Multi-dimensional measurements of parton shower in *pp* collisions at RHIC

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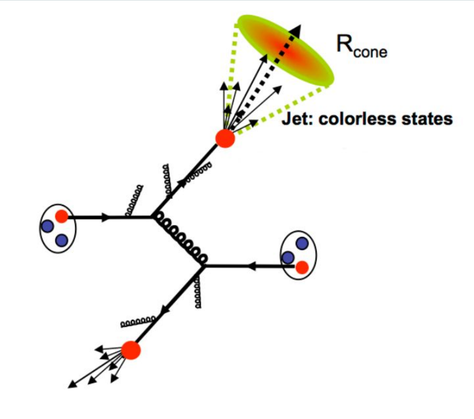
Jets and jet algorithms



- Hard scattered partons evolve via parton shower and hadronize
- Jets are collimated sprays of hadrons
- Jets are defined using clustering algorithms
    - **anti-k_T** - Start clustering from particles with highest p_T

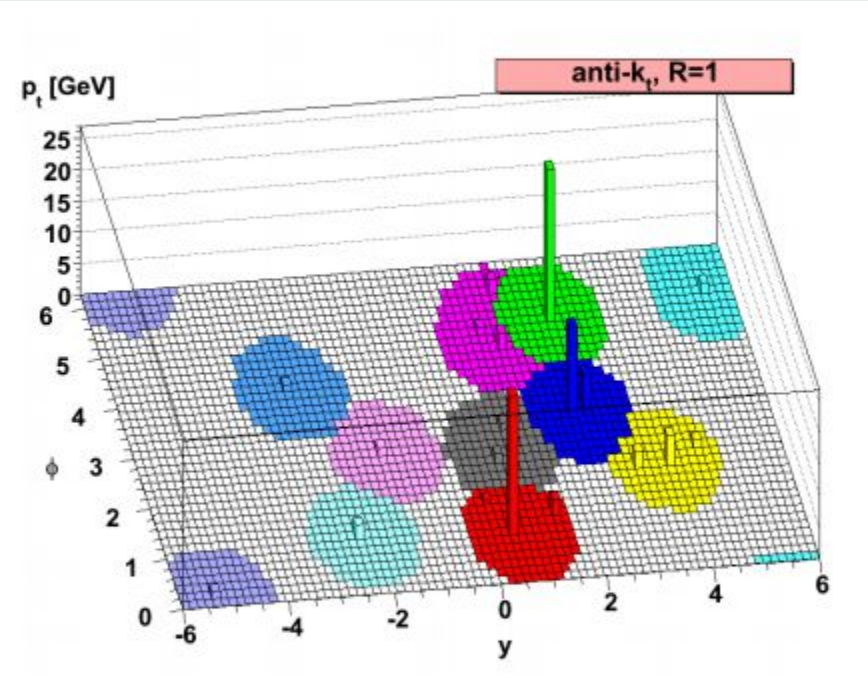
      $$d_{ij} = \frac{\min(1/p_{\mathrm{T}i}^2, 1/p_{\mathrm{T}j}^2)\Delta R_{ij}^2}{R}, \; d_{i\mathrm{B}} = 1/p_{\mathrm{T}j}^2$$

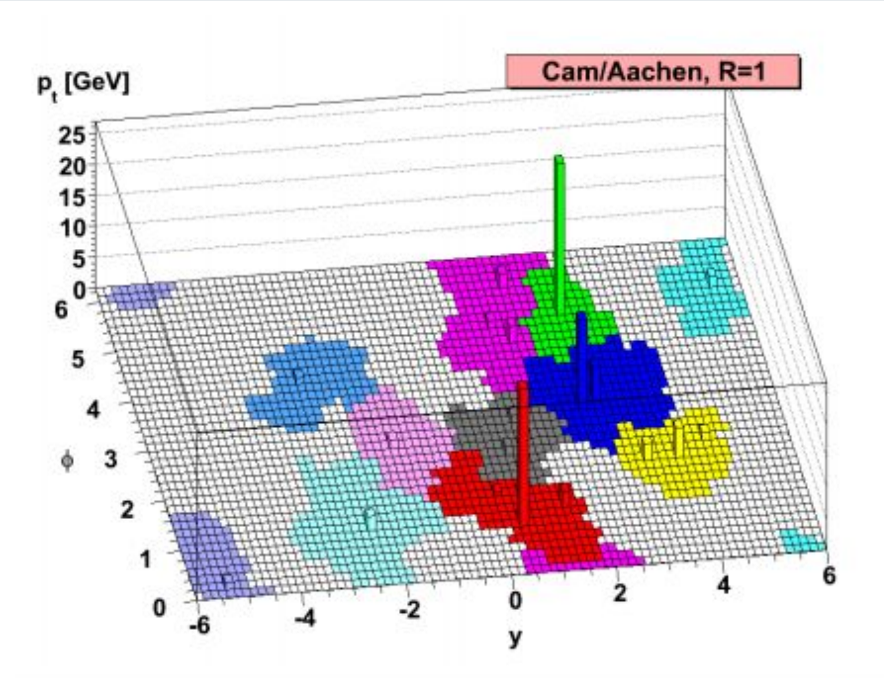
    - **C/A (Cambridge/Aachen)** - Particles are clustered exclusively based on angular separation -> ideal to resolve jet substructure

