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Heavy-flavour correlations in pp, p-Pb and Pb-Pb collisions with ALICE

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Abstract. Heavy quarks (charm and beauty) are produced in initial hard scattering processes in heavy-ion collisions, before the formation of a strongly-interacting medium, the Quark-Gluon Plasma (QGP). The measurement of angular correlations between open heavy-flavour hadrons and charged particles can provide insight into the effects of the medium on charm and beauty production. For instance, in Pb-Pb collisions, the azimuthal correlations can provide information on the energy-loss mechanisms of heavy quarks in the QGP. Additionally, azimuthal correlations are sensitive to possible modifications of the heavy-quark parton shower and hadronisation in the presence of the medium. The observed double-ridge long-range correlations between light hadrons in p-Pb collisions could originate from a collective expansion of the system, as well as from gluon saturation in the initial state (color-glass condensate). The same effect can be studied for heavier quarks via the correlation between heavy-flavour hadrons (or their decay electrons) and charged particles. In pp collisions, the azimuthal correlations allow to measure the beauty production cross section as well as they represent a powerful tool to test pQCD models.

1. Introduction

The transverse-momentum (p_{T}) differential production cross section of D mesons and electrons from heavy-flavour hadron decays at central rapidity has been measured by the ALICE collaboration in pp, p-Pb and Pb-Pb collisions at $\sqrt{s} = 2.76$ and 7 TeV, $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV, respectively [1, 2, 3, 4, 5, 6, 8, 7]. A strong suppression of the open-charm hadron yields was observed for $p_{\mathrm{T}} > 3$ GeV/c in Pb-Pb collisions. In p-Pb collisions no modification of the spectra was observed in the p_{T} range $1 < p_{\mathrm{T}}\,(\mathrm{D}) < 24$ GeV/c within the 15-20% uncertainties. This suggests that the suppression measured in Pb-Pb collisions can be attributed to a substantial in-medium energy loss of the heavy quarks [5].

Further insight into the charm energy loss mechanism in the QGP can be obtained with measurements of angular correlations between heavy-flavour hadrons (or their decay electrons) and the charged particles produced in the same di-jet as the heavy quark. The angular correlation distribution on the near side (i.e. the same azimuthal direction as the heavy-flavour "trigger" particle) is sensitive to possible modifications of the jet properties (e.g. shape and number of constituent particles) in the medium. On the other hand, the away side (i.e. the direction opposite in azimuth with respect to the trigger particle) is sensitive to the path-length dependence of the energy loss. The main observable to quantify the angular correlation distribution is I_{AA}, defined as

$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}, \quad \text{with} \quad Y = \frac{1}{N_{trig}} \int \frac{dN^{assoc}(\Delta\varphi)}{d\Delta\varphi} d\Delta\varphi \tag{1}$$

which measures the associated yield in a given $\Delta\varphi$ (the difference in the azimuthal angle between the trigger and the associated particle) region and which can be compared in different collision systems.

In hadron-hadron correlations, measured in p-Pb collisions, a long-range azimuthal correlation, extended in pseudorapidity η, has been observed, after the jet contribution has been subtracted. This can be interpreted both as a final-state effect related to collective motion described by hydrodynamics or as an initial-state color-glass condensate (CGC) effect [9, 10]. One of the goals of the measurements of heavy-flavour triggered correlations in p-Pb collisions is to verify if this effect is observed also in the heavy-flavour sector.

In pp collisions, the azimuthal correlation of electrons from heavy-flavour decays with charged particles can be used to separate the beauty and charm contributions. This allows for the measurement of the relative fraction of electrons originating from a decay of a beauty hadron in the inclusive sample of electrons from heavy-flavour decays, that is then used to calculate the beauty cross section.

