Leading-twist shadowing in inclusive and diffractive DIS

Vadim Guzey

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

Outline:

- Nuclear PDFs at small x
- Model of leading-twist nuclear shadowing
- Inclusive and diffractive structure functions in eA DIS
- Leading twist nuclear shadowing in γA scattering at the LHC: Exclusive J/ψ photoproduction

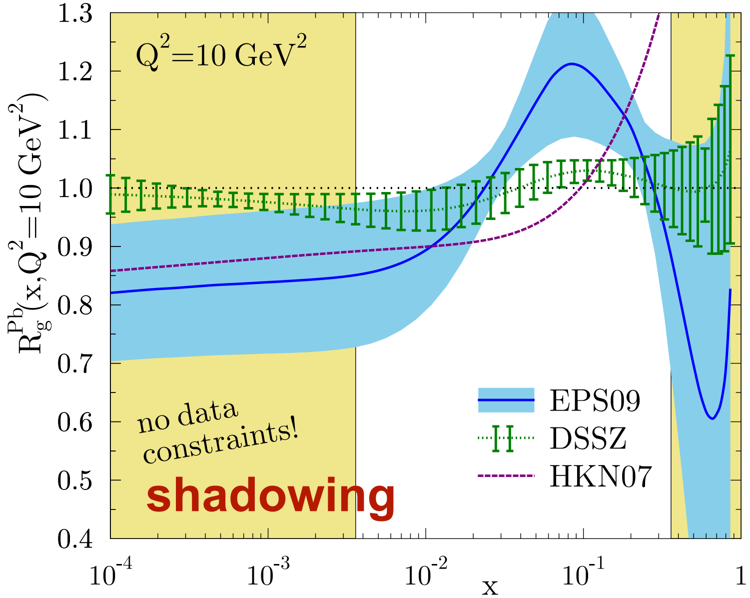
Exploring QCD with light nuclei at EIC, Stony Brook University, Jan 21-24, 2020 (remote presentation)

Nuclear parton distributions at small x

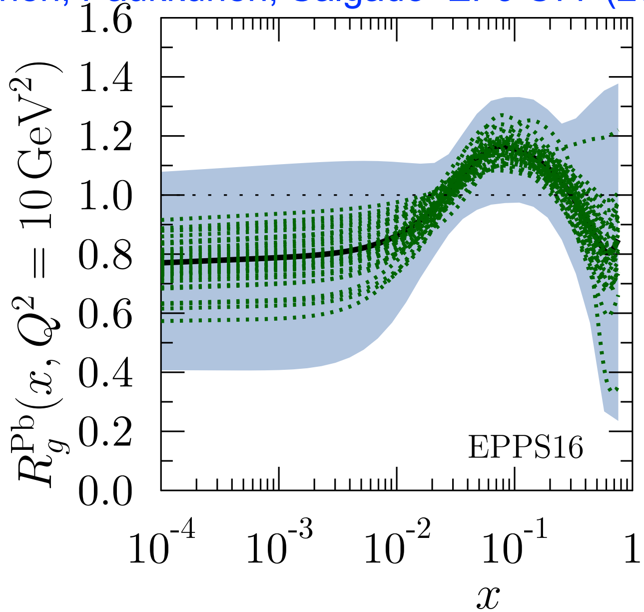
- Nuclear parton distributions (nPDFs) = densities/distributions of quarks and gluons in nuclei as function of momentum fraction x at resolution scale μ.
- Defined as matrix elements of quark and gluon fields between nuclear states in the framework of QCD collinear factorization.
- Essential for QCD phenomenology of hard processes with nuclei at high energies at RHIC, LHC, and future EIC, LHeC/FCC
- nPDFs are determined from global QCD fits to data on fixed-target DIS, hard processes in dA (RHIC) and pA (LHC) → $f_A(x,\mu^2)$ with significant uncertainties

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

Paukkunen, NPA 926 (2014) 24

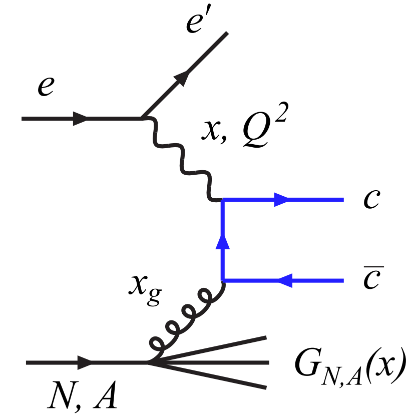


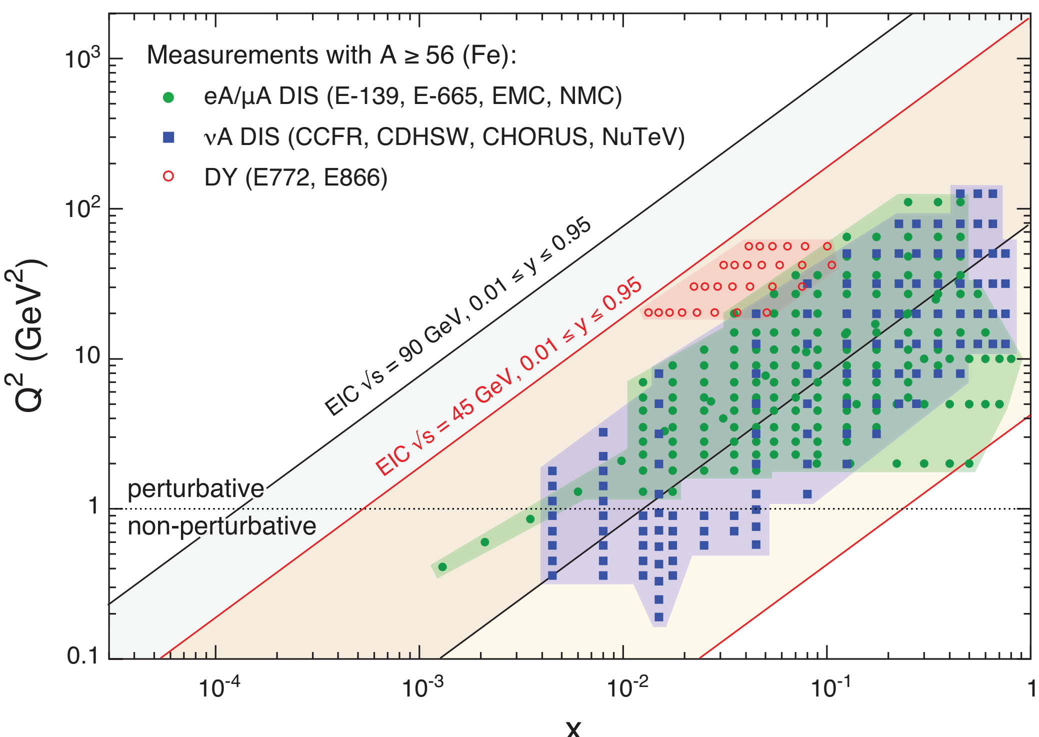
- pA@LHC data help little, EPPS16, Eskola, Paakkinen, Paukkunen, Salgado EPJ C77 (2017) 163