      $$d_{ij} = \Delta R_{ij}^2 / R^2, \; d_{i\mathrm{B}} = 1$$

$d_{i\mathrm{B}}$ - 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

Jet algorithms



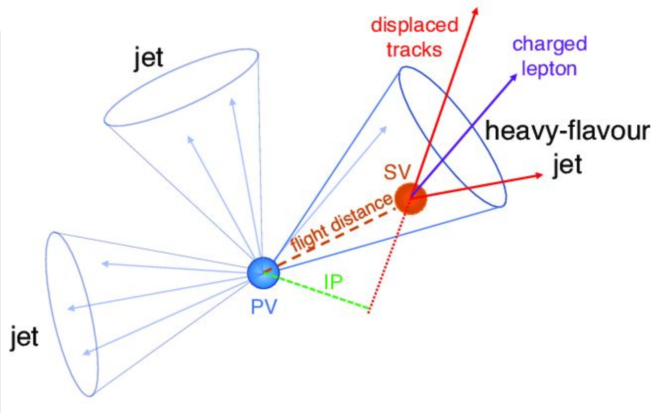


Jet properties

- Jet shape
- Invariant mass
- Flavor (*b*-jet, *c*-jet)
- Charge
- Subjets
- …

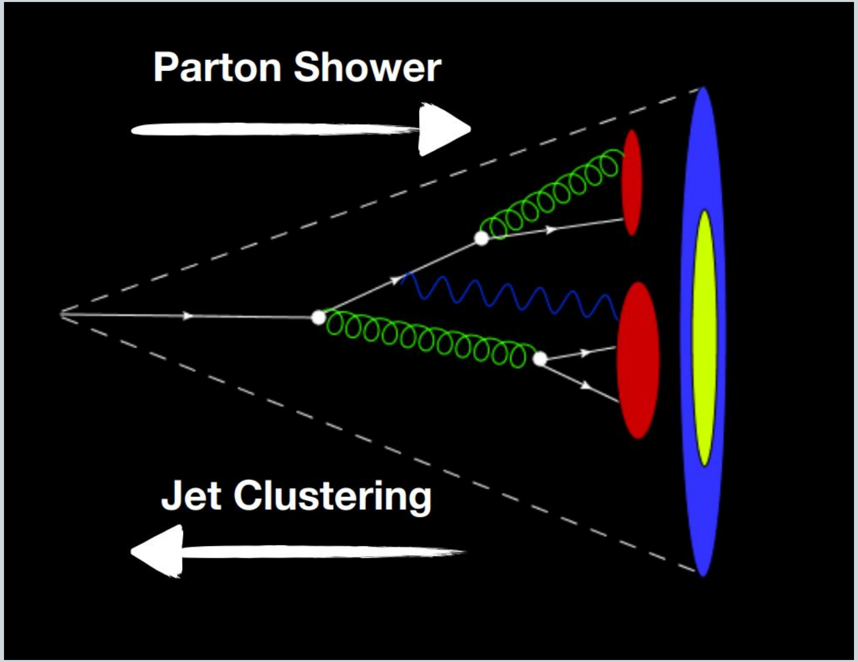
$$g = \sum_{i \in jet} \frac{p_{\mathrm{T}}^{\mathrm{i}}}{p_{\mathrm{T,jet}}} |\Delta R_{\mathrm{i,jet}}|$$

$$m_J = \left(\sum_i p_i \right)^2$$



Jet substructure

- Study of internal structure of hadronic jet



Motivation to study substructure

- Effects of the QGP on the internal structure of the jet
- EW resonances (Z/W, H)
- Physic beyond the Standard model
- QCD

