Forward Rapidity Hadron Production in Deuteron Gold Collisions from Valence Quarks

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Abstract

We consider hadron production in deuteron gold collisions at RHIC in the forward rapidity region. Treating the target nucleus as a Color Glass Condensate and the projectile deuteron as a dilute system of valence quarks, we obtain good agreement with the BRAHMS minimum bias data on charged hadron production in the forward rapidity ($y = 3.2$) and low $p_t$ region. We provide predictions for neutral pion production in minimum bias deuteron gold collisions in the forward rapidity region, $y = 3.8$, measured by the STAR collaboration at RHIC.
1 Introduction

The recent observation of the suppression of the charged hadron spectra in the forward rapidity region \cite{1} at RHIC, and its centrality dependence has generated a lot of interest and excitement in the high energy heavy ion community. The suppression of particle spectra and disappearance of the Cronin effect at forward rapidity had been predicted \cite{2, 3} in the Color Glass Condensate formalism \cite{4}, unlike the more conventional models which predicted a stronger enhancement of the spectra in the forward rapidity as compared with mid rapidity \cite{5}. The forward rapidity data strongly suggest that the high gluon density region of QCD phase space, the Color Glass Condensate, has been observed at RHIC. While the Color Glass Condensate has been successful in predicting some global features of the data, such as multiplicities and their energy, rapidity and centrality dependence in gold gold and deuteron gold collisions \cite{6} as well as qualitative predictions \cite{2, 3} of the suppression of the hadron spectra and their centrality dependence, there has not been a quantitative analysis of the forward rapidity hadron spectra using the Color Glass Condensate formalism. Here, for the first time, we provide a limited, but quantitative analysis of the low $p_t$, forward rapidity RHIC data, using the Color Glass Condensate formalism.

As emphasized in \cite{7}, the forward rapidity region at RHIC is the best kinematic region to look for the signatures of the Color Glass Condensate since this is the region where one probes the smallest $x$ in the target nucleus so that the Color Glass Condensate will be manifest more strongly in this kinematic region. Also, forward rapidity deuteron gold collisions are ideal since one does not have the final state (Quark Gluon Plasma) interactions, present in mid rapidity heavy ion collisions.

It is important to note that at very forward rapidities ($y > 3$), one is probing the small $x$ region of the nucleus and the large $x$ region of the deuteron projectile. For example, at $y \sim 3.2$ and $p_t \sim 2$, the deuteron wave function at $x \sim 0.25$ is probed. This is the region where valence quarks dominate over gluons and sea quarks in the deuteron wave function while the relevant $x$ for the target nucleus is $x \sim 4 \times 10^{-4}$ so that gluons are the dominant parton species in the target nucleus.

In this work, we concentrate in the very forward rapidity region ($y \geq 3.2$) so that the target nucleus is treated as a Color Glass Condensate while only the valence quarks in the projectile deuteron are included. We use the results of \cite{7} for the scattering of valence quarks on a Color Glass Condensate to calculate charged hadron and neutral pion $p_t$ spectra as well as the nuclear modification factor $R_{dA}$ in the forward rapidity region at RHIC.

2 Scattering of quarks on a Color Glass Condensate

In \cite{7}, scattering of quark on a target described as a Color Glass Condensate was considered and the scattering cross section was calculated. The incoming quark is taken to be massless and carries zero transverse momentum. The scattering cross section is given by...
\[
q^- \frac{d\sigma^{qA \to qX}}{dq^- dq X} = -\frac{1}{(2\pi)^2} q^- \delta(q^- - p^-) \int d^2 b_t d^2 r_t e^{i q_t \cdot r_t} \sigma_{\text{dipole}}(r_t, b_t, x_g) \tag{1}
\]

Here, \(p^-\) is the light cone energy of the incoming quark while \(q^-\) is the light cone energy of the outgoing quark with transverse momentum \(q_t\) and \(\sigma_{\text{dipole}}\) is the cross section for scattering of a quark anti-quark dipole on a target described as a Color Glass Condensate. The dipole cross section satisfies the non-linear JIMWLK \[8\] (BK \[9\] at large \(N_c\) evolution equation. To relate this quark-nucleus (proton) target scattering cross section to hadron production in deuteron gold collisions, we convolute this cross section with the quark distribution function in a deuteron and quark-hadron fragmentation function. We get

\[
\frac{d\sigma^{dA \to h(y,k_t)x}}{dy d^2 k_t} = -\frac{1}{(2\pi)^2} \sqrt{\frac{k_t^2}{s}} e^y \int_{z_{\text{min}}}^{1} dz q_d(x_q) D_{q/h}(z) \times \int d^2 b_t d^2 r_t e^{i k_t \cdot r_t/z} \sigma_{\text{dipole}}(r_t, b_t, x_g) \tag{2}
\]

where we have used the following kinematical relations \(x_q = k_+ e^y/z\sqrt{s}, x_g = k_- e^{-y}/z\sqrt{s}, z_{\text{min}} = k_+ e^y/\sqrt{s}\) (\(\sqrt{s}\) is the center of mass energy) while \(y\) and \(k_t\) are the rapidity and transverse momentum of the measured hadron. Both the quark distribution and fragmentation functions depend on a factorization scale \(Q_f^2\) which is not written out explicitly. In our calculation, we set \(Q_f = k_t\) where \(k_t\) is the transverse momentum of the observed particle. Eq. \[2\] is the formula used in this work to calculate the hadron spectra at forward rapidities in deuteron gold collisions.

