A heuristic description of high-$p_T$ hadron production in heavy ion collisions

Jan Nemchík$^{1,2}$, Roman Pasechník$^3$, and Irina Potashnikova$^4$

$^1$Czech Technical University in Prague, FNSPE, Břežová 7, 11519 Prague, Czech Republic
$^2$Institute of Experimental Physics SAS, Watsonova 47, 04001 Košice, Slovakia
$^3$Department of Astronomy and Theoretical Physics, Lund University, SE-223 62 Lund, Sweden
$^4$Departamento de Física, Universidad Técnica Federico Santa María; Centro Científico-Tecnológico de Valparaíso, Casilla 110-V, Valparaíso, Chile

Using a simplified model for in-medium dipole evolution accounting for color filtering effects we study production of hadrons at large transverse momenta $p_T$ in heavy ion collisions. In the framework of this model, several important sources of the nuclear suppression observed recently at RHIC and LHC have been analysed. A short production length of the leading hadron $l_p$ causes a strong onset of the color transparency effects manifested themselves as a steep rise of the nuclear modification factor $R_{AA}(p_T)$ at large hadron $p_T$'s. A dominance of quarks with higher $l_p$ leads to a weaker suppression at RHIC than the one observed at LHC. In the RHIC kinematic region we include an additional suppression factor steeply falling with $p_T$, which is tightly related to the energy conservation constraints. The latter is irrelevant at LHC up to $p_T \lesssim 70$ GeV while it causes a rather flat $p_T$ dependence of the $R_{AA}(p_T)$ factor at RHIC c.m. energy $\sqrt{s} = 200$ GeV and even an increasing suppression with $p_T$ at $\sqrt{s} = 62$ GeV. The calculations contain only a medium density adjustment, and for an initial time scale $t_0 = 1$ fm we found the energy-dependent maximal values of the transport coefficient, $\hat{q}_0 = 0.7, 1.0$ and 1.3 GeV$^2$/fm corresponding to $\sqrt{s} = 62, 200$ GeV and 2.76 TeV, respectively. We present a broad variety of predictions for the nuclear modification factor and the azimuthal asymmetry which are in a good agreement with available data from experiments at RHIC and LHC.

PACS numbers: 13.85.Ni, 11.80.Cr, 11.80.Gw, 13.88.+e

I. INTRODUCTION

The available data on high-$p_T$ hadron production in heavy ion collisions at LHC [1,3] and RHIC [4,7] clearly demonstrate a strong nuclear suppression exhibiting rather different features at distinct c.m. energies. The nuclear modification factor $R_{AA}$ measured at LHC reaches significantly smaller values than those at RHIC. Simultaneously, the $R_{AA}(p_T)$ factor steeply rises with $p_T$ at LHC while it exhibits a rather flat $p_T$ dependence at RHIC c.m. energy $\sqrt{s} = 200$ GeV and even a significant fall at $\sqrt{s} = 62$ GeV.

An explanation of the observed high-$p_T$ suppression may be connected to our understanding of the hadronization phenomenon [8], namely, an energy loss scenario of a created color parton after a heavy ion collision discussed in detail e.g. in Ref. [9]. Production of such a parton with a high transverse momentum initiates the hadronization process, which is finalized by the formation of a jet of hadrons. In this paper, we are focused on a specific type of jets when the main fraction $z_h$ of the jet energy $E$ is carried by a single (leading) hadron. Here, $z_h$ of the detected hadron cannot be measured. However, the convolution of the steeply falling jet momentum distribution with the fragmentation function leads to typically large values $z_h \gtrsim 0.5$ [9].

An extremely high initial virtuality of these jets, which is of the same order as the jet energy scale (see e.g. Ref. [9]), leads to a very intensive gluon radiation and energy dissipation during the early stage of hadronization. There are two time scales controlling the hadronization process [8,10]. The first scale is connected to the energy conservation in production of a high-$z_h$ hadron resulting in stopping the radiative dissipation of energy by production of a colorless hadronic configuration (QCD dipole). The production length $l_p$ of a colorless dipole at a later stage of hadronization was calculated within a model of perturbative hadronization and is found to be rather short [8,11]. The observation of a weak dependence of $l_p$ on $p_T$ is a result of two main effects working in the opposite directions. While the Lorentz factor is expected to stretch the $l_p$ scale at higher $p_T$, an increase of the energy dissipation rate with $p_T$ causes a shortening of $l_p$.

The short $l_p$ scale means that the produced colorless dipole has to survive during its propagation through the medium in order to be detected. The evolution of this dipole in the medium up to formation moment of the final hadronic wave function is controlled by the second time scale called the formation time $t_f$ (or the formation length $l_f$) as is discussed in Refs. [8]. Here, the key phenomenon controlling the dipole surviving probability is the color transparency (CT), which corresponds to the enhanced transparency of the medium for small-size dipoles [12]. We employ the relation between the dipole cross section and the transport coefficient (broadening) found in Ref. [13,14]. Correspondingly, the observed magnitude of hadron attenuation can be used as a probe for the transport coefficient which characterizes the medium density.

