Generalized color transparency in coherent photoproduction of J/ψ mesons on nuclei at the LHC

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Based on series of papers with E. Kryshen, M. Zhalov, M. Strikman, L. Frankfurt

Outline:

- Generalized CT and QCD factorization for exclusive processes
- Leading twist nuclear shadowing model
- Gluon nuclear shadowing from coherent J/ψ photoproduction in Pb-Pb UPCs at the LHC

The Future of Color Transparency and Hadronization Studies at Jefferson Lab and beyond, Virtual workshop @ Jefferson Lab, USA, June 7-8, 2021

Generalized color transparency

• Color transparency = the vanishing of nuclear initial and final-state interactions mediated by small-size color-neutral probes, Frankfurt, Miller, Strikman, Ann. Rev. Nucl. Part. Sci. 44 (1994) 501; Dutta, Hafidi, Strikman, Prog. Part. Nucl. Phys. 69 (2013) 1

• In perturbative QCD due to color gauge invariance, CT is realized as smallness of the cross section of small-size quark-antiquark dipoles, Low, PRD 12 (1975) 163; Nussinov, PRL 34 (1975) 1286; Gunion, Soper, PRD 15 (1977) 2617; Blaettel, Baym, Frankfurt, Strikman, PRL 70 (1993) 896; Frankfurt, Miller, Strikman, PLB 304 (1993) 1

$$\hat{\sigma}(x,r) \;=\; \frac{\pi^2}{3} r^2 \left[\alpha_s(\mu^2) x g(x,\mu^2)\right]_{\mu^2=C/r^2}$$

dipole transverse size

gluon density of target

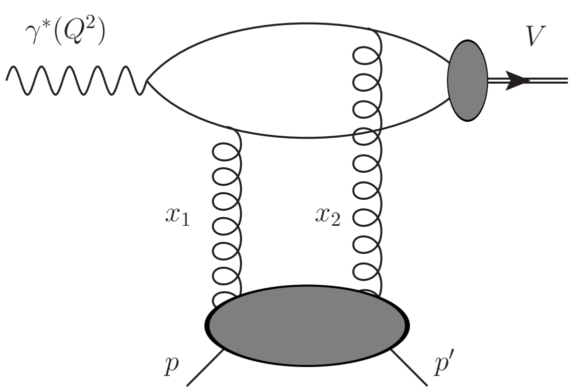
hard scale from matching to collinear expression for $\sigma_L(x,Q^2)$

• The dipole cross section ~ $xg(x,\mu^2)$, which becomes large at small x → naive CT is replaced by color opacity (generalized CT), which also includes, Frankfurt, Strikman, Zhalov, PLB 540 (2002) 220

- leading twist nuclear shadowing
- gradual blackness of the interaction and gross violation of LT approximation

Generalized color transparency and high-energy factorization for J/ψ photoproduction

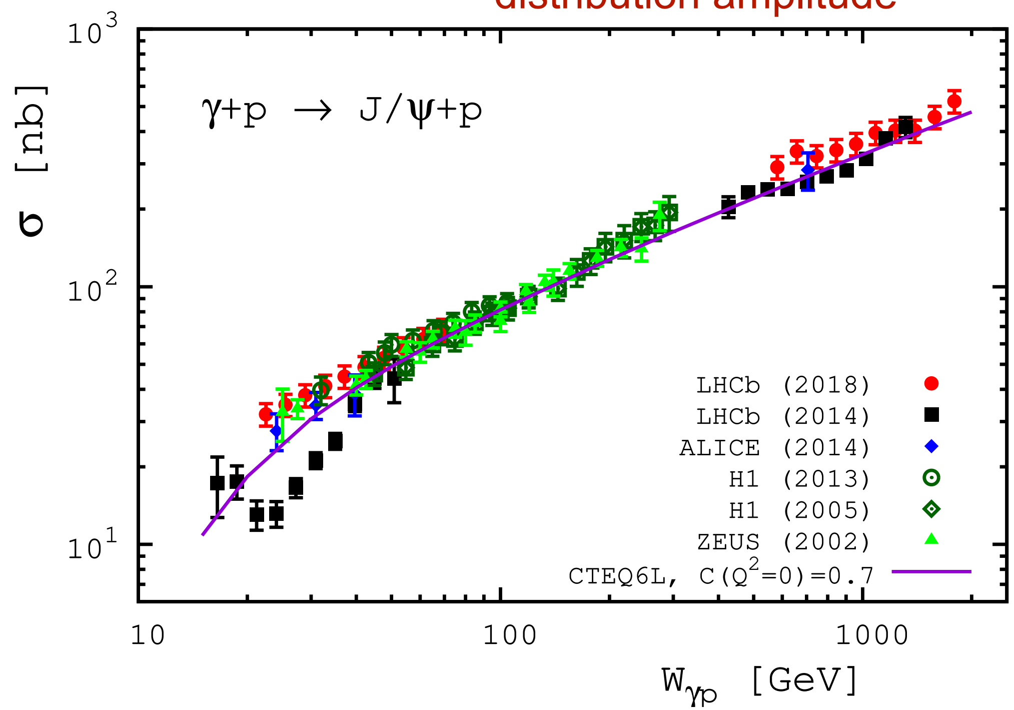
- In the case of J/ψ photoproduction at high energies, the coherence length $l_c=2E_\gamma/(M_V)^2=1/(xm_N)$ and formation time $\tau_f=2E_\gamma/[(M_{V'})^2-(M_V)^2]$ >> R_A → the amplitude factorizes into three blocks, Ryskin, Z. Phys. C 57 (1993) 89; Frankfurt, Koepf, Strikman, PRD 57 (1998) 512; Frankfurt, McDermott, Strikman, JHEP 03 (2001) 045



$$\frac{d\sigma^{\gamma p\to J/\psi p}(t=0)}{dt}=\frac{12\pi^3}{\alpha_{\rm e.m.}}\frac{\Gamma_V M_V^3}{(4m_c^2)^4}\left[\alpha_s(Q^2_{\rm eff})xg(x,Q^2_{\rm eff})\right]^2 C(Q^2=0)$$

$x=(M_V)^2/W^2$, $Q_{\rm eff}^2=2.5\text{-}4$ GeV^2

depends on details of charmonium distribution amplitude



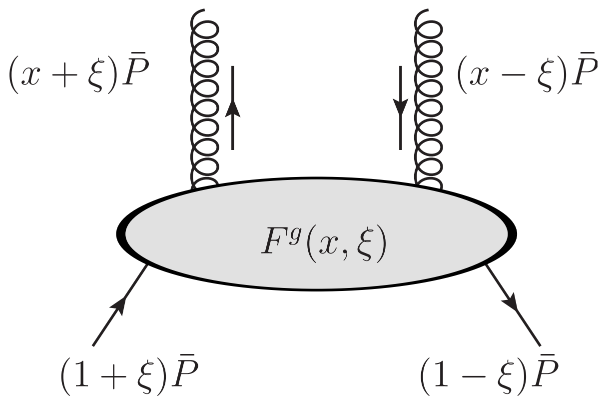
- Describes all available collider data, update of Guzey, Zhalov, JHEP10 (2013) 207

Generalized color transparency and collinear factorization

• This high-energy factorization is related to collinear QCD factorization for hard exclusive processes, Collins, Frankfurt, Strikman, PRD 56 (1997) 2982

• Within collinear framework, the amplitudes are expressed as convolutions of generalized parton distributions (GPDs) with non-equal mom.fractions.

• The GPD-based phenomenology for exclusive J/ψ photoproduction is complicated by model-dependent relation of GPDs to PDFs, Shuvaev, Golec-Biernat, Martin, Ryskin, PRD 60 (1999) 014015, large NLO QCD radiative Ivanov, Schaefer, Szymanowski, Krasnikov (2015); Jones, Martin, Ryskin, Teuber (2015) and relativistic corrections, Lappi, Mantysaari, Penttala, PRD 102 (2020) 5, 054020



• This is partially circumvented in the color dipole framework, where an account of quark k_T (Fermi motion) suggests, Frankfurt, McDermott, Strikman, JHEP 03 (2001) 045

$$GPD(x_1, x_2) \approx g(x_{\rm eff} = \frac{x_1 + x_2}{2}) \approx g(x)$$

Note the resulting skewness is smaller than that given by Shuvaev transform.

