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Recent high-p_T results from STAR

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Abstract We present selected recent results of multi-hadron correlation measurements in azimuth and pseudorapidity at intermediate and high p_T in Au + Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, from the STAR experiment at RHIC. At intermediate p_T, measurements are presented that attempt to determine the origin of the associated near-side (small $\Delta\phi$) yield at large pseudo-rapidity difference $\Delta\eta$ that is found to be present in heavy ion collisions. In addition, results are reported on new multi-hadron correlation measures at high-p_T that use di-hadron triggers and multi-hadron cluster triggers with the goal to constrain the underlying jet kinematics better than in the existing measurements of inclusive spectra and di-hadron correlations.

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1 Introduction

The goal of research with high-energy nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) is to study bulk matter systems where the strong nuclear force as described by Quantum Chromo Dynamics (QCD) is the dominant interaction. In particular, it is expected that there is a phase transition of bulk QCD matter to a deconfined state at high temperature.

In heavy ion collisions, products of initial state hard scatterings, such as high-p_T hadrons, photons and heavy mesons, can be used to probe the soft matter generated in the collision. Initial state production of high-p_T partons is relatively unaffected by the presence of the soft medium, but the partons lose energy when traversing the medium, dominantly due to gluon radiation. The goal of high-p_T measurements is to study these interactions and to use them to measure the density and temperature of the soft matter.

It has also been found at RHIC that at intermediate $p_T \approx$ 2–6 GeV/c, the baryon/meson ratio is much larger in heavy ion collisions than in proton-proton collisions [1, 2]. This could imply that soft production mechanisms, e.g. hadron formation by coalescence of quarks from thermal matter [3–5], have a significant contribution to baryon (and meson) production up to $p_T \sim 6$ GeV/c.

The underlying (di-)jet structure for particle production at high-p_T can be probed using azimuthal di-hadron correlations, which measure the associated particle distribution in azimuth with respect to some higher p_T 'trigger' particle [6]. This technique has been applied with trigger hadrons from low to high p_T. In the following, we will first discuss di-hadron measurements at intermediate p_T, where the soft matter from the medium seems to contribute to correlation structures. The last part of these proceedings deals with high-p_T measurements, where jet-quenching followed by jet-fragmentation in the vacuum seems to dominate.

2 Intermediate p_T: near-side ridge

One of the striking results in di-hadron correlations at intermediate p_T at RHIC is that near-side (small $\Delta\phi$) associated yield is observed at large $\Delta\eta$ with respect to the trigger in heavy ion collisions. This is illustrated in Fig. 1 which shows associated particle distributions in pseudo-rapidity difference $\Delta\eta$ and azimuthal angle difference $\Delta\phi$, with respect to the trigger hadron direction for associated particles with $2\ \mathrm{GeV}/c < p_T^{\mathrm{assoc}} < p_T^{\mathrm{trig}}$. The upper panel shows the results for trigger hadrons $3 < p_T^{\mathrm{trig}} < 4$ GeV/c and the lower panel for $4 < p_T^{\mathrm{trig}} < 6$ GeV/c. The associated particle distribution shows a clear peak at $(\Delta\eta, \Delta\phi) \approx (0, 0)$ as expected from jet fragmentation. Additional associated yield is seen at large $\Delta\eta \gtrsim 1$, which is unique to heavy ion collisions. Within the experimental acceptance, the additional yield is approximately independent of $\Delta\eta$, and therefore referred to as the *ridge*. For higher p_T^{trig} (lower panel of Fig. 1), the

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ridge yield is less prominent, because the yield in the jet-like peak increases with p_T^{trig}. Quantitative analysis of the yields shows that ridge yield is independent of p_T^{trig} within the statistical and systematic uncertainties [7].

Various production mechanisms for the ridge have been proposed in the literature. Here we would like to classify these mechanisms into two broad categories, namely 'jet-like' and 'bulk-like'. Jet-like production mechanisms are based on the idea that the ridge is formed mainly from jet fragments, which couple to the longitudinal flow [8–10]. Bulk-like production mechanisms, on the other hand, start from the assumption that the passage of the jet through the longitudinally extended bulk matter locally increases the yield, for example by increasing the mean-p_T through collisions [11], or heating of the medium [12]. A variant on these bulk-like mechanisms is that the enhancement does not need to be due to interactions between the jet and the medium, but could be the result of radial flow combined with trigger bias [13, 14].

