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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Jets and clustering algorithms

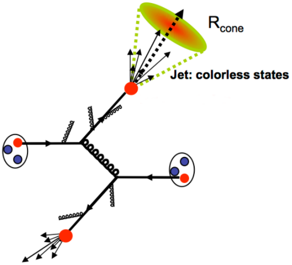
- Jets are collimated sprays of hadrons
- Jets are defined using algorithms

Anti-k_T algorithm

- $d_{ij} = \frac{\min(1/p_{\mathrm{T}i}^2, 1/p_{\mathrm{T}j}^2)\Delta R_{ij}^2}{R}$, $d_{i\mathrm{B}} = 1/p_{\mathrm{T}j}^2$
- Clustering starts from the particles with the highest transverse momentum

Cambridge/Aachen (C/A) algorithm

- $d_{ij} = \Delta R_{ij}^2/R^2$, $d_{i\mathrm{B}} = 1$
- Particles are clustered exclusively based on angular separation, ideal to be used to resolve jet sub-structure



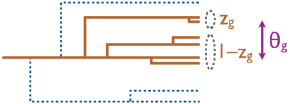
$d_{i\mathrm{B}}$ - distance of the particle i from the beam
p_T - transverse momentum
ΔR_{ij} - distance between the particle i and j
R - jet resolution parameter

- At present, the jet sub-structure is being increasingly studied

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. Recluster jet constituents using the C/A algorithm
3. Jet j is broken into two subjets j_1 and j_2 by undoing the last stage of C/A clustering
4. Jet j is final SoftDrop jet, if subjets pass the condition on the right, otherwise the process is repeated



Laroski, Marzani, Thaler, Tripathee, Xue,

Phys. Rev. Lett. 119, 132003 (2017)

- **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 $\theta = \frac{\Delta R_{12}}{R}$

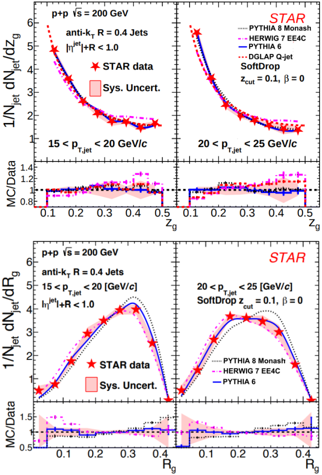
- **Groomed radius** R_g - first ΔR_{12} that satisfies SoftDrop condition

$p_{T,1}, p_{T,2}$ - transverse momenta of the subjets
z_{cut} - threshold (0.1)
β - angular exponent (0)

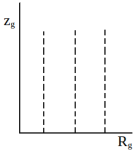
ΔR_{12} - distance of subjets in the

Motivation

- Measurements of jet sub-structure serve as an experimental tool for studying QCD
- Parton shower in vacuum is described by the momentum and angular scales
- So far these two scales were measured independently via z_g and R_g
- **Our goal is to study correlation betweeen z_g and R_g as a function of $p_{T,jet}$**

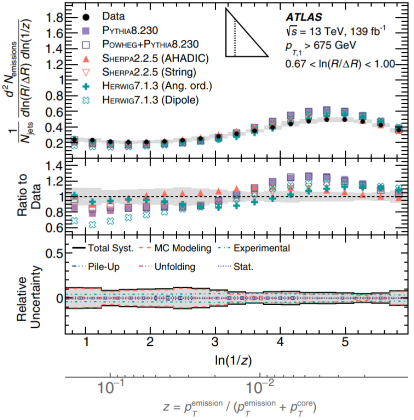


STAR, Phys. Lett. B 811 (2020) 135846



Motivation

- Previous ATLAS measurement uses Lund jet plane
- Significant differencies in varying hadronization models at high $p_{\mathrm{T,jet}}$ at the LHC → we want to study this at lower $p_{\mathrm{T,jet}}$, where non-perturbative effects are expected to be larger
- While Lund jet plane integrates over all splits, we focus on the first split



ATLAS, Phys. Rev. Lett. **124**, 222002 (2020)

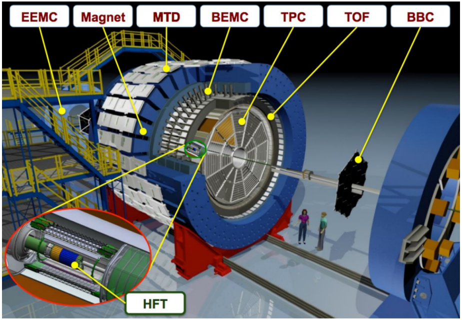
STAR experiment

TPC - *Time Projection Chamber*

- Reconstruction of charged particle tracks
- Full azimuthal angle, $|\eta| \leq 1$

