Azimuthal angular correlations of D mesons with charged particles in pp collisions at $\sqrt{s}$ = 7 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the ALICE experiment at the LHC

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Abstract. Heavy flavour studies played an important role in the understanding of energy loss in the formed medium in heavy-ion collisions through different observables (the nuclear modification factor R_{AA}, the elliptic flow v_2). In this paper, results on heavy-flavour correlations will be presented. This observable is sensitive to the fragmentation processes of heavy flavours as well as the system of the collisions. First, the reason why studies on correlations are interesting will be discussed. The ALICE experimental step will be presented. Then the analysis strategy is explained. Finally, the results are presented.

1 Introduction

Several heavy-flavour observables were studied in pp and p-Pb collisions at the LHC, in particular the nuclear modification factor R_{AA}, the elliptic flow v_2 and two-particle correlations. In this paper, we are interested in correlations between D mesons with charged particles. Heavy flavours (charm and beauty quarks) have played an important role to understand and probe the medium that is created in heavy-ion collisions. They are also exploited to investigate the medium created in p-Pb collisions that could shed light on cold nuclear matter effects. In pp collisions, where measurements are used as a reference to those obtained in p-Pb and Pb-Pb collisions, heavy flavours allow us to verify Quantum Chromodynamics calculations in the perturbative regime by comparing the measured p_{T}-differential cross sections to the ones obtained from theoretical predictions. This was done in ALICE (see figure. 1) where the cross section of D mesons (D^{*+}, D^0 and D^+) obtained from FONLL and GM-VFNS was compared to the one from measurements in ALICE [1]. Measured cross sections show a good compatibility with theoretical predictions. Due to the large mass of heavy flavours, the strong coupling constant is smaller than 1 which makes perturbative QCD calculations applicable. Particles containing heavy flavours are characterised by a short life time, even shorter than the formation time of the Quark Gluon Plasma (QGP) and may help to reveal the properties of this dense and hot matter created in heavy ion collisions [2]. The purpose of correlations in the ALICE experiment is to provide differential observables to study heavy-quark production

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mechanisms and fragmentation properties in pp collisions and to understand possible medium effects in p-Pb and Pb-Pb collisions.
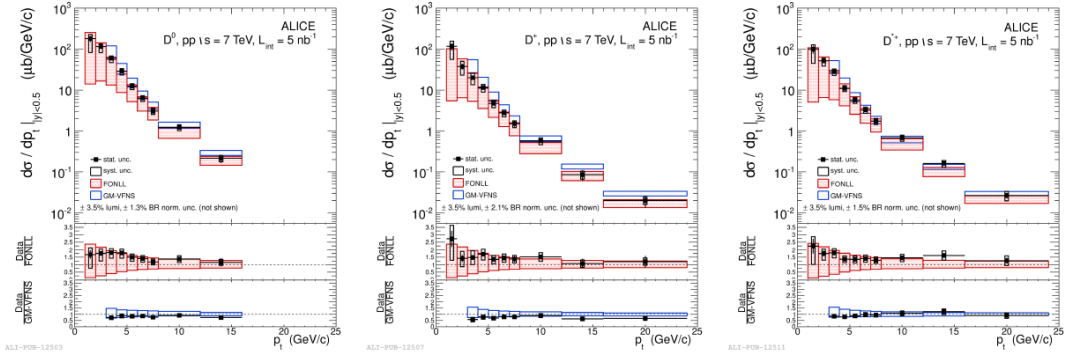