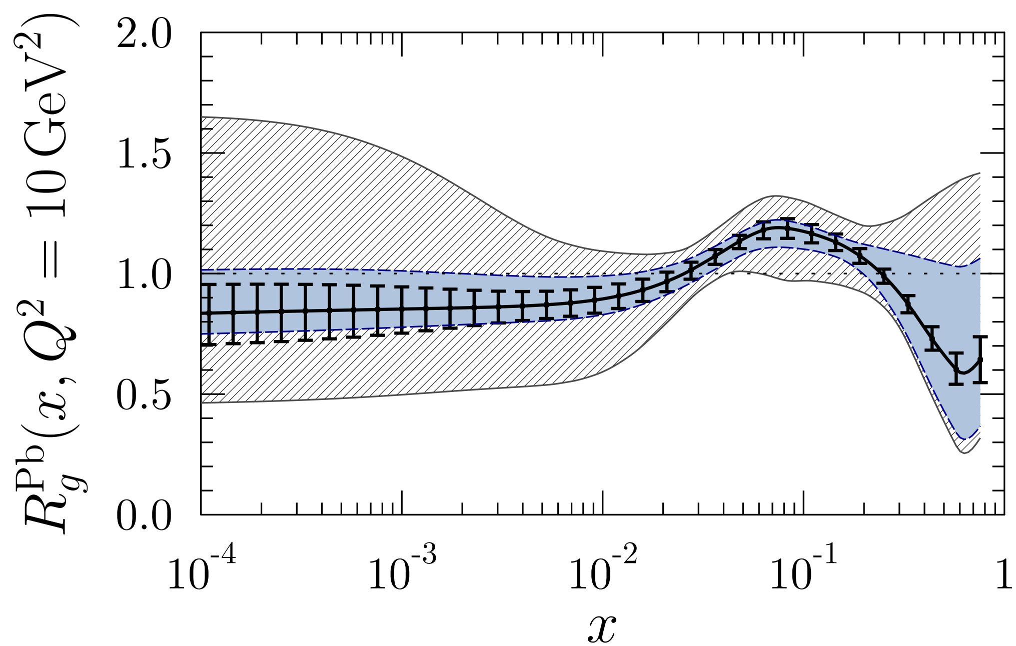


Nuclear shadowing at EIC and LHeC

- In the future, nPDFs at small-x will be further constrained at EIC, Accardi et al, EPJ A52 (2016) no.9, 268 and LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001 due to wide Q^2-x kinematic coverage, $F_L^A(x,Q^2)$ and $F_2^{charm}(x,Q^2)$ measurements:







Aschenauer, Fazio, Lamont, Paukkunen, Zurita, PRD 96 (2017) no.11, 114005

Hatched: baseline fit
Blue: EIC inclusive
Black error: EIC inclusive + charm

Nuclear shadowing: πD scattering

- At small x, a high-energy probe interacts *coherently (simultaneously)* with all nucleons of the nucleus target.
- Nuclear shadowing is a result of destructive interference among the amplitudes for the interaction with 1, 2, 3, etc. nucleons of the target.
- Total pion-deuteron cross section:

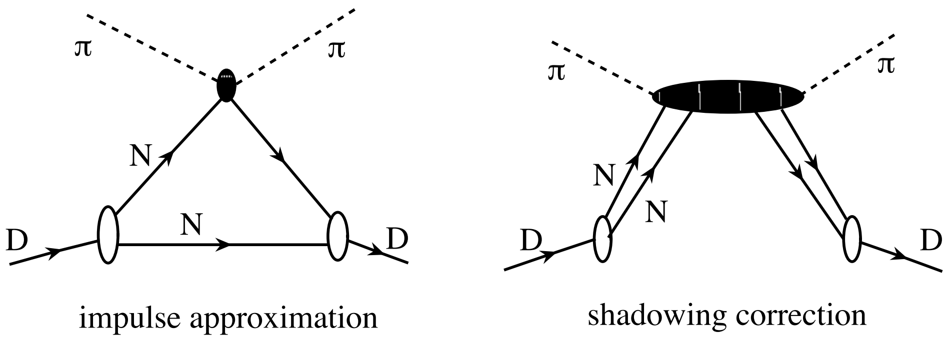
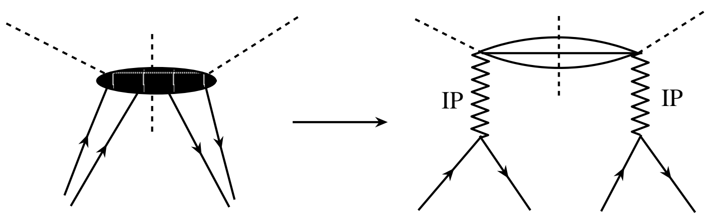


Figure 2: Graphs for pion-deuteron scattering.



The shadowing term can be expressed in terms of pion-proton diffractive cross section

$$\sigma_{\rm tot}^{\pi D} = 2\sigma_{\rm tot}^{\pi N} - 2\int d\vec{k}^2 \rho_D(4\vec{k}^2)\frac{d\sigma_{\rm diff}^{\pi N}(k)}{d\vec{k}^2}$$

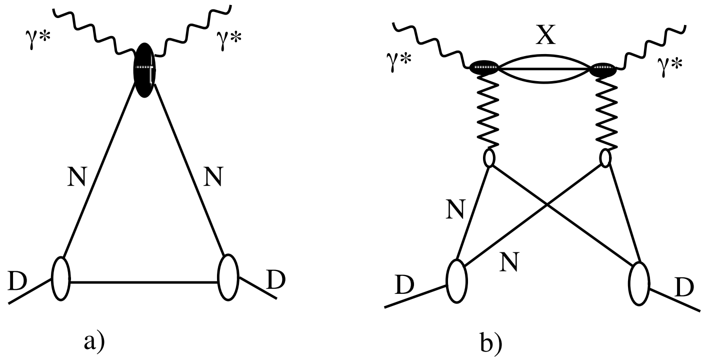
Glauber (1955); Gribov (1969)

Deuteron form factor

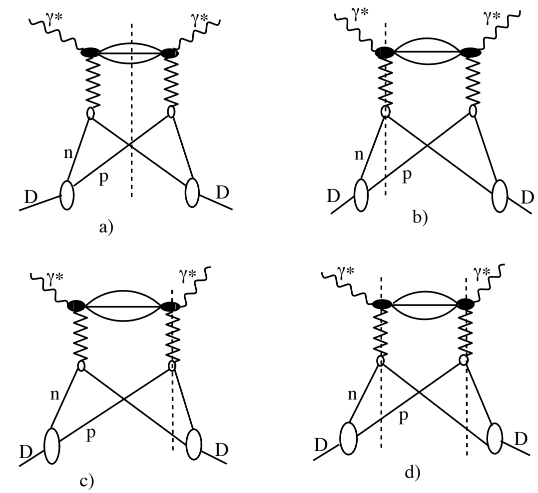
Pion-proton diffractive cross section

Leading-twist shadowing in DIS on deuteron

- Forward Compton scattering amplitude:



Impulse approx. Shadowing correction



Imaginary part of shadowing is given by diffractive cut due to AGK cutting rules

Abramowski, Gribov, Kancheli (1973)

- Calculation using Gribov-Glauber theory or direct evaluation of Feynman graphs in the virtual nucleon approximation (VNA):

$$F_{2D}(x,Q^2) = F_{2p}(x,Q^2)+F_{2n}(x,Q^2) -2\frac{1-\eta^2}{1+\eta^2}B_{\rm diff}\int_x^{0.1} dx_{I\!P}\, dk_t^2\, F_2^{D(3)}\left(\beta,Q^2,x_{I\!P}\right) e^{-B_{\rm diff}\,k_t^2}\rho_D\left(4k_t^2+4(x_{I\!P}m_N)^2\right)$$

Frankfurt, VG, Strikman (2012)

$B_{\rm diff} \approx 6$ GeV^{-2} ± 15% (HERA)

