Jet substructure measurements elucidating partonic evolution in *p+p* collisions at RHIC

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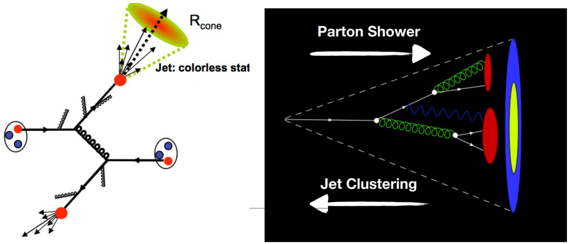
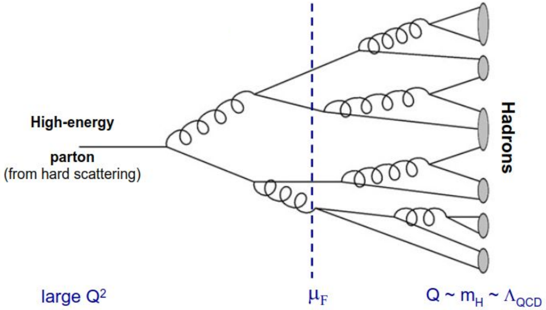
Overview

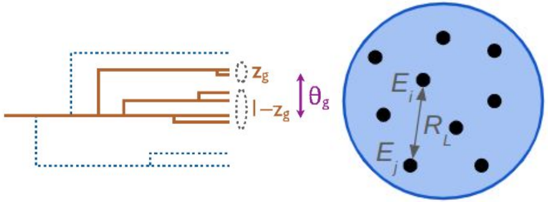
What is jet?
What is jet substructure?



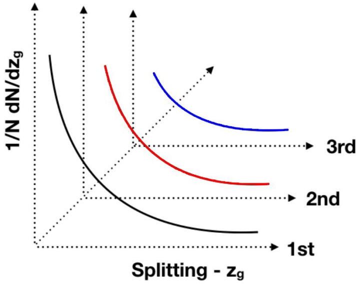
Why do we study jet substructure?



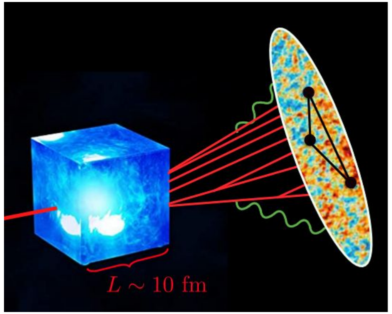
How do we study jet substructure?



What are the results of our study?



What are our future steps?



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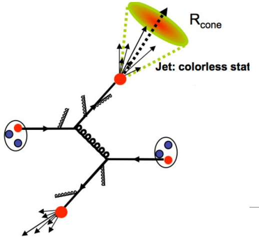

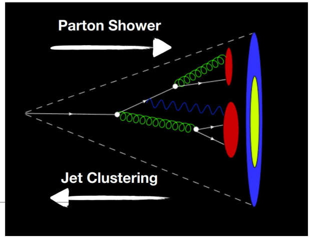

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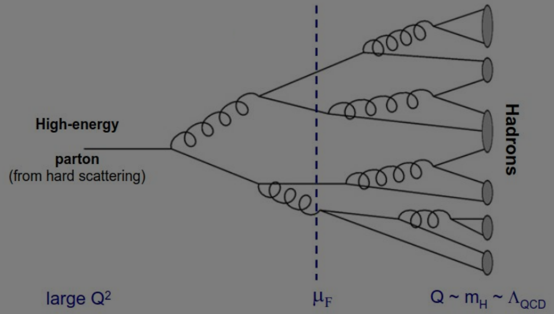

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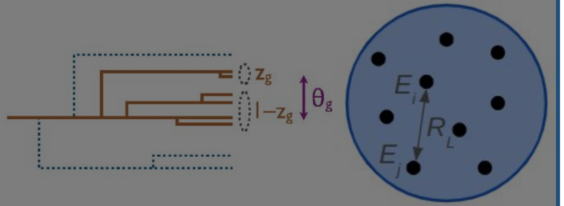

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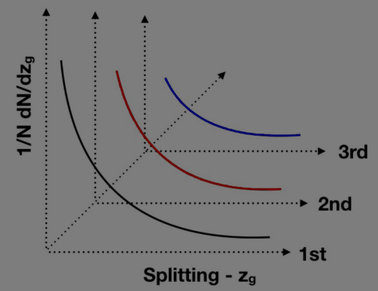

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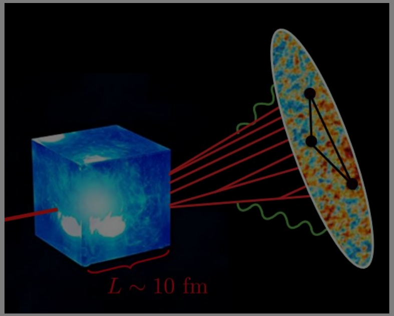
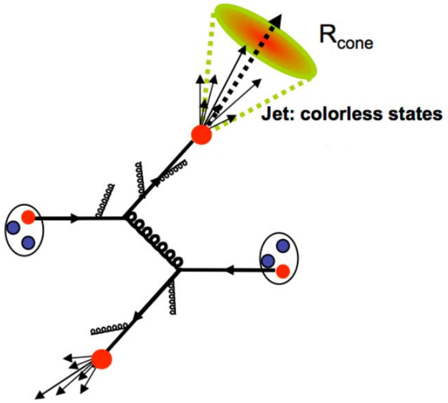


