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CHARMONIUM PRODUCTION IN P-A COLLISIONS

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Abstract

A review of J/Ψ and Ψ' production (charmonium) in proton-nucleus collisions is given including results from measurements at fixed target experiments at both Fermilab (E866/NuSea) and CERN(NA50) and some discussion of planned measurements at RHIC and NA60. The important physics that contributes to the large suppression in production of charmonium will be discussed as will be information from complementary measurements of open-charm production, and the Drell-Yan process. The differences in the results from Fermilab and CERN and the evolution of this physics to RHIC energies will be shown. The importance of a clear understanding of these effects in order to use J/Ψ suppression as a tool for study of the Quark-gluon plasma in nucleus-nucleus collisions at RHIC will be highlighted.

The structure and dynamics relevant to parton level processes is modified in nuclei. Parton momentum distributions of the nucleons embedded in nuclei are modified, e.g. by shadowing, or the depletion of low-momentum partons, as seen in Fig. 1 for the Drell-Yan process, which is dominated by the $\bar{q}q$ annihilation process and thus involves $\bar{q}$ and q shadowing.

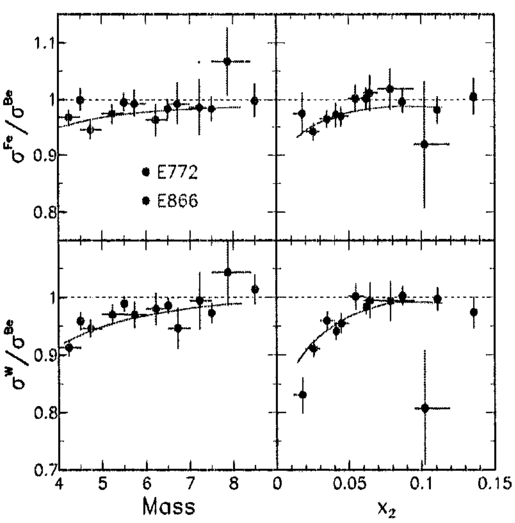

Figure 1: Ratio of per nucleon cross sections between W and Be versus x_2 for Drell-Yan dimuon production by 800 GeV/c protons from E866[1] and E772[2].

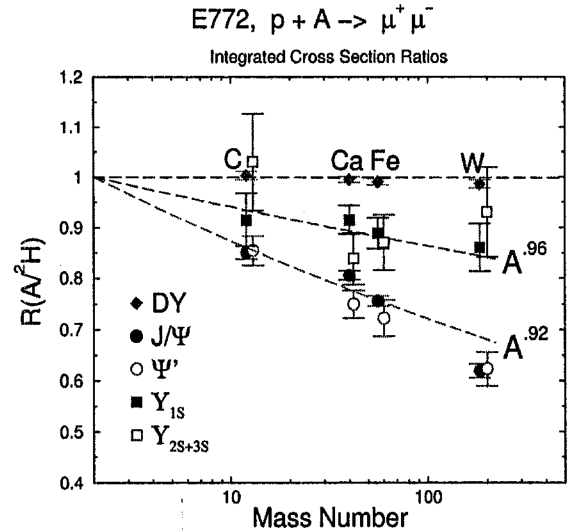

Figure 2: Nuclear dependence for Drell-Yan, J/Ψ and Ψ' production by 800 GeV/c protons from E772[2, 3, 4].

