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Testing perturbative QCD calculations with charm-tagged jets and correlations of charm hadrons with charged particles

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Measurements of the properties of jets initiated by a charm quark represent a valuable tool to investigate the properties of quantum chromodynamics (QCD) processes such as the evolution of the heavy-flavour-quark parton shower and hadronisation. Casmir colour effects that are different for quarks and gluons and mass effects driven by the dead cone of heavy quarks, impact the properties of the resultant showers and can be accessed by the study of heavy-flavour tagged jets. In a complementary approach to charm-tagged jets, azimuthal correlations between charmed hadrons and charged particles provide a differential description of charm-jet shape and composition in terms of the transverse momentum of associated particles. Additionally, the comparison of correlation-peak measurements for different charm-hadron species can help to better understand the charm hadronisation mechanism, and investigate the possibility of different mechanisms in addition to in-vacuum fragmentation.

The measurement of the longitudinal jet momentum fraction carried by Λ_c^+ baryons compared to D^0 mesons in pp collisions at $\sqrt{s}$ = 13.6 TeV, collected during LHC Run 3 by the ALICE experiment is reported. The measurements of the first perturbative splitting identified with the Soft Drop algorithm in D^0-meson tagged jets, which are directly related to the charm splitting function are presented. In addition, the new results on azimuthal correlations between strange and non-strange D mesons and charged particles in pp collisions at $\sqrt{s}$ = 13.6 TeV, to investigate the influence of strangeness on the charm hadronisation process are reported. Correlations between charm baryons and charged particles are also studied and compared with those of D mesons.

The results are compared with the calculations of state-of-the-art Monte Carlo event generators and theoretical models which implement different charm production and hadronisation mechanisms. Finally, we present new results on Λ_c^+–proton correlations, which probe the angular range of baryon-number conservation in the charm-hadronisation process.

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1. Introduction

The production cross sections of heavy-flavour hadrons can be described within the factorisation approach [1], which involves the convolution of three terms: the parton distribution functions (PDFs) of the incoming protons, the hard-scattering cross section, calculated perturbatively as a power series in the strong coupling constant α_s, and the fragmentation functions (FFs) describing the hadronisation of heavy quarks into specific hadron species. Several experimental observables can be employed to improve our understanding of charm-quark hadronisation, such as the azimuthal correlations between charm hadrons and charged particles, and measurements involving charm-tagged jets. In the first case, a reconstructed charm hadron is selected as the trigger particle, and the azimuthal angular difference between its direction and that of the surrounding charged particles is measured. This measurement provides a multidifferential investigation of the charm hadronisation process, and can be used to characterise the jet shape and its particle composition. At leading order in perturbative quantum chromodynamics (QCD), charm–anticharm quark pairs are produced back-to-back in azimuth. As a consequence, the azimuthal correlation distribution between a trigger charm hadron and associated charged particles is expected to exhibit a characteristic two-peak structure: a near-side peak centred at $\Delta\varphi = 0$, and an away-side peak at $\Delta\varphi = \pi$. These peaks represent the azimuthal distribution and particle multiplicity within the jets produced by charm quarks, providing insights into the charm production and hadronisation processes. Next-to-leading order (NLO) production mechanisms can modify the correlation patterns [2][3].

Charm-tagged jet measurements focus on jets having charm hadrons among their constituents and study the charm-jet production yield as a function of the longitudinal-momentum fraction ($z_{||}^{\mathrm{ch}}$) carried by the charm hadron within the jet. These distributions provide information about the hadronisation process of charm quarks and can be used to constrain the charm fragmentation function. In addition, by reconstructing the substructure of charm-tagged jets using the Soft Drop grooming algorithm, it is possible to access the charm splitting function providing a deeper understanding of the role of parton mass and Casimir color factors in the QCD parton shower [4].

2. Non-strange D and $\mathrm{D_s^+}$ meson azimuthal correlations

ALICE has measured the azimuthal correlations of prompt non-strange and strange D mesons with charged particles as a function of both the D-meson transverse momentum (p_{T}) and the associated charged-particle transverse momentum ($p_{\mathrm{T}}^{\mathrm{assoc}}$) in pp collisions at a centre-of-mass energy of $\sqrt{s}$ = 13.6 TeV. The azimuthal correlation distributions were fitted with the sum of two Gaussian functions, describing the near- and away-side peaks, and a constant term accounting for the baseline. From these fits, physical observables such as the peak yields and widths were extracted.

