UPC studies at EIC/LHC

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ERC adG YoctoLHC

Outline:

- UPCs as real-photon probes of nucleus and proton structure in QCD
- Exclusive J/ψ photoproduction in UPCs at the LHC
- Dijet photoproduction in Pb-Pb UPCs at the LHC
- UPCs@LHC as a precursor of EIC
- Summary and Outlook

2nd Workshop on Advancing the Understanding of Non-perturbative QCD Using Energy Flow,
Stony Brook University (Online), 6-9 November, 2023

Ultraperipheral collisions as photon-hadron collider

• Ultraperipheral collisions (UPCs): ions pass each other at large impact parameters $b \sim \mathcal{O}(50\ \text{fm}) >> R_A+R_B$ → strong interactions suppressed → interaction via quasi-real photons in Weizsäcker-Williams equivalent photon approximation, Budnev, Ginzburg, Meledin, Serbo, Phys. Rept. 15 (1975) 181

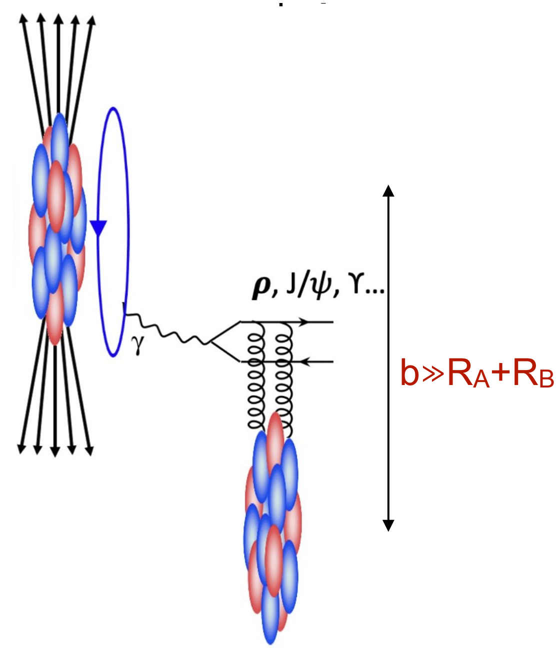


Figure credit: A. Stahl, LPCC CERN Seminar, 6.12.2022

• Photon flux scales as Z^2 and photon energy as γ_L → $\gamma\gamma$, γp and γA interactions at high energies.

• Pioneering studies of UPCs at RHIC, recent impetus at the LHC → $W_{\gamma p}$=5 TeV, $W_{\gamma A}$=700 GeV/A, $W_{\gamma\gamma}$=4.2 TeV.

• In UPCs, real photons are used as probes to study open questions of nucleus and proton structure (e.g., small-x PDFs) and strong interaction dynamics in QCD as well as to search for new physics.

Bertulani, Klein, Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271; Baltz et al, Phys. Rept. 458 (2008) 1; Contreras and Tapia-Takaki, Int. J. Mod. Phys. A 30 (2015) 1542012; Klein and Mäntysaari, Nature Rev. Phys. 1 (2019) no.11, 662; Snowmass LoI, Klein et al, arXiv:2009.03838

Coherent and incoherent scattering in UPCs

• UPCs have very distinct experimental signatures → two leptons from J/ψ decay (two pions from ρ decay) in otherwise empty detector.

• The underlying photon-nucleus scattering can be coherent (target stays intact) and incoherent (target breaks up) → distinguished by measuring p_T of lepton pair (J/ψ) and comparing to STARlight Monte Carlo, Klein, Nystrand, Seger, Gorbunov, Butterworth, Comput. Phys. Commun. 212 (2017) 258

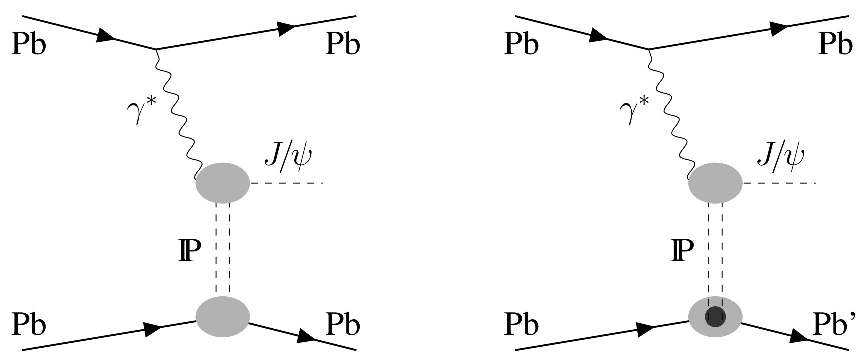
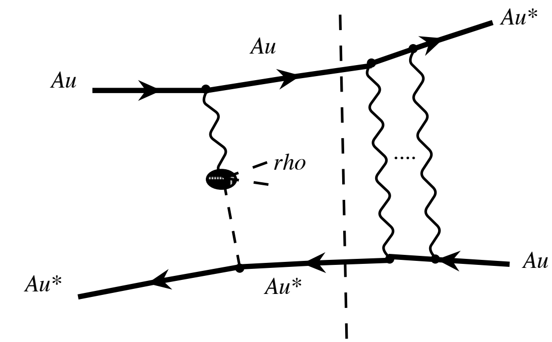


Figure credit: Aaij et al [LHCb], JHEP 07 (2022) 117

• Both coherent and incoherent scattering can be accompanied by mutual e.m. excitation of colliding ions followed by forward neutron emission, Pshenichnov et al, PRC 64 (2001) 024903; Baltz, Klein, Nystrand, PRL 89 (2002) 012301 → UPCs in different channels (0n0n, 0nXn, XnXn) separate $W^{\pm}$ terms → probe lower x, Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942

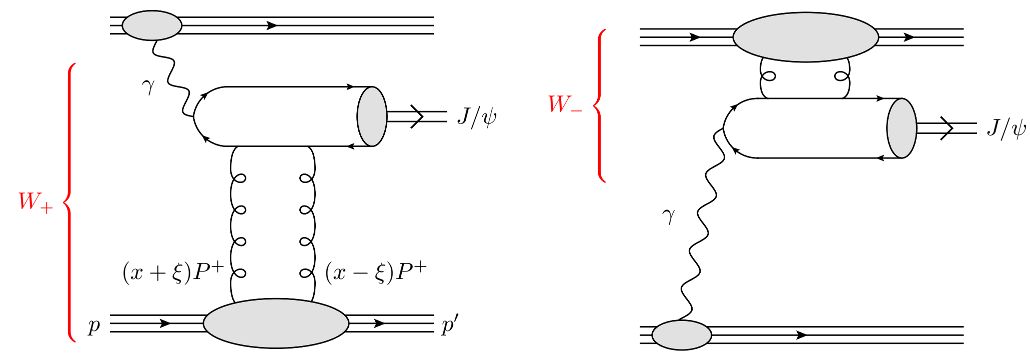


Ions de-excite by emitting neutrons detected in ZDCs

Exclusive J/ψ photoproduction

- Most thoroughly studied process in UPCs.

- In UPCs, both ions can be a source of photons and a target $\rightarrow$ cross section is a sum of two terms for high W^+ (high photon momentum k^+) and low W^- (low photon momentum k^-):



$$\frac{d\sigma^{AB\rightarrow AJ/\psi B}}{dy} = \left[k\frac{dN_{\gamma/B}}{dk}\sigma^{\gamma A\rightarrow J/\psi A}\right]_{k=k^+} + \left[k\frac{dN_{\gamma/A}}{dk}\sigma^{\gamma B\rightarrow J/\psi B}\right]_{k=k^-}$$

Photon flux from QED + Glauber-model suppression of soft strong interactions for $b < 2R_A$ (rapidity gap survival probability)

Photoproduction cross section

$$kdN^{\rm pl}_{\gamma/A}(k) = \frac{2Z^2\alpha_{\rm e.m.}}{\pi}[\zeta K_0(\zeta)K_1(\zeta) + \frac{\zeta^2}{2}(K_0^2(\zeta) - K_1^2(\zeta)]$$

$$\zeta = 2R_A k/\gamma_L$$

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \rightarrow k^{\pm} = \frac{M_{J/\psi}}{2}e^{\pm y}$$

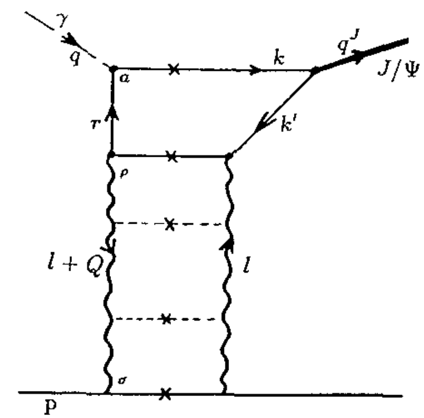
$$W^{\pm} = \sqrt{(k^{\pm}+E_A)^2}$$

- Ambiguity in relating J/ψ rapidity y to photon momentum k $\rightarrow$ ambiguity in momentum fraction $x_A=(M_{J/\psi})^2/W^2$ $\rightarrow$ difficult to probe small x_A since $N_\gamma(k^+) \ll N_\gamma(k^-)$

