Multi-dimensional measurements of the parton shower in $p+p$ collisions at $\sqrt{s}$ = 200 GeV

Monika Robotková
for the STAR Collaboration

Nuclear Physics Institute, Czech Academy of Sciences
Czech Technical University in Prague

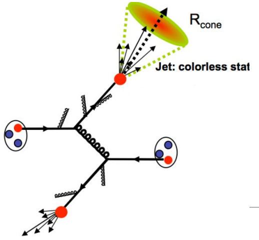
Hot Quarks 2022
Dao House, Colorado

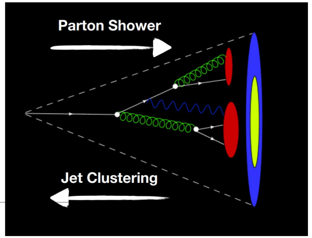
October 15, 2022

Supported in part by the
U.S. DEPARTMENT OF ENERGY | Office of Science

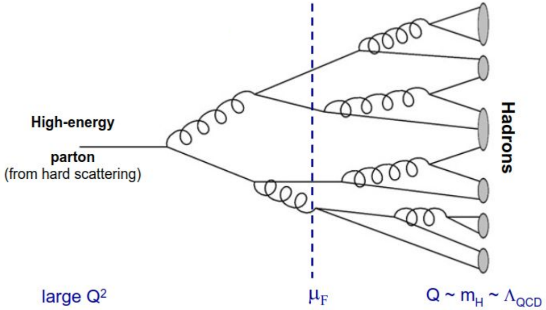
Overview

What is jet?
What is jet substructure?

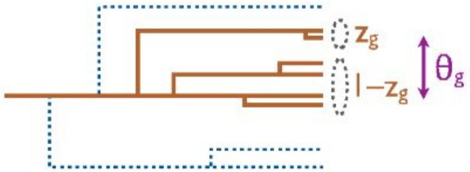




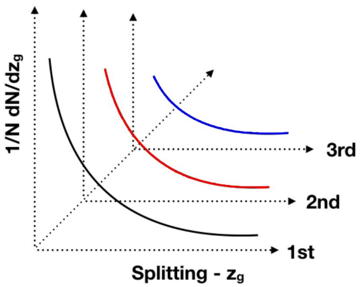
Why do we study jet substructure?



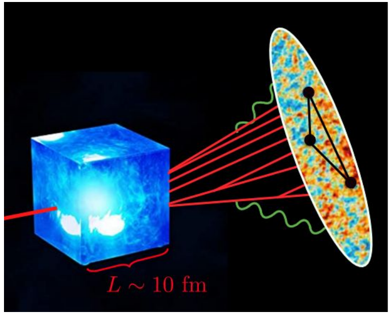
How do we study jet substructure?



What are the results of our study?

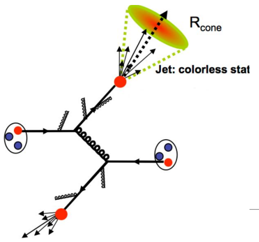


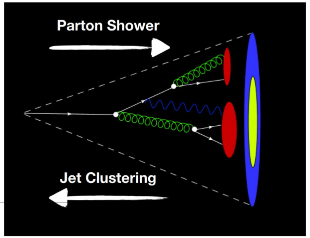
What are our future steps?



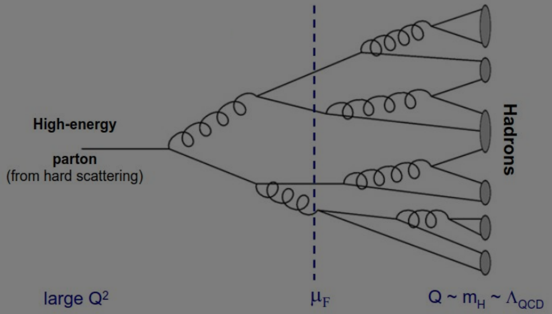
Overview

What is jet?
What is jet substructure?



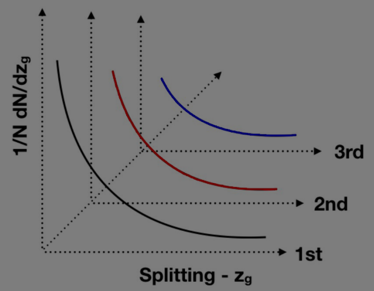


Why do we study jet substructure?

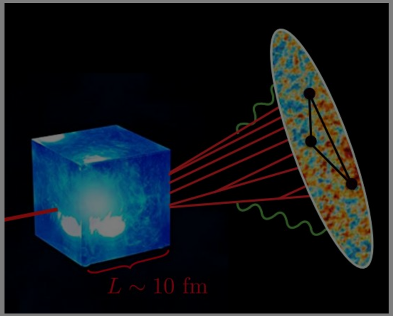


How do we study jet substructure?

What are the results of our study?

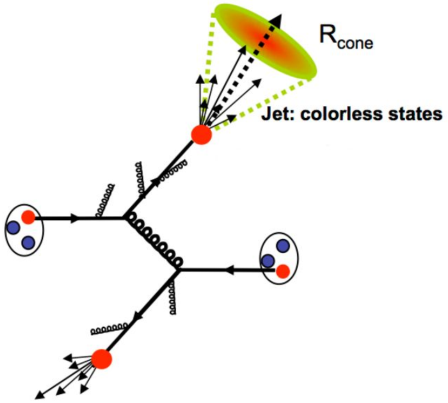


What are our future steps?



