Constraints on nuclear gluons at small x

Vadim Guzey

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

Outline:

- Nuclear gluon distribution at small x: fixed-target DIS, pA@LHC, future EIC and LHeC
- Leading twist nuclear shadowing model
- Gluon nuclear shadowing from coherent J/ψ photoproduction on nuclei at the LHC

"Opportunities with Heavy Flavor at the EIC", CFNS Ad hoc Workshop, Nov 4-6, 2020

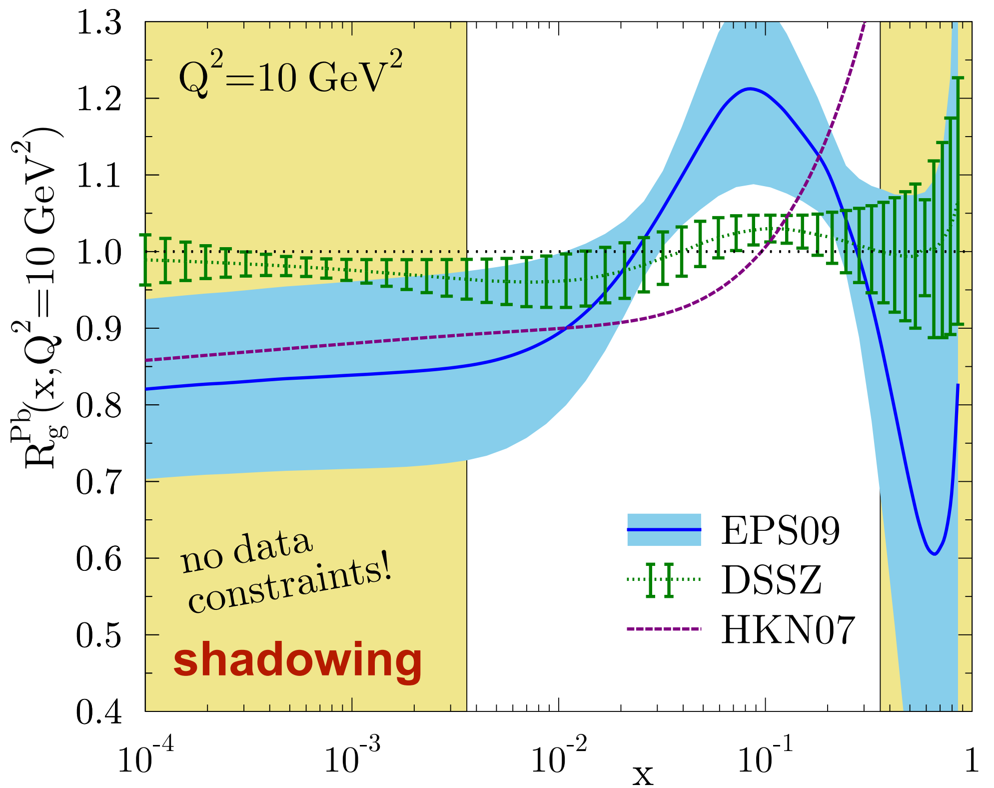
Gluon distributions in nuclei: fixed-target DIS

• Nuclear parton distributions (nPDFs) $f_A(x,\mu^2)$ = densities/distributions of quarks and gluons in nuclei as function of momentum fraction x at resolution μ.

• Due to collinear QCD factorization, nPDFs are universal quantities required for calculations of various hard processes with nuclei at high energies at RHIC, LHC, and future EIC and LHeC/FCC.

• $f_A(x,\mu^2)$ are determined from global QCD fits to data on fixed-target DIS, nuclear Drell-Yan, hard processes in dA (RHIC) and pA (LHC) → $f_A(x,\mu^2)$ with significant uncertainties:

• For small $x < 0.005$, nPDFs are suppressed due to nuclear shadowing:
$f_A(x,\mu^2) < A\, f_N(x,\mu^2)$



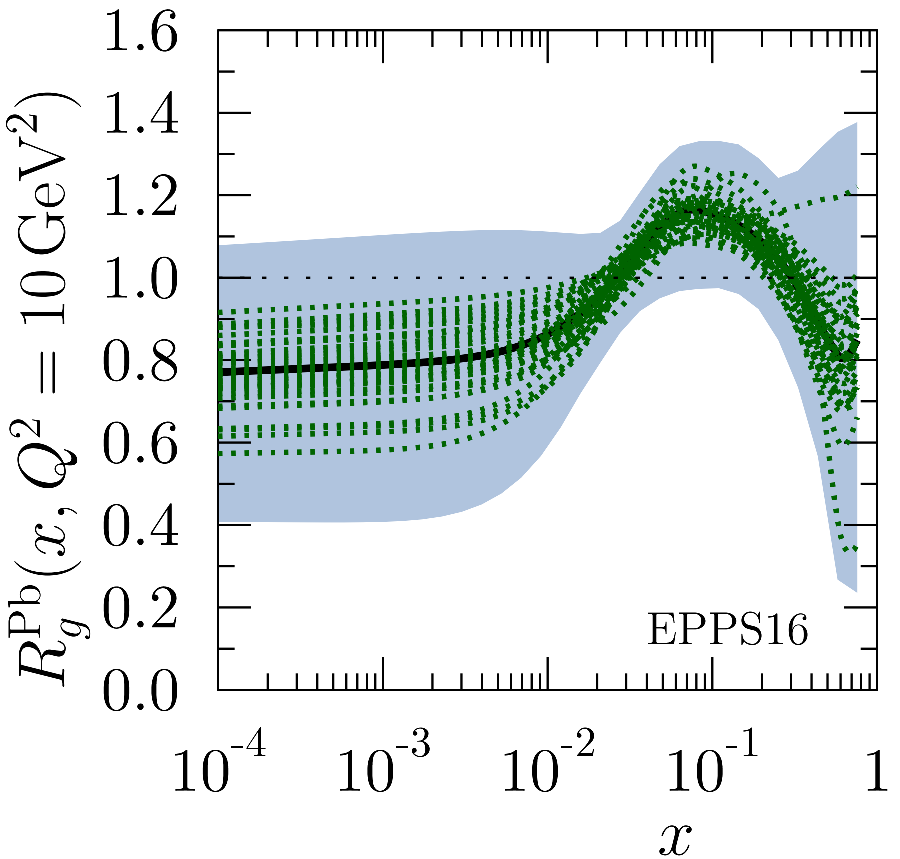
$$R_g(x,Q^2) = \frac{g_A(x,Q^2)}{A g_p(x,Q^2)}$$