Jets and clustering algorithms

- 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

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

Cambridge/Aachen (C/A) algorithm

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

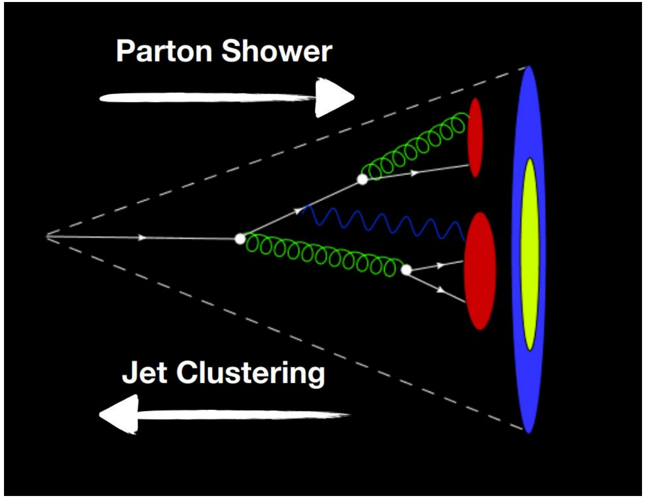
- $$d_{ij} = \Delta R_{ij}^2/R^2, \; d_{iB} = 1$$
- Particles are clustered exclusively based on angular separation, ideal for resolving jet substructure

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



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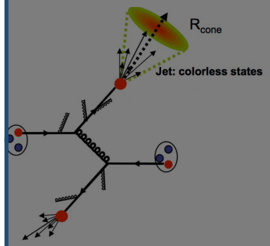

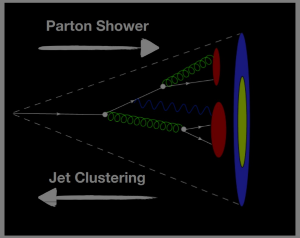

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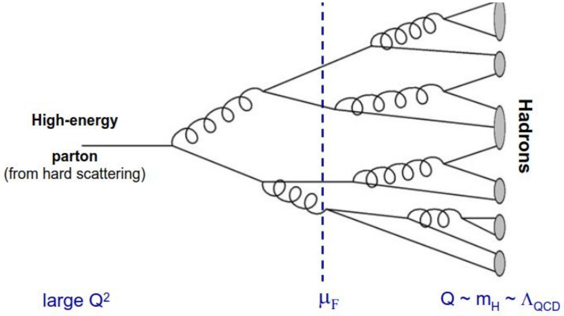

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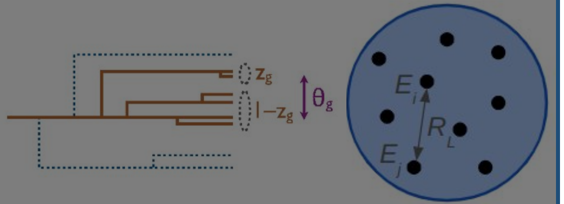

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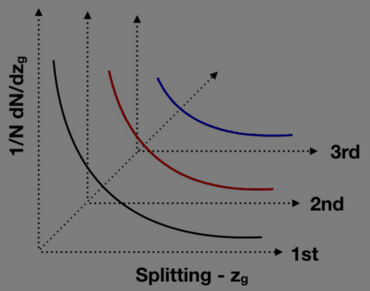

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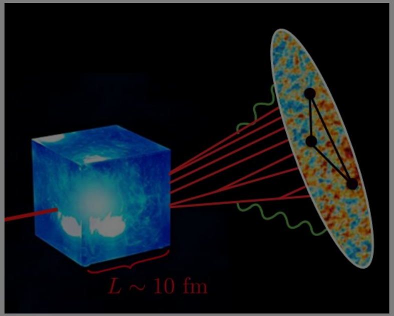
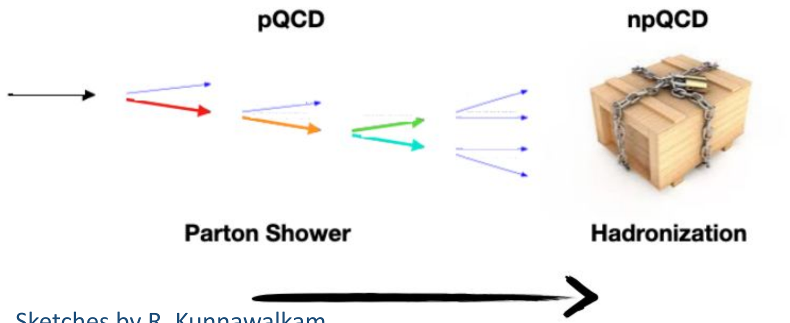
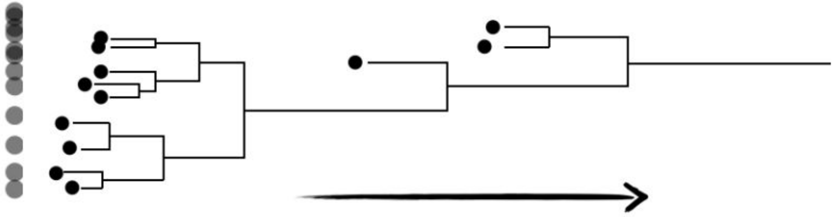


Motivation to study jet substructure

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





Sketches by R. Kunnawalkam Elayavalli

- ***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

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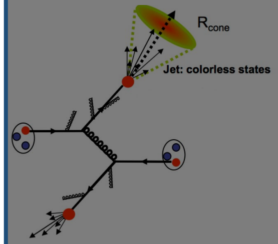

