Evidence for x-dependent proton color fluctuations in pA collisions at the LHC

M. Alvioli,1 B.A. Cole,2 L. Frankfurt,3 and M. Strikman4

1Consiglio Nazionale delle Ricerche, Istituto di Ricerca per la
Protezione Idrogeologica, via Madonna Alta 126, I-06128 Perugia, Italy
2Columbia University, New York, NY 10027, USA
3Tel Aviv University, Tel Aviv, Israel
4104 Davey Lab, The Pennsylvania State University, University Park, PA 16803, USA

(Dated:)

We argue that the pattern of violation of the Glauber picture for centrality dependence of the rate of forward jet production observed in pA collisions at the LHC provides evidence that configurations in the proton containing a parton with large $x_p$ interact with a significantly smaller than average cross section and have smaller than average size. Implementing effects of the fluctuations of the interaction strength and using the ATLAS analysis of the dependence of the hadron production at backward rapidities on the number of wounded nucleons, we make quantitative predictions for the centrality dependence of the jet production rate as a function of the interaction strength $\sigma(x_p)$. For $x_p = 0.6$ we find $\sigma(x_p) \sim \sigma_{tot}(pp)/2$ which sheds light on the origin of the EMC effect.

PACS numbers: 14.20.Dh, 25.40.Ve, 13.85.-t, 25.75.q

Studies of microscopic nucleon structure have progressed from probing one-dimensional single parton distributions (parton distribution functions) to the study of generalized parton distributions - 3D single parton distributions, to the study of parton - parton correlations in multi-parton interactions. Here, we argue that studies of correlations between soft and hard scattering processes in very high energy proton-nucleus (pA) collisions provide an effective tool for addressing another aspect of the nucleon structure - whether the transverse area occupied by partons in a fast nucleon decreases with increased parton momentum $x_p \geq 0.5$. The possibility of such studies is based on the Lorentz slowing down of interaction in the collider kinematics where projectile nucleon propagates through the nucleus in frozen configurations and on the color screening property of high energy QCD which implies that the strength of the interaction drops with decrease of the overall size of the configuration. Recent measurements of the centrality dependence of single jet or dijet production in pA collisions at the LHC [1, 2] have provided puzzling results that may provide insight on this problem.

To visualize the generic gauge theory phenomenon of the fluctuation of the strength of the interaction, it is instructive to consider the interaction of electrically neutral bound states in QED. As a consequence of the gauge invariance in QED, the cross section of the interaction of such a state with a neutral target decreases with the decrease of the transverse area occupied by charge: $\sigma(r_t^2) \propto r_t^2$ at small $r_t$. Such a behavior explains the observation that the interaction of muonium in media is much weaker than that for positronium. A less well-known effect is the correlation between the size of the configuration and its parton structure. Namely, configurations of smaller size (high relative momenta of the valence constituents) contain fewer Weizecker-Williams photons. Indeed, the photon field at $p_t \lesssim 1/r_t$ in a fast positronium is canceled out for configurations of transverse size $r_t$ due to conservation of the electromagnetic current. The combination of the two effects leads to a change in the absorption pattern for the propagation of the ultra-relativistic positronium through a slab of density $\rho$ and length $L$. That change is controlled by a coherence length that follows from the uncertainty principle and that rapidly increases with collision energy $l_{coh} \sim (1/\Delta E)^{-1/2}$.

Here, $M$ is the mass of intermediate (diffractive) state. At sufficiently high energies, $l_{coh} \gg L \approx 1/\sigma_{inel}\rho$ where $\sigma_{inel}$ is for (positronium - atom) scattering. Then, using the semi-classical approximation and after summing over diffractively produced $e^+e^-$ states the positronium survival rate is given by

$$\kappa = \int \psi^2(z,r_t)dzd^2r_t \exp \left[-\sigma_{inel}(r_t^2)\rho L\right]. \quad (1)$$

