Leading twist nuclear shadowing and J/ψ photoproduction in ultraperipheral collisions at the LHC

Vadim Guzey

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

VG, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290 — J/ψ in Pb-Pb: gluon shadowing
VG, Zhalov, JHEP 1310 (2013) 207 — J/ψ in Pb-Pb: gluon PDFs in Pb & p
VG, Zhalov, JHEP 1402 (2014) 046 — J/ψ in pPb
VG, Strikman, Zhalov, arXiv:1312.6486 — J/ψ in Pb-Pb: coh./incoh, n tagging
VG, Zhalov, arXiv:1404.6101 and 1405.7529 — J/ψ and ψ(2S) in Pb-Pb & pp UPCs

Workshop on photon-induced reactions at the LHC
CERN, June 2-4, 2014

Outline:

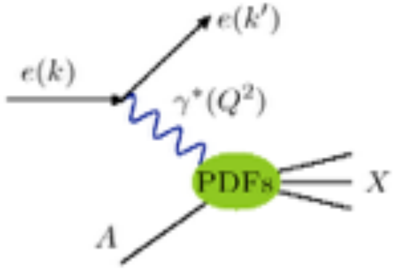
- Leading twist nuclear shadowing in nuclear PDFs

- Photoproduction of J/ψ in Pb-Pb UPCs at the LHC:
  - coherent case: ALICE data favors large gluon shadowing consistent with leading twist predictions
  - incoherent case: leading twist overpredicts shadowing suppression, issue of nucleon dissociation contribution
  - UPCs accompanied by nucleus e.m. excitation of with subsequent neutron emission: method to extend probed x.

- Photoproduction of ψ(2S) in Pb-Pb UPCs

Nuclear shadowing

- Deep inelastic scattering (DIS) with nuclear targets

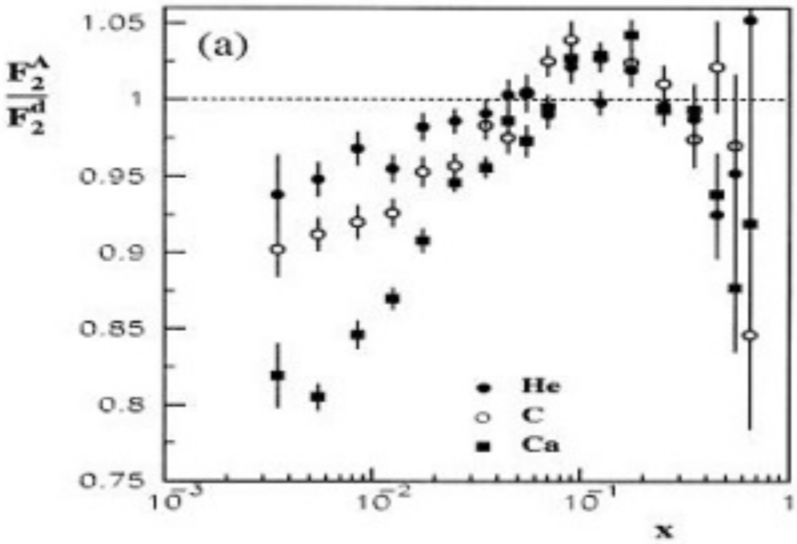


$$F_{2A}(x) \neq \int_x^A \frac{dy}{y} n(y) F_{2N}(x/y) \approx A F_{2N}(x)$$

$$(k' - k)^2 = q^2 = -Q^2$$

$$x = A \frac{Q^2}{2(p_A \cdot q)}$$

Piller, Weise, Phys. Rept. 330 (2000) 1

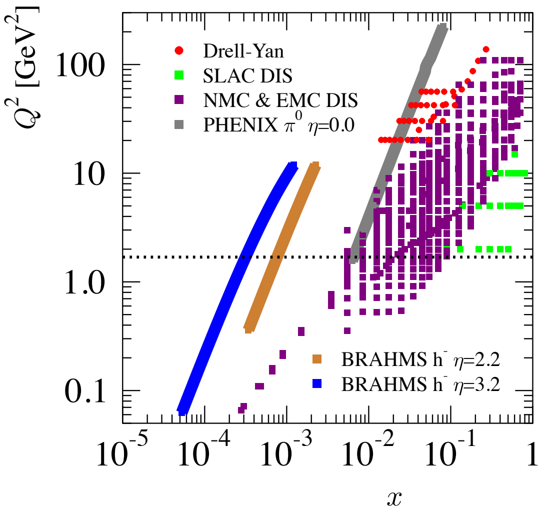


- 4 regions: **shadowing** (x < 0.05), antishadowing (0.05< x <0.2), EMC effect (0.2 < x < 0.8), Fermi motion (x > 0.8).

