Photon structure and energy dependence of diffraction

Vadim Guzey

Petersburg Nuclear Physics Institute (PNPI),
National Research Center “Kurchatov Institute”,
Gatchina, Russia

Outline:

- Cross section fluctuations for proton: models and applications for soft coherent pA diffraction
- Cross section fluctuations for light vector mesons and applications for coherent photoproduction in heavy-ion UPCs
- Cross section fluctuations for real photons and γA scattering in UPCs

**CFNS Adhoc Workshop: Target fragmentation and diffraction physics with novel processes: Ultraperipheral, electron-ion, and hadron collisions,
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Large l_c and hadronic structure of projectiles

- At high energies, the longitudinal distance essential for a given process increases with the beam momentum p_{lab}, Feinberg, Pomeranchuk, Suppl. Nuovo Cim. III (1956) 652; Gribov, Ioffe, Pomeranchuk, Yad. Fiz. 2 (1965) 768; Ioffe, PLB 30 (1969) 123

$$l_c = \frac{1}{\Delta E} = \left(\sqrt{M^{*\,2} + p_{\rm lab}^2} - \sqrt{m_h^2 + p_{\rm lab}^2}\right)^{-1} \simeq \frac{2p_{\rm lab}}{M^{*2} - m_h^2} \gg R_{\rm target}$$

- In this case, the projectile of mass m_h can fluctuate into hadronic fluctuations of mass M^*, whose interactions with the target are Lorentz-dilated.

- This picture is especially fruitful for description of diffractive dissociation in target frame.

- In soft hadron-nucleus scattering, it is realized via eigenstates of the scattering operator (cross section fluctuations), Good, Walker, PR 120 (1960) 1857

- In QCD, it is realized as quark-gluon color dipoles of different transverse sizes; color fluctuations of the gluon density correlated with proton size, Frankfurt, Strikman, Treleani, Weiss, PRL 101 (2008) 202003; fluctuations of the proton shape (hot spots), Mäntysaari, Schenke, PRL 117 (2016) 5, 052301; Cepila, Contreras, Tapia Takaki, PLB 766 (2017) 186.

- Correspondence between fluctuations and dipole model valid only at t=0!

Good-Walker cross section fluctuations

- The notion of composite structure of energetic projectiles can be realized by expansion in terms of eigenstates of the scattering operator, Good, Walker, PR 120 (1960) 1857

$$|\Psi\rangle = \sum_k c_k |\Psi_k\rangle \qquad \mathrm{Im}T|\Psi_k\rangle = t_k|\Psi_k\rangle \qquad \sum_k |c_k|^2 = 1 \ .$$

- Total diffractive cross section:

$$\left(\frac{d\sigma}{dt}\right)^{\mathrm{diff}}_{t=0} = \frac{1}{16\pi}\sum_k |\langle\Psi_k|\mathrm{Im}T|\Psi\rangle|^2 = \frac{1}{16\pi}\sum_k |c_k|^2 t_k^2 \equiv \frac{1}{16\pi}\langle\sigma^2\rangle$$

- Elastic cross section:

$$\left(\frac{d\sigma}{dt}\right)^{\mathrm{el}}_{t=0} = \frac{1}{16\pi}|\langle\Psi|\mathrm{Im}T|\Psi\rangle|^2 = \frac{1}{16\pi}\left(\sum_k |c_k|^2 t_k\right)^2 \equiv \frac{1}{16\pi}\langle\sigma\rangle^2 \, .$$

- Diffractive dissociation (inelastic diffraction) is possible only if different fluctuations interact with different cross sections, i.e. when there are cross section fluctuations:

$$\left(\frac{d\sigma}{dt}\right)^{\mathrm{diss}}_{t=0} = \left(\frac{d\sigma}{dt}\right)^{\mathrm{diff}}_{t=0} - \left(\frac{d\sigma}{dt}\right)^{\mathrm{el}}_{t=0} = \frac{1}{16\pi}\left(\langle\sigma^2\rangle - \langle\sigma\rangle^2\right)$$

Probability of cross section fluctuations

- In applications, it is more convenient to work with continuous version, Miettinen, Pumplin, PRD 18 (1978) 1696; Blättet, Baym, Frankfurt, Heiselberg, Strikman, PRD 47 (1992) 2761:

$$\sum_k |c_k|^2 \to \int d\sigma P(\sigma)\,,$$
$$\langle\sigma\rangle = \int d\sigma P(\sigma)\sigma\,,$$
$$\langle\sigma^2\rangle = \int d\sigma P(\sigma)\sigma^2$$

- Except for small σ, the distribution P(σ) is non-perturbative and needs modeling. It satisfies the following constraints:

$$\int d\sigma P(\sigma) = 1\,,$$
$$\int d\sigma P(\sigma)\sigma = \sigma_{\rm tot}$$
$$\int d\sigma P(\sigma)(\sigma^2/\sigma_{tot}^2-1) = \left(\frac{d\sigma}{dt}\right)_{t=0}^{\rm diss} \Big/ \left(\frac{d\sigma}{dt}\right)_{t=0}^{\rm el} \equiv \omega_\sigma$$

- Small-σ from quark counting rule, where n_q is number of valence quarks:

$$P_h(\sigma) \propto \sigma^{n_q-2} \quad \to \quad \begin{aligned} &P_p(\sigma) \sim \sigma\,, \\ &P_\pi(\sigma) \sim \mathrm{const} \end{aligned}$$

- For definiteness, Gaussian decay for large σ.