Similar shadowing effects occur for gluons, whose fusion is the dominant process involved in vector meson (J/Ψ, Ψ' or Υ) production. Traditionally shadowing is thought of as a property of the structure functions in nuclei, but in some theoretical models it is not, but rather is dependent on the reaction process to which it is being applied[5]. Other dynamical effects including energy loss of the partons as they propagate through nuclei and multiple scattering effects (Cronin effect[6]), which in some models are correlated with the energy loss are also important. When vector mesons or precursor $\bar{c}c$ pairs are produced then other issues come into play, including 1) whether the $\bar{c}c$ is created in a color singlet or octet state and if the latter, the color-neutralization time for the colored state, 2) the hadronization time for the $\bar{c}c$ to become a fully formed J/Ψ or Ψ', 3) the coherence time for the $\bar{c}c$ fluctuations which controls shadowing in the Kopeliovich model, 4) the absorption (or breakup) of $\bar{c}c$, and 5) the contribution of J/Ψ's that comes from feed-down from higher mass resonances, princibly the χ_c. The measured reduction in the per nucleon cross section (or nuclear suppression) for the integrated cross sections from E772 is shown in Fig 2, where one can see that the resonances have much stronger nuclear suppression than does the Drell-Yan process.

At the SPS and at RHIC the suppression of J/Ψ production due to color screening is thought to be an important signature of the creation of a Quark-Gluon Plasma (QGP); but how effective is it? Since ordinary nuclear effects in cold nuclear matter are already quite significant we need a comprehensive understanding of charmonium production and suppression in proton-nucleus (p-A) collisions. Competing effects my be identified by their strong kinematic dependencies, together with complementary studies of the Drell-Yan process and also of open-charm production.

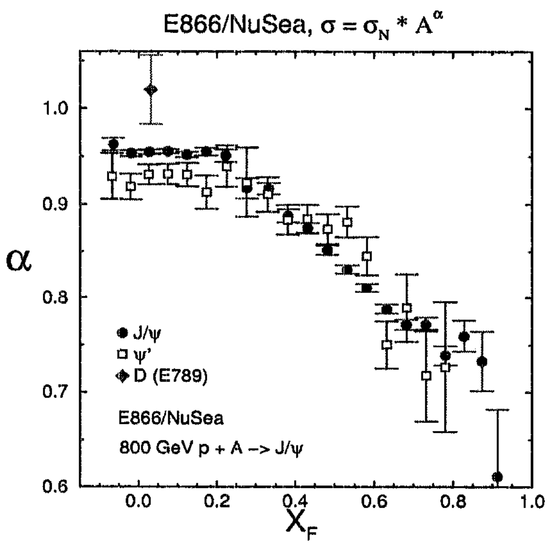

Figure 3: α versus x_F for the J/Ψ and Ψ' from E866/NuSea[7] (800 GeV/c)

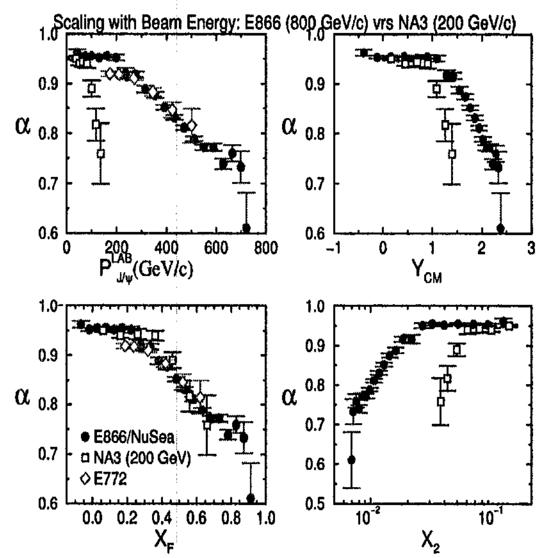

Figure 4: α versus laboratory momentum of the J/Ψ ($P^{LAB}_{J/\Psi}$), rapidity(Y_{CM}), x_F and x_2 for J/Ψ production from E866/NuSea (800 GeV/c) compared to E772 and NA3[8] (200 GeV/c) showing the non-scaling of the suppression versus any variable except x_F.

