Nuclear shadowing and heavy ion UPCs at the LHC

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Based on series of papers with E. Kryshen, M. Zhalov, M. Strikman, L. Frankfurt, M. Klasen

Outline:

- Nuclear shadowing: global fits vs. leading twist model
- Gluon nuclear shadowing from coherent J/ψ photoproduction in Pb-Pb UPCs at the LHC
- Gluon nuclear shadowing from inclusive and diffractive dijet photoproduction in Pb-Pb UPCs at the LHC

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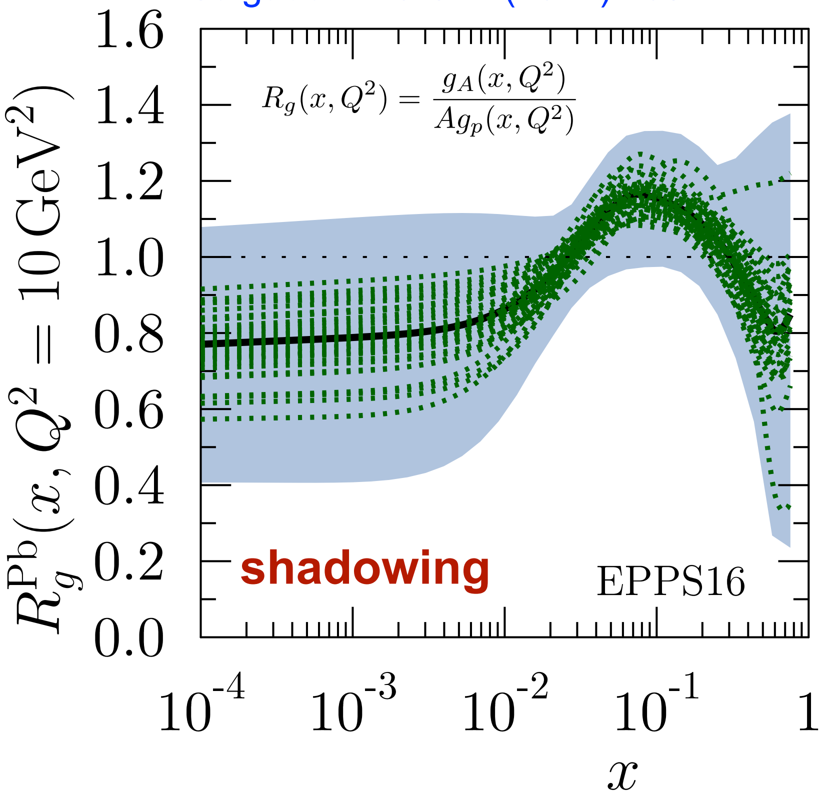
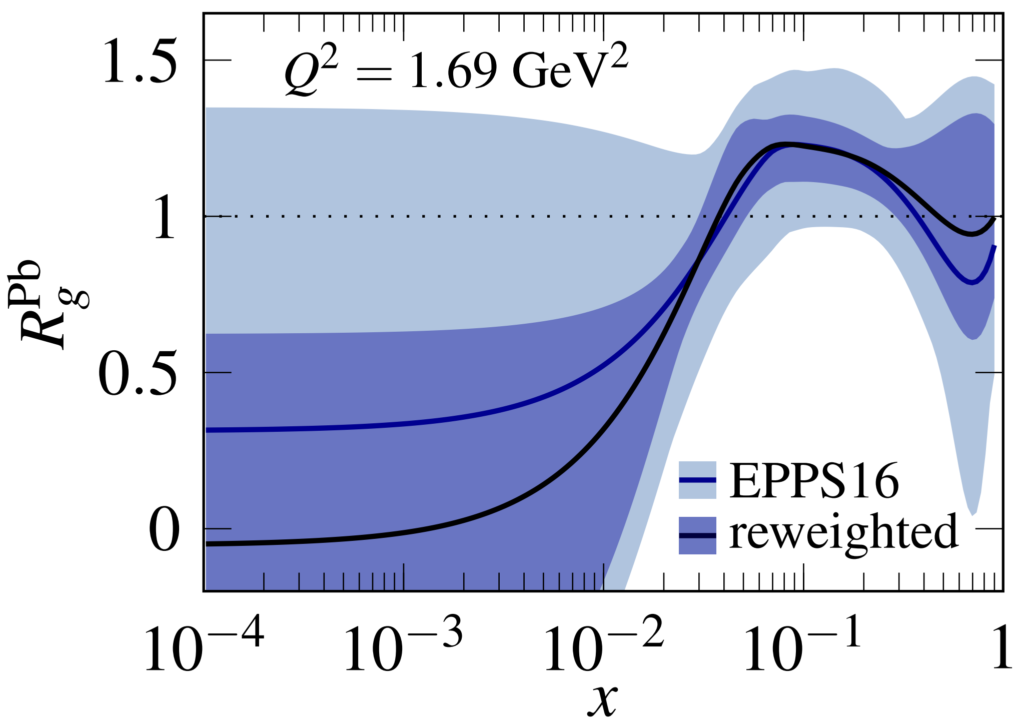
Gluon shadowing at small x: global fits

- Nuclear shadowing: suppression of nuclear cross sections and nuclear parton distribution functions (nPDFs) for small $x < 0.05$, $f_A(x,\mu^2) < A\, f_N(x,\mu^2)$
- Important for QCD phenomenology of hard processes with nuclei at RHIC, LHC, future EIC, LHeC/FCC → cold nuclear matter effects, gluon saturation.
- $f_A(x,\mu^2)$ are determined from global QCD fits to data on fixed-target DIS, hard processes in dA (RHIC) and pA (LHC) → $f_A(x,\mu^2)$ with significant uncertainties

EPPS16, Eskola, Paakkinen, Paukkunen, Salgado EPJ C77 (2017) 163

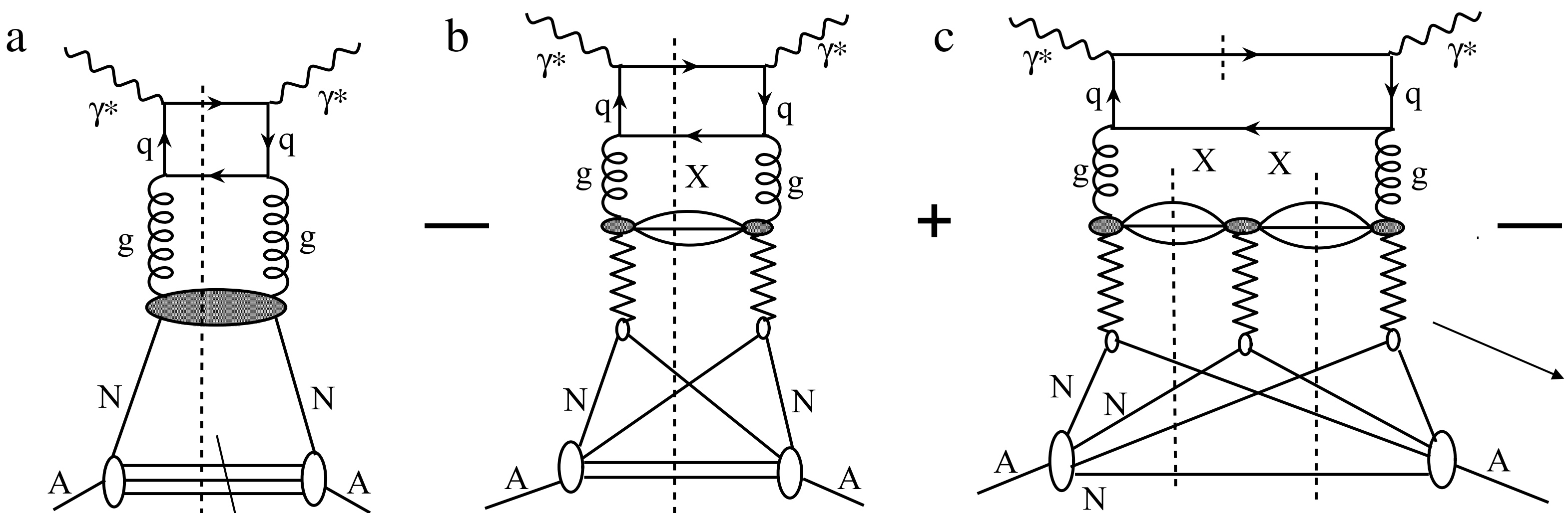


Run 2 CMS jets, Eskola, Paakkinen, Paukkunen, EPJC 79 (2019) 6, 511



Leading twist model of nuclear shadowing

- Alternative to extrapolation of nPDFs into x < 0.05 region: leading twist model of 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