The CT effect in production of high-$p_T$ hadrons in heavy ion collisions was calculated within the rigorous quantum-mechanical description based on the path-
integral formalism in Ref. [9]. In order to avoid complicated numerical calculations but retain a simple physical understanding of the main features of the underlying dynamics, in the present paper we start from a simplified model of Ref. [13]. Further, we generalize this model also for non-central heavy ion collisions at various energies with different contributions of quark and gluon jets to leading high-p_T hadron production (see Sect. II). In addition, we incorporate the color filtering effects describing an expansion of the dipole in a medium during the formation time. We found an analytical solution of the corresponding evolution equation (2.10) for the mean dipole size. Our manifestly simple formulation enables us to compare the predicted nuclear suppression factor R_{AA} with the data, as a function of p_T, collision energy and centrality of collisions (see Sect. III). This comparison involves only one fitted parameter, q_0, which is the maximal transport coefficient of the medium created in a central collision of given nuclei, at a given energy. Otherwise, this parameter is universal for all observables.

By a comparison with the data, we found that for an initial time t_0 = 1 fm the transport coefficient ranges from q_0 = 0.7 GeV^2/fm at \( \sqrt{s} = 62 \) GeV up to 1.3 GeV^2/fm at \( \sqrt{s} = 2.76 \) TeV. These values of q_0 are much larger than the value found in Ref. [15] due to color filtering effects in dipole size evolution, Eq. (2.10). Simultaneously, they are only slightly smaller than those found in Ref. [9] within a rigorous quantum-mechanical description. However, all the values of q_0 found within both the simplified model [13] and the rigorous quantum-mechanical description [9] are an order of magnitude smaller than what was found in Ref. [10], based on the energy loss scenario (see e.g. Ref. [17]), which relies on an unjustified assumption of the long production length l_p. It is worth emphasizing that our approach, based on perturbative QCD (pQCD), is irrelevant to data at small p_T \lesssim 6 \) GeV, which are dominated essentially by hydrodynamics.

At large values of x_L \equiv x_F = 2 p_L/\sqrt{s} and/or x_T = 2 p_T/\sqrt{s} we incorporate an additional effect related to initial state interactions (ISI) of the colliding nuclei as was described in Refs. [9, 10, 18, 19] (see Sect. III B). The corresponding enhanced nuclear suppression is predicted to be important in the p_T dependence of R_{AA} factor at RHIC c.m. energies \( \sqrt{s} = 200 \) GeV and 62 GeV. For the LHC kinematics, this effect causes a levelling of the R_{AA}(p_T) behavior at the maximal measured p_T \gtrsim 70 \div 100 \) GeV. Finally, as a complementary test of our approach, in Sect. III C we compared the results on the azimuthal anisotropy of produced hadrons with the corresponding RHIC/LHC data and a good agreement has been found.

II. ATTENUATION AND EVOLUTION OF A DIPOLE IN A DENSE MEDIUM

For calculation of the invariant cross section of inclusive hadron production we employ a \( k_T \)-factorization based model proposed in Ref. [20]:

\[
\frac{d\sigma_{pp}}{dy d^2p_T} = K \sum_{i,j,k,l} \int dx_i dx_j d^2k_{iT} d^2k_{JT} F_{i/p}(x_i, k_{iT}, Q^2) F_{j/p}(x_j, k_{JT}, Q^2) \frac{d\sigma}{dt}(ij \to kl) \frac{1}{\pi z_h} D_{h/j}(z_h, Q^2). \quad (2.1)
\]

Here \( d\sigma/(ij \to kl)/dt \) is the cross section of hard parton scattering; the kinematic variables and their relations can be found in Ref. [20]. Similarly, we assume a factorized form of the transverse momentum distribution,

\[
F_{i/p}(x, k_T, Q^2) = F_{i/p}(x, Q^2) g_p(k_T, Q^2), \quad (2.2)
\]

where

\[
g_p(k_T, Q^2) = \frac{1}{\pi} \left\langle k_T^2(Q^2)^2 \right\rangle e^{-k_T^2/\left\langle k_T^2(Q^2)^2 \right\rangle}. \quad (2.3)
\]

The scale dependence of \( \left\langle k_T^2(Q^2)^2 \right\rangle \) was parameterized in Ref. [21] as \( \left\langle k_T^2 \right\rangle^2_{N}(Q^2) = 1.2 \) GeV^2 + 0.2 \alpha_S(Q^2)Q^2, with parameters adjusted to next-to-leading order calculations. We use the phenomenological parton distribution functions (PDFs) \( F_{i/p}(x, Q^2) \) from the MSTW08 leading order (LO) fits [21]. For the fragmentation function \( D_{h/j}(z_h, Q^2) \) we rely on the LO parameterization given in Ref. [22]. As was explicitly checked in Ref. [9], this model describes well the data on p_T-dependence of pion production in pp collisions at \( \sqrt{s} = 200 \) GeV and charged hadron production at \( \sqrt{s} = 7 \) TeV.