Exclusive J/ψ photoproduction at LO

- Hard scale by charm quark mass m_c → in leading $\ln(Q^2)\ln(1/x)$ double logarithmic approximation of perturbative pQCD and static approximation for J/ψ vertex, Ryskin, Z. Phys. C57 (1993) 89

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



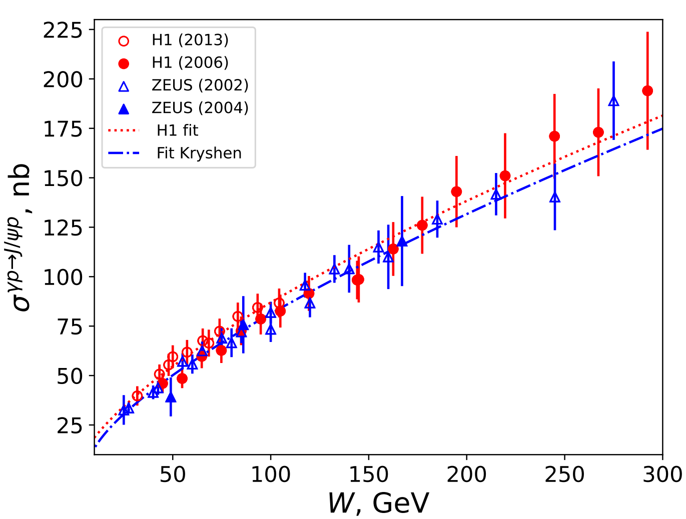
Γ_V is J/ψ leptonic decay width

Gluon density at $x=(M_{J/\psi})^2/W^2$ and $Q_{\rm eff}^2=O(m_c^2)$

Depends on charmonium distribution amplitude; $C(Q^2=0)=1$ in NR limit.

- Application to nuclear targets:

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



From fits to HERA data

Ratio of nucleus and proton gluon densities

Nuclear form factor

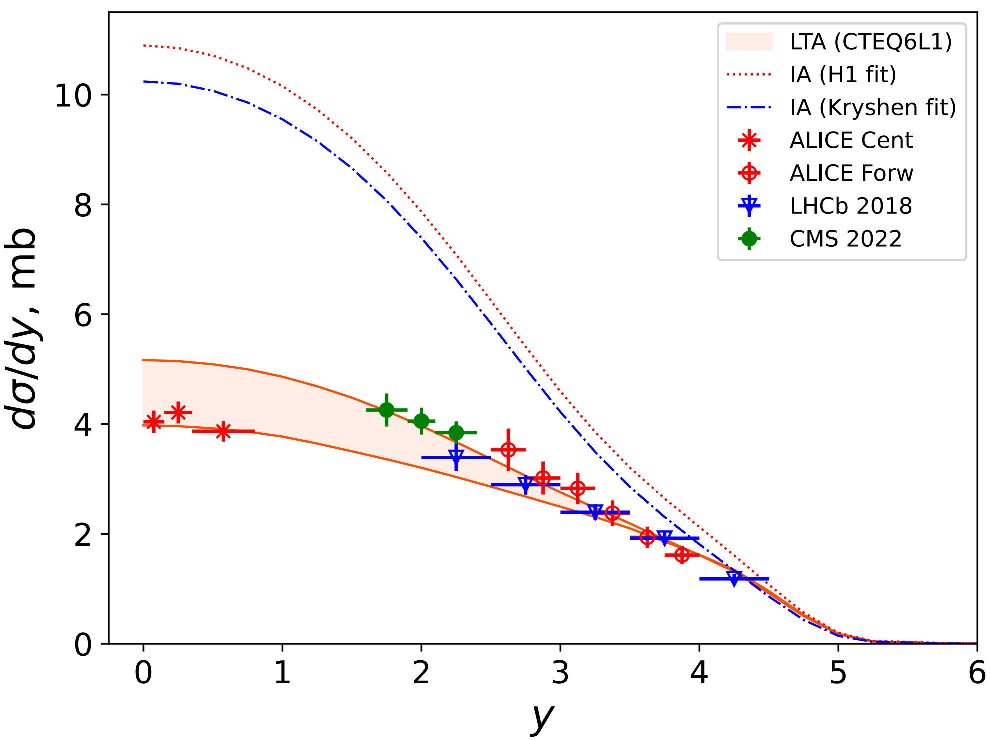
Global QCD analyses of nPDFs (nCTEQ15, EPPS21, nNNPDFs,…)

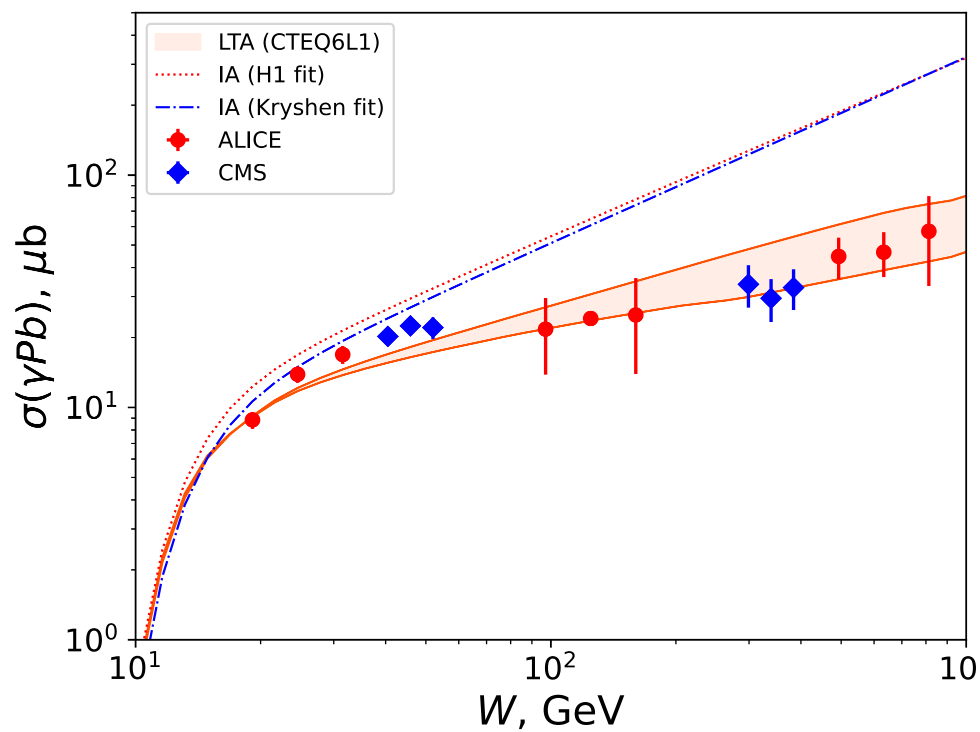
Leading twist approximation (LTA) to nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

LTA shadowing vs. Run 2 LHC data

- Left: rapidity-differential cross section of coherent J/ψ photoproduction in Pb-Pb UPCs at 5.02 TeV, Acharya *et al*. [ALICE], EPJC 81 (2021) no.8, 712 and PLB 798 (2019), 134926; Aaij *et al*. [LHCb], JHEP 06 (2023), 146; Tumasyan *et al*. [CMS], arXiv:2303.16984 [nucl-ex]

- Right: cross section of J/ψ photoproduction on Pb as function of W from UPCs with forward neutrons, [ALICE], arXiv:2305.19060 [nucl-ex]; Tumasyan *et al*. [CMS], arXiv:2303.16984 [nucl-ex]





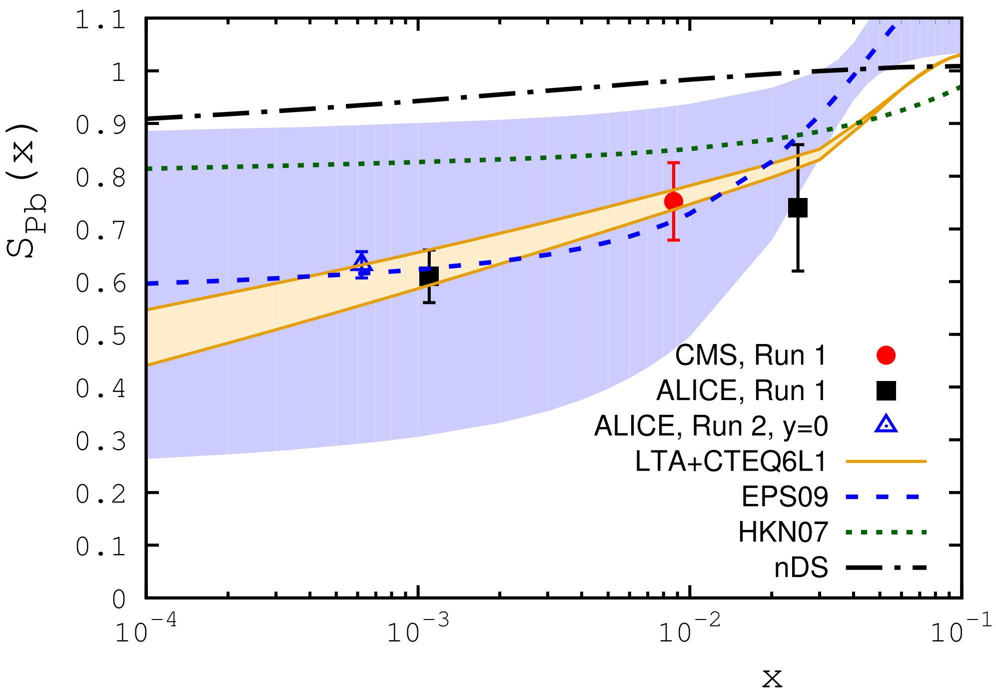
- Small-x nuclear suppression down to $x{\sim}10^{-5}$ is captured by LTA shadowing.
- → also good description by EPPS21, nCTEQ15 down to $x{\sim}10^{-3}$.

