

# Production of hadrons in proton-nucleus collisions: from RHIC to LHC

Michal Krelina<sup>1,a</sup> and Jan Nemchik<sup>1,2,b</sup>

<sup>1</sup>Czech Technical University in Prague, FNSPE, Brehova 7, 11519 Prague, Czech Republic

<sup>2</sup>Institute of Experimental Physics SAS, Watsonova 47, 04001 Kosice, Slovakia

**Abstract.** We study nuclear effects in production of large- $p_T$  hadrons on nuclear targets at different energies corresponding to RHIC and LHC experiments. For calculations we employ the QCD improved parton model including the intrinsic parton transverse momenta and the nuclear broadening. Besides nuclear modification of parton distribution functions we include also the complementary effect of initial state interactions causing a significant nuclear suppression at large- $p_T$  and at forward rapidities violating so the QCD factorization. Numerical results for nucleus-to-nucleon ratios are compared with available data from experiments at RHIC and LHC. We perform also predictions for nuclear effects at LHC expected at forward rapidities.

## 1 Introduction

Recent experimental measurements of particle production at different transverse momenta  $p_T$  in proton-nucleus ( $p + A$ ) collisions at RHIC and LHC allows to study various nuclear phenomena. This gives a good baseline for interpretation of the recent heavy-ion results.

Nuclear effects in inclusive hadron (h) production are usually studied through the nucleus-to-nucleon ratio, the so called nuclear modification factor,  $R_A(p_T) = \sigma_{p+A \rightarrow h+X}(p_T) / A \sigma_{p+p \rightarrow h+X}(p_T)$ .

The Cronin effect, resulting in  $R_A(p_T) > 1$  at medium-high  $p_T$ , was studied in [1] within the color dipole formalism. Corresponding predictions were confirmed later by data from the PHENIX Collaboration [2] at RHIC and recently by the ALICE experiment [3] at LHC. However, none from other models presented in a review [4] was able to describe successfully the last ALICE data [3].

Another interesting manifestation of nuclear effects leads to nuclear suppression at large  $p_T$ ,  $R_A(p_T) < 1$ . Such a suppression is indicated by the PHENIX data [2] on  $\pi^0$  production in  $d+Au$  collisions at mid rapidity,  $y = 0$ . However, much stronger suppression has been investigated at forward rapidities by the BRAHMS ( $y = 1, 2$  and  $3.2$ ) and STAR ( $y = 4$ ) Collaborations [5]. This forward region is expected to be studied also at LHC since the target Bjorken  $x$  is  $\exp(y)$  times smaller than at  $y = 0$ . This allows to investigate already in the RHIC kinematic region the coherent phenomena (shadowing, Color Glass Condensate (CGC)), which are expected to suppress particle yields.

The interpretation of large- $y$  suppression at RHIC via CGC [6] should be done with a great care since the assumption that CGC is the dominant source of suppression leads to severe problems with understanding of a

wider samples of data at smaller energies (see examples in [7]) where no coherence effects are possible. These data demonstrate the same pattern of nuclear suppression increasing with Feynman  $x_F$  and/or with  $x_T = 2p_T / \sqrt{s}$ , where  $\sqrt{s}$  is c. m. energy. Therefore it is natural to expect that the mechanisms, which cause the nuclear suppression at lower energies, should be also important and cannot be ignored at the energy of RHIC and LHC. Such a mechanism related to initial state interactions (ISI), which is not related to coherence and is valid at any energy, was proposed in [7] and applied for description of various processes in  $p(d) + A$  interactions [8] and in heavy ion collisions [9].