Coherent J/ψ photoproduction on nuclei

- Application to nuclear targets → probe of nuclear gluon GPD (PDFs), Brodsky, Frankfurt, Gunion, Mueller, Strikman, PRD 50 (1994) 3143; Frankfurt, Strikman, Zhalov, PLB 540 (2002) 220

$$\sigma_{\gamma A\to J/\psi A}(W_{\gamma p}) = \kappa^2_{A/N}\frac{d\sigma_{\gamma p\to J/\psi p}(W_{\gamma p}, t=0)}{dt}\left[\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)}\right]^2\Phi_A(t_{\min})$$

Small correction $k_{A/N}$ ≈ 0.90-95 due to different skewnesses of nuclear and nucleon GPDs

From HERA and LHCb

Nucleus/proton gluon ratio R_g

From nuclear form factor

$$\Phi_A(t_{\min}) = \int_{-\infty}^{t_{\min}} dt |F_A(t)|^2$$

- Well-defined impulse approximation (IA), or naive CT:

$$\sigma^{\text{IA}}_{\gamma A\to J/\psi A}(W_{\gamma p}) = \frac{d\sigma_{\gamma p\to J/\psi p}(W_{\gamma p}, t=0)}{dt}\Phi_A(t_{\min})$$

- Nuclear suppression factor S → direct access to R_g +cancellation of corrections

$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb\to J/\psi Pb}}{\sigma^{\text{IA}}_{\gamma Pb\to J/\psi Pb}}\right]^{1/2} = \kappa_{A/N}\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)} = \kappa_{A/N}R_g$$

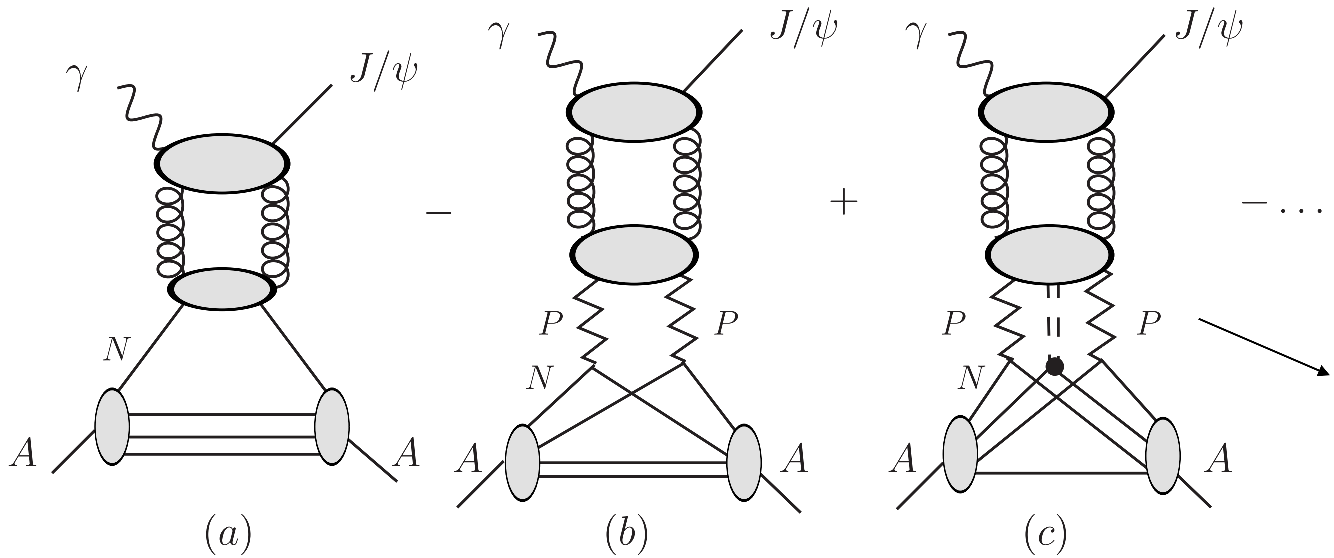
Model-independently* from data on UPC@LHC at (ALICE, CMS, LHCb) and HERA, LHCb Abelev *et al*. [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489; Acharya et al [ALICE], arXiv:2101:04577 [nucl-ex]

From global QCD fits or leading twist nuclear shadowing model

Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290, Guzey, Zhalov, JHEP 1310 (2013) 207

Leading twist model of nuclear shadowing

- Combination of Gribov-Glauber shadowing model with QCD factorization theorems for inclusive and diffractive DIS, Frankfurt, Strikman, EPJ A5 (1999) 293; Frankfurt, Guzey, Strukman, JHEP 02 (2002) 027; Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255 $\longrightarrow$ nuclear PDFs in terms of diffractive PDFs of proton + model for soft rescattering



diffractive (Pomeron) exchange

$$
xf_{j/A}(x, Q_0^2) = Axf_{j/N}(x, Q_0^2) - 8\pi A(A-1)\, \Re e \frac{(1-i\eta)^2}{1+\eta^2} B_{\rm diff} \int_x^{0.1} dx_{\mathbb{P}} \beta f_j^{D(3)}(\beta, Q_0^2, x_{\mathbb{P}})
$$

$$
\times \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b}, z_1) \rho_A(\vec{b}, z_2) e^{i(z_1-z_2)x_{\mathbb{P}} m_N} e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}^j(x,Q_0^2)\int_{z_1}^{z_2} dz' \rho_A(\vec{b},z')}
$$

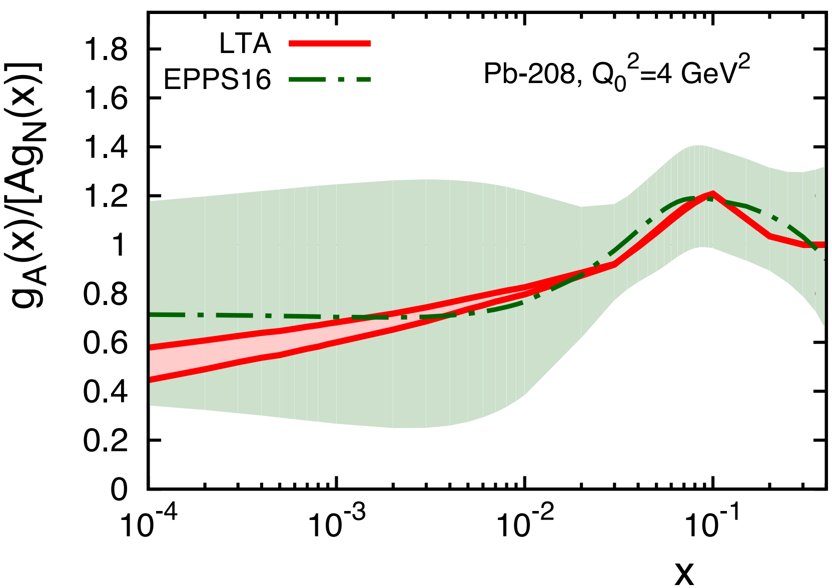
nuclear density

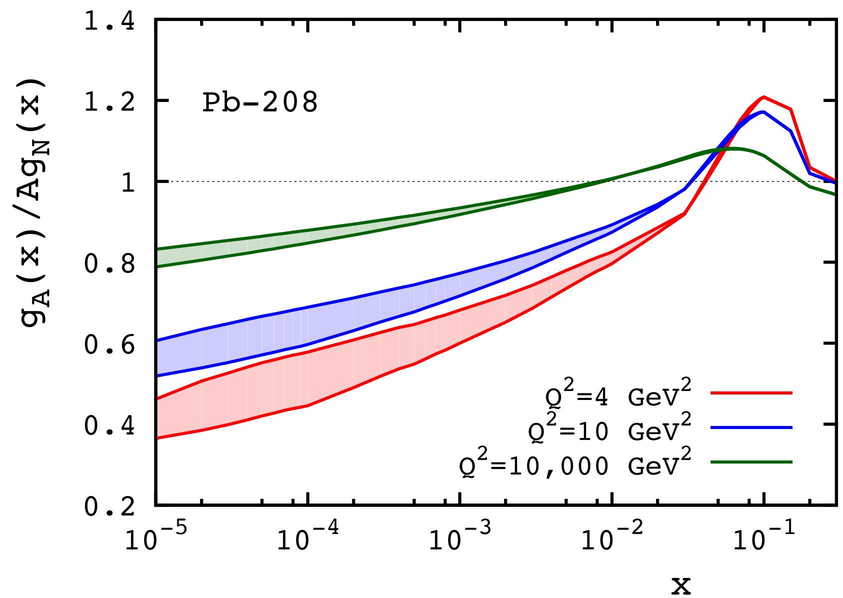
proton diffractive PDFs from HERA

model-dependent effective cross section

Leading twist model of nuclear shadowing (2)

- Predicts a leading twist component of nuclear shadowing, which is determined by leading twist diffractive PDFs measured at HERA.
- Naturally predicts large shadowing for $g_A(x,\mu^2)$.
- Predicts nuclear PDFs at μ^2=3-4 GeV^2 → input for DGLAP evolution.



