An estimate of the prehadron production time

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A semi-quantitative estimate of the prehadron production time based on recent preliminary HERMES data on hadron transverse momentum broadening in nuclear DIS is presented. The obtained production time can well explain the data except for their dependence on the photon virtuality, which remains a challenge to current theoretical models. A few mechanisms that may contribute to its explanation are suggested, along with possible experimental tests. The average time scale at HERMES is found to be of the order of 4-5 fm, comparable to heavy nuclei radii, so that by suitable kinematic cuts it will be possible to study both the case in which hadronization starts inside and the case in which it starts outside the nucleus. A comparison with recent CLAS preliminary data, which qualitatively but not quantitatively agree with HERMES, is performed.

I. INTRODUCTION

Nuclear modifications of hadron production in high-energy collisions have been observed in both Deep Inelastic lepton-nucleus Scattering (nDIS) \cite{1} and in heavy ion collisions \cite{2–5}. One typically observes: (i) a suppression of hadron multiplicities, called hadron quenching or jet quenching; (ii) hadron transverse momentum ($p_T$) broadening; (iii) the related modification of the hadron $p_T$-spectrum also known as Cronin effect. The nuclear modifications can be attributed to the interactions of the scattered partons and of the hadrons formed in their fragmentation with the surrounding medium. Experimentally, partonic in-medium interactions can be isolated by studying Drell-Yan (DY) lepton pair production in hadron-nucleus collisions. In nDIS and hadron-nucleus collisions, the medium is the nuclear target itself, also called “cold nuclear matter”. In nucleus-nucleus collisions, the fragmenting parton must also traverse the hot and dense medium created in the collisions, be it a hadron gas at low energy, or a Quark-Gluon Plasma (QGP) at high energy. This medium is also called “hot nuclear matter”.

A precise knowledge of parton propagation and hadronization mechanisms obtained from nDIS and DY data is essential for testing and calibrating our theoretical tools, and to determine the properties of the QGP produced at the Relativistic Heavy Ion Collider. Conversely, a well known nuclear medium like a target nucleus allows testing the hadronization mechanism and color confinement dynamics in nDIS. Knowledge of partonic in-medium propagation gained from nDIS, can be used in DY scatterings to factor out parton energy loss and measure the nuclear modifications of parton distributions in the initial state \cite{6}. Finally, hadron quenching is an important source of systematic uncertainty in neutrino oscillation experiments such as MINOS, which use nuclear targets and need to reconstruct the event’s kinematics from the hadronic final state \cite{7, 8}.

Understanding and modeling nuclear modifications of hadron production requires knowledge of the space-time evolution of the hadronization process \cite{9}. However, hadronization is a non-perturbative process, and its theoretical understanding is still in its infancy: one has to resort to phenomenological models to describe its space-time evolution \cite{10–16}. Nonetheless, a few features can be expected on general grounds. A parton created in a high-energy collision can travel as a free particle only for a limited time because of color confinement: it has to dress-up in a color-field of loosely bound partons, which eventually will evolve into the observed hadron wave function. While the naked, asymptotically free, parton has a negligible inelastic cross section with the surrounding medium constituents, the dressed parton is likely to develop an inelastic cross section of the order of the hadronic one. Hence, the dressed parton will be subject to nuclear absorption in a similar way a fully formed hadron is. For this reason, it is usually called “prehadron”, and denoted by $h_\ast$. The prehadron may for some time be in a colored state, $h_\ast^c$, because color neutrality is only required for the final state hadron. However, it is likely to neutralize its color before hadron formation, and the colorless prehadron is denoted $h_\ast^0$. We can therefore identify 3 relevant time scales, see Fig. 1: (1) the “prehadron production time” or “quark lifetime” $t_p$, at which the dressed quark develops a sizable inelastic cross section, (2) the “color neutralization time” $t_{cn}$, at which gluon bremsstrahlung stops, and (3) the “hadron formation time” $t_h$, at which the final hadron is formed.

For practical applications, hadronization is generally pictured as a 2 step process in which the prehadron pro-

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1}
\caption{Sketch of the time evolution of the hadronization process with definition of the relevant time scales. A quark $q$ created at time 0 in a hard collision turns into a colored prehadron $h_\ast^c$, which subsequently neutralizes its color, $h_\ast^0$, and collapses on the wave function of the observed hadron $h$.}
\end{figure}
duction time and color neutralization time are identified, \( t_p = t_{\text{cn}} \). This is a somewhat crude approximation of the more complex process sketched above, but is adequate to the present status of the theoretical and experimental investigation and will be used in this paper.