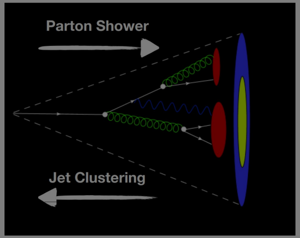

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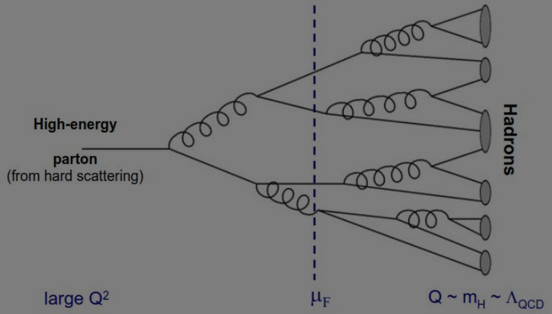

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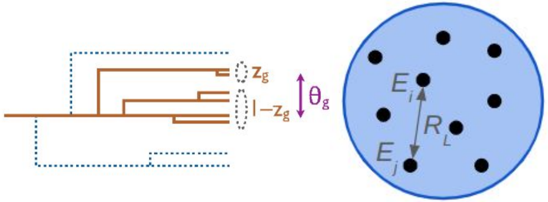

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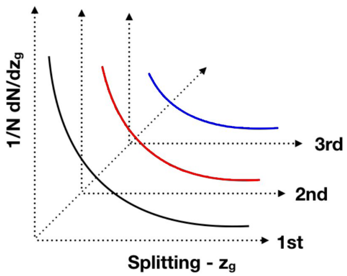

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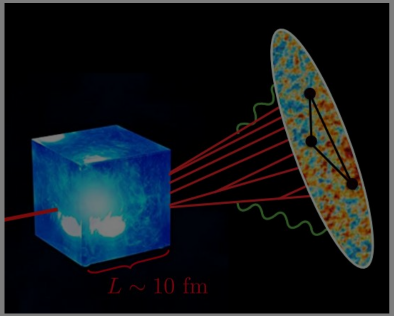
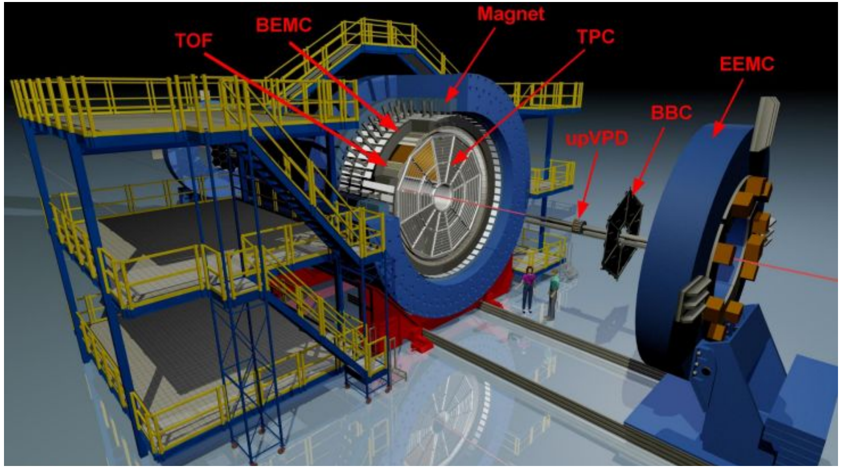


STAR experiment for jet studies

- 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*

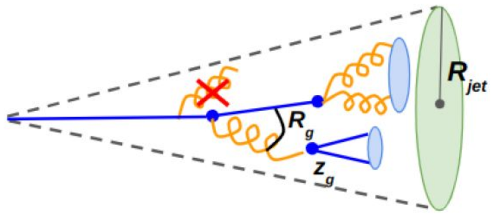
- Detection of neutral particles for jet reconstruction
- Granularity $(\Delta\eta \times \Delta\varphi) = (0.05 \times 0.05)$
- Jet Patch (JP) trigger
- Tower requirements: $0.2 < E_T < 30$ GeV

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

Jet substructure tools used in STAR experiment

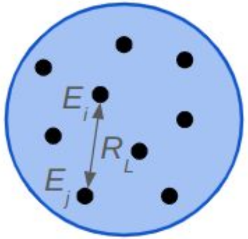
Soft Drop/Collinear Drop

- Grooming is used to remove soft radiation
- Allows to study different splittings



Energy-energy correlators

- Final state constituents are used to study jet evolution
- No additional clustering is needed



Soft Drop/Collinear Drop

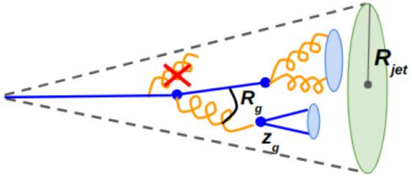
Soft Drop

- Grooming technique by removing soft wide-angle radiation in order to mitigate non-perturbative effects
- Declustering is done using C/A algorithm
- Connects parton shower and angular tree

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

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

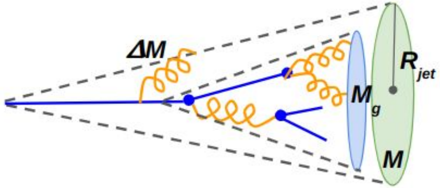
- $p_{T,1}, p_{T,2}$ - transverse momenta of the subjets
- z_{cut} - threshold ($=0.1$)
- β - angular exponent ($=0$)
- ΔR_{12} - distance of subjets in the rapidity-azimuth plane



