Probing hadronization with the charge correlator ratio in p+p, Ru+Ru and Zr+Zr collisions at STAR

Youqi Song[1,*] for the STAR Collaboration

[1]Wright Laboratory, Yale University

Abstract. The parton-to-hadron transition, known as hadronization, is dominated by non-perturbative Quantum Chromodynamics (QCD) effects and thus challenging to study from first-principle calculations. On the other hand, experimental studies of observables sensitive to hadronization could provide valuable input. The charge correlator ratio r_c studies the charge correlation between the leading two hadrons in jets and is sensitive to hadronization effects. With data taken at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV at STAR, we measure r_c in p+p collisions to probe for string-like fragmentation, and in Ru+Ru and Zr+Zr collisions to probe for potential modification to hadronization in the Quark-Gluon Plasma (QGP). These measurements, compared with various model predictions, are expected to distinguish between phenomenological model descriptions for hadronization in vacuum, and provide insight into jet-medium interaction in the QGP.

1 Introduction

In high-energy particle collisions, jets can be created in hard scattering, and encode information from the subsequent processes of the parton shower and hadronization. Since hadronization is dominated by non-perturbative effects, it is challenging to understand from first-principle QCD calculations, thereby highlighting the crucial role of experimental inputs. Investigation of the internal structure of jets, known as jet substructure, can shed light on the dynamics of jet evolution.

One novel jet substructure observable, the charge correlator ratio r_c, is sensitive to hadronization effects [1], [2]. For leading and subleading hadrons in jets h_1 and h_2, r_c quantifies the tendency of production of h_2 or its anti-particle $\bar{h}_2$, in the presence of h_1 production. It is defined as

$$r_c(x) = \frac{d\sigma_{h_1 h_2}/dx - d\sigma_{h_1 \bar{h}_2}/dx}{d\sigma_{h_1 h_2}/dx + d\sigma_{h_1 \bar{h}_2}/dx}, \tag{1}$$

where x is a generic kinematic variable such as the jet p_{T}. Specifically, for inclusive charged hadrons, $h_1 h_2$ denotes that the leading and subleading hadrons in jets carry the same electric charge, while $h_1 \bar{h}_2$ denotes that they carry opposite electric charges. In the extreme limit where string-like fragmentation is the only mechanism for hadron production, we expect a perfect charge correlation between a hadron and an anti-hadron, $r_c \to -1$; in the other limit where the environment for hadron production is an infinite charge bath with no net charge, we expect no charge correlation between pairs, $r_c \to 0$. We anticipate the measurement of r_c to be between -1 and 0, with its exact value sensitive to the fragmentation mechanism.

*e-mail: youqi.song@yale.edu

Jets produced in heavy ion collisions interact with the soft partons in the QGP and lose energy. Uncovering the potential modification of jet substructure due to the presence of the QGP is important for understanding of jet-medium interaction. By measuring r_c in heavy ion collisions, we probe for potential modification to hadronization in the core of the jet [3].

In these proceedings, we present measurements of the charge correlator ratio r_c in jets in p+p collisions at $\sqrt{s}$ = 200 GeV at STAR, to probe for string-like fragmentation. We compare the results with predictions from Monte Carlo event generators. In addition, we present ongoing studies on the first measurement of r_c in heavy-ion collisions, in *Ru*+*Ru* and *Zr*+*Zr* collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV at STAR.

2 r_c in p+p collisions

2.1 Analysis details

The STAR experiment [4] recorded data from $\sqrt{s}$ = 200 GeV p+p collisions during the 2012 RHIC run. Tracks are reconstructed from the Time Projection Chamber (TPC), and neutral energy deposits are measured from the Barrel Electro-Magnetic Calorimeter (BEMC) towers. Events are required to have primary vertices within ±30 cm from the center of the detector along the beam axis, and to pass the jet patch trigger which requires a minimum transverse energy $E_{\mathrm{T}} > 7.3$ GeV deposited in a 1×1 patch in $\eta \times \phi$ in the BEMC. We reconstruct jets from TPC tracks ($0.2 < p_{\mathrm{T}} < 30$ GeV/c) and BEMC towers ($0.2 < E_{\mathrm{T}} < 30$ GeV) using the anti-k_{T} sequential recombination clustering algorithm [5] with a resolution parameter of $R = 0.4$. We apply the selections of $p_{\mathrm{T}} > 15$ GeV/c, $|\eta| < 0.6$, transverse energy fraction of all neutral components < 0.9, and number of charged constituents $N_{ch} \geq 2$ on reconstructed jets.

