Nuclear shadowing and coherent J/ψ production in Pb-Pb UPCs at LHC

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Outline:

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

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Nuclear shadowing and small-x nuclear PDFs

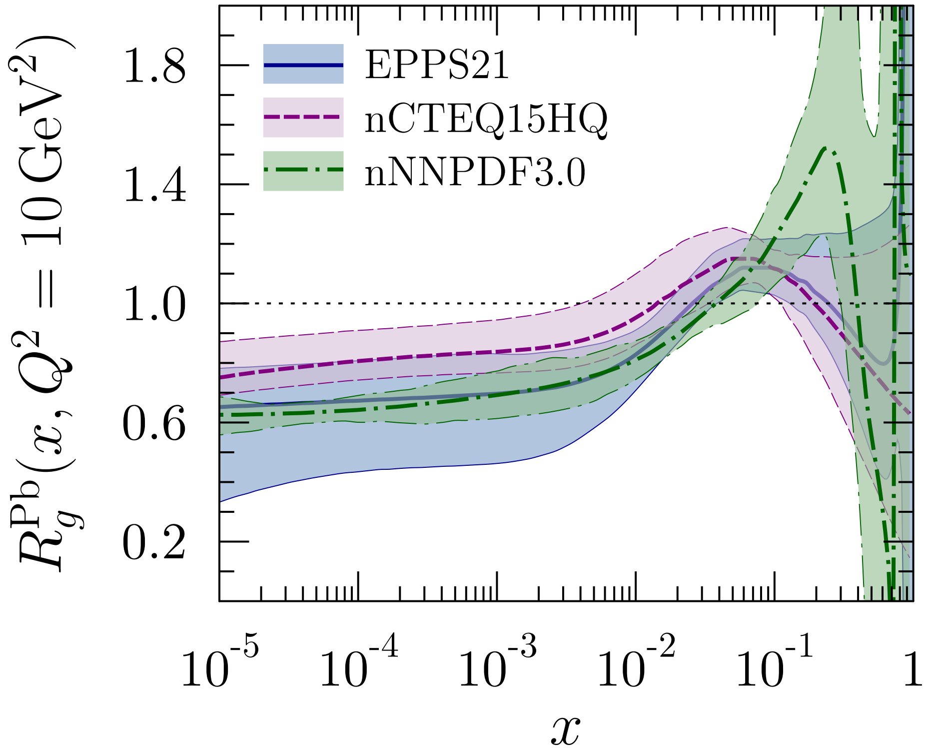
- Nuclear shadowing is general phenomenon of high-energy scattering → $\sigma_A < A\sigma_N$

- Hard processes with nuclei within collinear factorization → suppression of nuclear parton distributions (PDFs) for small $x < 0.05$, $f_{i/A}(x)[A f_{i/p}(x)] < 1$

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

- Global fits of available data → data-driven extraction of nuclear PDFs, 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

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



- Hard pA scattering at LHC and eA deep inelastic scattering (DIS) at EIC → incremental improvement of nuclear PDFs $f_{i/A}(x, Q^2)$ for wide range of x, Q^2 and nuclear targets (from D to Au).

Nuclear shadowing and parton saturation

• Global fits are agnostic to underlying to mechanism of nuclear shadowing.

• Competing explanations of nuclear shadowing, providing good description of data, Paakkinen, Guzey, 2606.08830 [hep-ph]

- Multiple scattering in Gribov-Glauber model combined with HERA proton diffractive PDFs (Leading twist approximation, LTA), Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