Cross section fluctuations for protons

• Distribution P(σ) for protons, Blättet, Baym, Frankfurt, Heiselberg, Strikman, PRD 47 (1992) 2761:

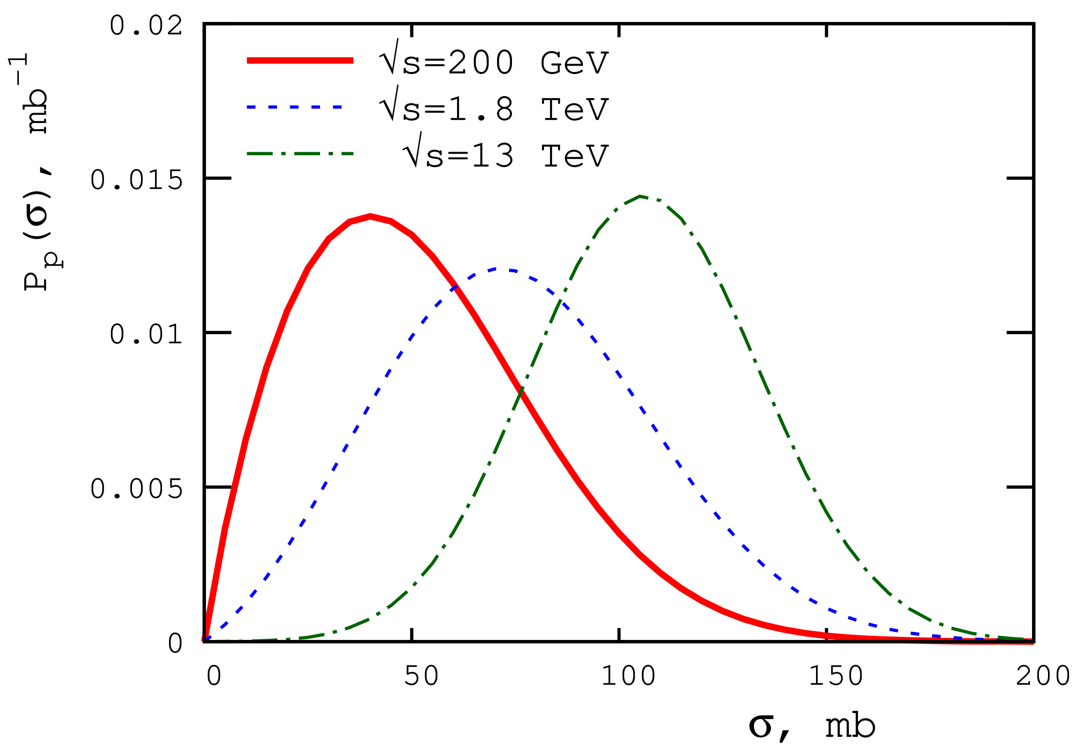
$$P_p(\sigma) = N_p \frac{\sigma/\sigma_0}{\sigma/\sigma_0 + 1} e^{-(\sigma-\sigma_0)^2/(\Omega\sigma_0)^2}$$

• Width of fluctuations ω_σ → from data on anti-p-p single diffraction and nucleon-deuteron total cross section data at fixed target and collider energies, Guzey, Strikman, PLB 633 (2006) 245

$$\omega_\sigma(s) = \begin{cases} \beta\sqrt{s}/(24\,\mathrm{GeV})\,, & \sqrt{s} < 24 \text{ GeV}\,, \\ \beta\,, & 24 < \sqrt{s} < 200 \text{ GeV}\,, \\ \beta - 0.056\ln(\sqrt{s}/200\,\mathrm{GeV})\,, & \sqrt{s} > 200 \text{ GeV}\,, \end{cases}$$

where $\beta = 0.30 \pm 0.05$.

• Resulting P(σ) for protons, Frankfurt, Guzey, Stasto, Strikman, review submitted to ROPP



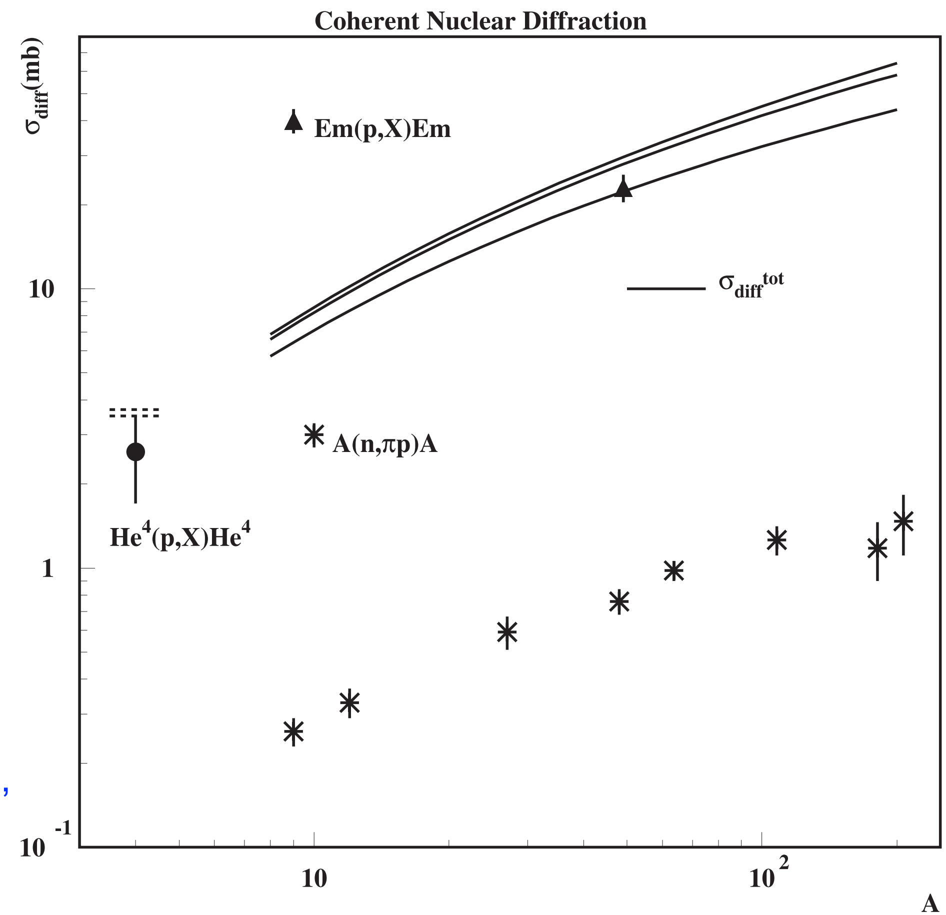
pA coherent diffraction dissociation

• This formalism gives rise to diffraction dissociation of hadrons on nuclei and provides a good description of the available fixed-target data, Frankfurt, Guzey, Strikman, J. Phys. G: Nucl. Part. Phys. 27 (2006) R27