Here, we would like to highlight two recent results from STAR that may shed further light on the origin of the ridge.

Figure 2 shows the p/π ratio in the ridge and jet-like peak as a function of p_T^{assoc} for $4 < p_T^{\mathrm{trig}} < 6$ GeV/c. The inclusive p/π ratios are also shown for comparison. Clearly, the p/π ratio in the ridge is similar to the inclusive p/π ratio in Au + Au events, which is much larger than in p + p events. The p/π ratio in the jet-like peak is similar to the inclusive ratio in p + p events. These results clearly suggest that the ridge is formed from bulk matter and not from jet fragments.

The second result that addresses the origin of the ridge yield is the analysis of three-particle $\Delta\eta$–$\Delta\eta$ correlations. Figure 3 shows the distribution of associated hadron pairs as a function of $\Delta\eta_1$ and $\Delta\eta_2$, the pseudo-rapidity difference between the trigger hadron and the first and second associated hadron, for particles with $1 < p_T^{\mathrm{assoc}} < 3$ GeV/c and $3 < p_T^{\mathrm{trig}} < 10$ GeV/c. Combinatorial backgrounds have been subtracted (for details on the procedure, see [15]). This measurement is sensitive to the event-by-event substructure of the ridge: an excess along the diagonal would indicate that ridge particles tend to be close together in η, which would be expected if the ridge hadrons are fragmentation products of radiated gluons that are carried along with the longitudinal flow. No such excess is observed, indicating that (within the statistical reach of the analysis) the particles in the ridge are distributed evenly in η in every event. Another remarkable feature in the figure is the absence of a horizontal and vertical band (i.e. $\Delta\eta_1 \approx 0$ or $\Delta\eta_2 \approx 0$), which should arise from events where one associated particle is inside the jet-like peak and the other is part of the ridge. Further work is

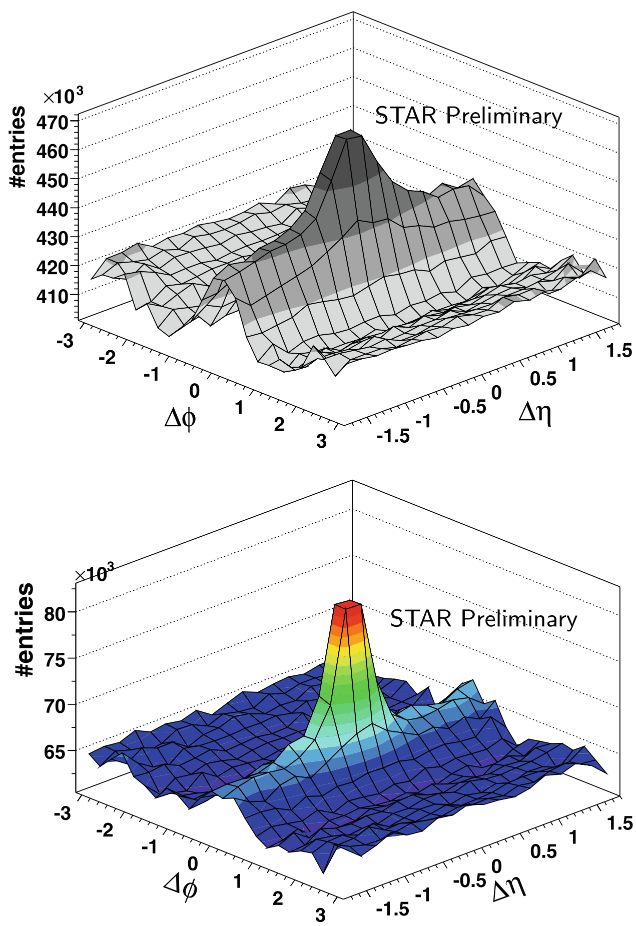

Fig. 1 (Color online) Preliminary associated particle distributions in $\Delta\eta$ and $\Delta\phi$ with respect to the trigger hadron for associated particles with 2 GeV/$c < p_T^{\mathrm{assoc}} < p_T^{\mathrm{trig}}$ in 0–12% central Au + Au collisions. Two different trigger p_T selections are shown: $3 < p_T^{\mathrm{trig}} < 4$ GeV/c (*upper panel*) and $4 < p_T^{\mathrm{trig}} < 6$ GeV/c (*lower panel*). No background was subtracted