Paukkunen, NPA 926 (2014) 24

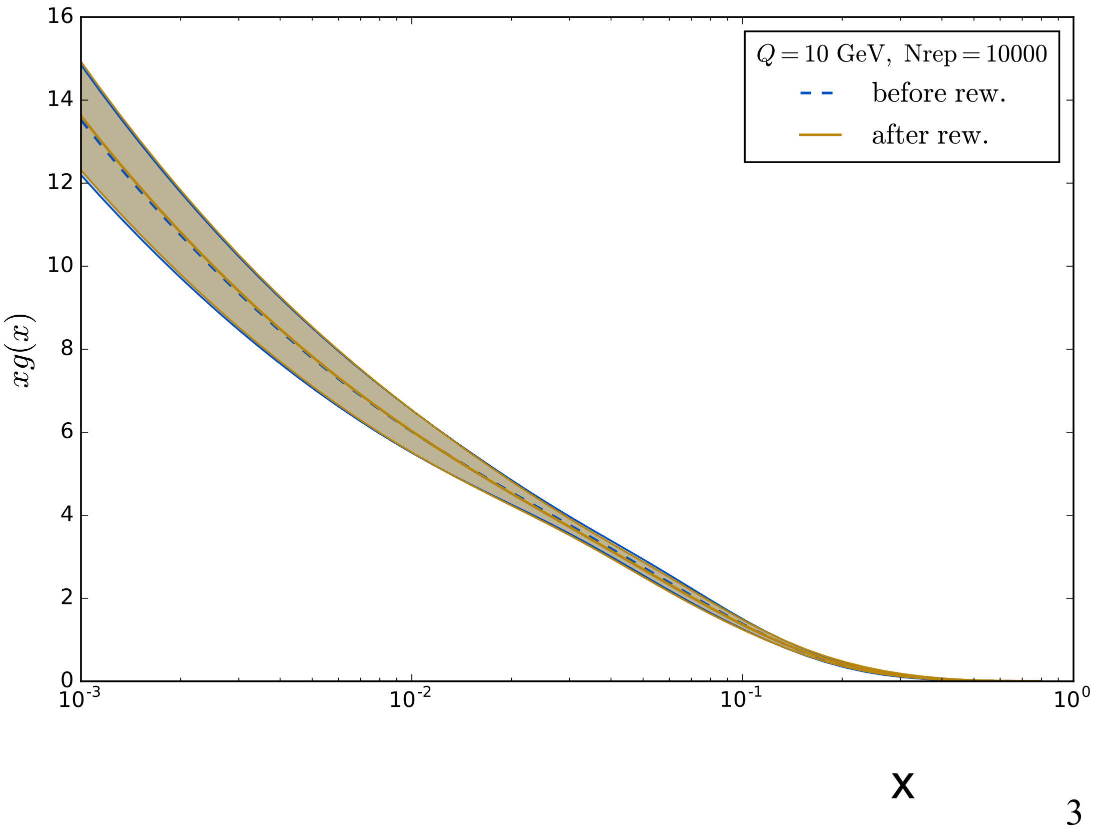
Gluon distributions in nuclei: adding dijet and W,Z production in pA@LHC

- One of the goals of the LHC heavy ion program is to better constrain nPDFs.
- However, Run 1 pA data on dijet and W,Z production does not really help
  - EPPS16 includes these data in the fit
  - nCTEQ15 does reweighting

