Nuclear effects in UPCs and implications for EIC

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Outline:

- Nuclear PDFs and nuclear shadowing
- Coherent J/ψ photoproduction in Pb-Pb UPCs at LHC and gluon nuclear shadowing
- Inclusive dijet photoproduction in Pb-Pb UPCs at LHC and nuclear PDFs
- Summary and Outlook

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Nuclear PDFs and nuclear shadowing

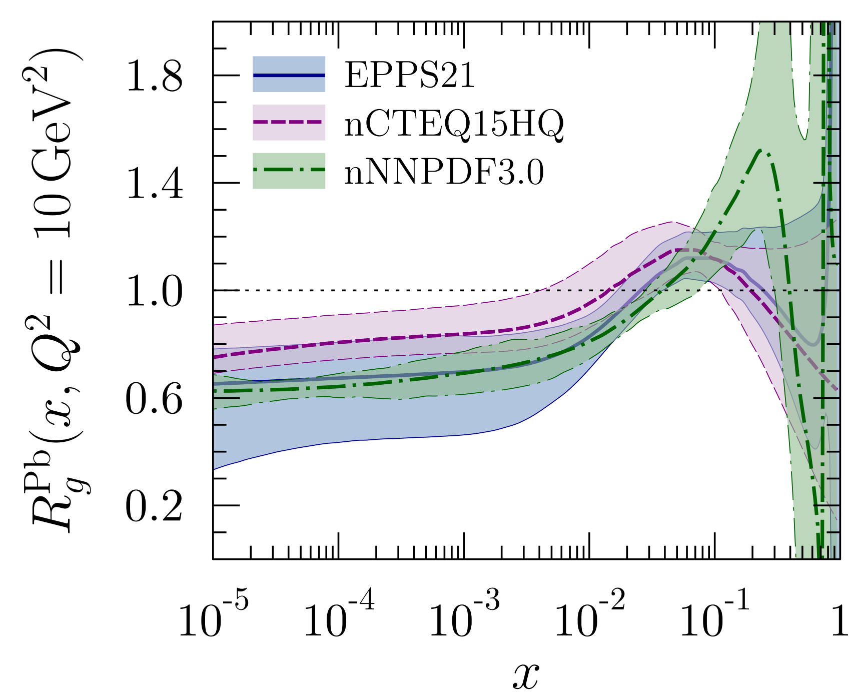
- Hard processes with nuclei → QCD factorization → nuclear parton distribution functions (nPDFs)

- Collinear nPDFs $f_{i/A}(x, Q^2)$ = probabilities of finding parton $i = q, g$ with momentum fraction x at resolution scale Q

- 40+ years of experiments → $f_{i/A}(x, Q^2) \neq Z f_{i/p}(x, Q^2) + (A - Z) f_{i/n}(x, Q^2)$
  - **nuclear shadowing** $(x < 0.05)$
  - anti-shadowing $(x \approx 0.1)$
  - EMC effect $(0.2 < x < 0.7)$
  - Fermi motion $(x > 0.7)$

- Competing explanations of **nuclear shadowing**:
  - Gribov-Glauber model with proton diffractive PDFs (LTA), Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255
  - nuclear enhancement of saturation scale in dipole model, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303
  - nuclear enhancement of higher-twist (HT) corrections, Qiu, Vitev, PRL 93 (2004) 262301

$R_g^{Pb} = g_A(x, Q^2)/[A g_p(x, Q^2)]$



Klasen, Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 49

- Open questions:
  - What are the mechanisms of nuclear shadowing?
  - How can one distinguish them experimentally?
  - What is the relation between shadowing and saturation?

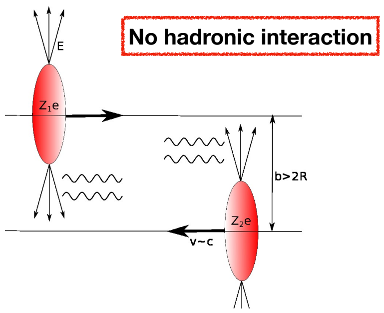
Nuclear PDFs: from UPCs to EIC

- pA scattering at LHC $\rightarrow$ incremental improvement in determination of $f_{i/A}(x, Q^2)$ using production of gauge bosons, jets, D^0, EPPS21: Eskola et al., EPJC 82 (2022) 5, 413; nCTEQ15: Kusina et al., EPC 80 (2020) 10, 968; nNNPDF3.0: Abdul Khalek et al., EPJC 82 (2022) 6, 507

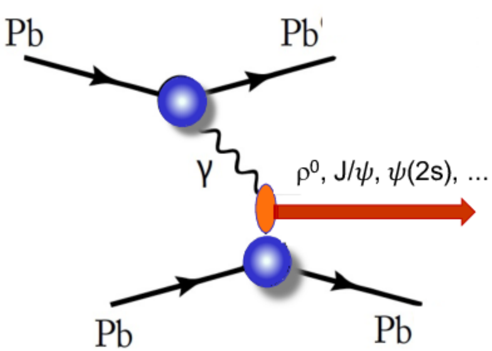
- eA scattering at planned EIC $\rightarrow$ dramatic progress due to
  - wide $x - Q^2$ coverage
  - array of nuclei from D to Au
  - first measurements of longitudinal $F_L^A(x, Q^2)$ and diffractive $F_A^{D(3)}(x, x_P, Q^2)$ structure functions

- γA scattering through ultraperipheral collisions (UPCs) $\rightarrow$ complementary to EIC

  - Large impact parameters $b = \mathcal{O}(50\,\text{fm}) \gg 2R_A$
  - Interaction via quasi-real photons in equivalent photon approximation
  - Photon flux $N_{\gamma/A}(k) \sim Z^2$, photon energy $k \sim \gamma_L$
  - LHC is a high-energy photon collider $\rightarrow$ both $\gamma\gamma$ and γA (γp) scattering



