Coherent vector meson production off heavy nuclei - lessons from studies of ultraperipheral collisions at the LHC”

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Novel directions in UPC QCD studies

1st Yellow report workshop , Temple, March 20, 2020

Ultraperipheral (UPC) - photon - nucleus & nucleon interactions at LHC has provided first experimental information about dynamics in the kinematics overlapping with EIC:

Wide range of W in the same setting (Bonus for studying HE dynamics)

Forward physics at central rapidities - small x at smaller virtualities than pA at LHC.

EIC vs UPC - W in UPC is larger, minimal x for moderate virtualities is smaller, but it is more difficult though not impossible) to change virtuality of the probe

Photon is a multi scale state:

Color fluctuations in photon - nucleus collisions

Presence in the photon of soft "vector meson like" and hard

$q\bar{q}, c\bar{c}$ components - relative contribution of soft and hard components

can be regulated by selecting different final states

Analyses of the UPC data (mostly LHC) have provided unique information about interaction of both small dipoles like configurations and hadron like configurations with nuclei.

Roadmap of the talk:

Small dipoles interactions with several nucleons is much larger than in the eikonal approximation - leading twist nuclear shadowing for J/psi coherent scattering

Shadowing for hadron (ρ-meson) - nucleus interaction is much larger than in the Glauber model - expected in the Gribov picture of hA high energy interactions

Expectations of large color fluctuations (fluctuations of the strength of of interaction) inelastic(virtual) photon nucleus interactions

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

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

small but rapidly growing with energy.

In case T= nucleus, LT interactions with 2,3… nucleons are hidden in g_{T}(x,Q)

Theory of the leading twist nuclear shadowing for pdfs is based on

AGK cutting rules

$$\sigma_{eD}=\sigma_{imp}-\sigma_{double},\sigma_{diff}=\sigma_{double},$$
$$\sigma_{single\ N}=\sigma_{imp}-4\sigma_{double};\sigma_{two\ N}=2\sigma_{double}$$

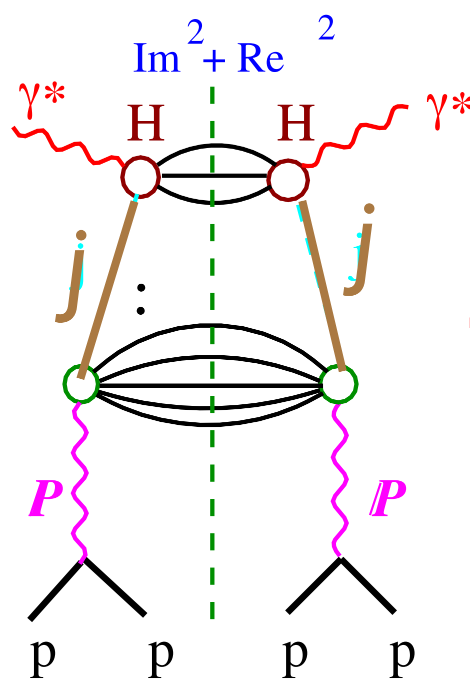
Collins factorization theorem for hard diffractive processes

tested at HERA for Q^2 > few GeV^2 - *larger probability of diffraction for gluon induced diffraction*

$f_j^D(\frac{x}{x_{I\!P}},Q^2,x_{I\!P},t)$

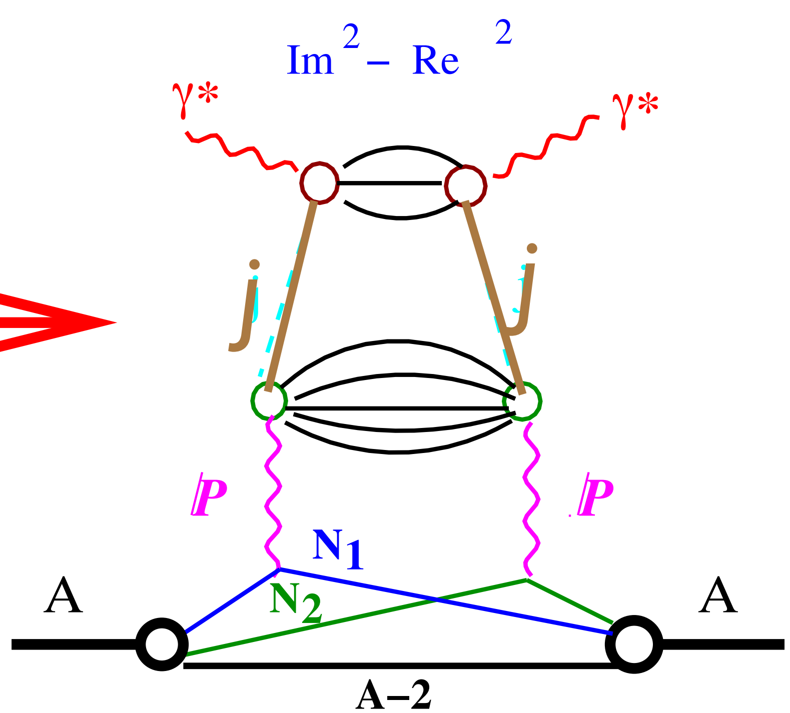
nucleon diffractive parton densities (j=q̄,g)

Frankfurt and MS, 1998



Hard diffraction

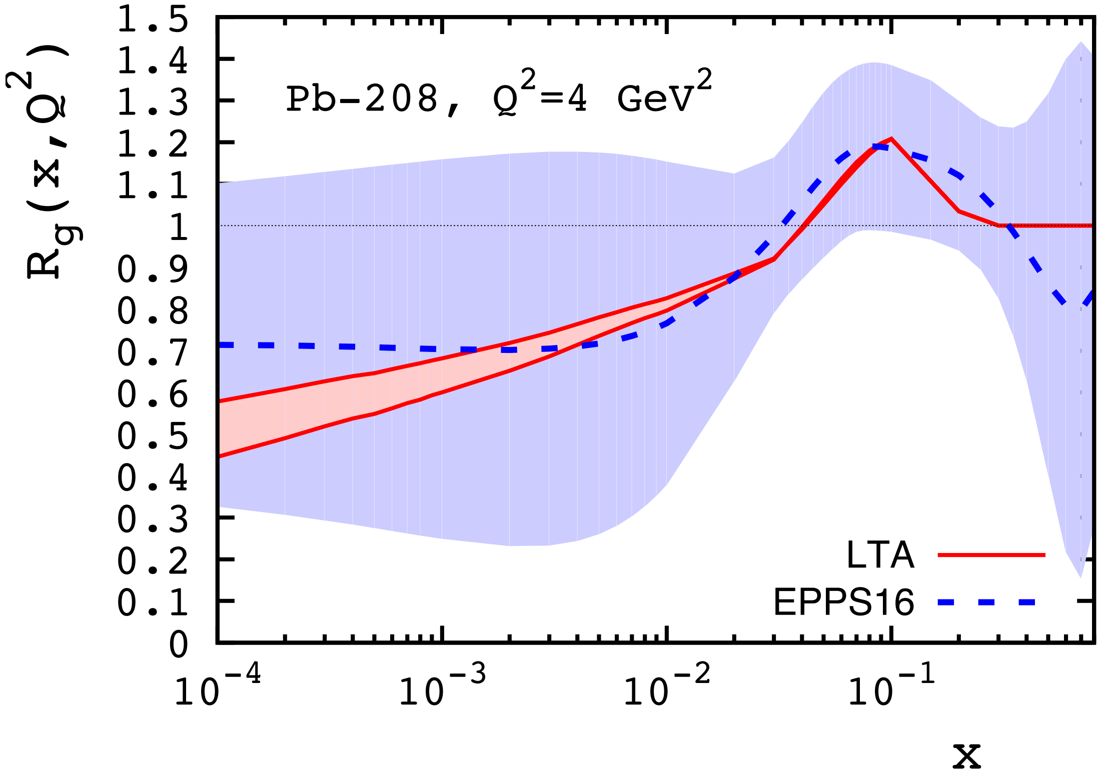
off parton "j"