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

Collinear Drop

- Probes the soft component of the jet
- Difference of an observable with two different SoftDrop settings of parameters ($z_{cut,1}$, β_1) and ($z_{cut,2}$, β_2)
- Our case: ($z_{cut,1}$, β_1) = (0, 0), ($z_{cut,2}$, β_2) = (0.1, 0)



Soft Drop observables

- **Shared momentum fraction z_g**

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

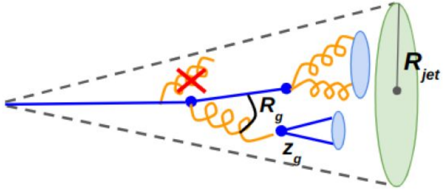
- **Groomed radius R_g**
    - First ΔR_{12} that satisfies Soft Drop condition
- **Splitting scale k_T**

$$k_T = z_g p_{T,\text{jet}} \sin R_g$$

- **Jet mass M**

$$M = \Big|\sum_{i \in \text{jet}} p_i\Big| = \sqrt{E^2 - |\vec{p}|^2}$$

- **Groomed jet mass M_g**
    - Jet mass after grooming



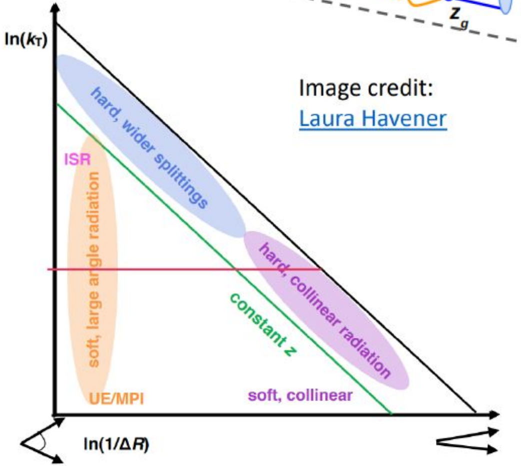
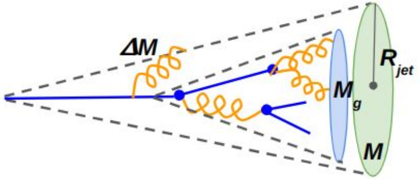