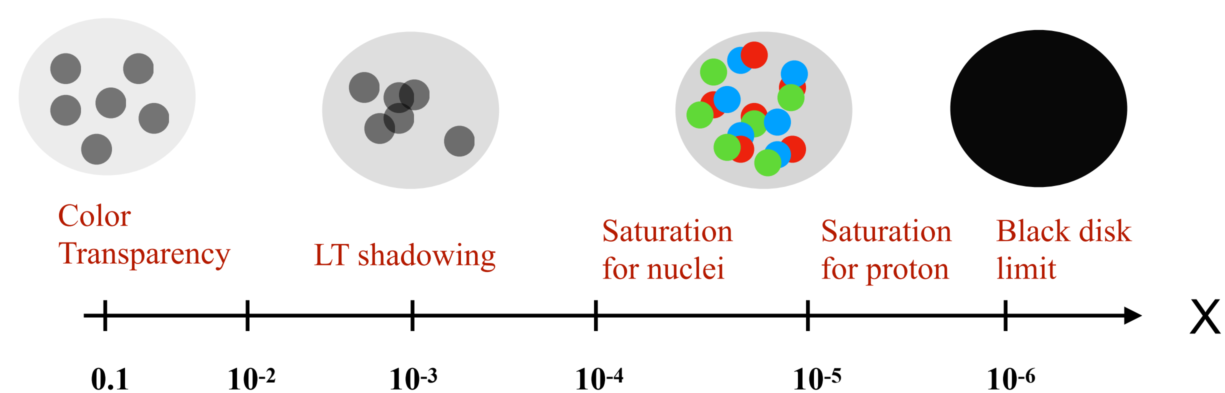
- Nuclear absorption in dipole model (nuclear enhancement of saturation scale $Q^2_{s,A}$), Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303

- Nuclear enhancement of higher-twist (HT) corrections, Qiu, Vitev, PRL 93 (2004) 262301

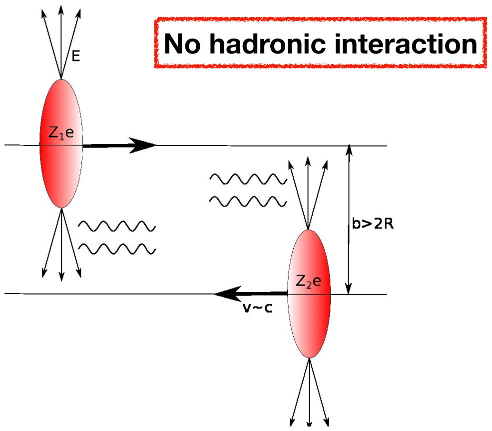
• Open questions:

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

→ Verify and quantify the sketch of regimes of high-energy scattering off nuclei



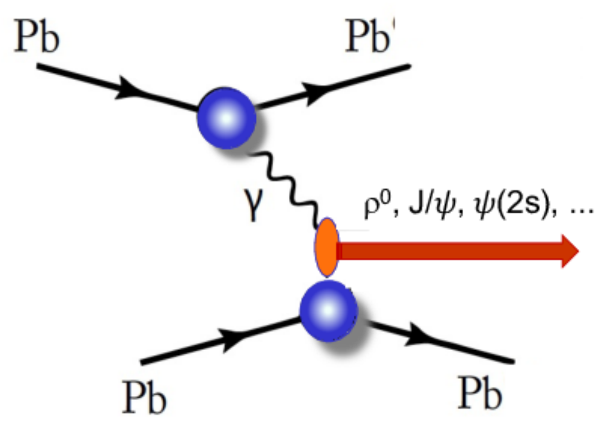
Nuclear shadowing from UPCs



- Utraperipheral collisions (UPCs) at very large impact parameters $b = \mathcal{O}(50\,\mathrm{fm}) \gg 2R_A \rightarrow$ hadronic interactions are suppressed → interactions via quasi-real photons in equivalent photon approximation (EPA).

- Photon flux $N_{\gamma/A}(k) \sim Z^2$, photon energy $k \sim \gamma_L$

- γA scattering in UPCs → complementary to pA scattering at LHC and eA DIS at EIC.