EPPS16, Eskola et al, EPJ C77 (2017) 163



nCTEQ15, Kusina at al, EJC 77 (2017) 7

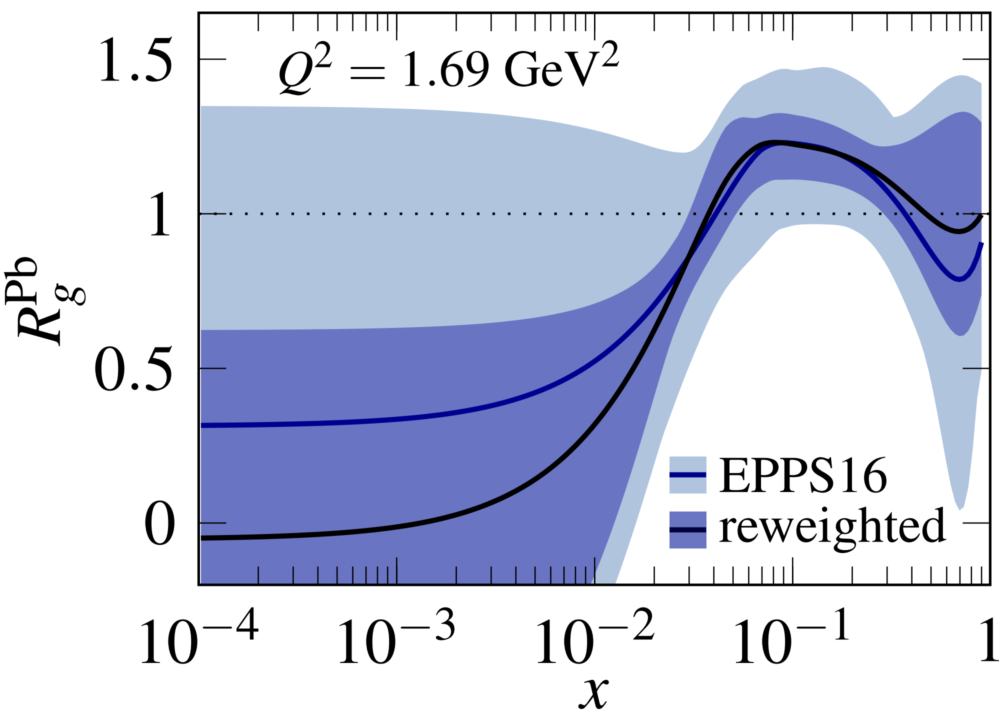


Gluon distributions in nuclei: adding Run 2 pA data

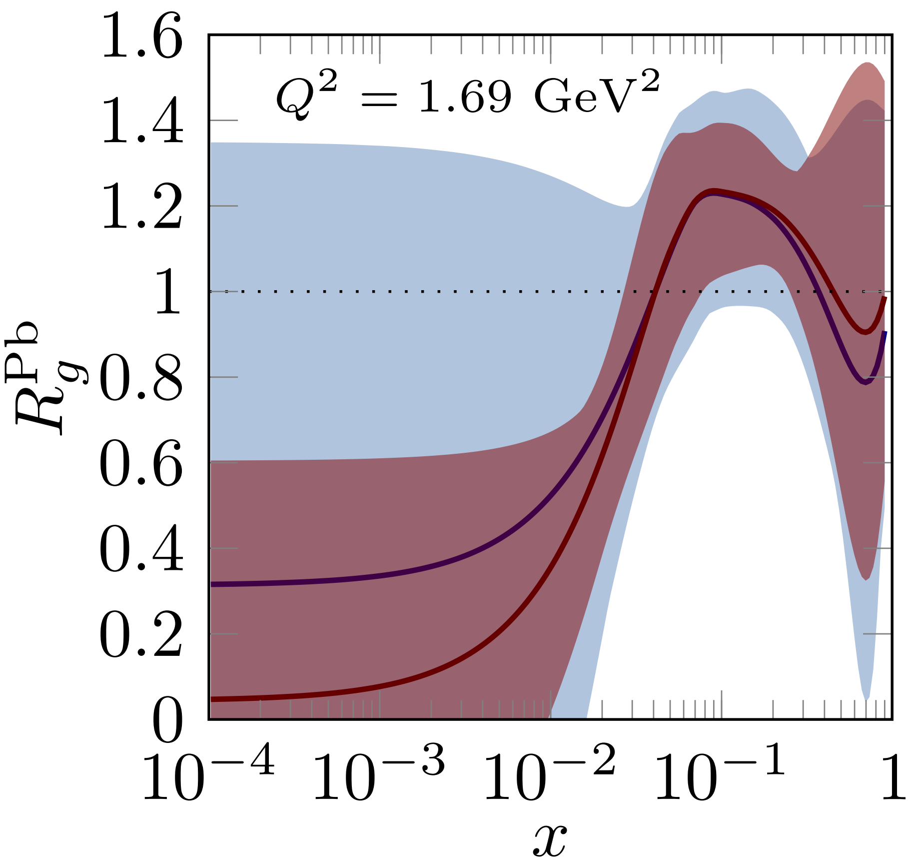
- Run 2 data and additional processes, e.g. heavy flavor production, may/should give additional constraints on nPDFs, Paukkunen, arXiv:1811.01976 [hep-ph].

- Two examples of Hessian reweighing to study impact of Run 2 data:

Run 2 CMS jets, Eskola, Paakkinen, Paukkunen, EPJ C 79 (2019) 6, 511



Run 2 LHCb D0, Eskola, Helenius, Paakkinen, JHEP 05 (2020) 037



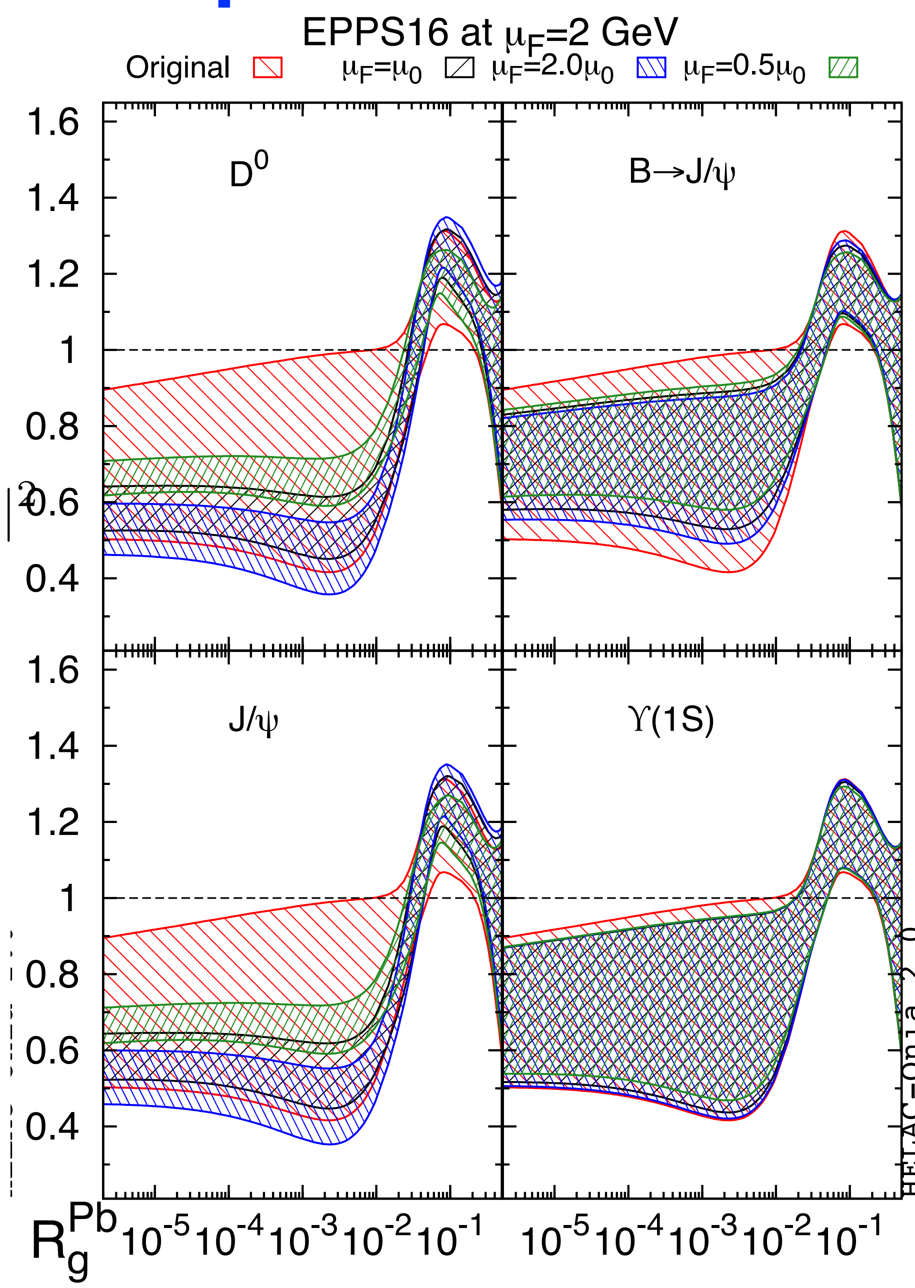
Gluon shadowing and antishadowing from heavy flavor production in pA