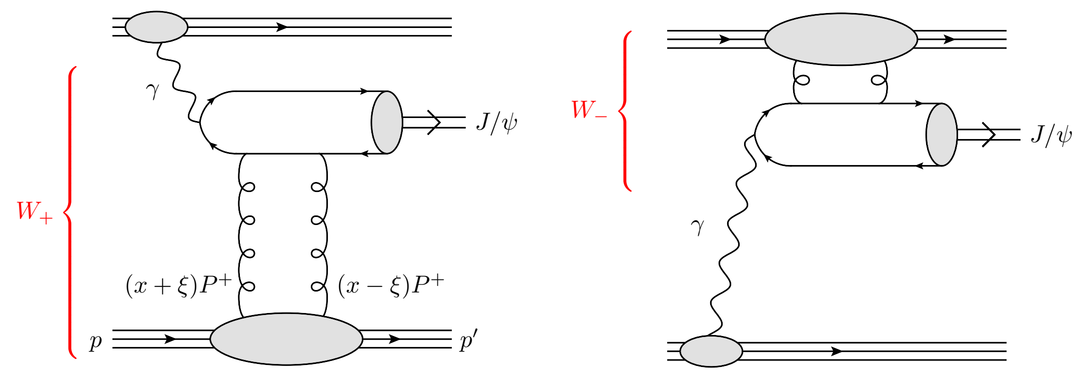
- J/ψ production in Pb-Pb UPCs $\rightarrow$ access to very large photon-nucleon energy up to $W_{\gamma p} \approx 1\,\text{TeV}$ and very small $x_A = M^2_{J/\psi}/W^2_{\gamma p} \approx 10^{-5} - 10^{-2}$



Bertulani, Klein, Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271; Baltz et al, Phys. Rept. 458 (2008) 1; Contreras, Tapia-Takaki, Int. J. Mod. Phys. A 30 (2015) 1542012; Klein and Mäntysaari, Nature Rev. Phys. 1 (2019) no.11, 662

Coherent J/ψ production in Pb-Pb UPCs at LHC

- Most studied UPC process.
- Motivation → nuclear gluon density at small x, Ryskin, Z. Phys. C57 (1993) 89



- Both ions can be a source of photons and a target → sum of high and low photon-nucleon energies $W^{\pm}_{\gamma p}$:

$$\frac{d\sigma^{PbPb \to PbPbJ/\psi}}{dy} = \left[N_{\gamma/A}\, \sigma^{\gamma Pb \to J/\psi Pb}\right]_{k=k^+} + \left[N_{\gamma/A}\, \sigma^{\gamma Pb \to J/\psi Pb}\right]_{k=k^-}$$

Photon flux from QED + $\Gamma_{AA}(\vec{b})$ to suppress strong interactions for $b < 2R_A$.
Point-like (PL) approximation:

$$N^{\rm PL}_{\gamma/A}(k) = \frac{2Z^2\alpha_{\rm em}}{\pi}\left[\zeta K_0 K_1 + \frac{\zeta^2}{2}\left(K_0^2 - K_1^2\right)\right] \quad K_{0,1} = K_{0,1}\left(\zeta = \frac{2R_A k}{\gamma_L}\right)$$

Photoproduction cross section

$$y = \frac{E+p_z}{E-p_z} \to k^{\pm} = \frac{M_{J/\psi}}{2} e^{\pm y}$$

$$W^{\pm}_{\gamma p} = \left[\sqrt{s_{NN}} M_{J/\psi} e^{\pm y}\right]^{1/2}$$

- Ambiguity in relating J/ψ rapidity y to photon momentum k → ambiguity in momentum fraction $x_A = M^2_{J/\psi}/W^2_{\gamma p}$ → difficult to probe small x_A since $N_{\gamma/A}(k^+) \ll N_{\gamma/A}(k^-)$ → circumvented by UPCs accompanied by forward neutrons from e.m. dissociation, Baltz, Klein, Nystrand, PRL 89 (2002) 012301, Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942

Coherent J/ψ production in Pb-Pb UPCs at LHC (2)

- Nuclear photoproduction cross section in leading logarithmic approximation (LLA),
Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290; Guzey, Zhalov, JHEP 1310 (2013) 207

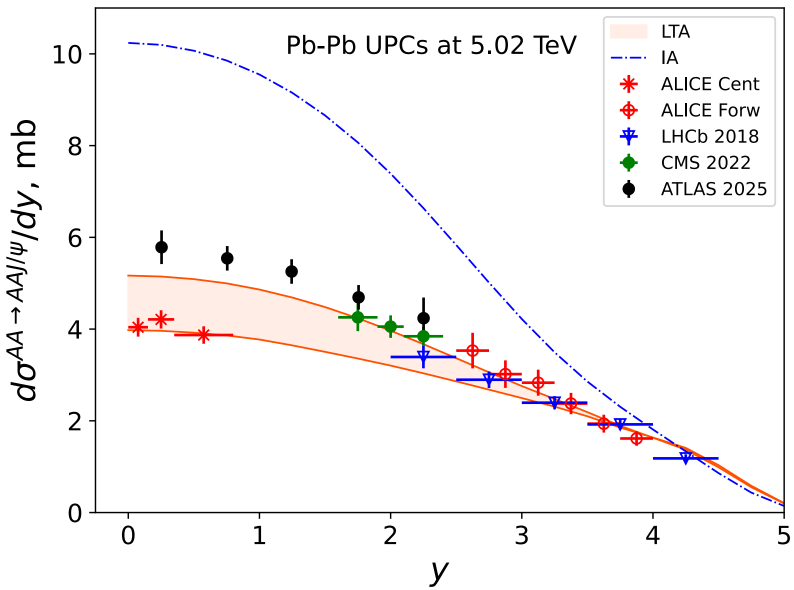
$$\sigma^{\gamma Pb\to J/\psi Pb}(W_{\gamma p}) = \frac{d\sigma^{\gamma p\to J/\psi p}(W_{\gamma p}, t=0)}{dt}\left[\frac{xg_A(x,Q^2_{\text{eff}})}{Axg_p(x,Q^2_{\text{eff}})}\right]^2 \int_{|t_{\min}|}^{\infty} dt\,|F_A(t)|^2$$

