Leading twist nuclear shadowing from photoproduction of charmonia in ultraperipheral collisions at the LHC

Vadim Guzey

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

Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290

Guzey, Zhalov, JHEP 10 (2013) 207; JHEP 02 (2014) 046

Guzey, Strikman, Zhalov, EPJ C (2014) 74: 2942

Guzey, Zhalov, arXiv:1404.6101

Guzey, Kryshen, Zhalov, arXiv:1602.01456

Workshop "Next generation nuclear physics with JLab12 and EIC",
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Outline

- Gluon distribution in nuclei at small-x and ion ultraperipheral collisions (UPCs)

- Photoproduction of J/ψ and $\psi(2S)$ in Pb-Pb UPCs at the LHC at $\sqrt{s_{NN}}$=2.76 TeV and constraints on leading twist nuclear shadowing of $g_A(x,\mu^2)$ at small x

- Summary, discussion and outlook

Gluon distribution in nuclei

• The gluon distribution in nuclei $g_A(x,\mu^2)$ = the probability (at LO) to find a gluon with the momentum fraction x at the resolution scale μ^2.

• Describes QCD structure of nuclei probed in hard processes.

• Important element of QCD phenomenology:

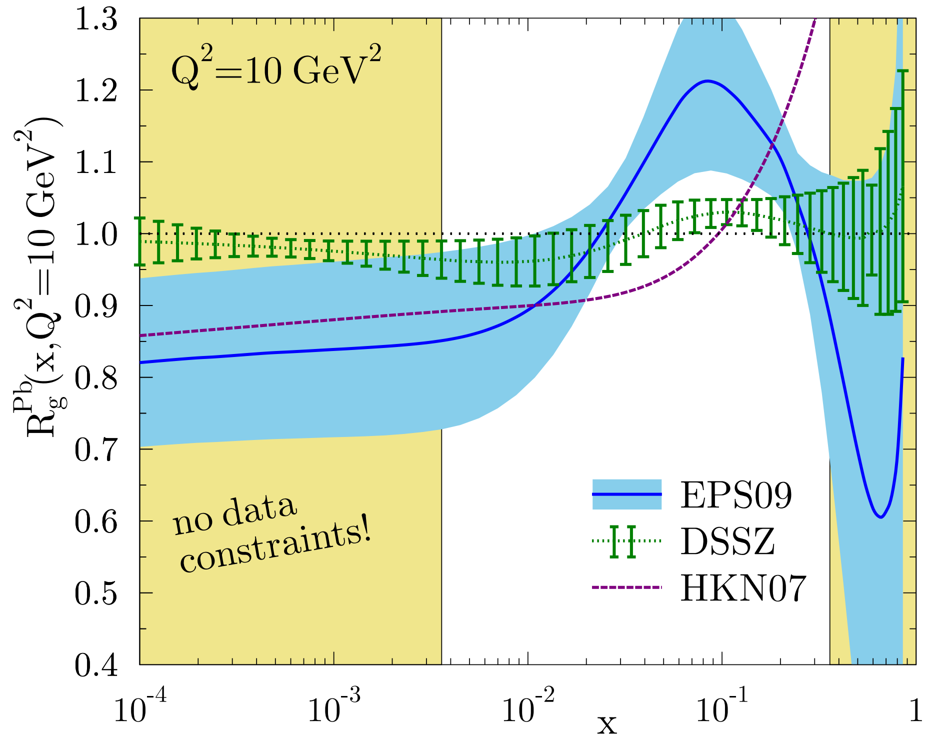
- cold nuclear matter effects for HI collisions
- quantitative analysis of gluon saturation in nuclei.

$$R_g(x,Q^2) = \frac{g_A(x,Q^2)}{A g_p(x,Q^2)}$$

• $g_A(x,\mu^2)$ is determined from global QCD fits to fixed-target + RHIC data.

• Significant uncertainties due to:

- limited kinematics
- indirect extraction via DGLAP evolution
- different assumptions about shape