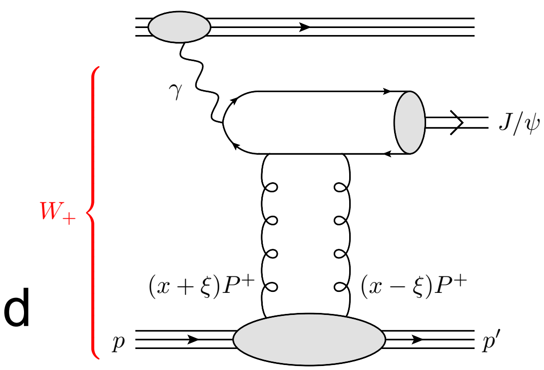


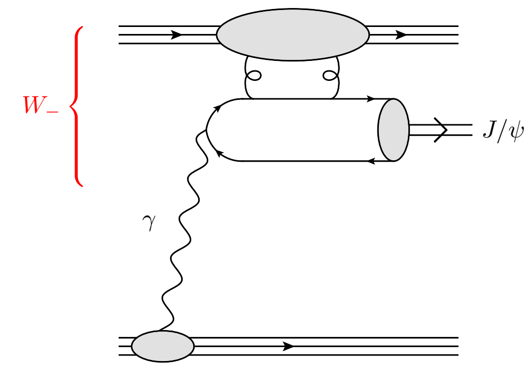
- J/ψ production in Pb-Pb UPCs → access to very large photon-nucleon energy up to $W_{\gamma p} \approx 1\,\mathrm{TeV}$ and very small $x_A = M^2_{J/\psi}/W^2_{\gamma p} \approx 10^{-5} - 10^{-2}$

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 serve a source of photons and a target → sum of terms for high and low photon-nucleon energies $W_{\gamma p}^{\pm}$:

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

Photon flux from EPA, e.g., in point-like (PL) approximation:

Photoproduction cross section

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

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

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

- Ambiguity in relating J/ψ rapidity y to $W_{\gamma p}^{\pm}$ → difficult to probe small $x_A = M_{J/\psi}^2/W_{\gamma p}^2$ since $N_{\gamma/A}(k^+) \ll N_{\gamma/A}(k^-)$ → can be 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, Guzey, Strikman, PRC 110 (2024) 4, 045201

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

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

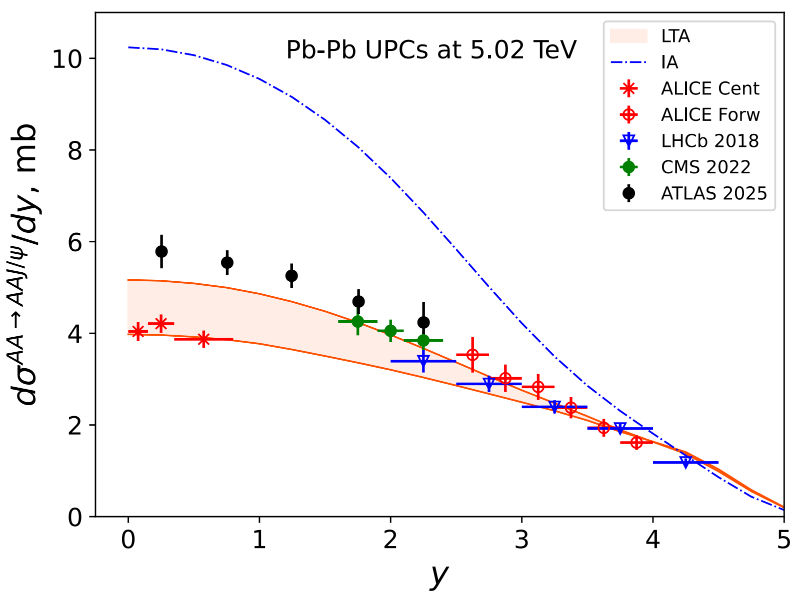
$$Q^2_{\rm eff} = \mathcal{O}(m_c^2) = 3\,{\rm GeV}^2$$