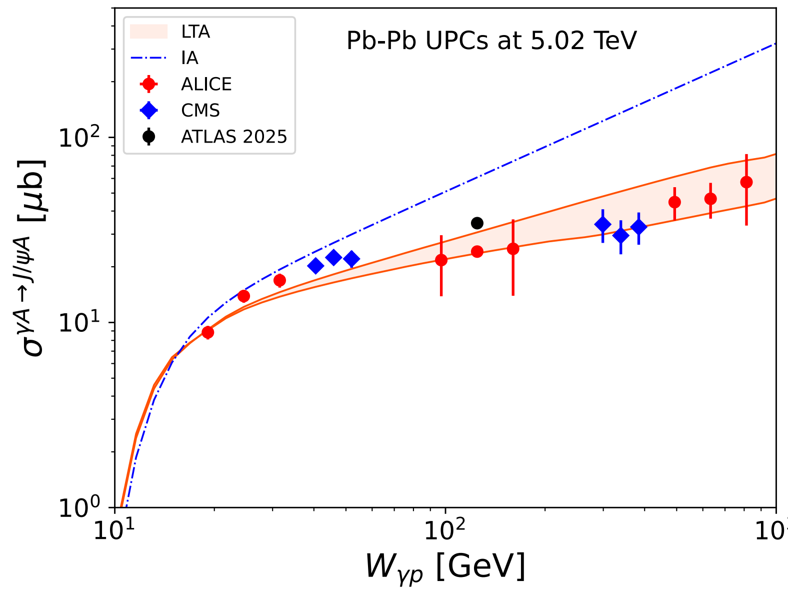
$$x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}}$$

$$Q^2_{\text{eff}} = \mathcal{O}(m_c^2) = 3\,\text{GeV}^2$$

From HERA data — From LTA and nPDFs — Factorized t-dependence using nuclear form factor

- Comparison to LHC data at 5.02 TeV, [ALICE] EPJC 81 (2021) no.8, 712, PLB 798 (2019) 134926, JHEP 10 (2023) 119; [LHCb] JHEP 06 (2023)146; [CMS] PRL 131, no. 26 (2023) 262301; [ATLAS] 2509.04135 [hep-ex]





- Leading twist approximation (LTA)-based predictions made > 10 years ago describe the data for all y and $W_{\gamma p} > 100\,\text{GeV}$ → but note Run 3 ATLAS data.
- Good description using EPPS21, nCTEQ15, nNNPDF3.0 nPDFs with large nPDF uncertainties

Nuclear suppression factor

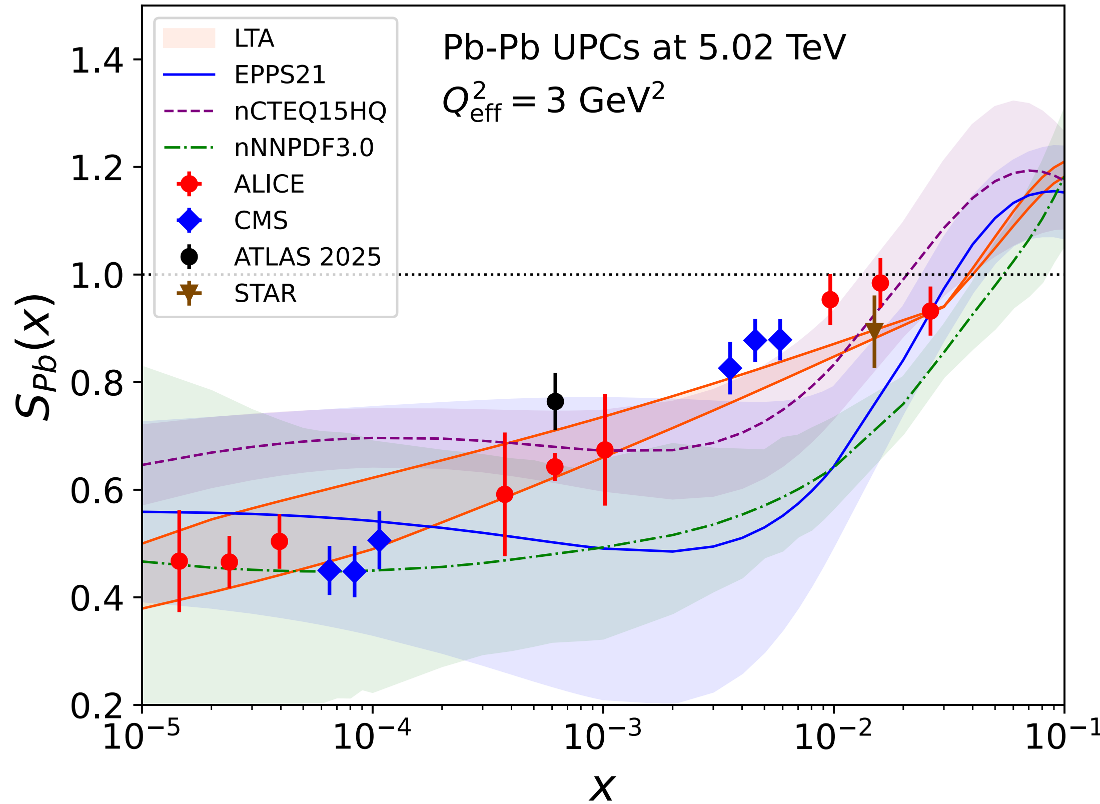
- Convert cross sections into nuclear suppression factor $S_{Pb}(x)$, Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290; Guzey, Zhalov, JHEP 1310 (2013) 207

$$S_{Pb}(x) = \left[\frac{\sigma^{\gamma Pb \to J/\psi Pb}(W_{\gamma p})}{\sigma_{\mathrm{IA}}^{\gamma Pb \to J/\psi Pb}(W_{\gamma p})}\right]^{1/2} = \frac{x g_A(x, Q^2_{\mathrm{eff}})}{A x g_p(x, Q^2_{\mathrm{eff}})}$$

