PoS(EPS-HEP2023)261

Characterisation of heavy-quark fragmentation via jets and correlations with ALICE

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Fragmentation functions are a key component of quantum chromodynamics (QCD) calculations based on the factorisation approach. They are typically determined from the analysis of electron–positron (e^-e^+) and electron–proton (ep) collision data. Recent measurements of charm-hadron spectra and of the ratios of charm-hadron abundances in pp collisions have questioned the universality of fragmentation functions across leptonic and hadronic collision systems. In these proceedings, measurements of heavy-flavour jets and angular correlations are presented, which are sensitive to the "local" hadronic environment surrounding a heavy-flavour hadron. In detail, the final measurement on the fraction of longitudinal momentum ($z_{||}$) of jets carried by heavy-flavour hadrons is reported. The azimuthal correlations of Λ_c^+ baryons and D mesons (D^0, D^+, and D^{*+}) with primary charged particles in pp collisions at $\sqrt{s}$ = 13 TeV are reported as well. Together, these observables provide quantitative access to the angular profile, transverse momentum (p_T) and constituent-multiplicity distributions of the jets produced by the fragmentation of a heavy quark. These measurements allow to investigate the charm fragmentation and hadronisation processes in hadronic collisions, setting constraints for their modelling in event generators.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

1. Introduction

In ultra-relativistic heavy-ion collisions, a state of matter known as quark-gluon plasma (QGP) is formed in which quarks and gluons are not confined into hadrons. Heavy quarks (charm and beauty) are produced via hard-parton scatterings at time scales smaller than the formation time of the QGP. Their thermal production and in-medium annihilation rates are negligible. Therefore, they are ideal probes to study the properties of the QGP as they experience the full evolution of the medium. The mass of heavy quarks is larger than the non-perturbative QCD scale (Λ_{QCD}), and the hard parton scattering cross section can be evaluated perturbatively. Therefore, studies of heavy-flavour hadron production provide the necessary inputs to test and constrain perturbative QCD calculations [1]. The production cross section for a heavy-flavour hadron ($\mathrm{H_Q}$) can be calculated using the factorization approach [2]:

$$\frac{\mathrm{d}\sigma^{\mathrm{NN}\to\mathrm{H_Q X}}}{\mathrm{d}p_{\mathrm{T}}{}^{\mathrm{H_Q}}} = \sum_{\mathrm{i,j=q,\bar{q},g}} f_{\mathrm{i}}(x_1,\mu_{\mathrm{F}}^2)\otimes f_{\mathrm{j}}(x_2,\mu_{\mathrm{F}}^2)\otimes \mathrm{d}\hat{\sigma}^{\mathrm{ij}\to\mathrm{Q\bar{Q}}}(\alpha_{\mathrm{s}}(\mu_{\mathrm{R}}^2),\mu_{\mathrm{F}}^2,M_{\mathrm{Q}},x_1,x_2,s_{\mathrm{NN}})\otimes D_{\mathrm{Q}}^{\mathrm{H_Q}}(\mathrm{z},\mu_{\mathrm{F}}^2). \quad (1)$$

The heavy-flavour hadron production cross section is a convolution of the parton distribution functions (f_{i}, f_{j}) of the interacting nucleons, partonic hard-scattering cross section ($\mathrm{d}\hat{\sigma}^{\mathrm{ij}\to\mathrm{Q\bar{Q}}}$), and fragmentation function $D_{\mathrm{Q}}^{\mathrm{H_Q}}$, as shown in the left panel of Fig. 1. The fragmentation function is the probability that a heavy quark (Q) will hadronise producing a given hadron with momentum fraction $z = p_{\mathrm{H_Q}}/p_{\mathrm{Q}}$. Up to recent findings, fragmentation functions were assumed to be universal, i.e. independent of the collision system, and usually extracted from measurements at $\mathrm{e^+e^-}$ and ep colliders [3]. In pp measurements, at low and intermediate p_{T}, the ALICE Collaboration observed a $\Lambda_{\mathrm{c}}^+/\mathrm{D}^0$ production yield ratio significantly higher than previous measurements in $\mathrm{e^+e^-}$ collisions and than expectations from the PYTHIA 8 event generator [4, 5]. This observation questions the universality of fragmentation functions across different collision systems. In order to retrieve