Jets and clustering algorithms

- Hard scattered partons evolve via showering and hadronizing
- Jets are collimated sprays of hadrons
- Jets are defined using algorithms



Anti-k_T algorithm

Cacciari *et al.*, JHEP 04 (2008) 063

- $d_{ij} = \frac{\min(1/p_{Ti}^2, 1/p_{Tj}^2)\Delta R_{ij}^2}{R}$, $d_{iB} = 1/p_{Tj}^2$
- Clustering starts from the particle with the highest transverse momentum

Cambridge/Aachen (C/A) algorithm

Dokshitzer *et al.*, JHEP 08 (1997) 001

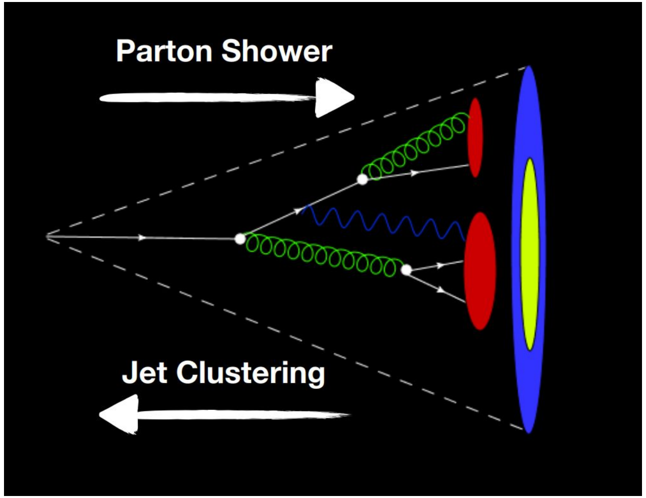
- $d_{ij} = \Delta R_{ij}^2/R^2$, $d_{iB} = 1$
- Particles are clustered exclusively based on angular separation, ideal for resolving jet substructure

d_{ij} - distance between the particle i and j
d_{iB} - distance of the particle i from the beam
p_T - transverse momentum
ΔR_{ij} - distance between the particle i and j in (y, ϕ) space
R - jet resolution parameter

Jet substructure

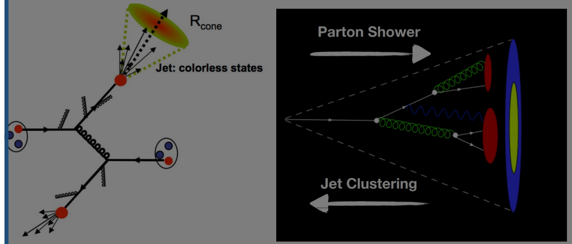
- Distribution of particles inside the jet
- Parton shower is described by momentum and angular scales

Sketches by J. Thaler

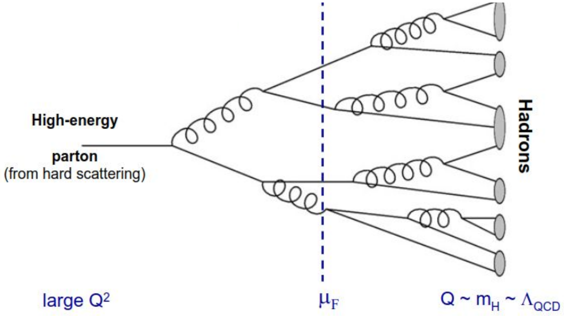


Overview

What is jet?
What is jet substructure?

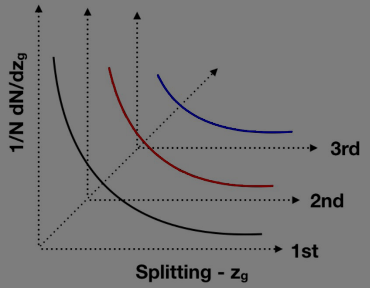


Why do we study jet substructure?

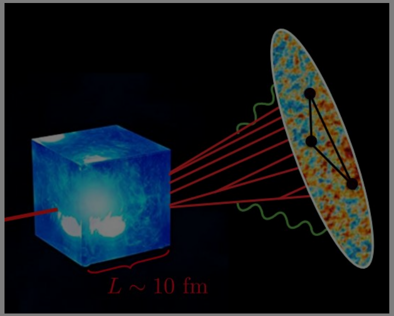


How do we study jet substructure?

What are the results of our study?



What are our future steps?

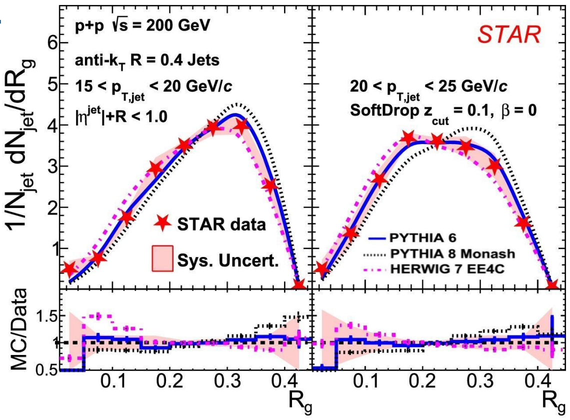


Motivation to study jet substructure

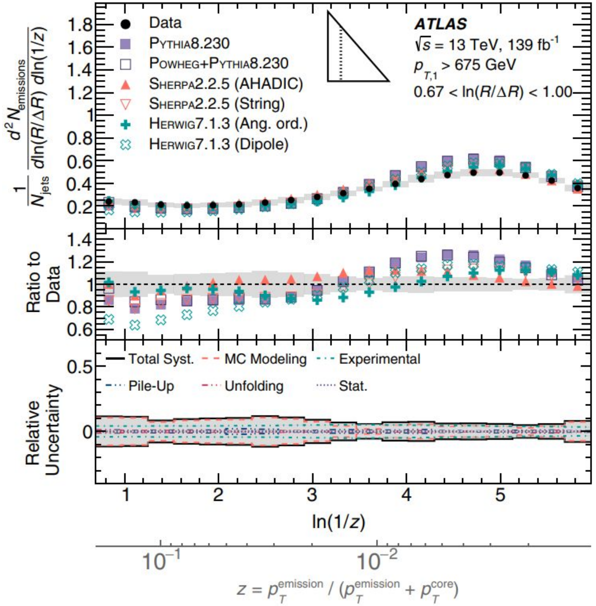
- Jets and their substructure contain information on parton shower (perturbative-QCD) and fragmentation (non-perturbative-QCD) processes

- ***p+p* collisions:**
  - To study vacuum QCD shower at RHIC energies
  - Allow detailed comparisons with QCD predictions and MC generators