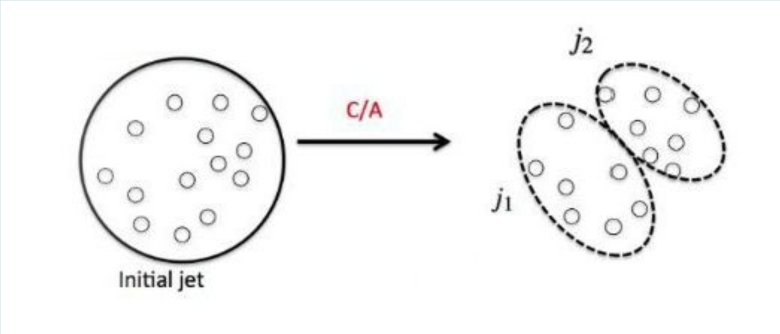
Jet substructure tools

- Prong finders
  - QCD jets and W/Z/H jets have different number of prongs
- Groomers
  - remove soft wide-angle radiation
- Radiation constraints
  - color structure of the jet

Prong finders and groomers

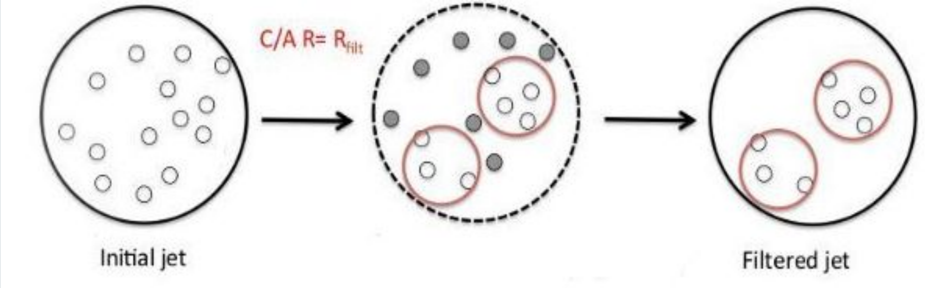
Mass-drop tagger

- two conditions
  - “mass drop” →$\max(m_i, m_j) > m_{i+j}\mu_{cut}$
  - symmetric cut →$\min(p^2_{T,i}, p^2_{T,j})\Delta R^2_{ij} > y_{cut}m^2_{i+j}$
- modified mass-drop tagger



Filtering

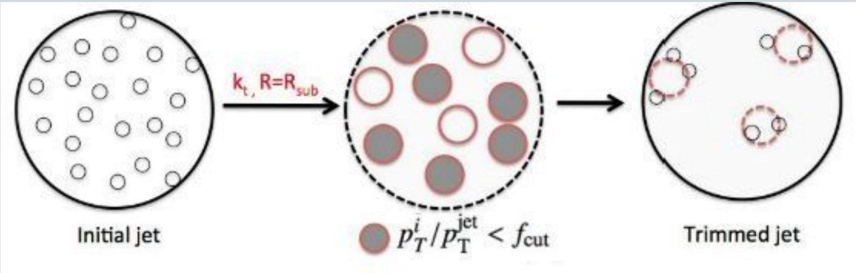
- recluster jet with C/A algorithm with small radius R_{filt}
- only keeps n_{filt} larger p_T subjets
- $n_{filt} = n_{prong} + 1$



Prong finders and groomers

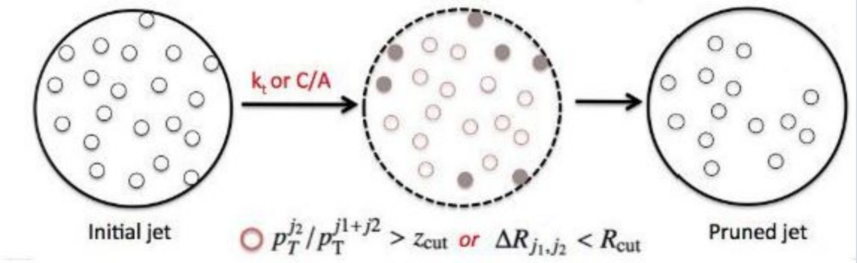
Trimming

- reclustere jet with C/A or k_T with small radius R_{trim}
- subjets with $p_{Ti}/p_T < f_{trim}$ are removed



Pruning

- $R_{prune} = 2f_{prune}m_{jet}/p_{T,jet}$
- $\min(p_{T,i}, p_{T,j}) \geq z_{prune}p_{T,(i+j)}$
- I and Y-pruning