H. Pauukunen, NPA 926 (2014) 24

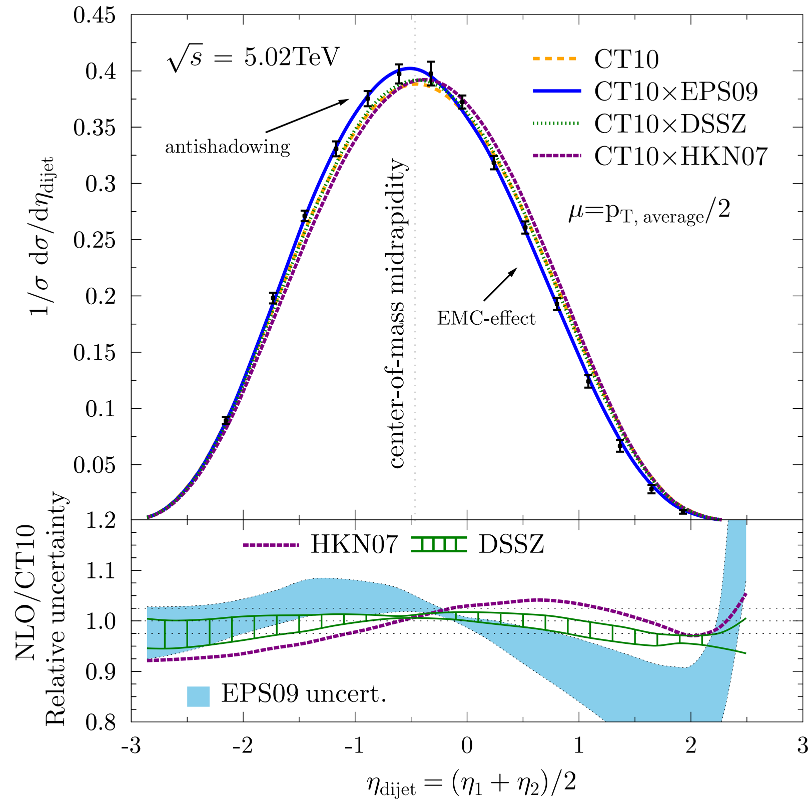
Gluon distribution in nuclei (2)

• pA@LHC data on production of W, Z, jets consistent with current nPDFs fits and give little to further constrain them, N. Armesto et al, arXiv:1512.01528

• Notable exemption: dijets at CMS favoring EPS09 (large) gluon antishadowing

★ similar antishadowing in leading twist nuclear shadowing model

• EIC will constrain $g_A(x,Q^2)$ in wide range: down to $x \approx 10^{-3}$ (5×10^{-4}) for $Q^2 \approx 4$ GeV^2

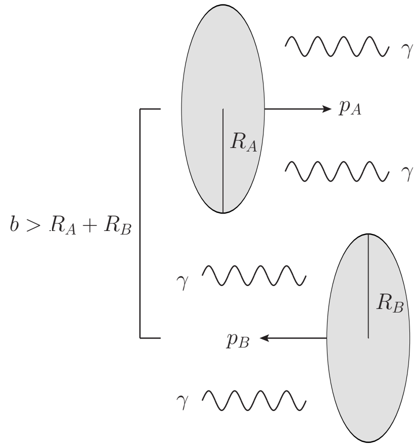


Eskola et al, JHEP 1310 (2013) 213

Photoproduction of charmonia (J/ψ, ψ(2S)) in AA UPCs at the LHC probes $g_A(x,\mu^2)$ in similar kinematic point.

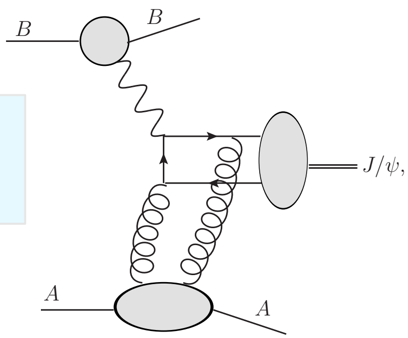
Ultraperipheral collisions at the LHC

- In pp, pA and AA collisions, ions can scatter at large impact parameters $b > R_A + R_B$ =10-20 fm— ultraperipheral collisions (UPCs).



UPC events correspond to empty detector with two lepton tracks (from J/ψ decay).

- In UPCs the strong interact is suppressed and ions interact via quasi-real photons, E. Fermi (1924), C.F. von Weizsäcker; E.J. Williams (1934)



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

photon flux — photoproduction cross section

$y = \ln(2\omega/M_{J/\psi}) = \ln(W_{\gamma p}^2/(2\gamma_L m_N M_{J/\psi}))$ is J/ψ rapidity

UPCs at the LHC (2)

• Photon flux of point-like source:

