Small-x nuclear PDFs and exclusive J/ψ photoproduction

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Frankfurt, VG, Strikman, Phys. Rept. 512 (2012) 255
VG, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290
VG, Zhalov, JHEP 1310 (2013) 207
VG, Strikman, Zhalov, EPJC 74 (2014) 2942
VG, Zhalov, JHEP 1402 (2014) 046

Sapore Gravis Workshop, Padova, Dec 9-12, 2014

Outline:

- Nuclear parton distributions functions (PDFs)

- Small-x nuclear PDFs from leading twist nuclear shadowing approach

- Photoproduction of J/ψ in Pb-Pb UPCs at the LHC
  - coherent
  - incoherent
  - with neutron emission

- Conclusions

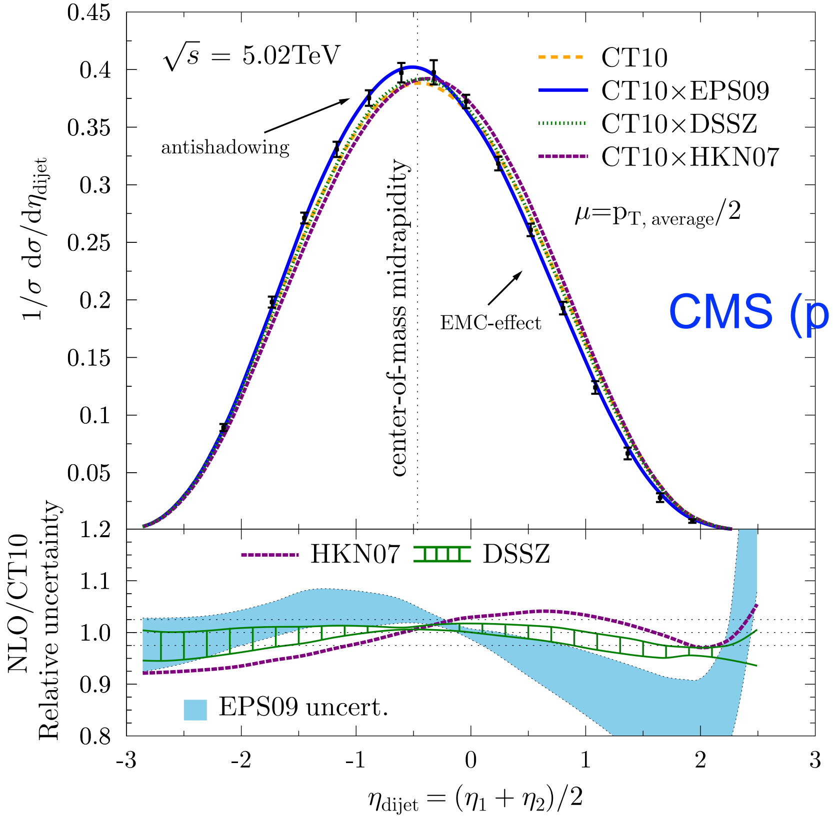
Nuclear parton distributions

- Nuclear PDF $f_j(x,\mu^2)$ = probability density to find parton j (quark, gluon) in a nucleus with the momentum fraction x at the resolution scale μ^2.

- Fundamental quantity of collinear factorization in Quantum Chromodynamics, describes the nucleus structure in QCD.

- Essential element of QCD phenomenology of hard processes with nuclei:

pA → 2jets+X



CMS (prelim.)

- Required for interpretation of AA results at RHIC and LHC and searches of new states of matter in QCD.

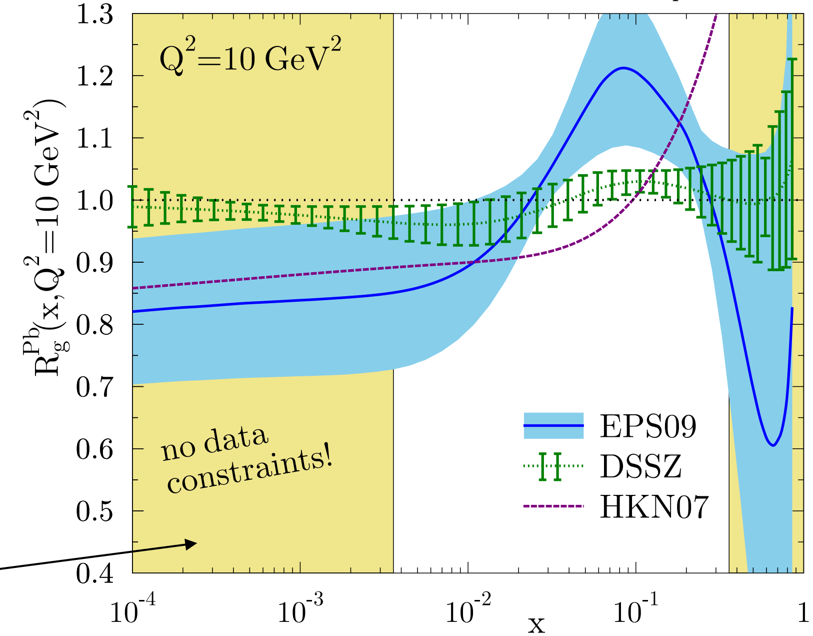
H.Paukkunnen, K.J. Eskola, C. Salgado, arXiv:1408.4563

Nuclear parton distributions from global fits

- Using collinear factorization, nuclear PDFs are determined from global fits to data.

- At small x, resulting PDFs, especially gluon PDF $g_A(x,\mu^2)$, have significant uncertainty due to:
  - limited kinematics
  - indirect access to gluons via scaling violations
  - different assumptions for input form
  - different selection of fitted data

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



Rg < 1 at small x = nuclear shadowing

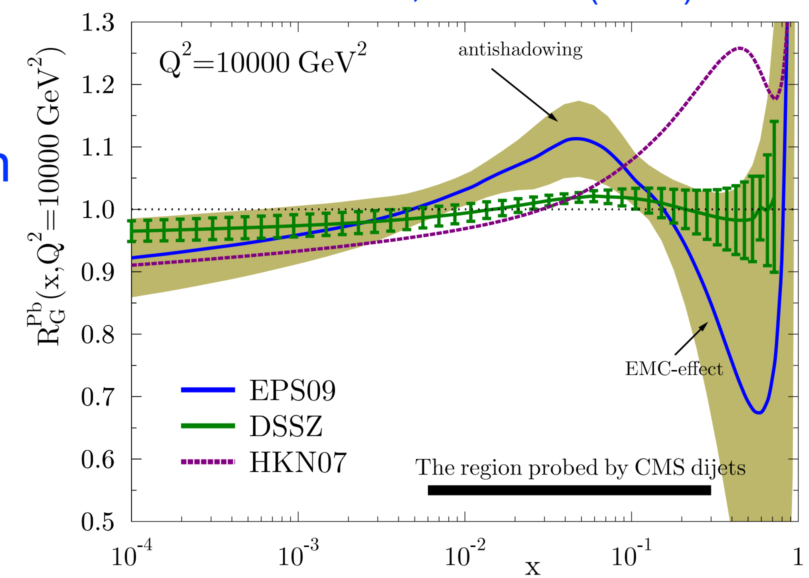
H. Pauukunen, NPA 926 (2014) 24

- LHC data on production of jets, direct photons, and gauge bosons in p+A scattering → new constrains on nuclear gluon distribution $g_A(x,\mu^2)$.