- Data-driven analysis of inclusive heavy quark production in hadron scattering,
  Kusina, Lansberg, Schienbein, Shao, PRL 121 (2018) 5, 052004

$$\frac{d\sigma(pA \to \mathcal{H}X)}{d\Phi_2} = \frac{1}{2s}\int dx_p dx_A f_A(x_A) f_p(x_p) |\mathcal{A}(k_1 k_2 \to Q + k_3)|^2$$

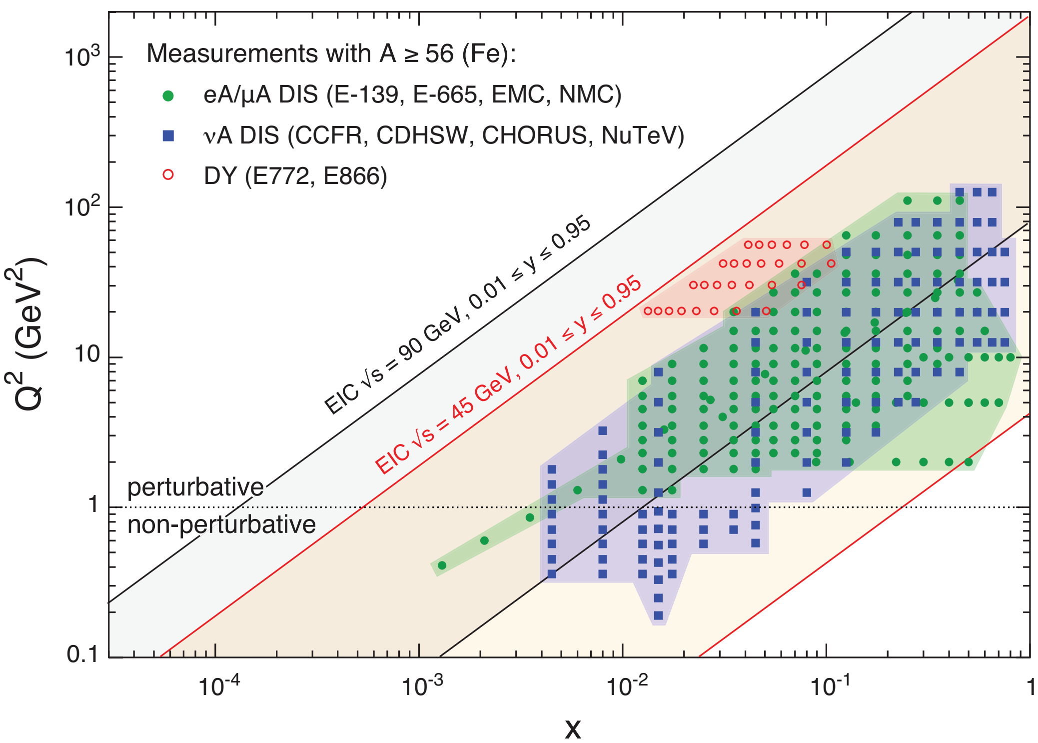
- Re-weighting reduces the uncertainties and shows distinct and large shadowing and antishadowing of gluon distribution

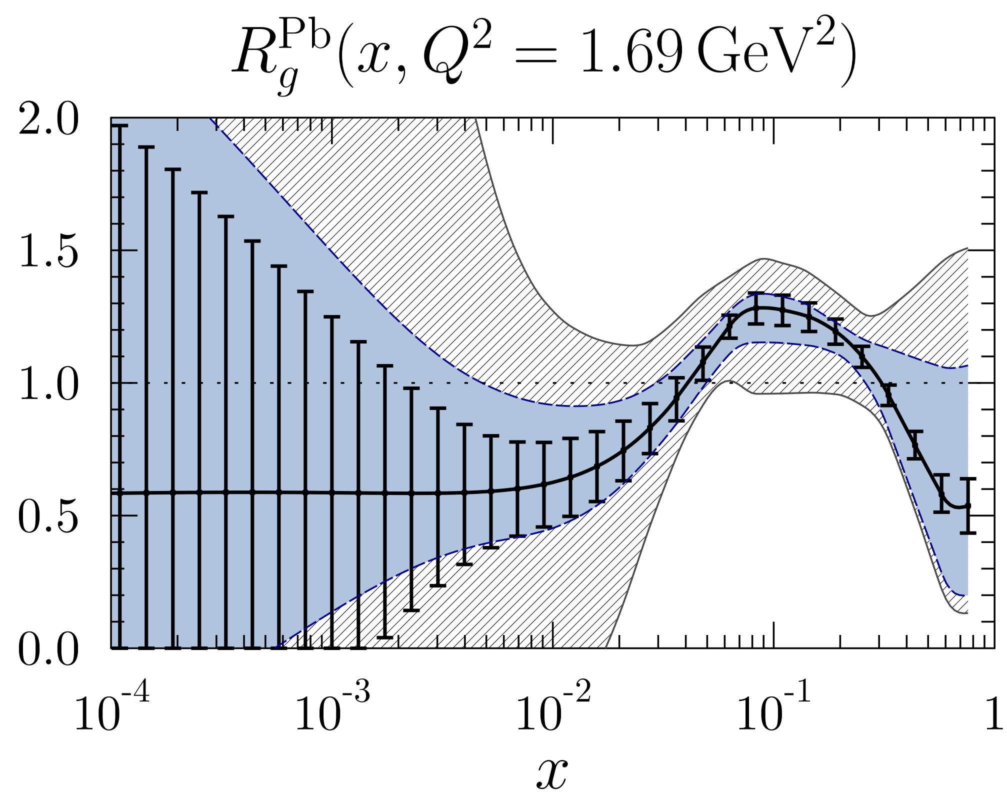
- This data can also be explained by energy loss, Arleo, Peigne, JHEP 03 (2013) 122 and CGC, Ducloue, Lappi, Mäntysaari, PRD91 (2015) 114005, PRD94 (2016) 074031 ⟶ not possible to single out the main nuclear modification mechanism.



