QUARKONIUM AT STAR

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For the STAR Collaboration
I discuss some of STAR's expectations for reconstruction of J/ψ, ψ', χ and Υ resonances, and describe some of the planned measurements of production properties.

1 Introduction

Charmonium and bottomonium particles have a number of properties that make them interesting subjects for study in relativistic heavy-ion collisions. There are narrow states that decay with sizable electromagnetic branching fractions to relatively unusual (and therefore easily visible) products. Because the constituent quarks are heavy, they form non-relativistic bound states that can easily be assigned J^{PC} quantum numbers.

While the details of quarkonium production are still murky, that these states are produced dominantly by gluon-gluon fusion is incontrovertible. So the yield of these particles depends on the free gluon flux, anticipated to be higher in a quark-gluon plasma (QGP) than ordinary nuclear matter. Additionally, in a quark-gluon plasma, the free color charges can act to screen the attraction between the quark and antiquark, and this can serve to suppress the J/ψ and other states. This suppression should be a function of the separation between quarks, so should vary among different states. Finally, there are production models in which ${}^3S_1$ states like the J/ψ arise from gluon fragmentation, and where they carry nearly all of the momentum of the parent gluon. If this turns out to be true, the p_T spectrum of J/ψ's can be used to measure energy loss in the nuclear medium.

2 Detector

The heart of the STAR detector is a large radius (2 m) Time Projection Chamber (TPC) mounted inside a 0.5 T solenoidal magnet. The TPC measures charged particle momenta to a resolution of

$$\frac{\Delta p_T}{p_T} \approx 0.01 p_T$$

(where p_T is measured in GeV/c) in the interval $|\eta| \leq 1$. Inside the TPC is a Silicon Vertex Tracker (SVT) which allows precise measurement of impact parameter, which in turn improves the momentum resolution by a factor of approximately 3. Outside the TPC is an Electromagnetic Calorimeter (EMC) with a cell size of 0.05×0.05 in $\eta - \phi$ space, energy resolution of better than $20\%/\sqrt{E}$, a gas wire-strip chamber (SMD, for Shower Maximum Detector) with $10\times$ finer position resolution at the depth of maximum shower development and independent readout of the energy deposited in the first two radiation lengths of shower development. There are no muon detectors.

STAR has a four tiered trigger design. The input of the lowest level is the RHIC crossing clock (at approximately 10 MHz) and the output of the highest level is approximately 1 Hz of events stored on permanent media. Intermediate levels of the trigger have intermediate decision times and rejection factors.

Except where mentioned elsewhere, I describe the capabilities of a completed STAR (SVT and EMC fully installed), not the Day One configuration. This is appropriate, since the bulk of our data will be taken at full RHIC luminosity, which is not expected to be reached during the early part of the STAR experiment.

3 J/ψ Prospects

The decay mode $J/\psi \rightarrow e^+e^-$ has the largest branching fraction of any J/ψ decay (6%). There are several handles STAR has for identifying electrons:

• Electrons deposit all of their energy in the EMC; hadrons typically deposit substantially less (around 220 MeV).

• The shower development, both transverse (as measured by the SMD) and longitudinal (as measured by the energy deposited in the presampler) differs for electrons and hadrons.

• The energy deposition in the TPC and SVT differs for electrons and hadrons.

The first two have been measured for prototype calorimeters in a test beam, and we observe a hadron rejection of between 100:1 and 150:1 above a p_T of 2 GeV. This rejection is momentum dependent. GEANT studies on dE/dx show an independent $e-h$ separation of over 10:1. Despite planned improvements to the calorimeter, in this paper I assume a conservative combined $e-h$ separation of 800:1.

To estimate the yield, we need to know the cross-section for J/ψ production in pp collisions, and how it scales to AA. Unfortunately, HIJING, because of it's PYTHIA parentage, uses as a production model a theory that does not agree well with existing collider data. To avoid this problem, we use the CDF measured cross-section at $\sqrt{s} = 1800$ GeV and use PYTHIA only to scale the cross-section to 200 GeV. We then use the Hard Probes Collaboration prescription to extrapolate that to central Au-Au collisions. There are, of course, large uncertainties in this calculation. Until measurements are available at RHIC, *all* estimates are uncertain.