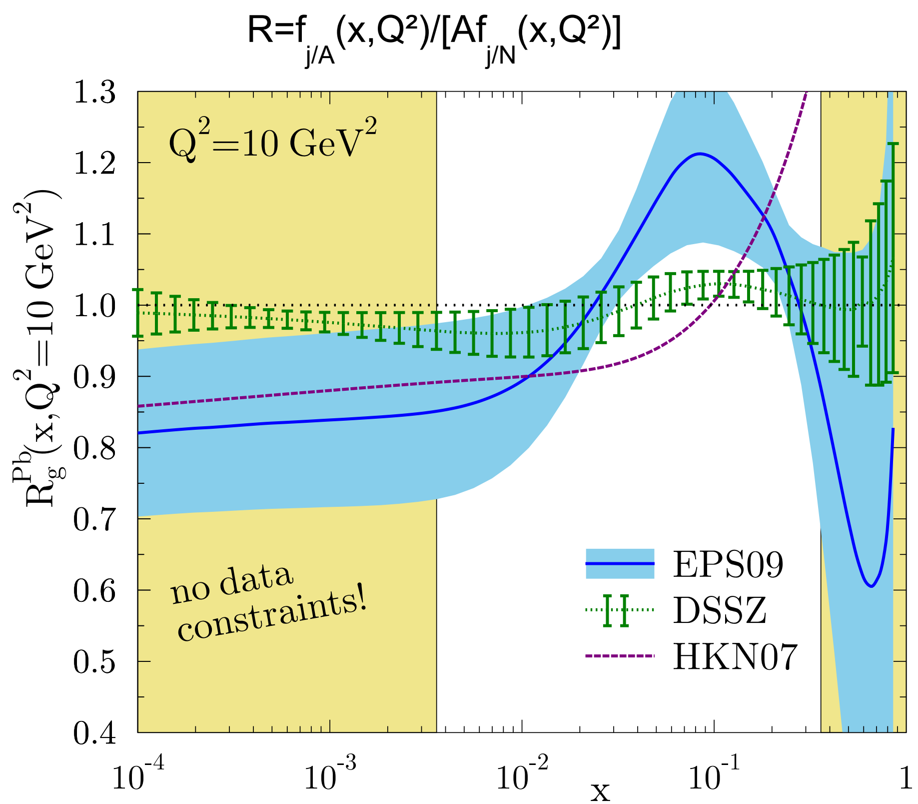
Nuclear parton distributions

- Nuclear PDFs from global QCD fits: data + collinear factorization + DGLAP (Q^2) evolution

$$F_{2A}(x,Q^2) = x \sum_{j=q,\bar{q},g} \int_{\beta}^{1} \frac{dy}{y} C_j\left(\frac{x}{y},Q^2\right) f_{j/A}(y,Q^2)$$



Eskola, Puukkunen, Salgado, JHEP 04 (2009) 065



Eskola, Puukkunen, arXiv:1401.2345

- Resulting nuclear gluon PDF has rather large uncertainty due to:
  - limited kinematics of used data
  - indirect extraction of gluons via Q^2 evolution
  - assumptions about the initial shape
  - different choice/treatment of data used in fits

Leading twist theory of nuclear shadowing

Method to evaluate parton (sea quark and gluon) distributions in nuclei for small *x* as a function of *x* and impact parameter *b* at certain input scale Q_0.
Further Q^2 dependence given by DGLAP.

<u>The approach is based on:</u>

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

- The picture of the strong interactions at high energies in the laboratory frame, Gribov-Glauber shadowing theory and its extension to eA DIS → expression for $F_{2A}(x,Q^2)$ in terms of proton diffractive structure function

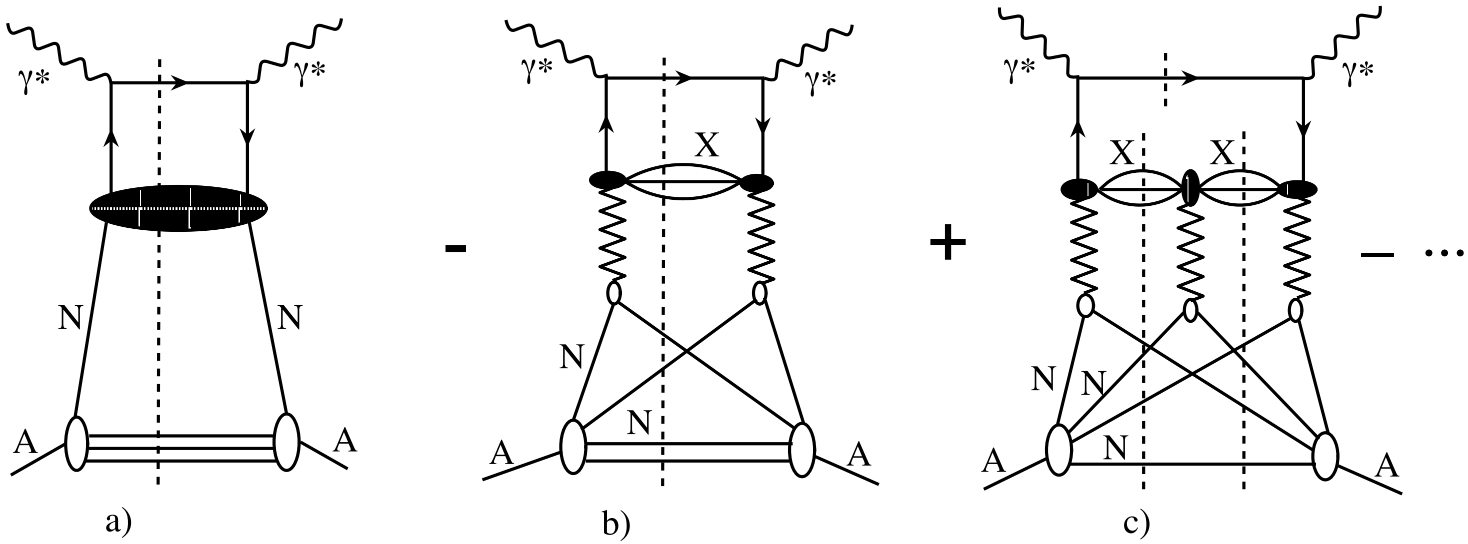
- Collinear factorization for total and diffractive DIS cross sections → from $F_{2A}(x,Q^2)$ to individual nuclear parton distributions $f_{j/A}(x,Q^2)$

- Diffractive parton distributions in the proton (HERA) → input for predictions

The name "*leading twist*": shadowing in terms of diffraction which is leading twist (one of major HERA results)

Leading twist nuclear shadowing and nuclear PDFs

Gribov-Glauber multiple scattering series can be generalized from hA to eA DIS.
Using QCD factorization, the series can be written for individual parton flavors **j**:



interaction with
N > 3 nucleons

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

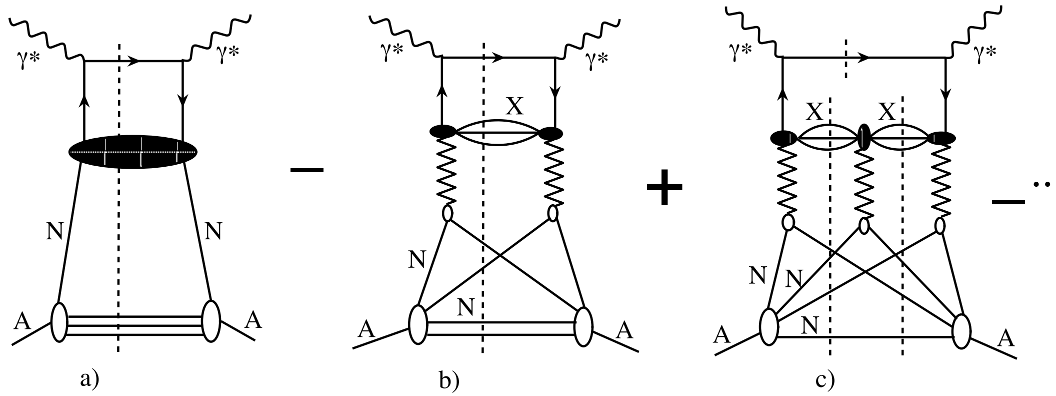
$$\times \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2) e^{i(z_1-z_2)x_P m_N} e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}^j(x,Q_0^2)\int_{z_1}^{z_2} dz' \rho_A(\vec{b},z')}$$