The produced leading hadron carries a significant fraction \( z_h \gtrsim 0.5 \) of the initial light-cone parton momentum [4]. The energy conservation requires that the hadronization process should be stopped promptly by the color neutralization, i.e. by production of a colorless “pre-hadron” (dipole), otherwise the leading parton looses too much energy such that it becomes unable to produce a hadron with a large z_h fraction any longer. The corresponding time scale for production of a colorless dipole is thereby rather short and practically does not rise with p_T, as was demonstrated in Ref. [9].

In comparison with the vacuum case, as long as this process occurs in a dense medium, multiple interactions of the parton generate an additional energy loss, which makes the production time even shorter [9]. Thus, we can evaluate the survival probability \( W \), i.e. the chance for
a pre-hadron (dipole) to escape from the dense medium having no inelastic interactions on its way out. This is a subject of the CT effect [12], i.e. the attenuation rate of small-size dipoles vanishes quadratically with the dipole transverse separation \( r \),

\[
\frac{dW}{dl} \bigg|_{r \to 0} = -\frac{1}{2} \hat{q}(l) r^2, \tag{2.4}
\]

where the broadening rate \( \hat{q}(l) = \partial \Delta q^2 / \partial l \) is usually called the transport coefficient and used as an important characteristics of the medium 23.

We rely on the popular, although poorly justified model for \( \hat{q} \), which is assumed to be proportional to the number of participants \( n_{\text{part}}(\vec{b}, \vec{\tau}) \) and diluted with time as \( \rho(t) = 1/t \). Correspondingly, the transport coefficient depends on impact parameter and time (the path length is \( l = t \)) as 24,

\[
\hat{q}(l, \vec{b}, \vec{\tau}) = \frac{\hat{q}_0 l_0 n_{\text{part}}(\vec{b}, \vec{\tau})}{l n_{\text{part}}(0,0)} \Theta(l - l_0), \tag{2.5}
\]

where \( \vec{b} \) and \( \vec{\tau} \) are the impact parameter of nuclear collision and the hard parton-parton collision relative to the center of one of the nuclei, respectively. The variable \( \hat{q}_0 \) here represents the broadening rate of a quark propagating in the maximal medium density produced at impact parameter \( \tau = 0 \) in central collisions (\( b = 0 \)) at the time \( t = t_0 = l_0 \) after the collision. The corresponding transport coefficient for gluons should be by a factor of 9/4 bigger. The equilibration time \( t_0 \) is a model dependent quantity. Our results are not very sensitive to it, and we fix it naively at \( t_0 = l_0 = 1.0 \) fm which is sufficient for our purposes here. Then, high-\( p_T \) hadron production is considered as a probe for the medium properties via the single fitted parameter \( \hat{q}_0 \) in Eq. 2.5, which depends on energy and atomic number \( A \) of the colliding nuclei.

We start with a simplified description of the time evolution, in terms of the mean dipole transverse separation. The dipole produced with a very small initial size \( r = r_0 \sim 1/p_T \) starts to expand with a speed given by the uncertainty relation \( dr/dt \propto 1/r \) 13, 25, 26. Correspondingly, the \( l \)-dependence of \( r \) is described by the following linear differential equation,

\[
\frac{dr}{dl} = \frac{1}{r(t) E_{h} \alpha (1-\alpha)}, \tag{2.6}
\]

where \( \alpha \) and \( 1-\alpha \) are the fractions of the dipole light-cone momentum carried by the quark and antiquark, respectively, and \( E_{h} = p_T \) is the dipole energy. The solution of Eq. 2.6 reads,

\[
r^2(l) = \frac{2l}{\alpha (1-\alpha)p_T} + r_0^2. \tag{2.7}
\]

The mean value of \( r^2(l) \) can be used in Eq. 2.4 in order to evaluate the attenuation of a dipole which evolves in a medium characterized by the transport coefficient \( \hat{q} \),

\[
R_{AB}(\vec{b}, \vec{\tau}, p_T) = \frac{\int d^2 \tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) R_{AB}(\vec{b}, \vec{\tau}, p_T)}{\int d^2 \tau T_A(\tau) T_B(\vec{b} - \vec{\tau})}. \tag{2.9}
\]

This expression represents the medium attenuation factor for a dipole produced from a high-\( k_T \) parton (\( k_T = p_T/z_h \)) at impact parameter \( \vec{\tau} \) in a collision of nuclei \( A \) and \( B \) at impact parameter \( \vec{b} \). The produced hadron is detected at azimuthal angle \( \phi \) relative to \( \vec{b} \), i.e. \( \vec{b} \cdot \vec{\tau} = l b \cos \phi \). The bottom limit of \( l \)-integration is \( L = \max\{l_p, l_0\} \). The dependence of the transport coefficient on coordinates is given by Eq. 2.5. In Eq. 2.8 we fixed \( \alpha = 1/2 \) relying on the Berger’s approximation 27.

