Proceedings of the PHOTON-2017 Conference, Geneva, Switzerland, 22 – 26 May 2017, edited by David d'Enterria, Albert de Roeck and Michelangelo Mangano, CERN Proceedings, Vol. 1/2018, CERN-Proceedings-2018-001 (CERN, Geneva, 2018)

Color fluctuation phenomena in γA collisions at the LHC

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Abstract
We explain that color fluctuations (CFs) in the light-cone photon wave function lead to much stronger shadowing in the coherent production both in the soft regime (ρ -meson photoproduction) and in the hard regime (J/ψ photoproduction). We make CF based predictions for the distribution over the number of wounded nucleons ν in the inelastic photon–nucleus scattering. We show that CFs lead to a dramatic enhancement of this distribution at $\nu = 1$ and large $\nu > 10$. Our predictions can be tested in proton–nucleus and nucleus–nucleus ultraperipheral collisions.

Keywords
photon-nucleus interactions; color fluctuations

1 Introduction

It is instructive to consider hadron (photon) high energy collisions in the target rest frame where the wave function of a projectile is the superposition of coherent (so-called frozen) configurations [1, 2], as a consequence of the uncertainty principle and Lorentz slowing down of the interaction time. In QCD coherence of high energy processes is well understood theoretically and established experimentally, for a review, see, e.g. [3, 4]. A distinctive feature of the QCD dynamics is that the interaction strength of different configurations of quarks and gluons, which are QCD constituents of projectile hadrons, photons, etc., varies. We refer to this phenomenon as color fluctuations (CFs). In the literature one alternatively uses the term cross section fluctuations, which refer predominantly to soft hadron (photon) interactions at high energies.

This space time picture is qualitatively different from the Glauber model where only planar diagrams for the total cross section of a projectile –nucleus collision are considered since this contribution tends to zero with an increase of the collision energy, similar to the case of hadron-hadron interactions [5, 6]. This theoretical puzzle was solved by Gribov in Refs. [1] where contribution of non-planar diagrams was calculated and duality between non-planar diagrams and a sum of the elastic contribution and the diffractive intermediate states (duality between s and t channels) was used to rewrite formulae in the form rather similar to the Glauber approximation [1] with a Glauber like elastic term and inelastic diffraction term.

The relative importance of the inelastic term grows with decrease of the strength of interaction of average configurations in the projectile. So deviations from prediction of the Glauber model are expected to be small for the proton projectile, strongly increase for the pion case and photoproduction of ρ mesons and be even larger for the J/ψ photoproduction. The same effect is present for the nuclear shadowing for the DIS cross section. For example, in the case $\sigma_{tot}(\gamma_L A)$ elastic (dipole) term gives only a higher twist contribution to the shadowing, while multiparton states give the leading twist contribution. Hence the inelastic term dominates in this case.

https://doi.org/10.23727/CERN-Proceedings-2018-001.151

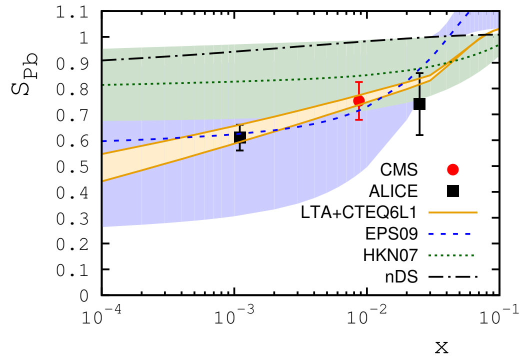

Fig. 1: Comparison of the suppression factor S for the J/ψ production extracted [8] from ALICE [9] and CMS [10] data. Prediction of the leading twist gluon shadowing approximation [7] is the yellow band. The range of expectations for the gluon shadowing in a number of models based on the fits to existing DIS data is also shown.

Ultraperipheral collisions at the LHC opened a new avenue for studies of CF since photon wave function contains components of very different size which interact with nucleon with very different strengths. In this talk we consider exclusive coherent vector meson production and effects of CFs for inclusive γA scattering.

2 Coherent production of vector mesons off nuclei

Recently coherent production of ρ mesons and J/ψ was studied at the LHC in the ultraperipheral heavy ion collisions. It was observed that the ρ-meson cross section is reduced as compared to the impulse approximation by a factor of ten, while in the J/ψ reduction is by a factor of three. Both reductions are much larger than naive expectations. The standard Glauber model predicts a factor of two smaller reduction for ρ production, while eikonal dipole models of J/ψ production predict only a 20% reduction.