- New constrains on $g_A(x,\mu^2)$ at small x from:

- J/ψ photoproduction in AA and pA UPC at LHC

- Electron-Ion Collider (EIC) in the future



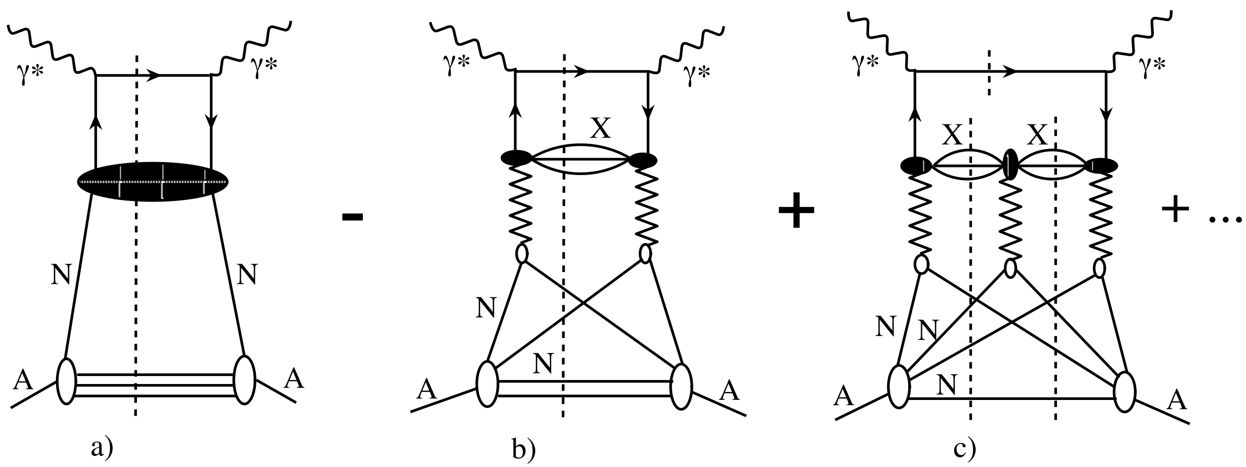
H.Paukkunen, K.J. Eskola, C. Salgado, arXiv:1408.4563

Leading twist nuclear shadowing model

- Model for nuclear PDFs for small $10^{-5}<x<0.2$ at input scale Q_0^2=2.5-4 GeV^2. The Q^2 dependence is through DGLAP.

- Based on generalization of Gribov-Glauber shadowing theory and QCD collinear factorization theorems for inclusive and diffractive DIS

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



interaction with N > 3 nucleons

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

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

nuclear density

diffractive slope $B_{\rm diff}$ and diffractive PDFs f_j^D

model for interaction with N ≥ 3 nucleons

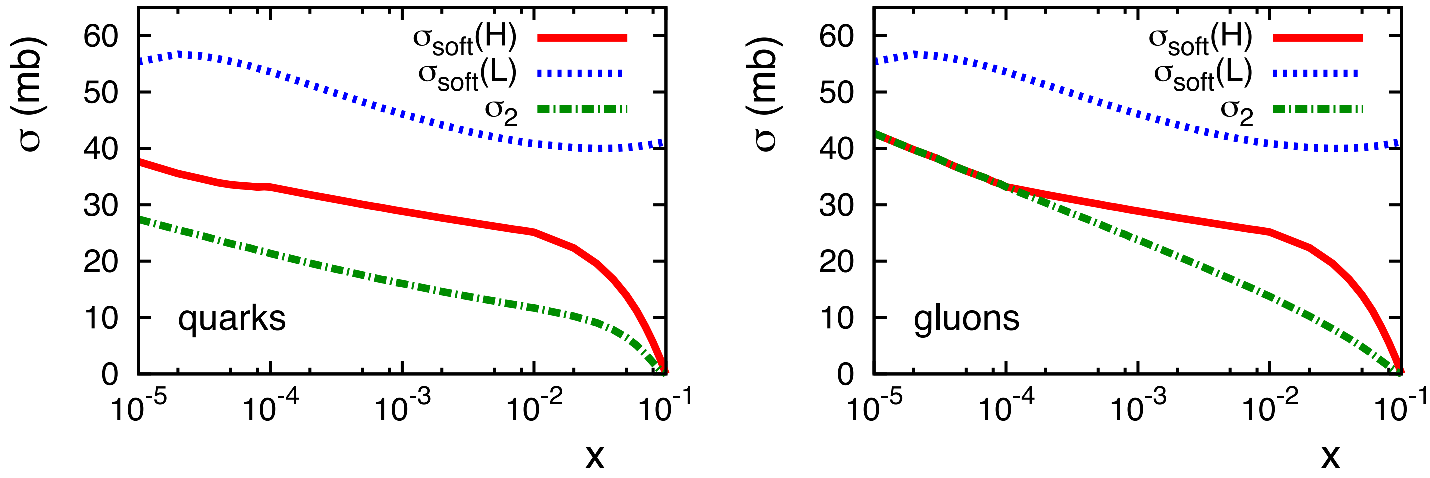
Leading twist nuclear shadowing model (2)

• Shadowing correction to nuclear PDFs in terms of proton diffractive PDFs f_j^D

• Contribution of interaction with two nucleons is model-independent Gribov inelastic shadowing with cross section σ_2:

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

• Interaction with N ≥ 3 nucleons is modeled using soft cross section fluctuations with cross section σ_{soft} → two scenarios of nuclear shadowing



