Exploiting Two- and Three-point Charge-Energy Correlators at STAR as Probes of Jet Evolution

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Abstract. The N-Point Energy correlator (ENC) is a jet substructure observable formed out of the distribution of angular distances between all particle groups of N constituents in a jet weighted by their energy product. This observable approximately separates non-perturbative and perturbative effects into the angular scales at which they dominate, reflecting a uniform distribution of hadrons at small angles and hard partonic splittings at large angles. Additionally, the energy scales at which hadron groups with different charge compositions form are sensitive to the hadronization mechanism, an effect shown in Monte-Carlo to be observable by charge-weighted ENCs.

We will present the first measurement of the projected three-point energy correlator (E3C) at RHIC, measured using data at $\sqrt{s} = 200$ GeV from the STAR experiment, and its ratio to the two-point correlator (EEC). These ENC measurements are shown for several jet transverse momentum ranges in the charge inclusive sample as well as in the charge-selected samples. The quark-rich sample at RHIC compared to the LHC allows for enhancement of charge-odd non-perturbative effects that are suppressed for gluons. This in tandem with the lower jet momentum allows for the observation window of these effects to move to more easily resolvable angular scales.

1 Introduction

In vacuum, hard-scattered partons in high-energy collisions shed their large virtuality via splitting, which can initially be described well by perturbative quantum chromodynamics (pQCD). The splittings both occur at smaller angles and become less energetic as the shower continues, causing non-perturbative effects to dominate. Eventually, the partons in the shower hadronize and the resulting final-state particles are then clustered into objects called jets that contain information about the associated parton shower. The constituents comprising a jet, its substructure, allow for the study of information encoded during the fragmentation and hadronization processes. Many jet observables are defined in such a way as to minimize the impact of non-perturbative effects, in order to allow more direct comparison to theory. However, the non-perturbative regime of jet evolution and the specifics of hadronization are less understood than the perturbative [1], and are therefore of unique interest to study.

The projected N-point energy correlator (ENC) [2] aims to separate non-perturbative effects from perturbative effects across an angular scale, allowing for individual study of both. In the case of the projected correlator, this angular distance is defined as $R_L = \sqrt{\Delta\eta^2 + \Delta\phi^2}$,

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where R_L is the largest distance between any two of the correlated particles. Up to power suppressed terms, this separates the time evolution of the jet into three regimes of R_L: scaling corresponding to the diffusion of non-perturbative hadrons at low angles and behavior corresponding to the perturbative fragmentation of the parton shower at large opening angles, separated by a transition region between them.

The equation for the three-point correlators (E3Cs), is given in equation 1. The energy weighting of each pairing of three particles is defined as the energy product of the involved tracks divided by the cube of jet transverse momentum, $E_i E_j E_k / p^3_{\mathrm{T,jet}}$, with i and j and k representing three tracks within a jet and R_L being the largest angular separation between any two. Correlations may include the same track twice, causing two-point correlations (EECs) to become a subset of three-point.

$$\text{Normalized E3C} = \frac{1}{\sum\limits_{\text{jets}} \sum\limits_{i \neq j \neq k} \left(\frac{E_i E_j E_k}{p^3_{\mathrm{T,jet}}} \right)} \frac{\mathrm{d}\left(\sum\limits_{\text{jets}} \sum\limits_{i \neq j \neq k} \left(\frac{E_i E_j E_k}{p^3_{\mathrm{T,jet}}} \right) \right)}{\mathrm{d}R_L} \tag{1}$$

Due to the angular-ordered nature of jets, moving from larger to smaller R_L can be interpreted as moving from earlier to later times in jet evolution. Although both EECs and E3Cs provide access to the same regimes of jet evolution, differences can be seen between the two distributions in the perturbative regime. In the perturbative regime, the slope of an ENC is proportional to $R_L^{1-\gamma_N}$, where γ_N is the $N+1$ moment of the splitting function [2] and N is 2 for EECs and 3 for E3Cs. Therefore, the ratio (E3C/EEC) will isolate the dependence on the splitting function and create an observable that is directly dependent on the strong coupling constant, α_s. The running of this coupling as a function of interaction energy can be seen in the changing slope of this ratio with jet transverse momentum. The first experimental measurement of the three-point energy correlator and its ratio over the EEC at RHIC is presented for several selections on jet transverse momentum (p_{T}).