- Impulse approximation (IA):

$$\sigma_{\mathrm{IA}}^{\gamma Pb \to J/\psi Pb}(W_{\gamma p}) = \frac{d\sigma^{\gamma p \to J/\psi p}(W_{\gamma p}, t=0)}{dt} \int_{|t_{\min}|}^{\infty} dt\, |F_A(t)|^2$$

- Avoids 2-fold ambiguity in photon energy
- Data-to-theory comparison with reduced theoretical uncertainties
- Independent on proton baseline



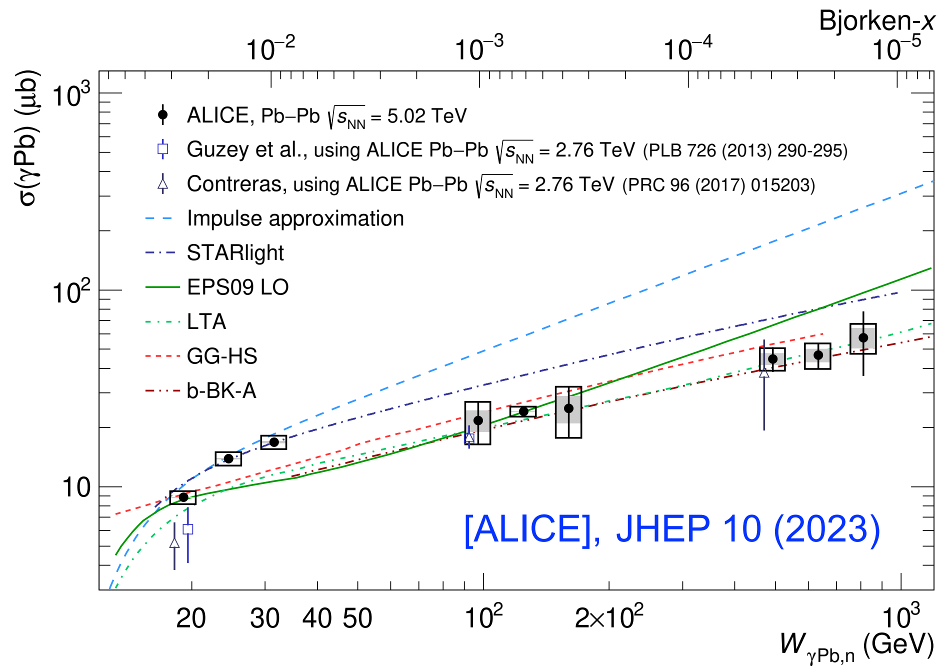
- Direct evidence of large gluon shadowing predicted by LTA: $R_g = g_A/(Ag_p) \approx 0.6$ at $x = 6 \times 10^{-4} - 10^{-3}$, and further decreasing down to $x = 10^{-5}$.

- Reasonable agreement with modern nPDFs within large error bands, which predict flat $S_{Pb}(x)$ for $x < 10^{-3}$.

Nuclear shadowing vs. saturation

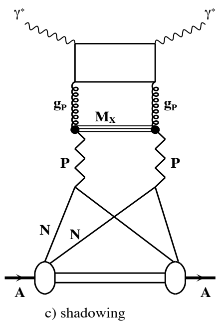
- Competing description based on color dipole model with gluon saturation, **GG-HS**: Cepila, Contreras, Krelina, PRC 97 (2018) 024901; **b-BK-A**: Bendova, Cepila, Contreras, Matas, PLB 817 (2021) 136306; Mãntysaari, Salazar, Schenke, PRD 106 (2022) no.7, 074019, PRD 109 (2024) no.7, L071504

- Status: no approach describes the data for all y, $W_{\gamma p}$, and x

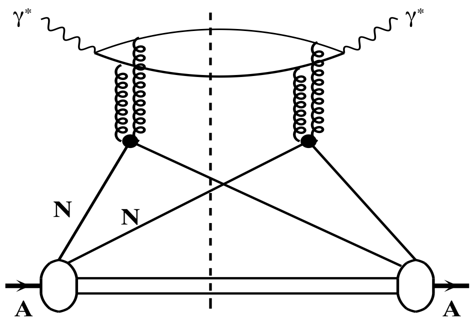


- Principal difference between LTA and dipole model: diffractive vs. elastic intermediate states in calculation of nuclear shadowing, Frankfurt, Guzey, McDermott, Strikman, JHEP02 (2002) 027

Shadowing in LTA: coupling to $N \geq 2$ nucleons through diffraction → inclusion of $q\bar{q}$, $q\bar{q}g$ states



Shadowing in dipole model: successive eikonal scattering of $q\bar{q}$ dipole



- Can be distinguished by observables dominated by small-size dipoles → Q^2 dependence of longitudinal structure function $F_L^A(x, Q^2)$ in eA DIS at EIC.