- **A+A collisions:**
  - Study medium modification of intra-jet distributions



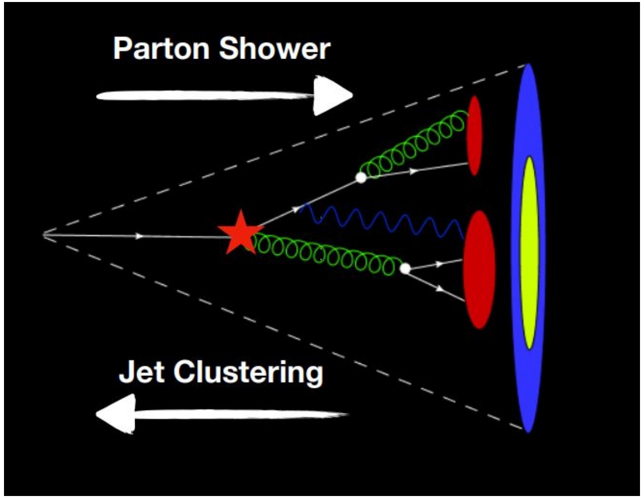
STAR, PLB 811 (2020) 135846

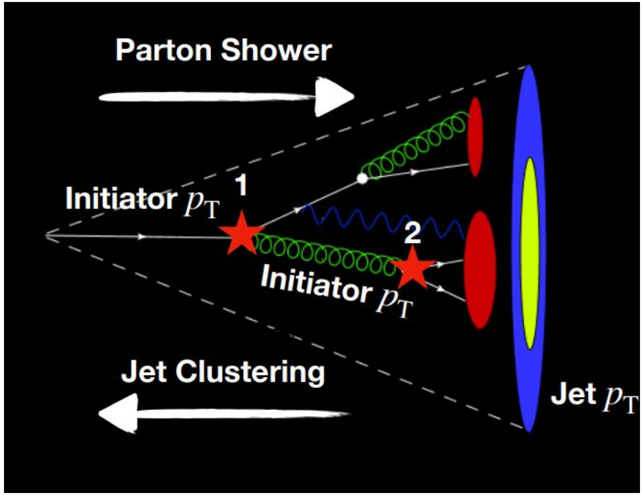


ATLAS, PRL 124 (2020) 222002

Motivation to study jet substructure

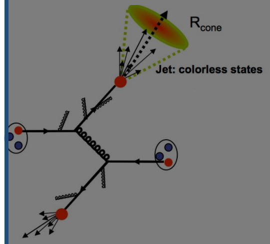
- Two ways to study the parton shower:
  - **Correlation between substructure observables at the first split**
  - **Evolution of the splitting kinematics as we travel along the jet shower**

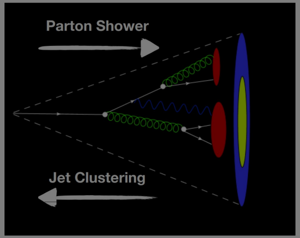




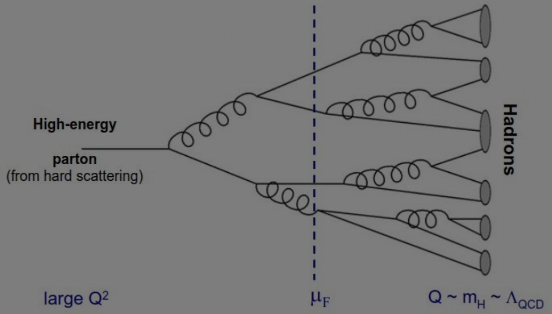
Overview

What is jet?
What is jet substructure?

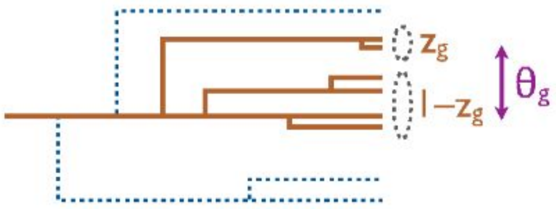




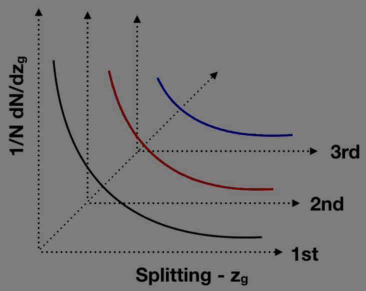
Why do we study jet substructure?



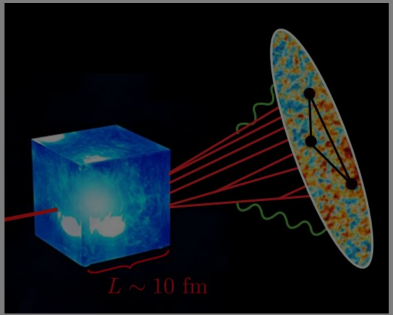
How do we study jet substructure?



What are the results of our study?

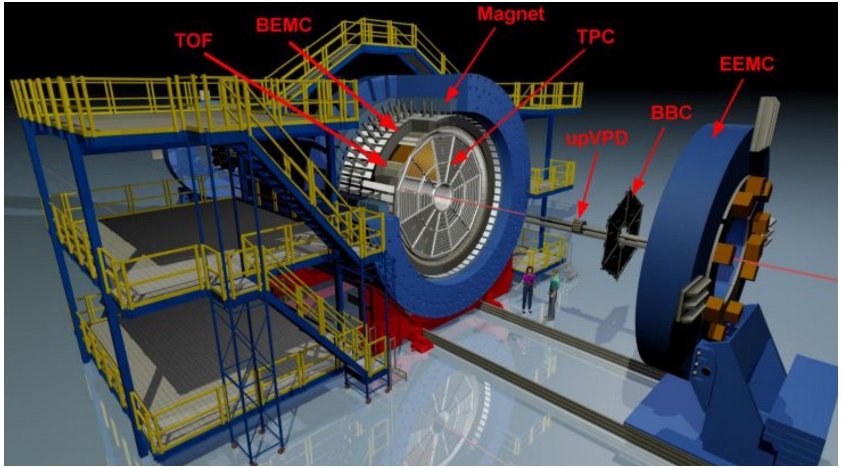


What are our future steps?