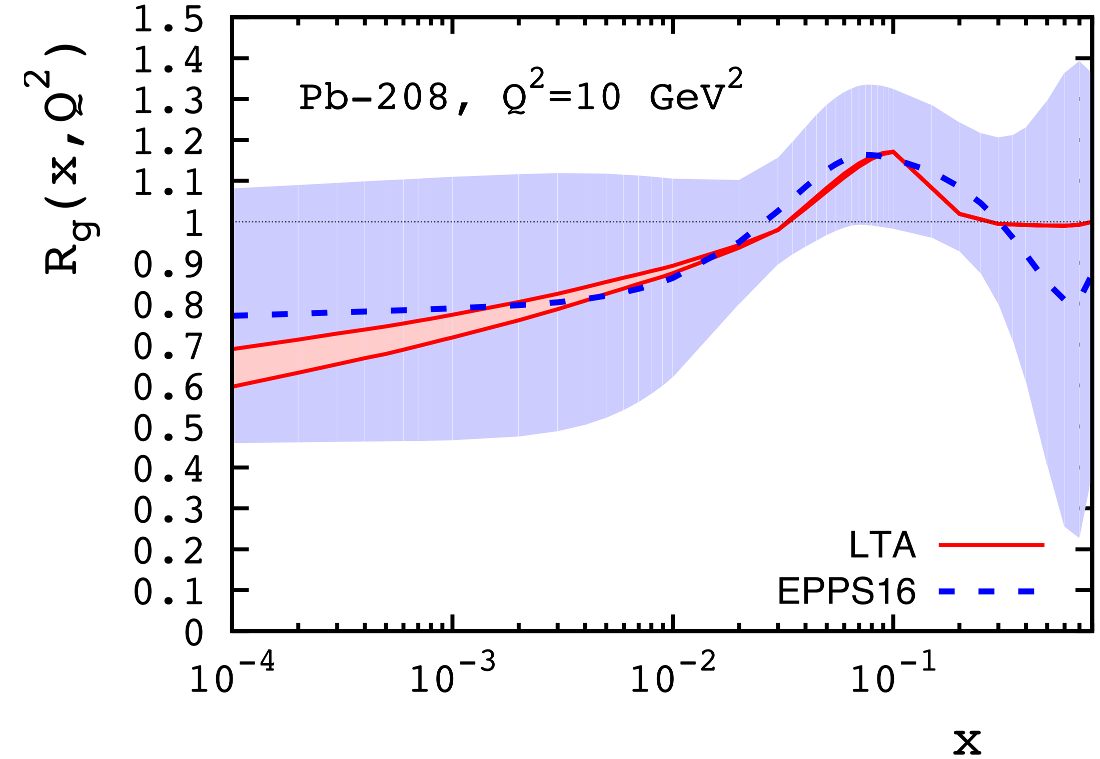


Leading twist contribution

to the nuclear shadowing for

structure function $f_j\,(x,Q^2)$





Comparison of predictions of FGS 10 and EPPS16 at Q^2= 4, 10 GeV^2

EPPS16 includes dijet LHC pA data - since p_t are large - shadowing is small and backward evolution is not stable

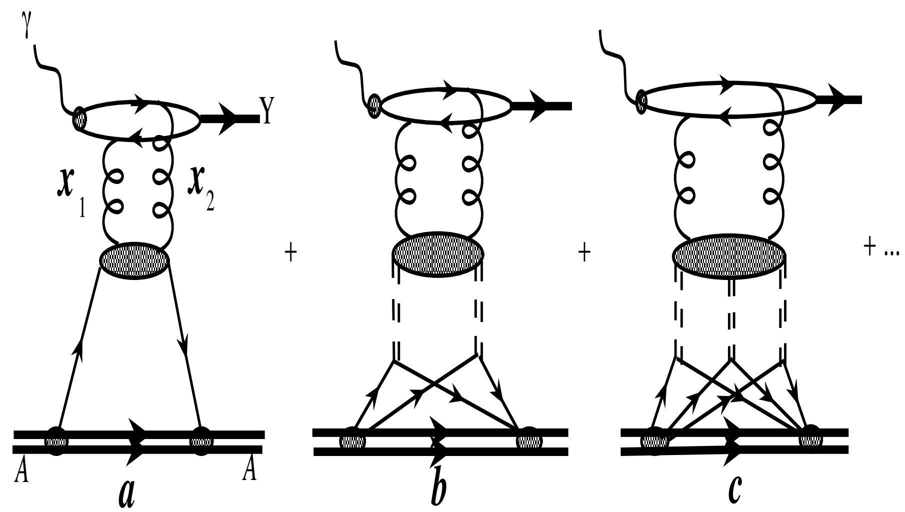
Exclusive vector meson production in DIS (onium in photoproduction)

--sensitive test of nuclear shadowing dynamics

The leading twist prediction (neglecting small t dependence of shadowing)

$$\sigma_{\gamma A\to VA}(s)=\frac{d\sigma_{\gamma N\to VN}(s,t_{min})}{dt}\left[\frac{G_A(x_1,x_2,Q^2_{eff},t=0)}{AG_N(x_x,x_2,Q^2_{eff},t=0)}\right]^2\int_{-\infty}^{t_{min}}dt\left|\int d^2b dz e^{i\vec{q}_t\cdot\vec{b}}e^{iq_l z}\rho(\vec{b},z)\right|^2.$$

$$where\ x=x_1-x_2=m_V^2/W_{\gamma N}^2$$



: High energy quarkonium photoproduction in the leading twist approximation.

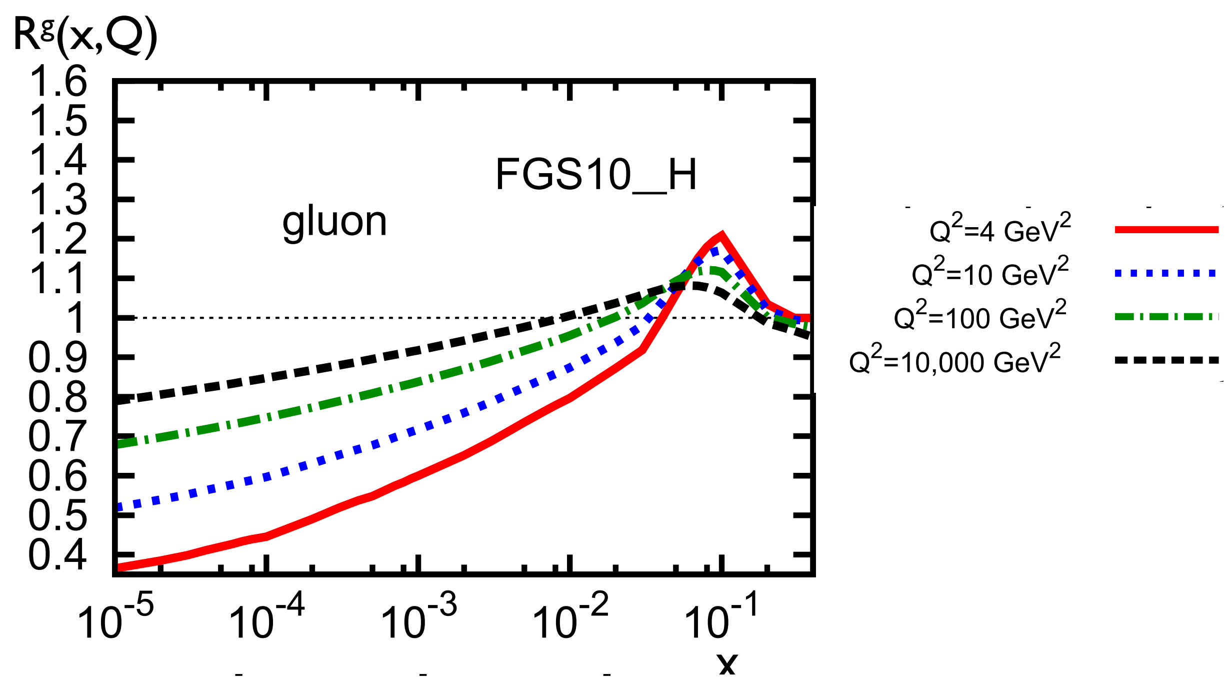
$$\Downarrow$$

$$\frac{G_A(x_1,x_2,Q^2_{eff},t=0)}{G_N(x_1,x_2,Q^2_{eff},t=0)}\approx\frac{G_A((x_1+x_2)/2,Q^2_{eff},t=0)}{G_N((x_1+x_2)/2,Q^2_{eff},t=0)}$$

For small sizes, d, dipoles - LT leads to much larger screening than eikonal models since in LT screening is proportional to $G_A(x, Q^2 \sim 1/d^2) / G_N(x, Q^2 \sim 1/d^2)$ while in the eikonal shadowing term is a higher twist - much smaller suppression.