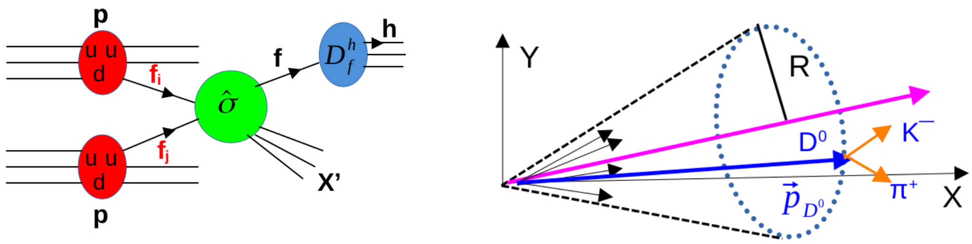

Figure 1: (Left) The interaction of partons of the colliding protons that create a heavy-flavour hadron and (right) sketch of a jet containing a D^0 meson.

additional information on the heavy-quark fragmentation, a study has to be done on fragmentation-specific observables sensitive to the kinematic correlation between the heavy-flavour hadron and the other hadrons resulting from the fragmentation of a heavy quark. In this context, two studies are presented in these proceedings. The first is the reconstruction of jets containing a heavy-flavour hadron, as depicted in the right panel of Fig. 1. The second is the measurement of the azimuthal correlation function of heavy-flavour hadrons with primary charged particles: the near-side (NS) and away-side (AS) correlation peaks are sensitive to the properties of the heavy-flavour (NS) and recoiling (AS) jets, as well as to the different heavy-quark production processes (e.g. to the relative contributions of leading-order and next-to-leading order terms) and hadronisation processes. In the former case, the reconstructed momentum of the jet (apart from neutral constituents that are not reconstructed) can be taken as the proxy of the momentum of the heavy-flavour quark ($\vec{p}_{\mathrm{Q}}$). This allows to study the longitudinal momentum fraction ($z_{||}^{\mathrm{ch}}$), defined in Eq. 2, which is the fraction of jet momentum carried by the heavy-flavour hadron along the direction of the jet.

$$z_{||}^{\mathrm{ch}} = \frac{\vec{p}_{\mathrm{ch\ jet}} \cdot \vec{p}_{\mathrm{HQ}}}{\vec{p}_{\mathrm{ch\ jet}} \cdot \vec{p}_{\mathrm{ch\ jet}}} \tag{2}$$

2. Analysis procedure

The measurements were performed analysing data from pp collisions at $\sqrt{s}$ = 13 TeV collected during the LHC Run 2 with the ALICE apparatus [6]. The sub-detectors used in the analysis are the Inner Tracking System (ITS) for tracking and reconstruction of primary and secondary vertices, the Time Projection Chamber (TPC) for tracking and particle identification, and the Time-Of-Flight (TOF) detector for particle identification. The jets containing charged particles and a heavy-flavour hadron were reconstructed using the anti-k_{T} jet finding algorithm of the FASTJET package [7], replacing the momentum vectors of the Λ_{c}^{+} and D^0-decay daughter particles with that of the parent particle. The D^0 meson and Λ_{c}^{+} baryon were reconstructed from their hadronic decays $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$ and $\Lambda_{\mathrm{c}}^{+} \rightarrow \mathrm{pK}^-\pi^+$, respectively. The azimuthal correlation of D mesons with the primary charged particles was studied on the same data sample, and exploiting also the reconstruction of the $\mathrm{D}^+ \rightarrow \mathrm{K}^-\pi^+\pi^+$ and $\mathrm{D}^{*+} \rightarrow \mathrm{D}^0\pi^+$ decays on top of that of $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$. Recently, also the correlation function of Λ_{c}^{+} baryons with charged primary particles was studied. The near-side peak in the correlation function is fitted with a generalised Gauss distribution to extract the the near-side yield and width.