Here, $\psi(z,r_t)$ is wave function of positronium normalized as $\int \psi^2(r)d^3r = 1$. At ultra-relativistic energies and for $\sigma\rho L \gg 1$, the survival rate reduces to $\kappa \approx [4/(\sigma\rho L)]^2$ instead of the conventional expression $\exp(-\sigma_{inel}\rho L)$, (see [3] and references therein). In Eq. [1] the sum over a complete set of diffractively produced states reduces to an average over configurations ($r_t$) of constituents in the projectile leading to the appearance of the fluctuations of strengths, $\sigma_{inel}(r_t)$. Furthermore, if a positronium had excited an anomalously small (large) number of atoms along its path in the media, electrons and positrons would be observed escaping from the target with larger (smaller) than average transverse momentum or with $x > 0.5$ (x very close to 0.5) fraction of the positronium longitudinal momentum. An analogous effect was observed long ago by Perkins [4] for the interaction in emulsion of $e^+e^-$ pairs produced in $\pi^0 \rightarrow \gamma e^+e^-$ decays. Hence, triggering on production of electrons or positrons...
with $x > 0.5$ escaping the media would post-select an incoming positronium in a small size configuration which would be leaving a weaker than average trail of the excited atoms.

In QCD, fluctuations of the strength of interaction may originate both from fluctuations of the size – as in the above positronium example – and from fluctuations in the number of the constituents. Generically, we will refer to both contributions as color fluctuations (CF). One can describe CFs by introducing a distribution, $P_h(\sigma)$, which is a generalization of $\int \psi(r,z)^2 dz$ in Eq. 1. This distribution describes the probability for components of the wave function of projectile $h$ to have cross section $\sigma$ when interacting with a nucleon of the nucleus. The sum rules: $\int P(\sigma)d\sigma = 1$ and $\int P(\sigma)\sigma d\sigma = \langle \sigma \rangle$ follow from the probability conservation and the definition of the total cross section. The variance of the distribution can be characterized by the parameter

$$\omega_\sigma = (\langle \sigma^2 \rangle / \langle \sigma \rangle^2 - 1) = \left. \frac{d\langle \sigma^2 \rangle}{d\langle \sigma \rangle} \right|_{\langle \sigma \rangle = 0}, \quad (2)$$

where a sum over diffractively produced states, $X$, including the triple Pomeron contribution [16] is implied. Eq. 2 follows directly from the optical theorem and the definition of $P(\sigma)$. It was derived originally in [6] using the approach of [7]. Analyses of fixed target data [9] indicate that $\omega_\sigma$ first grows with energy reaching $\omega_\sigma \sim 0.3$ for $\sqrt{s} \sim 100$ GeV. At higher energies, the variance decreases reaching $\omega_\sigma \sim 0.1$ at the LHC energies [10].

The shape of $P_h(\sigma)$ can be constrained using basic arguments [9]: the distribution of $P_h(\sigma)$ for $\sigma \sim \langle \sigma \rangle$ is expected to be Gaussian due to small fluctuations of the number of partons, of the transverse area occupied by partons, etc. However, for small $\sigma$, minimal [8] configurations should dominate, leading to $P_N(\sigma) \propto \sigma$ cf. discussion below. The resulting form of $P_N(\sigma)$ represents a smooth interpolation between both regimes with parameters constrained by the first three moments

$$P_N(\sigma_{\text{tot}}) = \frac{\rho}{\sigma_0} \left( \frac{\sigma_{\text{tot}}}{\sigma_0} \right) \exp \left\{ - \left( \frac{\sigma_{\text{tot}} - \langle \sigma_0 \rangle^2}{\Omega^2} \right) \right\}. \quad (3)$$

Numerically, $\Omega^2/2 \approx \omega_\sigma$. An analysis [9] of the data on the coherent diffraction off the deuteron at $E_p = 400$ GeV [25] shows that the $P_N(\sigma_{\text{tot}})$ distribution is approximately symmetric around $\sigma = \sigma_{\text{tot}}$ in agreement with the Gaussian distribution expectation. In practice, many of the results of numerical calculations depend only weakly on the form of $P_h(\sigma)$ as long as variance is fixed see [10] and references therein.

The CF formalism reproduces Gribov-Glauber expressions for the total cross section in hadron-deuteron scattering [5] since the Gribov inelastic shadowing is expressed through the cross section of diffractive scattering which, in turn, is related to the variance of the $P(\sigma)$ distribution (see [9] for extensive discussion and references).