$$\sigma_{dipole-A}/\sigma_{dipole-N} = 1 - cd^2$$

In LT approximation interaction of small dipoles with multiple nucleons are not suppressed by d^2 factor (LT DGLAP evolution)



Why eikonal works reasonably well for soft processes and not for small dipoles ?

for small dipoles: σ(inel diffraction)/σ(elast.) at t=0 >> 1

in soft physics: σ(inel diffraction)/σ(elast.) at t=0 << 1

Test: J/ψ-meson production: $\gamma + A \rightarrow J/\psi + A$

Small dipoles ➡ QCD factorization theorem

$$S_{Pb} = \left[\frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)}\right]^{1/2} = \frac{g_A(x,Q^2)}{g_N(x,Q^2)}$$

$$x = m^2_{J/\psi}/W^2$$

Much larger shadowing than in the eikonal dipole models

Two technical remarks:

a) elementary amplitudes are expressed through non-diagonal GPD . However in J/ψ case light-cone fractions of gluons attached to $c\bar{c}$ -- x_1 and x_2 are comparable $x_1 = 1.5\,x$, & $x_2 = 0.5\,x \rightarrow (x_1 + x_2)/2 = x$

$$\frac{(x_1+x_2)_{J/\psi}}{2} \approx x; \quad \frac{(x_1+x_2)_{\Upsilon}}{2} \approx x/2$$

So non-diagonality effect is small for J/ψ case.

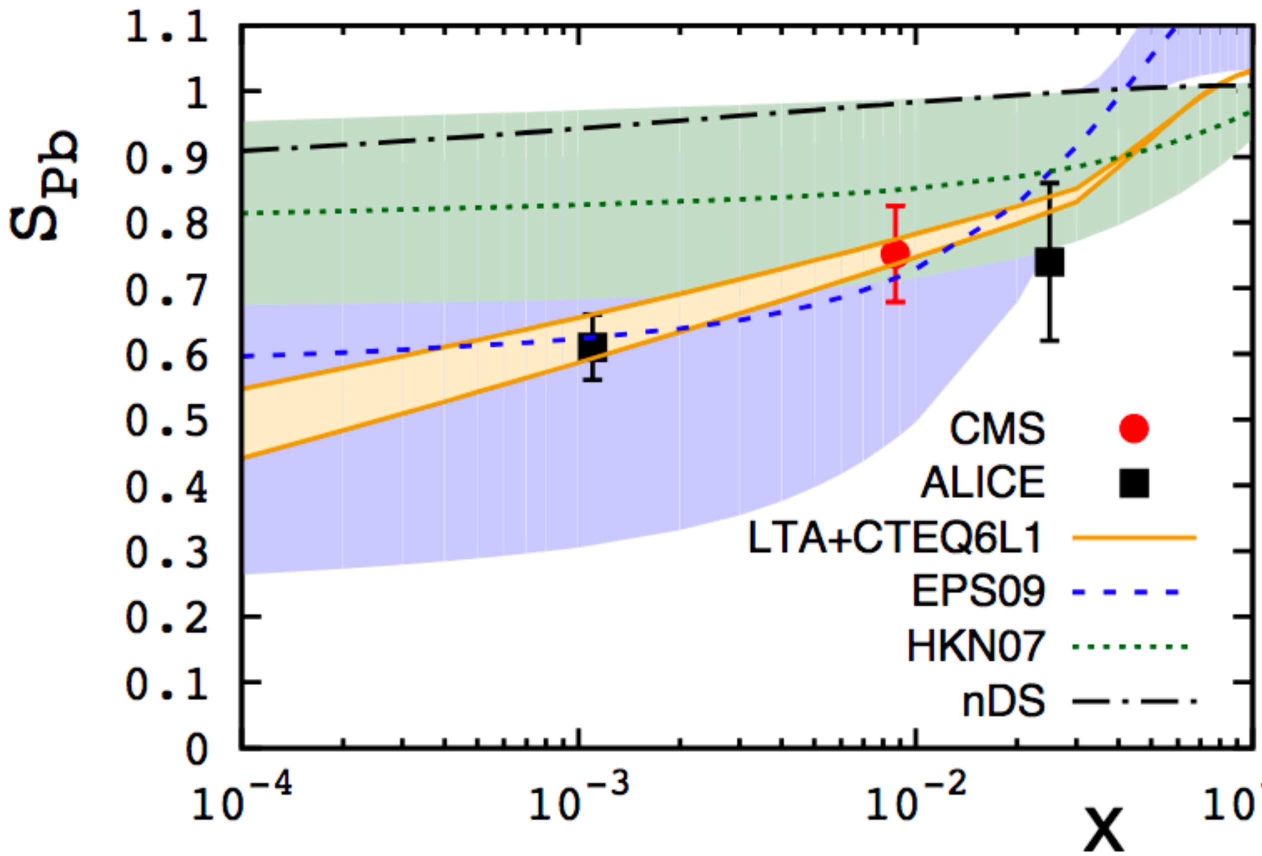
b) High energy factorization for onium production → HT effects are large but mostly cancel in the ratio of nuclear and elementary cross sections at t=0. However NLO effects require further studies. Stable results for S_A if Q_{eff} is chosen to reproduce W dependence of J/ψ photoproduction

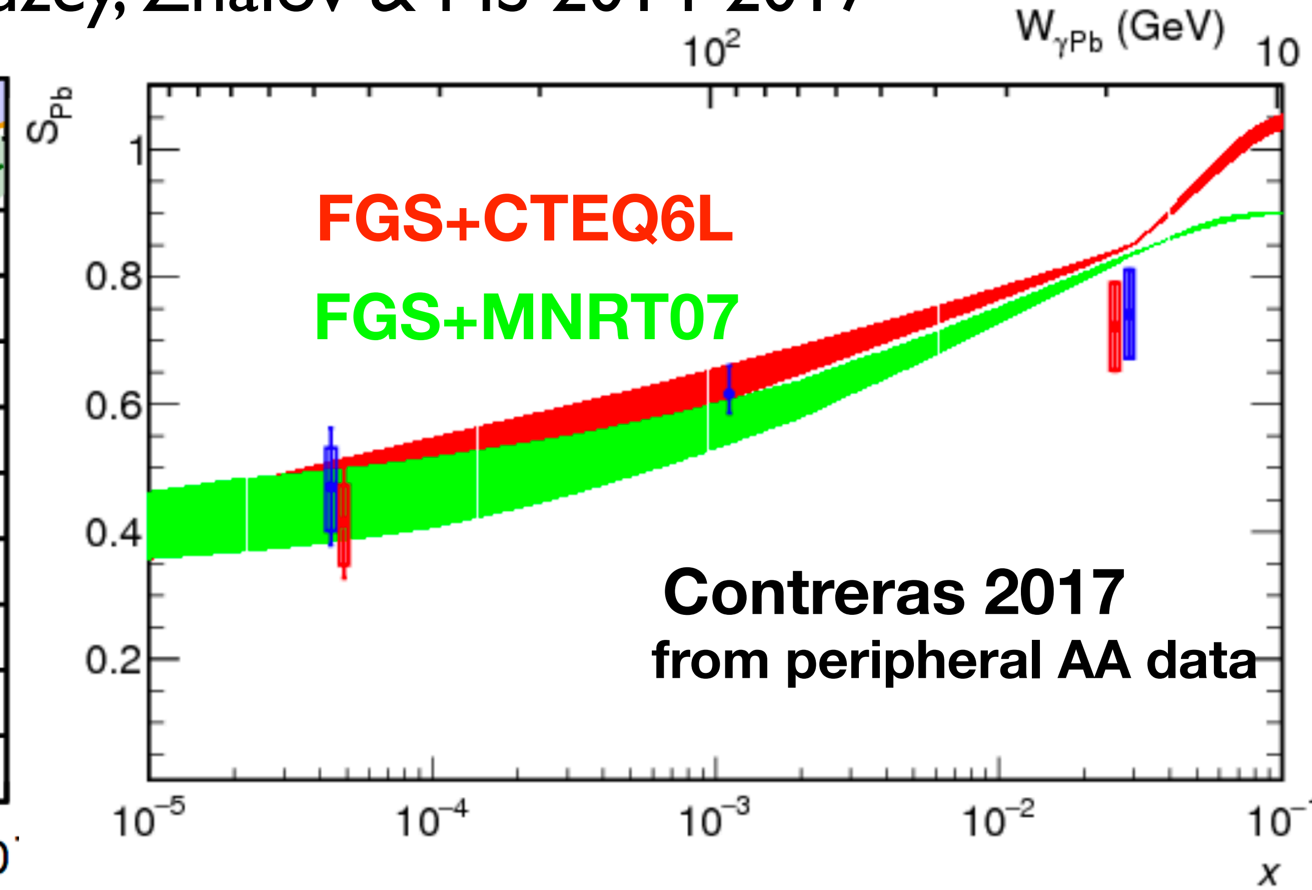
Guzey & Zhalov

Strong suppression of coherent J/ψ production observed by ALICE confirms our prediction of significant gluon shadowing on the $Q^2 \sim 3$ GeV^2 . Dipole models predict very small shadowing (S_{Pb}> 0.9).

$$S_{Pb} = \left[\frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)}\right]^{1/2} = \frac{g_A(x,Q^2)}{g_N(x,Q^2)}$$

$S_{Pb}(x)$ is extracted from the data by Guzey, Zhalov & MS 2014-2017





Large gluon shadowing consistent with the leading twist theory prediction of FGS2012.
LHCb data consistent with ALICE and CMS data.