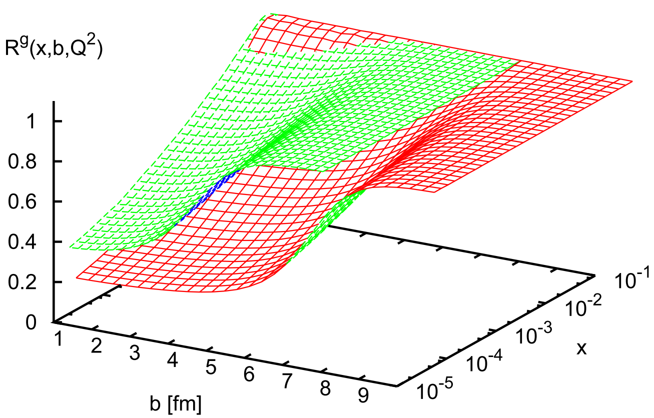
Spacial imaging of nuclear shadowing

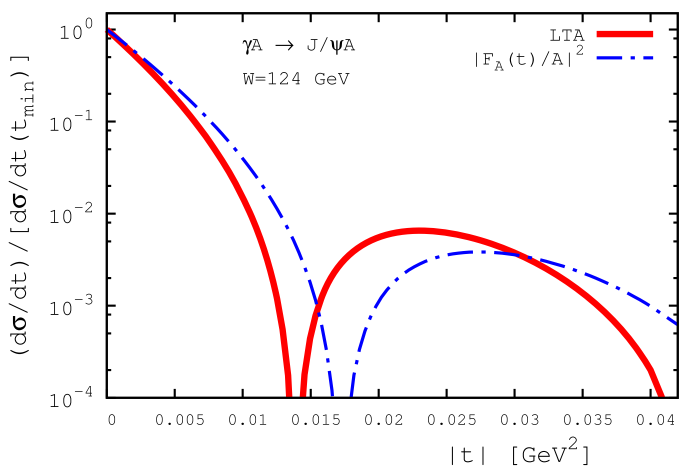
- LTA predicts transverse-position b dependence of nPDFs = nuclear GPDs at $\xi = 0$

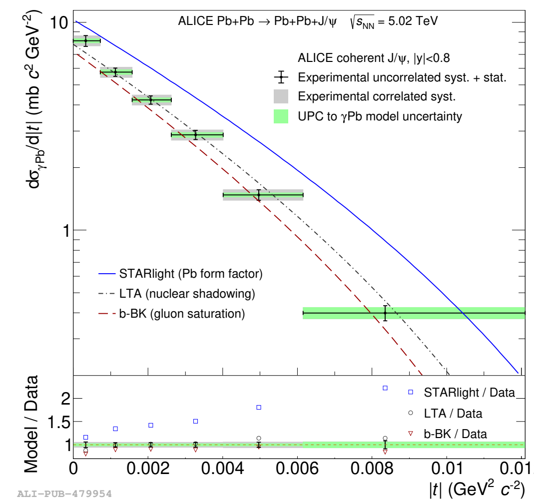
$$xf_{j/A}(x,Q_0^2,b) = A\,T_A(b)xf_{j/N}(x,Q_0^2) - 8\pi A(A-1)B_{\text{diff}}\,\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{\mathbb{P}}\beta f_j^{D(3)}(\beta,Q_0^2,x_{\mathbb{P}})$$
$$\times\int_{-\infty}^{\infty}dz_1\int_{z_1}^{\infty}dz_2\,\rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)\,e^{i(z_1-z_2)x_{\mathbb{P}}m_N}\,e^{-\frac{A}{2}(1-i\eta)\sigma_{\text{soft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

  - Note that b-dependent nPDFs can also be extracted from data using global QCD fits, EPS09s, Helenius, Eskola, Honkanen, Salgado, JHEP 07 (2012) 073.

- Shadowing stronger at nucleus center → broadening of nPDFs in b-space by $5-11\,\%$ → no t-factorization and shift of the diffractive dip of $d\sigma^{\gamma A\to J/\psi A}/dt$, Guzey, Strikman, Zhalov, PRC 95 (2017) 2, 025204 → confirmed by ALICE, Acharya et al., PLB 817 (2021) 1, 136280







- Similar effect by in color dipole model with saturation, Bendova, Cepila, Contreras, Matas, PLB 817 (2021) 136306; Mântysaari, Salazar, Schenke, PRD 106 (2022) 7, 074019

- At EIC: Shift of the diffractive dip of t-differential nuclear DVCS cross section with respect to BH and sharp dips in DVCS beam-spin asymmetry, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Exclusive J/ψ photoproduction in NLO pQCD

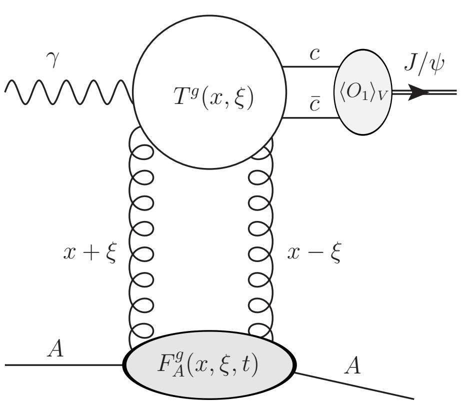
- Beyond LLA, $\gamma A \to J/\psi A$ amplitude in terms of generalized parton distribution functions (GPDs), Ji, PRD 55 (1997) 7114; Radyushkin PRD 56 (1997) 5524; Diehl, Phys. Rept. 388 (2003) 41

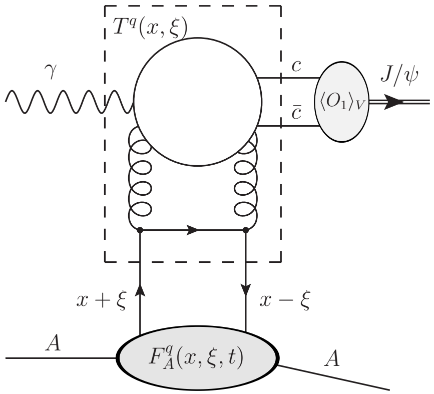
- Next-to-leading order (NLO) of perturbative QCD, Ivanov, Schafer, Szymanowski, Krasnikov, EPJ C 34 (2004) 297, 75 (2015) 75 (Erratum); Jones, Martin, Ryskin, Teubner, J. Phys. G: Nucl. Part. Phys. 43 (2016) 035002

$$\mathcal{M}^{\gamma A \to J/\psi A}(t) \propto \sqrt{\langle O_1 \rangle_{J/\psi}} \int_{-1}^{1} dx \left[T_g(x,\xi,m_c/\mu_f) F_A^g(x,\xi,t,\mu_f) + T_q(x,\xi,m_c/\mu_f) F_A^q(x,\xi,t,\mu_f) \right]$$

