Modification of jet fragmentation

We know jets experience “energy loss” — but what is their fragmentation pattern?

Jet substructure:
- Calculable in pQCD — no fragmentation functions needed
- Corrected for background and detector effects — direct comparison to theory

\[ \theta_i = \frac{\sqrt{\Delta y^2 + \Delta \varphi^2}}{R} \]
\[ z_i = \frac{p_{T,i}}{p_{T,jet}} \]

How can we relate this to theoretically calculable quantities?
What do we know about $z$ and $\theta$?

**Momentum**

Longitudinal momentum of hadrons in jets is softened: $D(z)$

- ATLAS PRL 123 (2019) 042001
- CMS PRC 90 (2014) 2, 024908

Little-to-no modification in jet core: $z_g$

- ALICE PRL 128 (2022) 10, 102001

**Angle**

Jet core is narrowed: $\theta_g$

ALICE PRL 128 (2022) 10, 102001

See talk by H. Bossi Thursday 18:10

\[
\theta_g = \frac{\sqrt{\Delta y^2 + \Delta \phi^2}}{R}
\]

But there are key open questions:
- Girth/mass puzzle
- Large-$z$ behavior

This talk
The girth-mass puzzle

Jet angularities

\[ \lambda_{\alpha} \equiv \sum_{i \in \text{jet}} z_i \theta_i^{\alpha} \]
\[ z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}} \]
\[ \theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R} \]

Parameter \( \alpha > 0 \) varies
weight of collinear radiation
Jet angularities

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha$$

$$z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}}$$

$$\theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}$$

Note: $$\lambda_2 = \left( \frac{m}{p_T} \right)^2 + \mathcal{O} \left( \lambda_2^2 \right)$$

Why is the girth modified, but the mass not significantly modified?
Perform systematic measurement to map the girth-mass transition:

- Generalize observable:
\[ g, m \rightarrow \lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha \text{ for } \alpha = 1, 1.5, 2, \ldots \]
- Groomed vs. ungroomed
- Multiple \( R \)

pp baseline is described by pQCD in perturbative regime — with expected breakdown in nonperturbative regime

Jet angularities — pp

**Fig. 5:** Measurements of the jet angularities in pp collisions at \( \sqrt{s} = 5.02 \) TeV for \( \alpha = 1, 1.5, 2, \ldots \). Comparison of ungroomed jet angularities with pQCD calculations.

**Small \( \lambda_\alpha \):** Non-perturbative

**Larger \( \lambda_\alpha \):** Good agreement with pQCD calculations

*Kang, Lee, Ringer JHEP 04 (2018) 110*
Apply grooming procedure to remove low-energy, wide-angle radiation

\[ \lambda_{\alpha,g} \equiv \sum_{i \in \text{groomed jet}} z_i \theta_i^\alpha \]

Jet grooming recovers larger region of successful perturbative description

See also: CMS arXiv 2109.03340
Ungroomed jet angularities

Little-to-no modification observed
Jet angularities — Pb-Pb

Ungroomed jet angularities

Little-to-no modification observed

Measured pp baseline results in smaller modification than with PYTHIA reference

Less modification than in $\sqrt{s_{NN}} = 2.76$ TeV measurement based on PYTHIA reference

*ALICE JHEP 10 (2018) 139*
Jet angularities — Pb-Pb

Groomed angularities are modified more strongly than ungroomed angularities

Could be due to counterbalancing effects:
1. Suppression of wide jets
2. In-jet broadening

Jet grooming reduces (2), leaving stronger collimation effects visible

Significant modification, strong ordering in $\alpha$
Jet angularities — theory comparisons

Models generally describe trends in data well, although some deviations

- **JEWEL**
  Zapp, EPJ C 74 2 (2014)

- **JETSCAPE**
  arXiv 2204.01163

- **Higher Twist**
  Chen, Zhang et al., CPC 45 (2021) 2, 024102

- **Hybrid Model**
  See Zach Hulcher, Tues 18:30

Additional $\alpha, p_T$ available:
https://alice-figure.web.cern.ch/node/21570

Additional available:
https://alice-figure.web.cern.ch/node/21570/uni03B1

**Ungroomed**

- ALICE 0-10% Pb-Pb data
- ALICE Preliminary
  $\sqrt{s_{NN}} = 5.02$ TeV
  Ch.-particle anti-$k_T$ jets
  $40 < p_T^{jet} < 60$ GeV/c
  $|\eta_{jet}| < 0.7, \ R = 0.2$

**Groomed**

- ALICE 0-10% Pb-Pb data
- ALICE Preliminary
  $\sqrt{s_{NN}} = 5.02$ TeV
  Ch.-particle anti-$k_T$ jets
  $40 < p_T^{jet} < 60$ GeV/c
  $|\eta_{jet}| < 0.7, \ R = 0.2$
  SD: $z_{cut} = 0.2, \beta = 0$

Additional $\lambda_{x=1}$ available:
ALI-PREL-506909

- JEWEL (recolls off)
- JEWEL (recolls on)
- JETSCAPE (MATTER+LBT)
- Higher-Twist parton $E$-loss
- Hybrid model (no elastic)
- Hybrid model (with elastic)
From hadron $z$ to subjet $z_r$

**Hadrons in jets**

![Graph showing ratio of jet fragmentation for different radii and energies.]