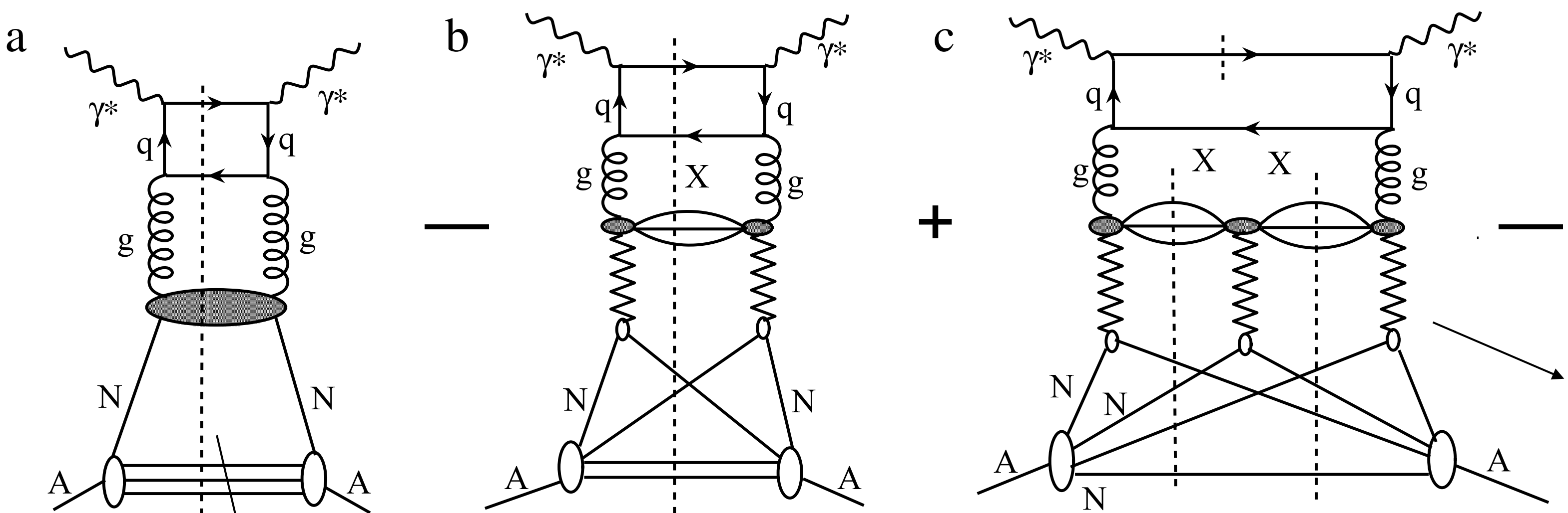
η=Re/Im ≈ 0.17

Leading-twist proton diffractive structure function, measured at HERA

deuteron FF from wave function

Model of leading-twist nuclear shadowing: heavy nuclei

- Alternative to extrapolation of nPDFs into x < 0.05 region : model of leading twist nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255
- Combination of Gribov-Glauber shadowing model with QCD factorization theorems for inclusive and diffractive DIS, Frankfurt, Strikman, EPJ A5 (1999) 293



diffractive exchange

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

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

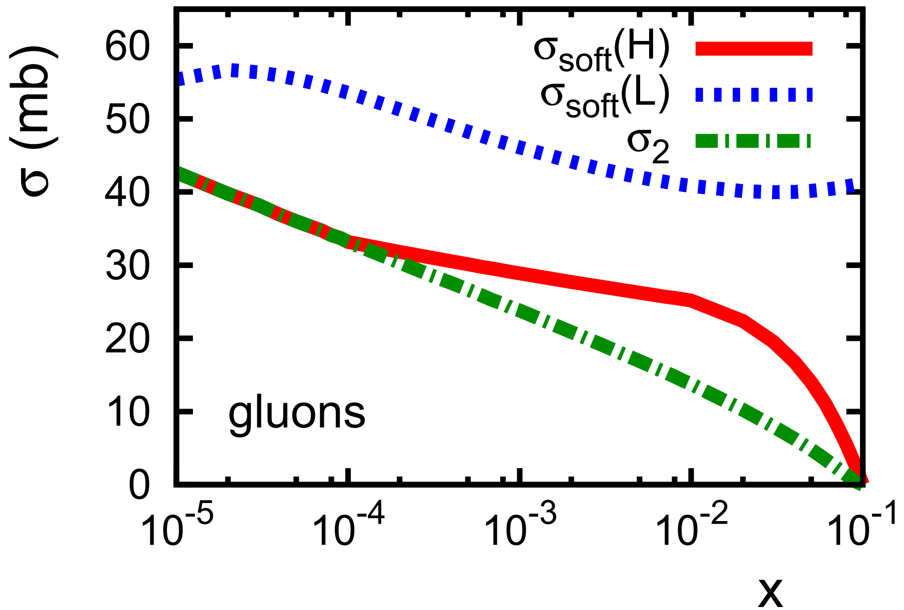
nuclear density

proton diffractive PDFs from HERA

effective cross section

Model of leading-twist nuclear shadowing (2)

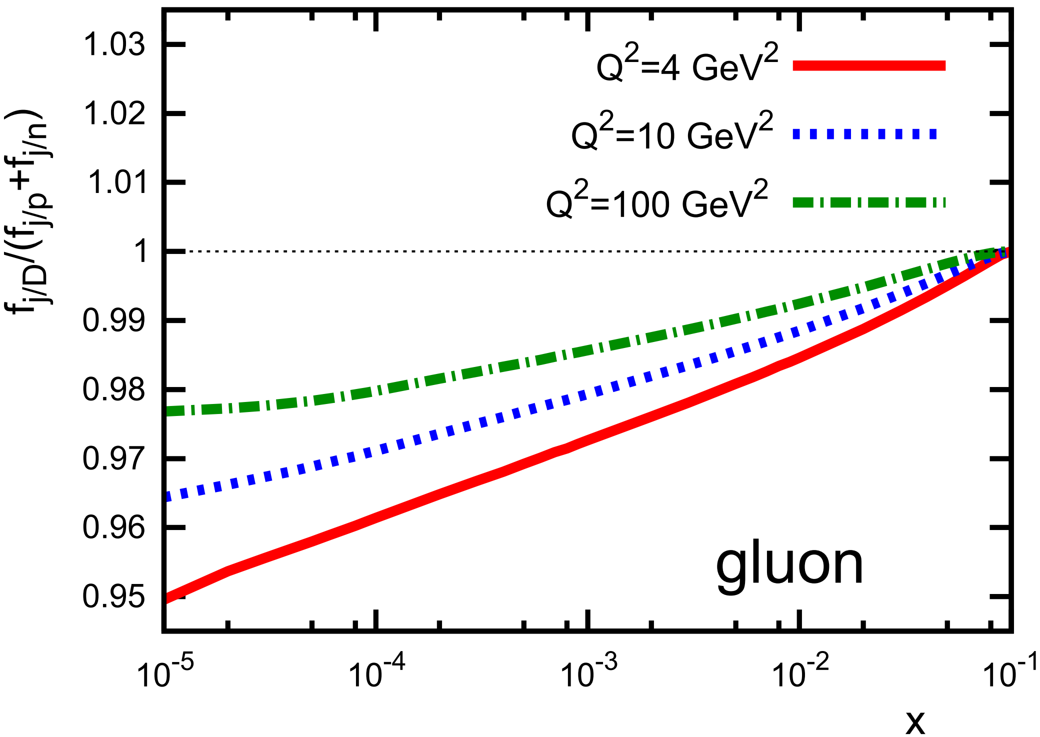
- Predicts nuclear PDFs at μ^2=3-4 GeV^2 → input for DGLAP evolution.
- Magnitude of shadowing is determined by proton diffractive PDFs, ZEUS, H1 2006 → naturally predicts large shadowing for $g_A(x,\mu^2)$.
- One free parameter: $$\sigma_{\rm soft}(x)=\frac{\int d\sigma P_\gamma(\sigma)\sigma^3}{\int d\sigma P_\gamma(\sigma)\sigma^2}$$
- Estimated using two models of the photon hadronic fluctuations using the Good-Walker approach to diffractive dissociation, Good, Walker, PR 120 (1960) 1857
  - P(σ) like in the pion, Blattel et al, 1993
  - P(σ) using the dipole model, McDermott, Frankfurt, Guzey, Strikman, 2000
  - Allows to describe coherent diffraction in p-He4 scattering, Strikman, Guzey, PRC 52 (1995) R1189