Figure 1 shows a comparison of the near-side yields and widths from azimuthal correlations of prompt $\mathrm{D^+}$ and $\mathrm{D_s^+}$ mesons (and their charge conjugates) with charged particles. The per-trigger-normalised near-side yield of prompt $\mathrm{D_s^+}$ mesons is systematically lower than that of prompt $\mathrm{D^+}$ mesons in all kinematic intervals considered. This hints to a more isolated production of $\mathrm{D_s^+}$ mesons compared to non-strange D mesons. The near-side peak width is in agreement for the two meson species. Since the width of the near-side peak reflects the angular spread of particles around the

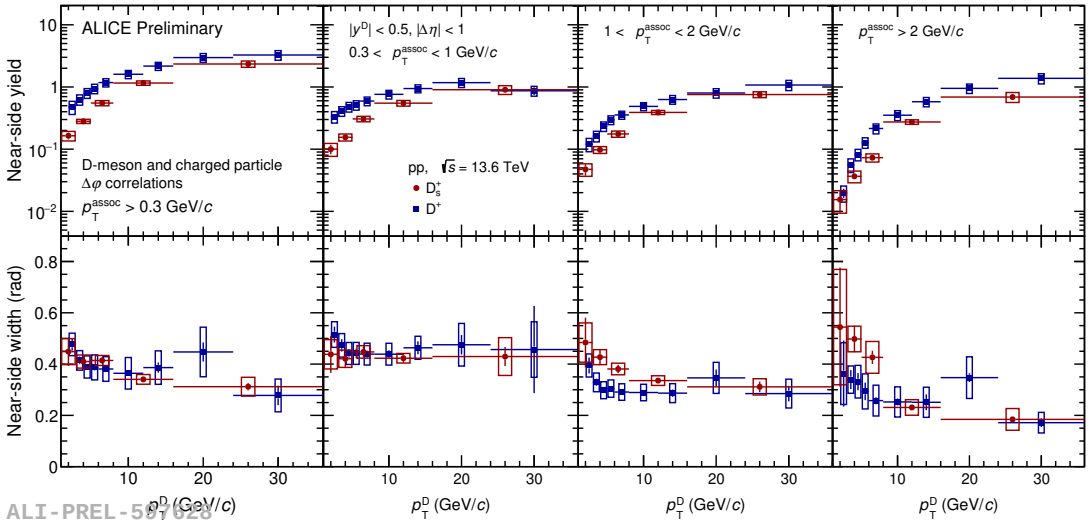

Figure 1: Comparison of the per-trigger-normalised near-side yields (top) and widths (bottom) from azimuthal correlations of D^+ mesons and D_s^+ mesons with charged particles as a function of the D-meson transverse momentum (p_T^D) and in different intervals of the associated particle transverse momentum (p_T^{assoc}).

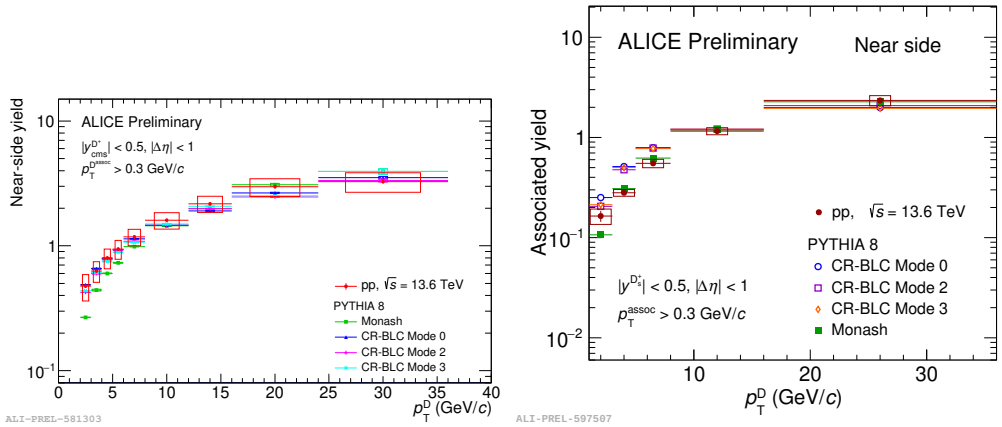

Figure 2: Comparison of the per-trigger-normalised near-side yields of charged particles associated to D^+ (left) and D_s^+ (right) mesons as a function of the D-meson transverse momentum (p_T^D) with predictions from PYTHIA 8 using the Monash and CR-BLC tunes.

trigger D meson, this agreement suggests that the angular distribution of particles inside the charm jet does not depend on the flavour content of the charm meson produced in the final state.

