Measurement of jet fragmentation at ATLAS

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Jet fragmentation

In leading-order QCD, well-separated jets and partons are exactly equivalent

Broken by evolution from fixed-order to “real” jets: a multi-scale phenomenon including both perturbative QCD radiation and non-perturbative hadronisation

Collectively this process can be considered as the fragmentation of a parton into the multi-hadron spray of a particle-level jet

Measuring jet fragmentation means understanding the emergence of jet structure
ATLAS jet fragmentation measurements

Previous ATLAS measurements of jet fragmentation:


Today: presentation of new ATLAS jet fragmentation measurement at 13 TeV
ATLAS jet fragmentation at 13 TeV — arXiv:1906.09254

Uses 33 fb$^{-1}$ dataset of 13 TeV pp collisions from 2016

- Increased phase space & jet $p_T$ reach wrt 7, 8 TeV
- Makes use of Run 2 tracker upgrades, e.g. IBL
- Dense-environment tracking, for $\langle \mu \rangle \approx 25$

At least two jets with $|\eta| < 2.1$, and $p_T > 60$ GeV

- $|\eta|$ requirement for full containment in tracker
- $p_{T1}/p_{T2} < 1.5$ balance to simplify interpretation
- $p_T > 100$ GeV at fiducial level
- Charged tracks ghost-associated to calo jets
Observables

Fragmentation function $D$ defined as $p_T$ fraction of hadron $h$ wrt its containing jet $p_T$, from parton $p$.

$\Rightarrow$ DGLAP pQCD evolution; mirror image of PDFs

This paper uses charged hadrons, but full (calo) jet

$\Rightarrow \langle n_{ch} \rangle$ and differential $1/N_{jet} \ dN_{jet} / d\langle n_{ch} \rangle$

+ summed fragmentation function:
differential in $p_T$ fraction $\zeta$ and jet $p_T \Rightarrow$ extract partial fractions, moments & weighted sums

+ Relative transverse momentum
Radial profile (non-$p_T$-weighted)
Detector-level variables

Raw distributions of $n_{\text{trk}}$, track momentum fraction, track $p_{T,\text{rel}}$, and track radial profile

For a 1 TeV jet, most probable $n_{\text{trk}}$ is ~15, and most probable momentum fraction ~1%

Track $p_{T,\text{rel}}$ and $r$ (radial profile) distributions peak at zero since radiation dominantly collinear
Detector correction & uncertainties

Unfolding from detector obs to fiducial phase space: particle-level tracks & jets from particles with $c_{T_0} > 10$ mm; muons and neutrinos excluded from jets

Unfolding by 2D iterative Bayes method (1 iter) sandwiched by explicit in/out migration corrs.

Main uncertainties: tracking, jet scale, binning & unfolding, depending on observable
Unfolded average observables

Average observables vs $p_T$ generally well-described by main shower MC codes (Pythia8, Herwig++ and Sherpa)

Hints of deviation from Sherpa, particularly in radial profiles — these are a standard component of MC tuning since 7 TeV jet-shape paper… but only for jet $p_T < 500$ GeV!
Unfolded partial sums: $n_{\text{ch}}$ fraction in bins of $\zeta$

$$\int_0^X F(\zeta) d\zeta / \int F(\zeta) d\zeta = n_{\text{ch}}(\zeta < X) / n_{\text{ch}}$$

Fractions of charged particles with $\zeta \leq 10\%$, 1\%, and 0.1\% vs jet $p_T$

Fraction of small-fraction particles increases with jet $p_T$, cf. hadronisation scale

Small mismodelling of 10\% by Herwig; with Sherpa & Py8 in less inclusive bins
Unfolded observable moments & weighted sums

Also observables computed as moments and weighted sums with the $p_T$ fraction $\zeta$ raised to powers $\kappa = 0.5$ and $\kappa = 2$:

$$\langle \zeta^\kappa \rangle = \frac{\int \zeta^\kappa F(\zeta) d\zeta}{\int F(\zeta) d\zeta}$$

$$\langle \sum_{i \in \text{jet}} \zeta_i^\kappa \rangle = \int \zeta^\kappa F(\zeta) d\zeta$$

Pythia 8 and Herwig++ mostly well-behaved; major discrepancies seen for Sherpa, esp. for $\kappa = 2$

[effectively a var($\zeta$) measurement]
And more!

Differential distributions of every core variable in bins of jet $p_T$

A treasure-trove of data for jet modelling & resummation studies!
Quark/gluon jet discrimination

An important application of jet structure data is development of methods to extract information about quark/gluon jet origins

Ideally in a well-defined, QCD-aware way!

- **Central/forward jet**: roughly, central and low-$p_T$ jets are more likely to be gluon-initiated
- ⇒ Extract q/g components with an MC-template procedure
- **New**: model-independent q/g extraction by data-driven “topic” modelling
Mean observables with central/forward-jet split

Aim of central/forward jet distinction is to bias quark or gluon jet origin

Biases allow extraction of separate q/g-like fragmentation functions by comparison of forward and central jet ones

Note Pythia mismodelling of split $n_{ch}$ distributions, unlike inclusive. Most c/f-split mean observables are well-described
Model-dependent quark/gluon jet characterisation

q/g extraction by use of MC flavour fractions $f$, nominally from Pythia:

\[ h_i^f = f_q h_i^q + (1 - f_q) h_i^g \]
\[ h_i^c = f_q h_i^q + (1 - f_q) h_i^g \]

Jet flavour defined by hardest parton geometrically associated to the jet: many theory issues, and potential sources of uncertainty

Extracted q/g-like fragmentation observables fit expectations:
Model-independent quark/gluon jet characterisation

Novel approach is to use “topic modeling” extraction.

The categories are defined by data rather than MC internals:

\[
h_i^{T_1} = \frac{h_i^f - \left( \min_j \{ h_j^f / h_j^c \} \right) \times h_i^c}{1 - \min_j h_j^f / h_j^c}
\]

\[
h_i^{T_2} = \frac{h_i^c - \left( \min_j \{ h_j^c / h_j^f \} \right) \times h_i^f}{1 - \min_j h_j^c / h_j^f}
\]

Interesting new approach. Limitation: alignment of topics to q and g template ideas relies on the existence of bins dominated by q or g: applies to \( n_{ch} \) distribution only
Comparing quark/gluon jet characterisations

Pythia-based vs topic modeling: good description by Pythia for quarks in both; less good for gluons. “Quark” topic also aligns well with quarks, worse for gluons.

pQCD normalization-anchored, since can’t handle non-perturbative physics: compares well to q/g extractions.
Conclusions

- New ATLAS measurement of jet fragmentation observables
- Very comprehensive study of charged jet constituent distributions, unfolded to fiducial phase-space for MC comparisons
- Inclusive / averaged observables generally described well by popular SHG MC generators; differential and weighted/moment observables reveal issues. Breakdowns in MC shower tuning to lower-$p_T$ jet moment observables?
- Extraction of quark/gluon fragmentation function components by model-dependent and new model-independent means. Both perform well for quarks, gluons more difficult. Comparisons with pQCD look consistent
- All data public on HepData for MC/pQCD development & tuning
ATLAS $g \rightarrow bb$ fragmentation — arXiv:1812.09283

Super-quick summary: b-tagged track subjets in boosted jets

Fiducial differential cross-sections in b-subjet separation, mass, $p_T$ balance, and polarisation angle

Key: flavour fit via signed impact param