Gluon distribution in the proton and nuclei at small x from photoproduction of charmonia in ultraperipheral collisions at the LHC

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Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290
Guzey, Zhalov, JHEP 10 (2013) 207 and JHEP 02 (2014) 046
Guzey, Strikman, Zhalov, EPJ C (2014) 74: 2942
Guzey, Zhalov, arXiv:1405.7529 and arXiv:1404.6101

Seminar at Institute for Theoretical Physics, University of Münster, Oct 26, 2015

Outline

- Gluon distributions in the nucleon and nuclei and ion ultraperipheral collisions (UPCs).

- Photoproduction of J/ψ and $\psi(2S)$ in pp and pA UPCs at the LHC and constraints on $g_p(x,\mu^2)$ at small x.

- Photoproduction of J/ψ and $\psi(2S)$ in Pb-Pb UPCs at the LHC and constraints on $g_A(x,\mu^2)$ at small x.

- Outstanding problems with pQCD description of some AA UPC measurements and possible future directions of UPC studies.

Gluon distribution in the nucleon

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

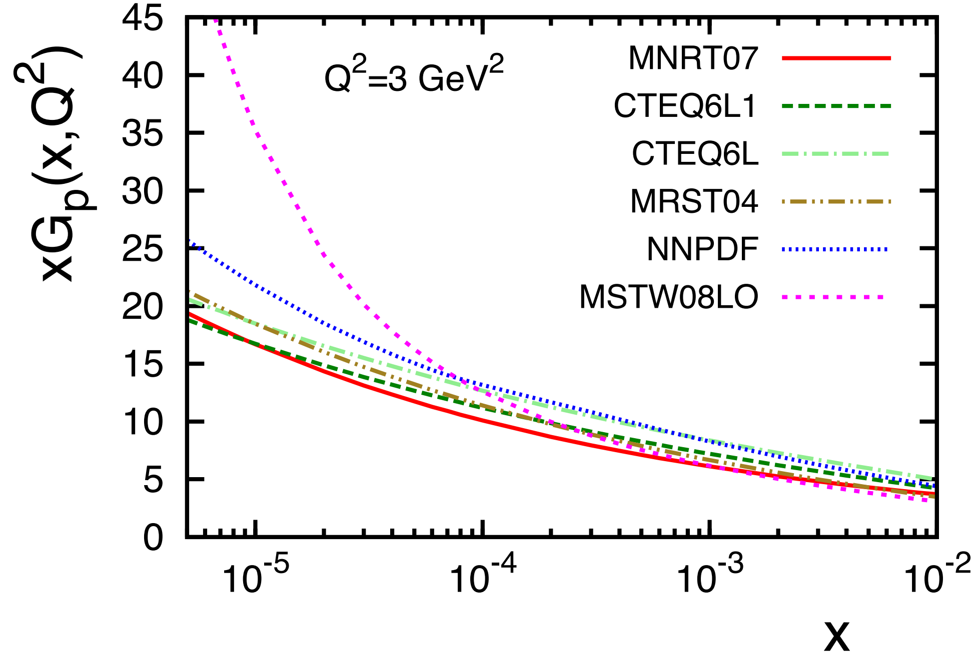
• Fundamental quantity of Quantum Chromodynamics (QCD) describing hadron structure in processes with large momentum transfer.

• Important element of phenomenology of hard processes in QCD (e.g. Higgs, QGP, etc.)

• At small x, the proton $g_p(x,\mu^2)$ is known with significant uncertainties →

• New constraints on $g_p(x,\mu^2)$ from production of jets, direct photons, W/Z bosons in pp@LHC.

• In distant future, EIC and LHeC.



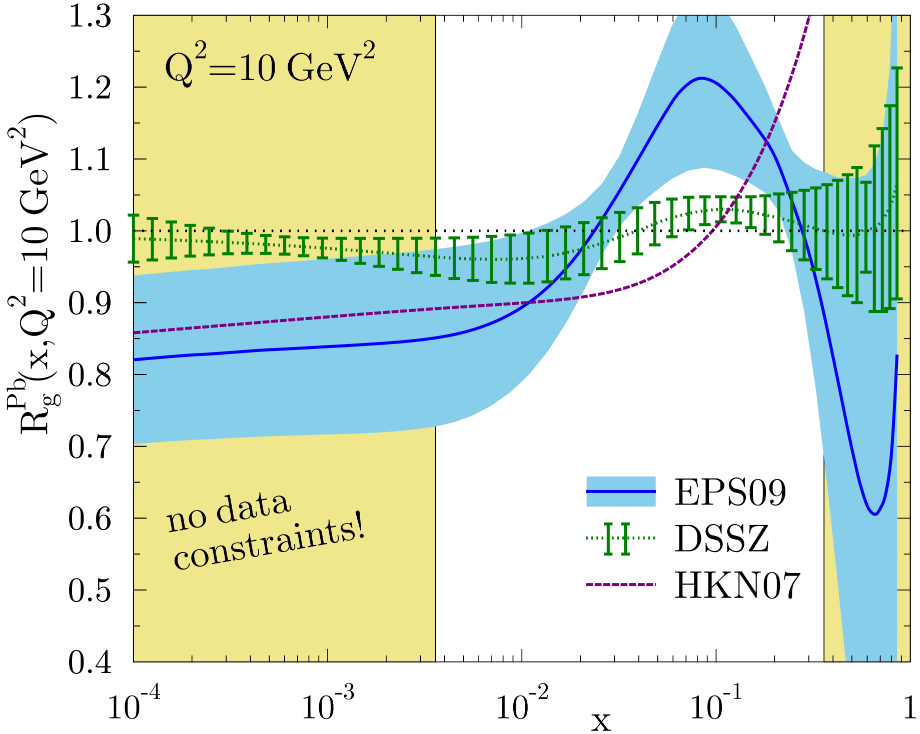
Right now: photoproduction of charmonia (J/ψ, $\psi(2S)$) in ion UPC@LHC.

Gluon distributions in nuclei

- Like in the proton case, $g_A(x,\mu^2)$ is determined from global QCD fits to data.

- Rather large uncertainties, especially at small x in nuclear shadowing region due to:
  - limited kinematics
  - indirect extraction via DGLAP evolution
  - different assumptions about shape

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



H. Pauukunen, NPA 926 (2014) 24

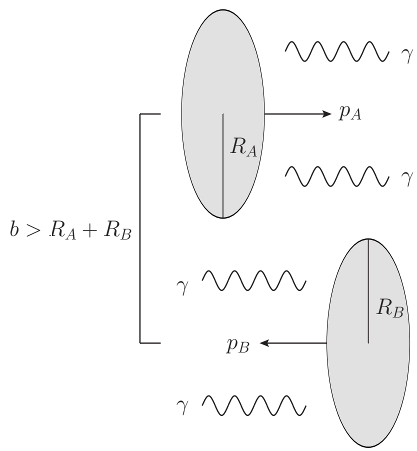
- New constraints on $g_A(x,\mu^2)$ from production of jets, direct photons, W/Z bosons in pA@LHC.