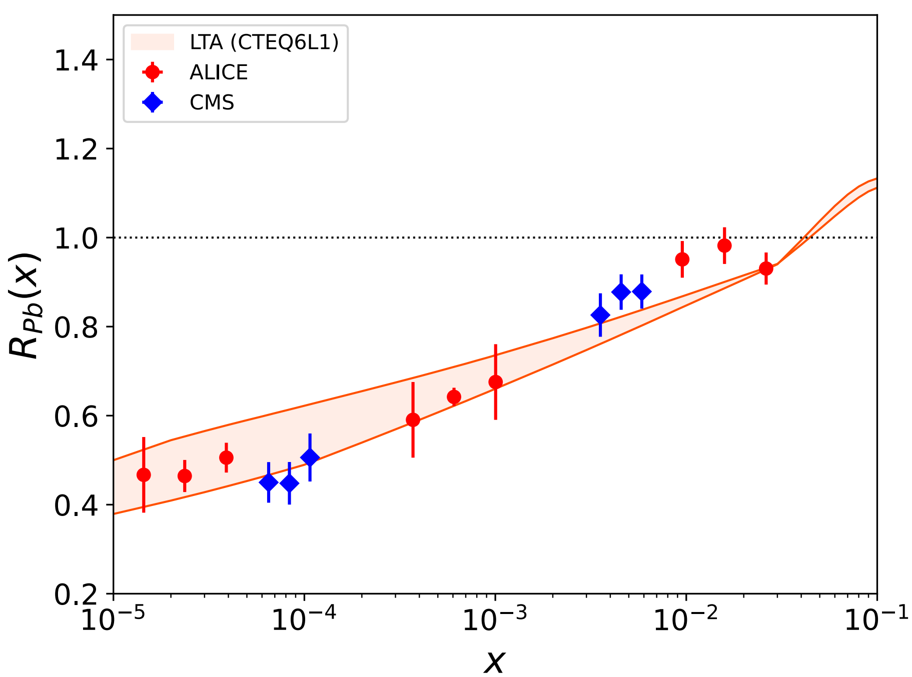
Nuclear suppression factor

- Nuclear suppression factor $S_{Pb}(x)$ from UPC data → direct comparison to $R_g(x)=g_A(x)/g_p(x)$, Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290; Guzey, Zhalov, JHEP 1310 (2013) 207

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

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





- Good agreement with data at small x → direct evidence of large gluon shadowing, $R_g(x=6\times10^{-4} - 0.001) \approx 0.6$ and further decreasing down to $x\sim10^{-5}$ → nice confirmation of LTA predictions.

Exclusive J/ψ photoproduction in NLO pQCD

- Collinear factorization for hard exclusive processes, Collins, Frankfurt, Strikman, PRD 56 (1997) 2982

- γA $\rightarrow$ J/ψA 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

- To 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

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

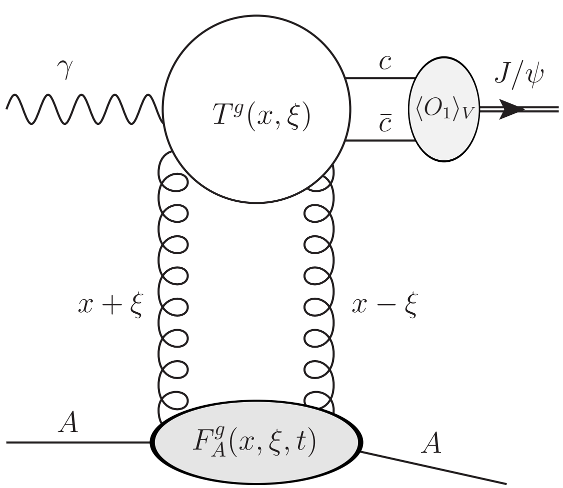
NRQCD matrix element from J/ψ leptonic decay

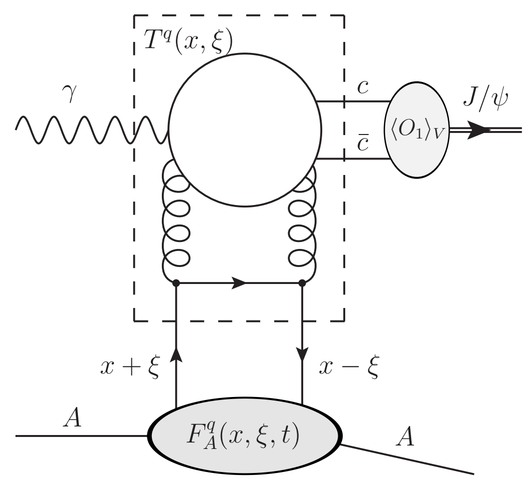
pQCD coeficient function

Gluon GPD

Quark contribution

- To leading order (LO), only gluons; both quarks and gluons at NLO.





skewness
$\xi=(1/2)(M_{J/\psi})^2/W^2 \ll 1$

Exclusive J/ψ photoproduction in NLO pQCD (2)

- In the limit of high W corresponding to small ξ=(1/2)$(M_{J/\psi})^2/W^2 \ll 1$

$$\mathcal{M}^{\gamma A \to J/\psi A} \propto i\sqrt{\langle O_1 \rangle_{J/\psi}}\Big[F_A^g(\xi,\xi,t,\mu_F) + \frac{\alpha_s N_c}{\pi}\ln\left(\frac{m_c^2}{\mu_F^2}\right)\int_\xi^1 \frac{dx}{x}F^g(x,\xi,t)$$
$$+\frac{\alpha_s C_F}{\pi}\ln\left(\frac{m_c^2}{\mu_F^2}\right)\int_\xi^1 dx(F^{q,S}(x,\xi,t) - F^{q,S}(-x,\xi,t))\Big]$$

+ less singular and non-log terms

→ helps to qualitatively understand the features of our numerical calculations.

- GPDs are hybrid distributions interpolating between usual PDFs and form factors → depend on momentum fractions x and ξ and momentum transfer t.

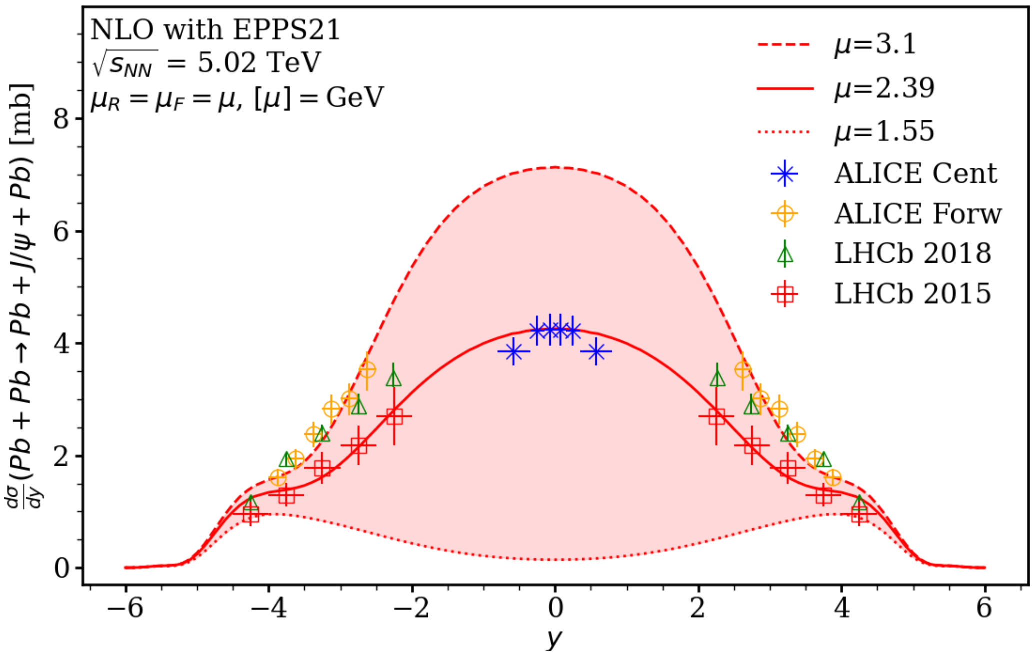
- Connection between GPDs is necessarily model-dependent. However, at small ξ, Q^2 evolution washes out information on input GPDs → GPDs in terms of PDFs, Shuvaev, Golec-Biernat, Martin, Ryskin, PRD 60 (1999) 014015; Dutrieux, Winn, Bertone, PRD 107 (2023) 11, 114019