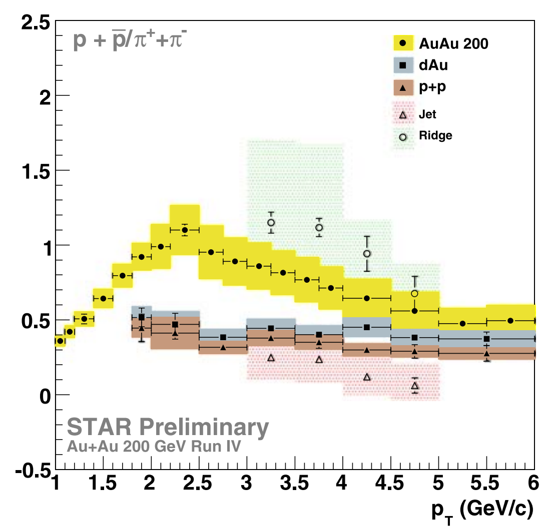

Fig. 2 (Color online) Preliminary p/π ratio in the ridge and jet-like peak and a function of p_T^{assoc} for $4 < p_T^{\mathrm{trig}} < 6$ GeV/c in 0–12% central Au + Au collisions (*open symbols*). For comparison, inclusive p/π ratios are shown with *solid symbols*

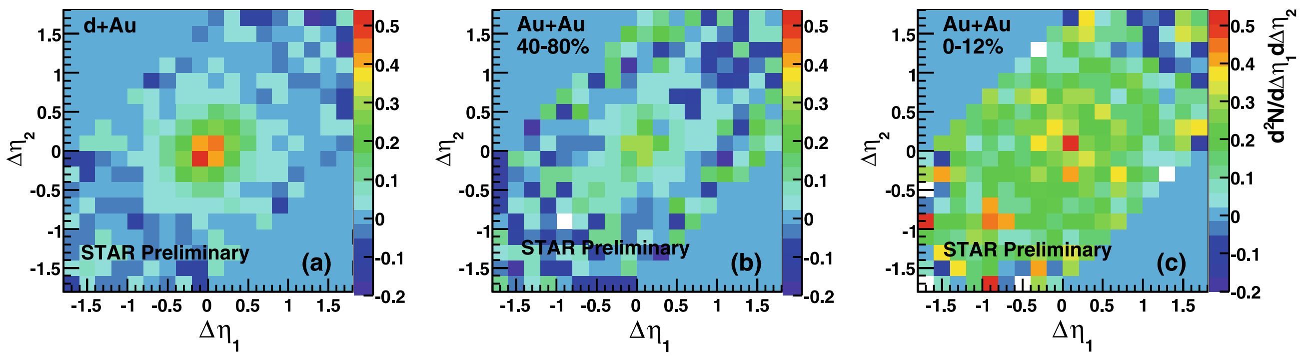

Fig. 3 (Color online) Background-subtracted associated hadron pair distribution as a function of $\Delta\eta_1$ and $\Delta\eta_2$ the pseudo-rapidity difference between the trigger hadron and the first and second associated hadron for particles with $1 < p_T^{assoc} < 3$ GeV/c and $3 < p_T^{trig} < 10$ GeV/c. The *left panel* shows results for d + Au collisions, *center* and *right panel* are Au + Au at 40–80% and 0–12% most central