No other data significantly constrain $g_A(x \sim 10^{-3})$ at relevant Q^2 scale

$$x_{min}(EIC) = 1.5 \cdot 10^{-3} \text{vs} \;\; x_{min}(UPC) = 6 \cdot 10^{-4}; x_{min}(UPC) = 10^{-4}$$

y=0 forward

How large is nuclear gluon density enhancement factor?

(a) No LT shadowing

$$U_{no\,shadowing} = \frac{A\pi r_g^2}{\pi R_A^2} \approx 0.3 \cdot A^{1/3}$$

since transverse radius, r_g, of gluon nucleon distribution is <0.6 fm.

(b) LT shadowing

$$U_{shadowing} = S_A \cdot U_{no\,shadowing} \cdot A^{1/3}$$

S_A = 0.6 — 0.4 strongly reduces difference between proton and nuclear GPDs at small impact parameters b.

$$U_{shadowing}(Pb, x = 10^{-3}, Q^2 \sim few\,GeV^2) \sim 1$$

Similar conclusion if comparison done for Pb and p for zero impact parameters.

advantage of nuclei - easier to study dynamics as a function of centrality using several nuclei. 30% win for Pb for ratio of gluon density in Pb at b=0, and proton density averaged over b.

However, 1.3 enhancement is eaten out by eA energy being smaller than ep energy

Testing the dynamics of interaction with nuclei for large configurations

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

Expectations:

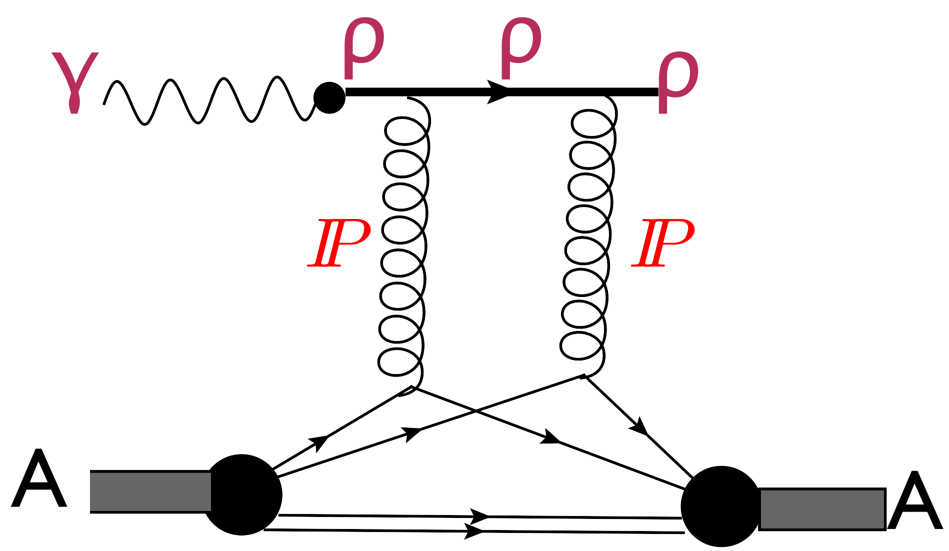
- *vector dominance model for scattering off proton*

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

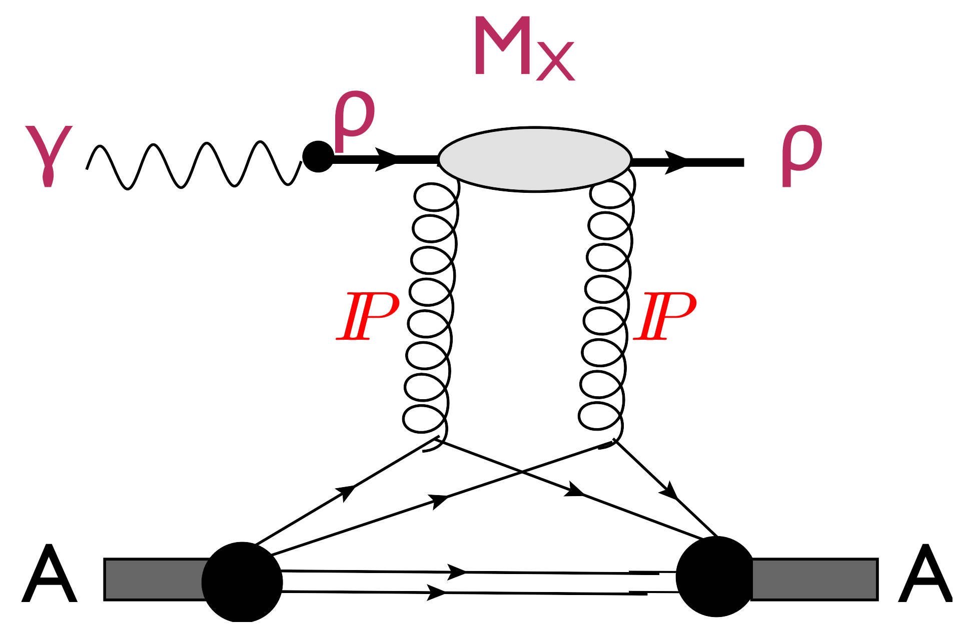
since overlapping integral between γ and ρ is suppressed as compared to $\rho \rightarrow \rho$ case

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)



