Jet substructure measurements in heavy-ion collisions

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Jets to probe the quark–gluon plasma

- **Jet quenching**: jets are modified in the quark-gluon plasma created in ultra-relativistic heavy-ion collisions

https://www.int.washington.edu/node/776
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- How does a color charge lose energy?

- What (angular) **length scales** can the QGP resolve? When do partons interact coherently?

- Signature of point-like scattering? Is there an emergent structure such as **quasi-particles** in the plasma?
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- Signature of point-like scattering? Is there an emergent structure such as **quasi-particles** in the plasma?

- Systematic study with **jets and their substructure** => constrain models for QGP dynamics

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Large-R jets (CMS)

• First measurement of large-radius jets in Pb-Pb

• Substantial suppression at high momenta from small to large radii in central Pb-Pb collisions

• Sensitivity to energy loss mechanism as well as medium response

• Tension with models => Analysis of jet substructure to explore physics in details
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Jet grooming

- **Grooming**: access to the hard parton structure of a jet
  - Remove large-angle soft radiation: mitigate influence from underlying event, hadronization
  - Direct interface with QCD calculations
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- **Soft-drop grooming**
  - Recluster a jet with Cambridge-Aachen algorithm (angular ordered)
  - Iteratively remove soft branches not fulfilling SD condition $z > z_{cut} \theta^\beta$

\[
z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} \quad \theta = \frac{\Delta R_{12}}{R}
\]

Larkoski et al., JHEP 05 (2014) 146
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\[ z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} \]
\[ \theta = \frac{\Delta R_{12}}{R} \]

- **Dynamical grooming**
  - Recluster the jet with the Cambridge-Aachen algorithm
  - Look for the hardest splitting

\[ \kappa^{(a)} = \frac{1}{p_T^{i \in C/A, \text{seq.}}} \max \left[ z_i (1 - z_i) p_{T,i} \left( \frac{\theta_i}{R} \right)^a \right] \]
- \( a = 0.5 \) more symmetrical, narrow splitting
- \( a = 1 \) splitting with largest \( k_T \sim \kappa^{(1)} p_T \)
- \( a = 2 \) shortest formation time splitting, \( t_f^{-1} \sim \kappa^{(2)} p_T \)

Larkoski et al., JHEP 05 (2014) 146

Mehtar-Tani et al., PRD 101.034004
High-$k_T$ emissions can be a signature of point-like scattering

- First measurement with dynamical grooming in Pb+Pb collisions
- Soft-drop grooming with $z_{\text{cut}} = 0.2$
- Grooming methods converge toward high-$k_T$
**Hardest-\(k_T\) splitting (ALICE)**

- **High-\(k_T\) emissions can be a signature of point-like scattering**
  - First measurement with dynamical grooming in Pb+Pb collisions
  - Soft-drop grooming with \(z_{\text{cut}} = 0.2\)
  - Grooming methods converge toward high-\(k_T\)
- **No clear enhancement at high-\(k_T\)**
- **Model without Molière scattering describes data better**
• Jets with wider opening angle lose significantly more energy
  – Jets with large $r_g$ are approximately twice as suppressed than at small $r_g$
  => Narrowing of jets
SD-groomed radius (ATLAS)

- Jets with wider opening angle lose significantly more energy
  - Jets with large $r_g$ are approximately twice as suppressed than at small $r_g$
- The suppression does not depend strongly on $p_T$, regardless of $r_g$
  - $p_T$-dependence of inclusive jets from change of $r_g$ distribution
  - qualitatively consistent with jet quenching from coherence
Jet reclustering

- Small-radius ($R=0.2$) jets are reconstructed with the anti-$k_T$ algorithm
- A $p_T^{\text{jet}}>35$ GeV/c threshold is applied
- The remaining jets are reconstructed into large-radius ($R=1.0$) jets
- The small-$R$ jets are reclustered using the $k_T$ algorithm to determine angular separation and splitting parameter

\[
\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta \phi_{12}^2}
\]
\[
\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12} \sim k_T
\]
Reclustered large-radius jets (ATLAS)

- Reclustered $R=1$ jets are slightly more suppressed than smaller-radii inclusive jets

- Significant difference in the quenching of large-radius jets having single sub-jet and those with more complex substructure

![Graph showing suppression of jets in heavy-ion collisions](image)
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- Significant difference in the quenching of large-radius jets having single sub-jet and those with more complex substructure

- No pronounced dependence on $\sqrt{d_{12}}$~$k_T$ separation

- => supports decoherence beyond a critical splitting angle
Jet axis differences

• **Standard axis**: formed by the sum of pseudo-jet four-momenta in the clusterization with E-scheme

• **Soft-Drop groomed jet axis**: sum of four-momenta of constituents accepted by the SD grooming

• **Winner-takes-all axis**: recluster with CA algorithm, always combine prongs in direction of the stronger one => insensitive to soft radiation

\[ \Delta R_{\text{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2} \]
Jet axis difference (ALICE)

- Narrowing in heavy-ion collisions compared to the vacuum
- Sensitivity to medium resolution length: comparison to the Hybrid model
  - Measurement favors incoherent energy loss
- Intra-jet $p_T$ broadening model does not describe data trend