Nuclear part same as in hA
(Glauber method)

Input:

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

Model independence and model-dependence



interaction with N > 3 nucleons

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

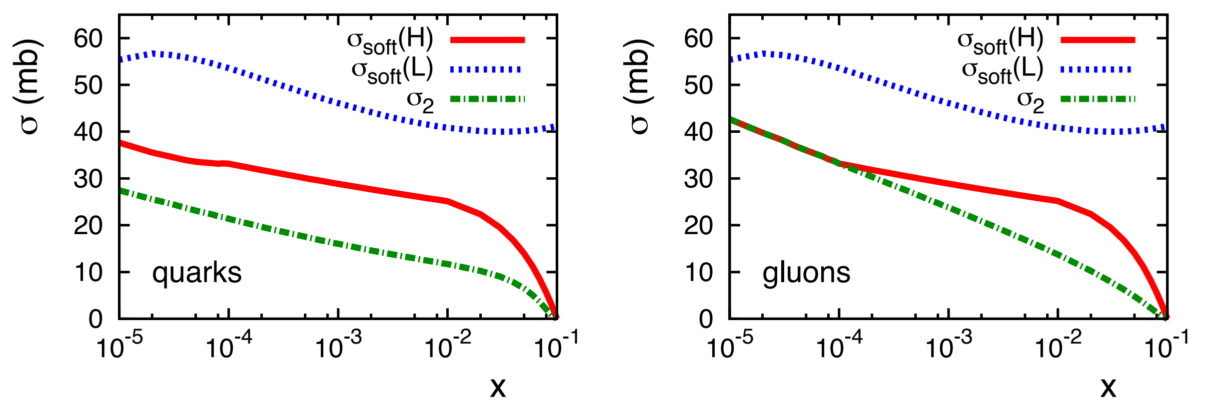
$$\times \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2) e^{i(z_1-z_2)x_P m_N} e^{-\frac{A}{2}(1-i\eta)\sigma^j_{\rm soft}(x,Q_0^2)\int_{z_1}^{z_2} dz' \rho_A(\vec{b},z')}$$

The interaction with N ≥ 3 nucleons requires model for $\sigma_{\rm soft}$

(we used the formalism of cross section fluctuations)

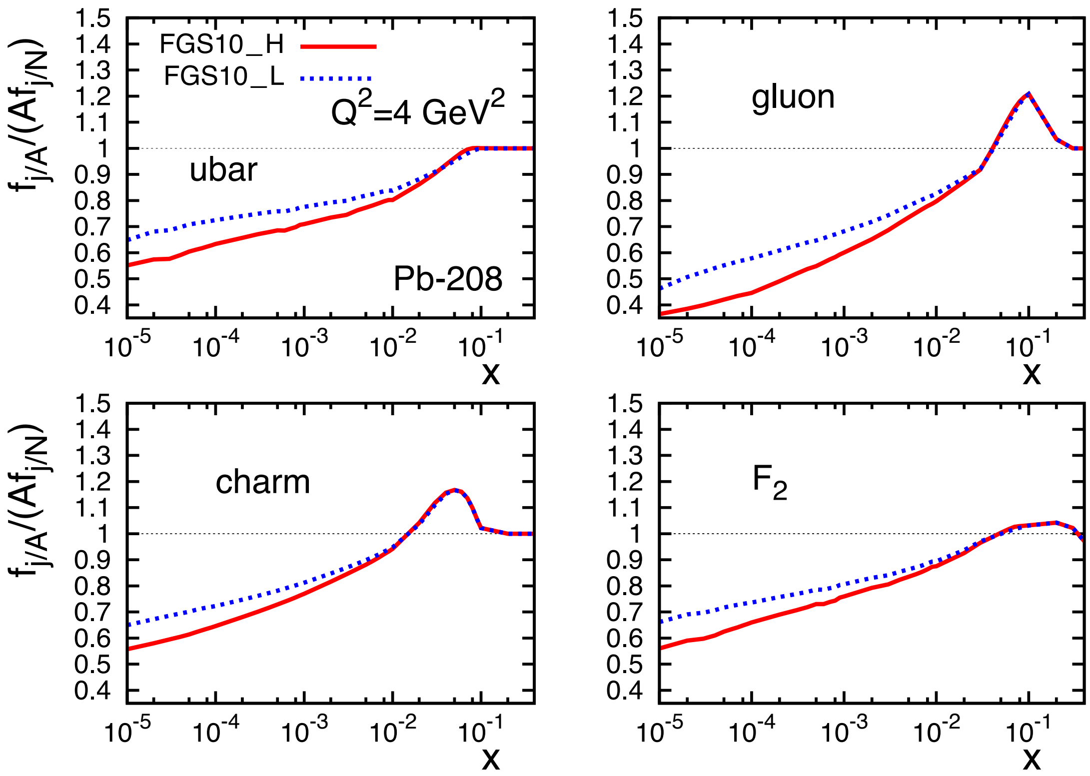
The result for double scattering is model-independent:

Gribov's connection between shadowing and elem. diffraction



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

Predictions for nuclear PDFs



- Model dependence is small for not too small x and medium A ➞ can be reduced by varying A

