Abstract

All measured Feynman $x_F$ distributions of the ratio, $R$, of $J/\Psi$ production in nuclei relative to production on protons fall off with $x_F$. They show that absorption of charmonium cannot be the only source of $J/\Psi$ suppression and that energy loss of the constituents of the incident proton prior to the $J/\Psi$ production, because of the exponential $\sqrt{s}$ dependence of the charmonium cross section, should not be neglected. Including the effects of initial state energy loss we find that the latest measured Pb-Pb $J/\Psi$ cross sections do not provide any evidence for deconfinement.
Over a decade has passed since it was proposed that $J/\Psi$ suppression in p-nucleus collisions was evidence for creation of a quark-gluon plasma. It was soon shown from studies of the Feynman x distributions of relative p-A and p-p production of the $J/\Psi$ that initial state and final state interactions could account for the data. It is now claimed that recent measurements show an anomalous depression in the total cross section for $J/$Psi production in Pb-Pb interactions. No Feynman x distributions of these data have been reported.

This note gives results of the full analysis taking into account both initial state energy loss and final state $J/\Psi$ absorption. Fig. 1 shows the data for two of the many examples of the ratio, R, of the nuclear to hadronic $x_F$ distributions of the cross sections in pion and proton interactions.

FIG. 1.
The pion data are from ref. [3] and proton data from ref. [4].

The fact that the ratio is not independent of \( x_F \) rules out \( x_F \) independent absorption as the sole mechanism for \( J/\Psi \) suppression, and the difference in the suppression in pion- and proton induced reactions mirrors the experimentally measured difference in energy loss in the initial state soft interactions.

(Theoretical fits, superimposed on Fig 1., and reproduced from early work [3] [4], include an energy loss per collision, \( d\sqrt{s}/dn = 0.4 \). These fits showed the effect of a final state \( J/\Psi \) -nucleon interaction with a \( J/\Psi + n \to J/\Psi + X \) inelastic cross section of about ten millibarns, and a final state energy loss of 10 \% per collision. The fits are only illustrative since trade-off between them can also account for the data. Fortunately, the suppression in the total cross section is simpler to understand than that seen in the \( x_F \) distributions since it is unaffected by the inelastic scattering cross-section and energy loss of charmonium in the final state, only by the initial state energy loss and the open-charm absorption cross section.)

The energy loss of the particular nucleon constituents that finally form charmonium cannot be calculated because of the non-perturbative nature of the prior soft collisions. One can only estimate the prior energy loss per collision, \( d\sqrt{s}/dn \). The energy loss distributions for soft minimum bias collisions can be determined from the experimental event structures at a particular \( \sqrt{s} \). The ISAJET program of Frank Paige reproduces that data and allows for interpolations between different \( \sqrt{s} \). It allows one to estimate the relative values of \( a \) and \( b \) in the expression, \( d\sqrt{s}/dn = a + b\sqrt{s} \). This relationship has been well tested in studies of low \( p_t \) interactions in nuclei [4] [5]. Nevertheless for different high \( p_t \) final states \( a \) and \( b \) should be taken as parameters that can be extracted by studying data for widely varying \( A \).

(Another equivalent method is to assign an energy loss to the quarks or gluons that are responsible for the production of the particular final state that is being studied, e.g, \( J/\Psi \)'s or Drell-Yan pairs, again assuming some energy loss parameter. This was the approach of the work of Gavin and Milana. [4]. Their ratio of energy loss for Drell-Yan relative to \( J/\Psi \) production, \((4/9)\), is actually close to the values obtained in refs. [3], [3], and [13].)