For the average characteristics of the hadron-heavy nucleus interaction like total or inelastic cross sections and the average number of wounded nucleons or participants, $N_{\text{part}}$, the Gribov-Glauber and Glauber models give similar results. The formulae for the number of collisions, $\nu$, suffered by the projectile hadron in hadron-nucleus collisions at high energies were derived within the Gribov formalism in [11] neglecting CF effects. It is straightforward to generalize the results of that calculation applying the analysis used in the QED example considered above to inelastic hadron - nucleus interactions [12]. In the approximation when the radius of the nucleon-nucleon ($NN$) interaction is neglected as compared to the average distance between the neighboring nucleons:

$$\sigma_{\text{in}}^{hA} = \sum_{\nu=1}^{A} \sigma_\nu, \quad \sigma_\nu = \int d\sigma P_h(\sigma), \quad (4)$$

where $x(b) = \sigma T(b)/A$, $T(b) = \int_{-\infty}^{\infty} ds \rho(z,b)$ and $\rho$ is the nuclear density distribution normalized such that $\int d\sigma \rho = A$. The probabilistic structure of the expression holds when nucleon-nucleon correlations and the finite size of the $NN$ interaction are included which allowed implementation as a Monte Carlo algorithm [10]. Note that the energy-momentum conservation as implemented within the CF approach, within the Gribov-Glauber model does not produce additional factors in Eq. 1. [10]

It was observed early on [12] that the tail of $F_N(\sigma)$ for $\sigma > \langle \sigma \rangle$ leads to broadening of the $\nu$ distribution in $pA$ and $AA$ collisions. Recently, ATLAS studied [13] hadron production in $pA$ collisions at the LHC at rapidities close to the nuclear fragmentation region and developed a model for the distribution of hadron transverse energy, $\Sigma E_T$, over the number of wounded nucleons using distribution over multiplicity of the produced hadrons as a function of $N_{\text{part}} = \nu + 1$. They concluded that the Glauber model (Eq. 1) for the distribution over $N_{\text{part}}$ leads to too narrow distribution over number of produced hadrons. The CF approach with $\omega_\sigma \sim 0.1$ (which is consistent with the $pp$ LHC diffractive data) gives a reasonable description of the data, while the CF approach with $\omega_\sigma \sim 0.2$ results in an overly broad distribution. The results of [13] allow the contributions of collisions with different $N_{\text{part}}$ or $\nu$ to the centrality classes to be determined; results are shown in Fig. 1. In spite of a broad distribution over $\Sigma E_T$, the centrality classes trace well $\nu$. Theoretically, the kinematic region used for the ATLAS $\Sigma E_T$ measurement appears well-motivated, as energy conservation effects weakly influence hadron production close to the nucleus fragmentation region due to approximate Feynman scaling.

A challenging question is whether the fluctuations can be modified or amplified if an additional constraint is imposed that a parton carrying fraction of projectile
momentum $x$ is present in the parton configurations of the projectile? The example of the positronium considered above suggests that large $x$ trigger corresponds to smaller, and therefore weaker, interacting configurations with a weaker gluon field and, hence, to CF with $\sigma \ll \sigma_{\text{tot}}$. Similar results follow from QCD inspired models: the quarkonium models of a hadron, pQCD models of hadron wave function which explain an observed $x$ dependence of parton distributions in the normalization point $Q_0^2 \sim \text{few GeV}^2$. Due to $Q^2$ evolution, both the number of recoiling partons accompanying a parton with leading $x$ and the transverse size of the dominant parton configuration decrease when $x$ tends to one. In this case, a smaller number of gluons and sea quarks is also the consequence of gauge invariance i.e. cancellation of long-range color field within the colorless configurations. In particular, selection of $x$ much larger than average value of $x$ should suppress the nucleon’s $q\bar{q}$ cloud leading to reduction of the soft cross section. Therefore, such configurations interact with a nuclear target with a smaller cross section already on non-perturbative scale [14]. At the same time, within the Feynman parton model, such an effect does not appear automatically. In the case of the pion projectile, such an understanding was tested via the observation of the color transparency in the coherent dijet production in the pion - nucleus scattering [15].

Measurements [11] of single jet production in $p\Lambda$ collisions at the LHC can address this question. Those measurements confirmed pQCD expectations for the rate of jet production in inclusive $p\Lambda$ collisions. The rates of the jet production for different centralities were compared with the Glauber model expectation

$$\frac{\sigma_{\text{hard}}(\nu)}{\sigma(\nu)} = \nu \frac{\sigma_{\text{hard}}(NN)}{\sigma_{\text{in}}(NN)},$$

obtained in the approximation where finite size effects for $NN$ soft and hard interactions are neglected. Large deviations from Eq. [5] were observed for the jets produced along proton direction: namely, an enhancement for peripheral collisions and suppression for central collisions which is compensated in the inclusive cross section. The finite size effects amplify the discrepancy (see Fig. 4 of [16]).

