J/ψ photoproduction on nuclei

Vadim Guzey

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

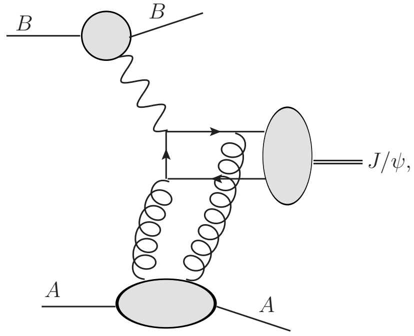
Outline:

- Ultraperipheral collisions (UPCs) and gluon nuclear shadowing
- Gluon nuclear shadowing from J/ψ photoproduction at the LHC
- Outlook and Conclusions

Workshop on LHCb Heavy Ion and Fixed Target Physics
CERN, Jan 9-10, 2017

Ultraperipheral collisions (UPCs)

- Ions can interact at large impact parameters $b >> R_A+R_B$ → ultraperipheral collisions (UPCs) → strong interaction suppressed → interaction via quasi-real photons, Fermi (1924), von Weizsäcker; Williams (1934)



- UPCs correspond to empty detector with only two lepton tracks
- Nuclear coherence by veto on neutron production by Zero Degree Calorimeters and selection of small pt

- Coherent photoproduction of vector mesons in UPCs:

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

Photon flux: Photoproduction cross section

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

- Photon flux from QED:
- high intensity ~ Z^2
- large photon energies $\zeta = k(2R_A/\gamma_L)$

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

UPCs = γp and γA interactions at unprecedentedly large energies,
Baltz *et al.*, The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1

Nuclear shadowing

• Nuclear shadowing (NS) = suppression of cross section on a nucleus compared to sum of cross sections on individual nucleons: $\sigma_A < A\ \sigma_N$.

• Observed for beams of nucleons, pions, real and virtual photons, neutrinos, other hard probes of large energies (> 1 GeV)

• Explained by multiple rescattering of the projectile on target nucleons → destructive interference among amplitudes for interaction with 1, 2, …nucleons → nucleons in rear of the nucleus "see" smaller (shadowed) flux: $\sigma_A \sim A^{2/3}$.

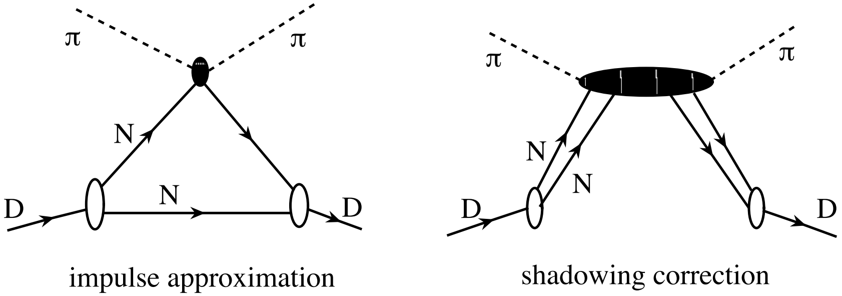


Figure 2: Graphs for pion-deuteron scattering.

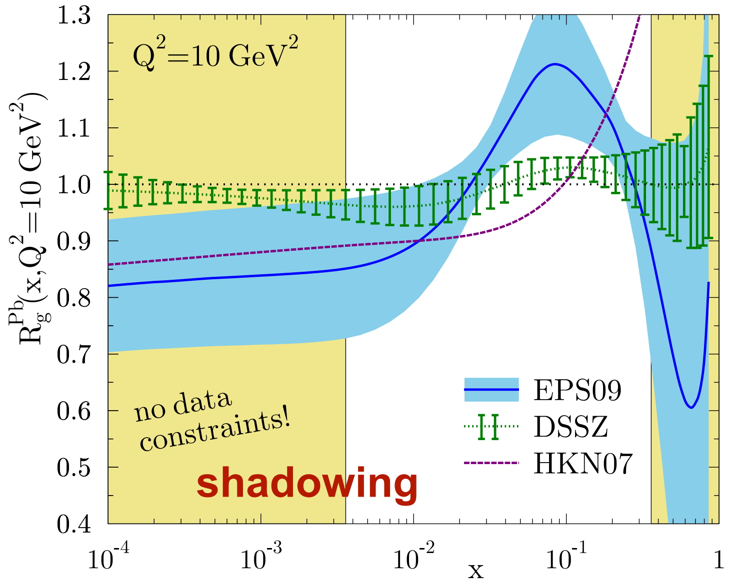
• NS in photoproduction of J/ψ, $\psi(2S)$, Y on nuclei:

- new constraints on nuclear gluon distribution $g_A(x,\mu^2)$ at small x and models of NS: VG, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290; VG, Zhalov, JHEP 10 (2013) 207; JHEP 02 (2014) 046; VG, Strikman, Zhalov, EPJ C 74 (2014) 2942; VG, Kryshen, Zhalov, PRC 93 (2016) 055206