3. Results

As discussed in Ref. [1] the $p_{\mathrm{T,ch\ jet}}$-differential cross section and $z_{||}^{\mathrm{ch}}$-differential yield of jets containing a prompt D^0 meson is well described by the PYTHIA 8 Soft QCD Mode 2 [8, 9] and the POWHEG+PYTHIA 8 [8, 10] within the uncertainties. In the case of Λ_{c}^{+}-tagged jets, the $z_{||}^{\mathrm{ch}}$ distribution [11] was studied for $7 \leq p_{\mathrm{T,ch\ jet}} < 15$ GeV/c, and shows a good agreement with PYTHIA 8 CR-BLC Mode2, as shown in the left panel of Fig 2. The comparison of $z_{||}^{\mathrm{ch}}$ between the Λ_{c}^{+} baryon and D^0 meson shows a hint of a softer fragmentation for the $\mathrm{c} \rightarrow \Lambda_{\mathrm{c}}^{+}$ case with respect to $\mathrm{c} \rightarrow \mathrm{D}^0$ case. Furthermore, the ratio of the two $z_{||}^{\mathrm{ch}}$-differential yields was evaluated and compared with model predictions. As shown in the right panel of Fig. 2, the data is well described by the PYTHIA 8 CR-BLC Mode2, while PYTHIA 8 Monash tune predicts a ratio slighlty increasing with $z_{||}^{\mathrm{ch}}$ which is not favoured by the data.

As discussed in Ref. [12], the compatibility of PYTHIA 8 and POWHEG+PYTHIA 8 predictions and the measured azimuthal correlation function of D mesons with charged particles suggests that the fragmentation and hadronization of charm-quarks into D mesons is well modelled inside those Monte Carlo generators. The analysis of Λ_{c}^{+} correlations with primary charged particles suggests that a difference is present between the D-meson and Λ_{c}^{+}-baryon results. For D mesons, the

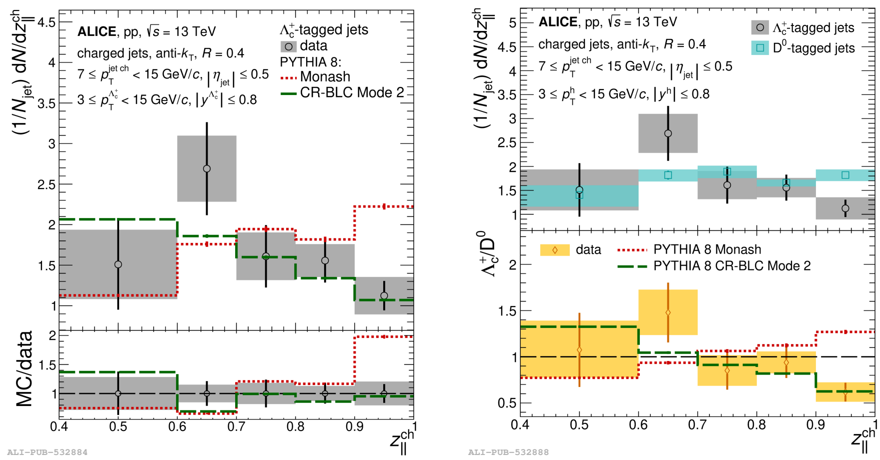

Figure 2: Longitudinal momentum fraction $z_{||}$ of Λ_c^+-tagged jets (left) and its ratio (right) to D^0-tagged jets [1]. Comparison with different PYTHIA 8 predictions are also provided.

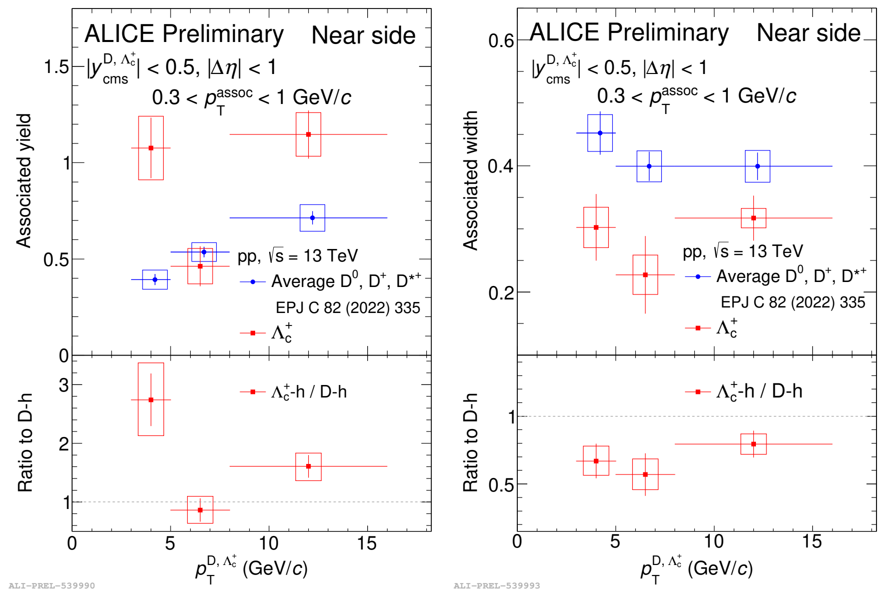

Figure 3: Comparison of near-side associated peak yields (left) and widths (right) for Λ_c^+ and D meson-charged particle azimuthal correlation functions.

