QCD factorization at forward rapidities

J. Čepila\textsuperscript{1}, J. Nemchik\textsuperscript{1,2} and M Šumbera\textsuperscript{3}
\textsuperscript{1} Czech Technical University in Prague, FNSPE, Břehová 7, 11519 Prague, Czech Republic
\textsuperscript{2} Institute of Experimental Physics SAS, Watsonova 47, 04001 Košice, Slovakia
\textsuperscript{3} Nuclear Physics Institute AS CR, 25068 Řež/Prague, Czech Republic
E-mail: jan.cepila@fjfi.cvut.cz ; nemchik@saske.sk ; sumbera@ujf.cas.cz

Abstract. We analyze particle production in several reactions on nuclear targets at forward rapidities and different energies. The forward kinematic region at high energies allows to access the smallest Bjorken $x$. Nuclear effects are then usually interpreted as a result of the coherence effects associated with shadowing or the Color Glass Condensate. QCD factorization of soft and hard interactions requires the nucleus to be an universal filter for different Fock components of the projectile hadron. We demonstrate, however, that this is not the case in the vicinity of the kinematic limit, $x \to 1$, where sharing of energy between the projectile constituents becomes an issue. The rise of suppression of particle production with $x$ is confirmed by the E772 and E886 data on Drell-Yan and heavy quarkonia. We show that this effect can also be treated alternatively as an effective energy loss proportional to initial energy. This leads to a nuclear suppression at any energy, and predicts Feynman $x_F$ scaling of the suppression. We demonstrate how the kinematic limit influences the high-$p_T$ particle production at mid-rapidity where the Cronin enhancement at medium-high $p_T$ switches to a suppression at larger $p_T$ violating thus QCD factorization. Such an expectation seems to be confirmed by RHIC data for pion and direct photon production. We show that this effect as an additional large-$p_T$ suppression significantly revises calculations for jet quenching in heavy ion collisions at RHIC.

1. Introduction

If a particle with mass $m$ and transverse momentum $p_T$ is produced in a hard reaction then the corresponding values of the Bjorken variable in the beam and the target are $x_{1,2} = \sqrt{m^2 + p_T^2} e^{\pm y}/\sqrt{s}$. Thus, at forward rapidities the target $x_2$ is $e^y$ times smaller than at midrapidities, $y = 0$. This allows to study coherent phenomena (shadowing, Color Glass Condensate (CGC)), which are expected to suppress particle yields.

The forward rapidity region, $y > 0$, was studied already in the fixed target experiments \cite{1} investigating a production of different species of hadrons in $p + A$ collisions, in charge pion \cite{2} and charmonium production \cite{3, 4} at SPS, in the Drell-Yan process and charmonium production at Fermilab \cite{5, 6} and later on at larger RHIC energies in the production of high-$p_T$ particles in $d + Au$ collisions \cite{7, 8}. This region is expected to be studied also at LHC by the ALICE Collaboration \cite{9}.

The interpretation of large-$y$ suppression at RHIC via coherent phenomena should be done with great care since there is no consensus so far about the strength of gluon shadowing and CGC. The model proposed in \cite{10} contains few parameters fitted to the BRAHMS data \cite{7}. Moreover, the recent global leading order (LO) analysis \cite{11} including besides DIS also this BRAHMS data leads to grossly exaggerated gluon shadowing which conflicts with the unitarity bound \cite{12}.

Besides, an energetic universality of a significant suppression at large $y$ is manifested so far for any reaction. Namely, all fixed target experiments have too low energy for the onset of
coherence effects since \(x_2\) is not small. The rise of suppression with \(y\) (with Feynman \(x_F\)) shows the same pattern as observed at RHIC. Such an energy independent feature common for all known reactions allows to favor another mechanism \([13]\) which describes observed suppression via corrections for energy conservation in initial state parton rescatterings and could also be interpreted as a parton effective energy loss proportional to initial energy leading so to \(x_F\) scaling of nuclear effects.

This suppression can also be interpreted as the decomposition of the projectile hadron into different Fock states. In comparison to the proton case, the nucleus has a higher resolution due to multiple interactions and so can resolve higher Fock components containing more constituents. The corresponding parton distributions fall off steeper at \(x \to 1\).

