
JET SUBSTRUCTURE MEASUREMENTS ELUCIDATING PARTONIC EVOLUTION IN $p+p$ COLLISIONS AT RHIC

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Abstract

Jets are multiscale objects that connect partons to hadrons, making jet substructure measurements crucial for probing both perturbative and non-perturbative processes in QCD. At STAR, a variety of jet substructure observables, such as SoftDrop groomed splittings and N-Point Energy Correlators (ENC), provide insights into parton evolution and hadronization mechanisms. SoftDrop-groomed observables and ENCs both connect measurement to fundamental QCD at the parton level, allowing for comparisons to first-principles theoretical calculations. Additionally, by also including charge information, as in the charge-weighted ENC, details about the hadronization mechanism can be obtained. In these proceedings, we present preliminary results on measurements of SoftDrop observables and ENCs across different jet momenta and radii in $p+p$ collisions at $\sqrt{s} = 200$ GeV using STAR data.

1 Introduction

Jets are collimated sprays of hadrons resulting from the fragmentation and hadronization of high-energy partons produced in hard QCD scatterings. The internal structure of jets, or jet substructure, provides insight into both perturbative and non-perturbative QCD dynamics. Studies of jet substructure in proton-proton ($p+p$) collisions serve as a baseline for understanding medium-induced modifications in heavy-ion collisions, as well as testing QCD-based models and Monte Carlo generators.

Jet substructure can be probed using several techniques. One common method is jet grooming, which removes soft wide-angle radiation and reveals the hard core of the jet. In particular, the SoftDrop [1] algorithm removes soft radiation based on condition:

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

where $p_{T,i}$ is the transverse momentum of the corresponding subjet, R is the resolution parameter of the jet, and ΔR_{12} is the distance between the two subjets. There are two parameter, β and z_{cut} . The angular exponent β , controlling how the grooming depends on the angle between subjets. A threshold parameter z_{cut} sets the minimal momentum sharing required for a branching to be considered hard and not groomed away. While the CollinearDrop [2] method targets soft radiation by comparing observables under different grooming settings. These tools allow us to investigate the jet shower evolution at different stages.

In addition to grooming-based observables, energy-energy correlators (EECs) [3] offer a complementary approach by studying angular correlations among final-state particles within a jet. These observables enable separation of perturbative and non-perturbative regimes and have the advantage of not relying on jet reclustering procedures. The projected N -point correlators, including the two-point (EEC) and three-point (E3C) versions, provide powerful handles on the multi-prong structure of jets and their scale evolution.

2 Experimental Setup and Data Sample

The analysis is based on $p+p$ collision data at $\sqrt{s} = 200$ GeV collected by the STAR experiment [4] at RHIC in 2012. Jets are reconstructed from charged particles measured in the Time Projection Chamber (TPC) [5] and neutral energy deposits from the Barrel Electromagnetic Calorimeter (BEMC) [6]. Jet reconstruction employs the anti- k_T algorithm [7] with radius parameters $R = 0.4$ and $R = 0.6$.

Charged particles are selected with $0.2 < p_T < 30$ GeV/c, while neutral towers must satisfy $0.2 < E_T < 30$ GeV. Events are triggered using the jet patch (JP) trigger implemented in the BEMC, which requires the uncorrected summed

patch ADC value to exceed $\sum E_T > 7.3$ GeV within one of eighteen partially overlapping regions of size 1.0×1.0 in (η, ϕ) , each defined by a grouping of calorimeter towers. The primary vertex is required to be reconstructed within $|v_z| < 30$ cm.

The SoftDrop grooming procedure is applied using reclustering with the Cambridge/Aachen (C/A) algorithm [8]. The SoftDrop parameters are chosen as $(z_{\text{cut}}, \beta) = (0.1, 0)$. For CollinearDrop, two grooming settings are compared: $(z_{\text{cut},1}, \beta_1) = (0, 0)$ and $(z_{\text{cut},2}, \beta_2) = (0.1, 0)$.

3 Jet Substructure Observables

We investigate several jet substructure observables derived from grooming techniques and constituent-level correlations. One of the fundamental observables is the shared momentum fraction z_g , defined as

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

which characterizes the momentum balance of the first hard splitting in the SoftDrop-declustered jet. Complementary to this, the groomed radius R_g represents the angular distance ΔR_{12} between the two subjets that satisfy the SoftDrop condition, giving insight into the spatial extent of the splitting.

The splitting scale k_T is defined as

$$k_T = z_g \cdot p_{T,\text{jet}} \cdot \sin R_g, \quad (3)$$

which combines the momentum and angular information into a single variable, probing the phase space of the Lund plane.