It appears that the reason for an underestimate of the reductions is neglect by inelastic intermediate states. In the J/ψ case the effects of the inelastic states can be taken into account by absorbing these effects into the nuclear gluon density, $g_A(x, Q^2)$. The nuclear shadowing (g_A/g_N) can be calculated using gluon diffractive PDFs measured at HERA in $\gamma^* + p \to X + p$ and few other channels (for a review and references see [7]). One finds

$$S_A = \frac{\sigma(\gamma A \to J/\psi A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi A)} = \frac{g_A(x, Q^2)}{g_N(x, Q^2}, \tag{1}$$

where $x = m^2_{J/\psi}/W^2, Q^2 \approx 3$ GeV^2, Our predictions agree well with the LHC data, see Fig.1. Note that elementary amplitudes of J/ψ production are expressed through non-diagonal generalized parton densities. However in J/ψ case light cone fractions of gluons attached to $c\bar{c} - x_1$ and x_2 are comparable: $x_1 \sim 1.5x, x_2 \sim x/2$ so that $(x_1 + x_2)/2$ is close to x.

In the case of ρ production the challenge is that the coherent cross section is described very well by the Glauber model for moderate energies ~ 10 GeV [11], so a factor of two larger shadowing observed by ALICE [12] signals presence of new physics. The Gribov theory of inelastic shadowing provides the framework to take into account a different picture of high energy scattering. The configurations which are present in the intermediate states are frozen and cannot go back to ρ during the passage of the nucleus.

In the hadronic basis one needs to include not only transitions $\gamma \to \rho \to \rho$ but also transitions $\gamma \to M_X \to \rho$ (for scattering off two nucleons). It has been suggested that the interaction matrix of the initial hadron or diffractively produced hadronic states with target nucleons, which arises within Gribov–Glauber approach, can be diagonalized [13, 14]. In the particular case, when diffractive intermediate states are resonances, this diagonalisation has been performed in Ref. [15]. The method of CFs developed in [16] and discussed below is the further generalization of the Gribov–Glauber approximation, which allows one to account for the fluctuations of the interaction strength and other implications of QCD.

For the soft dynamics we need to introduce $P(\sigma)$ – probability that the frozen configuration of the projectile interacting with the nucleus has interaction cross section σ. In the case of ρ coherent photoproduction this amounts to the presence of the addition factor $P(\sigma)$ in the Glauber expression:

$$\sigma_{\gamma A\to\rho A} = \left(\frac{e}{f_\rho}\right)^2 \int d^2\vec{b} \left| \int d\sigma P(\sigma) \left(1 - e^{-\frac{\sigma}{2}T_A(b)}\right) \right|^2 , \tag{2}$$

Based on the similarity between the pion and ρ meson wave functions suggested by the additive quark model, it is natural to assume that $P(\sigma)$ for the ρN interaction should be similar to the pion $P_\pi(\sigma)$, which we additionally multiply by the factor of $1/(1 + (\sigma/\sigma_0)^2)$ to take into account the enhanced contribution of small σ in the photoproduction due to singular behavior of the photon wave function at small quark-antiquark separations leading to

$$P(\sigma) = C \frac{1}{1 + (\sigma/\sigma_0)^2} e^{-(\sigma/\sigma_0 - 1)^2/\Omega^2} . \tag{3}$$

The parameterization of Eq. (3) satisfies the basic QCD constraint of $P(\sigma = 0) \neq 0$ and also $P(\sigma \to \infty) \to 0$. The free parameters C, σ_0 and Ω are found from the following constraints:

$$\int d\sigma P(\sigma), \int d\sigma P(\sigma)\sigma\langle\sigma\rangle , \int d\sigma P(\sigma)\sigma^2 = \langle\sigma\rangle^2(1 + \omega_\sigma) , \tag{4}$$

where $\langle\sigma\rangle = \hat{\sigma}_{\rho N}$ in the modified VMD model, and ω_σ is equal to the ratio of inelastic and elastic diffraction at t=0, see discussion in [17]. The results of calculation are in a reasonable agreement with the data obtained at the LHC [12] and at RHIC [18–20].