In this letter we will focus on the analysis of the ATLAS jet production data [13] though qualitatively similar data were obtained by CMS. The reason is that the ATLAS data are presented as a function of the fraction of the energy of the proton carried by the jet: $x = E_{\text{jet}}/E_p$ which for kinematics of interest practically coincides with $x$ of the parton of the proton involved in the hard interaction. Also, the analysis demonstrated that for fixed energy release in the nuclear hemisphere, the rate of the jet production compared to the inclusive rate is predominantly function of $x$ and not $p_t$ of the jet.

In our analysis, we combine the model of [13] for the distribution over $\Sigma E_T$ for collisions with given $\nu$ and the CF approach as implemented in [10, 16]. The later is based on Eq. [4] improved by taking into account the finite transverse size of the $NN$ interaction which at the LHC is comparable to the inter-nucleon distance, the transverse spread of partons in the colliding nucleons given by the generalized parton densities of the nucleon which allows to take into account much stronger localization of hard interactions than the soft interactions as well as $NN$ correlations in nuclei [17].

The qualitative expectation is that if the rate of jets is studied as a function of $\nu$, the relative strength of events corresponding to small $\sigma$ would be enhanced for small $\nu$ since $\langle \nu \rangle$ is smaller for this subset and it should be strongly suppressed for large $\nu$. This is in a good agreement with the results of the numerical calculation shown in Fig. [2] of the rate of hard collisions for a trigger with $\sigma$ different from the average one normalized to the rate for the generic jet trigger normalized to the ratio of the corresponding inclusive dijet cross sections - $R_{\text{hard}}$. For the generic hard collisions we used Eq. [2] with $\omega_\sigma = 0.1$, which provides a good description of soft data of ATLAS. For the small $\sigma$ trigger, we considered a range of $\langle \sigma(x) \rangle / \sigma_{\text{tot}}$ and variances between 0.1 and 0.2. The figure shows that for $\nu$ corresponding to relatively peripheral collisions, $R_{\text{hard}}$ primarily depends on $\langle \sigma(x) \rangle$ and, as a result, the sensitivity to the fluctuations of a cross section is small. However, for central collisions there is a stronger sensitivity to the variance of the distribution over $\sigma$ for fixed $x$.

Hence, we predict the dependence of $R_{\text{hard}}$ on $\nu$ essentially in terms of one free parameter: $\langle \sigma(x) \rangle$. To convert the result into bins of centrality, we use the relation between the energy release in the nuclear fragmentation region and $\nu$ from Ref. [13]. Using results for $R_{\text{hard}}$ taken from the preliminary ATLAS data for $x \sim 0.6$, we find that $\langle \sigma(x) \rangle / \langle \sigma \rangle \sim 0.6$ gives a good description of the data as shown in Fig. [3]. It is worth emphasizing here that a naive explanation of the data as due to energy-
momentum conservation does not work as one observes both suppression and enhancement of $R^{\text{hard}}$.

![Graph](image1.png)

**FIG. 2:** Relative probability of hard processes corresponding to a small $\sigma$ selection and generic hard processes.

With the final data becoming available, it would be possible to perform a comparison with the model for different $x$ with essentially one free parameter: $\langle \sigma(x) \rangle / \langle \sigma \rangle$

Overall, we find that $\langle \sigma(0.6) \rangle \sim (0.5 \div 0.6)\sigma_{\text{tot}}$ gives a reasonable description of the data giving a strong support to the idea that large $x$ configurations have a weaker interaction strength. A natural question is to what $\sigma$ these configurations correspond to at fixed target energies. This can be estimated from the probability conservation property of $P(\sigma)$:

$$\int_0^{\sigma(s_1)} P(\sigma, s_1) d\sigma = \int_0^{\sigma(s_2)} P(\sigma, s_2) d\sigma,$$

leading to the estimate $\sigma(x \sim 0.6)/\sigma_{\text{tot}} \sim 1/4$ for $\sqrt{s} = 30$ GeV. This value is a factor of two smaller than that obtained for the LHC. This reflects an important feature of pQCD that the cross section of small size configurations grows faster with collision energy than for the average configurations.

