EPJ manuscript No.
(will be inserted by the editor)

J/Ψ and Heavy-Quark Production in E866/FNAL and PHENIX

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Received: date / Revised version: date

Abstract. The production of heavy quarks in nuclei is modified from that for a free nucleon by a number of nuclear effects including shadowing of the nuclear gluon distributions, energy loss of the incident gluon, and, in the case of the J/Ψ, disassociation of the $c\bar{c}$ pair (absorption) as it exits the nucleus. Measurements in the E866/NuSea 800 GeV fixed target experiment show a large suppression of the closed-charm yield with strong kinematical dependencies and with a slightly stronger suppression for the Ψ' than for the J/Ψ near $x_F = 0$. On the other hand, a measurement of the D meson nuclear dependence near $x_F = 0$ shows no suppression. At RHIC the J/Ψ is thought to be a key signature for the creation of a quark-gluon plasma (QGP) in heavy-ion collisions, but the non-QGP suppression already seen in p-A collisions at lower energies shows that we must first understand these non-QGP effects on the J/Psi in order to gain a clear understanding of its production in nucleus-nucleus collisions. The most recent run at RHIC included deuteron-gold collisions and will serve as a baseline for these cold nuclear matter effects at RHIC energy. Here I report on the first results for the J/Ψ and for open-charm at PHENIX including the d-Au results. The present knowledge of gluon shadowing is very uncertain, especially in the large rapidity region of the PHENIX muon arms, and these measurements should help us determine how strong it is and perhaps even its dependence on impact parameter.

PACS. 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes – 25.75.-9 Relativistic heavy-ion collisions – 25.75.Dw Particle and resonance production – 14.65.Dw Charm quarks – 14.40.Lb Charm mesons

1 Introduction

Here I will review results and prospects for J/Ψ and heavy-quark production from the E866/NuSea experiment at

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Fermilab and from the PHENIX experiment at RHIC. The topics I will cover include 1) gluon shadowing and energy loss in nuclei, 2) J/Ψ production mechanisms and absorption in nuclei, 3) the Cronin effect, and 4) early results from PHENIX for the just completed d-Au run at RHIC.

2 Shadowing

Shadowing is the depletion of small momentum-fraction (x) gluons in nuclei relative to the nucleon. One way to understand the origin of shadowing is that very low-momentum-fraction partons, by the uncertainty principle, have large size, overlap more with their neighbors and fuse together thus enhancing their population at higher momenta at the expense of lower momenta. Another picture involves coherence between different scattering centers where for large coherence length, larger than the typical intra-nucleon distance, can result in destructive interference and an effective "shadowing" of the partons deeper inside a nucleus. Some theorists have told me that these two pictures are equivalent, but this is beyond the scope of this talk.

An example of shadowing is seen in the nuclear suppression of the Drell-Yan process in our E866/E772 data is shown in Fig. 1, where one sees a clear depletion of the anti-quarks at target-parton momentum fractions(x_2) below about 0.06.

In Fig. 2 is shown the ratio between lead and hydrogen gluon structure functions from the parameterization of Eskola et al[3]. The production of heavy-quarks goes mainly through gluon-fusion, so the shadowing shown here is relevant for charm production. In this phenomenological approach the main information comes from deep-inelastic muon scattering and the gluon information comes mainly from the Q^2 evolution of these structure functions. In addition to the shadowing at small x values one also sees

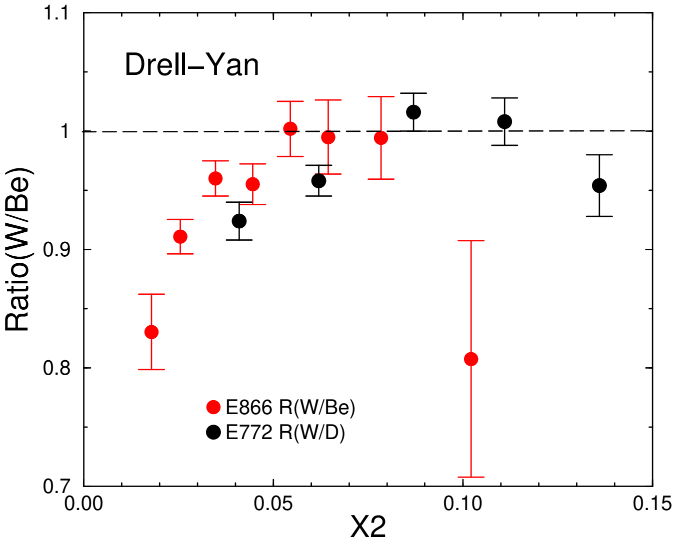

Fig. 1. Ratio of per nucleon cross sections between W and Be versus x_2 for Drell-Yan dimuon production by 800 GeV/c protons from E866[1] and E772[2].

