of flight, measured with the TOF detector. The electron identification can include, in addition, the information from the Transition Radiation Detector (TRD) and the Electromagnetic Calorimeter (EMCal).

Muons with momenta larger than 4 GeV/c are reconstructed and identified in the pseudo-rapidity interval $-4 < \eta < -2.5$ with the Muon Spectrometer. This consists, as seen from the interaction point, of a composite frontal absorber, 5 stations of tracking chambers, an iron wall and 2 stations of trigger chambers [1]. Charged particles are bent by a dipole magnet providing a 3 T$\times$m magnetic field and are identified as muons if they reach the trigger stations placed downstream the iron wall of about 7.2 interaction length thickness.

The event centrality is estimated event by event from the signal amplitudes in two arrays of scintillator hodoscopes (VZERO), covering the full azimuth in the pseudo-rapidity regions $2.8 < \eta < 5.1$ and $-3.1 < \eta < -1.7$.

Charmed mesons are measured through the exclusive reconstruction of the hadronic decay channels: $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$ and $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ and their charge conjugates. The large combinatorial background is reduced by selections based on the decay topology. At low momenta, the background is further suppressed by the kaon identification with the TPC and TOF detectors. D-meson raw yields are then extracted through the analysis of the invariant mass of their decay products. The results include both the prompt contribution and the feed down from the decay of hadrons containing beauty. The latter is estimated with perturbative QCD calculations in the framework of Fixed-Order Next-to-Leading Log (FONLL) [7] and subtracted (see [6] for further details).

The measurement of electrons from heavy-flavour decays at mid-rapidity ($|\eta| < 0.8$) requires the subtraction of several background contributions from the inclusive electron sample. The most important are photon conversions in the beam pipe and detector material, Dalitz decays of light neutral mesons, di-electron decays of vector mesons and direct radiation. Such contributions are described by a Monte Carlo cocktail based on the measured distributions of π^0, with the resonance decay contributions obtained through m_T scaling. Alternatively, the contribution of electrons from Dalitz decay and gamma-conversions was evaluated from the opposite-sign electron pairs with an invariant mass close to zero [8].

Muons from heavy-flavour decays are measured at forward rapidity. The main source of background in the inclusive transverse momentum distribution consists of muons from the decay of light hadrons. This contribution dominates the low-p_T region of the spectrum, and can therefore be rejected by a cut on the muon p_T. The remaining contamination at larger transverse momenta is estimated with Monte Carlo simulations in pp collisions and with a data driven method (based on the the extrapolation at forward rapidity of the pion and kaon yields measured at mid-rapidity) in Pb–Pb collisions and it is subtracted [9].

3. Suppression and azimuthal anisotropy in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The study of the relative variation of particle production in heavy-ion collisions with respect to the pp reference is commonly performed through the nuclear modification factor (R_{AA}), which is defined as:

$$R_{AA}(x) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dx}{d\sigma_{pp}/dx} \tag{1}$$

where dN_{AA}/dx ($d\sigma_{pp}/dx$) is the yield (cross-section) of particles as a function of a variable x measured in heavy-ion (pp) collisions, and $\langle T_{AA} \rangle$ is the nuclear overlap function calculated in the framework of the Glauber model. In the absence of initial-state or medium effects, R_{AA} is expected to be one for heavy flavours, whose yields are proportional to the number of binary nucleon-nucleon collisions (binary-scaling).

The nuclear modification factors of D mesons [6] and electrons from heavy-flavour decays [10] at mid-rapidity and of muons from heavy-flavour decays at forward rapidity [9] have been measured with ALICE: all of the results show a strong reduction of the yields at large transverse momenta ($p_\mathrm{T} \gtrsim 5$ GeV/c) in the most central collisions. The R_AA of D mesons was also compared with the one of charged particles and pions [11, 12]: a similar suppression is observed, although the uncertainties do not allow yet to draw a strong conclusion on the colour charge dependence of the parton energy loss. The nuclear modification factor of D mesons was recently measured as a function of centrality (estimated as the average number of participant nucleons, scaled with the number of nucleon-nucleon collisions from the Glauber model) [11]. The results are shown in the left panel of Figure 1 (black squares): R_AA depends on centrality, decreasing from peripheral to central collisions. The blue filled circles in the same figure show the equivalent measurement for non-prompt J/ψ (i.e. coming from beauty hadron decays) from CMS [13]. A similar suppression pattern is observed, but with a value of R_AA which is about two times larger than for D mesons. The p_T range of the two results is chosen in such a way that the average p_T of the parent B mesons is compatible with the one of D mesons, thus allowing for a consistent comparison of charm and beauty hadrons. The result is therefore an indication of a smaller in-medium energy loss for beauty than for charm quarks.