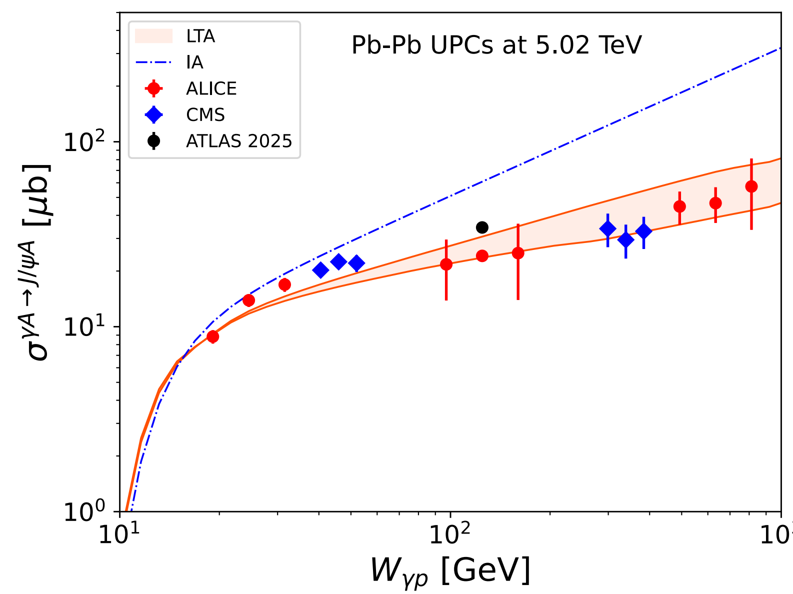
From HERA data

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] JHEP 04 (2026) 020





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

Nuclear suppression factor

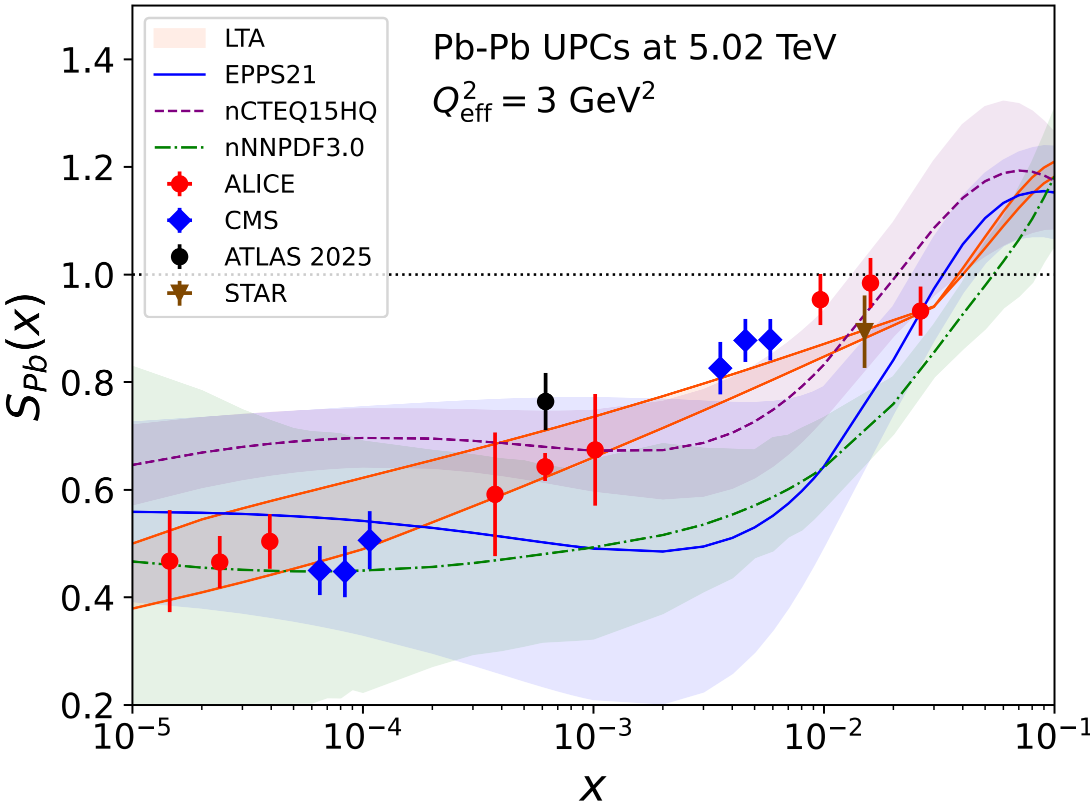
- Convert cross sections into nuclear suppression factor $S_{Pb}(x)$, Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290; Guzey, Zhalov, JHEP 1310 (2013) 207, Guzey, Strikman, PRC 110 (2024) 4, 045201

