PROCEEDINGS OF SCIENCE

Measurement of semi-inclusive γ+jet and hadron+jet distributions in heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV with STAR

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8 The STAR collaboration presents measurements of the semi-inclusive distribution of charged-particle jets recoiling from photon and hadron triggers in p+p and heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV. The large uncorrelated background in heavy-ion collisions is removed using the event mixing technique, enabling systematically well-controlled measurements at very low jet transverse momentum p_T^{jet} and large jet radius R. We report corrected distributions as a function of both p_T^{jet} and recoil azimuthal deflection with respect to γ and π^0 trigger axis for R = 0.2 and 0.5 jets in p+p and Au+Au collisions. These measurements probe the medium-induced jet yield suppression, intra-jet broadening, and jet acoplanarity as well as their dependence on the color charge in heavy-ion collisions. Jet yields in Ru+Ru and Zr+Zr collisions are also studied for the system size dependence of jet energy loss.

26-31 March 2023
Aschaffenburg, Germany

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1. Introduction

A jet is a collimated spray of hadrons produced by an energetic quark or gluon, which is produced in vacuum and can be well described by perturbative quantum chromodynamics (pQCD). In high energy heavy-ion collisions, a deconfined state of matter called quark-gluon plasma (QGP) is created [1]. When energetic partons propagate through the hot QCD medium, they lose energy resulting in the jet modification, termed as jet quenching. The parton-medium interaction will modify jets in various ways [2], such as jet energy loss, jet substructure modification, or medium-induced jet acoplanarity.

In this study, semi-inclusive recoil jet yield suppression and recoil jet yield as a function of the azimuthal angle difference ($\Delta\phi = \phi_{\rm trig} - \phi_{\rm jet}$) between trigger particles and recoil jets, are measured to explore jet energy loss and acoplanarity. Semi-inclusive jet yields are measured with high transverse momentum ($p_{\rm T}$) trigger-particle-normalized recoil jet yield distribution: $\frac{1}{N_{\rm trig}} \cdot \frac{d^3 N_{\rm jet}}{dp^{\rm ch}_{\rm T,jet} d\eta_{\rm jet}}$, as described in Ref. [3].

Thus, the observable can be used to quantify the jet energy loss with the ratio of recoil jet yield as a function of $p^{\rm ch}_{\rm T,jet}$ in A+A collisions to that in p+p collisions, which is denoted as $I_{\rm AA}$.

$$I_{\rm AA}(p^{\rm ch}_{\rm T,jet}) = \frac{Y^{\rm AA}(p^{\rm ch}_{\rm T,jet})}{Y^{\rm pp}(p^{\rm ch}_{\rm T,jet})}. \quad (1)$$

The term "direct photon" typically denotes both prompt photons and thermal photons. When we select the direct photon, $\gamma_{\rm dir}$, (not coming from any hadronic decay) as a trigger in this analysis, the photon candidates are primarily from hard QCD processes. Direct photon triggers are of special interest due to their lack of color charge, which provides a kinematic constraint on the associated recoil jets [4]. As a reference, we also studied π^0 as a trigger, making use of its difference compared to the $\gamma_{\rm dir}$ trigger [5]. Firstly, the quark fraction of recoil parton from $\gamma_{\rm dir}$ is significantly larger than that from π^0. It can be attributed to the dominating channel of $\gamma_{\rm dir}$+jet, which is Compton scattering ($qg \to q\gamma$). Another difference is that high-$p_{\rm T}$ π^0 are predominantly produced at the periphery of the QGP fireball whereas $\gamma_{\rm dir}$ is produced everywhere inside the fireball. This surface bias results in a longer in-medium path-length for the recoil jets from π^0 triggers, compared to that from direct photon [6]. Therefore, semi-inclusive $\gamma_{\rm dir}$+jet and π^0+jet measurements can provide comparison of recoil jets with different quark/gluon relative populations and path-length distributions.