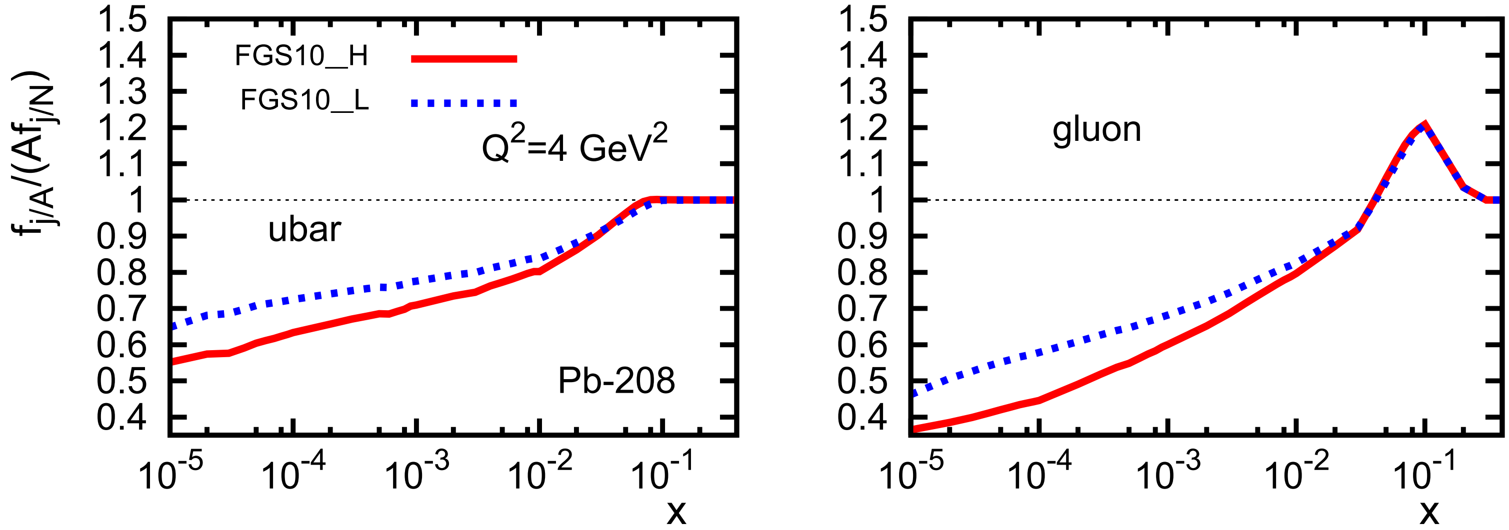
• Diffraction in ep DIS at HERA is a leading twist phenomenon → approach gives leading twist nuclear shadowing

Predictions for nuclear PDFs

• QCD analysis of ep diffraction in DIS at HERA → large gluon diffractive PDF → large gluon shadowing > quark shadowing

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

http://hepdata.cedar.ac.uk/pdfs/



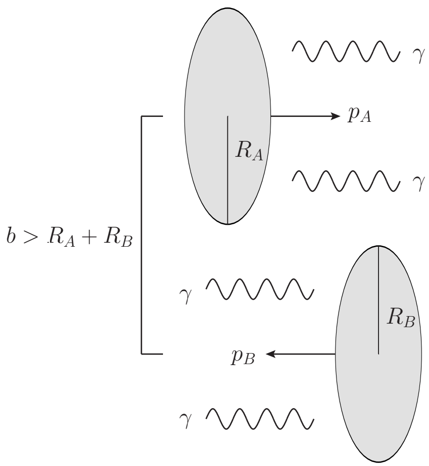
• Gluon antishadowing "by hand" from momentum sum rule.

• Magnitude of shadowing is similar to EPS 09, Eskola, Puukkunen, Salgado, JHEP 04 (2009) 065

• While EIC and LHeC are ideal places to test these predictions, photoproduction of charmonium in Pb-Pb UPCs at the LHC can also be used to constrain gluon shadowing

Ultraperipheral collisions at the LHC

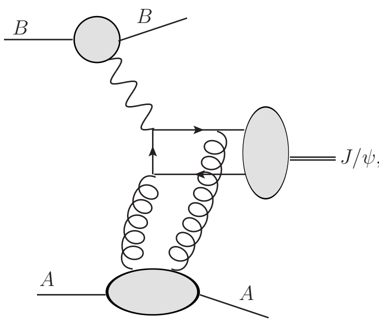
- In pp, pA and AA collisions, nuclei can scatter at large impact parameters $b > R_A + R_B = 10\text{-}20$ fm — ultraperipheral collisions (UPCs).



UPC events correspond to two lepton tracks in otherwise empty detector.

- In UPCs, strong interaction is suppression and ions interact via exchange of 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

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

Ultraperipheral collisions at the LHC (2)

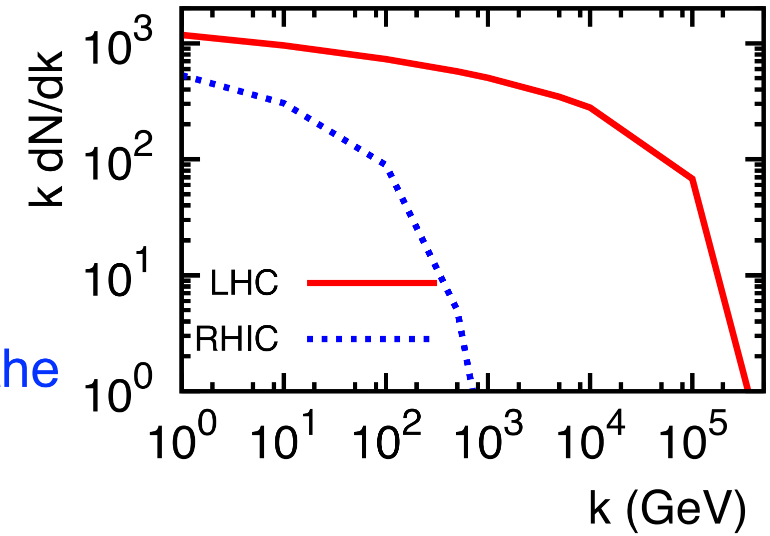
• Photon flux ~Z^2 (Z^2≈7000 for Pb) and corresponds to HUGE maximal photon energy in the target nucleus rest frame due to large γ_L:

γ_L≈1500 for Pb-Pb UPCs at 2.76 TэВ → ω_{max} ≈ 120 TeV:

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

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

Photon spectrum in Pb-Pb UPCs in the rest frame of the target nucleus →

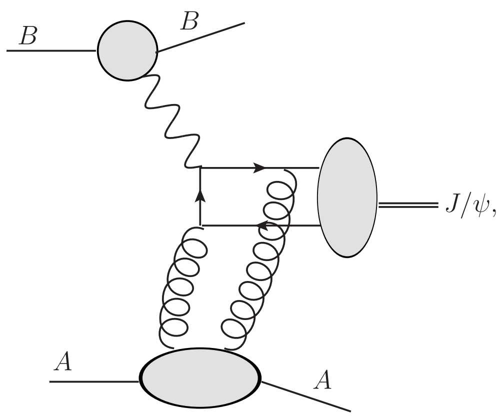


• One also needs to take into account the charge distribution and suppression of the strong interaction at small small b → additional suppression of $N_{\gamma/Z}$ at large k, where $N_{\gamma/Z}$ is small: up to 20% for pp and several times (!) for pA.