Glauber double scattering

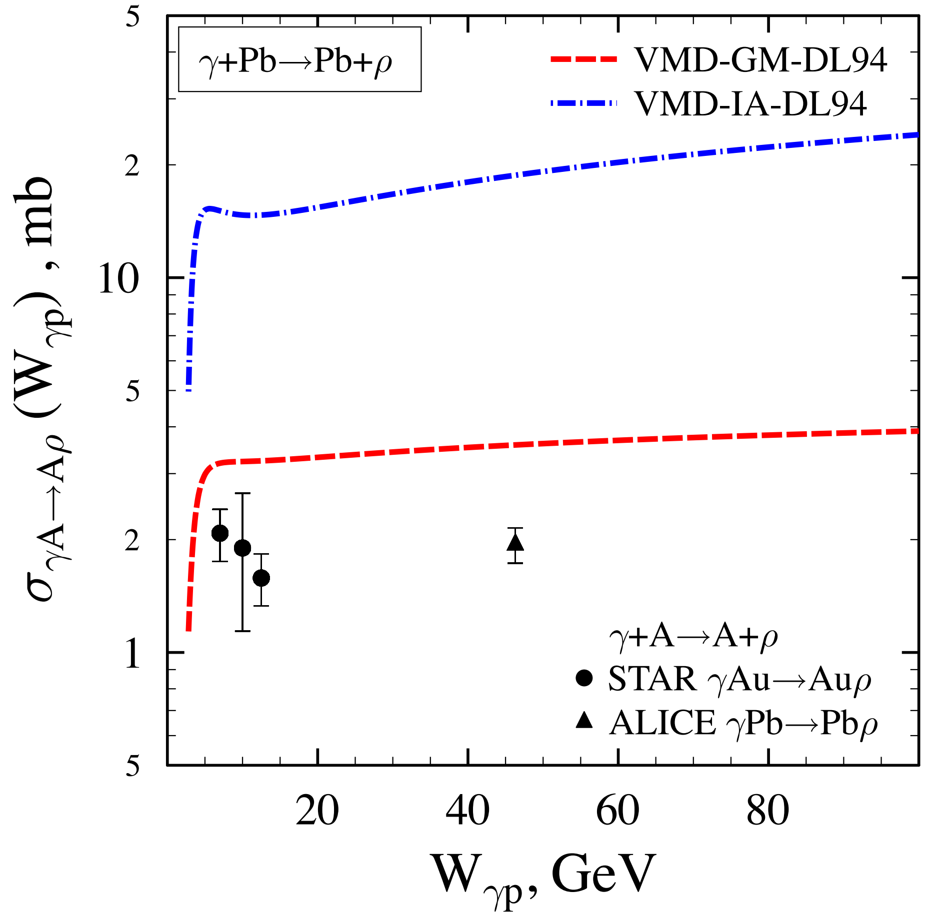


Gribov inelastic shadowing

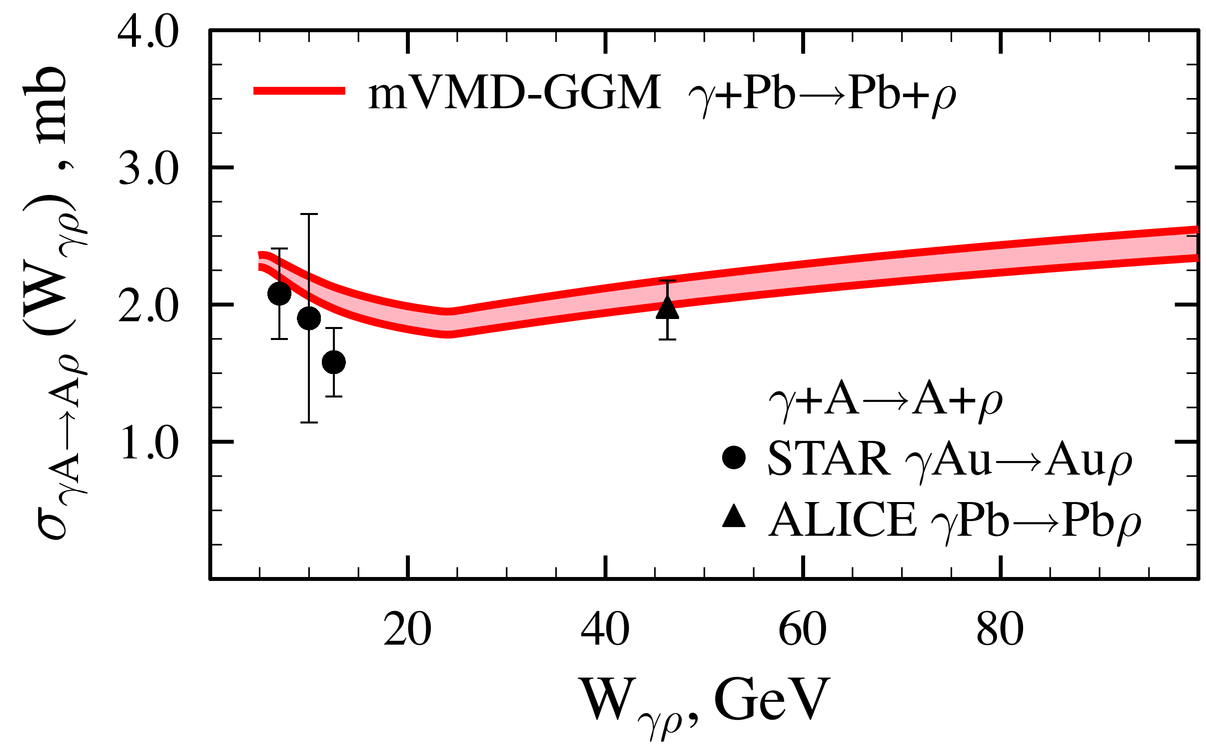
❖ Gribov type inelastic shadowing is enhanced in discussed process - fluctuations grow with decrease of projectile - nucleon cross section. We estimate variance, $\omega_{\gamma\to\rho}\sim 0.5$ of $P_{\gamma\to\rho}(\sigma)$ - distribution of configurations in transition over σ and model it.

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

- Glauber model predicts large shadowing, still grossly overestimates the cross section (at LHC factor ~2)



- Gribov - Glauber model with cross section fluctuations



$S_{Pb}(\rho) \approx 0.3$ **as compared to** $S_{Pb}(J/\psi) \approx 0.6$

At EIC for heavy nuclei diffraction would be strongly suppressed as compared to the impulse approximation:

$$S^2_{Pb}(soft/low\,Q^2) \approx 1/10$$

$$S^2_{Pb}(hard/\sigma_L\,) \approx 0.4$$

Note - these numbers are for ratio to the impulse approximation - much large (closer to S_{Pb} for the ratio to the inclusive γ^* A cross section)

Fixed W, increasing Q^2:

coherent ρ-meson production— suppression should be from 1/10 at Q^2=0, to 0.4 at Q^2=10 GeV^2, x=10^{-3}.

coherent J/ψ-meson production - slow variation S_A with Q^2 for fixed x and $Q^2 < m^2_{J/\psi}$

Inclusive diffraction — intermediate suppression between ρ and J/ψ case - different for different final states - aligned jet vs larger p_t final states.

Inclusive diffraction - impossible to measure t; more difficult to separate coherent and incoherent diffraction, and to measure diffractive mass (since typical masses at EIC are rather small)

incoherent diffraction= (nucleus break up) + (production of hadrons)

$\sigma(t) \propto \exp(5t)$ $\sigma(t) \propto \exp(2t)$

at -t >0.6 —0.8 GeV^2 hadron production term wins

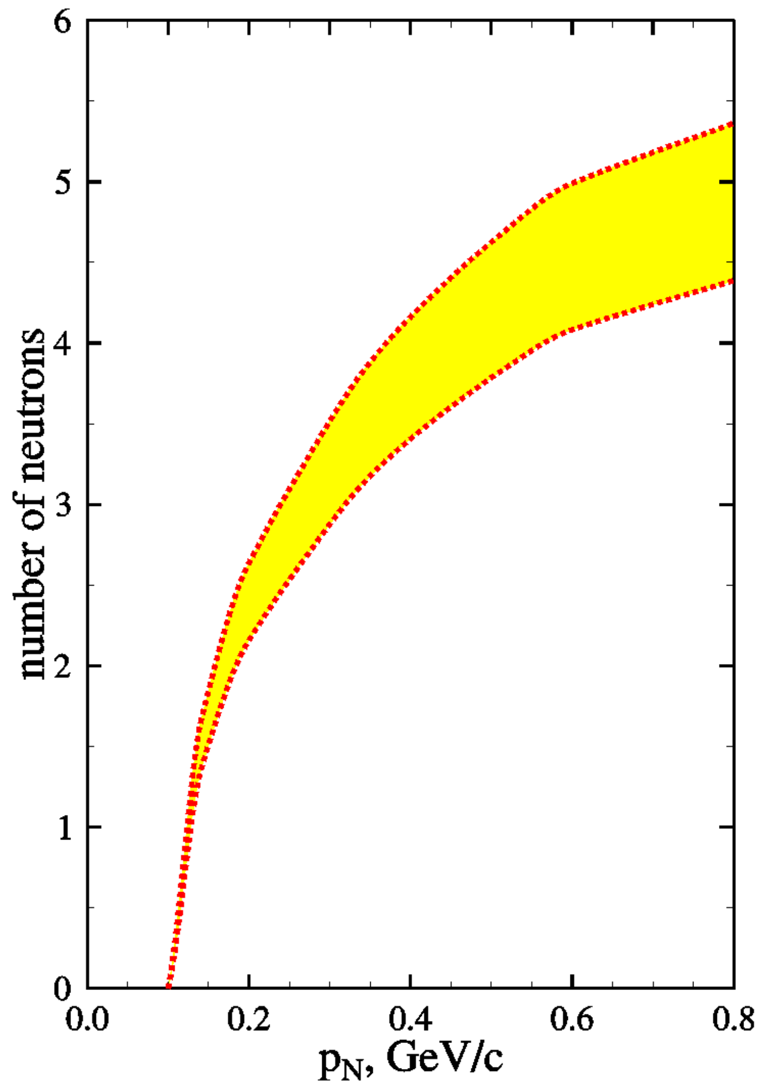
Both processes are sensitive to dynamics of diffraction.

