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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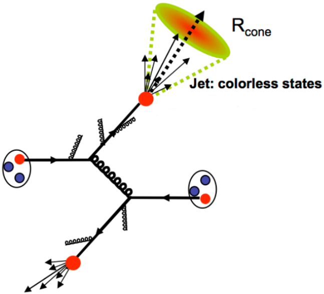
Jets

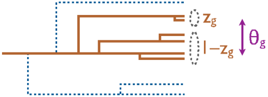
- Hard scattered partons evolve via parton shower and hadronize
- Jets are collimated sprays of hadrons



- 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



Larkoski, 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 $\theta = \frac{\Delta R_{12}}{R}$

$p_{T,1}, p_{T,2}$ - transverse momenta of the subjets
z_{cut} - threshold (0.1)
β - angular exponent (0)
ΔR_{12} - distance of subjets in the rapidity-azimuth plane

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

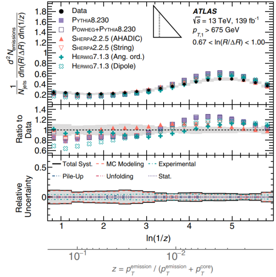
Overview of jet sub-structure measurements

***p*+*p* collisions:**

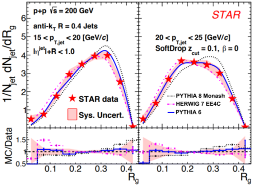
- Allow detailed comparisons with QCD predictions and tuning of MC generators

A+A collisions:

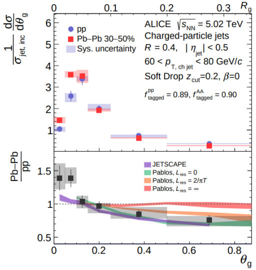
- Study medium modification of intra-jet distributions
- Probe various jet quenching effects (energy loss, broadening, color coherence)



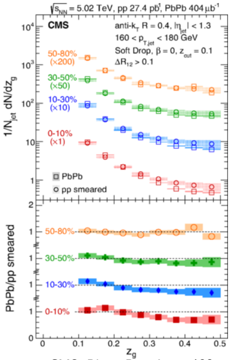
ATLAS, Phys. Rev. Lett. **124**, 222002 (2020)



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



ALICE, arXiv:2107.12984



CMS, Phys. Rev. Lett. **120**, 142302 (2018)

STAR experiment

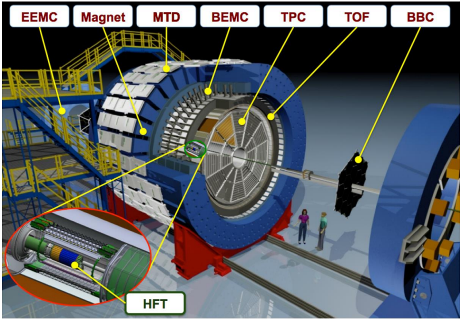
TPC - *Time Projection Chamber*

- Reconstruction of charged particle tracks
- Full azimuthal angle, $|\eta| \leq 1$
- Transverse momenta of tracks: $0.2 < p_T < 30$ GeV/c

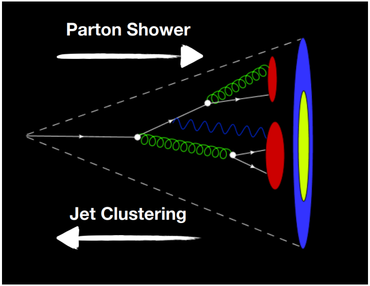
BEMC - *Barrel Electromagnetic Calorimeter*

- 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: $0.2 < E_T < 30$ GeV

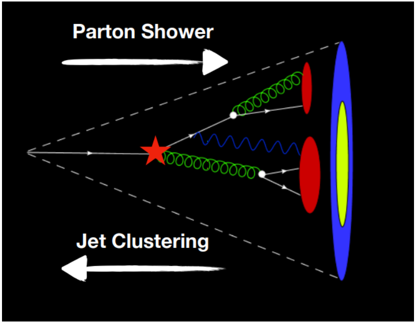
- Located at the *Relativistic Heavy Ion Collider* (RHIC) in *Brookhaven National Laboratory* (BNL)