• UPCs gives possibility to study photon-proton and photon-nucleus interaction at photon energies **10 times** larger that at HERA → new info on $g_p(x,\mu^2)$ и $g_A(x,\mu^2)$.

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

Exclusive J/ψ photoproduction in Pb-Pb UPCs at LHC



- Recently ALICE at the LHC measured exclusive J/ψ photoproduction in Pb-Pb UPCs

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

$$d\sigma^{\rm coh}(y \approx -3)/dy = 1 \pm 0.18^{+0.24}_{-0.26}\ {\rm mb}$$
$$d\sigma^{\rm coh}(y \approx 0)/dy = 2.38^{+0.34}_{-0.24}\ {\rm mb}$$

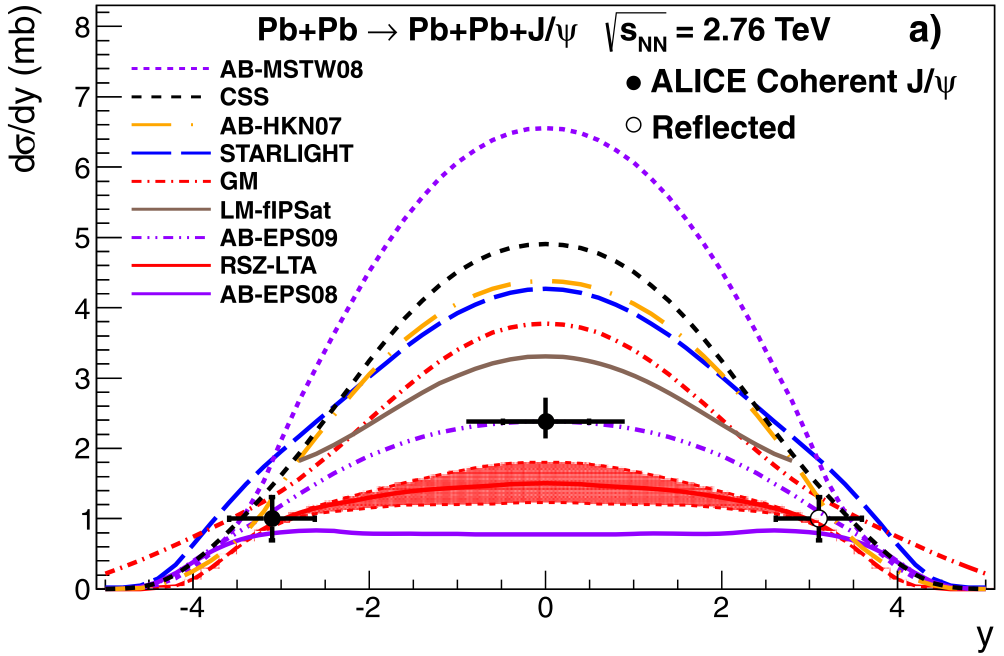
$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$ is rapidity of J/ψ

- Main conclusion: data in agreement with models with nuclear gluon shadowing

y=-3 → **x=0.02**
y=0 → **x=0.001** in probed $g_A(x,Q^2)$

$$x = \frac{M_{J/\psi}}{\sqrt{s}} e^{-y}$$

shadowing



Nuclear suppression factor

- Using experimental $d\sigma_{PbPb\to PbPbJ/\psi}/dy$ and calculated $N_{\gamma/A}(y)$

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

$$\sigma_{\gamma Pb\to J/\psi Pb}(W_{\gamma p} = 92.4\,\mathrm{GeV}) = 17.6^{+2.7}_{-2.0}\ \mu\mathrm{b}\,,$$
$$\sigma_{\gamma Pb\to J/\psi Pb}(W_{\gamma p} = 19.6\,\mathrm{GeV}) = 6.1^{+1.8}_{-2.0}\ \mu\mathrm{b}$$

- It is convenient to define nuclear suppression factor *S*: $S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\exp}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}\right]^{1/2}$

- The denominator is the cross section in impulse approximation (IA):

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

From HERA and LHCb

Using nuclear form factor: $\Phi_A(t_{\min}) = \int_{-\infty}^{t_{\min}} dt |F_A(t)|^2$

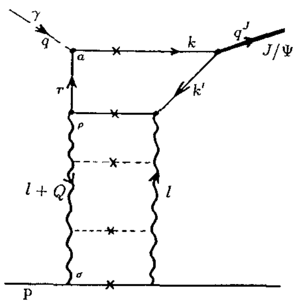
- Model-independent determination of *S*:

$$S(W_{\gamma p} = 92.4\,\mathrm{GeV}) = 0.61^{+0.05}_{-0.04}$$
$$S(W_{\gamma p} = 19.6\,\mathrm{GeV}) = 0.74^{+0.11}_{-0.12}$$

VG, Kryshen, Strikman, Zhalov, PLB726 (2013) 270

Exclusive J/ψ photoproduction in QCD

- In leading logarithmic approximation of perturbative QCD and non-relativistic limit for J/ψ wave function:



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

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

M. Ryskin (1993)

- Relativistic corrections (in k_T formalism), non-diagonal kinematics and real part of the scattering amplitude:

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

- $F^2(\mu)$ parameterizes relativistic corrections:
  - $F^2(\mu) = 1$, Ryskin, Roberts, Martin, Levin, Z. Phys. C 76 (1997) 231, due to cancellation of 2 effects
  - $F^2(\mu) \approx 0.5$, VG, Zhalov, JHEP 1310 (2013) 207, from data fitting, where μ is a free parameter: $\mu^2 = 3$ GeV^2
  - $F^2(\mu) \approx 0.2$, Frankfurt, Koepf, Strikman, PRD 57 (1997) 231, due to strong relativistic effects

