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Charmonium Production at STAR

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Abstract

The yields of various charmonium particles (J/ψ, χ and ψ') that could be expected if STAR implements a dielectron trigger are calculated, based on PYTHIA predictions and CDF data. A brief discussion of aspects of the pp, pA and AA physics programs possible with data sets of this size is presented.

1 Introduction

Charmonium production by hadrons has been mysterious ever since the 1974 discovery of the J/ψ. [1] Many models have been suggested [2], but even after 20 years they have difficulty predicting the J/ψ, ψ' and χ cross sections, even at TeVatron collider energies, where perturbative QCD is supposed to work well. [3] Some discrepancies are as large as a factor of 50!

The *pp* program at STAR provides a unique opportunity to add more experimental data to this puzzle. The center-of-momentum energies of 200 GeV and 500 GeV at STAR lie between the lowest existing collider data ($\sqrt{s}$ = 630 GeV at UA1) and the highest existing fixed-target data ($\sqrt{s}$ = 40 GeV at Fermilab E-771). Because the branching fraction $BF(J/\psi \rightarrow e^+ + e^-)$ is large - about 6% - a dielectron trigger would allow us to write several hundred thousand J/ψ events to tape.

Should a clear understanding of how charmonium is formed in hadronic interactions develop, the possibility arises of extending these measurements into the realm of spin. For example, in models where charmonium arises from gluon fragmentation in the process $gg \rightarrow gg$, the J/ψ often carries virtually all of the momentum of the parent gluon. This therefore gives us exceedingly well measured "jets" at very low E_T: around 6 GeV. Also, in some models the charmonium states (especially χ's and ψ's) are polarized, and this polarization is strongly correlated to the polarization of the parent gluon. Once can test this family of theories by comparing the measured polarization to the prediction using the polarized $pp \rightarrow$ 2jets data, also from STAR. STAR is unique in that it can use spin degrees of freedom as an additional tools in understanding the mechanism of charmonium production. Once charmonium production is reasonably well understood, we can then turn it around and use charmonium production as a way of better understanding the spin structure of the proton, especially at lower E_T than we can reach with jets.

There has been talk of looking at s-channel formation of χ_2's as a measurement of $\Delta G(x)$. These are predominantly low p_T particles, and the particles described above are high p_T: $p_T \geq\sim m$. These are clearly different processes.

In heavy ions, charmonium production is sensitive to shadowing, the softening of the gluon structure functions in nuclei relative to nucleons, and to the effects of quark-gluon plasmas, which are expected to suppress charmonium production.

Besides being of intrinsic physics interest, having a large number of identified electrons allows us an *in situ* calibration of the EMC, via E/p distributions. Additionally, having a large number of track pairs of a known mass can be used to check various systematic effects in the tracking (such as false curvature). This might well be critical in high luminosity pp running, where space charge effects might be large and time dependent.

2 J/ψ Yields

The basic strategy is to determine the yields from CDF measurements. The elements that enter into this calculation are the relative integrated luminosities, the relative cross sections and the relative acceptance.

2.1 Integrated Luminosities and CDF Yields

CDF recorded approximately 86,000 $J/\psi \rightarrow \mu^+\mu^-$ events in 19pb^{-1} during the 1992-1993 run. The expectations for 100 days of pp running at STAR are 800pb^{-1} at 500 GeV and 320pb^{-1} at 200 GeV.

Of these 80,000 events, 64,900 had both muons inside $\eta \leq 0.6$. This region had the most uniform trigger and instrumentation, so we use it for the extrapolation to STAR. The muon fiducial acceptance in this region was a little less than 85%.

2.2 Relative Cross Sections

To get the J/ψ cross sections at 500 GeV and 200 GeV, we use PYTHIA, and assume that the *ratio* of cross sections between 1800 GeV and STAR energies is correct. (There is no difference between pp and $\overline{p}p$ in PYTHIA, since the charmonium process PYTHIA simulates is $gg \to g\psi$. Because of CPT, the gluon distributions for protons and antiprotons are identical.) This assumption is not justified, since we don't have a model that accurately predicts ths cross section. The whole point of making a charmonium cross section measurement is because we do not know the answer.