The azimuthal angle distribution between trigger particles and recoil jets is also studied. The azimuthal angle distribution of dijets or $\gamma_{\rm dir}$+jet can differ from back-to-back productions due to higher-order QCD corrections in vacuum and medium effects, such as multiple scatterings, medium induced gluon radiations, or large-angle deflection of hard partons off quasi-particles in QGP. To explore the medium effect on the azimuthal de-correlation, we measured $\frac{1}{N_{\rm trig}} \cdot \frac{dN^3_{\rm jet}}{dp^{\rm ch}_{\rm T,jet} d(\Delta\phi) d\eta_{\rm jet}}$ as a function of $\Delta\phi$.

Regarding the system size dependence of jet quenching phenomena, the STAR Collaboration has conducted a study of hadron $R_{\rm AA}$ in different systems, and observed similar suppression at comparable $\langle N_{\rm part}\rangle$, which indicates that it is the energy density that drives the quenching rather than the collision geometry. We are interested in investigating whether the same picture applies to reconstructed jets. Since STAR has measured hadron+jet (h+jet) in Au+Au collsions, the final part of this proceedings is an outlook on h+jet study in relatively smaller systems: Zr+Zr and Ru+Ru.

2. Analysis

This study is conducted by the STAR experiment, using the Time Projection Chamber (TPC) to obtain information about charged particles [7], and the Barrel Electromagnetic Calorimeter (BEMC) to measure transverse energies ($E_{\rm T}$) for $\gamma_{\rm dir}$ and π^0 [8], with discrimination between these two types of triggers carried out by the Barrel Shower Maximum Detector (BSMD).

In this proceeding, the datasets for p+p and Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, taken in 2009 and 2014, respectively, are analyzed. The datasets for Zr+Zr and Ru+Ru collisions at the same collision energy, taken in 2018, are also analyzed. In p+p and Au+Au collisions, high $E_{\rm T}$ direct-photon ($\gamma_{\rm dir}$) and neutral-pion (π^0) triggers are selected by BEMC, with $9 < E_{\rm T}^{\rm trig} < 20$ GeV and $|\eta_{\rm trig}| < 0.9$. Discrimination between these particles was achieved via the Transverse Shower Profile (TSP) method as discussed in Ref. [9]. In Zr+Zr and Ru+Ru collisions, we use charged particles as triggers, which are selected with transverse momentum $7 < p_{\rm T}^{\rm trig} < 25$ GeV/c and $|\eta_{\rm trig}| < 1$.

Recoil jets are reconstructed with two jet radii R = 0.2 and 0.5 by the anti$-k_{\rm T}$ algorithm with charged particles at mid-rapidity $|\eta_{\rm jet}| < 1$ [10]. Combinatorial jets are removed using the mixed-event (ME) technique in A+A collisions [3]. Here, ME method refers to picking one random track per real event and combining them to generate a new event, which is the mixed-event. In this way, it is possible to create an estimate of the background where all tracks are uncorrelated to each other. Same jet reconstruction procedure is carried out on the mixed-events as used for real events to determine the combinatorial jet yields. Then, unfolding procedure is utilized to correct jets in different $p_{\rm T}$ bins for detector effects and heavy-ion background fluctuations.

3. Results

We measure semi-inclusive $\gamma_{\rm dir}$ and π^0 triggered recoil jet yields in central Au+Au and in p+p collisions. Figure 1 presents nuclear modification factor $I_{\rm AA}$ of central Au+Au (0 − 15%) to p+p collisions, with R values of 0.2 and 0.5. $E_{\rm T}^{\rm trig}$ bins for π^0 trigger are $(11, 15)$ GeV, while those for $\gamma_{\rm dir}$ are $(11, 15)$ and $(15, 20)$ GeV. Dark band represents statistical uncertainties and light band indicates systematic uncertainties, which are dominated by unfolding and direct photon purity uncertainties. $I_{\rm AA}$ is consistent between $\gamma_{\rm dir}$+jet and π^0+jet, within uncertainties. We also measure the ratio of recoil jet yields between R = 0.2 and 0.5, as shown in Fig. 2. The Green band is results in p+p collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. The dashed line is predictions from PYTHIA-8 Monash tune [11]. For central Au+Au collisions, this ratio is less than that of p+p, providing clear evidence of in-medium broadening of the jet shower.