It is worth reviewing some concepts of time evolution in the initial state. For example, in a p-p interaction resulting in the production of a pion, the produced
unclothed $q$-$\bar{q}$ pair eventually picks up the gluons needed to form the final on-shell pion. Because the pion has an extended structure the evolution of the bare pair is traditionally believed to take a time approximately equal to $r/c$ where $r$ is the pion dimension. However, in the case of point particles, there is no finite size, and, as in electron-electron scattering, the initial state quarks in a $p$-$p$ collision simply scatter, resulting only in a change in their momenta. (Even if the quarks and gluons within a proton are not exact points, they surely have a much smaller radius than a hadron and will have a correspondingly shorter evolution time.) Eventually the quarks will form a real on-shell pion but, before that occurs, gluon constituents in the colliding protons will have produced charmonium. Charmonium, the unclothed $J/\Psi$, will also take time to evolve into a real $J/\Psi$ but it is the charmonium state that actually interacts with other nucleons, causing its breakup into open charm. (Of course even the $\Delta t \Delta E$ argument that describes the time evolution in free space will be affected if the $q$-$\bar{q}$ pair is made, not in vacuum, but inside of nuclear matter.)

It is sometime argued that Drell-Yan production in nuclei shows that there are no initial state energy losses that affect the Drell-Yan cross-section and that, therefore, initial state interactions can be entirely neglected. It is claimed that this is shown by the measured $A^{\alpha}$ dependence of Drell-Yan production in nuclei. The data do show a value of $\alpha$ slightly less than unity so this conclusion cannot be correct. The suppression of the $J/\Psi$ relative to the suppression of Drell-Yan pairs depends both on the energy loss and the shape of the $x_F$ distribution. The $x_F$ distributions for $p$-$p$ interactions are quite different in these two cases, varying roughly as $(1 - x_f)^n$ with $n = 5.2$ for the $J/\Psi$ and 2 for the Drell-Yan. This makes the energy loss effects larger for the $J/\Psi$. Also, in Drell-Yan, if the dimuon is made in the first collision there is no energy loss, so events can appear at $x_F = 1$. In this case there is no final state absorption so the fraction of such events is just the Glauber probability of getting a single collision which is $1/ < n >$ where $< n >$ is the mean number of collisions. But, if there is energy loss, those dimuons will not populate $x_F = 1$. Thus the suppression will turn over and drop to $1/ < n >$ This will give larger depressions at $x_F = 1$ for heavy nuclei. One has to look, therefore, at the high $x_F$ region to learn about energy loss effects in Drell-Yan production in nuclei. The variation of the suppression with $x_F$ has been calculated for a few cases in references [6] and [16].
It should be understood that the energy loss of the gluons involved in charmonium production need not be the same as the energy loss of the quarks producing Drell-Yan pairs. It will be the task of non-perturbative physics in the future to calculate the relative energy losses. In our work we attempt to use approximate values taken from low $p_t$ experiments summarized in the ISAJET model. $d\sqrt{s}/dn$ for Drell-Yan production can be determined from the Drell-Yan data at large $x_F$ while $d\sqrt{s}/dn$ for the $J/\Psi$ data is complicated by the effects of final state absorption and scattering.

To constrain the new analysis we have made use of the independent determination of the $J/\Psi$ absorption cross section from photoproduction since that reaction has no initial state interactions. That value is $\sigma_{oc} = 6.6 \pm 2.2 \text{ mb}$, as obtained in reference [5].

To calculate the $J/\Psi$ suppression we have again used a full Monte Carlo calculation, generating nucleons according to the 3 parameter Woods-Saxon distribution, $\rho(r) = \frac{1}{1+e^{(r-R_0)/\sigma}}$ with $R_0 = 1.19A^{1/3} - 1.61A^{-1/3}$, and $\sigma = .545$. Protons are then scattered off the nucleons in the nuclei, to count the number of nucleon collisions prior to the $J/\Psi$ production, (which determines the energy loss), and to count the number of succeeding collisions of the charmonium, (which determines the absorption). This method removes the struck nucleon from the counting [11]. (This differs from calculations [1] which integrate the paths through a continuous nucleus matter distribution. Not taking into account the finite nucleon size underestimates determination of an absorption cross section and may account for differences in an extracted $\sigma_{oc}$.)