- In distant future, Electron-Ion Collider (EIC).

Right now: photoproduction of charmonia (J/ψ, $\psi(2S)$) in AA and pA UPCs at the LHC.

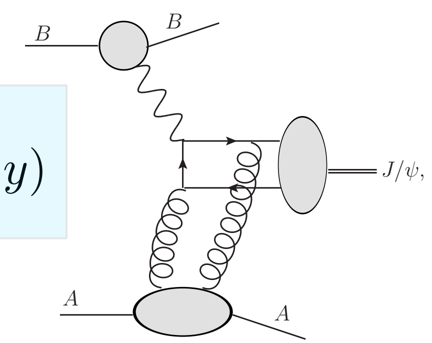
Ultraperipheral collisions at the LHC

- 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)



$$\frac{d\sigma_{AB\to ABJ/\psi}(y)}{dy} = k(y)N_{\gamma/A}(y)\sigma_{\gamma B\to J/\psi B}(y) + k(-y)N_{\gamma/B}(-y)\sigma_{\gamma A\to J/\psi A}(-y)$$

Only for pp: rapidity gap survival

photon flux

photoproduction cross section

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

UPCs at the LHC (2)

• Photon flux of point-like source:

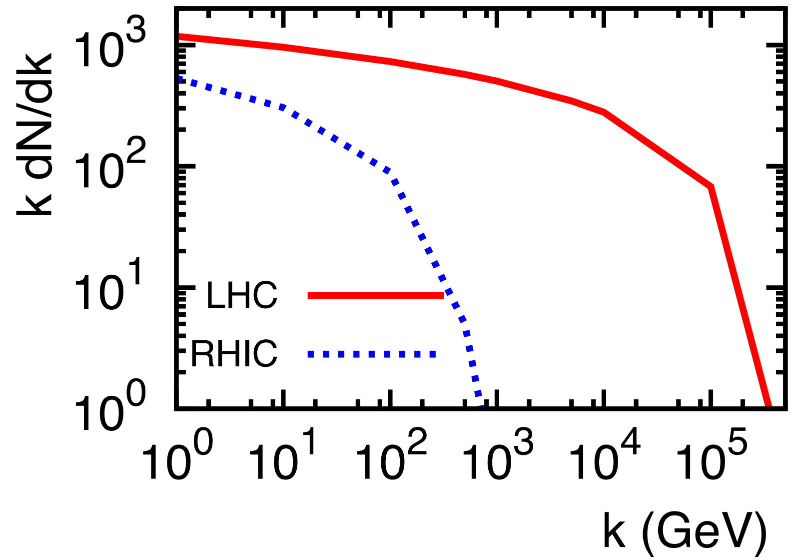
$$N_{\gamma/Z}(k) = \frac{2Z^2\alpha_{\rm em}}{\pi}[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}(K_1^2(\zeta) - K_0^2(\zeta))]$$

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 ТэВ → $\omega_{max} \approx 120$ 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 $g_A(x,\mu^2)$.

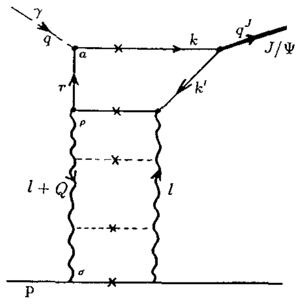
A. Baltz *et al*., The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1

Exclusive photoproduction of charmonium

• In leading order (LO) of perturbative QCD and non-relativistic limit for charmonium (J/ψ, ψ(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:

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

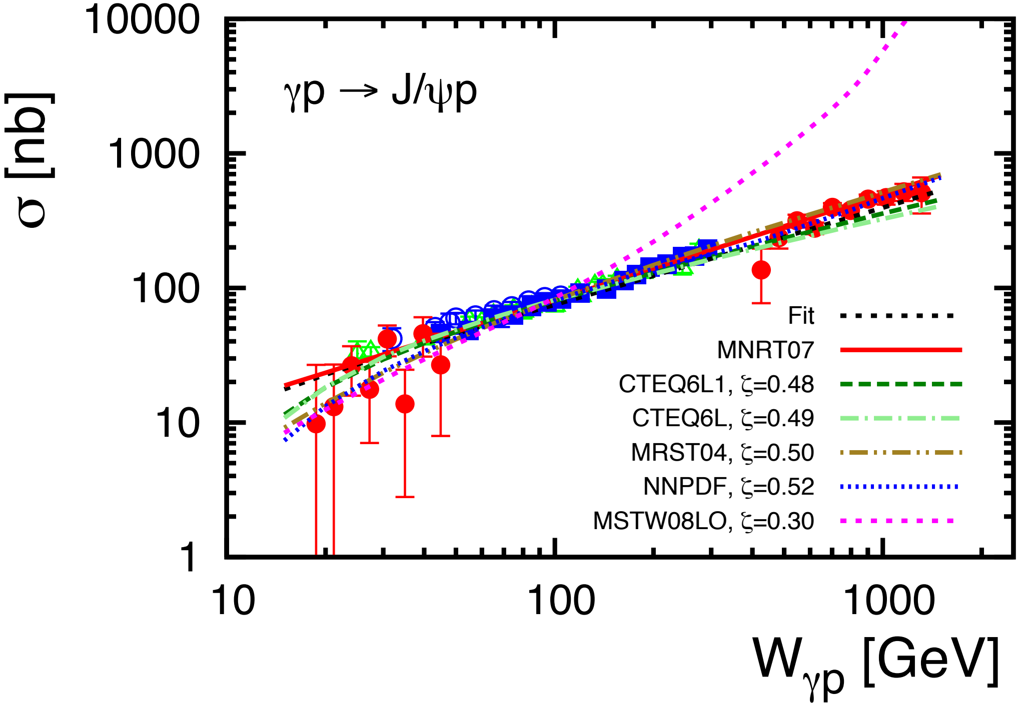
Ryskin, Roberts, Martin, Levin, Z. Phys. C 76 (1997) 231;
Frankfurt, Koepf, Strikman, PRD 57 (1997) 231

• Our phenomenological approach:
- choose scale μ^2 to describe the 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
- ψ(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