$$\sigma_{diff}^{pA} = \int d^2b \left[\int d\sigma P_p(\sigma) \langle p||\Gamma_A(b)|^2|p\rangle - \left(\int d\sigma P_p(\sigma) \langle p|\Gamma_A(b)|p\rangle \right)^2 \right]$$

$$\Gamma_A(b) = 1 - e^{-\frac{\sigma}{2}T_A(b)}$$

$$T_A(b) = \int dz \rho_A(b,z)$$

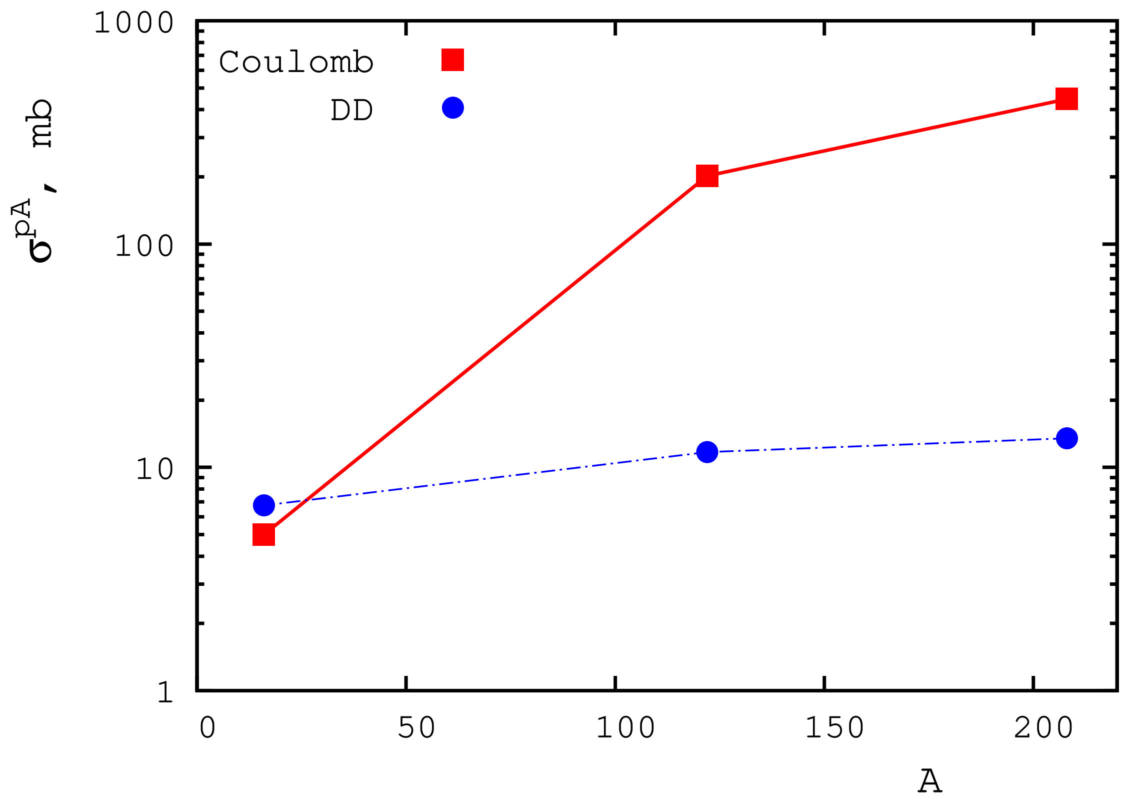


• Cross section fluctuations also account for major part of large E_T fluctuations in heavy-ion collisions at CERN SPS, Heiselberg, Baym, Blättel, Frankfurt, Strikman, PRL 67 (1991) 2946, and strongly affect charge particle multiplicity in pA scattering at 5 TeV, ATLAS Coll., EPJC 76 (2016) 4, 199 → also expected in γA

pA coherent diffraction dissociation (2)

• At collider energies and in wide range of impact parameters, inelastic diffraction is strongly suppressed due to blackness of interactions ($\omega_\sigma \to 0$) → it competes with the e.m. mechanism, Guzey, Strikman, PLB 633 (2006) 245

$$\sigma^{pA}_{e.m.} = \int \frac{d\omega}{\omega} N_{\gamma/A}(\omega) \sigma^{\gamma p}_{\rm tot}(s)$$



LHC energies, Frankfurt, Guzey, Stasto, Strikman, review submitted to ROPP

Cross section fluctuations for ρ mesons

• Similarly to the proton, one can construct P(σ) for pions, Blättel, Baym, Frankfurt, Strikman, PRL 70 (1992) 896 and ρ mesons, Frankfurt, Guzey, Strikman, Zhalov, PRB 752 (2016) 51