Nonetheless, as an estimate this is as reasonable as anything else we might use. Because of the near equality of the J/ψ cross sections using proton and antiproton beams on nuclear targets, we know that the process is gluon induced. The relative cross sections therefore depend mainly on $G(x)$ and its evolution, which PYTHIA probably gets right.

So, although this relative cross section calculation is not completely justified on theoretical grounds, it's the best we are likely to do before we actually take data.

The PYTHIA results (for $p_T(J/\psi) > 6$ GeV, which is where our acceptance starts) are that the cross section at 500 GeV is 0.18 times the cross section at 1800 GeV, and the cross section at 200 GeV is 0.038 times the cross section at 1800 GeV.

2.3 Acceptance and Yields

We assume that we can reconstruct and trigger on pairs of 3 GeV electrons. The threshold of 3 GeV was chosen on trigger bandwidth considerations. Reconstruction of these events is not expected to be too difficult: LEGO plots of these events are quite striking.

Lepton universality (and direct measurements) requires $BF(J/\psi \to e^+e^-) = BF(J/\psi \to \mu^+\mu^-)$ within small corrections for phase space. The STAR calorimeter covers $\eta \leq 1.0$ which according to a toy Monte Carlo (described later) doubles the J/ψ yield over CDF's $\eta \leq 0.6$. (There is a factor of 1.67 improvement on each muon, but since the muon rapidities are correlated, the actual improvement lies between 1.67 and 1.67^2 or 2.77.) Requiring both legs of the J/ψ to have transverse energies above 3 GeV costs us a factor of 5 relative to CDF's p_T requirement (this from CDF data). Finally, we assume 85% acceptance and efficiency for these electrons, which is the same as the 85% acceptance and efficiency for CDF muons.

Combining all these factors gives us a factor 0.4 in relative acceptance compared to CDF.

Putting everything together gives an expected yield of 200,000 reconstructed $J/\psi \rightarrow e^+e^-$ events at 500 GeV, and 16,600 (with the identical trigger - the possibility exists for a less severe trigger requirement and thus higher yield at lower $\sqrt{s}$) at 200 GeV.

3 J/ψ Resolution

A toy Monte Carlo was written to estimate the resolution on the J/ψ. Each electron had it's energy and momentum magnitude smeared according to the resolution functions $\Delta E/E = 16\%/\sqrt{E}$ and $\Delta p_T/p_T = 1\% p_T$. Next, the program used the "measured" p_T and E_T of the electron to calculate the expected uncertainties on these measurements and used these to calculate a weighted average E_T. For example, an electron at $\eta = 0$ with (measured) $E_T = 5.3$ GeV and $p_T = 5$ GeV has an energy uncertainty of 7% and a p_T uncertainty of 5%. The energy measurement is therefore assigned a weight of 5/12, and the momentum measurement a weight of 7/12. The best estimate of the electron's transverse momentum and energy is therefore 5.13 GeV.

Once the electron's total energy has been determined (after smearing), its four-momentum is calculated, assuming that the uncertainty on the angles from tracking is small compared to the uncertainty on the curvature. Next, dielectron masses are computed for pairs of "good electrons" - electrons in the Barrel EMC fiducial region with $E_T > 3$ GeV. The resultant mass spectrum shows a peak at the J/ψ mass with a width of 63 MeV. While this is larger than many experiments, it is still more than good enough to resolve the J/ψ and ψ'. (By about 6 standard deviations)

One interesting feature of STAR is that the tracking and calorimetry resolutions are comparable for the J/ψ. The crossover point, above which calorimetry is better than tracking, is 6 GeV. The average electron energy is about 5.5 GeV. Combining the tracking and calorimetry makes a dramatic improvement over simply picking one or the other reconstruction method.

