Energy loss and $x_2$ scaling breakdown in $J/\psi$ nuclear production†

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In addition to the final-state interactions, $J/\psi$ nuclear production might also be affected by parton energy loss. Using the upper limits from Drell-Yan data at SPS and Fermilab energies, we estimated energy loss contribution to $J/\psi$ production in $p$–$A$ collisions. The results indicated that the effects might be sizeable at 200 GeV while remaining small at higher energies.

1 Introduction

Charmonium production is one of the cleanest hard probes studied in high-energy hadron-hadron, hadron-nucleus, and nucleus-nucleus scatterings. If we look at the reaction in the center of mass frame, the parton model tells us that the production results from the fusion of a beam parton with energy-momentum fraction $x_1$ and a target parton with energy-momentum fraction $x_2$ which are converted into a $c\bar{c}$ pair that eventually gives the observed charmonium. In the absence of nuclear effects the integrated production rate in $A_1$–$A_2$ collision would be given by $A_1 \times A_2$ times that in $p$–$p$ reaction. The deviation from this is often interpreted within a conventional absorption model.

Recently the E866 collaboration provided the first evidence for a distinction between $J/\psi$ and $\psi'$ in the differential production ratio\(^1\)

$$R = \frac{d\sigma(p + W \rightarrow \psi + X)/dx_F}{A d\sigma(p + Be \rightarrow \psi + X)/dx_F}. \quad (1)$$

The distinction occurs in the kinematical region where the charmonia have relatively small energies $E_{c\bar{c}}$ in the target rest frame. This is a definite departure from the observation of identical ratios for larger $c\bar{c}$ energies. It is tempting to describe this result by saying that for small $c\bar{c}$ energies the nucleus “acts as a detector” for the formation of the charmonium states. A possible interpretation of this is that for large $c\bar{c}$ energies a common precursor to $J/\psi$ and $\psi'$ passes through the target and final-state formation takes place outside the nuclear volume. At low $c\bar{c}$ energies formation occurs within the target, leading to a weaker absorption for $J/\psi$ than $\psi'$ due to the smaller size of the former. At the time E866 data became available we decided to

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take these ideas at face value and to test them in a simple but quantitative scenario of nuclear absorption.

A direct consequence of such an approach is an \( x_2 \) scaling. At high energy the charmonium energy amounts to \( E_{c\bar{c}} = x_1 E \) in the target rest frame where \( E \) is the beam energy in this frame. In terms of the charmonium invariant mass \( M_{c\bar{c}} \) one has \( E_{c\bar{c}} = M_{c\bar{c}}^2/(2m_p x_2) \). Consequently, if the production ratio is in actual facts driven by \( E_{c\bar{c}} \) one expects \( R \) to be independent of the beam energy at a given \( x_2 \) (\( x_2 \) scaling).

Unlike what we expected, a comparison of \( J/\psi \) differential production between 800 GeV (E866) and earlier less precise 200 GeV data (NA3) as a function of \( x_2 \) seems to indicate that \( c\bar{c} \) production does not follow an \( x_2 \) scaling. However, it could happen that NA3 data reveal that at intermediate energies there is a mechanism involved in \( c\bar{c} \) nuclear production beside the above mentioned nuclear suppression.

In fact, it has been argued for a long time that an incoming parton might lose some energy while scattering through nuclear matter. Its momentum fraction is then shifted from \( x_1 + \Delta x_1 \) to \( x_1 \) at the point of fusion resulting in a modification of the effective beam parton density by a factor \( F(x_1 + \Delta x_1)/F(x_1) \). Because the parton distributions \( F(x) \) drop dramatically at intermediate and large \( x \), the effective density of beam partons and consequently the production ratio might decrease significantly.

The aim of these proceedings is to investigate whether energy loss could be a relevant mechanism to explain a breakdown of \( x_2 \) scaling in \( J/\psi \) production.

2 Methods

Since a corresponding quark energy loss may be expected in Drell-Yan (DY) pair production which is moreover not overwhelmed by final-state interactions, we first used the DY process to extract limits on parton energy loss. Energy loss is then combined with \( c\bar{c} \) absorption to examine the consequences in the \( J/\psi \) channel.