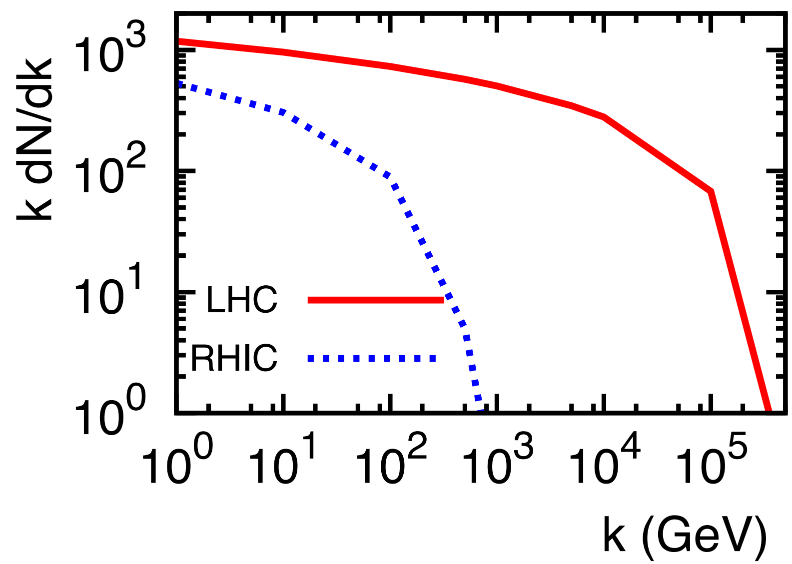
$$N_{\gamma/Z}(k) = \frac{2Z^2\alpha_{\rm em}}{\pi}[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}(K_1^2(\zeta) - K_0^2(\zeta))]$$

k=photon energy, $\zeta = k(2R_A/\gamma_L)$

- scales as Z^2 ($Z^2 \approx 7000$ for Pb)

- corresponds to HUGE maximal photon energy in the target rest frame due to large γ_L: $\gamma_L \approx 1500$ for Pb-Pb UPCs@2.76 TэВ → $\omega_{max} \approx 120$ TeV:

Spectrum of equivalent photons in Pb-Pb UPCs in nucleus rest frame →

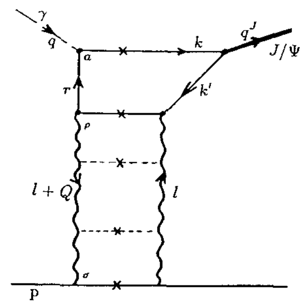


• UPCs give an opportunity to study γp and γA interactions at energies 10 larger than at HERA → new constraints on $g_p(x,\mu^2)$ and $g_A(x,\mu^2)$.

A. Baltz *et al.*, The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1

Exclusive photoproduction of charmonium

• In leading logarithmic approximation of perturbative QCD and non-relativistic limit for charmonium (J/ψ, $\psi(2S)$) wave function:



$$\frac{d\sigma_{\gamma T\to J/\psi T}(W,t=0)}{dt} = C(\mu^2)\left[xG_T(x,\mu^2)\right]^2$$

$$x = \frac{M^2_{J/\psi}}{W^2}, \quad \mu^2 = M^2_{J/\psi}/4 = 2.4\ \mathrm{GeV}^2 \quad C(\mu^2) = M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s(\mu^2)/(48\alpha_{em}\mu^8)$$

M. Ryskin (1993)

• Relativistic corrections (k_T-formalism), skewed kinematics, real part:

$$C(\mu^2) \to (1+\eta^2)R_g^2F^2(\mu)C(\mu^2) \to 1.5F^2(\mu)C(\mu^2)$$

Ryskin, Roberts, Martin, Levin, Z. Phys. C 76 (1997) 231;
Frankfurt, Koepf, Strikman, PRD 57 (1997) 231

• Our phenomenological approach:
- use freedom in μ^2 and choose it to describe W-dependence of HERA data
- fix normalization $C(\mu^2)$ using the W=100 GeV HERA data point

• Our results:
- J/ψ: $\mu^2 \approx 3$ GeV^2, $F^2(\mu^2) \approx 0.5$, Guzey, Zhalov JHEP 1310 (2013) 207
- $\psi(2S)$: $\mu^2 \approx 4$ GeV^2, $F^2(\mu^2)$ from $\sigma_{\gamma p\to\psi(2S)p} = 0.17\sigma_{\gamma p\to J/\psi p}$ Guzey, Zhalov, arXiv:1405.7529

Coherent charmonium photoproduction on nuclei and gluon nuclear shadowing

- Applying to coherent charmonium photoproduction on nuclei:

$$\sigma_{\gamma A \to J/\psi A}(W_{\gamma p}) = \frac{(1+\eta_A^2)R_{g,A}^2}{(1+\eta^2)R_g^2} \frac{d\sigma_{\gamma p \to J/\psi p}(W_{\gamma p}, t=0)}{dt} \left[\frac{G_A(x,\mu^2)}{A G_N(x,\mu^2)}\right]^2 \Phi_A(t_{\min})$$

