Differential measurements of jet sub-structure observables and their correlations in $p+p$ collisions at $\sqrt{s} = 200$ GeV in STAR

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- Hard scattered partons evolve via parton shower and hadronize
- Jets are collimated sprays of hadrons

- Measurements of jet sub-structure serve as an experimental tool for studying QCD - increasingly studied in recent years
SoftDrop

- Grooming technique used to remove soft wide-angle radiation from the jet in order to mitigate non-perturbative effects
- Connects parton shower and angular tree
- Parton shower is described by the momentum and angular scales

\[
\frac{z^g = \min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \theta^\beta,
\]

where \( \theta = \frac{\Delta R_{12}}{R} \)

- **Shared momentum fraction** \( z^g \)

**Groomed radius** \( R_g \) - first \( \Delta R_{12} \) that satisfies SoftDrop condition

\( p_{T,1}, p_{T,2} \) - transverse momenta of the subjets
\( z_{\text{cut}} \) - threshold (0.1)
\( \beta \) - angular exponent (0)
\( \Delta R_{12} \) - distance of subjets in the rapidity-azimuth plane

Overview of jet sub-structure measurements

\( \text{p+p collisions:} \)
- Allow detailed comparisons with QCD predictions and tuning of MC generators

\( \text{A+A collisions:} \)
- Study medium modification of intra-jet distributions
- Probe various jet quenching effects (energy loss, broadening, color coherence)


ALICE, arXiv:2107.12984


**STAR experiment**

**TPC - Time Projection Chamber**
- Reconstruction of charged particle tracks
- Full azimuthal angle, $|\eta| \leq 1$
- Transverse momenta of tracks: $0.2 < p_T < 30 \text{ GeV/c}$

**BEMC - Barrel Electromagnetic Calorimeter**
- Reconstruction of neutral component of the jets
- Full azimuthal angle, $|\eta| < 1$
- Segmentation $(\Delta \eta \times \Delta \phi) = (0.05 \times 0.05)$
- Tower requirements: $0.2 < E_T < 30 \text{ GeV}$

- Located at the *Relativistic Heavy Ion Collider* (RHIC) in *Brookhaven National Laboratory* (BNL)
Our goal is to access parton showers through experimental observables.

Two options how to study parton showers:

- Correlation between sub-structure observables at the first split
- Evolution of the splitting observables as we travel along the jet shower
Correlation between sub-structure observables at the first split
Correlation between sub-structure observables at the first split

- So far the momentum and angular scales have been measured independently via $z_g$ and $R_g$ at STAR.

- We focus on the correlation between $z_g$ and $R_g$ as a function of $p_{T,\text{jet}}$.

Correlation between sub-structure observables at the first split
Correction in 2+1D for $z_g$, $R_g$, and $p_{T,\text{jet}}$

- Results are in 3D $\rightarrow z_g$ vs. $R_g$ is unfolded in 2D and correction for $p_{T,\text{jet}}$ in 1D is needed
  - For each particle-level $p_{T,\text{jet}}$ bin, we do projection of this bin into detector-level $p_{T,\text{jet}}$, and get the weights from detector-level $p_{T,\text{jet}}$ bins

We unfold $z_g$ vs. $R_g$ via iterative Bayesian unfolding in 2D using RooUnfold and unfolded spectra for each detector-level $p_{T,\text{jet}}$ bin are weighted and summed

- Additional corrections for trigger and jet finding efficiencies are applied

Details on systematic uncertainties available in back up
Unfolded $z_g$ distributions with respect to $R_g$ for $20 \leq p_{T,\text{jet}} < 25 \text{ GeV/c}$ with $R = 0.4$

When we go from small to large $R_g$ we move from collinear hard splitting to softer wide angle splitting
Unfolded $z_g$ distributions with respect to $R_g$ for different $p_{T,\text{jet}}$ with $R = 0.4$

- Distributions change mildly with varying $p_{T,\text{jet}} \rightarrow R_g$ is the driving factor for the change in shape of $z_g$ distributions
Evolution of the splitting observables as we travel along the jet shower
Evolution of the splitting observables as we travel along the jet shower