Gluon nuclear shadowing at EIC

• In the future, gluon nuclear shadowing will be constrained at EIC, Accardi et al, EPJ A52 (2016) no.9, 268; 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:



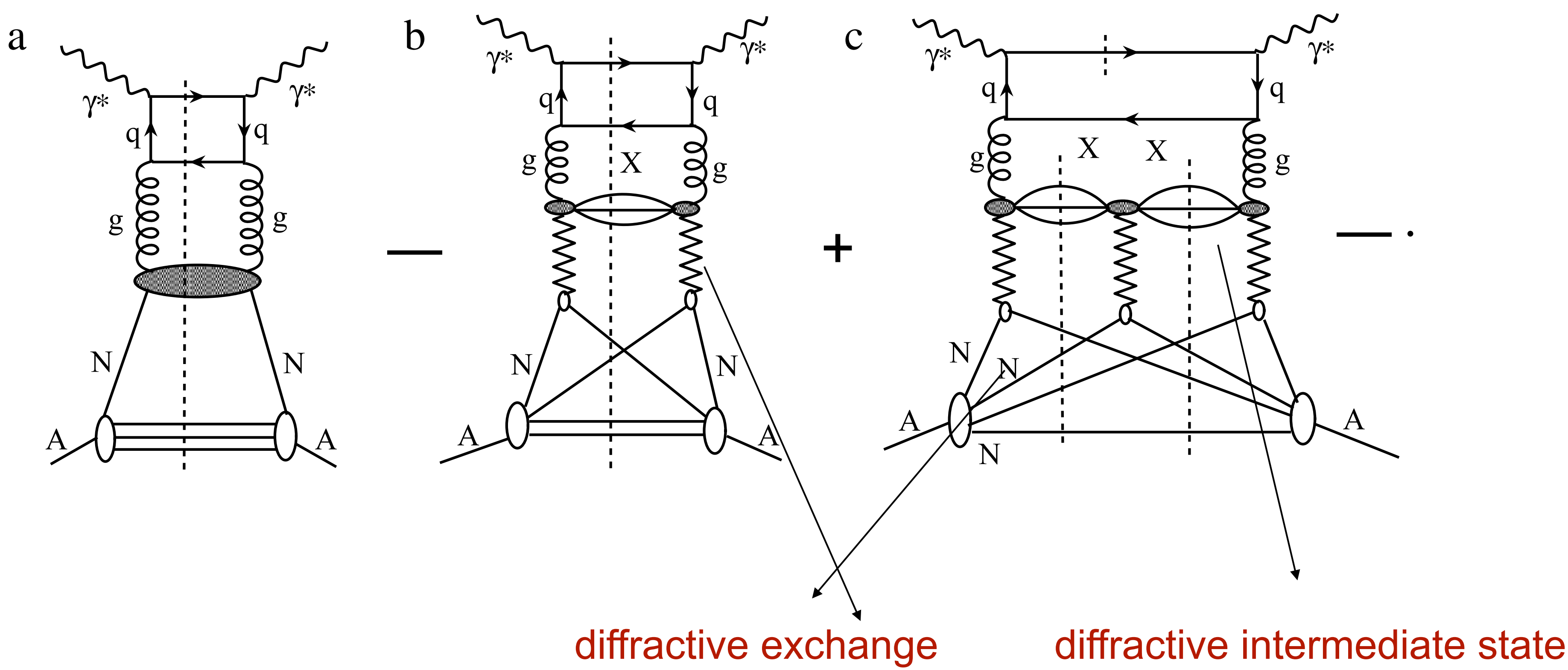


Aschenauer, Fazio, Lamont, Paukkunen, Zurita, PRD 96 (2017) 11

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

Leading twist nuclear shadowing model

- Combination of Gribov-Glauber nuclear shadowing model for soft interactions with QCD factorization theorems for inclusive and diffractive DIS → shadowing is driven by diffraction for individual partons j, Frankfurt, Strikman (1999); Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255
- Double scattering term (N=2) is a model-independent result of unitarity (AGK cutting rules). Higher terms (N > 3) require modeling.
- Graphs for $g_A(x,Q^2)$:



Leading twist nuclear shadowing model-2

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

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

proton diffractive PDFs

- Measured in diffractive DIS on proton at HERA, H1, ZEUS

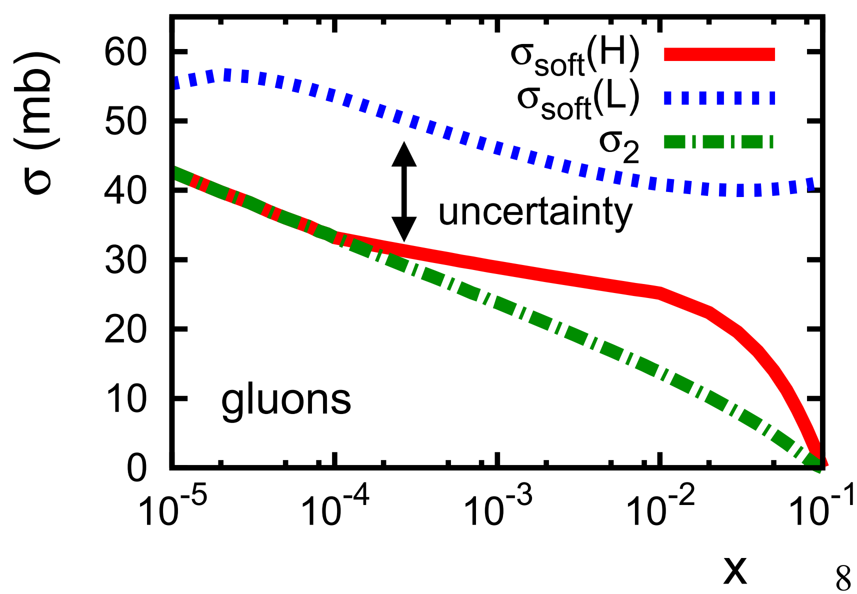
$$F_2^{D(4)}(x,Q^2,x_{\mathbb{P}},t) = \beta\sum_{j=q,\bar q,g}\int_\beta^1\frac{dy}{y}C_j\left(\frac{\beta}{y},Q^2\right)f_j^{D(4)}(y,Q^2,x_{\mathbb{P}},t)$$

- One of main HERA results: diffraction in DIS is a leading-twist phenomenon → hence the name "leading twist shadowing"

- **Beware**: While extrapolated pQCD fits describe the HERA data well for $Q^2 < 6.5$ GeV^2, higher-twist effects are potentially large for $Q^2 < 5$ GeV^2, Motyka, Sadzikowski, Slominski, PRD 86 (2012) 111501

effective cross section

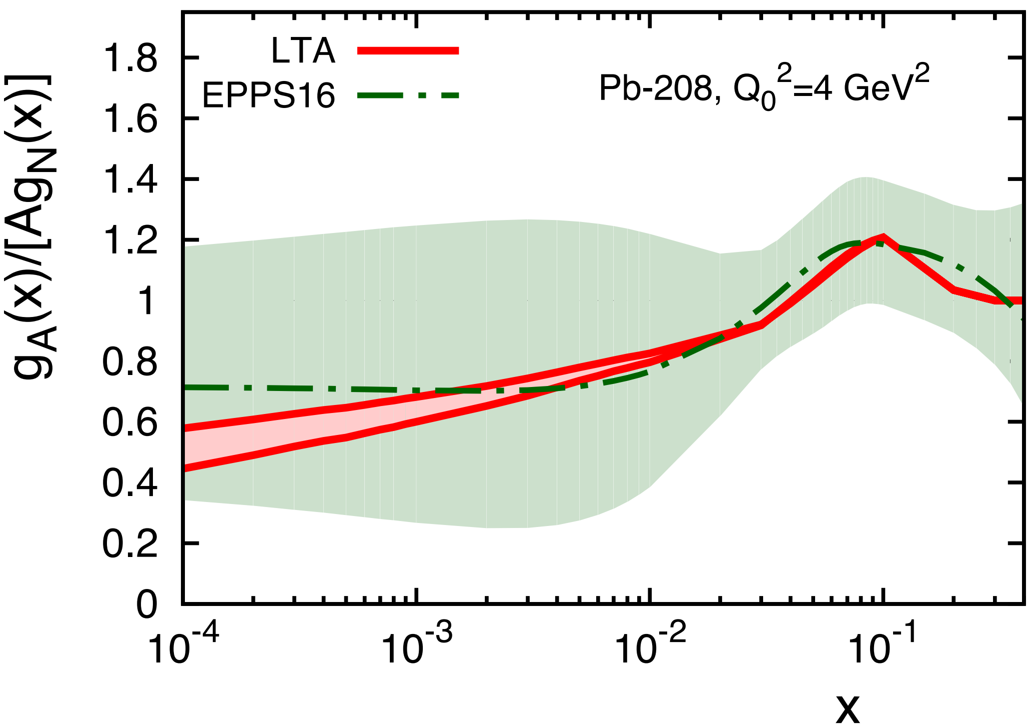
- Estimated using two models of photon fluctuations:
  - like in the pion, Blattel et al, 1993
  - like in the dipole model, McDermott, Frankfurt, Guzey, Strikman, 2000