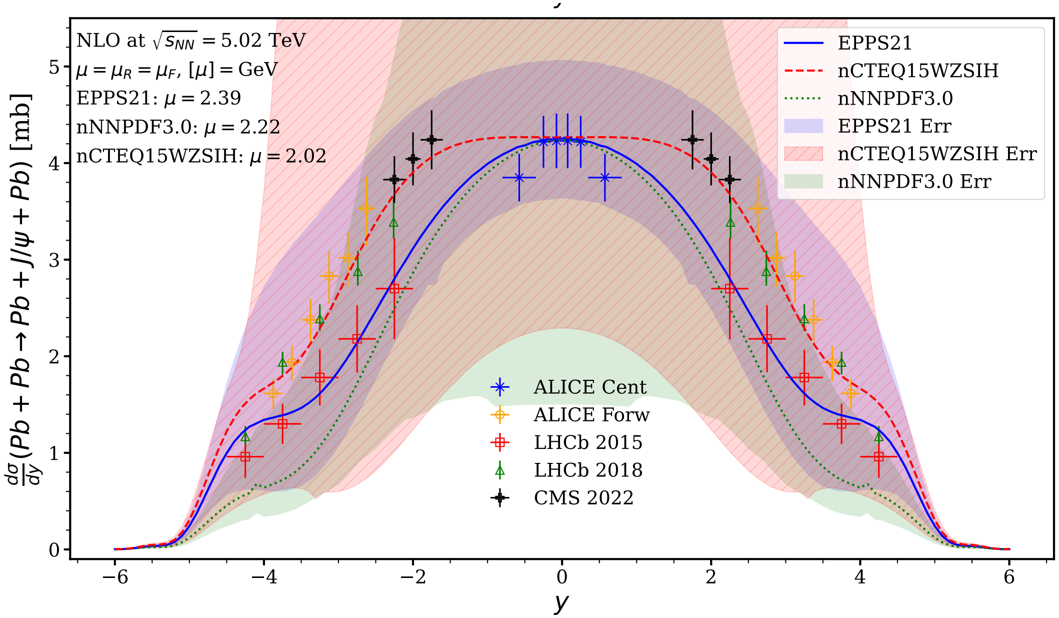
$$F_A^g(x,\xi,t,\mu_F) = x g_A(x,\mu_F) F_A(t)$$

Nuclear PDFs: EPPS16, nCTEQ15, nNNPDF2.0 + update with EPPS21, nCTEQ15WZSIH, nNNPDF3.0

Nucleus (Woods-Saxon) form factor

NLO pQCD predictions for J/ψ photoproduction in Pb-Pb UPCs at LHC





- Scale dependence for $m_c \leq \mu \leq 2m_c$ is expectedly very strong → consequence of $\ln(m_c^2/\mu^2)\ln(1/\xi)$ terms in NLO coefficient functions.

- Can find an "optimal scale" μ=2.39 GeV (EPPS21) giving simultaneously fair description of Run 1&2 UPC data → note that γ+p→J/ψ+p proton data is somewhat overestimated.

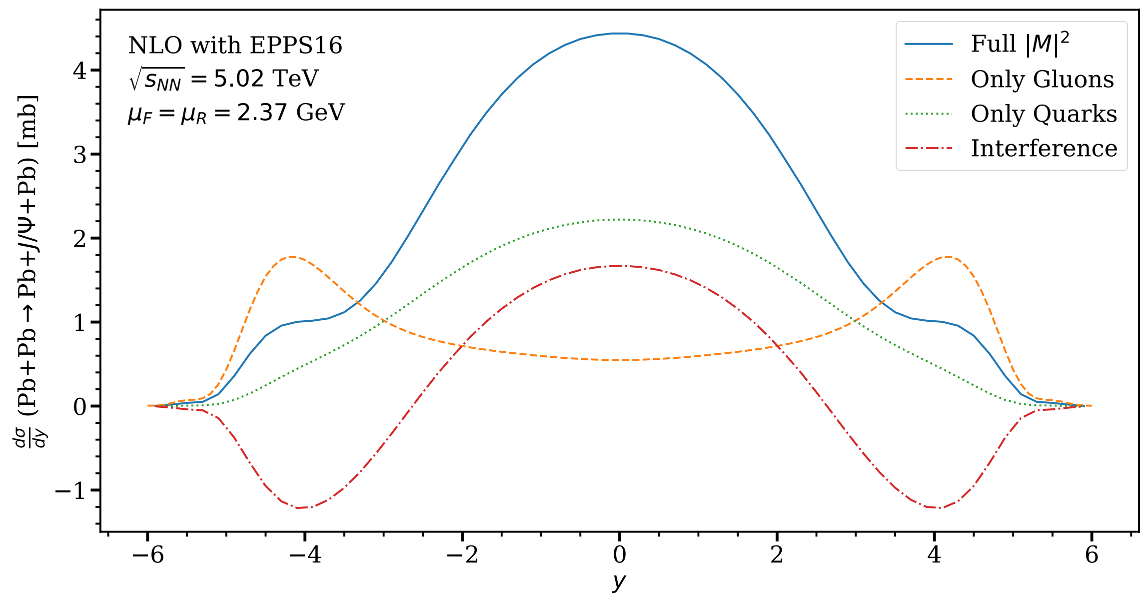
- Uncertainties due nPDFs are quite significant → opportunity to reduce them using these data.

Eskola, Flett, Guzey, Löytäinen, Paukkunen, PRC 106 (2022) 3, 035202 and PRC 107 (2023) 4, 044912

Shown data: Acharya et al [ALICE], EPJC 81 (2021) no.8, 712 and PLB 798 (2019) 134926; Aaij et al [LHCb], JHEP 07 (2022) 117

Dominance of quark contribution in NLO pQCD

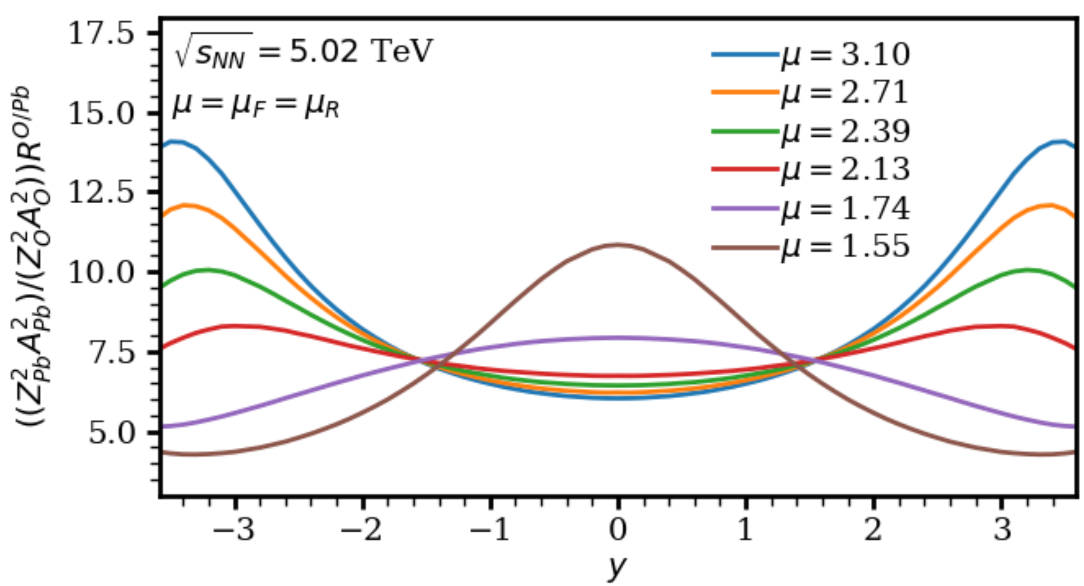
- Consequence of very large NLO corrections → dominance of quark contribution for |y|<2 due to strong cancellations between LO and NLO gluons, Eskola, Flett, Guzey, Löytäinen, Paukkunen, PRC 106 (2022) 3, 035202



- At the face value, this totally changes the interpretation of data on coherent J/ψ photoproduction in heavy-ion UPCs as a probe of small-x nuclear gluons.

- Perturbative stability of NLO pQCD improves for scaled ratio of oxygen and lead UPC cross secs:

$$\left(\frac{208 Z_{\rm Pb}}{16 Z_{\rm O}}\right)^2 \frac{d\sigma({\rm O+O \to O}+J/\psi+{\rm O})/dy}{d\sigma({\rm Pb+Pb \to Pb}+J/\psi+{\rm Pb})/dy}$$