NRQCD matrix element from J/ψ leptonic decay — Coefficient function — Gluon GPD — Quark contribution

- Both gluons and gluons at NLO:





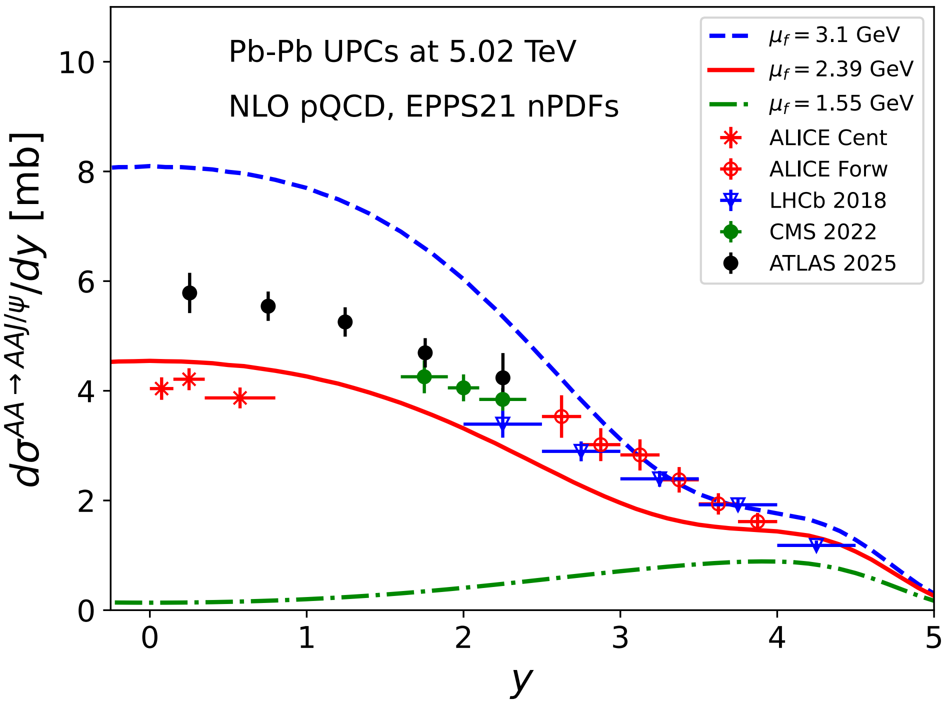
- At high $W_{\gamma p}$ and small skewness $\xi = \dfrac{M_{J/\psi}^2}{2W_{\gamma p}^2} \ll 1$ → forward model for nuclear GPDs at input scale:

$$F_A^g(x,\xi,t,\mu_f) = x g_A(x,\mu_f) F_A(t)$$

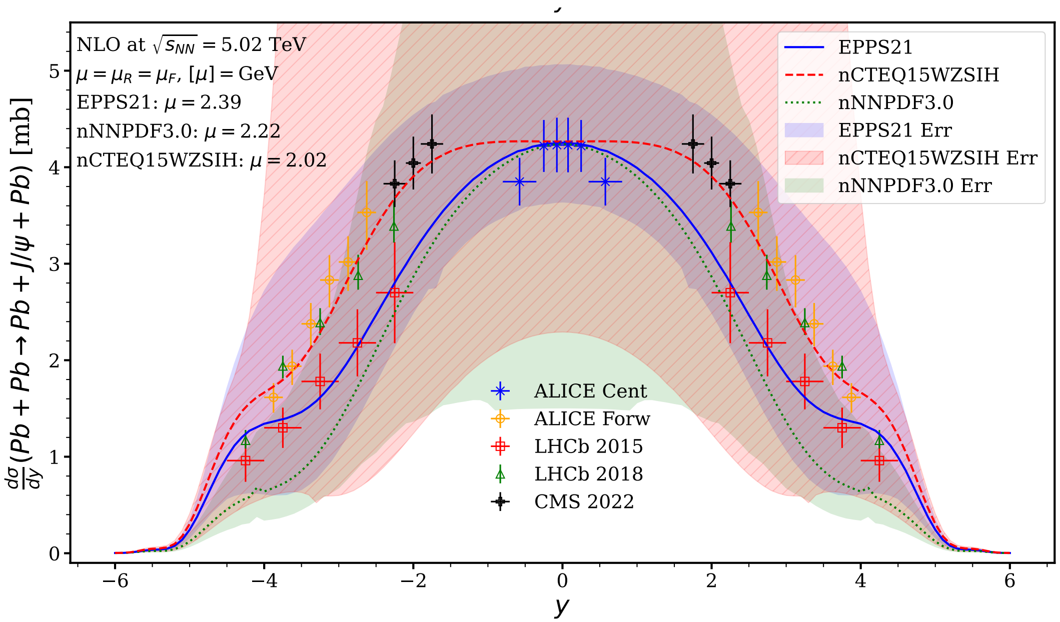
LTA or nPDFs — Factorized t-dependence using nuclear form factor (Woods-Saxon)

- Forward model is accurate for small ξ → all ξ-dependence generated by Q^2 evolution of GPDs, Dutrieux, Winn, Bertone, PRD 107 (2023) 11, 114019

