Cronin effect and geometrical shadowing in d+Au collisions: pQCD vs. CGC

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Abstract. Multiple initial state parton interactions in p(d)+A collisions are calculated in a Glauber-Eikonal formalism, which incorporates the competing pattern of low-$p_T$ suppression due geometrical shadowing, and a moderate-$p_T$ Cronin enhancement of hadron spectra. Dynamical shadowing effects, which are not included in the computation, may be extracted by comparing experimental data to the baseline provided by the Glauber-Eikonal model. Data for $\pi^0$ production at midrapidity show absence of dynamical shadowing in the RHIC energy range, $\sqrt{s} \sim 20-200$ GeV. Recent preliminary data at forward rapidity are addressed, and their interpretation discussed.

In proton (p), or deuteron (d), reactions involving heavy nuclei ($A \sim 200$) at $\sqrt{s} < 40$ AGeV, the moderate transverse momentum ($p_T \sim 2-6$ GeV) spectra are enhanced relative to linear extrapolation from $p + p$ reactions. This “Cronin effect” [1] is generally attributed to multiple scattering of projectile partons propagating through the target nucleus [2]. In this talk, we discuss multiple parton scattering in the Glauber-Eikonal (GE) approach [3, 4], in which sequential multiple partonic collisions are computed in pQCD, and unitarity is naturally preserved. The low-$p_T$ spectra in $p + A$ collisions are suppressed by unitarity. At moderate $p_T$, the accumulation of transverse momentum leads to an enhancement of transverse spectra. At high $p_T$ the binary scaled $p + p$ spectrum is recovered: no high-$p_T$ shadowing is predicted in this approach.

Hadron production in p+p collisions. The first step to understand $p + A$ collisions is to understand $p + p$ collisions. The pQCD formula for the single inclusive hadron transverse spectrum is:

$$\frac{d\sigma}{dp_T^2 dy} = \sum_{i=q,g} \left\{ \langle x f_i/p \rangle_{y, p_T} \frac{d\sigma_i}{dy d^2p_T} \bigg|_{y=0} + \langle x f_i/p' \rangle_{y, p_T} \frac{d\sigma_{ip}}{dy d^2p_T} \bigg|_{y=-y} \right\} \otimes D_{i \to h}(z, Q^2) .$$  \(1\)

Here we considered only elastic parton-parton subprocesses, which contribute to more than 98% of the cross section at midrapidity. In Eq. (1),

$$\langle x f_i/p \rangle_{y, p_T} = \frac{K}{\pi} \sum_j \frac{1}{1 + \delta_{ij}} \int dy_2 x_2 f_j/p'(x_2, Q^2) \frac{d\hat{\sigma}^{ij}}{dt} (\hat{s}, \hat{t}, \hat{u}) x_2 f_j/p'(x_2, Q^2) / \frac{d\sigma_{ip'}}{d^2p_T dy_i}$$  \(2\)

$$\frac{d\sigma_{ip'}}{d^2p_T dy_i} = \frac{K}{\pi} \sum_j \frac{1}{1 + \delta_{ij}} \int dy_2 \frac{d\hat{\sigma}^{ij}}{dt} (\hat{s}, \hat{t}, \hat{u}) x_2 f_j/p'(x_2, Q^2)$$  \(3\)
are interpreted, respectively, as the average flux of incoming partons of flavour $i$ from the hadron $p$, and the cross section for the parton-hadron scattering. The rapidities of the $i$ and $j$ partons in the final state are labelled by $y_i$ and $y_2$. Infrared regularization is performed by adding a small mass to the gluon propagator and defining the Mandelstam variables $\hat{t}(\hat{u}) = -m_T^2(1 + e^{\pm y_i \pm y_2})$, with $m_T = \sqrt{p_T^2 + p_0^2}$. For more details, see Ref. [3]. Finally, inclusive hadron production is computed as a convolution of Eq. (11) with a fragmentation function $D_{i \rightarrow h}(z, Q_h^2)$.

In Eqs. (11)-(13), we have two free parameters, $p_0$ and the K-factor $K$, and a somewhat arbitrary choice of the factorization and fragmentation scales, $Q_p = Q_h = m_T/2$. After making this choice, we fit $p_0$ and $K$ to hadron production data in $pp$ collisions at the energy and rapidity of interest. Equation (11) is very satisfactory for $q_T > 5$ GeV, but overpredicts the curvature of the hadron spectrum in the $q_T=1$-5 GeV range. This can be corrected for by considering an intrinsic transverse momentum, $k_T$, for the colliding partons [3]. We found that a fixed $\langle k_T^2 \rangle = 0.52$ GeV leads to a dramatic improvement in the computation, which now agrees with data at the $\pm 40\%$ level [3]. Finally, we obtain, at midrapidity $\eta = 0$, $p_0 = 0.7 \pm 0.1$ GeV and $K = 1.07 \pm 0.02$ at Fermilab, and $p_0 = 1.0 \pm 0.1$ GeV and $K = 0.99 \pm 0.03$ at RHIC.

