Progress on Quarkonium Studies in STAR

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Abstract. We review recent progress on the study of quarkonium production with the STAR detector. We discuss the results of a J/ψ → e⁺e⁻ test trigger for p + p collisions during Run V at RHIC. For the Au+Au data from Run IV, we discuss the implementation of a test trigger for Υ → e⁺e⁻. We obtain an upper limit on Υ production from the test trigger data. The prospects for future runs with upgraded detectors are outlined.

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1. Introduction

In the study of relativistic heavy-ion collisions, one of the main goals is to create a system of deconfined quarks and gluons in the laboratory and to study its properties. In the experiments performed at the Relativistic Heavy Ion Collider (RHIC) the expectation is that the state formed in the collision of the nuclei will be the one described by high-temperature Quantum Chromodynamics (QCD), the Quark-Gluon Plasma (QGP). One of the key properties that needs to be addressed is if the state produced requires a description that invokes deconfined quarks and gluons. This question is a longstanding one in the field. One of the avenues which experimentalists have used to explore the issue of deconfinement dates back more than 20 years: the idea that the charmonium states will be suppressed due to screening in the QGP [1]. More recently, studies in the Lattice QCD have aimed to put these ideas on first-principles footing, and the latest avenues of inquiry invoking studies of the charmonium correlators and the modification of the spectral functions suggest that perhaps the suppression might not be due to color screening[2]. From the experimental side, there are now measurements of J/ψ production from SPS to RHIC energies. The magnitude of the suppression observed by the NA50 collaboration [3] at √sNN = 17.2 GeV on Pb+Pb collisions, which has been corroborated with
much improved statistics by the NA60 experiment (In+In at the same beam energy)\cite{4}, is intriguingly similar to the one from the PHENIX preliminary results at $\sqrt{s_{NN}} = 200$ GeV\cite{5}. One possible interpretation of the results is that the charmonium excited states such as the $\psi'$ and $\chi_c$ could be suppressed while the prompt $J/\psi$ might still survive at least up to RHIC energies. It has become increasingly clear that further progress can be achieved by the measurement of a full spectroscopy of quarkonium states, including both charm and beauty. A measurement of the ratios of the various quarkonia states in-medium might be a key to connecting with first principles Lattice QCD above the deconfinement temperature \cite{6}.

In this paper, we will report on the progress in the STAR collaboration towards the measurement of quarkonia. We first summarize the capabilities of the detector for the measurement of electrons, since we will focus on the di-electron decay channel for quarkonia. We then discuss on the development of a di-electron trigger, its expected performance, and compare with data taken with a test implementation of the quarkonia triggers during RHIC Run IV. We end by discussing the prospects for the implementation of the triggers for the long RHIC p+p Run VI.

2. Electron Identification in STAR

The STAR experiment\cite{7} has as its main component a large-acceptance Time Projection Chamber (TPC) surrounded by a solenoidal magnetic field, covering $|\eta| < 1$ for tracks crossing the entire TPC volume. The TPC is complemented by the addition of Electromagnetic Calorimetry (EMC), both as a barrel\cite{8} surrounding the TPC and an endcap\cite{9} in the forward region $1 < \eta < 2$. The EMC increases the electron identification capabilities and allows to trigger on electromagnetic showers with energy depositions of $\sim 1$ GeV or above. For the triggers discussed in this paper, we used the Barrel EMC (BEMC) only. During Run IV, the BEMC coverage with operating detectors was limited to $0 < \eta < 1$. For Run VI, the BEMC has been completed, affording the full $|\eta| < 1$ coverage.