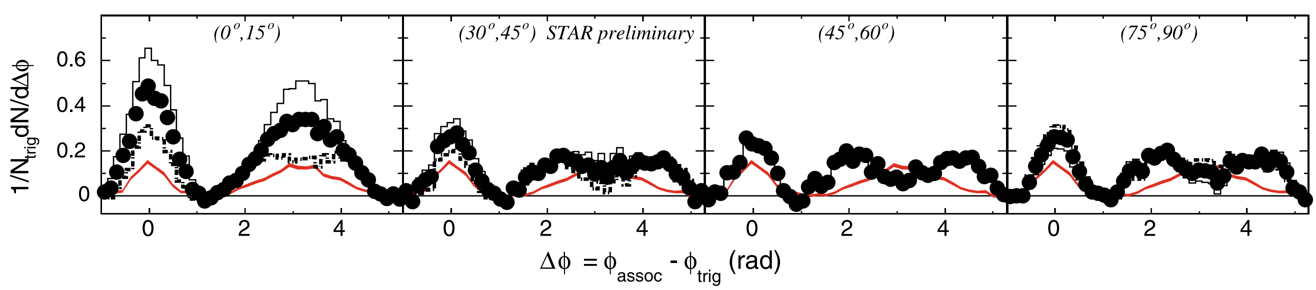

Fig. 4 Preliminary background subtracted distributions of associated hadrons with $1.0 < p_T^{assoc} < 1.5$ GeV/c relative to a trigger hadron $3.0 < p_T^{trig} < 4.0$ GeV/c in four different ranges for the angle ϕ_s between the trigger hadron and the event plane for 20–60% central Au + Au collisions. The *solid* and *dashed histogram* represent the systematic uncertainty due to the uncertainty in the strength of the elliptic flow v_2. The (*red*) *line* shows the result from d + Au collisions for reference

ongoing to determine how significant the absence of the various structures is. Future RHIC runs will provide increased statistics which will reduce the uncertainties and will make it possible to perform this analysis with larger p_T^{trig} and p_T^{assoc}, where backgrounds are smaller.

3 Path length dependence

To vary the path length of high-p_T partons through the medium, measurements are performed as a function of the angle with respect to the event plane. Figure 4 shows the background subtracted distributions of associated hadrons with $1.0 < p_T^{assoc} < 1.5$ GeV/c relative to a trigger hadron $3.0 < p_T^{trig} < 4.0$ GeV/c in four different ranges for the angle ϕ_s between the trigger hadron and the event plane. On the near side, a decrease of the associated yield with increasing ϕ_s is visible. The recoil peak shape changes from a broad single peak at $\phi_s = 0$ to a doubly-peaked structure for larger angles. The systematic uncertainty on the background subtraction due to the uncertainty in elliptic flow v_2 is indicated by the dashed and solid histograms. For details of the analysis, see [16].

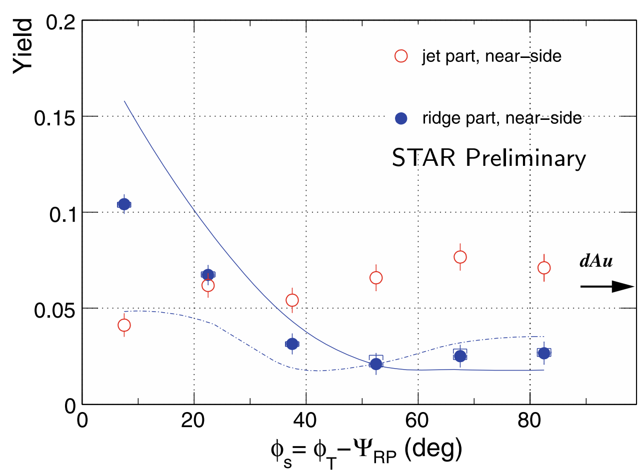

Fig. 5 Preliminary results for the near-side yield as a function of the angle between the event plane and the trigger hadron ($3.0 < p_T^{trig} < 4.0$ GeV/c), for associated hadrons $1.5 < p_T^{assoc} < 2.0$ GeV/c for 20–60% central Au + Au collisions. Open red circles show the jet-like yield, and solid blue circles show the ridge yield

Figure 5 shows the dependence of the near-side yield on ϕ_s, for the ridge and the jet-like peak separately. It can be seen that the jet-like peak has almost no dependence on the angle with respect to the event plane, while the ridge component is significantly larger for small ϕ_s, i.e. in-plane. This implies that the ridge yield is larger for smaller path lengths, while naively one would expect larger jet modifications for longer path lengths. The observed trend might be due to a trigger bias effect, for example because jets with large energy loss do not give rise to a trigger particle. Another possible interpretation is that the ridge effect may depend on the local flow velocity in the medium.

Figure 6 shows the dependence of the recoil yield in two angular regions around $\Delta\phi = \pi$ and $\Delta\phi \approx 2/3\pi$ ('double peak region') on ϕ_s. The associated yield at $\Delta\phi \approx 2/3\pi$ shows no significant dependence on ϕ_s, while the yield at $\Delta\phi = \pi$ is largest in-plane ($\phi_s = 0$) and then decreases. This indicates that the change of the shape of the recoil distribution is mostly due to changing yield at $\Delta\phi = \pi$. The doubly-peaked away-side occurs when the yield at $\Delta\phi = \pi$ is smaller than in the 'double peak region'. It is also interesting to note that while the double peak structure is associated with large path length, the strongest increase of the yield at $\Delta\phi = \pi$ with respect to d + Au collisions is seen for the shortest path lengths, $\phi_s = 0$.