Figure 1. Measured differential production cross section as a function of the transverse momentum p_T of D^0(left panel), D^+(middle panel) and D^{*+}(right panel) in pp collisions at 7 TeV compared to predictions FONLL and GM-VFNS [1].
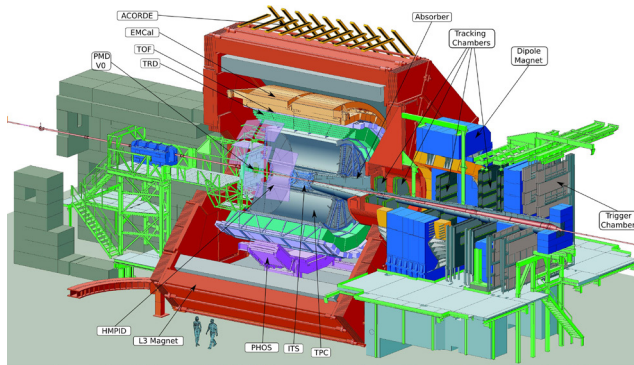
2 ALICE detector

Figure 2. Layout of the ALICE detector [3].

Data from pp collisions at $\sqrt{s} = 7$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV were collected with the ALICE experiment. ALICE detector was designed to study the observables useful to characterize the hot and dense medium formed in heavy-ion collisions to study the QGP, the state of matter that existed in the primordial universe in the first micro-seconds after the Big Bang. ALICE consists of three main parts: the central barrel, the muon spectrometer and some forward detectors used for triggering and event characterization (figure. 2) [3]. The data used for correlation analysis were collected in the central barrel, precisely three detectors were used to reconstruct D mesons: the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Time-Of-Flight (TOF). The ITS is the closest detector

to the interaction point and it consists of six layers: two layers of Silicon Pixel Detectors (SPD), two layers of Silicon Drift Detectors (SDD) and two layers of Silicon Strip Detectors (SSD). The principal role of the ITS is the determination of primary and secondary vertices. The ITS is used also for tracking and particle identification. The TPC is used for tracking by matching the reconstructed tracks in the ITS with those reconstructed in the TPC. The TPC is the main detector used for particle identification based on the determination of the energy loss which depends on the mass of the particle passing through the gas that fills the TPC drift volume. The TOF is mainly used for particle identification based on the measurement of the time of flight of particles passing through the detector and which is also mass dependent. More details about particles identification in ALICE can be found in [4].

3 Analysis strategy

The final results are obtained by applying the following steps:

- **Reconstruction of D mesons:** D^0, D^+ and D^{*+} mesons are reconstructed in their hadronic decay channels $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^{*+} \rightarrow D^0 \pi^+$ with the branching ratios: 3.88%, 9.13% and 67.7%, respectively. The decay products are reconstructed applying some selection criteria. D meson candidates are reconstructed by optimizing a number of parameters (topological cuts) in order to maximise the significance of the signal which is defined by $\frac{S}{\sqrt{S+B}}$ where S and B are the signal and the background, respectively. Among the main parameters to be used in the candidate selection, we can mention the transverse momentum of the daughters (π, K), the track impact parameter d_0 (K, π) which is the perpendicular closest distance of the trajectory of K or π to the primary vertex, the product of the impact parameters $d_0(K) \times d_0(\pi)$, the distance of the closest approach (DCA) between the pion and the kaon, the pointing angle (θ_{point}) which is the angle between the reconstructed D^0 momentum and the vector pointing from the primary to the secondary vertex. The obtained mass spectra of the three D mesons are shown in figure. 3. For more details see [5]. The range of the signal in the invariant mass spectra is $[\mu - 2\sigma, \mu + 2\sigma]$ where μ and σ are the peak position and width of the peak, respectively and they are obtained by doing a fit with a Gaussian function for the signal and an exponential term for the background. The sideband range is $[\mu + 4\sigma, \mu + 8\sigma]$ for D^{*+} mesons. For D^0 and D^+, the range of the sideband is $[\mu + 4\sigma, \mu + 8\sigma]$ and $[\mu - 4\sigma, \mu - 8\sigma]$.
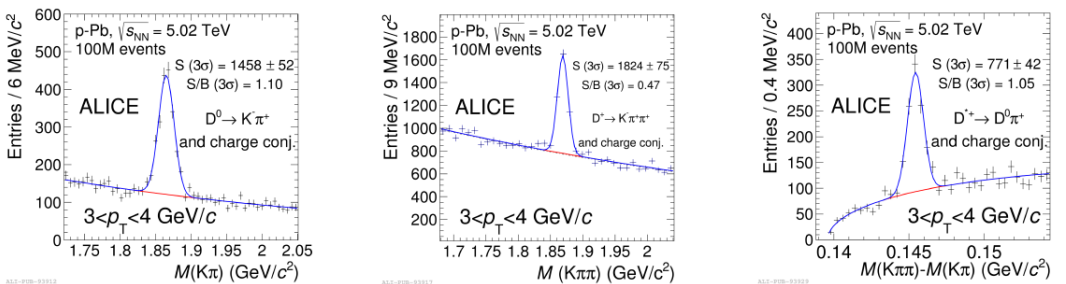