2. Heavy-flavour angular correlation analysis

Heavy-flavour production is measured in two different ways with ALICE at mid rapidity: by fully reconstructing D-meson hadronic decays and by measuring electrons originating from heavy-flavour hadron decays. D mesons are reconstructed in the ALICE central barrel via their hadronic decay channels, $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$. The identification of the D mesons is possible thanks to the resolution of a few tens of μm on the track position close to the primary vertex provided by the Inner Tracking System (ITS). Indeed, the D-meson decay vertices are displaced from the primary vertex, and this feature is used to reduce the otherwise overwhelming combinatorial background. The measurement of the specific energy loss dE/dx with the Time Projection Chamber (TPC) and of the time of flight with the Time Of Flight (TOF) detector allows for a reliable identification of kaons and pions up to $p_{\mathrm{T}} = 2$ GeV/c which is used to further suppress the combinatorial background. The invariant mass distribution of D-meson candidates is fitted with a gaussian distribution for the signal and a parametrisation for the background. The D-meson candidates, whose reconstructed invariant mass falls within a $\pm 2\,\sigma$ (the width of the Gaussian function obtained from the fitting procedure) window around the nominal D-meson mass are paired with charged particles produced in the collision, and for each "trigger"-associated particle pair the difference in pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\varphi$) is calculated. Every correlation pair in the obtained two dimensional ($\Delta\varphi$,$\Delta\eta$) distribution is weighted with the inverse of the trigger particle reconstruction efficiency and the inverse of the reconstruction efficiency of the associated tracks. The resulting angular correlation distributions include the contributions of both signal and background candidates. The latter contribution is subtracted using the sidebands (4-8 σ region) of the D-meson peak in the invariant mass distribution to build the background distribution.

Electrons are identified using the TPC and TOF detectors and by exploiting the measurement of the electron energy E with the Electromagnetic Calorimeter (EMCal). The inclusive sample of electrons does not only contain electrons from heavy-flavour decays, but also photonic electrons. Photonic electrons are electrons from Dalitz decays of light mesons (in particular π^0 and η) and electrons from photon conversions, that are identified using the invariant mass of the electron-positron pair[14, 6]. The ($\Delta\varphi$,$\Delta\eta$) distribution is calculated in the same way as for the D meson, and the respective reconstruction efficiency corrections are applied.

To correct for the effects of detector inhomogenities and of limited detector acceptance, the event mixing technique is used. D mesons (or electrons) are paired with charged tracks from other events with similar multiplicity and position of the collision vertex along the beam axis. The obtained distribution is normalized to 1 for ($\Delta\varphi$,$\Delta\eta$) = (0,0) and the inverse of the latter is used as a weight map for the distribution obtained from correlations in the same event.
In addition, for the D meson–charged particle azimuthal correlation analysis, the angular distribution of D mesons originating from B-meson decays must be subtracted. The fraction of the latter is computed using the efficiency calculated for prompt and secondary D mesons and the p_{T}-differential cross sections obtained from a FONLL perturbative QCD calculation [1, 15], while the correlation distribution of D mesons from B decays with charged particles is obtained from simulations performed with the PYTHIA generator [11].
The fully corrected distribution, obtained after normalization to the number of heavy-flavour candidates, is studied differentially as function of the transverse momentum of the trigger particle and of the associated tracks and, in the case of the electrons, where the available statistics allows this, also as function of the event multiplicity (p-Pb) and centrality (Pb-Pb).

3. Results

The D meson–charged particle azimuthal correlation analysis has been performed on a data sample of $3.14 \cdot 10^8$ minimum bias pp collisions and $1.3 \cdot 10^8$ minimum bias p-Pb collisions. The minimum-bias trigger required the arrival of bunches from both directions and coincident signals in both scintillator arrays of the V0 detector, covering the regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$. The analysis was performed in three D-meson p_{T} intervals in pp collisions ($3 < p_{\mathrm{T}}\,(\mathrm{D}) < 5$ GeV/c, $5 < p_{\mathrm{T}}\,(\mathrm{D}) < 8$ GeV/c and $8 < p_{\mathrm{T}}\,(\mathrm{D}) < 16$ GeV/c) and in two p_{T} intervals in p-Pb collisions ($5 < p_{\mathrm{T}}\,(\mathrm{D}) < 8$ GeV/c and $8 < p_{\mathrm{T}}\,(\mathrm{D}) < 16$ GeV/c). Different minimum thresholds for the associated track p_{T} were studied ($p_{\mathrm{T}}^{assoc} >$0.3, 0.5 and 1 GeV/c).