Implications for nuclear gluon shadowing

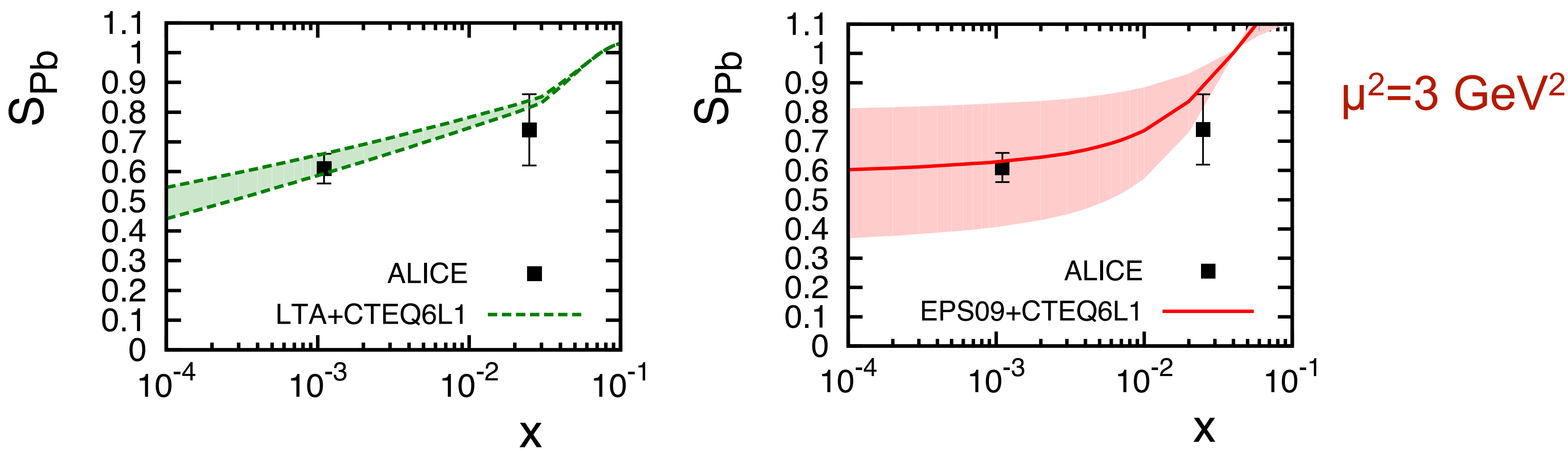
- Applying to nuclei:

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

$$S(W_{\gamma p}) = \kappa_{A/N}\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)} = \kappa_{A/N}R_g(x,\mu^2) \qquad x = M_{J/\psi}^2/W_{\gamma p}^2$$

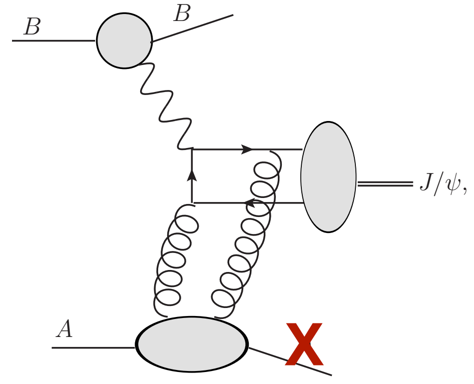
- S is described well in approaches with large gluon shadowing:

VG, Kryshen, Strikman, Zhalov, PLB726 (2013) 270
VG, Zhalov JHEP 1310 (2013) 207



- First direct evidence of large gluon shadowing at x=0.001.

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

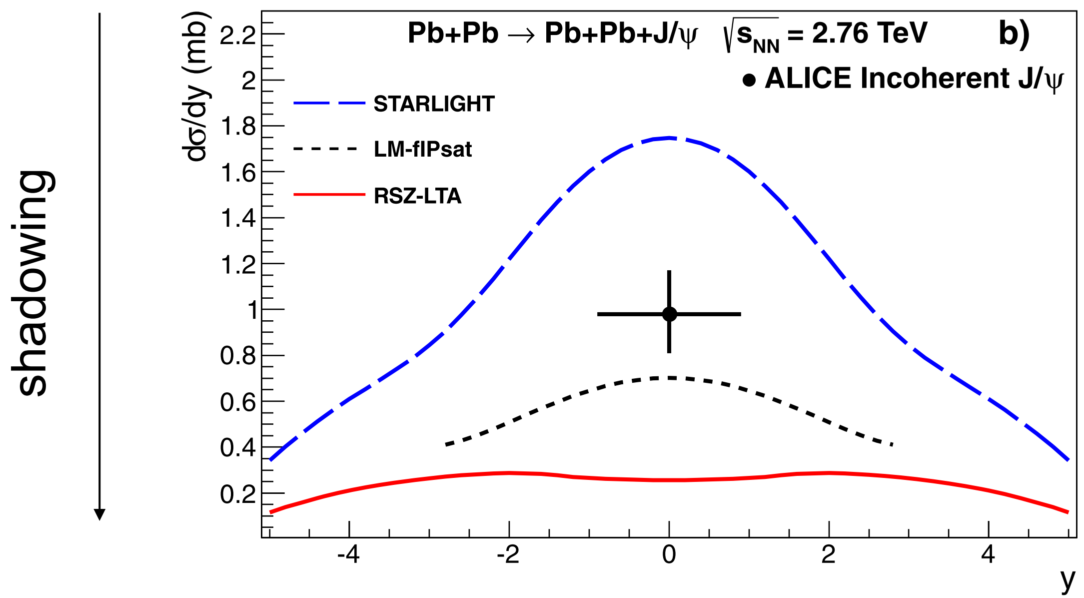


- ALICE also measured incoherent J/ψ photoproduction in Pb-Pb UPCs, Abbas *et al.* [ALICE], EPJ C (2013) 73:2617