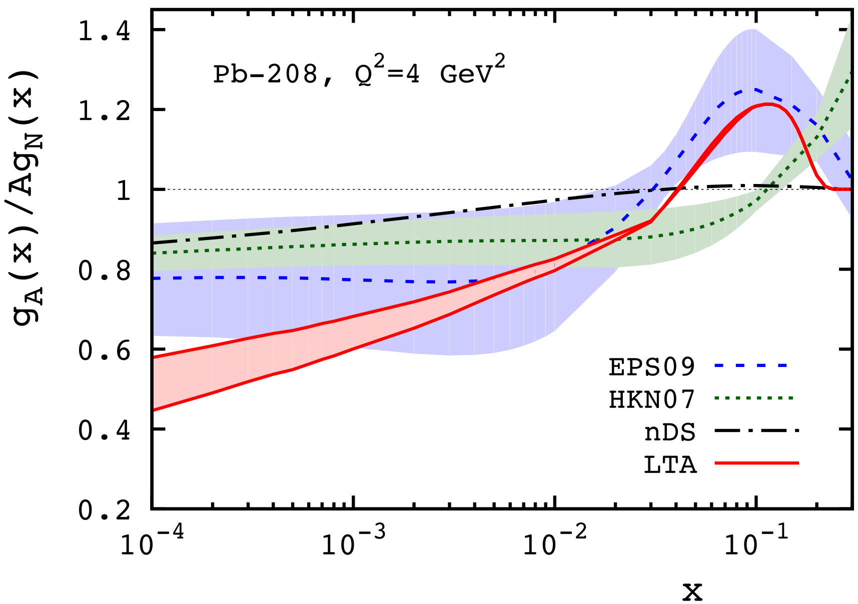
Gluon nuclear shadowing

- Gluon nuclear shadowing: $g_A(x,Q^2) < A\, g_N(x,Q^2)$ for small x.
- Nuclear PDFs extracted from (mostly) fixed-target DIS data using global QCD fits and also predicted by dynamical models:

H. Pauukunen, NPA 926 (2014) 24



Global fits vs. Leading Twist approx, Frankfurt, VG, Strikman 2012



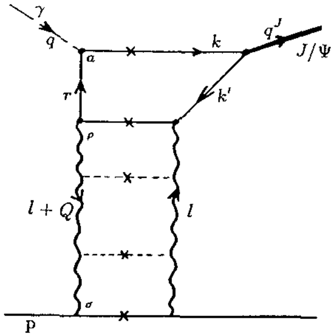
- Gluon nPDF $g_A(x,\mu^2)$ is known with large uncertainties → **I.Schienbein's talk**
- pA@LHC data help little and mostly in antishadowing region, Armesto et al, arXiv:1512.01528; Eskola et al, JHEP 1310 (2013) 213; Eskola et al, arXiv:1612.075 (EPPS16 nPDFs)
- Future: Electron-Ion Collider in the US, Accardi et al, ArXiv:1212.1701; LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001
- Option right now: Charmonium photoproduction in Pb-Pb UPCs@LHC

Exclusive J/ψ photoproduction

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

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

M. Ryskin (1993)



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

• In collinear factorization for exclusive processes, at LO in α_S and NR expansion for J/ψ wave function:

$$\frac{d\sigma_{\gamma T \to J/\psi T}(W, t=0)}{dt} = \frac{16\pi^3 \Gamma_{ee}}{3\alpha_{\rm e.m.} M_V^5}\left[\alpha_S(\mu^2) H^g(\xi, \xi, t=0, \mu^2)\right]^2$$

• NLO corrections are very large, Ivanov, Schafer, Szymanowski, Krasninov, EPJ C 75 (2015) 2, 75; Jones, Martin, Ryskin, Teubner, J. Phys. G43 (2015), no.3, 035002, but can be tamed by choice of factorization scale $\mu = m_c$ and other tricks, Jones et al, Eur.Phys.J. C76 (2016) no.11, 633.

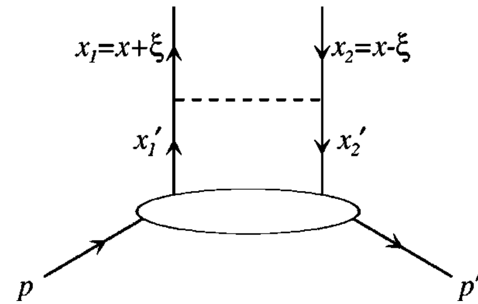
• I will stay at LO in my talk.

Exclusive J/ψ photoproduction (2)

- At high energies (small ξ) and LO in α_S, GPDs can be connected to PDFs in a weakly model-dependent way.

- At low μ_0, $x_{1,2} \gg \xi \rightarrow$ skewness can be neglected

- All skewness at $\mu > \mu_0$ due to evolution, Frankfurt, Freund, VG, Strikman, PLB 418 (1998) 345; Shuvaev et al., RPD 60 (1999) 014015



$$H^g(\xi, \xi, t=0, \mu^2) = R_g x g(x_B, \mu^2)$$

$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+5/2)}{\Gamma(4+\lambda)} \approx 1.2, \text{ for } xg \sim 1/x^{\lambda} \text{ with } \lambda \approx 0.2$$

- At LO, this ansatz somewhat overestimates HERA DVCS data, Freund, McDermott, Strikman, PRD67 (2003) 036001; Belitsky, Mueller, Kirchner, NPB 629 (2002) 323.