- Antishadowing is modeled using momentum sum rule

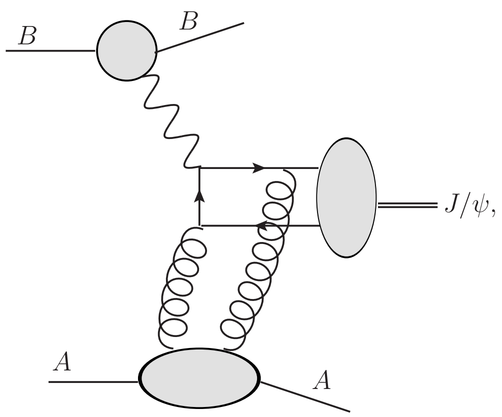
- Predicted large shadowing for sea quarks and gluons
- Gluon shadowing > quark shadowing ➞ large shadowing for $F_L^A(x,Q^2)$

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

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



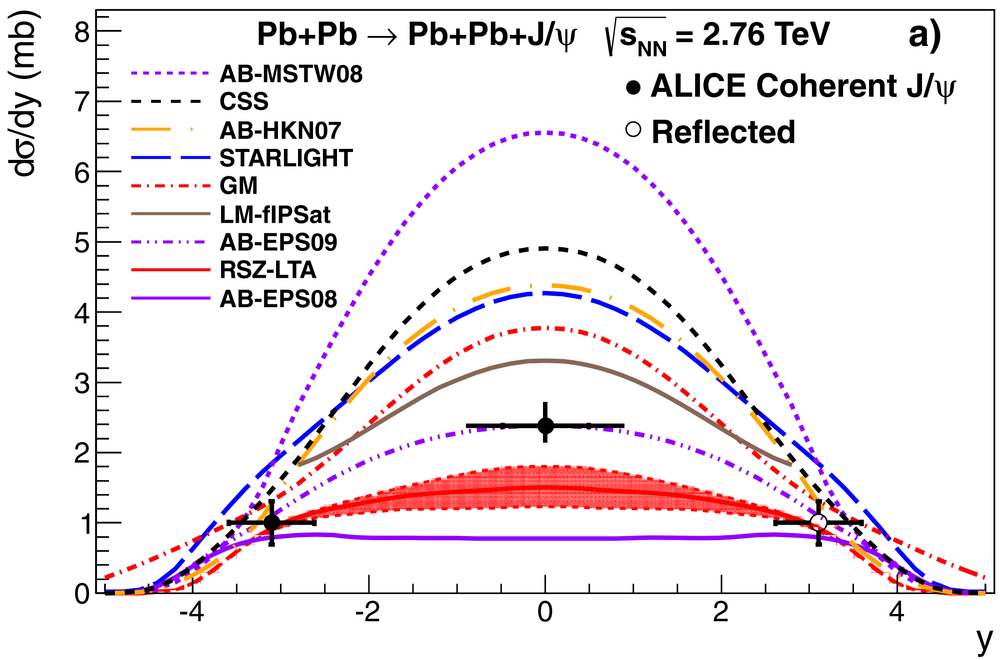
$$d\sigma^{\rm coh}(y \approx -3)/dy = 1 \pm 0.18^{+0.24}_{-0.26}\ {\rm mb}$$
$$d\sigma^{\rm coh}(y \approx 0)/dy = 2.38^{+0.34}_{-0.24}\ {\rm mb}$$

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

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

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

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



Shadowing suppression from J/ψ photoproduction in Pb-Pb UPC

- AA UPCs = photon-nucleus interactions

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

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

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

Photon flux of Pb (known with a few percent accuracy)

- The ALICE experimental values for $d\sigma_{PbPb\to PbPbJ/\psi}/dy$ can be converted to:

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

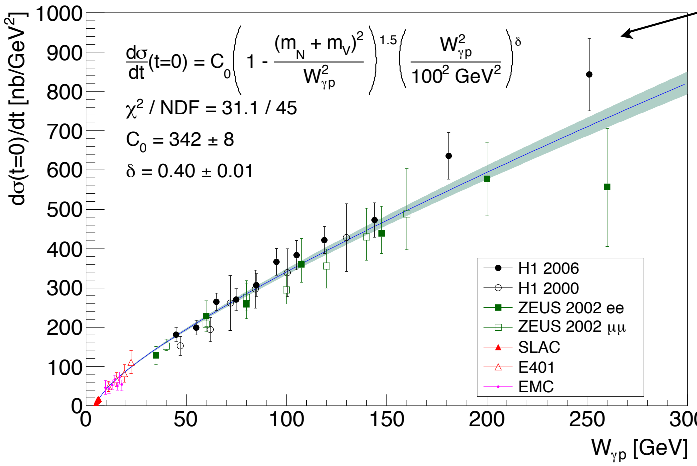
Shadowing suppression from J/ψ photoproduction in Pb-Pb UPC (2)

- In is convenient to express the result in terms of the suppression factor *S*:

$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\rm exp}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})} \right]^{1/2}$$

- The denominator of *S* is the cross section in the impulse approximation:

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



Calculated using nuclear form factor

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

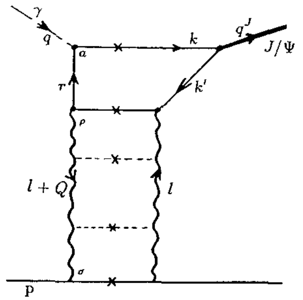
- Model-independent determination of *S*:

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

- ***S* can be interpreted as suppression due to the nuclear gluon shadowing.**

Implications for nuclear gluon shadowing

- At the leading order pQCD and non-relativistic limit for the J/ψ wave function :



M. Ryskin (1993)

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

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

- Applying to nuclear and proton targets :