STAR experiment

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



Full azimuthal angle, $|\eta| < 1$

TPC - *Time Projection Chamber*

- Detection of charged particles for jet reconstruction
- Transverse momenta of tracks: $0.2 < p_T < 30$ GeV/c

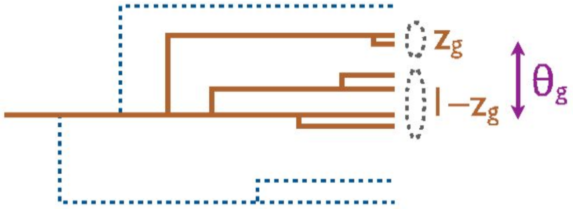
BEMC - *Barrel Electromagnetic Calorimeter*

- Detection of neutral particles for jet reconstruction
- Granularity $(\Delta\eta \times \Delta\varphi) = (0.05 \times 0.05)$
- Jet Patch (JP) trigger
- Tower requirements: $0.2 < E_T < 30$ GeV

Dataset: $p + p$ collisions at $\sqrt{s} = 200$ GeV, 2012
Algorithms: anti-k_T + C/A algorithms
Jet resolution parameters: R = 0.4, R = 0.6
Transverse momenta of jets: $15 < p_{T,jet} < 50$ GeV/c

SoftDrop

- Grooming technique by removing soft wide-angle radiation in order to mitigate non-perturbative effects
- Connects parton shower and angular tree



Larkoski *et al.*, PRL 119 (2017) 132003

SoftDrop:
Larkoski *et al.*, JHEP 05 (2014) 146

- **Shared momentum fraction z_g**

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

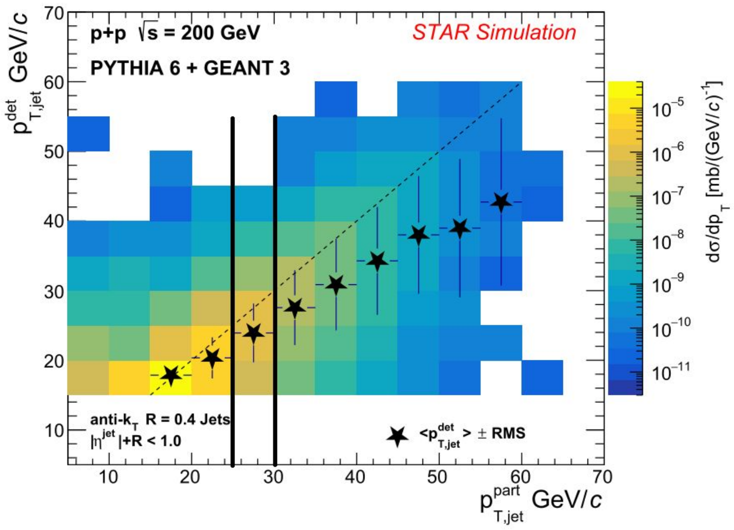
$$\text{where } \theta = \frac{\Delta R_{12}}{R}$$

- $p_{T,1}, p_{T,2}$ - 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

2+1D unfolding at the first split

- Measurements are affected by finite efficiency and resolution of the instrumentation
- Our goal is to deconvolve detector effects and obtain truth (particle-level) distribution
- Results are in 3D: z_g vs. R_g vs. $p_{T,jet}$
- We unfold z_g vs. R_g via 2D iterative Bayesian unfolding using RooUnfold in detector-level $p_{T,jet}$ bins
- Correction for $p_{T,jet}$ is applied:
  - For each particle-level $p_{T,jet}$ bin, we do projection of this bin onto detector-level $p_{T,jet}$, and get the weights for detector-level $p_{T,jet}$ bins

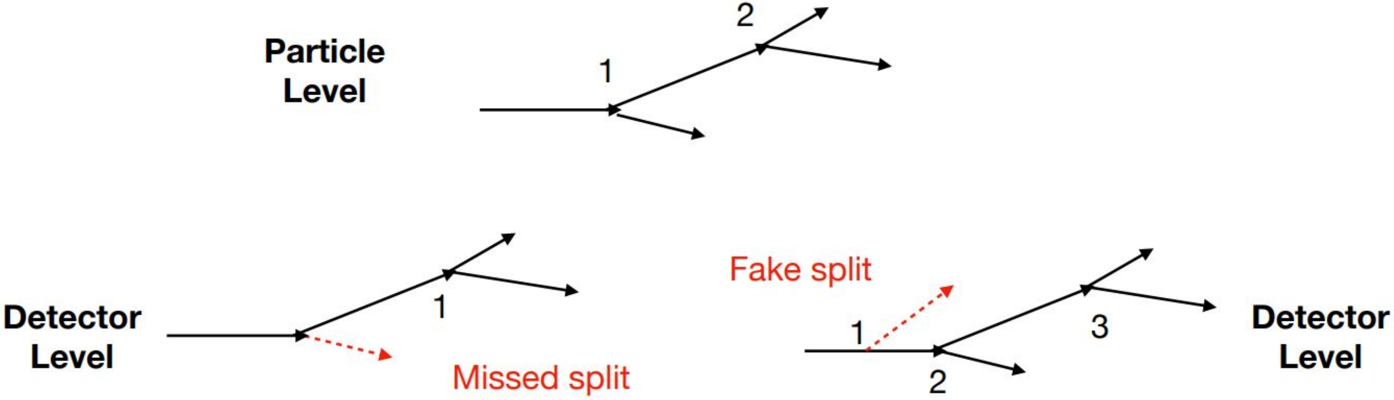


STAR, PLB 811 (2020) 135846

- Unfolded spectra for each detector-level $p_{T,jet}$ bin are weighted and summed
- Additional corrections for trigger and jet finding efficiencies are applied