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

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

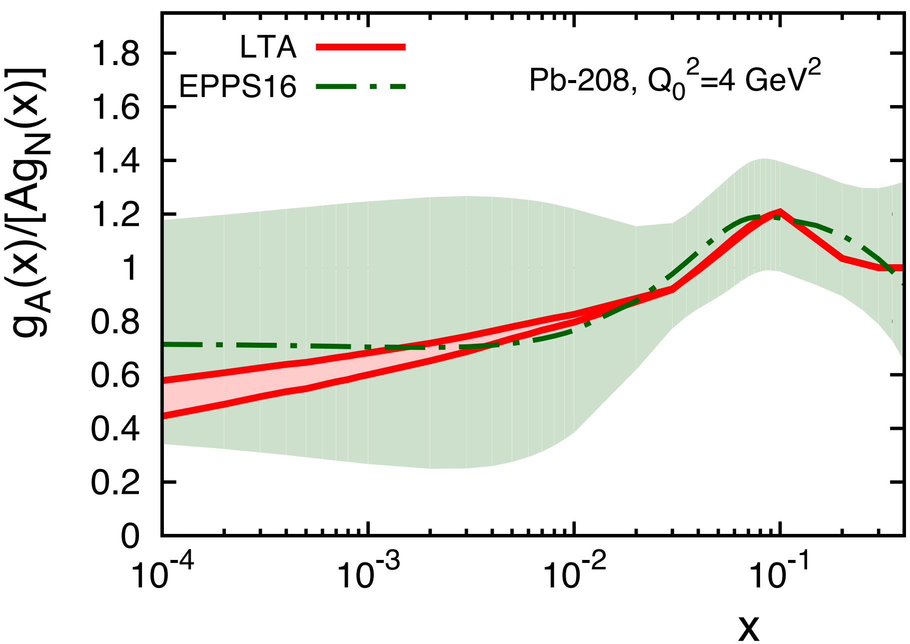
nuclear density

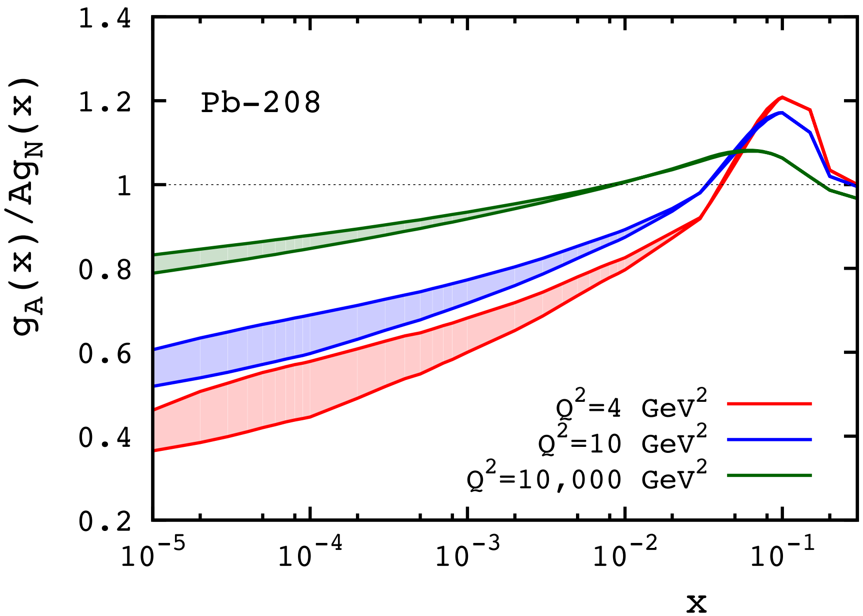
proton diffractive PDFs from HERA

model-dependent effective cross section

Leading twist model of 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 $g_A(x,\mu^2)$.





- Future Electron-Ion Collider can best test these predictions due to:

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

- Different approaches to shadowing can also be studied in **UPCs@LHC**, which can be viewed as a forerunner of EIC.

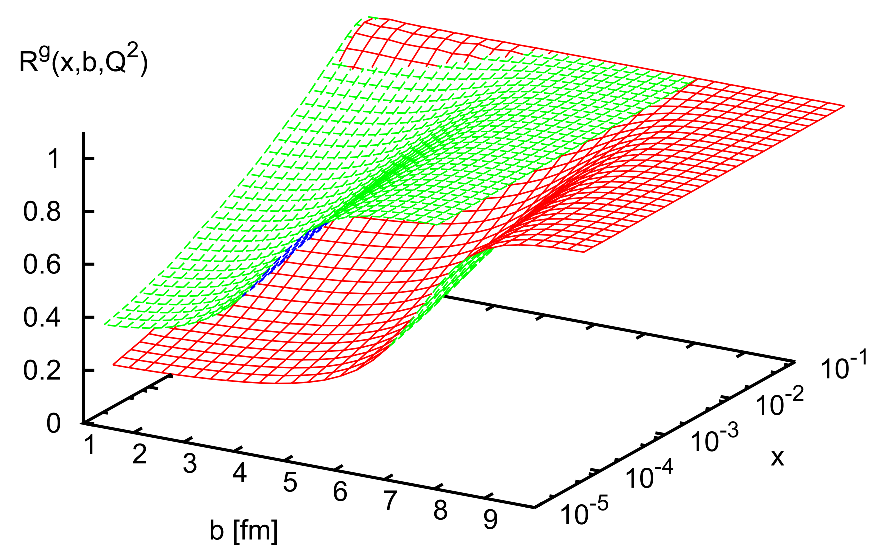
Impact parameter dependence of nPDFs

- The model of leading twist nuclear shadowing allows one to predict the dependence of nPDFs on the impact parameter b:

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

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

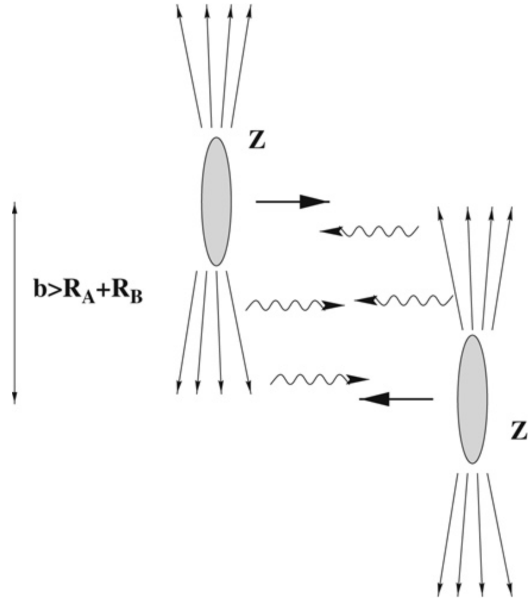
- → correlations between b and x → shadowing is stronger in nucleus center → shift of t-dependence of $\gamma A \to J/\psi A$ cross section → confirmed by LHC data on coherent J/ψ photoproduction in Pb-Pb UPCs (see later).