Integrating Eq. 2.8 over the impact parameter \( \vec{\tau} \) of the hard collision one obtains the nuclear attenuation factor for inclusive high-\( p_T \) hadron production in heavy ion \( A + B \) collision at relative impact parameter \( b \),

\[
R_{AB}(b, p_T) = \frac{\int d\phi T_A(\phi) T_B(b - \phi) R_{AB}(\vec{b}, \vec{\tau}, p_T)}{\int d\phi T_A(\phi) T_B(b - \phi)}. \tag{2.9}
\]

This simplified approach was employed in Ref. 15 describing quite well the first data from the ALICE experiment 28 for central collisions assuming the gluon jets contribution to leading hadron production only. Eqs. 2.8 and 2.9 generalize this simplified model making it suitable also for the analysis of suppression at different centralities. Such an analysis at smaller RHIC energies requires an additional contribution of quark jets to leading hadron production. Consequently, the mean production length \( l_p \) is different for quark and gluon jets as was demonstrated in Ref. 9. Therefore, the numerator in Eq. 2.9 is calculated separately for quark and gluon jets whose contributions are then summed up with the weights given by Eq. 2.4.

Although this simplified heuristic model allows to understand the main features of the underlying dynamics, the corresponding Eq. 2.6 does not describe the expansion of the dipole in a medium where the color filtering effects modify the path/length dependence of the mean dipole separation. Correspondingly, the mean transverse separation in a dipole propagating in a medium should be smaller than in the vacuum. Introducing an absorptive term we arrive at a modified evolution equation,

\[
\frac{dr^2}{dl} = \frac{2}{E_{h} \alpha (1-\alpha)} - \frac{1}{2} r^4(l) \hat{q}(l), \tag{2.10}
\]

which can be solved analytically with respect to an explicit form for the mean dipole size squared,
\[ r^2(l) = 2 X \int \Theta(l_0 - l) - \Theta(l - l_0) \frac{\sqrt{l}}{Y} \times \]
\[ I_1(\sqrt{l}) \left( Z l_0 K_0(\sqrt{l} l_0) / 2 + \sqrt{l} l_0 K_1(\sqrt{l} l_0) \right) + \left( Z l_0 I_0(\sqrt{l} l_0) / 2 - \sqrt{l} l_0 I_1(\sqrt{l} l_0) \right) K_1(\sqrt{l}) \]
\[ I_0(\sqrt{l}) \left( Z l_0 K_0(\sqrt{l} l_0) / 2 + \sqrt{l} l_0 K_1(\sqrt{l} l_0) \right) + \left( Z l_0 I_0(\sqrt{l} l_0) / 2 - \sqrt{l} l_0 I_1(\sqrt{l} l_0) \right) K_0(\sqrt{l}) \]
\[ , \quad (2.11) \]

where we neglect the initial dipole size \( r_0 \), \( \Theta(x) \) represents the step function; \( I_0(x) \), \( I_1(x) \), \( K_0(x) \) and \( K_1(x) \) are the modified Bessel functions and factors \( X = 1/\alpha(1 - \alpha)p_T \), \( Y = \hat{q}(l) \) with \( Z = 4XY \).

![Graph showing the mean dipole size evolution for different energies](image)

**FIG. 1**: (color online) Time evolution of the mean dipole size squared at \( p_T = 10, 30 \) and 100 GeV. Dashed and solid curves are computed within the simplified model without (Eq. (2.7)) and with (Eq. (2.10)) color filtering effects, respectively. Solid curves are computed for different fixed values of \( \hat{q}_0 = 0.1, 0.5 \) and 2.0 GeV\(^2/\text{fm} \) from top to bottom.

In comparison with Eq. (2.6), the color filtering effects in Eq. (2.10) result in a reduction of the mean dipole size demonstrated in Fig. 1 for fixed values of \( p_T = 10, 30 \) and 100 GeV. Here, we fix \( \alpha = 1/2 \) again [27]. Such a reduction makes the medium more transparent and depends strongly on \( \hat{q}_0 \). The larger is \( \hat{q}_0 \), the stronger is reduction. Fig. 1 also demonstrates that the reduction gradually decreases with an increase of \( p_T \). Correspondingly, we should expect that the analysis of ALICE data performed in Ref. [15] should lead to an underestimated medium density, i.e. to a smaller parameter \( \hat{q}_0 \).