Figure 3. Invariant mass spectra of D^0 (left panel), D^+ (middle panel) and D^{*+}(right panel) mesons measured in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

- **Reconstruction of the associated tracks:** The reconstructed tracks that fulfill the selection criteria are associated with the D-meson candidates.

- **Single and mixed events:** In this step, each D meson (trigger particle) is correlated with all the charged particles (associated particles). For each correlated pair D meson - charged particle, the difference of the azimuthal angle and the pseudo-rapidity is calculated,

$$\Delta\varphi = \varphi^{assoc} - \varphi^{trigg}, \Delta\eta = \eta^{assoc} - \eta^{trigg} \tag{1}$$

If the D meson and the associated track are from the same event, the obtained distribution is a single event distribution. If they are from two different events, we obtain a mixed event distribution. Both single and mixed events distributions are obtained in the signal region and sideband region if D meson candidates are from the signal and the sideband region, respectively. The mixed event technique is used in correlation analysis to correct for inhomegeneities that could exist in the detector as well as for the limited acceptance of the detector.

An example of the single event and normalised mixed event distributions is presented in the left and middle panels of figure. 4. Every single event distribution is corrected by the corresponding normalised mixed event distribution as it is stated in the equation,

$$\frac{dN^{corr}(\Delta\varphi, \Delta\eta)}{d\Delta\varphi\Delta\eta} = \frac{\frac{dN^{SE}(\Delta\varphi,\Delta\eta)}{d\Delta\varphi\Delta\eta}}{\frac{dN^{ME}(\Delta\varphi,\Delta\eta)}{d\Delta\varphi\Delta\eta}/\frac{dN^{ME}(0,0)}{d\Delta\varphi\Delta\eta}} \tag{2}$$

Where $\frac{dN^{SE}(\Delta\varphi,\Delta\eta)}{d\Delta\varphi\Delta\eta}$ is the single event distribution and $\frac{dN^{ME}(\Delta\varphi,\Delta\eta)}{d\Delta\varphi\Delta\eta}/\frac{dN^{ME}(0,0)}{d\Delta\varphi\Delta\eta}$ is the normalised mixed event distribution to the central bin $(\Delta\varphi,\Delta\eta)=(0,0)$. The obtained distribution using this correction is presented in the right panel of figure. 4.
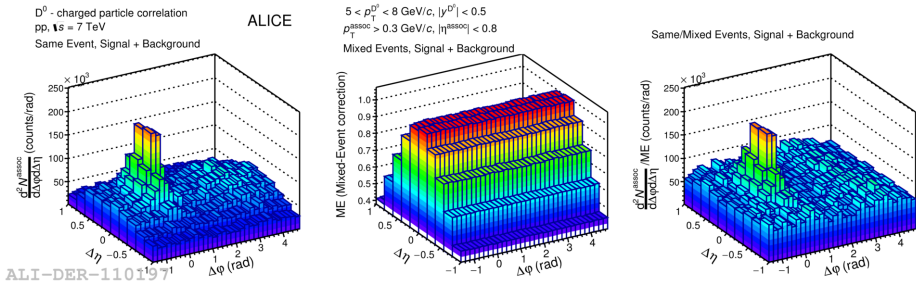

Figure 4. Example of single event distribution (left panel), mixed event distribution (middle panel) and corrected single event distribution (right panel) obtained in signal region for D^0-charged particles correlations in the range $5 < p_T(D^0) < 8$ GeV/c in pp collisions at 7 TeV.

