Nuclear shadowing in exclusive processes

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Outline:

- Nuclear PDFs at small-x and UPCs
- Gluon nuclear shadowing from coherent J/ψ photoproduction on nuclei
- Theoretical issues in pQCD studies of coherent J/ψ photoproduction
- Imaging of nuclear gluons at small x

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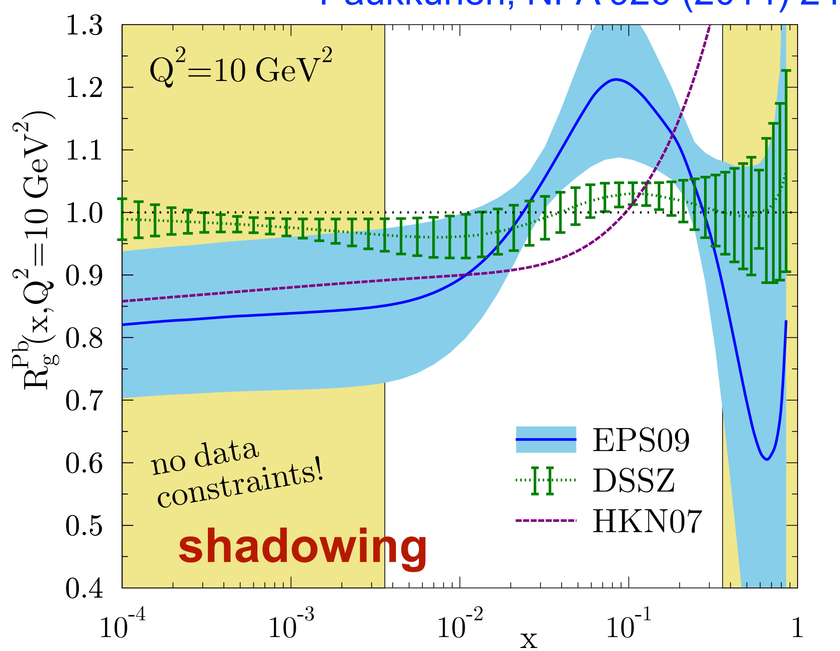
Nuclear shadowing and nPDFs at small-x

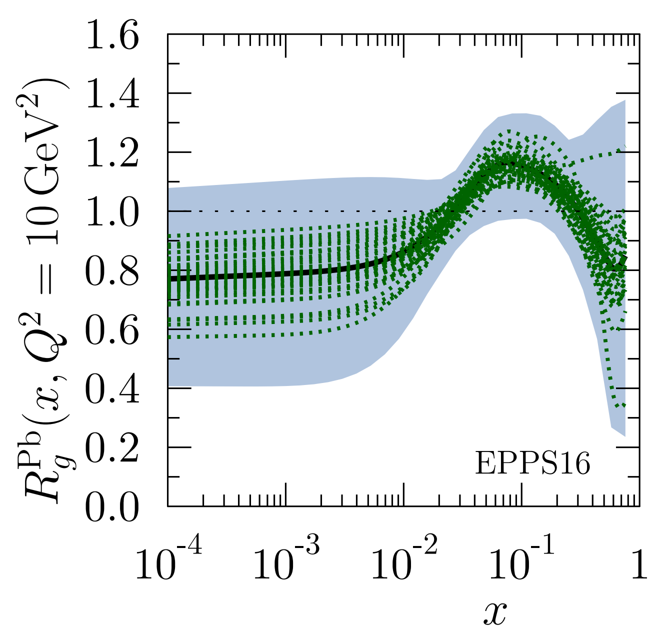
- Nuclear shadowing: suppression $f_A(x,\mu^2) < A\, f_N(x,\mu^2)$ for small $x < 0.005$.
- Important for QCD phenomenology of hard processes with nuclei: cold nuclear matter effects, gluon saturation (RHIC, LHC, EIC, LHeC/FCC)
- $f_A(x,\mu^2)$ are determined from global QCD fits to data on fixed-target DIS, hard processes in dA (RHIC) and pA (LHC) $\rightarrow f_A(x,\mu^2)$ 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