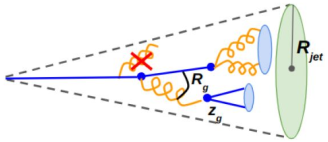
Image credit:
Laura Havener

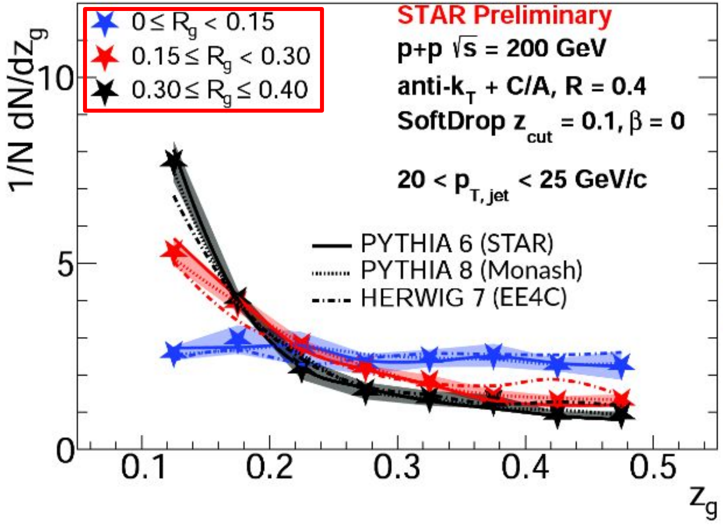
$$\Delta M = M - M_g \text{ [GeV]}$$

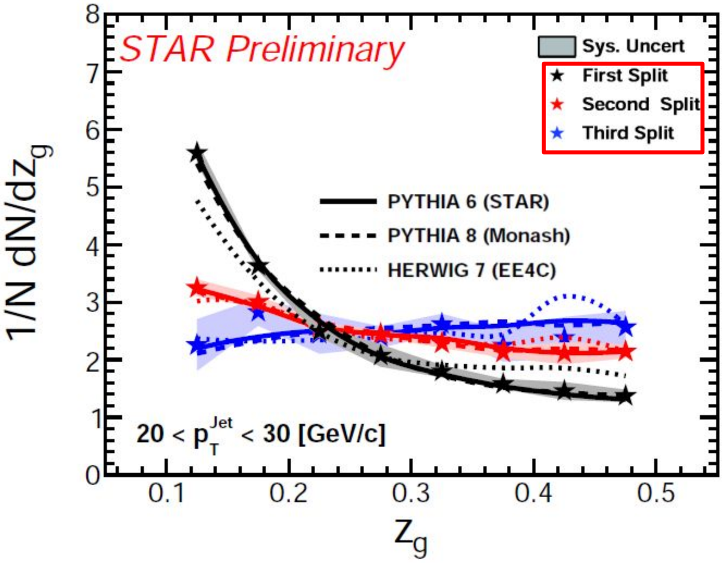


z_g vs. R_g at the first split and z_g for the different split number

$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$$



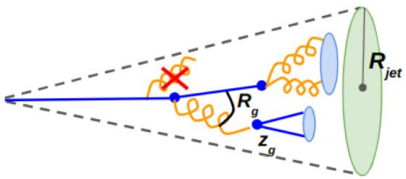




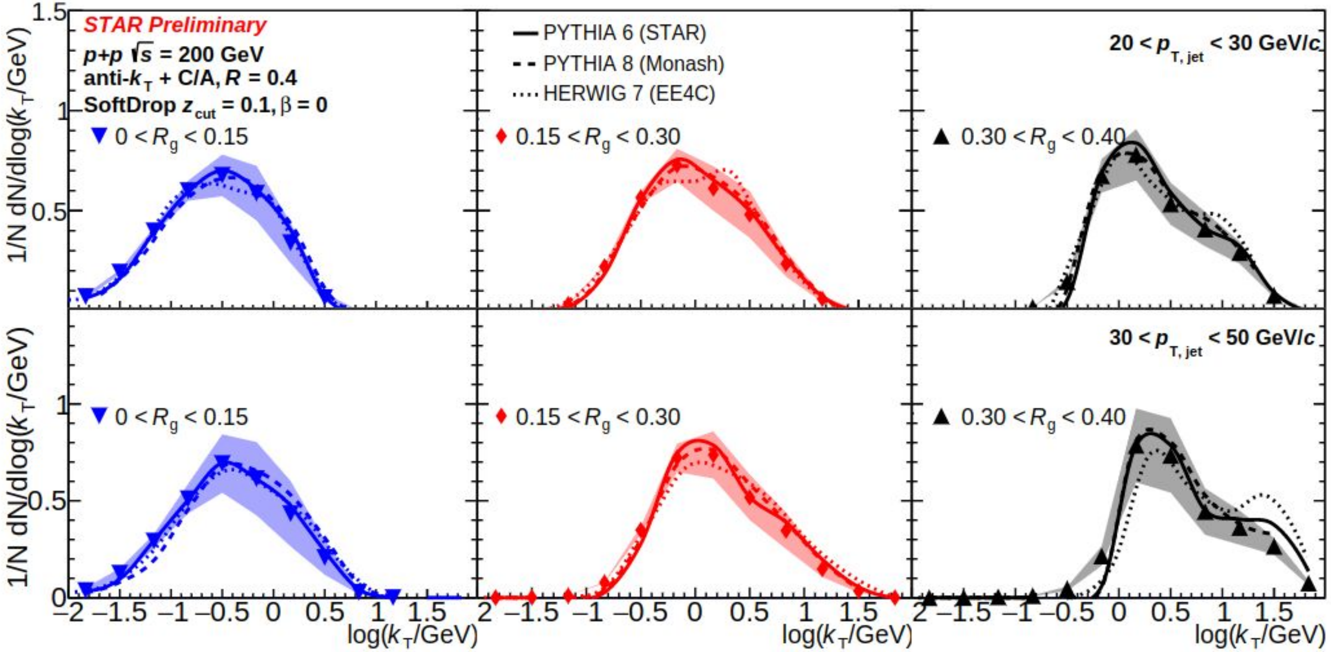
- (2+1)D correction is used
- When we move from collinear hard splitting/third split to softer wide angle splitting/first split, z_g distribution becomes **steeper** and more **perturbative**
- MC models describe the trend of the data

Previous STAR jet substructure measurement:
STAR, PLB 811 (2020) 135846

$\log(k_T)$ vs. R_g at the first split



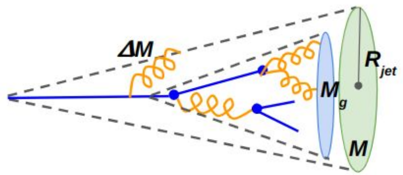
$$k_T = z_g p_{T,jet} \sin R_g$$



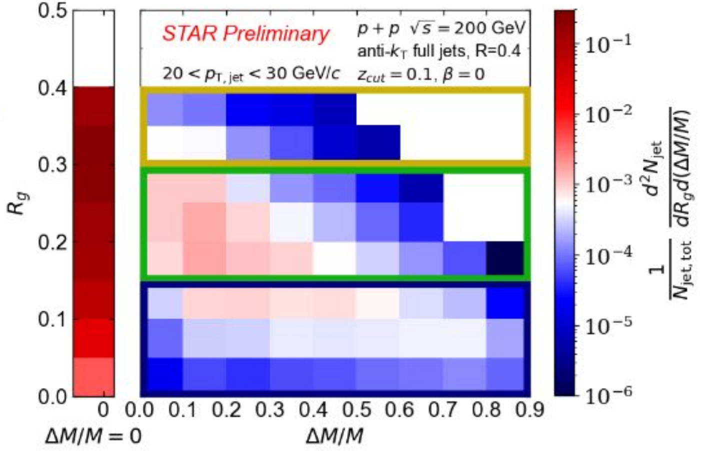
- $\log(k_T)$ has **strong** dependence on R_g and **weak** dependence on $p_{T,jet}$
- 0 value corresponds to 1 GeV →we move from **non-perturbative** to **perturbative** region by increasing R_g

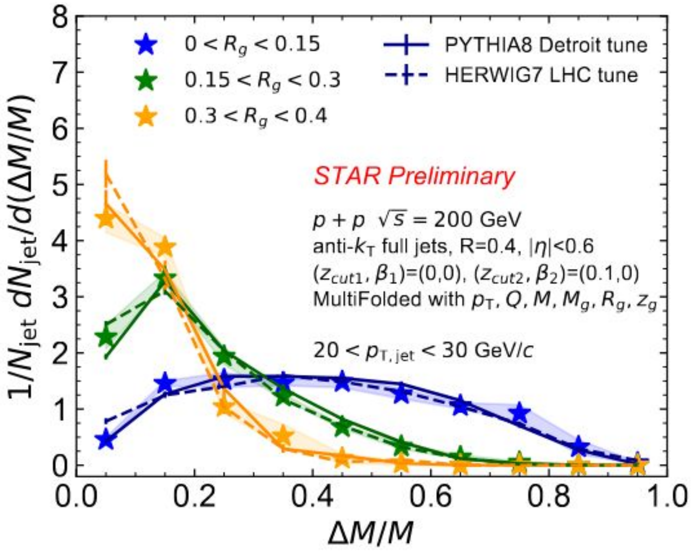
R_g vs. $\Delta M/M$ at the first splits

$$\Delta M = M - M_g \; [\text{GeV}]$$



- Unfolded with **MultiFold**
  Andreassen et al. PRL 124, 182001 (2020)
- **Collinear Drop** used to study soft component of the jet