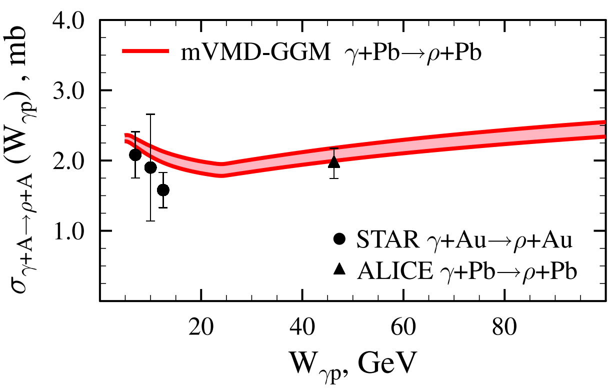

Fig. 2: The $\sigma_{\gamma A\to\rho A}$ cross section as a function of $W_{\gamma p}$. The theoretical predictions of Ref. [17] using the modified VMD model for the $\gamma p \to \rho p$ cross section and the Gribov–Glauber model with cross section fluctuations for the $\gamma A \to \rho A$ amplitude are compared to the STAR (circle) [18–20] and ALICE (triangle) data [12]. The shaded area reflects the theoretical uncertainty associated with the estimate of the strength of cross section fluctuations [17].

3 Color fluctuations in inelastic γA scattering [21]

Coherent production of vector mesons considered above give examples of processes which select configuration in the photon interacting with very different strength. We combine the information about interaction of small dipoles and soft, light vector meson like configurations probed in coherent ρ photoproduction to build the probability distribution $P_\gamma(\sigma, W)$ for the interactions of the photon. Specifically we use the dipole approximation for $\sigma \leq 10$ mb, Eq. 3 adjusted for the contributions of ω, ϕ mesons for $\sigma \geq 20$ mb and interpolate in between:

$$P_\gamma(\sigma, W) = \begin{cases} P_\gamma^{\rm dipole}(\sigma, W)\,, & \sigma \leq 10 \text{ mb}\,, \\ P_{\rm int}(\sigma, W)\,, & 10 \text{ mb} \leq \sigma \leq 20 \text{ mb}\,, \\ P_{(\rho+\omega+\phi)/\gamma}(\sigma, W)\,, & \sigma \geq 20 \text{ mb}\,. \end{cases} \quad (5)$$

where $P_{\rm int}(\sigma, W)$ is a smooth interpolating function which matches dipole expression especially well for $m_q = 300$ MeV. The resulting $P_\gamma(\sigma, W)$ is shown by the red solid curve in Fig. 3. The derived $P_\gamma(\sigma, W)$

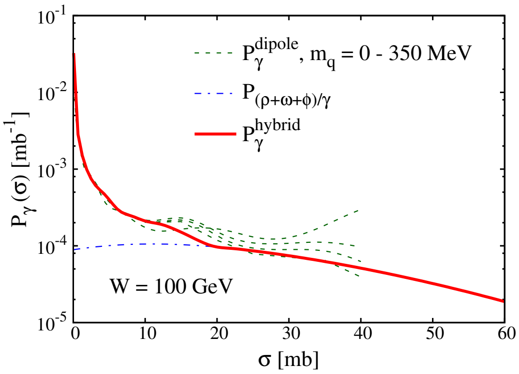

Fig. 3: The distributions $P_\gamma(\sigma, W)$ for the photon at $W = 100$ GeV. The red solid curve shows the full result of the hybrid model, see Eq. (5). The green dashed and blue dot-dashed curves show separately the dipole model and the vector meson contributions.

can be used to calculate distribution over the number of inelastic interaction, ν in the color fluctuation model. Also, one can include shadowing effects for the interaction of small dipoles which is smaller than for soft configurations but still significant as we have seen on the example of the J/ψ production. The results of the calculation are presented in Fig. 4. One can see that probability of interactions with $\nu = 1$ corresponding to the γp scattering is very sensitive to CF and LT nuclear shadowing. Same holds for the $\nu \geq 10$ tail.

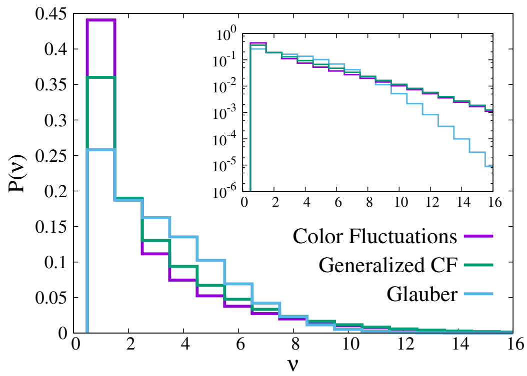

Fig. 4: The probability distributions $P(\nu, W)$ of the number of inelastic collisions ν. Predictions based on the color fluctuation model with $P_\gamma(\sigma, W)$ given by Eq.5 are labeled “Color Fluctuations”, the predictions including leading twist gluon shadowing are labeled “Generalized CF”.For comparison, the CF model calculation with $\sigma = 25$ mb, which neglects the effect of CFs, is shown by the curve labeled “Glauber”.