During the short path from \( l = l_0 \) to \( l = l_p \) (for \( l_p > l_0 \)) the parton experiences multiple interactions, which induce an extra radiation of gluons and consequently an additional loss of energy [23],

\[ \Delta E = \frac{3 \alpha_s}{4} \frac{l_p}{l_0} \int_{l_0}^{l_p} dl \int_{l_0}^{l} dl' \hat{q}(l') \cdot (2.12) \]

Although this is a small correction, we have explicitly included it in the calculations by making a proper shift of the variable \( z_h \) in the fragmentation function.

**III. COMPARISON WITH DATA**

Here, we compare our simple model including the color filtering effects with numerous results from the recent precise measurements at RHIC and LHC.

**A. Quenching of high-\( p_T \) hadrons**

Comparison of the \( R_{AA}(b = 0, p_T) \) factor calculated above in the framework of the simplified model with the first data from the ALICE experiment [28] at \( \sqrt{s} = 2.76 \text{ TeV} \) was performed in Ref. [13]. The maximal value of the transport coefficient was adjusted to these data and fixed at \( \hat{q}_0 = 0.4 \text{ GeV}^2/\text{fm} \). The growing \( p_T \)-dependence of \( R_{AA}(p_T) \) follows from the reduction of the mean dipole size at higher \( p_T \) (in accordance with Eq. (2.7)) and due to a Lorentz dilation of the dipole size expansion. This leads to a more transparent medium for more energetic smaller dipoles in accordance with the CT effect. An analogous growing energy dependence of the medium transparency was predicted and observed in the case of virtual photoproduction of vector mesons on nuclei [29].

Being encouraged by the first success of the simplified model, we have generalized this model for studies of production of various high-\( p_T \) hadrons at distinct energies by
FIG. 2: (color online) The suppression factor $R_{AA}(p_T)$ for central $(0 - 5\%)$ Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV. Dashed line represents the simple model prediction given by Eqs. (2.4), (2.11), (2.9), and the space- and time-dependent transport coefficient (2.5) with the adjusted parameter $\hat{q}_0 = 1.3$ GeV$^2$/fm. Solid curve, in addition, includes the effect of initial state interactions in nuclear collisions [10, 18] described in Sect. III B. The data for $R_{AA}(p_T)$ are from the ALICE [1] and CMS [2, 3] measurements.

FIG. 3: (color online) The centrality dependence of the suppression factor $R_{AA}(p_T, b)$ measured by the ALICE experiment [1]. The data at different centralities obtained by ALICE [1] in Fig. 3, and by CMS [2, 3] in Fig. 4. In all the cases we observe a rather good agreement.

FIG. 4: (color online) The same as in Fig. 3 but with the data from CMS [2, 3].

incorporating additional quark jet contributions to leading hadron production besides gluon ones with relative weights given by Eq. (2.1). The original treatment, which was suitable only for central heavy ion collisions, has now been extended also to non-central collisions. Moreover, for the first time we have incorporated also the color filtering effects in the evolution equation for the mean dipole size, Eq. (2.10).

The results for central $(0 - 5\%)$ Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV are shown by dashed curve in Fig. 2 compared to the data from ALICE [1] and CMS [2, 3]. The only free parameter, the maximal value of the transport coefficient defined in Eq. (2.5), was adjusted to the data and fixed at $\hat{q}_0 = 1.3$ GeV$^2$/fm for all further calculations valid for Pb-Pb collisions at this energy.

Notice that while our calculations describe well the data at high $p_T \gtrsim 6$ GeV, the region of smaller $p_T$ is apparently dominated by thermal mechanisms of hadron production.

The variation of the suppression factor $R_{AA}(b, p_T)$ with impact parameter $b$ given by Eqs. (2.4), (2.11) and (2.9) is plotted by dashed curves and compared to the data at different centralities obtained by ALICE [1] in Fig. 3, and by CMS [2, 3] in Fig. 4. In all the cases we observe a rather good agreement.
B. Additional suppression at large $x_T$ due to energy conservation

At large Feynman $x_L \equiv x_F$, or transverse fractional momentum $x_T$ any initial state interactions (ISI) leading to energy dissipation, should result in a suppressed production rate of particles and the energy conservation may become an issue as was stressed in Refs. [10, 18]. Such an additional nuclear suppression represents an energy independent feature common for all known reactions, experimentally studied so far, with any leading particle (hadrons, Drell-Yan dileptons, charmonium, etc.). Following to Ref. [18], we apply exactly the same model developed in Ref. [18, 19] to high-$p_T$ hadron production, at large $x_L$ and with the same physical parameters.