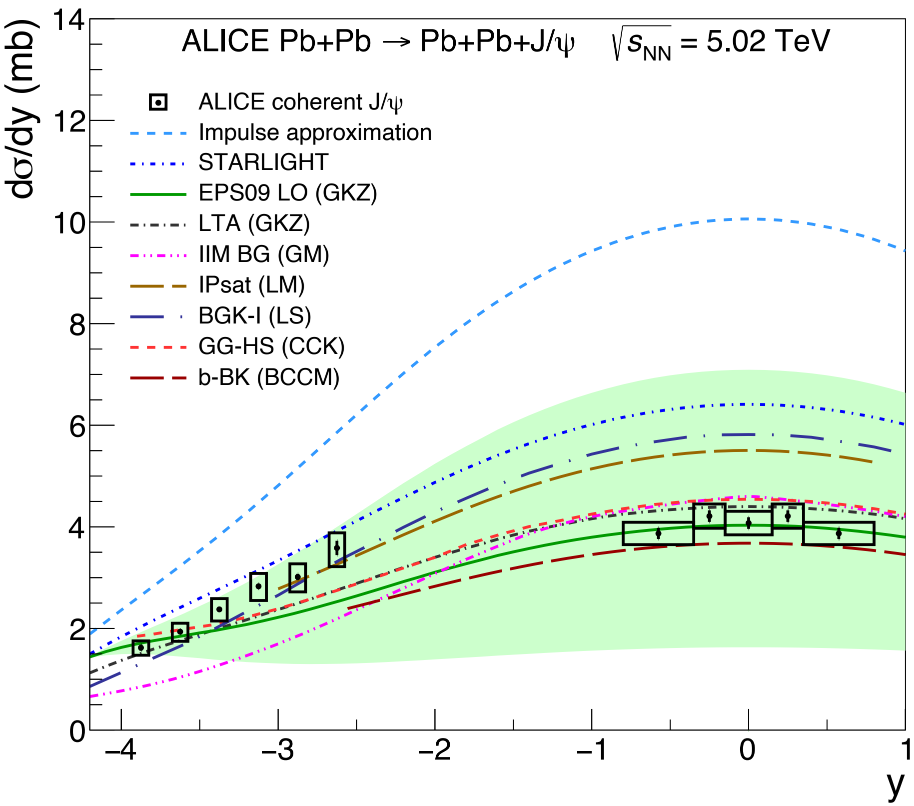


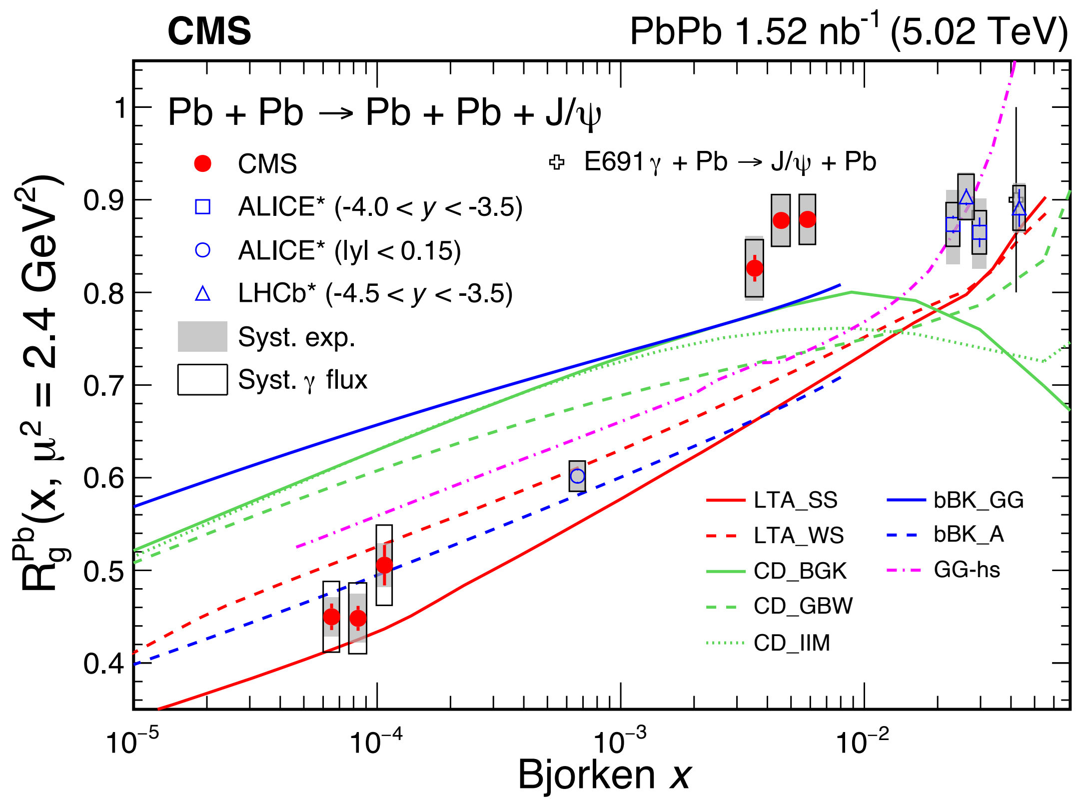
Eskola, Flett, Guzey, Löytäinen, Paukkunen, PRC 107 (2023) 4, 044912

Coherent J/ψ photoproduction in Pb-Pb UPCs

Acharya et al [ALICE], EPJC 81 (2021) no.8, 712

CMS, arXiv:2303.16984 [nucl-ex]





- None of the approaches describe the data in the entire range of J/ψ rapidity y.

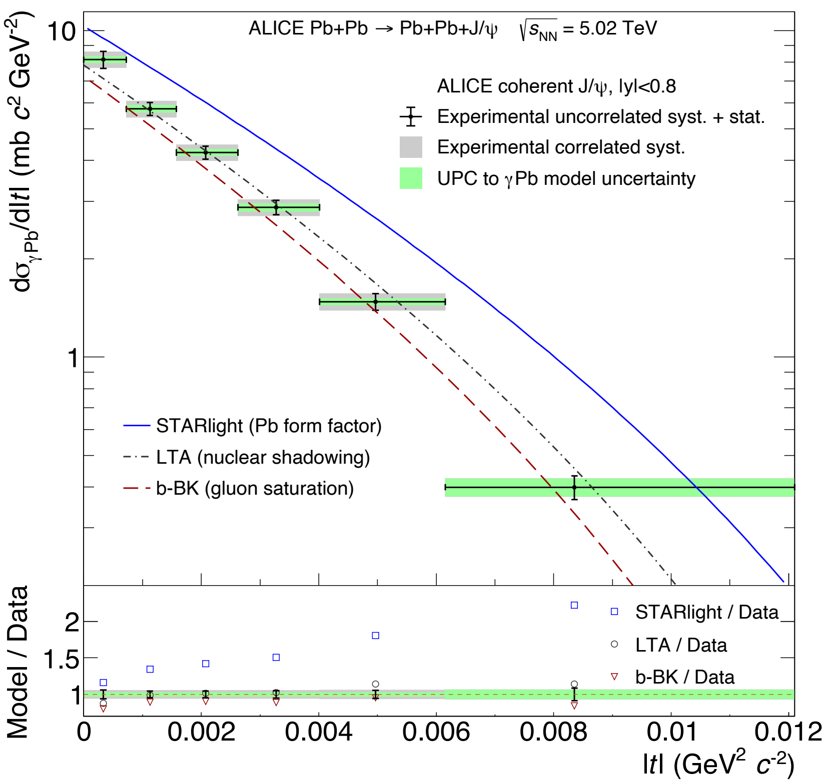
- Suppression at y=0 → strong leading-twist gluon shadowing at small x, or importance of $q\bar{q}g$ dipoles, or a sign of saturation in nuclei in dipole picture.

- Behavior at large |y| and $x_A > 0.01$ → all approaches close to the border of applicability → require refinements: e.g., earlier onset of antishadowing,…

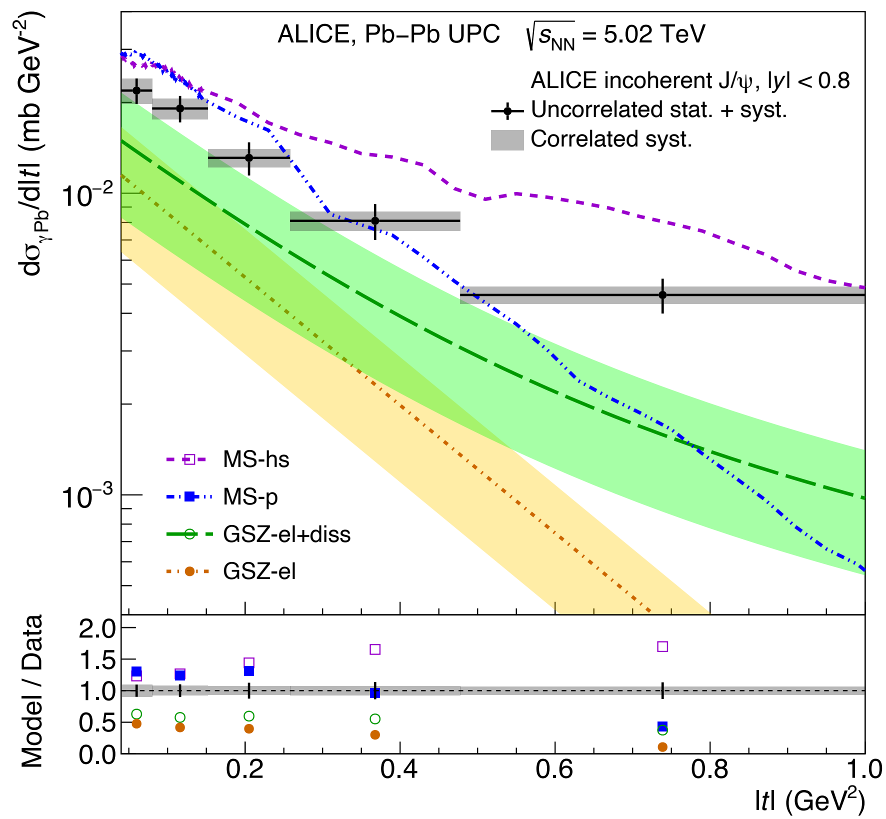
t-dependence of coherent and incoherent J/ψ photonuclear cross section

