Nuclear Suppression of Dileptons at Large-$x_F$

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We study a significant nuclear suppression of the relative production rates $(p(d)+A)/(p+d(p))$ for the Drell-Yan process at large Feynman $x_F$. Since this is the region of minimal values for the light-front momentum fraction variable $x_2$ in the target nucleus, it is tempting to interpret this as a manifestation of coherence or of a Color Glass Condensate. We demonstrate, however, that this suppression mechanism is governed by the energy conservation restrictions in multiple parton rescatterings in nuclear matter. To eliminate nuclear shadowing effects coming from the coherence, we calculate nuclear suppression in the light-cone dipole approach at large dilepton masses and at energy accessible at FNAL. Our calculations are in a good agreement with data from the E772 experiment. Using the same mechanism we predict also nuclear suppression at forward rapidities in the RHIC energy range.

1. INTRODUCTION

Recent study of small-$x$ physics is realized at RHIC by measurements of high-$p_T$ particles in $d+Au$ collisions at forward rapidities $y > 0$ \cite{2}. If a particle with mass $m_h$ and transverse momentum $p_T$ is produced in a hard reaction then the corresponding values of Bjorken variable in the beam and the target are $x_{1,2} = \sqrt{m_h^2 + \frac{p_T^2}{s}} \pm \frac{y}{\sqrt{s}}$. Thus, at forward rapidities the target $x_2$ is $e^{y/2}$ times smaller than at midrapidity. This allows to study coherent phenomena (shadowing, Color Glass Condensate (CGC)), which are expected to suppress particle yields.

However, a significant suppression at large $y$ for any reaction is observed so far at any energy. Namely, all fixed target experiments (see examples in \cite{3}) have too low energy for the onset of coherence effects since $x_2$ is large. The rise of suppression with $y$ (with Feynman $x_F$) shows the same pattern as observed at RHIC. This allows to favor another mechanism common for all reactions arising at any energy. Such a common mechanism based on energy conservation effects in initial state parton rescatterings and leading to $x_F$ scaling of nuclear effects was proposed in \cite{3}.

The projectile hadron can be decomposed over different Fock states. A nucleus has a higher resolution than a proton due to multiple interactions and so can resolve higher Fock components containing more constituents. Corresponding parton distributions fall off steeper at $x \to 1$ where any hard reaction can be treated as a large rapidity gap (LRG) process where no particle is produced within rapidity interval $\Delta y = -\ln(1 - x)$. The suppression factor as a survival probability for LRG was estimated in \cite{3}, $S(x) \sim 1 - x$. Each of multiple interactions of projectile partons produces an extra $S(x)$ and the weight factors are given by the AGK cutting rules \cite{4}. As was shown in \cite{3} the effective projectile parton distribution correlates with the nuclear target and reads

$$f_{q/N}^{(A)}(x) = C f_{q/N}(x) \times \int d\beta \frac{e^{-\alpha_{sff}T_A(b)} - e^{-\alpha_{sff}T_A(b)}}{(1-x) \int d\beta \frac{1 - e^{-\alpha_{sff}T_A(b)}}},$$ \hspace{1cm} (1)

where $T_A(b)$ is the nuclear thickness function, $\alpha_{sff}$ was evaluated in \cite{3} and the normalization factor $C$ is fixed by the Gottfried sum rule.

In this paper we study the rise of suppression with $y$ ($x_1$) at FNAL reported by the E772 Collaboration \cite{5} for the Drell-Yan (DY) process. We predict similar nuclear effects also at RHIC in the forward region expecting the same suppression pattern as seen at FNAL.

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2. THE COLOR DIPOLE APPROACH

The DY process in the target rest frame can be treated as radiation of a heavy particle/dilepton by a projectile quark. The transverse momentum $p_T$ distribution of photon bremsstrahlung in quark-nucleon interactions, $\sigma^{qg}(\alpha, p_T)$, reads [6]:

$$\frac{d\sigma(qN \to \gamma^* X)}{d(n\alpha) d^2p_T} = \frac{1}{(2\pi)^2} \sum_{m_f} \int d^2r_1 d^2r_2$$

$$e^{i\vec{p}_T \cdot (\vec{r}_1 - \vec{r}_2)} \Phi_{\gamma^* q}(\alpha, \vec{r}_1) \Phi_{\bar{q}q}(\alpha, \vec{r}_2) \times$$

$$\frac{1}{2} \left\{ \sigma_{qq}(x, \alpha r_1) + \sigma_{\bar{q}q}(x, \alpha r_2) - \sigma_{\bar{q}q}(x, \alpha |r_1 - r_2|) \right\},$$

where $\alpha = p_T^2 / p_T^2$ and the light-cone (LC) wave functions of the projectile quark $q + \gamma^*$ fluctuation $\Phi_{\gamma^* q}(\alpha, \vec{r})$ are presented in [6]. Feynman variable is given as $x_F = x_1 - x_2$ and in the target rest frame $x_1 = p_T^2 / p_T^2$. For the dipole cross section $\sigma_{\bar{q}q}(x, \alpha r)$ in Eq. (2) we used parametrization from [7].

