Probing photon structure and small x dynamics using fluctuation effects in high energy $\gamma - A$ scattering

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Outline

Intro: Color fluctuations in hadrons - new pattern of high energy hadron - nucleus scattering - going beyond single parton structure of nucleon.

A new frontier: probing color fluctuations in photon in $\gamma A$ collisions starting with UPC data from LHC (pre-sequel of EIC & LHeC studies)

Evidence for $x$-dependent color fluctuations in nucleons - nucleon squeezing
Fluctuations of overall strength of high energy NN interaction

High energy projectile stays in a frozen configuration distances $l_{coh} = c \Delta t$

$$\Delta t \sim \frac{1}{\Delta E} \sim \frac{2p_h}{m_{int}^2 - m_h^2}$$

At LHC for $m_{int}^2 - m_h^2 \sim 1 \text{GeV}^2$ $l_{coh} \sim 10^7 \text{fm} >> 2R_A >> 2r_N$

coherence up to $m_{int}^2 \sim 10^6 \text{GeV}^2$

Hence system of quarks and gluons passes through the nucleus interacting essentially with the same strength but changes from one event to another different strength

Strength of interaction of white small system is proportional to the area occupies by color.

QCD factorization theorem for the interaction of small size color singlet wave package of quarks and gluons.

For small quark - antiquark dipole

$$\sigma(q\bar{q}T) = \frac{\pi^2}{3} r_{tr}^2 x g_T(x, Q^2 = \lambda/r_{tr}^2) \alpha_s(Q^2)$$

For small 3 quark tripole

$$r_{tr}^2 \rightarrow (r_1 - (r_2 + r_3)/2)^2 + (r_2 - (r_1 + r_3)/2)^2 + (r_3 - (r_1 + r_2)/2)^2$$

small but rapidly growing with energy
dependence of $\sigma_{tot}(hN)$ on size holds in the nonperturbative regime

$$\sigma_{tot}(KN) < \sigma_{tot}(\pi N)$$

Global fluctuations of the strength of interaction of a fast nucleon/pion/photon, can originate from fluctuations of the overall size/shape, number of constituents.

**Example: quark -diquark model of nucleon**

We will refer fluctuations of the strength of interaction of nucleon, photon,.. as color fluctuations of interaction strength - studying them allows to go beyond single parton 3-D mapping of the nucleon
Constructive way to account for coherence of the high-energy dynamics is Fluctuations of interaction = cross section fluctuation formalism. Analogy: consider throwing a stick through a forest - with random orientation relative to the direction of motion. (No rotation while passing through the forest - large $l_{coh}$.) Different absorption for different orientations.

Classical low energy picture of inelastic $hA$ collisions implemented in Glauber model based Monte Carlos

High energy picture of inelastic $hA$ collisions consistent with the Gribov - Glauber model - interaction of frozen configurations

Expect effects similar positronium example = correlation between size and number of wounded nucleons
Formal account of large $l_{coh}$ – different set of diagrams describing $pA$ scattering:

**Glauber model**

- in rescattering diagrams proton propagates in intermediate state - zero at high energy - cancelation of planar diagrams (Mandelstam & Gribov) - no time for a proton to come back between interactions.

**High energies = Gribov - Glauber model**

- $X=$ set of frozen intermediate states the same as in $pN$ diffraction
- deviations from Glauber are small for $E_{inc} < 10$ GeV as inelastic diffraction is still small.

\[
\sigma_2 \propto \int dt F_A^2(t) \frac{d\sigma(p + p \to p + X(p + \text{inel diff}))}{dt}
\]
Convenient quantity - \( P(\sigma) \) - probability that hadron/photon interacts with cross section \( \sigma \) with the target. \[
\int P(\sigma)d\sigma = 1, \quad \int \sigma P(\sigma)d\sigma = \sigma_{\text{tot}}, \]
\( \text{cf } P_{\text{MC Glauber}}(\sigma) = \delta(\sigma-\sigma_{\text{tot}}) \)

\[
\frac{d\sigma(pp\rightarrow X+p)}{dt} = \frac{\int (\sigma - \sigma_{\text{tot}})^2 P(\sigma)d\sigma}{\sigma_{\text{tot}}^2} \equiv \omega_{\sigma} \quad \text{variance}
\]