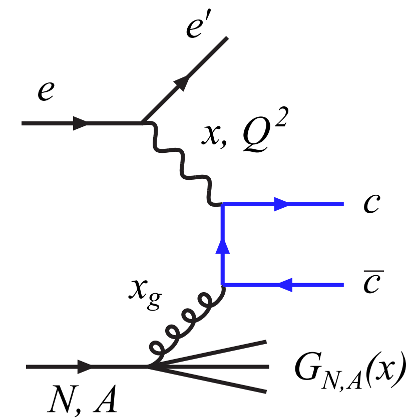
- pA@LHC data help little, EPPS16, Eskola, Paakkinen, Paukkunen, Salgado EPJ C77 (2017) 163

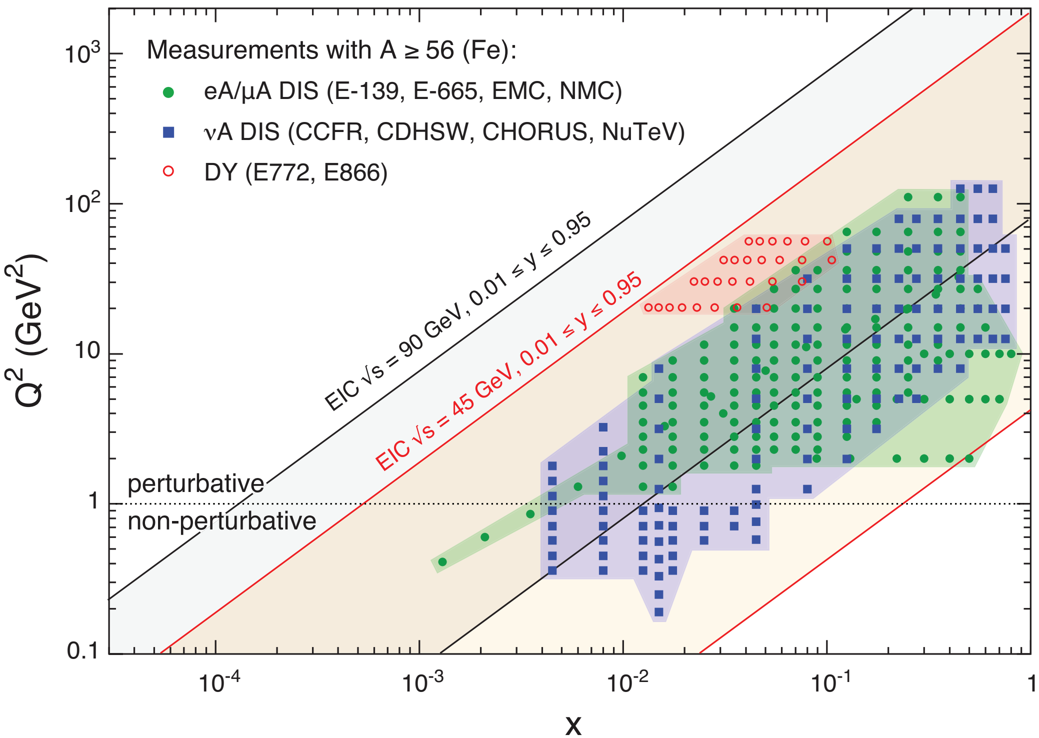


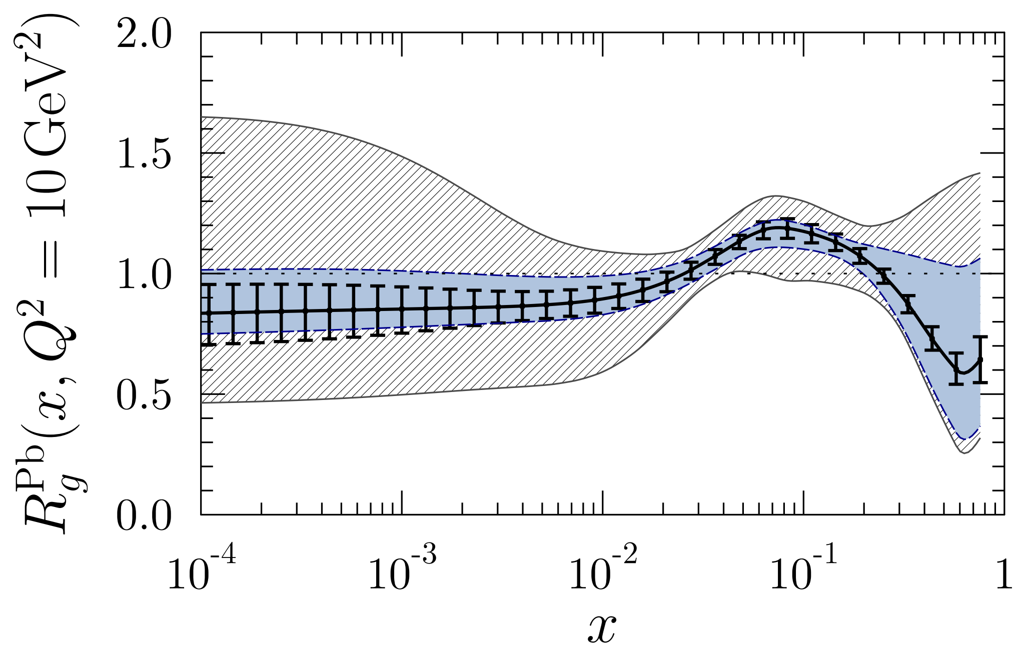
- Alternative: leading twist nuclear shadowing model, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Gluon nuclear shadowing at EIC and LHeC