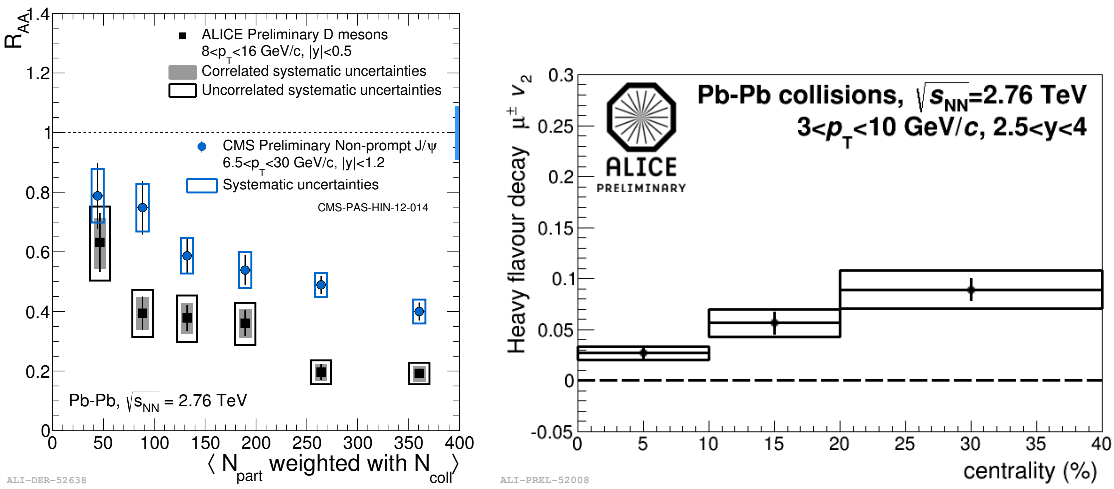

Figure 1. Left panel: nuclear modification factor as a function of centrality for D mesons measured with ALICE (black squares) and non-prompt J/ψ from CMS [13] (blue filled circles). Right panel: elliptic flow of muons from heavy-flavour decays as a function of centrality. The bars (open boxes) are the statistical (systematic) uncertainties.

In semi-central heavy-ion collisions, the initial geometrical azimuthal anisotropy can be converted into an anisotropy in momentum space in case of thermalisation or rescattering of particles with the medium. This anisotropy is quantified by the Fourier expansion of the azimuthal distributions of particles with respect to the plane defined by the impact parameter and the collision axis (Ψ_{RP}):

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \Psi_{RP})\right)\right) \tag{2}$$

The coefficient of the second order harmonic of the expansion (v_2) is called elliptic flow.

The ALICE Collaboration measured the elliptic flow of D mesons [14] and electrons from heavy-flavour decays [10] at mid-rapidity: a positive value of v_2 is observed at intermediate p_T in semi-central collisions. The measured v_2 of D mesons in the 30-50% centrality is comparable in magnitude to the one of charged hadrons, thus suggesting that the relaxation time of charm quarks in the medium is similar to that of light partons [14]. The v_2 of muons from heavy-flavour decays at forward rapidity was also measured for the first time with ALICE, in the transverse momentum range $3 < p_T < 10$ GeV/c [15]. The results are shown in the right panel of Figure 1 as a function of the collision centrality: the value of v_2 increases from central to peripheral collisions. A positive value of v_2 is observed, thus indicating that heavy quarks participate in the collective motion of the system. These measurements are a powerful test for theoretical models implementing different mechanisms for the energy loss of charm and beauty quarks: while many of them are able to reproduce the reduction of yields at high p_T (see e.g. [12] and references therein), the simultaneous description of R_{AA} and v_2 is challenging.

4. Nuclear modification factor in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The ALICE Collaboration measured heavy-flavour production in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV: the first results are shown in Figure 2. The left panel shows R_{pPb} of electrons

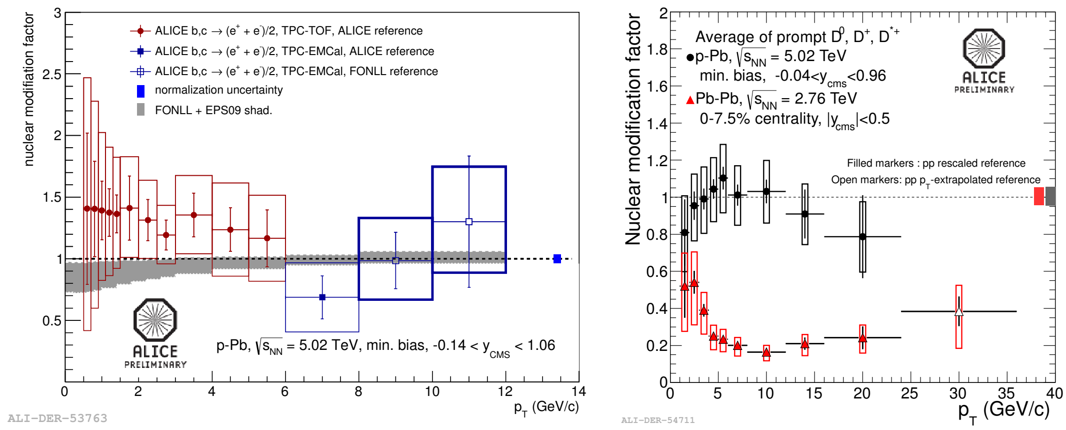

Figure 2. Left panel: nuclear modification factor of electrons from heavy-flavour decays in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Measurements were performed using the TPC-TOF (red circles) or TPC-EMCal (blue squares). At high p_T, the open symbols denote that FONLL [7] calculations were used as a reference instead of rescaled data (see text). pQCD predictions [16] with EPS09 [3] implementation of the nuclear modification of PDFs are also shown (grey band). Right panel: nuclear modification factor of D mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (black circles) compared to Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (red triangles).

