Toward understanding relativistic heavy-ion collisions with the STAR detector at RHIC

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This project is a study of high-energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC). The focus of the study is on two probes of the dense, partonic matter created in these collisions: 1) direct-photon-triggered jets and 2) heavy-quarkonium production.

Investigating Energy Loss through Photon-Triggered Jet Measurements

The hard production of a direct photon back-to-back with a jet (γ-jet) is a probe of the parton energy loss in heavy-ion collisions [1]. In the "γ-jet" coincidence measurement, the measured energy of the trigger particle (the photon) serves as a calibrated baseline for the total energy of the jet particles on the recoil side (i.e. opposite in azimuth) of the trigger. The mean-free path of the γ in the medium is large enough so that its momentum is preserved, regardless of the position of the initial scattering vertex. Thus it does not suffer from the geometric biases, i.e. the non-uniform spatial sampling of hadron triggers due to energy loss in the medium, of *e.g.* π^0 triggers. Because of the difference in path length traversed, on average, between a direct-γ and a π^0 trigger, comparisons of γ-jet to hadron (π^0)-jet measurements can provide insight into the path-length dependence of the energy loss.

As the dominant background to direct photons are π^0 (decaying to two photons), the Barrel Shower Maximum Detector (BSMD) has provided the capability of distinguishing direct photons from neutral pions via the transverse shower shape. Our group has used this method in the measurement of direct photon+hadron correlations [2]. The γ-hadron correlation studies can be extended to studies of γ-triggered jet reconstruction measurements (as has been done at the LHC [3, 4]). The away-side jet will then be reconstructed in coincidence with triggers selected as direct photon candidates or (for p_T<20 GeV using the shower shape with the BSMD) identified π^0 triggers. The advantage of this should be the ability to reach lower energy fragments in the jet to study jet-shape modification and possible redistribution of energy.

Photon- and Pion-Triggered Recoil-Jet Measurements in p+p Collisions

The Run-9 data set in p+p collisions has been fully analyzed for charged jets recoiling from a high-energy neutral trigger particle. We have chosen to concentrate initially on charged-particle jets, for simplicity, recoiling from the trigger particle. Charged-jet reconstruction is performed using the anti-k_T algorithm from the Fastjet package [5]. In this analysis, charged particles with transverse momentum between $0.2 < p_T < 30$ GeV/c are included as constituents. A fiducial cut is made on the pseudorapidity of the jet axis, $|\eta_{jet}| < 1-R_{jet}$, where R_{jet} is the jet resolution parameter associated with the radial size of the jet.

STAR is able to selectively record events for a γ-jet analysis by triggering on a high-energy signal in the Barrel Electromagnetic Calorimeter (BEMC). Events are triggered on high-energy BEMC towers (requiring approximately 6 GeV in a single tower), Level-0 "High-Tower" triggers. In addition, our group had previously implemented a Level-2 clustering algorithm in STAR to select events with approximately 8 GeV in a calorimeter cluster (1 or 2 towers) and produce a separate data stream ("L2Gamma") of these events. In the offline analysis, single photons are separated from closely positioned pairs of photons (in the BEMC), originating from high-p_T π^0 decays, based on their shower shape measured in the BSMD. The discrimination is done using cuts on the transverse-shower profile as measured by the BSMD. The shower shape is quantified by the Transverse Shower Profile (TSP), which was determined by optimizing the discrimination using a GEANT simulation. The cuts on the TSP are made to select a nearly pure sample of π^0 triggers and a sample of triggers denoted as γ_{rich}, with an enhanced fraction of direct photons. The purity of direct- γ triggers in the γ_{rich}, population is determined by the same procedure as in our group's previous publications of γ+hadrons [2], which is based on our definition of photon triggers not having a correlated near-side signal of charged hadrons within $\Delta\varphi<1.2$. The fraction of background triggers is determined statistically for each trigger E_T bin, using charged hadrons with $p_T > 0.9$ GeV/c in p+p collisions and 1.2 GeV/c in central Au+Au collisions.

To reconstruct jets, the "anti-kT" algorithm in the FastJet [5] package is used to cluster tracks into jets. The p_T threshold for clustering is kept low (p_T>0.2 GeV/c) in order to be able to access much of the lowest energy fragments in the jet (where the lost energy is expected to go). Reconstructed jets with resolution parameter R_{jet} varying between 0.2 and 0.5 are compared. The background energy (from the underlying event) is subtracted on an event-by-event basis using a background energy density also calculated by FastJet. The charged-jet p_T spectra are corrected for tracking efficiency and resolution by unfolding the measured-jet p_T spectra back to the true distributions (based on a GEANT simulation of the detector effects on PYTHIA-produced jets). PYTHIA is a Monte-Carlo event generator for p+p collisions [6].