Jet mass M and groomed jet mass M_g are computed from the four-momentum of the jet constituents before and after grooming, respectively:

$$M = \sqrt{E^2 - |\vec{p}|^2}. \quad (4)$$

Their difference normalized to the original mass defines the CollinearDrop mass ratio:

$$\frac{\Delta M}{M} = \frac{M - M_g}{M}, \quad (5)$$

which quantifies the amount of soft radiation removed by the grooming procedure. The jet mass serves as a sensitive probe of the internal structure of jets, reflecting the virtuality of the initiating parton and capturing both perturbative radiation and non-perturbative effects such as hadronization.

Beyond grooming-based observables, we utilize energy-energy correlators to study the angular correlations of final state charged particles. The two-point projected energy-energy correlator (EEC) is defined as

$$\text{Normalized EEC} = \frac{1}{\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}} \cdot \frac{d \left(\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2} \right)}{d(R_L)} \quad (6)$$

where E_i, E_j are the energies of the two constituents and R_L is the angular separation between them. This correlator captures the structure of jet radiation without requiring a clustering algorithm.

To explore more complex topologies such as three-prong splittings, we include the three-point correlator (E3C), defined as

$$\text{Normalized E3C} = \frac{1}{\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j E_k}{p_{T,\text{jet}}^3}} \cdot \frac{d \left(\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j E_k}{p_{T,\text{jet}}^3} \right)}{d(R_L)} \quad (7)$$

These observables allow for a comprehensive, grooming-independent exploration of radiation patterns and color coherence within jets. They also allow for isolation of perturbative effects.

Altogether, the combination of SoftDrop, CollinearDrop, and energy correlators enables a multifaceted investigation of jet internal dynamics across different kinematic regimes and stages of evolution.

4 Results

Jet substructure observables show distinct correlations that are consistent with parton shower dynamics. In Fig. 1, the z_g distribution steepens with wider R_g which is consistent with the expectations from DGLAP evolution providing the appropriate perturbative description for the first hard splitting in a jet. We observe the same trend in Fig. 2, where the z_g

distribution becomes more flatter with higher split number, which means that the symmetric emission is enhanced when we go from the first to the third split. Both figures also include comparison with different Monte Carlo simulations, namely PYTHIA 6 Perugia tune [9, 10], PYTHIA 8 Monash tune [11, 12], and HERWIG EE4C tune [13, 14]. All of the models describe the trend of the data. The main difference between HERWIG and PYTHIA lies in their parton shower and hadronization models. PYTHIA uses a p_T -ordered parton shower based on the dipole picture and employs the Lund string model for hadronization. In contrast, HERWIG uses an angular-ordered parton shower, which better preserves coherence effects, and applies a cluster hadronization model.

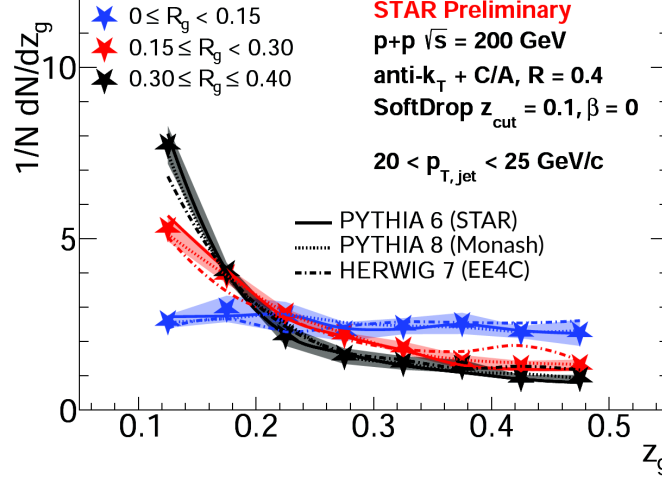


Figure 1: Correlation between z_g and R_g at the first split for jets with $R = 0.4$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV.

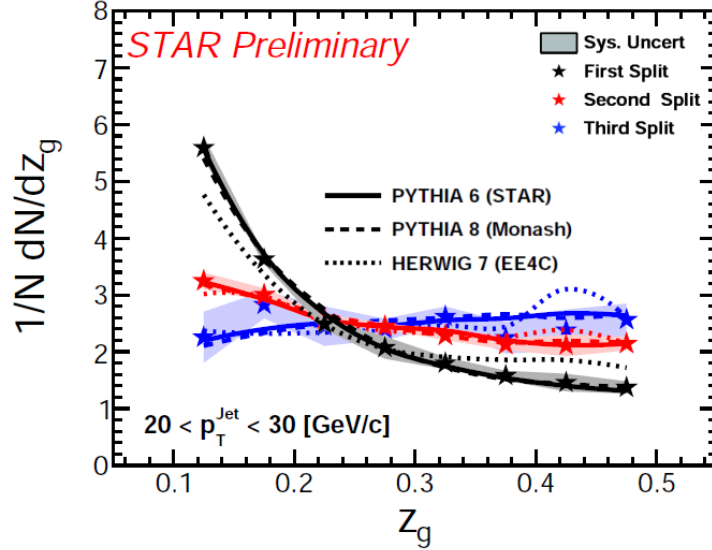


Figure 2: z_g at the different split number for jets with $R = 0.4$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV.