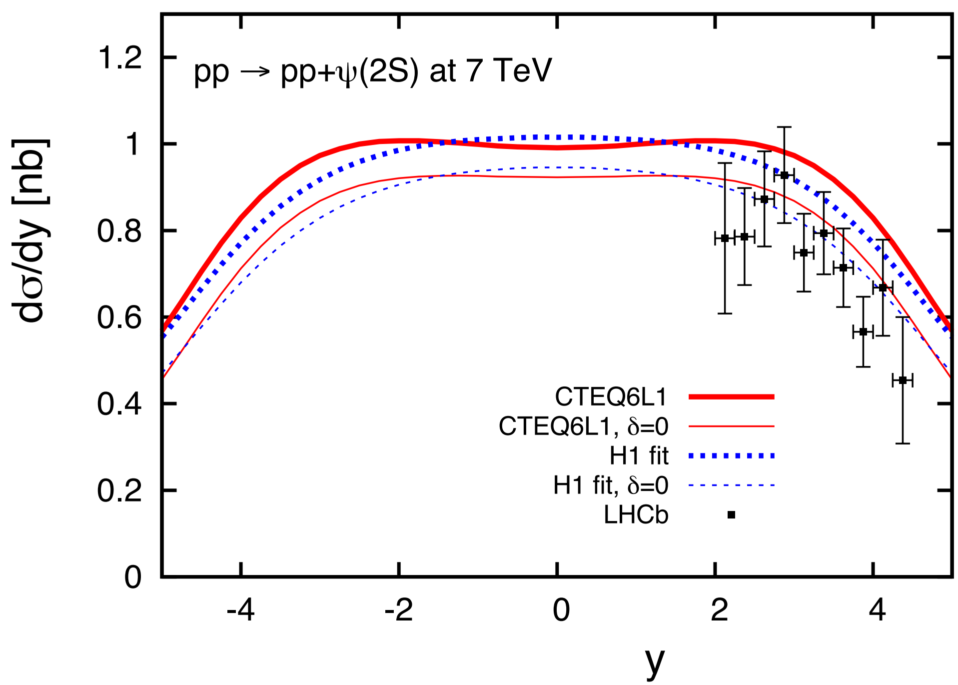
Comparison to LHCb data on pp UPCs

Guzey, Zhalov JHEP 1310 (2013) 207



R. Aaij et al., (LHCb) J. Phys. G. 40 (2013) 045001

Guzey, Zhalov, arXiv:1405.7929



R. Aaij et al., (LHCb) J. Phys. G. 41 (2014) 055002

- Extraction of $\sigma_{\gamma p \to J/\psi p}$ from the pp UPC requires additional input: the soft rapidity gap survival probability k ≈ 0.8 and separation of two solutions.

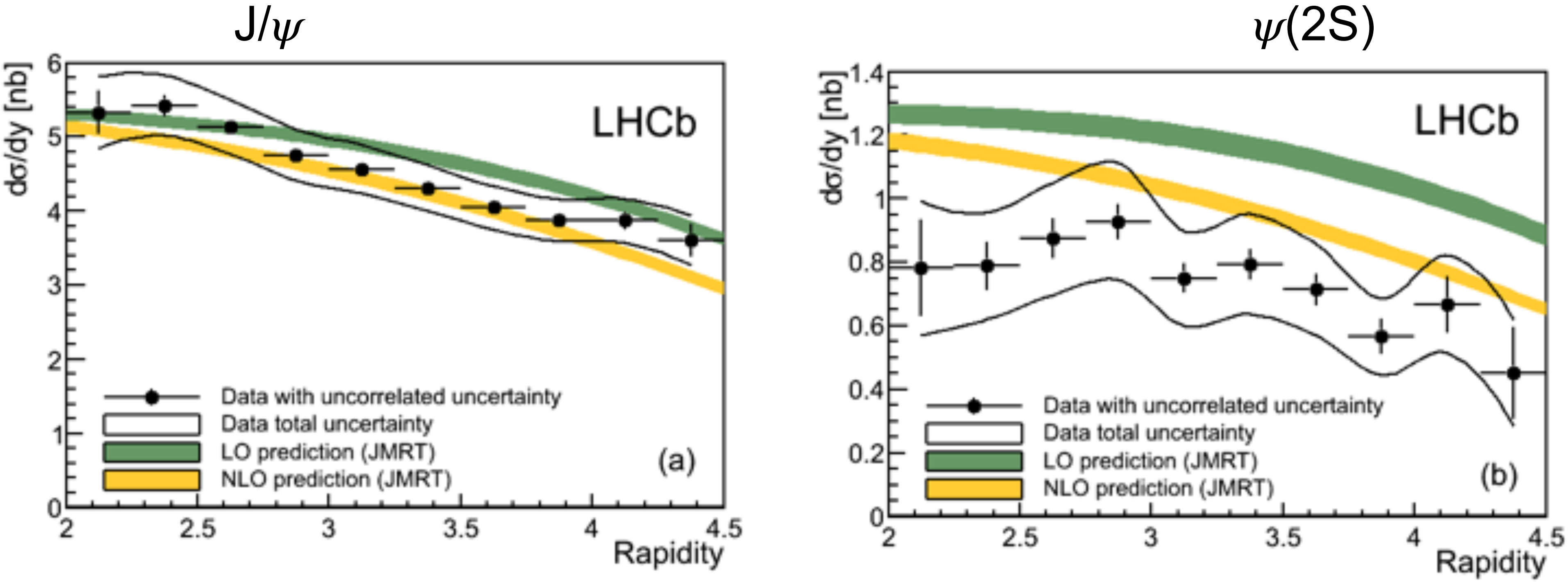
- The data is described by LO perturbative QCD with $g_p(x,\mu^2) \propto 1/x^{0.2} \to$ new constraints on $g_p(x,\mu^2)$ for $6\times10^{-6} < x < 0.01$.

- Simple power-law HERA fit $\sigma_{\gamma p \to J/\psi} \propto W_{\gamma p}^{\delta}$ with δ=0.7-0.8 → no saturation.

Comparison to LHCb data on pp UPCs (2)

- This LHCb data can be also described by NLO pQCD:

R. Aaij et al., (LHCb) J. Phys. G. 41 (2014) 055002



Jones, Martin, Ryskin, Teubner (JMRT), JHEP 11 (2013) 084

- JMRT approach based on k_t factorization: LO and NLO $g_p(x,\mu^2)$ are determined by fitting HERA and LHCb (2013) J/ψ data using Ryskin's formula → predictions for $\psi(2S)$.