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

- Impulse approximation (IA):

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

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



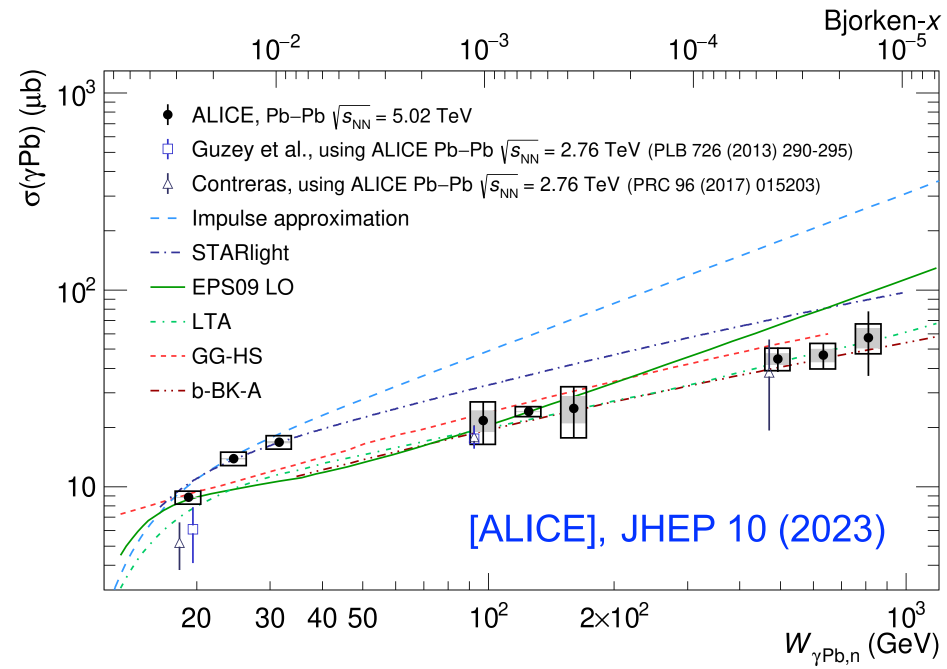
- Direct evidence of large gluon shadowing predicted by LTA: $R_g = g_A/(Ag_p) \approx 0.6$ at $x = 6 \times 10^{-4} - 10^{-3}$, and further decreasing down to $x = 10^{-5}$.

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

Nuclear shadowing vs. saturation in UPCs

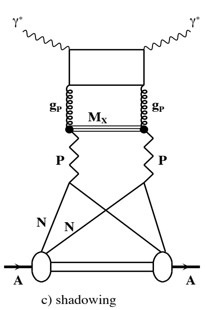
- Competing description based on color dipole model with gluon saturation, **GG-HS**: Cepila, Contreras, Krelina, PRC 97 (2018) 024901; **b-BK-A**: Bendova, Cepila, Contreras, Matas, PLB 817 (2021) 136306; Mãntysaari, Salazar, Schenke, PRD 106 (2022) no.7, 074019, PRD 109 (2024) no.7, L071504

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

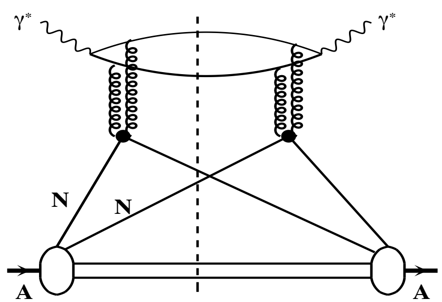


- Principal difference between LTA and dipole model: inelastic vs. elastic* intermediate states in calculation of nuclear shadowing, Frankfurt, Guzey, McDermott, Strikman, JHEP02 (2002) 027

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.

