Exploring the Phase Space of Jet Splittings at ALICE

Nima Zardoshti
Motivation: Jet Splittings

- Systematically investigate jet splittings at different scales.
- Utilise different reclustering algorithms and grooming procedures.
- In pp collisions: Expected to be sensitive to fundamental QCD parameters.
- In Pb-Pb collisions: Expected to be sensitive to quenching effects such as coherence and medium induced semi-hard radiation.

Tywniuk et al. Novel tools and observables for jet physics in heavy-ion collisions

Mehtar-Tani et al., JHEP 1704 (2017) 125
Exploring the Phase Space: Lund Maps

- Lund maps are 2D maps of jet splittings.
- Derived from pQCD splitting functions.
- Powerful tools for controlling the phase space.
- Flexible metric: Can be filled in a variety of ways.
- Multi-dimensional realisation of jet shapes.

\[ P = \frac{1}{N_{\text{splittings}}} \frac{dN}{d \ln(z \Delta R) \ln(1 / \Delta R)} \]

Based on method from Salam et al, arXiv:1807.04758
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ALICE Simulation
PYTHIA $\sqrt{s} = 2.76$ TeV
$80 < p_{T,jet}^{ch} < 120$ GeV/c, anti-$k$, $R = 0.4$
Cambridge-Aachen Reclustering

Projection of x-axis
$\Delta R : \eta-\phi$ distance between subjets

Limited by $R=0.4$ jet radius

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ΔR : η-φ distance between subjets

Straight Line
z : momentum fraction of subleading prong

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Number of entries: $n$: number of splittings obtained by iteratively unclustering and following the hardest subjet

Projection of x-axis: $\Delta R$ : $\eta$-$\phi$ distance between subjets

Straight Line: $z$ : momentum fraction of subleading prong

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Experimental Access to Splittings: Reclustering Jets

- Recluster jet constituents with a variety of algorithms.
- Reclustering history is unwound to access the axes that were brought together in the final steps.
- Reclustered axes give experimental access to splittings.
- We then measure jet shapes relative to these axes.
- We also define variables to scan the iterative reclustering itself fill Lund diagram.
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Reclustering Algorithms

- $k_T$ $p_T$ sensitive
- Cambridge/Aachen (C/A) No $p_T$ dependence sensitive to largest splitting.
- C/A + minimisation of $\tau_N$ Expected to reduce sensitivity to uncorrelated soft radiation.
- Soft Drop (C/A) Large angle soft structures groomed sensitive to hard splittings.
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Soft Drop condition: \( z > z_{\text{cut}} \theta^\beta \)
Default values: \( z_{\text{cut}} = 0.1 \quad \beta = 0 \)
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Dasgupta et al, JHEP 1309 (2013) 029
Larkoski et al, JHEP 1405 (2014) 146
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Lund diagram filled with only the first splitting which passes Soft Drop.

- Soft Drop condition: $z > z_{\text{cut}} \theta^\beta$
  - Default values: $z_{\text{cut}} = 0.1$, $\beta = 0$
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Fully Corrected Soft Drop Shapes in pp

- Soft Drop variables are projections of the Lund map.
- For $z_g$ and $R_g$ the Lund map is only filled with the first splitting satisfying Soft Drop.
- Pythia describes all three measured variables well.
- Fully corrected with 2D Bayesian Unfolding: directly comparable to particle level

Normalising to the total number of jets in the reconstructed $p_T, \text{jet}$ bin.

Jets satifying $z > z_{\text{cut}} = 0.1$
- Data : 97.3(0.5)%
- PYTHIA : 98.9(0.1)%
Full Jets : $z_g$ Measurements in Differential $p_T^{\text{jet}}$ and Jet Resolution Bins in pp

- Larger data set at $\sqrt{s} = 13$ TeV : $L_{\text{int}} = 11.5$ nb$^{-1}$ (Min Bias) $L_{\text{int}} = 4$ pb$^{-1}$ (Triggered)
- Extending data set further by measuring full jets: Charged tracking + EMCal towers.

- Allows for a more detailed probing of QCD:
  - Can help constrain non-perturbative effects?
**N-subjettiness**

- The N-subjettiness, $\tau_N$, jet shape is a measure of how $N$-pronged a jet’s substructure is.
- $\tau_N$ is calculated relative to the $N$ returned axes.
- Initially developed to tag jets from Higgs decays such as $\text{Higgs} \rightarrow W^+W^-$. 

\[
\tau_N = \frac{\sum_{i=1}^{N} p_{T,i} \cdot \text{Min}(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \cdot \sum_{i=1}^{N} p_{T,i}}
\]

- $\Delta R_{i,j} \rightarrow \eta-\phi$ distance between track $i$ and subjet $j$
- $p_{T,i} \rightarrow p_T$ of $i^{th}$ jet constituent
- $R_0$ : Jet resolution parameter

- $\tau_N \rightarrow 0$ Jet has $N$ or fewer well defined cores
- $\tau_N \rightarrow 1$ Jet has at least $N+1$ cores
- $\tau_N/\tau_{N-1} \rightarrow 0$ Jet has $N$ cores
- $\tau_2/\tau_1 \rightarrow 0$ Jet is two-pronged

[Thaler et al, JHEP 1103 (2011) 015]
Alignement of radiation relative to returned axes ($\tau_2/\tau_1$) *reasonably well* described by PYTHIA.