Pumplin & Miettinen

\[
\int (\sigma - \sigma_{\text{tot}})^3 P(\sigma)\ d\sigma = 0,
\]
Baym et al from pD diffraction

\[ P(\sigma)|_{\sigma\rightarrow 0} \propto \sigma^{n_q-2} \]
Baym et al 1993 - analog of QCD counting rules

probability for all constituents to be in a small transverse area

+ additional consideration that for a many body system fluctuations near average value should be Gaussian

\[
P_N(\sigma_{\text{tot}}) = \rho \frac{\sigma_{\text{tot}}}{\sigma_{\text{tot}} + \sigma_0} \exp\left\{ -\frac{(\sigma_{\text{tot}}/\sigma_0 - 1)^2}{\Omega^2} \right\}
\]

\[ P_\gamma(\sigma)|_{\sigma\rightarrow 0} \propto \sigma^{-1} \]
\( \gamma = \text{mix of small } \bar{q}q \text{ and mesonic configurations} \)

Test: calculation of coherent diffraction off nuclei: \( \pi A \rightarrow XA, pA \rightarrow XA \) through \( P_h(\sigma) \)


\[ P_N(\sigma) \text{ extracted from pp, pd diffraction and } P_{\pi}(\sigma); \text{ Baym et al 93} \]

Flat \[ P_N(\sigma) \text{ in a wide range of } \sigma \text{ - can suggests few effective constituents at this energy scale like in quark - diquark model.} \]

Extrapolation of Guzey & MS before the LHC data

Variance drops with increase of energy, overall shift of distribution to larger \( \sigma \)

Fast drop of \[ P_N(\sigma) \text{ at small } \sigma \text{, with increase of energypQCD?} \]
Photon is a multiscale state:

Probability, \( P_{\gamma}(\sigma) \) for a photon to interact with nucleon with cross section \( \sigma \), gets contribution from point-like configurations and soft configurations (VM like)

\[
P_{\gamma}(\sigma) \propto 1/\sigma \quad \text{for} \quad \sigma \ll \sigma(\pi N) \quad \quad \quad \quad P_{\gamma}(\sigma) \propto P_\pi(\sigma) \quad \text{for} \quad \sigma > \sigma(\pi N)
\]
Exclusive processes of vector meson production off nuclei at LHC in ultraperipheral collisions allow to test theoretical expectations for small and large $\sigma$. $P_\gamma(\sigma)$ for small $\sigma$ from photon wave function and dipole DGLAP formula. Need model for large enough $\sigma$. Build a realistic model and check in

$\rho$-meson production: $\gamma+A \rightarrow \rho+A$

Expectations:

**vector dominance model for scattering off proton**

$\sigma(\rho N) < \sigma(\pi N)$

since overlapping integral between $\gamma$ and $\rho$ is suppressed as compared to $\rho \rightarrow \rho$ case

observed at HERA but ignored before our analysis: $\sigma(\rho N)/\sigma(\pi N) \approx 0.85$

*Analysis of Guzey, Frankfurt, MS, Zhalov 2015 (1506.07150)*
Gribov type inelastic shadowing is enhanced in discussed process - fluctuations grow with decrease of projectile - nucleon cross section. We estimate $\omega_{\gamma \rightarrow \rho} \sim 0.5$ and model $P_{\gamma \rightarrow \rho}(\sigma)$ - distribution of configurations in transition over $\sigma$.

Next we use $P_{\gamma \rightarrow \rho}(\sigma)$ to calculate coherent $\rho$ production. Several effects contribute to suppression a) large fluctuations, b) enhancement of inelastic shadowing is larger for smaller $\sigma_{\text{tot}}$. for the same $W$, c) effect for coherent cross section is square of that for $\sigma_{\text{tot}}$. 

Glauber double scattering  

Gribov inelastic shadowing
Glauber model grossly overestimates the cross section (at LHC factor ~2)

Gribov - Glauber model with cross section fluctuations
Outline of calculation of inelastic $\gamma A$ scattering -
distribution over number of wounded nucleons

Modeling $P_\gamma(\sigma)$

For $\sigma > \sigma(\pi N)$,

$$P_\gamma(\sigma) = P_{\gamma \rightarrow \rho}(\sigma) + P_{\gamma \rightarrow \omega}(\sigma) + P_{\gamma \rightarrow \phi}(\sigma)$$

For $\sigma \leq 10 \text{mb}$ (cross section for a J/$\psi$ -dipole) use pQCD for $\psi_\gamma(q\bar{q})$

$$\sigma (d, x) = \frac{\pi^2}{3} \alpha_s(Q_{eff}^2) d^2 x G_N(x, Q_{eff}^2)$$

+ smooth interpolation in between

Smooth matching for $m_q \sim 300 \text{ MeV}$
Calculation of distribution over the number of wounded nucleons