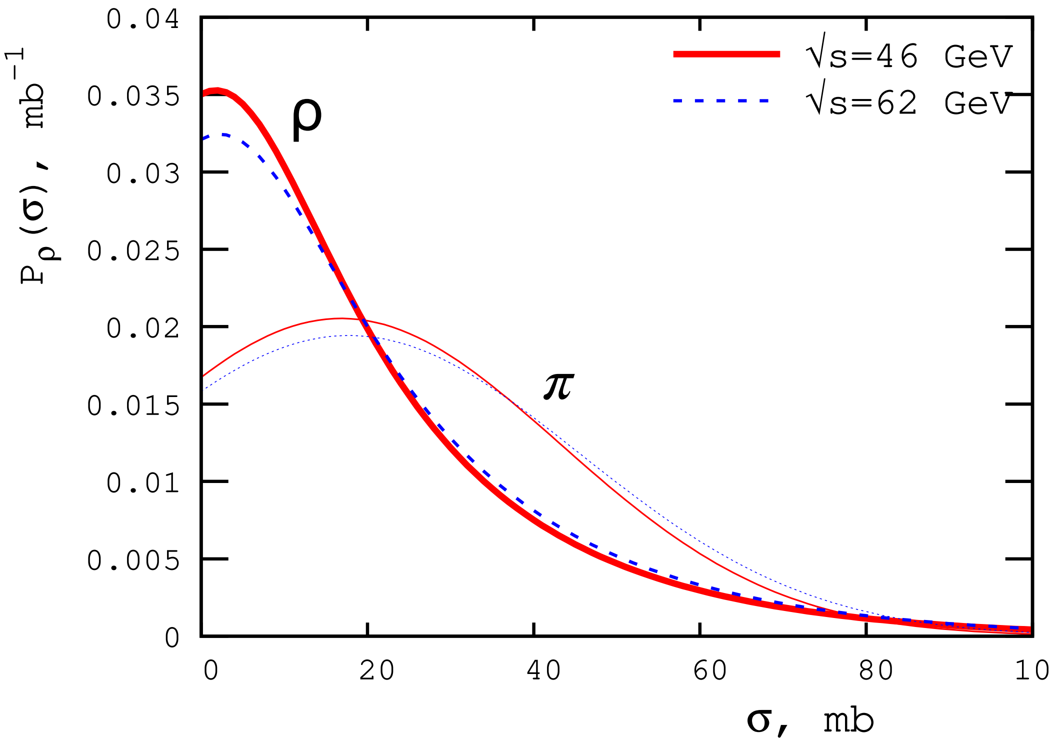
• Contribution of small-σ fluctuations is enhanced compared to pion due to point-like γ-ρ coupling (VMD), which is also supported by HERA data on σ(γp→ρp) cross section

$$P_\rho(\sigma) = N_\rho \frac{1}{(\sigma/\sigma_0)^2+1} e^{-(\sigma-\sigma_0)^2/(\Omega\sigma_0)^2}$$

• In addition, the width of fluctuations ω_σ is enhanced by small-σ fluctuations with large p_T and M*. Using relation (factorization) between σ(γp→Xp) and σ(πp→Xp)

$$\omega_\sigma^\rho = \left(\frac{f_\rho}{e}\right)^2 \frac{\sigma_{\gamma p}\sigma_{\pi p}}{\sigma_{\rho N}^2} \frac{3}{2} \omega_\sigma^\pi$$

• Resulting P(σ) for ρ mesons, Frankfurt, Guzey, Stasto, Strikman, review submitted to ROPP



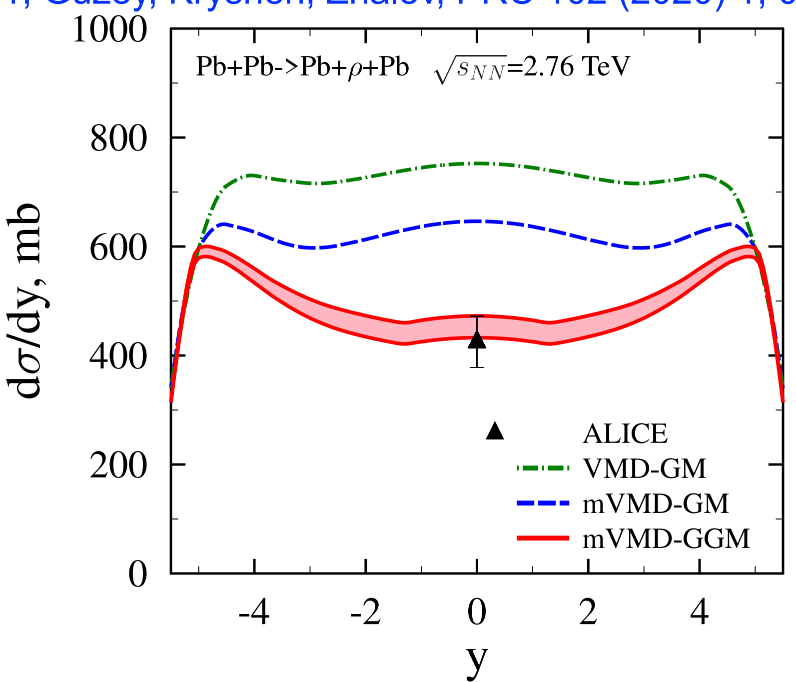
Coherent ρ photoproduction in heavy-ion UPCs