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

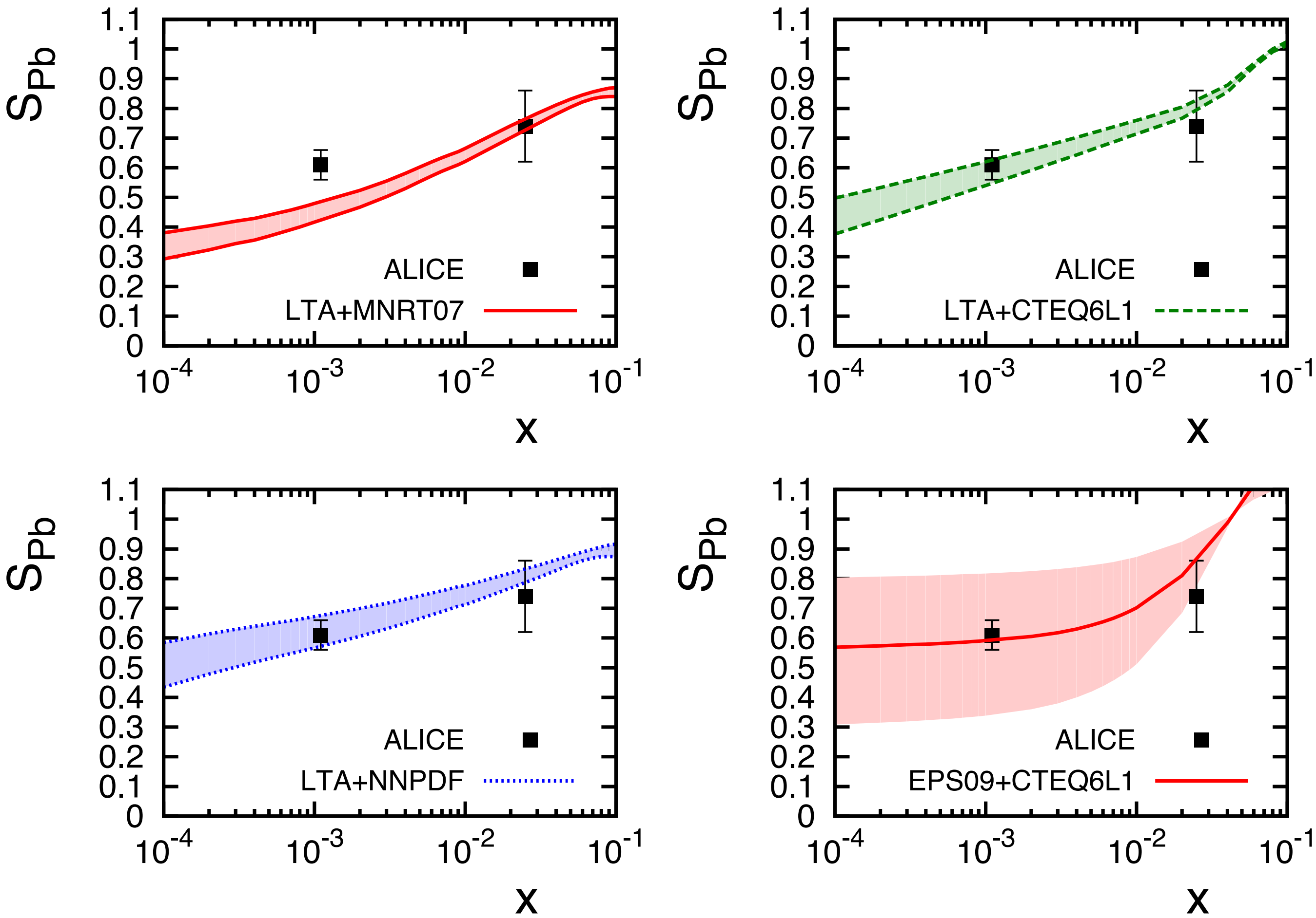
$$S_A(W)=\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)}$$

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

- In practice, we also included several corrections (real part, skewness) and slightly varied μ^2 to reproduce W-dependence of $\gamma + p \to J/\psi + p$ cross section.

Implications for nuclear gluon shadowing (2)

- Taking $\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)}$ from the leading twist theory of nuclear shadowing and global fits:



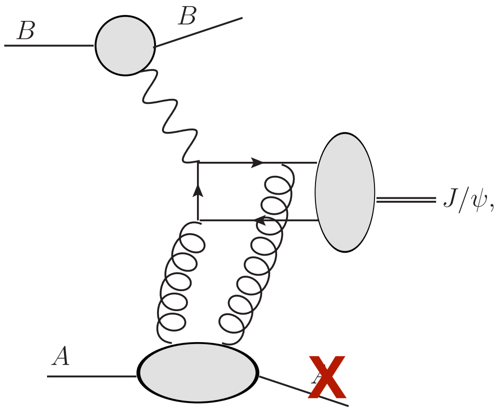
μ^2=3 GeV^2

ALICE data gives first direct evidence of large nuclear gluon shadowing at x=0.001.

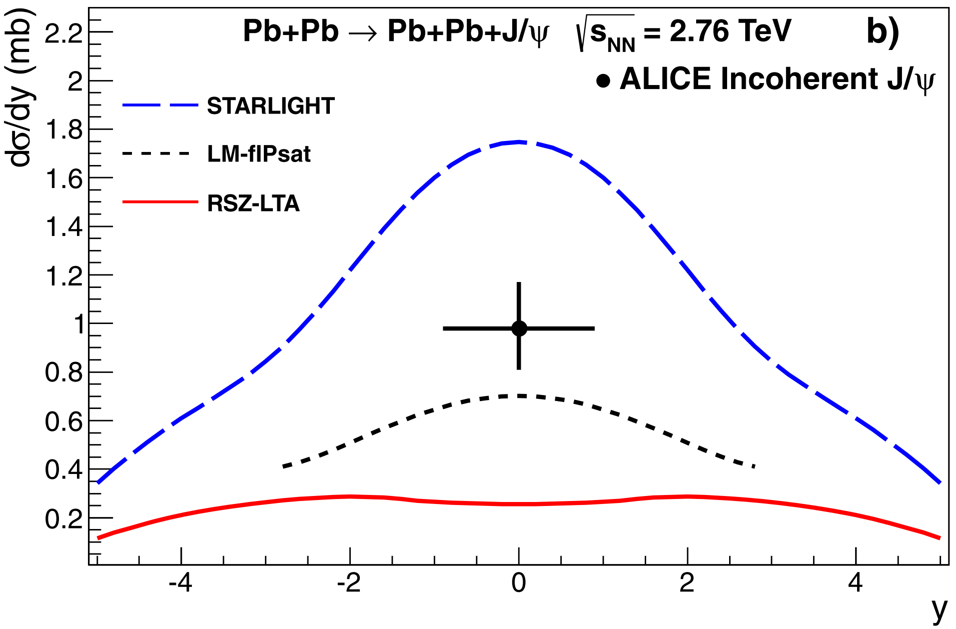
Incoherent J/ψ photoproduction in Pb-Pb UPCs at LHC

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

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



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



However, see talks of V. Goncalves and H. Mäntysaari at this workshop.