We use the LO GRV98 quark distribution function \[10\] and the LO KKP quark hadron fragmentation function \[11\]. It should be noted that there is no available fragmentation function for negatively charged hadrons so therefore we use the fragmentation function for \((h^+ + h^-)/2\). However, in the transverse momentum range considered here \((p_t < 2\, \text{GeV})\), this should not make a sizable difference. Since we are sensitive only to the large \(x_q\) \((\sim 0.2 - 0.5)\) region of the deuteron wave function, there is practically no sensitivity to the choice of the quark distribution function. Also, the nuclear modification of valence quarks in the deuteron wave function is minimal in this \(x_q\) range and is therefore neglected here.

To proceed further, we need to know the dipole cross section \(\sigma_{\text{dipole}}\) which satisfies the JIMWLK equation. This is a very complicated functional equation \[12\] which simplifies in the large \(N_c\) limit, known as the BK equation. The BK equation for the dipole cross section has been numerically solved by various people in different limits \[13\]. Iancu, Itakura and Munier proposed a parameterization of the dipole cross section which has all the properties of the solution to the BK equation and used it to fit the HERA data on the proton structure function \(F_2\) \[14\]. This is a very simple and economical parameterization (it basically has three free parameters, in addition to the light quark mass) which does an excellent job of describing the HERA data at \(x < 0.01\). Therefore, we use this parameterization in this work. The dipole cross section is given by

\[
\int d^2 b_t \sigma_{\text{dipole}}(x_g, b_t, r_t) \equiv 2\pi R^2 \mathcal{N}(x_g, r_t Q_s) \tag{3}
\]
where
\[
\mathcal{N}(x, r_t Q_s) = 1 - e^{-a \ln^2 b r_t Q_s} \quad r_t Q_s > 2
\]
and
\[
\mathcal{N}(x, r_t Q_s) = N_0 \exp \left\{ 2 \ln \left( \frac{r_t Q_s}{2} \right) \left[ \gamma_s + \frac{\ln 2}{\kappa \lambda \ln 1/x_g} \right] \right\} \quad r_t Q_s < 2 \quad (4)
\]
The constants \(a, b\) are determined by matching the solutions at \(r_t Q_s = 2\) and \(\gamma_s = 0.63\) and \(\kappa = 9.9\) are determined from LO BFKL. The form of the proton saturation scale \(Q_s^2\) is taken to be \(Q_s^2 \equiv (x_0/x)^n GeV^2\) with \(x_0, \lambda, N_0\) determined from fitting the HERA data on proton structure function \(F_2\). We refer the reader to [14] for details of the fit.

In Fig. (1), we show our results for charged hadron production at \(y = 3.2\) in proton-proton collisions in arbitrary units while in Fig. (2), our results for charged hadron production in deuteron gold collisions is shown. Both figures are for minimum bias events. The proton-proton cross section is normalized to the data at \(k_t = 1.1\) GeV by multiplying by a \(K\) factor of 2.57. To get the normalization of the \(dA\) spectra, we again multiply by a \(K\) factor which is slightly less than the \(K = 1.8\) factor for the proton-proton case. This is not unreasonable since Next to Leading Order corrections are typically large at low \(k_t\) and that the \(K\) factors used can be different for nuclei [15]. However, the ratio \(R_{dA}\) is calculated without any \(K\) factor. The agreement with the slope of the spectra for \(k_t < 2\) GeV is quite reasonable specially since there are no free parameters in this calculation.

In Fig. (3), we show the nuclear modification factor \(R_{dA}\) for hadron production in deuteron gold collisions at \(y = 3.2\). We define
\[
R_{dA} \equiv \frac{d\sigma_{dA \rightarrow hX}}{dy dk_t} \frac{2 A}{d\sigma_{pp \rightarrow hX}} \frac{dy dk_t}{2}\quad (5)
\]
Again, the agreement with the data at low \(k_t\) is quite good but the higher \(k_t\) points start to show a deviation. This is discussed in more detail later. We emphasis the point that the ratio \(R_{dA}\) is calculated without multiplying by any \(K\) factor and with no free parameters.

It should be noted that the BRAHMS data is for negatively charged hadrons while our calculations are done for the average of positively and negatively charged hadrons since fragmentation functions for negatively charged hadrons are not available. Recently, Guzey et al. [16] investigated the dependence of the suppression and showed that isospin symmetry considerations can make a huge effect on the observed suppression. This effect is most pronounced in the \(k_t > 2\) GeV and can affect our results by \((15 - 20)\%\) in the kinematic region we cover.

