Investigating Hard Splittings via Jet Substructure in pp and Pb–Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE

Raymond Ehlers$^1$ for the ALICE Collaboration

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$^1$:Oak Ridge National Lab
raymond.ehlers@cern.ch

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Jet substructure provides access to the evolution of jet splittings.

Can visualize the splitting phase space via the Lund Plane.

Three variables define our splittings via the leading (1) and subleading (2) subjets:

- \( \Delta R = \sqrt{(\varphi_1 - \varphi_2)^2 + (\eta_1 - \eta_2)^2} \)
- \( z = \frac{p_T^{\text{sublead}}}{p_T^{\text{lead}} + p_T^{\text{sublead}}} \)
- \( k_T = p_T^{\text{sublead}} \sin \Delta R \)

Selecting on these variables provides a lever for exploring the phase space.

- pp: Limit contamination of QCD background.
- Pb–Pb: Select hard component of quenched jets.
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Jet substructure measurements take advantage of precise ALICE tracking in the ITS and TPC.

- Provide precise angular resolution down to low $p_T$.
- For these analyses, we measured $R = 0.4$ charged particle jets measured within $|\eta| < 0.9$.
- Jets are measured for $60 < p_{T,\text{jet}}^{\text{ch}} < 80$ GeV/c for both 2017 pp and 2018 Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.
Understanding Background Contributions

- Different strategies used by ALICE to suppress combinatorial background:
  - Measure small $R$ jets.
  - Increase $z_{cut}$.
  - Measure in semi-central collisions.
    - Reduces jet quenching relative to central, but combinatorial background is heavily suppressed.
  - See James Mulligan’s talk on Wed. 10:20 for strategies in central collisions.

- Utilize event-wise constituent subtraction JHEP 08 (2019) 175.
  - Parameters optimized for Pb–Pb collisions.

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Fully Unfolded $z_g$, $n_{SD}$ in 30–50% Pb–Pb Collisions

**$z_g$**

- ALICE Preliminary
- $\sqrt{s_{NN}} = 5.02$ TeV
- Charged jets anti-$k_T$
- $R = 0.4$, $|\eta_{jet}| < 0.5$
- $60 < p_{T, ch jet} < 80$ GeV/$c$
- Soft Drop $z_{cut} = 0.2$, $\beta = 0$
- $f_{tagged}^{pp} = 0.89$, $f_{tagged}^{AA} = 0.88$

**$n_{SD}$**

- ALICE Preliminary
- $\sqrt{s_{NN}} = 5.02$ TeV
- Charged jets anti-$k_T$
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- $60 < p_{T, ch jet} < 80$ GeV/$c$
- Soft Drop $z_{cut} = 0.2$, $\beta = 0$

Consistent with no modification.

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Fully Unfolded $R_g$ in 30–50% Pb–Pb Collisions

- Suppression of large angles and enhancement of small angles for both $z_{\text{cut}}$.
- Tested for consistency with unity, as determined by $\chi^2$ CDF for sys + stat in quadrature.
  - $z_{\text{cut}} = 0.2$: $p=0.03$
  - $z_{\text{cut}} = 0.4$: $p=0.029$

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ALICE Preliminary $\sqrt{s_{\text{NN}}} = 5.02$ TeV
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$60 < p_{T, \text{ch jet}} < 80$ GeV/c
Soft Drop $z_{\text{cut}} = 0.2$, $\beta = 0$

$R_g$ $z_{\text{cut}} = 0.2$

$R_g$ $z_{\text{cut}} = 0.4$
More symmetric splittings seem to be more suppressed in agreement with detector level measurements in the $\sqrt{s_{NN}} = 2.76$ TeV data (PLB 2020.135227).
Model Comparisons for $R_g$ in 30–50% Pb–Pb Collisions

- **JETSCAPE**: MATTER+LBT
  arxiv:1903.07706

- Pablos et al. Hybrid model
  JHEP 01 (2020) 044
  - $L = 0, 2/\pi T, \infty$

\[ R_g \text{ } z_{\text{cut}} = 0.2 \]

\[ R_g \text{ } z_{\text{cut}} = 0.4 \]

James Mulligan, Wed. 10:50 for 0–10%
What is the impact of the medium on jet substructure?

Can we detect with jet substructure observables high-$k_T$ emissions which are signature of point-like scatterers in the medium?
- Searching for signatures of point-like scattering centers in the medium via large-angle hadron-jet decorrelation.

- ALICE has measured large-angle recoil jet deflections in $\sqrt{s_{NN}} = 2.76$ TeV: JHEP 09 (2015) 170.

- Consistent with no acoplanarity of recoil jets within uncertainties.

- ALICE measurements are ongoing in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
  - See Jaime Norman, Monday 12:55.
As an alternative approach, we consider using jet substructure as a tool to search for large angle scatterings.

If a subjet is deflected at a large angle by a scattering center, it will increase the $k_T$ of that splitting.

- Point-like scatterers in the medium would appear as an excess of large $k_T$ emissions in Pb–Pb collisions relative to pp collisions.