- Note recent works within dipole formalism including both $q\bar{q}$ and $q\bar{q}g$ intermediate states, Kopeliovich, Krelina, Nemchik, Potashnikova, PRD 107 (2023) 5, 054005; Łuszczak and Schäfer, PLB 856 (2024) 138917.

Spacial imaging of nuclear shadowing

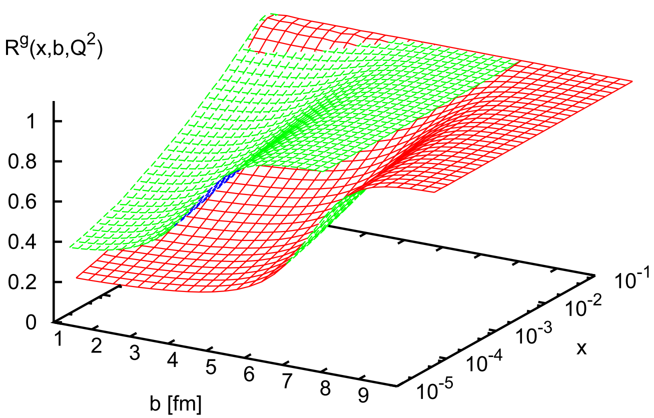
- LTA predicts transverse-position b dependence of nPDFs = nuclear GPDs at $\xi = 0$

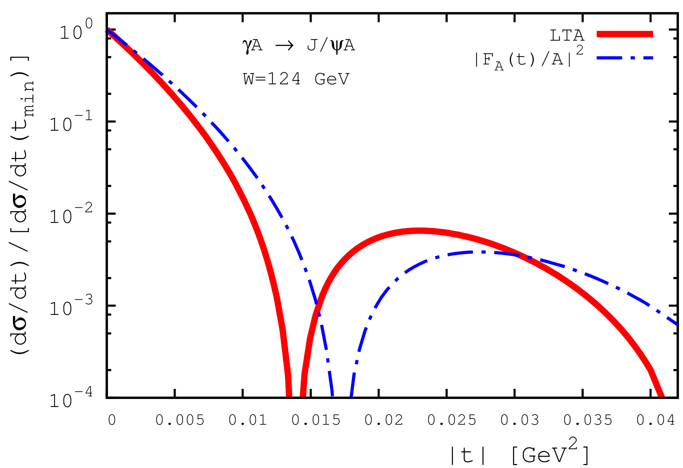
$$xf_{j/A}(x, Q_0^2, b) = A\,T_A(b)xf_{j/N}(x, Q_0^2) - 8\pi A(A-1)B_{\rm diff}\,\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{\mathbb{P}}\beta f_j^{D(3)}(\beta, Q_0^2, x_{\mathbb{P}})$$

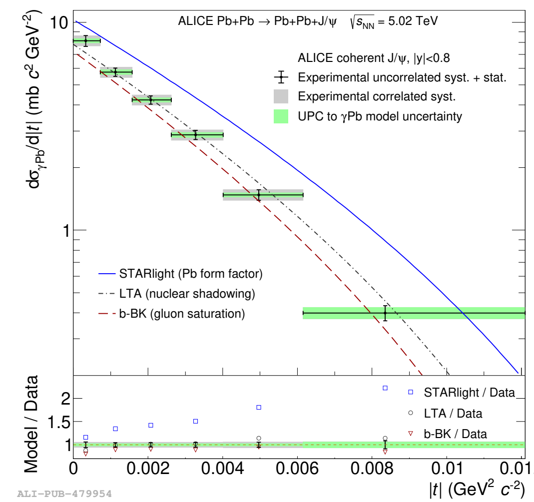
$$\times \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\, \rho_A(\vec{b}, z_1)\rho_A(\vec{b}, z_2)\, e^{i(z_1-z_2)x_{\mathbb{P}}m_N} e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}^j(x,Q_0^2)\int_{z_1}^{z_2} dz'\rho_A(\vec{b},z')}$$