Figure 2 presents a comparison of the per-trigger-normalised near-side yields of charged particles associated to D^+ and D_s^+ mesons with predictions from PYTHIA 8 with the Monash [5] and CR-BLC [6] tunes. For D_s^+ mesons, both tunes reproduce the measured near-side yields reasonably well for $p_T > 8$ GeV/c, whereas for $p_T < 5$ GeV/c, PYTHIA 8 with CR-BLC tends to overestimate the data. For D^+ mesons, the Monash tune underestimates the data for D-meson triggers having $p_T < 8$ GeV/c.

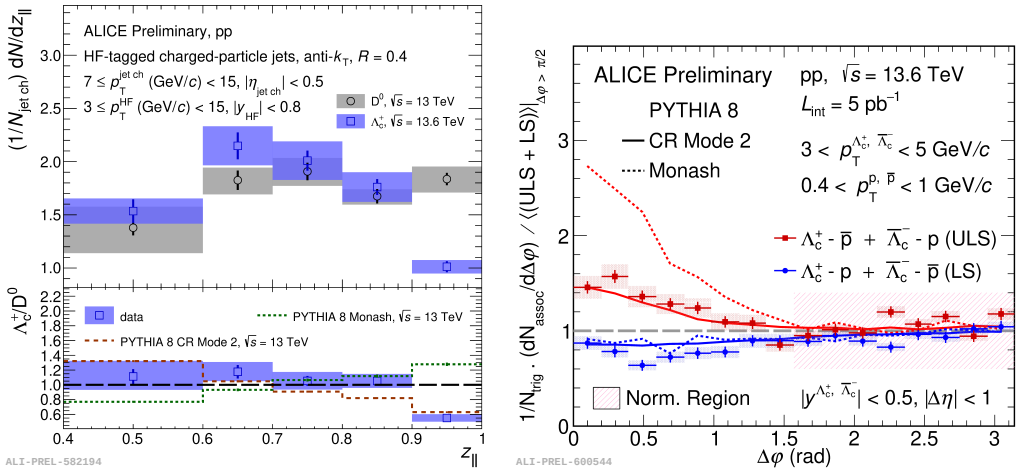

Figure 3: Left: Per-jet-normalized yield of Λ_c^+- and D^0-tagged charged-particle jets as a function of the longitudinal-momentum fraction ($z_{||}^{ch}$) carried by the charmed hadron for the reconstructed jet transverse momentum interval $7 \le p_T^{jet\ ch} \le 15$ GeV/c. Right: azimuthal correlation distributions of Λ_c^+–$\bar{p}$ and Λ_c^+–p pairs, normalised to the average value of ULS + LS in the $\Delta\varphi > \pi/2$ region, for $3 < p_T(\Lambda_c^+, \overline{\Lambda_c^-}) < 5$ GeV/c and $0.4 < p_T(p, \bar{p}) < 1$ GeV/c.

3. Λ_c^+ azimuthal correlations and tagged-jet measurements

ALICE has measured the azimuthal correlations between prompt Λ_c^+ baryons and charged particles in pp collisions at $\sqrt{s} = 13$ TeV, as well as Λ_c^+-tagged jets in pp collisions at $\sqrt{s} = 13.6$ TeV. By comparing the azimuthal correlation distributions of non-strange D mesons and Λ_c^+ baryons, for $p_T(D, \Lambda_c^+) > 5$ GeV/c, a good agreement of the two hadron species correlation patterns is observed, indicating similar charm fragmentation behaviour at high p_T. At lower p_T values, a tendency of an enhancement of both the near- and away-side peaks for Λ_c^+ baryons compared to D mesons is observed [7].

The study of Λ_c^+-tagged jets provides additional insight into charm-quark hadronisation into Λ_c^+ baryons. Figure 3 (left panel) shows a comparison between Λ_c^+- and D^0-tagged jets as a function of the longitudinal-momentum fraction ($z_{||}^{ch}$) carried by the charmed hadron. A larger yield of Λ_c^+-tagged jets compared to D^0-tagged jets is observed at intermediate $z_{||}^{ch}$ values. This suggests that, within the studied kinematic range, since the normalised Λ_c^+-tagged jet distribution shows larger values at intermediate $z_{||}^{ch}$ ($0.6 < z_{||}^{ch} < 0.7$) compared to D^0, the Λ_c^+ baryon carries, on average, a smaller fraction of the jet momentum.

This observation, together with the larger near-side yield seen in the azimuthal correlations of Λ_c^+ baryons compared to non-strange D mesons, tends to support the hypothesis of a potentially softer charm fragmentation into charm baryons.