- **Correction for the selection efficiency for D mesons and associated tracks:** The single and mixed event distributions and the invariant mass spectra of D mesons should be corrected for the efficiency of finding a candidate D meson and the associated tracks. The efficiency is evaluated as a function of p_T and multiplicity for D mesons and as a function of p_T, Z vertex position and rapidity for the associated tracks. The previous distributions (single and mixed events and invariant mass spectra) are weighted by the

inverse of the efficiency, $1/\epsilon_D$ for D mesons and $1/(\epsilon_D \times \epsilon_{tracks})$ for single and mixed event distributions. The efficiency $\times$ acceptance as a function of p_T for D^0 is shown as an example in figure. 5 [6] where the acceptance factor also includes the detector acceptance for D meson reconstruction.
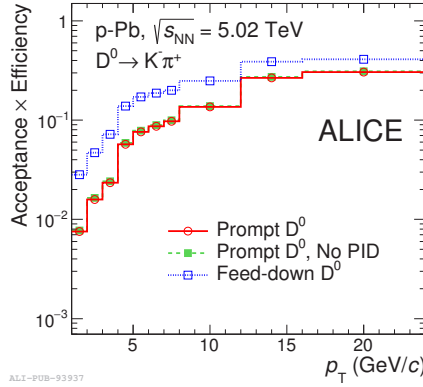

Figure 5. Acceptance $\times$ Efficiency of D^0 mesons as a function of the transverse momentum obtained in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

- **Projection on $\Delta\varphi$:** Each single event is corrected using the mixed event technique. Two distributions are obtained: the corrected single event distribution in the signal region and in the sideband region. Due to the limited available statistics, the correlations are projected onto the $\Delta\varphi$ axis. The obtained $\Delta\varphi$ distribution in the sideband region is scaled to the one in the signal region using a scale factor as a weight. The scale factor is defined by the equation,

$$Scale_{factor} = \frac{\int_{Peak} Background}{\int_{Sideband} Background} \tag{3}$$

Where $\int_{Peak} Background$ is the integral of the invariant mass spectra in the signal region and $\int_{Sideband} Background$ is the integral in the sideband region. The obtained correlation in the sideband region is then subtracted from the one obtained in the signal region and the final correlation is normalised to the number of triggers (D mesons) in the considered p_T range.

- **Correction for the B feed-down:** In this step, since we are interested in D mesons coming from the fragmentation of charm quarks only, those coming from B mesons decay are removed. This correction is based on Monte Carlo simulations using PYTHIA event generator, used to obtain a template of D-hadron correlations coming from B-meson decay. The obtained distribution is then subtracted from the inclusive D-hadron correlation distribution from data to obtain the correlations of prompt D-meson with charged particles. This is achieved using the following equation,

$$\widetilde{C}_{promptD}(\Delta\varphi) = \frac{1}{f_{prompt}}\left(\tilde{C}_{inclusive}(\Delta\varphi) - (1 - f_{prompt})\tilde{C}_{feed-down}^{MCtempl}(\Delta\varphi)\right) \tag{4}$$

5

where f_{prompt} is the fraction of prompt D mesons and is evaluated from FONLL calculations of charm and beauty quarks. More details can be found in [7].