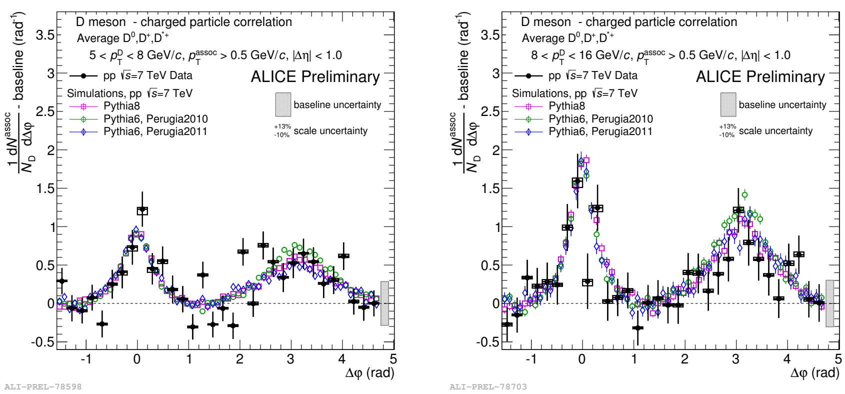

Figure 1. Left: D meson–charged particle $\Delta\varphi$ correlations for 5 GeV/c $< p_{\mathrm{T}}\,(\mathrm{D}) <$ 8 GeV/c and $p_{\mathrm{T}}^{assoc} > 0.5$ GeV/c compared with results from different PYTHIA generators [11, 12]. Right: Same as left panel, but for 8 GeV/c $< p_{\mathrm{T}}\,(\mathrm{D}) <$ 16 GeV/c.

Figure 1 shows the D meson–charged particle azimuthal correlation in pp collisions for 5 GeV/c $< p_{\mathrm{T}}\,(\mathrm{D}) <$ 8 GeV/c (left panel) and 8 GeV/c $< p_{\mathrm{T}}\,(\mathrm{D}) <$ 16 GeV/c (right panel), with $p_{\mathrm{T}}^{assoc} > 0.5$ GeV/c. The distributions from data are compared to the distributions obtained from Monte-Carlo simulations obtained with different tunes of the PYTHIA generator [11, 12].

The baseline, that is due to the uncorrelated background, is calculated from the transverse region $\pi/4 < |\Delta\varphi| < \pi/2$, and has been subtracted in order to study the near-side and away-side peak properties. The variation of the baseline upon redefinition of the above mentioned interval is treated as a systematic uncertainty. All the different Monte-Carlo distributions describe well the distributions from data within the relatively large statistical uncertainties.

The left panel of Fig.2 shows the azimuthal correlation distribution between D mesons and

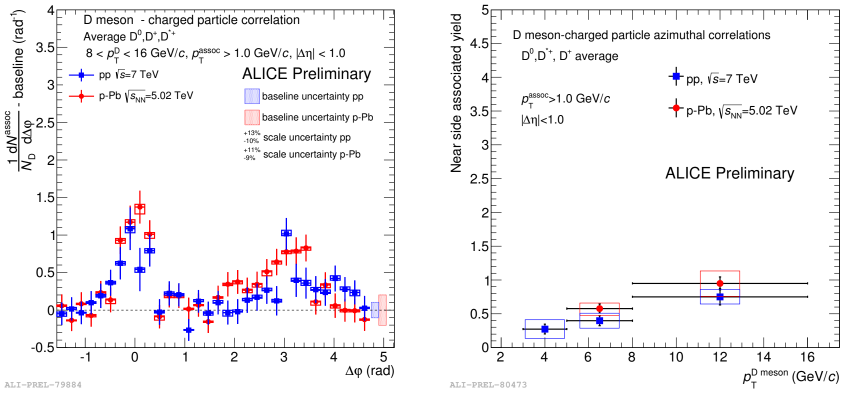

Figure 2. Left: D meson–charged particle $\Delta\varphi$ correlations for 8 GeV$/c < p_{\mathrm{T}}$ (D) $<$ 16 GeV$/c$ and p_{T}^{assoc} >1 GeV$/c$. Right: near-side yield as function of the D-meson p_{T}.