Hadronization effects are further probed by measuring the ENC in terms of hadron groupings that have specific arrangements of electric charge, in order to inform how charge correlations are carried through the hadronization process [3, 4]. For the two-point energy correlator, this involves looking at pairs that have like or opposite electric charge. For the three-point correlator, positive or negative charge products are considered. Comparisons with leading Monte-Carlo models with different hadronization mechanisms can attempt to identify the cause of these effects. Comparisons with HERWIG 7 [5], which utilizes cluster hadronization, and PYTHIA 8 [6], which uses string-breaking hadronization, are presented. The first measurement of both charge-selected EECs as well as charge-selected E3Cs are presented in these proceedings.

2 Experimental Details

The data used in this analysis were collected by STAR in 2012, from p+p collisions at the center-of-mass energy $\sqrt{s} = 200$ GeV, which delivered a total integrated luminosity of 36 pb^{-1}. The STAR Barrel Electromagnetic Calorimeter (BEMC) is used to measure neutral energy deposits and inform the trigger used to create a jet-enriched data sample. This trigger requires an energy deposit of at least 7.3 GeV in one of 18 possible BEMC patches 1 in $\eta - \phi$ space. Additionally, the STAR Time Projection Chamber (TPC) is used to find charged tracks to the high angular precision required for this analysis. Charged tracks from the TPC are matched to the BEMC, subtracting 100 % of their p_T from the tower they are matched to, discarding any towers with negative resulting energy.

Corrections for detector effects are informed using both a particle-level sample, p+p events generated at $\sqrt{s}$ = 200 GeV via the PYTHIA 6 STAR-Tuned event generator [7], and a detector-level sample. The detector-level sample is created by propagating the particle-level events through a GEANT-3 [8] simulation of the STAR detector and embedding them within zero-bias events collected by randomly triggering during beam crossings during p+p running. Matching is performed between jets found independently in each sample, considering the jets to be matched if they are within one jet radius of each other in η-ϕ space. If multiple candidates for matching are available at the detector level, the one closer in momentum to the particle-level jet is taken. Tracks within the jets are then matched on a similar basis, with $\sqrt{(\Delta\eta_{\text{track}})^2 + (\Delta\phi_{\text{track}})^2} \leq 0.01$. Correlations are considered to be missed or fake if any of the constituents involved in the correlation are missed or fake, respectively. The full sample of missed, fake and matched correlations are then used to build a response matrix for the purposes of Bayesian Iterative Unfolding[9]. The RooUnfold software package [10] is used to create a multi-dimensional response matrix mapping particle-level jets to detector-level jets. Correction is then performed via Bayesian unfolding [1] in R_L, $p_{\text{T,jet}}$ and energy weight simultaneously. The energy weight used in correction is $E_iE_j/p^2_{\text{T,jet}}$ in the case of the two-point correlators and $E_iE_jE_j/p^3_{\text{T,jet}}$ in the three-point case.

Several sources of systematic uncertainty are estimated by varying parameters used in the simulation of the STAR detector. This includes varying the BEMC tower energy according to its uncertainty of 3.8% and the tracking efficiency of the TPC by its uncertainty of 4%. The hadronic correction, the subtraction of charged tracks matched to the BEMC, is varied between 100% and 50% of the matched track p_{T}. The uncertainty associated with the unfolding process itself is estimated by varying the number of unfolding iterations and the prior, the latter of which is achieved by reweighting the detector-level sample according to HERWIG.

3 Results

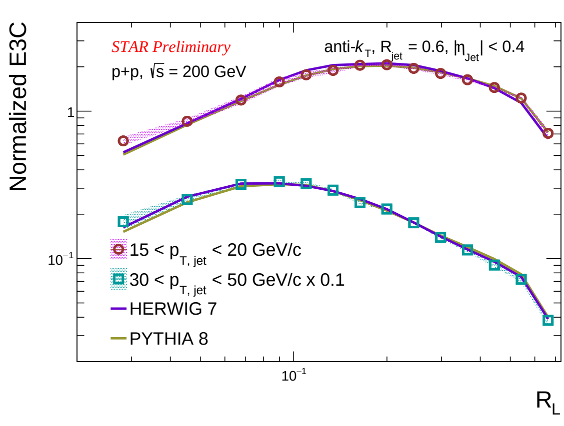

Figure 1. Corrected distributions of the normalized E3C differential in R_L for R_{jet} = 0.6, with jet transverse momentum selections $15 < p_{\text{T,jet}} < 20$ GeV/c and $30 < p_{\text{T,jet}} < 50$ GeV/c (scaled for comparison). Monte-Carlo predictions are presented alongside data [5, 11].