- **Correction for the purity:** Only the primary charged particles are taken into account. To remove the contribution of secondary tracks we run on Monte Carlo to obtain the purity defined as:

$$Purity = \frac{\int_0^{DCA_{XY}^{cut}} f_{prim}(DCA_{XY})dDCA_{XY}}{\int_0^{DCA_{XY}^{cut}} f_{prim}(DCA_{XY}) + f_{sec}(DCA_{XY})dDCA_{XY}} \tag{5}$$

Where DCA_{XY} is the distance of the closest approach of the tracks trajectory to the primary vertex in the plane XY. The purity is then used as a weight for the correlation distribution obtained in the previous step as it is stated in the following equation,

$$C_{promptD}(\Delta\varphi) = purity \times \widetilde{C}_{promptD}(\Delta\varphi) \tag{6}$$

More details can be found in [7].

- **Average of D mesons (D^{*+}, D^0, D^+):** after the application of all corrections on each D meson separately, we do the average of the three D mesons.
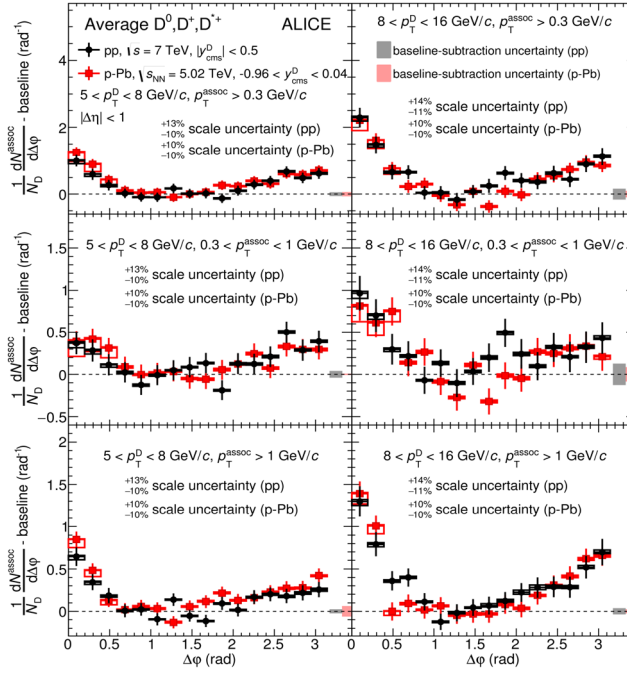
4 Results

The analysis strategy was applied on a data sample of 3×10^8 minimum bias events with integrated luminosity of 5 nb^{-1} in pp collisions at $\sqrt{s} = 7$ TeV and 10^8 minimum bias events with integrated luminosity of 50 nb^{-1} in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

We obtain the correlations of prompt D mesons with primary charged particles in the two systems: pp collisions and p-Pb collisions. D mesons are reconstructed in a wide transverse momentum range [3,16] GeV/c that allowed to define 3 p_T bins [3,5], [5,8] and [8,16] GeV/c. The associated tracks were reconstructed in a transverse momentum range $p_T > 0.3$ GeV/c and that was divided into [0.3,1] GeV/c and $p_T > 1$ GeV/c.

Correlation distributions are expected to have two peaks around $\Delta\varphi = 0, \pi$ which are interpreted as the presence of particles in the same/opposite direction relative to the trigger particles (D mesons). A baseline is expected as well and it is interpreted as coming from the underlying event. In figure. 6 the subtracted baseline azimuthal D-hadron correlations are shown for both collision systems. The results for D-meson p_T ranges [5,8] and [8,16] GeV/c are compatible within present uncertainties once the baseline is subtracted. This suggests that cold nuclear matter effects are smaller compared to the current level of uncertainties.

Other interesting results are shown in figure. 7. The left panel presents correlations in pp collisions at $\sqrt{s} = 7$ TeV for the three p_T ranges of D mesons (3 columns) and the three ranges of the associated tracks (3 rows) where correlations from data were compared to those obtained using different event generators: PYTHIA6 with different tunes, PYTHIA8 and POWHEG + PYTHIA6. There is no significant difference between different event generators and the measurements and the Monte Carlo simulations are in agreement within uncertainties.