- Recent NLO calculation in collinear factorization: D.Yu. Ivanov et al, arXiv:0401151v2 (May 2015)

Exclusive photoproduction of J/ψ in p-Pb UPCs at the LHC

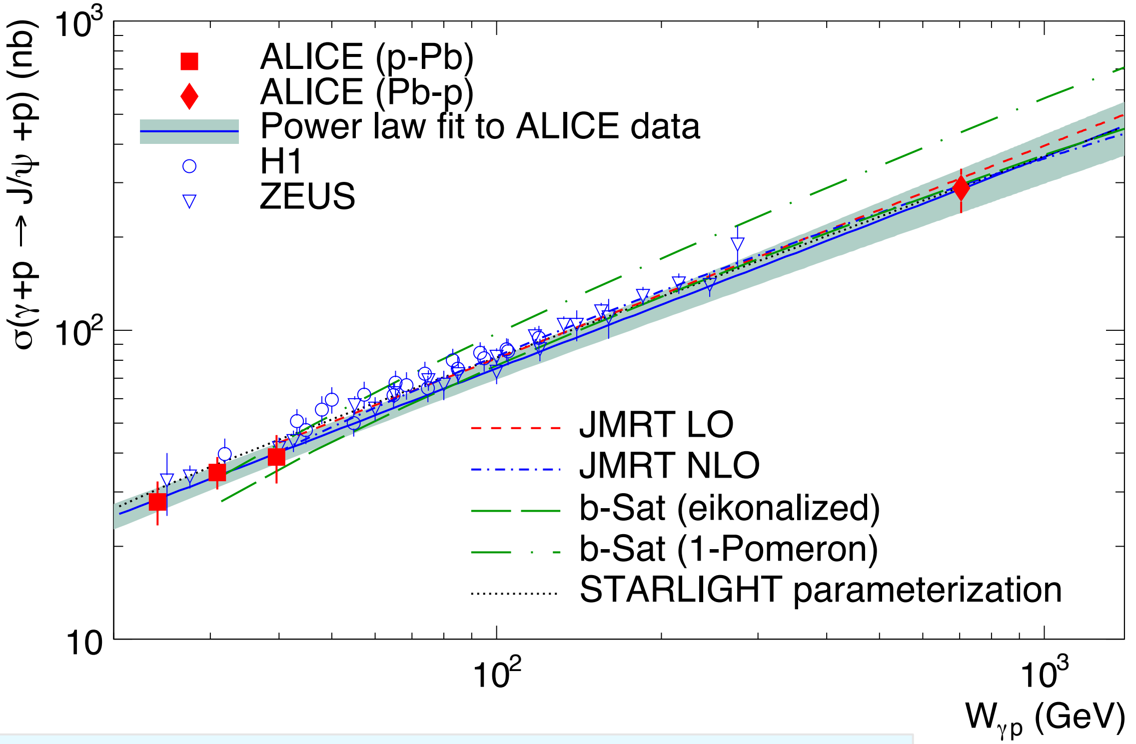
- ALICE measured exclusive photoproduction of J/ψ in p-Pb UPCs at 5 TeV and presented the result in terms of $\sigma_{\gamma p \to J/\psi p}(W_{\gamma p})$

B. Abelev et al., (ALICE), PRL 113 (2014) 23, 232504

- Extracted from: $$\frac{\sigma_{pPb \to pPbJ/\psi}(y)}{dy} = N_{\gamma/Pb}(y)\sigma_{\gamma p \to J/\psi p}(y) + N_{\gamma/p}(-y)\sigma_{\gamma Pb \to J/\psi Pb}(-y)$$

- Photon flux from p is small, but not negligible at small p_T.

- Constrains on $g_p(x,\mu^2)$ down to $x=2\times10^{-5}$.



- General agreement with HERA and LHCb pp UPC measurements.

Exclusive charmonium photoproduction on nuclei and gluon nuclear shadowing

- In leading order of perturbative QCD:

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

Small correction ≈ 0.95

From HERA and LHCb

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

From nuclear form factor

- Nuclear suppression factor S:

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

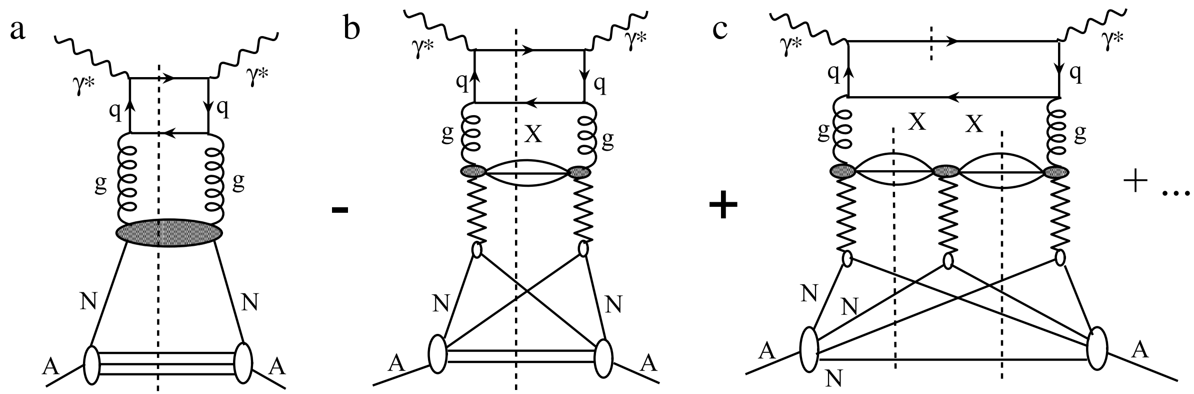
- S extracted from ALICE data on J/ψ and ψ(2S) photoproduction in Pb-Pb UPCs@LHC at 2.76 TeV can be compared to predictions for gluon shadowing $R_g(x)$, Guzey, Kryshen, Strikman, Zhalov, PLB726 (2013) 270, Guzey, Zhalov JHEP 1310 (2013) 207

- $R_g(x)$ is taken from global fits of nuclear PDFs or the model of leading twist nuclear shadowing.

Model of leading twist nuclear shadowing

- Based on the 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!

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

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

Nuclear part same as in hA (Glauber model)

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

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:

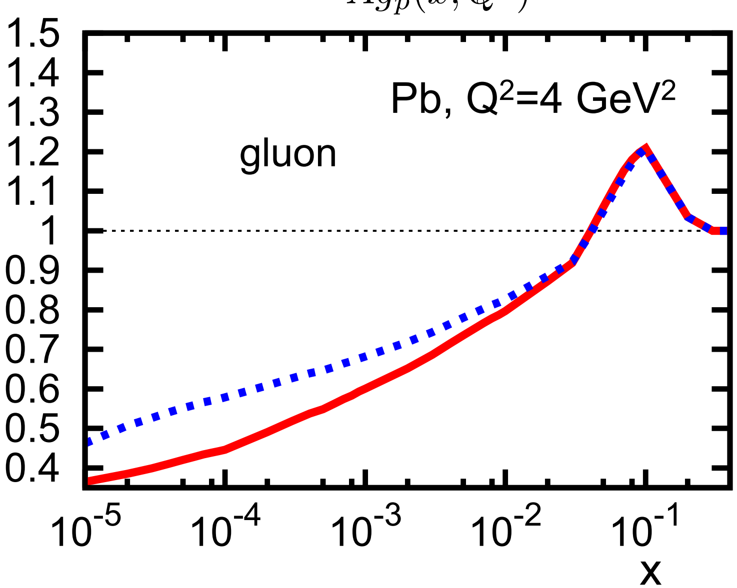
$$\frac{\langle \sigma^2 \rangle}{\langle \sigma \rangle} \equiv \sigma_2(x,\mu^2) = \frac{16\pi B_{\rm diff}}{(1+\eta^2) x G_N(x,\mu^2)} \int_x^{0.1} dx_{I\!P} \beta G_N^{D(3)}(\beta,\mu^2,x_{I\!P})$$