Ref. [1] proposes to only include jets whose leading and subleading particles are charged for the measurement of r_c. That is, if the leading and/or subleading particle of a truth-level jet is a π^0, for example, then the jet should not be included for the measurement of r_c. However, since each of the decay products of the π^0 (most likely γ) measured shares only a fraction of the parent p_{T}, at the detector level, the jet could still be misidentified as having leading and subleading charged particles. Due to this complication, we use a definition slightly different from that in [1] for our measurement and Monte Carlo simulations; we measure the charge correlation between the leading and subleading track pairs in jets, regardless of whether there is any neutral constituent with a higher energy.

We fully correct for detector effects through a two-step procedure. First, we carry out "mistagged subtraction" on r_c to account for possible misidentification of tracks that are not leading or subleading, due to tracking inefficiency. Then, we apply a bin-by-bin jet p_{T} correction to account for jet energy scale.

2.2 Results

Figure 1 shows the r_c as a function of jet p_{T}, for the fully corrected STAR data in black solid lines, with comparison with predictions from HERWIG7 [6], PYTHIA8 [7] Detroit tune [8] and PYTHIA6 [9] STAR tune [10], in purple, gold and green lines, respectively. As expected, the r_c values lie below 0, which is the limit of a charge bath.

Figure 1 also shows in black dashed lines the effective r_c as a function of jet p_{T} for random track pairs in jets in data. We randomly sample without replacement two tracks from a jet, and their charge information is used for calculation of the effective r_c. The effective r_c values for the random tracks are negative (around -0.2). This shows that there is already some effect of local charge conservation between the random tracks, and is consistent with the result that the average and peak values of jet charge are around 0 for jets measured in similar kinematics at STAR [11].

Compared with the effective r_c for random track pairs, the r_c values are more negative (around -0.3) with the requirement for the tracks to be leading and subleading in jets, highlighting the additional correlation from fragmentation. The r_c values from both the STAR data and event generator predictions exhibit no jet p_{T} dependence in $20 < p_{\mathrm{T}} < 40$ GeV/c. Given that PYTHIA uses the Lund string fragmentation model while HERWIG uses the cluster hadronization model, it is interesting that both event generators underpredict r_c in data to a similar extent.

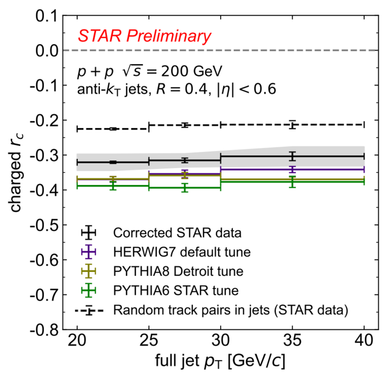

Figure 1. r_c as a function of jet p_{T} in p+p collisions, for the fully corrected STAR data (black solid), with comparison with predictions from HERWIG7 [6] (purple), PYTHIA8 [7] Detroit tune [8] (gold) and PYTHIA6 [9] STAR tune [10] (green). Effective r_c for random track pairs in jets in STAR data is shown in black dashed lines.