Coherent J/ψ photoproduction on nuclei

- Application to nuclear targets:

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

Small correction $k_{A/N} \approx 0.90$-95

From HERA and LHCb

Gluon shadow. Rg

From nuclear form factor: approximation

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

- Nuclear suppression factor S → direct access to R_g

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

experiment

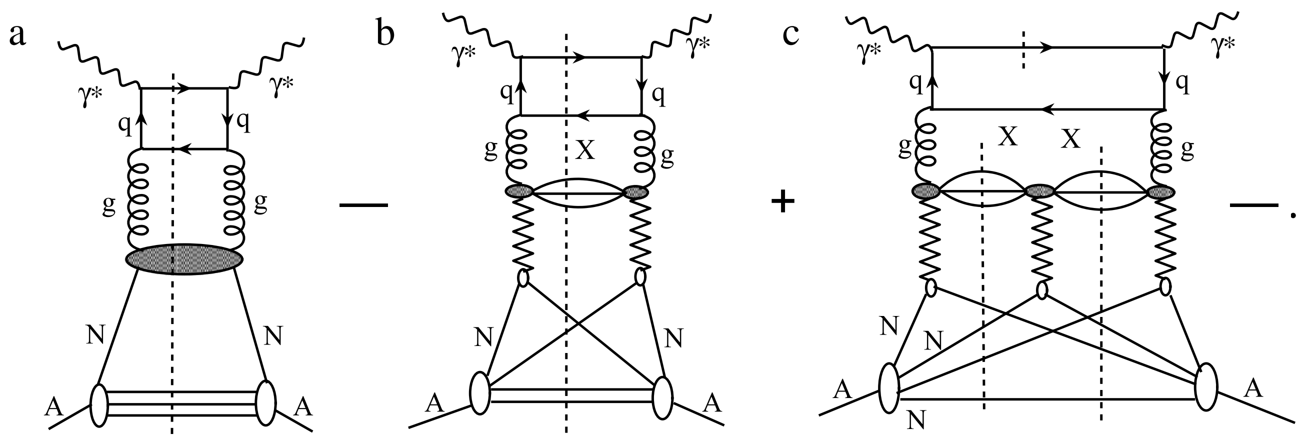
IA=Impulse Approximation

From QCD fits or theory (LTA)

- Side remark: we choose μ^2=3 GeV^2 to correctly reproduce W-dependence of HERA data on $\gamma p \to J/\psi p$.

Leading twist nuclear shadowing model

- Combination of Gribov-Glauber NS model with QCD factorization theorems for inclusive and diffractive DIS → shadowing for individual partons j, Frankfurt, Strikman (1999)



- Interaction with 2 nucleons: model-indep via diffractive PDFs:

$$\sigma_2^j(x) = \frac{16\pi}{x f_{j/N}(x,\mu^2)} \int_x^{0.1} dx_P \beta f_{j/N}^{D(4)}(x,\mu^2,x_P,t=0)$$

- Interaction with ≥ 3 nucleons: via soft hadronic fluctuations of γ^*

$$\sigma_{\text{soft}}(x) = \frac{\int d\sigma P_\gamma(\sigma)\sigma^3}{\int d\sigma P_\gamma(\sigma)\sigma^2}$$

P(σ) is probability to interact with Xsection σ

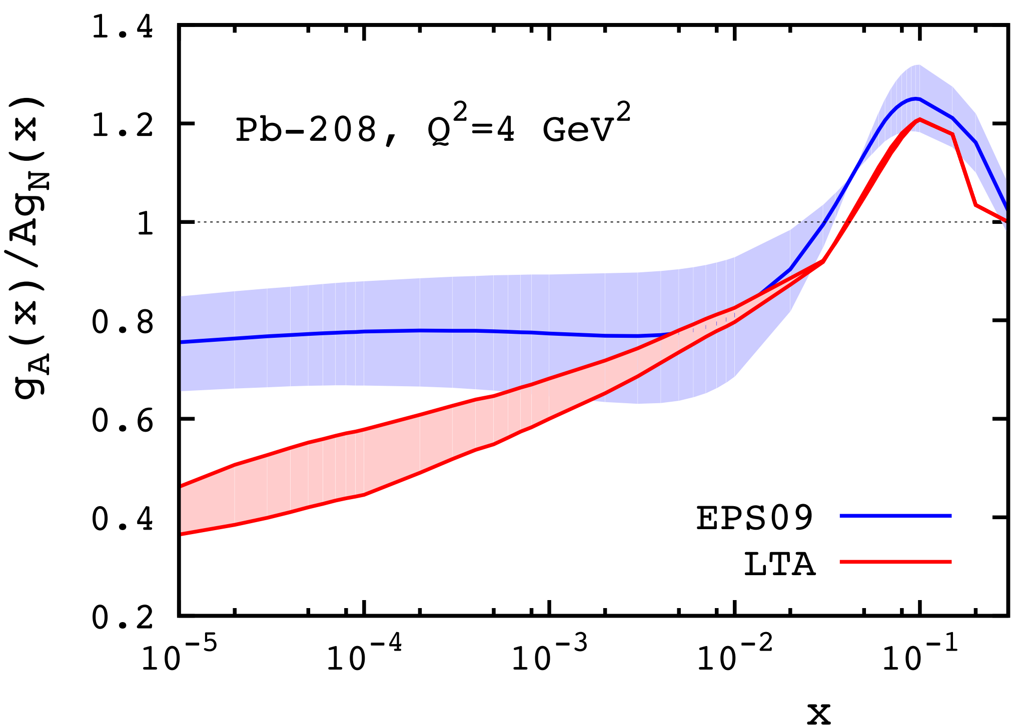
- Quasi-eikonal approximation in low-x limit, Frankfurt, Guzey, Strikman 2012:

$$x f_{j/A}(x,\mu^2) = A f_{j/N}(x,\mu^2) - \frac{2\sigma_2^j f_{j/N}(x,\mu^2)}{[\sigma_{\text{soft}}^j(x)]^2} \int d^2b \left(e^{-\frac{1}{2}\sigma_{\text{soft}}^j(x) T_A(b)} - 1 + \frac{\sigma_{\text{soft}}^j(x)}{2} T_A(b) \right)$$

