Can we use UPC production to constrain gluon density in nuclear PDFs?

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Outline:

- Nuclear PDFs and UPCs
- Gluon nuclear shadowing from coherent J/ψ photoproduction on nuclei
- Theoretical issues in pQCD studies of coherent J/ψ photoproduction
- Implications for gluon nPDF at small x
- Inclusive jet photoproduction in UPCs

Workshop “Low-x gluon structure of nuclei and signals of saturation at LHC”
GERN, Geneva, March 27 2018

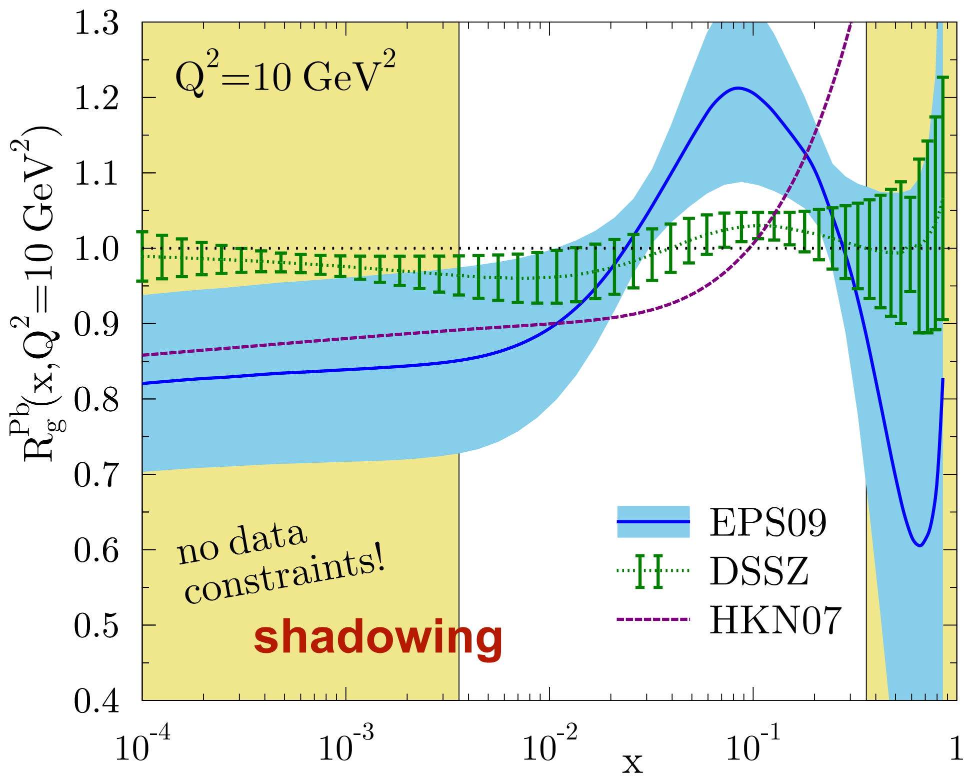
Parton distributions in nuclei at small x

- Collinear nPDF for small $x < 0.01$ are suppressed due to nuclear shadowing: $f_A(x,\mu^2) < A\, f_N(x,\mu^2)$