results show that the near-side yield increases with p_T, while the width of the peak decreases. For the Λ_c^+, at low p_T of the associated charged particles ($0.3 < p_T < 1$ GeV/c), the yield is larger and the width is smaller with respect to the D mesons, though uncertainties prevent firm conclusions, as shown in Fig. 3. Possible reasons for the larger near-side yield are a softer fragmentation of the charm-quark into the Λ_c^+ and the existence of excited charm-baryon states with higher mass, whose decay particles increase the number of associated tracks in the NS jet. The existence of such states, predicted by the Relativistic Quark Model (RQM) was proposed as a possible cause of the larger Λ_c^+/D^0 baryon-to-meson ratio observed in pp collisions with respect to e^+e^- collisions [4]. The results for NS yields and widths are further compared to PYTHIA 8 expectations using the Monash tune and different CR-BLC modes, as shown in Fig. 4. All model predictions underestimate the associated yields, while the widths are overestimated.

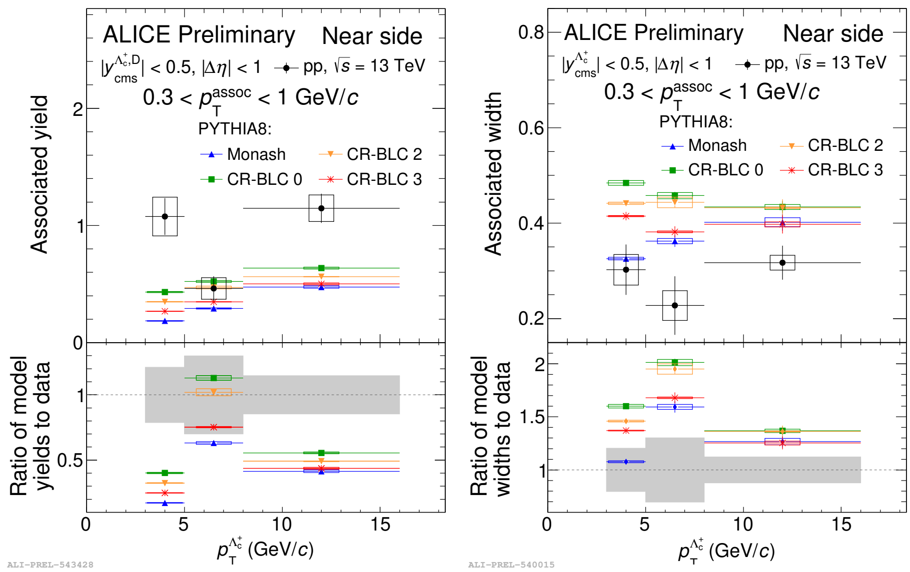

Figure 4: Comparison of data and PYTHIA 8 predictions for near-side yields (left) and widths (right) of Λ_c^+-charged particle correlations.

4. Conclusion

The fragmentation of charm quarks into D mesons and Λ_c^+ has been investigated by studying the properties of the jets containing a charm hadron. There is a hint for a softer fragmentation of charm quarks into Λ_c^+ baryons with respect that to D^0 mesons. The results for the azimuthal correlations of a charm hadron with primary charged particles were also presented to get a deeper understanding of the showering profile of the jet. The comparison of yields and widths of the NS jets shows larger values for the Λ_c^+-baryon case than the D-meson one, though the uncertainties prevent firm conclusions. The possible reasons for the larger yield are a different parton-to-hadron momentum scale for the Λ_c^+ baryon and D meson or a large number of associated particles coming from the decay of higher-mass states.

The results shown, as well as future measurements from the analysis of Run 3 data, which will benefit from the upgrade of the ALICE detector to improve the precision and the kinematic reach, will set important constraints for modelling the fragmentation and hadronisation of charm quarks in theoretical models.

Acknowledgments

I want to thank the colleagues from the ALICE Bari group, Italy for the discussion on these studies. In addition, I would also like to acknowledge Istituto Nazionale di Fisica Nucleare (INFN), Italy for providing the funding support to present the research in the conference.

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