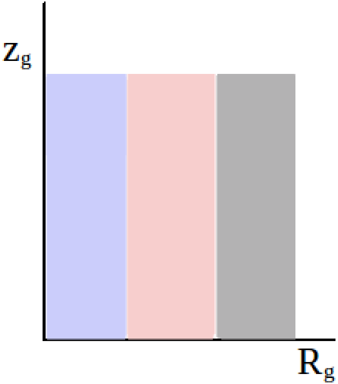


- Our goal is to access parton showers through experimental observables
- Two options how to study parton showers:
  - **Correlation between sub-structure observables at the first split**
  - **Evolution of the splitting observables as we travel along the jet shower**



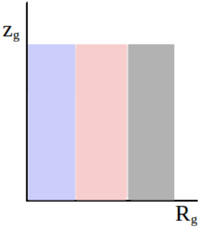
Correlation between sub-structure observables at the first split

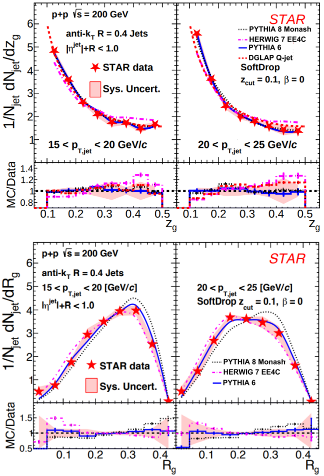




Correlation between sub-structure observables at the first split

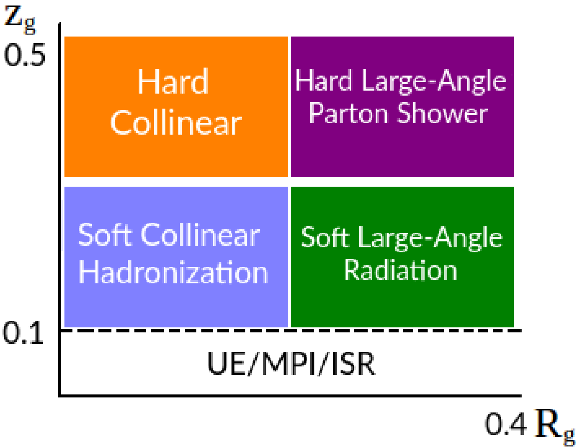
- So far the momentum and angular scales have been measured independently via z_g and R_g at STAR
- **We focus on the correlation between z_g and R_g as a function of $p_{T,jet}$**





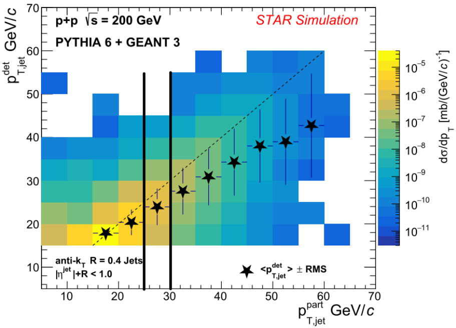
STAR, Phys. Lett. B 811 (2020) 135846

Correlation between sub-structure observables at the first split



Correction in 2+1D for z_g, R_g, and $p_{T,jet}$

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

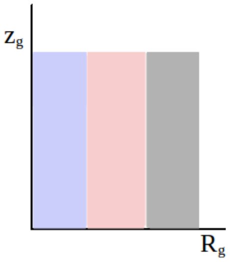


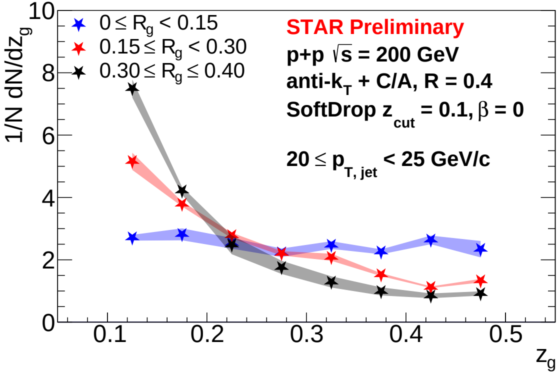
STAR, Phys. Lett. B 811 (2020) 135846

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

Details on systematic uncertainties available in back up

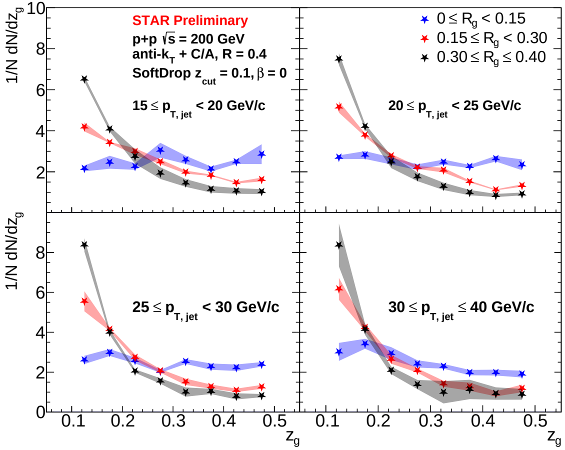
Unfolded z_g distributions with respect to R_g for $20 \leq p_{T,jet} < 25$ GeV/c with $R = 0.4$