- Data points for $\gamma$-tag (pT = 80-126 GeV, pT = 63-144 GeV)
- Inclusive jets (pT = 80-110 GeV)
- Data points for pp (25 pb⁻¹)
- Data points for Pb+Pb (0.49 nb⁻¹)
- SCET G results of theoretical calculations at particle level.

**Subjets in jets**

Cluster inclusive jets with radius $R$, then recluster with anti-$k_t$ with radius $r$

\[ z_r = \frac{p_{T_{ch\,subjet}}}{p_{T_{ch\,jet}}} \]

- Probe higher $z$ than hadron fragmentation measurements
- Opportunity to test universality of jet fragmentation functions

\[ J_{r,med}(z) = J_{med}(z) \]

parton $\rightarrow$ subjet $\rightarrow$ jet

See also: CMS PRC 90, 024908 (2014)

ATLAS PRL 123 042001 (2019)

Qiu, Ringer, Sato JHEP 07 (2019) 041
Kang, Ringer, Waalewijn JHEP 07 (2017) 064
Subjet fragmentation — pp

Measurements described well by pQCD in \(0.1 \lesssim z_r \lesssim 0.9\)

\(Kang, Ringer, Waalewijn \ JHEP 07 (2017) 064\)

At small \(z_r\), the pQCD calculation fails due to lack of small \(z_r\) resummation

□ Connection to parton-hadron duality

\(Neill, Ringer JHEP 06 (2020) 086\)
\(Neill JHEP 03 (2021) 081\)
**Subjet fragmentation — Pb-Pb**

### Leading subjets

<table>
<thead>
<tr>
<th>ALICE-PUBLIC-2022-016</th>
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<tbody>
<tr>
<td><strong>ALICE Preliminary</strong></td>
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**Pb-Pb/pp**

- Medium jet functions
- JETSCAPE
- JEWEL, recoils on
- JEWEL, recoils off

**New**

**Hint of hardening distribution at intermediate $z_r$**

- Large quark-gluon differences in vacuum
- Competing effects
  - Gluon suppression $\rightarrow$ larger $z_r$
  - Soft radiation $\rightarrow$ smaller $z_r$

**Well-described by most theoretical predictions**

- Consistent with universality of jet fragmentation in QGP

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**Quark Matter 2022, Kraków**

April 6, 2022
Subjet fragmentation — Pb-Pb

**Leading subjets**

*ALICE-PUBLIC-2022-016*

- **ALICE Preliminary**
  - $\sqrt{s_{NN}} = 5.02$ TeV
  - Charged-particle anti-$k_T$ jets
  - $R = 0.4$, $|\eta| < 0.5$
  - $80 < p_T^{ch, jet} < 120$ GeV/c
  - anti-$k_T$ subjets $r = 0.1$

- **Pb-Pb 0–10%**

- Systematic uncertainty

![Graph showing subjet fragmentation](image)

**Turnover of ratio as $z_r \to 1$**

- At $z_r \to 1$, the sample becomes closer to purely quark jets!
- Expose region depleted by soft medium induced emissions

**New path to disentangle quenching effects**

*ALICE-PUBLIC-2022-016*

- **Medium jet functions**
  - JETSCAPE
  - JEWEL, recoils on
  - JEWEL, recoils off

- **Pythia8 pp** $\sqrt{s} = 5$ TeV

- Anti-Quark, $R=0.4$, $|\eta| < 1$ jets from ch. part.; subjet $r=0.1$
  - Quark fraction, inclusive subjets
  - Gluon fraction, inclusive subjets
  - Quark fraction, leading subjets
  - Gluon fraction, leading subjets

James Mulligan, LBNL

Quark Matter 2022, Kraków

April 6, 2022
Subjet fragmentation — Pb-Pb

Ratio of Pb-Pb distributions for different $r$

- Partial cancellation of systematic uncertainties

Models capture general trend, but quantitatively disagree with data

- Note self-normalization condition

Measured data indicates broader jets at large $z_r$ than models

ALICE Preliminary Pb–Pb 0–10%
$\sqrt{s_{NN}} = 5.02$ TeV
Charged-particle anti-$k_T$ jets
$R = 0.4$, $n_{\text{jet}} < 0.5$
$100 < p_T^{\text{ch jet}} < 150$ GeV/c
anti-$k_T$ subjets

Models capture general trend, but quantitatively disagree with data

- Note self-normalization condition

Measured data indicates broader jets at large $z_r$ than models
Summary

By measuring carefully chosen observables…

- Calculable in proton-proton collisions
- Corrected for background and detector effects

...we are producing an emerging picture of the jet fragmentation pattern

New measurements of groomed and ungroomed jet angularities

- Insight into girth/mass puzzle
- Systematic measurement for Bayesian inference of medium properties

New measurements of subjet fragmentation distributions

- Access large \( z_r \) region — quark-gluon separation using substructure
- Universality tests of jet fragmentation in QGP
backup
Jet angularities in Pb-Pb

Deviations in pp baseline can induce disagreement in Pb-Pb/pp ratio