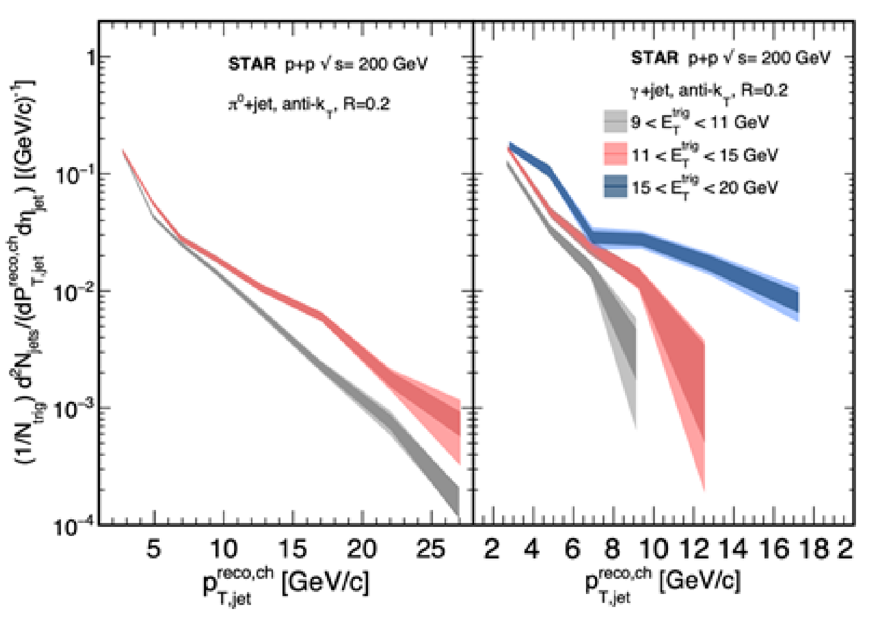

Fig. 1. Semi-inclusive jet yields per trigger for π^0 triggers (left) and direct-γ triggers (right) for different ranges in measured E_T of the trigger, in p+p collisions.

Fig. 1 shows the charged recoil-jet spectra for γ and π^0 triggers measured with transverse energy E_T=9-11 GeV, 11-15 GeV, and 15-20 GeV. These results have been shown by Derek Anderson at the Quark Matter 2022 conference and were the main results of his Ph.D. thesis (submitted to TAMU in the Spring semester of 2022).

Nuclear Modification (I_{AA}) of Per-Trigger Charged-Jet Yields

The analysis details in the Run-14 Au+Au data set largely mirror those employed in the p+p data, as discussed in the previous section. A mixed-event technique was developed to subtract the combinatoric background, which was also used in the published STAR results of semi-inclusive charged-jet reconstruction (using charged-hadron triggers) [7].

Fig. 2 shows the STAR results for the ratio of per-trigger jet yields in central (0-15%) Au+Au collisions to those in p+p collisions, IAA.