The offline electron identification capabilities have been discussed in Ref. \cite{10}. The main thrust is to combine the TPC energy loss measurement ($dE/dx$) with the energy of the shower measured in the BEMC. The electrons will deposit all their energy in the calorimeter, so the momentum $p$ measured in the TPC should be equal to the energy $E$ measured in the calorimeter. Hadrons will not deposit all their energy, so a selection on the ratio $E/p \sim 1$ is a first step in the electron selection. Next, from the TPC $dE/dx$ vs. $p$ measurement, a selection of tracks consistent with the electron hypothesis is performed. For example, a selection at the $2\sigma$ level (after the BEMC selection), yields an electron efficiency of 95%, with 80% purity. For this paper, the more important aspect are the online capabilities, which we now turn our focus to.
3. Quarkonia Triggers

At the trigger level, the information available is EMC. Since the EMC is sensitive to both electrons and photons, a further photon-veto is desirable for the $J/\psi$ trigger in order to reduce backgrounds. For the $\Upsilon$ trigger, the larger mass allows to place a more stringent requirement on the measured energies, keeping the event rate low enough so no additional photon-veto was deemed necessary. We discuss each trigger scheme now in greater detail.

3.1. Level-0

The STAR Level-0 trigger (the hardware trigger) consists of a four layer tree structure of data storage and manipulation boards (DSM). A trigger decision from any of the trigger detectors is made every 104 ns, i.e., for each RHIC bunch crossing. For the calorimeters, only a subset of the information is available at the bunch crossing rate of 9.4 MHz. The BEMC towers are combined in groups of 16 in their front-end electronics. For each group, the energy sum and the largest signal within the group (“High-tower”) is available with a resolution of 6 bits.

For the $\Upsilon$, the High-tower Level-0 trigger was found to give the best combination of efficiency and background rejection. For the $J/\psi$ a more elaborate “Topology” trigger was implemented. The BEMC was divided into 6 separate sections in azimuth, each having $20 \times 20$ towers (a coverage of roughly $1 \times 1$ in $\eta$ and $\phi$). The trigger then looked for High-towers in those sections consistent with a back-to-back topology: if a High-tower was found in one of the sections, the trigger logic looked for a High-tower in any of the 3 opposite sections in $\phi$ to issue a trigger. This is illustrated in Fig. 3.1.

Fig. 1. The $J/\psi$ Level-0 “Topology” trigger.
The electron-positron pair from the $J/\psi$ decay will create a signal in BEMC towers roughly back-to-back. In the example in the Figure, one track heads towards the 12 o’clock section in the detector and the logic looks for another High-tower in the 4, 6 or 8 o’clock sections (dot-dashed lines). There is no requirement to look at the adjacent 2 or 10 o’clock sections (dashed lines), an adjacent section would be ignored by the trigger logic. This effectively places a cutoff for $J/\psi$’s produced at large momenta, which is $p_{\perp} = 5.4$ GeV/c at $y = 0$. This is quite acceptable since a $J/\psi$ with such transverse momentum will produce higher energy electrons which can also be picked up by the standard single High-tower trigger that runs at a higher energy threshold.

3.2. Level-2

The STAR Level-2 trigger (the software trigger) consists of a fast CPU running software algorithms, with the requirement to issue decisions at a rate of 1 KHz. All the trigger information, in particular the individual tower data with full 12-bit resolution can be sent to the Level-2 CPU. The online calibration achieves a resolution of $17%/\sqrt{E}$ (compared to $14%/\sqrt{E}$ for the final offline performance).

The Level-2 quarkonium trigger uses the individual tower information to tag any tower above threshold as an electron candidate. In order to reject photons, another of the trigger detectors is used. The Central Trigger Barrel (CTB)[11], which consists of scintillator slats covering the TPC and located in front of each BEMC module, is used for this purpose. Charged particles will generate signals in the scintillator, so a coincidence between the BEMC tower and the slat that is in front of the tower is required by the trigger algorithm. Each slat covers 20 individual towers, so the veto works best for low multiplicity p+p events. In the high-multiplicity environment of a Au+Au collision, the rejection power of the $J/\psi$ trigger is sufficiently degraded that it is not worthwhile to run a trigger.