4 χ Yields

Most experiments have measured about 40% for the fraction of J/ψ's that are χ daughters, independent of energy. Because of this, we can simply take the number of

χ's per J/ψ seen by CDF and multiply by the expected number of J/ψ's. CDF [4] observes 67 $\chi \rightarrow J/\psi + \gamma$ decays in 896 $J/\psi \rightarrow \mu^+\mu^-$ decays. These muons came in on a 3 GeV (each leg) dimuon trigger, which matches our proposed 3 GeV trigger for electrons. We therefore expect about 15000 reconstructed $\chi_{1,2} \rightarrow J/\psi + \gamma$ (followed by $J/\psi \rightarrow e^+e^-$) events at 500 GeV. The PHENIX prediction is 1200 χ_2 events. At 200 GeV, the expected $\chi_{1,2}$ yield is about 1250 events. (total)

This is rather conservative. CDF reconstructed photons down to 1 GeV. Below 1 GeV, the backgrounds and contamination from the underlying event energy in the χ photon tower were both simply too large to warrant including the extra signal. The STAR calorimeter is similar, but has finer granularity: $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ rather than the 0.1×0.3 of CDF. This means that the average energy per tower at 1800 GeV would be only 1/3 what it is at CDF. But STAR isn't running at 1800 GeV; it is running at 500 and 200 GeV. So the underlying event energy in the tower is only 4-9% what it is at CDF. The number of background π^0's from the underlying event is also smaller.

The same toy Monte Carlo as described above gives a width of the χ signal of 53 MeV. The χ_1 and χ_2 are 45 MeV apart from each other, so the single 53 MeV signal arises from two 25 MeV wide signals 40 MeV apart. (The χ mass is calculated via $m(ee\gamma) - m(ee) + m(J/\psi)$, which allows for better resolution than the $J/\psi \rightarrow e^+e^-$ width, which may at first seem counterintuitive) A width on a single signal of 25 MeV is not sufficient to resolve the two χ peaks separately: the separation will have to be done statistically.

The χ_0 decay has a branching fraction to photons of only 0.7%, barely 1/20 of the branching fraction $BF(\chi_1 \rightarrow J/\psi + \gamma)$. Spin counting suggests that its yield will be three times smaller, so we expect a total signal 1/120 as large as the merged χ_1 and χ_2 peaks, or just over 100 events at 500 GeV. Fortunately, it lies 100 MeV below the χ_1, so it will not be swallowed by the larger peak unless there are substantial non-Gaussian tails in the resolution. However, the yield is so small it is likely to be swallowed by background fluctuations unless our signal to noise ratio is substantially better than CDF's. The reconstruction of the decay $\chi_0 \rightarrow J/\psi + \gamma$ looks marginal at best.

5 ψ' Yields

The ratio of ψ' to J/ψ yields is about 2% for all experiments with $\sqrt{s} > 25$ GeV. This (odd as it may seem) is more or less independent of experiment, beam species and center of momentum energy. This ratio implies we should see about 4000 $\psi' \rightarrow e^+e^-$

events at 500 GeV, and 330 at 200 GeV.

There are other decay modes of the ψ', for example $J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, and $J/\psi\eta$. There is some possibility of reconstructing ψ's in the first channel, but channels involving multiple photons are extremely difficult.

6 Heavy Ion Physics

6.1 pA

If the dominant charmonium production mechanism is $gg \to (c\bar{c})g$, one can probe the gluon structure function with charmonium production. This isn't terribly new: fixed target experiments have been doing this for years. By comparing nucleons with nuclei, such as with asymmetric colliding beams or with proton beams on nuclear targets, one can study the change in the gluon distributions as one goes from nucleons to nuclei. Fermilab Experiment 705, for example, showed a 4σ preference for forward going J/ψ's in pLi interactions [5], which was interpreted as a softening of the gluon structure function in lithium nuclei relative to protons.

