# From light- to heavy-quark fragmentation in jets: current measurements in pp collisions with the ALICE detector and perspectives

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**Abstract.** The goal of the ALICE experiment at the LHC is to investigate the properties of the high-density state of strongly-interacting matter produced in Pb–Pb collisions. Partons propagating in a coloured medium interact with it leading to a softening of the parton $p_{\rm T}$ spectrum. The parton fragmentation function can be influenced by in-medium interactions leading to particle dependent modifications. Fragmentation function measurements in pp collisions are fundamental as reference for the Pb–Pb measurements and per se in order to constrain fragmentation models. The jet fragmentation into charged particles, pions, kaons, and protons measured by ALICE in pp collisions are presented. Different PYTHIA tunes are challenged in reproducing jet fragmentation into light particles. The measurement of the fragmentation of charm into heavier hadrons like the D mesons is being explored as well. The first studies and the perspectives for the LHC-Run2 are reported.

## 1. Introduction

Jets are collimated sprays of particles associated with hard-scattered partons. The study of jet production and fragmentation allows us to test our understanding of perturbative and non-perturbative aspects of QCD. Heavy quarks ($Q$), charm and beauty, are formed in initial hard scattering processes, hence on a shorter time scale with respect to the early hot and dense quark-gluon plasma phase. They interact with the medium via both inelastic (medium-induced gluon radiation) and elastic (collisional energy loss) processes [1]. Quarks are expected to lose less energy with respect to gluons ($g$), due to their smaller colour coupling factor. The small-angle gluon radiation is reduced for heavier quarks with moderate energy-over-mass values (so called "dead-cone effect") [2], with respect to light quarks ($q$). A hierarchy $E_{\rm loss}(Q) < E_{\rm loss}(q) < E_{\rm loss}(g)$ is hence expected. The fragmentation process inside a dense medium could thus be modified with respect to the vacuum in different ways for different partons.

## 2. Light quark and gluon fragmentation

At the LHC gluons are the most abundant, but the modelling of their fragmentation is poorly constrained by data, since the $e^+e^-$ experiments mostly constrain quarks. Charged jets are reconstructed in the ALICE central barrel from primary charged particle tracks measured in the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). Tracks with transverse momentum $p_{\rm T} > 0.15$ MeV/$c$ in the pseudo-rapidity interval $|\eta| < 0.9$ are clustered with the
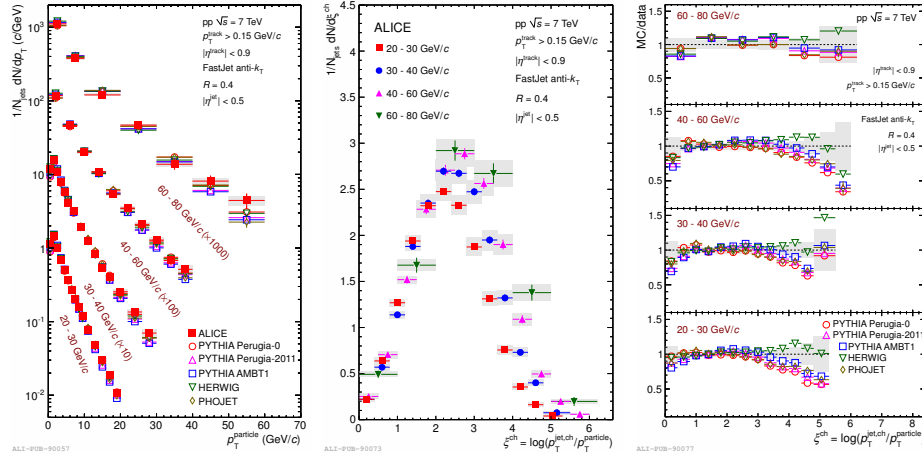
**Figure 1.** Transverse momentum distribution of charged tracks inside the jet (left) and their momentum fraction $\xi$ (middle) in $p_T^{\mathrm{jet,ch}}$ intervals from 20 to 80 GeV/$c$. The particle-$p_T$ spectra are compared with Monte Carlo simulations (see legend) in the left panel, while the right panel shows the ratios of the $\xi$ distribution in data and Monte Carlo simulations [8].

FastJet [3] anti-$k_T$ algorithm with a resolution parameter $R = 0.4$ using the boost-invariant $p_T$ recombination scheme. Jets which are fully contained within the detector acceptance are selected. The jet constituents' transverse momentum spectra (jet fragmentation) are measured in the leading (highest $p_T$) jets (Fig. 1, left panel). The distribution is corrected for detector effects bin-by-bin using simulations.

The middle panel of Fig. 1 shows the distribution of $\xi = \log(1/z^{\mathrm{ch}}) = \log(p_T^{\mathrm{jet,ch}}/p_T^{\mathrm{particle}})$. The subtracted underlying contribution was measured inside perpendicular cones transverse to the jet axis. The data are compared with different PYTHIA 6 tunes [4], HERWIG [5], and PHOJET [6]. The ratio of Monte Carlo to data in the right panel shows a general agreement at $\xi < 3$ and a slightly better description of the data by HERWIG at larger $\xi$.