• In the future, gluon nuclear shadowing will be further 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:





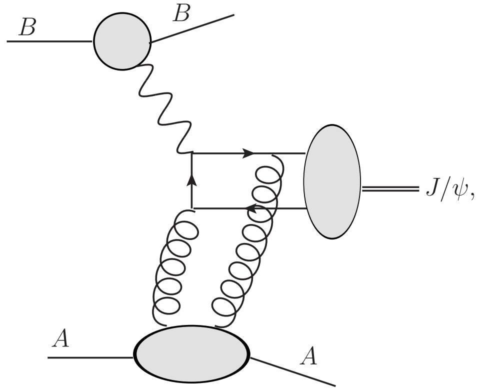


Aschenauer, Fazio, Lamont, Paukkunen, Zurita, PRD 96 (2017) no.11, 114005

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

Ultraperipheral collisions

- Ultraperipheral collisions (UPCs): ions interact at large impact parameters $b \gg R_A+R_B$ → 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

UPCs at the LHC

- To probe partonic structure of (nuclear) targets, one selects UPC processes with a hard scale → heavy vector meson mass or jet p_T

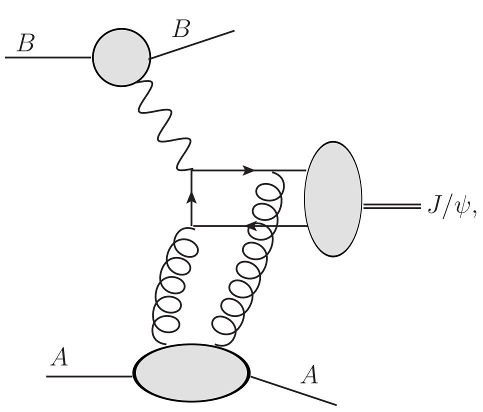
  - Run1: photoproductuon of quarkonia J/ψ, $\psi(2S)$ in:
    Pb-Pb UPCs, [ALICE] Abelev *et al*. PLB 718 (2013) 1273; Abbas *et al.*, EPJ C 73 (2013) 2617; Adam *et al*, PLB 751 (2015) 358; [CMS] PLB 772 (2017) 489,
    p-Pb UPCs, [ALICE] Abelev *et al*., PRL 113 (2014) 232504,
    pp UPCs, [LHCb], Aaij *et al*, J. Phys. G 40 (2013) 045001; J. Phys. G 41 (2014) 055002

  - Photoproduction of bottomonia Υ(1S,2S,3S) in pp UPCs, [LHCb], Aaij *et al*, JHEP 1509 (2015) 084, and pA UPCs, [CMS], Chudasama et al, PoS ICPAQGP 2015 (2017) 042 [arXiv:1607.00786 [hep-ex]]

  - Also photoproduction of ρ, [ALICE] Adam *et al*. JHEP 1509 (2015) 095 → soft nuclear shadowing

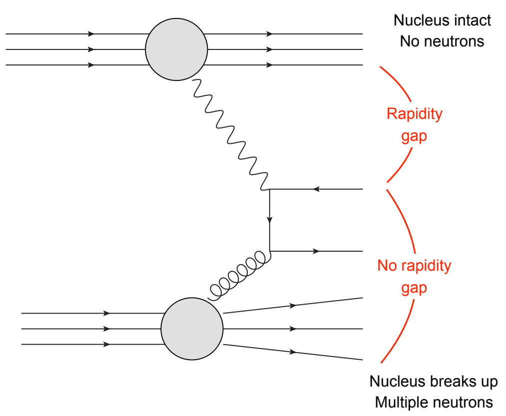
  - Run 2: quarkonia, Kryshen, arXiv:1705.06872; Klein, arXiv:1704.04715, dijets, ATLAS-CONF-2017-011