- Additional information compared to Lund map: subleading subjet.
- Subleading C/A axis follows soft radiation: jet not expected to be two-pronged relative to this axis.
- The Soft Drop groomer increases the $p_T$ sensitivity of the subleading axis.
Fully Corrected $\Delta R$ Shape in pp

- Clean observable describing the distance between different types of splittings in the jet.
- Returned axes ($\Delta R$) well described by PYTHIA.
- C/A: soft scale acts at large distances from the jet core.
- $k_T$ and Soft Drop: hard splittings primarily in jet core.
Accounting for the Heavy Ion Background: Embedding

- PYTHIA jets embedded in real 0-10% most central Pb-Pb events.
- Embedded level reconstructed jets matched to PYTHIA level jets.
- **Background and detector effects** reproduced at embedded level.

Subtraction methods applied to subtract the pedestal background per jet simultaneously from the shape and the $p_T$:

- **Constituent Subtraction**
  - Berta *et al*, JHEP 1406 (2014) 092
- **Derivative Subtraction**
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- Lund diagram can be used to isolate the background contribution.
- Enhancement of splittings at low $z_g$ purely background effect.
Sensitivity of Jet Shapes to the Background

- $\Delta R$ sensitive to background fluctuations at large angles which replace subleading axis (fake splittings). Double peak structure of response inhibits unfolding.

- $\tau_2/\tau_1$ resilient to shift in axes due to soft/large angle background.

The background fluctuation needs to carry a significant fraction of the jet momentum to modify $\tau_2/\tau_1$. 
Sensitivity of Jet Shapes to the Background

- Uncorrelated background adds splittings at low $z_g$.
- Fake splittings appear at large $R_g$ due to the background.
- $n_{SD}$ appears relatively robust to the presence of background.

- Embedding accounts for background effects (fake splittings etc):
  Allows for direct comparison with uncorrected data.
Inclusive $z_g$ Shape in Pb-Pb

- **No net enhancement** of splittings passing the Soft Drop criteria observed at $\Delta R > 0.1$.

- $\sim 10\%$ **reduction** in the number of jets with a splitting that passes Soft Drop.
Inclusive $z_g$ Shape in Pb-Pb

- **Collimated splittings enhanced.**
- **Large angle splittings suppressed.**
- No low $z_g$ enhancement observed at large angles.
Number of Splittings in the Jet that Satisfying the Soft Drop Condition in Pb-Pb

- **No enhancement** in number of splittings passing Soft Drop.

- Enhancement in number of untagged jets (first bin).

- In contrast to expected correlated medium response or coherent collinear emissions.
Inclusive $\Delta R$ Shape in Pb-Pb

- **No modification** observed within statistical limits.
- Suppression of large $\Delta R$ would be expected for “resolved” jets.
- Enhancement of low $\Delta R$ would be expected with medium induced semi-hard radiation.
- Possible modifications can be smeared by the **fake splittings** reduction of signal to background ratio.
- Need to **reject fake splittings** to uncover potential physics signal.
Probing Lower $p_T$ Jets: Recoil Jets

- Combinatorial jets dominant at low $p_T$ and large jet resolution.
- Unfolding requires a combinatorial free input leads to a fully corrected measurement which is directly comparable to particle level.

Use semi-inclusive hadron-jet coincidence measurements to suppress combinatorial background:
- The yield of jets recoiling from two exclusive high $p_T$ trigger classes is measured.
- The difference in yield of the two classes provides an IRC-safe and combinatorial free jet distribution that can be unfolded.
Recoil Jets in 2D: Raw Recoil Jet Shapes

Extension of technique to 2D:

\[
\text{Difference} = \left( \frac{1}{N_{\text{trig}}} \cdot \frac{dN_{\text{jet}}}{d(\text{shape})d\mathbf{p}_{\text{T,jet}}} \right)_{\text{TTsignal}} - \left( \frac{1}{N_{\text{trig}}} \cdot \frac{dN_{\text{jet}}}{d(\text{shape})d\mathbf{p}_{\text{T,jet}}} \right)_{\text{TTreference}}
\]

- Difference yield approaches signal yield with increasing \( p_{\text{T,jet}} \).
- Raw uncorrected distributions.
Fully Corrected $\tau_2/\tau_1$ Recoil Shape in Pb-Pb

- Alignment of radiation relative to returned axes is similar in Pb-Pb and PYTHIA.
- No quenching modifications observed in a variety of different types of splittings.
- $k_T$ and Soft Drop:
  - A shift to larger values expected if jets are "resolved".
  - A shift to lower values expected with medium induced semi-hard radiation.
Conclusions

- Reclustering algorithms varied to probe **different scales** in the splittings.
- **No modification** of the **two-pronged substructure** of jets observed in the medium.
- A **significant modification** of the $z_g$ **distribution** observed in the medium.
- **Large angle splittings** appear **suppressed** in data.
- The **number of hard splittings** are **not enhanced** in data.
- These measurements represent an ongoing effort to systematically investigate jet substructure at ALICE.
BACKUP
ALICE Detector

- **EMCal**: neutral constituents
  - $p_{T,\text{cutoff}} = 300 \text{ MeV}/c$
  - $|\eta| < 0.7$
  - $1.4 < \varphi < 3.1$
  - Jet trigger

- **ITS + TPC**: charged constituents
  - $p_{T,\text{cutoff}} = 150 \text{ MeV}/c$
  - $|\eta| < 0.9$