The jet fragmentation measurement of identified particles ($\pi$, K, p) is shown in Fig. 2. The measurement utilizes the TPC for the d$E$/d$x$ information. At high ($> 4$ GeV/$c$) $p_T$ the d$E$/d$x$ is very similar for the three species, hence advanced techniques based on fits to the TPC signal [9, 10] were used to identify particles. The results are corrected for detector effects, including tracking efficiency, track $p_T$ resolution, jet $p_T$ resolution, secondary particle and muon (fake pion) contamination. The fragmentation function distribution peaks at about $z^{\mathrm{ch}} \sim 0.1$ and a scaling is visible in the two higher $p_T^{\mathrm{jet,ch}}$ bins.

Figure 3 shows the ratio of the measured $p_T$ spectra of identified particles in jets over simulations with different PYTHIA 6 tunes (Perugia0 with and without colour reconnection and Perugia2011 [7]). The simulations reproduce fairly well the distribution of kaons and of pions at $p_T^{\mathrm{track}} \gtrsim 400$ MeV/$c$. Protons are more challenging for models to be reproduced.

## 3. Heavy quark fragmentation

Measurements of the D$^{*\pm}$ meson momentum fraction ($X_E = E/E_{beam}$, where $E$ is the D$^{*\pm}$ meson energy) from $e^+e^-$ and $ep$ experiments [11, 12] showed that charm quarks fragment harder than light quarks, namely with $z \approx 0.6$. Direct charm production via pair creation, gluon splitting into a charm pair, and beauty feed-down contribute to the D$^{*\pm}$ meson yields. The D$^{*\pm}$ mesons originating from gluon splitting can be isolated via topological selection of the region of phase space where the largest invariant mass is concentrated. The fragmentation is softer than that of charm from pair creation and it is well reproduced by JETSET Monte Carlo simulations [11].
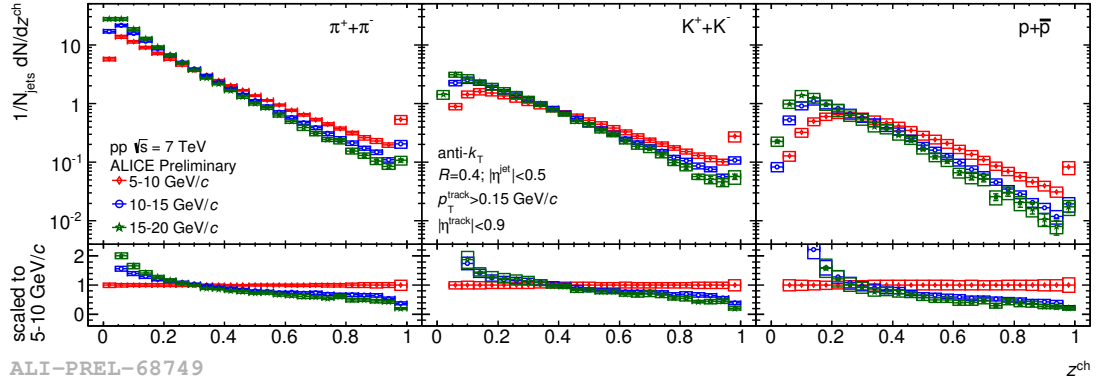
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**Figure 2.** Jet momentum fraction $z^{ch}$ of $\pi^+ + \pi^-$ (left), $K^+ + K^-$ (middle), and $p + \bar{p}$ (right) in jets for the ranges $p_T^{jet,ch}$ 5-10 GeV/$c$ (red), 10-15 GeV/$c$ (blue), 15-20 GeV/$c$ (green).
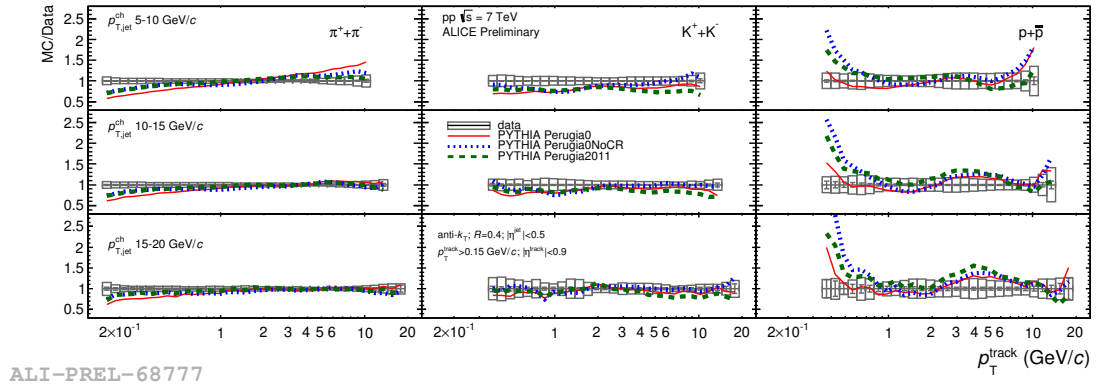


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**Figure 3.** Ratio of the measured $p_T$ spectrum of identified particles (left to right $\pi^+ + \pi^-$, $K^+ + K^-$, and $p + \bar{p}$) in charged jets and different PYTHIA tunes (see legend).

