PROCEEDINGS OF SCIENCE

Exploring charm-quark fragmentation with correlation and jet measurements by ALICE

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Fragmentation functions, one of the key components of the factorisation theorem used for computing cross sections for heavy-flavour hadron production, are typically constrained in e^+e^- and e^-p collisions due to their non-perturbative nature. However, recent measurements of charm-hadron spectra and ratios at the LHC have questioned the universality of fragmentation functions across leptonic and hadronic collision systems. This contribution presents measurements of heavy-flavour tagged jets and correlation measurements involving heavy-flavour hadrons. These measurements provide complementary, and more differential, insights on heavy-quark production, fragmentation and hadronization with respect to more inclusive observables. The studies presented include measurements of the p_T-differential cross section of D^0-tagged charm-jets and the longitudinal jet momentum fraction carried by D^0 mesons and Λ_c^+ baryons reconstructed inside jets in pp collisions. The measurements of azimuthal correlations between D mesons and charged particles in pp collisions are presented, to provide a quantitative access to the angular profile, transverse-momentum and multiplicity distributions of the jets produced by the heavy-quark fragmentation. To gain a deeper understanding on possible differences in charm-quark hadronization into mesons or baryons, the comparison of azimuthal correlations between Λ_c^+ baryons and D mesons with charged particles in pp collisions is also discussed.

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1. Introduction

Heavy-flavor (HF) measurements in ultra-relativistic hadronic collisions hold significance in validating perturbative Quantum Chromodynamics (pQCD). Within this theoretical framework, the factorization theorem is employed to calculate the HF hadron production cross-section by separating perturbative quantities, including the hard parton scattering cross-sections, from non-perturbative quantities, such as parton distribution functions (PDFs) and fragmentation functions (FFs), which are determined using experimental measurements. The recent observation of enhanced charm baryon-to-meson ratios at low and intermediate transverse momenta in hadronic collisions compared to e^+e^- and e^-p collisions has disproven the universality of fragmentation fractions across colliding systems [1–3]. Discrepancies between experimental measurements in hadronic collisions and models that rely on fragmentation functions constrained to e^+e^- and e^-p data have also been observed. Charm-tagged jet measurements and azimuthal correlations between charmed hadrons and other charged particles offer additional insights into charm hadronization mechanisms.

2. Experimental apparatus

A detailed description of the ALICE detector and its operational characteristics can be found in Refs. [4, 5]. The reconstruction of HF hadrons and charged particles was performed using detectors located in the central barrel, covering a pseudorapidity of $|\eta| < 0.9$ and subject to a magnetic field of 0.5 T parallel to the beam axis. In particular, the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) were used to reconstruct charged particles. The primary interaction vertex and the decay vertices of charm hadrons were reconstructed exploiting the excellent spatial resolution provided by the Silicon Pixel Detector (SPD), which constituted the two innermost layers of the ITS. The TPC, in conjunction with the Time-of-Flight (TOF) detector, provided information for charged-particle identification (PID). Additionally, detectors positioned along the beam line, covering forward and backward rapidity, played a essential role in the analysis. The V0 detector is a set of scintillators covering the pseudorapidity ranges $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C), used for triggering and background-event rejection. The T0 detector, an array of Cherenkov counters, located along the beam line at a distance of +370 cm (T0A) and −70 cm (T0C) from the nominal interaction point, provided the collision starting time used by the TOF.

3. Heavy-flavour tagged jets

Measurements of heavy-flavour tagged jets provide a unique sensitivity to explore the mechanisms involved in the production of heavy quarks and contributions from next-to-leading-order processes, such as gluon splitting and flavour excitation. Charm-tagged jets were identified by detecting prompt charmed hadrons, such as D mesons or Λ_c^+ baryons, reconstructed from hadronic decay channels, among their components. Charged particle jets were reconstructed with the anti-k_T algorithm [6] to define the jet produced by the charm shower process. Corrections for D-meson (Λ_c^+-baryon) reconstruction efficiency and acceptance were applied to the reconstructed jet observables, addressing the limitations of the experimental setup in detecting charged particles and in reconstructing charm hadrons. The contribution from beauty-hadron feed-down, where beauty hadrons