In summary, the key quantity we need to investigate in order to understand this complex dynamics is the hadronization time scale, \( t_p \). It is the most general information about the space-time evolution of the hadronization process which can be extracted from experimental data. It is the purpose of this paper to provide a semiquantitative and model independent estimate of the prehadron production time from recent preliminary data on the \( p_T \)-broadening taken by the HERMES experiment in lepton-nucleus scatterings at the HERA accelerator [17–19]. These data show rich features in terms of their dependence on the kinematic variables, which are confirmed by preliminary data taken by the CLAS experiment at Jefferson Lab [20–22], and are not always simple to interpret theoretically. I will show to what extent a consistent picture of the space-time evolution of hadronization can be inferred from these data, and how they are beginning to expose the limits of current theoretical modeling of this process.

II. PRODUCTION TIME SCALING

Hadron quenching in nDIS is studied in terms of the multiplicity ratio

\[
R^h_M(z, \nu, p_T^2, Q^2) = \frac{N_h(z, \nu, p_T^2, Q^2)}{N_e(z, \nu, Q^2)} \frac{A}{D},
\]

where \( N_h \) is the yield of semi-inclusive hadrons in a given kinematic bin, and \( N_e \) the yield of inclusive scattered leptons in the same (\( \nu, Q^2 \))-bin. The kinematic variables \( z, \nu, p_T^2, Q^2 \) are the usual DIS invariants, namely, the hadron fractional energy, the virtual photon energy, the hadron transverse momentum and the lepton 4-momentum transfer squared.

In Ref. [23] it is conjectured that \( R_M \) should not depend on \( z \) and \( \nu \) separately but should depend on a combination of them:

\[
R_M = R_M[\tau(z, \nu)],
\]

where the scaling variable \( \tau \) is defined as

\[
\tau = C (1 - z) \nu.
\]

The scaling exponent \( \lambda \) can be obtained by a best fit analysis of data or theoretical computations. Obviously, the proportionality constant \( C \) cannot be determined by the fit. A possible scaling of \( R_M \) with \( Q^2 \) is not considered because of its model dependence, and because of the mild dependence of HERMES \( R_M \) data on \( Q^2 \).

As discussed below, the proposed functional form of \( \tau \), Eq. (3), is flexible enough to encompass both absorption models, which assume short production times and in-medium hadronization, and energy loss models, which assume long lived quarks with \( \langle t_p \rangle \gg R_A \), where \( R_A \) is the nuclear radius. The 2 classes of models are distinguished by the value of the scaling exponent: a positive \( \lambda \geq 0 \) is characteristic of absorption models, while a negative \( \lambda \leq 0 \) is characteristic of energy loss models. Thus, the exponent \( \lambda \) extracted from experimental data can identify the leading mechanism for hadron suppression in nDIS, and distinguish short from long hadronization time scales.

The scaling of \( R_M \) is quite natural in the context of hadron absorption models [10–15]. Indeed, prehadron absorption depends on the in-medium prehadron path length, which depends on the prehadron production time \( \langle t_p \rangle \), as long as \( \langle t_p \rangle \leq R_A \). In the Lund string model [24] hadronization is modeled by the breaking of the color string stretching from the struck parton to the target remnant. The production time is

\[
\langle t_p \rangle = f(z)(1 - z) \frac{zE_q}{\kappa_{\text{str}}}
\]

where \( E_q \) is the struck quark energy, and \( \kappa_{\text{str}} \) the string tension. At leading order (LO) in the Strong coupling constant \( \alpha_s \), the partonic subprocess is \( \gamma^* + q \rightarrow q \) and one obtains

\[
E_q = \nu.
\]

The factor \( zE_q \) can be understood as a Lorentz boost factor. The \( (1 - z) \) factor is due to energy conservation: a high-\( z \) hadron carries away an energy \( zE_q \); the string remainder has a small energy \( \epsilon = (1 - z)E_q \) and cannot stretch farther than \( L = \epsilon/\kappa_{\text{str}} \). Thus the string breaking must occur on a time scale proportional to \( 1 - z \). The function \( f(z) \) is a small deformation of \( \langle t_p \rangle \), which can be computed analytically in the standard Lund model [10, 13]. The main features of the estimate (4) are dictated by kinematics and 4-momentum conservation, hence are of general nature. Indeed they can be obtained also by perturbative considerations based on the uncertainty principle, similarly to what is discussed in Ref. [25], or in the perturbative hadronization model of Ref. [11].