To estimate the background, we begin with HIJING central Au-Au events. 6% of the photons (this number comes from GEANT simulations of the STAR detector) are converted to e^+e^- pairs. A simple photon conversion veto algorithm (based on finding the track of the conversion partner) is applied to this sample of "electrons". Next, each hadron is assigned a probability (based on test beam data) to be misidentified as an electron. The two backgrounds are then added to the sample of real electrons (after correcting for efficiency and acceptance) and the result provides a model for what STAR will see in a given e^+e^- mass plot. Figure 1 shows such a plot for one standard RHIC year's running. The yield of reconstructed J/ψ's is approximately 11,000 events per year. Figure 2 shows the effect of raising the p_T cut on the electrons from 1.5 GeV to 1.9 GeV. Figure 3 shows Figure 1 with a suppressed zero, to show that the signal to noise, while not ideal, is not too poor to preclude precise measurements of the yield. Figure 4 shows the improvement to be gained by including calorimeter presampler and tracking dE/dx information. These quantities differ from the others in that test beam data is not available.

The 11,000 event J/ψ dataset refers to only the most central events. 10% of the J/ψ's are produced in the top 3% of events in centrality. There are another 100,000 or so J/ψ's produced in less central events. One indication of a quark-gluon plasma is the suppression of J/ψ's in the most central events: hence our emphasis on extremely central collisions, where the reconstruction is most difficult because of the larger backgrounds. Note that PHENIX often quotes the total J/ψ yields, so one must be careful in comparing expected yields from the two experiments.

The background in Figure 4 is roughly half composed of hadron pairs where both hadrons are misidentified as electrons. Half of the remainder is composed of one real electron (from a photon conversion) and one misidentified hadron; the other half is composed of two real electrons. Dalitz decays are negligible. This indicates that we are nearing the limit of improved signal to background with improved calorimetry. The area where improvements will soon have to be made is in that of rejecting conversion electrons. This improvement will probably come from the SVT, which enable us to do the following:

- Track down to lower p_T than the TPC, which will improve our efficiency of finding the conversion partner.
- Identify photons that have converted inside or beyond the SVT by the

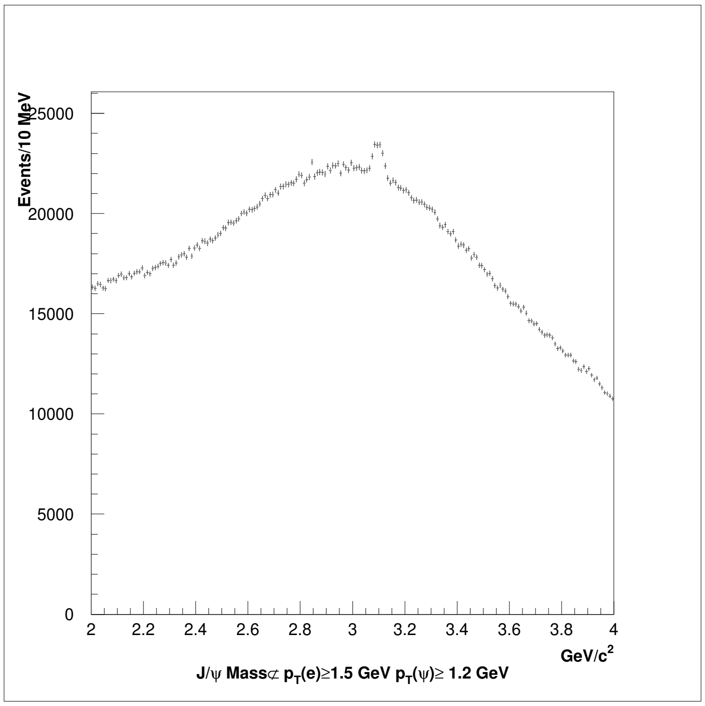

Figure 1: Simulated dielectron mass spectrum for central Au-Au collisions. Electron candidates are required to have $p_T(e) > 1.5$ GeV. No calorimeter pre-converter energy requirements nor tracking specific ionization requirements have been applied.