BEMC - *Barrel Electromagnetic Calorimeter*

- Reconstruction of neutral component of the jets
- Full azimuthal angle, $|\eta| < 1$
- Segmentation $(\Delta\eta \times \Delta\phi) = (0.05 \times 0.05)$



Data analysis

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

Event and track selection

- Transverse momenta of tracks: $0.2 < p_{\mathrm{T}} < 30$ GeV/c
- Tower requirements: $0.2 < E_{\mathrm{T}} < 30$ GeV

Jet reconstruction

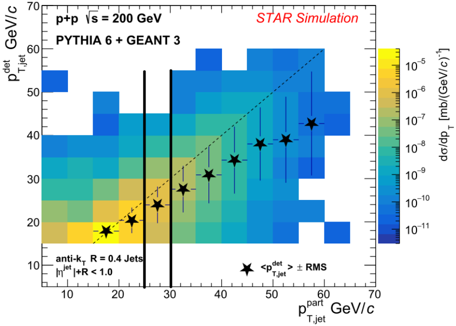
- Jets reconstructed with anti-k_{T} algorithm, reclustered with the C/A algorithm
- Transverse momenta of jets: $15 < p_{\mathrm{T,jet}} < 40$ GeV/c
- Resolution parameters: $R = 0.4$, $R = 0.6$
- SoftDrop parameters: $z_{\mathrm{cut}} = 0.1$, $\beta = 0$

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

Unfolding

- Measurement is affected by finite efficiency and resolution of the instrumentation
- Our goal is to deconvolve detector effects and obtain particle-level distribution

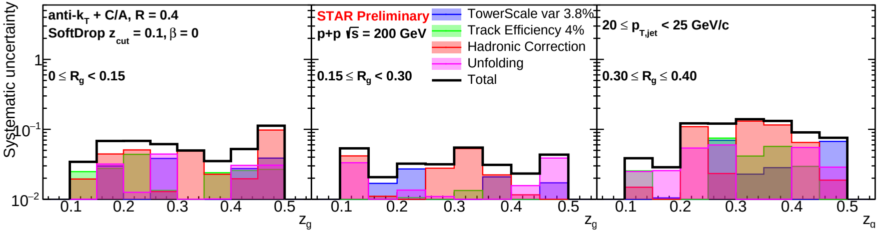
- Results are in 3D - correction for $p_{\mathrm{T,jet}}$ is needed
  - For each particle-level $p_{\mathrm{T,jet}}$ bin, we do projection of this bin into detector-level $p_{\mathrm{T,jet}}$, and get the weights from detector-level $p_{\mathrm{T,jet}}$ bins
- We unfold z_g vs. R_g via iterative Bayesian unfolding in 2D using RooUnfold and unfolded spectra for each detector-level $p_{\mathrm{T,jet}}$ bin are weighted and summed
- Additional corrections for trigger and jet finding efficiencies are applied



STAR, Phys. Lett. B 811 (2020) 135846

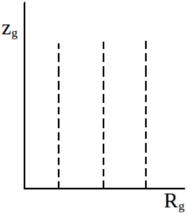
Systematic uncertainties

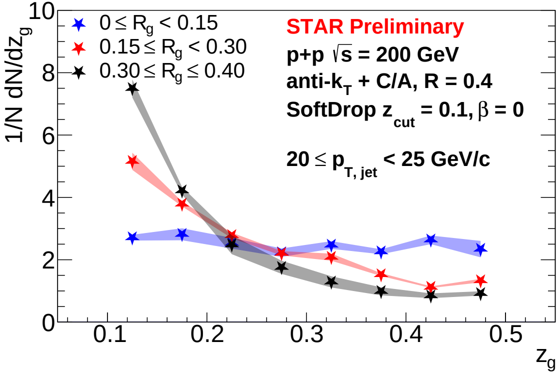
- Systematic uncertainties estimated by varying the detector response
  - Hadronic correction - fraction of track momentum subtracted is varied
  - Tower scale variation - tower gain is varied by 3.8%
  - Tracking efficiency - efficiency is varied by 4%
  - Unfolding - iterative parameter is varied from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