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

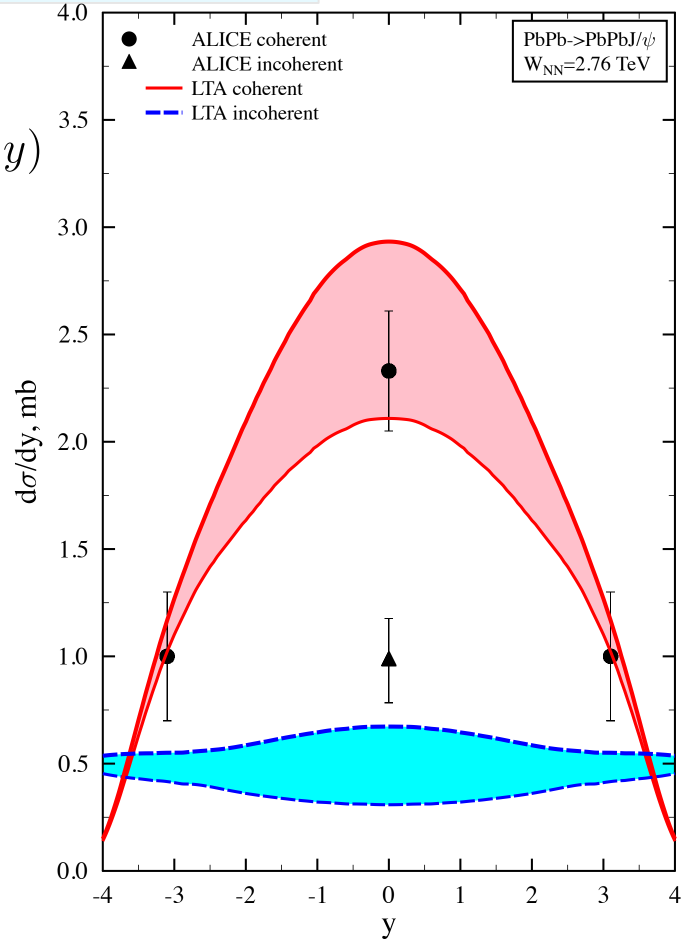
- Leading twist theory of nuclear shadowing makes predictions for incoherent case without introducing extra parameters:

VG, Strikman, Zhalov, arXiv:1312.6486

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

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

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



- ... and predicts too much shadowing

- One possible source of discrepancy: contribution of nucleon dissociation $\gamma + N \to J/\psi + Y$

This contribution:

- sizable: $(d\sigma_{\gamma p\to J/\psi Y}/dt)/(d\sigma_{\gamma p\to J/\psi p}/dt) \approx 0.15$ at $t \approx 0$

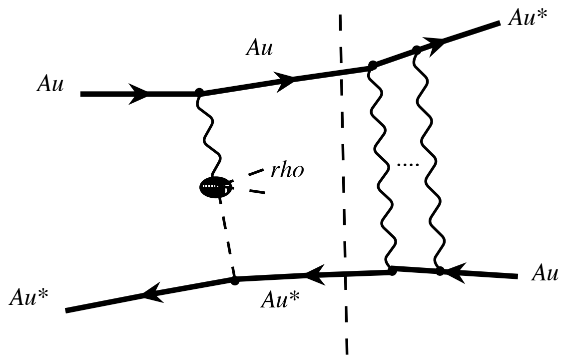
$\sigma_{\gamma p\to J/\psi Y}/\sigma_{\gamma p\to J/\psi p} \approx 0.8$ for the t-integrated cross sections

- has different t-dependence → can be used to constrain experimentally.

UPCs accompanied by neutron emission

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

Baltz, Klein, Nystrand (2002)



- Additional photon exchanges cost $Z^2\alpha_{\rm e.m.}^2 \approx 0.3-04$ 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)

- Measuring any two channels one can separate high-ω (ω_1) and low-ω (ω_2) contrib's:

Rebyakova, Strikman, Zhalov (2012)

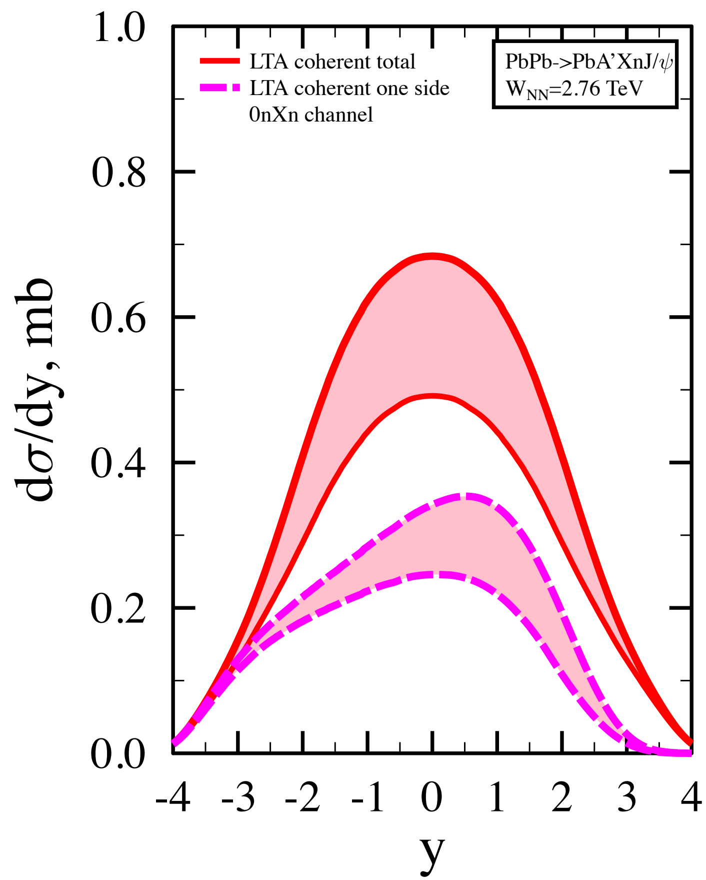
$$d\sigma^{0nXn}/dy = N_\gamma^{0nXn}(\omega_1)\sigma_{\gamma\to J/\psi}(\omega_1) + N_\gamma^{0nXn}(\omega_2)\sigma_{\gamma\to J/\psi}(\omega_2)\,,$$

$$d\sigma^{XnXn}/dy = N_\gamma^{XnXn}(\omega_1)\sigma_{\gamma\to J/\psi}(\omega_1) + N_\gamma^{XnXn}(\omega_2)\sigma_{\gamma\to J/\psi}(\omega_2)$$