- Enables a study of self-similarity and effect of restricting available phase space for radiation due to virtuality evolution
- Two ways how to look at the observables:
  - Vary jet kinematics ($p_T^{\text{jet}}$) and compare $z_g$ and $R_g$ distributions at the 1st, 2nd and 3rd splits
  - Vary initiator kinematics ($p_T^{\text{initiator}}$) and compare $z_g$ and $R_g$ distributions at the 1st, 2nd and 3rd splits
Correction in 2+1D for $p_{T,\text{jet/initiator}}, z_g, R_g$

- Splits can be affected by detector efficiency and resolution
- Observables at a given split are smeared
- Splitting hierarchy is modified going from particle level to detector level

![Diagram showing particle level and detector level splits, including missed and fake splits.]
Unfolded $z_g$ and $R_g$ distributions at 1st, 2nd and 3rd splits for various $p_T,\text{jet}$

- Differences between first, second and third splits

- $z_g$ distribution becomes flatter and $R_g$ distribution becomes narrower with higher split, i.e. collinear emissions are enhanced
Unfolded $z_g$ and $R_g$ distributions at 1st, 2nd and 3rd splits for various $p_T^{\text{initiator}}$

- Splits have same $p_T^{\text{initiator}}$ but different positions in the shower.

- Distributions show a gradual variation in the available phase space.

- Hint of differences in shape for $p_T^{\text{initiator}}$ vs. $p_T^{\text{jet}}$ points to jets/splits of varying kinematics → enables a forthcoming detailed study of self-similarity of jet splittings.
Comparison with MC models

- Leading order MC models describe the trend observed in data
- Further studies aim to disentangle the impact of perturbative and non-perturbative effects in the MC

**First split**
First measurement of $z_g$ vs. $R_g$ as a function of $p_{T,\text{jet}}$ was shown
- 2+1D unfolding was applied

Observed significantly **harder/symmetric** splitting at the **third/narrow** split compared to the first and second splits

Jet sub-structure measurements at RHIC energies allow to disentangle perturbative and non-perturbative dynamics of jet evolution

**Next steps:**
- Compare to different MC models and theoretical calculations
  - Different hadronization (Sherpa) and parton shower (Herwig, Pythia) models
- Sub-structure observables, **splitting scale** $k_T$ and **groomed mass fraction** $\mu$, are being studied (not shown in this presentation)
- We are exploring other unfolding methods, e.g. machine learning techniques such as OmniFold (Phys. Rev. Lett. **124**, 182001 (2020))
$1/N \frac{dN}{dz_g} = 0$

$\beta = 0.1$, cut

SoftDrop $z_{\text{cut}} = 0.1$, $\beta = 0$

$T_{\text{anti-k}} < 25 \text{ GeV/c}$

$T_{\text{jet}} p_{T} \leq 20 = 200 \text{ GeV}$

$p+p$ STAR Preliminary

$0 \leq R_g < 0.15$

$0.15 \leq R_g < 0.30$

$0.30 \leq R_g \leq 0.40$

$0.15 \leq R_g < 0.30$

$0.30 \leq R_g \leq 0.40$

Thank you for your attention!
Back up
Jet clustering algorithms

- Jets are defined using algorithms

**Anti-\(k_T\) algorithm**
- \(d_{ij} = \frac{\min(1/p_{T_i}^2, 1/p_{T_j}^2)\Delta R_{ij}^2}{R}, \quad d_{iB} = 1/p_{Tj}^2\)
- Clustering starts from the particles with the highest transverse momentum

**Cambridge/Aachen (C/A) algorithm**
- \(d_{ij} = \Delta R_{ij}^2/R^2, \quad d_{iB} = 1\)
- Particles are clustered exclusively based on angular separation, ideal to be used to resolve jet sub-structure

\(d_{iB}\) - distance of the particle \(i\) from the beam
\(p_T\) - transverse momentum
\(\Delta R_{ij}\) - distance between the particle \(i\) and \(j\)
\(R\) - jet resolution parameter

SoftDrop

- Grooming technique used to remove soft wide-angle radiation from the jet
- Connects parton shower and angular tree

1. Jets are first found using the anti-$k_T$ algorithm
2. Reclasser jet constituents using the C/A algorithm
3. Jet $j$ is broken into two sub-jets $j_1$ and $j_2$ by undoing the last stage of C/A clustering
4. Jet $j$ is final SoftDrop jet, if sub-jets pass the condition on the right, otherwise the process is repeated