To achieve a better energy resolution, a simple 3-tower cluster is created instead of using the single tower energy. Since the charge of the particle is not known, a straight line is assumed, whereby we take the position vector of the cluster and make a straight line from the cluster to the center of the detector. With the set of candidate clusters, all pair combinations are made in order to calculate an approximate invariant mass given by $m^2 \simeq E_1 E_2 (1 - \cos \theta)$, where $E_1, E_2$ are the energies of each cluster in the pair, and $\theta$ is the 3-D opening angle between the straight-line vectors.

Since the total time for all Level-2 algorithms to run must be kept below 1 KHz, the aim was to keep the CPU time for each algorithm that runs on Level-2 below $t \leq 300 \mu s$. The quarkonium triggers were the only ones using Level-2 in Run IV so timing was not of the utmost concern at that time. After these triggers blazed the trail and proved a working Level-2 system, there are now several algorithms implemented and running in Run VI, so the timing requirements are now a reality.

The two quarkonia triggers implemented in STAR can then be summarized as follows. For the $J/\psi$, the full trigger consisted of the Topology trigger at Level-0
followed by the Level-2 invariant-mass algorithm with the photon veto. The trigger was deployed in Run V only for p+p collisions. The Level-0 stage of the trigger was first commissioned for a period of ~ 4 weeks, followed by Level-2 commissioning until the end of the p+p run. For the Υ, the trigger path involved the High-tower Level-0 followed by the Level-2 invariant-mass algorithm (with no additional photon veto). The Υ trigger can withstand the high-multiplicity environment of a Au+Au collision, and was commissioned during Au+Au data-taking in Run IV.

4. Results

We now discuss the performance of the quarkonia triggers in STAR. From the Υ triggers, we can first scrutinize the output at each of the trigger stages. The cluster energies obtained after Level-0 are shown in Fig. 2, left panel.

The calibration of the BEMC was expected to be uniform in transverse energy, $E_\perp$. There was an unfortunate miscalibration which was not discovered until after the run was over. The figure shows the cluster energies for the triggered sample. The $E_\perp$ threshold was set at 3.5 GeV. Since for the algorithm we use $E$, this is what appears in the ordinate of the Figure. The conversion from $E_\perp$ to $E$ should produce some smearing, but there was an additional smearing due to the miscalibration. This has been corrected for future runs. The right panel of Fig. 2 shows the invariant mass of the candidate pairs seen at Level-2. The threshold at $m > 7$ GeV is clearly visible. Similar results are obtained for the $J/\psi$ triggered events with the corresponding threshold ($m \gtrsim 2$ GeV).

The Υ trigger data from Au+Au collisions in Run IV was then analyzed offline[12]. The right panel of Fig. 3 shows the integrated luminosity for Run IV Au+Au running. The full line is the minimum bias luminosity seen at Level-0 and the dashed line is the fraction when the Υ trigger was live. The ordinate axis is the day number (in 2004). (The period around day 60 where no events are counted is from a dataset where the STAR magnetic field was ramped down from its full magnitude of 0.5 T.
Fig. 3. Left Panel: The integrated luminosity for Au+Au minbias events seen at Level-0. The dashed line is the total and the full line is the part where the Υ trigger was live. Right Panel: Upper limit for Υ production from the null result from the Au+Au sample collected by STAR in Run IV.

to 0.25 T as part of a $D^{*+}$ search.) The search for a signal in the Υ data sample yielded a null result. With the integrated luminosity achieved during the run, we estimate an upper limit for the Υ cross section, shown in the right panel of Fig. 4. The upper limit is consistent with binary scaling of the Υ cross section from p+p to Au+Au, as well as with scaling with $(AA)^{\alpha}$ where $\alpha = 0.96$ obtained from E866 results \footnote{13}. The addition of BEMC coverage in the $-1 < \eta < 0$ region, together with the correct calibration of the BEMC, should both allow for a measurement of a $4\sigma$ signal or better in a future Au+Au run.