Exclusive J/ψ photoproduction

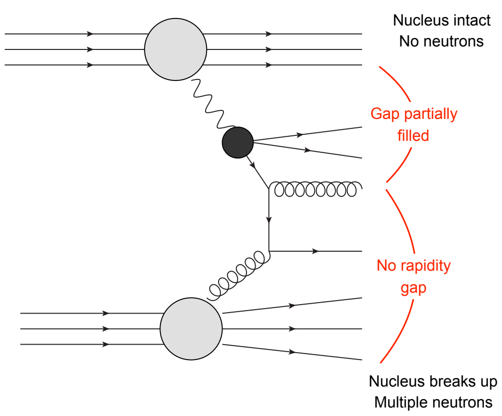


Inclusive dijet photoproduction

direct photon



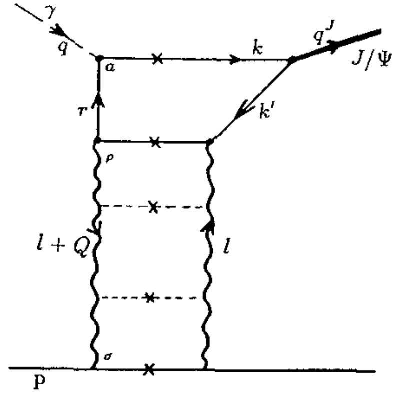
resolved photon



Exclusive charmonium photoproduction

• In leading logarithmic approximation (LLA) of pQCD and non-relativistic approximation for charmonium wave function (J/ψ, $\psi(2S)$), 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 $g(x,\mu^2)$ + 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:

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

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):

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

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

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

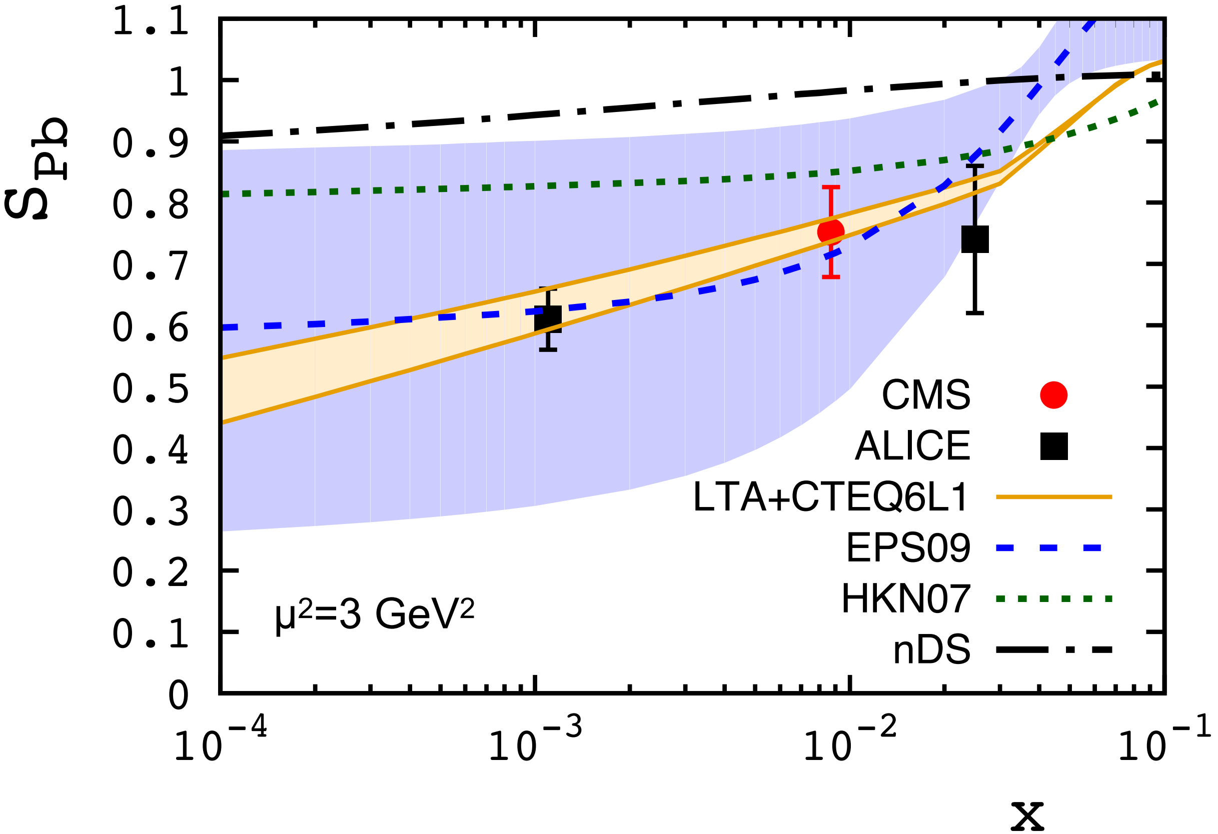
Model-independently from data on UPC@LHC (ALICE, CMS) and HERA, LHCb Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489