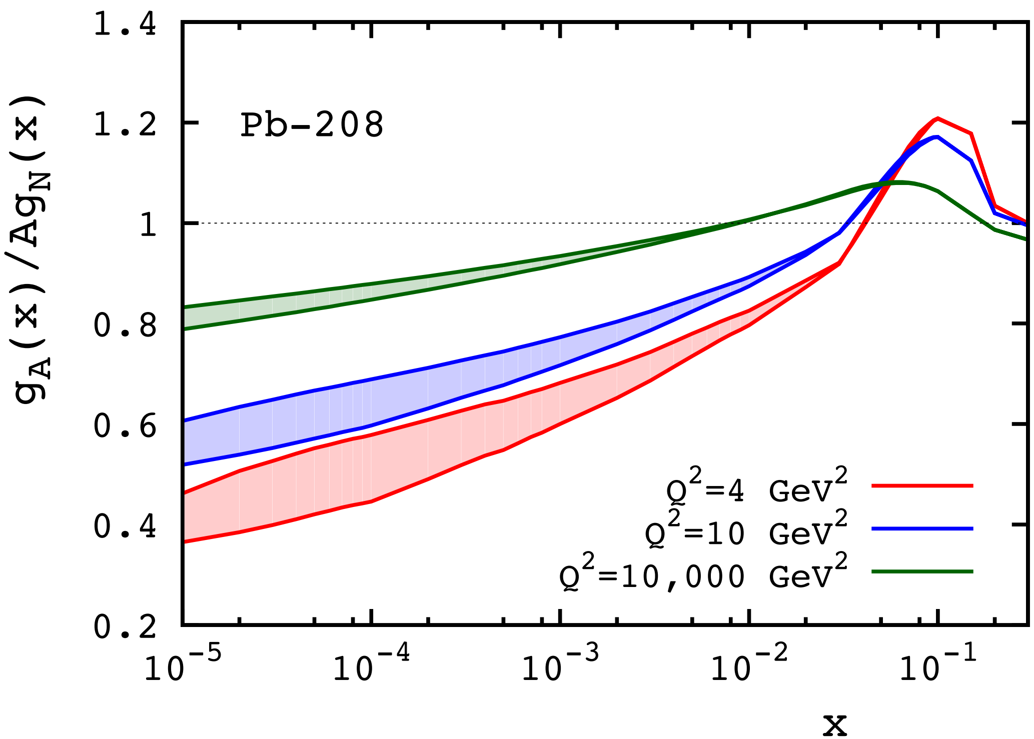
Leading twist nuclear shadowing model-3

- Predicts form of 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 $g_A(x,\mu^2)$.
- Presents alternative to small-x extrapolation of nPDFs from global QCD fits.

Leading twist (LTA) vs. EPPS16



DGLAP evolution



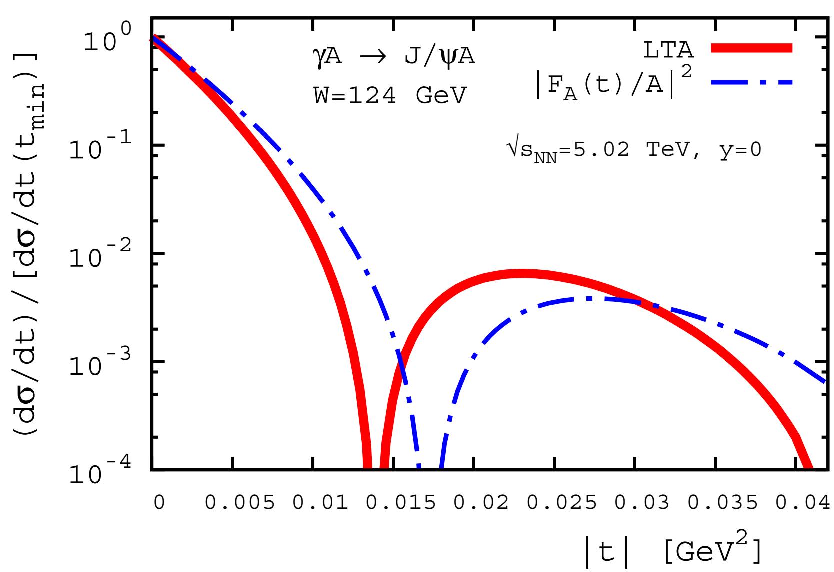
- LTA shadowing does NOT level off at small x.
- EIC and LHeC are ideal to test these predictions at small x.

Leading twist nuclear shadowing model: b-dep.

- Model also predicts impact parameter dependent nuclear PDFs $g_A(x,b,Q^2)$ (GPDs in a special limit):

$$xf_{j/A}(x,Q_0^2,b) = A\,T_A(b)xf_{j/N}(x,Q_0^2) - 8\pi A(A-1)B_{\rm diff}\,\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{\mathbb{P}}\beta f_j^{D(3)}(\beta,Q_0^2,x_{\mathbb{P}})$$
$$\times\int_{-\infty}^{\infty}dz_1\int_{z_1}^{\infty}dz_2\,\rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)\,e^{i(z_1-z_2)x_{\mathbb{P}}m_N}\,e^{-\frac{A}{2}(1-i\eta)\sigma^j_{\rm soft}(x,Q_0^2)\int_{z_1}^{z_2}dz'\rho_A(\vec{b},z')}$$

- Correlations between impact parameter b and x (shadowing is stronger in nucleus center) can be experimentally tested:
  - shift of t-dependence of $\gamma A \rightarrow J/\psi A$ cross section in UPCs
  - oscillations of beam-spin nuclear DVCS asymmetry at EIC and LHeC.

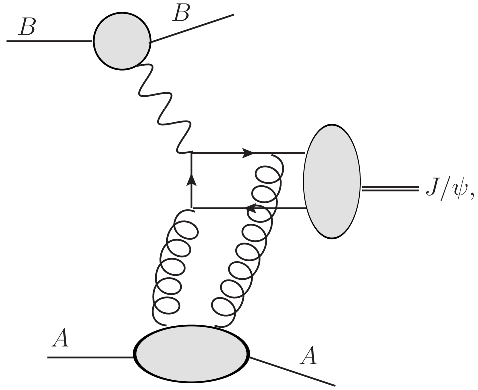


- Resulting shift = **5-11% broadening** in impact parameter space of gluon nPDF, Guzey, Strikman, Zhalov, PRC 95 (2017) 025204

- 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

Ultraperipheral collisions

- 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/pion tracks from vector meson decay
- Nuclear coherence by veto on neutron production by Zero Degree Calorimeters (ZDCs) 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 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

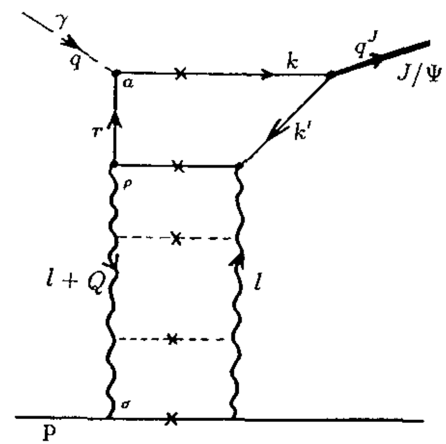
UPCs@LHC = γp and γA interactions at unprecedentedly large energies, Baltz *et al.*, The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1

