Exploring medium properties using jet substructure measurements in pp and Pb–Pb collisions with ALICE

Hannah Bossi (Yale University → MIT) for the ALICE Collaboration

Quark Matter 2023
Houston, Texas
Jets and jet substructure

Jets are formed from the fragmentation (via parton shower) and hadronization of a hard-scattered parton.

Resulting jet and its substructure can be used to probe physics at different scales!
Types of jet substructure

Jet splittings

Focus on hard substructure (parton level)

- In vacuum: used to probe perturbative/non-perturbative QCD, BSM searches etc.
- In medium: used to probe the modification of jet substructure due to QGP

Jet shapes

Focus on distribution of radiation within the jet (hadron level)

See talks by W. Fan Wed @ 08:50 and N. Zardoshti Wed @ 16:50
See posters by S. Wehymiller and C. Pliatskas Stylianidis

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Jet splittings

* Use declustering history to experimentally probe hard splittings within jets.

\[ k_T = p_{T,2} \sin(\Delta R) \]

\[ p_{T,1} = (1 - z)p_T \]

\[ \theta \equiv \frac{\Delta R}{R} \]

\[ p_{T,2} = zp_T \]

\[ z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} = \frac{p_{T,2}}{p_T} \]

\[ \tau \approx \frac{p_{T,1} + p_{T,2}}{p_{T,1}p_{T,2}(\Delta R)^2} \]

\( z \): shared momentum fraction between subjets (asymmetry)

\( \theta \): opening angle between subjets (width)

\( \tau \): time it takes splitting to become an independent source of radiation (formation time)

\( k_T \): relative transverse momentum of subjets (hardness)

[Apolinário et al. EPJC 81, 561 (2021)]
Grooming methods

* In vacuum: mitigate impact of hadronization, MPIs, pileup
* In medium: reduce sensitivity to soft background, removes some soft signal from momentum broadening and medium response. (Focus on hard structure modification)

**Soft Drop Grooming:**
- Select hard splittings

\[ z > z_{\text{cut}} \left( \frac{\Delta R}{R} \right)^{\beta} \]
- In heavy-ion collisions, increasing \( z_{\text{cut}} \) can be used to mitigate background

[Larkoski et al. JHEP 05 (2014) 146]

**Dynamical Grooming:**
- Grooming cutoff in \( z \) is generated on a jet-by-jet basis
- Different values of \( a \) specify different hardness measures

\[ \kappa^{(a)} = \frac{1}{p_T} \max_{i \in C/A} z_i (1 - z_i) p_{T,i} \left( \frac{\Delta R_i}{R} \right)^{a} \]


See student day talk from R. Kunnawalkam Elayavalli
Generalized angularities in Pb—Pb

Phase space of observables to probe the $p_T$ and angular distributions of constituents with relative weightings $\kappa$ and $\alpha$.

$$\lambda^{\kappa}_\alpha \equiv \left( \frac{p_{T,i}}{p_{T,\text{jet}}} \right)^\kappa \left( \frac{\Delta R_{i,\text{jet}}}{R} \right)^\alpha$$

[Larkoski et al. JHEP 11 (2014) 129]
Generalized angularities in Pb—Pb

Phase space of observables to probe the $p_T$ and angular distributions of constituents with relative weightings $\kappa$ and $\alpha$.

$$\lambda^\kappa_\alpha \equiv \left( \frac{p_{T,i}}{p_{T,jet}} \right)^\kappa \frac{\Delta R_{i,jet}}{R}$$

[Ref. Larkoski et al. JHEP 11 (2014) 129]
Generalized angularities in Pb–Pb

- Phase space of observables to probe the $p_T$ and angular distributions of constituents with relative weightings $\kappa$ and $\alpha$.

\[ \lambda \equiv \left( \frac{p_{T,i}}{p_{T,jet}} \right) \left( \frac{\Delta R_{i,jet}}{R} \right) \]

Core of the jet more modified than large angle distribution.

- Resolves the “girth-mass puzzle”

- Some tension with models, but good general agreement.

