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Measurements of groomed heavy-flavour jet substructure with ALICE

Vít Kučera[a,*] **for the ALICE collaboration**

[a] *CERN,*
Esplanade des Particules 1, P.O. Box, 1211 Geneva 23, Switzerland

E-mail: vit.kucera@cern.ch

We report the first measurements of the groomed heavy-flavour jet substructure variables z_g, R_g, and n_{SD} using the Soft Drop algorithm for charged-particle jets tagged by fully reconstructed D^0 mesons in pp collisions at $\sqrt{s} = 13\,\text{TeV}$.

Iterative declustering techniques access the jet splitting tree of track-based jets, with grooming techniques isolating the perturbative branches. D^0-tagged jets give access to an enriched quark-initiated sample of jets down to low jet transverse momenta ($p_T^{\text{jet ch}}$). This provides a new opportunity to explore the differences between quark and gluon fragmentations in vacuum in the region of phase space where the inclusive-jet sample is dominated by gluon-initiated jets and where the mass effects of heavy-flavour quarks are also expected to be the strongest [1].

The shared momentum fraction of the first splitting accepted by the grooming procedure, z_g, and the aperture angle between the prongs of that splitting, R_g, fully corrected to particle level, are presented. The grooming is performed using the iterative Soft Drop [2] technique with parameters $z_{cut} = 0.1$ and $\beta = 0$. In addition, the number of splittings per jet satisfying the grooming condition, n_{SD}, is also reported. The results are presented in the $15 \le p_T^{\text{jet ch}} < 30\,\text{GeV}/c$ range and are compared to complementary measurements of inclusive jets as well as to theoretical models. These results also provide a reference for future D^0-tagged jet substructure measurements in heavy-ion collisions, to explore the different energy loss of gluon, light-quark, and heavy-quark jets in the presence of a deconfined QCD medium.

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[*] Speaker

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1. Introduction

Jets are collimated bunches of hadrons resulting from the fragmentation of partons scattered in the initial stages of collisions. The topology of the resulting jet depends on the flavour of the initiating parton, with gluon-initiated jets expected to have a broader and softer fragmentation pattern compared to quark-initiated jets [3], due to their different Casimir colour factors. For heavy-flavour jets, mass effects are also expected to arise from the dead-cone effect [1], whereby the emission phase space of a massive emitter is suppressed in an area defined by an angle which is proportional to the mass of the emitter.

Jet substructure observables allow for measurements that expose particular aspects of jet fragmentation patterns. Iterative declustering techniques in particular give access to individual splittings inside a jet, under the assumption of angular ordering [4]. In this work, splittings are tagged using the Soft Drop grooming condition which uncovers perturbative splittings in the jet. This allows for the construction of jet substructure observables which are calculable in the pQCD framework. This is particularly important at low $p_{\mathrm{T}}^{\text{jet ch}}$, where non-perturbative effects could dominate ungroomed observables.

Charm-tagged jets are identified by the presence of a D^0 meson amongst their constituents. The full reconstruction of the D^0-meson decay kinematics allows for the replacement of the D^0-meson decay daughters with the four-momentum of the D^0 meson, prior to jet clustering. This ensures that the full D^0 meson momentum is contained within the jet cone and also makes tracking of the D^0 meson in the splitting tree possible. In this way, the branch containing the D^0 meson candidate can be followed iteratively [5]. As the charm flavour is conserved throughout the jet evolution, this is equivalent to following the charm quark through the splitting tree.

