Toward Understanding the QGP with the STAR Experiment at RHIC

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1 Introduction

1.1 Abstract

RHIC at Brookhaven National Laboratory has been providing high energy heavy-ion collisions since the year 2000. New sub-detectors within the STAR experiment are capitalizing on the high luminosities currently provided. As the high-statistics Au+Au data-taking may be coming to an end in the next few years, it is important to maximize the impact of the data recorded. This is a proposal to contribute in that direction, with data analyses to be performed by two Ph.D. students and one postdoctoral research associate. Rare-probe measurements are challenging because of the limited statistics. Two of these are addressed in this project, i.e. to continue the studies of direct photon correlation measurements and heavy quarkonium production.

1.2 Summary of Accomplishments on Grant Period

- Draft of paper of STAR γ+hadron correlations measurement, for which PI, postdoc, and former postdoc are the sole 'Principal Authors', to be submitted for publication before this grant period ends in June, 2016.
- Presentation of STAR γ+hadron correlations measurements by A. Hamed at Quark Matter 2014.
- Presentation of STAR γ+hadron correlations measurements by N. Sahoo at Quark Matter 2015.
- Major group involvement in 9 peer-reviewed STAR publications of physics results.
- Major involvement in 1 additional STAR paper draft to be submitted for publication before this grant period ends in June, 2016.
- PI is co-convener of Jet Correlations Physics Working Group in STAR (since July, 2011).
- First STAR Υ spin-alignment measurement completed (waiting to include in a broader-scope STAR publication).
- Level-2 Trigger monitoring of high-p_T photon trigger in Au+Au data-taking in Run 14.
- Simulation studies for p+p/p+A STAR Letter of Intent (for 2020+ Running at RHIC), specifically of J/ψ in p+A collisions at forward rapidity.
- PYTHIA study of photon+hadron correlations vs. π^0+hadron correlations.
- Study of transverse-shower profile of π^0 decays vs. single photons in Barrel Shower Maximum Detector using simulated particles embedded in real data.
- Study of background rejection of pions, protons, and kaons, using simulated particles embedded into Au+Au data, using the Muon Telescope Detector.
- Study of trigger efficiencies of Single-Muon and Di-Muon triggers in Run-14 Au+Au data.

1.3 List of Personnel on Project

1. Saskia Mioduszewski, the PI, joined the faculty at Texas A&M University in September, 2005.
2. Nihar Sahoo, posdoc, joined the group in Dec. 2013 and was subsequently fully funded on this grant.
3. Yanfang Liu, a physics graduate student, joined the group in Sep. 2014 and was subsequently fully funded on this grant.
4. Derek Anderson, a physics graduate student, joined the group in June 2015 and was funded from this grant starting in the summer 2015.

5. Ahmed Hamed, a former postdoc, was still collaborating on physics analysis on this grant and officially associated with TAMU to retain his membership in the STAR collaboration. On the past grant period, Ahmed received funding to travel to BNL to help TAMU fulfill its shift requirements and to travel to present results at Quark Matter 2014, and partial funding to travel to Egypt to give an invited talk at a conference.
6. Matthew Cervantes, a former postdoc, received funding on the past grant period until September, 2014.

Student Tracking:

Student	Entered Grad. School	Joined Group	Degree Program	Date Degree Expected	Advisor
Yanfang Liu	Fall 2014	Fall 2014	Ph.D.	Summer 2019	S. Mioduszewski
Derek Anderson	Fall 2014	Summer 2015	Ph.D.	Fall 2019	S. Mioduszewski

2 Accomplishments on Grant Period

2.1 Contributions on Publications from STAR Collaboration

In the STAR Collaboration, data analysis is presented, discussed, and further developed within Physics Working Groups. Papers for publication are also prepared with feedback and guidance from the Physics Working Groups. Subsequently each paper is assigned to a God Parent Committee, which further discusses the physics results and progresses the paper to a state of readiness for publication.