Radiation constraints

Angularities and general angularities

- $$\lambda_\beta^\kappa = \sum_{i\in \text{jet}} z_i^\kappa \left(\frac{\Delta R_{i,\text{jet}}}{R}\right)^\beta$$ $$z_i = \frac{p_{t,i}}{\sum_{j\in\text{jet}} p_{t,j}}$$ $$\Delta R_{i,\text{jet}}^2 = (y_i - y_{\text{jet}})^2 + (\phi_i - \phi_{\text{jet}})^2$$

N-subjettiness

- Discriminate jets according the number *N* of subjets they are made of
- Axes can be defined in several ways

$$\tau_N^{(\beta)} = \sum_{i\in\text{jet}} p_{ti} \min(\Delta R_{ia_1}^\beta, \ldots, \Delta R_{ia_N}^\beta)$$

$$\tau_{N,N-1}^{(\beta)} = \frac{\tau_N^{(\beta)}}{\tau_{N-1}^{(\beta)}}$$

Radiation constraints

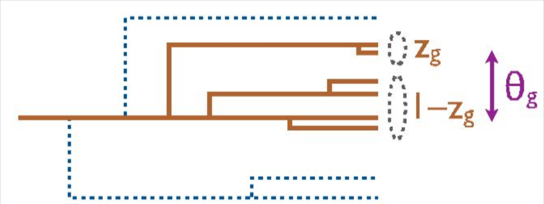
Energy-Correlation Function

$$
\begin{aligned}
{}_1e_2^{(\beta)} &\equiv e_2, \\
{}_3e_3^{(\beta)} &\equiv e_3, \\
{}_2e_3^{(\beta)} &= \sum_{i<j<k\in\text{jet}} z_i z_j z_k \min\left(\Delta R_{ij}^{\beta} \Delta R_{ik}^{\beta} \Delta R_{ij}^{\beta} \Delta R_{jk}^{\beta} \Delta R_{ik}^{\beta} \Delta R_{jk}^{\beta}\right), \\
{}_1e_3^{(\beta)} &= \sum_{i<j<k\in\text{jet}} z_i z_j z_k \min\left(\Delta R_{ij}^{\beta}, \Delta R_{ik}^{\beta}, \Delta R_{jk}^{\beta}\right), \\
&\vdots \\
{}_ke_N^{(\beta)} &= \sum_{i_1<\ldots<i_N\in\text{jet}} \left(\prod_{j=1}^{N} z_{i_j}\right)\left(\prod_{\ell=1}^{k} \overset{\ell}{\min_{u<v\in\{i_1,\ldots,i_N\}}} \Delta R_{uv}^{\beta}\right),
\end{aligned}
$$

$$z_i = p_{t,i} / \sum_j p_{t,j}$$

$$
\begin{aligned}
C_2^{(\beta)} &= \frac{{}_3e_3^{(\beta)}}{\left({}_1e_2^{(\beta)}\right)^2} \equiv \frac{e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^2}, \\
N_2^{(\beta)} &= \frac{{}_2e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^2},
\end{aligned}
$$

Soft Drop



- 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

Steps:

1. Jets are first reconstructed using the anti-k_T algorithm
2. Recluster jet constituents using C/A algorithm
3. Jet j is broken into two subjets j_1 and j_2 by undoing the last step of C/A clustering
4. Jet j is considered as final Soft Drop jet if subjets pass the Soft Drop condition, 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 ΔR_{12} that satisfies SoftDrop condition

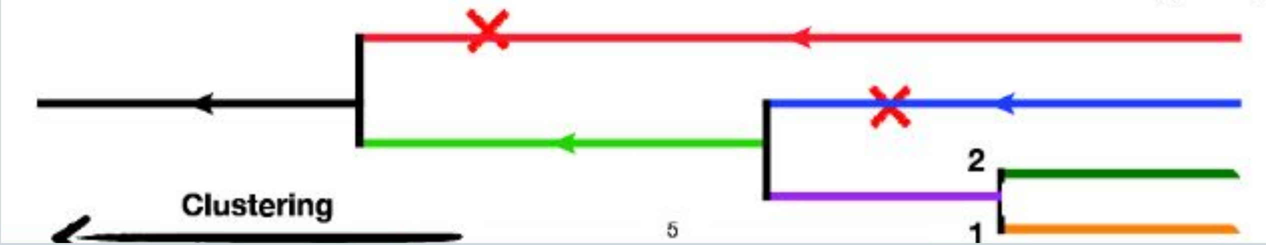
$p_{T,1}, p_{T,2}$ - transverse momenta of the subjets
z_{cut} - threshold (0.1)
β - angular exponent (0)
ΔR_{12} - distance of subjets in the rapidity-azimuth plane