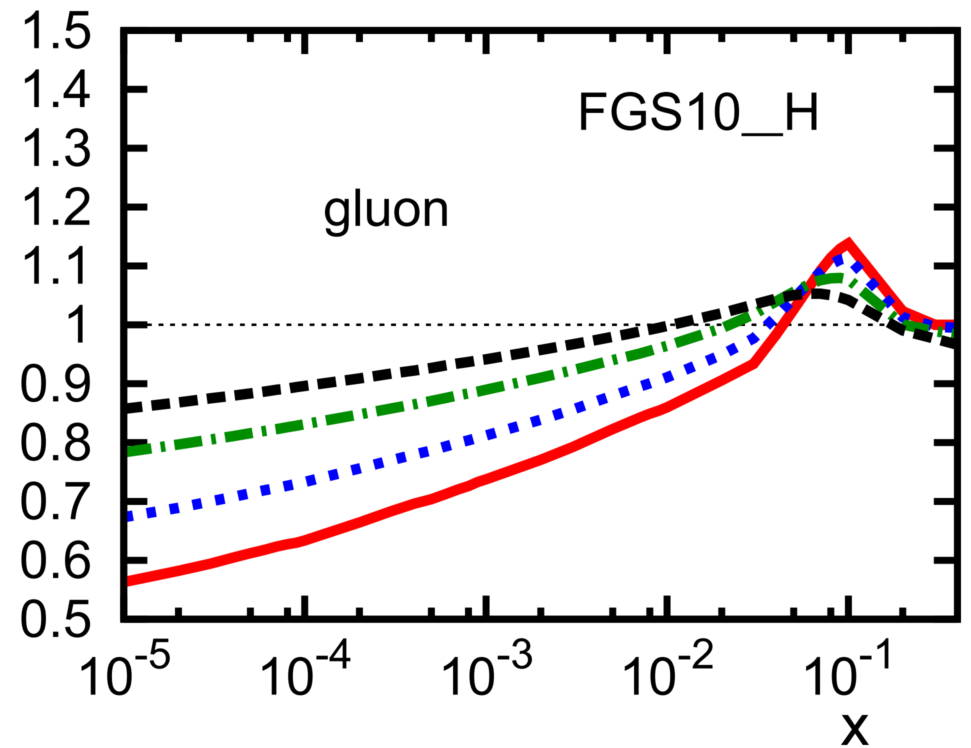
- The model also predicts impact-parameter-dependent nuclear PDFs $g_A(x,b,Q^2)$
- shift of t-dependence of $\gamma A \to J/\psi A$ cross section in UPCs
- oscillations of beam-spin nuclear DVCS asymmetry at EIC.

Predictions of leading twist model for deuteron and light nuclei

Deuteron



Ca-40



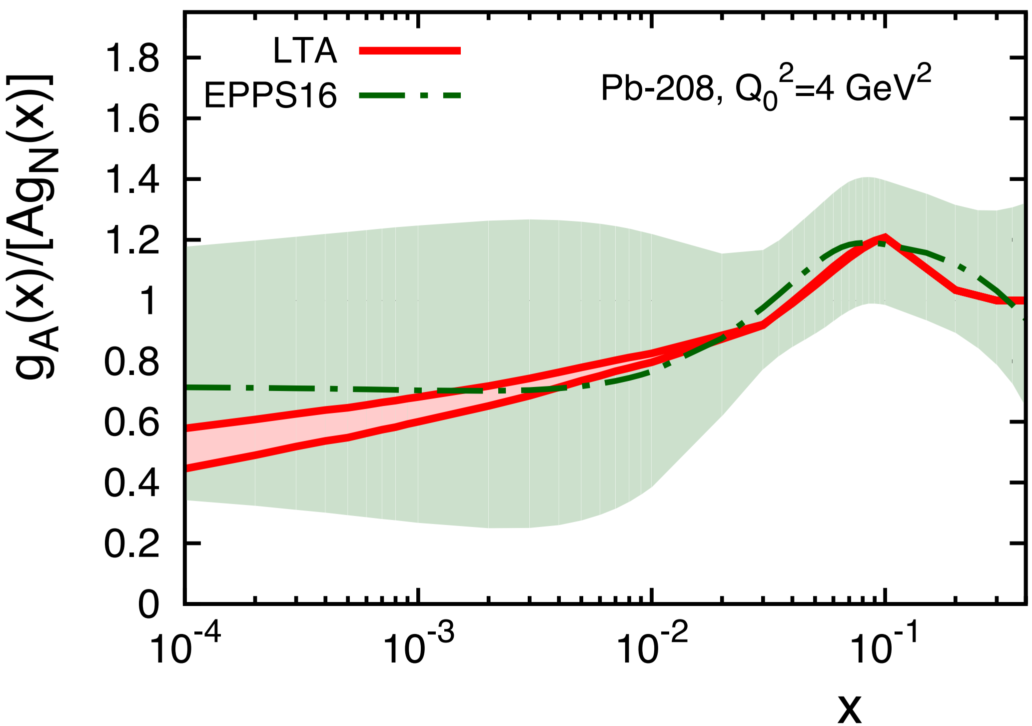
- Predictions for D are model-independent: shadowing is a few % effect.

- Can be generalized to the case of tagged DIS on D with spectator tagging, where shadowing is expected to be larger, Guzey, Strikman, Weiss (work in progress), JLab LDRD project

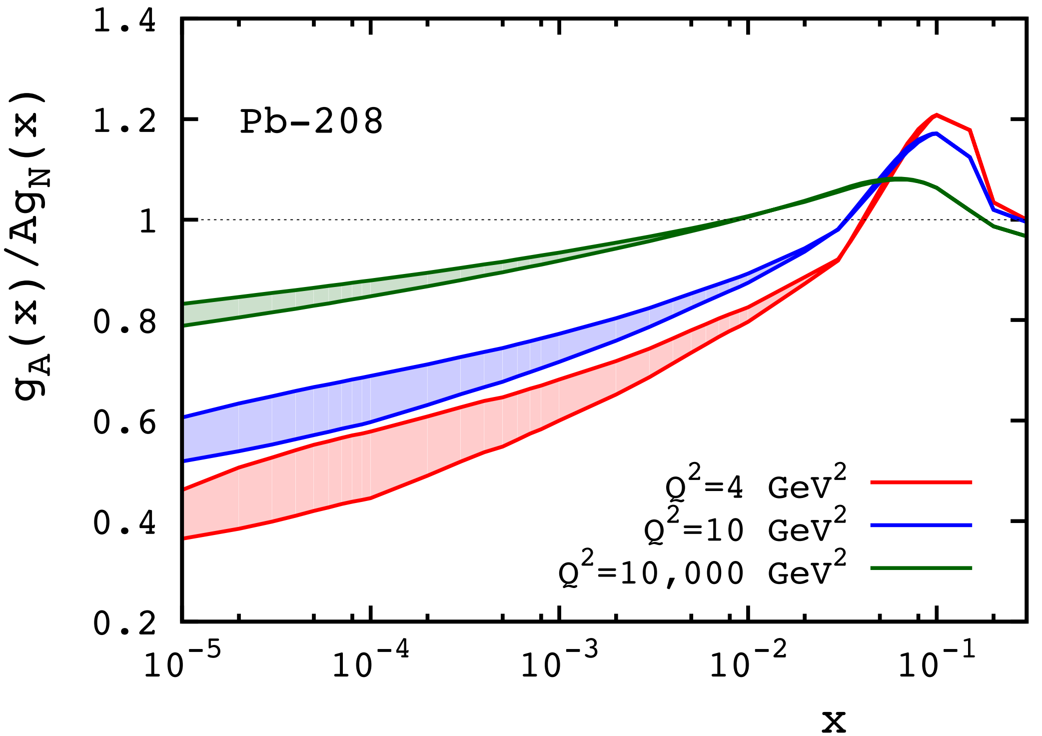
- Predictions for light nuclei (weakly) depend on σ_{soft}. Fixing it in DIS on light nuclei, one reduces the uncertainty for heavier nuclei.