The production time (4) is well described by the proposed scaling variable \( \tau \) with \( \lambda > 0 \). E.g., in the Lund model \( \lambda \approx 0.7 \) [23]. In energy loss models [26–28], which assume \( \langle t_p \rangle \gg R_A \), the scaling is less obvious and holds only approximately on a theoretical ground. When performing the scaling analysis of the full energy loss models, one finds in general \( \lambda \lesssim 0 \) [23].

The central result of the analysis of HERMES data at \( E_{\text{lab}} = 27 \text{ GeV} \) performed in Ref. [23] is that pion data clearly exhibit

\[
\lambda \approx 0.5 \gtrless 0.
\]

As discussed, this is a signal of in-medium prehadron formation, with production times \( \langle t_p \rangle = O(R_A) \). Therefore,
the atomic number
types produced from several nuclear targets as a function of
the scaling variable $\tau$:

$$\langle t_p \rangle \equiv \tau .$$

(7)

The proportionality constant $C$ in Eq. (3), hence the magnitude of the production time, will be estimated in
Section III. A similar analysis has been attempted in Ref. [1], but arbitrarily fixing $\lambda = 0.35$. The resulting
$R_M(\tau)$ shows a rough scaling, with the 2 lowest-$z$ data point in each data set deviating from the scaling curve
and aligning in the vertical direction. This breaking of the scaling behavior is more probably due to the particular choice of $\lambda$, rather than to rescattering effects as argued by the authors.

III. $p_T$-BROADENING AND PREHADRON FORMATION

The scaling analysis just described gives only indirect evidence for a short production time $\langle t_p \rangle$, and cannot measure its absolute scale. An observable which is more directly related to the prehadron production time, and allows an estimate of the coefficient $C$ in Eq. (3), is the hadron’s transverse momentum broadening in DIS on a nuclear target compared to a proton or deuteron target [11, 29],

$$\Delta \langle p_T^2 \rangle = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D .$$

(8)

When a hadron is observed in the final state, neither the quark nor the prehadron from which it originates could have had inelastic scatterings. Since the prehadron-nucleon elastic cross section is very small compared to the quark cross section, the hadron’s $p_T$-broadening originates dominantly during parton propagation. As shown in [30, 31], the quark’s momentum broadening $\Delta \langle p_T^2 \rangle$ is proportional to the quark path-length in the nucleus. If the prehadron production time has the form (3) as argued in the last section, and as long as the prehadron is formed inside the nucleus, we obtain

$$\Delta \langle p_T^2 \rangle \propto \langle t_p \rangle \propto z^{0.5}(1-z)\nu ,$$

(9)

where the exponent 0.5 is determined by the scaling analysis discussed in Section II. Then, a decrease of $\Delta \langle p_T^2 \rangle$ with increasing $z$ or decreasing $\nu$ would be a clear signal of in-medium prehadron formation: indeed, if the quark were traveling through the whole nucleus before prehadron formation, $\Delta \langle p_T^2 \rangle$ would only depend on the nucleus size and not on $z$ or $\nu$. In addition to the dependence of $\Delta \langle p_T^2 \rangle$ on $z$ and $\nu$, which primarily stems from energy conservation and the Lorentz boost of the hadron, Ref. [11] argues that

$$\Delta \langle p_T^2 \rangle \propto \frac{1}{Q^2} .$$

(10)

The physics behind this proposed behavior is that a quark which is struck by a photon of large virtuality radiates more intensely than for a lower virtuality: as a consequence, it will be able to only travel a shorter way before hadronization, hence it will experience less $p_T$-broadening. A related observable is the Cronin effect, which is likewise expected to decrease with increasing $z$ or decreasing $\nu$, and possibly with increasing $Q^2$ [11].