Small correction $\kappa_{A/N} \approx 0.95$

From HERA and LHCb

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

From nuclear form factor

- Comparing to theoretically-defined impulse approximation (IA):

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

- Nuclear suppression factor:

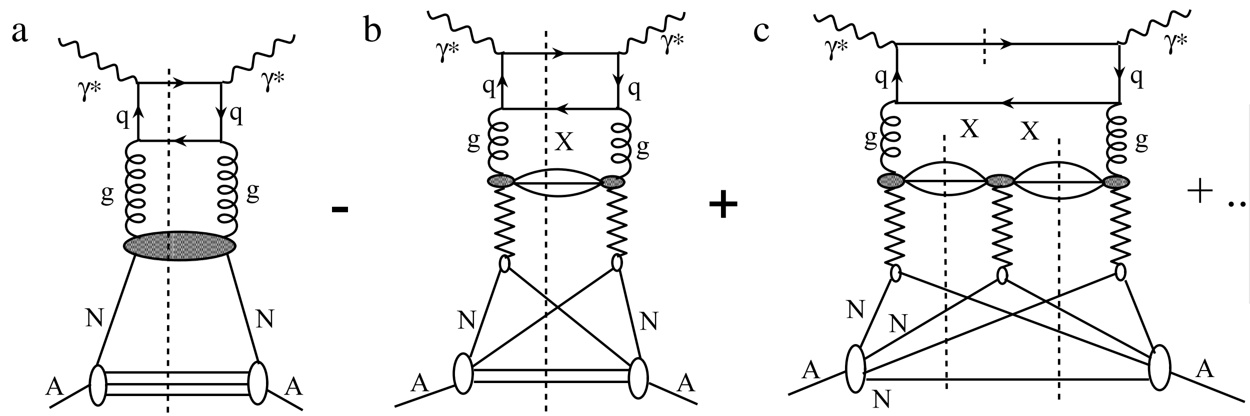
$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\mathrm{exp}}_{\gamma Pb \to J/\psi Pb}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma Pb \to J/\psi Pb}(W_{\gamma p})}\right]^{1/2} \longrightarrow S(W_{\gamma p}) = \kappa_{A/N} \frac{G_A(x,\mu^2)}{A G_N(x,\mu^2)} = \kappa_{A/N} R_g(x,\mu^2)$$

- S gives direct measure of gluon shadowing ratio $R_g(x,\mu^2)$.

Model of leading twist nuclear shadowing

- Based on generalization of the Gribov-Glauber theory of nuclear shadowing and QCD factorization theorems:

Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255



Shadowing in eA DIS is driven by diffraction in ep DIS!

$$x f_{j/A}(x, Q_0^2) = A x f_{j/N}(x, Q_0^2) - 8\pi A(A-1)\, \Re e \frac{(1-i\eta)^2}{1+\eta^2} B_{\rm diff} \int_x^{0.1} dx_P \beta f_j^{D(3)}(\beta, Q_0^2, x_P)$$

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

Nuclear part from Glauber model

Input:

- proton diffractive PDFs $f_j^{D(3)}$
- diffractive slope $B_{\rm diff}$
- model-dep. effective cross section $\sigma_{\rm soft}$

Model of leading twist nuclear shadowing (2)

- Characteristic feature — large nuclear gluon shadowing due to large gluon diffractive PDF of the proton as measured in ep diffraction in DIS at HERA.

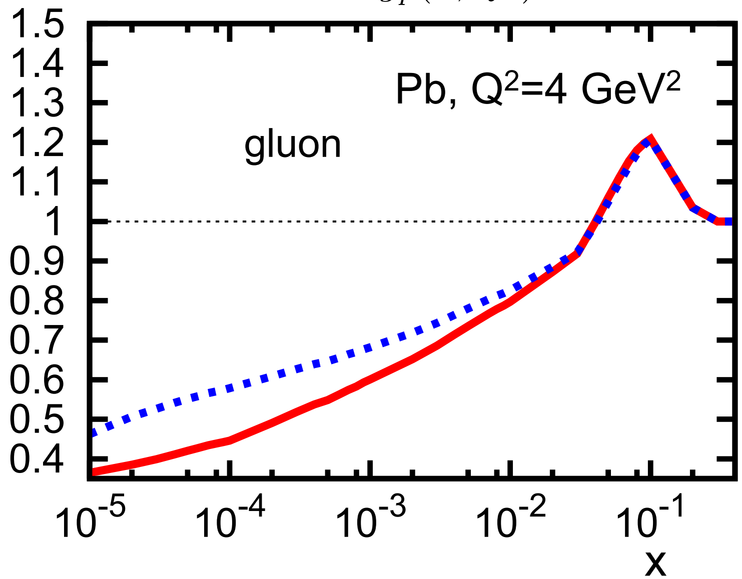
- Shadowing due to interaction with two nucleons is driven by:

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

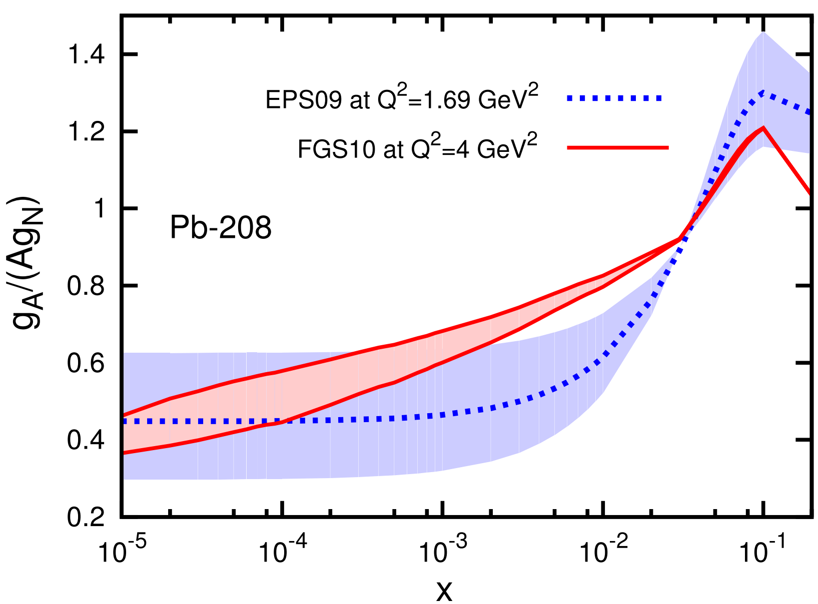
- Interaction with N ≥ 3 nucleons modeled using eikonal app. with $\sigma_{soft}=\sigma_3=$30-50 mb.

- Predictions for the gluon nuclear shadowing:

$$R_g(x,Q^2) = \frac{g_A(x,Q^2)}{Ag_p(x,Q^2)}$$



☆ Similar to EPS09 nuclear PDFs

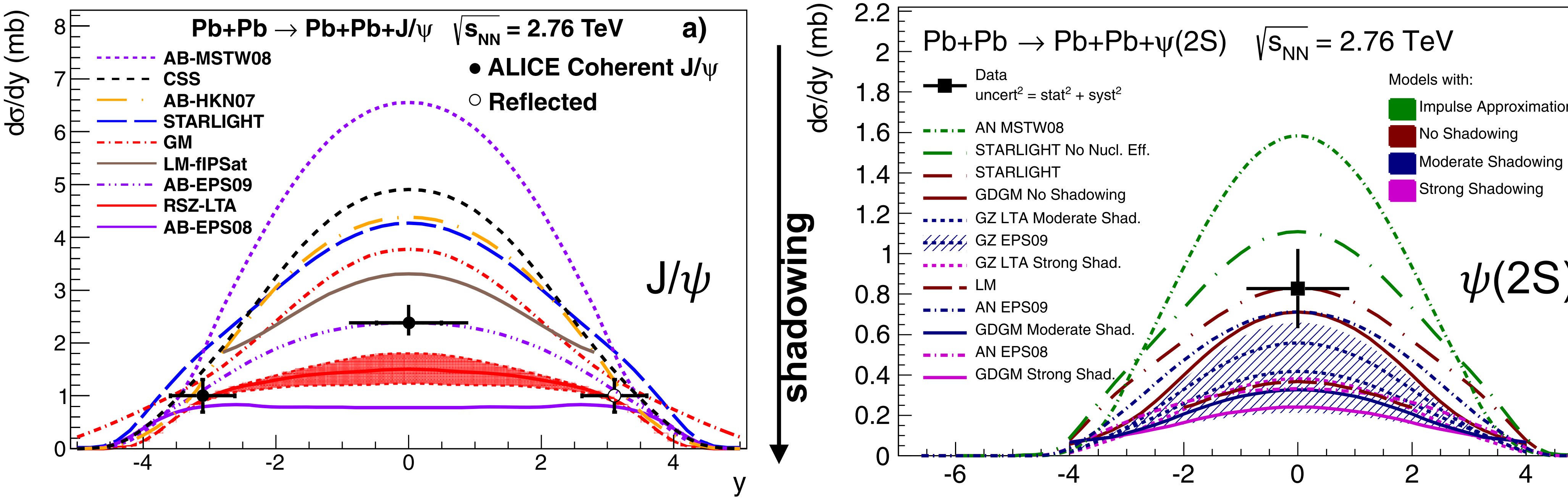


Coherent photoproduction of charmonia at LHC

- ALICE measured J/ψ, $\psi(2S)$ photoproduct. in Pb-Pb UPCs at $\sqrt{s_{NN}}$=2.76 TeV

Abelev *et al*. [ALICE], PLB718 (2013) 1273;
Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617

Adam *et al*. [ALICE], PLB751 (2025) 358

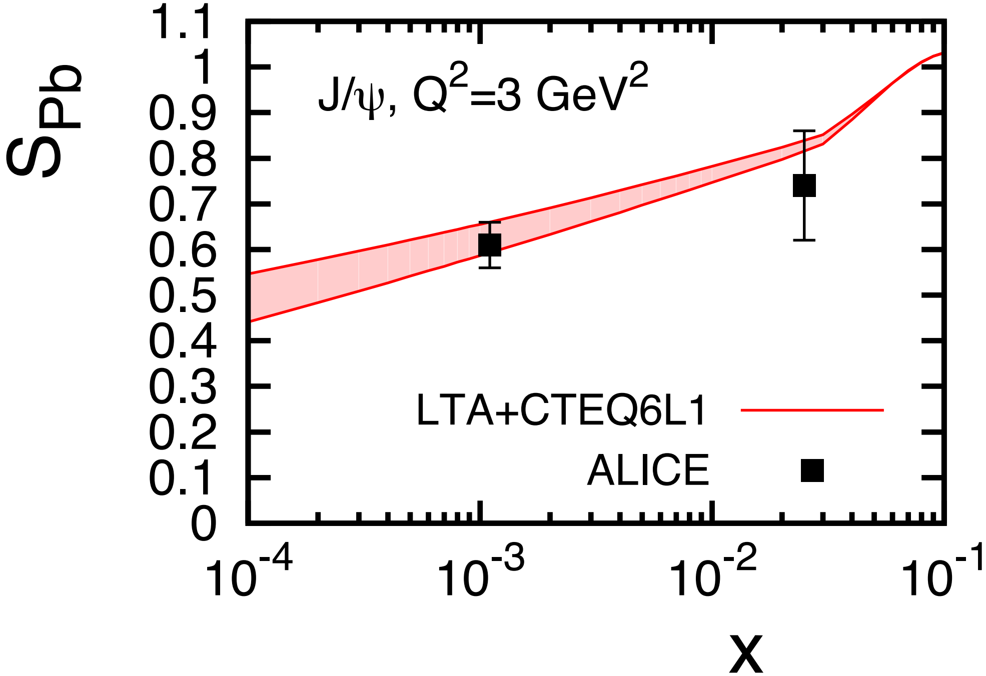


- "Consistent with models incorporating moderate nuclear gluon shadowing at $x \approx 10^{-3}$"

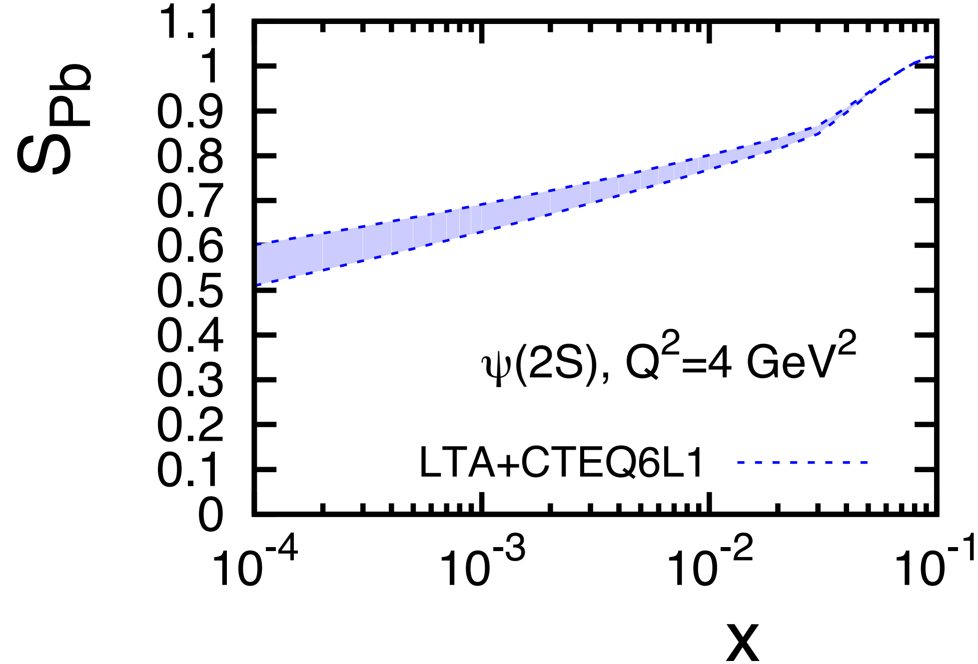
- "Disfavors models implementing strong nuclear gluon shadowing"