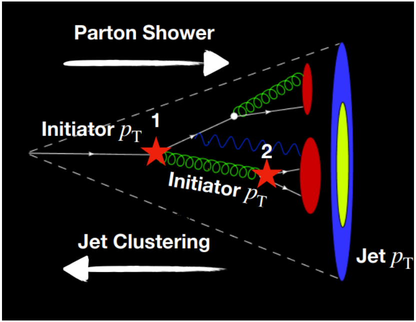
- When we go from small to large R_g we move from collinear hard splitting to softer wide angle splitting

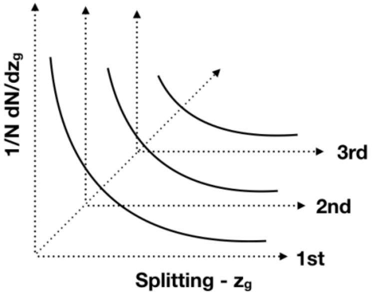
Unfolded z_g distributions with respect to R_g for different $p_{T,jet}$ with $R = 0.4$



- Distributions change mildly with varying $p_{T,jet} \rightarrow R_g$ is the driving factor for the change in shape of z_g distributions

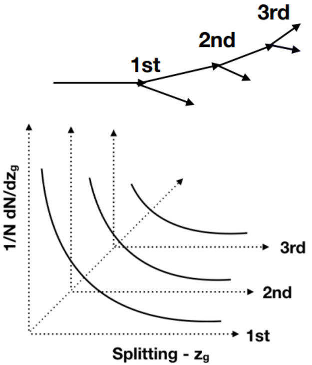
Evolution of the splitting observables as we travel along the jet shower





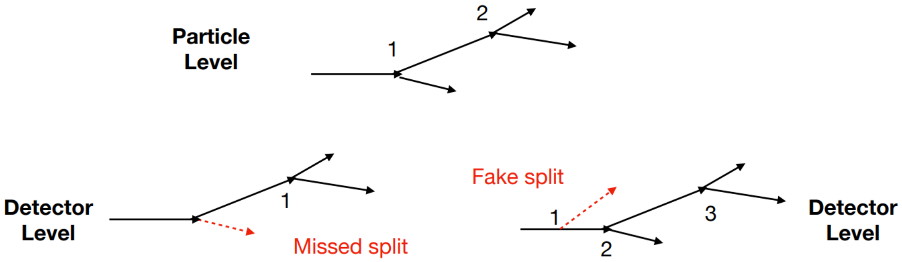
Evolution of the splitting observables as we travel along the jet shower

- 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 ($p_{\mathrm{T,jet}}$) and compare z_g and R_g distributions at the 1st, 2nd and 3rd splits
  - Vary initiator kinematics ($p_{\mathrm{T,initiator}}$) and compare z_g and R_g distributions at the 1st, 2nd and 3rd splits



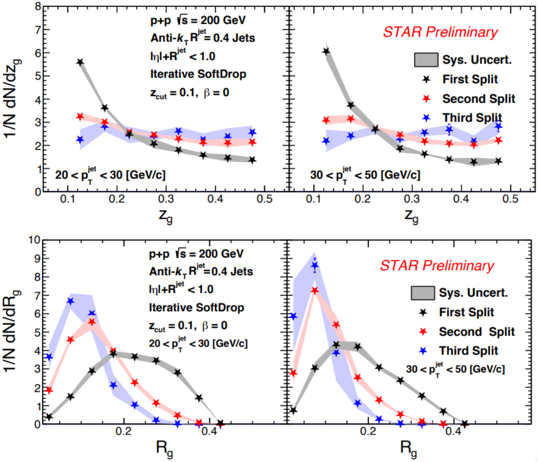
Correction in 2+1D for $p_{\mathrm{T,jet/initiator}}$, z_g, R_g