The baseline, the width of the near side peak as well as the associated yields were extracted from the correlations for pp collisions at $\sqrt{s} = 7$ TeV using a fit function consisting

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Figure 6. Average azimuthal correlations of D^0, D^+, D^{*+} mesons with charged particles measured in pp collisions at $\sqrt{s} = 7$ TeV (black) compared to those obtained in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (red) (with subtracted baseline) in the p_T ranges [5,8] GeV/c and [8,16] GeV/c.

of a constant term (baseline) and two Gaussians (Near side and away side peaks). They are all shown in figure. 7 where they are also compared to those obtained with different event generators. The measured baseline is well reproduced by Monte Carlo simulations. The width and the associated yield are in agreement within uncertainties with simulations. More results and details can be found in [7].

5 Conclusions and outlook

The azimuthal correlations between D mesons with charged particles were measured in pp collisions at $\sqrt{s} = 7$ TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The similarity between correlations in pp collisions and p-Pb collisions indicates that with the current level of uncertainties no modifications due to cold nuclear matter effects are observed. The results from measurements and Monte Carlo simulations (using PYTHIA6, PYTHIA8 and POWHEG + PYTHIA6 event generators) are in agreement within uncertainties. Better results are expected in Run 2 with higher statistics from pp and p-Pb collisions and in Run 3 with the higher statistics and the upgrade of the ALICE ITS [8] .
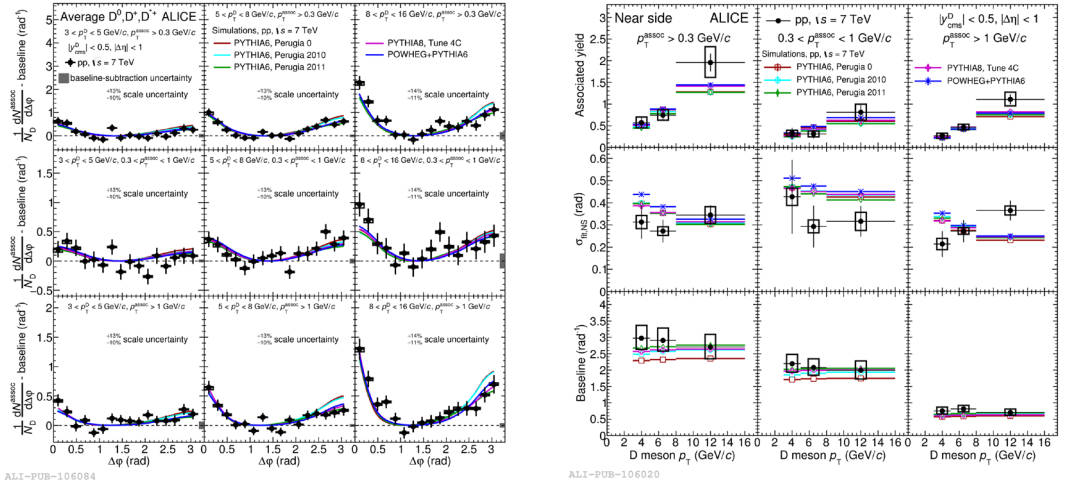
Figure 7. Left panel: Azimuthal correlations of D mesons (average D^0, D^+, D^{*+}) with charged particles measured in pp collisions at $\sqrt{s} = 7$ TeV compared to azimuthal correlations obtained using Monte Carlo simulations with different event generators (different tunes of PYTHIA6, PYTHIA8, PYTHIA6+POWHEG) where the baseline is subtracted in both measurements and simulations. Right panel: Comparison between the associated yield (upper row), the width of the near side peak (middle row) and the baseline (lower row) obtained from measurements (black) and Monte Carlo simulations (colour lines) in pp collisions at $\sqrt{s} = 7$ TeV.

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