The ratio of $z_{||}^{ch}$ distributions measured in Λ_c^+- and D^0-tagged jets is compared to predictions from PYTHIA 8 using the Monash and CR-BLC tunes. PYTHIA 8 with CR-BLC describes the data better than the Monash tune.

An additional measurement that can be performed to study charm-quark hadronisation into

baryons, and to probe local baryon-number conservation, is the azimuthal correlation between prompt Λ_c^+ and $\overline{\Lambda_c^-}$ baryons and identified protons. Correlations of Λ_c^+ with identified anti-protons (unlike-sign pairs, ULS) and with identified protons (like-sign pairs, LS), and their charge conjugates, have been investigated. Figure 3 (right panel) shows the azimuthal correlation distributions of Λ_c^+–$\bar{\mathrm{p}}$ and Λ_c^+–p pairs, normalised to the average value of ULS + LS in the $\Delta\varphi > \pi/2$ region, for $3 < p_{\mathrm{T}}(\Lambda_c^+, \overline{\Lambda_c^-}) < 5$ GeV/c and $0.4 < p_{\mathrm{T}}(\mathrm{p}, \bar{\mathrm{p}}) < 1$ GeV/c. A clear correlation peak in the near-side is observed for ULS pairs, whereas no significant correlation is visible for LS pairs. This observation is consistent with the expectation from local baryon-number conservation: when a Λ_c^+ baryon is produced, the production of a nearby anti-baryon in the final state is required to locally conserve the baryon number. The measured correlations are compared with predictions from PYTHIA 8 using the Monash and CR-BLC tunes. PYTHIA 8 with the CR-BLC tune provides a better overall description of the data, while the Monash tune significantly overestimates the ULS near-side correlation peak.

4. Accessing the charm splitting function

Recent experimental advances in jet-substructure techniques have made it possible to isolate and characterise gluon emissions from heavy quarks. To reconstruct the sequence of parton splittings inside a jet, the jet constituents are reclustered using the Cambridge–Aachen (C/A) algorithm [8]. To suppress non-perturbative effects and enhance sensitivity to perturbative QCD emissions [9], the Soft Drop grooming condition [10] is applied. This procedure selects only particular splittings of interest along the followed branch of the clustering tree.
For each splitting along this branch, the Soft Drop condition is tested:

$$z = \frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{1,2}}{R}\right)^{\beta} \tag{1}$$

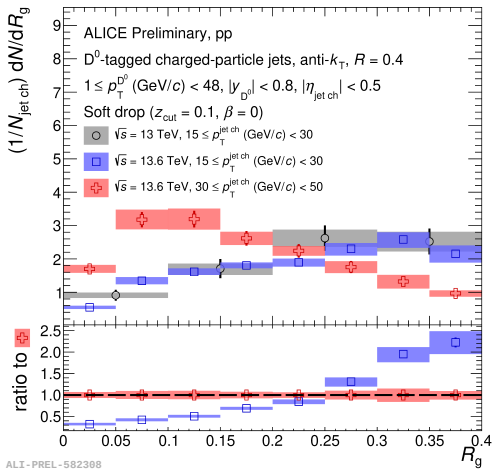

Figure 4: D^0-tagged jet yield as a function of R_{g}, compared with the corresponding measurement performed by ALICE in Run 2 in the transverse-momentum interval of the reconstructed jet $15 \le p_{\mathrm{T}}^{\mathrm{jet\ ch}} \le 30$ GeV/c and $30 \le p_{\mathrm{T}}^{\mathrm{jet\ ch}} \le 50$ GeV/c.

where $p_{T,1}$ and $p_{T,2}$ are the transverse momenta of the leading and subleading prongs of the splitting, $\Delta R_{1,2}$ is the aperture angle between the prongs, and R is the jet resolution parameter. The parameters z_{cut} and β determine how strictly soft, wide-angle emissions are removed by controlling the balance between the shared momentum fraction z and the splitting angle. Values of $z_{cut} = 0.1$ and $\beta = 0$ are chosen. Two groomed substructure observables are constructed from the first splitting that satisfies the soft drop condition $z_g = z$ and $R_g = \Delta R_{1,2}$, as given in Eq.(1).
Figure 4 shows the D^0-tagged jet yield as a function of R_g, compared with the corresponding measurement performed by ALICE in Run 2 [11]. Thanks to the larger data sample collected during LHC Run 3, the measurement has been extended to a wider kinematic range of reconstructed jet transverse momentum and performed with greater granularity in R_g. Access to higher jet transverse momenta allows for a detailed investigation of the evolution of parton mass effects with increasing energy.

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