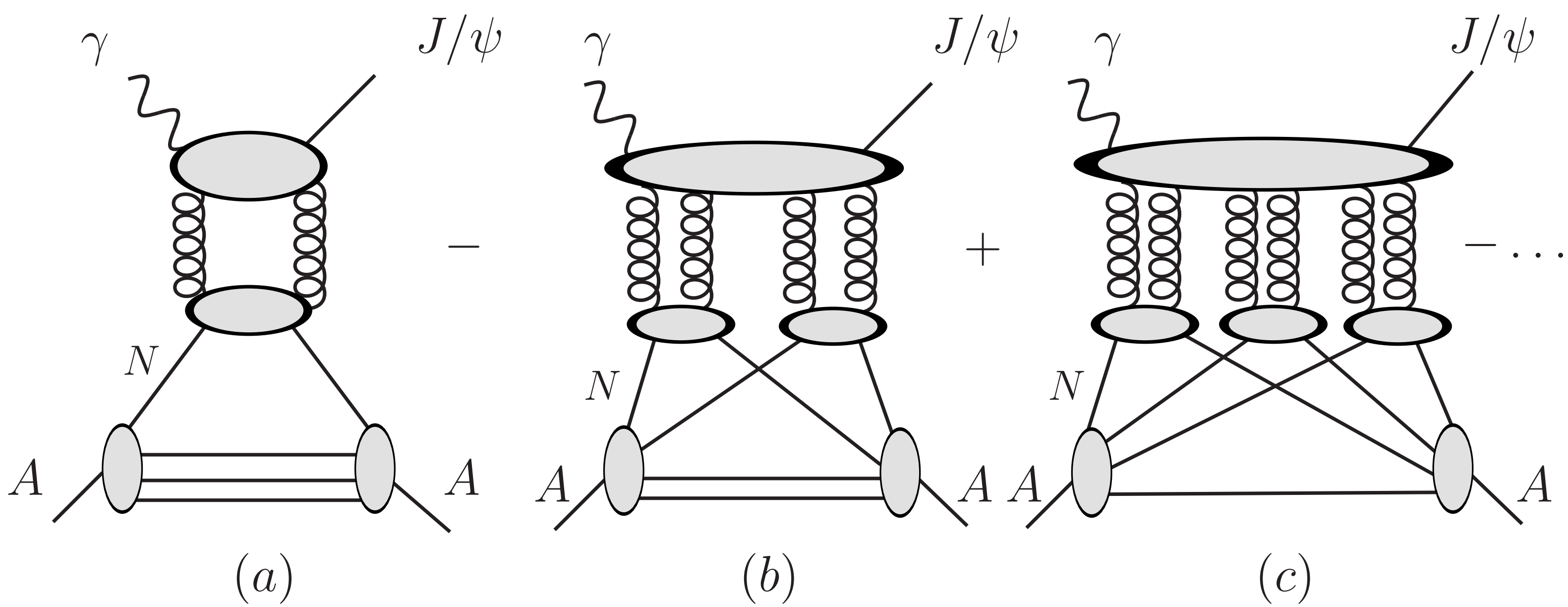


- EIC can test predictions of this model and others due to:
- wide x-Q^2 coverage
- measurements of the longitudinal structure function $F_L^A(x,Q^2)$ sensitive to gluons
- measurements of diffraction in eA DIS

- This can also be done using UPCs@LHC → last part of this talk.

Coherent J/ψ photoproduction on nuclei in dipole model

- In contrast to the leading twist model, where the diffractive exchange (Pomeron) couples to 2 different nucleons, the dipole model takes into account a different, higher-twist set of contributions leading to smaller nuclear shadowing, Nikolaev, Comm. Nucl. Part. Phys. 21 (1992) 1, 41



- → Color dipole models generally underestimate the suppression, Goncalves, Machado (2011); Lappi, Mäntysaari, 2013, but the answer strongly depends on the choice of the dipole cross section and charmonium wave function, Mäntysaari, Schenke, PLB 772 (2017) 681

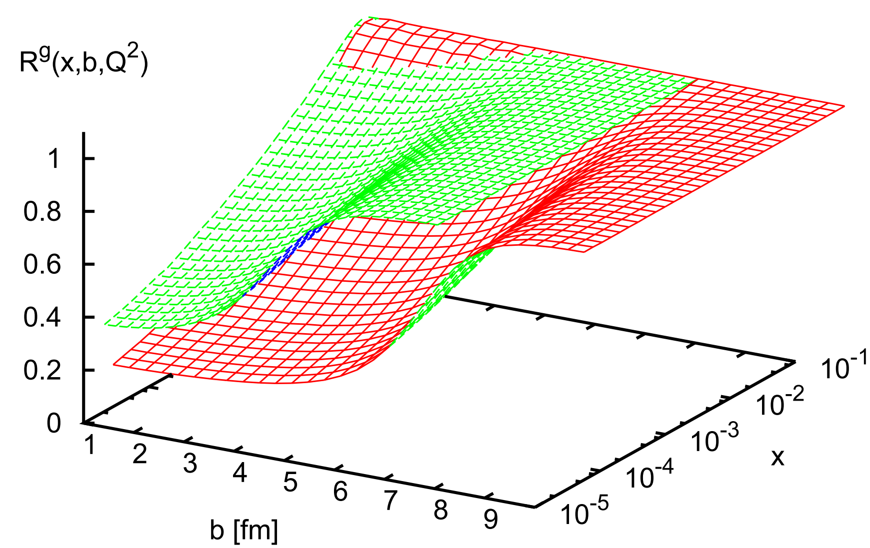
Impact parameter dependence of nPDFs

- The model of leading twist nuclear shadowing allows one to predict the dependence of nPDFs on the impact parameter b:

$$xf_{j/A}(x, Q_0^2, b) = A\,T_A(b)xf_{j/N}(x, Q_0^2) - 8\pi A(A-1)B_{\mathrm{diff}}\,\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{\mathbb{P}}\beta f_j^{D(3)}(\beta, Q_0^2, x_{\mathbb{P}})$$

$$\times \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\, \rho_A(\vec{b}, z_1)\rho_A(\vec{b}, z_2)\, e^{i(z_1-z_2)x_{\mathbb{P}}m_N} e^{-\frac{A}{2}(1-i\eta)\sigma_{\mathrm{soft}}^j(x,Q_0^2)\int_{z_1}^{z_2} dz' \rho_A(\vec{b},z')}$$

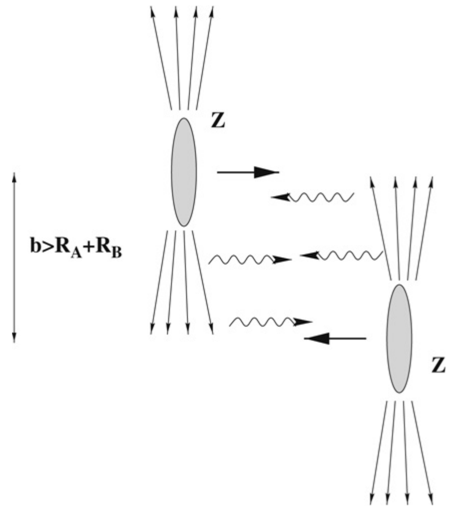
- → correlations between b and x → shadowing is stronger in nucleus center → shift of t-dependence of γA → J/ψA cross section → confirmed by LHC data on coherent J/ψ photoproduction in Pb-Pb UPCs.



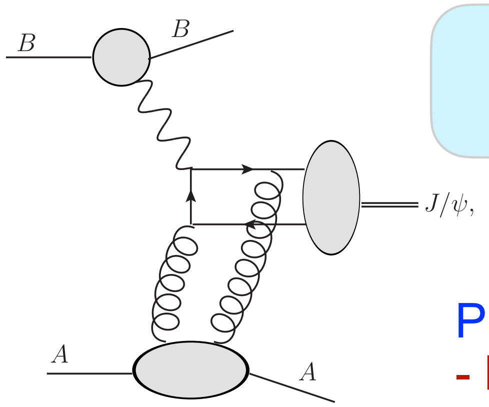
- With additional assumptions, global QCD fits can also extract b-dependence of nPDFs, EPS09s, Helenius, Honkanen, Salgado, JHEP 1207 (2012) 073.