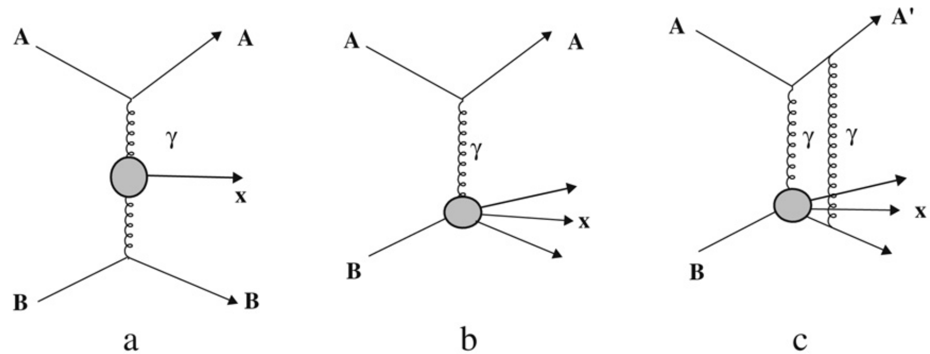
- With additional assumptions, global QCD fits can also extract b-dependence of nPDFs, EPS09s, Helenius, Honkanen, Salgado, JHEP 1207 (2012) 073.

Ultraperipheral collisions

• Ultraperipheral collisions (UPCs): ions interact at large impact parameters $b >> R_A+R_B$ → hadron interactions suppressed → interaction via quasi-real photons in Weizsäcker-Williams equivalent photon approximation, Budnev, Ginzburg, Meledin, Serbo, Phys. Rept. 15 (1975) 181



• UPCs@LHC allow one to study $\gamma\gamma$, γp and γA interactions at unprecedentedly high energies (energy frontier) reaching: $W_{\gamma p}$=5 TeV, $W_{\gamma A}$=700 GeV/A, $W_{\gamma\gamma}$=4.2 TeV

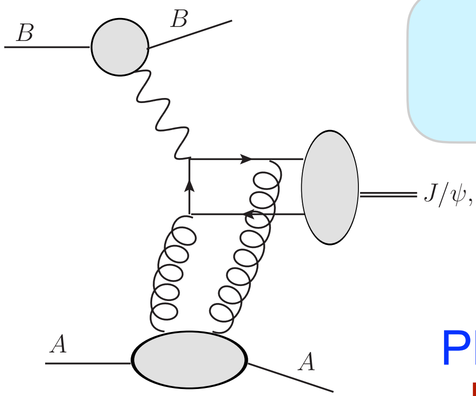


• UPCs can be used to study open questions of proton and nucleus structure in QCD and search for new physics → e.g., **new info on gluon nuclear shadowing**.

Bertulani, Klein, Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271; Baltz et al, Phys. Rept. 480 (2008) 1; Contreras and Tapia-Takaki, Int. J. Mod. Phys. A 30 (2015) 1542012; Snowmass LoI, Klein et al, arXiv:2009.03838

Exclusive J/ψ photoproduction in UPCs

• Cross section of coherent J/ψ photoproduction in Pb-Pb UPCs → two terms corresponding to low-x and high-x



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

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

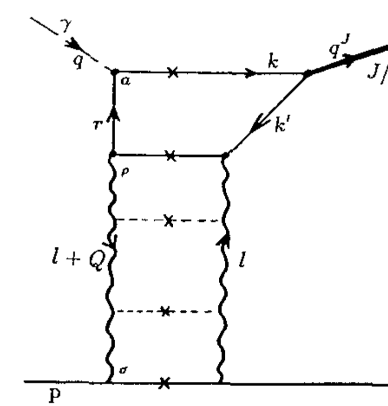
= J/ψ rapidity

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

Photoproduction cross section

• In leading logarithmic approximation (LLA) of pQCD, Ryskin, Z. Phys. C57 (1993) 89; Frankfurt, Koepf, Strikman, PRD 57 (1998) 512; Frankfurt, McDermott, Strikman, JHEP 03 (2001) 045

$$\frac{d\sigma^{\gamma p\to J/\psi p}(t=0)}{dt} = \frac{12\pi^3}{\alpha_{\rm e.m.}}\frac{\Gamma_V M_V^3}{(4m_c^2)^4}\left[\alpha_s(Q^2_{\rm eff})xg(x,Q^2_{\rm eff})\right]^2 C(Q^2=0)$$



$x=(M_V)^2/W^2$, Q_{eff}^2=2.5-4 GeV^2

depends on details of charmonium distribution amplitude

Coherent J/ψ photoproduction on nuclei

- Application to nuclear targets:

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

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

From HERA and LHCb

Nucleus/proton gluon ratio R_g

From nuclear form factor

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

- Well-defined impulse approximation (IA):

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

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

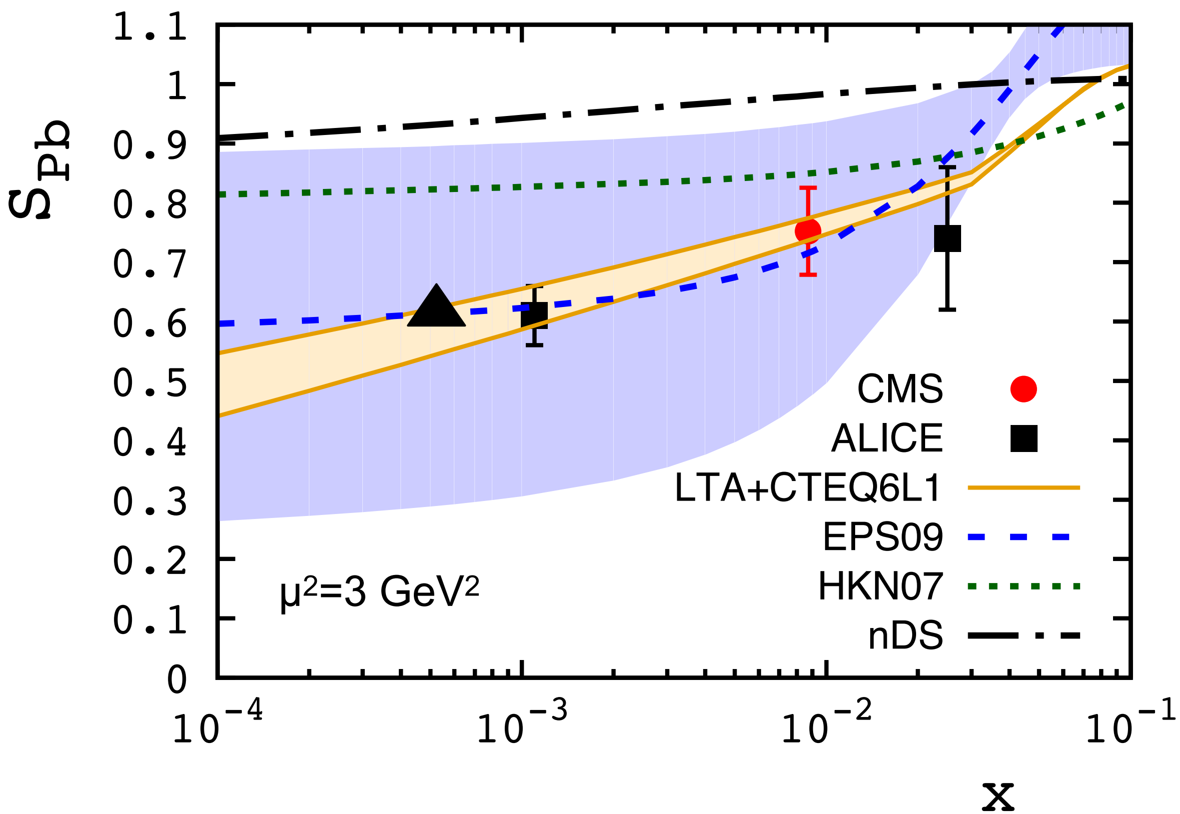
$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb\to J/\psi Pb}}{\sigma^{\rm IA}_{\gamma Pb\to J/\psi Pb}}\right]^{1/2} = \kappa_{A/N}\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)} = \kappa_{A/N}R_g$$