Results for the nuclear dependence of J/Ψ and Ψ' production versus x_F from E866/NuSea[7] for 800 GeV/c p-A are shown in Fig. 3. At large x_F both resonances are presursor $c\bar{c}$ pairs which, within the accuracy of these measurements, experience the same suppression; while at mid-rapidity the ψ' is absorbed more strongly than the J/Ψ, presumably because these resonances are beginning to be fully formed and the Ψ' is a larger object that should be absorbed more strongly. Also in the figure is the measurement for open-charm from E789[9] which shows no suppression (at mid-rapidity with a larger uncertainty due to the difficulty of this measurement). This result supports the interpretation of the resonance suppression at mid-rapidity as primarily from absorption.

A comparison of our results with earlier results from E772 at 800 GeV/c[3] and also with NA3's measurement at 200 GeV/c[8] is shown in Fig. 4 and illustrates that the bulk of the suppression seen for J/Ψ production scales with x_F and not with the laboratory momentum of the produced J/ψ, the rapidity nor with x_2. Evidently we should not look for explanations of the bulk of this suppression from effects which are properties of the initial parton distributions.

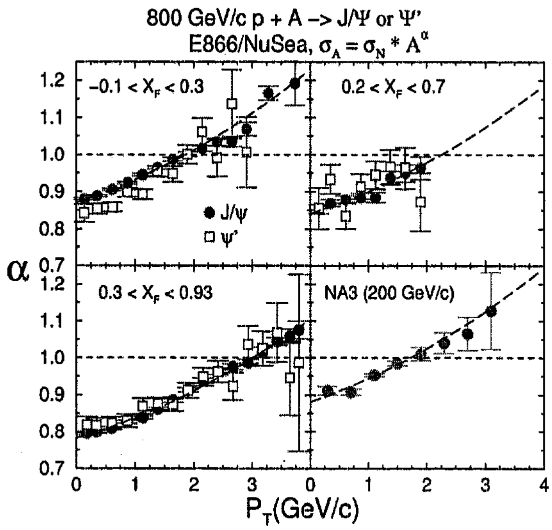

Figure 5: α versus p_T for J/Ψ and Ψ' from E866/NuSea (800 GeV/c) and from NA3 (200 GeV/c)

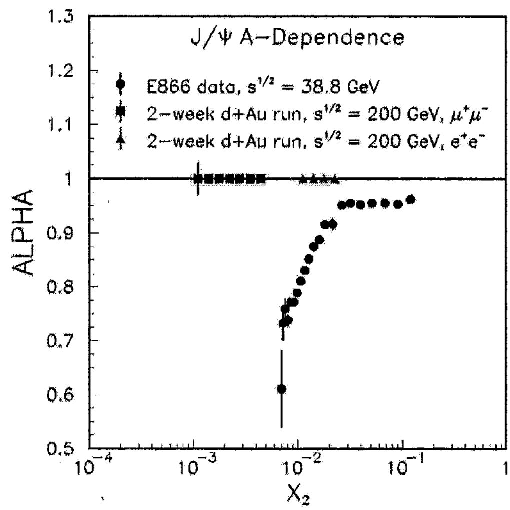

Figure 6: Expected ranges in x_2 for J/Ψ's from a d-Au run at PHENIX compared to data from E866/NuSea (from Jen-Chieh Peng)

Fig. 5 shows the p_T broadening associated with multiple scattering or the "Cronin" effect. The three different x_F ranges of E866/NuSea and the result from NA3 at lower energy all exhibit the same universal behavior of α.

In order to understand the contribution of the more mundane nuclear effects that are present for cold nuclear matter on the suppression of vector meson production in heavy-ion collisions, it is especially important to know what the suppression for p-A is at mid-rapidity. The average α from E866/NuSea at mid-rapidity is 0.954 ± 0.001 at 800 GeV/c, while that from NA50[10] is 0.925 ± 0.018 at 450 GeV/c. Although not of huge statistical significance, this difference suggests a possible energy dependence to the mid-rapidity suppression. Both experiments have good p_T coverage, so this difference is not caused by a difference in their p_T acceptances and the steep dependence of the suppression with p_T. It is also not likely to be caused by a difference in shadowing since both experiments, at mid-rapidity, lie above the shadowing region in x.

