Saturating Cronin effect in ultrarelativistic proton-nucleus collisions

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Experimental results on pion and photon production in high-energy hadron-nucleus collisions show an extra increase at high transverse momentum ($p_T$) over what would be expected based on a simple scaling of the appropriate proton-proton ($pp$) cross sections. The nuclear enhancement is referred to as the Cronin effect \cite{1}, and is most relevant at moderate transverse momenta (3 GeV $\lesssim p_T \lesssim$ 6 GeV) \cite{2}. In relativistic nuclear collisions this momentum region is at the upper edge of the $p_T$ window in Super Proton Synchrotron (SPS) experiments at $\sqrt{s} = 20$ AGeV, and is measurable at the Relativistic Heavy Ion Collider (RHIC) at $\sqrt{s} = 200$ AGeV. The importance of a better theoretical understanding of the Cronin effect continues to increase \cite{3,4} as new data appear from the SPS heavy-ion program and as the commisioning of RHIC approaches. This calls for a systematic study of particle production moving from $pp$ to proton-nucleus ($pA$) collisions. In the present work we analyze the Cronin effect in inclusive $\pi^0$ and $\gamma$ production.

In the past two decades the perturbative QCD (pQCD) improved parton model has become the description of choice for hadronic collisions at large $p_T$. The pQCD treatment of hadronic collisions is based on the assumption that the composite structure of hadrons is revealed at high energies, and the parton constituents become the appropriate degrees of freedom for the description of the interaction at these energies. The partonic cross sections are calculable in pQCD at high energy to leading order (LO) or next-to-leading-order (NLO) \cite{5,6}. The parton distribution function (PDF) and the parton fragmentation function (FF), however, require the knowledge of non-perturbative QCD and are not calculable directly by present techniques. The PDFs and FFs, which are believed to be universal, are fitted to reproduce the data obtained in different reactions. In recent NLO calculations the various scales ($Q, \Lambda_{QCD}$, etc.) are optimized to improve the agreement between data and theory \cite{7,8}.

In theoretical investigations of $\pi^0$ and $\gamma$ production in $pA$ collisions another method appeared and became popular \cite{1,9}: the different scales of the pQCD calculations are fixed and the NLO pQCD theory is supplemented by an additional non-perturbative parameter, the intrinsic transverse momentum ($k_T$) of the partons. The presence of an intrinsic transverse momentum, as a Gaussian type broadening of the transverse momentum distribution of the initial state partons in colliding hadrons was investigated as soon as pQCD calculations were applied to reproduce large-$p_T$ hadron production \cite{10,11}. The average intrinsic transverse momentum needed was small, $\langle k_T \rangle \sim 0.3 - 0.4$ GeV, and could be easily understood in terms of the Heisenberg uncertainty relation for partons inside the proton. This simple physical interpretation was ruled out as the only source of intrinsic $k_T$ by the analysis of new experiments on direct photon production, where $\langle k_T \rangle \sim 1$ GeV was obtained in the fix target Tevatron experiments \cite{12,13} and $\langle k_T \rangle \sim 4$ GeV was found at the Tevatron collider for muon, photon and jet production \cite{14}. New theoretical efforts were ignited to understand the physical origin of $\langle k_T \rangle$ \cite{15,16}. Parallel to these developments, $k_T$ smearing was applied successfully to describe ultrarelativistic nucleus-nucleus collisions \cite{17} and $J/\psi$ production at Tevatron and HERA \cite{18}. One possible explanation of the enhanced $k_T$-broadening is in terms of multiple gluon radiation \cite{17}, which makes $\langle k_T \rangle$ reaction and energy dependent. In the absence of a full theoretical description, intrinsic $k_T$ can be used phenomenologically in $pp$ collisions. A reasonable reproduction of the $pp$ data is a prerequisite for the isolation of the nuclear enhancement we intend to focus on.