Exclusive J/ψ photoproduction in ultraperipheral collisions (UPCs)

• Ultraperipheral collisions (UPCs): ions interact at large impact parameters $b >> R_A+R_B$ → hadron interactions suppressed → interaction via quasi-real photons in Weizsäcker-Williams equivalent photon approximation, Budnev, Ginzburg, Meledin, Serbo, Phys. Rept. 15 (1975) 181; Bertulani, Klein, Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271; Baltz et al, Phys. Rept. 480 (2008) 1; Contreras and Tapia-Takaki, Int. J. Mod. Phys. A 30 (2015) 1542012; Snowmass LoI, Klein et al, arXiv:2009.03838



• Cross section of coherent J/ψ photoproduction in Pb-Pb UPCs → two terms corresponding to low-x and high-x



$$\frac{d\sigma_{AA\to AAJ/\psi}(y)}{dy} = N_{\gamma/A}(y)\sigma_{\gamma A\to AJ/\psi}(y) + N_{\gamma/A}(-y)\sigma_{\gamma A\to AJ/\psi}(-y)$$

Photon flux from QED:
- high intensity ~ Z^2
- high photon energy ~ γ_L

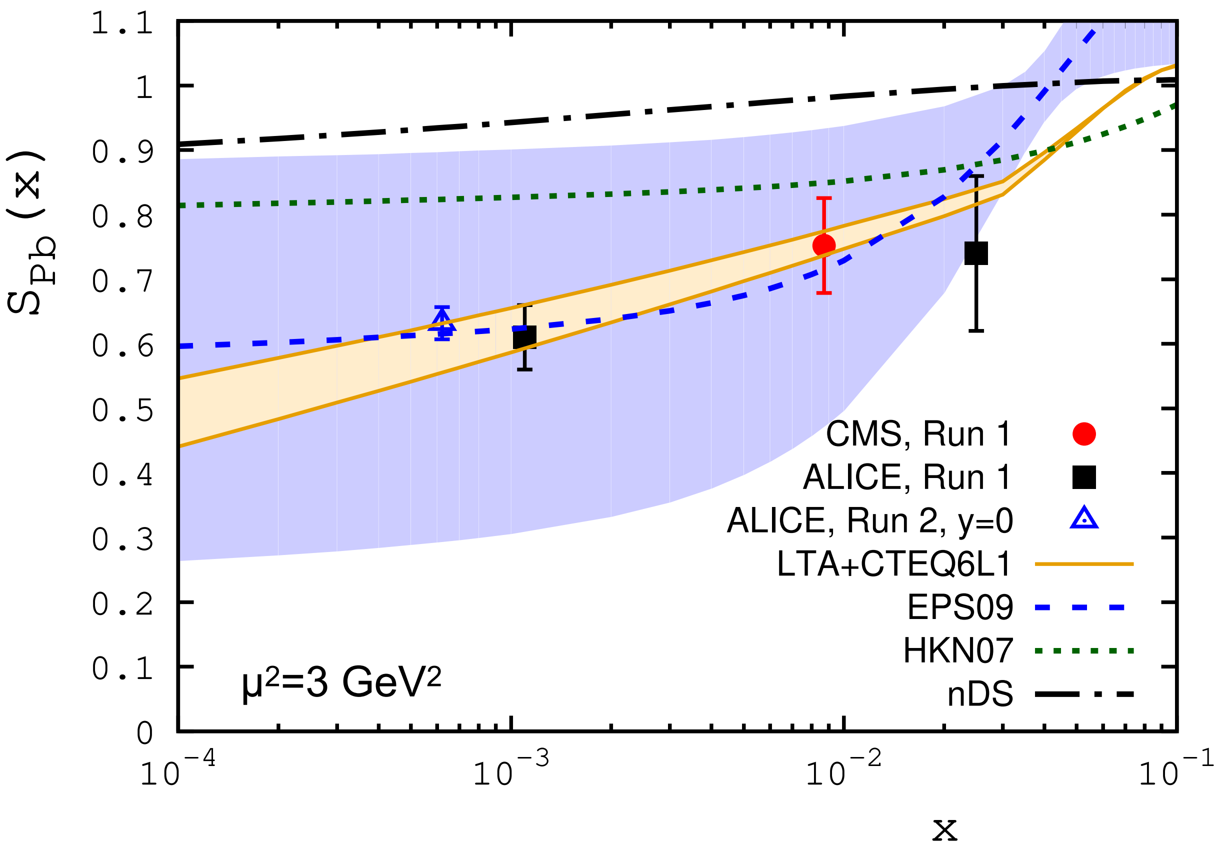
Photoproduction cross section

$$y = \ln[W^2/(2\gamma_L m_N M_V)]$$

= J/ψ rapidity

S_{Pb} from ALICE and CMS UPC data vs. theory

- Model-independently at y=0 and mostly large-x at forward |y|, Abelev *et al*. [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; CMS Collab., PLB 772 (2017) 489, Acharya et al [ALICE], arXiv:2101:04577 [nucl-ex] → suppression factor S_{Pb}



LTA: Guzey, Zhalov JHEP 1310 (2013) 207
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028

- Good agreement with ALICE data at 2.76 and 5.02 TeV → direct evidence of large gluon shadowing, $R_g(x=6\times10^{-4} - 0.001) \approx 0.6$, predicted by the LT model.
- Also good description using central value of EPS09, EPPS16, large uncertainty.

Imaging of nuclear gluons at small x

- In case of non-negligible nuclear shadowing, $\gamma A \to J/\psi A$ cross section should be modified:

$$\frac{d\sigma_{\gamma A\to J/\psi A}}{dt} = \frac{d\sigma_{\gamma p\to J/\psi p}(t=0)}{dt}\left(\frac{R_{g,A}}{R_{g,p}}\right)^2\left(\frac{g_A(x,\mu^2)}{Ag_p(x,\mu^2)}\right)^2 F_A^2(t)$$

$$\Downarrow$$

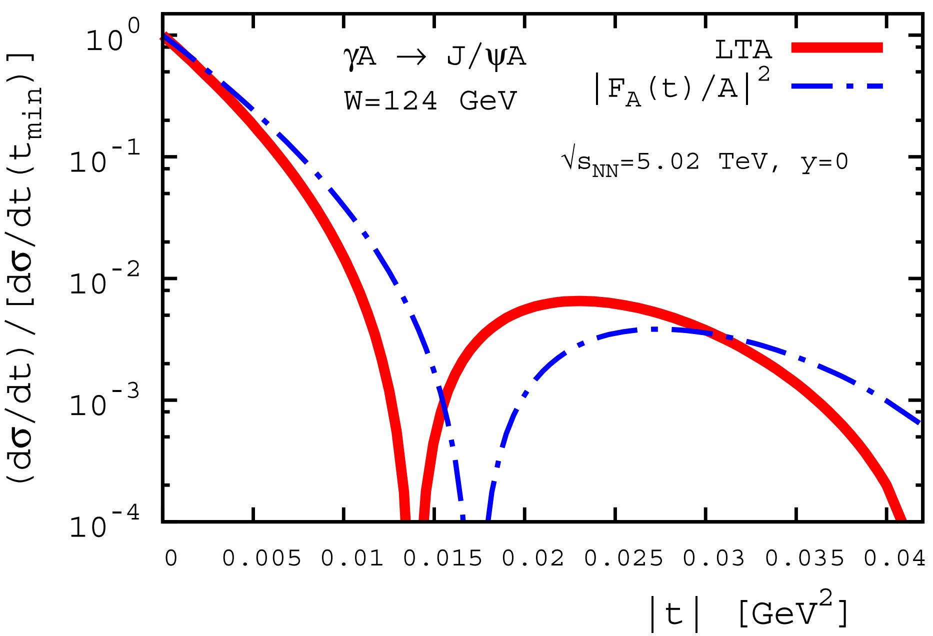
$$\frac{d\sigma_{\gamma A\to J/\psi A}}{dt} = \frac{d\sigma_{\gamma p\to J/\psi p}(t=0)}{dt}\left(\frac{R_{g,A}}{R_{g,p}}\right)^2 \boxed{\left(\frac{g_A(x,t,\mu^2)}{Ag_p(x,\mu^2)}\right)^2}$$

- Answer in terms of nuclear GPD in the $x_1=x_2$ limit, i.e. in terms of impact-parameter-dependent nPDF $f_{j/A}(x,Q_0^2,b)$, Guzey, Strikman, Zhalov, PRC 95 (2017) 025204