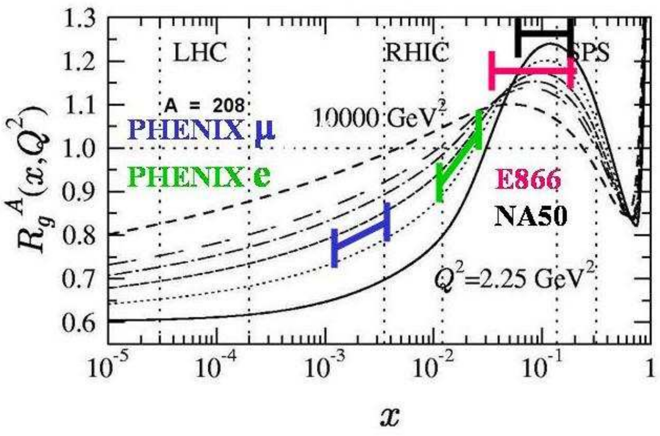

Fig. 2. Gluon shadowing from Eskola et al[3]. Marked in colored bars are shown the approximate x ranges covered by PHENIX $\mu^+\mu^-$ (Blue), PHENIX e^+e^- (Green), E866 (Red) and NA50 (Black).

an enhancement called anti-shadowing which results from the conservation of momentum and balances the depletion at small x. The ranges in x sampled for the measurements I will discuss are shown. The fixed target measurements from Fermilab and CERN both lie in the anti-shadowing region, while the PHENIX measurements lie in the shadowing region.

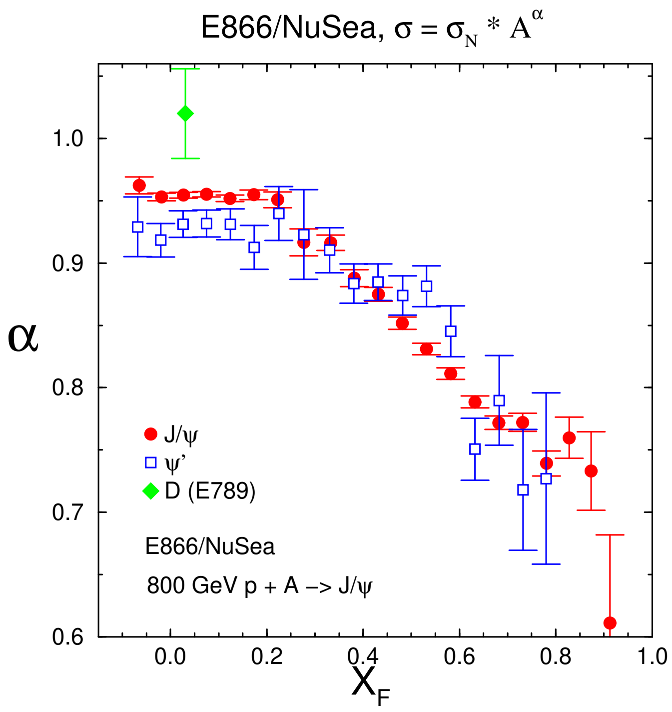

Fig. 3. Nuclear dependence of J/Ψ and Ψ production and of open charm versus x_F for 800 GeV/c protons from E866[5] and E789[6].

The main results from E866/NuSea are shown in Fig. 3 where the nuclear suppression is represented by α, where $\sigma_A = \sigma_p A^{\alpha}$. The horizontal axis here is the fraction of the maximum allowed momentum that the J/Ψ or $c\bar{c}$ have, or roughly speaking how fast they are going. One sees a substantial suppression which grows much stronger at larger x_F. The J/Ψ and Ψ' look similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus (since they would not hadronize at these x_F values until they are far outside of the nucleus). But at small x_F these resonances may be beginning to hadronize in the nuclear medium and the Ψ', which is larger and more loosely bound, is absorbed a little more strongly than the J/Ψ. Also shown is a single point for the neutral D-meson from E789[6]. The lack of suppression for the D supports the idea that the suppression of the closed-charm resonances is due to absorption (or dissociation of the $c\bar{c}$) which cannot occur for the D. The stronger suppression of the resonances at large x_F is thought to be caused by a combination of shadowing (since $x_F = x_1 - x_2$ and large x_F corresponds to small x_2) and energy-loss of the incident gluon before the hard interaction. However, if one compares these results versus x_2 to those from NA3[7] at lower (200 GeV/c) energy the bulk of the observed suppression does not scale with x_2 as would be expected if it were all shadowing. This remains a puzzle.