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Thrust and mass related, but show some differences!

\[ \lambda_2^1 = \left( \frac{m}{R_{p_T}} \right) + \mathcal{O}(\lambda_2^1)^2 \]
Ungroomed vs. groomed jet mass

Ungroomed jet mass

Groomed jet mass

Groomed distribution shows more modification in the jet mass.

Grooming isolates quenching effects in the hard jet core.

See possible shift towards lower mass consistent with narrowing.
**Hardest $k_{T,g}$ splittings**

* Use jet substructure techniques to search for point-like (Molière) scattering

$$k_T = p_{T,2} \sin(\Delta R)$$

* Experimentally appears as an excess of (large) $k_T$ splittings in Pb—Pb collisions relative to pp collisions

* Also sensitive to substructure modification as probed by $z_g$ and $R_g$.

  * Use various grooming methods to identify the hardest $k_T$ splitting within a jet

  - Soft Drop with a $z_{cut}$ of 0.2

  - Dynamical Grooming $a = 0.5$

  - Dynamical Grooming $a = 1.0$ (w/ $z_{cut}$)

  - Dynamical Grooming $a = 2.0$

**See talk by J. Norman**

*Tues. @ 09:50*

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Comparing grooming methods in pp and Pb—Pb

In vacuum some deviation between grooming methods at low $k_{T,g}$, converge at high $k_{T,g}$

First dynamical grooming in Pb—Pb

$z_{cut}$ dominates over grooming details

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Searching for Molière in Pb–Pb

No clear evidence of Molière scattering.

Data well described by JETSCAPE and Hybrid model w/o Molière

Modification of $k_{T,g}$ similar to narrowing seen in other substructure observables

Run 3 data and new experimental techniques can potentially help here!

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Probing time evolution of jets

Probe the temporal structure of the jet, study boundary between parton shower and hadronization.

In Pb—Pb could be used to probe time structure of jet quenching

\[ \tau \approx \frac{p_{T,1} + p_{T,2}}{p_{T,1}p_{T,2}(\Delta R)^2} \]

Recluster in a $\tau$-motivated way by setting $p = 0.5$ in sequential recombination algorithm

\[ d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \frac{\Delta R_{ij}^2}{R^2} \sim p_T \theta^2 \sim \frac{1}{\tau} \]

Apolinário et. al. EPJC 81, 561 (2021)

Cacciari et al. JHEP 0804:063 (2008)
Hints that $\tau$ reclustering selects wider splittings in $R_g$ (earlier times)
Reclustering based on $\tau$

- Hints that $\tau$ reclustering selects wider splittings in $R_g$ (earlier times)

- $z_g$ appears to be less sensitive to choice of reclustering method
Reclustering based on $\tau$

Hints that $\tau$ reclustering selects wider splittings in $R_g$ (earlier times)

$z_g$ appears to be less sensitive to choice of reclustering method

* Ratio well described with models, some deviations in underlying distributions.

Probing time evolution with $\tau_g$

* First measurement of groomed $\tau$ distribution ($\tau_g$) at the LHC!

* Hints that $\tau$ reclustering finds earlier splittings

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New

ALICE Preliminary pp, $\sqrt{s} = 5.02$ TeV
Ch-particle jets, anti-$k_T$, $R = 0.4$, $|\eta_{\text{jet}}| < 0.5$

40 < $p_T$, ch. jet < 60 GeV/c
Soft Drop, $z_{\text{cut}} = 0.2$

1. $\frac{1}{\sigma_{\text{jet, inc}}} \frac{d\sigma}{d\tau_g} \times 10^8$
   - $\tau$ Reclustered
   - C/A Reclustered

2. Ratio ($\tau/(C/A)$)

3. $\tau_g$ (fm/c)

ALICE Preliminary pp, $\sqrt{s} = 5.02$ TeV
Ch-particle jets, anti-$k_T$, $R = 0.4$, $|\eta_{\text{jet}}| < 0.5$

60 < $p_T$, ch. jet < 80 GeV/c
Soft Drop, $z_{\text{cut}} = 0.2$

1. $\frac{1}{\sigma_{\text{jet, inc}}} \frac{d\sigma}{d\tau_g} \times 10^8$
   - $\tau$ Reclustered
   - C/A Reclustered

2. Ratio ($\tau/(C/A)$)

3. $\tau_g$ (fm/c)
Probing time evolution with $\tau_g$

- First measurement of groomed $\tau$ distribution ($\tau_g$) at the LHC!