A detailed description and interpretation of the additional suppression is presented in detail in Refs. [9, 18, 19]. As a result the ISI causes the breakdown of QCD factorization in $pA$ collisions at large $x_T$ and/or $x_F$. Relying on the factorization formula, Eq. (2.1), this leads to a replacement of the PDF in the proton by a nuclear modified one $F_{i/p}(x_i, Q^2) \rightarrow F_{i/p}^{(A)}(x_i, Q^2, b)$. Considering heavy ion collisions such a modification should be done for the bound nucleons in both nuclei.

Summing over multiple interactions and applying the AGK cutting rules [30] with the Glauber weight factors, the ISI-modified PDF of the proton in a $pA$ collision at impact parameter $b$ reads,

$$F_{i/p}^{(A)}(x_i, Q^2, b) = C F_{i/p}(x_i, Q^2) \times \frac{e^{-\sigma_{eff} T_A(b)} - e^{-\sigma_{eff} T_A(b)}}{(1 - \xi) [1 - e^{-\sigma_{eff} T_A(b)}]} , \quad (3.1)$$

where $\sigma_{eff} = 20 \text{mb}$ [18, 31] is the effective hadronic cross section controlling multiple interactions and $\xi = \sqrt{x_T^2 + x_T^2}$. The normalization factor $C$ in Eq. (3.1) is fixed by the Gottfried sum rule.

Using PDFs modified by ISI, Eq. (3.1), we achieved a good parameter-free description of available data at large $x_L$ and $x_T$ [10, 18, 19]. These corrections are expected to be important at RHIC and even at LHC for $p_T \geq 70 \text{ GeV}$. This is demonstrated in Figs. 3 and 4 by solid lines which show a flattening of the $R_{AA}(p_T)$ factor at large $p_T$.

In the RHIC energy range this additional suppression reduces $R_{AA}(p_T)$ significantly at large $p_T$ as is demonstrated in Fig. 5 including only CT effects and repeating the same calculations as done above for the LHC, we get $R_{AA}$ steeply rising with $p_T$, as is depicted by the dashed curve. Only the transport coefficient was re-adjusted to a smaller value $\hat{q}_0 = 1.0 \text{ GeV}^2/\text{fm}$ at this energy. Inclusion of the ISI effects, Eq. (3.1), leads to a sizeable additional suppression, as is shown by the solid curve.

By fixing $\hat{q}_0 = 1.0 \text{ GeV}^2/\text{fm}$ we can obtain other observables for Au-Au collisions at $\sqrt{s} = 200 \text{ GeV}$. Fig. 6 shows our results for the suppression of $\pi^0$ at different centralities, in comparison with the PHENIX data [4].
sion. Our calculations again demonstrate a good agreement with the data. Here, the hot medium properties are changed, so in order to account for that we have re-adjusted the parameter \( \hat{q}_0 = 0.7 \text{ GeV}^2/\text{fm} \).

\[ v_2(p_T) = \frac{\int d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \frac{2\pi}{0} d\phi \cos(2\phi) R^\phi_{AB}(\vec{b}, \vec{\tau}, p_T) \right)}{\int d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \frac{2\pi}{0} d\phi R^\phi_{AB}(\vec{b}, \vec{\tau}, p_T) \right)} \] (3.2)

where \( R^\phi_{AB}(\vec{b}, \vec{\tau}, p_T, \phi) \) is given by Eq. (2.8) but without integration over \( \phi \). The results of this calculation are compared with ALICE \[32\] and CMS data \[33\] in Figs. 8 and 9 and are found to be in a good overall agreement.

Similarly to the data on \( R_{AA} \), our pQCD calculations for \( v_2(p_T) \) grossly underestimate the data at small \( p_T \lesssim 6 \text{ GeV} \) due to the presence of two different mechanisms discussed earlier in Ref. \[9\]: the dominant hydrodynamic mechanism of elliptic flow, leading to a large and increasing anisotropy \( v_2(p_T) \) at high \( p_T \)’s, which abruptly switches to the pQCD regime having a much smaller azimuthal anisotropy.

FIG. 7: (color online) The same as in Fig. \[6\] but at \( \sqrt{s} = 62 \text{ GeV} \). The data are taken from Ref. \[6\].

C. Azimuthal anisotropy

The observed suppression of high-\( p_T \) hadrons propagating through a dense medium reflects a contribution of some effective volume of the medium. Thus one should expect that the resulting suppression depends on the propagation path/length in the medium such that the propagation direction perpendicular to the medium surface is preferable. For a non-central collision with an almond shape of the intersection area this effect should lead to an azimuthal asymmetry in the high-\( p_T \) hadron angular distribution.