Finally, since the STAR collaboration has measured neutral pions at rapidity \(y = 3.8\) in deuteron gold collisions, we show our predictions for neutral pion nuclear modification factor \(R_{dA}\) at \(y = 3.8\) in Fig. (4). A slightly stronger suppression of \(R_{dA}\) is seen at lowest \(k_t\) as compared to charged hadrons at \(y = 3.2\).
Figure 1: The invariant yield of charged hadrons at $y = 3.2$ at RHIC in proton-proton collisions at $\sqrt{s} = 200$ GeV. The normalization is a fit to the data.
Figure 2: The invariant yield of charged hadrons at $y = 3.2$ at RHIC in minimum bias deuteron-nucleus collisions at $\sqrt{s} = 200$ GeV.
Figure 3: The nuclear modification factor for charged hadrons at $y = 3.2$ in minimum bias deuteron-nucleus collisions at RHIC, $\sqrt{s} = 200$ GeV.
Figure 4: The nuclear modification factor for neutral pions at $y = 3.8$ in minimum bias deuteron-nucleus collisions at RHIC, $\sqrt{s} = 200$ GeV.
3 Discussion

In deuteron gold collisions in the forward rapidity and low \( k_t \) region at RHIC considered in this work, the valence quarks are the most abundant parton species in the deuteron. They scatter on the target nucleus, which has its wave function fully developed (evolved in \( x_g \) as much as allowed by the kinematics) and is characterized by the nucleus saturation scale \( Q_s^A(x_g) \). The valence quark gets a transverse momentum kick of order \( Q_s^A \) and is then “produced”.

To get a rough idea of the scales involved and estimate where our approach should break down, we note that hadrons carry a fraction of the parent parton energy and that \( <z> \approx 0.7 - 0.8 \) in this rapidity (for hadron production in \( pp \) collisions). The saturation scale of the nucleus is around \( Q_s^A \approx 1.5 - 1.8 \) GeV (minimum bias) at rapidity of \( y = 3.2 \). The geometric scaling region \([17, 18]\) extends to a little higher momentum \( Q_{es} \equiv Q_s^2/Q_{s0} \) and can be as high as 2.5 GeV. This means that our formalism should describe hadron production in minimum bias deuteron gold collisions in the forward rapidity region up to \( k_t \approx z Q_{es} \approx 2 \) GeV. We emphasize that these estimates are for minimum bias events only and the Color Glass Condensate formalism is expected to be valid at higher \( k_t \) for more central collisions.

As one goes to higher \( k_t \), gluon radiation becomes important \([19]\) and will eventually dominate the hadron production cross section. This has not been included here and would presumably improve the high \( k_t \) behavior of the spectra. Another caveat of our approach is the use of the dipole parameterization advocated in \([14]\). This parameterization does not have the Cronin effect \([20, 21, 22]\). This may be partly responsible for the deviation of calculated \( R_{dA} \) from the data. Also, this parameterization does not have the right high \( k_t \) behavior since the double log limit is not built into it. This is the reason for the decrease of the \( R_{dA} \) at higher \( k_t \) which is not expected from pQCD. However, none of the other simple parameterizations of the dipole model \([23]\) which have been used to fit the HERA data have the right (BFKL) anomalous dimension. Therefore, we use this parameterization because it has the right anomalous dimension and we are staying in a limited kinematic region and since it is experimentally known that the Cronin effect goes away in the forward rapidity region.

In order to extend this formalism to mid rapidity, one needs to include gluon production as considered in \([19]\). The contribution of gluons to hadron production in mid rapidity is more important than the contribution of valence quarks since at mid rapidity, one probes small values of \( x \) in the deuteron wave function where there are a lot more gluons than quarks. Nevertheless, a practical problem with inclusion of gluons is that there is no available parameterization of the gluon-gluon dipole cross section which has been tested in other processes unlike the quark anti-quark dipole cross section which is probed in DIS processes.

An important observable which has not been considered here is the centrality dependence of the hadron suppression factor in the forward rapidity region, recently shown by the BRAHMS collaboration in the Quark Matter 2004 \([1]\). It will be very interesting to see whether our formalism can also describe the centrality dependence of the data. This
would require the application of the Monte Carlo Glauber method to our formalism since this is the method used by experimentalists to extract centrality dependence of the data. This is beyond the scope of this work and will be pursued later.

The agreement of our calculations with the forward rapidity data becomes even more significant due to the fact we have not used any free parameters (for $R_{dA}$ and the slope of the spectra) in this calculation. All the necessary ingredients, the dipole cross section (for a proton) and the value of the nucleus saturation scale (for minimum bias events) have already been known for a while and used by various authors [6, 14]. The fact that our simple and parameter free calculation based on the Color Glass Condensate formalism can reproduce the experimental data at low $k_t$ is a strong indication that the physics of forward rapidity region at RHIC is that of high gluon density QCD and the Color Glass Condensate.

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