- 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



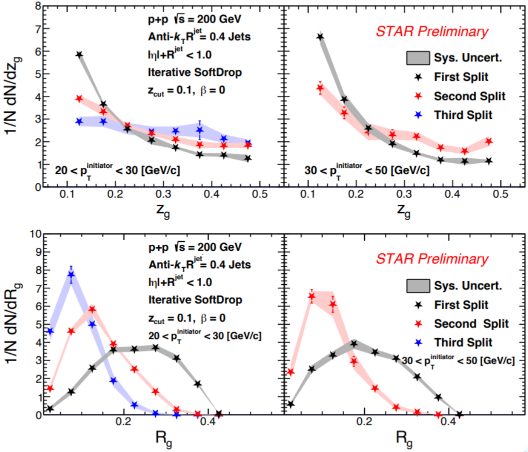
Unfolded z_g and R_g distributions at 1st, 2nd and 3rd splits for various $p_{T,jet}$

- 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



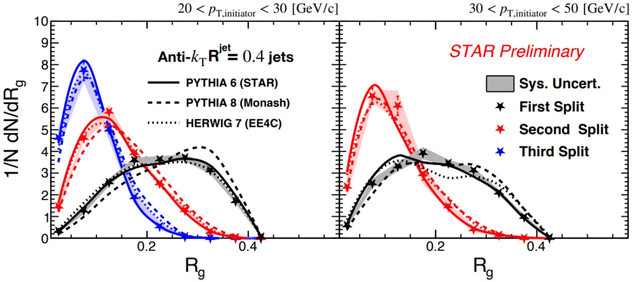
Unfolded z_g and R_g distributions at 1st, 2nd and 3rd splits for various $p_{T,\mathrm{initiator}}$

- Splits have same $p_{T,\mathrm{initiator}}$ but different positions in the shower
- Distributions show a gradual variation in the available phase space
- Hint of differences in shape for $p_{T,\mathrm{initiator}}$ vs. $p_{T,\mathrm{jet}}$ → points to jets/splits of varying kinematics → enables a forthcoming detailed study of self-similarity of jet splittings

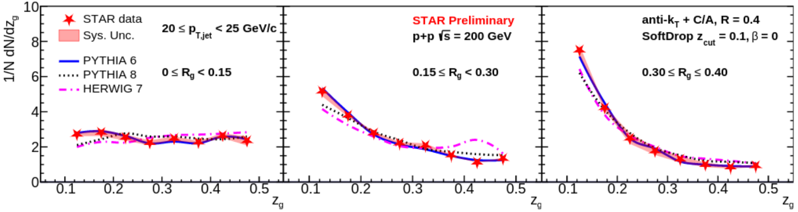


Comparison with MC models

- 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

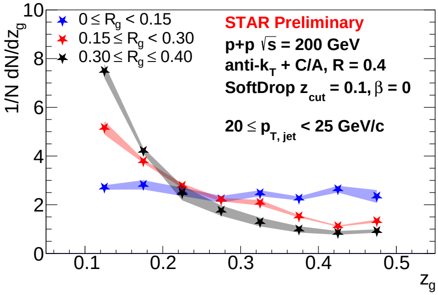


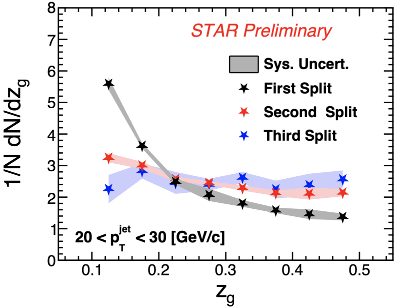
Summary

- First measurement of z_g vs. R_g as a function of $p_{T,jet}$ 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 disentagle 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** 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

Jet clustering algorithms

- Jets are defined using algorithms

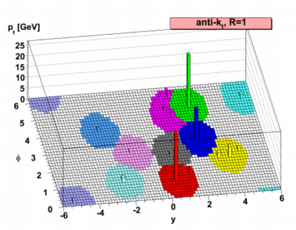
Anti-k_T algorithm

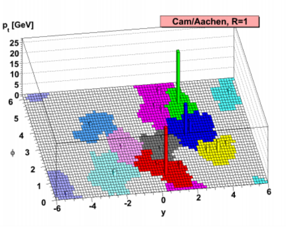
- $d_{ij} = \frac{\min(1/p_{\mathrm{T}i}^2, 1/p_{\mathrm{T}j}^2)\Delta R_{ij}^2}{R}$, $d_{i\mathrm{B}} = 1/p_{\mathrm{T}j}^2$
- Clustering starts from the particles with the highest transverse momentum

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



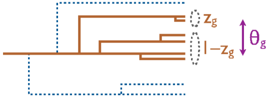


Cacciari, Salam, Soyez,
JHEP 0804:063 (2008)

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 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