The HERMES preliminary data on the $p_T$-broadening, reproduced in Figs. 2 and 3 for the reader’s convenience, show a linear increase with $A^{1/3}$, and a clear decrease of $\Delta \langle p_T^2 \rangle$ at large $z$ consistent with Eq. (9) and HERMES data on the Cronin effect [1]. However, HERMES data

FIG. 2: Left: $p_T$-broadening at HERMES for different hadron types produced from several nuclear targets as a function of the atomic number $A$ (from Refs. [17, 18]). Right: Ratio $\langle p_T^2 \rangle_A/\langle p_T^2 \rangle_D$ as a function of $x_B$ (from Ref. [19]). The inner error bars represent the statistical error and the outer ones the quadratic sum of the statistical and systematic uncertainties.

FIG. 3: As Figure 2, but for the $p_T$-broadening as a function of $z$ (upper panel), $\nu$ (middle panel), and $Q^2$ (lower panel). Plots taken from Refs. [17, 18].
These 2 remarks allow setting the scale for the production time in Eq. (3):

\[
C \approx \frac{\langle L_{Xe}\rangle}{z^\lambda (1 - z) \bar{\nu}} \approx 0.8 \text{ fm/GeV}
\]

with \( \bar{z} = 0.4 \) and \( \bar{\nu} = 14 \text{ GeV} \). The average in-medium path-length of the hadronizing system can be approximated as \( \langle L_{Xe}\rangle \approx (3/4)R_A \) with \( R_A = (1.12 \text{ fm})A^{1/3} \), as if nucleons were uniformly distributed in the nucleus. The resulting production time,

\[
\langle t_p \rangle \approx 0.8 \bar{z}^{0.5} (1 - \bar{z}) \nu \text{ fm/GeV},
\]

with \( \nu \) measured in GeV, is plotted in Fig. 4. In principle, \( C \) should be allowed to depend on \( Q^2 \) and \( x_B \), but one can neglect it in first approximation at least for the discussion of the \( A_r \), \( z_r \)-, where \( \langle Q^2 \rangle \) and \( \langle x_B \rangle \) are rather constant. With Eq. (12), we can compute the production times for each experimental bin, see Table I.

The \( \nu \)-distribution is also consistent with this estimate: given the production times in Table I, it is not too surprising that the \( \nu \)-dependence is basically flat, because the prehadron is formed on average on the surface or outside the nucleus. Three effects can contribute to tilt the curve and producing the slightly decreasing data: (i) a possible dependence of the prehadron cross section with \( \nu \), as it happens for the hadron cross section; (ii) medium modifications of the DGLAP parton shower [33–36], which can modify the linear dependence of \( \Delta(p_T^2) \) on the energy loss \( \Delta E \) found in [30], and implicit in Eq. (9); (iii) the correlation between the \( p_T \)-broadening and the average Bjorken variable, \( \langle x_B \rangle \), whose origin will be discussed in detail in the next Section, and which may in fact be the dominant effect.

IV. \( p_T \)-BROADENING VS. \( Q^2 \) AND \( x_B \)

We are now in the position to address the intriguing \( Q^2 \) distribution. The linear increase of \( \Delta(p_T^2) \) with \( Q^2 \) is in sharp contrast with the inverse power dependence obtained in the color dipole model, see Eq. (10). On the other hand also a flat \( Q^2 \), as would be obtained in most
string-based models, seems at variance with these data. To my knowledge, no model predicts a substantial rise of \(\langle t_p \rangle\) with virtuality: how can we explain these data? From the production times shown in Table I, we can see that the prehadron is always formed on the surface or outside the nucleus, so that the observed \(Q^2\)-dependence must predominantly have a partonic origin. It cannot simply come from multiple parton elastic scatterings, because it would be in first order proportional to the intermediate path-length, which is basically fixed. The following 3 mechanisms may contribute to explain these data:

1. **Medium-enhanced DGLAP evolution.** The DGLAP evolution in the kinematics under consideration happens entirely inside the nucleus, because the prehadron is produced at its surface. The scale \(Q^2\) at which hadronization takes place is not expected to strongly depend on the presence of a medium [44]. Therefore, in the large-\(Q^2\) bins, a longer and medium-enhanced DGLAP evolution [33–36] would imply a larger \(p_T\)-broadening than at low \(Q^2\). How strong this effect is, and whether it can lead to a linear increase of the \(p_T\)-broadening with \(Q^2\) remains to be seen. This mechanism can be investigated with a \(\nu > \nu_{\text{min}}\) cut in the experimental data: as \(\nu_{\text{min}}\) is increased, the DGLAP evolution would increasingly happen outside the nucleus, and the slope in \(Q^2\) should become smaller and smaller.