(a) Color fluctuation model

$$\sigma_\nu = \int d\sigma P_\gamma(\sigma) \left( \frac{A}{\nu} \right) \times \int d\vec{b} \left[ \frac{\sigma_{in}(\sigma)T(b)}{A} \right]^{\nu} \left[ 1 - \frac{\sigma_{in}(\sigma)T(b)}{A} \right]^{A-\nu}$$

$$p(\nu) = \sum_{1}^{\infty} \frac{\sigma_\nu}{\sigma_{in}}.$$

(b) Generalized Color fluctuation model (includes LT shadowing for small $\sigma$)

interaction of small dipoles is screened much stronger than in the eikonal model

$$P_\gamma(\sigma) \left( \frac{A}{\nu} \right) \times \frac{\sigma_{in}}{\sigma_{eff}} \int d\vec{b} \left[ \frac{\sigma_{eff}T(b)}{A} \right]^{\nu} \left[ 1 - \frac{\sigma_{eff}T(b)}{A} \right]^{A-\nu}$$

$$\frac{\sigma_{eff}}{\sigma} \quad \text{calculated in the LT nuclear shadowing theory for small } \sigma$$

\[\text{using } \sigma_{in} = \sigma_{tot} - \sigma_{tot} / (16\pi B)\]
Quantitative agreement with predictions of the LT shadowing theory

Phenomenological models have large uncertainties as no data constrain $g_A(x \sim 10^{-3})$

$S_{Pb}(x)$ is extracted from the data by Guzey, Zhalov & MS 2014-2017
Ultraperipheral minimum bias γA at the LHC ($W_{γN} < 0.5$ TeV)
Huge fluctuations of the number of wounded nucleons, $ν$, in interaction with both small and large dipoles

Alvioli, Guzey, Zhalov, LF, MS

CF broaden very significantly distribution over $ν$.
“pA ATLAS/CMS like analysis” using energy flow at large rapidities would test both presence of configurations with large $σ \sim 40$ mb, and weakly interacting configurations.
The probability distributions over the transverse energy in the Generalized Color Fluctuations (GCF) model assuming distribution over $y$ is the same for pA and γA collisions for same $\nu$.

Using CASTOR for centrality via measurement of “$y$” advantageous: larger rapidity interval - smaller kinematical/energy conservation correlations. For using $\Sigma ET$ for centrality determination one needs $\Delta y > 4$
\[ \gamma A \rightarrow \text{jets} + X \]

1) *Direct photon & } x_A > 0.01, \nu = 1?*

   Color change propagation through matter.
   Color exchanges? \[\rightarrow\] nucleus excitations, ZDC & CASTOR

2) *Direct photon & } x_A < 0.005 - nuclear shadowing increase of \nu*

3) *Resolved photon - increase of \nu with decrease of } x_\gamma \text{ and } x_A \text{ W dependence}*

Centrality dependence of the forward spectrum in \[ \gamma A \rightarrow h + X \]
— connection to modeling cosmic rays cascades in the atmosphere
Tuning strength of interaction of configurations in photon using forward (along \( \gamma \) information). Novel way to study dynamics of \( \gamma \) &\( \gamma^* \) interactions with nuclei.

“2D strengthonometer” - EIC & LHeC - \( Q^2 \) dependence - decrease of role of “fat” configurations, multinucleon interactions due to LT nuclear shadowing.

Comment: Forward \( \gamma A \) & \( \gamma p \) physics at the LHC mostly within acceptance of central ATLAS, CMS detectors.
Inclusive jet production is consistent with pQCD expectations (CMS)
ATLAS and CMS studied dijet production in pA at the LHC. Both observed very small nuclear effects for inclusive dijet production which rules out energy loss interpretation. However nuclear effects are strong function of $\nu$ which was estimated using negative rapidities. Forward jet production in central collisions is strongly suppressed - suppression is mainly function of $x_p$. and not $p_t$ of the jet. Consistent with expectation that configurations in protons with large $x$ -belong to configurations which are smaller and interact with $\sigma < \sigma_{\text{tot}}$.

$R_{\text{CP}}$, is a function of $x$ of the quark. No $p_T$ dependence for fixed $x_p=E_{\text{jet}}/E_{\text{proton}}$.
In order to compare with the data we need to use a model for the distribution in $E_T^{\text{Pb}}$ as a function of $\nu$. We use the analysis of ATLAS. Note that $E_T^{\text{Pb}}$ was measured at large negative rapidities which minimizes the effects of energy conservation (production of jets with large $x_p$) suggested as an explanation of centrality dependence.