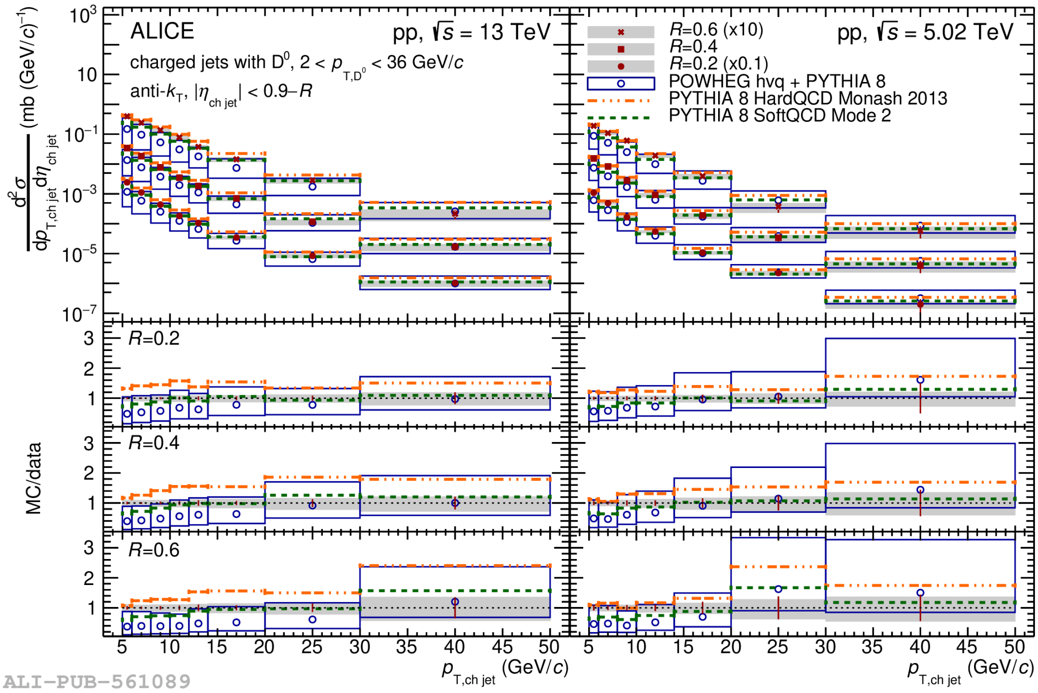

Figure 1: D^0-jet production cross-section measurements in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV for three different resolution parameters R = 0.2, 0.4 and 0.6, compared to POWHEG + PYTHIA8 and PYTHIA8 Monte-Carlo predictions.

decay into D^0 or Λ_c^+, was subtracted to isolate the direct charm contribution. An unfolding procedure was used to correct detector effects on the jet kinematic properties, such as non-reconstructed particles and limited jet momentum resolution, to provide a more accurate representation of the true jet distributions and momenta.

The ALICE Collaboration has measured the p_{T}-differential cross section of D^0-tagged charm jets [7]. Fig. 1 presents the results for three different values of the jet resolution parameter R, compared to PYTHIA8 simulations using the Monash-2013 tune and color reconnection beyond-leading-colour (CR-BLC) Mode 2 [8, 9] tune, as well as with POWHEG + PYTHIA8 [10] simulations, in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV. PYTHIA8 with hardQCD tends to overpredict the cross sections, especially at $\sqrt{s}$ = 13 TeV, while POWHEG+PYTHIA predictions are consistent with the data within the experimental and theoretical uncertainties. PYTHIA8 SoftQCD reproduces well the measured $p_{\mathrm{T}}^{\mathrm{ch\ jet}}$-differential cross sections for both collision energies.

The hardness of the fragmentation of charm quarks into hadrons can be studied by quantifying the fraction of the jet momentum that is carried by the hadron along the jet direction with respect to the momentum of the charged jets. This is quantified by the parallel jet momentum fraction $z_{||}^{\mathrm{ch}}$, defined in Eq. 1.

$$z_{||}^{\mathrm{ch}} = \frac{\vec{p}^{\ \mathrm{HF}}.\vec{p}^{\ \mathrm{ch\ jet}}}{\vec{p}^{\ \mathrm{ch\ jet}}.\vec{p}^{\ \mathrm{ch\ jet}}} \tag{1}$$

ALICE measured the $z_{||}^{\mathrm{ch}}$ of Λ_c^+ baryons in pp collisions at $\sqrt{s}$ = 13 TeV [11], as shown in Fig. 2. Comparison is given to a measurement of D^0-tagged charged jets and to PYTHIA8 simulations