Model-independently* from data on UPC@LHC at (ALICE, CMS, LHCb) and HERA, LHCb Abelev *et al*. [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489; Acharya et al [ALICE], arXiv:2101:04577 [nucl-ex]

From global QCD fits 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

- Model-independently at y=0 and mostly large-x at forward |y|, Abelev *et al*. [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; CMS Collab., PLB 772 (2017) 489, Acharya et al [ALICE], arXiv:2101:04577 [nucl-ex] → 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 at 2.76 and 5.02 TeV → direct evidence of large gluon shadowing, $R_g(x=6\times10^{-4} - 0.001) \approx 0.6$, predicted by the LT model.
- 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

Imaging of nuclear gluons at small x

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

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

$$\Downarrow$$

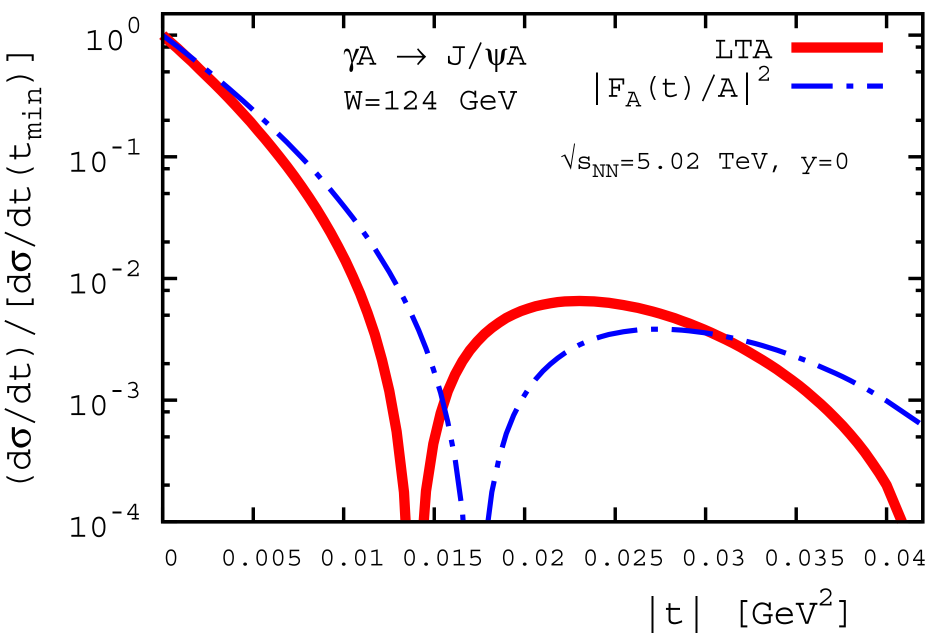
$$\frac{d\sigma_{\gamma A \to J/\psi A}}{dt} = \frac{d\sigma_{\gamma p \to J/\psi p}(t=0)}{dt} \left(\frac{R_{g,A}}{R_{g,p}}\right)^2 \left(\frac{g_A(x,t,\mu^2)}{A g_p(x,\mu^2)}\right)^2$$

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

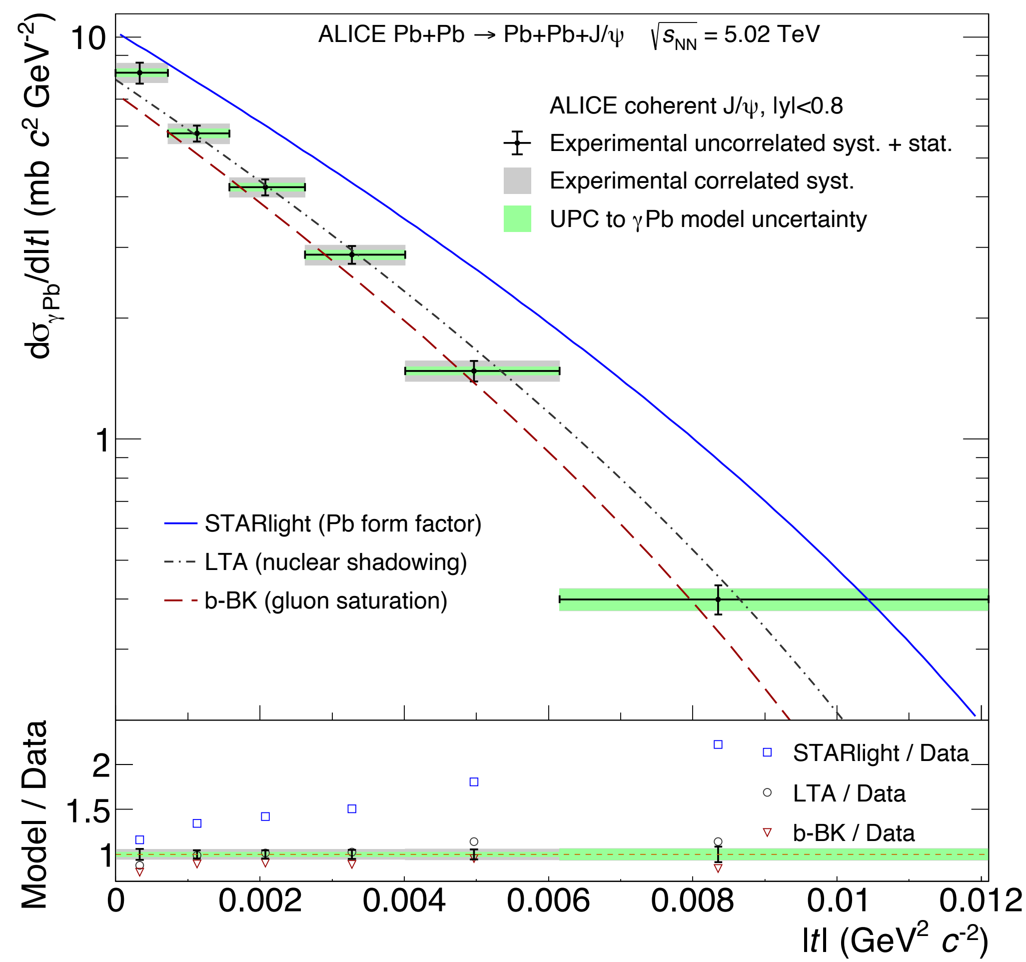
- Correlations between b and x → shift of t-dependence of $\gamma A \to J/\psi A$ cross section.