- LTA predicts stronger shadowing at nucleus center → 5-11% broadening of gluon distribution in impact parameter space → shift of minima of t-dependence, Guzey, Strikman, Zhalov, PRC 95 (2017) 025204

Acharya *et al.* [ALICE] PLB 817 (2021) 1, 136280



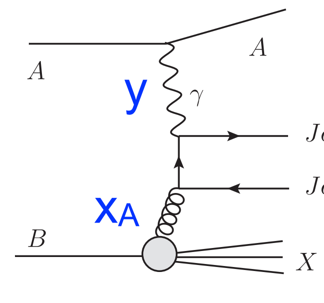
Acharya *et al.* [ALICE], 2305.06169 [nucl-ex]



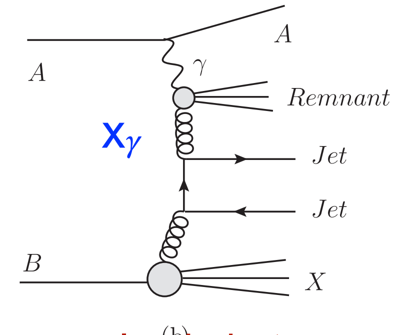
- Similar effect by saturation in dipole picture, Bendova, Cepila, Contreras, Matas, PLB 817 (2021) 136306.
- Incoherent: Strong sensitivity to sub-nucleon fluctuations ("hot spots") at large |t|, Mäntysaari, Schenke, PLB 772 (2017) 832

Inclusive dijet photoproduction in Pb-Pb UPCs@LHC

- Collinear factorization and NLO pQCD,
  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



direct photon



resolved photon

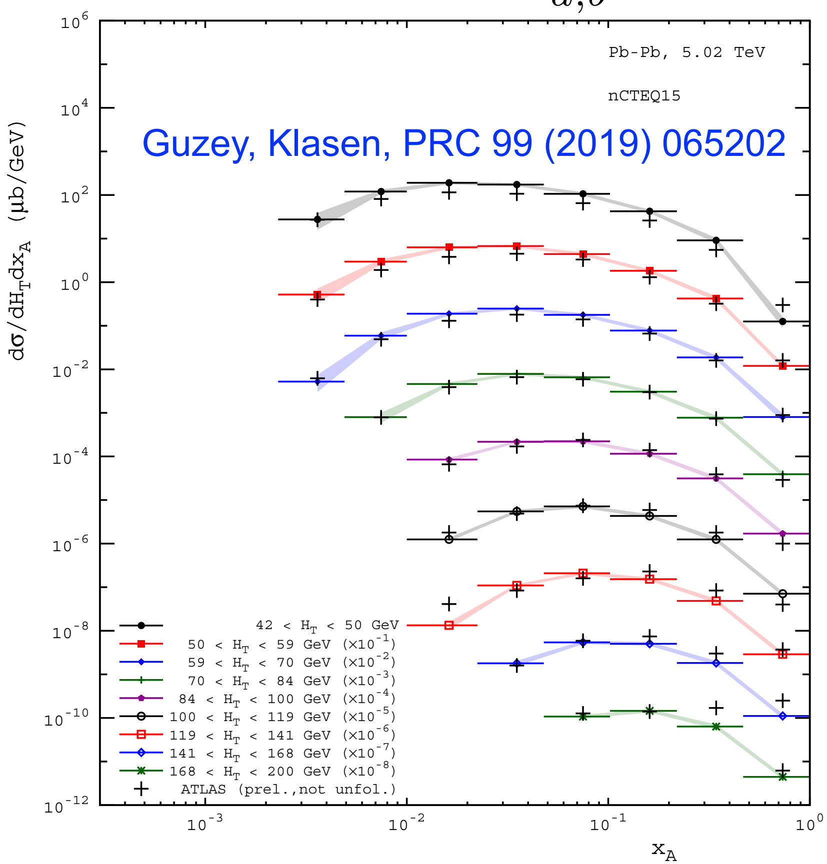
$$d\sigma^{AA\to A+2\text{jets}+X} = \sum_{a,b}\int dy \int dx_\gamma \int dx_A f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma,\mu^2) f_{b/A}(x_A,\mu^2)\hat{\sigma}_{ab\to\text{jets}}$$

Photon flux

Photon PDFs for resolved case

Nuclear PDFs (nCTEQ15, EPPS16)

Hard parton cross section



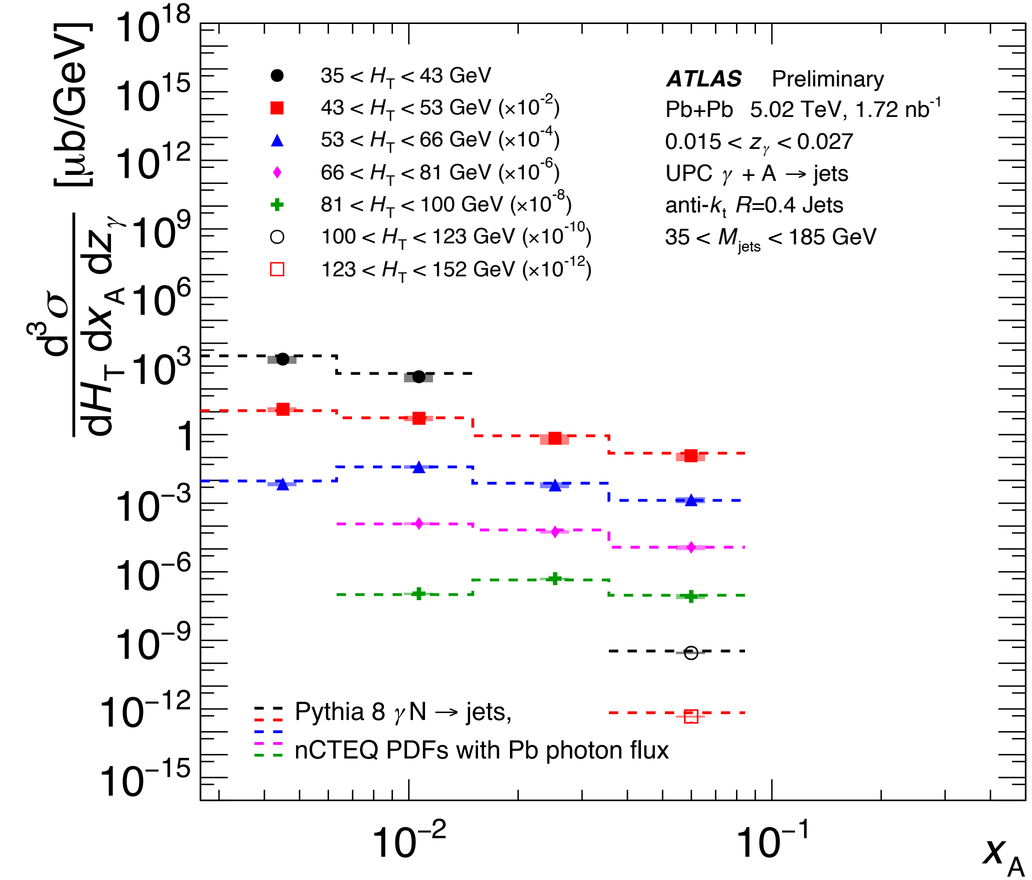
- NLO pQCD describes shape and normalization of unfolded ATLAS data, ATLAS-CONF-2017-011

- Sensitivity to nuclear modifications of PDFs at 10-20% level → can be used to reduce uncertainty of gluon density by factor 2 at $x_A \sim 5\times10^{-3}$, Guzey, Klasen, EPJ C 79 (2019) 5, 396

- 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

Inclusive dijet photoprod. in Pb-Pb UPCs@LHC(2)

- A more recent analysis of newer data, now unfolded for detector response, ATLAS-CONF-2022-021.

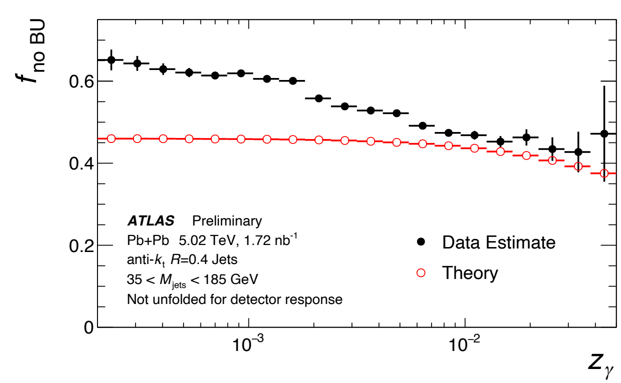


- Generally the data agree with the breakup-adjusted PYTHIA 8 MC.

- Data probes $x_A \sim 5\times10^{-3}$.