In the lowest-order pQCD parton model, direct pion production can be described in $pp$ collisions by

$$ E_x \frac{d\sigma_{pp}}{d^3p} = \sum_{abcd} \int dx_1 dx_2 f_{a/p}(x_1, Q^2) f_{b/p}(x_2, Q^2) $$

$$ K \frac{d\sigma}{dt} (ab \to cd) \frac{D_{z/c}(x_c, Q^2)^2}{\pi x_c}, $$

(1)

where $f_{a/p}(x, Q^2)$ and $f_{b/p}(x, Q^2)$ are the PDFs for the colliding partons $a$ and $b$ in the interacting protons as
functions of momentum fraction \(x\) and momentum transfer \(Q\), and \(\sigma\) is the LO hard scattering cross section of the appropriate partonic subprocess. The K-factor accounts for higher order corrections \[3\]. Comparing LO and NLO calculations one can obtain a constant value, \(K \approx 2\), as a good approximation of the higher order contributions in the \(p_T\) region of interest \[3\]. In eq. \((1)\) \(D_{\pi f}(z_c, \tilde{Q}^2)\) is the FF for the pion, with the scale \(\tilde{Q} = p_T/z_c\), where \(z_c\) indicates the momentum fraction of the final hadron. We use a NLO parameterization of the FFs \[24\]. Direct \(\gamma\) production is described similarly \[3\].

The generalization to incorporate the \(k_T\) degree of freedom is straightforward \[3\]. Each integral over the parton distribution functions is extended to \(k_T\)-space,

\[
dx f_{a/p}(x, Q^2) \rightarrow dx \, d^2k_T \, g(k_T) \, f_{a/p}(x, Q^2), \quad (2)
\]

and, as an approximation, \(g(k_T)\) is taken to be a Gaussian:

\[
g(k_T) = \exp(-k_T^2/(\Delta k_T^2)) / \pi \langle k_T^2 \rangle. \quad (k_T^2) \text{ is the 2-dimensional width of the } k_T \text{ distribution and it is related to the average transverse momentum of one parton as } \langle k_T^2 \rangle = 4\langle k_T \rangle^2 / \pi.
\]

![FIG. 1. The best fit values of \(\langle k_T^2 \rangle\) in \(p+p \rightarrow \pi^0 X\) \[12\] and \(p+p \rightarrow \gamma X\) reactions \[12\] \[20\] (upper panel), and a calculated \(\langle k_T \rangle\) (lower panel). See text for the lines.](image)

We applied this model to describe the measured data in \(p+p \rightarrow \pi^0 X\) reactions \[12\] \[20\]. If \(\pi^+\) and \(\pi^-\) production was measured, we constructed the combination \(\pi^0 = (\pi^+ + \pi^-)/2\), given by the FFs \[20\] we use. The calculations were corrected for the finite rapidity windows of the data. The Monte-Carlo integrals were carried out by the standard VEGAS-routine \[27\]. For the PDFs we used the MRST98 set \[28\], which incorporates an intrinsic \(k_T\). The scales are fixed, \(\Lambda_{\overline{MS}}(n_f = 4) = 300\) MeV and \(Q = p_T/2\). We fitted the data minimizing \(\Delta^2 = \sum (\text{Data} - \text{Theory})^2 / \text{Theory}^2\) in the midpoints of the data. Fig.1. shows the obtained fit values for \(\langle k_T^2 \rangle\). The error bars display a \(\Delta^2 = \Delta_{\text{min}}^2 \pm 0.1\) uncertainty in the fit procedure. The uncertainty is small at \(\sqrt{s} = 20 - 30\) GeV and relatively large at \(\sqrt{s} \approx 60\) GeV, indicating that \(\langle k_T^2 \rangle\) is more sharply determined at lower energies. We use a value of \(\langle k_T^2 \rangle = 3\) GeV\(^2\) for \(\pi^0\) at \(\sqrt{s} = 27.4\) GeV. The value of \(\langle k_T^2 \rangle\) appears to increase with energy. The dashed line serves to guide the eye and indicates a linear increase to a value of \(\langle k_T \rangle = 3.5\) GeV at \(\sqrt{s} = 1800\) GeV \[3\].