I would now like to highlight the large uncertainty in our expectations for J/Ψ suppression at RHIC energies due to the poor knowledge of shadowing effects on the gluon structure functions. First note the regions in x_2 that are covered for E866/NuSea and

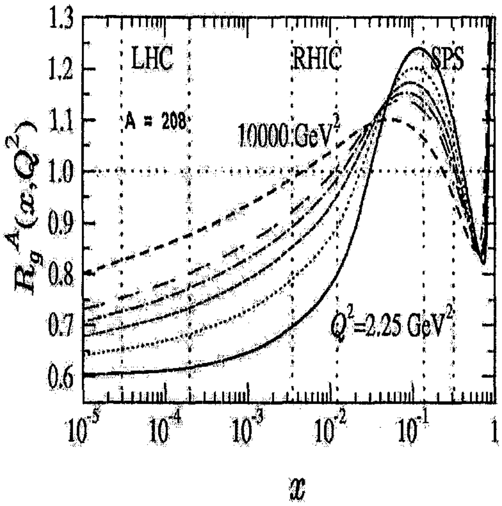

Figure 7: Gluon shadowing for ^{208}Pb from Eskola et al.[11]

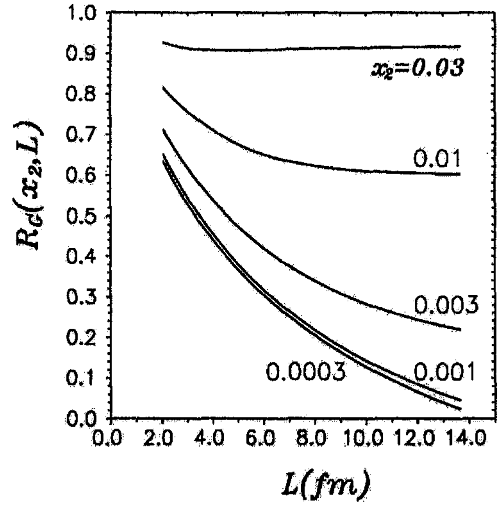

Figure 8: Gluon shadowing for *Au* from Kopeliovich et al.[5].

for PHENIX d-A $\mu^+\mu^-$ and e^+e^- measurements, indicated in Fig. 6. Next consider several different gluon shadowing predictions as shown in Figs. 7-9. The phenomological approach from Eskola et al.[11](Fig. 7) predicts a $\sim$ 20% suppression of the gluons in the acceptance region for PHENIX $\mu^+\mu^-$'s, little or no effect in the PHENIX e^+e^- region and anti-shadowing of $\sim$ 10 to 20% for the central-rapidity part of E866/NuSea. The NA50 measurements also lie in this region of anti-shadowing. It is interesting to note that if one believes this anti-shadowing, the default suppression of α = 0.92 for J/Ψ's that is often taken from NA50 when discussing RHIC measurements should actually be reduced to about 0.87 just to compensate for the anti-shadowing in the NA50 measurements. As seen in Figs. 8 and 9, other shadowing predictions give substantially larger shadowing for the PHENIX $\mu^+\mu^-$ measurements, with values for all three shadowing predictions varying between a $\sim$ 20% reduction to as large as a $\sim$ 60% reduction. Clearly d-A measurements at RHIC will be necessary to resolve these uncertainties and to provide a reliable baseline for heavy-ion collision studies at RHIC.

It is also quite interesting to compare the production of open-charm with charmonium to try to isolate the absorption mechanisms that will only affect charmonium. Present measurements on the nuclear dependence of open-charm (e.g. Fig. 3) have large uncertainties and provide only limited guidance. However the new NA60 experiment at CERN will soon be able to make more accurate measurements after adding a silicon vertex detector in front of the NA50 muon spectrometer. Another important issue that NA60 hopes to address is the nuclear dependence of χ_c production, which will help us understand the χ_c's effect on the nuclear dependence of the $\sim$ 40% of J/Ψ's that are produced indirectly through its decays. Another talk at this meeting has presented the status and plans for NA60.