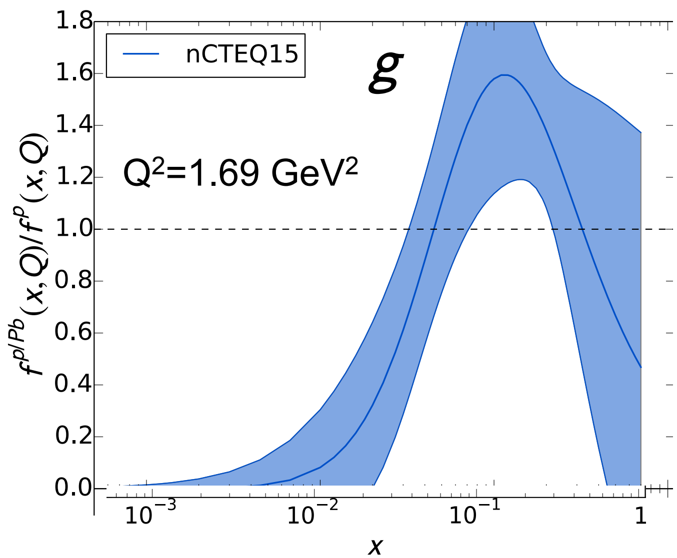
• Interaction with N ≥ 3 nucleons modeled using eikonal app. with $\sigma_{soft}=\sigma_3=30\text{-}50$ mb.

• Predictions for the gluon nuclear shadowing:

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

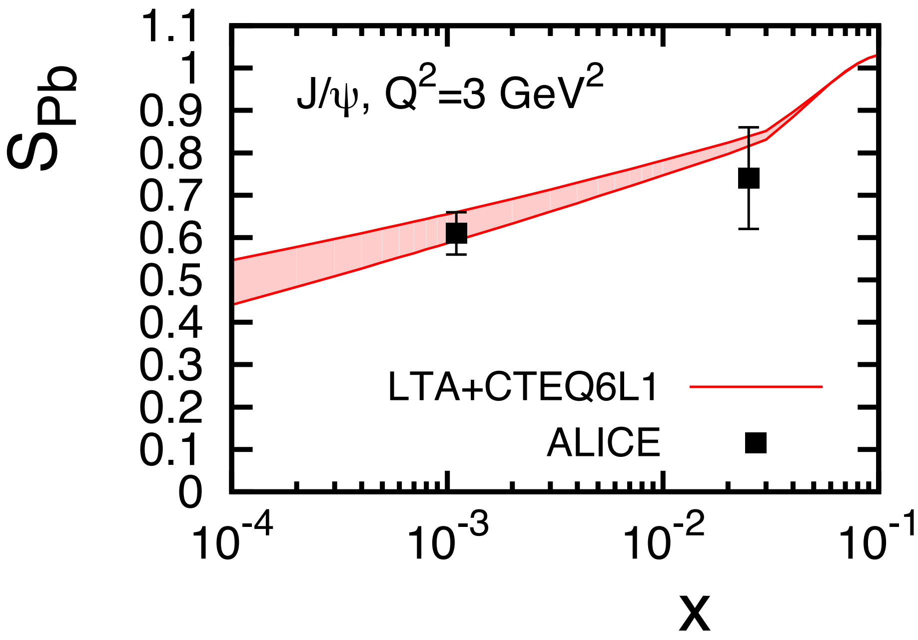
Compare to recent nCTEQ15 fit, K. Kovaric *et al*, arXiv: 1509.00792



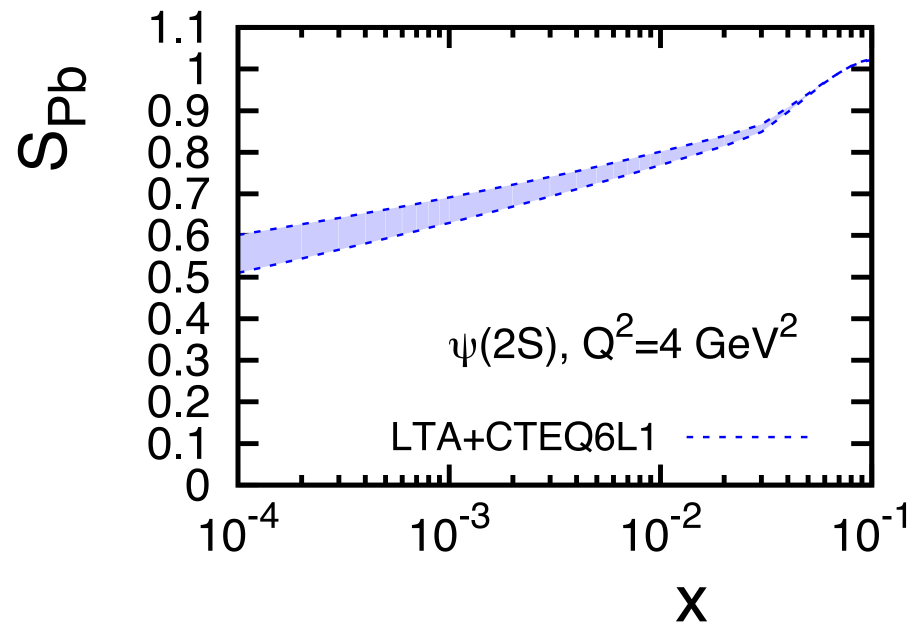


Comparison to the ALICE data

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



Guzey, Zhalov JHEP 1310 (2013) 207



Guzey, Zhalov, arXiv:1404.6101

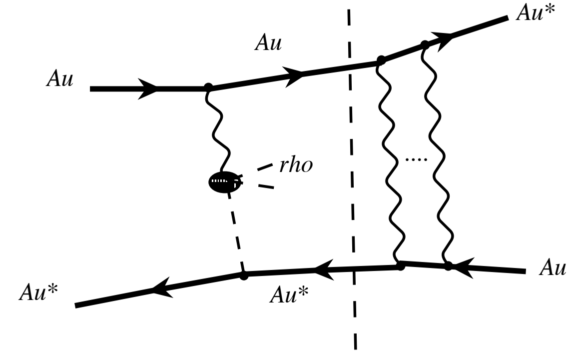
- Very good agreement with ALICE data on exclusive J/ψ production in Pb-Pb UPCs at 2.76 TeV → first direct evidence of large nuclear gluon shadowing at x=0.001.