2. **Next-to-leading order processes.** The basic hard partonic process considered so far is the leading order in \(\alpha_s\) quark elastic scattering \(\gamma^* + q\rightarrow q\). It is the dominant process in the valence region at large \(x_B\). As \(x_B\) decreases, however, the gluon distribution in the nucleon quickly rises, so that the photon-gluon fusion process \(\gamma^* + g\rightarrow q + \bar{q}\), which is a next-to-leading order (NLO) process, becomes non negligible. In this case the photon energy \(\nu\) is shared by the quark and the antiquark, so that \(E_q < \nu\), therefore reducing the quark lifetime and its \(p_T\)-broadening compared to the LO case where \(E_q = \nu\). As can be seen from Table I, the average \(\langle x_B \rangle\) spanned in the \(Q^2\) distribution lies in the transition region between sea partons and valence quark dominance. Hence, the competition between LO and NLO process might alter the naive picture of \(p_T\)-broadening adopted so far, and lead to its increase with \(Q^2\). This mechanism may also be at work in \(\nu\)-distributions, although with smaller effects because of the more limited range spanned by \(\langle x_B \rangle\), and contribute to tilt their slope downwards. Note that if this mechanism is indeed at work, the estimate of \(C\) presented in Eq. (11) only gives a lower limit on the hadron production time. Experimentally, this mechanism can be tested by measuring \(Q^2\)-distributions with suitable cuts on \(x_B\). The slope in \(Q^2\) should become flat at very small or large \(\langle x_B \rangle\), see the discussion below.

3. **Colored prehadrons with short formation times.** A more radical possibility is that at these values of \(\nu\), the quark does not propagate freely for a long time; instead, shortly after the hard interaction, it turns into a colored prehadron \(h_c\) which can lose energy by gluon bremsstrahlung, thereby broadening its transverse momentum. The prehadron may have an inelastic cross section \(\propto 1/Q^2\), growing in time to the full hadronic one. If the time evolution is slow enough, at low \(Q^2\) the prehadron would be subject to more nuclear absorption than at large \(Q^2\), explaining the linear rise of \(\Delta(p_T^2)\) with \(Q^2\) [45]. An extreme version of this mechanism would involve

\[
\langle t_p \rangle \approx 0 \\
\langle t_{cn} \rangle \approx 0.8 \times 0.5(1 - z) \nu \text{ fm/GeV} .
\]

Note that this scenario does not contradict the dipole model prediction that \(\langle t_p \rangle \propto 1/Q^2\), but would require the prehadron to propagate as a colored state for a time of the order of the nuclear radius. An experimental investigation of this scenario needs very large \(\nu\), outside the reach of the HERMES experiment but attainable at the Electron-Ion Collider (EIC) [37, 38], in order to significantly boost \(\langle t_p \rangle\) and allow the quark to propagate as a free particle inside the nucleus.

In order to study the physics behind the experimental correlation of \(\Delta(p_T^2)\) with \(x_B\) and \(Q^2\), one needs to simultaneously address \(Q^2\)-distributions binned in \(x_B\) and \(x_B\)-distributions binned in \(Q^2\). In this way, one can factor out the trivial kinematic correlation \(\nu = Q^2/(2m_N x_B)\) which affects the production time. For example, if \(\langle t_p \rangle \propto \nu/\kappa\) with \(\kappa\) fixed, as in the Lund string model, for the LO \(\gamma^* + q\rightarrow q\) scattering we should expect

\[
Q^{-2} \Delta(p_T^2)_{x_B\text{-bins}} \approx \text{const.} \\
x_B \Delta(p_T^2)_{Q^2\text{-bins}} \approx \text{const.}
\]

The deviation from this combined scaling is going to expose the underlying dynamics, see Table II: if mechanism number 2 is dominant, we would observe \(Q^{-2} \Delta(p_T^2)_{x_B}\) constant in \(Q^2\) but \(x_B \Delta(p_T^2)_{Q^2}\) increasing with \(x_B\); mechanisms number 1 or 3 would produce an increasing \(Q^{-2} \Delta(p_T^2)_{x_B}\) but a constant \(x_B \Delta(p_T^2)_{Q^2}\). In the color dipole model [11], \(t_p \propto \nu/Q^2 \propto 1/x_B\) hence \(Q^{-2} \Delta(p_T^2)_{x_B}\) would be decreasing and \(x_B \Delta(p_T^2)_{Q^2}\) constant.