$$d\sigma^{\rm incoh}(y \approx 0)/dy = 0.98^{+0.19}_{-0.17}\ {\rm mb}$$

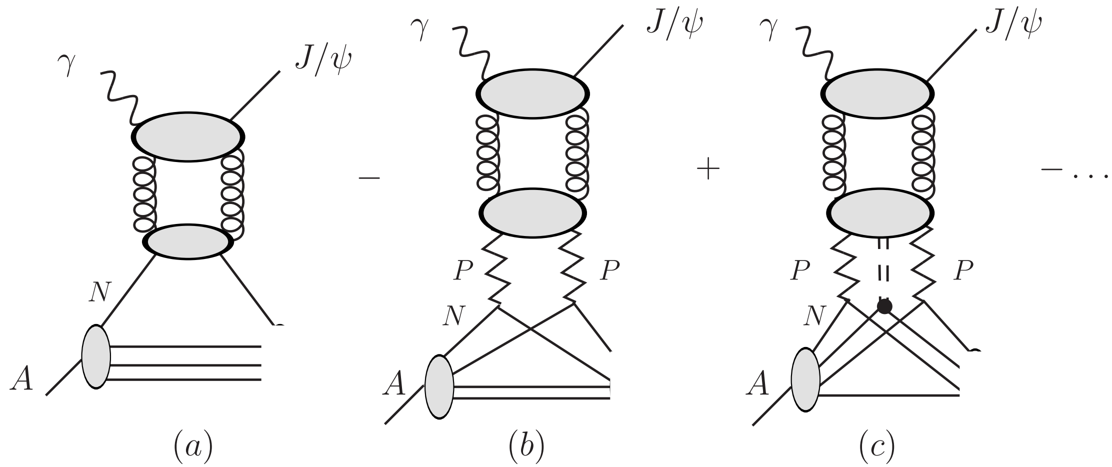
- Coherent and quasi-elastic scattering are separated by the J/ψ transverse momentum p_T: p_T < 200-300 MeV/c ($\langle p_T \rangle$=50 MeV/c) for coherent and p_T > 200-300 MeV/c ($\langle p_T \rangle$=500 MeV/c) for incoherent.

- Conclusion at the time of publication: models cannot reproduce the data



Incoherent J/ψ photoproduction in Pb-Pb UPCs at LHC (2)

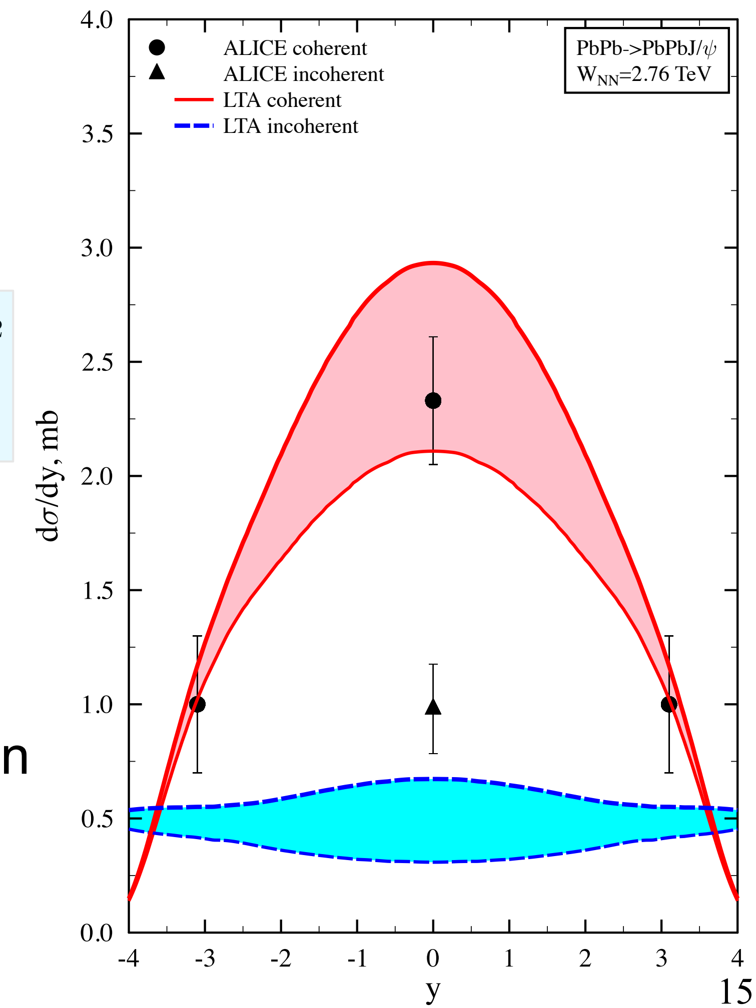
• Model for leading twist nuclear shadowing → nuclear suppression factor for incoherent case:



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

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

$\sigma_3 = \sigma_{\rm soft}$



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

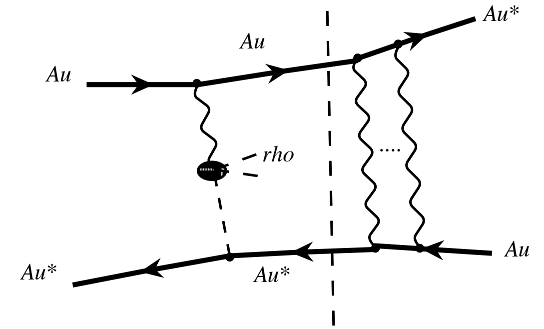
• Potential source of discrepancy: contribution of nucleon dissociation $\gamma + N \to J/\psi + Y$ (measured at HERA)

UPCs accompanied by forward neutron emission

- UPCs can be also accompanied by additional photon exchanges leading to e.m. excitation of one or both nuclei with subsequent neutron emission.

Baltz, Klein, Nystrand (2002)

Rebyakova, Strikman, Zhalov (2012)

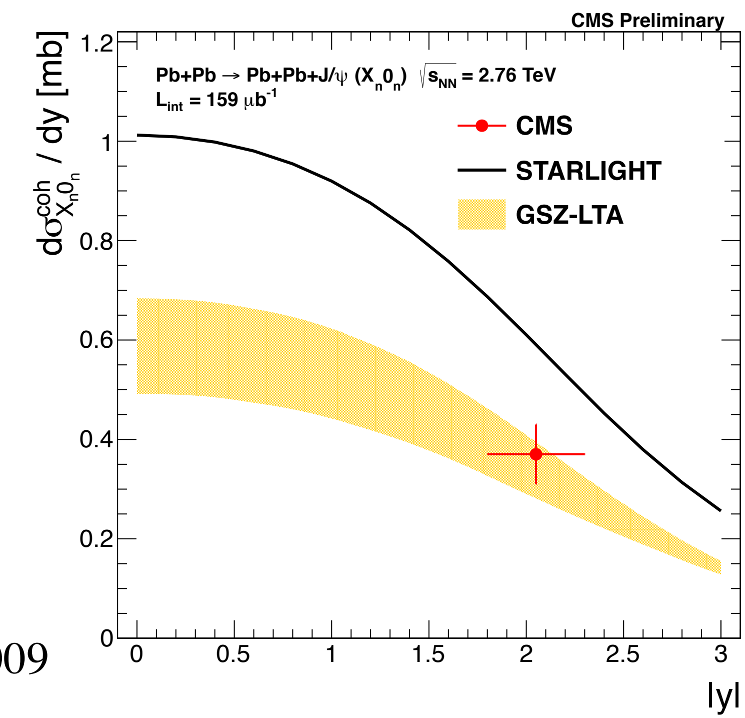


- Additional photon exchanges cost $Z^2\alpha^2_{\rm e.m.} \approx 0.3 - 04$ and can be taken into account by modification of photon flux:

$$N^i_{\gamma/A}(\omega) = \int_{2R_A}^{\infty} d^2b\, N_{\gamma/A}(\omega,\vec{b}) P_i(\vec{b}) \,,$$

impact-parameter dependent factor for different decay channels (i=0n0n,Xn0n,XnXn)