Predictions of leading twist model for heavy nuclei

Leading twist (LTA) vs. EPPS16



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

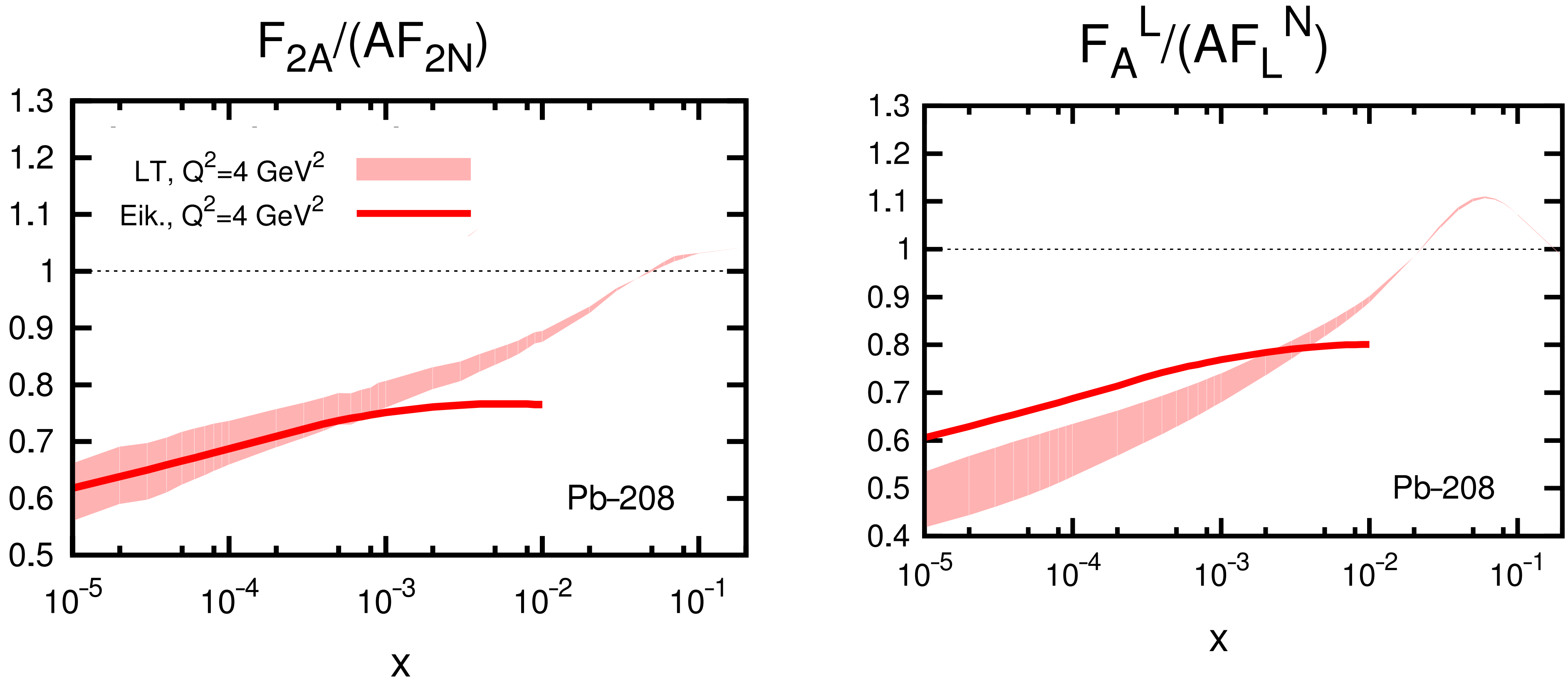


EIC is an ideal machine to test predictions of this model and distinguish it from other approaches due to:

- wide x-Q^2 coverage
- measurements of the longitudinal structure function $F_L^A(x,Q^2)$
- measurements of diffraction in eA DIS

Longitudinal structure function $F_L^A(x,Q^2)$

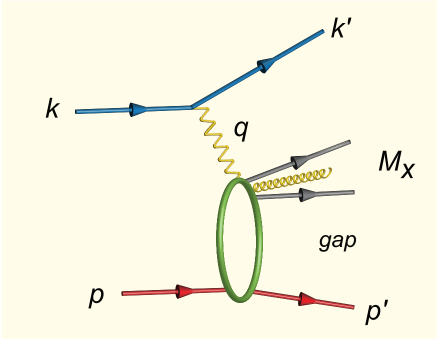
$F_{2A}(x,Q^2)$ and $F_L^A(x,Q^2)$ structure functions in the leading twist and dipole models:

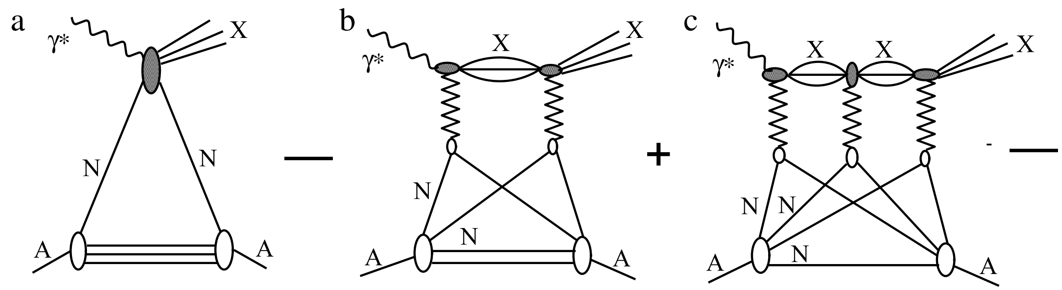


- While for $F_{2A}(x,Q^2)$ predictions are similar, $F_L^A(x,Q^2)$ is dominated by small dipoles → smaller (higher-twist) shadowing in the dipole model
- The same is true for exclusive J/ψ photoproduction at the LHC: dipole models tend to underestimate the observed shadowing effect.