An important systematic effect in the measurement of azimuthal correlations as a function of the angle with respect to the event plane, is that the jet-like azimuthal correlations may bias the event plane. In order to reduce this effect, the event plane is reconstructed using tracks with $\Delta\eta > 0.5$ with respect to the trigger hadron. Some of the observed effects, however, could be due to such an event plane bias, so further tests of this systematic effect are still ongoing.

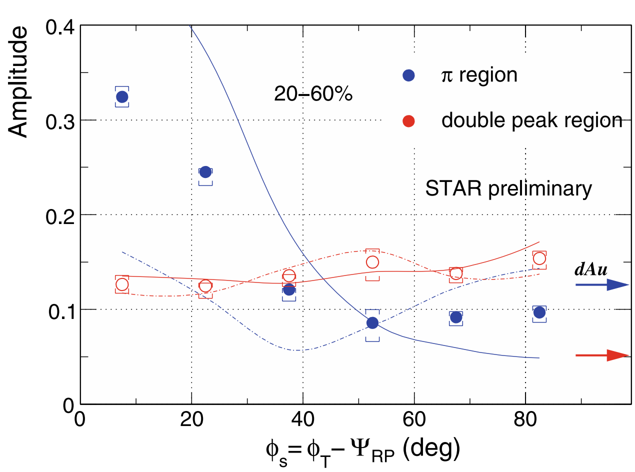

Fig. 6 Preliminary results for the recoil yield as a function of the angle between the event plane and the trigger hadron ($3.0 < p_T^{trig} < 4.0$ GeV/c), for associated hadrons $1.0 < p_T^{assoc} < 1.5$ GeV/c for 20–60% central Au + Au collisions. *Solid blue circles* show the yield in $|\Delta\phi - \pi| < 0.42$ (jet-region) and *open red circles* show the yield at $0.78 < |\Delta\phi - \pi| < 1.65$

4 High p_T multi-hadron correlations

At high $p_T \gtrsim 6$ GeV/c, both the hadrochemistry, as measured by the baryon/meson ratio [1] and the jet-like peak shapes in the di-hadron analysis [6] are very similar in heavy ion collisions and p + p collisions, which suggests that at high p_T, the dominant particle production mechanism in heavy ion collisions is parton fragmentation.

In-medium parton energy loss leads to a suppression of high-p_T hadron production, which can be modeled using perturbative QCD techniques. Recently, progress has being made towards determining medium properties by systematically confronting the data with several models for energy loss [17–19]. However, inclusive spectra and di-hadron correlations are rather insensitive to details of the energy loss process, such as the probability distribution for energy loss, because the initial parton energy is not measured [20]. As a result, a number of energy loss models are able to describe the data, despite significant differences in the underlying energy loss distributions. To further address this, more differential measurements are needed, preferable including a direct measure of the initial parton energy.

Direct-photon jet measurements are especially promising in this regard [21, 22], since the photon energy is a direct measure of the initial parton energy. Direct photon measurements, however, have the difficulty that the event-samples are smaller than for hadronic signatures and that the backgrounds are large. Another approach is to perform jet reconstruction in heavy ion collisions, where the jet energy is a measure of the initial parton energy. Results from both types of measurement will be discussed in other contributions to this volume [23–26].

Here, we would like to present two analyses which provide more differential information that the inclusive spectra and di-hadrons, but do not provide a direct measurement of the initial parton energies.

4.1 Di-hadron triggered correlations

In the standard di-hadron measurement [6], the near-side trigger hadron p_T selects jets within a relatively broad energy range. As a result, the p_T-cut on associated hadrons on the away-side can impose an additional bias on the underlying jet distribution. The analysis presented here aims to reduce this effect by using a di-jet trigger, i.e. selecting events with a back-to-back pair of high-p_T hadrons. Associated hadrons can then be studied with respect to this pair.