Soft Drop extensions

$$n_{\mathrm{SD}},\ z_{\mathrm{g}}^{n},\ R_{\mathrm{g}}^{n}$$

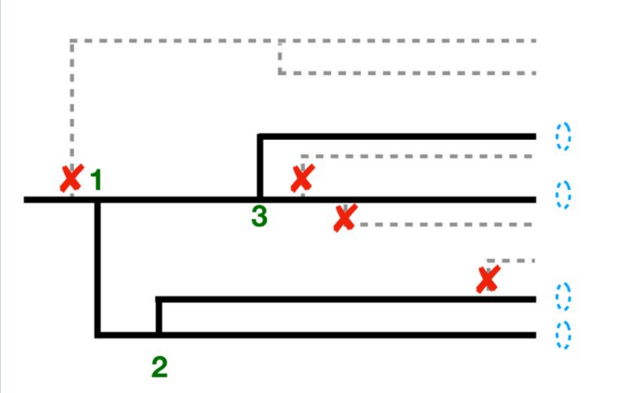
Iterative Soft Drop

- Follow the hardest branch

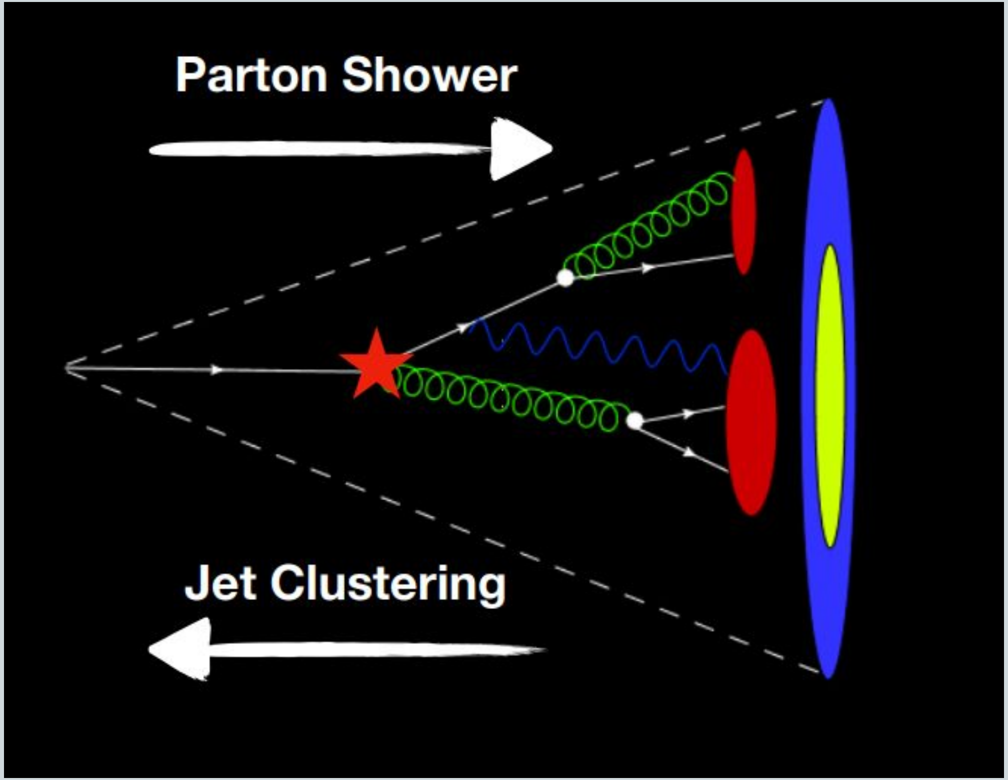


Recursive Soft Drop

- Follow all branches



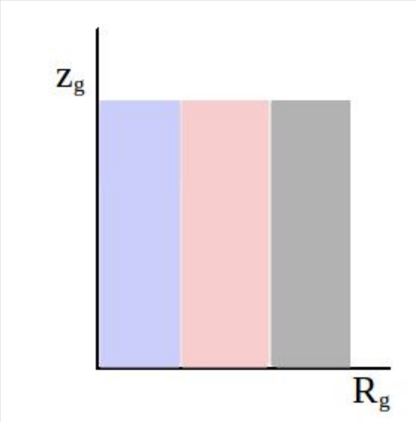
Correlation between substructure observables at the first split