→ **possibility to extend probed values of x!**

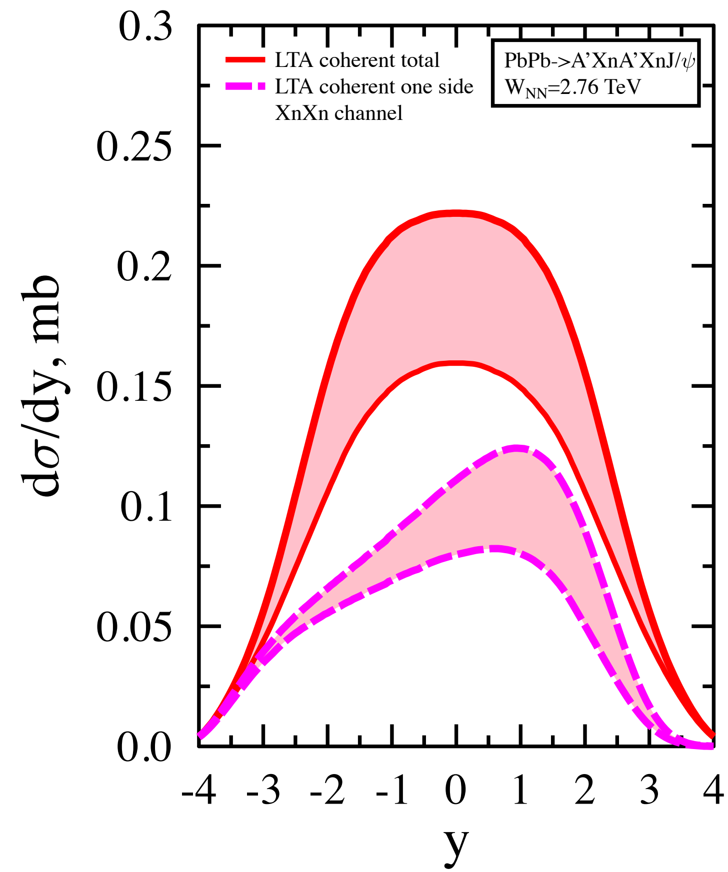
UPCs accompanied by neutron emission (2)

0nXn



XnXn

VG, Strikman, Zhalov, arXiv:1312.6486



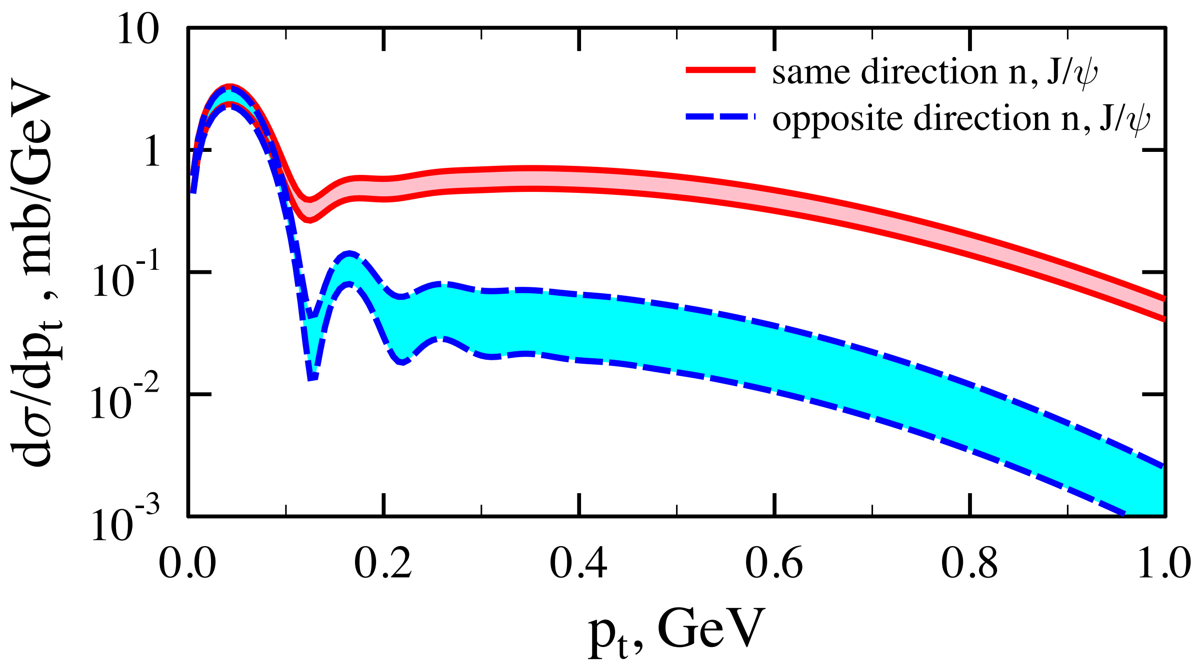
In the rapidity range $1.5 < y < 2.5$, the separation of the ω_1 and ω_2 terms will allow one to probe gluon density in Pb down to $x=10^{-4}$

→ order of magnitude smaller than can do without neutron tagging.

UPCs accompanied by neutron emission (3)

In the incoherent case in the 0nXn-channel, one can separate the ω_1 and ω_2 terms by studying correlation between direction of J/ψ and neutrons.

VG, Strikman, Zhalov, arXiv:1312.6486



$$Pb + Pb \to Pb + Xn + J/\psi$$

$$\sqrt{s} = 2.76 \text{ TeV}$$

$$1.5 < y < 2.5$$

Coherent+incoherent
- upper: low-ω
- lower: high-ω

- For coherent contribution at small pt, directions of J/ψ and neutrons are not correlated since e.m. excitation is independent from coherent photoproduction.