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

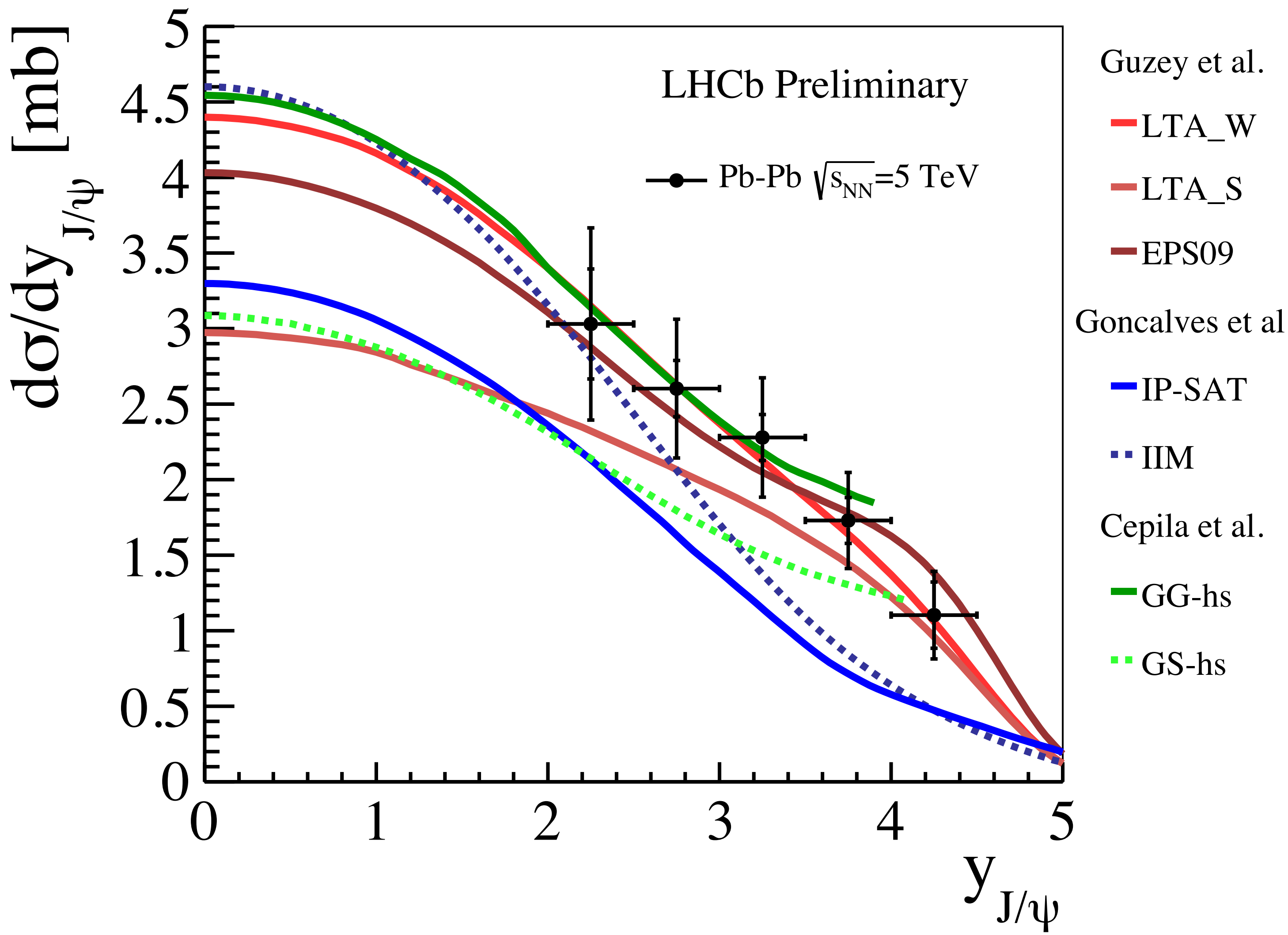
- J/ψ photoproduction in Pb-Pb UPCs at LHC, Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; CMS Collab., PLB 772 (2017) 489 → suppression factor S_{Pb}