2. Groomed observables

Soft Drop grooming begins by reclustering the constituents of a given jet into a splitting tree with the Cambridge-Aachen (C/A) algorithm [6], which respects angular ordering. The jet is subsequently declustered along the splitting tree, following the hardest branch at each step. In this way, the history of the parton shower is uncovered in chronological order. At each declustering step the splitting is tested against the Soft Drop condition, as given by

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

where $p_{\mathrm{T},1}$ and $p_{\mathrm{T},2}$ are the transverse momenta of the leading and subleading prongs of the splitting, respectively, and R is the jet resolution parameter. The grooming behaviour is defined by parameters z_{cut} and β which control the interplay between the shared momentum fraction z and the aperture angle between the prongs $\Delta R_{1,2} \equiv \sqrt{(y_1 - y_2)^2 + (\varphi_1 - \varphi_2)^2}$, where y and φ are the rapidity and azimuth of prongs 1 and 2, respectively. In this work, values of $z_{\mathrm{cut}} = 0.1$ and $\beta = 0$ are chosen, such that the Soft Drop condition is satisfied if the subleading prong carries more than 10% of the sum of prong transverse momenta.

Two groomed substructure observables are constructed against the first splitting that satisfies the Soft Drop condition: $z_{\mathrm{g}} = z$ and $R_{\mathrm{g}} = \Delta R_{1,2}$, as given in Eq. 1. The total number of splittings on

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the hardest branch that satisfy the Soft Drop condition is expressed by the third groomed substructure observable, n_{SD}, which is sensitive to the number of perturbative emissions from the charm quark.

Distributions of these variables are shown in Fig. 1 for simulated events generated using PYTHIA 8 [7] for both D^0-tagged jets and inclusive jets. The inclusive-jet sample is split into quark-initiated jets and gluon-initiated jets to disentangle the effects arising from the dead cone (heavy quarks vs light quarks) and the differing Casimir colour factors (quarks vs gluons). The D^0-tagged jets exhibit a steeper z_{g} distribution and the R_{g} distributions reveal differences in collimation between D^0-tagged jets and their inclusive counterparts. There is also a significant separation for the n_{SD} variable compared to the two components of the inclusive-jet sample, with D^0-tagged jets having fewer splittings that pass the Soft Drop condition, owing to the harder fragmentation of the charm quark compared to light quarks and gluons.