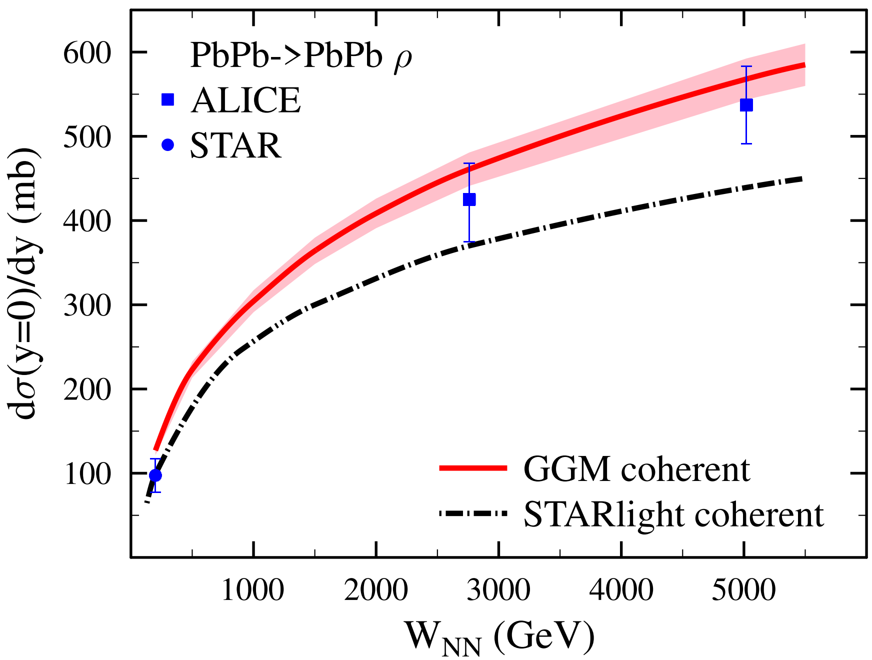
• The natural application/test of this formalism is coherent photoproduction of ρ mesons on nuclei

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

• It generalizes VMD+Glauber model giving most of nuclear suppression **S^2~0.17** by accounting for inelastic diffractive intermediate states leading to additional **30%** Gribov shadowing correction .

• Good agreement with RHIC and ALICE (Runs 1&2) data on coherent ρ photoproduction in Au-Au and Pb-Pb UPCs, Frankfurt, Guzey, Strikman, Zhalov, PRB 752 (2016) 51; Guzey, Kryshen, Zhalov, PRC 102 (2020) 1, 015208





Cross section fluctuations for photons

• It is well known that real and virtual photons reveal their hadronic structure in strong interactions, e.g. VMD accounts for ~70% of $\sigma(\gamma p)$.

• Two types of hadronic fluctuations: (i) aligned quark-antiquark pairs with asymmetric momentum sharing, small p_T and large $\sigma \sim \sigma_{\rho N}$, (ii) small-$\sigma$ perturbative dipoles. The relative importance of these two components depends on Q^2 and M^* of the produced diffractive state, e.g. ρ vs. J/ψ.

• As in the case of p, π, ρ, it is convenient to introduce $P(\sigma)$ for photons

$$\int d\sigma P_\gamma(\sigma)\sigma = \sigma_{\gamma p}(W)\,,$$
$$\int d\sigma P_\gamma(\sigma)\sigma^2 = 16\pi \frac{d\sigma_{\gamma p\to Xp}(t=0)}{dt}$$

• $\int d\sigma P_\gamma(\sigma)=\infty$ due to infinite renormalization of photon Green's function.

• A model for $P_\gamma(\sigma)$ should interpolate between the small-σ (pQCD) and large-σ (VMD) regimes.

Cross section fluctuations for photons (2)

- For small σ, we used the dipole model by rewriting $\sigma(\gamma p)=\int d^2r|\Psi_\gamma|^2\,\sigma_{\text{dipole}}$ in terms of $\sigma(\gamma p)=\int d\sigma P_\gamma(\sigma)\sigma$, Alvioli, Frankfurt, Guzey, Strikman, Zhalov, PLB 767 (2017) 450

$$P_\gamma^{\text{dipole}}(\sigma)=\sum_q e_q^2\left|\frac{\pi d\mathbf{r}^2}{d\sigma_{q\bar{q}}(r,m_q)}\right|\int dz|\Psi_\gamma(z,r(\sigma_{q\bar{q}}),m_q)|^2|_{\sigma_{q\bar{q}}(r,m_q)=\sigma}$$

$$\sigma_{q\bar{q}}(r,m_q)=\frac{\pi^2}{3}r^2\alpha_s(Q_{\text{eff}}^2)x_{\text{eff}}g(x_{\text{eff}},Q_{\text{eff}}^2)$$

is the dipole cross section, McDermott, Frankfurt, Guzey, Strikman, Zhalov, EPJC 16 (2000) 641

$$|\Psi_T^f(r,Q,z)|^2 = \frac{3\alpha_{\text{em}}}{2\pi^2}e_f^2\left\{[z^2+(1-z)^2]Q_f^2K_1^2(Q_fr)+m_f^2K_0^2(Q_fr)\right\}$$

is the photon wf

- For large σ, we approximate $P_\gamma(\sigma)$ by $P(\sigma)$ for ρ mesons + ω, ϕ in SU(3) limit

$$P_{(\rho+\omega+\phi)/\gamma}(\sigma)=\frac{11}{9}\left(\frac{e}{f_\rho}\right)^2P_\rho(\sigma)$$

- Smooth interpolation between small and large σ:

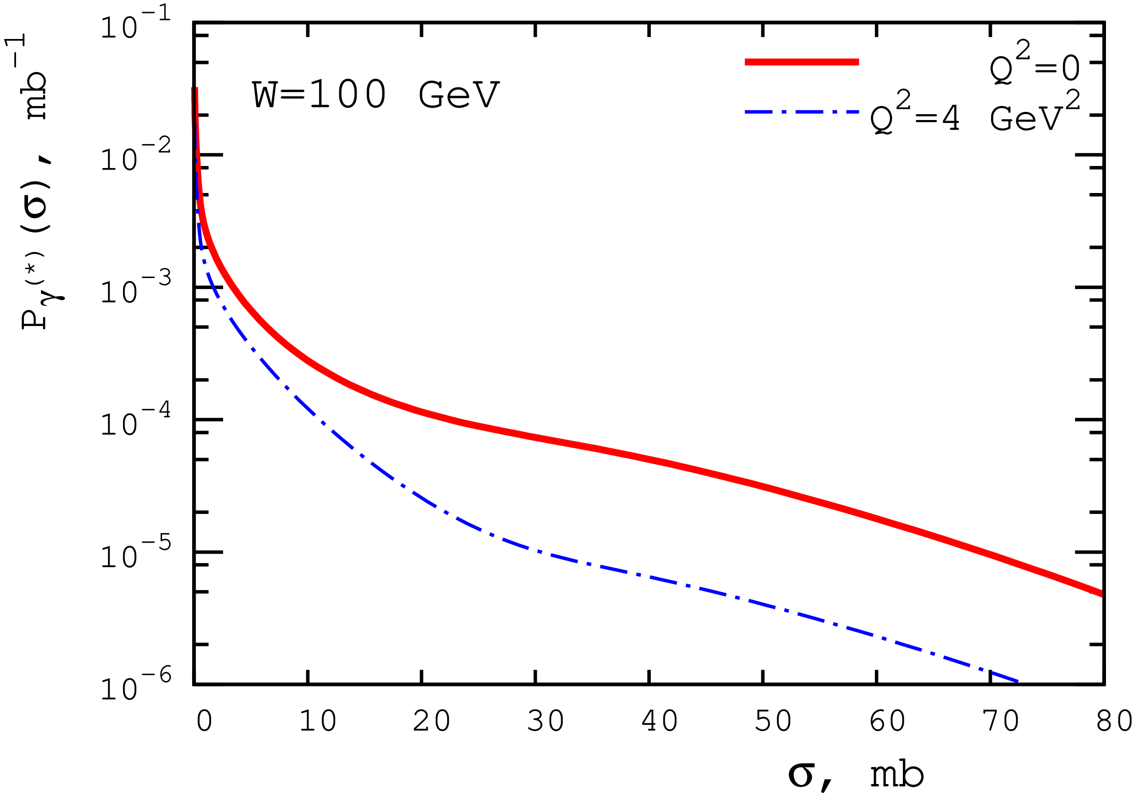
$$P_\gamma(\sigma,W)=\begin{cases}P_\gamma^{\text{dipole}}(\sigma,W)\,, & \sigma\leq 10\ \text{mb}\,,\\ P_{\text{int}}(\sigma,W)\,, & 10\ \text{mb}\leq\sigma\leq 20\ \text{mb}\\ P_{(\rho+\omega+\phi)/\gamma}(\sigma,W)\,, & \sigma\geq 20\ \text{mb}\,.\end{cases}$$

Cross section fluctuations for photons (3)

• For virtual photons, we used both T and L photon wf's for small-σ and VMD for large-σ

$$P_{(\rho+\omega+\phi)/\gamma^*}(\sigma) = \frac{11}{9}\left(\frac{e}{f_\rho}\right)^2 \frac{m_\rho^2}{Q^2+m_\rho^2} P_\rho(\sigma)$$

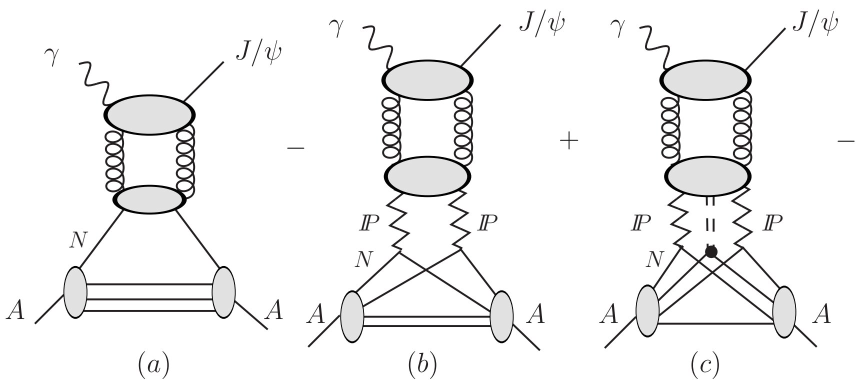
• Resulting P(σ) for real and virtual photons, Frankfurt, Guzey, Stasto, Strikman, review submitted to ROPP



• The model for $P_\gamma(\sigma)$ gives good description of $\sigma(\gamma p)$ and $d\sigma(\gamma p \to Xp)/dt(t=0)$.

Coherent J/ψ photoproduction in heavy-ion UPCs

• Like coherent photoproduction of ρ mesons on nuclei probes P(σ) for ρ mesons, coherent J/ψ probes moments $P_\gamma(\sigma)$, Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942



$$\mathcal{M}_{\gamma A\to J/\psi A}(t=0)$$
$$= \varkappa \int_0^\infty d\sigma P(\sigma) \int d^2\mathbf{b} \left[\frac{\sigma T_A(\mathbf{b})}{2} - \frac{\sigma^2 T_A^2(\mathbf{b})}{2^2\, 2!} + \frac{\sigma^3 T_A^3(\mathbf{b})}{2^3\, 3!} - \ldots\right]$$

$$d\sigma^{\rm pQCD}_{\gamma p\to J/\psi p}(t=0)/dt = \varkappa^2 \langle\sigma\rangle^2/(16\pi)$$

• Combining the Gribov-Glauber model of nuclear shadowing with collinear QCD factorization for hard diffraction, one has for the leading contribution to nuclear shadowing (interaction with 2 nucleons), Frankfurt, Strikman, EPJA 5 (1998) 293

$$\frac{\langle\sigma^2\rangle}{\langle\sigma\rangle} \equiv \sigma_2(x,\mu^2) = \frac{16\pi B_{\rm diff}}{(1+\eta^2)xG_N(x,\mu^2)} \int_x^{0.1} dx_{I\!P}\, \beta G_N^{D(3)}(\beta,\mu^2,x_{I\!P})$$

• Higher terms are summed using quasi-eikonal approximation assuming a single effective cross section σ_3 calculated using $P_\gamma(\sigma)$

$$\frac{\langle\sigma^3\rangle}{\langle\sigma^2\rangle} \equiv \sigma_3$$

$$\langle\sigma^N\rangle = \langle\sigma^2\rangle \sigma_3^{N-2}$$

Coherent J/ψ photoproduction in heavy-ion UPCs(2)