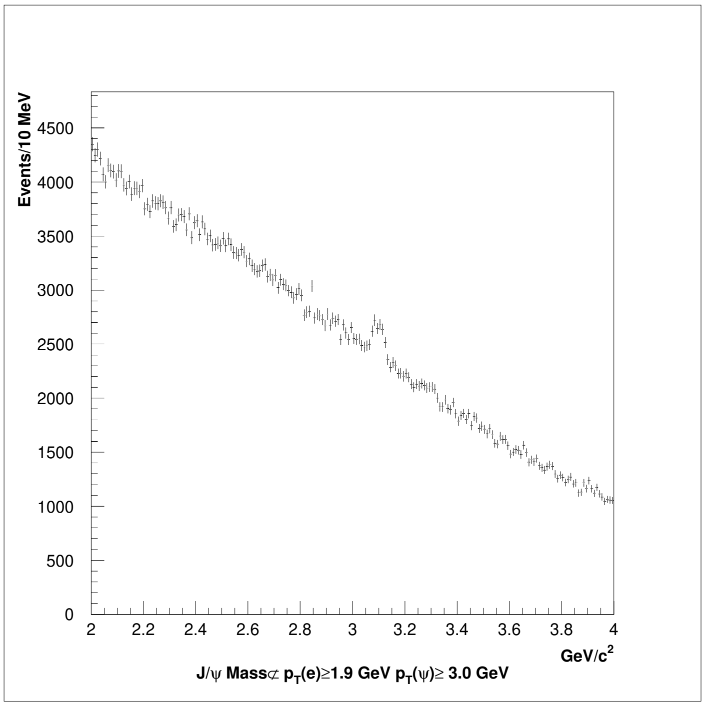

Figure 2: Simulated dielectron mass spectrum for central Au-Au collisions. Electron candidates are required to have $p_T(e) > 1.9$ GeV. No calorimeter pre-converter energy requirements nor tracking specific ionization requirements have been applied.

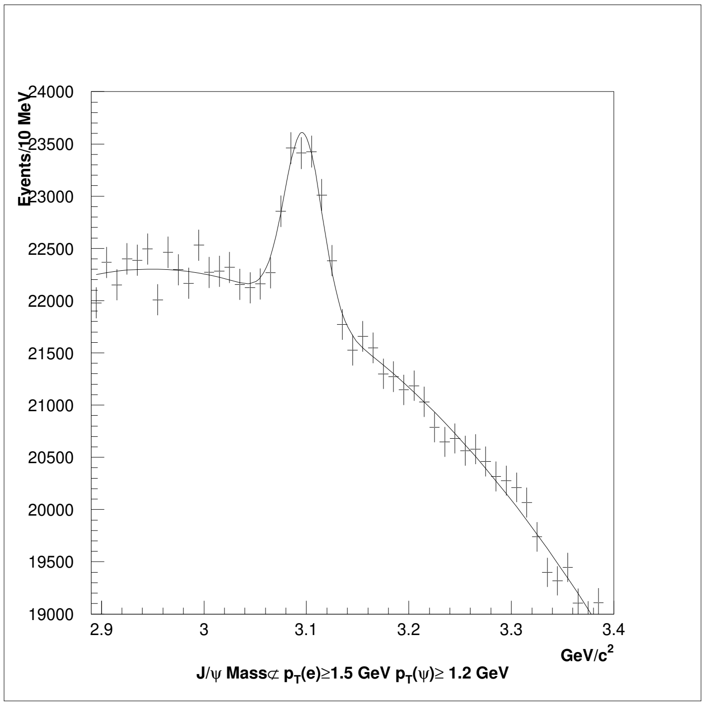

Figure 3: Simulated dielectron mass spectrum for central Au-Au collisions. Electron candidates are required to have $p_T(e) > 1.5$ GeV. No calorimeter pre-converter energy requirements nor tracking specific ionization requirements have been applied. This is the same as Figure 1, with a suppressed zero.