1. “Beam energy dependence of moments of the net-charge multiplicity distributions in Au+Au collisions at RHIC”, thesis work of postdoc Nihar Sahoo. He was Principal Author of this paper and a member of the TAMU group while preparing the paper for publication.
2. “Neutral pion cross section and spin asymmetries at intermediate pseudorapidity in polarized proton collisions at $\sqrt{s}$=200 GeV”, Ahmed Hamed served on the God Parent Committee.

The PI worked with the principal authors, Li Yi and Fuqiang Wang (Purdue University), on the following two papers.
3. “Long-range pseudorapidity dihadron correlations in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV”, PI was co-convener of Physics Working Group and also served on the God Parent Committee.
4. “Effect of event selection on jetlike correlation measurement in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV”, PI was co-convener of Physics Working Group and also served on the God Parent Committee.
5. “Dielectron azimuthal anisotropy at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV”, PI was chair of the God Parent Committee.
6. Nature paper on “Measurement of interaction between antiprotons”, PI served on God Parent Committee.

7. Longer paper on “Event-plane-dependent dihadron correlations with harmonic v_n subtraction in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV”, PI served on the God Parent Committee.
8. “Jet-Hadron Correlations in $\sqrt{s_{NN}}$ = 200 GeV p+p and Central Au+Au Collisions” – PI was co-convener of Physics Working Group and served on God Parent Committee.
9. “Di-hadron correlations with identified leading hadrons in 200 GeV Au+Au and d+Au collisions at STAR”, PI was co-convener of Physics Working Group and also served on God Parent Committee.
10. “Direct Photon + Hadron Correlations to Study Parton Energy Loss at RHIC” is currently under collaboration review (not yet submitted to PLB). The PI, postdoc Nihar Sahoo, and former postdoc Ahmed Hamed are the principal authors of this paper (see section 3.2 for the results).

2.2 Photon-Hadron Correlation Measurements

The postdoc Nihar Sahoo led an analysis of direct photon + hadron correlations, performed together with the PI and the former postdoc Ahmed Hamed. Here, single photons were 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 Barrel Shower Maximum Detector (BSMD). While the shower-shape cuts can effectively select π^0 triggers at high p_T (resulting in an almost pure sample of π^0), the single γ sample (γ_{rich}) is not purely direct-γ (γ_{dir}) triggers. It contains background photons from asymmetric π^0 and η decays and fragmentation photons. All background to γ_{dir} is subtracted with the assumptions that 1) γ_{dir} have no associated particles on the same side and 2) the background triggers have the same correlation function as the π^0 sample. Previous results from our group [1] were from Run-7 Au+Au collisions and Run-6 p+p collisions. The most recent results from Nihar’s analysis were from higher-statistics data sets, Run-11 Au+Au collsions and Run-9 p+p collisions, allowing extension of the kinematic reach of the measurement. To help understand this apparent lack of dependence on the path length through the medium, the measurement was extended to lower z_T (z_T is the ratio of the p_T of the associated particle to the p_T of the trigger particle, $z_T=p_{T,assoc}/p_{T,trig}$), where theoretical models predict the greatest sensitivity [2].

To reach lower z_T, one can increase the trigger-particle p_T, which requires higher statistics, or lower the associated-particle p_T. To avoid the large uncertainties associated with background subtraction when lowering the associated-particle p_T, the trigger-particle p_T was increased from 8-16 GeV/c (studied in the previous publication [1]) to 12-20 GeV/c.

To measure the effect of the medium, Fig.1 shows the ratio of per-trigger yields I_{AA}, defined as the yield measured in Au+Au to that measured in p+p, as a function of z_T.