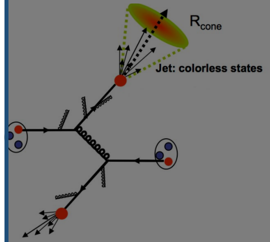
2+1D unfolding at the first, second and third split

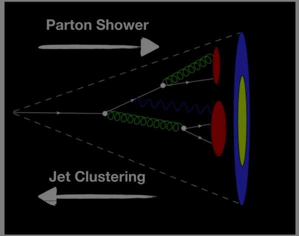
- Splits can be affected by detector efficiency and resolution
- Observables at a given split are smeared
- Splitting hierarchy is modified going from particle level to detector level
- Hierarchy matrix with particle-level splits on *x*-axis and detector-level splits on *y*-axis is used to obtain weights for 2D unfolded data



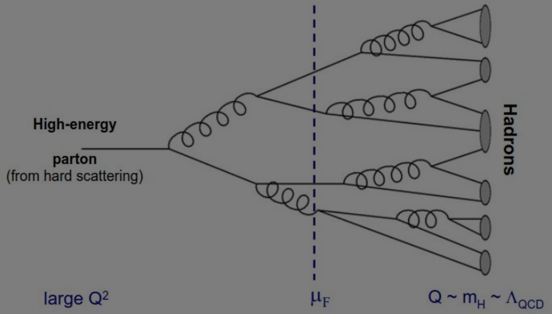
Overview

What is jet?
What is jet substructure?



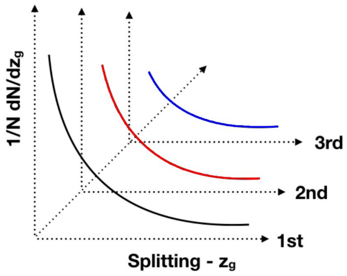


Why do we study jet substructure?

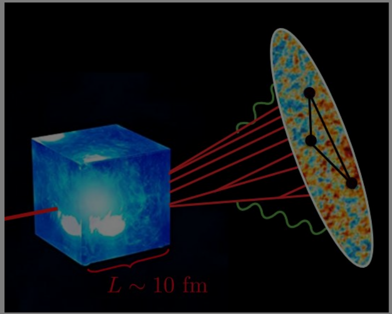


How do we study jet substructure?

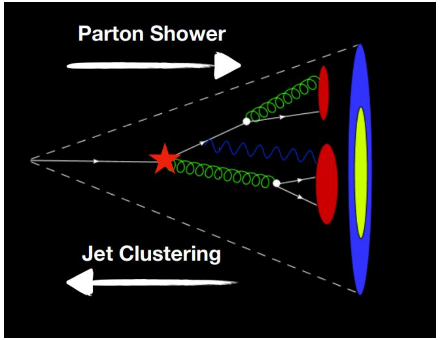
What are the results of our study?

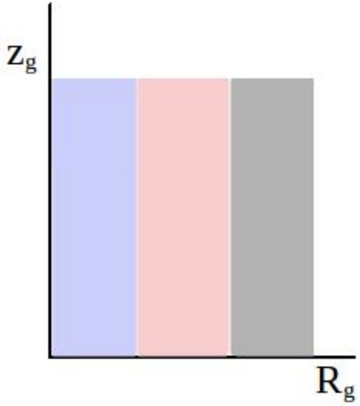


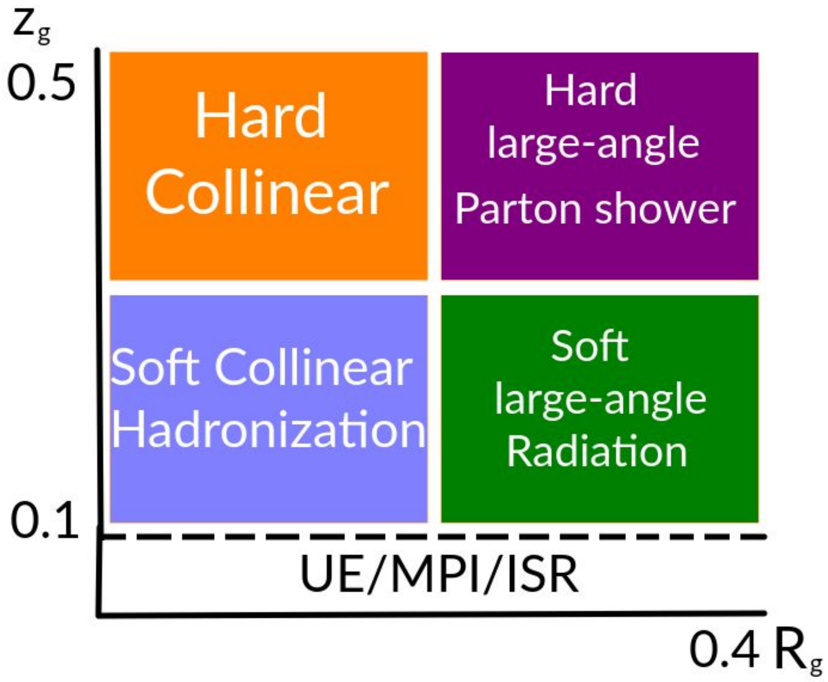
What are our future steps?