Figure 7 presents a first result from STAR for this type of analysis, using charged particle trigger pairs with $5 < p_{T,1}^{trig} < 10$ GeV/c and $4 < p_{T,2}^{trig} < 5$ GeV/c and associated charged particles $1.5 < p_T^{assoc} < 4$ GeV/c. The combinatorial backgrounds have been subtracted, including jet-background cross-terms. For details, see [27]. For comparison, the line shows the associated hadron distribution for a single trigger particle with $4 < p_T^{\mathrm{trig}} < 5$ GeV/c and the same p_T^{assoc} selection as the di-hadron trigger. The figure shows two notable features. Firstly, the associated yields with di-hadron triggers are larger than with the single-hadron trigger. This is because the di-hadron trigger selects more energetic jets than a single hadron trigger. The second observation from the figure is that the distributions are very similar in d + Au and Au + Au events, indicating that the selected di-jets fragment like in the vacuum. This also implies that there are no events with a larger energy-difference between the two jets, as one might expect for Au + Au events with energy loss. It should be realized, however, that the fact that the p_T-selection for the two trigger hadrons are similar in the current measurement is likely to select events with small energy-asymmetry between the jets.

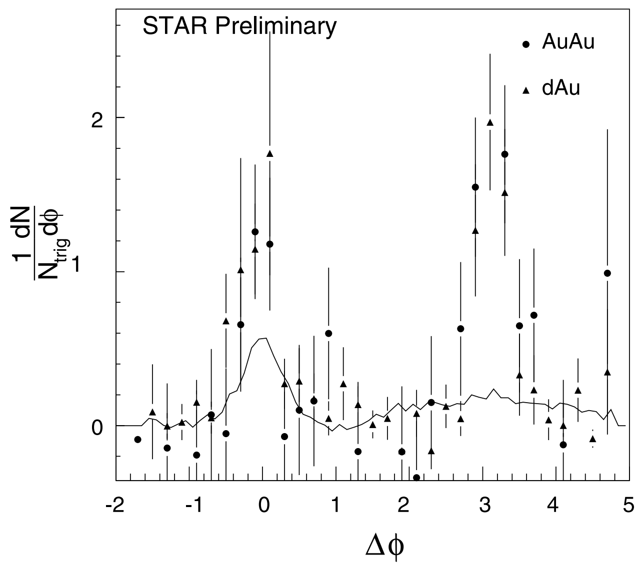

Fig. 7 Preliminary associated hadron distribution with respect to a di-hadron trigger with back-to-back hadrons of $5 < p_{T,1}^{\mathrm{trig}} < 10$ GeV/c and $4 < p_{T,2}^{\mathrm{trig}} < 5$ GeV/c in 0–12% central Au + Au collisions. Associated hadrons have $1.5 < p_T^{\mathrm{assoc}} < 4$ GeV/c. The angular difference $\Delta\phi = \phi_A - \phi_{T2}$ is between the associated hadron and the second trigger. Combinatorial backgrounds, including jet-background combinations, have been subtracted. The *line* shows the di-hadron distribution with $4 < p_T^{\mathrm{trig}} < 5$ GeV/c and $1.5 < p_T^{\mathrm{assoc}} < 4$ GeV/c from central Au + Au collisions for comparison

The first model calculations for this kind of measurement are already available [28]. They indicate that by changing the p_T-cuts for the trigger hadrons independently, one can select events with larger difference between the energies of the jets. The larger triggered data sample from RHIC run-7 may allow to perform this measurement with more asymmetric cuts.

4.2 Multi-hadron cluster triggered correlations

A different approach to reduce the jet-energy bias in di-hadron correlation measurements is to cluster hadrons into a 'proto-jet' and use this as the trigger object. A first analysis of this type is being performed in STAR, using particles with $p_T^{\mathrm{seed}} > 5$ GeV/c as 'seed' particles. Secondary particles with $p_T >$ GeV/c are added to the cluster if they are within $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ from the seed particle. The sum of the transverse momenta of the particles in the cluster is used as the multi-hadron trigger p_T. For details of the analysis, see [29]. In particular, it should be noted that at the moment, no correction is made for 'background triggers',