t-dependence of coherent J/ψ photonuclear cross section

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



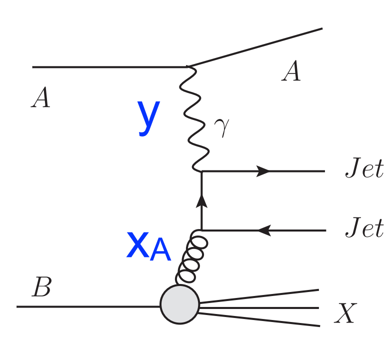
Acharya et al. [ALICE] arXiv:2101.04623 [nucl-ex]



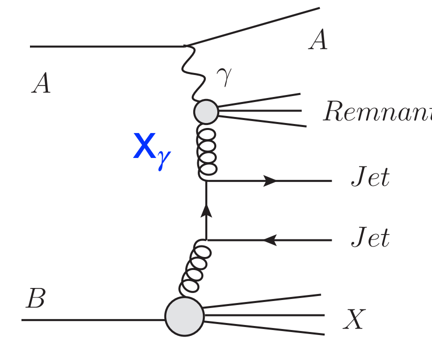
- Shift of t-dependence = **5-11% broadening** in impact parameter space of gluon nPDF
- Similar effect is predicted to be caused by saturation, Cisek, Schafer, Szczurek, PRC86 (2012) 014905; Lappi, Mäntysaari, PRC 87 (2013) 032201; Toll, Ullrich, PRC87 (2013) 024913; Goncalves, Navarra, Spiering, arXiv:1701.04340

Inclusive dijet photoproduction in Pb-Pb UPCs@LHC

- Cross section of dijet photoproduction using collinear factorization and next-to-leading (NLO) pQCD, which is successful for HERA data on dijet photoproduction in ep scattering, Klasen, Kramer, Z.Phys. C 72 (1996) 107, Z. Phys. C 76 (1997) 67; Klasen, Rev. Mod. Phys. 74 (2002) 1221; Klasen, Kramer, EPJC 71 (2011) 1774



(a)
direct



(b)
resolved

$$d\sigma(AA \to A + 2\text{jets} + X) =$$

$$\sum_{a,b} \int dy \int dx_\gamma \int dx_A f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma, \mu^2) f_{b/A}(x_A, \mu^2) d\hat{\sigma}_{ab\to\text{jets}}$$

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

Photon PDFs (resolved photon), from e+e- data

Hard parton cross section

$$f_{\gamma/A}(y) = \frac{2\alpha_{\text{e.m.}} Z^2}{\pi} \frac{1}{y} \left[\zeta K_0(\zeta) K_1(\zeta) - \frac{\zeta^2}{2} (K_1^2(\zeta) - K_0^2(\zeta)) \right]$$

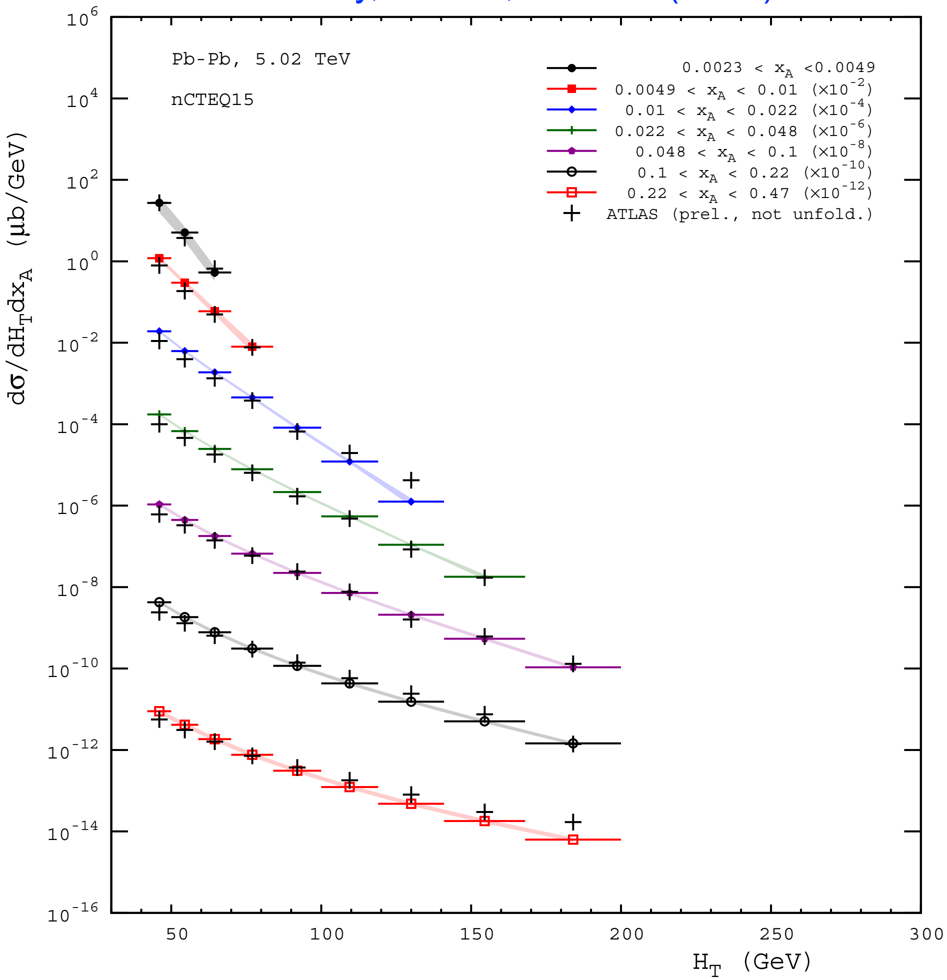
Nuclear PDFs (nCTEQ15, EPPS16)

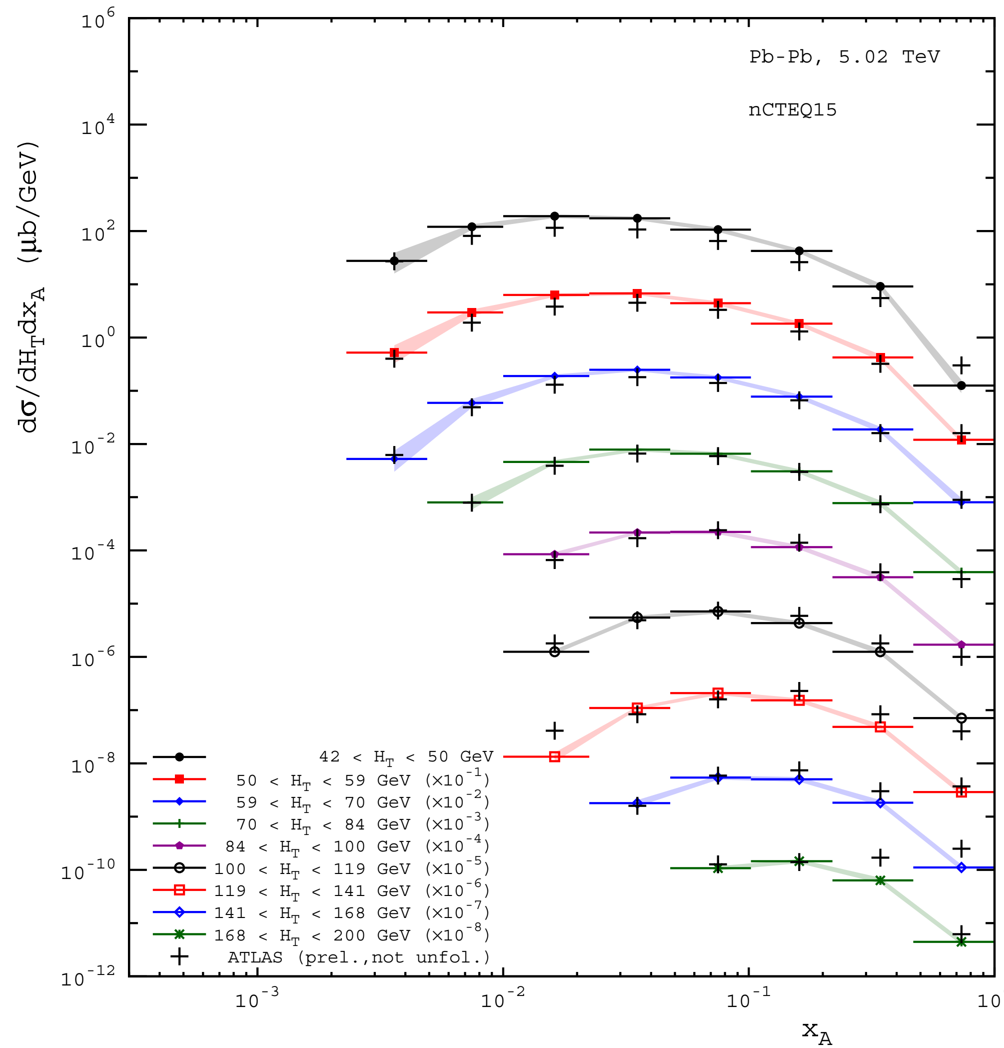
$$\zeta = y m_p b_{\text{min}} \approx y m_p (2R_A)$$