It is also important to extend as much as possible the range in \(x_B\) over which the \(p_T\)-broadening is measured: at small \(x_B \lesssim 0.01\) the NLO photon-gluon fusion is the dominant partonic process, while at \(x_B \gtrsim 0.3 - 0.4\) the photon dominantly scatters at LO valence quarks. Hence, with mechanism number 2, one may expect \(\Delta(p_T^2)\) to flat in \(Q^2\) in these 2 regions.
TABLE II: Expected results of the scaling analysis of the $p_T$-broadening for the models and mechanisms discussed in this paper. The numbers in parenthesis refer to the mechanisms listed in Section IV. The up and down pointing arrows indicate increasing or decreasing $p_T$-broadening, the double horizontal arrow an approximately constant behavior.

| model                          | $Q^{-2} \Delta \langle p_T^2 \rangle_{x_B}$ vs. $Q^2$ | $x_B \Delta \langle p_T^2 \rangle_{Q^2}$ vs. $x_B$ |
|-------------------------------|--------------------------------------------------------|--------------------------------------------------|
| $t_p \propto \nu/k$ (LO)      | $\leftarrow$                                          | $\leftarrow$                                    |
| mDGLAP (1)                    | $\uparrow$                                             | $\rightarrow$                                   |
| NLO vs. LO (2)                | $\uparrow$                                             | $\rightarrow$                                   |
| colored $h_c^*$(3)            | $\downarrow$                                           | $\rightarrow$                                   |
| $t_p \propto \nu/Q^2$ color dipole (11) | $\downarrow$                                           | $\rightarrow$                                   |

V. COMPARISON TO CLAS PRELIMINARY DATA

A last question needs to be addressed: how do the HERMES data and these scenarios compare to preliminary CLAS data [20–22] on the $p_T$-broadening and Cronin effect?

At CLAS, the higher beam luminosity allows multidimensional binning which is only partly accessible at HERMES. The kinematics is a bit different due to the lower beam energy, $E_{beam} = 5$ GeV compared to 27 GeV. The main difference is that $\langle \nu \rangle = 2 - 5$ GeV is much smaller than at HERMES, therefore prehadron production should typically happen on shorter time scales, mainly inside the nucleus according to the estimate (9). Note also that $Q^2 = 1 - 4$ GeV$^2$, and that, typically, $\langle x_B \rangle_{CLAS} > \langle x_B \rangle_{HERMES}$. The main features of CLAS data on C, Fe, and Pb targets are the following:

- The $p_T$-broadening is linear in $A^{1/3}$ at low $A$, but tends to saturate for large nuclei. The flattening is confirmed by the lack of increase in the Cronin effect from the Fe target to the Pb target. This shows the prehadron forming on a time scale $t_p \gtrsim (4/3) R_{Fe} e = 4.3$ fm, smaller than at HERMES.
- The $p_T$-broadening is rising and then saturating with $\nu$. The saturation appears at $\nu \gtrsim 4$ GeV, where the HERMES $p_T$ is also approximately flat.
- The Cronin effect decreases with $z$ as it happens at HERMES.
- The Cronin effect markedly increases as $x_B$ increases from 0.1 to 0.5. This confirms the $x_B$ dependence of HERMES $p_T$-broadening.

All these features corroborate the discussed HERMES data. However, the production time I have estimated is about a factor 5 smaller than the production time extracted in Ref. [29] from CLAS $\nu$-distributions using the color dipole formalism [31]. On the other hand, based on this paper’s analysis, and taking into account the uncertainty in the estimate of $\langle L_A \rangle$, HERMES data can only support up to a doubling of $t_p$, which would otherwise become incompatible with the large-$z$ decrease of the $p_T$-broadening. The HERMES and CLAS data sets may be qualitatively reconciled by taking into account the observed increase of the $p_T$-broadening with $\langle x_B \rangle$ discussed in the previous Section. Indeed, $\langle x_B \rangle_{CLAS} > \langle x_B \rangle_{HERMES}$, which implies a larger $p_T$-broadening at CLAS.