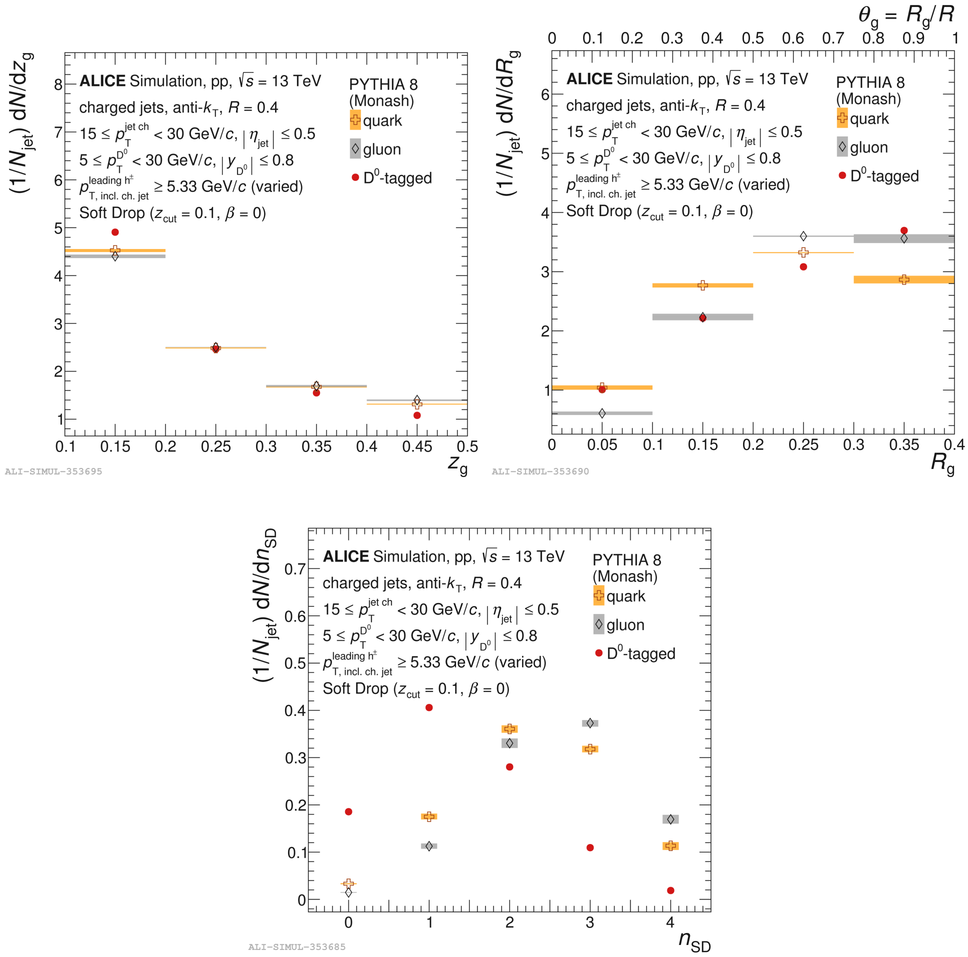

Figure 1: The distributions of z_{g} (left), R_{g} (right), and n_{SD} (bottom) for events simulated with PYTHIA 8, using the Monash tune [8], in the $15 \leq p_{\mathrm{T}}^{\text{jet ch}} < 30\,\mathrm{GeV}/c$ range.

3. Analysis procedure

The D^0 mesons were reconstructed through the $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ decay channel. Combinatorial background was reduced by applying PID and topological cuts [9] on the secondary vertices and

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daughter tracks. The daughter tracks were replaced by the D^0 meson candidate four-momentum vector, which was calculated by adding the four-momenta of the daughters. Jet finding was then performed with the anti-k_t algorithm [10], with a resolution parameter of $R = 0.4$ and E-scheme recombination [11]. For every D^0 meson candidate in an event, jet finding was performed independently, with only the daughters of that particular candidate replaced each time. Once jet finding had been performed, the D^0 meson candidate jets were reclustered using the C/A algorithm and the z_g, R_g, and n_SD observables were calculated for each one.

The fraction of jets tagged by a background D^0 candidate was removed via a sideband subtraction procedure [12] in intervals of D^0 meson candidate transverse momentum, $p_\mathrm{T}^{\mathrm{D}^0}$. The signal distributions in each $p_\mathrm{T}^{\mathrm{D}^0}$ interval were scaled by the reconstruction efficiency of prompt D^0-tagged jets, that had been estimated from Monte Carlo simulations using PYTHIA 6 and GEANT 3 [13]. The efficiency-corrected distributions were summed over the full $p_\mathrm{T}^{\mathrm{D}^0}$ range and corrected further to remove the feed-down component coming from non-prompt (b-quark-initiated) D^0-tagged jets, which was estimated using POWHEG [14] + PYTHIA 6 + EvtGen simulations. The prompt D^0-tagged jet substructure observables and $p_\mathrm{T}^{\text{jet ch}}$ were simultaneously corrected for detector effects by two-dimensional Bayesian unfolding [15]. The unfolded distributions were normalised to the number of measured jets, corrected to particle level, passing Soft Drop in the reported phase space.

The z_g, R_g, and n_SD jet observables were also measured for inclusive jets. The constraint on the interaction Q^2 implied by the selection of D^0 mesons with $p_\mathrm{T}^{\mathrm{D}^0} \geq 5\,\mathrm{GeV}/c$ was mimicked for the inclusive jets by requiring a leading track with $p_\mathrm{T} \geq 5.33\,\mathrm{GeV}/c$, which corresponds to the p_T of a charged pion with the same transverse mass as a D^0 meson with $p_\mathrm{T}^{\mathrm{D}^0} = 5\,\mathrm{GeV}/c$. The inclusive-jet distributions were then corrected for detector effects via unfolding.