Unlike charmonium, produced in a high $Q^2$ reaction, the low $Q^2$ $q - \bar{q}$ pairs (e.g., off-shell pions), produced in the soft nucleon-nucleon collisions have a longer evolution time. This is in fact the basis for the difference between counting participants (“wounded nucleons”) in predicting minimum bias event structures [12], rather than the number of scatters as needed for high $Q^2$ charmonium production. Thus pions produced in the final state should not contribute significantly to charmonium absorption, are not included in the calculation, and, as we shall see, are not needed to account for the new nucleus-nucleus data. We also do not distinguish between charmonium absorption by unstruck nucleons, as in the p-A case, and on absorption on previously struck protons, as in the B-A case.

The parameterization [13] of the $J/\Psi$ production cross section, proportional to
\( e^{-\gamma M/\sqrt{s}} \), \((\gamma M = 45)\), is used. It is responsible for the \( \sqrt{s} \) dependence of the suppression, with \( \sqrt{s(n)} = \sqrt{s(0)} - (d\sqrt{s}/dn)n \), where \( n \) is the number of prior collisions.

We show in Fig. 2 our calculations for both the mean \( \sigma_{oc} \) obtained from our prior photoproduction analysis and a somewhat larger value, using our estimate of the energy loss, \( d\sqrt{s}/dn = 0.5 + 0.018\sqrt{s} \). One can make small trade-offs of \( \sigma_{oc} \) with \( d\sqrt{s}/dn \) to get other suitable fits to the data. The filled points show the data for \( \sqrt{s} = 38.8 \) GeV (circles), \( \sqrt{s} = 19.4 \) GeV (triangles) and \( \sqrt{s} = 17.4 \) GeV (squares) which are the results of different experiments [14]. The open squares are the calculations for \( \sigma_{oc} = 6.3 \) mb., while the open circles are for 7.9 mb.

In Fig. 2 we have drawn a straight line, obtained by fitting only the low higher accuracy \( A^{1/3} + B^{1/3} \) points, which appear to show an exponential behavior. It extrapolates to a value well above the value for Pb-Pb. However there is no theoretical reason for an exponential extrapolation procedure to be valid out to large \( A^{1/3} + B^{1/3} \), even if absorption were the only mechanism. In fact it is shown [13] that, even with
pure absorption, analytic calculations and the functional dependence of prior and sub-
sequent scatters as a function of $A^{1/3} + B^{1/3}$ should cause a small enhancement of $R$
above experiment at very high $A^{1/3} + B^{1/3}$.

The $J/\Psi$ suppression is a valuable tool for studying many features of reactions that
have simultaneously both low $Q^2$ and high $Q^2$ interactions. We need to know more
about the time evolution of charmonium into the on-shell $J/\Psi$, the changes in nucleon
structure functions resulting from the prior soft interactions, and the possible variation
of the $J/\Psi$ absorption cross section with outgoing energy. This requires more data and
analysis of photoproduction as well as Drell-Yan production, especially the small, but
not zero, energy losses that occur in the latter reaction. The Drell-Yan $x_F$ distribution
measurements should be extended to $x_F = 1$, to verify that $R(x_f = 1)$ depends only
on the Glauber probability that the dimuon is made in the first collision [16].

Conclusion: Incorporating the presence of energy loss in the soft interactions prior
to $J/\Psi$ production, we find no evidence for effects of deconfinement.
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Figure Captions

Fig. 1 Two examples of the ratios of hadron-nucleus to hadron-proton $J/\Psi$ cross sections vs. Feynman $x$. The fits are taken from ref. \cite{5} and described in this text.

Fig. 2 Comparison of $J/\Psi$ suppression ratios, $R$, for experiments at different $\sqrt{s}$, plotted vs $A^{1/3} + B^{1/3}$. Fits are shown for two different values of $\sigma_{oc}$, showing agreement of our theoretical predictions with the data for Pb-Pb collisions which fall below a straight line extrapolated from the logarithmic plot of lower $A^{1/3} + B^{1/3}$ data.