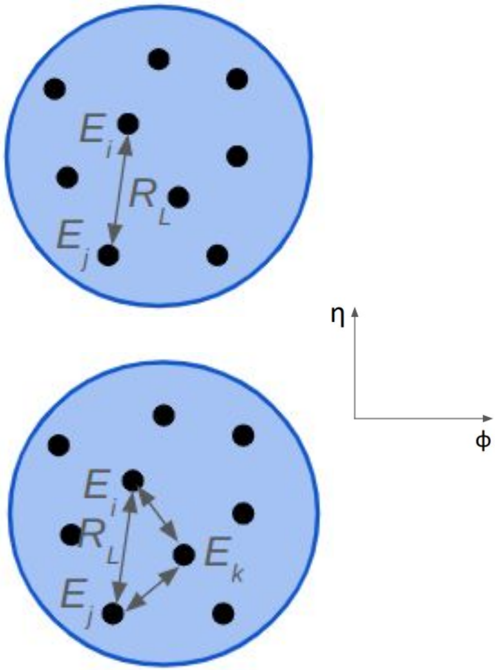
- The $\Delta M/M$ distribution is **anti-correlated** with R_g, which is consistent with angular ordering of the parton shower
- Large groomed jet radius → little/no soft wide angle radiation (small $\Delta M/M$) in the shower
- MC models describe the trend of the data

Projected N-point energy correlator

Theoretical definition of projected N-point correlator

$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N} \int d\Omega_{\vec{n}_k}\right) \delta(R_L - \Delta\hat{R}_L) \cdot \frac{1}{(E_{\mathrm{jet}})^N} \langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N)\rangle$$

Chen et al. PRD 102, 5 (2020)



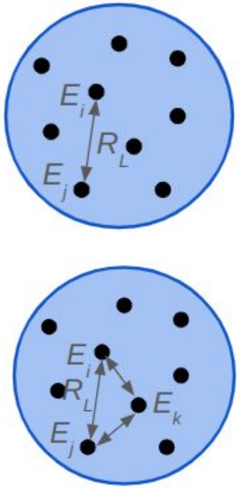
Experimental construction of two-point and three-point correlator

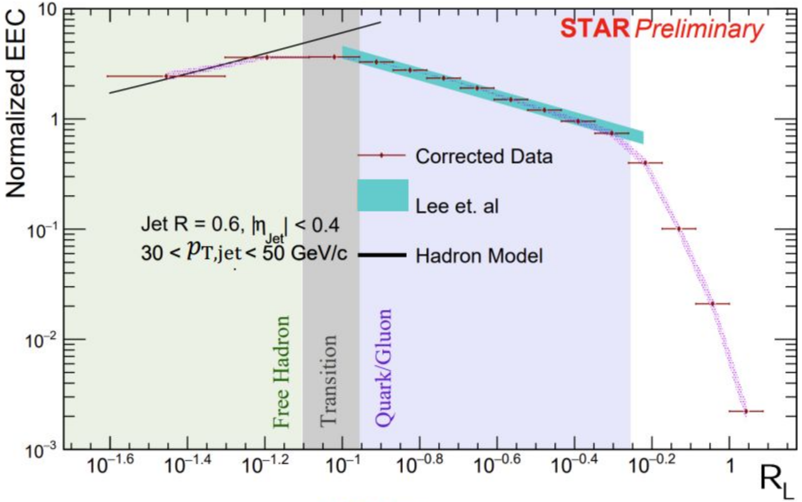
$$\text{Normalized EEC} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}{}^2}} \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}{}^2}\right)}{d\,(R_L)}$$

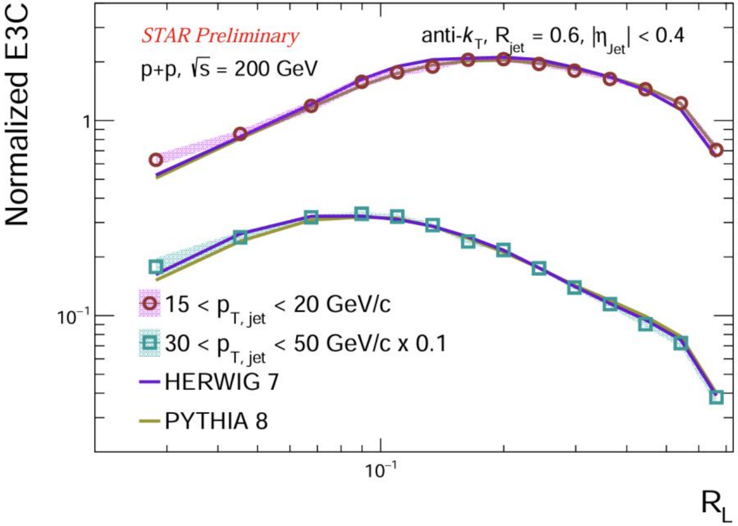
$$\text{Normalized E3C} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_iE_jE_k}{p_{T,Jet}{}^3}} \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_jE_k}{p_{T,Jet}{}^3}\right)}{d\,(R_L)}$$