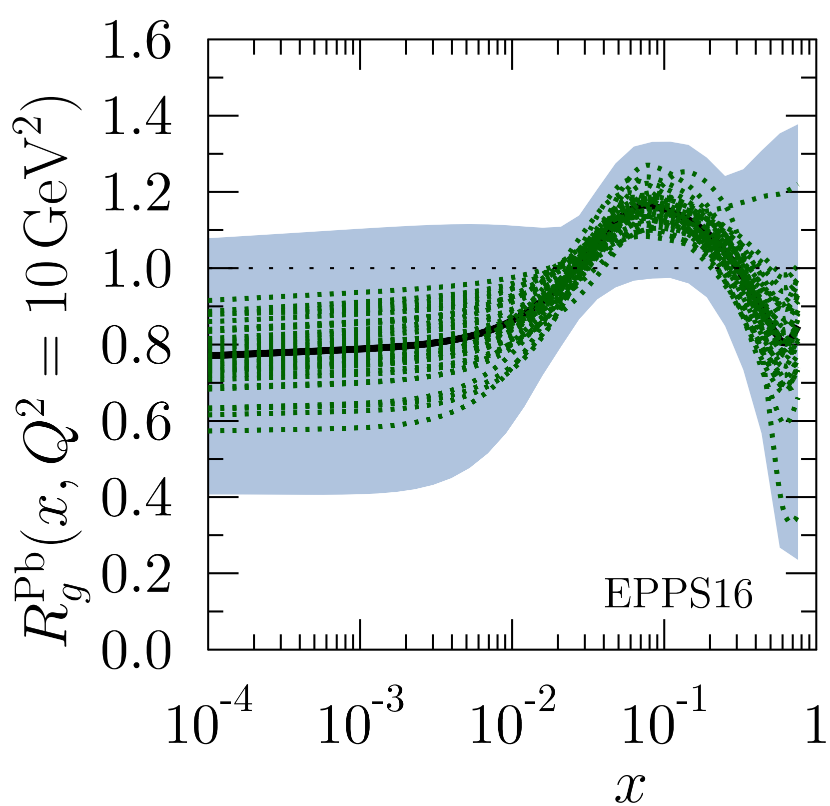
- $f_A(x,\mu^2)$ is determined from global QCD fits to data on fixed-target DIS, hard processes in dA (RHIC) and pA (LHC) $\rightarrow f_A(x,\mu^2)$ with significant uncertainties

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

Paukkunen, NPA 926 (2014) 24

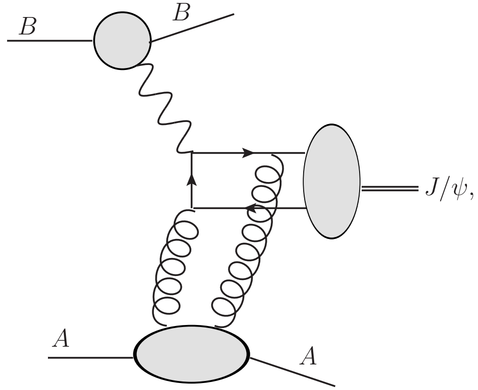


- pA@LHC data help little, EPPS16, Eskola, Paakkinen, Paukkunen, Salgado EPJ C77 (2017) 163



Charmonium production in 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

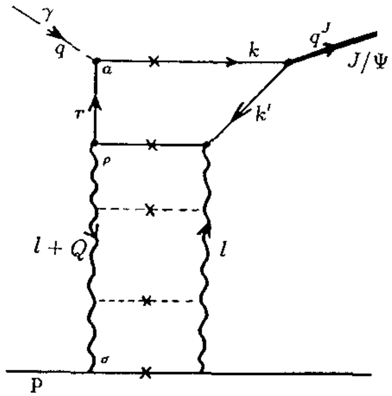
Photoproduction cross section

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



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

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

Ryskin, Z. Phys. C57 (1993) 89

- Application to nuclear targets:

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

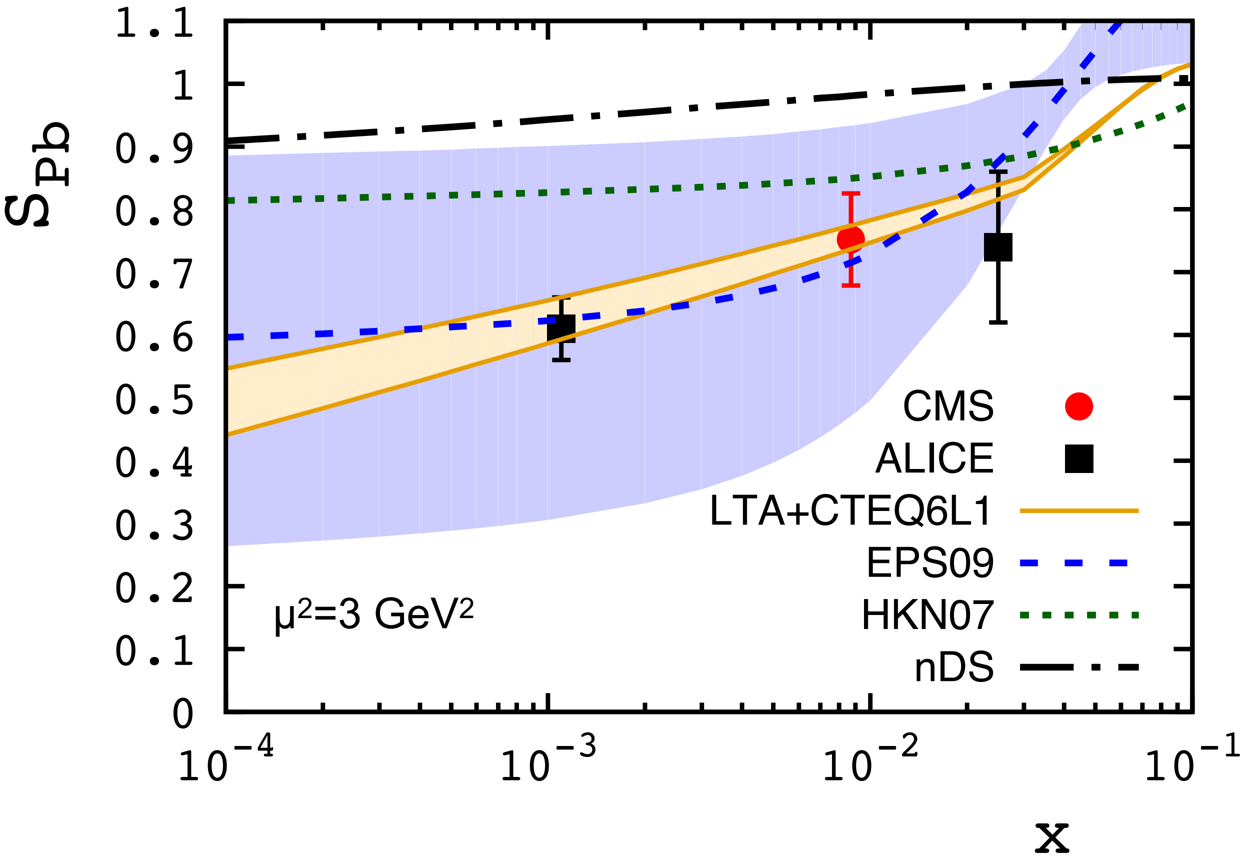
Small correction due to skewness: $\kappa_{A/N} \approx$ 0.90-95

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

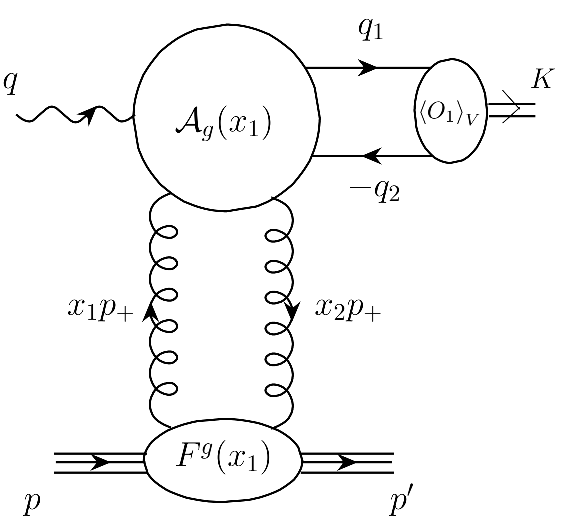
- Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV → evidence of large gluon NS, $R_g(x=0.001) \approx 0.6$.
- Also good description using central value of EPS09, EPPS16, large uncertainty.

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

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

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

Theoretical issues: other approaches

- **Beyond LLA using k_T factorization + relativistic effects in J/ψ wf**, 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 → some NLO effects using unintegrated $g(x,k_T)$, which reduces 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

- **Another use of k_T factorization**, Cisek, Schafer, Szczurek, JHEP 1504 (2014) 159 → unintegrated gluon distribution with saturation seems to be preferred by LHCb data on J/ψ photoproduction

- **Color dipole model**, Frankfurt, Koepf, Strikman (1998) → relativistic effects in charmonium wf are very important; gluon virtualities are much higher than in NR case; effect of skewness is small.