4. Results

The first measurements of groomed jet substructure observables (z_g, R_g, and n_SD) for prompt D^0-tagged jets, fully corrected to particle level, are reported for the interval $15 \leq p_\mathrm{T}^{\text{jet ch}} < 30\,\mathrm{GeV}/c$ in Fig. 2. This kinematic range provides access to a region of phase space where mass effects are expected to play a significant role. Complementary measurements of an inclusive-jet sample, fully corrected to particle level, are also presented. Comparisons of the D^0-tagged jet and inclusive-jet samples can be used to study the influence on jet substructure arising from both the mass of the heavy quark and the initiating parton flavour of the jet. In particular, the n_SD variable shows a significant sensitivity to differences in the two samples, with the distributions shifted to smaller values of n_SD for the D^0-tagged jets. This indicates that the fragmentation of the charm quark is hard throughout the showering process. These results are in agreement with the expectation of the charm-quark fragmentation to be harder than the fragmentation of light quarks and gluons.

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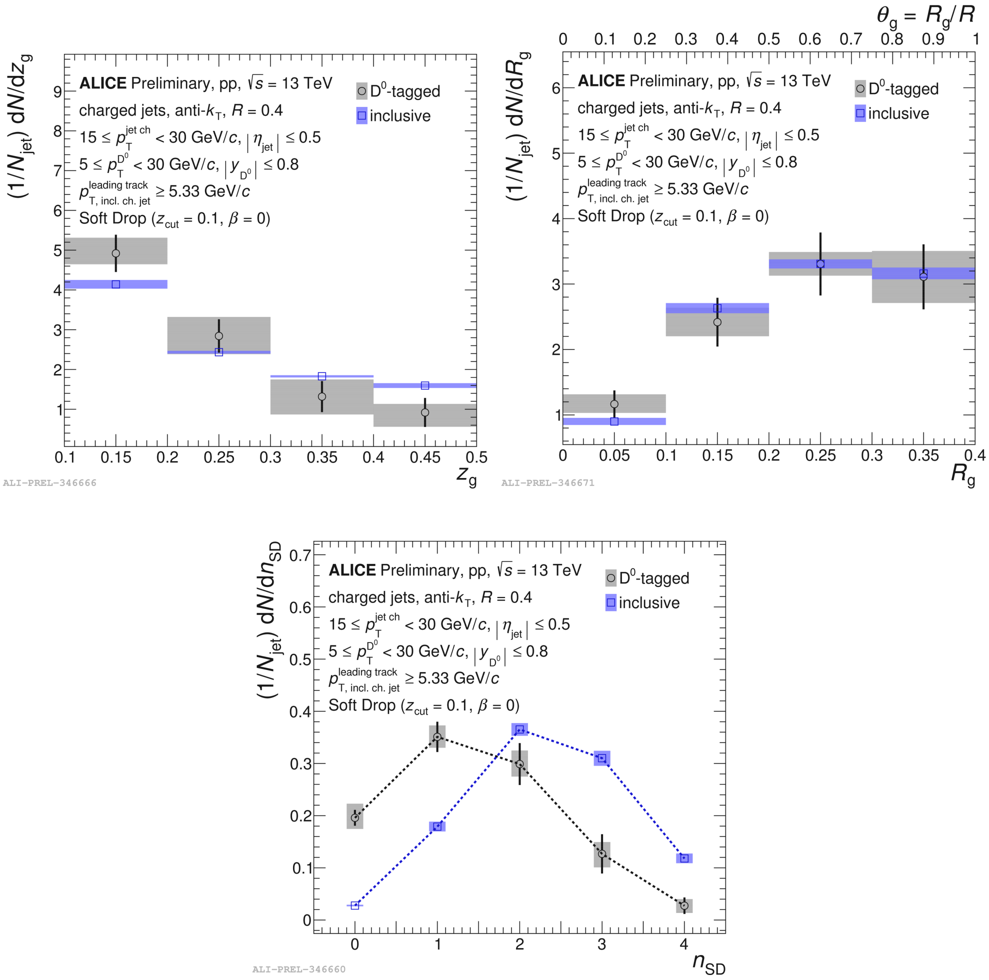

Figure 2: The measured z_g (left), R_g (right), and n_{SD} (bottom) distributions, corrected to particle level, for prompt D^0-tagged jets and inclusive jets in the $15 \le p_T^{\text{jet ch}} < 30\,\text{GeV}/c$ interval.

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