NLO pQCD for J/ψ production in Pb-Pb UPCs@LHC



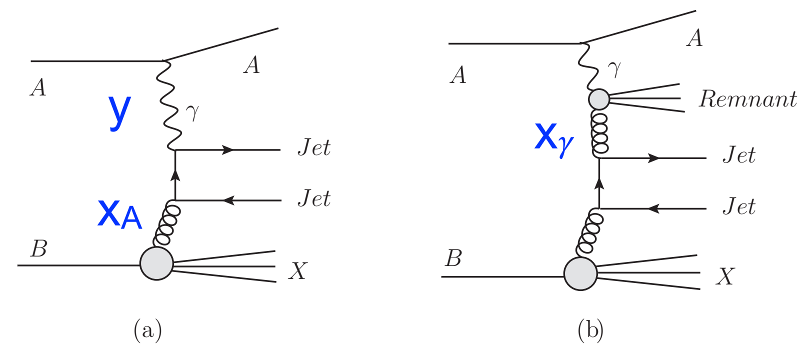
- Very strong factorization scale μ_f dependence due to $\ln(m_c^2/\mu_f^2)\ln(1/\xi)$ terms in NLO coefficient functions.
- "Optimal scale" $\mu_f = 2.39\,\mathrm{GeV}$ (EPPS21) giving fair description of Run 1-2 data, Eskola, Flett, Guzey, Löytäinen, Paukkunen, PRC 106 (2022) 3, 035202, PRC 107 (2023) 4, 044912
- Large uncertainties due to nPDF errors → opportunity to reduce them using UPC data.



- Large $\ln(1/\xi)$ can be resummed using high-energy factorization (HEF) → reduced μ_f, μ_R dependence, Flett, Lansberg, Nabeebaccus, Nefedov, Sznajder, Wagner, PLB 859 (2024) 139117
- Sizable relativistic corrections to J/ψ wave function in dipole model, Frankfurt, Koepf, Strikman, PRD 57 (1998) 512; Lappi, Mäntysaari, Penttala, PRD 102 (2020) no.5, 054020 → work in progress in collinear approach.

Inclusive dijet photoproduction in Pb-Pb UPCs@LHC

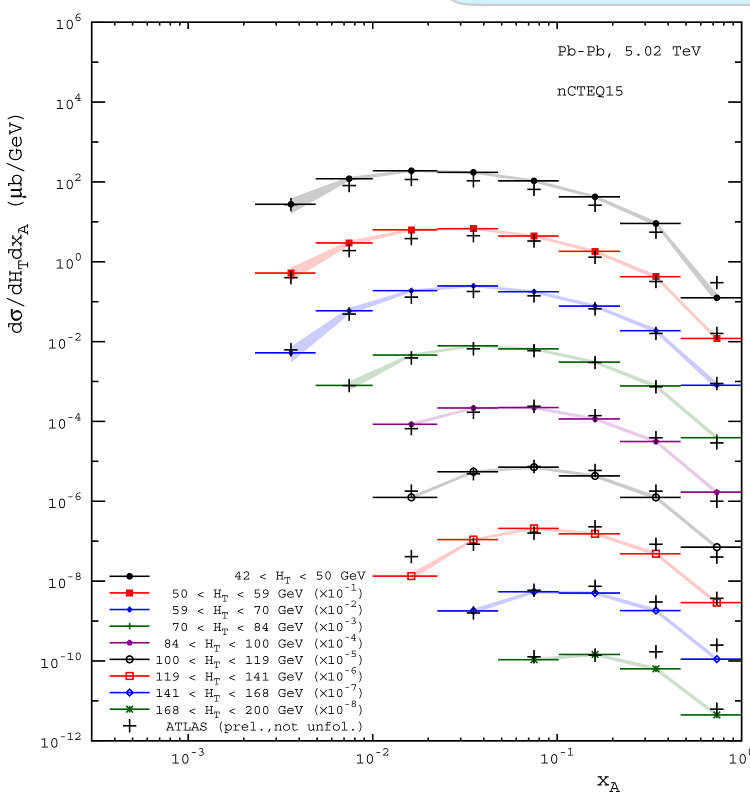
- Jets are complementary probes of nPDFs and QCD dynamics.
- First measurement of inclusive dijet production in Pb-Pb UPCs at 5.02 TeV for $0.002 < x_A < 0.5$ and $35 < Q < 212.5\,\text{GeV}$, [ATLAS], PRD 111 (2025) no.5, 052006
- Collinear factorization of pQCD, Guzey, Klasen, PRC 99 (2019) 065202



direct photon — resolved photon

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

Photon flux — Photon PDFs for resolved photon — nPDFs — Hard parton cross section