- **Color dipole model framework,** Goncalves, Machado 2008-present; Lappi, Mäntysaari, PRC 87 (2013) 032291→ 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 underestimated.

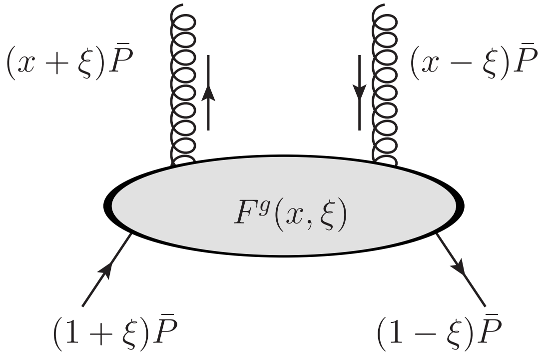
Implications for gluon nPDF at small x

- 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 γp →J/ψp, 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) ~(1/x)$^\lambda$

Implications for gluon nPDF at small x

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

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

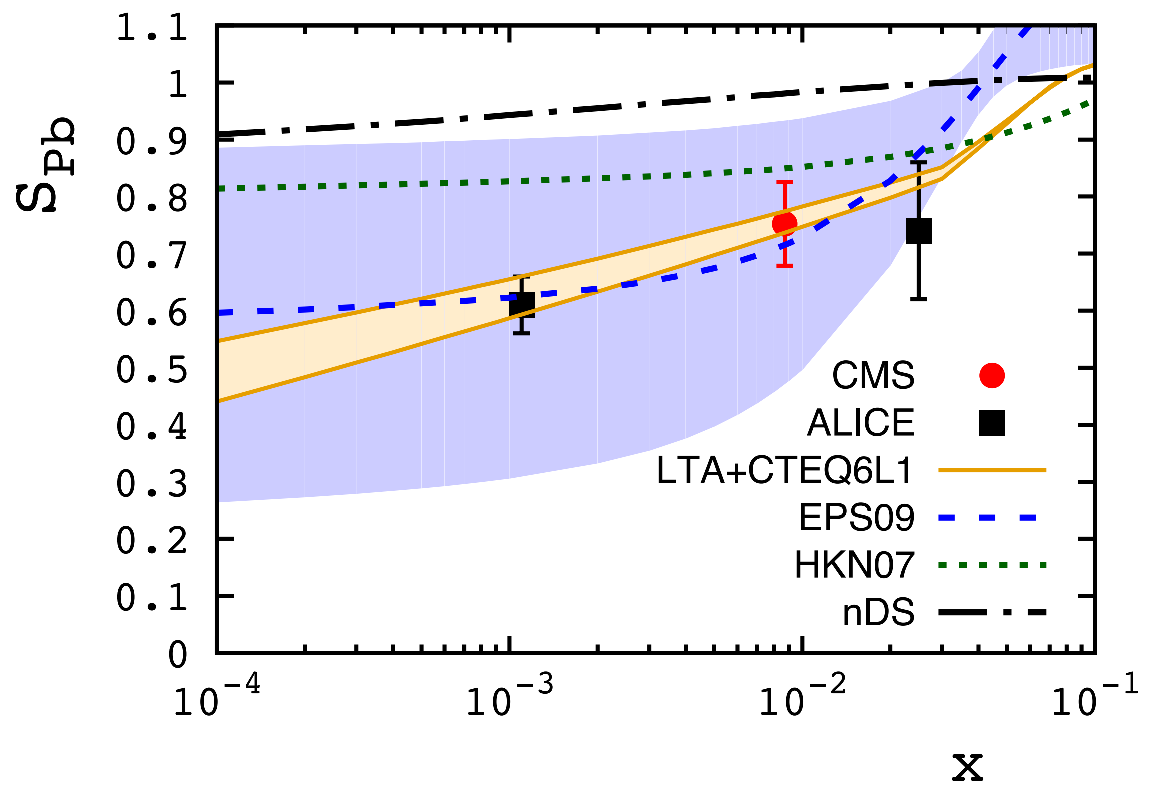
$k=R_A/R_N$

- One needs to check further:
  - cancellation of GPD/PDF connection in ratio
  - to what extent unaccounted corrections cancel in ratio (beyond collinear)
  - useful guide to estimate the magnitude of corrections is provided by the dipole model, Frankfurt, Koepf, Strikman 1996,1998