Furthermore, we analyzed the data from \(p+p \rightarrow \gamma X\) reactions \[25\] \[26\] \[29\] \[33\]. These results are also shown in Fig.1. In this case much lower values are obtained for \(\langle k_T^2 \rangle\) with large uncertainty. The dotted line represents the results obtained in Ref. \[13\] from diphoton and dimuon data. In the following we use \(\langle k_T^2 \rangle = 1.2\) and \(1.5\) GeV\(^2\) at \(\sqrt{s} = 31.6\) and 38.8 GeV, respectively.

![FIG. 2. The ratio of data to theory for \(p+p \rightarrow \pi^0 X\) reactions \[12\] \[20\] applying the best fit for \(\langle k_T^2 \rangle\), \(x_T = 2p_T/\sqrt{s}\).](image)
simplicity, we use a sharp sphere nucleus with \( t_A(b) = 2p_0 \sqrt{R_A^2 - b^2} \), where \( R_A = 1.144 A^{1/3} \) and \( p_0 = 0.16 \text{ fm}^{-3} \). Next we discuss the nuclear enhancement of \( \langle k_T^2 \rangle \).

The standard physical explanation of the Cronin effect is that the proton traveling through the nucleus gains extra transverse momentum due to random soft collisions and the partons enter the final hard process with this extra \( k_T \). In our approximation initial soft processes increase the value of \( \langle k_T^2 \rangle \), but this effect does not depend on the scale, \( Q^2 \), of the hard process to occur later. However, it may depend on the initial center-of-mass energy, \( \sqrt{s} \). Furthermore, it is important to note, that in our description not all participant protons are automatically endowed with the extra \( \langle k_T^2 \rangle \) enhancement, only the parton distribution of the colliding protons is affected according to the number of soft collisions suffered. To characterize the \( \langle k_T^2 \rangle \) enhancement, we write the width of the transverse momentum distribution of the partons in the incoming proton as

\[
\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C \cdot h_{pA}(b) .
\]

Here \( h_{pA}(b) \) describes the number of effective nucleon-nucleon (NN) collisions at impact parameter \( b \) which impart an average transverse momentum squared \( C \).

Naively all possible soft interactions are included, \( h_{pA}(b) = \nu_A(b) - 1 \), where \( \nu_A(b) = \sigma_{NN} t_A(b) \) is the collision number at impact parameter \( b \) with \( \sigma_{NN} \) being the total inelastic cross section. Applying this model to \( \pi^0 \) production in \( pA \) (\( A = Be, Ti, W \)) collisions at \( \sqrt{s} = 27.4 \text{ GeV} \), we extract \( C_{pBe} = 0.8 \pm 0.2 \text{ GeV}^2 \), \( C_{pTi} = 0.4 \pm 0.2 \text{ GeV}^2 \), and \( C_{pW} = 0.3 \pm 0.2 \text{ GeV}^2 \). The target dependence of the extra enhancement in \( \langle k_T^2 \rangle \) is inconsistent with the assumption of a target-independent average transverse momentum transfer per NN collision and/or with the form of \( h_{pA}(b) \).

Inspired by the \( A \)-dependence, we propose another physical picture of the nuclear enhancement effect. According to this mechanism, the incoming nucleon first participates in a semi-hard \( (Q^2 \sim 1 \text{ GeV}^2) \) collision resulting in an increase of the width of its \( k_T \) distribution. There is at most one collision able to impart this increased value of \( \langle k_T^2 \rangle \), characteristic of the no-longer coherent nucleon. Further soft or semi-hard collisions do not affect the \( k_T \) distribution of the partons in the incoming nucleon. This saturation effect can be approximated well by a smoothed step function \( h_{pA}^\text{sat}(b) \) defined as

\[
h_{pA}^\text{sat}(b) = \begin{cases} 0 & \text{if } \nu_A(b) < 1 \\ \nu_A(b) - 1 & \text{if } 1 \leq \nu_A(b) < 2 \\ 1 & \text{if } 2 \leq \nu_A(b) \end{cases}.
\]

The saturated Cronin factor is denoted by \( C^\text{sat} \).