- CMS measurement of coherent J/ψ photoproduction accompanied by forward neutron emission:
- agreement with large gluon shadowing
- also agreement with Starlight for ratios of diff. break-up modes

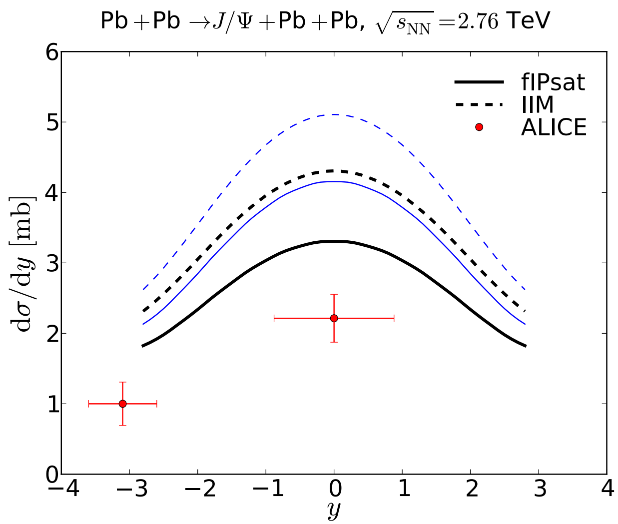


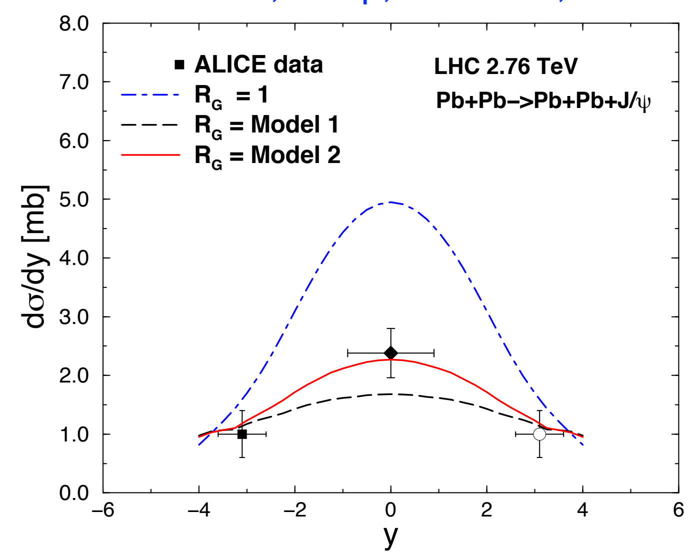
CMS PAS HIN-12-009

Dipole model predictions

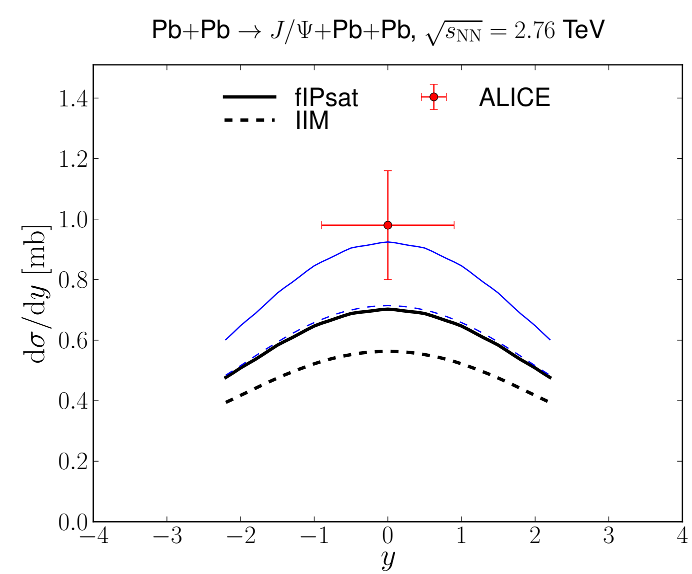
• In dipole models, photoproduction of J/ψ corresponds to small-size dipoles → suppression due to nuclear shadowing is small → ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs **overestimated**

Ducati, Griep, Machado, PRC 88 (2013) 014910





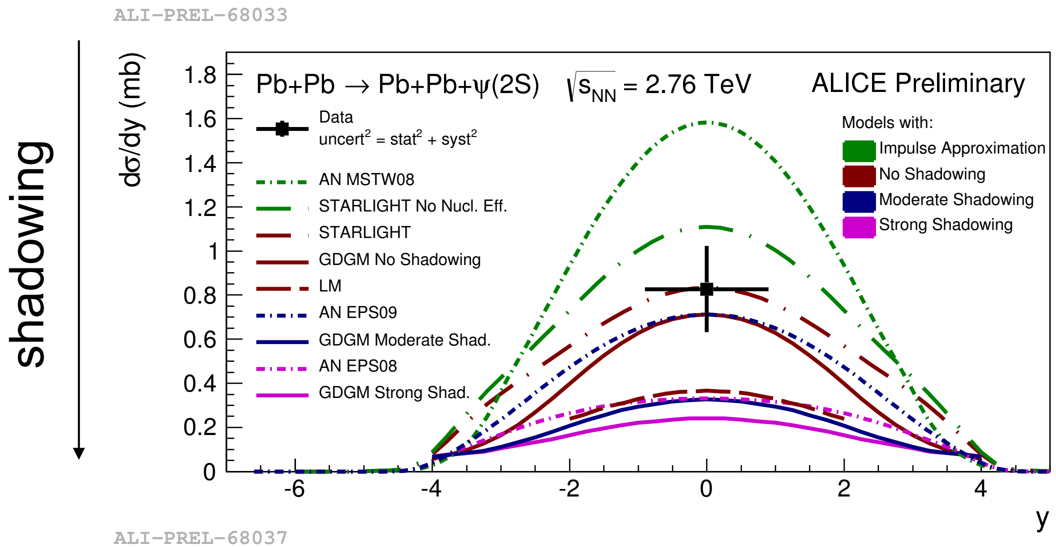
Lappi, Mäntysaari, arXiv:1406.2877 (DIS 2014)