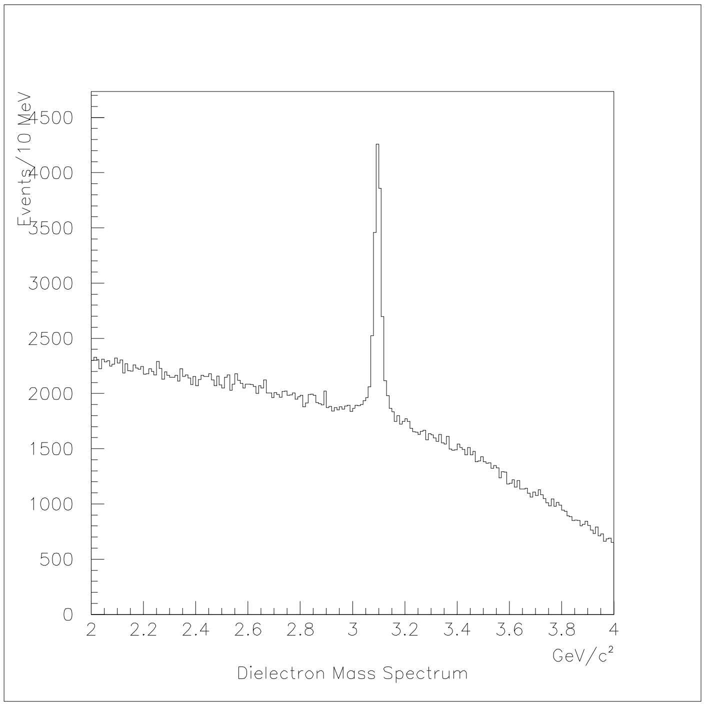

Figure 4: Simulated dielectron mass spectrum for central Au-Au collisions. Electron candidates are required to have $p_T(e) > 1.5$ GeV. The calorimeter pre-converter layer is required to measure an energy at least twice that of a minimum ionizing particle. The tracking detectors must measure an ionization consistent with an electron.

absence of SVT tracks or hits.

• Identify some photons which have converted before the SVT via the impact parameter of the tracks.

Work on these improvements is underway.

The yield of J/ψ's depends critically on the minimum p_T where electrons can be identified. Figure 1 assumes a minimum p_T of 1.5 GeV. While electron-hadron separation does get poorer at lower p_T, the limitation appears to be at the trigger level: the minimum p_T will be determined by dead-time considerations. The assumption in making this plot is that we will trigger on centrality at Level 0, and at Level 3 select events with an apparent electron pair in the appropriate mass window. For peripheral collisions, we instead trigger on electrons (actually, two calorimeter towers above a threshold) at Level 0, and refine the selection at Level 3. We have not investigated the use of the middle trigger levels, but clearly it will improve things, especially at mid-centrality.

4 Heavier Charmonium States

The suppression of quarkonium production in a Quark-Gluon Plasma from color screening is related to the radius (and therefore the binding energy, and therefore the mass) of the meson: the larger the radius, the larger the screening, and the greater supression.

4.1 ψ'

There are two decay modes of the ψ' that are of interest, $\psi' \to e^+e^-$ and $\psi' \to J/\psi\pi^+\pi^-$. The ψ' was included in the simulation shown in Figure 1, and it shows just under a 3σ signal. This corresponds to a $\pm 30\%$ measurement of the ψ' yield, which is probably at the threshold of being interesting. Work on improving $e-h$ separation and on rejecting photon conversions will improve this, but it is premature to invest too much time on this before there is real data in hand.

The other decay mode, $\psi' \to J/\psi\pi^+\pi^-$, has not been investigated. It's not obvious that the large number of pions will drown the signal in combinatoric background. The requirement that $m(J/\psi + \pi) \leq m(\psi')$ removes a majority of the pions. If additionally rejection is necessary, requiring that $m(\pi\pi)$ be near $m(\psi') - m(J/\psi)$ can provide additional rejection.

4.2 χ *Mesons*

The J/ψ and ψ' are both S-wave states. Comparing with the P-wave χ states would be interesting if it were practical. Unfortunately, it seems that it is not.

In the mode $\chi \rightarrow J/\psi\gamma$, the combinatorics for the photon are fierce. There can be dozens of photons per event that cause a $J/\psi - \gamma$ combination in the χ mass window.

Hadronic modes (such as $\chi \rightarrow \pi^+\pi^-$) might appear to have potential, but again, combinatoric backgrounds overwhelm the signal. Figure 1 shows the approximate shape of the hadronic background, although a factor of 30,000 lower. This mode does not appear promising in the RHIC environment.