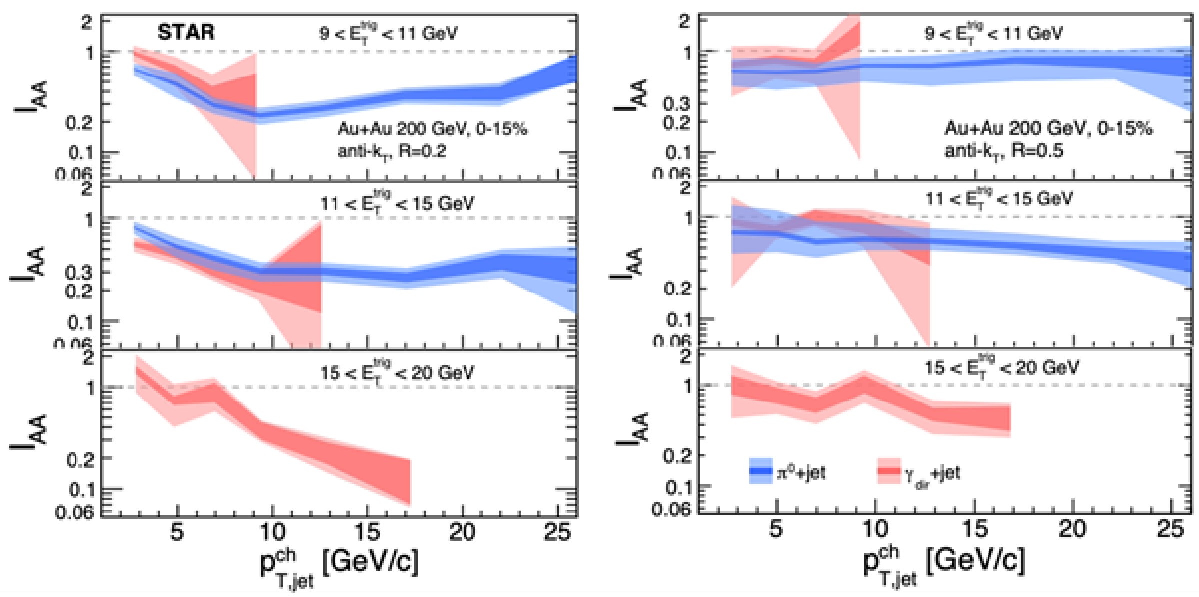

Fig. 2. I_{AA} of jets recoiling from neutral pions (blue) and direct photons (red), for trigger E_T measured within 9-11 GeV (top), 11-15 GeV (middle), and 15-20 GeV (bottom), for jet resolution parameter R=0.2 (left) and R=0.5 (right).

These results show the suppression of jet yields in central Au+Au collisions relative to the p+p baseline for both γ and π^0 triggers for jet resolution parameter R=0.2 (left panel). On the other hand, the larger jet radius of R=0.5 (right panel), shows significantly less suppression. In fact, the I_{AA} ratio is consistent with 1, which would indicate a full restoration of the lost energy within the larger jet cone.

Another direction that we have been pursuing with this analysis is the angular dependence of the jet yields relative to the trigger particle. Large angle scatterings due to parton interactions in the medium can be investigated by comparing the azimuthal direction of the trigger particle Φ_{trig} to the direction of the recoil jet axis Φ_{jet}.

Machine Learning to Discriminate and "isolated" triggers

When averaging over a sample of events, a clear near-side signal of associated hadrons can be seen in π^0 triggers, as opposed to γ triggers, since high-p_T pions are created as part of a jet. Our current method of discrimination requires very tight cuts on the π^0 selection based on the shower shape in the BSMD, greatly reducing the available statistics. For γ-triggered jet yields, the (non-direct) background contribution to the triggers must be subtracted on a statistical basis.

The question is whether machine learning can improve the γ/π^0 discrimination by "learning" the patterns of the near-side event activity. Jinjin Pan has worked on this question in Au+Au data. He provides thousands of images to different machine-learning algorithms that he has tested and further developed. For learning the near-side activity of π^0 triggers, he takes the nearly pure sample of π^0 that our shower-shape criteria selects. For the direct-γ triggers, he uses minimum-bias events and selects a random direction to be the photon. This gives the event activity of the underlying Au+Au background, which is what we expect for a direct-photon trigger. This project is still evolving, but we are anticipating results soon.

Unraveling Cold Nuclear Matter Effects in J/ψ Suppression

The J/ψ has long been considered one of the most promising direct probes of deconfinement. According to theoretical predictions in 1986 [8], the produced $c\bar{c}$ pair will not be able to form a J/ψ bound state in the QGP, if a sufficiently high temperature is reached where the screening radius is smaller than the binding radius of the J/ψ resonant state. The "Debye" screening radius is the distance at which the color charges of two quarks are screened from one another, so that the confinement force is not able to hold the quarks together. A suppression in the yield of J/ψ was first observed in Pb+Pb collisions by the NA50 experiment at the CERN SPS (see, for example, [9]).

At RHIC, the predicted suppression of J/ψ due to screening in the QGP is much larger than the suppression observed at SPS due to the higher initial density of the produced medium [10]. The RHIC measurements, however, show a level of suppression similar to NA50 at mid-rapidity [11], which is significantly smaller than expectations due to color screening effects alone. This can be understood in a scenario where charmonium is regenerated due to the large initial production of charm + anti-charm quarks at $\sqrt{s_{NN}}$ = 200, in conjunction with their possible thermalization in the created medium [12]. If charm quarks (partially) thermalize in RHIC collisions, then the coalescence of $c\bar{c}$ could lead to a smaller than expected suppression [13].