We further investigate if effects other than fragmentation could influence the value of r_c. Using events generated with HERWIG7 and PYTHIA8 (default tune), we cluster jets with the anti-k_{T} algorithm and a radius of $R = 0.4$, with selections of $p_{\mathrm{T}} > 20$ GeV/c and $|\eta| < 0.6$, and study the origin of π^+ if they are the leading tracks in jets. We find that about 50% of the π^+ come from quarks or diquarks in PYTHIA, while only about 30% of them come from clusters in HERWIG. Since in the event generator simulations we have disabled hadronic decays mediated by the electroweak forces, the rest of leading π^+ in jets come from resonance decays mediated by the strong force. The effect of resonance decays reduces r_c's sensitivity to fragmentation, although in sign-preserving decays such as $\rho^+ \to \pi^+\pi^0$, the π^+ maintains the charge information from its parent ρ^+. It is possible that this discrepancy between HERWIG and PYTHIA in fragmentation vs. resonance decay fractions arises from their different hadronization mechanisms, so additional measurements of resonance production in p+p collisions might also help distinguish hadronization models.

3 r_c in Ru+Ru and Zr+Zr collisions

The STAR experiment recorded data from $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV Ru+Ru and Zr+Zr (isobar) collisions during the 2018 RHIC run. Tracks and neutral energy deposits are measured from the TPC and BEMC, respectively. Events are required to have primary vertices within $(-35, 25)$ cm along the beam axis from the center of the detector, and within 2 cm radially away from the beam axis. In addition, to reject pileup events, the location of the primary vertex along the beam axis reconstructed from the TPC is required to be within 5 cm from that reconstructed from the Vertex Position Detector. The charged particle multiplicity in $|\eta| < 0.5$ measured from the TPC is used for centrality determination, as detailed in [12].

To understand the background present in isobar collision events, we also reconstruct jets using the k_T [13] clustering algorithm with $R = 0.4$ and $|\eta| < 0.6$. After excluding the hardest two jets in each event, we calculate the background momentum density $\rho = \text{median}(p_{Ti}/A_i)$ with the remaining jets, where A_i denotes the jet area of jet i. Figure 2 shows the ρ distribution for the four most central centralities, 0 – 5% in red, 5 – 10% in green, 10 – 15% in orange, and 15 – 20% in blue. We find that the ρ distribution in the 0 – 5% central events has a mean of about 40 GeV/c and a width of about 4 GeV/c, so for an anti-k_T jet with an area of 0.5, the background fluctuation underlying the jet, $\sigma(\rho A)$, is expected to be less than 2 GeV/c. To suppress combinatorial jets, we therefore require a background subtracted jet p_T to be more than 10 times of this fluctuation, $p_T - \rho A > 20$ GeV/c.

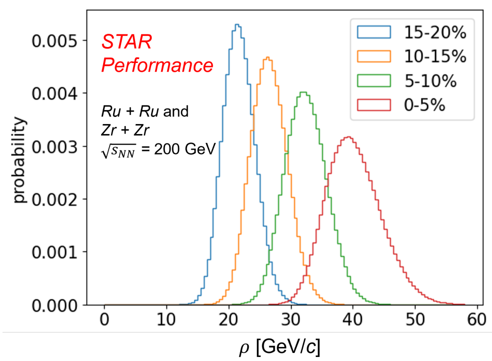

Figure 2. ρ distribution for isobar collision events, with centralities of 0 – 5% (red), 5 – 10% (green), 10 – 15% (orange), and 15 – 20% (blue).

Next, to understand how jets and their two leading tracks are affected by the background, we create a toy sample by embedding PYTHIA jets into isobar data. We generate events of p+p collisions at $\sqrt{s} = 200$ GeV with PYTHIA8 Detroit tune, and for each event with at least one jet that passes the jet selection in Section 2.1, we embed all the jet constituents into an event from 0 – 20% central isobar collisions. Then with the embedded events, we re-cluster jets using the anti-k_T clustering algorithm with $R = 0.4$ and $|\eta| < 0.6$, with the same track and tower selection as detailed in Section 2.1 and jet $p_T - \rho A > 20$ GeV/c, where ρ is calculated with the embedded events as well. Among all these jets, we find that 21% of the jets (1) contain a leading or subleading track from the isobar data; and (2) are not "combinatorial"[1]. This significant fraction suggests that even though the leading and subleading tracks in jets are more robust against background contamination than inclusive hadrons [3], to measure r_c in central isobar collisions, we still need to account for jets arising from fragmentation while containing background particles.