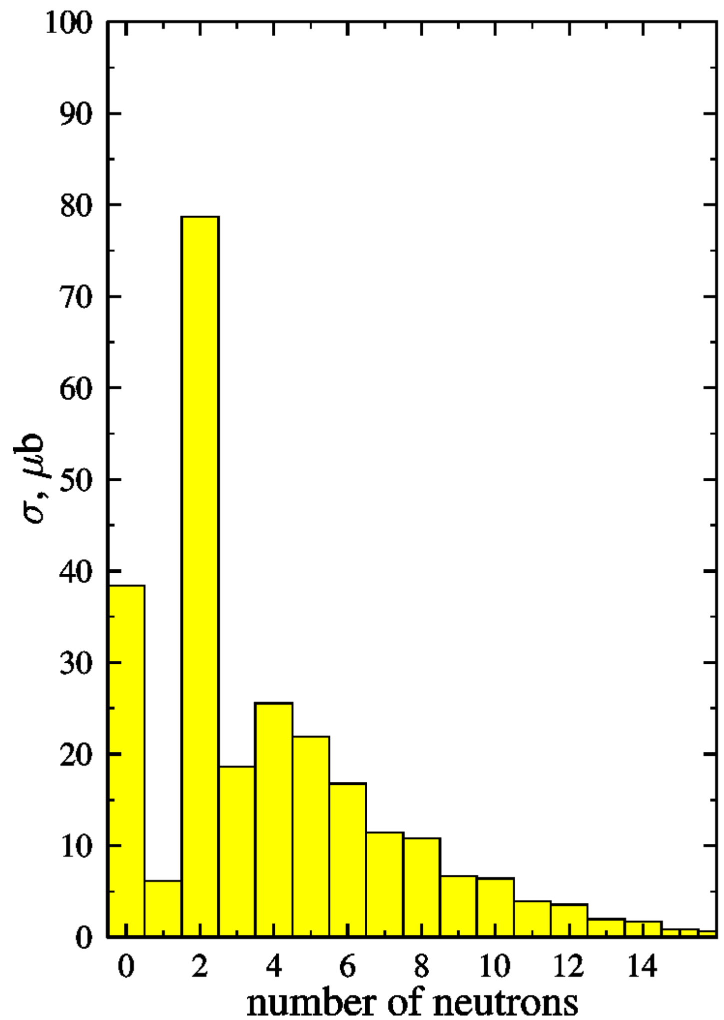
For example, breakup rate in Gribov - Glauber model for ρ-meson production strongly differs from STARlight Monte-Carlo (V. Guzey, E. Kryshen, M. Zhalov 2020)

In most cases both breakup processes are accompanied by production of neutrons which could be detected in ZDC.

Modeling was done in Zhalov , Tverskoi , MS and more recently by Larionov and MS.

for quasielastic channel the average neutron multiplicity is ~4 neutrons.





Average number of neutrons for the incoherent production of J/ψ in UPC of Au at RHIC as a function of the recoiled nucleon momentum and distribution over number of neutrons integrated over t. Tables of the distribution over number of neutrons in quasielastic process as a function of nucleon momentum was generated by Larionov. Shadowing effects were not included so far.

Tests are possible / highly desirable in UPC at the LHC and RHIC.

Neutron rates for inelastic channels are sensitive to formation time of hadrons produced say in

$$\gamma^* N \to J/\psi + M_Y$$

A separate issue is the region of moderately small p_t ~ 200 MeV/c. Process of nucleus excitation becomes important:

$$\gamma^* A \to J/\psi + A^*$$

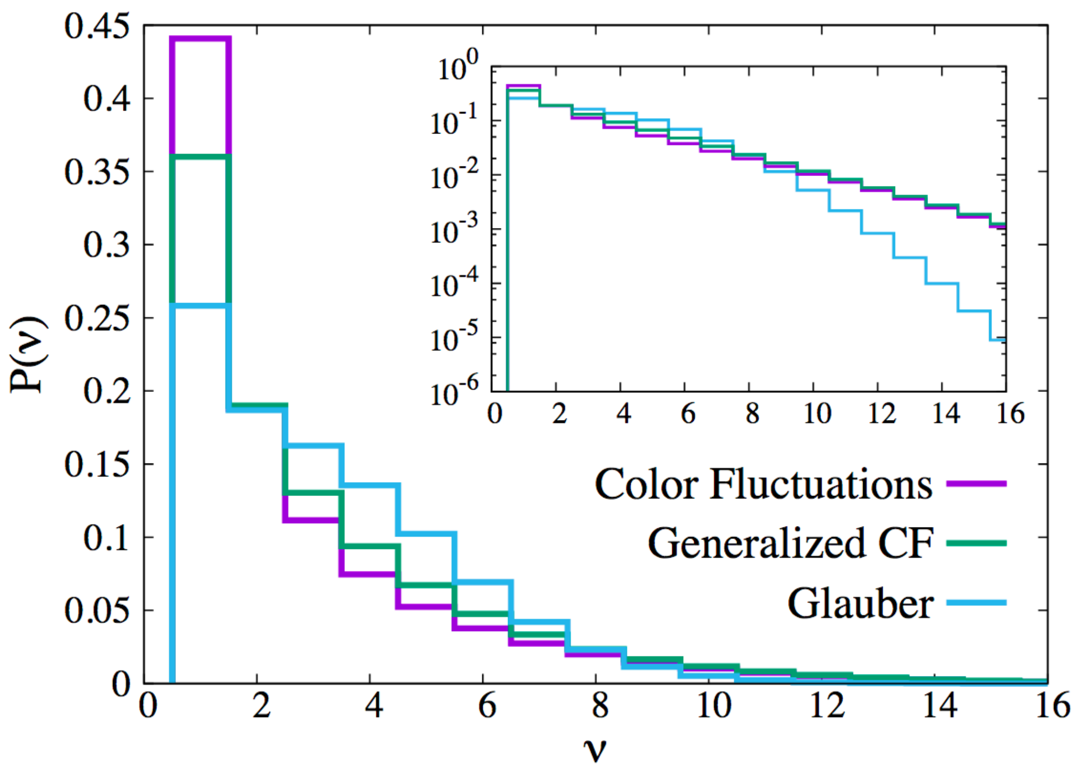
$$A^* \longrightarrow A + \gamma, A + \gamma\gamma$$

Challenge to veto these channels

*Diffraction and inelastic interactions are delicately connected in inelastic γ*A scattering - distribution over number of wounded nucleons ν is given by the same diagrams which determine shadowing for total cross sections*

$$\langle\nu\rangle \approx 1/S_A$$

+ Huge fluctuations of ν in the interaction with nuclei of both small and large dipoles



Distribution over number of wounded nucleons in γ Pb collisions at W=70 GeV

Alvioli et al, Phys.Lett. B767 (2017) 450-457

A better granularity of ZDC would be desirable

Summary

- **LT DGLAP framework for calculation of nuclear pdfs, etc passed the J/ψ coherent production test. Possible onset of black regime is pushed to much smaller x.**

- 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,…). EIC will allow to study CF in photons at different Q, W - novel tests of interplay of soft and hard physics in γ^* interactions. Studies of *UPC at the LHC would help to optimize EIC detector for diffraction studied*

- Complementarity of coherent diffraction information and information about average (fluctuations of) number of wounded nucleons in γ^*A - - critical tests of nuclear shadowing dynamics.

supplemental slides

Outline of calculation of inelastic γA scattering - distribution over number of wounded nucleons ν