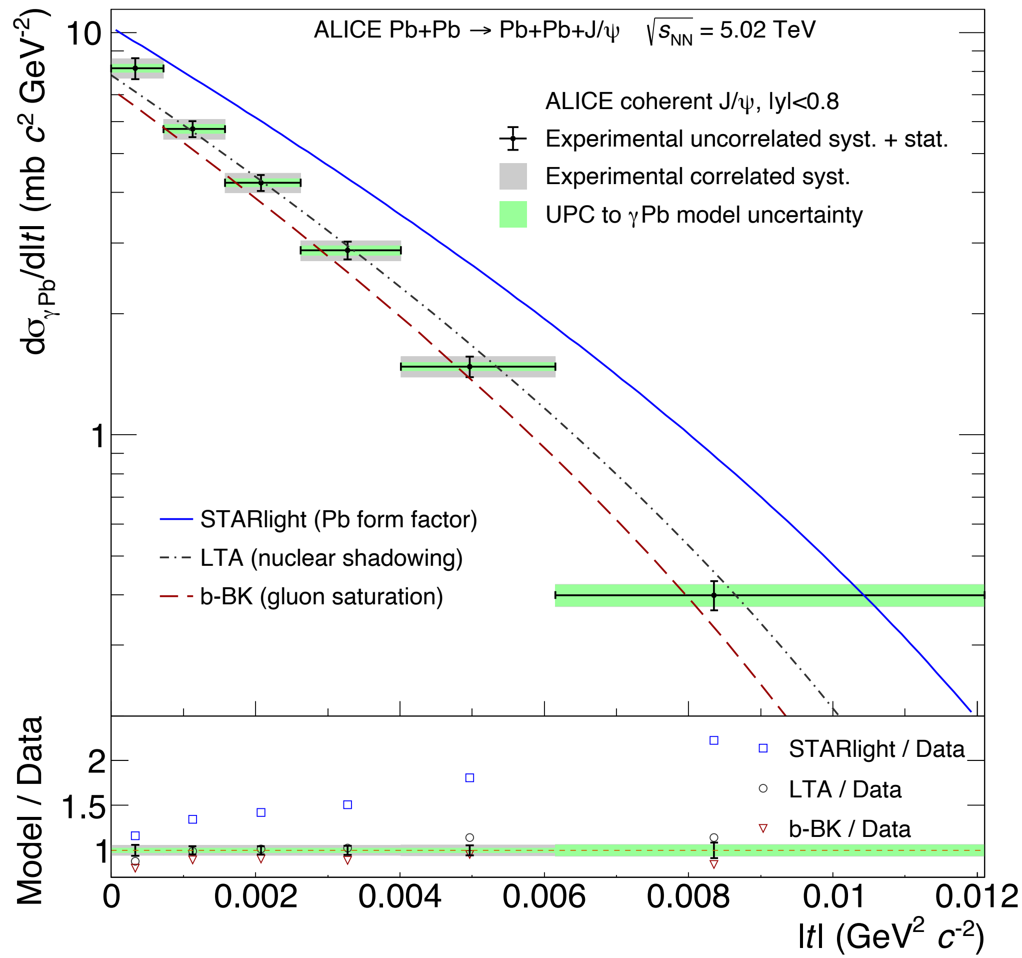
- Correlations between b and x $\to$ shift of t-dependence of $\gamma A \to J/\psi A$ cross section:

t-dependence of coherent J/ψ photonuclear cross section

Guzey, Strikman, Zhalov, PRC 95 (2017) 025204



Acharya et al. [ALICE] arXiv:2101.04623 [nucl-ex]



- Shift of t-dependence = **5-11% broadening** in impact parameter space of gluon nPDF
- Similar effect is predicted to be caused by saturation, Cisek, Schafer, Szczurek, PRC86 (2012) 014905; Lappi, Mäntysaari, PRC 87 (2013) 032201; Toll, Ullrich, PRC87 (2013) 024913; Goncalves, Navarra, Spiering, arXiv:1701.04340

Reweighting of J/ψ UPC data

- Strictly speaking, new constraints on gluon shadowing from coherent J/ψ photoproduction in Pb-Pb UPCs@LHC include many effects: connection of GPDs to PDFs, NLO radiative and relativistic corrections, etc.
- Before full analysis, one can estimate the power of the data using the statistical method of Bayesian reweighting commonly used for pA data, Armesto et al. JHEP 1311 (2013) 015; Paukkunen, Zurita, JHEP 1412 (2014) 100; Kusina et al, EPJC 77 (2017) 488
- Using error nPDFs, one generates N (N=10,000) replicas:

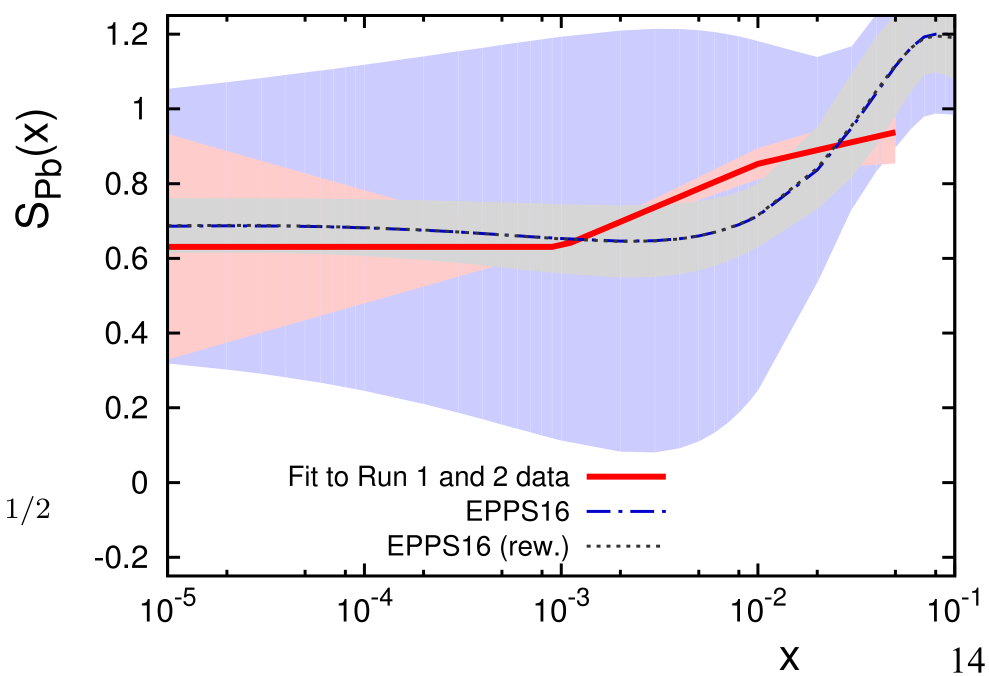
$$g_A^k(x,\mu^2) = g_A^0(x,\mu^2) + \frac{1}{2}\sum_{i=1}^{N}\left(g_A^{i+}(x,\mu^2) - g_A^{i-}(x,\mu^2)\right) R_{ki} \longrightarrow \text{random numbers}$$

Guzey, Kryshen, Strikman, Zhalov, PLB 816 (2021) 136202

- For each replica, calculate $S_{Pb}(x)$ and $d\sigma/dy$ and the weight w_k from comparison to data.
- Reweighted gluon density and error:

$$\langle g_A(x,\mu^2)\rangle = \frac{1}{N_{\rm rep}}\sum_{k=1}^{N_{\rm rep}} w_k g_A^k(x,\mu^2)\,,$$

$$\delta\langle g_A(x,\mu^2)\rangle = \left[\frac{1}{N_{\rm rep}}\sum_{k=1}^{N_{\rm rep}} w_k\left(g_A^k(x,\mu^2) - \langle g_A(x,\mu^2)\rangle\right)^2\right]^{1/2}$$



Summary

- For hard exclusive processes, generalized CT can be identified with the use of QCD factorization theorems.

- Amplitude of coherent J/ψ photoproduction in Pb-Pb UPCs is expressed in terms of the presently poorly constrained nuclear gluon distribution at small x.

- Coherent photoproduction of J/ψ in Pb-Pb UPCs at LHC gives direct evidence of large gluon nuclear shadowing $R_g(x=6\times10^{-4}-10^{-3}, \mu^2 \approx 3\ \mathrm{GeV}^2) \approx 0.6$ and can help to significantly reduce uncertainties in wide region of x.

- Thus, generalized CT has been observed in coherent J/ψ photoproduction on nuclei!

- This agrees with predictions of the leading twist nuclear shadowing model and allows one to distinguish it from the higher-twist dipole model predictions.

- Heavy quarkonium photoproduction in UPCs gives access to transverse imaging of gluon distribution at small x.