The hadron cross section is given convolving the parton cross section, Eq. (2), with the corresponding parton distribution functions (PDFs) $f_q$ and $f_{\bar{q}}$ [6,5],

$$\frac{d\sigma(pp \to \gamma^* X)}{dx_F d^2p_T dM^2} = \frac{\alpha_{em}}{3 \pi M^2} \frac{x_1}{x_2} \frac{1}{\alpha^2} \sum_q Z_q^2$$

$$\times \left\{ f_q \left( \frac{x_1}{\alpha}, Q^2 \right) + f_{\bar{q}} \left( \frac{x_1}{\alpha}, Q^2 \right) \right\} \frac{d\sigma(qN \to \gamma^* X)}{d(n\alpha) d^2p_T},$$

where $Z_q$ is the fractional quark charge, PDFs $f_q$ and $f_{\bar{q}}$ are used with the lowest order (LO) parametrization from [9] at the scale $Q^2 = p_T^2 + (1 - x_1) M^2$ and the factor $\alpha_{em} / (3 \pi M^2)$ accounts for decay of the photon into a dilepton.

3. DILEPTON PRODUCTION ON NUCLEAR TARGETS

The rest frame of the nucleus is very convenient for study of coherence effects. The dynamics of the DY process is regulated by the coherence length $l_c$ related to the longitudinal momentum transfer, $q_L = 1 / l_c$, which controls the interference between amplitudes of the hard reaction occurring on different nucleons. The condition for the onset of shadowing in a hard reaction is sufficiently long coherence length (LCL) in comparison with the nuclear radius, $l_c \gtrsim R_A$, where

$$l_c = \frac{2E_q \alpha (1 - \alpha)}{(1 - \alpha) M^2 + \alpha^2 m_q^2 + p_T^2},$$

and $E_q = x_q s / 2m_N$ and $m_q$ is the energy and mass of the projectile quark. The fraction of the proton momentum $x_q$ carried by the quark is related to $x_1$ as $\alpha x_q = x_1$. In the LCL limit the special advantage of the color dipole approach allows to incorporate nuclear shadowing effects via a simple eikonalization of $\sigma_{qq}(x, r)$ [10], i.e. replacing $\sigma_{qq}(x, r)$ in Eq. (2) by $\sigma_{qq}^{A}(x, r)$:

$$\sigma_{qq}^{A} = 2 \int d^2b \left\{ 1 - \left[ 1 - \frac{1}{2A} \sigma_{qq} T_A(b) \right]^A \right\}.$$

The corresponding predictions for nuclear broadening in DY reaction based on the theory [6] for LCL limit were presented in [11].

In the short coherence length (SCL) regime the coherence length is shorter than the mean inter-nucleon spacing, $l_c \lesssim 1 / 2$ fm. In this limit there is no shadowing due to very short duration of the $\gamma^* + q$ fluctuation. The corresponding theory for description of the quark transverse momentum broadening can be found in [12,13]. Here the probability distribution $W_A^{q}(\vec{k}_T, x_q, \vec{b}, z) = d\sigma / d^2k_T$ that a valence quark arriving at the position $(\vec{b}, z)$ in the nucleus $A$ will have acquired transverse momentum $\vec{k}_T$ can be written in term of the quark density matrix, $\Omega_q(\vec{r}_1, \vec{r}_2) = (b_0^2 / \pi) \exp[-(b_0^2 r_1^2 + r_2^2)/2]$,

$$W_A^{q}(\vec{k}_T, x_q, \vec{b}, z) = \frac{1}{(2\pi)^2} \int d^2r_1 d^2r_2 e^{i \vec{k}_T \cdot (\vec{r}_1 - \vec{r}_2)}$$

$$\times \Omega_q(\vec{r}_1, \vec{r}_2) e^{-\frac{1}{2} \sigma_{\bar{q}q}(x_q, r_1 - r_2) T_A(\frac{\vec{b} + \vec{z}}{2})},$$

where $b_0^2 = 2 / \lambda_{\gamma^* n}$ with $\lambda_{\gamma^* n} = 0.79 \pm 0.03$ fm$^2$ represents the mean-square charge radius of the proton. $T_A(b, z)$ in Eq. (3) is the partial nuclear thickness function, $T_A(b, z) = f_{\gamma^*}(z') \rho_A(b, z')$.

Transverse momentum acquired by a quark on the nucleus, $W_A^{q}\langle\vec{k}_T, x_q\rangle$, is obtained averaging Eq. (3) over the nuclear density $\rho_A(b, z)$:

$$W_A^{q} = \frac{1}{A} \int d^2b d\rho_A(b, z) W_A^{q}(\vec{k}_T, x_q, \vec{b}, z).$$