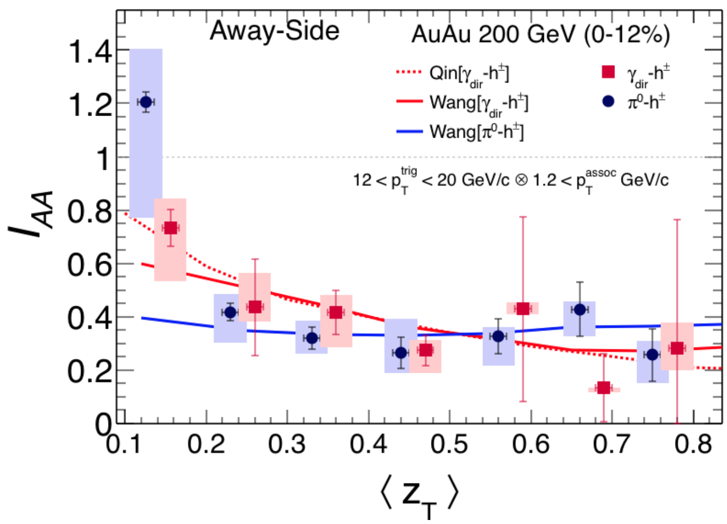

Figure 1. Ratio I_{AA} of the yields measured in Au+Au collisions to those measured in p+p collisions for π^0-$h^\pm$ (blue) and γ-$h^\pm$ (red) as a function of z_T. Data is compared to theoretical calculations [2, 3, 4].

At low z_T ($0.1<z_T<0.2$), both the suppression levels in π^0-triggered yields, $I_{AA}{}^{\pi^0}$, and in γ^{dir}-triggered yields, $I_{AA}{}^{\gamma dir}$, are less than at higher z_T. At high z_T, the suppression factor is approximately 3–5. The theory calculations, labeled Wang [2, 3] and Qin [4] describe the data for γ^{dir}+$h^\pm$ correlations. Since the model calculations do not include a redistribution of the lost energy to the low-p_T jet fragments, the rise in $I_{AA}{}^{\gamma dir}$ at low z_T is likely due to the volume emission of the γ^{dir} triggers (vs. surface emission of π^0 triggers). Also shown is the calculation for $I_{AA}{}^{\pi^0}$ [2, 3], which does not show the same rise at low z_T. However, within the measured uncertainties, there is no difference in the suppression of π^0-triggered yields and γ^{dir}-triggered yields, even at low z_T. It will be important to measure this more precisely with higher-statistics data (allowing for more systematic studies), in order to understand whether the rise is due to a redistribution of lost energy or effects of surface vs. volume emission trigger biases. This figure is included in the manuscript written by our group, which has been published in PLB.

2.3 Upsilon Polarization Measurement

The systematics of prompt production of heavy quarkonium is not fully understood by common production models, e.g. the Color Singlet Model (CSM) and the Color Octect Model (COM). Historically, CSM calculations grossly under-predicted production cross sections of heavy quarkonium, but recent development with higher-order corrections can describe data better [5]. The COM can describe the p_T spectra of heavy quarkonia, but the spin-alignment ("polarization") prediction disagrees with experimental data from Fermilab experiments [6].

A measurement that puts constraints on theoretical models of the production mechanism is the spin-alignment (or "polarization") of the Υ. Here, the angle between the direction of the e^+ momentum is measured in the Υ's rest frame with respect to the Υ's direction of motion, i.e. the "polarization axis". The distribution of Υ-particle yields as a function of this angle θ is then fit with the function $dN/d\theta = A(1 + \lambda_\theta \cos^2\theta)$, where λ_θ is the polarization. The value of λ_θ can vary from -1 to 1; with -1 corresponding to a fully longitudinal polarization, 0 no polarization, and +1 fully transverse polarization.

The most difficult part of the experimental analysis was removing the possible background due to Drell-Yan and $b\bar{b}$ production, which can have its own polarization (i.e. θ dependence) and its own acceptance correction. From simulation/theory studies, as well as a fit to the mass line-shape, it was concluded that, while at √s=200 GeV the contributions to background from Drell-Yan and $b\bar{b}$ are comparable, at 500 GeV the background is dominated by (open) $b\bar{b}$ pair production.