• At the same time, incoherent photoproduction of J/ψ in Pb-PB UPCs is described better, but strong model-dependence

Photoproduction of ψ(2S)

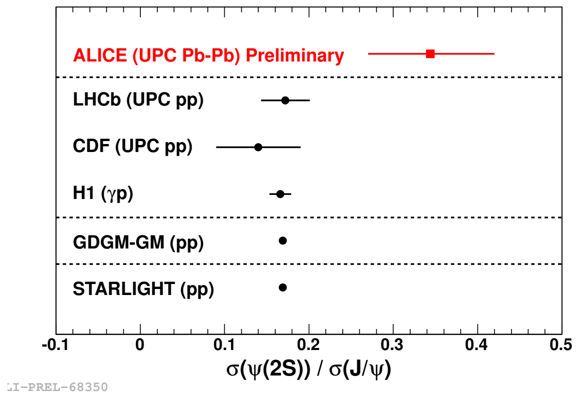
- ALICE measured coherent ψ(2S) photoproduction in Pb-Pb UPCs at 2.76 TeV



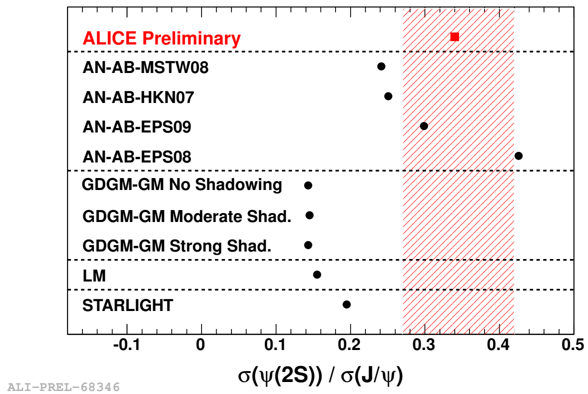
- Data agrees with small nuclear shadowing.
- R is much larger than theory predictions

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

Comparison with pp



Comparison with AA



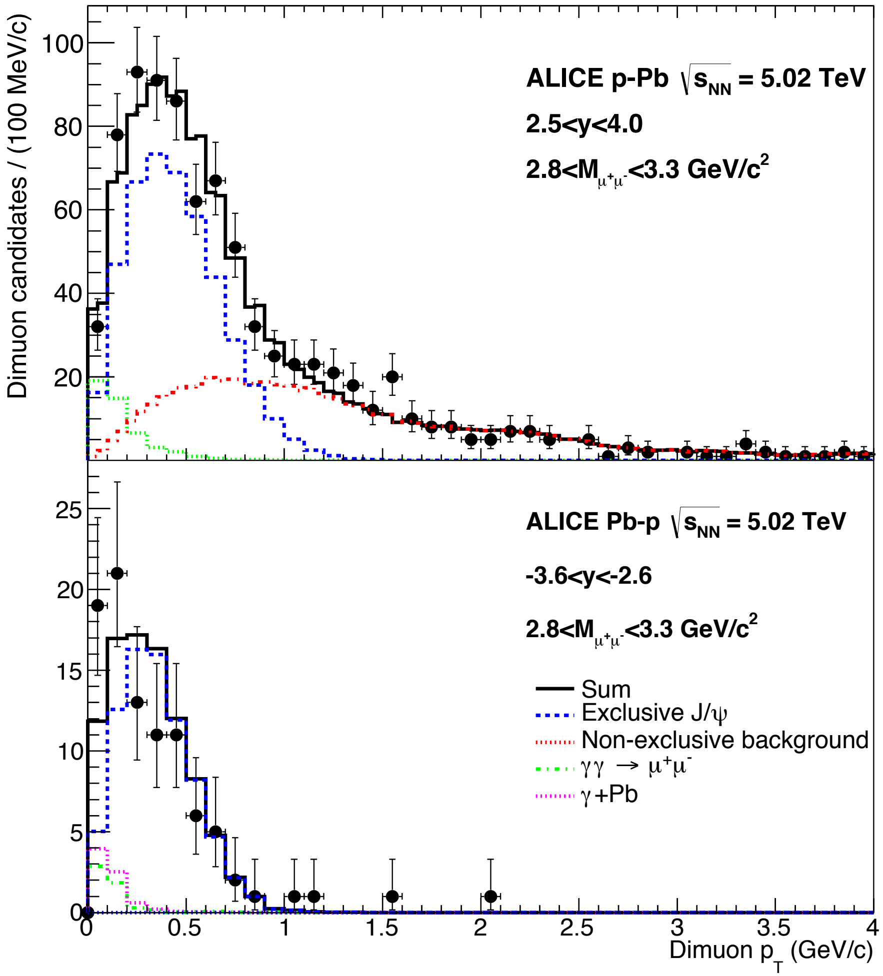
- Cannot be explained in leading twist nuclear shadowing model predicting similar shadowing suppression in J/ψ and ψ(2S) cases.

J/ψ photoproduction in PA UPCs

- ALICE measured coherent J/ψ photoproduction in p-Pb UPCs at 5.02 TeV

- The cross section is dominated by photon-proton scattering → very weak sensitivity to nuclear shadowing except for small pT in Pb-p mode.

B. Abelev et al., (ALICE) arXiv:1406.7819



Conclusions

- Nuclear parton distributions at small x are suppressed compared to free proton ones – nuclear shadowing. The magnitude of shadowing of the gluon distribution in unknown for $x < 0.01$.

- The leading twist model of nuclear shadowing predicts large gluon shadowing. Predictions can be tested in photon-nucleus processes in UPCs at the LHC.

- Coherent photoproduction of J/ψ in Pb-Pb UPCs at the LHC gives first direct evidence of large nuclear gluon shadowing at $x=0.001$ consistent with our predictions and in contradiction to the dipole framework.

- In the incoherent channel, there is discrepancy between the data and our predictions, which we attribute to nucleon dissociation contribution (requires more work).

- Large gluon shadowing agrees with preliminary CMS data on coherent photoproduction of J/ψ in Pb-Pb UPCs accompanied by forward neutron emission.

- Models disagree with ALICE data on $\psi(2S)$ photoproduction in Pb-Pb UPCs consistent with small shadowing.