In Fig. 3, $\Delta M/M$ is anti-correlated with R_g , reflecting angular ordering. We observe that for large groomed radii (indicated in yellow), the $\Delta M/M$ distribution peaks at low values, suggesting that little to no soft wide-angle radiation is present in the parton shower. The data have been compared to various Monte Carlo simulations, specifically PYTHIA 8 (Detroit tune) [11, 15] and HERWIG 7 (LHC tune), both of which reproduce the overall trend of the measurement.

Figure 4 presents the distributions of $\log(k_T)$ for three different selections of the groomed radius R_g and two intervals of jet transverse momentum $p_{T,jet}$. The data clearly exhibit a strong sensitivity to variations in R_g , while the dependence

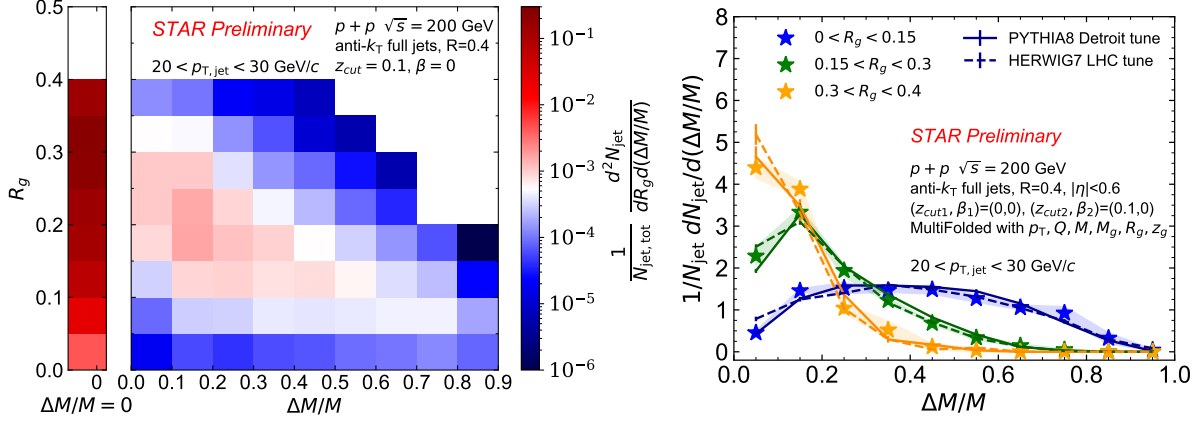


Figure 3: Correlation between $\Delta M/M$ and R_g at the first split (left) and the projection of $\Delta M/M$ for three different R_g selections (right) for jets with $R = 0.4$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV.