The production of J/Ψ and Ψ' is dominated by gluon-gluon fusion and for the small x values sampled at forward rapidity at RHIC the shadowing of these gluons is quite important, but largely unknown. Different models for gluon shadowing give answers that vary by a factor of two or more. For example the shadowing from Eskola[3], as shown in Fig. 2, for the forward di-muon acceptance in PHENIX gives a reduction of the gluons of about 20%. On the other hand, the model of Kopeliovich[8] gives over a 50% reduction. The effect of these two shadowed gluon structure functions is shown in Fig. 4 for dimuon measurements in PHENIX and gives a huge difference in the cross section at forward rapidity. Clearly we must measure the shadowing at RHIC to resolve this uncertainty.

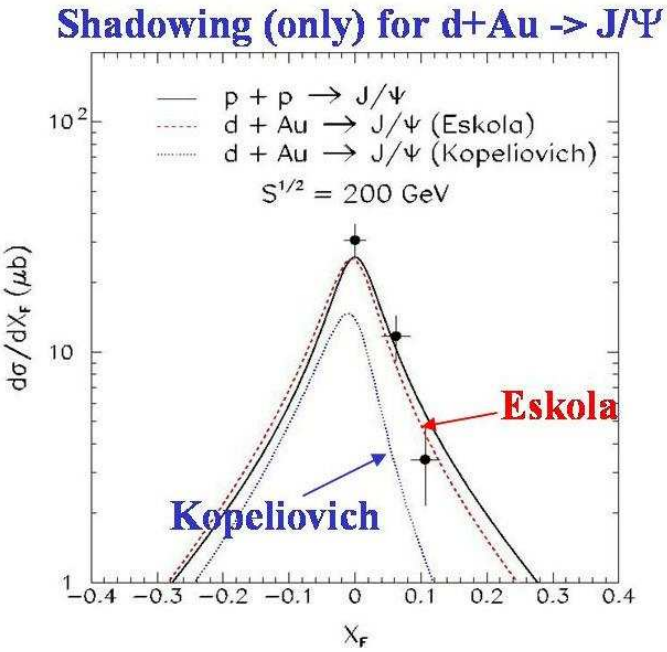

Fig. 4. Rapidity distribution for $J/\Psi \to \mu^+\mu^-$ in PHENIX for two different gluon shadowing models from Eskola et al[3] and Kopeliovich[8].

Since J/Ψ suppression is one of the leading signatures for QGP in heavy-ion Collisions, it is clearly critical to understand the suppression for normal nuclear matter. This is often expressed in terms of the atomic mass dependence of the nuclear cross section in terms of α, as in $\sigma_A = \sigma_p * A^\alpha$. For early measurements in fixed target experiments α values of 0.92 (E772[9]) and 0.919 ± 0.015(NA50[11]) were found. More recently E866 determined 0.954 ± 0.003 at mid-rapidity[5], where this result is larger than that found in the earlier E772 experiment using the same spectrometer because of biases caused by a narrow p_T acceptance in the earlier measurements which is much smaller and corrected for in E866. In addition E866 found a small but significantly larger absorption for Ψ which was discussed earlier. Finally, the most recent result from the NA50 CERN experiment[12], with more p-A data included in the analysis, indicates a larger value of α for the J/Ψ of 0.934 ± 0.014 which is consistent with the E866 result. This latest NA50 result corresponds to a J/Ψ nuclear cross section in a simple absorption model of 4.4 mb compared to the earlier result of 6.2 mb. Since these results may be sampling the gluon distributions in the anti-shadowing region (see Fig. 2), they should be interpreted with care when considering RHIC energies where measurements are not in the anti-shadowing region.