- **Shared momentum fraction** $z_g$

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \theta^\beta,$$

where $\theta = \frac{\Delta R_{12}}{R}$

- **Groomed radius** $R_g$ - first $\Delta R_{12}$ that satisfies SoftDrop condition

$p_{T,1}, p_{T,2}$ - transverse momenta of the subjets
$z_{cut}$ - threshold (0.1)
$\beta$ - angular exponent (0)
$\Delta R_{12}$ - distance of subjets in the rapidity-azimuth plane
Previous ATLAS measurement uses Lund jet plane

Significant differences in varying hadronization models at high $p_{T,jet}$ at the LHC → we want to study this at lower $p_{T,jet}$, where non-perturbative effects are expected to be larger

While Lund jet plane integrates over all splits, we focus on the first split

Data analysis

- $p + p$ collisions at $\sqrt{s} = 200$ GeV, 2012
- $\sim$11 million events analyzed

Event and track selection
- Transverse momenta of tracks: $0.2 < p_T < 30$ GeV/c
- Tower requirements: $0.2 < E_T < 30$ GeV

Jet reconstruction
- Jets reconstructed with anti-$k_T$ algorithm, reclustered with the C/A algorithm
- Transverse momenta of jets: $15 < p_{T,jet} < 40$ GeV/c
- Resolution parameters: $R = 0.4$, $R = 0.6$
- SoftDrop parameters: $z_{cut} = 0.1$, $\beta = 0$

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left( \frac{\Delta R_{12}}{R} \right)^\beta$$
2D Bayesian Unfolding

- 2D iterative Bayesian method implemented in the RooUnfold
- Procedure has following steps:
  1. The jets at the detector and particle level are reconstructed separately
  2. Jets are matched based on $\Delta R < 0.6$
  3. Jets without match - missed jet (particle level) and fake jets (detector level)
  4. Response between detector level and particle level for observables is constructed
- We use RooUnfold response which contains Matches and Fakes
  - Unfolding is done separately for $p_T^{det}$ intervals 15-20, 20-25, 25-30, 30-40 GeV/$c$

- Then unfolded spectra are weighted with values from our projection and put together

- Together with trigger missed and unmatched weighted spectra we get our fully unfolded spectrum
**Systematic uncertainties**

- Systematic uncertainties estimated by varying the detector response
  - Hadron correction: fraction of track momentum subtracted is varied
  - Tower scale variation: tower gain is varied by 3.8%
  - Tracking efficiency: efficiency is varied by 4%
  - Unfolding: iterative parameter is varied from 4 to 6
- Systematics due to prior shape variation will be included in the final publication

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**Graphs**

- $0 \leq R_g < 0.15$
- $0.15 \leq R_g < 0.30$
- $0.30 \leq R_g \leq 0.40$
Unfolded $z_g$ distributions with respect to $R_g$ for $20 \leq p_{T,\text{jet}} < 25$ GeV/c with $R = 0.4$ and $R = 0.6$

- **$R = 0.4$**
  - $0 \leq R_g < 0.15$
  - $0.15 \leq R_g < 0.30$
  - STAR Preliminary
  - $p+p \sqrt{s} = 200$ GeV
  - anti-$k_T + C/A$, $R = 0.4$
  - SoftDrop $z_{\text{cut}} = 0.1$, $\beta = 0$
  - $20 \leq p_{T,\text{jet}} < 25$ GeV/c

- **$R = 0.6$**
  - $0 \leq R_g < 0.15$
  - $0.15 \leq R_g < 0.30$
  - STAR Preliminary
  - $p+p \sqrt{s} = 200$ GeV
  - anti-$k_T + C/A$, $R = 0.6$
  - SoftDrop $z_{\text{cut}} = 0.1$, $\beta = 0$
  - $20 \leq p_{T,\text{jet}} < 25$ GeV/c

- No significant change of distributions is observed with larger resolution parameter
Comparison with MC models

- Flattering of the splitting $z_g$ as we increase split number captured by the MC simulations
- Small differences between PYTHIA and HERWIG seen in the first split