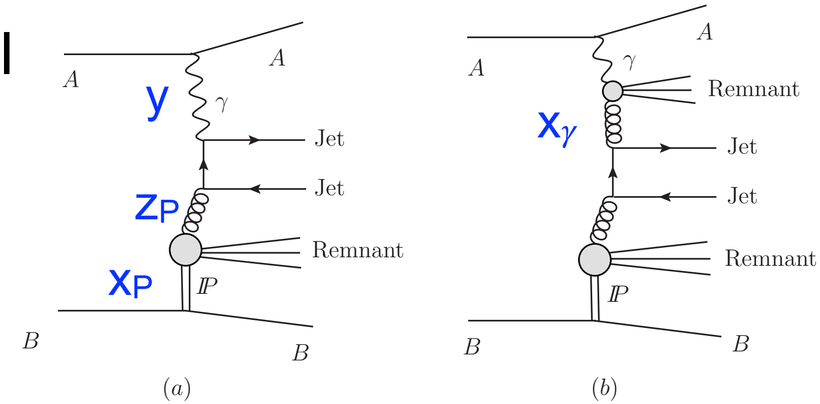
- Fraction of events when the photon-emitting nucleus doesn't break up:

$$f_{\text{no BU}} \equiv \frac{d\sigma/dz_\gamma|_{0nXn}}{d\sigma/dz_\gamma|_{XnXn} + d\sigma/dz_\gamma|_{0nXn}}$$



Diffractive dijet photoproduction in Pb-Pb UPCs@LHC

- Collinear factorization and NLO pQCD → novel nuclear diffractive PDFs, test of QCD factorization breaking.
- Contribution of right-moving photon source:



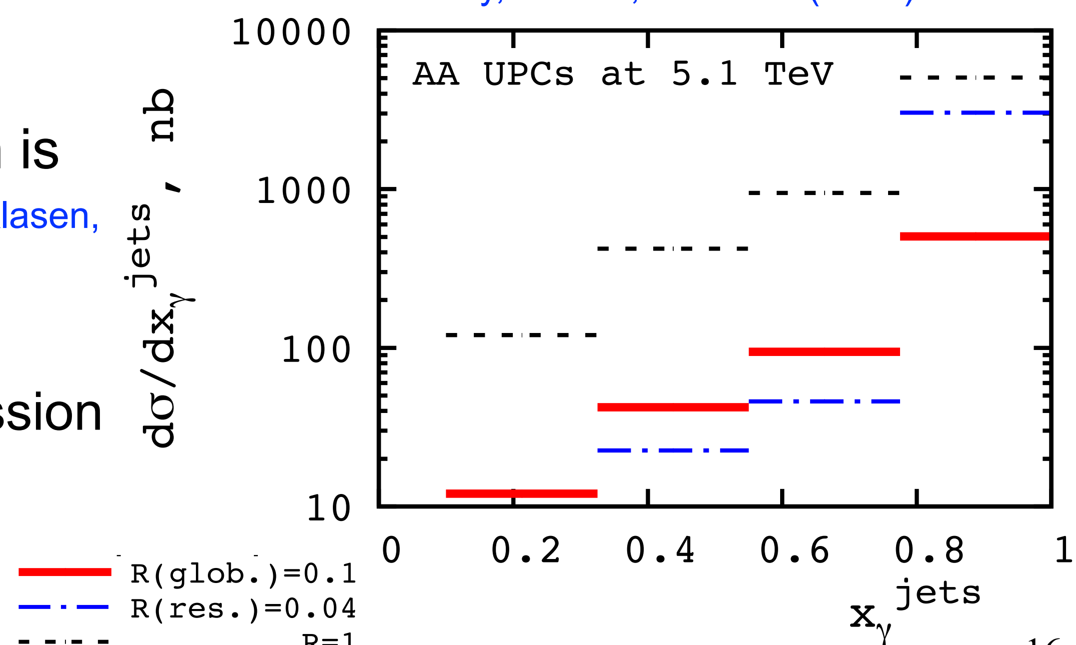
$$d\sigma(AA \to A + 2\text{jets} + X + A)^{(+)} =$$

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

Nuclear diffractive PDFs

Guzey, Klasen, JHEP 04 (2016) 158

- Diffractive dijet photoproduction in ep scattering@HERA → QCD factorization is broken, Klasen, Kramer, EPJ C 38 (2004) 93; Guzey, Klasen, EPJ C 76 (2016) 8, 467
- Pattern unknown: global suppression by R(glob.)=0.5 or the resolved-only suppression R(res.)=0.34
- One can differentiate between these scenarios by studying x_γ distribution.



UPC@LHC is a precursor of EIC

• Studies of UPCs@LHC and RHIC can be viewed as precursor of EIC → systematics of Q^2 and A dependence for various inclusive, diffractive and exclusive observables.

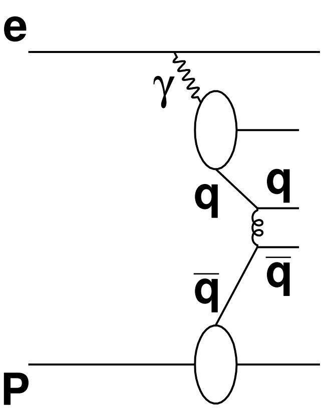
• Exclusive VM electroproduction → dramatic change of Q^2 scaling between high-Q^2 (LT) and low-Q^2 (saturation) regimes, Frankfurt, Guzey, McDermott, Strikman, PRL 87 (2001) 192301; Mäntysaari, Venugopalan, PLB 781 (2018) 664.

$$\mathcal{A} = i \int \mathrm{d}^2\mathbf{r}_T \mathrm{d}^2\mathbf{b}_T \frac{\mathrm{d}z}{4\pi} [\Psi_{\gamma^* \to q\bar{q}} \Psi^*_{q\bar{q} \to VM}](\mathbf{r}_T, z, Q^2) \; e^{-i(\mathbf{b}_T + (1-z)\mathbf{r}_T)\cdot\mathbf{\Delta}} \frac{\mathrm{d}\sigma_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{b}_T}(\mathbf{b}_T, \mathbf{r}_T, x_{\mathbb{P}})$$

	Longitudinal, low Q^2	Longitudinal, high Q^2	Transverse, low Q^2	Transverse, high Q^2
$\mathrm{d}\sigma^{\gamma^*+A\to V+A}/\mathrm{d}t\,(t=0)$	$Q^2 A^{4/3}$	$Q^{-6} A^2$	$Q^0 A^{4/3}$	$Q^{-8} A^2$
$\sigma^{\gamma^*+A\to V+A}$	$Q^2 A^{2/3}$	$Q^{-6} A^{4/3}$	$Q^0 A^{2/3}$	$Q^{-8} A^{4/3}$

• Possibility of new studies of the unpolarized and polarized partonic structure of quasi-real photons at EIC using dijets,

Chu, Aschenauer, Lee, Zheng, PRD 96 (2017) 7, 074035



Summary and Outlook

- There is continuing interest in using UPCs at the LHC and RHIC to obtain new constraints on proton and nucleus PDFs and strong dynamics at small x.

- The data challenge both collinear factorization and dipole model frameworks.

- Strong nuclear suppression of coherent J/ψ photoproduction in Pb-Pb UPC@LHC → large gluon/quark shadowing at small x, or importance of $q\bar{q}g$ dipoles, or a sign of saturation → test in Υ photoproduction.

- In the collinear framework, extraction of nPDFs is feasible using ratios of AA/pp UPCs cross sections, where strong scale dependence, modeling of GPDs, and relativistic corrections partially cancel.

- Outstanding challenges are the treatment of J/psi vertex beyond the static approximation and taming of small-ξ behavior of NLO coefficient functions.

- Inclusive and diffractive dijet photoproduction in UPCs@LHC provides complementary constraints on small-x nPDFs and factorization breaking.

- I didn't have time to cover coherent J/ψ photoproduction in Pb-Pb UPC@LHC in dipole picture and tamed collinear factorization for small-x gluons in the proton from pp UPCs@LHC — please see extra slides.

Exclusive J/ψ photoproduction in dipole picture

- Space-time picture of strong interaction at high energies in target rest frame → photon is a superposition of long-lived $q\bar{q}$, $q\bar{q}g$,… dipoles.

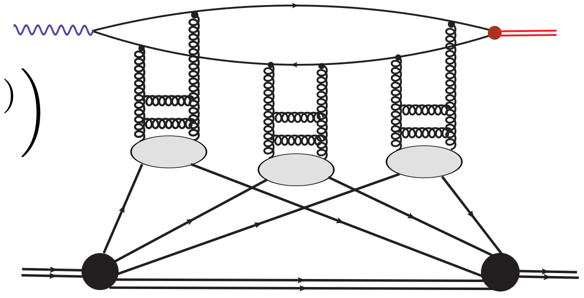
- Dipoles successively, elastically scatter on target nucleons → high-energy factorization for γ+A→J/ψ+A amplitude:

$$\mathcal{M}^{\gamma A\to J/\psi A} = \int d^2\mathbf{r}_T \int \frac{dz}{4\pi} \int d^2\mathbf{b}_T [\Psi^*_{J/\psi}\Phi_\gamma] 2\left(1 - e^{-\frac{1}{2}\sigma_{\rm dip}(\mathbf{r}_T)T_A(\mathbf{b}_T)}\right)$$