The $\Delta\phi$ distribution between trigger and recoil jets is measured in Au+Au collisions, and compared to the PYTHIA-8 Monash tune. Figure 3 illustrates azimuthal correlations in Au+Au collisions with both $\gamma_{\rm dir}$ and π^0 triggers. We lack enough data to measure small $\Delta\phi$ for R = 0.2. However, for R = 0.5, excess yield at $\Delta\phi \sim \pi/2$ at angles away from the back-to-back configuration is evident in central Au+Au collisions relative to PYTHIA. Nonetheless, the interpretation of this

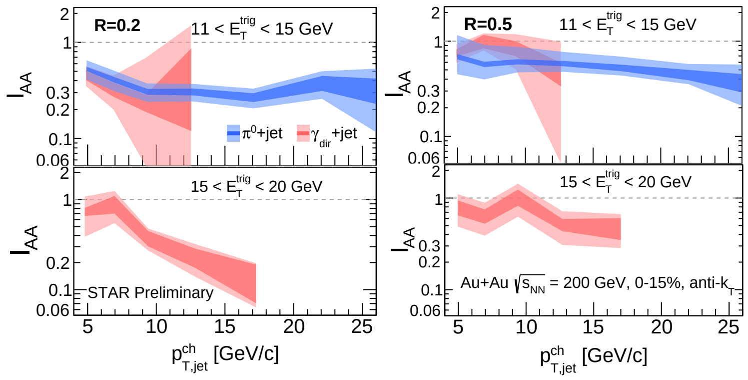

Figure 1: Nuclear modification factor $I_{\rm AA}$ for central Au+Au ($0-15\%$) collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV with R = 0.2 (left) and 0.5 (right), for $11 < E_{\rm T}^{\rm trig} < 15$ GeV (upper panels) and $15 < E_{\rm T}^{\rm trig} < 20$ GeV (lower panels).

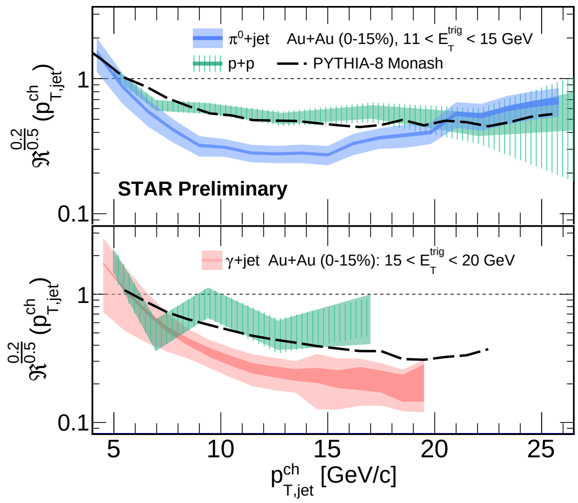

Figure 2: Ratio of recoil jet yields between R = 0.2 and 0.5 in central Au+Au ($0-15\%$) collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. The results are compared to PYTHIA-8 Monash predictions (dashed line). The upper panel shows results of π^0+jet for $11 < E_{\rm T}^{\rm trig} < 15$ GeV in p+p collisions (green line) and Au+Au collisions (blue line). The lower panel shows results of $\gamma_{\rm dir}$+jet for $15 < E_{\rm T}^{\rm trig} < 20$ GeV in p+p collisions (green line) and Au+Au collisions (pink line).

enhancement is not definitive, as jet deflection in the medium and medium response can both account for it. Differential measurements with respect to jet R and $p_{\rm T}^{jet}$, which require more statistics, will shed light on this.