Measurements of the A dependence of J/ψ production gives information on shadowing. The cross section as a function of A is often parameterized as A^α. Typical values of α from fixed target experiments are around 0.92 [6]; an absence of shadowing would suggest $\alpha = 1$.

The luminosity of pAu running is $5 \times 10^{28}\mathrm{cm}^{-2}/\mathrm{s}$, as compared to $8 \times 10^{31}\mathrm{cm}^{-2}/\mathrm{s}$ for pp. So, before A dependence is included, there is a factor of 1600 difference. A dependence (assuming $\alpha = .92$ reduces this to a factor of only 12.4. That will give us about 1300 $J/\psi \to e^+e^-$ events, about 100 $\chi \to J/\psi + \gamma$ events, and perhaps two dozen $\psi' \to e^+e^-$ events.

Statistically, this will let us measure α to about 0.5%. However, achieving this level of precision requires a precise and accurate measurement of the luminosity in both pp and pA collisions, something which is difficult to do to better than 10%. Factoring this in gives us a 2% measurement on α overall, but we can also compare α at several p_T points to comparable precision.

6.2 AA

One signature of a deconfined state is suppression of J/ψ yields. The idea is that the free color charges in quark gluon plasma act to suppress the attraction between the charmed quark and its antiquark. Because the ψ' is a larger object with the same decay mode, one expects a larger suppression there, in an environment with similar efficiencies and systematics to the J/ψ. The ratio $N(\psi')/N(J/\psi)$ may therefore be a very sensitive test of observation of a deconfined state.

At the present time, there have been no detailed studies of low energy electron reconstruction in the busy AuAu events. Nonetheless, just hand scanning a few AA events suggests that 3 GeV is not grossly off. Here we assume 3 GeV on each leg, and once the ability simulate many *background* events is at hand through GSTAR+EFS, we can revisit this threshold.

The luminosity in AuAu is $2 \times 10^{26}\mathrm{cm}^{-2}/\mathrm{s}$, as compared to $5 \times 10^{28}\mathrm{cm}^{-2}/\mathrm{s}$ for pAu, or a factor 250 lower, again, before A dependence. If we take another factor of $A^{0.92}$, that gives us yields a factor of 2 smaller than pAu, or give us about 650 $J/\psi \to e^+e^-$ events. In the busy environment of AuAu, it is unlikely that χ decays can be reconstructed - identifying and accurately measuring the correct photon in an environment where there are a thousand incorrect photons is difficult. Similarly, although there will be about a dozen ψ's, accurate counting of a number this small over a background is also quite difficult. It is unlikely that the method involving the ratio $N(\psi')/N(J/\psi)$ will be competitive with the direct measurement.

If one divides the sample into the 10% most plasma-like and 90% least plasma-like events once can ask how much sensitivity one gets with 650 events. Assuming the background does not dominate the ability to count J/ψ's, the one sigma measurement is a 13% suppression (or enhancement - the technique is sensitive to this surprising possibility too) in J/ψ yields. A 40% suppression would produce a 3σ effect.

It is important to stress that these conclusions can and probably will change once we learn what our real electron threshold is for AuAu. Is it 3 GeV? 2 GeV? 4 GeV? The ultimate yields and therefore sensitivity depend on this answer.

7 A Brief Word on Other Particles

This same analysis can be extended to other $q\overline{q}$ states. Ideally, other STAR Notes describing the physics of these states will be written. For now, we just briefly touch on what we might expect with Υ's and ϕ's.

7.1 Bottomonium

CDF has had no problem reconstructing the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states via their decays to $\mu^+\mu^-$. Since our J/ψ yields are larger than theirs, it is probable that we will also be able to detect them as well, and extend this study to $b\bar{b}$ states as well as $c\bar{c}$. To make a more definite statement, however, we need to calculate the yields and the resolution: can we resolve the three states event by event? If not can we resolve them statistically?

