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 their correlations) and 2) heavy-quarkonium production and suppression.

1 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. π0 triggers. Because of the difference in path length traversed, on average, between a direct-γ and a π0 trigger, comparisons of γ-jet to hadron(π0)-jet measurements can provide insight into the path-length dependence of the energy loss.

As the dominant background to direct photons are π0 (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 pT <20 GeV using the shower shape with the BSMD) identified π0 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.

The Run-14 photon-triggered data set in Au+Au collisions has been fully analyzed for charged jets recoiling from a high-energy neutral (π0 or γ) trigger. 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-kT algorithm from the Fastjet package [5]. In this analysis, charged particles with transverse momentum between 0.2 < pT < 15 GeV/c are included as constituents. A fiducial cut in jet pseudorapidity, |ηjet| < 1−Rjet, where Rjet is the jet resolution parameter associated with the radial size of the jet.

Fig. 1 shows the charged recoil-jet spectra for a sample of π0, using cuts on the transverse-shower profile as measured by the BSMD, for two different ranges of transverse energy (E_T) of the trigger. In this figure, the jet yields are corrected for the background energy density (ρ) but have not been corrected for instrumental effects. The low panel clearly shows the growing signal of “true” jets over combinatorial jets, as estimated by a mixed-event technique [6].
Fig. 2 shows our STAR preliminary result of the fully corrected charged recoil-jet spectra for $\pi^0$ and direct-$\gamma$ triggers (presented at the Hard Probes Conference, 2018).

As a baseline measurement, we have also analyzed Run-9 p+p collisions. Fig. 3 shows the result of the fully corrected charged-jet spectrum on the recoil side of a $\pi^0$ trigger with $E_T=9$-11 GeV, in p+p collisions, compared to the same from PYTHIA [7]. This shows that PYTHIA describes the p+p data for semi-inclusive recoil jets well.
FIG. 2. (Left Panel) Fully corrected charged-jet spectra on the recoil of $\pi^0$ triggers with $E_T=9$-11 GeV (blue) and $E_T=11$-15 GeV (pink) compared to their respective PYTHIA [7] baselines (dashed lines, also in blue and pink). (Right panel) Fully corrected charged-jet spectra on the recoil of direct-$\gamma$ triggers with $E_T=9$-11 GeV (brown) and $E_T=11$-15 GeV (green) compared to their respective PYTHIA baselines (dashed lines, also in brown and green).

FIG. 3. (Upper Panel) Fully corrected charged-jet spectrum measured in Run-9 p+p collisions on the recoil of $\pi^0$ triggers with $E_T=9$-11 GeV, compared to the same spectrum reconstructed in PYTHIA events. (Lower Panel) The ratio of the measurement to PYTHIA. The inner (darker) band represents the statistical uncertainties, and the outer (lighter) band represents the systematic uncertainties.
2 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 c̅c 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 $\sqrt{s_{NN}} = 200$ GeV, in conjunction with their possible thermalization in the created medium [12]. If charm quarks (partially) thermalize in RHIC collisions, then the coalescence of c̅c could lead to a smaller than expected suppression [13].

With counteracting effects, it is a challenge to disentangle the suppression from the regeneration. Further complicating this task is that the J/Ψ-particle yields that are measured are not all primordial; some ~40% are feed-down from $\chi_c$ (approximately 30%) and $\psi'$ (approximately 10%) decays. Since the survival rate of different charmonium states may be different, due to the different sizes, it is important to know these feed-down fractions precisely. 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 have a measurement of charmonium production in p+Au collisions as a function of “centrality” or “event activity”. Quite some effort has gone into the centrality determination for this data set. We based the centrality determination on an event multiplicity of the number of good primary tracks, for which we calculated corrections for the luminosity and vertex dependence.

Thus far, we have extracted J/Ψ yields, as a function of $p_T$. Fig. 4 shows the mass distribution of muon pairs (unlike-sign in black and like-sign in blue) obtained as a function of $p_T$. We have started working on the “centrality”-dependent yields.
For the efficiency corrections, we have been analyzing “embedding” data (simulated particles embedded into real data). In particular, we have analyzed J/ψ particles embedded into the Run-15 p+Au data set and are currently calculating the centrality-dependent corrections. The fully corrected centrality-dependent J/ψ yields are expected to be finalized within the following year.