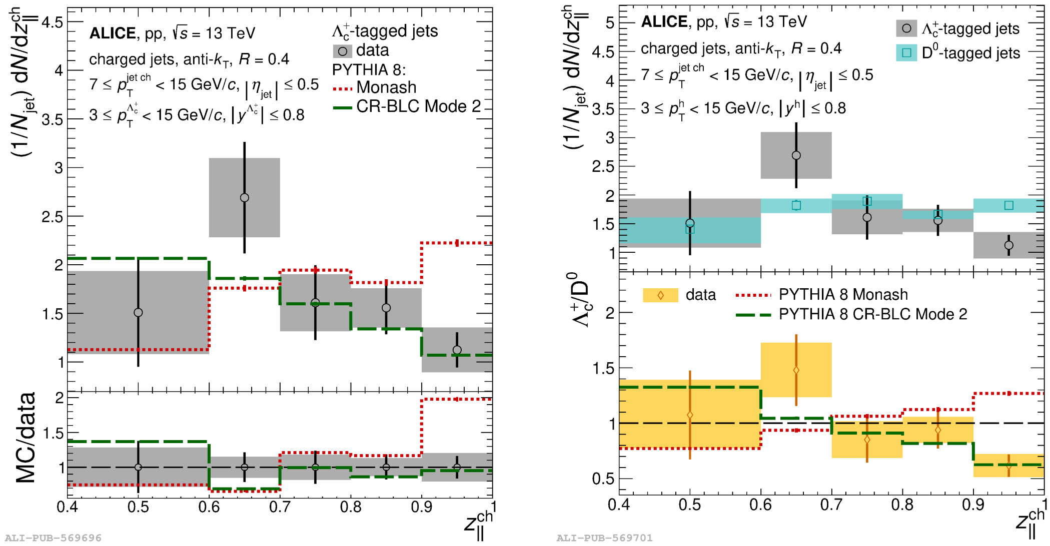

Figure 2: Left: fully corrected $z_{||}^{\mathrm{ch}}$ distribution of Λ_c^+-tagged charged jets in pp collisions at $\sqrt{s}$ = 13 TeV, compared with predictions from different PYTHIA8 tunes. The ratios of the MC simulations to the data are shown in the bottom panel. Right: comparison (top panel) and ratio (botton panel) of the measured $z_{||}^{\mathrm{ch}}$ of Λ_c^+- and D^0-tagged jets for both the data and the different PYTHIA tunes.

in the kinematic region $3 \leq p_{\mathrm{T}}^{\mathrm{D}^0,\Lambda_c^+} < 15$ GeV/c and $7 \leq p_{\mathrm{T}}^{\mathrm{ch\ jet}} < 15$ GeV/c. The results suggest that the charm quark fragmentation into charm baryons could be softer compared to charm mesons in the measured kinematic interval, as predicted by hadronization models that include color correlations beyond leading-color in string formation.

4. Azimuthal correlations between charm hadrons and charged particles

Angular correlations of prompt charm hadrons with charged particles in small systems provide additional insights into charm fragmentation compared to charm-tagged jets. The typical structure of two-dimensional correlation functions between "trigger" charm hadrons and "associated" charged particles is characterized by a near-side (NS) peak at $(\Delta\varphi, \Delta\eta) = (0, 0)$ and an away-side (AS) peak at $\Delta\varphi = \pi$, extending over a wide pseudorapidity range. The shape and yields of the near-side peak reveal details about the internal composition of the charm jet, including the p_{T} distribution and multiplicity of its constituents. Furthermore, studying how the peak features vary with the p_{T} of associated charged particles offers insights into the redistribution of charm-quark momentum among the fragmentation products and their radial displacement from the jet axis.

ALICE has measured azimuthal correlation distributions of Λ_c^+ baryons and charged particles in pp collisions at $\sqrt{s}$ = 13 TeV. Comparing these measurements with previous measurements of D meson-charged particle azimuthal correlations in the same collision system [12] can offer insights into potential modifications of charm fragmentation and provide clues regarding different hadronization mechanisms when the final state comprises either mesons or baryons. A discrepancy in the azimuthal correlations for $3 < p_{\mathrm{T}}^{\mathrm{D},\Lambda_c^+} < 5$ GeV/c and $0.3 < p_{\mathrm{T}}^{\mathrm{asssoc}} < 1$ GeV/c can be observed, as illustrated in Fig. 3 (left), suggesting a larger multiplicity of low-momentum associated particles