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

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



Winn, arXiv: 1808.08152

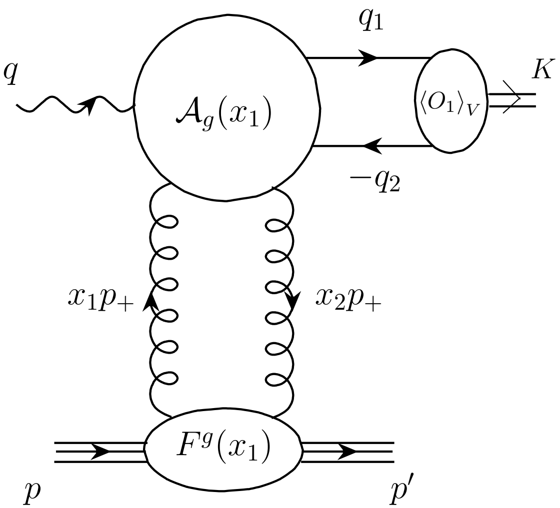
- Good agreement with LTA, EPS09, and certain versions of the dipole model with proton shape fluctuations.

Theoretical issues: collinear factorization

- Ryskin's formula is derived in leading $\alpha_s \ln(1/x) \ln Q^2$ approx.+ NR approx. for charmonium wf (charm quarks have $k_T=0$, $z=1/2$, J/ψ via its J/$\psi \to$ e+e- decay)

- Electroproduction of J/ψ in leading $\alpha_s \ln(1/x) \ln Q^2$ approx., Brodsky, Frankfurt, Gunion, Mueller, Strikman, PRD50 (1994) 3134: answer in terms of $xg(x,\mu^2)$ and J/ψ distribution amplitude

- Collinear factorization for hard exclusive processes, Collins, Frankfurt, Strikman, PRD56 (1997) 2982, and its application to J/ψ photoproduction at NLO, Ivanov, Schaefer, Szymanowski, Krasnikov, EPJ C34 (2004) 297; EPJ C75 (2015) 75; Jones, Martin, Ryskin, Teuber, EPJ C 76 (2015) 633



- Amplitude = convolution of generalized parton distributions (GPDs) with hard coefficients
- Information on J/ψ via NR matrix element

$$\mathcal{M} = \left(\frac{\langle O_1 \rangle_V}{m}\right)^{1/2} \sum_{p=g,q,\bar{q}} \int_0^1 dx_1\, A^p_H(x_1, \mu_F^2)\, \mathcal{F}^p_\zeta(x_1, t, \mu_F^2)$$

- NLO corrections and scale dependence are very large, ~200% in HERA kinematics $\to$ problematic to build successful phenomenology, Ivanov, Schaefer, Szymanowski, Krasnikov, EPJ C75 (2015) 75

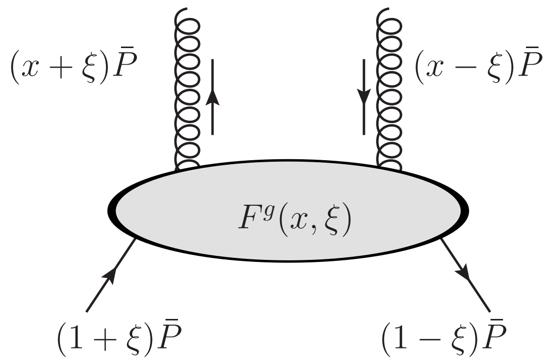
Our phenomenological approach

- In our approach, Guzey, Zhalov, JHEP 1310 (2013) 207, we took Ryskin's formula at face value, chose μ^2=3 GeV^2 to fit W-dependence of HERA data on γ+p → J/ψ+p, and corrected it by skewness and real part → describe well W-dependence of HERA, LHCb data, but overestimate normalization by factor of two.