Comparison to nuclear suppression extracted from ALICE data

Guzey, Zhalov JHEP 1310 (2013) 207



Guzey, Zhalov, arXiv:1404.6101



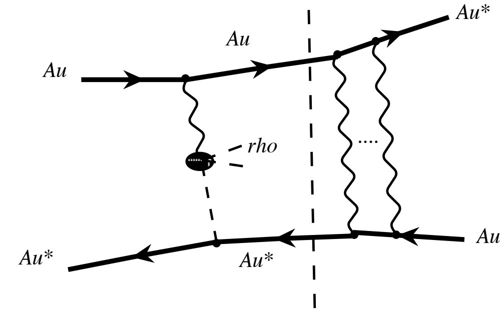
- Very good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs at 2.76 TeV → first direct evidence of large nuclear gluon shadowing at x=0.001.

- Theory predicts similar nuclear suppression in J/ψ and ψ(2S) cases → contradicts ALICE data on ψ(2S) photoproduction in Pb-Pb UPCs at central rapidity → may be resolved with more statistics in Run 2.

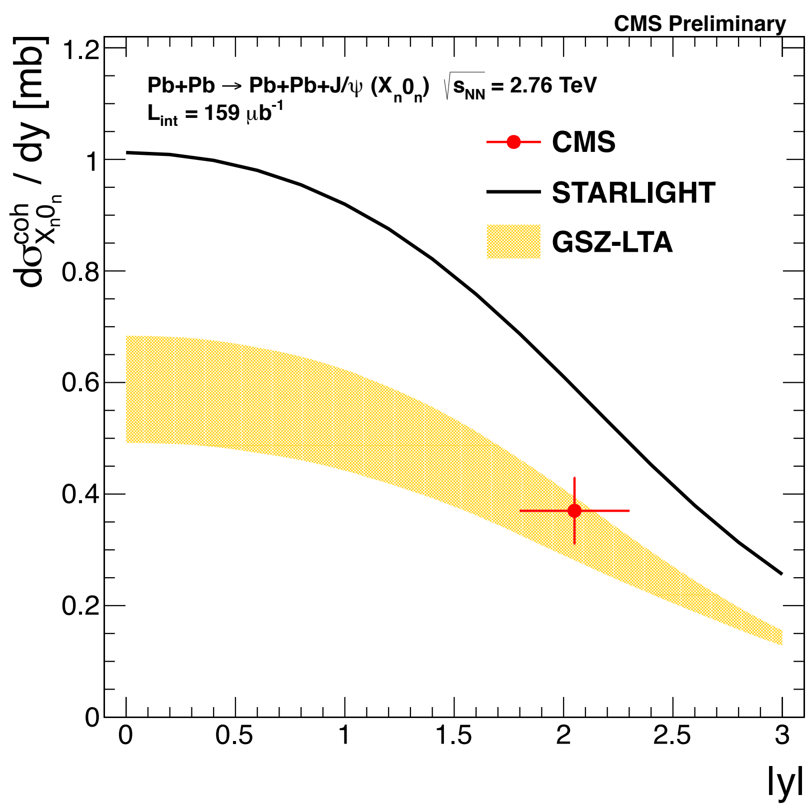
Coherent photoproduction of J/ψ in Pb-Pb UPCs accompanied by neutron emission