To subtract the background, the θ dependence of e^+e^- pairs in the mass region outside of the Υ mass region, 6.0-7.5 GeV/c^2 and 12-14 GeV/c^2 (the "side-band" regions) was analyzed and compared to PYTHIA [7]. The Level-2 trigger criteria (energy and momentum cuts) were loosened to enhance the background in this region. Then PYTHIA was used to extrapolate from the "side-band" regions to the Υ mass-window region, since the acceptances are different for different mass regions and different cuts. Using this method, the fraction of background from $b\bar{b}$ production in the Υ mass-window region relative to the integrated combinatorial-background-subtracted invariant mass distribution was found to be approximately 22%. This is consistent with an alternate method to estimate the fraction of background, where the mass line shape was fit, resulting in 26 ± 4%.

With the subtraction of this background, and an in-depth study of the systematic errors, the main physics result is shown in Fig. 2. The systematic uncertainties include the simulation of the trigger cuts, the input polarization for the embedded Υ's used for the acceptance correction, and the particle-identification cuts (which affect the purity of the electrons).

Matthew Cervantes prepared a paper draft on the spin-alignment results from Run-11 √s=500 GeV p+p collisions. However, the Heavy-Flavor Physics Working Group has decided to incorporate it into a paper with a larger scope. Theoretical calculations are reliable only at high p_T (p_T>15 GeV/c) [8], and thus predictions from production models are not available within our measured p_T range.

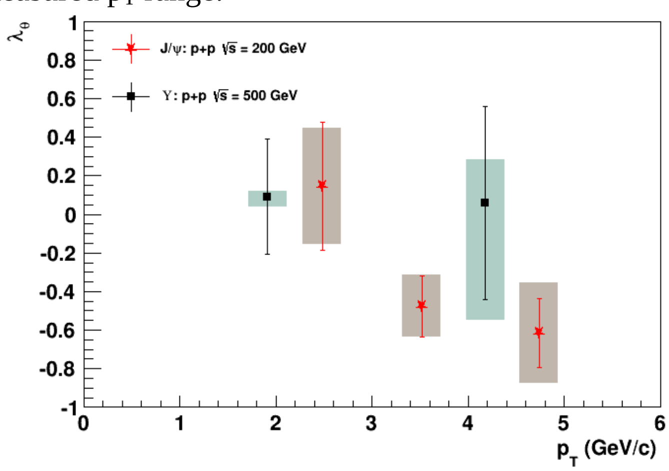

Figure 2. Polarization parameter λ_θ as a function of p_T, measured in Run-11 √s=500-GeV p+p collisions, for Υ particles (our results), compared to J/ψ particles measured in √s=200-GeV collisions (another STAR group's results) [9].

Due to the limited conclusions that can be made from the Y polarization measurement in its current p_T reach, the paper will include the J/ψ polarization results from $\sqrt{s}$=500 GeV p+p collisions. The finalized result is now awaiting the completion of the J/ψ polarization results from the same $\sqrt{s}$=500 GeV p+p data set (preliminary result in [10]), for publication.

2.4 Simulation Studies for STAR p+p/p+A Letter of Intent

In preparation for a possible transition from RHIC to eRHIC, the BNL ALD had requested STAR to submit a letter of intent [11], outlining the measurements that can be made in years 2020+, with the planned forward upgrades in STAR. The postdoc Nihar Sahoo and the PI were involved in this task. Specifically, Nihar performed simulations of J/ψ measurements in p+A vs. p+p collisions with planned forward upgrade detectors in STAR. The ratio of yields from the two systems R_{pA} provides a measurement of cold nuclear matter effects. Forward rapidities provide particularly strong discrimination of initial- vs. final-state effects of J/ψ suppression in p+A collisions. Nihar simulated J/ψ particles in PYTHIA events and reconstructed the invariant mass. With the planned forward upgrades, STAR will be able to measure J/ψ for $2.5<y<4.0$ through the mass reconstruction of electron-positron pairs. Tracking in the Forward Tracking System (FTS) together with the calorimetry of the planned Forward Calorimetry System (FCS) will provide electron/positron candidates for the invariant mass calculation. The Pre-Shower in the FCS will provide further rejection of hadrons.