Exclusive charmonium photoproduction

• 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

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

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



• **Beyond LLA and NR approximation for charmonium:**

- **k_T-factorization,** Ryskin, Roberts, Martin, Levin, Z. Phys. C76 (1997) 231; Martin, Nockles, Ryskin, Teubner, PLB 662 (2008) 252; Jones, Martin, Ryskin, Teubner, JHEP 1311 (2013) 085: gluon and quark kT → additional suppression by factor 1/2; some NLO effects using unintegrated g(x,k_T) reducing to NLO g(x,μ^2) + skewness factor to relate GPDs and PDFs → successful LO and NLO pQCD description of HERA and LHCb data on charmonium photoproduction

-**kT-factorization,** Cisek, Schafer, Szczurek, JHEP 1504 (2014) 159: unintegrated gluon distribution with saturation seems to be somewhat preferred by LHCb data on J/ψ photoproduction

- **color dipole model framework,** Frankfurt, Koepf, Strikman (1998): relativistic effects in charmonium wf are very important; gluon virtualities are much higher than in NR case; Goncalves, Machado 2008-present; Lappi, Mäntysaari (2013): dipole cross section with/without saturation; large dependence on charmonium wf; phenomenological description of HERA and UPC data for proton. For Pb targets, nuclear suppression due to shadowing is generally underestimated.

– **Collinear factorization at NLO,** Ivanov, Schaefer, Szymanowski, Krasnikov (2015); Jones, Martin, Ryskin, Teuber (2015): large ~200% NLO corrections and scale dependence

Coherent charmonium photoproduction on nuclei

- Application to nuclear targets:

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

Small correction $k_{A/N} \approx 0.90\text{-}95$ due to different skewness 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}) → direct access to R_g

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

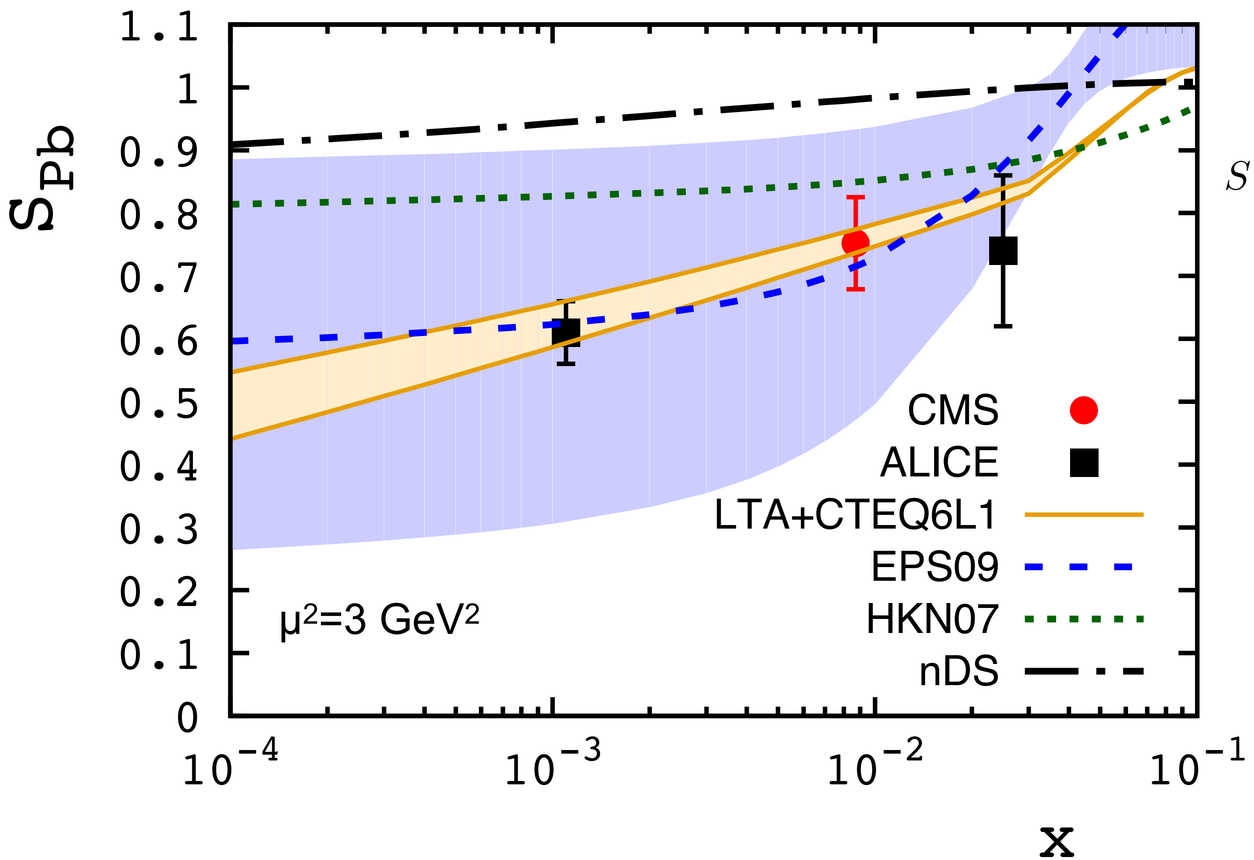
Model-independently from data on UPC@LHC (ALICE, CMS) and HERA, LHCb Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489

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}



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

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 → evidence of large gluon shadowing, $R_g(x=0.001) \approx 0.6$.

• Also good description using central value of EPS09, EPPS16, large uncertainty.

• Color dipole models generally give too little suppression, Goncalves, Machado (2011); Lappi, Mäntysaari, 2013, but proton shape fluctuations help, Mäntysaari, Schenke, PLB 772 (2017) 681

Summary

• Small-x nPDFs — especially the gluon nPDFs — are poorly constrained constrained by available fixed-target and Runs 1 and 2 pA LHC data.

• An alternative is leading twist nuclear shadowing model, which connects shadowing and diffraction and predicts large gluon shadowing.

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

• There are several opportunities to extend current theoretical approaches to the calculation of charmonium and dijet photoproduction in UPCs@LHC.

• Challenge: include UPC data in global QCD fits for nPDFs.

• UPCs@LHC = forerunner of measurements of nPDFs at an EIC and LHeC/FCC-eh, where nPDFs in a wide x-Q2 range will be determined with high precision.