Larkoski, Marzani, Thaler, Tripathee, Xue, Phys. Rev. Lett. 119, 132003 (2017)

- **Shared momentum fraction** z_g

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

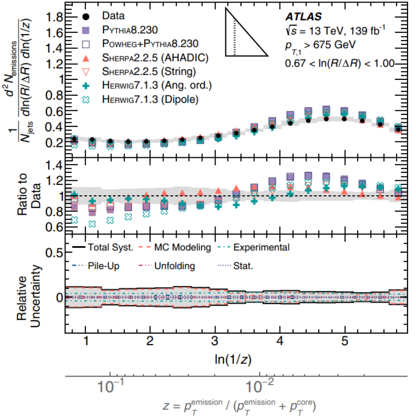
where $\theta = \frac{\Delta R_{12}}{R}$

- **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 rapidity-azimuth plane

Lund Plane measurement

- Previous ATLAS measurement uses Lund jet plane
- Significant differences in varying hadronization models at high $p_{T,jet}$ at the LHC $\rightarrow$ 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



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

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: $z_{\mathrm{cut}} = 0.1$, $\beta = 0$

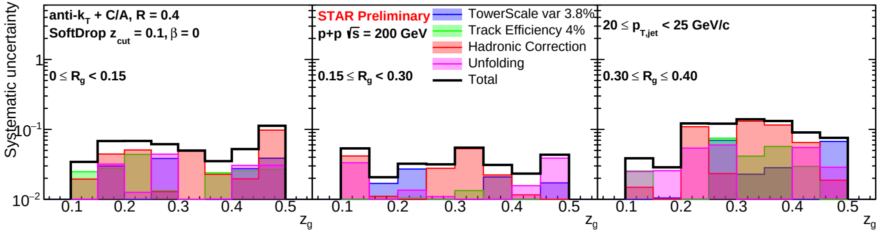
$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R} \right)^{\beta}$$

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

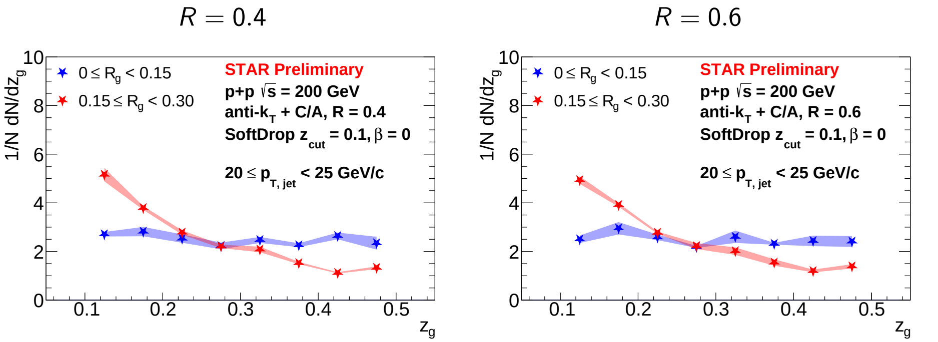
Systematic uncertainties

- Systematic uncertainties estimated by varying the detector response
  - 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



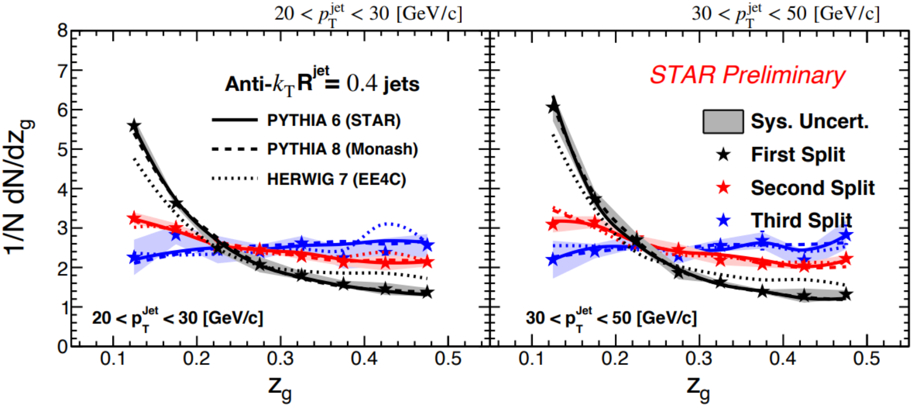
$0 \leq R_g < 0.15$ $\quad$ $0.15 \leq R_g < 0.30$ $\quad$ $0.30 \leq R_g \leq 0.40$

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



- 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