Calculations of the J/ψ cross section as a function of rapidity predict $Bd\sigma/dy$~7 nb at y=3 (where B is the branching fraction of J/ψ to electron-positron pairs) in p+p collisions at RHIC, with a nearly linear decrease in the range of y=2.5 to 3.5 [12]. Such calculations describe the PHENIX measurement of J/ψ in p+p collisions for $-2.2<y<2.2$ well [13]. Therefore an approximate cross section of 7 nb was assumed in our forward acceptance window, which was multiplied by the suppression factor of 0.4 (from the predicted R_{pA} at y=3, giving us a cross section of 2.8 nb. With a pp-equivalent luminosity of 500 pb^{-1}, STAR can expect 1.4 million J/ψ produced in the forward acceptance window. This number is further reduced due to the decay opening angle, by momentum cuts on the electron/positron candidates (p>10 GeV/c), and by the electron/positron detection efficiency of approximately 0.8, as estimated in a similar study on Drell-Yan production (by another STAR group). The final expected numbers as a function of J/ψ p_T are shown in Fig. 3 (left). Also shown in Fig. 3 (right) is a simulation of the invariant mass of J/ψ scaled by its relative cross section and superimposed onto the invariant mass reconstructed from charged-particle background. The rejection factors of hadrons are again taken from estimates made in the study of Drell-Yan production and applied to the PYTHIA simulation.

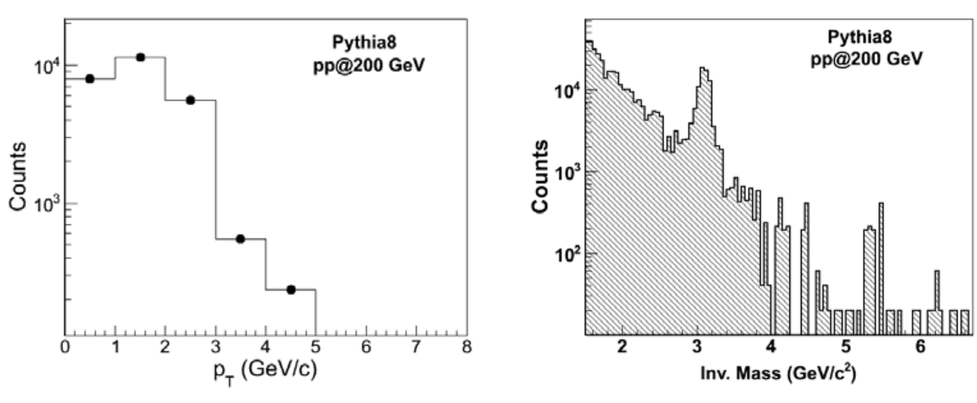

Figure 3. Simulation result of (left) J/ψ dN/dp_T distribution, showing the expected number of reconstructed J/ψ in the forward acceptance and (right) invariant mass distribution (log scale) of J/ψ within estimated hadronic background.

2.5 Service Work for Muon Telescope Detector (MTD)

The new graduate student Yanfang Liu has been working on determining the trigger efficiency in Run-14 Au+Au collisions. She has done this for low-luminosity and mid-luminosity data separately. The high-luminosity data was not yet reconstructed when she started this study, but it will also be analyzed soon. Shown in Fig. 4 (left panel) is the “Single-Muon” trigger efficiency, requiring an energy signal within a “trigger patch” (region) in the MTD, as a function of p_T, in the mid-luminosity data. It is found to approach 91% at high p_T.