from heavy-flavour decays (see also [8]). At low transverse momenta, the analysis is performed by using the TPC-TOF information (red circles) while at larger momenta, the EMCal is also used for electron identification (blue squares). The reference consists of p_T-differential cross sections of heavy flavour decay electrons measured in pp collisions at $\sqrt{s} = 7$ TeV [8] and extrapolated to $\sqrt{s} = 5.02$ TeV with a scaling procedure based on the FONLL [7] predictions at both energies. At high transverse momenta, however, where the statistical uncertainties of the pp results are large, the FONLL predictions at $\sqrt{s} = 5.02$ TeV are used directly (open blue square). The results are consistent within uncertainties with pQCD calculations [16] with EPS09 [3] implementation of the nuclear modification of PDFs (grey band).

The right panel of Figure 2 shows the R_{pPb} of D mesons (black circles). Also in this case, the data are well described by pQCD calculations with shadowing (see [17] for further details).

The initial-state effects are indeed rather small, and cannot account for the small R_{AA} observed in heavy-ion collisions (red triangles), which is therefore a genuine effect of the interaction with the hot and dense medium.

5. Summary

The ALICE Collaboration measured heavy-flavour production in pp, p–Pb and Pb–Pb collisions at the LHC. In Pb–Pb collisions, new results on the nuclear modification factor of D mesons as a function of the collision centrality allow for a comparison with the non-prompt J/ψ measured with CMS in a consistent transverse momentum range of the D and B mesons. The results give an indication of a smaller energy loss for beauty than for charm. The first measurement of the elliptic flow of muons from heavy-flavour decays in $2.5 < y < 4$ has been presented: the value of v_2 is larger than zero, thus indicating that heavy quarks participate in the collective motion of the system. The simultaneous reproduction of R_{AA} and v_2 measurements in the wide rapidity range of ALICE is a challenge for theoretical models implementing different mechanisms of heavy quark energy loss in medium.

The nuclear modification factor of D mesons and electrons from heavy-flavour decays was also measured for the first time in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The $\mathsf{R}_{\mathrm{pPb}}$ is consistent within uncertainties with perturbative QCD calculations [16] with EPS09 [3] implementation of the nuclear modification of PDFs. The resulting effect is small with respect to the large reduction of heavy-flavour yields observed in Pb–Pb collisions, which is therefore an effect of the charm (beauty) quark in-medium energy loss.

References

[1] Aamodt K *et al.* (ALICE Collaboration) 2008 *JINST* **3** S08002

[2] Armesto N, Dainese A, Salgado C A and Wiedemann U A 2005 *Phys.Rev.* **D71** 054027

[3] Eskola K, Paukkunen H and Salgado C 2009 *JHEP* **0904** 065

[4] Blaizot J P, Gelis F and Venugopalan R 2004 *Nucl.Phys.* **A743** 13–56

[5] Bala R (ALICE Collaboration) Open-charm production as a function of charged particle multiplicity in pp collisions at $\sqrt{s} = 7$ TeV with ALICE *These proceedings*

[6] Abelev B *et al.* (ALICE Collaboration) 2012 *JHEP* **1209** 112

[7] Cacciari M, Frixione S, Houdeau N, Mangano M L, Nason P *et al.* 2012 *JHEP* **1210** 137

[8] Heide M (ALICE Collaboration) Measurement of electrons from heavy-flavour hadron decays in pp and p–Pb collisions with ALICE at the LHC *These proceedings*

[9] Abelev B *et al.* (ALICE Collaboration) 2012 *Phys.Rev.Lett.* **109** 112301

[10] Thomas D (ALICE Collaboration) Measurement of electrons from heavy flavour decays in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with ALICE *These proceedings*

[11] Bruna E (ALICE Collaboration) D-meson nuclear modification factor and v_2 in Pb–Pb collisions *These proceedings*

[12] Conesa del Valle Z (ALICE Collaboration) 2013 *Nucl.Phys.* **A904-905** 178c–185c

[13] Chatrchyan S *et al.* (CMS Collaboration) 2012 *CMS-PAS-HIN-12-014*

[14] Abelev B *et al.* (ALICE Collaboration) 2013 *Phys.Rev.Lett.* **111** 102301

[15] Zhang X (ALICE Collaboration) Nuclear modification factor and elliptic flow of muons from heavy-flavour decays in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with ALICE *These proceedings*

[16] Mangano M L, Nason P and Ridolfi G 1992 *Nucl.Phys.* **B373** 295–345

[17] Luparello G (ALICE Collaboration) Measurement of D-meson production in p–Pb collisions with the ALICE detector *These proceedings*