Using the same \( pA \) data as previously, \( C^\text{sat} = 1.2 \text{ GeV}^2 \) gives a good fit for all three targets, Be, Ti and W. Fig.3. displays our results with (full line) and without (dashed line) the Cronin enhancement. The lower panel shows the data/theory ratio on a linear scale for the \( pW \) case. It is interesting to note that with the saturated Cronin effect the remaining deviation from one in the data/theory ratio is similar in shape to the \( pT \)-dependent K factor obtained in Ref. \( [4] \). The \( pBe \rightarrow \pi^0 X \) data at energies \( \sqrt{s} = 31.6 \text{ GeV} \) and \( 38.8 \text{ GeV} \) \( [12] \) are also described quite well with the same saturating Cronin effect \( [4] \).

Let us now discuss photon production in the same energy region. We speculate that the nuclear enhancement does not depend on the outgoing particle, and thus use the same \( C^\text{sat} \) for \( \gamma \) as for \( \pi^0 \) production. Fig.4. shows the \( pBe \rightarrow \gamma X \) reaction at energies \( \sqrt{s} = 31.6 \text{ GeV} \) and \( \sqrt{s} = 38.8 \text{ GeV} \). The data are from Ref. \( [13] \). The calculations are carried out with \( C^\text{sat} = 1.2 \text{ GeV}^2 \) (full lines). For comparison we show the results without nuclear enhancement, \( C^\text{sat} = 0 \) (dashed lines). In the lower panel the data/theory ratio is displayed for \( \sqrt{s} = 31.6 \text{ GeV} \).

The common value of \( C^\text{sat} \) in the studied energy range indicates that the extra enhancement in \( pA \) collision is independent of the produced final state particle. We interpret this \( C^\text{sat} \) as the square of the characteristic transverse momentum imparted in one semi-hard collision prior to the hard scattering. Independent of the details of the mechanism, the extra nuclear enhancement in eq. (4) appears to have the same total value, which is on the scale of the intuitive dividing line between hard and soft physics, \( C \cdot h_{pA}(0) \approx 1 \text{ GeV}^2 \). For RHIC predictions it would be necessary to see the energy dependence.
of $C^{sat}$, and whether the same nuclear enhancement is obtained at much higher energies.

![Cross section per nucleon in the $pBe \rightarrow \gamma + X$ reaction at $\sqrt{s} = 38.8$ GeV (dots) and at $\sqrt{s} = 31.6$ GeV (full triangles)](image)

FIG. 4. Cross section per nucleon in the $pBe \rightarrow \gamma + X$ reaction at $\sqrt{s} = 38.8$ GeV (dots) and at $\sqrt{s} = 31.6$ GeV (full triangles). Solid lines indicate $C^{sat} = 1.2$ GeV$^2$, dashed lines mean $C^{sat} = 0$. Lower panel shows data/theory for $\sqrt{s} = 31.6$ GeV.

In the present letter we separated the $pp$ and nuclear contributions to the width of the parton transverse momentum distribution, and proposed a saturating model of the Cronin effect in proton-nucleus collisions. According to our picture, the incoming proton suffers at most one semi-hard scattering prior to the hard parton scattering. In the semi-hard collision the width of the transverse momentum distribution of the partons inside the incoming proton increases. This prescription describes the $p_T$ dependence of the nuclear enhancement in $p^0$ and $\gamma$ production remarkably well. We are confident that complete NLO calculations, which are left for future work, will improve the agreement further. Systematic $p_T$ experiments are needed to determine the energy dependence of $C^{sat}(s)$ and to extrapolate to $AA$ collisions at RHIC.

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