- Theory predicts similar nuclear suppression in J/ψ and ψ(2S) cases → contradicts preliminary ALICE data on ψ(2S) photoproduction in Pb-Pb UPCs at central rapidity.

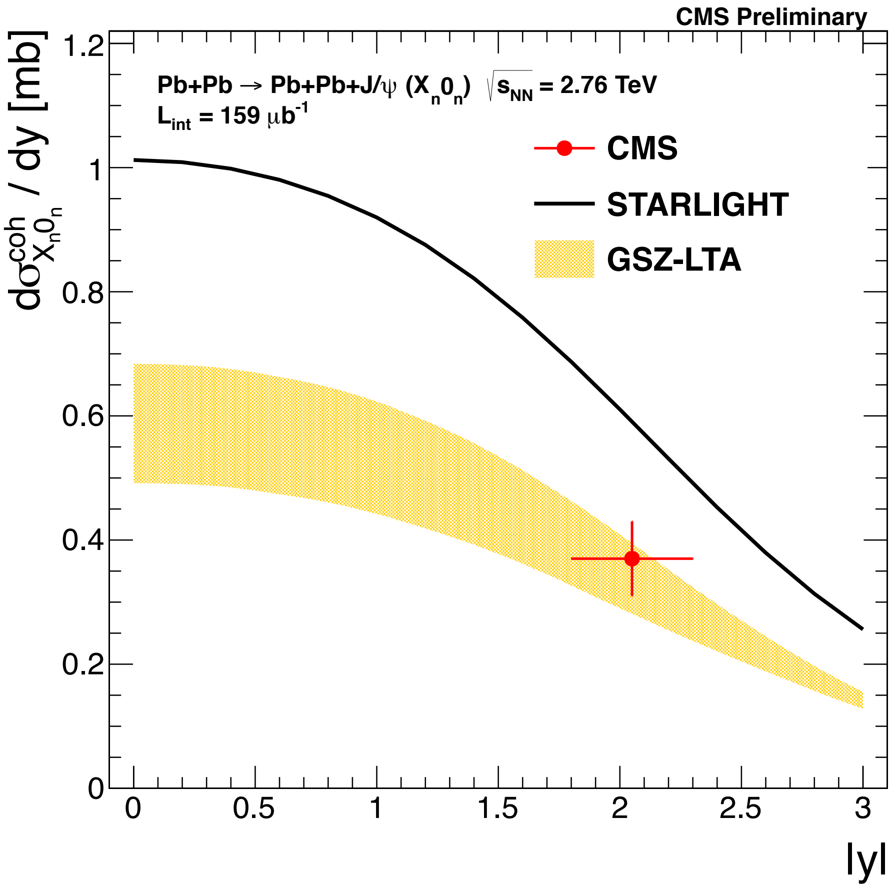
Coherent photoproduction of J/ψ in Pb-Pb UPC accompanied by neutron emission

- UPCs can be accompanied by mutual e.m. excitation of nuclei with their subsequent neutron emission:

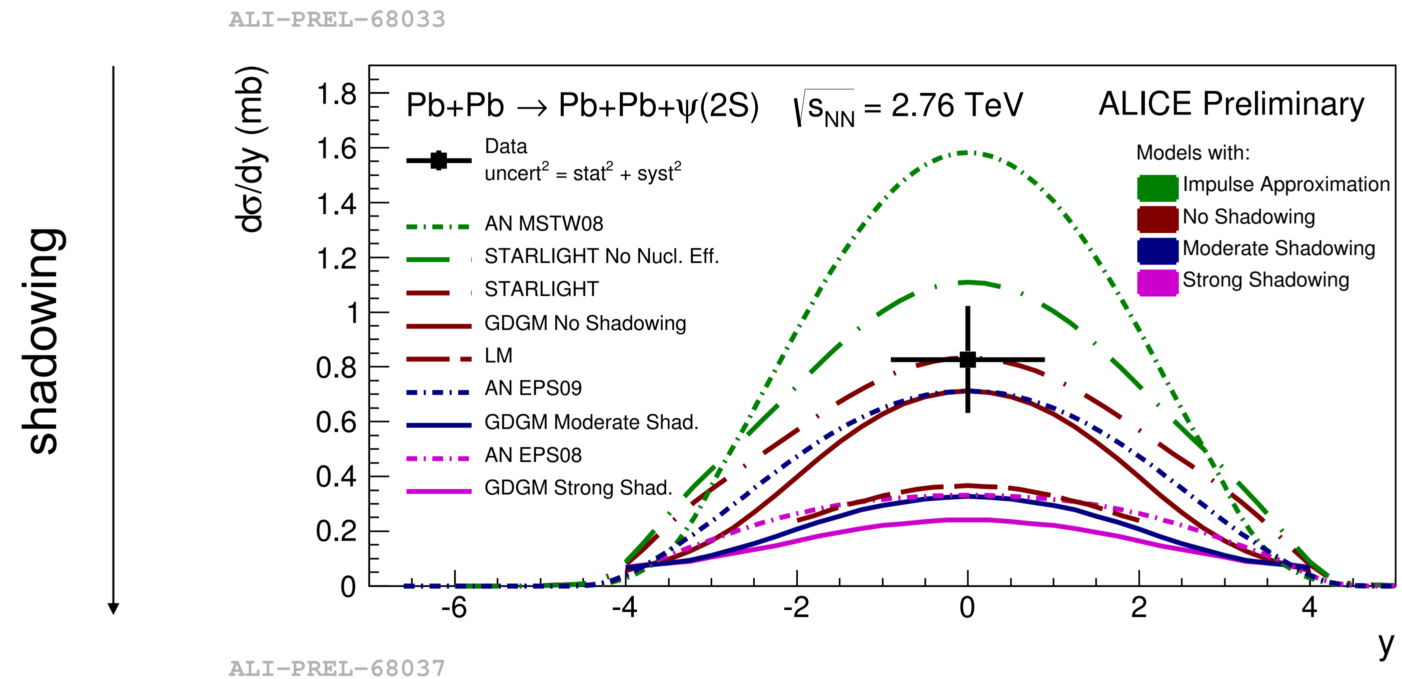
Baltz, Klein, Nystrand, PRL 89 (2002) 012301



- Preliminary CMS measurement in (Xn,0n)-channel nicely agrees with predictions of large nuclear gluon shadowing, Guzey, Strikman, Zhalov, EPJ C (2014) 74: 2942