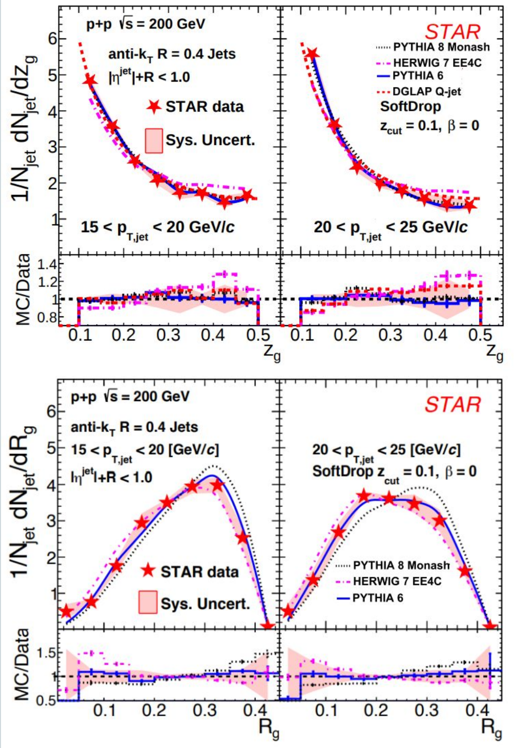


Motivation to study correlation

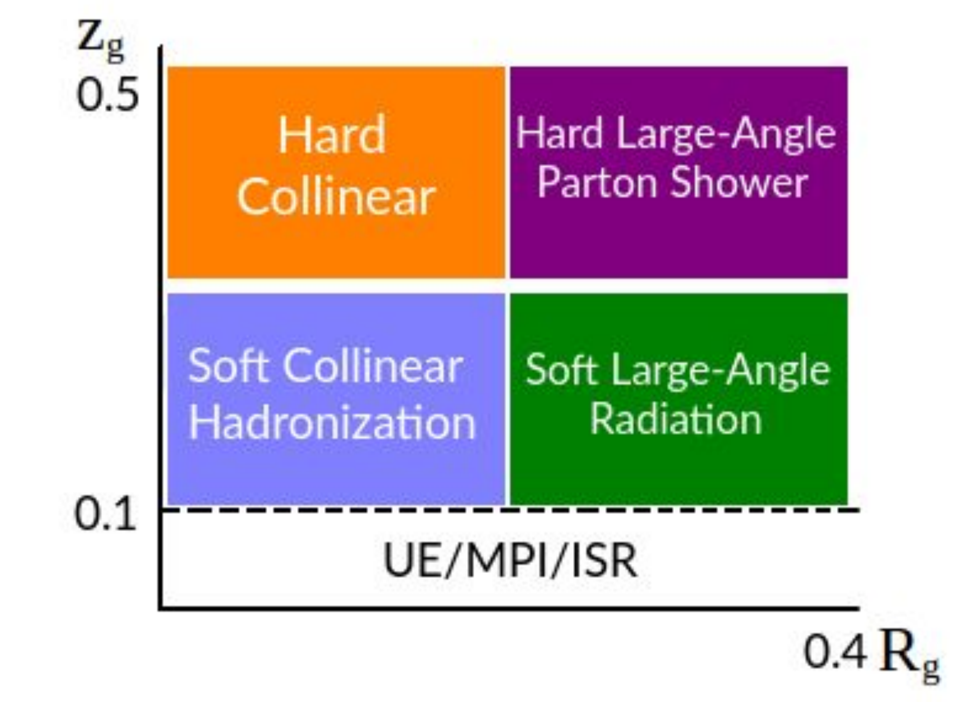
- So far angular and momentum scale were measured independently via z_g and R_g observables at STAR

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





Correlation between z_g and R_g



Unfolding

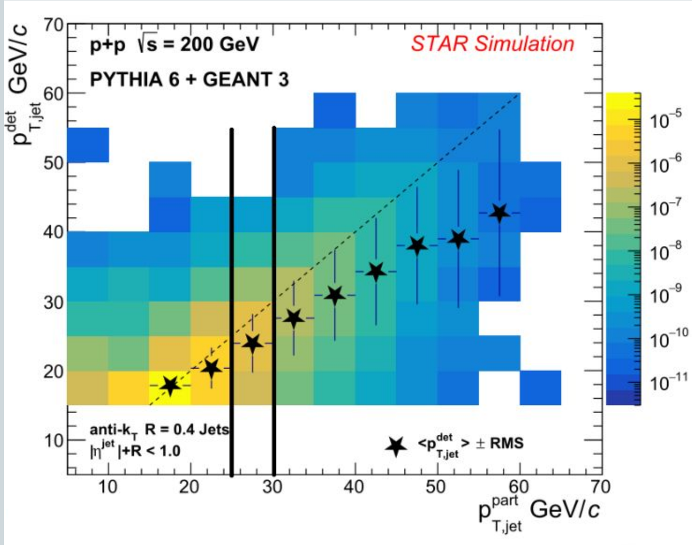
- Experimental measurements are affected by the finite efficiency and resolution of the instrumentation