$0 \leq R_g < 0.15$ $0.15 \leq R_g < 0.30$ $0.30 \leq R_g \leq 0.40$

Unfolded z_g distributions with respect to R_g for $20 \leq p_{T,jet} < 25$ GeV/c with $R = 0.4$

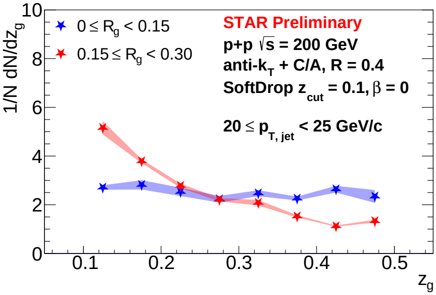




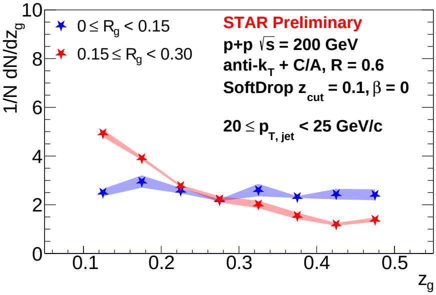
- When we go from small to large R_g we move from collinear hard splitting to softer wide angle splitting

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

$R = 0.4$

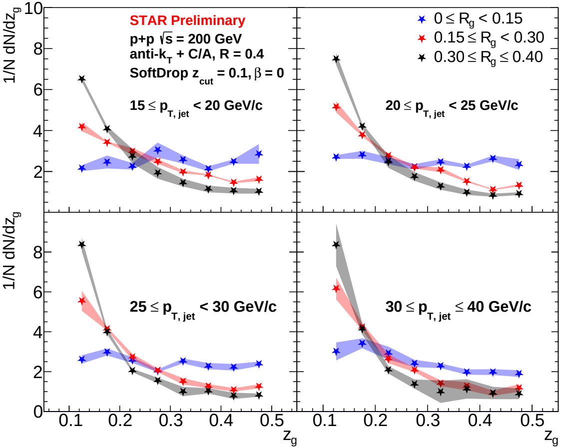


$R = 0.6$



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

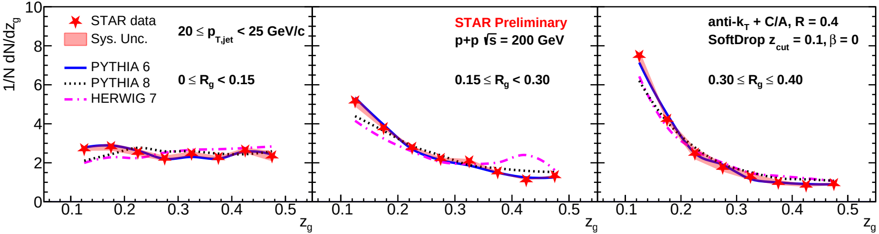
Unfolded z_g distributions with respect to R_g for different $p_{T,jet}$ bins with $R = 0.4$



- Distributions change mildly with varying $p_{T,jet}$ → R_g is the driving factor

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 models in the MC



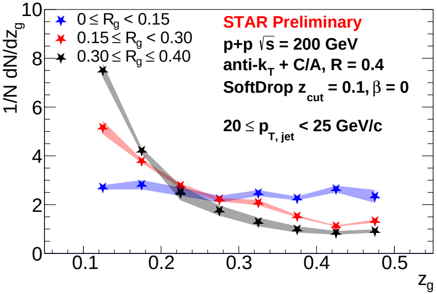
$0 \leq R_g < 0.15$ $0.15 \leq R_g < 0.30$ $0.30 \leq R_g \leq 0.40$

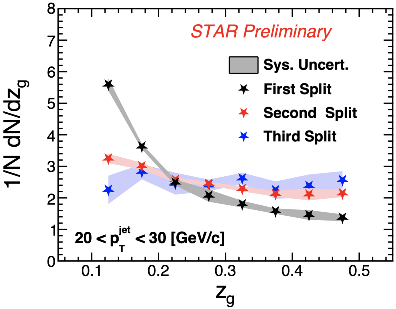
Summary

- First measurement of z_g vs. R_g as a function of $p_{T,\text{jet}}$ was shown
  - 2+1D unfolding was applied
- z_g has a **weak** dependence on $p_{T,\text{jet}}$ and a **strong** dependence on R_g
- We can select significantly softer splits by selecting wider angle splits

Next steps:

- Comparing 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** μ, 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))





Thank you for your attention!

Back up

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