The mass resolution $(\Delta m/m)$ in the J/ψ case works out to 2%. If we maintain the same resolution for the Υ, we expect widths of the Υ's of about 200 MeV. Since the separations between the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ are 563 and 332 MeV, resolving the $\Upsilon(2S)$ and $\Upsilon(3S)$ peaks looks difficult (although statistical resolution will probably be quite good), but resolving the $\Upsilon(1S)$ and $\Upsilon(2S)/\Upsilon(3S)$ peaks looks promising.

Upsilon kinematics are quite different from J/ψ kinematics. To get two 3 GeV electrons from a J/ψ decay, the J/ψ has to have a substantial boost. The Υ, on the other hand, has sufficient mass that even Υ's at rest can decay into electrons with $p_T > 3$ GeV. Being able to reconstruct lower p_T Υ's, where the cross section is large, partially compensates for the lower total cross-section. This advantage turns into a liability for reconstructing the decay $\chi_b \to \Upsilon + \gamma$, however. Because the Υ's have very low boosts, these photons are very soft and harder to detect than the corresponding $\chi_c \to J/\psi + \gamma$ photons.

7.2 Strangeonium

Light quark spectroscopy is complicated, both because of large mixing, and because the non-relativistic assumption (already marginal with charm) is poor in bound states of strange quarks and antiquarks. A "strangeonium" spectrum of $s\bar{s}$ states is difficult to identify, with one exception: the $\phi(1020)$ is almost purely a $^3S_1$ $s\bar{s}$ state. One item of particular interest about the ϕ is its branching fraction to dileptons in AuAu collisions.

Will the ability to reconstruct 3 GeV electrons in AuAu let us measure this? Unfortunately, even crude calculations don't look promising: reconstructing 3 GeV electrons will let us reconstruct those ϕ's with $p_T(\phi) > 6$ GeV or so. STAR [7] predicts 12,000 charged particles with $p_T > 10$ GeV, so there should be about a million charged particles with $p_T > 6$ GeV. In e^+e^- annihilation, $N(\phi)/N(\pi)$ is about 7×10^{-3}, so we expect about 7,000 ϕ's in the p_T range of interest. Since $BF(\phi \to e^+e^-)$ is 3×10^{-4}, that works out to a total yield of 2 events. This is not a very firm number, but nonetheless I think that we can correctly conclude that the ability to reconstruct 3

GeV electrons in AuAu collisions at STAR is not sufficient to measure the change in $BF(\phi \to e^+e^-)$ as a function of other event variables.

8 Conclusions

If STAR implements a dielectron trigger, we can expect to record about 200,000 J/ψ's in the 500 GeV pp program. That will provide 400,000 track pairs of known mass to understand tracking systematics (such as space charge effects), and put about 330 electrons in each tower for *in situ* calibration. The 5.6% width of the E/p distribution from a toy Monte Carlo should allow an absolute calibration of better than 0.5%. The data can be broken up into several sections, each calibrated to within 1%, to study long term effects on the calorimeter.

Along with these 200,000 $J/\psi \to e^+e^-$ events, we expect 15,000 $\chi_{1,2} \to J/\psi\gamma$ and 4000 $\psi' \to e^+e^-$ events. The χ expectations are conservative.

At 200 GeV, we expect 16,600 J/ψ, 1200 χ and about 330 ψ' events. Lower trigger thresholds could substantially improve this.

In heavy ions, we expect 1300 $J/\psi \to e^+e^-$ events, about 100 $\chi \to J/\psi + \gamma$ events, and perhaps two dozen $\psi' \to e^+e^-$ events in pAu collisions. This will allow us to probe gluon shadowing/softening to the few percent level. In AuAu we expect several hundred J/ψ decays, enough to see a moderate suppression in J/ψ yields due to a deconfined phase, but probably too few to see the same effect in heavier charmonium states. The yields in AuAu are sensitive to our threshold for electron reconstruction in these events, and this threshold is not well known at the present time. More simulation will clearly be beneficial here.

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