The only option not presently excluded is that of measuring the polarization of J/ψ's, and from this polarization to infer the fraction of χ daughters, which may have different polarizations. Until the first polarization measurements from hadron collider experiments are available, this remains speculative.

5 Open Charm

Since there are effects that can serve to both increase and decrease J/ψ yields in a QGP, it is highly desirable to have independent measurements that can be used to disentangle the various effects. One could be the ratio of J/ψ production to open charm production. The signature $\mathrm{Au} + \mathrm{Au} \rightarrow c(\rightarrow e^+ + s) + \bar{c}(\rightarrow e^- + \bar{s}) + X$, where the electron-positron pair is reconstructed is particularly appealing, since it is both easily triggerable and has the same final state as the J/ψ. The excess in opposite sign pairs with mass between 4 and 10 GeV/c^2 over same sign pairs in the same window in HIJING has statistical significance comparable to the J/ψ itself. Unfortunately, adding b-quark decays complicates the matter. Bottom quarks produce both same sign and opposite sign pairs, and their dielectron yields can be comparable (even larger, for some selection requirements) to charm. How best to remove this contribution (or whether it is even necessary, since b quarks are also produced by gluon fusion) is the subject of present study.

6 Bottom Quarks and Upsilons

One might ask if STAR have any sensitivity to bottomonium as well as charmonium: is the $\Upsilon \rightarrow e^+e^-$ decay visible?

Unfortunately, the yields at STAR are expected to be substantially (a factor of 500) smaller. We expect only a few dozen events in the bin of highest centrality, probably too few to confirm any effect. This yield may be surprising in light of CDF data, where their $\Upsilon \rightarrow \mu^+\mu^-$ signal is only down by an order of magnitude relative to $J/\psi \rightarrow \mu^+\mu^-$. The reason is that CDF is restricted to triggering on J/ψ's at high p_T: $p_T > m(J/\psi)$, but can reconstruct Υ's down to $p_T \approx 0$. STAR can trigger on and reconstruct J/ψ's down to $p_T \approx 0$, which greatly increases the fraction of J/ψ's on tape. Unfortunately, once this gain is accomplished, it can't be applied a second time to increase the Υ yield further.

However, this does not mean that we are insensitive to bottom quark physics. In addition to the continuum dielectron pairs mentioned earlier, roughly 10-15% of all J/ψ mesons are daughters of b hadron decay. This should be insensitive to $\sqrt{s}$, since both are produced by gluon fusion; their cross-sections change together. We therefore expect 1000-1500 J/ψ's from b decay in the bin of maximum centrality.

Monte Carlo studies show an average flight distance of the b hadron (before decay) of approximately 600 μm. This is comparable to the two-track resolution of the SVT, between 400 and 700 μm. We can therefore measure the fraction of J/ψ's from b's to a precision of about 10% in each bin of centrality. This provides new information on J/ψ suppression. The only J/ψ's that are suppressed in a QGP are those produced promptly - those born of weak decays are too far away for QGP effects to have any effect. So a signature of a QGP is an increase in the average lifetime of the J/ψ, since bottom quark production is being enhanced (by the increase in effective gluon flux) at the same time the J/ψ fragmentation is being suppressed by the color screening.

7 Conclusions

The STAR detector is capable of reconstruction the J/ψ meson in its dielectron decay channel, along with continuum dielectrons from heavy quark decay. The limitation is not instrumental - the ability of the STAR detector to identify electrons - rather, the primary limitation is yield. We expect to reconstruct of order 10,000 events per year in the bin of highest centrality, with perhaps ten times that many integrated over all bins of centrality.

This is enough for a rather detailed study of J/ψ production. The yields for ψ' and the high p_T χ mesons which are in a low enough background region of phase space to permit reconstruction are too small for precision measurements. The only parent of the J/ψ with a large enough yield for clear observation is the b quark.

Even limited to just the J/ψ, there is a rich physics program available to STAR: the yield provides information on the gluon flux as well as color screening, especially when compared to the open charm and $b \to J/\psi X$ yields. The p_T distribution measures energy loss in a nuclear medium, either by comparison with pp data or across different bins in centrality. The STAR quarkonium program should provide several unique windows into the physics of heavy ion collisions at RHIC.