J. Casalderrey-Solana, JHEP 10 (2014) 019

arXiv:2303.13347 NEW!
Generalized jet angularities and jet mass

• **Angularities**: class of observables that depend on both the longitudinal and angular properties of jet splittings

\[ \lambda_{\alpha}^{\kappa} = \sum_{i \in \text{jet}} z_{i}^{\kappa} \theta_{i}^{\alpha} \]

\[ z_{i} = \frac{p_{T,i}}{p_{T,\text{jet}}} \quad \theta_{i} = \frac{\Delta R_{i,\text{jet}}}{R} \]

• IRC-safe observables for \( \kappa = 1, \alpha > 0 \)

\( \Rightarrow \) Theoretically accessible in the vacuum case

• Generalization of existing jet properties with continuously tunable parameters
  
  - **Jet girth** \( \lambda_{1}^{1} \)
  
  - **Jet thrust** \( \lambda_{2}^{1} \)
  
  - **Jet mass**: related to jet thrust

\[ \lambda_{2}^{1} = \left( \frac{m}{R_{p_{T}}} \right)^{2} + \mathcal{O}[(\lambda_{2}^{1})^{2}] \]

Kang et al., JHEP 1804 (2018) 110
Generalized jet angularities (ALICE)

\[ \lambda_\alpha^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\alpha \]

- Groomed and ungroomed generalized jet angularities reveal effect of soft radiation
  
- Shift toward lower angularities
  => Narrowing of jets for both the groomed and ungroomed case
Jet mass (ALICE)

- Jet mass related to thrust
  \[ m_{\text{jet}} \sim z^2 \theta^2 \]
- Shift towards lower masses
  \( \Rightarrow \) Narrowing of jets
  - Several models describe jet quenching
- Grooming enhances sensitivity to modification of jet fragmentation
  - Modification of the jet core?

NEW!

Jet mass related to thrust

\[ m_{\text{jet}} \sim z^2 \theta^2 \]

Shift towards lower masses

\( \Rightarrow \) Narrowing of jets

Several models describe jet quenching

Grooming enhances sensitivity to modification of jet fragmentation

Modification of the jet core?
Jet shapes

• Jets clustered with anti-\(k_T\) using the E-scheme
• Axis calculated using WTA algorithm
• Jet shapes defined as

\[
\rho(\Delta r) = \frac{1}{\delta r N_{\text{jets}}} \frac{1}{\sum_{\text{jets}} \sum_{\text{tracks} \in (r_a, r_b)} \rho_{T}^{\text{ch}}}
\]

• Complementary information to groomed substructure measurements
• Sensitive to soft radiation, background needs to be under control
Dijet shapes (CMS)

- Back-to-back dijet shapes
  \[ \rho(\Delta r) = \frac{1}{\delta r N_{\text{jets}}} \sum_{\text{jets}} \sum_{\text{tracks} \in (r_a, r_b)} \rho_{T}^{\text{ch}} \]

- in terms of momentum imbalance
  \[ x_j = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}}} \]

- Leading jets:
  - redistribution of energy from small angles w.r.t. the jet axis to larger angles
  - Stronger for balanced jets

=> path length dependence

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CMS Supplementary

PbPb 1.7 nb\(^{-1}\) (5.02 TeV) pp 320 pb\(^{-1}\) (5.02 TeV)

Cent: 0-10%

\[ \rho(\Delta r)_{\text{PbPb}} / \rho(\Delta r)_{pp} \]

Anti-\(k_T\) jets, R=0.4
\[ p_T^{\text{lead}} > 120 \text{ GeV}, p_T^{\text{sub}} > 50 \text{ GeV} \]
\[ |\eta_{\text{jet}}| < 1.6, \Delta\phi > \frac{5\pi}{6} \]
b-jet shapes (CMS)

- First study of jet shapes in HI collisions

\[
\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{jets}} \frac{\sum_{jets} \sum_{tracks \in (r_a, r_b)} p_T^{ch}}{\sum_{jets} \sum_{tracks \in r \leq 1} p_T^{ch}}
\]

- Low-\(\Delta r\) depletion of b-jets
- => consistent with a dead-cone

- High-\(\Delta r\) enhancement of b-jet shapes compared to inclusive jets, stronger in HI than in pp collisions
- => increased medium response to the propagation of a heavier quark
Summary

• Jet substructure in heavy-ion collisions: a rapidly evolving area with lots of new measurements

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• Jet substructure in heavy-ion collisions: a rapidly evolving area with lots of new measurements

• A tiny selection of the new results was shown
  – No clear evidence for point-like scattering centers
  – Jet suppression strongly dependent on jet substructure
  – General narrowing of the jet core
  – Pathlength-dependent modification patterns
  – Increased medium response to a heavier quark

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• Increased sensitivity and new observables with the advent of Run 3
  – Energy-energy correlators, photon-tagged systems, $v_2$ with substructure etc...
  – Extended heavy-flavor measurements
Thank you!
Lund planes

• Soft drop grooming

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• Dynamical grooming

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- **Back-to-back dijet shapes**

\[ \rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \sum_{\text{tracks} \in (r_a, r_b)} \frac{p_T^{\text{ch}}}{p_T^{\text{leading}}} \]

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\[ x_j = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}}} \]

- **Subleading jets**
  - redistribution of energy from small angles w.r.t. the jet axis to larger angles
  - In unbalanced jets, fragmentation pattern consistent with a third jet