charged particles in the interval $|\Delta\eta| < 1$ for $8 < p_{\mathrm{T}}$ (D) $<$ 16 GeV$/c$ and p_{T}^{assoc} >1 GeV$/c$. The azimuthal correlation distributions measured in pp and p-Pb collisions agree within uncertainties after subtracting the baseline due to the uncorrelated background. The same is observed also for the other minimum thresholds of the associated tracks that were studied. The azimuthal correlation distributions are fitted with a double Gaussian (one for the near-side and one for the away-side peaks). The near-side associated yields are obtained as the integral of the Gaussian distribution that is centered at $\Delta\varphi = 0$. The main source of systematic uncertainty is the definition of the baseline as described above, and it is estimated by recalculating the near side yield upon redefinition of the interval where the baseline is computed. The right panel of Fig. 2 shows the trends of the near-side associated yield as function of the D-meson p_{T} in pp and p-Pb collisions, confirming the agreement within uncertainties already observed in the comparison of the azimuthal correlation distributions in the two collision systems.

The angular correlation distribution between heavy-flavour decay electrons and charged particles has been measured in pp, p-Pb and in Pb-Pb collisions [7]. The pp analysis has been performed on the EMCal-triggered data sample at $\sqrt{s} = 2.76$ TeV, containing $6.4 \cdot 10^5$ events. The measured angular correlation of electrons from heavy-flavour decays and charged particles is composed of electrons originating from beauty hadrons and charm hadrons. By exploiting the different decay kinematics (that is due to the fact that beauty hadrons are heavier than charm hadrons) the two contributions can be separated, and the fraction of electrons from beauty decays, r_B, can be extracted using PYTHIA Monte-Carlo templates [11]. The fraction r_B is defined as

$$r_B = \frac{N_B}{N_C + N_B} \tag{2}$$

where N_B represents the total number of electrons originating from beauty decays, while N_C represents the total number of electrons originating from charm decays.

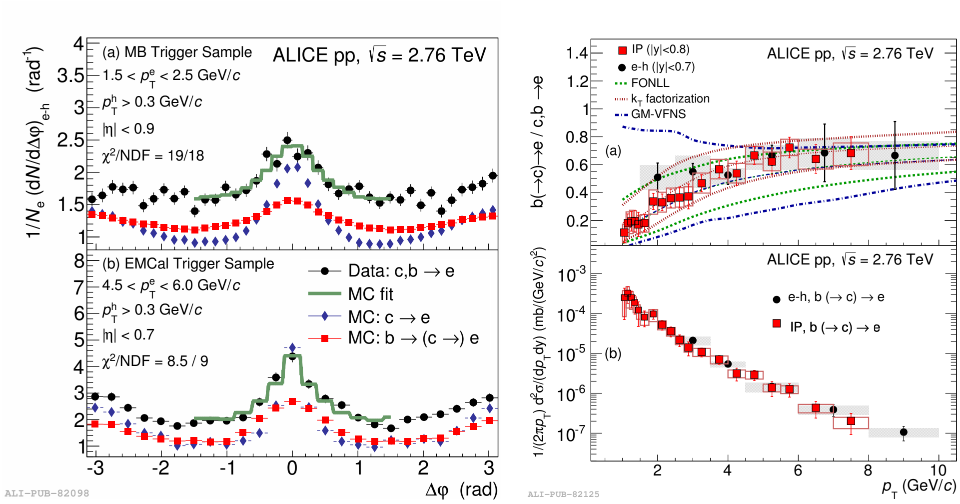

Figure 3. Upper left: azimuthal correlation of electrons from heavy-flavour decays and charged particles in pp collisions at $\sqrt{s} = 2.76$ TeV, for 1.5 GeV/c < p_{T} (e) < 2.5 GeV/c and p_{T}^{assoc} >0.3 GeV/c. Lower left: same as Upper left, but for 4.5 GeV/c < p_{T} (e) < 6 GeV/c. Upper right: r_B fractions using the azimuthal correlation method as function of the electron p_{T}compared to the r_B ratio using the impact parameter method [13] and different model predictions. The dashed line represent different model prediction. Lower right: The beauty cross section as function of the beauty-decay electron p_{T}, following the same colouring scheme as the upper-right figure.