- Iterative Bayesian unfolding

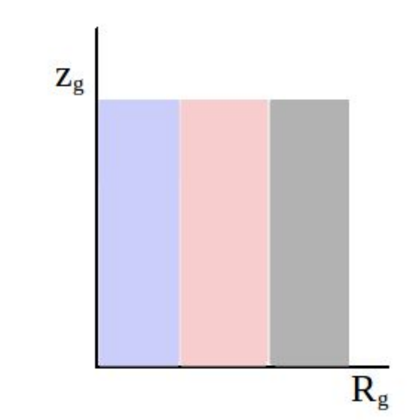
1. The jets at the detector (GEANT) and particle (PYTHIA) level are reconstructed separately
2. Jets are matched based on $\Delta R < 0.6$
3. Jets without match - missed jet (particle level) and fake jets (detector level)
4. Response between detector level and particle level for observables is constructed

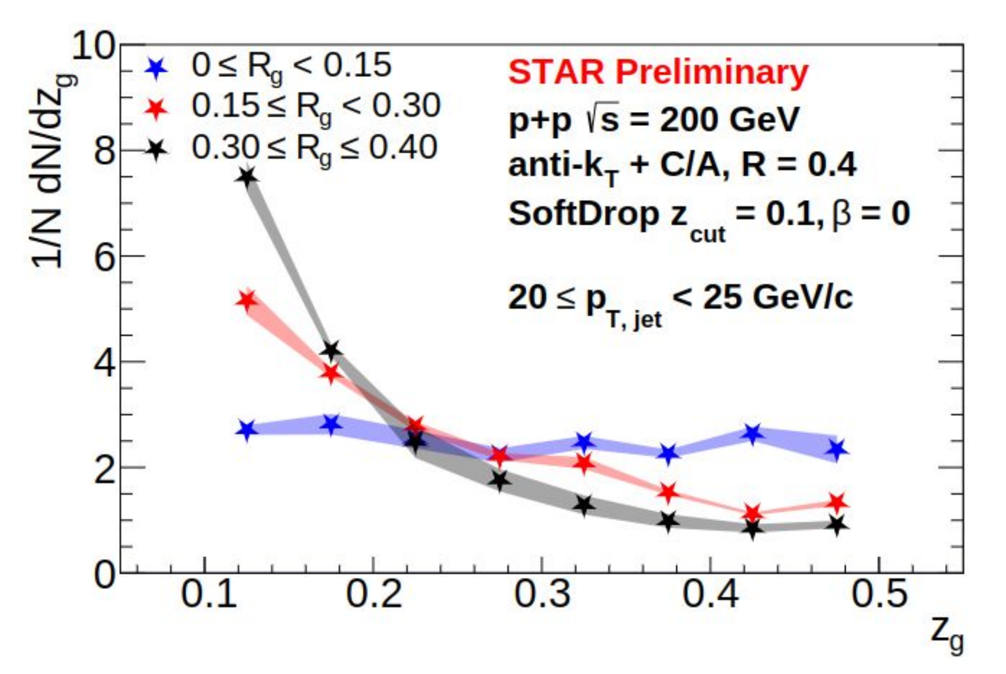
2+1D unfolding for z_g, R_g and $p_{T,jet}$

- Results are in 3D → 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
- 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