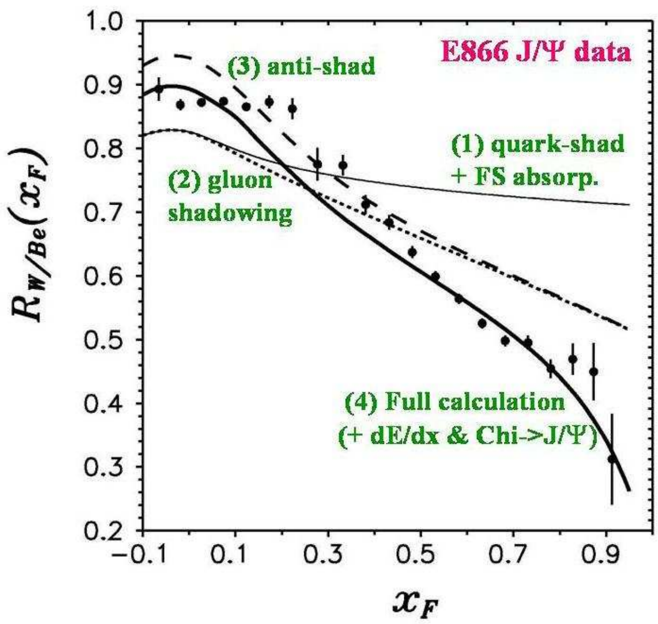

Fig. 5. The effect of energy loss (difference between solid and long-dashed curves) on J/Ψ suppression at fixed target energies from the model of Kopeliovich[13].

2.1 Parton Energy Loss and the Cronin Effect

Another important nuclear effect is energy loss of the gluons in nuclear matter before the hard interaction. A calculation from Kopeliovich[13] illustrates how this causes a general increase in nuclear suppression for larger values of x_F as shown in Fig. 5. However, this effect is thought to be negligible at RHIC energies, since the energy loss is thought to be fixed and is therefore small compared to the typical energies of partons at higher energies.

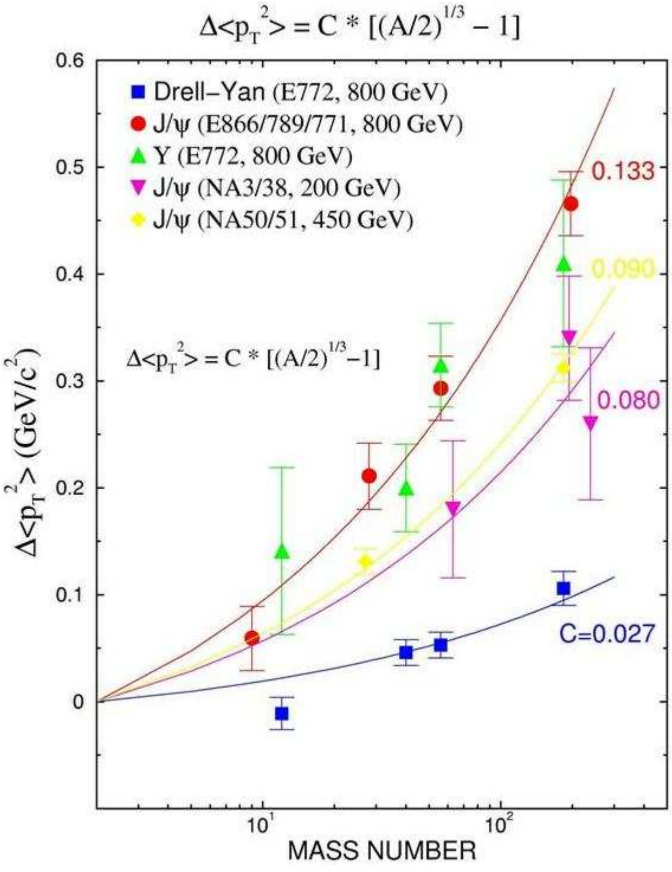

Fig. 6. Broadening of p_T in nuclear production for heavy-vector mesons and for the Drell-Yan process.

The Cronin effect, or p_T broadening, is a general phenomena[14] attributed to multiple scattering of the incident parton that is seen for various produced particles and is also seen for J/Ψ production. The systematics for measurements at several energies compared to the broadening for the Drell-Yan process is shown in Fig. 6 in terms of $\Delta < p_T^2 >$, where $\Delta < p_T^2 >$ is the difference in the average p_T^2 between a heavy nucleus and deuterium. Broadening for the heavy vector mesons is substantially larger than that for the Drell-Yan process and grows with increasing $\sqrt{s}$.