Elastic shadowing in ρ photoproduction

- Standard method: Glauber shadowing model combined with vector meson dominance (VMD) for γ-ρ transition, Bauer, Spital, Yennie, Pipkin, Rev. Mod. Phys. 50 (1978) 261

- The coherent cross section including elastic intermediate states:

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

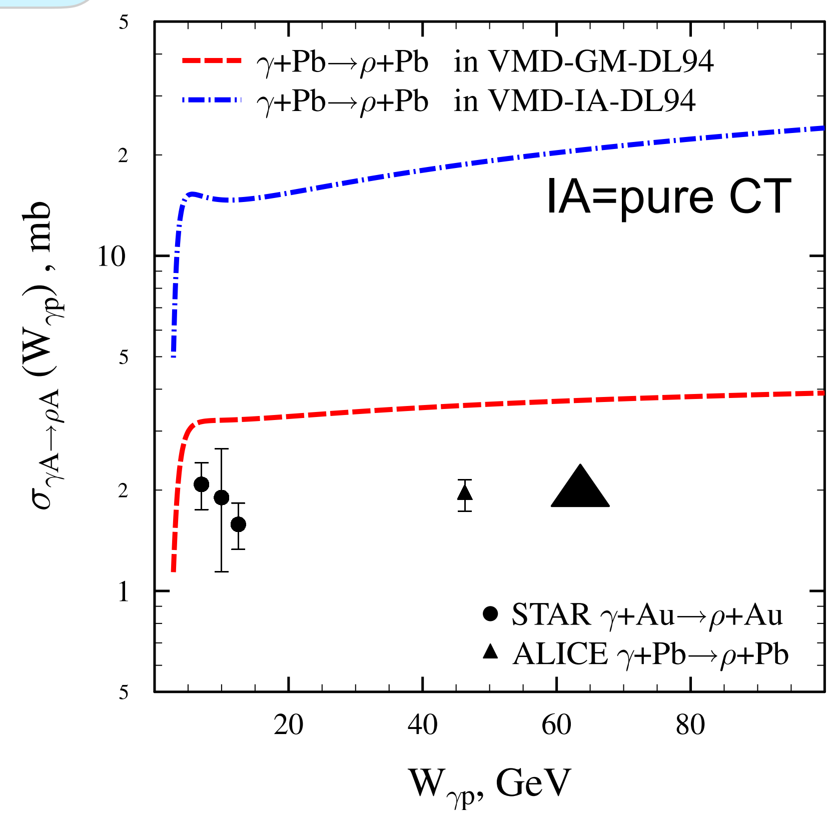
$\sigma_{\rho N}$=total cross section from VMD and constituent quark model

nuclear optical density:

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

- The Glauber method correctly takes into account the bulk of nuclear suppression by factor ~ 6 раз.

- However, it still overestimates the RHIC and LHC data by ~ 50%, Frankfurt, Guzey, Strikman, Zhalov, PLB 752 (2016) 51



Modified model of vector meson dominance (mVMD)

• To include inelastic (diffractive) intermediate states, it is convenient to use the formalism of cross section fluctuations, which takes into account presence of different hadronic fluctuations in the photon, Good, Walker (1960), Blaettel et al, Phys. Rev. D 47 (1993) 2761

• The distribution P(σ) = probability to find the fluctuation interacting with σ.

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

• Правила сумм для P(σ):

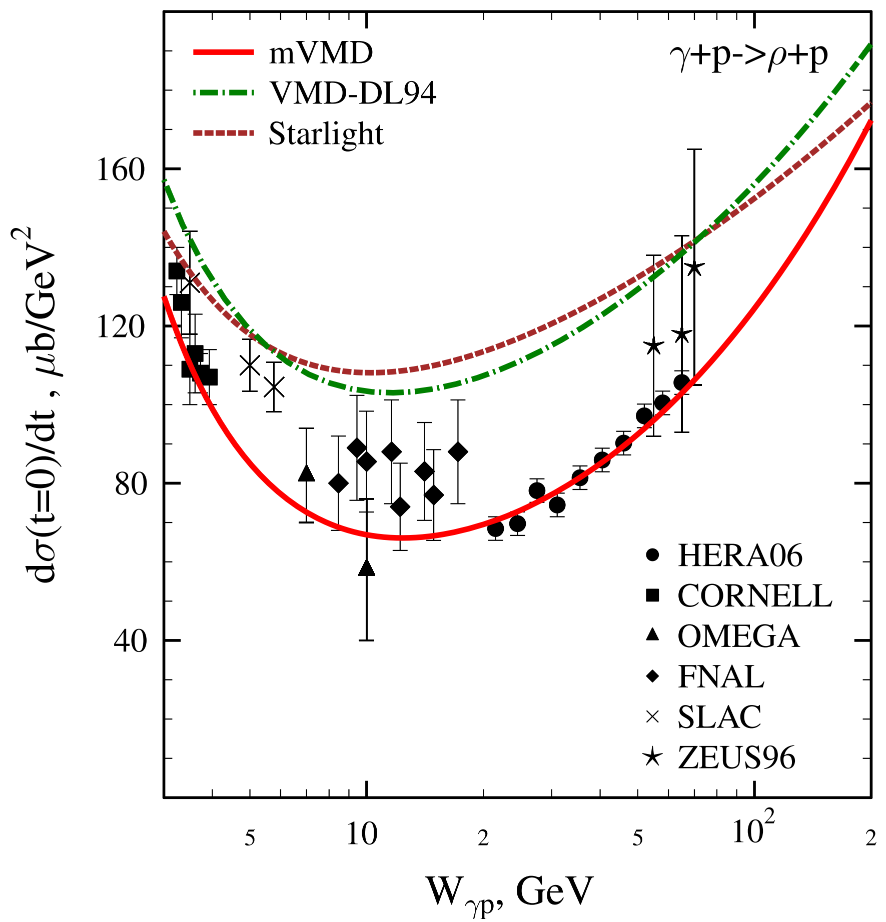
$$\int d\sigma\, P(\sigma) = 1\,,$$

$$\int d\sigma\, P(\sigma)\sigma = \langle\sigma\rangle\,,$$

→ from data on $d\sigma(\gamma p \to \rho p)/dt$

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

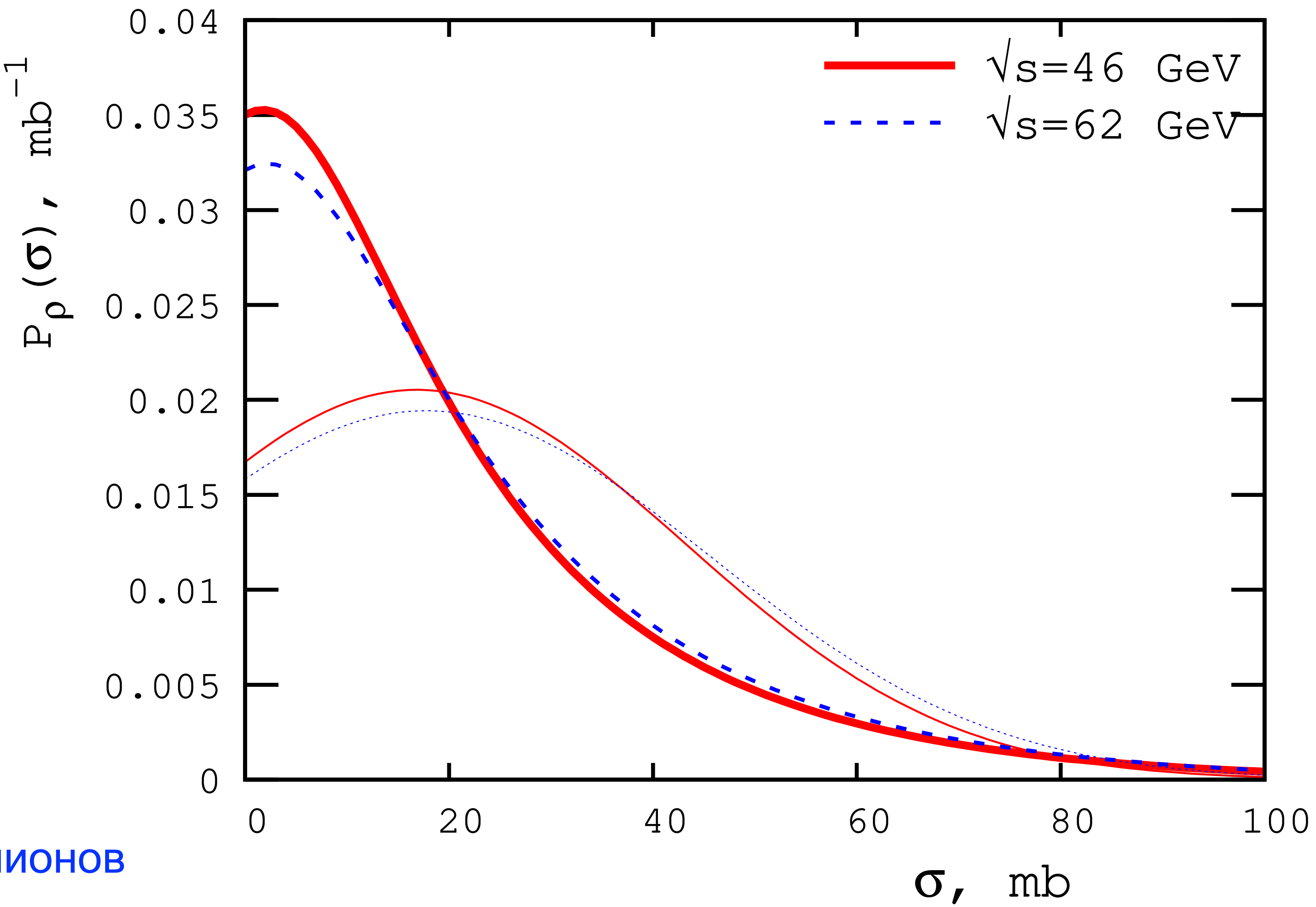
→ from diffractive dissociation of photons in large masses, Chapin 1985