- For incoherent contribution, high-energy photons correspond to J/ψ and neutrons (target) moving in opposite directions → **possibility to probe smaller x_A**

Photoproduction of ψ(2S) in Pb-Pb UPCs

- In the leading logarithmic approximation of pQCD, photoproduction of ψ(2S) and J/ψ on the same footing:

$$\frac{d\sigma_{\gamma T\to J/\psi[\psi(2S)]T}}{dt}(W_{\gamma p},t_{\min})=C(\mu^2)[\alpha_s(\mu^2)xG_T(x,\mu^2)]^2F_T^2(t_{\min})$$

- In our implementation, the only difference is the value of μ^2

  - μ^2=3 GeV^2 for J/ψ to reproduce $\sigma(\gamma p\to J/\psi p)\propto W^{0.8}$ H1, ZEUS
  - μ^2=4 GeV^2 for ψ(2S) to reproduce $R\equiv\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\propto\left(\frac{W_{\gamma p}}{90\ \mathrm{GeV}}\right)^{\Delta\delta}$ $\Delta\delta=0.24\pm0.17$ H1 (2002)

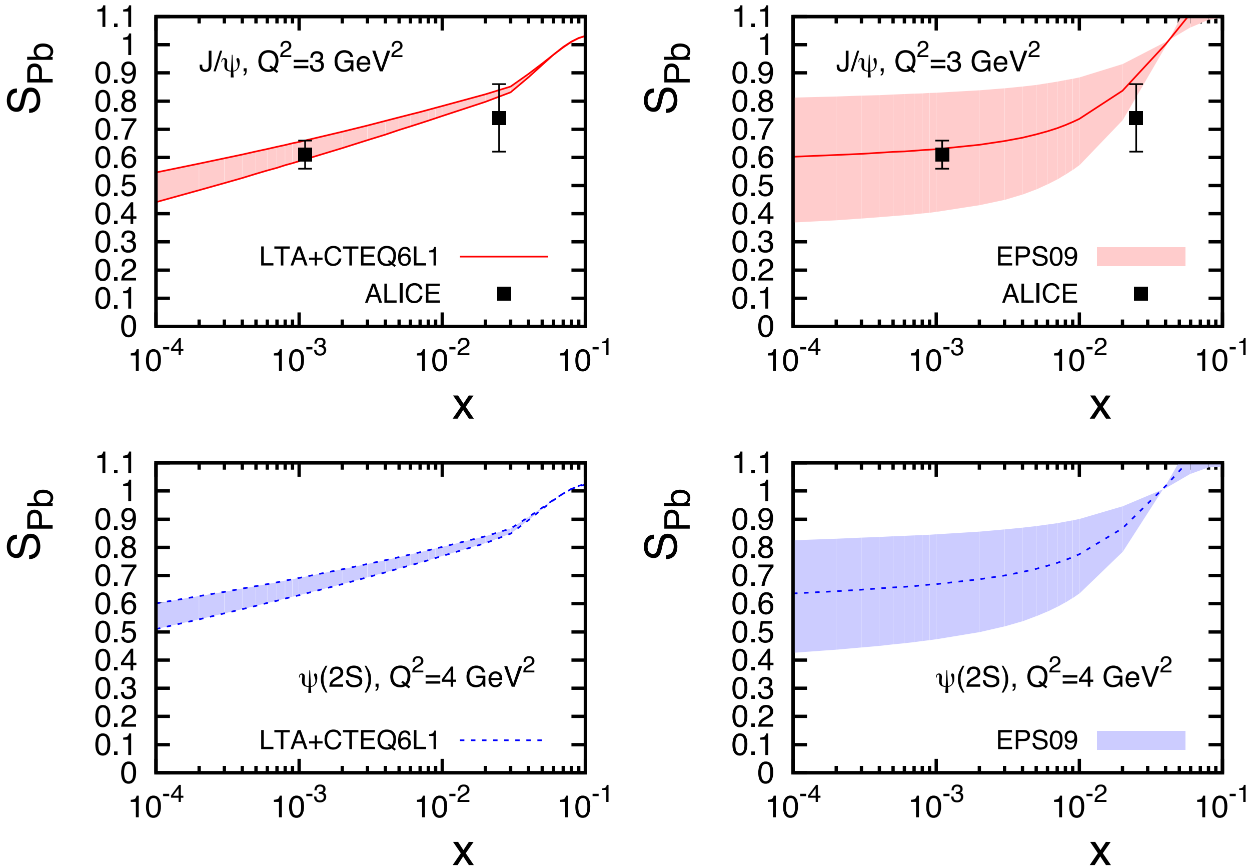
- Thus, the formalism predicts only the W-dependence of $\sigma(\gamma p\to\psi(2S)p)$. The normalization is fixed using the H1 result:

$$\frac{\sigma_{\gamma p\to\psi(2S)p}}{\sigma_{\gamma p\to J/\psi p}}=0.166\pm0.007(\mathrm{stat.})\pm0.008(\mathrm{sys.})\pm0.007(\mathrm{BR})$$

C. Adloff *et al.* [H1 Collaboration], PLB 541 (2002) 251

Photoproduction of ψ(2S) in Pb-Pb UPCs (2)

- Leading twist shadowing suppression is very similar in J/ψ and ψ(2S) cases:



VG, Zhalov, arXiv:1404.6101

- The ratio of ψ(2S) and J/ψ photoproduction cross sections in Pb-Pb UPCs is the same as in the proton case :

$$\frac{d\sigma_{AA\to AA\psi(2S)}(y)/dy(y=0)}{d\sigma_{AA\to AAJ/\psi}(y)/dy(y=0)} = \begin{cases} 0.15-0.16\,, & \text{LTA}+\text{CTEQ6L1} \\ 0.15^{+0.03}_{-0.01}\,, & \text{EPS09}\,. \end{cases}$$

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 theory 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 consistent with our predictions.

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

- UPCs accompanied by e.m. excitations of nuclei with subsequent neutron emission can help to probe the nuclear gluon distribution at smaller x.

- Shadowing suppression for photoproduction of ψ(2S) and J/ψ in Pb-Pb UPCs is predicted to be very similar.