In this paper we perform predictions for  $R_A(p_T)$  in hadron production in  $p(d) + A$  interactions at RHIC and LHC within the QCD improved parton model. First we verify a successful description of particle spectra in  $p + p$  collisions. For evaluation of the Cronin effect we include nuclear broadening calculated within the color dipole formalism [10]. We demonstrate that nuclear modification of the parton distribution functions leads to a modification of  $R_A(p_T)$  especially at small and medium  $p_T$ . Effects of ISI cause a strong nuclear suppression at large  $p_T$  and/or at forward rapidities. Model calculations of  $R_A(p_T)$  are in a good agreement with PHENIX and STAR data at RHIC and with the first data from the ALICE experiment at LHC. We perform also calculations for  $R_A(p_T)$  at forward rapidities in the LHC kinematic region. Predicted strong nuclear suppression can be verified in the future by the CMS and ALICE experiments.

## 2 $p + p$ collisions

Within the QCD improved parton model for the invariant inclusive cross section of the process  $p + p \rightarrow h + X$  we use the standard convolution expression based on QCD factor-

<sup>a</sup>e-mail: michal.krelina@fjfi.cvut.cz

<sup>b</sup>e-mail: nemcik@saske.sk

ization [11]

$$E \frac{d^3 \sigma^{pp \rightarrow hX}}{dp^3} = K \sum_{abcd} \int d^2 k_{Ta} d^2 k_{Tb} \frac{dx_a}{x_{Ra}} \frac{dx_b}{x_{Rb}} \times g_p(k_{Ta}, Q^2) g_p(k_{Tb}, Q^2) f_{a/p}(x_a, Q^2) f_{b/p}(x_b, Q^2) \times D_{h/c}(z_c, \mu_F^2) \frac{1}{\pi z_c} \frac{d\hat{\sigma}^{ab \rightarrow cd}}{d\hat{t}} \quad (1)$$

where  $K$  is the normalization factor,  $K \approx 1.0 - 1.5$  depending on the energy,  $d\hat{\sigma}/d\hat{t}$  is the hard parton scattering cross section,  $x_a, x_b$  are fractions of longitudinal momenta of colliding partons and  $z_c$  is a fraction of the parton momentum carried by a produced hadron. The radial variable is defined as  $x_{Ri}^2 = x_i^2 + 4k_{Ti}^2/s$ .

The intrinsic parton transverse momentum distribution  $g_N$  is described by the Gaussian distribution

$$g_N(k_T, Q^2) = \frac{1}{\pi \langle k_T^2 \rangle_N(Q^2)} e^{-k_T^2 / \langle k_T^2 \rangle_N(Q^2)}, \quad (2)$$

with a non-perturbative parameter  $\langle k_T^2 \rangle_N(Q^2)$  representing the mean intrinsic transverse momentum with the scale dependent parametrization taken from [12]

$$\langle k_T^2 \rangle_N(Q^2) = 2.0(\text{GeV}^2) + 0.2 \alpha_S(Q^2) Q^2. \quad (3)$$

For the hard parton scattering cross section we use regularization masses  $\mu_q = 0.2 \text{ GeV}$  and  $\mu_G = 0.8 \text{ GeV}$  for quark and gluon propagators, respectively [1].

In all calculations we took the scale  $Q^2 = \mu_F^2 = p_T^2/z_c^2$ . The parton distribution and fragmentation functions were taken with NNPDF2.1 parametrization [13] and with DSS parametrization [14], respectively.

### 3 $p + A$ collisions

The invariant differential cross section for inclusive high- $p_T$  hadron production in  $p + A$  collisions reads

$$E \frac{d^3 \sigma^{pA \rightarrow hX}}{dp^3} = K \sum_{abcd} \int d^2 b T_A(b) \int d^2 k_{Ta} d^2 k_{Tb} \frac{dx_a}{x_{Ra}} \frac{dx_b}{x_{Rb}} \times g_A(b, k_{Ta}, Q^2) g_p(k_{Tb}, Q^2) f_{a/p}(x_a, Q^2) f_{b/A}(b, x_b, Q^2) \times D_{h/c}(z_c, \mu_F^2) \frac{1}{\pi z_c} \frac{d\hat{\sigma}^{ab \rightarrow cd}}{d\hat{t}}, \quad (4)$$

where  $T_A(b)$  is the nuclear thickness function normalized to the mass number  $A$ . The nuclear parton distribution functions (NPDF)  $f_{b/A}(b, x_b, Q^2)$  were obtained using the nuclear modification factor  $R_f^A(x_b, Q)$  from EPS09 [15] or nDS [16] for each flavour,

$$f_{b/A}(x_b, Q^2) = R_f^A(x_b, Q^2) \left[ \frac{z}{A} f_{b/p}(x_b, Q^2) + \left(1 - \frac{z}{A}\right) f_{b/n}(x_b, Q^2) \right]. \quad (5)$$