At RHIC the first of two muon arms in PHENIX has just started taking data and the luminosity in this years run is expected to be high enough that the first J/Ψ's can be seen in both the $\mu^+\mu^-$ and e^+e^- decay channels. For a nominal RHIC year of running approximately 1.2M $J/\Psi \to \mu^+\mu^-$ for two muon arms and 55K $J/\Psi \to e^+e^-$ are expected; numbers comparable to the 1.5M J/Ψ's obtained in the E866/NuSea results presented

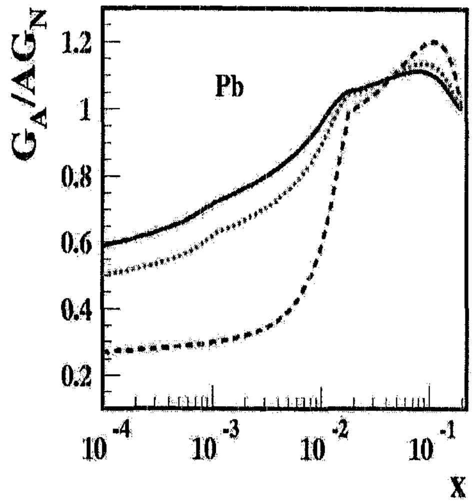

Figure 9: Gluon shadowing for *Pb* from Strikman et al.[12].

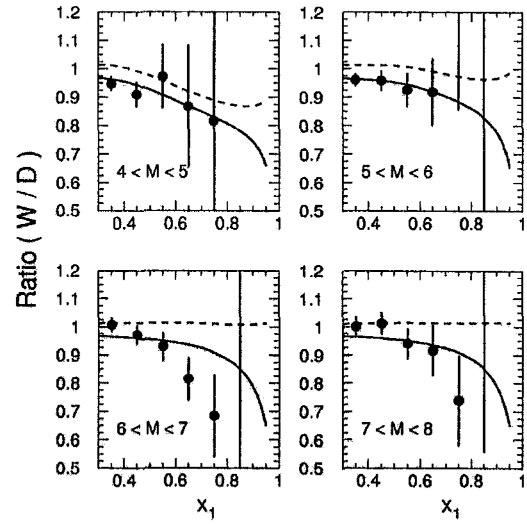

Figure 10: Isolation of energy loss in comparisons to Drell-Yan data within the model of Kopeliovich et al.[13].

above. PHENIX also hopes to run d-Au collisions during the next run to help constrain the baseline for the Au-Au collisions.

A new analysis of the Drell-Yan data from E772 by Kopeliovich et al.[13] that extracts a value of $\sim 3 \pm 0.6\ GeV/fm$ for the incident anti-quark energy loss is shown in Fig. 10. In a previous analysis[1] of E866 and E772 data the shadowing description of Eskola[14] was relied on, but recently concerns have surfaced that this description, since it includes the E772 Drell-Yan data in its phenomological fit, may include attributethe effects of energy loss in the process as shadowing. The Kopeliovich approach instead calculates the shadowing from a light-cone dipole approach (dashed lines in the figure) and then finds an additional nuclear suppression that is interpreted as energy loss.

In summary, there is a strong suppression of charmonium production seen in proton-nucleus collisions. This suppression involves a non-trivial interplay of different effects and involves several timescales including that for hadronization and for the coherence of precursor states. The large variations with x_F and p_T help reveal the underlying mechanisms. Proton-nucleus (or deuteron-nucleus) charmonium measurements must serve as a basis for understanding charm in nucleus-nucleus collisions at RHIC. Gluon shadowing is certainly a very important effect at RHIC and must be measured in d-A collisions as soon as possible. Complimentary measurements of open charm and of χ_c production are also important to complete the picture and will soon be made by NA60 at SPS energies and are also important to make in the future at RHIC energies.

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