The left panel of Fig.3 shows the heavy-flavour decay electron (HFE)-charged particle $\Delta\varphi$ distribution from data and those from the Monte-Carlo templates: $\Delta\varphi^C_{templ}$, the template of electrons from charm-hadron decays and, $\Delta\varphi^B_{templ}$, the template of electrons from beauty-hadron decays. These measured distributions are fitted following the parametrisation:

$$\Delta\varphi = const + r_B \Delta\varphi^B_{templ} + (1 - r_B)\Delta\varphi^C_{templ} \tag{3}$$

From the fitting procedure it is possible to extract r_B and the result is shown in the upper right panel of Fig. 3 as function of the electron p_{T}. The r_B ratio obtained from azimuthal correlations is in good agreement with the one obtained using the impact parameter method [13] and the one obtained from FONLL predictions [15]. The lower right panel of Fig. 3 shows the beauty-decay electron production cross section, calculated by multiplying the inclusive heavy-flavour cross section with the r_B fraction.
The Pb-Pb analysis has been performed in two centrality classes: central (0-8%) and semi-central (20-50%) collisions, containing $1.6 \cdot 10^7$ and $9.5 \cdot 10^6$ events, respectively. The datasets have been acquired using centrality triggers based on the measured V0 amplitude. The left panel of Fig. 4 shows the comparison of the azimuthal correlations between heavy-flavour decay electrons and charged particles in pp collisions and in central and semi-central Pb-Pb collisions for 6 < p_{T} (e) < 8 GeV/c and 4 < p_{T}^{assoc} < 6 GeV/c. The baseline, including a modulation reflecting the correlation due to elliptic flow [14], has been subtracted from the Pb-Pb distributions. Within the statistical uncertainties, the three correlation distributions agree with each other. The right panel of Fig. 4 shows I_{AA} for the central and semi-central collisions. I_{AA} is compatible with one within the uncertainties. The current statistics does not allow to conclude on a possible modification of the near-side structure.
The electron–charged particle correlation distribution in p-Pb collision is shown in Fig. 5. The left panel shows a comparison of the correlation distributions for different p-Pb multiplicity classes from V0A (forward multiplicity detector with 2.8< η <5.1) and for pp collisions for 1

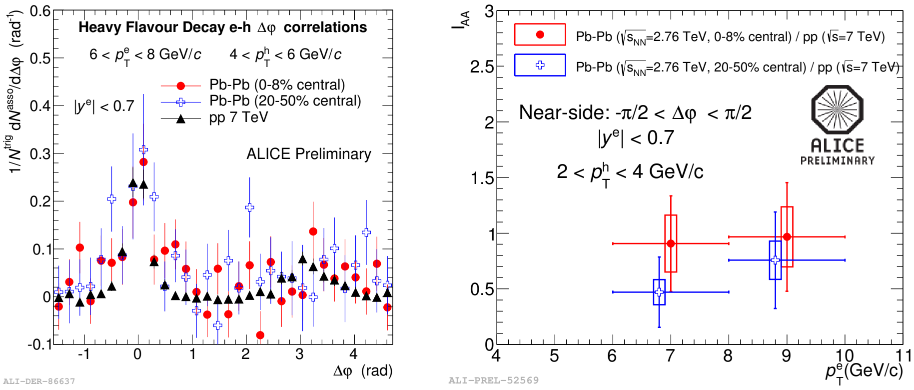

Figure 4. Left: Azimuthal correlations between heavy-flavour decay electrons and charged particles in pp collisions, central and semi-central Pb-Pb collisions for 6 GeV/c < p_T^e < 8 GeV/c and 4 < p_T^{assoc} < 6 GeV/c. Right: near side I_{AA} as function of p_T (e).