Nuclear diffractive parton distributions

- The model of leading-twist shadowing predicts nuclear diffractive PDFs that can be measured in diffractive eA DIS:

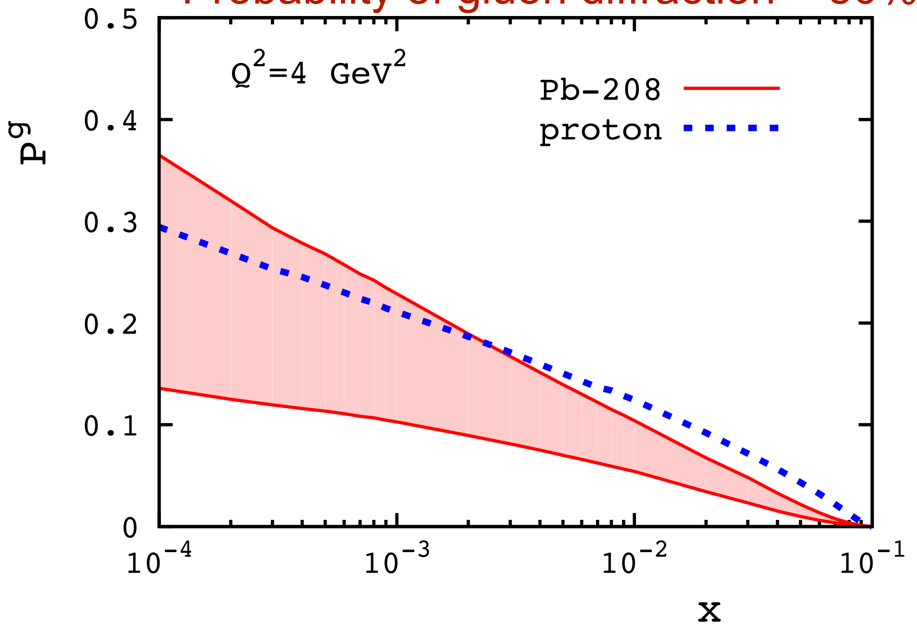




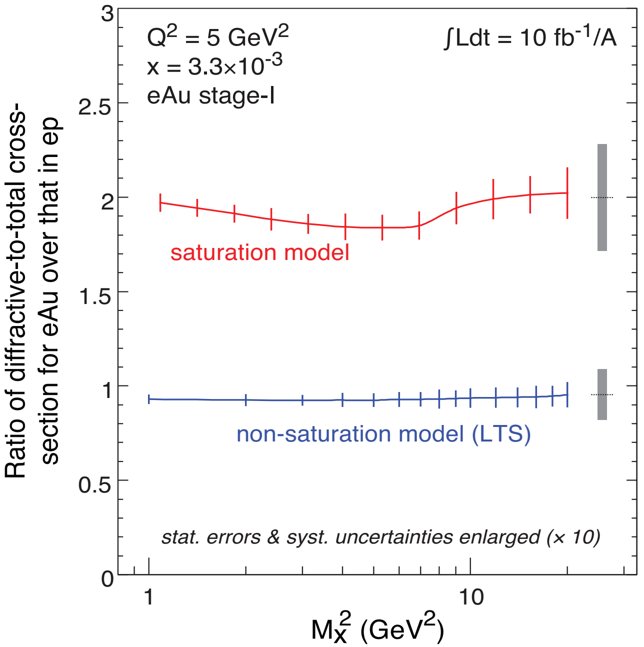
$$\beta f^{D(3)}_{j/A}(x,\mu^2,x_P) = 16\pi f^{D(4)}_{j/N}(x,\mu^2,x_P,t=0)\int d^2b\left(\frac{1-e^{-\frac{1}{2}\sigma^j_{\rm soft}(x)T_A(b)}}{\sigma^j_{\rm soft}(x)}\right)^2$$

- LT shadowing suppresses diffraction on nuclei → slows down approach to saturation :

Probability of gluon diffraction < 50%

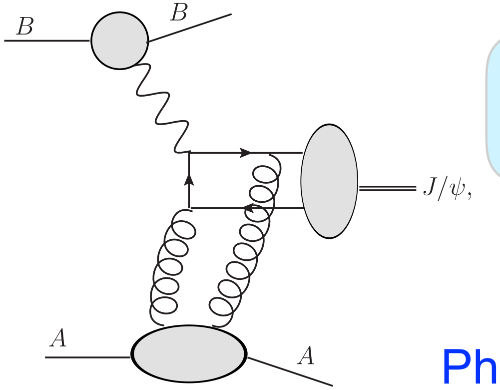


Accardi et al, EPJ A52 (2016) no.9, 268



Exclusive J/ψ photoproduction in UPCs

- Ultraperipheral collisions (UPCs) of ions at large impact parameters → γA scattering at high energies, Baltz *et al*., Phys. Rept. 480 (2008) 1.



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

Photon flux from QED:
- high intensity ~ Z^2
- high photon energy ~ γ_L

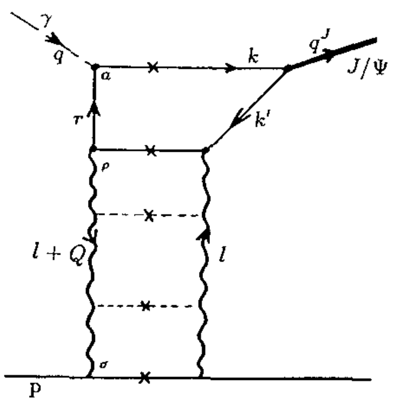
Photoproduction cross section

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

= J/ψ rapidity

- In leading logarithmic approximation (LLA) of pQCD and non-relativistic approximation for charmonium wave function (J/ψ, ψ(2S)), Ryskin, Z. Phys. C57 (1993) 89

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



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

Coherent J/ψ photoproduction on nuclei

- Application to nuclear targets:

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

Small correction $k_{A/N} \approx$ 0.90-95 due to different skewnesses of nuclear and nucleon GPDs

From HERA and LHCb

Nucleus/proton gluon ratio R_g

From nuclear form factor

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

- Well-defined impulse approximation (IA):

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

- Nuclear suppression factor S (like R_{pA} or R_{AA}) $\rightarrow$ direct access to R_g

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

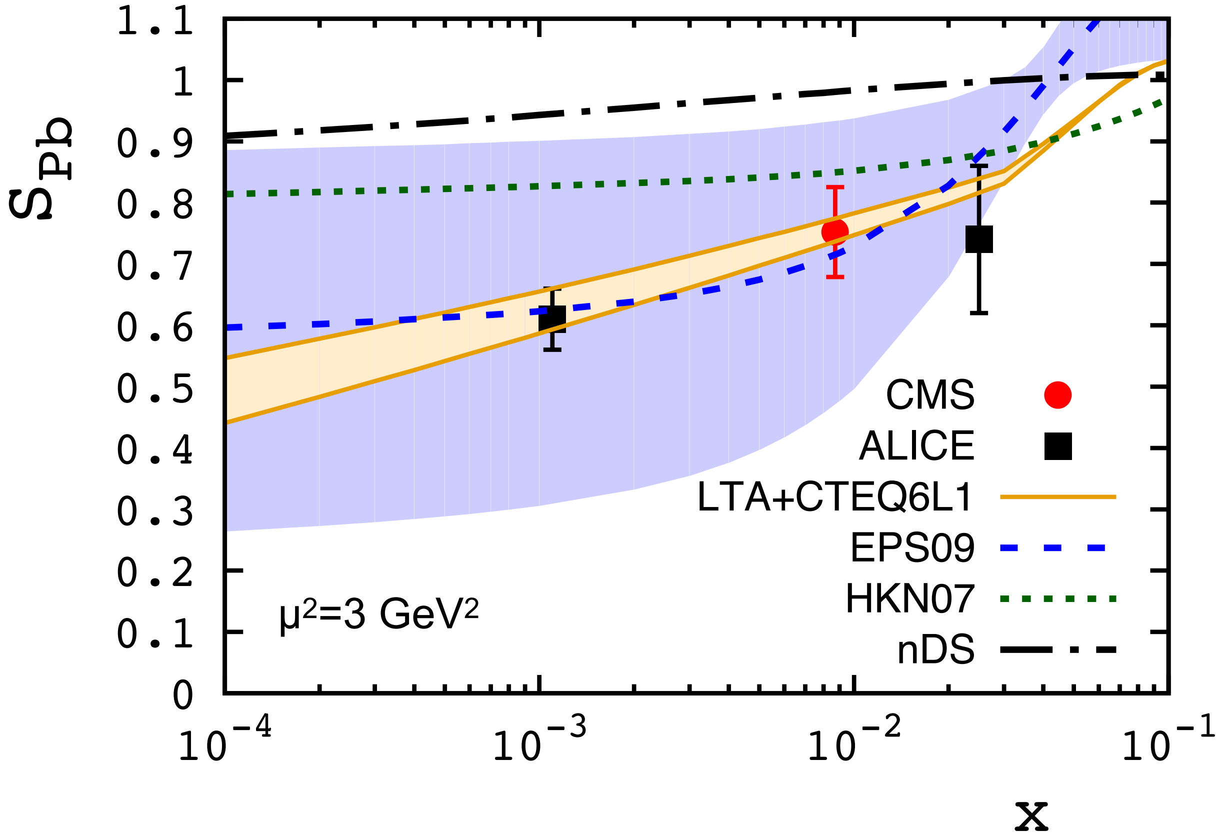
Model-independently from data on UPC@LHC (ALICE, CMS) and HERA, LHCb Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489