Inclusive dijet photoproduction in Pb-Pb UPCs@LHC (2)

- NLO pQCD vs. ATLAS data as a function of the dijet transverse momentum $H_T = E_T^{jet1} + E_T^{jet2}$ and nuclear momentum fraction $x_A = (m_{jets}/\sqrt{s_{NN}})e^{-y_{jets}}$

Guzey, Klasen, PRC 99 (2019) 065202

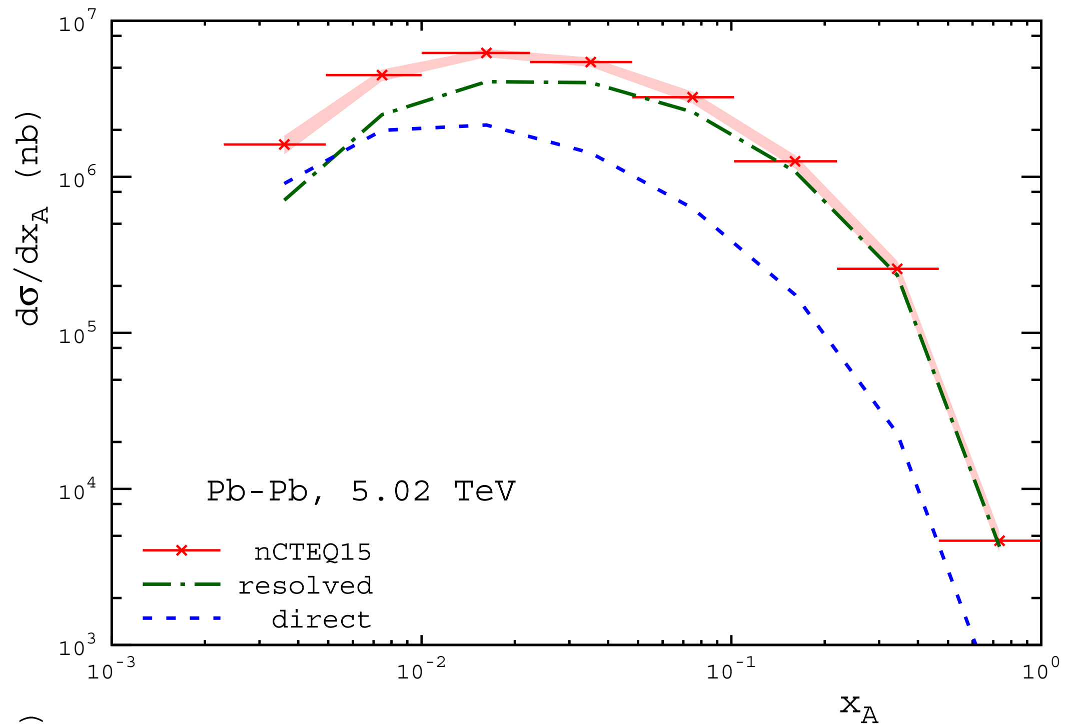




- Shape and normalization of the ATLAS data are reproduced well. Note that the data is preliminary and has not been corrected for detector response.

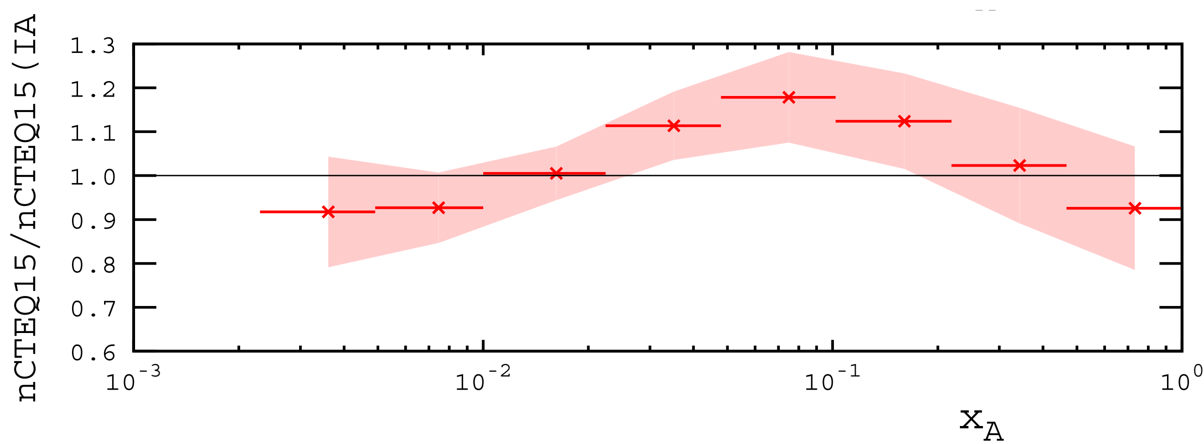
Inclusive dijet photoproduction in Pb-Pb UPCs@LHC (3)

- Resolved vs. direct photon contributions: resolved photons dominate for $x_A > 0.01$; resolved and direct are compatible for $x_A < 0.01$ → similar trend in leading order (LO) analysis in PYTHIA8 framework, Helenius, Rasmusen, EPJ C 79 (2019) 5, 413



- Nuclear modifications: shape of $R = \dfrac{d\sigma(AA \to A + 2\mathrm{jets} + X)}{d\sigma^{\mathrm{IA}}(AA \to A + 2\mathrm{jets} + X)}$ repeats that of $R_g(x) = g_A/Ag_N$: 10% shadowing for $x_A < 0.01$, 20% antishadowing at $x_A \sim 0.1$, 5-10% EMC effect for large x_A → can be compared to predictions for EIC, Klasen, Kovarik, PRD 97 (2018) 114013