- Hints that $\tau$ reclustering finds earlier splittings

- Ratio and distributions well described by models

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Summary and Conclusions

- Measurements of jet substructure are uniquely sensitive to different QCD scales and their modification in the QGP.

- ALICE has made significant progress in utilizing these powerful probes!
  - Vacuum substructure (shown here: angularities, $k_{T,g}$, $\tau_g$) provides precision tests of QCD and comparison of grooming techniques.
  - Substructure in medium (shown here: angularities, $k_{T,g}$) shows general narrowing trend, no clear Molière signal, tests of various jet-medium interactions.

- New techniques to help extend precision and kinematic reach needed.

New heavy-ion data later this month! More to come on the horizon!

See poster by G. Van Weelden
Backup
The girth-mass puzzle

Degree of modification different for the girth (left) and the mass (right)

When you use pp reference in both cases, discrepancy goes away!
$\tau$ introduction

$\Delta \tau \approx \tau_{\text{Parton Shower form}} - \tau_{\text{Unclustering form}}$

* Correlation between first unclustering step and the first parton shower emission

In Pb—Pb useful to see the time-structure of quenching!

\[1/N_{\text{jet}} \frac{dN_{\text{jet}}}{d\Delta\tau}\]

τ from STAR

STAR Preliminary

pp $\sqrt{s} = 200$ GeV
SD $z_{out} = 0.1$, $\beta = 0$
anti-$k_t$ R=0.4 Jets, $|y| < 0.6$

$1/N_{jets}$ vs $\ln(\tau_i)$ [fm/c]

$20 < p_{\tau_{jet}} < 30$ [GeV/c]

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dependence on jet $p_T$

No strong $p_T$ dependence, some bins more than others.
Jet-medium interactions

**Radiative**
- Multiple soft radiation

**Collisional**
- Multiple soft scattering

**Medium Induced Splittings**
- Moliere Scattering

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Expectations of jet quenching (1/2)

1. Parton energy loss leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).

2. Internal structure modification due to...

- Momentum broadening
- Medium-induced wake

Image Credit: Jing Wang

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Expectations of jet quenching (2/2)

3. Deflection of the jet centroid due to multiple soft scatterings or scatterings with QGP quasi-particles.

- Different jets with different partonic structures, flavors, transverse momenta, path lengths through the medium, etc. lose energy differently.

- The same jets can lose energy differently due to fluctuations in jet-medium interactions.

*Isolating the same jet population can be challenging, but useful for disentangling energy loss mechanisms.*

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Groomed momentum splitting fraction

- Increased $z_{\text{cut}}$ to reduce the background.
- No observed modification of the groomed momentum splitting fraction ($z_g$).
- Consistent with quenching models.

Pablos et al. JHEP (2020) 044
Caucal et al. JHEP (2019) 273
JETSCAPE arXiv:1903.07706

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Groomed jet radius

\[ \theta_g \equiv \frac{R_g}{R} \]

See a suppression of wide angle splittings, favored by models with decoherence.

Could this also be coherence with a high quark fraction?

\[ R = 0.2 \]

\[ R = 0.4 \]

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Selection bias

If some populations lose more energy than others, we will see a suppression purely from the selection bias by measuring modified jets at a fixed $p_T$.

Changing selection removes narrowing for more quenched jets.


JHEP, 2021, 206 (2021)

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The ALICE Detector

Dedicated heavy-ion experiment at the LHC.
Reconstructs jets at mid-rapidity in pp, p-Pb and Pb—Pb collisions.

Can utilize high precision tracker to measure charged-particle jets up to high $p_T$.

Full jets combine charged particle information with neutral particle information measured in the electromagnetic calorimeter.

ALICE is great for jet measurements, especially measurements of jet substructure!

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