The E3C for several momentum selections is shown in Fig. 1, which recovers the expected behavior of the transition regime shifting to smaller angles at higher jet energies. The

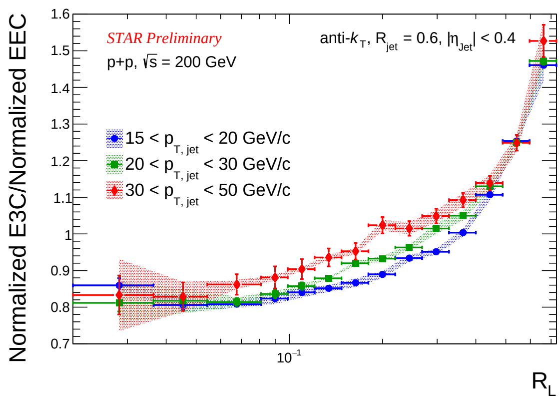

Figure 2. Ratios of the normalized E3C over the normalized EEC within jets, differential in R_L at $R_{\mathrm{jet}} = 0.6$ for several $p_{\mathrm{T,jet}}$ selections.

E3C is also described well by HERWIG 7 and PYTHIA 8 Detroit Tune [11]. In the perturbative regime, at angles larger than the peak, the difference in the slopes between the EEC and E3C is purely dependent on the different anomalous dimension governing the correlator. The ratio, therefore, cancels out non-perturbative considerations and creates a quantity that is sensitive to these dimensions, and by extension α_s. This ratio is shown for three momentum ranges in Fig. 2. The change in the slope of this ratio, is dependent on the running of the coupling constant α_s, with the smaller slope at larger momenta consistent with the decrease in α_s

The charge-selected EEC in the left panel of Fig. 3 shows the EEC for both like-charge and opposite-charge correlations. A systematic underprediction by Monte-Carlo models of the magnitude of like-charge correlations in the perturbative regime is observed. This is likely correlated to the prediction of a transition region at larger angles for like-charge correlations relative to opposite-charge correlations, which is not supported by the data. Another way to represent the charge-selected EEC is the charge-subtracted ratio, shown in the right panel of Fig. 3, which is the like-charge distribution subtracted by the opposite-charge distribution divided by the inclusive distribution. This describes the charge correlation present in the jet on a scale from 0 to 1, with a value of 0 expected for an infinite thermal bath with equal probability to form a particle with either electric charge. The charge-subtracted ratio shows that the fraction of opposite-charge correlations increases as the correlations move to smaller angles within the perturbative regime, but that this behavior reverses past the transition regime. This behavior is captured by neither Monte-Carlo model tested, which provides evidence of an aspect of charge correlation carried through hadronization that is not currently captured by leading hadronization models.

Many aspects of the ENC, such as the location of the transition regime, are expected to change with initiator flavor [12]. As the charge dependence of the E3C charge-subtracted ratio is charge-odd, a constant value of 0 is expected for charge-neutral initiators, such as gluons, while quarks have a non-zero signal expected to be inverse to the sign of their charge in the perturbative regime. It can be seen in the left panel of Fig. 5 that the relative contribution of the charge samples are on the same order of magnitude for the E3C. Differences in