Correlation between substructure observables at the first split

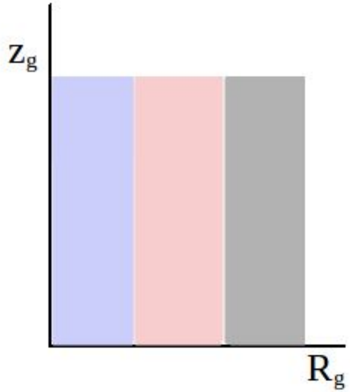


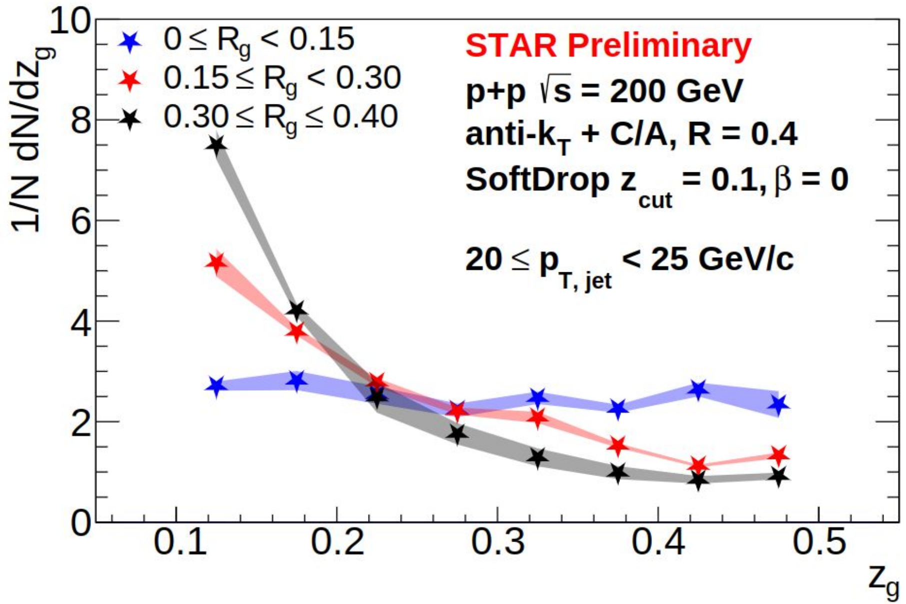




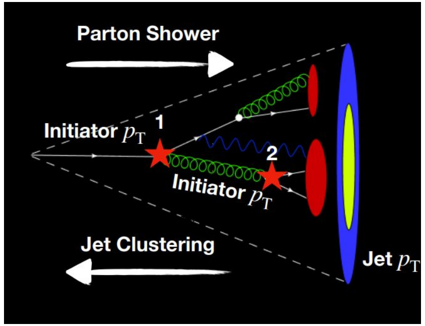
Unfolded z_g distributions with respect to R_g for $20 \leq p_T < 25$ GeV/c with $R = 0.4$

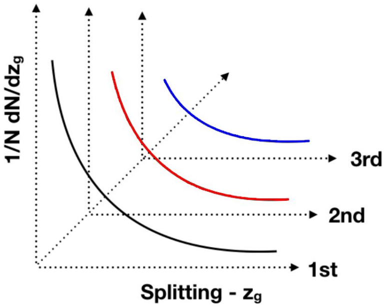
- z_g distributions become steeper with increasing R_g
- When we go from small to large R_g we move from collinear hard splitting to softer wide angle s

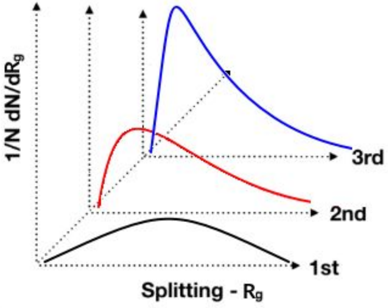


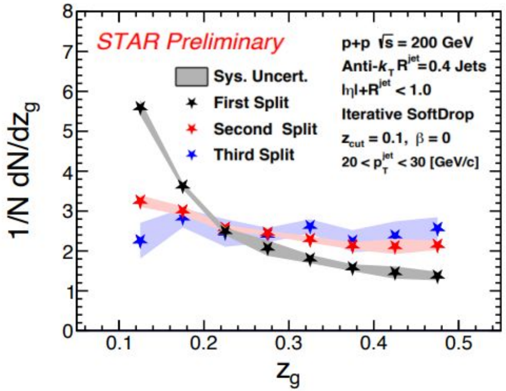


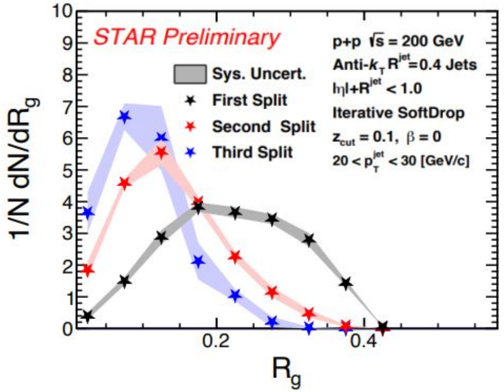
First, second and third splits







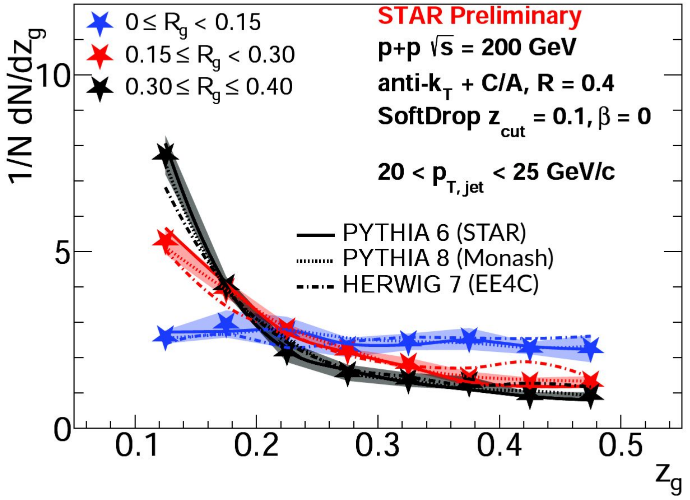


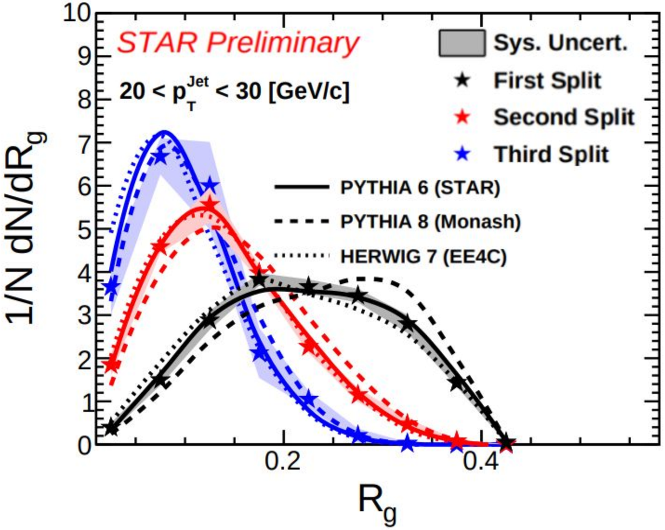


- Going from 1st → 3rd split
  - z_g distribution becomes **flatter**
  - R_g distribution becomes **narrower**
- **Collinear emissions are enhanced when we go from 1st to 3rd split**
- **Strong evolution of splitting kinematics**