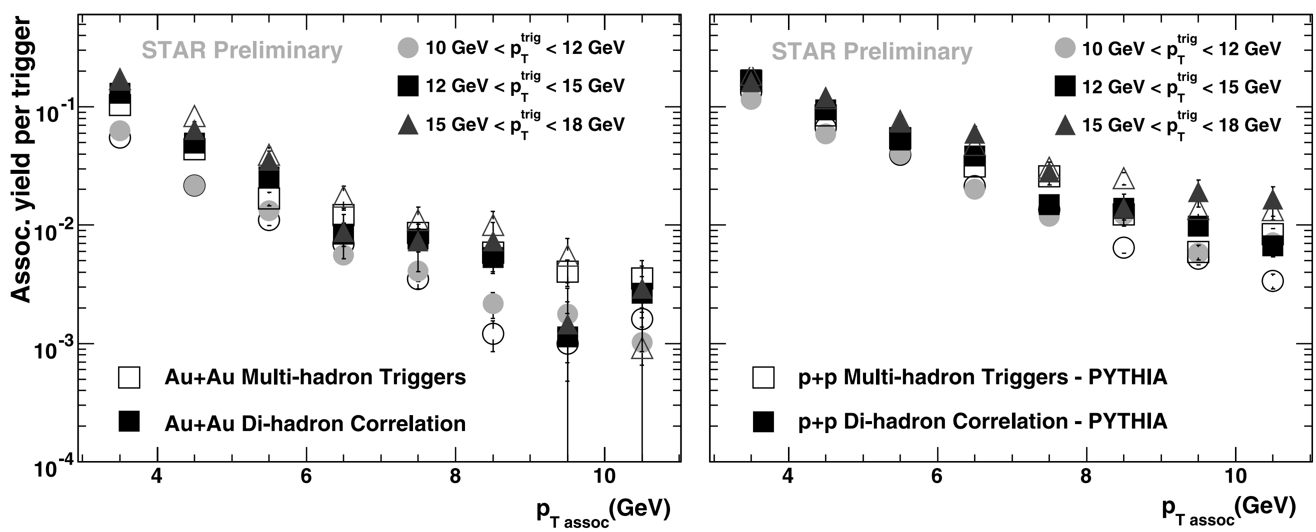

Fig. 8 Preliminary measurement of the recoil yield opposite multi-hadron trigger clusters consisting of at least one particle with $p_T > 5$ GeV/c and possible additional particles with $p_T > 3$ GeV/c inside a cone of $R = 0.3$ (*open symbols*) in 0–12% central Au + Au collisions. Results are shown for three selections of trigger-cluster energy and for data (*left panel*) and Pythia (*right panel*). *Solid symbols* show the results with a single-particle trigger for comparison

i.e. random combinations of particles that form a trigger cluster. The signal-to-background ratio for trigger clusters is estimated to be 0.7 [29].

Figure 8 shows the recoil yield for such multi-hadron cluster triggers in three different p_T ranges. The left panel shows the measurement in 0–12% central Au + Au collisions, while the right panel shows the result for the same analysis on PYTHIA events [30]. For comparison, results of the di-hadron analysis (single particle trigger) are also shown (solid symbols). It can be seen in the figure that the analysis with multi-hadron cluster triggers gives similar results to the single-hadron triggers, indicating that the underlying jet energy selection is similar in both cases. A similar trend is seen in the PYTHIA simulation. This implies that multi-hadron clusters with the current cuts do not provide a significantly better measure of the jet energy than the leading particle. Further studies with PYTHIA are ongoing to determine whether for example including electromagnetic energy in the cluster changes the result.

5 Conclusion and outlook

We have presented recent results on intermediate and high-p_T multi-hadron correlation measurements. At intermediate p_T, two results were highlighted that provide some insight in the origin of the near-side associated yield at large $\Delta\eta$, the ridge. Both the large baryon/meson ratios and the uniform event-by-event $\Delta\eta$-structure indicate that the ridge is likely formed from bulk matter and not from jet fragments.

Measurements of the associated hadron distribution as a function of the angle with the event plane show a clear evolution of the correlation structure with path length, on both the near and the away side. Comparisons to theoretical calculations are needed to interpret the interplay between trigger bias and path length dependent energy loss.

At high p_T, STAR is exploring multi-hadron analyses to provide more differential measures of energy loss and better constraints on parton energy loss models. Back-to-back di-hadron triggered correlations may provide a way to select events with large energy loss for further analysis. The current data sample is not large enough to provide the p_T-reach that is needed to fully exploit this technique. Another analysis uses multi-hadron clusters as triggers to reduce the trigger bias in correlation measurements. So far, the differences between the multi-hadron triggered analysis and the analysis with single-hadron triggers are found to be small. Simulated PYTHIA events are being used to further explore the potential of this technique.

In the coming years, STAR will collect substantially larger data samples for p + p and Au + Au events, which will allow more differential analyses to further test jet quenching models. We would like to urge theoretical physicists to help devise decisive tests of our understanding of parton energy loss mechanisms in heavy ion collisions.

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