The data on azimuthal asymmetry in particle production is usually presented in terms of the second moment of the \( \phi \)-distribution, \( v_2 \equiv \langle \cos(2\phi) \rangle \). We can calculate it with a slight modification of Eq. (2.9),

\[ v_2(p_T, \hat{b}) = \frac{\int d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \frac{2\pi}{0} d\phi \cos(2\phi) R^\phi_{AB}(\vec{b}, \vec{\tau}, p_T) \right)}{\int d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \frac{2\pi}{0} d\phi R^\phi_{AB}(\vec{b}, \vec{\tau}, p_T) \right)} \] (3.2)

where \( R^\phi_{AB}(\vec{b}, \vec{\tau}, p_T, \phi) \) is given by Eq. (2.8) but without integration over \( \phi \). The results of this calculation are compared with ALICE \[32\] and CMS data \[33\] in Figs. 8 and 9 and are found to be in a good overall agreement.

FIG. 8: (color online) The ALICE data \[32\] for azimuthal anisotropy, \( v_2 \), vs \( p_T \) for charge hadron production in Pb-Pb collisions at midrapidity, at \( \sqrt{s} = 2.76 \text{ TeV} \) and at different centralities indicated in the figure. The curves represent the results of calculation with Eq. (3.2).

FIG. 9: (color online) The same as in Fig. 8 but with the CMS data \[33\].

Finally, we have also evaluated the azimuthal anisotropy at smaller c.m. energies and compared with
the corresponding RHIC data. Our results agree well with PHENIX data for $\pi^0$ production which is demonstrated in Fig. 10.

**IV. SUMMARY**

In this paper, we contribute to a quantitative understanding of the strong nuclear suppression of leading high-$p_T$ hadrons produced inclusively in heavy ion collisions. The main motivation comes from the improved quality of data at RHIC and new high-statistics data at LHC which provide a strong potential for a more decisive verification of different models.

In contrast to popular energy loss scenarios based on the unjustified assumption about a long production length, we present here an alternative mechanism for nuclear suppression in high-$p_T$ hadron production. The key point is that the production length of leading hadrons does not rise with $p_T$ and is rather short as was earlier demonstrated in Ref. [9]. This is a consequence of a strong increase of the energy dissipation by a highly virtual parton produced in a high-$p_T$ process with the jet energy. The production moment of a colorless hadronic state (“pre-hadron”) ceases the energy loss. The main reason for such a suppression is related to the survival probability of the “pre-hadron” propagating through the dense matter. According to Eqs. (2.7) and (2.11), larger $p_T$’s prefer a smaller dipole size and the medium becomes more transparent in accordance with the color transparency effect. The corresponding increase of the nuclear suppression factor $R_{AA}(p_T)$ is indeed observed at LHC.

Although the attenuation of color dipoles propagating through a medium has already been studied in Ref. [9] within the rigorous quantum-mechanical approach based on the Green functions formalism, in this paper we present an alternative simplified description of the high-$p_T$ hadron production in heavy ion collisions. For this purpose, we start from the simple model of Ref. [13] and generalize it for non-central heavy ion collisions additionally including quark jet contributions to the leading hadron production. In the framework of this generalized model, we have incorporated for the first time the color filtering effects in the evolution equation for the mean dipole size and found its simple analytical solution, Eq. (2.11). As the main result of this study, we found that the color filtering effects lead to a reduction of the mean dipole size as demonstrated in Fig. 1 and, consequently, to a more transparent nuclear medium. Remarkably, such a simple formulation absorbs all the important physical effects which are naturally inherited from the much more involved Green functions formalism and enables immediate comparison of its predictions to various existing data on high-$p_T$ hadrons production in heavy ions collisions. Thus, technically our model is much more convenient for the practical use for testing of the underlined nuclear effects than more complicated path integral techniques.

First, we have compared the suppression factor $R_{AA}(p_T)$ to available data at different centralities and c.m. energies in corresponding RHIC and LHC kinematic domains. At large $x_T \geq 0.1$ we included an additional suppression factor arising from the initial-state multiple interactions. This factor, which falls steeply with $p_T$, causes a rather flat $p_T$ dependence of $R_{AA}(p_T)$ function at RHIC energy $\sqrt{s} = 200$ GeV and even leads to an increase of suppression at high $p_T$’s at lower $\sqrt{s} = 62$ GeV. At the next step, we calculated the azimuthal anisotropy of hadron production at different energies and centralities corresponding to measurements at RHIC and LHC.

In all the cases we found a good agreement with available data at high $p_T$. The only adjustable parameter, the maximal value of the transport coefficient, Eq. (2.5), was found to be $\hat{q}_0 = 1.3$ GeV$^2$/fm, 1.0 GeV$^2$/fm and 0.7 GeV$^2$/fm at $\sqrt{s} = 2.76$ TeV, 200 GeV and 62 GeV respectively, for an initial time scale $t_0 = 1$ fm and for heavy nuclei such as lead and gold. These values of $\hat{q}_0$ are much larger than was found in the analysis of the first ALICE data [12] due to the color filtering effects included in Eq. (2.10). However, they are similar and only slightly smaller than those found in Ref. [9] within a rigorous quantum-mechanical description. Thus, the simplified model including the color filtering effects in dipole size evolution represents a good simple alternative to a more sophisticated but technically much more involved quantum-mechanical approach based on the Green functions formalism.