- Modeling $P_\gamma(\sigma)$ **modeling color fluctuations in photon**

For

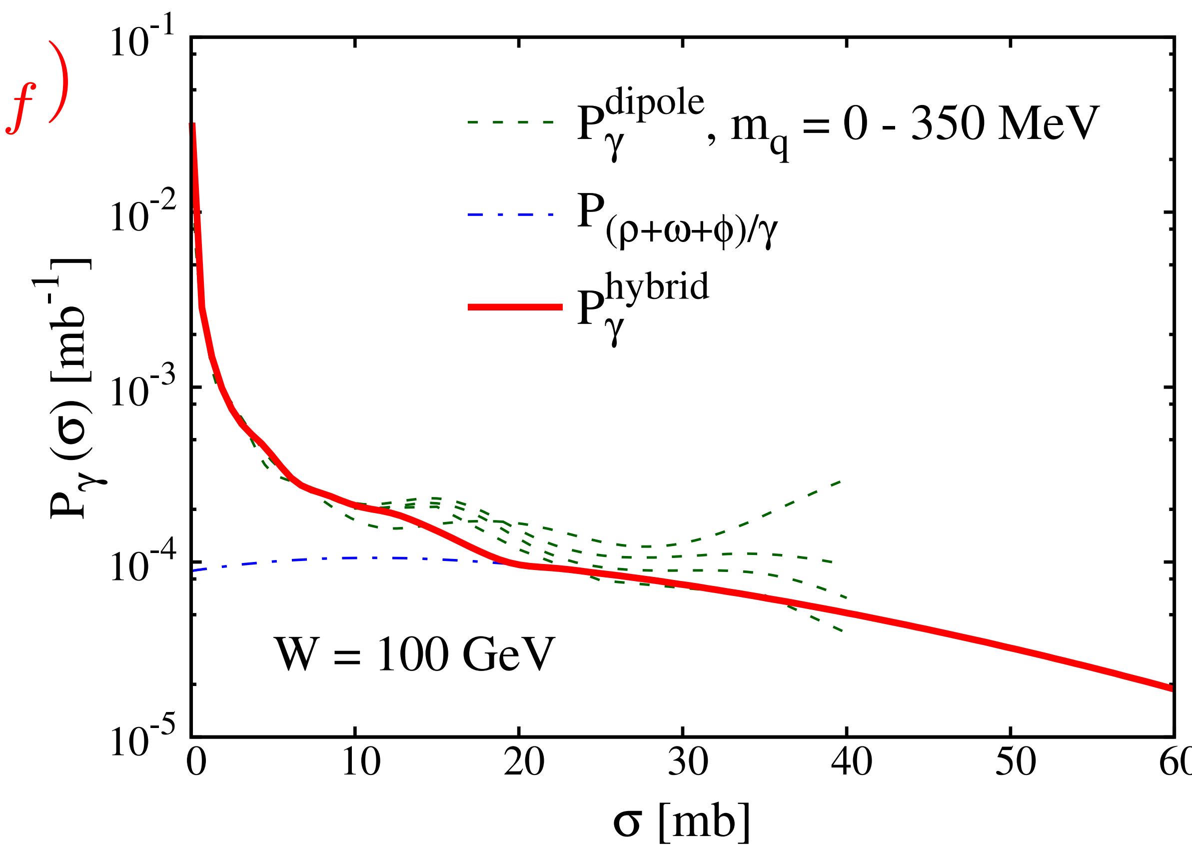
$$\sigma > \sigma(\pi N), P_\gamma(\sigma) = P_{\gamma\to\rho}(\sigma) + P_{\gamma\to\omega}(\sigma) + P_{\gamma\to\phi}(\sigma)$$

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

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

+ smooth interpolation in between

Smooth matching for m_q~ 300 MeV



Calculation of distribution over the number of wounded nucleons

(a) Color fluctuation model

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

$$p(\nu) = \frac{\sigma_\nu}{\sum_1^\infty \sigma_\nu}.$$

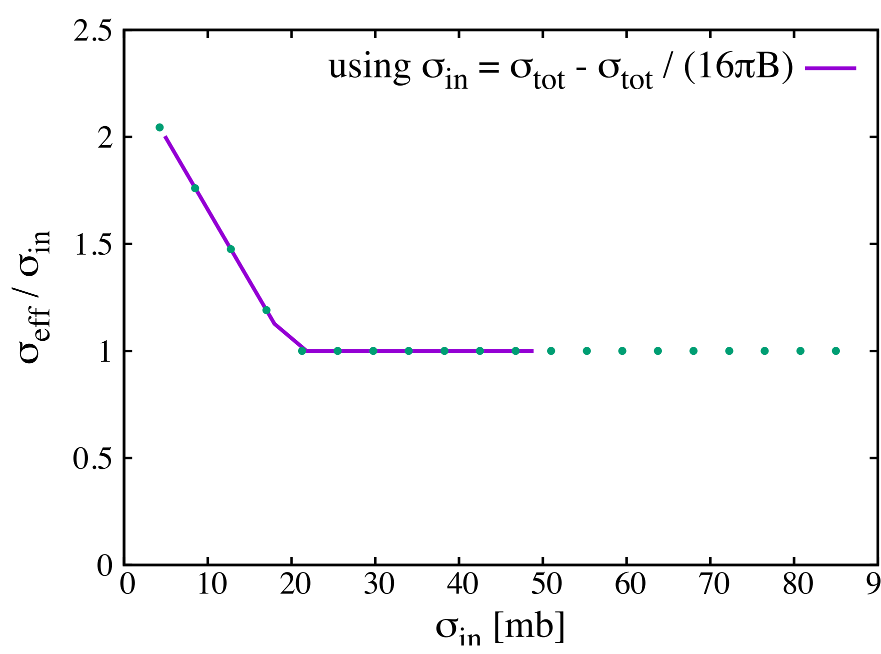
(b) Generalized Color fluctuation model (includes LT shadowing for small σ)

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

evidence from J/psi production - next slide

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

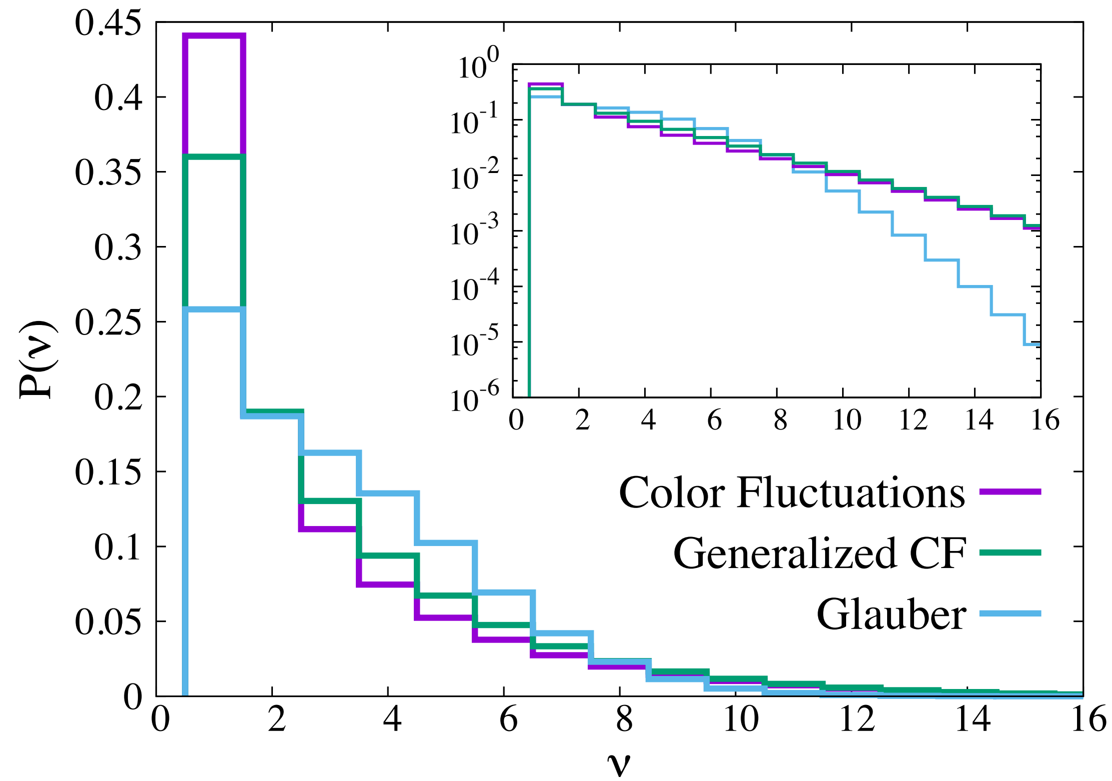
σ_{eff}/σ calculated in the LT nuclear shadowing theory for small σ



consistent with shadowing for J/ψ coherent production

Ultraperipheral minimum bias γA at the LHC ($W_{\gamma N} < 0.5$ TeV)

Huge fluctuations of the number of wounded nucleons, ν,.in interaction with both small and large dipoles