**From p+p to p+A collisions.** Having fixed all parameters in p+p collisions, and defined the parton-nucleon cross section [3], the GE expression for a parton-nucleus scattering is [5]:

$$
\frac{d\sigma^{iA}}{d^2p_Tdy^2b} = \sum_{n=1}^{\infty} \frac{1}{n!} \int d^2b d^2k_1 \cdots d^2k_n \delta(\sum_{i=1,n}^{n} \vec{k}_i - \vec{p}_T) \times \frac{d\sigma^{iN}}{d^2k_1} T_A(b) \times \cdots \times \frac{d\sigma^{iN}}{d^2k_n} T_A(b) e^{-\sigma^{iN}(p_0)T_A(b)} ,
$$

(4)

where $T_A(b)$ is the target nucleus thickness function at impact parameter $b$. The exponential factor in Eq. (11) represents the probability that the parton suffered no semihard scatterings after the $n$-th one, and explicitly implements unitarity at the nuclear level. Assuming that the partons from $A$ suffer only one scattering on $p$ or $d$, we may generalize Eq. (11) as follows, without introducing further parameters:

$$
\frac{d\sigma}{d^2p_Tdy^2b} \left\{ \langle x f_{i/p} \rangle_{y_i, p_T} \frac{d\sigma^{iA}}{d^2p_Tdy^2b} \mid_{y_i = y} + T_A(b) \sum_{b} \langle x f_{i/A} \rangle_{y_i, p_T} \frac{d\sigma^{ip}}{d^2p_Tdy^2b} \mid_{y_i = y} \right\} \otimes D_{i \rightarrow h}
$$

Unitarity introduces a suppression of parton yields compared to the binary scaled p+p case. This is best seen in integrated parton yields: $d\sigma^{iA}/dy^2b \approx 1 - e^{-\sigma^{iN}(p_0)T_A(b)}$. At low opacity $\chi = \sigma^{iN}(p_0)T_A(b) \ll 1$, i.e., when the number of scatterings per parton is small, the binary scaling is recovered. However, at large opacity, $\chi \gtrsim 1$, the parton yield is suppressed: $d\sigma^{iA}/dy^2b \ll 1 < \sigma^{iN}(p_0)T_A(b)$. This suppression is what we call "geometrical shadowing", since it is driven purely by the geometry of the collision through the thickness function $T_A$. As the integrated yield is dominated by small momentum partons, geometrical shadowing is dominant at low $p_T$. 

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Figure 1. Cronin effect on pion production at Fermilab [6] and RHIC [10] at \( \eta = 0 \).
The solid curve is the GE computation. Theoretical errors due to the fit of \( p_0 \) are shown as a shaded band around the solid curve. The rightmost panel shows the 0-20%/60-88% centrality classes ratio.

Beside the geometrical quark and gluon shadowing, which is automatically included in GE models, at low enough \( x \) one expects genuine dynamical shadowing due to non-linear gluon interactions as described in Colour Glass Condensate (CGC) models [9]. However, it is difficult to disentangle these two sources of suppression of \( p_T \) spectra, and to understand where dynamical effects begin to play a role beside the ubiquitous geometrical effects. The GE model computation outlined above can be used as a baseline to extract the magnitude of dynamical effects by comparison with experimental data.

Cronin effect at Fermilab and RHIC. The Cronin effect may be quantified by taking the ratio of hadron \( p_T \) spectrum in p(d)+A collision, and dividing it by the binary scaled p+p spectrum:

\[
R_{pA} \simeq \frac{\frac{d\sigma}{dq_T^2dydb}(b' = \hat{b})}{T_A(\hat{b})} \frac{d\sigma_{pp \rightarrow hX}}{dq_T^2dy},
\]

where \( \hat{b} \) is the average impact parameter in the centrality bin in which experimental data are collected (see [3]). The GE model reproduces quite well both Fermilab and PHENIX data at \( \eta = 0 \) (Fig.1, left and center). It also describe the increase of the Cronin effect with increasing centrality (Fig.1, right). If dynamical shadowing as predicted in CGC models was operating in this rapidity and energy range, the central/peripheral ratio should be smaller than the GE result: the more central the collision, the higher the parton density in the nucleus, the larger the non-linear effects. Therefore, we conclude that there is no dynamical shadowing nor Colour Glass Condensate at RHIC midrapidity.

To address the preliminary BRAHMS data at forward rapidity \( \eta \approx 3.2 \) [11], we would first need to fit \( p_0 \) and \( K \) in p+p collisions at the same pseudo-rapidity. Unfortunately the available data \( p_T \)-range \( 0.5 \lesssim p_T \lesssim 3.5 \) Ge is not large enough \( p_T \) for the fit to be done. Therefore, we use the parameters extracted at \( \eta = 0 \). The resulting Cronin ratio, shown by the solid line in Figure 2, overestimates the data at such low-\( p_T \). This may be corrected in part by considering elastic energy loss [12].
Furthermore, the opacity $\chi_0 = 0.95$ might be underestimated, due to the use of the mid-rapidity parameters: to check this we tripled the opacity, but the resulting dashed line still overestimates the data.

Does the discrepancy between our calculations and the BRAHMS data prove that a CGC has been observed? It is too early to tell. An important observation [11] is that the yield of positive charged hadrons exceeds the yield of negative charged hadrons at moderate pt by just the factor expected in HIJING due to dominance of valence quark fragmentation effects: gluon fragmentation is subdominant mechanism in this kinematic range. In addition, current simplified CGC scenarios predict asymptotic $1/p_T^4$ absolute behavior which overestimates by an order of magnitude the observed absolute cross sections. In our pQCD approach the absolute cross sections in both p+p and d+Au collisions are much closer to the data, though the modest discrepancies shown in Figure 2 remain. Gluon shadowing appears to be needed in this $x \sim 10^{-3} - 10^{-2}$ regime, though more data will be required to quantify the effect.

The optimal region to study the onset of dynamical shadowing is $3 \lesssim p_T \lesssim 6$ GeV, where the GE model expects the peak of the Cronin ratio to be. If in this region the final data at forward rapidity $0 \lesssim \eta \lesssim 4$ explored by the four RHIC collaboration will reveal a consistent pattern of suppression compared to the GE computation (as preliminary data seem to suggest), and nonperturbative fragmentation effects will not be able to explain it, then the case for the CGC will be made more solid. The case would be even stronger if at the same time a progressive disappearance of back-to-back jets in favour of an increased dominance of monojet production was observed.

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