Problem 1: Measured coherent photoproduction of ψ(2S) favors small shadowing



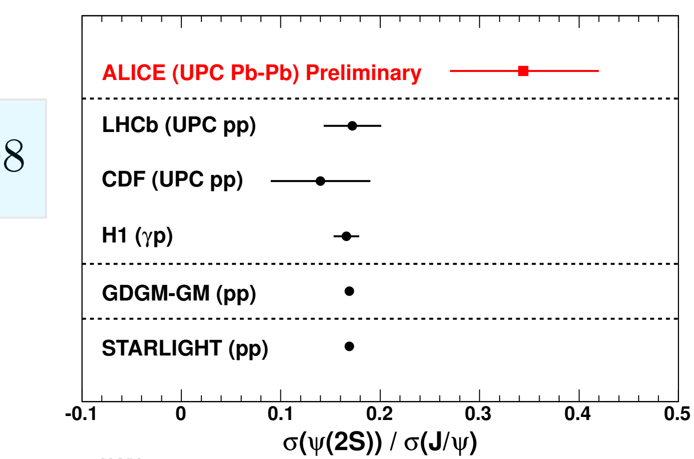
Comparison with pp

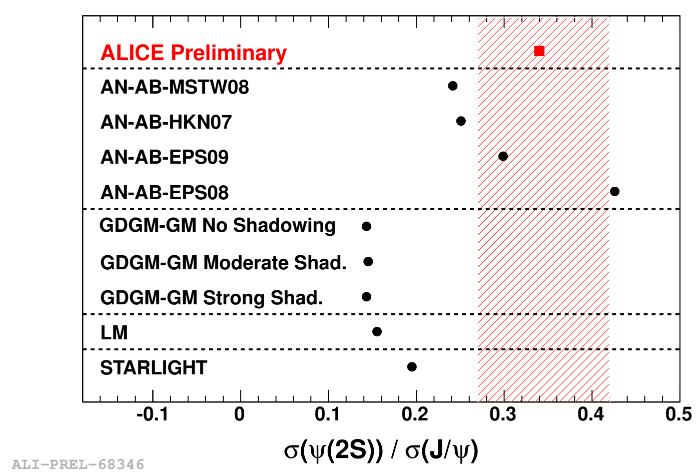
Comparison with AA

Ratio

$$R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi)} = 0.34 \pm 0.08$$

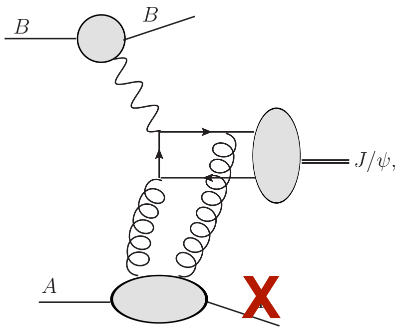
is significantly larger than in pp and many theoretical estimates.



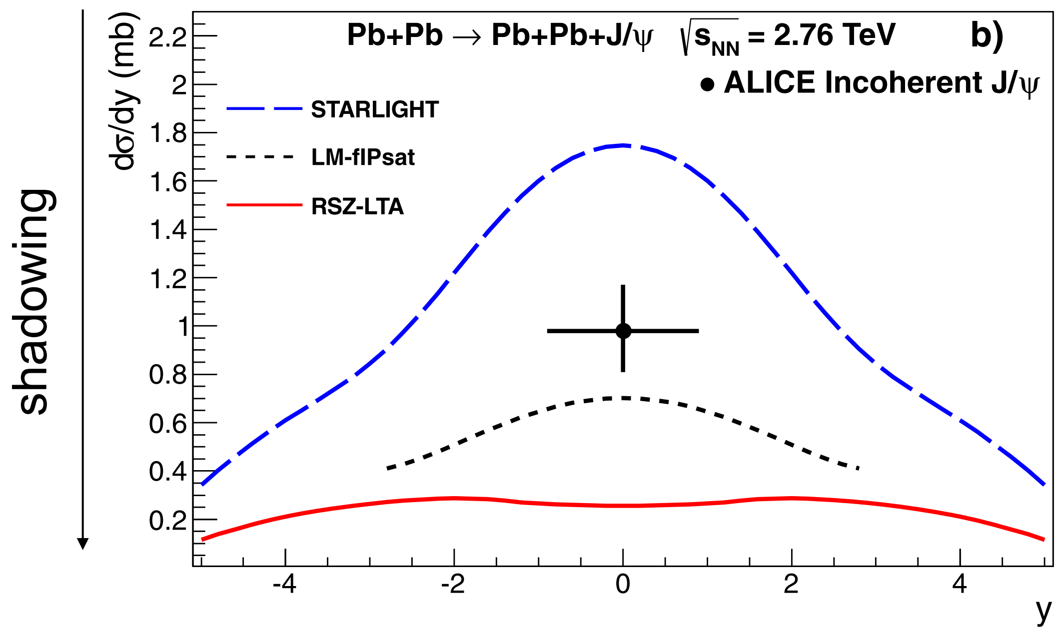


Problem 2: Incoherent photoproduction of J/ψ favors small shadowing

- ALICE also measured incoherent J/ψ in Pb-Pb UPCs at 2.76 TeV and found small suppression due to nuclear shadowing:



Abbas *et al.* [ALICE], EPJC 73 (2013) 2617

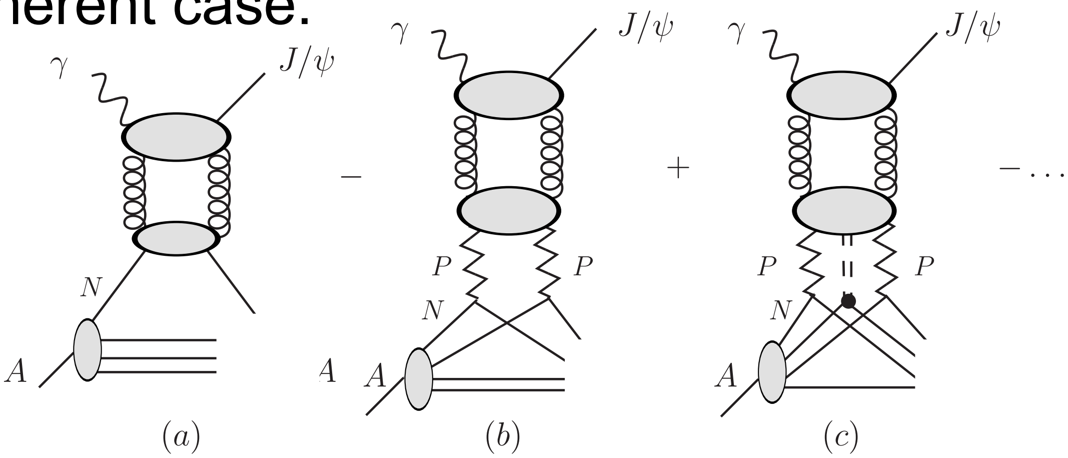


Coherent and quasi-elastic cross sections are separated by p_T of J/ψ: $\langle p_T \rangle$=50 MeV/c for coherent and $\langle p_T \rangle$=500 MeV/c for incoherent.

- This is a problem for our approach predicting large shadowing suppression both in coherent and incoherent cases.