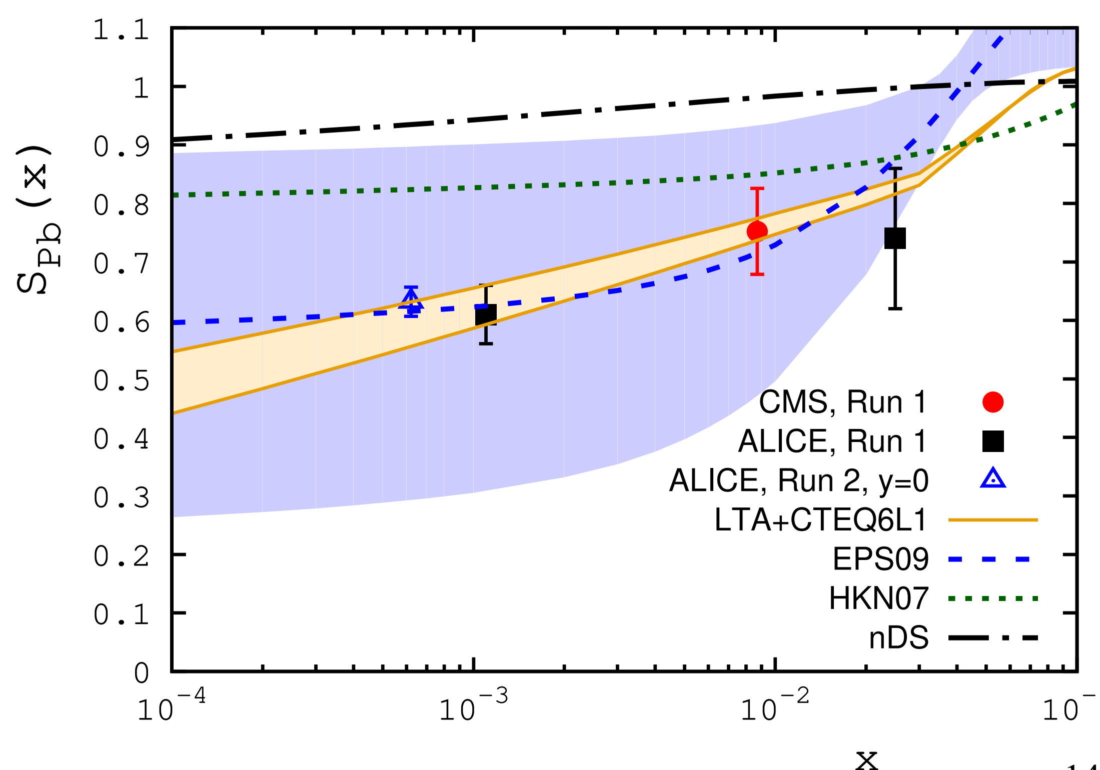
• The resulting differential cross section is expressed in terms of the leading twist nuclear gluon shadowing, Guzey, Strikman, Kryshen, Zhalov, PLB 726 (2013) 290; Guzey, Zhalov, JHEP 10 (2013) 207

$$\sigma^{\rm LTA}_{\gamma A\to J/\psi A}(W_{\gamma p}) = \frac{d\sigma^{\rm pQCD}_{\gamma p\to J/\psi p}(W_{\gamma p}, t=0)}{dt}\left[1-\frac{\sigma_2}{\sigma_3}+\frac{\sigma_2}{\sigma_3}\frac{\sigma_3^A}{A\sigma_3}\right]^2 \Phi_A(t_{\rm min})$$

$$= \frac{d\sigma_{\gamma p\to J/\psi p}(W_{\gamma p}, t=0)}{dt}\left[\frac{xg_A(x,\mu^2)}{Axg_N(x,\mu^2)}\right]^2 \int_{|t_{\rm min}|}^{\infty} dt |F_A(t)|^2$$

• The nuclear suppression factor

$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A\to J/\psi A}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W_{\gamma p})}} = \kappa_{A/N}\frac{xg_A(x,\mu^2)}{Axg_N(x,\mu^2)}$$



• Very nice agreement of ALICE (Runs 1&2) and CMS results with models predicting large nuclear gluon shadowing. In particular, with leading twist model of nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012)

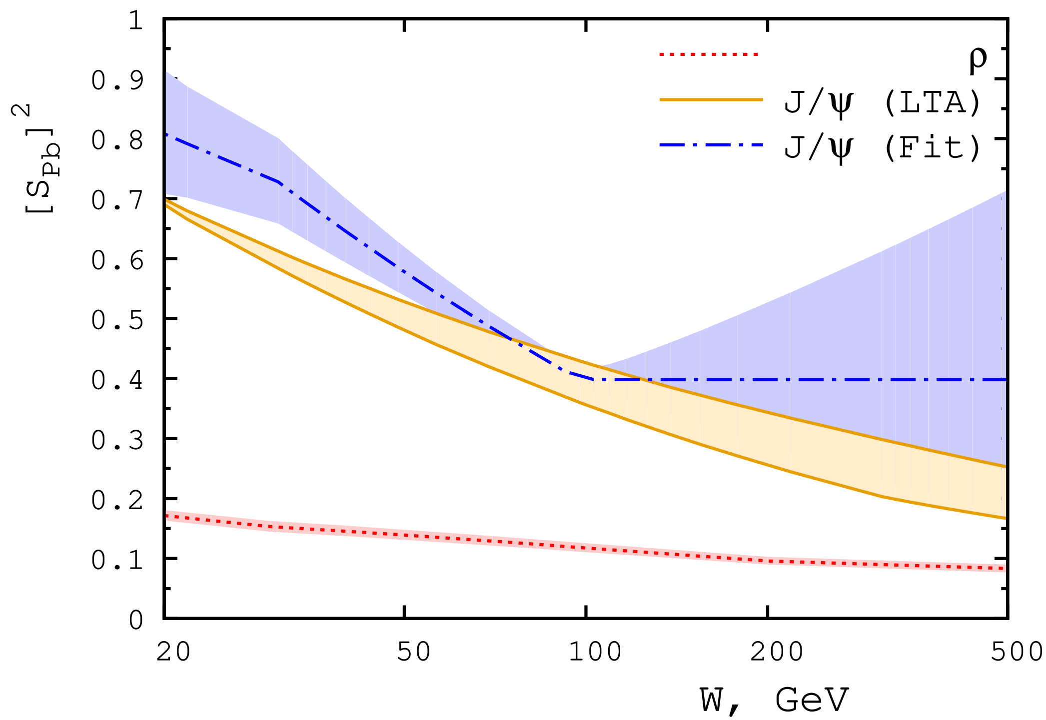
Coherent J/ψ photoproduction in heavy-ion UPCs(3)