With counteracting effects, it is a challenge to disentangle the suppression from the regeneration. In addition, there are cold nuclear matter effects [14], including modification of the parton distribution functions ("shadowing") and partonic multiple scattering, that also lead to suppression of heavy quarkonium and need to be disentangled from QGP suppression. In order to quantify effects of deconfinement, cold nuclear matter effects (via p+A collisions) must be measured and disentangled.

Our goal is to measure charmonium production in p+Au collisions as a function of "centrality". Ideally, centrality would be determined using the event activity in the forward region, away from the mid-rapidity region where the J/ψ is reconstructed. However, due to the performance of the STAR Beam-

Beam Counters (BBC) in the p+Au running period, we have concluded that we cannot use the BBC for this purpose. Alternatively, we have settled on using the number of primary tracks matched to a TOF hit in underlying event region (NMPTUE) as a measure of the event activity. The NMPTUE was chosen based on the following criteria. The number of tracks matched to TOF was found to be more robust for rejecting pile-up than other track-quality cuts. In order to remove the auto-correlation of centrality with the physics being measured as a function of the centrality, tracks are counted only in the underlying-event region, a region transverse to the direction of the reconstructed particle.

Charmonium Production in Run-15 p+Au data

Yanfang Liu's thesis project entails charmonium production in p+Au collisions as a function of "centrality" or "event activity". Yanfang has spent quite some time working on a centrality determination for this data set. However, there is a correlation between the *J/ψ* production and the number of charged particles produced in the event. In order to avoid this auto-correlation of the event classification to the physics observable, we studied different ways of classifying the event activity. Our first intention was to measure the multiplicities measured in the forward detectors, such as the Beam-Beam Counters (BBC's). However, the large beam backgrounds (and gain settings optimized for p+p collisions) rendered the distributions measured in the Au-going BBC unfavorable for extracting Glauber model quantities such as

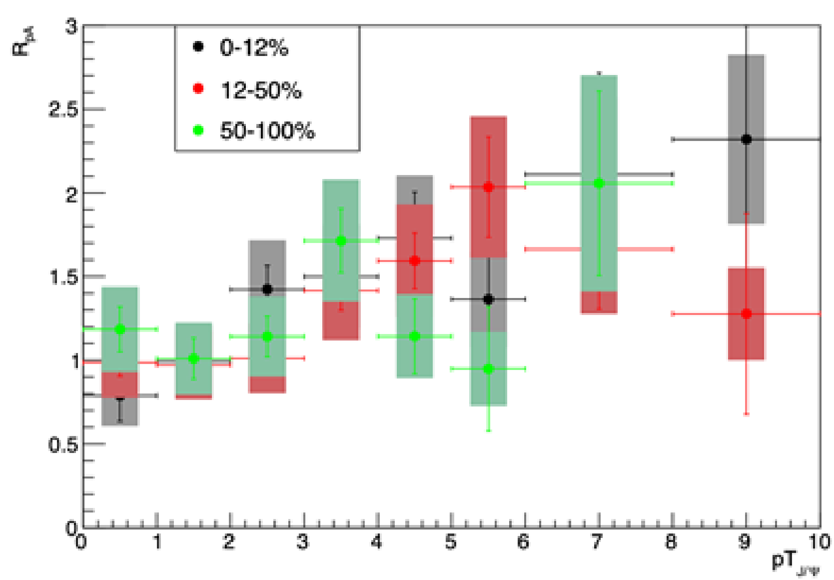

Fig. 3. Nuclear modification factor R_{pA} of *J/ψ* for different "centrality" p+Au events (with baseline being the yields measured in p+p collisions) as a function of p_T.

the number of binary nucleon-nucleon collisions (N_{binary}). We ultimately settled on a count of the number of charged tracks measured in a region separated from the reconstructed *J/ψ* candidate in the event $(1 < |\Delta\phi| < (\pi - 1))$. This region is within the so-called "underlying-event" region, since it is 1 radian away from the axis of the physics observable produced in a hard collision (in this case, the *J/ψ*).

She now has all of the ingredients to finalize the results. Fig. 3 shows a preliminary version of the results in the form of a nuclear modification factor,

$$R_{pA} = \frac{Yield^{p+Au}(p_T)}{N_{binary}^{p+Au} \times Yield^{p+p}}$$

In addition to the *J/ψ* analysis, we have looked into the feasibility of reconstructing the χ_c in p+A collisions. Since 30-40% of *J/ψ* are feed-down from χ_c and *ψ*‘ decays, it is important to measure cold nuclear matter effects on these separately.

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