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

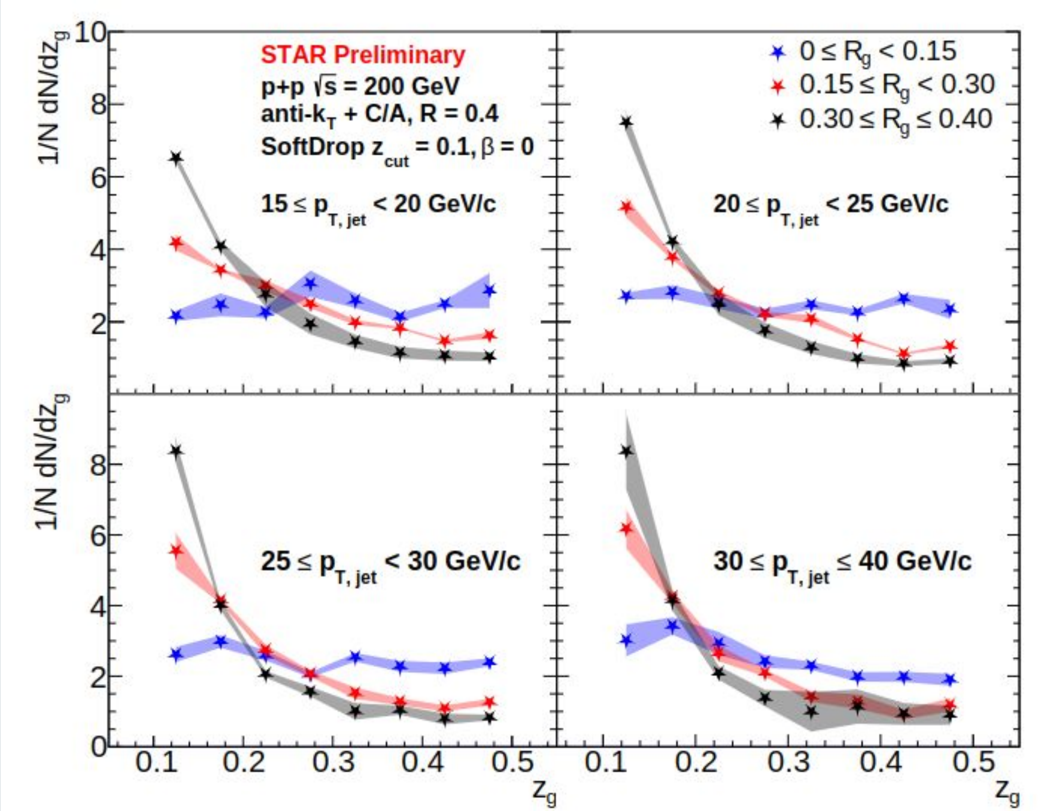




- When we go from small to large R_g we move from collinear hard splitting to softer wide angle splitting

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

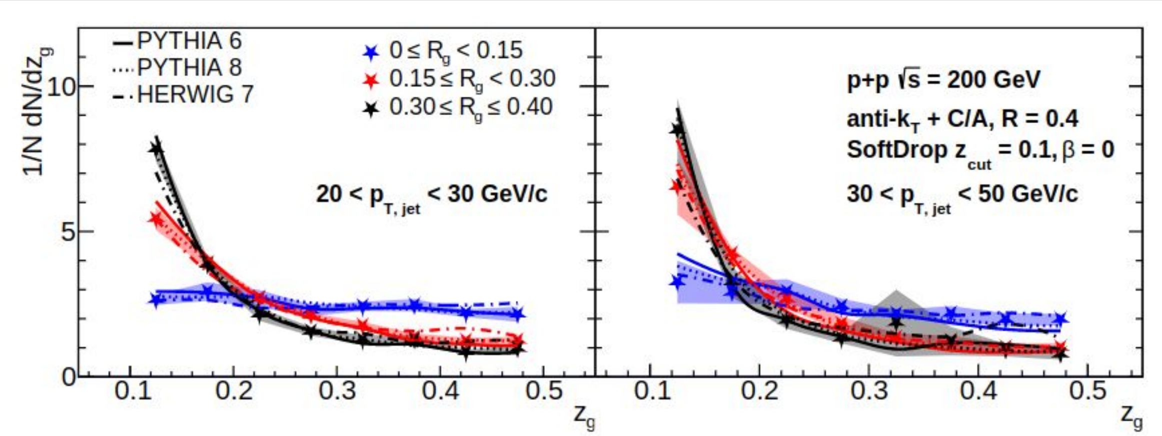
- Distributions change mildly with varying $p_{T,jet}$ → R_g is the driving factor for the change in shape of z_g distributions



Unfolded z_g distributions with respect to R_g for R = 0.4 with MC models

- Used several Monte Carlo models - PYTHIA6 (STAR tune), PYTHIA 8 (Monash), HERWIG 7

- All of the models describe trend of the data



Conclusion

- Study the jet substructure is very interesting and popular
- There are many ways how to study substructure
- First measurement of z_g vs. R_g as a function of $p_{T,jet}$ was shown
- Jet substructure measurements at RHIC energies allow to disentangle perturbative and mostly non-perturbative dynamics of jet evolution
- **Next steps:** Study other observables than z_g and R_g, compare different MC models and theoretical calculations

Thank you for your attention!