4 Color fluctuations and the distribution over transverse energy [21]

It is impossible to directly measure the number of inelastic interactions ν for $\gamma(h)A$ collisions. Modeling the distribution over the hadron multiplicity is also difficult due to the lack of the relevant data from γp scattering and issues with implementing energy–momentum conservation. However, the analysis of [22] suggests that the distribution over the total transverse energy, ΣE_T, sufficiently far away from the projectile fragmentation region (at sufficiently large negative pseudorapidities) is weakly influenced by energy conservation effects (due to the approximate Feynman scaling in this region) and is also weakly correlated with the activity in the rapidity-separated forward region. This expectation is validated by a recent measurement of ΣE_T as a function of rapidity of a dijet in pp collisions at the LHC [23].

Due to the weak sensitivity to the projectile fragmentation region, we expect that the ΣE_T distributions in pA and γA scattering at similar energies should have similar shapes for the same ν. In Ref. [22], a model was developed for the distribution over ΣE_T as a function of centrality (number, ν, of wounded nucleons) in pA scattering at large negative pseudorapidities (in the Pb-going direction) and $\sqrt{s} = 5.02$ TeV. We denote this distribution $f_\nu(\Sigma E_T) = 1/N_{\rm evt} dN/d\Sigma E_T$. In the spirit of the KNO scaling, it is natural to expect that the distribution over the ΣE_T total transverse energy in γA scattering, when normalized to the average energy release in pp scattering $\langle \Sigma E_T(NN)\rangle$, weakly depends on the incident collision energy. That is, the distribution over $y = \Sigma E_T(\gamma N)/\langle \Sigma E_T(\gamma N)\rangle$ has approximately the same shape at different energies. Hence we model the distribution over y for photon–nucleus collisions using $F_\nu(y) = \langle \Sigma E_T(NN)\rangle f_\nu(y)$, where the factor of $\langle \Sigma E_T(NN)\rangle$ is a Jacobian to keep normalization of $\int F_\nu(y)dy = P(\nu)$.

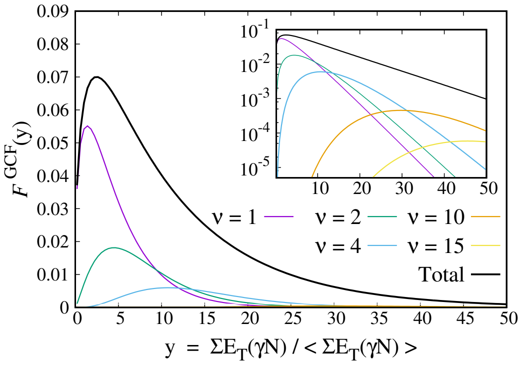

Fig. 5: The net probability distribution $\sum_\nu F_\nu(y)$ as a function of y for different models including (curves labeled "Generalized CFs" and "Color Fluctuations") and neglecting (the curve labeled "Glauber") CFs in the photon.

The results of the calculation of $F_\nu(y)$ are presented in Fig. 5 for the Generalized Color Fluctuations (GCF) model which includes leading twist nuclear shadowing. One can see that the net distribution is predicted to be much broader than that for the $\nu = 1$ case corresponding to the γp scattering. Also, our results indicate that for $y = \Sigma E_T(\gamma N)/\langle \Sigma E_T(\gamma N)\rangle \leq 1$, the contribution of the interactions with one nucleon dominates. On the other hand, the distribution over y in γp scattering can be measured in pA UPCs. A first step would be to test that the y distribution in γp and in the γA process with $\nu = 1$ [e.g., in the interaction of the direct photon ($x_\gamma = 1$) with a gluon with $x_A \geq 0.01$] is the same. Among other things this would give valuable information on the rapidity range affected by cascade interactions of slow (in the nucleus rest frame) hadrons which maybe formed inside the nucleus. It would be also interesting to measure separately the y distribution for processes with production of leading charm with moderate p_t. In this case the y-distribution should be broader than for dijet large x trigger, but more narrow than in the case min bias trigger. Another very interesting channel is hard resolved photon collisions where one expect a broadening of the y distribution with decrease of x_γ. This effect is analogous to observed centrality dependence of the forward jet production in pA scattering with increase of $x_p \geq 0.2$ which can be explained by decrease of the strength of interaction of configurations in protons for such x [24].