$$f^{\mathrm{IA}}_{b/A} = Z f_{b/p} + (A - Z) f_{b/n}$$



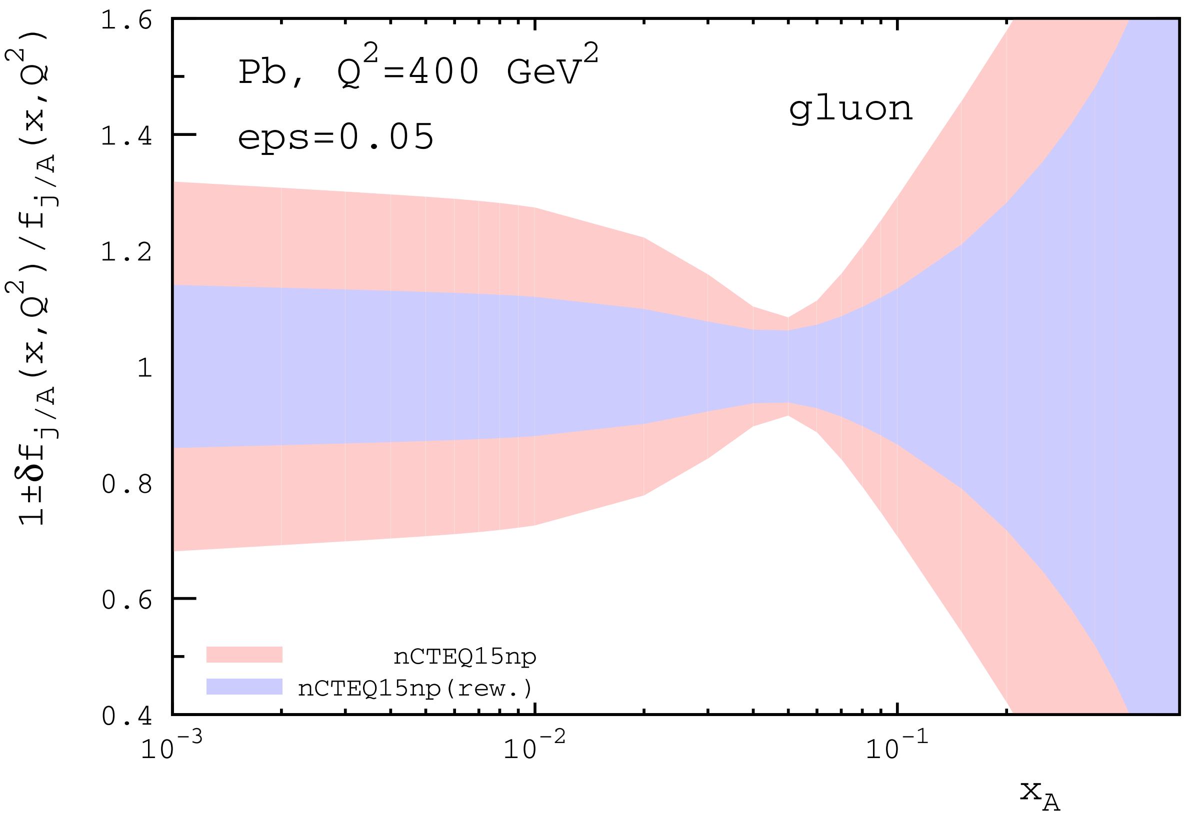
Reweighting of dijet UPC pseudo-data

- We used our NLO pQCD results in ATLAS kinematics as pseudo-data:

$$\chi_k^2 = \sum_{j=1}^{N_{\rm data}} \frac{(d\sigma^0/dx_A - d\sigma^k/dx_A)^2}{\sigma_j^2}$$

error on pseudo-data

- Effect of the pseudo-data on the nuclear gluon distribution and its uncertainty:

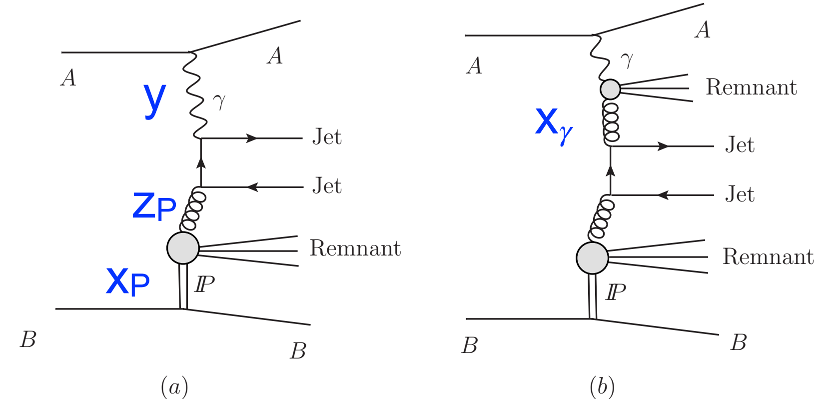


Guzey, Klasen, EPJ C 79 (2019) 5, 396

- Assuming 5% error → reduction of uncertainties by factor 2 at x_A=0.001.

Diffractive dijet photoproduction in Pb-Pb UPCs@LHC

- In framework of collinear factorization & NLO pQCD, it probes novel nuclear diffractive PDFs.
- Contribution of right-moving photon source:



$$d\sigma(AA \to A + 2\text{jets} + X + A)^{(+)} =$$

$$\sum_{a,b} \int dt \int dx_P \int dz_P \int dy \int dx_\gamma f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma, \mu^2) f_{b/A}^{D(4)}(x_P, z_P, t, \mu^2) d\hat{\sigma}_{ab\to\text{jets}}$$

- Nuclear diffractive PDF $f_{b/A}^{D(4)}$= conditional probability to find parton b with mom. fraction z_P with respect to the diffractive exchange (pomeron) carrying mom. fraction x_P provided the nucleus remained intact with mom. transfer t.

- $f_{b/A}^{D(4)}$ is subject to nuclear modifications. The leading twist nuclear shadowing model predicts strong nuclear suppression (shadowing), Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

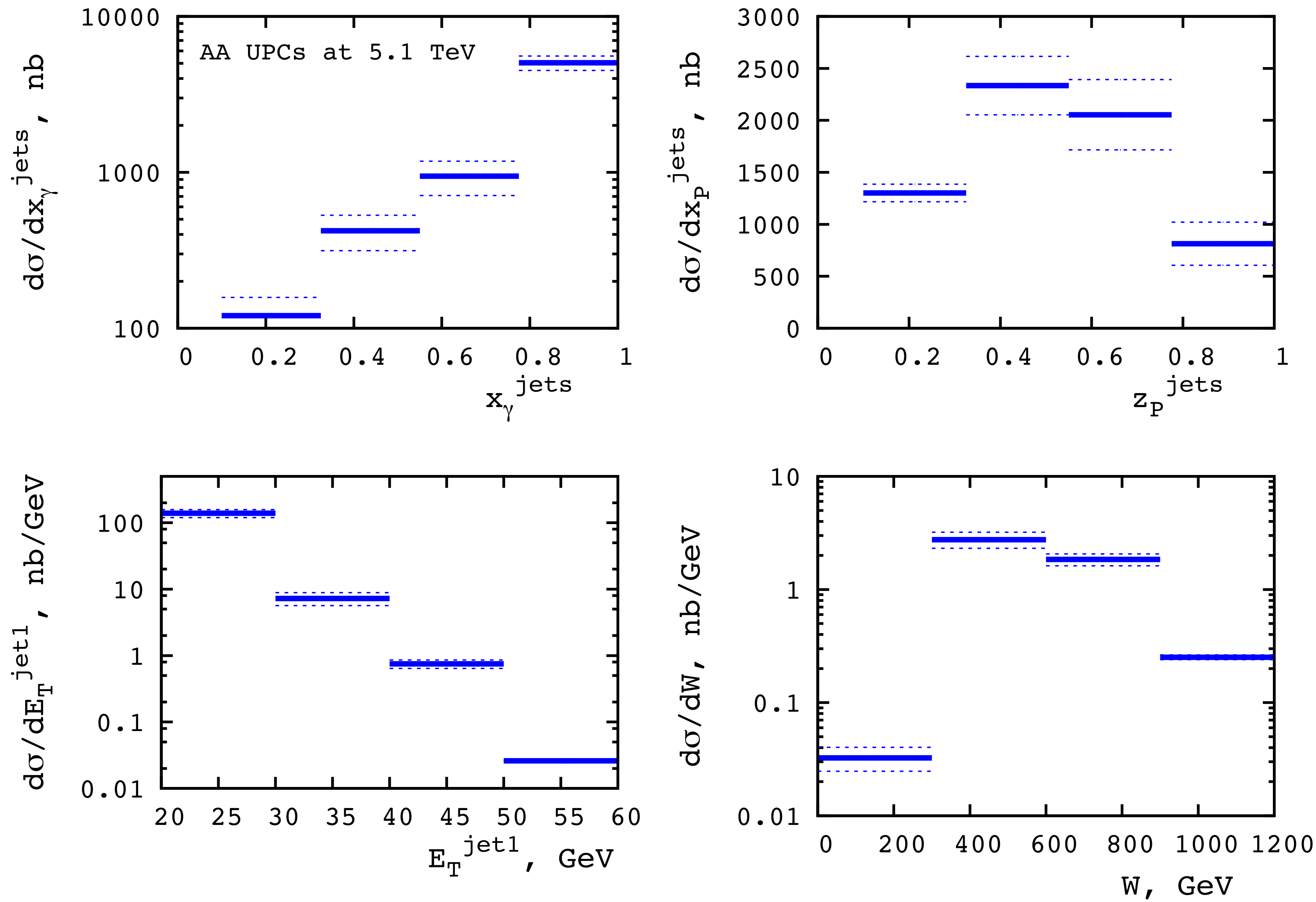
$$f_{b/A}^{D(4)}(x_P, z_P, t, \mu^2) = R_b(x_P, z_P, \mu^2) A^2 F_A^2(t) f_{b/p}^{D(4)}(x_P, z_P, t=0, \mu^2)$$