• Good description of S_{Pb} is a consequence of large leading twist nuclear gluon shadowing originating from large probability of diffraction on the proton.

• **All** of shadowing comes from inelastic Gribov shadowing → compare to a significantly smaller suppression coming from small dipole-nucleus scattering,

• It is a generic feature of cross section fluctuations: relative contribution of inelastic shadowing compared to eikonal approximation grows with increase of ω_σ (projectile size).

• Energy dependence of nuclear suppression for ρ and J/ψ photoprod. on Pb:



Frankfurt, Guzey, Stasto, Strikman, review submitted to ROPP

Number of wounded nucleons in γA scattering

• Gribov-Glauber model for hadron-nucleus scattering is unitary and satisfies AGK cancellation → cross section of physical process of inelastic production on ν nucleons (wounded nucleons), Bertocchi, Treleani, J. Phys. G: Nucl. Phys. 3 (1977) 147

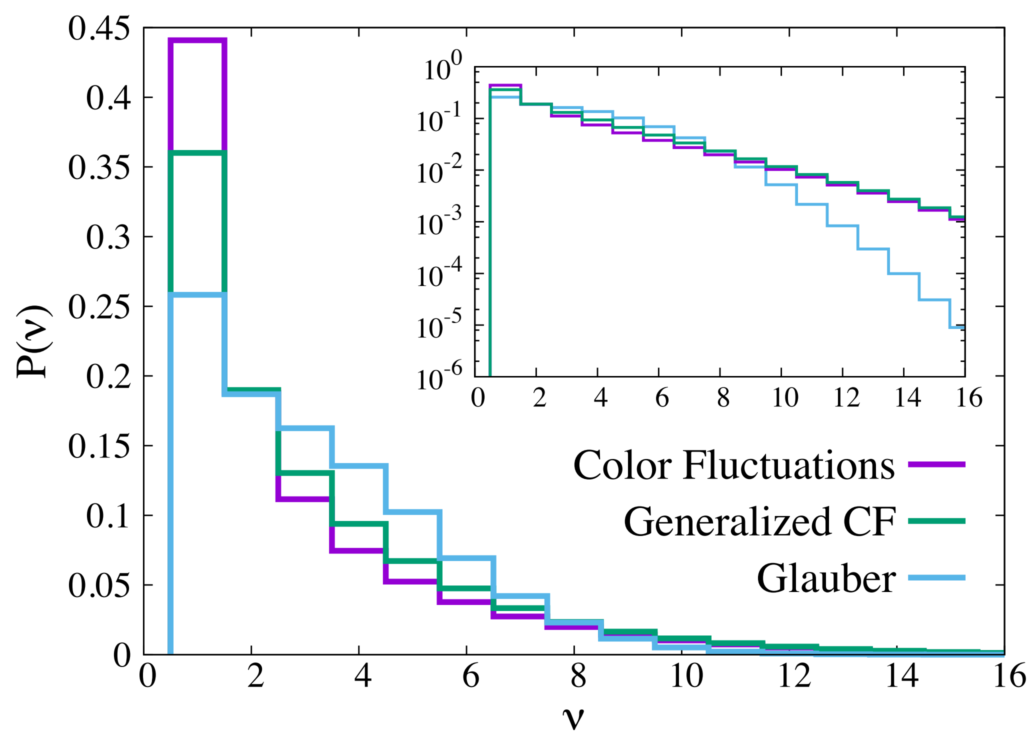
• Cross section fluctuations in the photon modify it, Alvioli, Frankfurt, Guzey, Strikman, Zhalov, PLB 767 (2017) 450

$$\sigma_\nu = \int d\sigma P_\gamma(\sigma, W) \binom{A}{\nu} \int d^2\vec{b} \left[\frac{\sigma_{in}(\sigma)T_A(b)}{A}\right]^\nu \left[1 - \frac{\sigma_{in}(\sigma)T_A(b)}{A}\right]^{A-\nu}$$

• Probability distribution to have exactly ν wounded nucleons

$$P(\nu, W) = \frac{\sigma_\nu}{\sum_1^\infty \sigma_\nu}$$

• Effect can be observed in distribution over transverse energy E_T.



Summary

• Composite structure of hadronic projectiles (p, π, ρ, γ) can be conveniently accounted for using the formalism of cross section (color) fluctuations.

• In scattering off nuclei, it naturally gives rise to diffractive dissociation and inelastic Gribov shadowing correction.

• The latter plays an important role in coherent photoproduction of light vector mesons and quarkonia in heavy-ion UPCs and lead to a good agreement with the existing data.

• This also applies to incoherent ρ and J/ψ photoproduction on nuclei.

• Knowledge of the photon hadronic structure is needed for calculation of rapidity gap survival probability for the resolved photon contribution in diffractive dijet photoproduction in UPCs.

• Less explored are predictions for the number of wounded nucleons and the total γA cross section, which can be studies during Run 3 at the LHC.