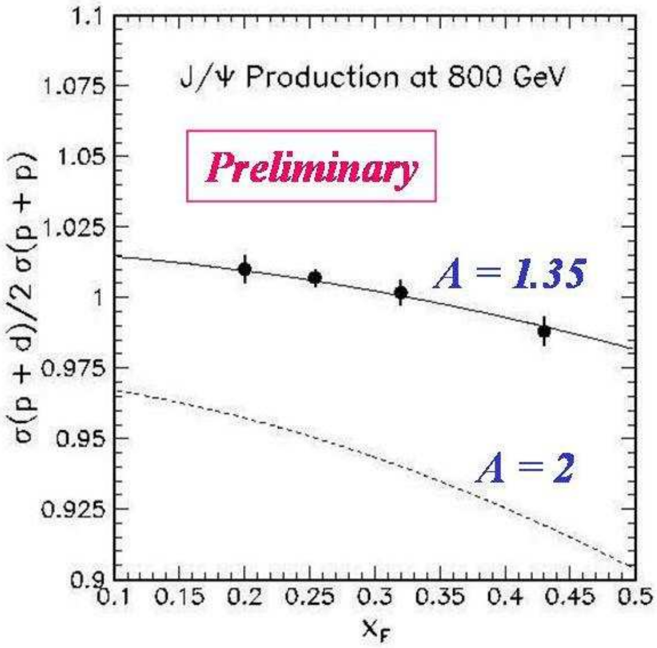

Fig. 7. Preliminary results from E866 showing small nuclear effects for deuterium versus x_F.

It is also interesting to note, as seen in some preliminary results from E866, shown in Figs. 7 and 8, that even in deuterium there appear to be some small but non-zero nuclear effects similar to those seen in heavier nuclei. Using a parameterization that works well for the heavy nuclei, but with an effective A that is smaller than 2 appears

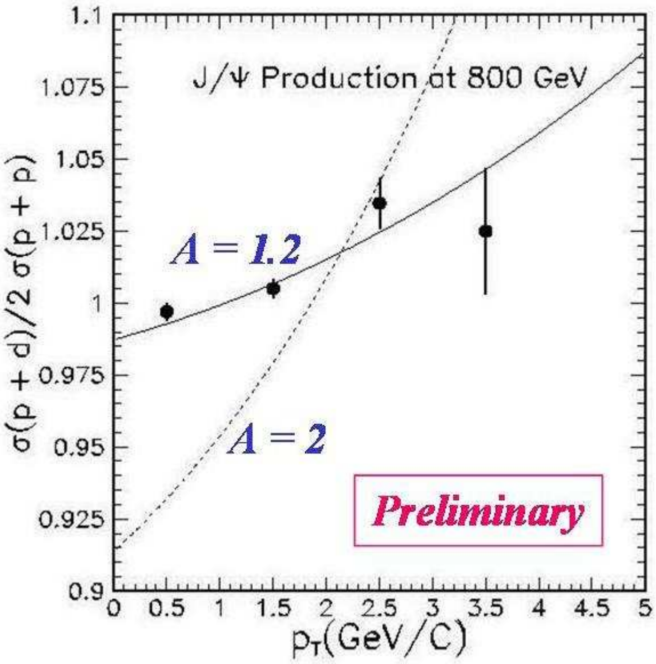

Fig. 8. Preliminary results from E866 showing small nuclear effects for deuterium versus p_T.

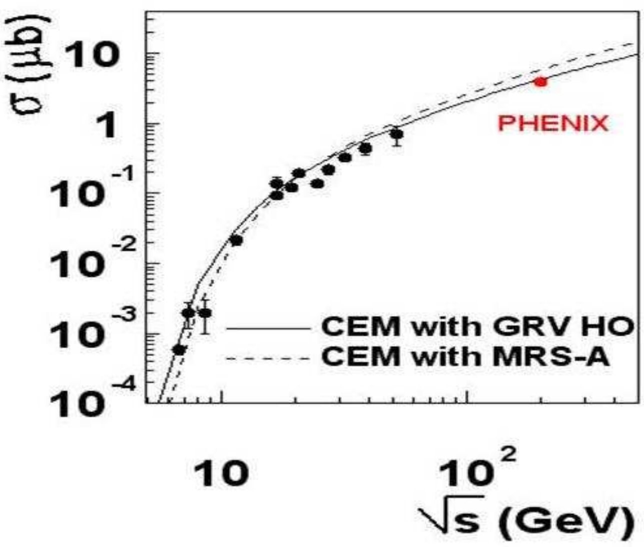

Fig. 10. The PHENIX total cross section for J/Ψ at 200 GeV/c p-p collisions compared to measurements at lower energies.

to explain the trends seen in this data as shown in the figure.