The origin of the discrepancy between the production times extracted from HERMES and CLAS data on the $p_T$-broadening remains to be clarified. On the theoretical side, the two discussed methods to determine the production time should be applied to both data sets, in order to check their consistency and further explore the issue. On the experimental side, it is very important to establish and study the correlation of $\Delta \langle p_T^2 \rangle$ with $x_B$ and $Q^2$, as emphasized in the previous section.

VI. CONCLUSIONS

In this paper, I attempted a semi-quantitative estimate of the prehadron production time, based on recent preliminary HERMES data on hadron $p_T$-broadening in nuclear DIS, see Eq. (12). The obtained production time can well explain the dependence of the $p_T$-broadening on $A$, $z$ and $\nu$. Its linear increase with $Q^2$ remains a challenge to current theoretical models, and I proposed a few mechanisms that may contribute to its explanation, also suggesting how to experimentally validate them. Furthermore, I discussed how the preliminary CLAS data qualitatively support the features observed at HERMES.

With the obtained estimate of $t_p$, the prehadrons at HERMES are typically formed around the nuclear surface or slightly outside, while at CLAS they are typically formed inside the target. However, a quantitative analysis indicates that $t_p|_{HERMES} \approx 0.2 t_p|_{CLAS}$. The observed $x_B$ dependence of the $p_T$-broadening can at least in part reconcile the 2 data sets, as well as explain the $Q^2$ dependence of the data. It also points at a non-negligible role of NLO processes in the hadronization process.

The measurement of hadron $p_T$-broadening, and the related Cronin effect, are beginning to test the limits of current theory models on the space-time evolution of hadronization, which are based on LO $\gamma^*\mathrm{quark}$ scattering, followed by color neutralization of the quark and hadron formation. The main theoretical challenges raised by these data are, in my opinion,

- the inclusion of NLO processes in the modeling of hadron quenching,
- the implementation at LO, and subsequently at NLO, of alternative models of energy loss, like a medium-modified DGLAP evolution;
- testing of alternative space-time pictures beyond the 2 time scale models currently accepted; for example, the role of a colored prehadron should be explored.
On the experimental side, the proposed physics mechanisms can be verified by measuring the $p_T$-broadening and the Cronin effect with suitable kinematic cuts. In particular,

- the role of parton energy loss can be highlighted by large-$\nu$/small-$z$ cuts, such that the parton lifetime exceeds the nuclear size;

- in-medium hadronization can be selected by small-$\nu$/large-$z$ cuts;

- the $x_B$ dependence of $\Delta(p_T^2)$, the Cronin effect, and the multiplicity ratio needs to be better studied over a large interval of $x_B$, including small $x_B \lesssim 0.01$ and large $x_B \gtrsim 0.4$; additionally, dihadron correlations and the hadron multiplicity per event as a function of $x_B$ can more directly reveal the role of NLO processes, in which 2 partons can be produced at the hard scattering;

- the combined analysis of $p_T$-broadening’s $x_B$-distributions binned in $Q^2$ and of $Q^2$-distributions binned in $x_B$ is likely to usefully expose the underlying dynamics.

Because of the available $\nu$ range, the HERMES experiment and the future Electron-Ion Collider are best suited to study the role of parton energy loss and propagation in cold nuclear matter. At CLAS, in-medium hadronization is likely to be dominant and can be studied in detail thanks to its high-statistics data, which allow multidimensional binning and the study of one kinematic variable at a time.

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[44] The partial deconfinement of bound nucleons in a nucleus [39] may induce an $A$-dependence of $Q_0$ and modify hadron fragmentation [12, 40]. However, such an effect is unfavored by the measured $Q^2$ dependence of $R_M$, which is opposite than what is expected in the partial deconfinement mechanism [41].

[45] A similar space-time evolution of hadronization has been implemented for leading prehadrons in the GiBUU absorption model of Refs. [14, 16], which however assumes $t_p = t_{cn} = 0$ for leading (but colorless) prehadrons, and does not address radiative energy loss. It would be interesting to phenomenologically include both a colored and a colorless prehadron in this model to test the proposed scenario.