From global QCD fits of nPDFs or leading twist nuclear shadowing model

Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290, Guzey, Zhalov, JHEP 1310 (2013) 207

S_{Pb} from ALICE and CMS UPC data vs. theory

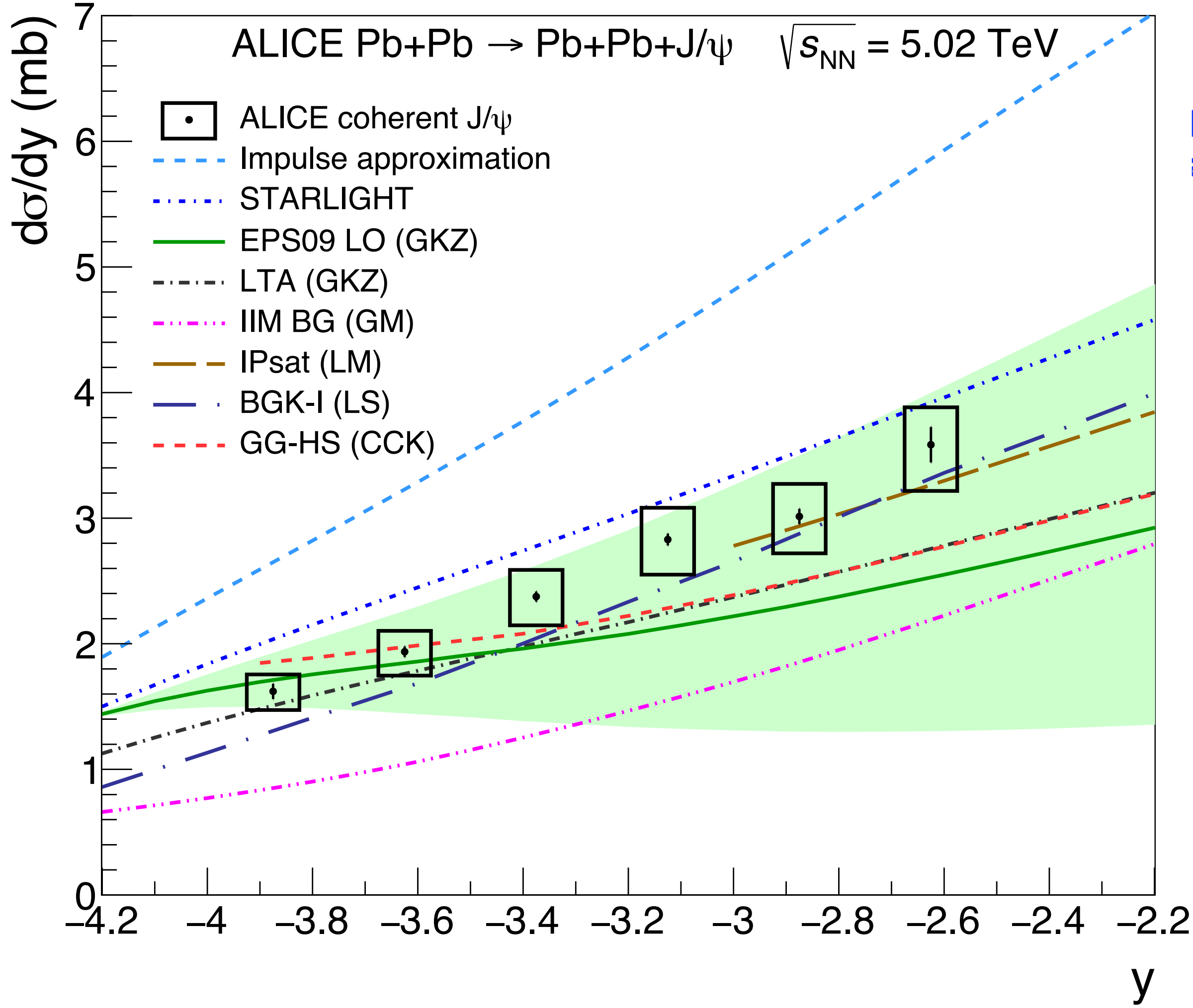
- J/ψ photoproduction in Pb-Pb UPCs at LHC, Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; CMS Collab., PLB 772 (2017) 489 → suppression factor S_{Pb}



LTA: Guzey, Zhalov JHEP 1310 (2013) 207
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028

- Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV → direct evidence of large gluon NS, $R_g(x=0.001) \approx 0.6$.
- Also good description using central value of EPS09, EPPS16, large uncertainty.
- Color dipole models generally underestimate the suppression, Goncalves, Machado (2011); Lappi, Mäntysaari, 2013, but proton shape fluctuations help, Mäntysaari, Schenke, PLB 772 (2017) 681