The  $k_T$ -broadening  $\Delta k_T^2$  represents a propagation of the high-energy parton through a nuclear medium that experiences multiple soft rescatterings. It can be imagined as parton multiple gluonic exchanges with nucleons. The initial parton transverse momentum distribution  $g_A(k_T, Q^2, b)$  of a projectile nucleon going through the target nucleon at

impact parameter  $b$  has the same Gaussian form as in  $p + p$  collisions,

$$g_A(k_T, Q^2, b) = \frac{1}{\pi \langle k_T^2 \rangle_A(Q^2, b)} e^{-k_T^2 / \langle k_T^2 \rangle_A(Q^2, b)}, \quad (6)$$

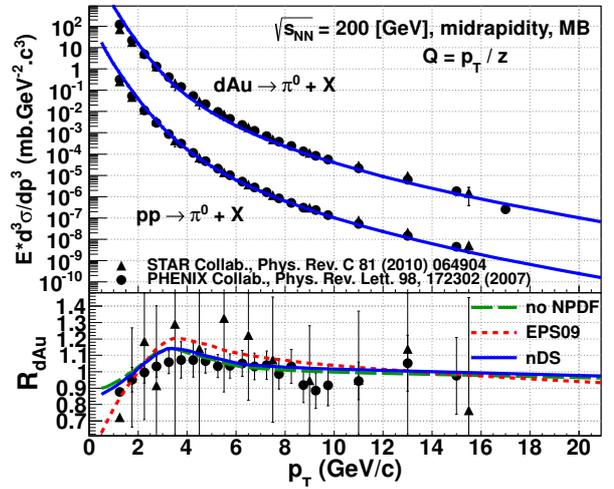
but with impact parameter dependent variance

$$\langle k_T^2 \rangle_A(Q^2, b) = \langle k_T^2 \rangle_N(Q^2) + \Delta k_T^2(b), \quad (7)$$

where we take  $k_T$ -broadening  $\Delta k_T^2(b) = 2 C T_A(b)$  evaluated within the color dipole formalism [10]. The variable  $C$  is related to the dipole cross section  $\sigma_{\bar{q}q}$  describing the interaction of the  $\bar{q}q$  pair with a nucleon as

$$C = \left. \frac{d\sigma_{\bar{q}q}^N(r)}{dr^2} \right|_{r=0}. \quad (8)$$

Note that for gluons the nuclear broadening is larger due to the Casimir factor 9/4. For the dipole cross section we adopt the GBW parametrization [17].



**Figure 1.** Single inclusive pion spectra in  $p + p$  and  $d + Au$  collisions and  $R_{dAu}(p_T)$  vs. PHENIX [2] and STAR [18] data.

In Fig. 1 we present inclusive  $\pi^0$ -spectra and  $R_{dAu}$  at RHIC c.m. energy 200 GeV in a good agreement with data from the PHENIX [2] and STAR [18] experiments. While the dashed line in calculations of  $R_{dAu}(p_T)$  corresponds to the pure effect of nuclear broadening the dotted and solid line additionally include NPDF with parametrization EPS09 and nDS, respectively.

The recent data on hadron production in  $p + Pb$  collisions from the ALICE experiment [3] at LHC allow to test our model predictions. The corresponding comparison is presented in Fig. 2 demonstrating a reasonable agreement. While the dashed line represents predictions without NPDFs, the dashed and solid lines including different parametrizations of NPDFs bring our calculations to a better agreement with data at small and medium-high  $p_T$ .