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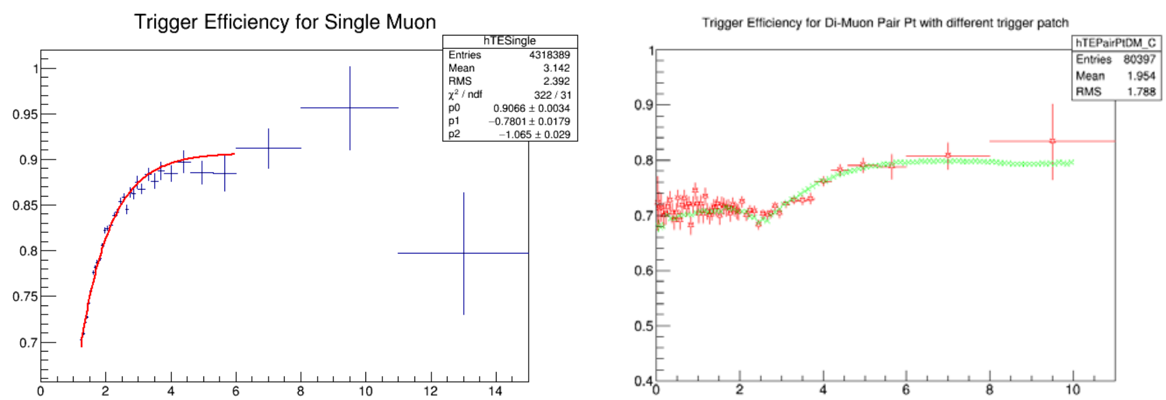

Figure 4. (Left) Single-muon trigger efficiency in Run-14 Au+Au mid-luminosity data, as a function of p_T. The line is a fit to the data. (Right) Di-muon trigger efficiency in Run-14 Au+Au mid-luminosity collisions, as a function of pair p_T. The red are the measured data points, and the green is the simulated di-muon efficiency taking as input the p_T distribution of muon candidates and the single-muon efficiency, as shown on the left panel.

The di-muon efficiency is also calculated and shown in Fig. 4 (right panel), as a function of the pair p_T, where $p_T^{pair} = \sqrt{(p_x^{\mu_1} + p_x^{\mu_2})^2 + (p_y^{\mu_1} + p_y^{\mu_2})^2}$. The measured di-muon efficiency agrees with a simple simulation of two uncorrelated muons, each having trigger efficiency as shown in the left panel of Fig. 4.

Last summer’s REU student (Matthew Breen) calculated survival probabilities of background particles in the MTD (pions, proton, and kaons). He used a sample of simulated particles embedded into and reconstructed within Au+Au collision data. He found that for p_T>1.2 GeV, muons had a 20% efficiency of being detected and passing the particle-identification criteria, while pions, protons, and kaons had less than 0.3% probability of detection and survival of the selection criteria.

The effort that the group has invested in understanding the response of the MTD and the triggers using the MTD will be useful for the J/ψ measurement in the next grant period.

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Appendix 1 - Summary of Publications

Period: June 2013 – December 2015

Name	Letter Publications	Other Refereed Journals	Invited Talks
Faculty			
S. Mioduszewski	21 (5)	22 (3)	1
Post-doc and former Post-docs			
N. Sahoo	19 (1)	18 (2)	2
M. Cervantes	19 (0)	16 (0)	1
A. Hamed	19 (0)	18 (3)	2

Appendix 2 - Principal Collaborators

Ahmed Hamed (University of Mississippi)
Peter Jacobs (Lawrence Berkeley Laboratory)
Alexander Schmah (Lawrence Berkeley Laboratory)
Fuqiang Wang (Purdue University)

Postdoctoral Advisors:
Dr. Samuel Aronson, Brookhaven National Laboratory.
Dr. Michael J. Tannenbaum, Brookhaven National Laboratory.

Ph.D. Thesis Advisor:
Prof. Kenneth Read, University of Tennessee.

Appendix 3 - Current and Pending Support

Support from this Grant:
The PI is currently supported by the following grant, which will expire at the start of the pending grant. The funds are expected to be nearly fully expended at the end of the funding period.

DE-FG02-07ER41485
"Toward Understanding the QGP with the STAR Experiment at RHIC"
Project dates: 06/15/2013-06/14/2017
- Total Project Costs:
$613K ($198K for the first year, $205K for the second, and $198K for the third, and $12K for the fourth on a no-cost extention)

Current (Renewed Grant):
The renewal grant support the PI for 3 years, one postdoc for 1.5 years, and 2 graduate students for 3 years.

DE-FG02-07ER41485
"Toward Understanding the QGP with the STAR Experiment at RHIC"
Project dates: 06/15/2016-06/14/2019
- Project Costs for the 3 years:
$620K ($226K for the first year, $217K for the second, and $177K for the third)