To account for all sources of background contamination, we use

$$r_c(\text{raw data}) = P(\text{comb}) \cdot r_c(\text{comb}) + P(\text{BB}) \cdot r_c(\text{BB}) + P(\text{SB}) \cdot r_c(\text{SB}) + P(\text{SS}) \cdot r_c(\text{SS}), \quad (2)$$

where P denotes probability, "comb" is short for combinatorial jet, "BB" stands for "Background-Background", meaning that the jet is not combinatorial but both leading tracks

[1] The "combinatorial" jets in the toy sample may be real jets from the central isobar collisions, but we call them "combinatorial" in the sense that they are not produced in PYTHIA, so they are not "signal" in the toy model. They are identified with an axis more than 0.4 away from the corresponding PYTHIA jet axis.

in jets are background particles, "SB" stands for "Signal-Background", meaning that one of the leading tracks in jets is a background particle, and "SS" stands for "Signal-Signal", meaning that both leading tracks in jets are from fragmentation.

We verify Equation 2 with the toy embedding sample, treating particles from PYTHIA jets as signal and particles from the isobar data as background. Figure 3 shows the values of r_c from various contributions. We determine r_c(raw data)[2], r_c(BB)[3] and P factors from the embedding, and estimate in a data-driven way with the 0 – 20% central events r_c(comb) and r_c(SB)[4]. Then we calculate r_c(SS) using Equation 2. The r_c(SS) values obtained this way, shown in pink crosses, agree with those obtained directly using the PYTHIA information from the embedding, shown in blue squares. This agreement demonstrates that we achieve closure with the background subtraction technique explained above.

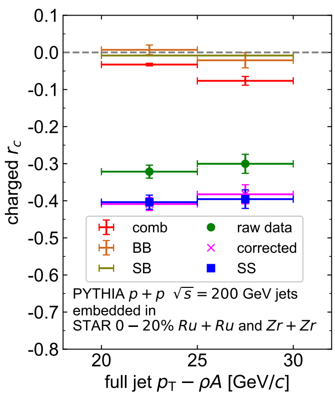

Figure 3. r_c from various contributions for two selections of background subtracted jet p_T.

On the other hand, when we move to data analysis with the actual isobar data, while we can use the decomposition of different sources of background as given by Equation 2, to find the P and r_c factors for each term, we need to use the mixed-event technique and background correlation estimation with perpendicular cones. For example, mixed events, constructed by properly sampling particles from different events to ensure no physical correlation, can be used to estimate r_c(comb); perpendicular cones, which are clusters of particles about $\Delta\phi = \pi/2$ away from jets, can be used to estimate r_c(BB).

4 Conclusions

In summary, to probe for string-like fragmentation, we measure r_c as a function of jet p_T in $\sqrt{s} = 200$ GeV $p+p$ collisions at STAR. Compared with predictions from event generators, the fully corrected data show a weaker correlation between the leading and subleading tracks in jets. The significant difference between HERWIG and PYTHIA in their relative fractions

[2] r_c(raw data) is estimated using the embedding only for this toy study, and will be measured with the actual data in the future.

[3] To estimate r_c(BB), we consider all jets that pass our selections from the embedding, and find the r_c using the leading and subleading background track charge information, even if the jet contains a signal track with a higher p_T.

[4] We estimate r_c(SB) using data instead of the embedding due to limited statistics. To estimate r_c(SB), we cluster jets without background subtraction and exclude the two leading jets. We find r_c(SB) to be independent of jet p_T. With jets from embedding, we have confirmed that r_c(BB) $\approx r_c$(SB), although with large uncertainties.

of fragmentation vs. resonance decays might explain why their predictions for r_c are similar despite different approaches to fragmentation.

In addition, we present progress towards the first measurement of r_c in heavy ion collisions, to probe for potential modification to hadronization due to the presence of the QGP. With data recorded by STAR from $\sqrt{s_{\mathrm{NN}}} = 200$ GeV $Ru+Ru$ and $Zr+Zr$ collisions, we study jets produced in 0 – 20% centrality events, discuss sources of background contributions, and demonstrate closure with our background subtraction technique.

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