The cross section, $\sigma_A^{q\gamma}(\alpha, p_T)$, for an incident quark to produce a photon on a nucleus $A$
with transverse momentum $p_T$ can be expressed convolving the probability function $W^A(k_T,x_q)$ with the cross section $\sigma^{N}(\alpha,k_T)$ (see Eq. (2)),

$$\sigma^{A}(\alpha,p_T) = \int d^2k_T W^A(k_T,x_q)\sigma^{N}(\alpha,\vec{r}_T), \quad (8)$$

where $\vec{r}_T = \vec{p}_T - \alpha \vec{k}_T$. To obtain the transverse momentum distribution for an incident proton one should integrate over $\alpha$ similarly as in Eq. (3):

$$d\sigma(pA \rightarrow \gamma^* X) = \frac{\alpha_{em}}{3 \pi M^2} \sum_{q} Z^2_{q} \sigma^A(\alpha,p_T) \times \left\{ f_q(x_1, Q^2) + f_{\bar{q}}(x_1, Q^2) \right\} \sigma^A(\alpha,p_T). \quad (9)$$

Nuclear effects in $p + A$ collisions are usually investigated via the so called nuclear modification factor, defined as

$$R_A(p_T, x_F, M) = \frac{\frac{d\sigma(pA \rightarrow \gamma^* X)}{d x_F d^2p_T dM^2}}{\frac{d\sigma(pN \rightarrow \gamma^* X)}{d x_F d^2p_T dM^2}}, \quad (10)$$

where the numerator is calculated in SCL and LCL regimes as described above. Corrections for the finite coherence length was realized by linear interpolation using nuclear longitudinal form-factor $^{13}$ (for more sophisticated Green function method see $^{6,13}$).

Note that at RHIC energy and at forward rapidities (large $x_F$) the eikonal formula for LCL regime, Eqs. (3) and (5), is not exact since higher Fock components containing gluons lead to additional corrections, called gluon shadowing (GS). The corresponding suppression factor $R_G$ was derived in $^{14,11}$ and included in calculations replacing in Eq. (3) $\sigma_{\bar{q}q}$ by $R_G \sigma_{\bar{q}q}$. GS leads to reduction of the Cronin effect $^{16}$ at moderate $p_T$ and to additional suppression (see Fig. 3).

For elimination of the coherence effects one can study production of dileptons at large $M$ (see Eq. (4)) as has been realized by the E772 Collaboration $^{5}$. Another possibility is to study the DY process at large $x_1 \rightarrow 1$, when also $\alpha \rightarrow 1$, and $t_c \rightarrow 0$ in this limit (see Eq. (4)).

4. NUCLEAR SUPPRESSION AT FNAL ENERGIES

We start with the DY process in $p + p$ collisions. Besides calculations based on Eq. (3) using GRV PDFs $^{9}$ (see the dashed line in Fig. 1) we present by the solid line also predictions using proton structure functions from $^{17}$. Fig. 1 shows a reasonable agreement of the model with data from the E886 Collaboration $^{18}$. This encourages us to apply the color dipole approach to nuclear targets as well.

![Figure 1. Differential cross section of dileptons in $p + p$ collisions at $x_F = 0.63$ and $M = 4.8$ GeV vs. E886 data $^{18}$.

The E772 Collaboration $^{5}$ found a significant suppression of DY pairs at large $x_1$ (see Fig. 2). Large invariant masses of the photon allows to minimize shadowing effects (see a small differences between lines calculated in SCL and LCL regimes). If effects of energy conservation are not included one can not describe a strong suppression at large $x_1$. In the opposite case a reasonable agreement of our model with data is achieved.

Finally, we present also predictions for $p_T$ dependence of the nuclear modification factor $R_{d+Au}$ at RHIC energy and at several fixed values of $x_F$. Similarly as in $^{5}$ instead of usual Cronin enhancement, a suppression is found (see Fig. 3). The onset of isotopic effects at large $p_T$ gives a value $R_{d+Au} \sim 0.73 \div 0.79$ and can not explain strong nuclear effects. The predicted huge rise of suppression with $x_F$ in Fig. 3 reflects much smaller survival probability $S(x_F)$ at larger $x_F$ and can be tested in the future by the new data from RHIC. Note that effects of GS depicted in Fig. 3 by the thick lines lead to additional suppression which rises with $x_F$. 


Figure 2. Ratio $R^{DY}(W/D)$ of Drell-Yan cross sections on W and D vs. E772 data for $6 < M < 7$ GeV. Predictions correspond to the long (LCL) and short coherence length (SCL) regimes, and their interpolation (REAL). The lower and upper series of curves are calculated with and without energy conservation effects, respectively.

5. SUMMARY

We present unified approach to large $x_1$ ($x_F$) nuclear suppression based on energy conservation effects in multiple parton rescatterings. We apply this approach for the DY process and explain well a significant suppression at large $x_1$ in accordance with the E772 data. The FNAL energy range and large invariant masses of the photon allow to minimize the coherence effects, what does not leave much room for other mechanisms, such as CGC. We predict a significant suppression also in $d+Au$ collisions at RHIC in the forward region (see Fig. 3). At moderate $p_T$ we show an importance of GS effects and their rise with $x_F$.

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Figure 3. Predictions for the ratio $R_{d+Au}(p_T)$ at $\sqrt{s} = 200$ GeV for several fixed values of $x_F$ with the energy conservation effects (thin lines). Thick lines additionally include gluon shadowing effects.

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