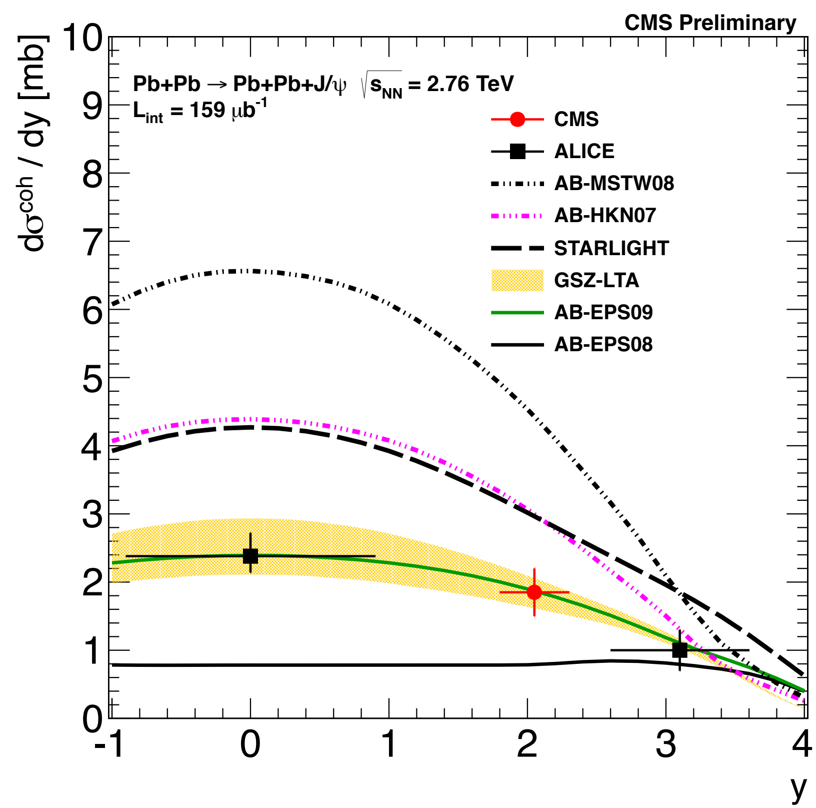
• UPCs can be accompanied by mutual e.m. excitation of nuclei followed by forward neutron emission:

Baltz, Klein, Nystrand, PRL 89 (2002) 012301



• CMS measurement in (Xn,0n)-channel (prel.) nicely agrees with our predictions of large nuclear gluon shadowing, CMS Note, CMS PAS HIN-12-99





Summary, discussion and outlook

- The gluon distribution in nuclei $g_A(x,\mu^2)$ for small x, $x < 0.005$, is poorly constrained.

- LHC pA data provide modest improvement, which possible exception of antishadowing. EIC should pin down $g_A(x,\mu^2)$ down to $x \approx 10^{-3}$ (5×10^{-4}) for $\mu^2 \approx 4$ GeV^2.

- ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs at 2.76 TeV gives first direct evidence of large nuclear gluon shadowing at $x=10^{-3}$ and $\mu^2 \approx 3$ GeV^2 which agrees with predictions of leading twist nuclear shadowing model and EPS09 fit.

- At the same time, there is discrepancy between models with large gluon shadowing and ALICE data on coherent $\psi(2S)$ photoproduction in Pb-Pb UPCs at the LHC at 2.76 TeV $\rightarrow$ Run 2 data may resolve this.

- Our leading twist approach overestimates nuclear suppression of *incoherent* J/ψ photoproduction in Pb-Pb UPCs at 2.76 TeV $\rightarrow$ account of nucleon dissociation $\gamma N \rightarrow J/\psi\, X$ may help to decrease the discrepancy.

Summary, discussion and outlook (2)

• Main competitor to pQCD description of considered processes — color dipole model. Since charmonium wf selects small-size dipoles, nuclear shadowing due to multiple rescattering on target nucleons is generically small, Lappi, Mantysaari, PRC 87 (2013) 032201; Goncalves, Machado, PRC 84 (2011) 011902

• Recent theoretical advances in the GPD framework, D.Yu. Ivanov et al, EPJC75 (2015) 2, 75; Jones, Martin, Ryskin, Teubner, J. Phys. G43 (2013) 3, 035002 : NLO corrections are very large.

• The UPC program at LHC will continue in Run 2 with measurements of light (ρ, ϕ) and heavy (J/ψ, $\psi(2S)$, Υ) vector mesons photoproduction in Pb-Pb UPCs at $\sqrt{s_{NN}}$=5.02 TeV.

• UPCs with e.m. excitations of the colliding ions followed by forward neutron emission and detection in ZDCs allow one to separate low-W and high-W terms in UPC cross section → access to lower $x < 10^{-3}$ in $g_A(x,\mu^2)$.

• New UPC processes for Run 2 at the LHC: diffractive photoproduction of dijets to address factorization breaking and measure nuclear diffractive PDFs.