The $J/\psi$ analysis of the trigger data from the commissioning period with p+p collisions is shown in Fig. 4 left panel. For comparison, the signal obtained from the analysis of the Au+Au data collected in Run IV is also shown \footnote{14}. The $J/\psi$ Level-0 trigger achieved a rejection power, defined as the number of background

Fig. 4. Left Panel: Raw $J/\psi$ signal in p+p obtained from the commissioning of the $J/\psi$ trigger during Run V. Right Panel: Raw $J/\psi$ signal from the offline analysis of Au+Au data from Run IV.
events that get rejected for every one that is triggered, of $\approx 10^3$. The addition of the Level-2 algorithm increased the rejection by a factor of $\sim 6$. The raw yield obtained in the trigger sample was consistent with simulations of the cross section folded with the detector acceptance and the trigger efficiency ($\epsilon = 0.36$). The mass resolution obtained offline for the triggered data-set is found to be 0.042 GeV/$c^2$, in excellent agreement with simulations. The mass resolution improves slightly in the Au+Au environment due to an improved vertex reconstruction with the larger track multiplicity. The reconstructed peak position is lower than the PDG value due to electron bremsstrahlung in the detector. The simulation results incorporating this effect gave a mass of 3.08 GeV/$c^2$, slightly above the 3.06 GeV/$c^2$ by $\sim 2\sigma$. The performance of the trigger is in general consistent with our expectations.

5. Future Prospects

The quarkonia triggers in STAR have been successfully implemented and the data from the test runs has proved that they are performing as expected. The Level-2 framework has proven to be a very useful tool, and is currently heavily used in Run VI for searches of jets and di-jet events, for example. As part of the p+p program for Run VI, STAR expects to collect enough statistics for a 3-4$\sigma$ signal in the $J/\psi \rightarrow e^+e^-$ channel.

The quarkonia triggers will benefit from the full installation of the Barrel EMC (completed for Run VI), which provides coverage in the region $|\eta| < 1$ over full azimuth. Thanks to this increased coverage, the acceptance for the di-electron events increases by a factor 4 over the acceptance from Run IV, as shown in Fig. 5.

![Fig. 5. The acceptance as a function of rapidity for $\Upsilon \rightarrow e^+e^-$ for the STAR BEMC in Run IV (dashed line) and in Run VI (full line)](image)

Longer term upgrades are also being considered. One avenue of improvement is to allow for a knowledge of the vertex position at Level-0. By upgrading the hardware and the electronics of the Time-of-Flight (TOF) Vertex Position Detector (used as a start-time for the TOF) a vertex resolution of $\sim 1 \text{ cm}$ could be available at Level-0. This would allow to select events near the center of the STAR detector; a benefit for all STAR analyses. For the quarkonia triggers, the knowledge of the vertex position would also allow for an improved online mass resolution.
Additional capabilities are also brought about by the full-barrel TOF upgrade (expected in 2009). The full-barrel TOF detector will enhance the electron identification capabilities over the same acceptance as the TPC and BEMC. At the trigger level, the finer segmentation of the TOF will also be an improvement over the current scheme of using the CTB as a photon-veto. The program for the future runs in STAR offers the exciting opportunity for studies in quarkonium production.

6. Conclusions

The quarkonia studies in heavy-ion collisions are a means to study the question of deconfinement in a QGP. This necessitates a full program of study of charmonium and bottomonium states. The STAR experiment has implemented two dedicated calorimeter-based triggers for the study of charmonium in p+p collisions and of bottomonium up to the highest-multiplicity Au+Au collisions. These have been put into production for p+p collisions in RHIC Run VI, where the barrel EMC is fully installed and instrumented. From the data collected during Run VI, we expect to make a 3-4σ measurement of $J/\psi$ production in p+p at $\sqrt{s_{NN}} = 200$ GeV.

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