- Access to the same physics as investigated via hadron-jet decorrelations.
Methods for Extracting Hardest $k_T$

- Use grooming methods to identify the hardest $k_T$ splitting in a jet:
  - For each considered splitting $i$, $k_T i = p_T i \sin \Delta R_i$
- We compare four main grooming methods:
  - Leading $k_T$: $\max \limits_{i \in C/A} k_T i$
  - Leading $k_T$ for all $z > 0.2$ splittings.
  - Dynamical grooming (PhysRevD.101.034004):
    \[ \kappa^a = \frac{1}{p_T} \max \limits_{i \in C/A} [z_i(1 - z_i)p_T i(\theta_i/R)^a] \]
    - $a = 1$ - Largest $k_T \sim \kappa^1 p_T$: "$k_T$Drop".
    - $a = 2$ - Shortest splitting time $t_i^{-1} \sim \kappa^2 p_T$: "TimeDrop".

PYTHIA8 Particle Level: Jet $p_T = 83.3 \text{ GeV}/c$
$k_T$ in node (GeV/c)
Iterative splitting
Harder subjet
Leading $k_T$ splitting
Each grooming method has different characteristic behavior in the Lund Plane.

**Leading $k_T$**

**Leading $k_T \ z > 0.2$**

**Dynamical $k_T$**
Number of splittings until the selected splitting converges at high $k_T$.

$k_T$ inclusive

$ALICE$ Simulation
$PYTHIA8 \sqrt{s} = 5.02$ TeV
Anti-\textit{k}_T charged jets
$R = 0.4, |\eta_{\text{jet}}| < 0.5$
$60 < \not{p}_{T,\text{ch jet}} < 80$ GeV/$c$

$k_T > 5$ GeV/$c$

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$k_T > 5$ GeV/$c$

- Leading $k_T$
- Leading $k_T z > 0.2$
- $k_T$ Drop
- timeDrop
Hardest $k_T$ Measured in pp Collisions

- $k_T$ follows characteristic steeply falling shape.
- PYTHIA in broad agreement with the data.

Leading $k_T$

\[ \frac{1}{N_{\text{jets}}} \frac{dN}{dk_T} (\text{GeV/c})^{-1} \]

ALICE Preliminary

$pp \sqrt{s} = 5.02$ TeV

Anti-$k_T$ charged jets $R = 0.4, |\eta_{\text{jet}}| < 0.5$

60 < $p_{T,\text{ch\,jet}}^\text{ch} < 80$ GeV/c

Leading $k_T z > 0.2$

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$f_{\text{PYTHIA}}^{tagged} = 0.89$

$f_{\text{data}}^{tagged} = 0.84$

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Hardest $k_T$ Measured in pp Collisions

- Dynamical grooming methods show same trends.
- PYTHIA in broad agreement with the data.

**Dynamical $k_T$**

![Graph showing $1/N_{jets} \, dN/dk_T (GeV/c)^{-1}$ for ALICE Preliminary data and PYTHIA8 Monash 2013 results]

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**Dynamical time**

![Graph showing timeDrop and PYTHIA8 Monash 2013 results]

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Comparison Between Grooming Methods

- Comparison of the different grooming methods in pp collisions.
- Ratio is relative to leading $k_T$.
- At low-mid $k_T$ there is some divergence between the methods.
- All grooming methods converge at high $k_T$.
- The exact same splitting is selected by all methods at very high $k_T$.
Toward Hardest $k_T$ in Pb–Pb

- To access feasibility in Pb–Pb, study the correlation between the hardest $k_T$ splitting in the parton graph and from declustering at particle level.
  - Identified the hardest $k_T$ graph, and then performed declustering for $R = 0.8$ jets.
- Compare pythia graph vs:
  - Particle level PYTHIA (as crosscheck).
  - Particle level PYTHIA + thermal background.
- **Strong correlation** between the hardest emission and the hardest splitting at large $k_T$.
- Studied at EMMI RRTF Workshop on the space-time structure of jet quenching.

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Summary and Outlook

- Measured $z_g$, $R_g$, and $n_{SD}$ in 30–50% Pb–Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
  - $z_g$, $n_{SD}$ consistent with no modification.
  - $R_g$ shows enhancement at small angles and suppression at large angles.
    - Both for $z_{cut} = 0.2$ and 0.4.
- Measured hardest $k_T$ splittings in pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
  - Grooming methods converge at high $k_T$.
  - PYTHIA broadly consistent with data.
- Hardest $k_T$ in Pb–Pb in progress.
- Further exploration of larger $R$ jets, jet splitting structure, and grooming methods.

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Backup
Jet Substructure Grooming

- Groomed jet substructure serves different purposes in pp vs Pb–Pb collisions.
  - In pp: Limit contamination of QCD background (and pileup) in a controlled way while retaining bulk of perturbative radiation
    - This isolates medium effects, making them easier to calculate.

[Diagram of jet substructure grooming]

MassDrop/SoftDrop
M. Dasgupta et al, JHEP1309 (2013) 029
A. Larkoski et al, JHEP 1405 (2014) 146
Grooming Method Characteristics - Lund Planes

Leading $k_T$

Dynamical time

Dynamical $k_T$
Comparison to PYTHIA

- Comparison of the grooming methods to PYTHIA 8.
- PYTHIA broadly consistent with data within statistical and systematic uncertainties.
- Some hints of shape differences between PYTHIA and the data.
  - Hints are consistent for different grooming methods.

![Graph showing comparison between PYTHIA and data](image-url)
Model Comparisons for $z_g$, $n_{SD}$ in 30–50% Pb–Pb

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