In the vicinity of the kinematic limit 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 found \([13]\) to be approximately,

\[
S(x) \approx 1 - x.
\] (1)

Each of the multiple interactions of the projectile partons produces an extra \(S(x)\), and the weight factors are given by the AGK cutting rules \([14]\). Then in terms of the nuclear thickness function \(T_A(\vec{b})\) and the effective cross section \(\sigma_{eff} = 20\text{ mb} \) \([13]\) the cross sections of hard reactions on a nuclear target \(A\) at impact parameter \(\vec{b}\) and on a nucleon \(N\) are related as,

\[
\frac{d\sigma_A}{dx d^2 b} = \frac{d\sigma_N}{dx} \frac{1}{\sigma_{eff}} e^{-\sigma_{eff} T_A(\vec{b})} \sum_{n=1}^{A} \frac{n!}{n!} \left[ \sigma_{eff} T_A(\vec{b}) \right]^{n} S(x)^{n-1} = \frac{d\sigma_N}{dx} T_A(\vec{b}) e^{-[1-S(x)]\sigma_{eff} T_A(\vec{b})}.
\] (2)

Consequently, the effective projectile parton distribution correlates with the nuclear target breaking thus expecting QCD factorization \([13]\).

In this paper using the mechanism from \([13, 15]\) and including also coherent phenomena (shadowing) at small \(x_2\) we analyze several reactions at forward rapidities and different energies.

Figure 1. (Left) Ratio, \(R_{p+p}(p_T)\), for \(\pi^\pm\) production rates in \(p+Pb\) and \(p+p\) collisions as function of \(p_T\) at \(E_{lab} = 158\text{ GeV}\) and two fixed \(x_F = 0.025\) and 0.375 \([16]\) vs. NA49 data \([2]\). (Right) The exponent describing the A-dependence (\(\propto A^\alpha\)) of the ratio for the production of different hadrons in \(p+A\) relative to \(p+p\) collisions as function of \(x_F\) \([13]\) vs. data \([1]\).

2. Nuclear suppression at small energies
Figs. 1 and 2 (see also Fig. 4) clearly exhibit the same pattern as that seen at RHIC \([7, 8]\) - a significant rise of suppression with \(x_F\) (\(x_1\)) at SPS, \(E_{lab} = 158\text{ GeV}\), and FNAL energy,
$E_{lab} = 800$ GeV. All those fixed target experiments have too low energy for the onset of coherent effects in gluon radiation since the target $x_2$ is not small and consequently the coherence length $l_c = P/(x_2 m_N)$, where $P \sim 0.1$ [17], is shorter than the mean inter-nucleon spacing.

The mechanism of nuclear suppression can be interpreted as a energy dissipation of the projectile hadron and its debris when propagating through the nucleus. As a result, the probability of production of a particle carrying the substantial fraction $x_F$ of the initial momentum decreases compared to a free proton target [13, 15].

Model predictions [13, 16] including corrections Eq. (1) for energy deficit in initial state parton multiple interactions lead to a reasonable agreement with low energy data.

3. Nuclear suppression of hadrons at RHIC

In 2004 the BRAHMS Collaboration [7] reported a significant suppression of $h^-$ at $\eta = 3.2$. Much stronger nuclear effects were found later on by the STAR Collaboration [8] for $\pi^0$ production at $\eta = 4$. All these data are consistent with model calculations [13] (see Fig. 3) including besides coherent phenomena also corrections for energy deficit Eq. (1). The onset of coherent effects alone cannot successfully describe a rise of nuclear effects with $y$. Namely corrections for energy
conservation reflecting much smaller survival probability $S(x)$ of a LRG at larger $x$ allows to describe data as is shown in Fig. 3.

4. Charmonium suppression at SPS and FNAL

Fig. 4 clearly demonstrates a strong suppression of charmonium production at large $x_F$ in the SPS (Left) and fixed target FNAL (Right) energy range where no shadowing effects are expected. This suppression represents another manifestation of the energy sharing problem in multiple initial state interactions Eq. (1) near the kinematic limit.

Figure 4. (Left) The exponent describing the $A$-dependence ($\propto A^\alpha$) of the nucleus-to-nucleon ratio for the charmonium production as a function of $x_F$ vs. NA3 data [3] at $E_{\text{lab}} = 158$ GeV. (Right) The exponent describing the $A$-dependence ($\propto A^\alpha$) of the nucleus-to-nucleon ratio for the charmonium production as a function of $x_F$ vs. E866 data [6] at $E_{\text{lab}} = 800$ GeV.