Modified model of vector meson dominance (2)

- P(σ) for ρ mesons, Frankfurt, Guzey, Strikman, Zhalov, PLB 752 (2016) 51

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



Thin lines= P(σ) для пионов

Elastic and inelastic shadowing in ρ photoproduction on nuclei

- With fluctuations:

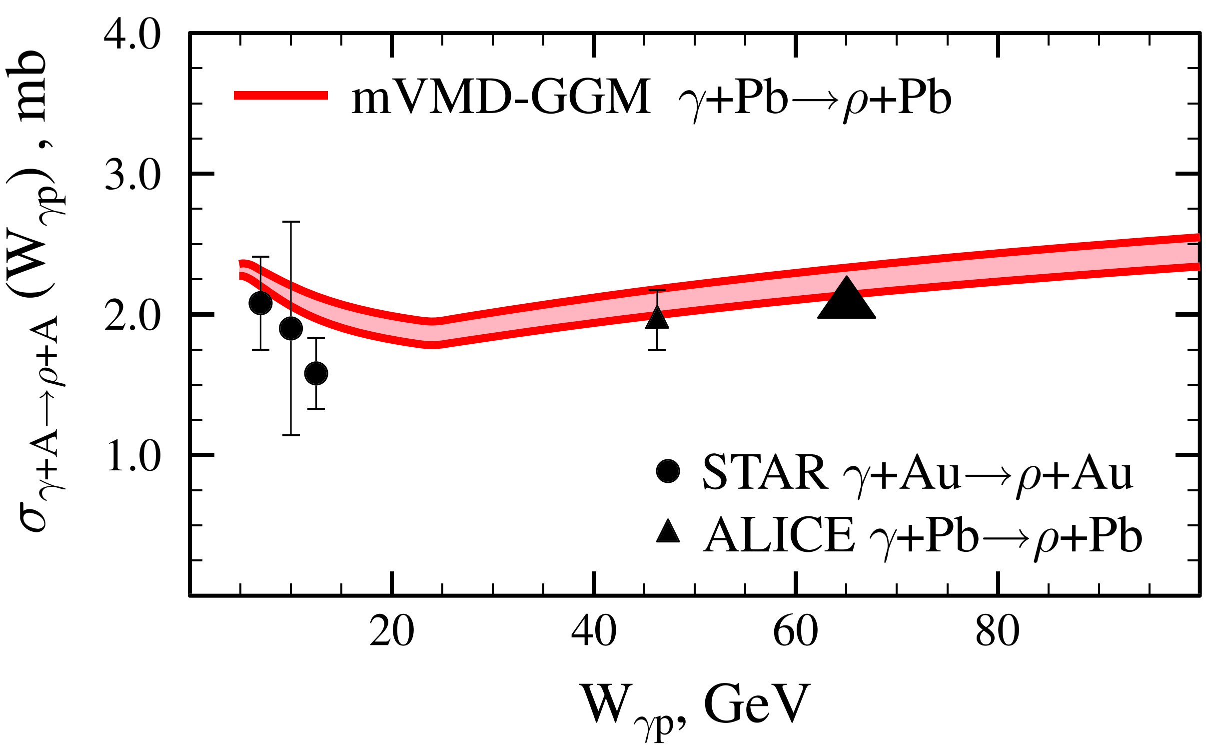
$$\sigma^{\text{mVMD-GGM}}_{\gamma A\to\rho A} = \left(\frac{e}{f_\rho}\right)^2 \int d^2\vec{b} \left| \int d\sigma\, P(\sigma) \left(1 - e^{-\frac{\sigma}{2}T_A(b)}\right)\right|^2$$

- This way we gain two effects: improved description of the $\gamma p\to\rho p$ cross section and take into account inelastic, Gribov shadowing in $\sigma_{\gamma A\to\rho A}$

- $\to$ good description of normalization and energy dependence of $\sigma_{\gamma A\to\rho A}$

Frankfurt, Guzey, Strikman, Zhalov, PLB 752 (2016) 51

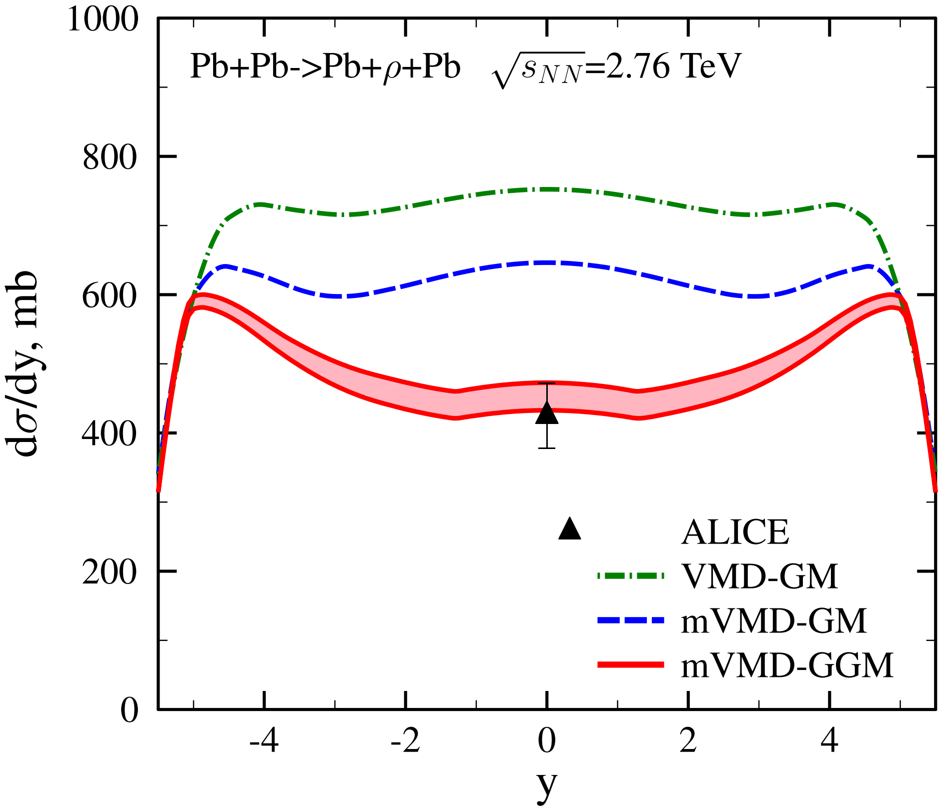
- Comparison to RHIC (STAR) Adler, et al, Phys. Rev. Lett. 89 (2002) 272302; Abelev et al., Phys. Rev. C 77 (2008) 034910; Agakishiev, et al., Phys. Rev. C 85 (2012) 014910 and LHC (ALICE) data, Adam et al (ALICE), JHEP 1509 (2015) 095; Acharya et al, JHEP 06 (2020) 035.