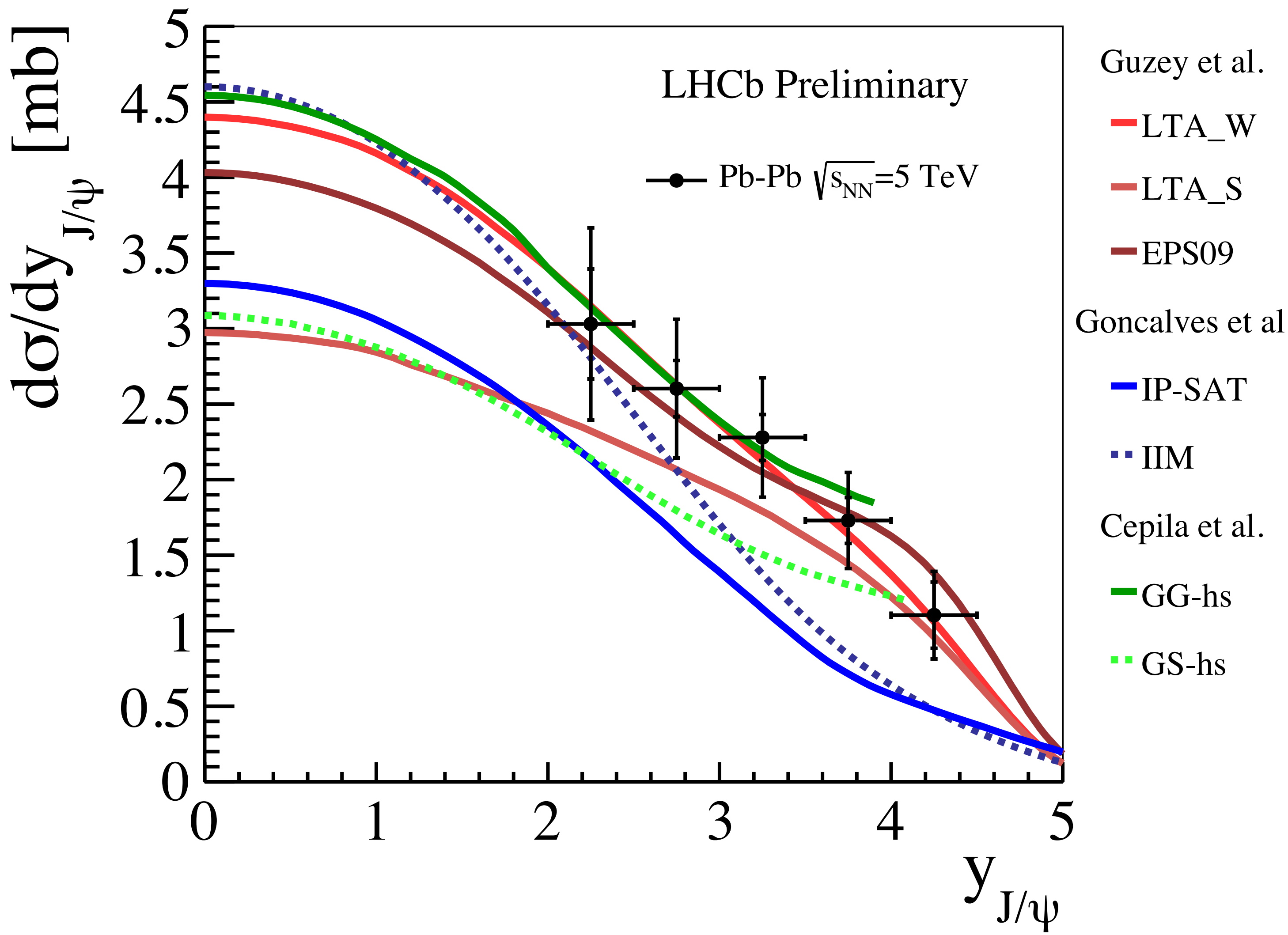
Run 2 results on exclusive J/ψ photoproduction in Pb-Pb UPCs from ALICE



PLB 798 (2019) 134926,
arXiv:1904.06272 [nucl-ex]

- Comparison to Impulse approximation and STARlight → indication of gluon shadowing
- LTA, EPS09 → somewhat underpredict the data, except at forward |y|
- (Some) dipole models also underpredict the data.

Run 2 results on exclusive J/ψ photoproduction in Pb-Pb UPCs from LHCb

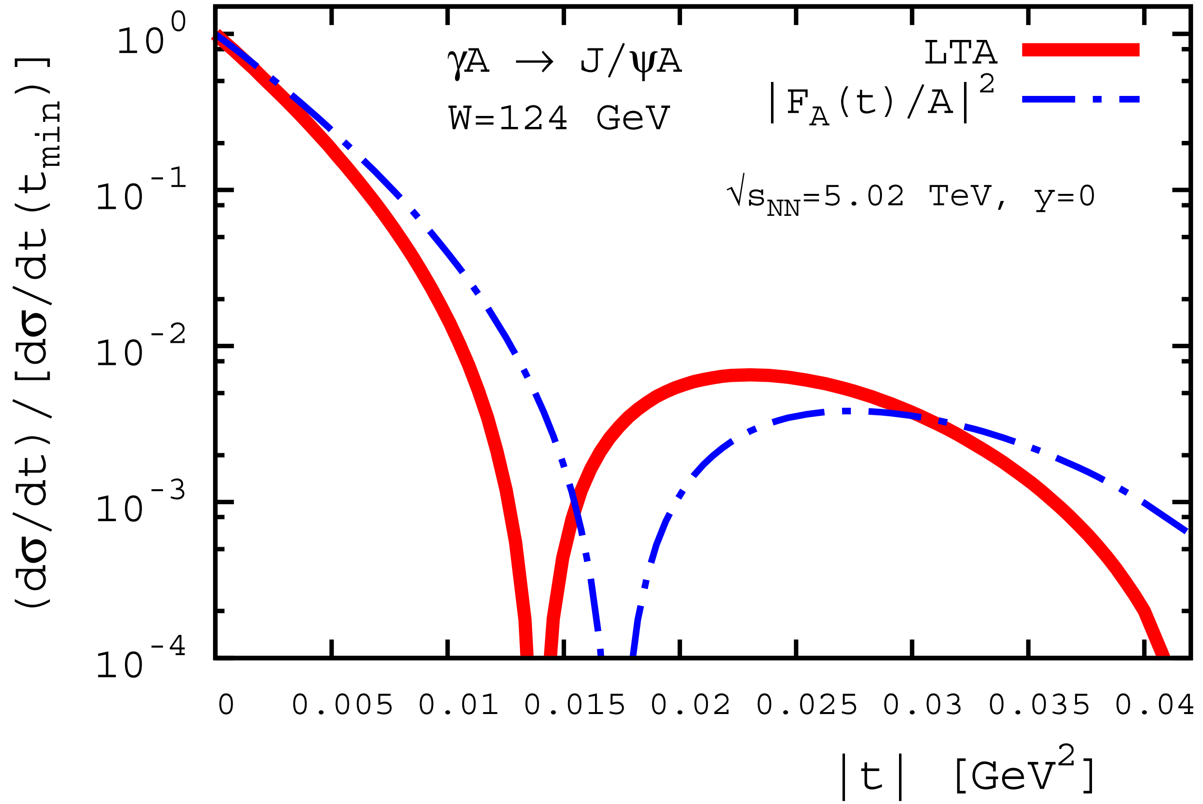


Winn, arXiv:1808.08152

• Good agreement with LTA, EPS09, and some versions of the dipole model with proton shape fluctuations.

Spacial imaging on nuclear gluons at small x

- S hadowing is stronger in nucleus center → correlations between impact parameter b and x → shift of t-dependence of $\gamma A \to J/\psi A$ cross section in UPCs:



Guzey, Strikman, Zhalov, PRC 95 (2017) 025204

- Resulting shift = **5-11% broadening** in impact parameter space of gluon nPDF
- Similar effect is predicted to be caused by saturation, Cisek, Schafer, Szczurek, PRC86 (2012) 014905; Lappi, Mäntysaari, PRC 87 (2013) 032201; Toll, Ullrich, PRC87 (2013) 024913; Goncalves, Navarra, Spiering, arXiv:1701.04340
- Oscillations of beam-spin nuclear DVCS asymmetry at EIC.

Summary

- Small-x nPDFs — especially gluon nPDF — are poorly constrained by available fixed-target nuclear DIS, dA RHIC, and pA LHC data. Additional processes and Run 2 data may help.

- The leading twist model of nuclear shadowing makes predictions of the effect of nuclear shadowing in various nPDFs (usual, diffractive, b-dependent), which can be best tested at an EIC.

- Before EIC and LHeC, new constrains on small-x nPDFs can obtained from Pb-Pb UPCs at the LHC: inclusive and diffractive dijet photoproduction, exclusive photoproduction of J/ψ.

- Coherent photoproduction of J/ψ in Pb-Pb UPCs at the LHC gives direct evidence of large gluon nuclear shadowing $R_g(x=0.001, \mu^2 \approx 3 \text{ GeV}^2) = 0.6$.

- Heavy quarkonium photoproduction in UPCs gives access to transverse imaging of (nuclear) gluon distribution at small x.

Mark, Happy Birthday!