- Jet evolution is studied using final state constituents
- Allows to separate **perturbative** and **non-perturbative** regimes

EEC and E3C results







Lee et al. arXiv:2205.03414 (2023)

- Correlation measurements separate distribution into **non-perturbative** and **perturbative** regimes, separated by **transition** region
- Transition region shifts with jet momentum, manifests universality when scaled by momentum
- Both MC generators and theoretical predictions describe the data well
  - But charge information within the jet is not captured by the MC models

For more details see HP2024 talk

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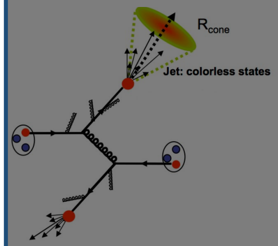

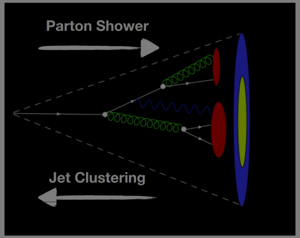

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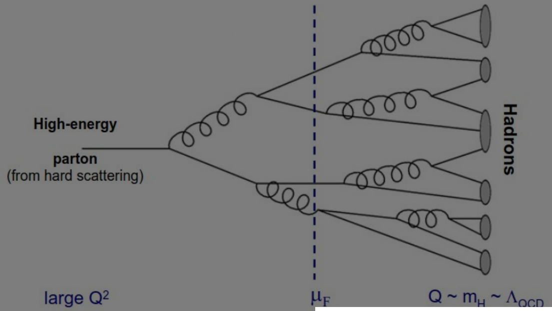

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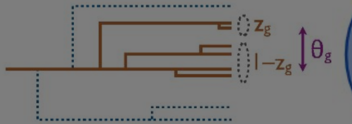

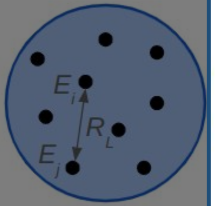

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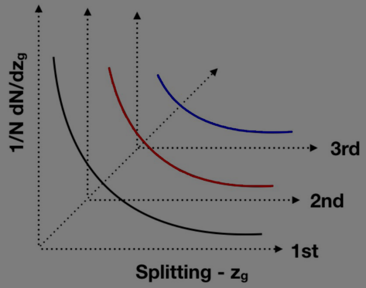
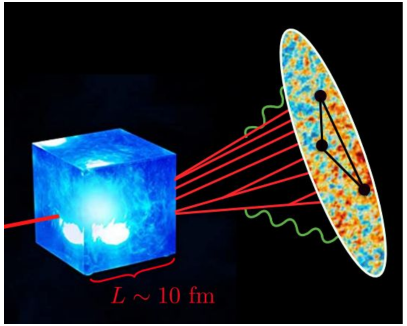


What are our future steps?

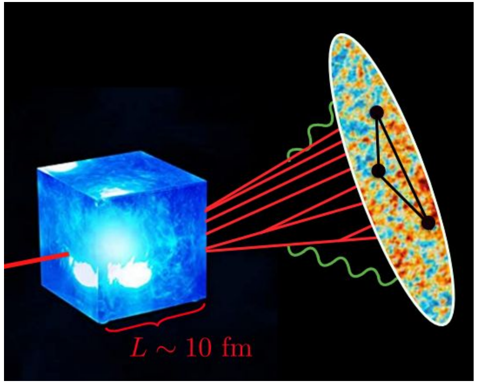


Conclusion and future steps

- Jet substructure can be studied by several different tools, such as **Soft Drop**, **Collinear Drop** and **Energy-Energy Correlators**
- Study of different Lund Plane regions allows us to observe the correlations between jet substructure observables
- Jet substructure measurements at RHIC energies allow to disentangle **perturbative** (early, wide splits) and mostly **non-perturbative** dynamics (late, narrow splits) within jet showers
- Trend of the *p*+*p* data is mostly captured by the MC models and theoretical predictions

Future steps:

- Extend preliminary jet substructure measurements in Au+Au to study medium effects in detail
- Implement ENCs in heavy-ion collisions



Andres *et al.*, arXiv: 2209.11236

Thank you for your attention!