**Acknowledgments** This work was supported in part by Fondecyt (Chile) grants 1130543, 1130549 and by Conicyt-DFG grant No. RE 3513/1-1. The work of J. N. was partially supported by the grant 13-20841S of the Czech Science Foundation (GAČR), by the Grant
[1] B. Abelev et al. [ALICE Collaboration], Phys. Lett. B 720, 52 (2013).
[2] Y.-J. Lee (for the CMS Collaboration), J. Phys. G 38, 124015 (2011).
[3] A. S. Yoon (for the CMS Collaboration), J. Phys. G 38, 124116 (2011).
[4] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 87, 034911 (2013).
[5] M. L. Purschke (for the PHENIX Collaboration), J. Phys. G 38, 124016 (2011).
[6] PHENIX Collaboration, preliminary data posted at www.phenix.bnl.gov/WWW/plots/show_plot.php?editkey=p1118
[7] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 91, 072304 (2003).
[8] B. Z. Kopeliovich, J. Nemchik, E. Predazzi and A. Hayashigaki, Nucl. Phys. A 740, 211 (2004).
[9] B. Z. Kopeliovich, J. Nemchik, I. K. Potashnikova, and I. Schmidt, Phys. Rev. C 86, 054904 (2012).
[10] B. Z. Kopeliovich and J. Nemchik, J. Phys. G 38, 043101 (2011).
[11] B. Z. Kopeliovich, H.-J. Pirner, I. K. Potashnikova and I. Schmidt, Phys. Lett. B 662, 117 (2008).
[12] B. Z. Kopeliovich, L. I. Lapidus and A. B. Zamolodchikov, JETP Lett. 33, 595 (1981) [Pisma Zh. Eksp. Teor. Fiz. 33, 612 (1981)].
[13] M. B. Johnson, B. Z. Kopeliovich and A. V. Tarasov, Phys. Rev. C 63, 035203 (2001).
[14] B. Z. Kopeliovich, I. K. Potashnikova and I. Schmidt, Phys. Rev. C 81, 035204 (2010).
[15] B. Z. Kopeliovich, I. K. Potashnikova and I. Schmidt, Phys. Rev. C 83, 021901 (2011).
[16] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 77, 064907 (2008).
[17] S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, Nucl. Phys. A 784, 426 (2007).
[18] B. Z. Kopeliovich, J. Nemchik, I. K. Potashnikova, M. B. Johnson and I. Schmidt, Phys. Rev. C 72, 054906 (2005).
[19] J. Nemchik, V. Petracek, I.K. Potashnikova and M. Sumbera, Phys. Rev. C 78, 025213 (2008).
[20] X.-N. Wang, Phys. Rev. C 61, 064910 (2000).
[21] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, Eur. Phys. J. C 63, 189 (2009).
[22] D. de Florian, R. Sassot and M. Stratmann, Phys. Rev. D 75, 114010 (2007); Phys. Rev. D 76, 074033 (2007).
[23] R. Baier, Y. L. Dokshitzer, S. Peigne and D. Schiff, Phys. Lett. B 345, 277 (1995); Nucl. Phys. B 484, 265 (1997).
[24] X. F. Chen, C. Greiner, E. Wang, X. N. Wang and Z. Xu, Phys. Rev. C 81, 064908 (2010).
[25] B. Z. Kopeliovich, I. K. Potashnikova and I. Schmidt, Phys. Rev. C 82, 024901 (2010).
[26] B. Z. Kopeliovich, Nucl. Phys. A 854, 187 (2011).
[27] E. L. Berger, Phys. Lett. B 89, 241 (1980).
[28] K. Aamodt et al. [ALICE Collaboration], Phys. Lett. B 696, 30 (2011).
[29] B. Z. Kopeliovich, J. Nemchik, N. N. Nikolaev and B. G. Zakharov, Phys. Lett. B 309, 179 (1993); Phys. Lett. B 324, 469 (1994).
[30] V. A. Abramovsky, V. N. Gribov and O. V. Kancheli, Yad. Fiz. 18, 595 (1973) [Sov. J. Nucl. Phys. 18, 308 (1973)].
[31] B. Z. Kopeliovich, I. K. Potashnikova and I. Schmidt, Phys. Rev. C 73, 034901 (2006).
[32] A. Dobrin (for the ALICE Collaboration), J. Phys. G 38, 124170 (2011).
[33] S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. Lett. 109, 022301 (2012).
[34] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 105, 142301 (2010).