- 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 $5-11\,\%$ → 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 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 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

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

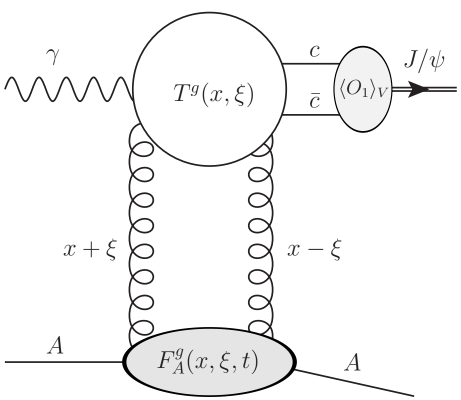
NRQCD matrix element from J/ψ leptonic decay

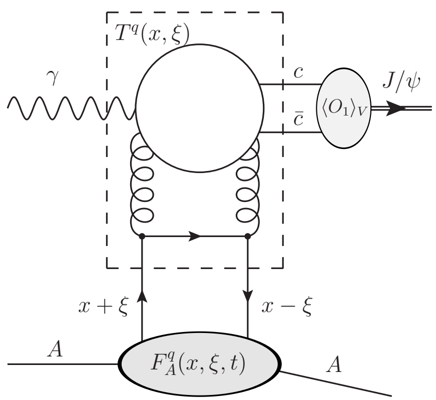
Coefficient function

Gluon GPD

Quark contribution

• Both gluons and quarks at NLO:





• At high $W_{\gamma p}$ and small skewness $\xi = \dfrac{M_{J/\psi}^2}{2W_{\gamma p}^2} \ll 1$

$\to$ forward model for nuclear GPDs at input scale:

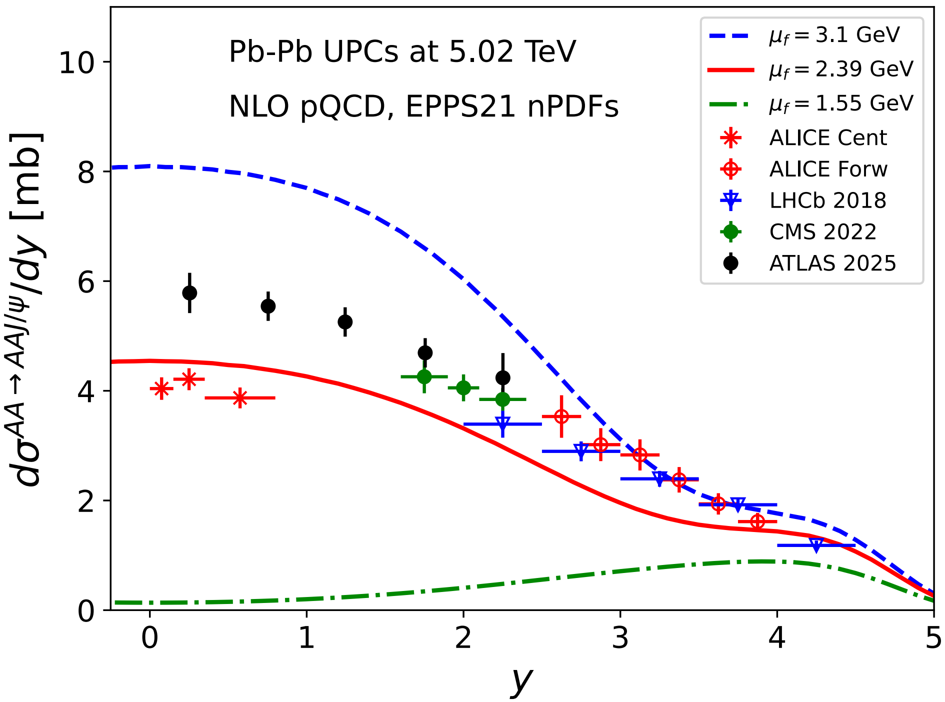
$$F_A^g(x, \xi, t, \mu_f) = x g_A(x, \mu_f) F_A(t)$$