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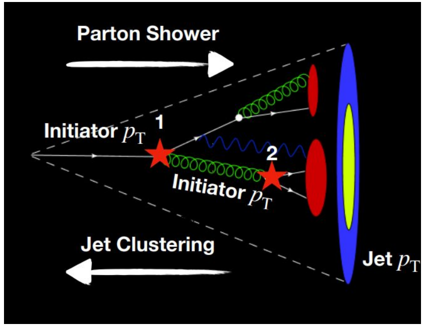
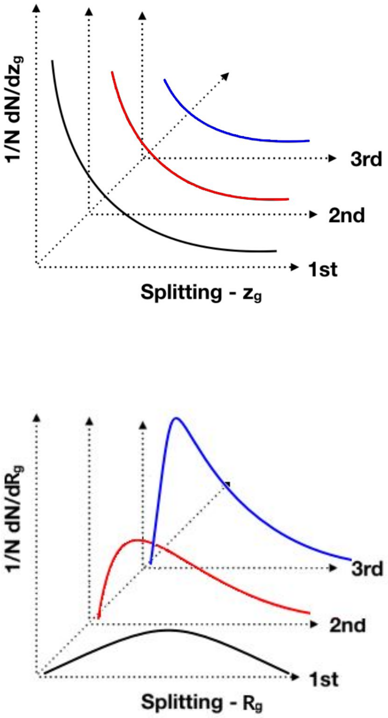
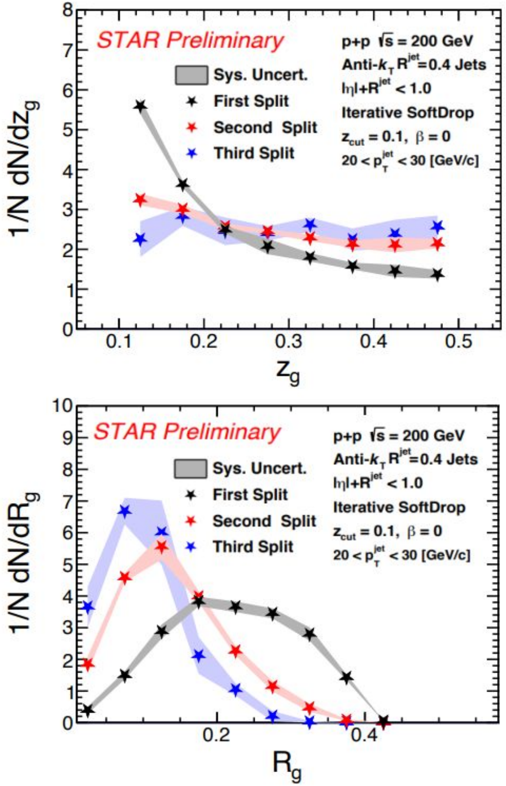
Backup

First, second and third splits



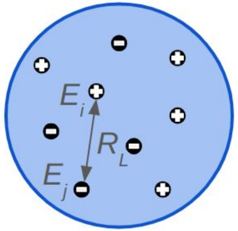


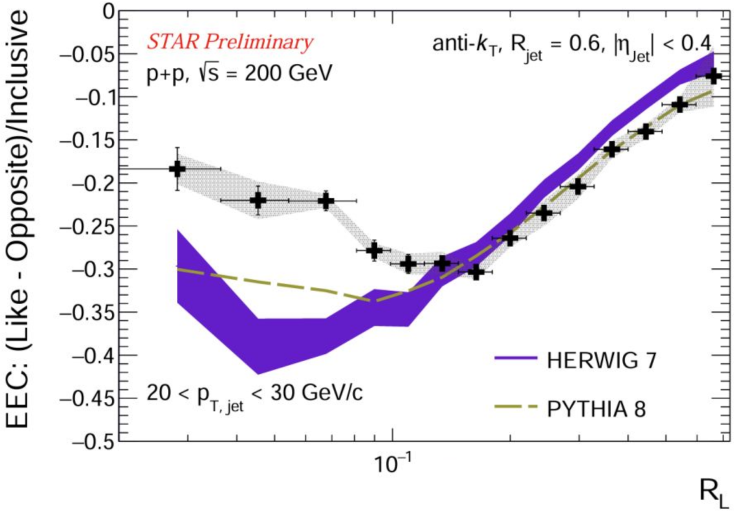


- Going from 1st → 3rd split
  - z_g distribution becomes **flatter**
  - R_g distribution becomes **narrower**
- **Collinear emissions are enhanced when we go from 1st to 3rd split**
- **Strong evolution of splitting kinematics**

EEC: charge-weighted ratio

- Pythia describes perturbative regime better, but neither describe data below transition region
- Implementation of charge dependence/conservation in hadronization mechanism may not fully capture effects





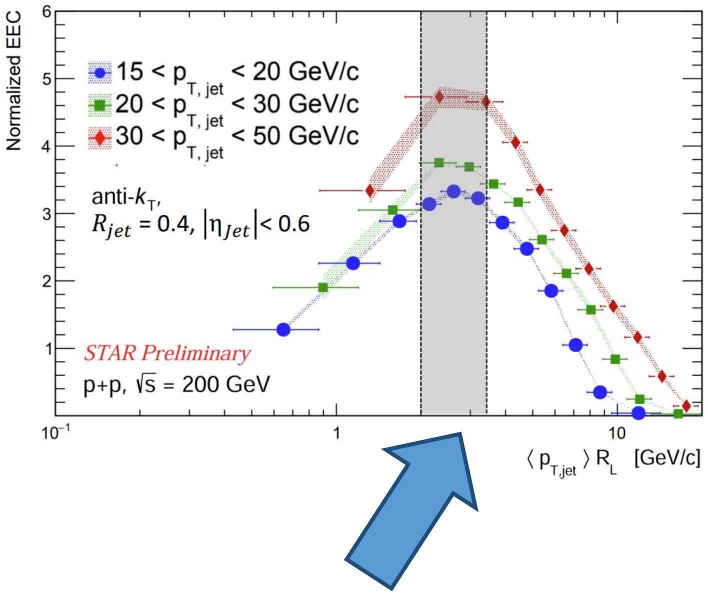
Charge-weighted EEC = $\dfrac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_i Q_i E_j Q_j}{p_{T,Jet}^{\,2}}\right)}{d\,(R_L)}$ = $\mathrm{EEC_{Like}}$ - $\mathrm{EEC_{Opposite}}$

For more details see HP2024 talk

EEC: $p_{T,jet}$-shifted distribution

- Shift corrected results on x axis by average $p_{T,jet}$ in a given bin
- Since location of turnover ∝ $\Lambda_{QCD}/p_{T,\,jet}$, scaled curves will turn over within the same region
- In this case, average momentum is determined via PYTHIA and applied postcorrection

For more details see HP2024 talk



$<p_{T,jet}> \Delta R_{Turnover} \sim 2 - 3.5$ GeV/c