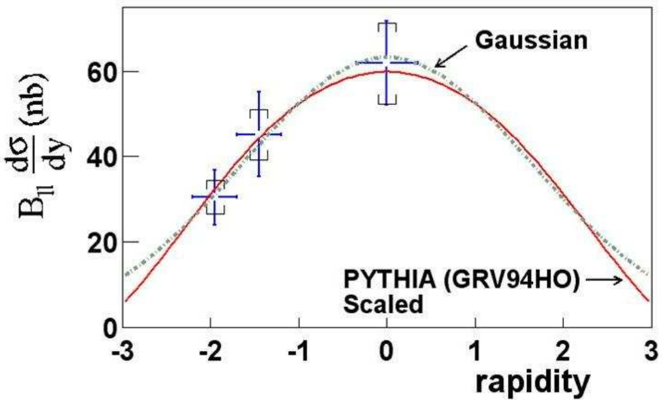

Fig. 9. First results for the rapidity distribution from PHENIX at RHIC for J/Ψ in 200 GeV/c p-p collisions.

2.2 Early PHENIX J/Ψ Measurements

At RHIC the program for charm physics is just beginning, and the first measurements of the J/Ψ in p-p collisions have just come out from the 2002 run[15], as shown in Figs. 9 and 10. These results are limited by the low luminosity and J/Ψ statistics (65 counts for the $\mu^+\mu^-$ channel) achieved in this RHIC run.

In 2003 new measurements of the J/Ψ for d-Au and p-p collisions at PHENIX are just being made. Mass peaks from an early partial analysis of the data are shown in Fig. 11. A substantial increase in the number of J/Ψs obtained in this years run compared to last year is seen and excellent mass resolutions of the two muon arms in PHENIX, approaching the design values, is seen. We estimate that the entire data sample, when analyzed, will have around 1000 J/Ψs in each muon arm (negative and

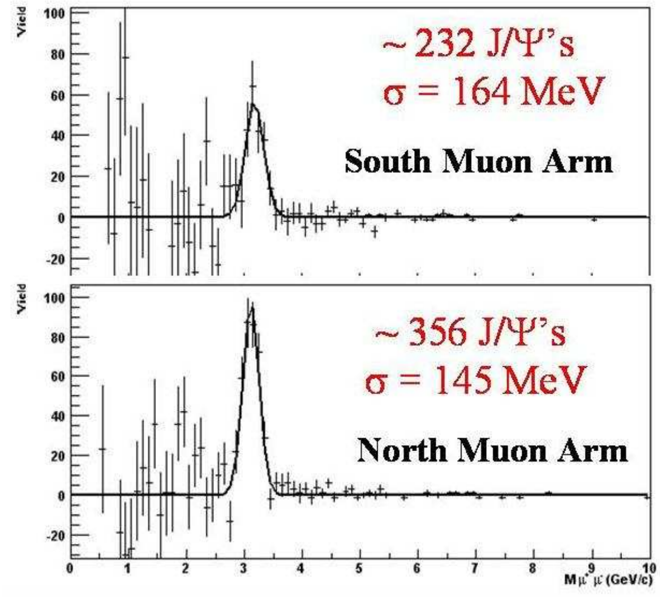

Fig. 11. Early results for the J/Ψ in 200 GeV/c d-Au for the PHENIX south and north muon arms showing a good mass resolution and a substantial number of counts from a portion of the 2003 runs data.

positive rapidity) and several hundred from the central rapidity measurement using e^+e^- pairs. Yields perhaps a factor of two below this are expected from this years p-p run. From these data we should be able to provide quantitative constraints on the nuclear shadowing of gluons, its centrality dependence, and on the p_T broadening. This will also serve as a firm basis for the long Au-Au run that we expect to have next year. In that run we expect to finally be able to address the question of J/Ψ suppression in the possible presence of a QGP.

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