- Indication of magnitude of corrections? Ryskin, Roberts, Martin, Levin, Z. Phys. C76 (1997) 231

- Our approach is equivalent to collinear factorization at LO:

$$\mathcal{M} = -\frac{8\pi\alpha_s e_c g(\epsilon_V^* \cdot \epsilon_\gamma)}{m_c} \int_{-1}^{1} dx \frac{F^g(x,\xi,t,\mu^2)}{(x-\xi+i\epsilon)(x+\xi-i\epsilon)}$$



- At LO, the imaginary part probes the most skewed situation, when GPDs are far from PDFs. The connection is model-dependent and based on forward input for DGLAP evolution for GPDs, Shuvaev, Golec-Biernat, Martin, Ryskin, PRD 60 (1999) 014015

$$R = \frac{H(\xi,\xi)}{H(2\xi,0)} = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+5/2)}{\Gamma(\lambda+3+p)}$$

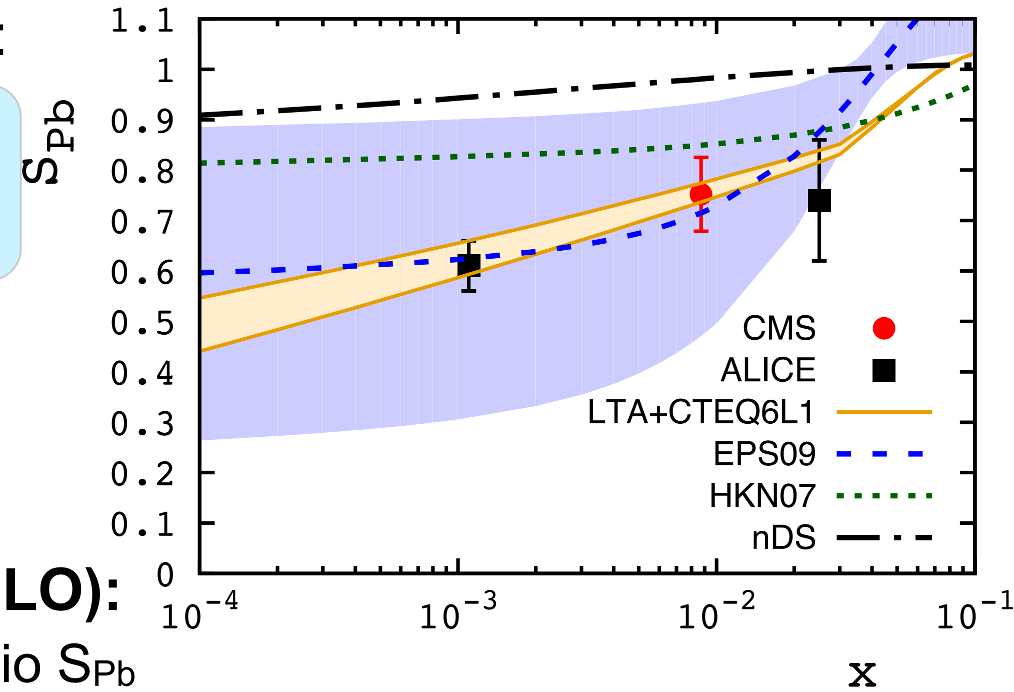
where $xg(x) \sim (1/x)^\lambda$

Implications for gluon nPDF at small x

- Taking nucleus/proton ratio, one might hope that most corrections cancel and S_{Pb} represents gluon shadowing at LO with small correction due to different skewness for nucleus and proton GPDs:

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

$k_{A/N}=R_A/R_N$



- **One needs to check further (LO and NLO):**
  - cancellation of GPD/PDF connection in ratio S_{Pb}
  - to what extent corrections beyond collinear approximation cancel in S_{Pb}
  - useful guide to estimate the magnitude of these corrections is provided by the dipole model, Frankfurt, Koepf, Strikman 1996,1998

- **Open questions:**
  - relativistic corrections to J/ψ distribution amplitude
  - resummation to reduce the large scale dependence at NLO
  - connection between collinear factorization (GPDs) and k_T factorization/dipole models; leading twist vs. all-twist nuclear shadowing