- The same can be done at NLO:
  - GPD/PDF connection is much more difficult/unknown/only numerical
  - check cancellation of NLO coefficient functions, scale dependence in ratio

Implications for gluon nPDF at small x

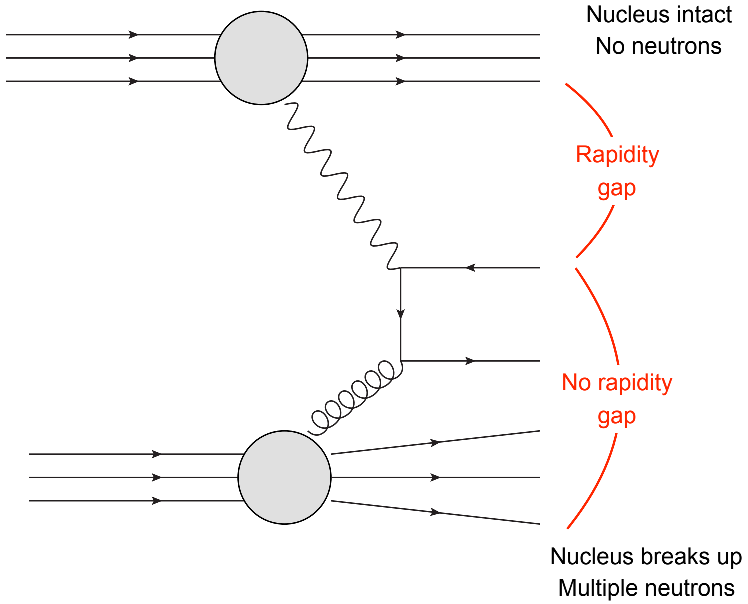
- In the end, one should be able to add theoretical errors to S_{Pb} and possibly use it for global QCD fits of nPDF at LO, NLO.

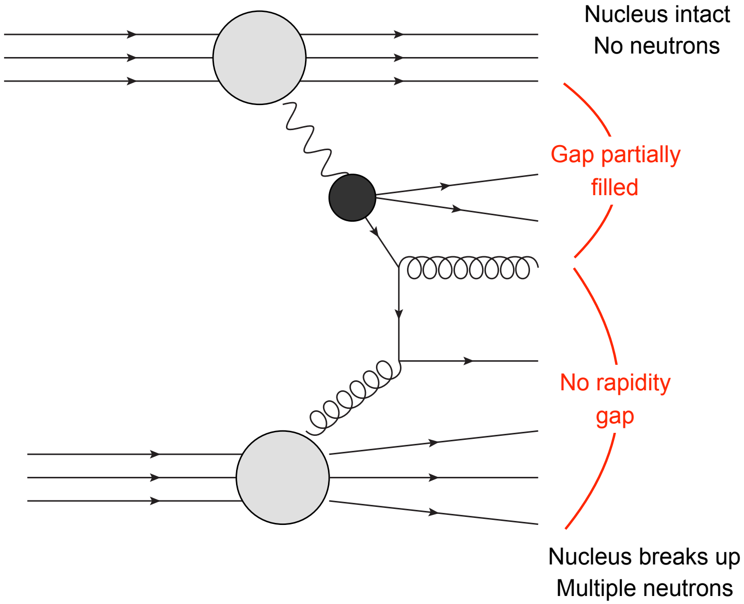


- Open questions:
  - relativistic corrections to J/ψ distribution amplitude
  - resummation to reduce the large scale dependence at NLO
  - connection between collinear factorization (GPDs) and k_T factorization/dipole models; leading twist vs. all-twist nuclear shadowing

Inclusive dijet photoproduction on nuclei in UPCs

- Run 2 results on inclusive jet photoproduction in Pb-Pb UPCs at LHC, ATLAS-CONF-2017-011.