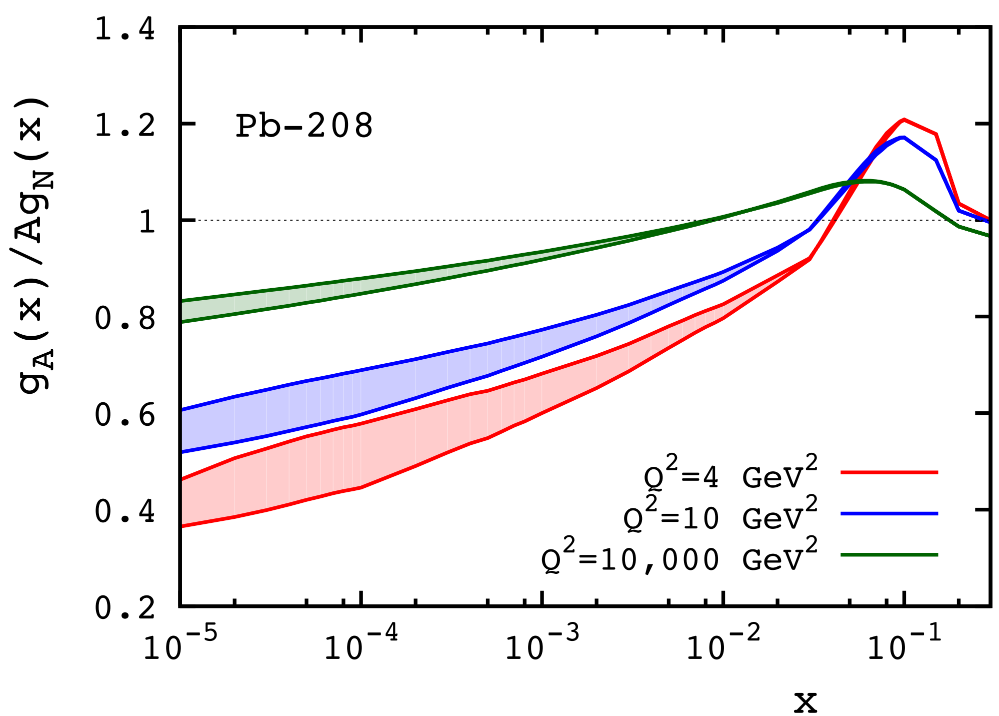
Leading twist nuclear shadowing model (2)

- Model gives nuclear PDFs at μ^2=3-4 GeV^2 for subsequent DGLAP evolution.
- Name "leading twist" since diffractive structure functions/PDFs measured at HERA scale with Q^2.
- Gluon diffractive PDFs are large, ZEUS, H1 2006 → predict large shadowing for $g_A(x,\mu^2)$, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Input: Leading twist (LTA) vs. EPS09



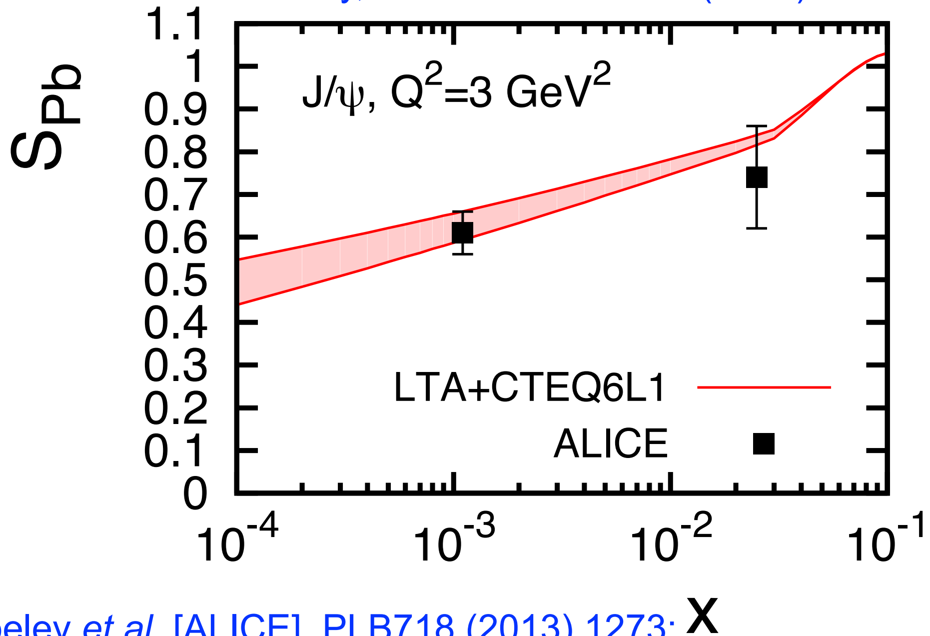
Results of DGLAP evolution: from Q^2=4 GeV^2 to Q^2=10 and 10,000 GeV^2



For quarks, the agreement between LTA and EPS09 is much better.