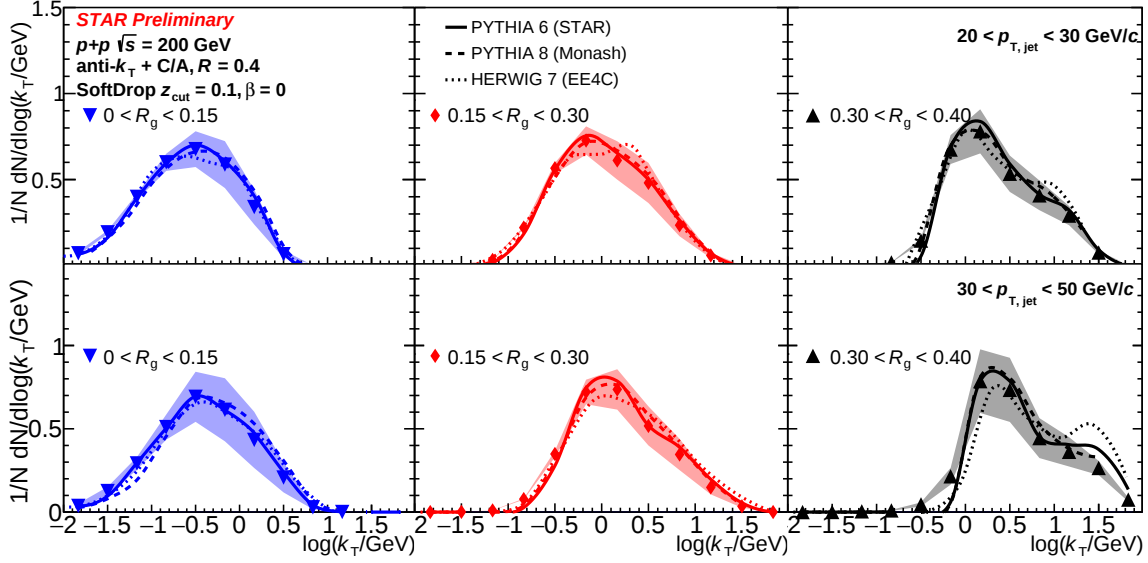


Figure 4: Correlation between $\log(k_T)$ and R_g at the first split for jets with $R = 0.4$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV. Individual panels correspond to different $p_{T,\text{jet}}$ intervals (see legend).

on $p_{T,\text{jet}}$ remains relatively weak. Given that the zero point on the x-axis corresponds to 1 GeV, we observe a transition in the distribution from the non-perturbative regime at smaller R_g values toward the perturbative regime at larger R_g . This behavior is consistent with the scaling of the formation time as $\tau \sim 1/R_g$. Overall, this measurement provides access to a wide kinematic range within the Lund Plane [16].

Energy correlators, EEC and E3C, in Fig. 5 reveal a clear separation of the distribution into two distinct regimes: a non-perturbative region at low momentum transfers and a perturbative region at higher scales. These two domains are divided by a transition region, which marks the shift from non-perturbative to perturbative dynamics in the parton shower. Notably, the location of this transition is not fixed, but it systematically shifts depending on the jet transverse momentum. When the relevant observables are appropriately scaled by the jet momentum, this transition region aligns across different momentum bins, suggesting universality in the evolution of the parton shower across energy scales. The figure on the left shows the two-point energy correlator and the figure on the right shows the three-point energy correlator. The trend is the same for both EEC and E3C. Theoretical predictions and Monte Carlo models (e.g. PYTHIA 8 Detroit tune [17], HERWIG 7) generally describe the trends of the data.

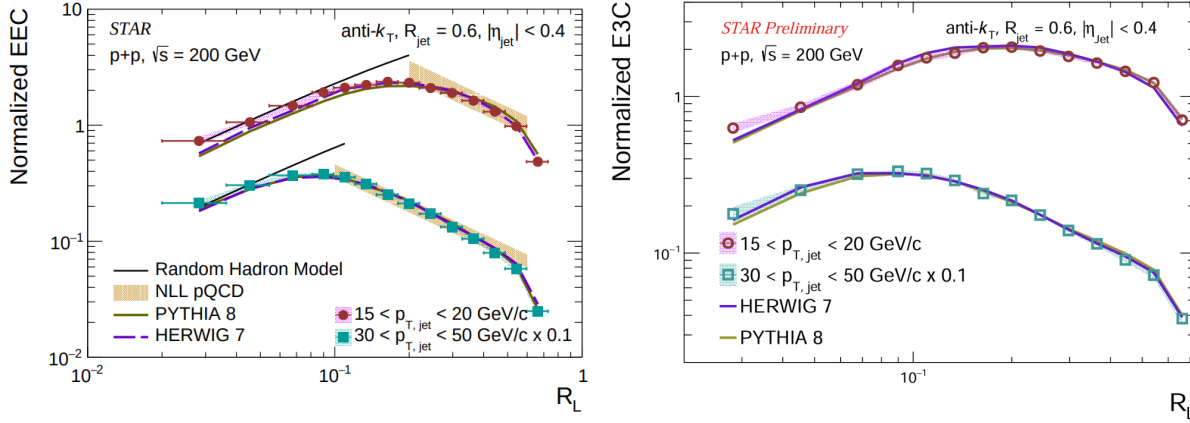


Figure 5: Normalized EEC in (left) and normalized E3C (right) in $15 < p_{T,jet} < 20$ GeV/c and $30 < p_{T,jet} < 50$ GeV/c for jets with $R = 0.6$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV.

5 Conclusion and Outlook

In these proceedings, we present STAR preliminary results on jet substructure in $p+p$ collisions at $\sqrt{s} = 200$ GeV. We presented correlations between jet substructure observables related to the first hard splitting, using the SoftDrop and CollinearDrop techniques, and complemented the analysis with energy-energy correlators. By selecting specific substructure observables and examining their correlations, including angular-dependent correlators such as the EEC, we gain access to a broad kinematic region of the Lund Plane. This approach provides valuable insights into the structure of jet showers, allowing us to disentangle perturbative dynamics from non-perturbative effects at RHIC energies. The results were compared to various Monte Carlo models, all of which qualitatively reproduce the observed trends.

Acknowledgments

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