Imaging of nuclear gluons at small x

- In case of large nuclear shadowing, $\gamma A \to J/\psi A$ cross section should be generalized:

$$\frac{d\sigma_{\gamma A \to J/\psi A}}{dt} = \frac{d\sigma_{\gamma p \to J/\psi p}(t=0)}{dt} \left(\frac{R_{g,A}}{R_{g,p}}\right)^2 \left(\frac{g_A(x,\mu^2)}{A g_p(x,\mu^2)}\right)^2 F_A^2(t)$$

$$\downarrow \qquad\qquad \downarrow$$

$$\frac{d\sigma_{\gamma A \to J/\psi A}}{dt} = \frac{d\sigma_{\gamma p \to J/\psi p}(t=0)}{dt} \left(\frac{R_{g,A}}{R_{g,p}}\right)^2 \boxed{\left(\frac{g_A(x,t,\mu^2)}{A g_p(x,\mu^2)}\right)^2}$$

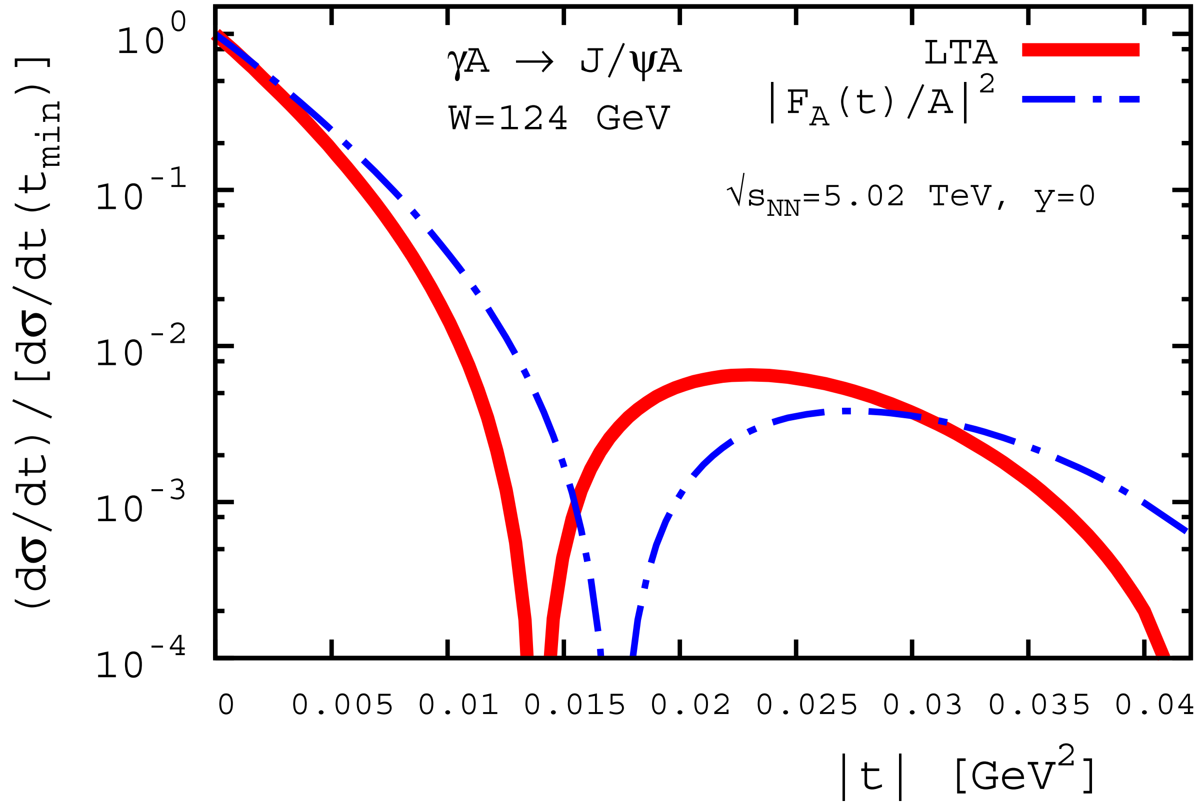
- Answer in terms of nuclear GPD in the $x_1=x_2$ limit → FT → impact-parameter-dependent nPDF $f_{j/A}(x,Q_0^2,b)$, Guzey, Strikman, Zhalov, PRC 95 (2017) 025204

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

- b-dependent nPDFs predicted in leading twist nuclear shadowing model, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255, and also fitted in EPS09s nPDFs, Helenius, Honkanen, Salgado, JHEP 1207 (2012) 073.

Shift of t-dependence

- Correlations between impact parameter b and x (shadowing is stronger in nucleus center) → 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 and LHeC.

Summary

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

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

• Theoretical challenge and open question: include UPC data on exclusive J/ψ in global QCD fits of nPDFs.

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