h+jet measurements in relatively smaller collision systems are in progress. They will bridge the jet quenching studies between smaller and larger collision systems. Figure 4 shows the raw spectra of recoil jets from hadron triggers from real events and mixed-events in central Zr+Zr collisions ($0-10\%$), using triggers selected with $p_{\rm T}$ between 7 to 25 GeV/c. In the background dominated negative $p_{\rm T}$ region, a good agreement between real events and mixed-events is observed,

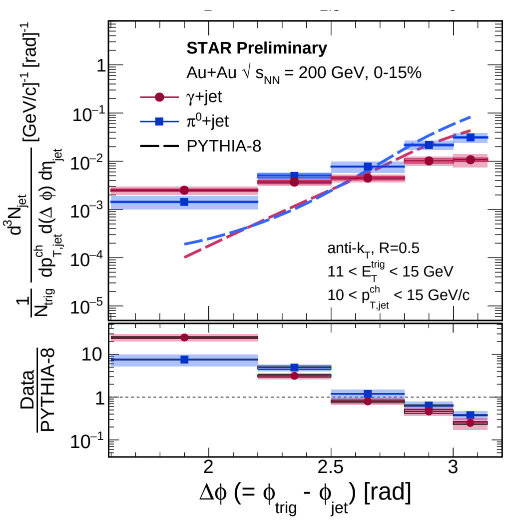

Figure 3: The $\Delta\phi$ distributions (upper panel) with $\gamma_{\rm dir}$ (red points) and π^0 triggers (blue points) for $R = 0.5$ in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV, and its ratio to PYTHIA-8 Monash tune (lower panel).

demonstrating the accuracy of the mixed-event method for estimating the background. The large difference between the two distributions at high $p_{\rm T}$ indicates a clear jet signal. The fully corrected h+jet results will be available soon.

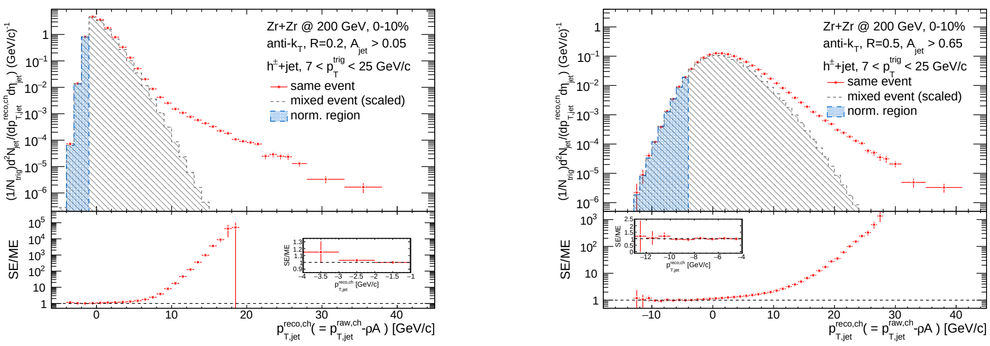

Figure 4: The h+jet spectra in Zr+Zr collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with $R = 0.2$ (left) and 0.5 (right), for $7 < p_{\rm T}^{\rm trig} < 25$ GeV/c. Upper panel shows the raw spectra of real events (red points) and mixed-events (shaded region). Lower panel shows the ratio of real events and mixed-events distributions

4. Summary

We report consistent $I_{\rm AA}$ results between $\gamma_{\rm dir}$+jet and π^0+jet in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The ratios of recoil jet yields between $R = 0.2$ and 0.5 show the intra-jet broadening in heavy-ion relative to p+p collisions. In Zr+Zr and Ru+Ru collisions, the h+jet analysis is ongoing. For the jet acoplanarity study, we report the $\Delta\phi$ distributions in Au+Au collisions with both $\gamma_{\rm dir}$ and π^0 triggers, and observe an excess of jet yield away from back-to-back. More inputs from both experimental and theoretical sides are needed in the future.

5. Acknowledgements

Yang He is supported by the National Natural Science Foundation of China (NSFC) under Grant Nos. 11890710 and 11890713.

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