$$\approx 0.15 A^2 F_A^2(t) f_{b/p}^{D(4)}(x_P, z_P, t=0, \mu^2)$$

Diffractive dijet photoproduction in Pb-Pb UPCs@LHC (2)

- NLO pQCD predictions as a function of momentum fractions x_γ and z_P, leading jet transverse momentum E_T^{jet1}, and photon-nucleus energy W.

Guzey, Klasen, JHEP 04 (2016) 158

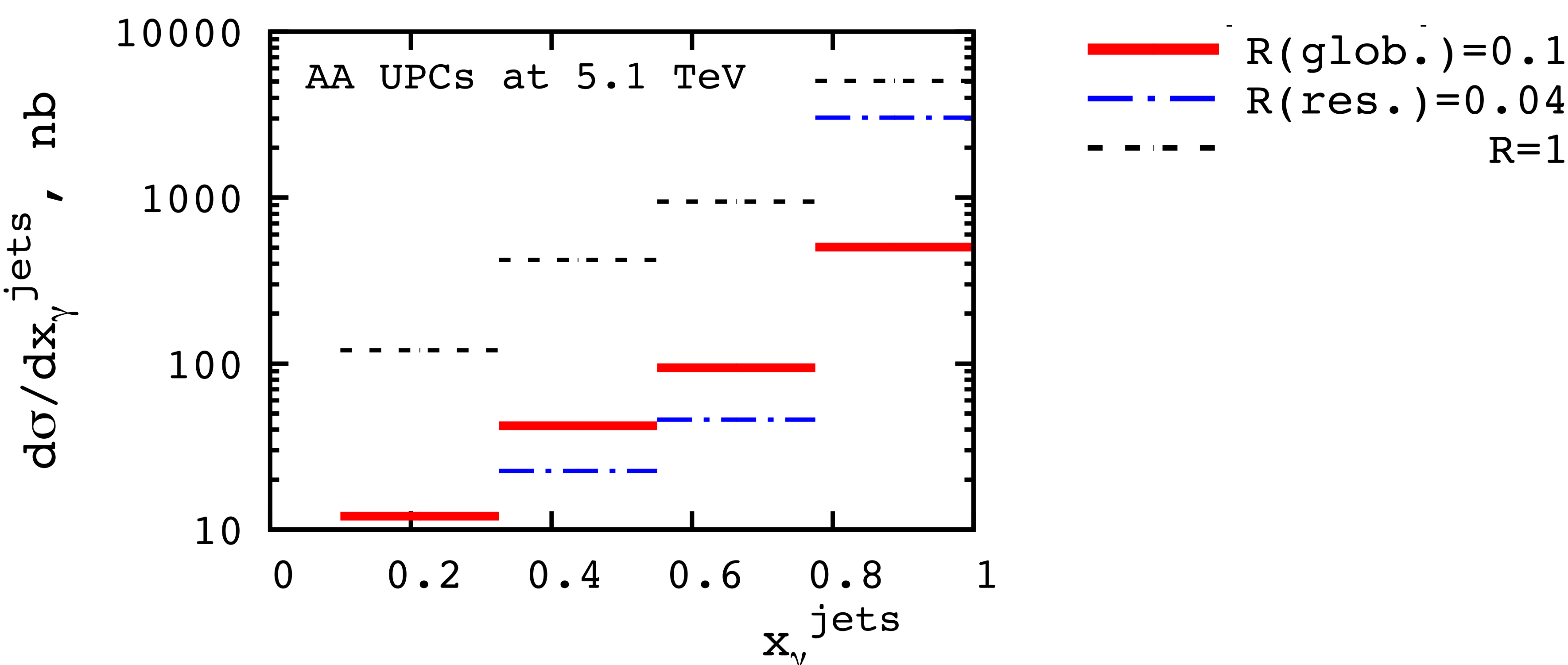


Diffractive dijet photoproduction in Pb-Pb UPCs@LHC (3)

- Analyses of diffractive dijet photoproduction in ep scattering@HERA → QCD factorization is broken, i.e., NLO calculations overestimate data by factor of ~2, Klasen, Kramer, EPJ C 38 (2004) 93; PRL 93 (2004) 232002; JPhys.G 31 (2005) 1391; MPLA 23 (2008) 1885; EPJ C 70 (2010) 91; PLB 508 (2001) 259; EPJ C 49 (2007) 957; PRD 80 (2009) 074006; Guzey, Klasen, EPJ C 76 (2016) 8, 467

- The pattern of unknown: either the global suppression factor R(glob.)=0.5 or the resolved-only suppression R(res.)=0.34, Kaidalov, Khoze, Martin, Ryskin, EPJ C 66 (2010) 373

- One can differentiate between these two scenarios by studying x_γ distribution in AA UPCs, Guzey, Klasen, JHEP 04 (2016) 158



Summary

• The gluon nuclear shadowing at small x is poorly constrained by available fixed-target nuclear DIS, dA RHIC, and pA LHC data.

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

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

• Coherent photoproduction of J/ψ in Pb-Pb UPCs at LHC gives direct evidence of large gluon nuclear shadowing $R_g(x=6\times10^{-4}-10^{-3}, \mu^2 \approx 3\ \mathrm{GeV}^2) \approx 0.6$ and can help to significantly reduce uncertainties in wide region of x.

• Heavy quarkonium photoproduction in UPCs gives access to transverse imaging of gluon distribution at small x.

• Inclusive dijet photoproduction in Pb-Pb UPCs@LHC probes nPDFs down to $x_A \sim 0.005$ and can reduce the current small-x_A uncertainties of the gluon distribution by factor of ~2.

• Diifractive dijet photoproduction in Pb-Pb UPCs@LHC accesses novel nuclear diffractive PDFs and may shed new light on mechanism of QCD factorization breaking in this process.