LTA or nPDFs

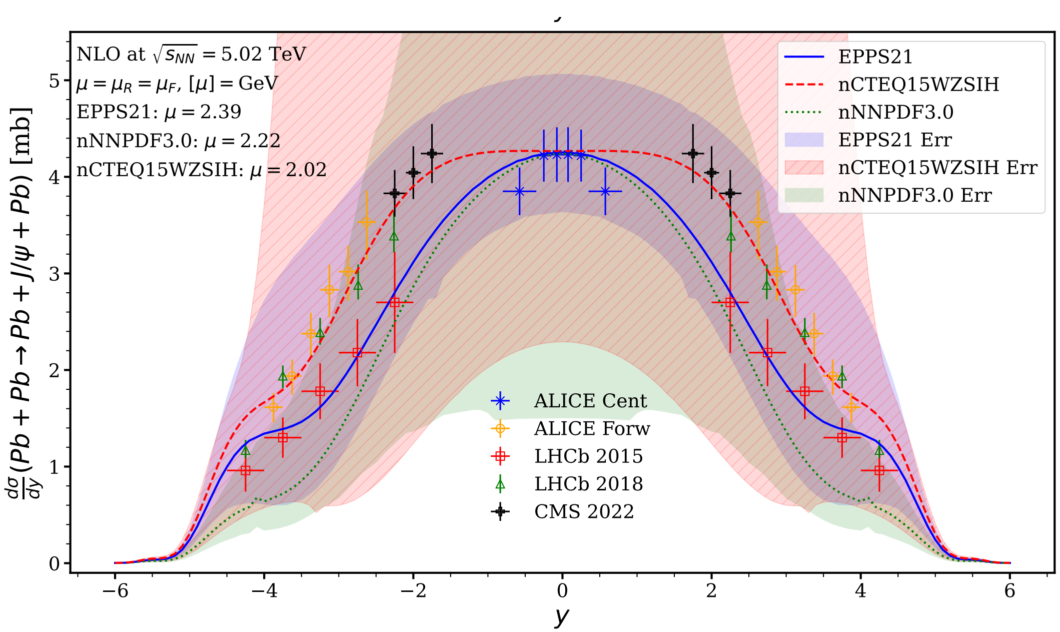
Factorized t-dependence using nuclear form factor (Woods-Saxon)

• Forward model is accurate for small $\xi \to$ 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 effective $\ln(m_c^2/\mu_f^2)\ln(1/\xi)$ terms in NLO amplitude.
- "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**: implementation of these 2 effects along with proper treatment of nuclear GPDs (modeling + scale evolution).

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 → series of UPC workshops

- UPCs are 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.

- Work in progress to implement small-x resummation, relativistic corrections and nuclear GPD evolution.

- Many ongoing studies of various heavy-ion UPC processes:
  - Inclusive dijet production, ATLAS, PRD 111 (2025) 5, 052006 → probe of nPDFs and nuclear geometry, Eskola, Guzey, Helenius, Paakkinen, Paukkunen, PRC 110 (2024) 5, 054906
  - Inclusive D^0 production, CMS, PRL136 (2026) 12, 122303 → test of nPDFs, Cacchiari, Innocenti, Stasto, PRD 112 (2025) 9, 094029, saturation, Gimeno-Estivill, Lappi, Mäntysaari, PRD 111 (2025) no.11, 114036, and uPDFs, Goncalves, Santana, Schäfer, PLB 869 (2025) 139859
  - 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