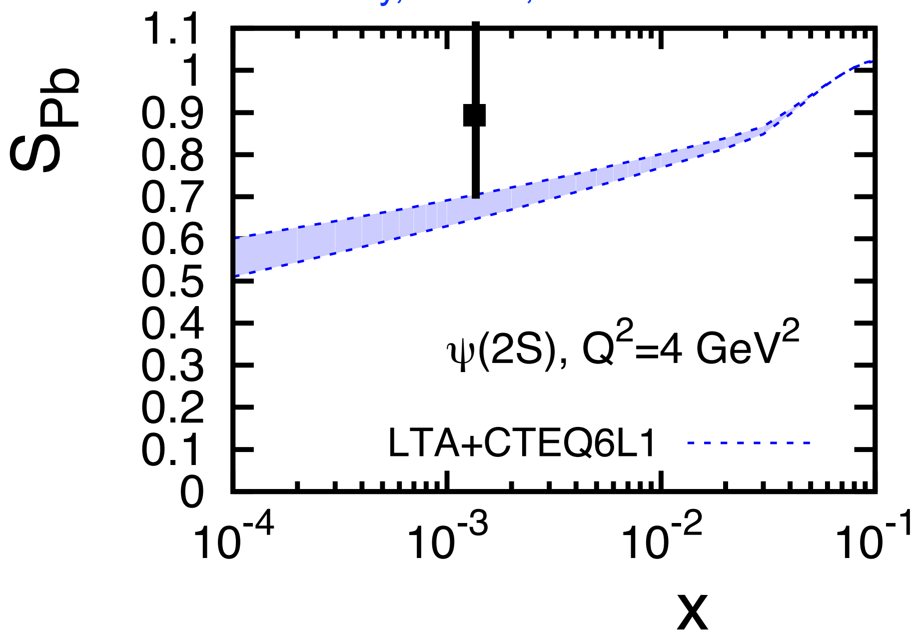
Comparison to S_{Pb} from ALICE UPC data

Guzey, Zhalov JHEP 1310 (2013) 207



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

Guzey, Zhalov, arXiv:1404.6101



Adam *et al*. [ALICE], PLB751 (2015) 358

- Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV → first direct evidence of large gluon NS, Rg(x=0.001) ≈ 0.6.

- Similarly good description using EPS09+CTEQ6L.

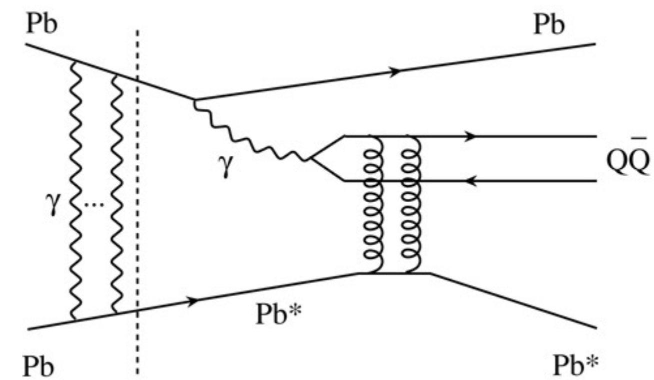
- Cannot be described by simple versions of the dipole model, Lappi, Mantysaari 2013

- We predict similar suppression for J/ψ and ψ(2S) → tension with ALICE data on ψ(2S) photoproduction in Pb-Pb UPCs at y=0 → wait for better precision Run 2 data.

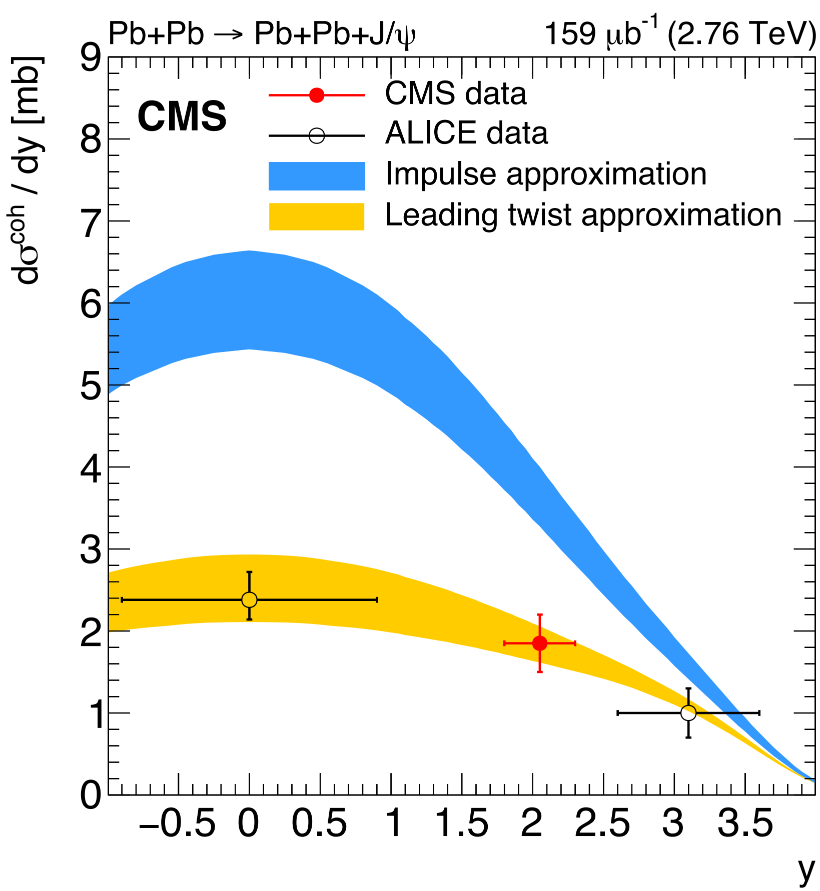
Coherent J/ψ photoproduction in Pb-Pb UPCs with forward neutron emission