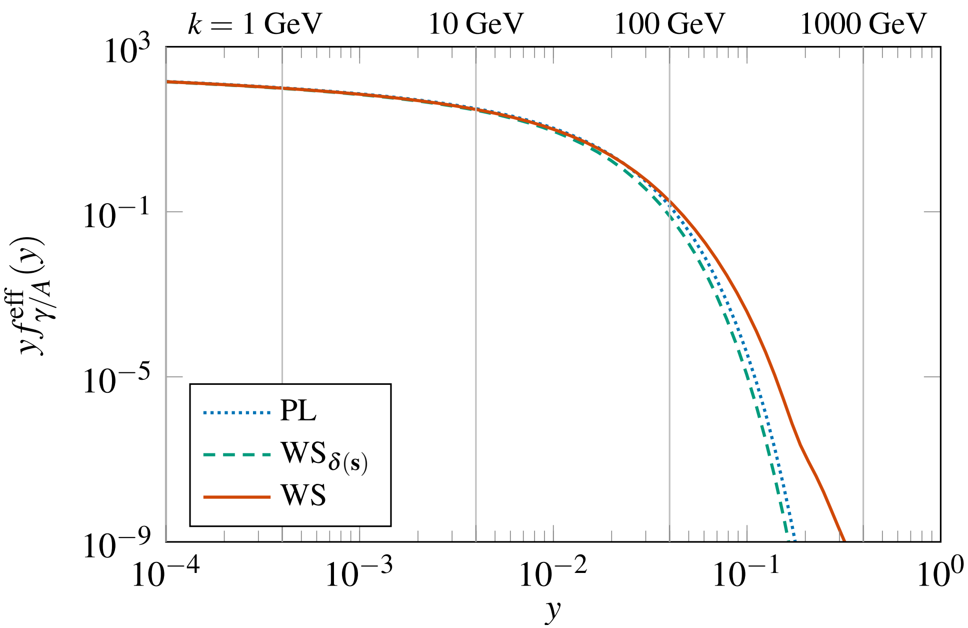


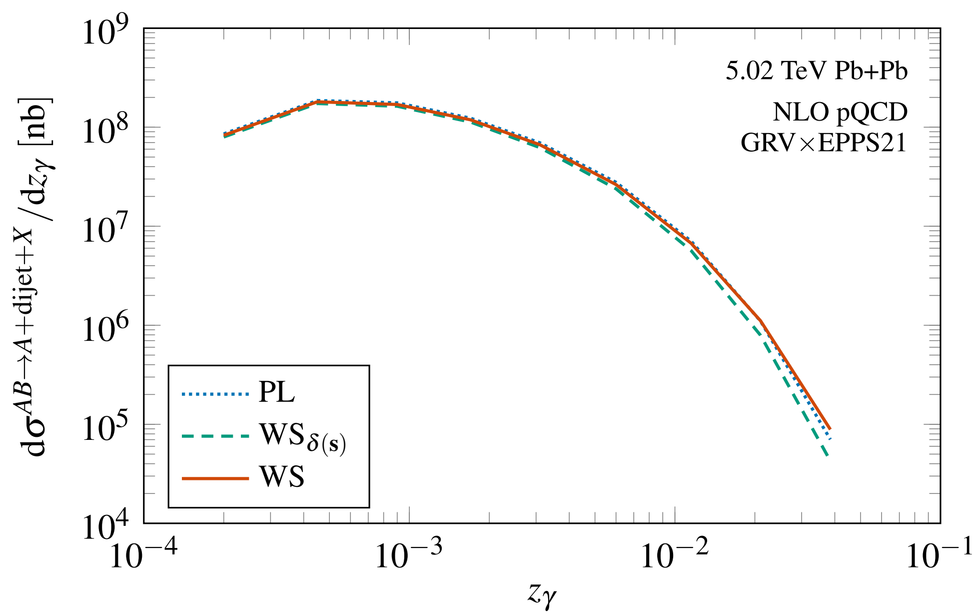
- NLO pQCD describes shape and normalization of preliminary ATLAS data, ATLAS-CONF-2017-011
- 10-20% effect of nPDFs → the data can be used to reduce uncertainty of gluon density by factor 2 at $x_A = 10^{-3}$, Guzey, Klasen, EPJ C 79 (2019) 5, 396
- Data can also be used to look for nonlinear effects in Color Glass Condensate framework, Kotko, Kutak, Sapeta, Stasto, Strikman, EPJ C 77 (2017) 5, 353

Transverse-plane geometry in dijet photoproduction

- ATLAS measurement in 0nXn neutron class → smaller impact parameters $b < \langle b \rangle$
- Sensitivity to the transverse-plane distributions of charge in photon-emitting nucleus ($f_{\gamma/A}(y, \vec{r}\,)$) and of partons in the nuclear target ($T_A(\vec{s}\,)$)
- Additional factor $\Gamma_{AA}^{\text{e.m.}}$ to veto the electromagnetic breakup of the photon-emitting nucleus.
- Effective photon flux, Eskola, Guzey, Helenius, Paakkinen, Paukkunen, PRC 110 (2024) 5, 054906

$$f_{\gamma/A}^{\text{eff}}(y) = \int d^2\vec{r} \int d^2\vec{s}\, f_{\gamma/A}(y, \vec{r}\,) T_A(\vec{s}\,) \Gamma_{AA}(\vec{r} - \vec{s}\,) \Gamma_{AA}^{\text{e.m.}}(\vec{r} - \vec{s}\,)$$





- Transverse-plane geometry effects important for large y and k (left) and large $z_\gamma = y x_\gamma$ (right) → correspond to small impact parameters $b < \langle b \rangle$.
- Sensitivity to b-dependence of nPDFs is small.

Summary and Outlook

- Continuing interest and strong theoretical support of UPCs at LHC and RHIC to obtain new constraints on nPDFs and QCD dynamics at small x → UPC2025 workshop

- Complementary to pA at LHC and eA at EIC: large $W_{\gamma p}$ in UPCs vs. Q^2 and nuclear mass A dependence at EIC.

- The data on coherent J/ψ production in Pb-Pb UPC at LHC challenges both collinear factorization and saturation frameworks.

- Strong nuclear suppression observed in this process → large leading-twist gluon nuclear shadowing at small x in collinear framework.

- Inclusive dijet production in Pb-Pb UPC at LHC probes nPDFs down to $x_A = 10^{-3}$ and can reduce the current uncertainties of the gluon distribution by factor of 2.

- Many ongoing studies of various heavy-ion UPC processes:
  - Coherent production of light vector mesons (ρ, ω, ϕ) → test of soft models of shadowing, Guzey, Kryshen, Zhalov, PRC 93 (2016) 5, 055206
  - Inclusive D^0 production → test of nPDFs, Cacchiari, Innocenti, Stasto, 2506.09893 [hep-ph], saturation, Gimeno-Estivill, Lappi, Mäntysaari, PRD 111 (2025) no.11, 114036, and uPDFs, Goncalves, Santana, Schäfer, 2506.02223 [hep-ph]
  - Incoherent J/ψ production → test of LTA, Guzey, Strikman, Zhalov, PRC 99 (2019) 1, 015201, hot spot model, Mäntysaari, Schenke, PLB 772 (2017) 832; Mäntysaari, Salazar, Schenke, PRD 109 (2024) 47, L071504