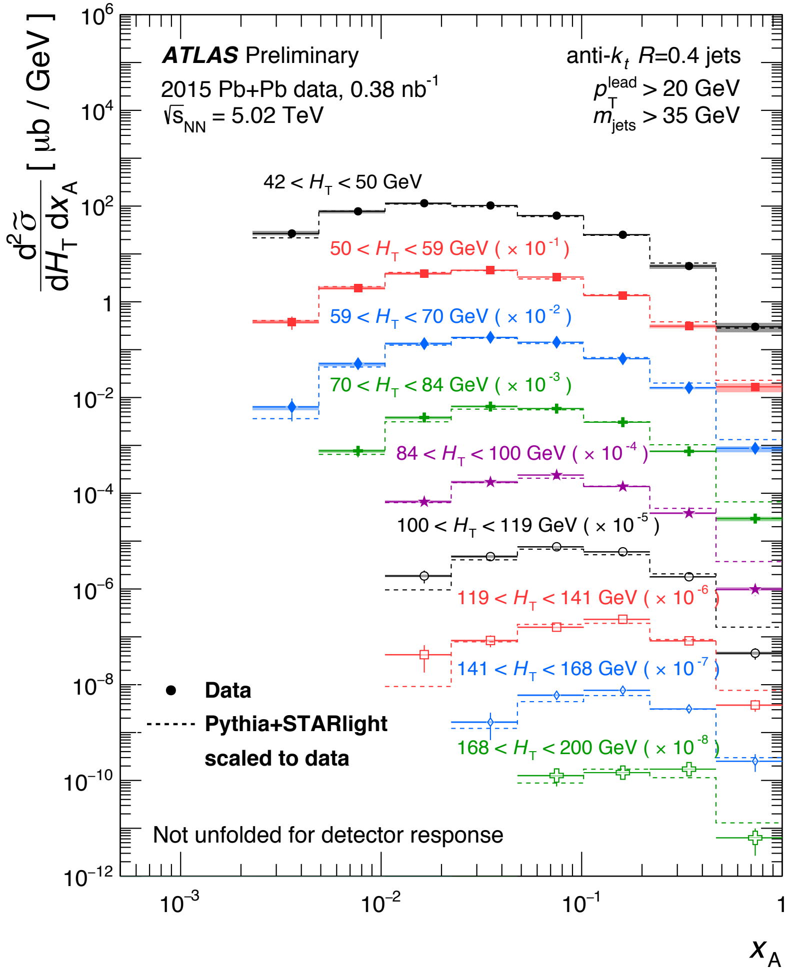


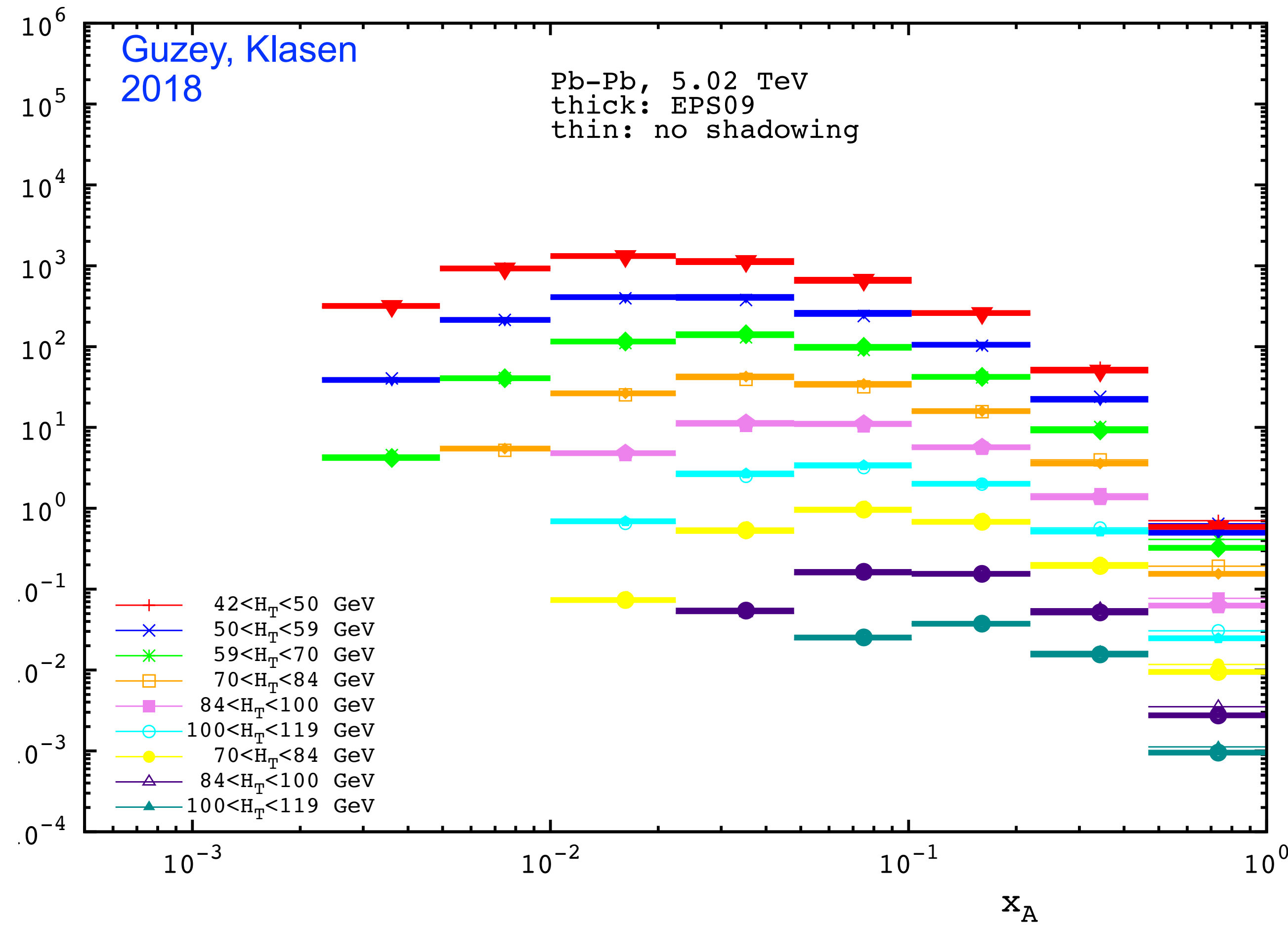
- $\sqrt{s_{NN}} = 5.02$ TeV
- Anti-kT algorithm with $R = 0.4$
- Leading jet $p_T > 20$ GeV, others > 15 GeV, which corresponds to $35 < H_T < 400$ GeV, where $H_T = E_T^{\text{jet1}} + E_T^{\text{jet2}}$
- All jets $|\eta| < 4.4$
- The combined mass of all reconstructed jets $35 < m_{\text{jets}} < 400$ GeV
- The parton momentum fraction on the photon side $z_\gamma = y x_\gamma$, $10^{-4} < z_\gamma < 0.05$
- The parton momentum fraction on the nucleus side x_A, $5 \times 10^{-4} < x_A < 1$.

Inclusive dijet photoproduction on nuclei in UPCs

- Adopted NLO pQCD formalism for dijet photoproduction, which explains well HERA (ZEUS, H1) data on dijet photoproduction in ep, Klasen, Kramer, Z.Phys. C 72 (1996) 107, Z. Phys. C 76 (19997) 67; Klasen, Rev. Mod. Phys. 74 (2002) 1221; Klasen, Kramer, EPJC 71 (2011) 1774.