• UPCs can be accompanied by e.m. excitation of colliding ions followed by forward neutron emission,

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



• CMS data in 0nXn-channel converted to the total coherent cross section agrees very well with our predictions of large gluon shadowing, CMS Collab., arXiv:1605.06966



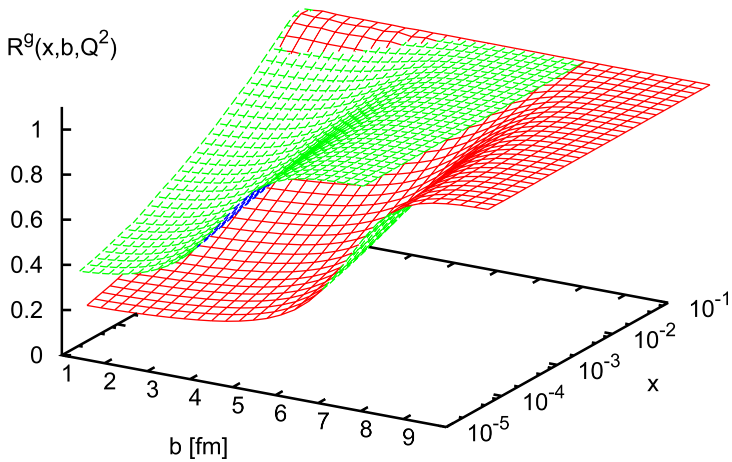
LT shadowing: Impact parameter dependence

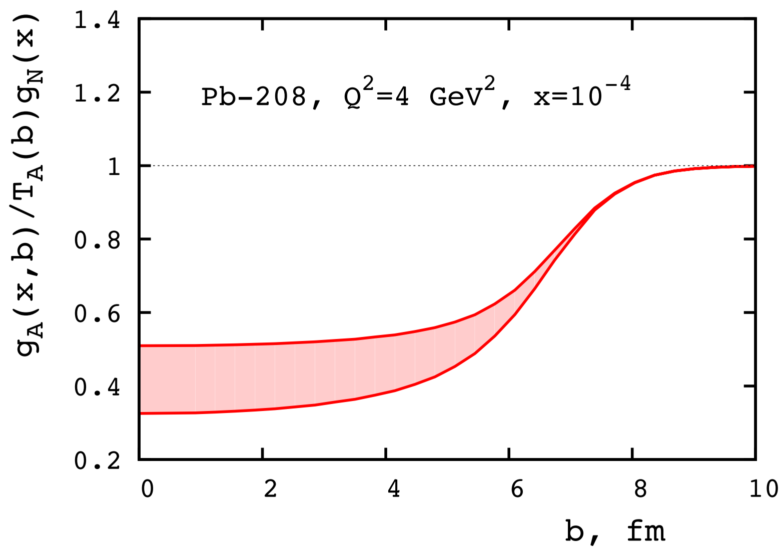
- Shadowing arises from rescattering on target nucleons at given impact parameter b.

- Removing integral over b → impact-parameter-dependent nuclear PDFs:

$$xf_{j/A}(x,b,\mu^2) = T_A(b)xf_{j/N}(x) - \frac{2\sigma_2^j f_{j/N}(x,\mu^2)}{[\sigma_{\text{soft}}^j(x)]^2}\left(e^{-\frac{1}{2}\sigma_{\text{soft}}^j(x)T_A(b)} - 1 + \frac{\sigma_{\text{soft}}^j(x)}{2}T_A(b)\right)$$