Comparison with different MC generators

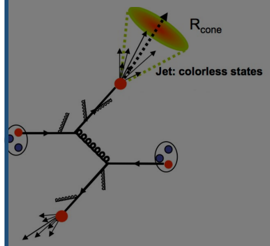
- Data compared with simulations from PYTHIA 6 (STAR tune), PYTHIA 8 (Monash tune) and HERWIG 7 (EE4C tune)
- Leading-order MC models describe trend of the data

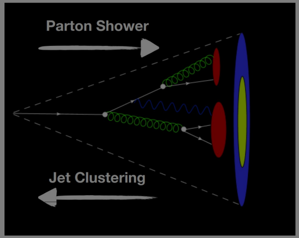




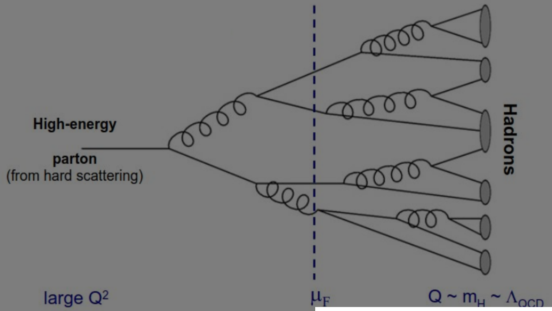
Overview

What is jet?
What is jet substructure?



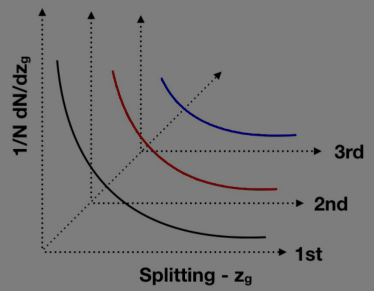


Why do we study jet substructure?

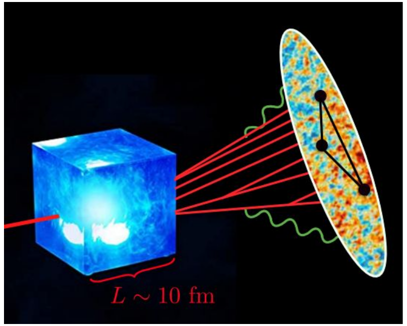


How do we study jet substructure?

What are the results of our study?



What are our future steps?



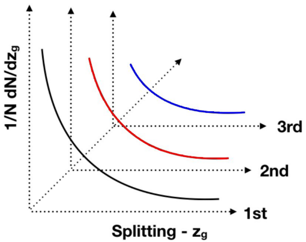
Conclusion and future steps

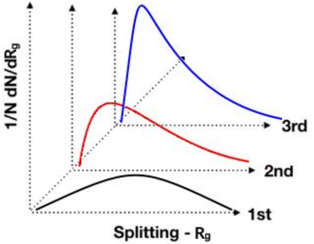
Correlation at the first split

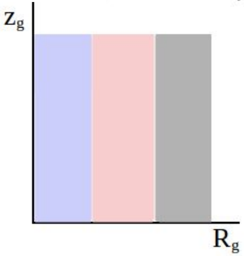
- z_g has a **strong** dependence on R_g
- We can select significantly softer splits by selecting wider angle splits

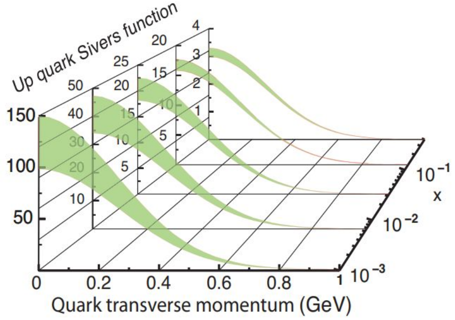
Splits along the shower

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







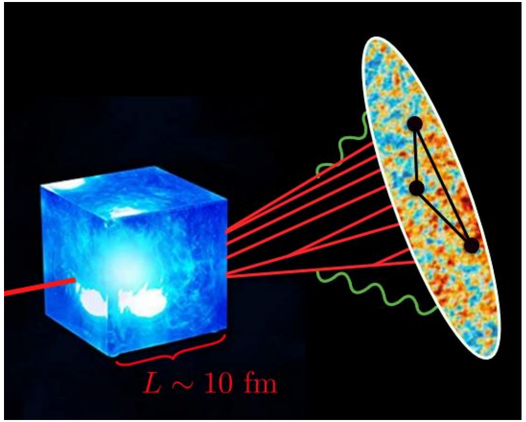


Accardi *et al.*, EPJA 52 (2016) 268

‘Spatio-temporal’ imaging of the jet

Future steps:

- Jet substructure measurements in A+A collisions to study effects of medium



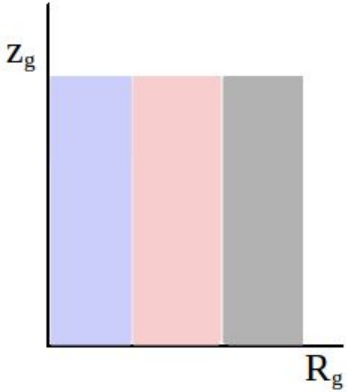
Andres *et al.*, arXiv: 2209.11236

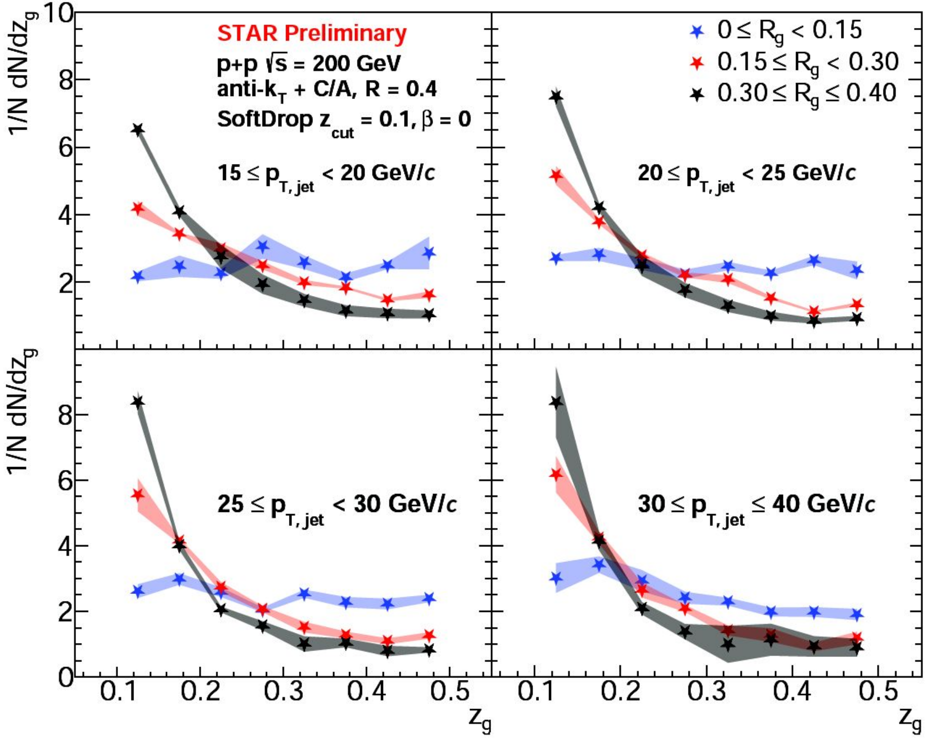
Thank you for your attention!

Back up

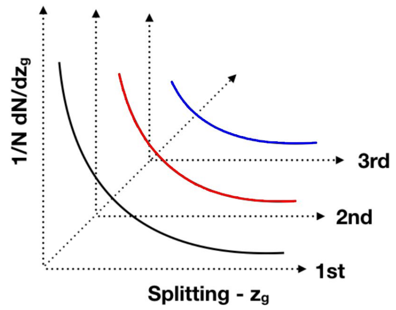
Correlation between observables at the first split

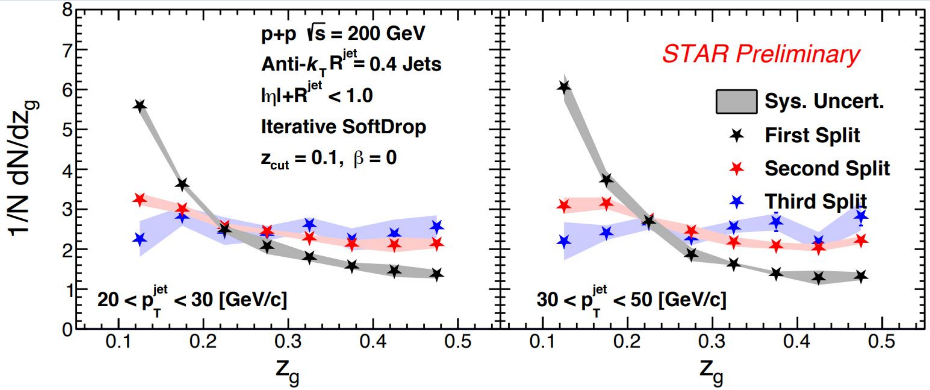
- z_g with respect to the R_g for different $p_{T,jet}$ bins
- Distributions change mildly with varying $p_{T,jet}$ → R_g is the driving factor for the change in shape of z_g distributions
- Jets with large R_g have steeper z_g distributions → softer splitting is enhanced





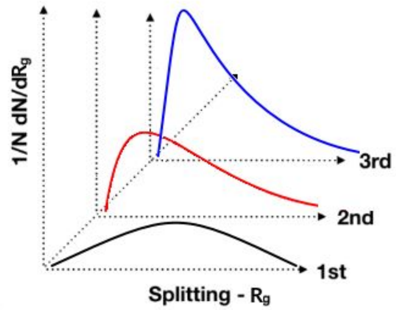
First, second and third splits

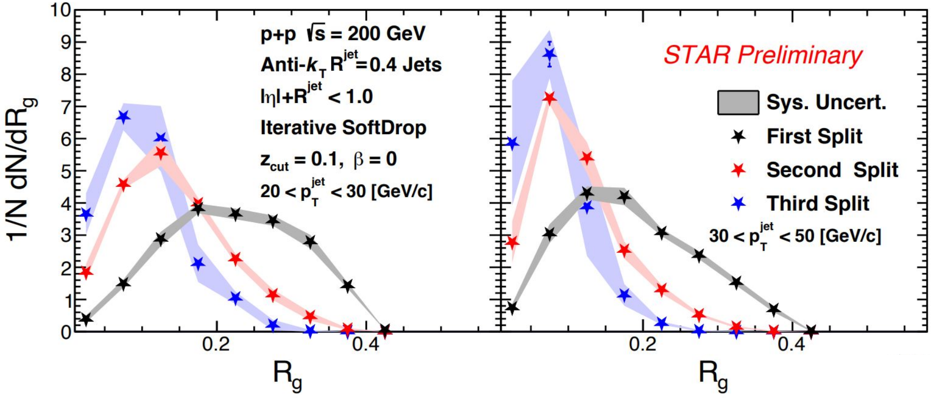




Going from 1st → 3rd split

- z_g distribution becomes **flatter**





Going from 1st → 3rd split

- R_g distribution becomes **narrower**

Strong evolution of splitting kinematics