< p_T (e) < 2 GeV/c and 0.5 < p_T^{assoc} < 2 GeV/c. A multiplicity dependence of the near-side and away-side correlation peaks is observed: the 60-100% p-Pb lowest multiplicity class is compatible with pp collisions, while an increase of the correlation yield is observed moving towards higher multiplicities.
After subtracting the correlation distribution of the 60-100% multiplicity class from the one of the 0-20% multiplicity class to remove jet-like contributions, within the limited statistics a long-range double-ridge structure is observed as shown in the right panel of Fig. 5. This distribution is qualitatively similar to the one observed in the hadron-hadron correlation analysis (dominated by light-flavour particles) [9]. This suggests that the mechanism that generates these long-range correlation structures may affect also heavy flavours.

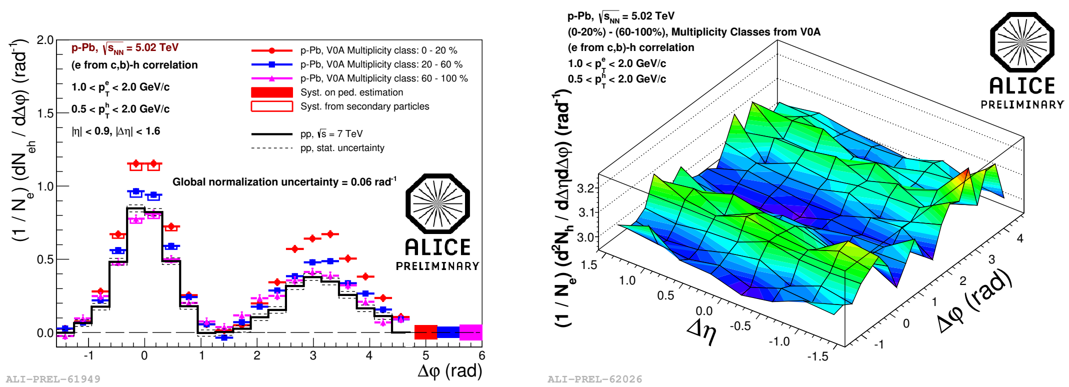

Figure 5. Left: Angular correlation between heavy-flavour decay electrons and charged particles in pp and p-Pb collisions with 1 GeV/c < p_T^e < 2 GeV/c with 0.5 GeV/c < p_T^{assoc} <2 GeV/c for three different multiplicity intervals. Right: ($\Delta\varphi$,$\Delta\eta$) correlations in the 20% highest multiplicity p-Pb collisions after subtracting the correlations in the multiplicity class 60-100%.

4. Conclusions

ALICE has measured D meson–charged particle azimuthal correlations in pp and p-Pb collisions and correlations of electrons from heavy-flavour decays with charged particles in pp, p-Pb and Pb-Pb collisions. Given the current uncertainties, from the comparison of the D meson–charged particle azimuthal correlation distributions in pp and p-Pb collisions it is not possible to conclude on any possible modification due to cold nuclear matter effects. In pp collisions, the correlation distributions are in agreement within the uncertainties with the calculation from PYTHIA Monte-Carlo simulations. The fraction of electrons originating from beauty-hadron to those originating from all heavy-flavour hadron decays has been measured through the azimuthal correlations and it is compatible with the fraction measured using the impact parameter method and with the model predictions.

The measured correlation distributions for the heavy-flavour decay electron–charged particle azimuthal correlation in central and semi-central Pb-Pb collisions are compatible, within uncertainties, with the one measured in pp collisions. The measured near-side I_{AA} is compatible with unity. Due to limited statistics of the Pb-Pb data sample, the current results do not allow to conclude on possible modifications of the heavy-flavour jet structure induced by medium effects. In p-Pb collisions, the ($\Delta\varphi$,$\Delta\eta$) correlation between heavy-flavour decay electrons and charged particles shows a long-range double-ridge structure resembling that observed in hadron-hadron correlations, suggesting that the same effect (hydrodynamics or CGC) might play a role also in the heavy-flavour sector. A reduction of the currently large statistical uncertainties is expected with the new data from LHC run II as well as from the ALICE ITS upgrades (after 2018).

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