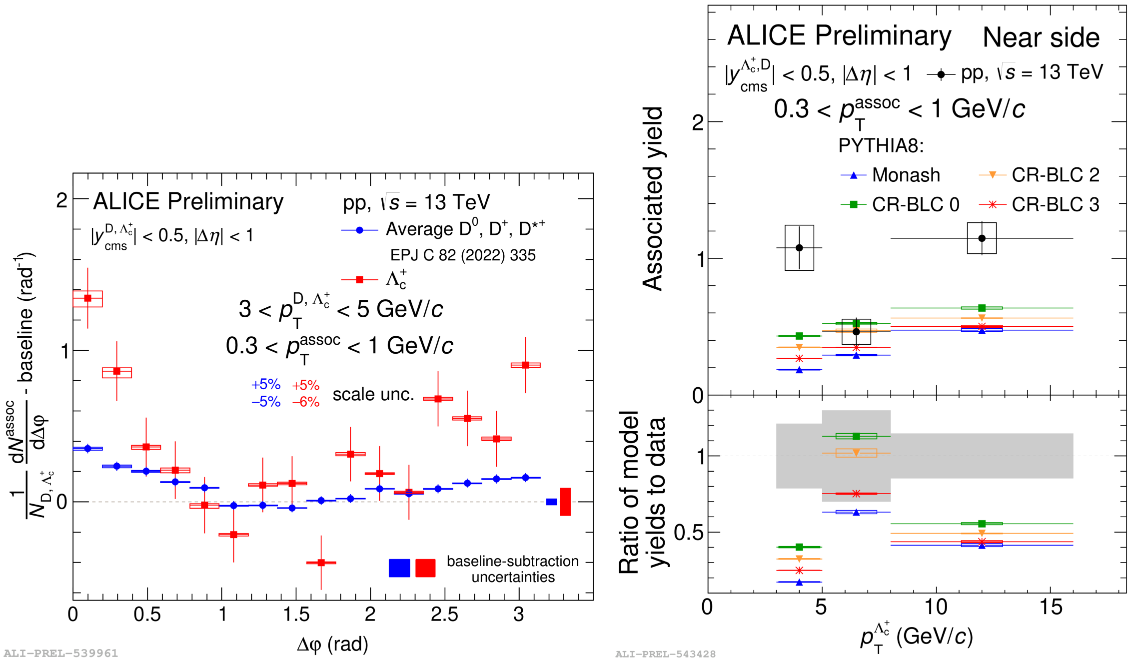

Figure 3: Left: comparison between Λ_c^+-hadron and D-hadron azimuthal correlation distributions. Right: comparison between the measured near-side yields of Λ_c^+-hadron azimuthal correlation distributions and PYTHIA8 predictions.

produced either collimated or in the opposite direction to the Λ_c^+ baryon, compared to the D^0 meson. Besides effects induced by different charm hadronization mechanisms, this enhancement could potentially be explained by assuming a softer fragmentation of charm when hadronizing into Λ_c^+ baryons compared to hadronization into D mesons. This translates to a higher initial energy of the charm parton and, consequently, a larger phase space available for the production of other fragmenting particles. PYTHIA8 simulations, both with the Monash tune and implementing CR-BLC, are unable to accurately reproduce the Λ_c^+-hadron distributions, significantly underestimating the NS yields, as shown in Fig. 3 (right) for $0.3 < p_T^{\mathrm{assoc}} < 1.0$ GeV/c. Likewise, the AS yields are also underestimated by the Monte Carlo simulations.

5. Conclusion

Charm jets and angular distributions of particles originating from charm quarks serve as a benchmark for investigating the fragmentation, and in general the hadronization process, of charm quarks. Measurements of charm baryons in pp collisions at $\sqrt{s} = 13$ TeV hint that charm fragmentation into baryons is possibly softer compared to fragmentation into D mesons. Although the PYTHIA8 Monash tune, which implements fragmentation functions constrained by e^+e^- and e^-p data, accurately reproduces D^0-meson measurements, it shows discrepancies in describing Λ_c^+ jets. Including mechanisms sensitive to the surrounding partonic density, such as color reconnections, improves the agreement for parallel jet momentum fraction distributions but does not fully account for the azimuthal correlation distributions of Λ_c^+ hadrons, which show signs of near- and away-side peak enhancement compared to those of D hadrons.

The larger data samples from LHC Run 3 and the enhanced detector performance in tracking and vertexing will enable ALICE to deliver more accurate and precise measurements in the charm baryon sector. Consequently, measurements of the proposed observables as a function of event multiplicity across different collision systems, including Pb-Pb collisions, will become possible, allowing for the investigation of potential modifications to charm fragmentation and hadronization mechanisms induced by the presence of a deconfined QCD medium.

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