5. Nuclear suppression at large $x_T$, central rapidity

Besides large $x_F$ one can approach the kinematic limit increasing $x_T = 2p_T/\sqrt{s}$. In this case again the energy conservation constraints Eq. (1) cause a nuclear suppression.

The $d+A$ to $p+p$ ratio was predicted correctly including also the Cronin effect at medium-high $p_T$ [18]. Assuming QCD factorization one expects that this ratio should approach one at large $p_T$ (with small corrections for isotopic effects). However, corrections for energy conservation Eq. (1) leads to a considerable suppression [16], which seems to be confirmed by data (see Fig. 5).
6. Direct photons at central rapidity

Assuming heavy ion collisions, production of prompt photons in a hard reaction should not be accompanied with any final state interaction, either energy loss, or absorption. Therefore, besides the Cronin enhancement at medium-high \( p_T \) and small isotopic corrections at larger \( p_T \) we should not expect any nuclear effects.

Unexpectedly, data from the PHENIX experiment [20] exhibit a significant suppression in \( Au + Au \) collisions at large \( p_T \) as is demonstrated in Fig. 6. No explanation for this behavior has been proposed so far. Central production of prompt photons with large \( p_T \) at RHIC cannot be accompanied by coherent phenomena and is again a subject to the energy sharing problem.

In Fig. 6 the PHENIX data are compared also with model predictions [16] for the ratio \( R_{Au+Au} \) as a function of \( p_T \). If the factor Eq. (1) suppressing multiple interactions is excluded model calculations depicted by the dashed lines give a value \( R_{Au+Au} \rightarrow 0.8 \) in accord with onset of isotopic effects and cannot describe a suppression at large \( p_T \) observed especially at \( \sqrt{s} = 200 \text{ GeV} \). Inclusion of corrections for energy conservation Eq. (1) leads to strong nuclear effects at large \( p_T \) as is demonstrated by solid lines.

![Figure 6](image_url)

**Figure 6.** Nuclear modification factor for direct photon production in \( Au + Au \) collisions at a centrality range 0 – 10% and at \( \sqrt{s} = 62 \text{ GeV} \) (Left) and \( \sqrt{s} = 200 \text{ GeV} \) (Right) vs. PHENIX data [20]. Solid and dashed curves correspond to calculations [16] done with and without the corrections for energy deficit, the factor Eq. (1) suppressing multiple interactions, respectively.

7. Jet quenching in heavy ion collision

Large-\( p_T \) hadrons produced in heavy ion collisions demonstrate a strong suppression, which surprisingly does not vanish at high \( p_T \), but seems to be constant giving thus a rise to breakdown of QCD factorization. Corrections for energy conservation Eq. (1) should cause a considerable additional suppression which is stronger at larger \( p_T \) compensating so an expected rise of \( R_{AA} \) (see Fig. 7).

8. Summary

- Interpretation of a strong nuclear suppression in the forward rapidity region allowing to access smallest Bjorken \( x \) should be presented with caution. Assuming that only gluon saturation induces the suppression observed at RHIC, one arrives at an astonishingly small amount of gluons in nuclei, which breaks down a bottom unitarity bound.
- Treating the nucleus to be an universal filter for different Fock components of the projectile hadron, one comes to factorization of soft and hard interactions. However, this is not the case at large either \( x_F \) or \( x_T \) where sharing of energy between the constituents becomes an issue and higher Fock components are resolved better.
- This effect can be treated as an effective energy loss proportional to initial energy.
• Energy loss proportional to energy leads to a nuclear suppression at any energy, and predicts Feynman $x_F$ scaling of the suppression. This provides also an explanation for the longstanding puzzle of $J/\Psi$ suppression scaling in $x_F$.

• Besides large $x_F \to 1$ the kinematic limit can be approached also in transverse momentum increasing $x_T$. Similar effects of energy conservation are expected to be manifested. As a result, the Cronin enhancement of particle production at medium-high $p_T$ switches to a suppression at larger $p_T$. Such an unexpected effect demonstrating a violation of the QCD factorization seems to be confirmed by data for pion production in d+Au collisions at RHIC, and even for direct photons.

• Additional suppression coming from the effective energy loss effects represents significant corrections to all calculations for jet quenching.

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