Our finding has a number of implications. It confirms the presence of the CF in $pA$ interactions, and, hence, suggests that CF should contribute to dynamics of the central $AA$ collisions$^{[12]}$. A weaker interaction strength of the $x \geq 0.5$ configurations also has important implication for the EMC effect. It was explained in $^{[14]}$ that smaller size configurations for bound nucleons should be suppressed as the consequence of the Le Chatelier’s principle. So the presence of the EMC effect of the suppression of quark distribution in nuclei as compared to the free nucleons starting at $x \sim 0.4$ and fully developed at $x \geq 0.5 \div 0.6$ matches nicely observation of the pattern of the suppression of the jet production observed at the LHC. A suppression observed for $x \sim 0.15$ where gluons still give a large contribution may reflect the fact that the gluon density enters at a scale $10^4$ GeV$^2$ which for $Q_0^2$ corresponds to significantly larger $x$ where we also expect squeezing for configurations with gluons hence suggesting presence of the EMC effect for gluons as well.

Further experimental studies are necessary to study the jet suppression pattern for the processes where gluons with $x_g \geq 0.3$ give significant contribution. This would allow to measure the effective size of these configurations and check directly how effective squeezing is in this case. Comparison of $W^+, W^-$ production at large $x_q$ would be also very interesting since there are indications of the different transverse structure for proton configurations with leading u and d quarks.

**Acknowledgments**

M.A.’s research was supported by grants provided by the Regione Umbria, under contract POR-FESR Umbria 2007-2013, asse ii, attivit`a a1, azione 5, and by the Dipartimento della Protezione Civile, Italy. B.A.C.’s research was supported by the US Department of Energy Office of
Science, Office of Nuclear Physics under Award No. DE-FG02-86ER40281. L.F.’s research was supported by the Binational Scientific Foundation Grant No. 0603216203. M.S.’s research was supported by the US Department of Energy Office of Science, Office of Nuclear Physics under Award No. DE-FG02-93ER40771.

[1] ATLAS Collaboration, Conference note ATLAS-CONF-2013-105, https://cds.cern.ch/record/1624014.
[2] CMS Collaboration, Eur. Phys. J. C 74, 2951 (2014) arXiv:1401.4433 [nucl-ex].
[3] L. Frankfurt and M. Strikman, Prog. Part. Nucl. Phys. 27, 135 (1991).
[4] D. H. Perkins, Phil. Mag., 46, 1146 (1955).
[5] V. N. Gribov, Sov. Phys. JETP 29 (1969) 483.
[6] H. I. Miettinen and J. Pumplin, Phys. Rev. D18, 1696 (1978).
[7] M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857.
[8] Y. Akimov, L. Golovanov, S. Mukhin, V. Tsarev, E. Malamud, R. Yamada, P. Zimmerman and R. Cool et al., Phys. Rev. D 14, 3148 (1976).
[9] B. Blaettel, G. Baym, L. L. Frankfurt and M. Strikman, Phys. Rev. Lett. 70, 896(1993); Phys. Rev. D 47, 2761(1993).
[10] M. Alvioli and M. Strikman, Phys. Lett. B 722, 347 (2013).
[11] L. Bertocchi and D. Treleani, J. Phys. G G 3 (1977) 147.
[12] H. Heiselberg, G. Baym, B. Blaettel, L. L. Frankfurt and M. Strikman, Phys. Rev. Lett. 67, 2946 (1991); Phys. Rev. C 52, 1604 (1995).
[13] ATLAS Collaboration, Conference note ATLAS-CONF-2013-096, https://cds.cern.ch/record/1599773.
[14] L. L. Frankfurt and M. I. Strikman, Nucl. Phys. B 250 (1985) 143.
[15] E. M. Aitala et al. [E791 Collaboration], Phys. Rev. Lett. 86, 4773 (2001) [hep-ex/0010014].
[16] M. Alvioli, L. Frankfurt, V. Guzey and M. Strikman, arXiv:1402.2868 [hep-ph].
[17] M. Alvioli, H.-J. Drescher and M. Strikman, Phys. Lett. B 680, 225 (2009).