**ATLAS-CONF-2015-019 analysis of pp data confirms this expectation**

![Diagram showing dependence on $x_{\text{proj}}$ and $x_{\text{targ}}$](image)

Measure $\Sigma E_T$ at large pseudorapidity vs.

- $x$ in the **projectile** proton (moving away)
- $x$ in the **target** proton (moving towards)
DISTRIBUTION OVER THE NUMBER OF COLLISIONS FOR PROCESSES WITH A HARD TRIGGER

Consider multiplicity of hard events \( \text{Mult}_{pA}^{HT} = \sigma_{pA}(HT + X)/\sigma_{pA}(in) \) as a function of \( N_{\text{coll}} \)

If the radius of strong interaction is small and hard interactions have the same distribution over impact parameters as soft interactions multiplicity of hard events:

\[
R_{HT}(N_{\text{coll}}) = \frac{\text{Mult}_{pA}^{HT}}{\text{Mult}_{pN}^{HT}N_{\text{coll}}} = 1
\]

Accuracy?

Two effects: Two scale dynamics of pp interaction at the LHC, large radius of NN interaction
Fluctuations for configurations with small \( \sigma \) maybe different than for average one so we considered both \( \omega_{\sigma}(x \sim 0.5) = 0.1 \) & 0.2

Sensitivity to \( \omega_{\sigma} \) is small, so we use \( \omega_{\sigma} = 0.1 \) for following comparisons
We extended our 2015 analysis of ATLAS data and extracted $R_{CP}(x)$

$$\lambda(x) = \frac{\sigma(x)}{\langle \sigma \rangle}$$

Alvioli, Frankfurt, Perepelitsa, MS

$\lambda = 0.75$

$x_p = 0.1845$

$\lambda = 0.08$

$x_p = 0.1225$

$\lambda = 0.73$

$x_p = 0.2285$

$\lambda = 0.70$

$x_p = 0.2765$

$\lambda = 0.68$

$x_p = 0.3395$

$\lambda = 0.65$

$x_p = 0.4165$

$\lambda = 0.62$

$x_p = 0.5055$

$\lambda = 0.60$

$x_p = 0.6065$

$\lambda = 0.57$

$x_p = 0.7305$
DAu PHENIX data at $y=0$ and large transverse momenta of the jets, $R_{CP}$, $\lambda(x) = \sigma(x)/<\sigma>$. Very different kinematics from the one studied at the LHC.
Implicit eqn. for relation of \( \lambda(x_p, s_1) \) and \( \lambda(x_p, s_2) \)

\[
\int_0 \lambda(x_p; \sqrt{s_1}) \sigma_{tot}(\sqrt{s_1})
\frac{d\sigma}{P_N(\sigma; \sqrt{s_1})} = \int_0 \lambda(x_p; \sqrt{s_2}) \sigma_{tot}(\sqrt{s_2})
\frac{d\sigma}{P_N(\sigma; \sqrt{s_2})}
\]

Eq. (*)

\( \lambda(x_p, s) \) grows with \( s \) since cross section at higher virtualities of the projectile grows faster with \( s \)

Highly nontrivial consistency check of interpretation of data at different energies and in different kinematics

Eq. (*) suggests \( \lambda(x_p=0.5, \text{low energy}) \sim 1/4 \). Such a strong suppression results in the EMC effect of reasonable magnitude due to suppression of small size configurations in bound nucleons (Frankfurt & MS83)
Summary

✱ Color fluctuations are a regular feature of high energy nucleon, photon collisions... Effects in very central AA collisions are present.

✱ Gross violation of the Glauber approximation for photoproduction of vector mesons due to CFs. CF are much stronger in photons than in nucleons. and can be regulated using different triggers (charm, jets,...)

✱ Jet production at RHIC and LHC produced first glimpse of the global quark - gluon structure of nucleons as a function of x. Nucleon becomes smaller at large x. Interact weaker than in average, but grows faster with energy. Need to separate gluons and quarks in hard processes at x ~0.1. Critic test pA at RHIC. Doable for photons as well in UPC at the LHC.
increase due to more central interactions of configurations with $\sigma < \sigma_{\text{tot}}$

Drop due to more localized hard interactions

Drop due increased role of configurations with $\sigma > \sigma_{\text{tot}}$ the cylinder in which interaction occur is larger but local density does not go up as fast in Glauber

Deviation of $R_{\text{HT}}(\nu=N_{\text{coll}})$ from 1