Problem 2: Incoherent photoproduction of J/ψ favors small shadowing (2)

- Model of leading twist nuclear shadowing → the suppression factor for incoherent case:



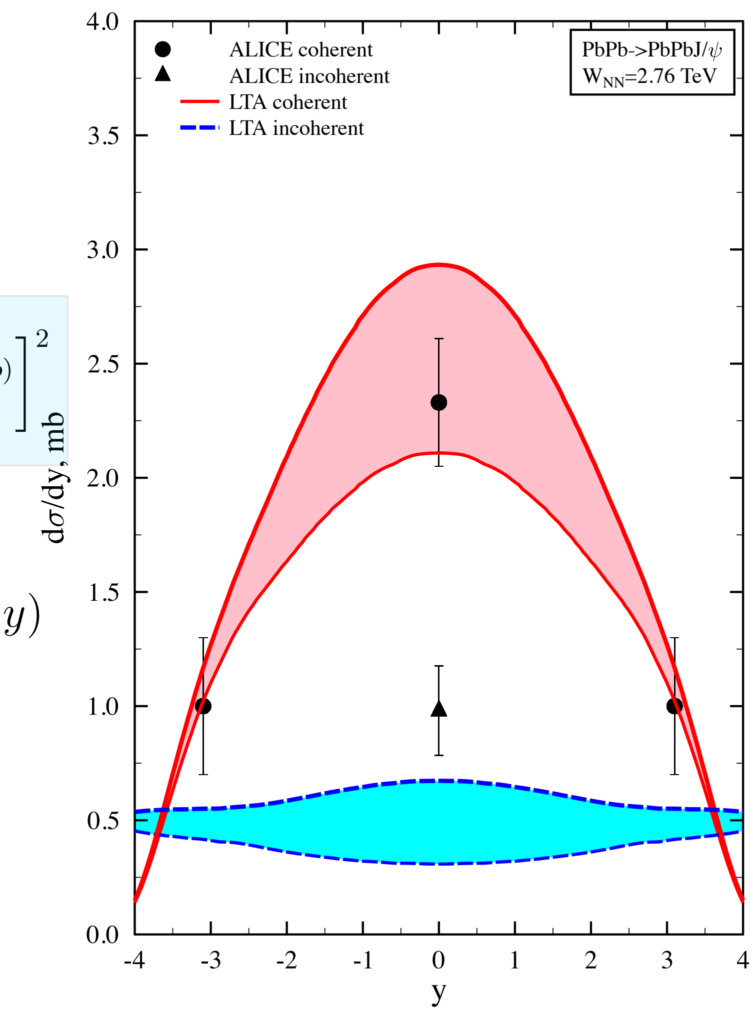
$$S_{\rm incoh}(W_{\gamma p}) \equiv \frac{d\sigma^{\rm pQCD}_{\gamma A\to J/\psi A'}(W_{\gamma p})/dt}{A d\sigma^{\rm pQCD}_{\gamma p\to J/\psi p}(W_{\gamma p})/dt} = \frac{1}{A}\int d^2\vec{b}\, T_A(b)\left[1-\frac{\sigma_2}{\sigma_3}+\frac{\sigma_2}{\sigma_3}e^{-\sigma_3/2T_A(b)}\right]^2$$

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

- Like in the earlier estimate (RSZ-LTA '12), nuclear suppression is overestimated by factor **1.5 - 2**.

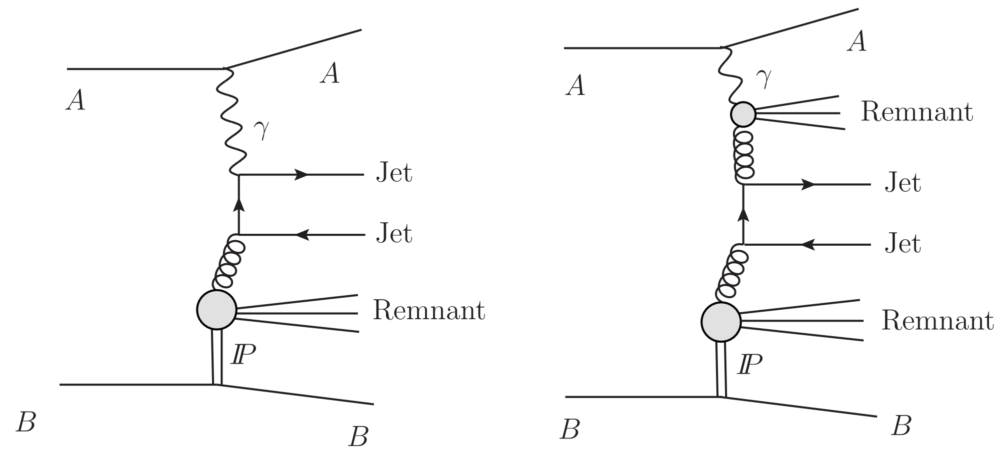
- Possible resolution: inclusion of nucleon diffractive dissociation $\gamma + N \to J/\psi + Y$

VG, Strikman, Zhalov, EPJC 74 (2014) 2942



Possible future direction: diffractive photoproduction of dijets in UPCs

direct photon contribution



(a) (b)

resolved photon contribution

- Subject of my research project at the University of Münster with the goals:

  - Using established formalism and code, M. Klasen, Rev. Mod. Phys. 74 (2002) 1221, NLO pQCD predictions for pp UPCs at 7-13 TeV and an analysis of sensitivity to the pattern of factorization breaking (unsettled at HERA), proton diffractive PDFs, photon flux.

  - Similar predictions for pA which benefit from the Z^2 enhanced photon flux.

  - NLO predictions for AA UPCs at 2.76-5.1 TeV. The calculation will use novel nuclear diffractive PDFs predicted by the model of leading twist nuclear shadowing and factorization breaking calculated using the vector meson dominance model for photon-nucleus scattering.

Conclusions

• The fundamental gluon distributions in the proton and nuclei at small x are known with large uncertainties.

• Perturbative QCD-based theoretical analyses of the LHCb, CMS and ALICE data on charmonium photoproduction in pp, p-Pb and Pb-Pb UPCs at the LHC give new constraints on $g_p(x,\mu^2)$ down to $x= 6\times10^{-6}$ and $g_A(x,\mu^2)$ down to x= 0.001.

• First direct evidence of large nuclear gluon shadowing at $x=10^{-3}$ and $\mu^2 \approx 3$ GeV^2 which agrees with predictions of the model of leading twist nuclear shadowing and the EPS09 fit.

• At the same time, there is discrepancy between theoretical predictions of our framework and the ALICE data on coherent $\psi(2S)$ and incoherent J/ψ photoproduction in Pb-Pb UPCs at the LHC at 2.76 TeV.

• UPC community is exploring new processes for Run 2 at the LHC. One such a possibility — diffractive photoproduction of dijets in UPCs to address factorization breaking and access proton and nuclear diffractive PDFs.