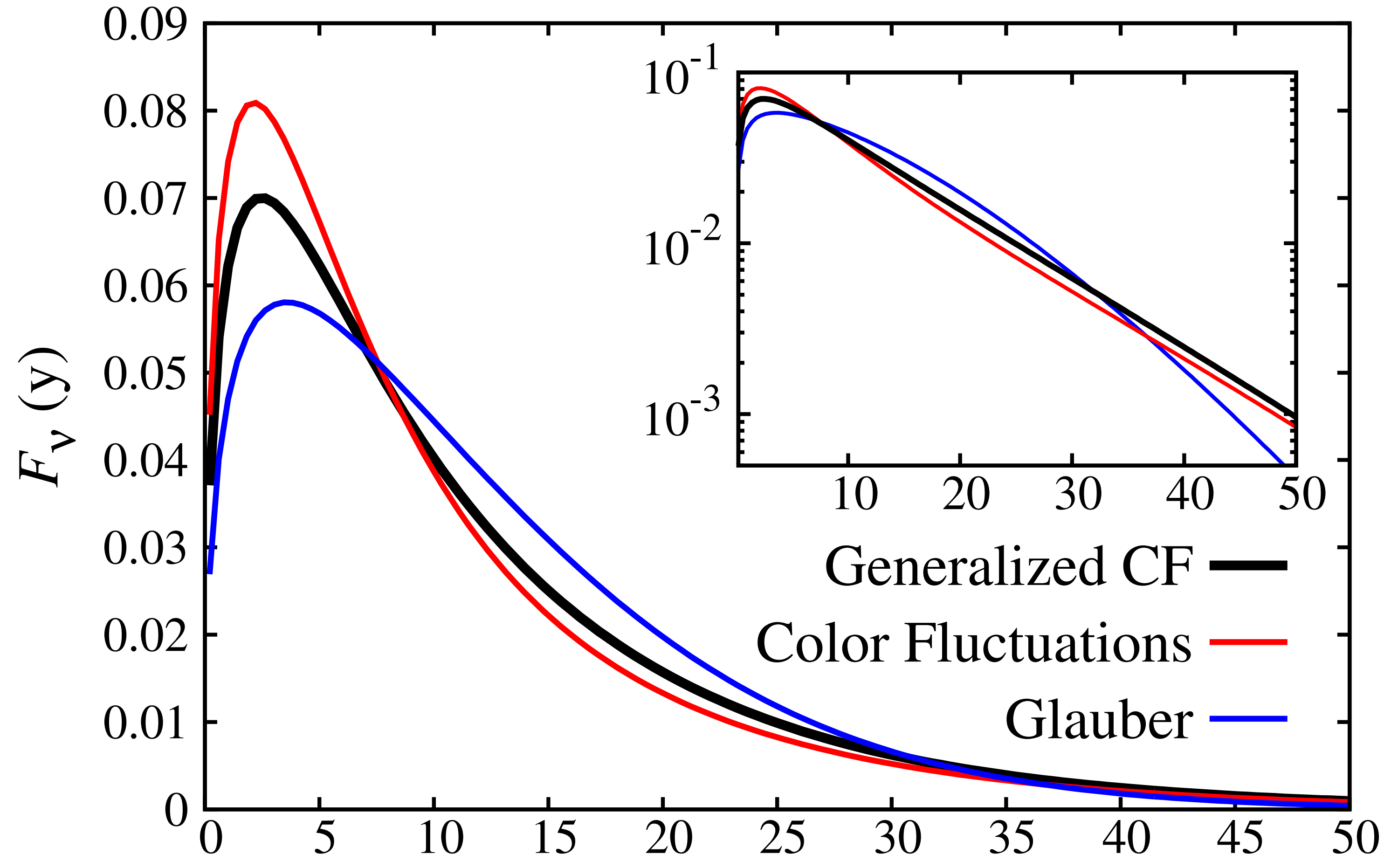


distribution over the number of wounded nucleons in γA scattering, W ~ 70 GeV

Alvioli, Guzey, Zhalov, LF, MS

Phys.Lett. B767 (2017) 450-457

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 ~40 mb, and weakly interacting configurations.



$$y = \Sigma E_T / \langle \Sigma E_T(hN) \rangle$$

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 ν.

Using forward detector (CASTOR?) for centrality via measurement of "y" advantageous : larger rapidity interval - smaller kinematical/ energy conservation correlations. For using ΣE_T for centrality determination one needs $\Delta y > 4$. Interesting alternative is to use information from ZDC.

$\gamma A \rightarrow$ jets + X

Observables which are easier to measure than shadowing for total cross sections (neutrons, ΣE_T

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

Color change propagation through matter.
Color exchanges ? ➠ nucleus excitations, ZDC & CASTOR

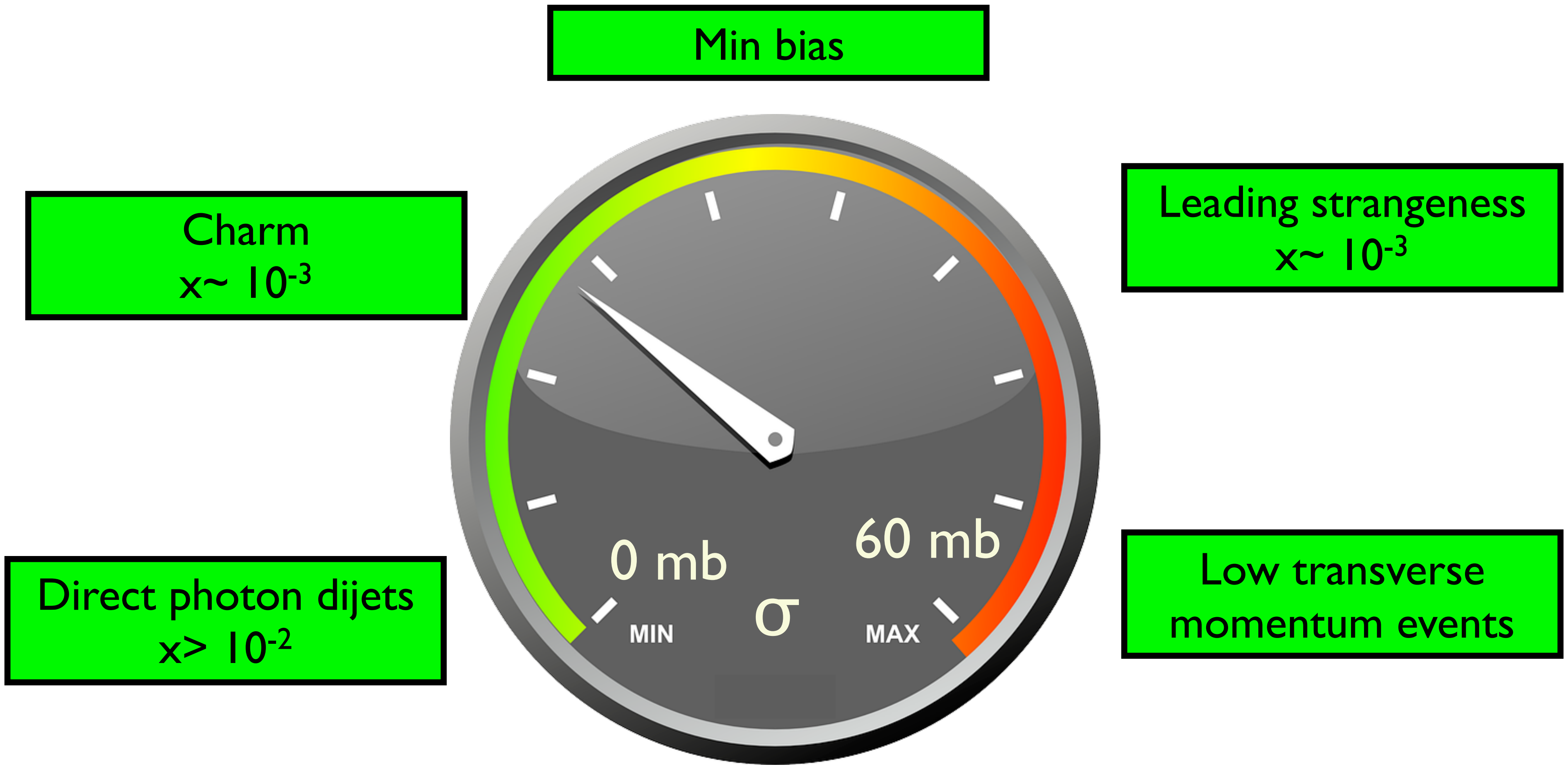
2) Direct photon & $x_A < 0.005$ - nuclear shadowing —> increase of ν

3) Resolved photon - increase of ν with decrease of x_γ and x_A

W dependence of distribution over ν

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 γ information) . Novel way to study dynamics of γ & γ^* 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 γA & γp physics at the LHC mostly within acceptance of central ATLAS, CMS detectors