In hadronic collisions the initial parton energy is not known and the momentum fraction is defined as $z = p_\parallel^D / p^{jet}$, where $p_\parallel^D$ is the component of the D meson momentum parallel to the jet axis and $p^{jet}$ is the jet momentum magnitude. The contribution from gluon splitting dominates at azimuthal angles close to the jet axis. At LHC energies gluons dominate, hence the charm production via gluon splitting is expected to become more important.

The ATLAS Collaboration published a measurement of the $D^{*\pm}$ meson production in jets in pp collisions at $\sqrt{s} = 7$ TeV and reported a large discrepancy between data and Monte Carlo simulations, both leading and next-to-leading order calculations [13]. Monte Carlo predictions fail to describe the data at small values of $z$, and this is most marked at low jet transverse momentum ($20 < p_T < 60$ GeV/$c$). The ALICE experiment can play an important role in the investigation of the low-$p_T$, low-$z$ region. The first studies were performed with the pp sample at $\sqrt{s} = 8$ TeV using events triggered by the ElectroMagnetic Calorimeter (EMCal). The reconstruction of the $D^{*\pm}$ candidates is performed with topological selections and particle identification as in [14]. Charged tracks are clustered in jets with the FastJet algorithm as (cf. Sec. 2) and finally $D^{*\pm}$ mesons in a radius[1] of 0.4 around their axis are selected as $D^{*\pm}$ mesons in jets. An invariant mass analysis is applied to the $D^{*\pm}$ mesons in jets. As an example, the extracted signal via a fits are shown in the left panel of Fig. 4 for 3 bins of uncorrected

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[1] The radial distance is defined as $R(D, jet) = \sqrt{(\phi_D - \phi_{jet})^2 + (\eta_D - \eta_{jet})^2}$
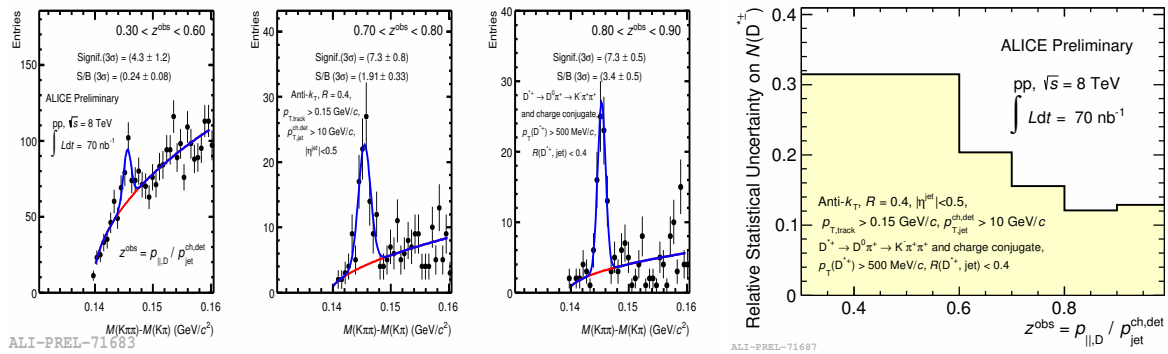
**Figure 4.** $D^{*\pm}$ meson invariant mass in 3 bins of uncorrected charged jet momentum fraction $z^{obs}$ (left) and relative uncertainties on the signal extraction (right) in pp collisions at $\sqrt{s} = 8$ TeV.

charged jet momentum fraction. The signal is extracted in bins of $z^{obs}$, where the subscript *obs* indicates that the $p_T$ spectrum of the jets is not yet corrected for detector effects. In the right panel of Fig. 4 the relative uncertainty on the signal as a function of $z^{obs}$ is reported. The large magnitude of the uncertainties does not allow to proceed to the corrections needed (the already mentioned $p_T^{jet,ch}$ correction, but also D meson efficiency and the feed-down subtraction). In order to explore the low-$p_T$, low-$z$ region a large minimum bias sample is needed. ALICE plan for LHC-Run2 is to collect a sample of $4 \times 10^9$ minimum bias events (10 times the current largest minimum bias sample at $\sqrt{s} = 7$ TeV) in pp collisions at $\sqrt{s} = 13$ TeV. This should be enough to perform the measurement down to $z < 0.3$ with a statistical uncertainty of 5%.

## 4. Summary
The current results on fragmentation function measurements in pp collisions performed with the ALICE detector were shown. The charged jet fragmentation function was measured in bins of $p_T^{jet,ch}$ in the region 20-80 GeV/$c$. Monte Carlo simulations do not reproduce the data in the region $\xi > 3.5 - 5$. The jet fragmentation in identified $\pi$, K, and p was also measured in the region $5 < p_T^{jet,ch} < 20$ GeV/$c$. Monte Carlo simulations fail in reproducing protons and pions at low-$p_T^{jet,ch}$ and low-$p_T^{track}$. The first studies for the measurement of the fragmentation function of $D^{*\pm}$ mesons were presented together with the outlook for Run2.

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