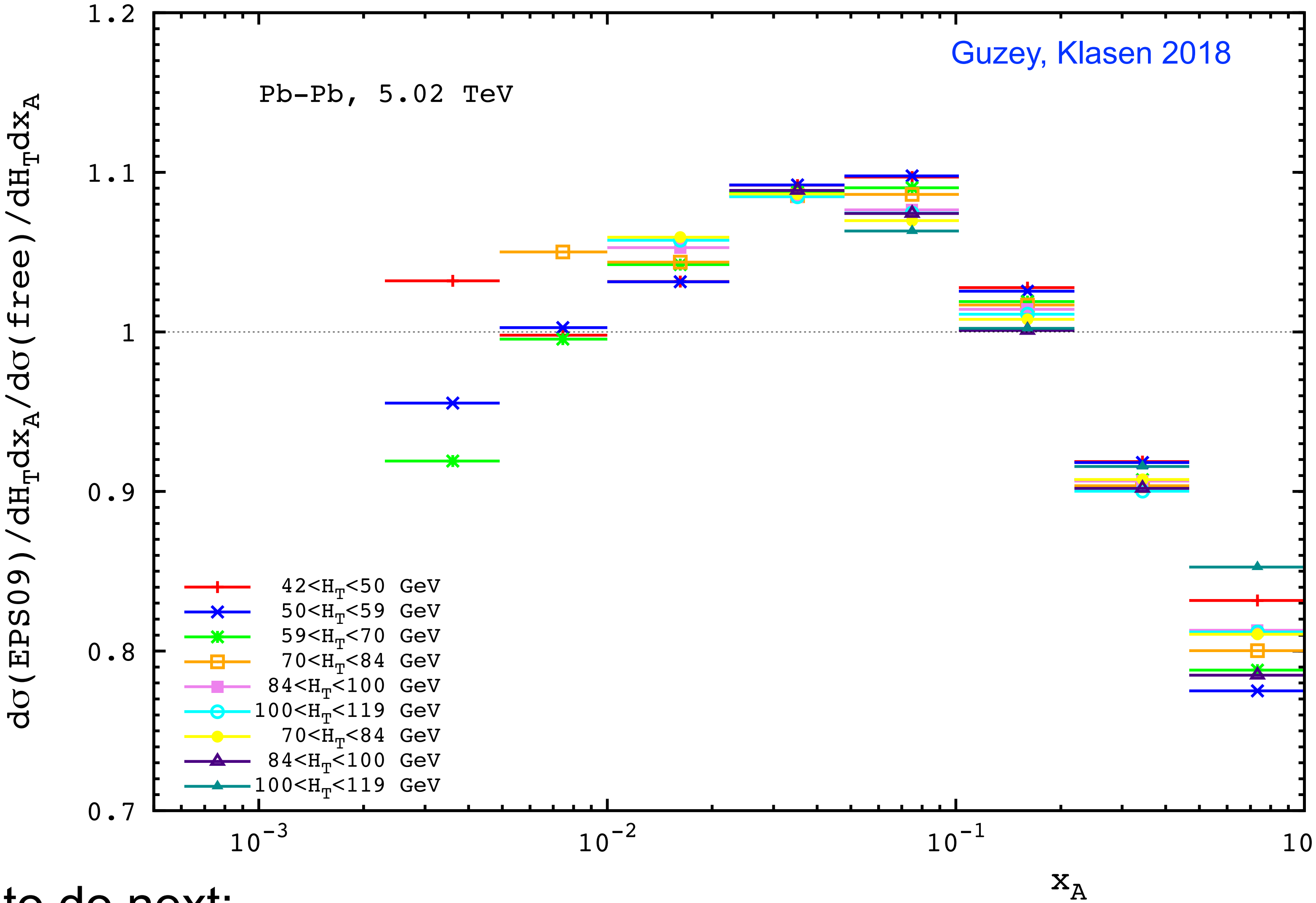
- At the moment, GRG-HO photon PDFs, CTEQ5M+EPS09 nuclear PDFs.





- Shape reproduced, normalization larger by factor 5-10.

Nuclear effects on inclusive dijet photoproduction on nuclei in UPCs



- Things to do next:
  - understand normalization
  - use nCTEQ15 and EPPS16 nPDFs, study PDF and scale uncertainties
  - compare with PYTHIA predictions Helenius, arXiv:1708.09759

Conclusions

• Collinear factorization for quarkonium photoproduction in UPCs is proven at LO and NLO.

• Straightforward use at LO shows that photoproduction of J/ψ in Pb-Pb UPCs at the LHC gives direct evidence of large gluon nuclear shadowing for collinear nPDFs: $R_g(x=0.001, \mu^2 \approx 3\ \mathrm{GeV}^2) = 0.6$.

• To assign theoretical uncertainties to this statement and potentially use S_{Pb} in global fits on nPDFs at LO and NLO, one needs to further study theoretical uncertainties associated with GPD/PDF connection, scale uncertainties, power-suppressed corrections.

• The question in the talk title can be answered after that.

• Additional information on small-x nPDFs can be obtained from inclusive and diffractive jet photoproduction in UPCs@LHC.