To be more specific we chose to test two alternative energy loss scenarios. The first is that put forward by Gavin and Milana (GM)\(^4\). It predicts a beam parton shift in momentum fraction

\[ \Delta x_1 = \kappa_1 x_1 A^{1/3}, \tag{2} \]

where \( \kappa_1 \) is a free parameter\(^*\). We stress that the shift depends on kinematics through \( x_1 \).

The second model was proposed by Brodsky and Hoyer\(^5\) in order to fix a potential defect in GM. On general grounds they showed that

\[ \Delta x_1 \leq \frac{\kappa_2}{s} A^{1/3}, \tag{3} \]

with \( \kappa_2 \sim 0.5 \text{ GeV}^2 \), an upper bound with which \( \Delta x_1 \) as given by Eq. (2) is incompatible at large energies. For accessible energies it also sets an upper bound on \( \kappa_1 \). In relation with these considerations an alternative scenario, denoted BH in the following, is then obtained by assuming a shift in \( x_1 \) that saturates the bound given by (3), i.e.,

\[ \Delta x_1 = \frac{\kappa_2}{s} A^{1/3}, \]

where it should be noted here that the dependence on kinematics occurs via the center of mass energy.

\(^*\kappa_1 \) might depend on \( Q^2 \) and we needed its value in the region around \( m_\psi^2 \). It turns out that the DY data are not precise enough and do not probe a sufficient range in \( Q^2 \) to make any definite statement about the latter dependence. We thus simply disregarded it.
The free parameter in each model was fixed with DY data. The data set encompassed, on the one hand, the 150 and 280 GeV pion beam data on $A = 1$ and 195 targets and, on the other hand, the 800 GeV proton beam data on $A = 9$ and 184. At 800 GeV the data set spans a range in $x_2$ where shadowing is known to be sizeable. We thus used data points corrected for shadowing as given in Ref. 7. At SPS energies the data points lie in the (weak) antishadowing region and the corresponding correction is small. Calculations were done using MRST parton distributions and shadowing corrections were given by the EKS parameterization.

The models were then used to assess the possible importance of energy loss in $J/\psi$ production at 200 and 800 GeV. We assumed that $J/\psi$ production results from gluon fusion and took into account the color factor correction to energy loss: $\Delta x_g = \frac{9}{4} \Delta x_q$. Subsequent energy loss was combined with nuclear absorption extracted from 800 GeV measurements and the result was compared to 200 GeV data. In the $J/\psi$ sector shadowing corrections were not considered (see discussion at the end of Section 3).

3 Results and Discussion

Drell-Yan production

In view to quantify parton energy loss, we first considered Drell-Yan dimuon production. At 800 GeV the wide kinematic acceptance ($0.2 \leq x_1 \leq 0.95$) and high statistics of E866/NuSea data make it possible to put stringent constraints on parton energy loss. The fitted parameter values were

$$\kappa_1 = 3 \times 10^{-4} \quad (\chi^2/\text{ndf} = 0.69),$$

for GM and

$$\kappa_2 = 0.08 \text{ GeV}^2 \quad (\chi^2/\text{ndf} = 0.72),$$

for BH. Their $1\sigma$ upper limits, i.e., $\chi^2/\text{ndf} = 1$, were

$$\kappa_1 + \Delta \kappa_1 = 11 \times 10^{-4},$$

and

$$\kappa_2 + \Delta \kappa_2 = 0.77 \text{ GeV}^2.$$

This suggested that the Drell-Yan data — corrected for shadowing — are consistent with zero energy loss within both models, but the $1\sigma$ upper-limits imply that energy loss effects at a level of a few hundreds of MeV/fm cannot be excluded.

Similarly, limits were estimated from a fit to the $\pi^-$ beam NA3 data at 150 and 280 GeV (Table I). The lowest $\chi^2/\text{ndf}$ were reached with essentially no energy loss for both models — with or without inclusion of shadowing. Table I also indicates that the consideration of shadowing effects tended to improve the fits and correlative to raise the upper limits of parton energy loss by a factor of four.

|                   | GM loss          | BH loss         |
|-------------------|------------------|-----------------|
|                   | $\kappa_1 \times 10^{-3}$ | $\chi^2/\text{ndf}$ | $\kappa_2 \text{ GeV}^2$ | $\chi^2/\text{ndf}$ |
| no shadowing      | 0.0 (1.0)        | 0.86            | 0.0 (0.2)         | 0.86               |
| with shadowing    | 0.2 (3.7)        | 0.43            | 0.0 (0.9)         | 0.43               |

Table 1: Energy loss parameters $\kappa_1$ and $\kappa_2$ from a fit to NA3 data, with and without shadowing corrections. The $1\sigma$ upper limits $\kappa_1 + \Delta \kappa_1$ and $\kappa_2 + \Delta \kappa_2$ are given between brackets.