### 4 Initial State Interactions

It was presented in [7–9] that there is a significant suppression of hadron production at  $\xi \rightarrow 1$ , where  $\xi = \sqrt{x_F^2 + x_T^2}$ .

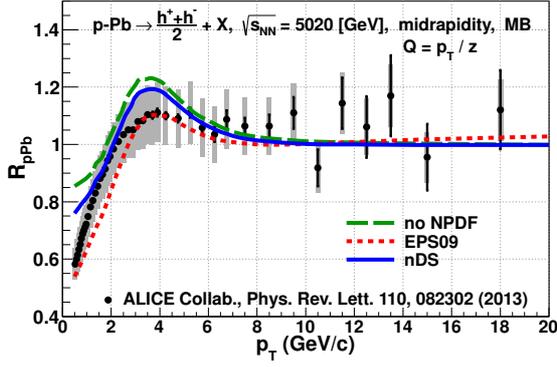


Figure 2. Predictions for the Cronin effect vs. ALICE data [3].

Such a suppression is observed experimentally at large  $x_F$  for variety of reactions at small energies (see examples in [7]) and is indicated also in  $d + Au$  collisions at RHIC [2]. The interpretation of this effect is based on dissipation of energy due to initial state interactions. As a result the QCD factorization is expected to be broken at large  $\xi$  and we rely on the factorization formula, Eq. (4), where we replace the proton PDF by the nuclear modified one,  $f_{a/p}(x, Q^2) \Rightarrow f_{a/p}^{(A)}(x, Q^2, b)$ , where

$$f_{a/p}^{(A)}(x, Q^2, b) = C_v f_{a/p}(x, Q^2) \frac{e^{-\xi \sigma_{eff} T_A(b)} - e^{-\sigma_{eff} T_A(b)}}{(1 - \xi)(1 - e^{-\sigma_{eff} T_A(b)})} \quad (9)$$

with  $\sigma_{eff} = 20$  mb and the normalization factor  $C_v$  is fixed by the Gottfried sum rule.

Besides predictions at  $y = 0$  in Fig. 2 where ISI effects are irrelevant we present also calculations for  $R_{p+Pb}(p_T)$  at forward rapidities, where we expect a significant nuclear suppression at large  $p_T$  due to ISI effects. The results are shown in Fig. 3 for rapidities  $y = 0, 2$  and  $4$ . The dotted lines represent calculations without ISI effects and NPDPs. The dashed lines include additionally ISI effects and solid lines represent the full calculation including both ISI effects and NPDPs.

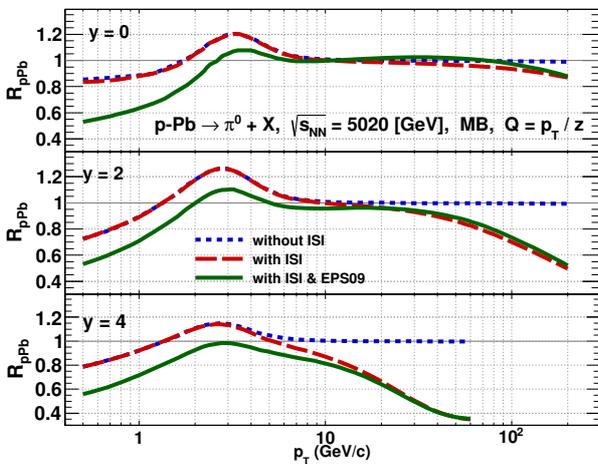


Figure 3. Nuclear modification factor  $R_{p+Pb}(p_T)$  for hadron production at c.m. energy 5.02 TeV and at several rapidities.

## 5 Conclusions

Using the QCD improved parton model we predict the correct magnitude and the shape of the Cronin effect in accordance with data from experiments at RHIC and LHC. Initial state energy loss is expected to suppress significantly inclusive hadron production at large  $p_T$  and/or at forward rapidities. Effects of ISI at LHC are irrelevant at  $y = 0$  but we predict a strong suppression at forward rapidities that can be verified by the future measurements.

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