5 Conclusions

In conclusion, studies of the ultraperipheral collisions at the LHC would allow to map in great detail photon wave function and investigate interplay of soft and hard physics in the photon-nucleus interactions. Selection of different final states in the photon fragmentation region would serve as an effective "strengthonometer" of the different components of the photon wave function.

Acknowledgments – L.F.'s and 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.

References

[1] V. N. Gribov, Sov. J. Nucl. Phys. **9** (1969) 369 [Yad. Fiz. **9** (1969) 640]; Sov. Phys. JETP **29** (1969) 483 [Zh. Eksp. Teor. Fiz. **56** (1969) 892].

[2] V. N. Gribov, hep-ph/0006158.

[3] L. L. Frankfurt, G. A. Miller and M. Strikman, Ann. Rev. Nucl. Part. Sci. (1994)**44**, 501 [hep-ph/9407274].

[4] L. Frankfurt, V. Guzey and M. Strikman, J. Phys. G **27** (2001) R23 [hep-ph/0010248].

[5] S. Mandelstam, Nuovo Cim. **30** (1963) 1148 .

[6] V. N. Gribov, Sov. Phys. JETP **26** (1968) 414 [Zh. Eksp. Teor. Fiz. **53** (1967) 654].

[7] L. Frankfurt, V. Guzey and M. Strikman, Phys. Rept. **512** (2012) 255 [arXiv:1106.2091 [hep-ph]].

[8] V. Guzey, E. Kryshen, M. Strikman and M. Zhalov, Phys. Lett. B **726** (2013) 290 [arXiv:1305.1724 [hep-ph]].

[9] B. Abelev *et al.* [ALICE Collab.], Phys. Lett. B **718** (2013) 1273 [arXiv:1209.3715 [nucl-ex]].

[10] V. Khachatryan *et al.* [CMS Collab.], Phys. Lett. B **772** (2017) 489 [arXiv:1605.06966 [nucl-ex]].

[11] T. H. Bauer, *et al.*, Rev. Mod. Phys. **50** (1978) 261 [Erratum-ibid. **51** (1979) 407].

[12] J. Adam *et al.* [ALICE Collab.], JHEP **1509** (2015) 095 [arXiv:1503.09177 [nucl-ex]].

[13] M. L. Good and W. D. Walker, Phys. Rev. **120** (1960) 1857 .

[14] H. I. Miettinen and J. Pumplin, Phys. Rev. D **18** (1978) 1696 .

[15] L. Frankfurt, V. Guzey and M. Strikman, Phys. Rev. D **58** (1998) 094039 [hep-ph/9712339].

[16] G. Baym, B. Blattel, L. L. Frankfurt, H. Heiselberg and M. Strikman, Phys. Rev. Lett. **67** (1991) 2946; Phys. Rev. C **52** (1995) 1604 [nucl-th/9502038].

[17] L. Frankfurt, V. Guzey, M. Strikman and M. Zhalov, Phys. Lett. B **752** (2016) 51 [arXiv:1506.07150 [hep-ph]].

[18] C. Adler *et al.* [STAR Collab.], Phys. Rev. Lett. **89** (2002) 272302 [nucl-ex/0206004].

[19] B. I. Abelev *et al.* [STAR Collab.], Phys. Rev. C **77** (2008) 034910 [arXiv:0712.3320 [nucl-ex]].

[20] G. Agakishiev *et al.* [STAR Collab.], Phys. Rev. C **85** (2012) 014910 [arXiv:1107.4630 [nucl-ex]].

[21] M. Alvioli, L. Frankfurt, V. Guzey, M. Strikman and M. Zhalov, Phys. Lett. B **767** (2017) 450 [arXiv:1605.06606 [hep-ph]].

[22] G. Aad *et al.* [ATLAS Collab.], Eur. Phys. J. C **76** (2016) 199 [arXiv:1508.00848 [hep-ex]].

[23] G. Aad *et al.* [ATLAS Collab.], Phys. Lett. B **756** (2016) 10 [arXiv:1512.00197 [hep-ex]].

[24] M. Alvioli, B. A. Cole, L. Frankfurt, D. V. Perepelitsa and M. Strikman, Phys. Rev. C **93** (2016) 011902 doi:10.1103/PhysRevC.93.011902 [arXiv:1409.7381 [hep-ph]].