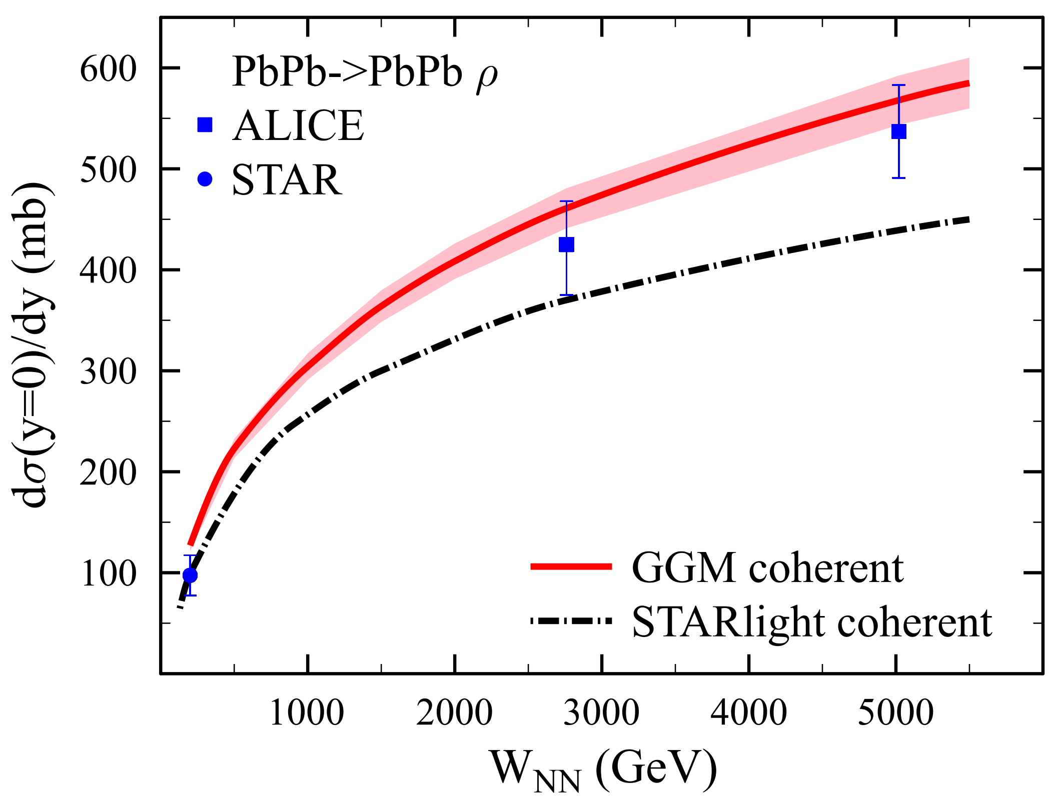
Photoproduction of ρ in Pb-Pb UPCs at LHC

- Good description of $\sigma_{\gamma A \to \rho A}$ means good description of RHIC and LHC (Run 1 and 2) data on coherent ρ photoproduction, $d\sigma(AA \to \rho AA)/dy$ at y=0.
- Left: Rapidity y dependence using Glauber model (GM) and Gribov-Glauber (GGM).
- Right.: Dependence on collision energy $W_{NN}=\sqrt{s_{NN}}$, comparison to STARlight.

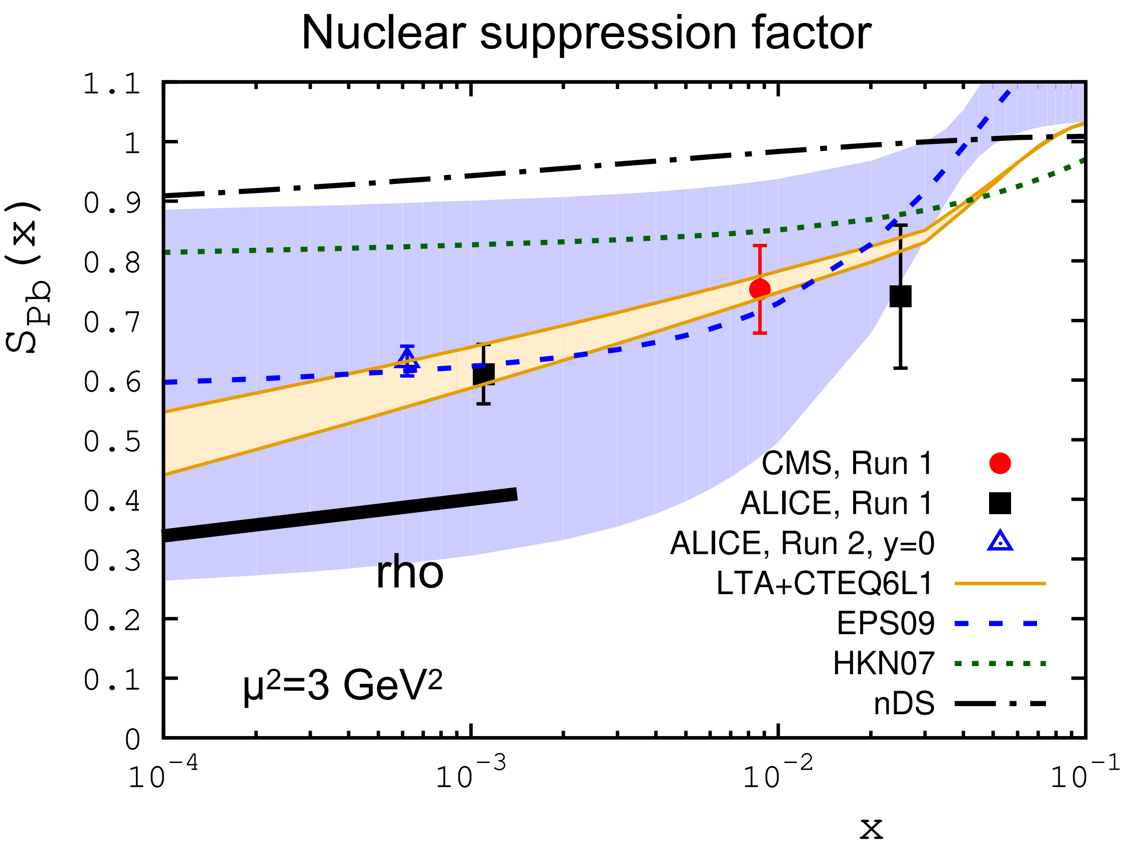
Frankfurt, Guzey, Strikman, Zhalov, PLB 752 (2016) 51

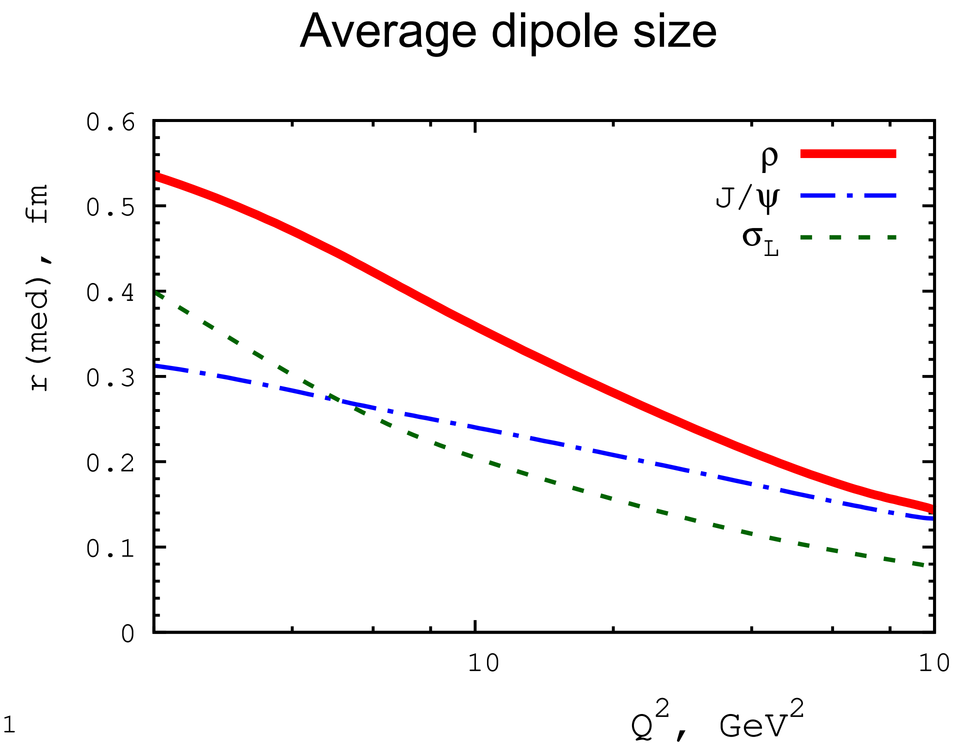


Guzey, Kryshen, Zhalov, PRC 102 (2020) 1, 015208



S_{Pb} for J/ψ and ρ





- For $Q^2=0$, nuclear suppression factor $S_{Pb}=0.6$ for J/ψ and $S_{Pb}=0.35$-0.4 for ρ.
- As Q^2 increases, S_{Pb} for J/ψ and ρ should become closer (see right plot).