$g_A(x,b)/[T_A(b)g_N(x)]$





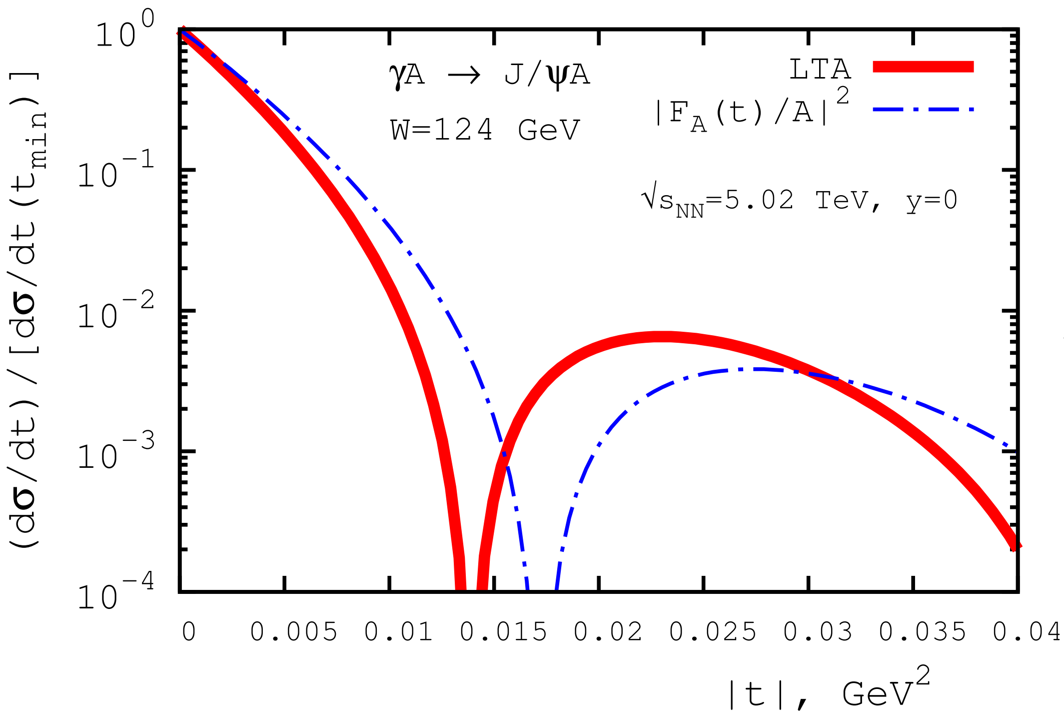
- Can be only indirectly determined using global QCD fits, EPS09s nPDFs, Helenius et al (2012)
- Can be probed and tested in:
  - centrality dependence of hard pA/AA processes, Helenius et al (2012)
  - *t* dependence of exclusive γ^*A and γA processes, e.g., $\gamma^*A \to \gamma A$, Frankfurt, VG, Strikman 2012, $\gamma A \to J/\psi A$, VG, Strikman, Zhalov, arXiv:1611.05471.

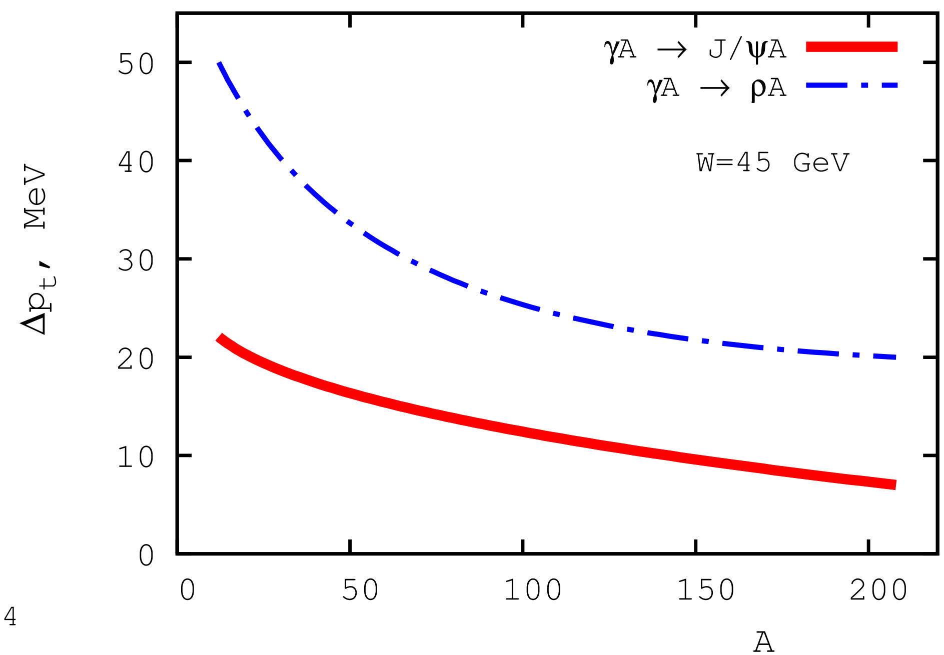
Accessing transverse nuclear gluon distribution

- Measurement of t-dependence of $\gamma A \rightarrow J/\psi A$: complementary constraint on $g_A(x,Q^2)$ and determination of impact parameter dependent nPDF $g_A(x,b,Q^2)$

$$\frac{d\sigma_{\gamma A\rightarrow J/\psi A}}{dt} = \frac{d\sigma_{\gamma p\rightarrow J/\psi p}(t=0)}{dt}\left(\frac{R_{g,A}}{R_{g,p}}\right)^2 \left[\frac{\int d^2b\, e^{i\vec{q}_\perp \vec{b}} g_A(x,b,\mu^2)}{A g_p(x,\mu^2)}\right]^2$$

- Impact parameter gluon nuclear shadowing leads to shift of t-dependence → can be interpreted as **5-11% broadening** in impact parameter space of gluon nPDF:





VG, Strikman, Zhalov, arXiv:1611.05471

J/ψ photoproduction on nuclei in fixed-target kinematics

- Collision energies are lower → nuclear gluons are probed at higher x. For Pb beam, $\sqrt{s_{NN}}$=72 GeV, x≈0.02 at y=0:
  - complimentary to ALICE and CMS measurements
  - cleaner theoretical interpretation using both global fits and LTA
  - still very interesting since affects $g_A(x,\mu^2)$ at all x via momentum sum rule
  - possibility to vary nuclear targets
  - possibility to study Pomeron-Odderon fusion mechanism in pp and pA UPCs, Lansberg, Szymanowski, Wagner, JHEP 1509 (2015) 087

- Fixed-target kinematics allows for better studies of nuclear break-up than collider mode (pT measurements, nuclear fragment detection):
  - understanding of incoherent background for coherent photoproduction, tuning of UPC MC STARLIGHT
  - resolution of discrepancy between ALICE data on incoherent J/ψ photoproduction in Pb-Pb UPCs at $\sqrt{s_{NN}}$=2.76 TeV and large nuclear gluon shadowing, VG, Strikman, Zhalov, EPJ C 74 (2014) 2942
  - possible insight into origin of excess of low-pt J/ψ in peripheral Pb-Pb collisions, which could be due to photoproduction on nucleus fragments, ALICE, PRL 116 (2016) 222301

Incoherent J/ψ photoproduction in Pb-Pb UPCs@LHC

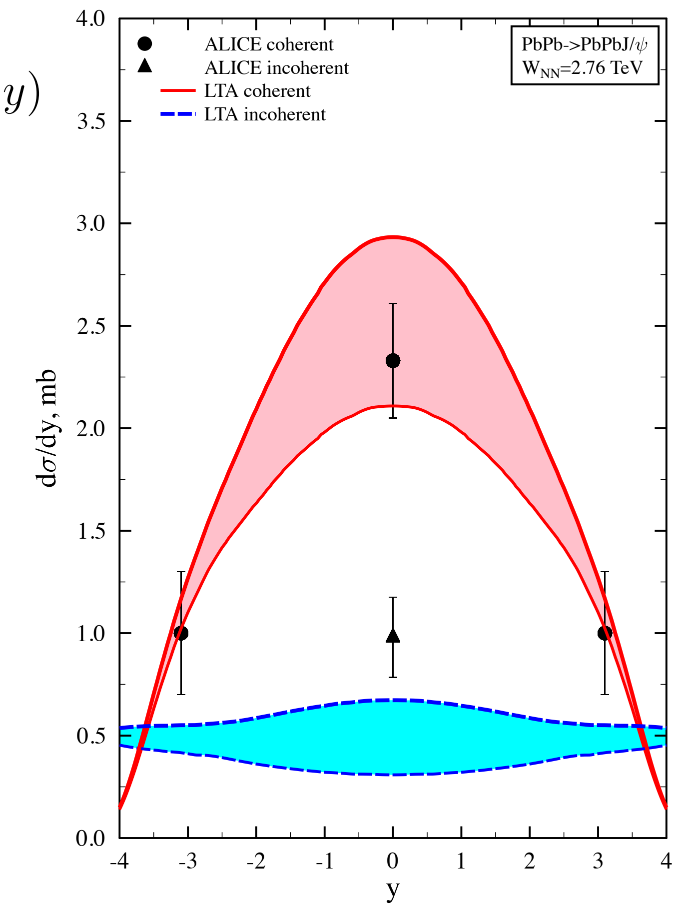
• Leading twist theory of nuclear shadowing allows one to make predictions without introducing extra parameters: VG, Strikman, Zhalov,EPJ C 74 (2014) 2942

$$S_{\rm incoh}(W_{\gamma p}) \equiv \frac{d\sigma^{\rm pQCD}_{\gamma A\to J/\psi A'}(W_{\gamma p})/dt}{A d\sigma^{\rm pQCD}_{\gamma p\to J/\psi p}(W_{\gamma p})/dt} = \frac{1}{A}\int d^2\vec{b}\, T_A(b)\left[1-\frac{\sigma_2}{\sigma_3}+\frac{\sigma_2}{\sigma_3}e^{-\sigma_3/2T_A(b)}\right]^2$$

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

• ... and predicts too much shadowing

• One possible source of discrepancy: contribution of nucleon dissociation $\gamma + N \to J/\psi + Y$ which can be singled out by different t-dependence → fixed-target might give advantage



Conclusions

- Coherent photoproduction of J/ψ on nuclei in UPCs@LHC gives direct access to nuclear gluon distribution $g_A(x,\mu^2)$ down to $x \approx 10^{-3}$ at $\mu^2 \approx 3$ GeV^2.

- ALICE and CMS data give first evidence of large nuclear gluon shadowing, which is consistent with predictions of LT NS model and EPS09 nPDFs.

- Measurement of t dependence of $\gamma A \rightarrow J/\psi A$ will access 3D nuclear gluon distribution $g_A(x,b,Q^2)$.

- Photoproduction of J/ψ in UPCs in fixed-target kinematics has certain advantages:
    - large x allows for smaller theoretical uncertainty in predictions for $g_A(x,\mu^2)$
    - detection of nuclear fragments and t-dependence measurements constrain incoherent photoproduction and help to solve several outstanding problems.

- UPCs@LHC = forerunner of measurements of nuclear gluon distributions at an Electron-Ion Collider.