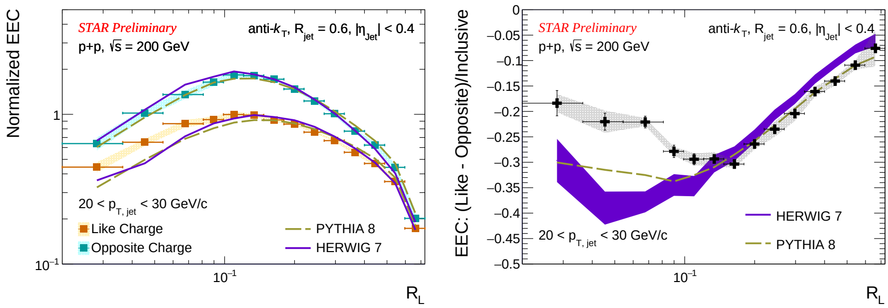

Figure 3. Corrected distributions of the charge-selected EEC compared with the inclusive case (top panel) and charged ratio (bottom panel) for $R_{\text{jet}} = 0.6$ with a jet transverse momentum selection of $20 < p_{\text{T,jet}} < 30$ GeV/c. Comparisons with the PYTHIA 8 Detroit Tune [11] and the default tune of HERWIG 7 are given [5].

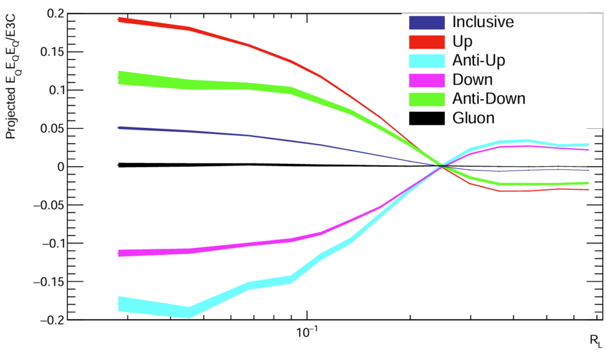

Figure 4. The Charged E3C ratio determied via PYTHIA 8: Detroit Tune for $R_{\text{jet}} = 0.6$ with a jet transverse momentum selection of $20 < p_{\text{T,jet}} < 30$ GeV/c for several identified jet initiator flavors

the samples can be better seen in the charge-subtracted ratio. The behavior of the this ratio for different initiator flavors as determined by PYTHIA 8 Detroit Tune is shown in Fig. 4.

Therefore, it is the abundant fraction of quark initiated jets, specifically valence quarks, present at STAR kinematics that allows for a nonzero measurement of the charge-subtracted E3C ratio, as sea quarks would be equally likely to be positive and negative. The observed ratio shown in the right panel of Fig. 5 is consistent with expectations for a sample dominated with up quarks in the perturbative regime, with a small negative value, however, this crosses over into a much larger positive signal at small angles. This behavior is supported by expectations from Monte-Carlo models, but the magnitude of the effect is not fully captured. The three-point charge correlations are described more accurately by PYTHIA than the two-point correlators. This indicates that the difference in the charge-selected EECs is not solely caused by a difference in average initiator flavor, but rather some other effect uniquely captured by two-point charge correlations.

4 Conclusions

The first measurement of the E3C and its ratio over the EEC at RHIC is presented, recovering the expected dependence on α_s. Additionally, a new method for extending the sensitivity to hadronization effects, the charge-selected ENC, is presented. Tension is observed in leading Monte-Carlo models attempting to describe two-point like-charge correlations, pointing towards an aspect in which current models of hadronization may be improved.

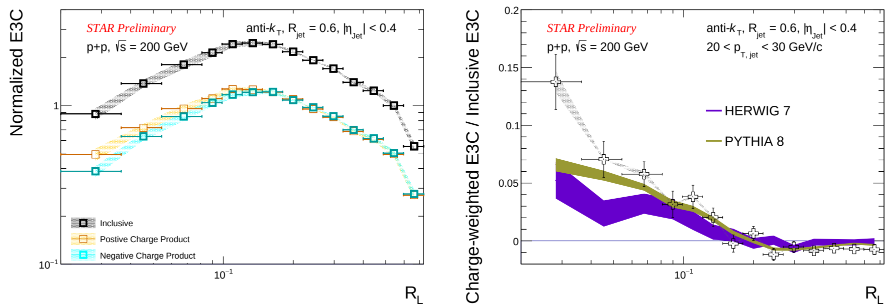

Figure 5. Corrected distributions of the charge-selected E3C compared with the inclusive case (top panel) and charged ratio (bottom panel) for $R_{\mathrm{jet}} = 0.6$ with a jet transverse momentum selection of $20 < p_{\mathrm{T,jet}} < 30$ GeV/c. Comparisons with the PYTHIA 8 Detroit Tune [11] and the default tune of HERWIG 7 are given [5].

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