†At large $x_1$, $q\bar{q}$ annihilation into $c\bar{c}$ becomes predominant. We checked that taking this channel into account did not change the overall results.
Fitting the nuclear dependence of Drell-Yan production in p – A and π – A reactions leads to the conclusion that quark energy loss has to be small if any. Contrary to what we expected, the comparison between 200 and 800 GeV data did not allow us to discriminate between the different energy behaviours of GM and BH scenarios. A closer look at the data showed that this is mostly due to the large error bars in NA3 data.

**J/ψ production**

In the parton model, production of c ¯c pairs proceeds via parton fusion and might therefore be affected by initial-state effects (e.g., energy loss and shadowing), as well as final-state interactions. From the preliminary Drell-Yan study, we assumed κ1 to be equal to 0.001 and κ2 to be equal to 0.5 GeV² to evaluate the possible energy loss contribution to J/ψ production.

![Graph showing energy loss effects on J/ψ production according to GM loss (dotted) and BH loss (dashed) at 200 GeV (left) and 800 GeV (right). The production ratio is defined as R(A/B) ≡ Bσ(A)/Aσ(B).](image)

Figure 1: Energy loss effects on J/ψ production according to GM loss (dotted) and BH loss (dashed) at 200 GeV (left) and 800 GeV (right). The production ratio is defined as R(A/B) ≡ Bσ(A)/Aσ(B).

Figure 1 shows the J/ψ production ratios R(Pt/p) at 200 GeV and R(W/Be) at 800 GeV. The most striking result is the large suppression seen at SPS according to BH mechanism whereas this suppression remains negligible at Fermilab energies. The J/ψ production at 200 GeV is already affected (R ≈ 0.9) at low x1, and decreases when x1 increases. The situation is different in the GM approach where the loss scales with x1, independently of the beam energy. This can be seen in Figure 2 which also demonstrates that the effect is moderate for κ1 = 0.001 with a decrease from 1 at small x1 to 0.8 at x1 = 0.7. The decrease seen in both approaches when going from small to large x1 is the behaviour that might be reflected by NA3 J/ψ data.

Once energy loss in the J/ψ sector was examined, J/ψ suppression was calculated taking in addition nuclear absorption into account. The results are compared with experimental data on Figure 2 as a function of x_F ≡ x_1 – x_2. First, Figure 2 reminds us that the model described in Ref. 2 for charmonium suppression (solid curve) is unable to describe large x_F NA3 data. Second, the energy loss mechanism proved to reduce the disagreement with large x_F data points. In particular, GM loss did not affect low x_F production ratios and somehow decreased J/ψ production at x_F ≈ 0.5. By contrast, the BH scenario could almost reproduce the large suppression seen at large x_F but tended to give too strong a suppression at small x_F. Though it is true that a first level comparison of both models would favor the GM approach, we should

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‡The difference between the two dotted curves in Figure 1 arises from the normalization with p and Be targets at 200 GeV and 800 GeV respectively.
however stress that the results depend strongly on the values chosen for the parameters $\kappa_1$ and $\kappa_2$. This prompted us not to draw too quantitative conclusions.

In summary, the results obtained may indicate that NA3 $J/\psi$ data result from a possible interplay between energy loss and nuclear suppression. In particular, the general trend of data is better reproduced when parton energy loss is taken into account. Consequently, the lack of $x_2$ scaling exhibited by NA3 and E866/Nusea data could be — at least partly — explained with such a mechanism. One limitation nevertheless arises from the remaining discrepancy between data and theoretical calculations. Further to that, we should mention that other mechanisms have been neglected in this study. In particular, gluon antishadowing calculated with EKS98 leads to an enhancement of $J/\psi$ production in platinum near $x_2 \approx 0.1$ (i.e. $x_F \approx 0.2$ for NA3).

It is hardly necessary to repeat that precise measurements of both Drell-Yan and charm differential production over a large kinematic window is mandatory to disentangle all the mechanisms involved in $J/\psi$ production.

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