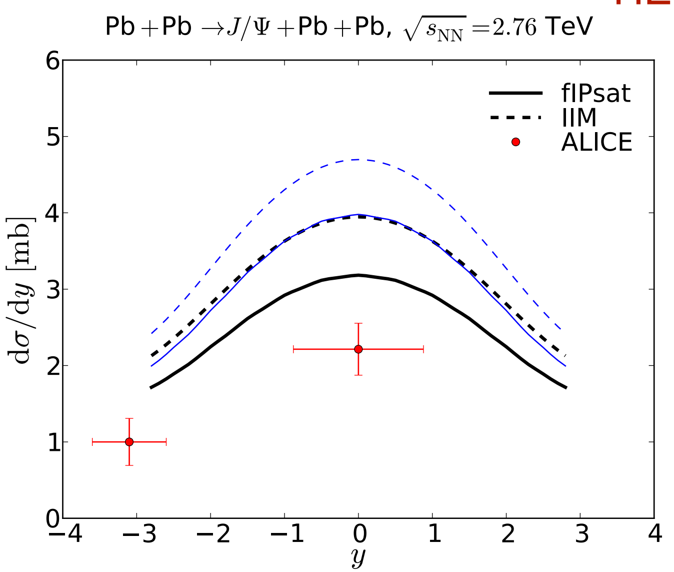
Overlap of photon (QED) and J/ψ (model) wf's

Dipole cross section from fits to HERA

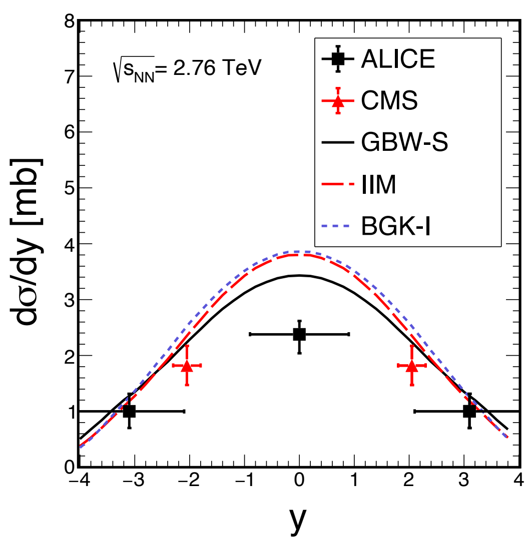
Nuclear density



Lappi, Mäntysaari, PRC 87 (2013) 3, 032201



Luszczak, Schäfer, PRC 99 (2019) 4, 044905



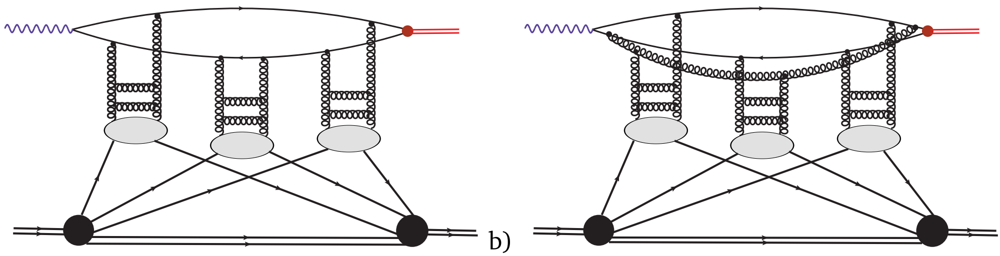
- This implementation over-predicts the data at y=0 since nuclear shadowing due to rescattering of small dipoles with $\langle r_T\rangle\sim 0.3$ fm is too weak.

Dipole picture: role of $q\bar{q}g$ dipoles

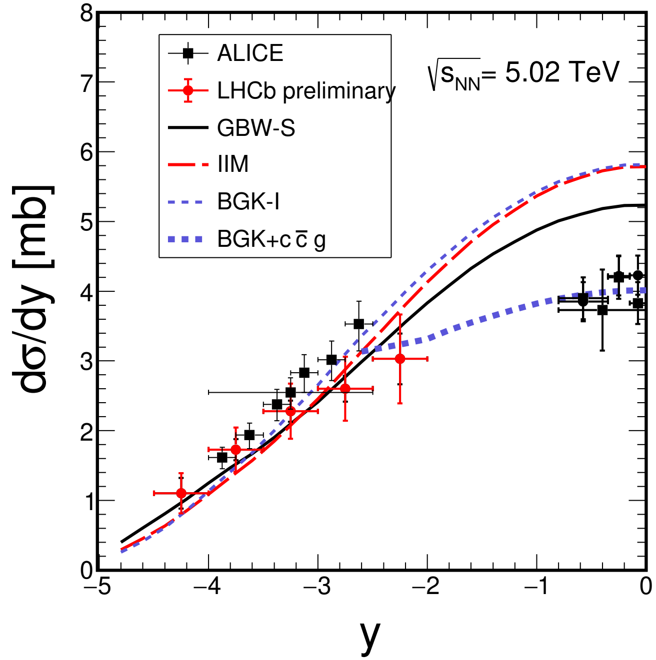
- Small-$\langle r_T \rangle$ $q\bar{q}$ dipoles provide higher-twist contribution to γ+A→J/ψ+A as well as to other nuclear observables, e.g. longitudinal structure function $F_L^A(x,Q^2)$,

Frankfurt, Guzey, McDermott, Strikman, JHEP 02 (2002) 027

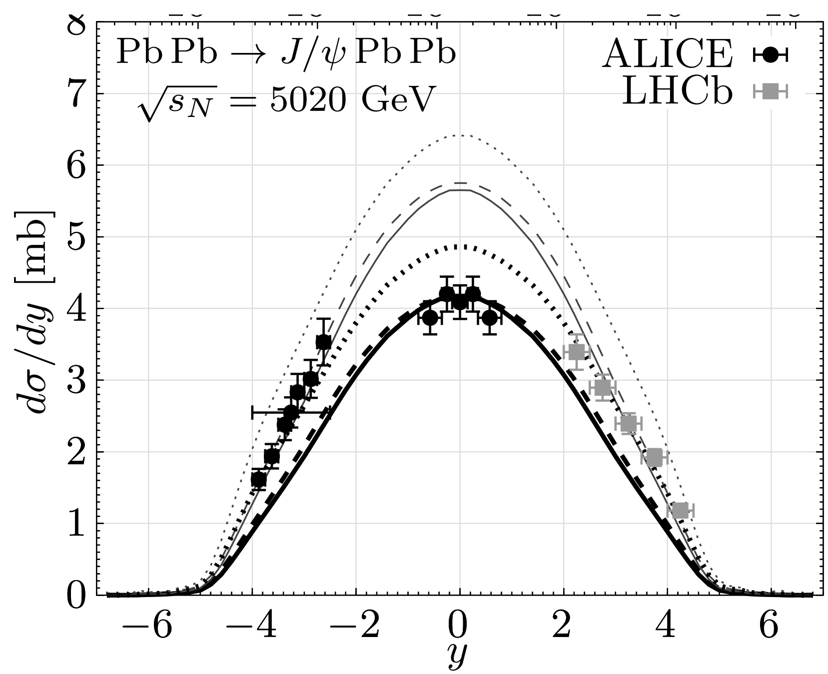
- Need to include higher $q\bar{q}g$ Fock states → modeling of 3-body "dipole" cross section and wave function.



Luszczak, Schäfer, SciPost Phys.Proc. 8 (2022) 109, arXiv:2108.06788 [hep-ph]



Kopeliovich, Krelina, Nemchik, Potashnikova, PRD 107 (2023) 5, 054005



- Includes elastic and inelastic nuclear shadowing → good description of data.

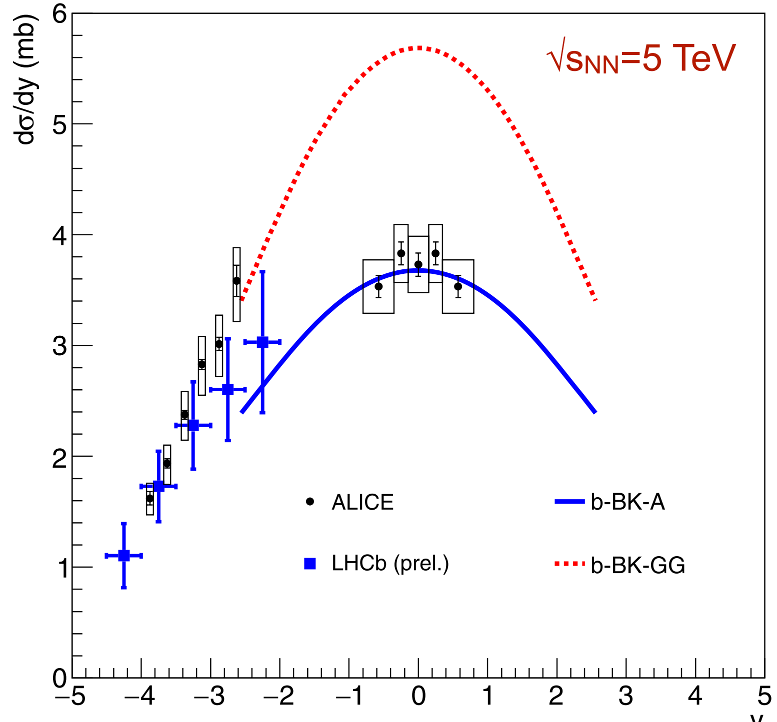
Dipole picture: saturation in nuclei

• Instead of Glauber-type dipole-nucleus scattering → nuclear geometry in initial condition for Balitsky-Kovchegov equation → saturation in nuclei, but not necessarily in nucleons.

$$\frac{\sigma^A_{\rm dip}(\mathbf{r}_T, \mathbf{b}_T)}{d^2\mathbf{b}_T} = 2\mathcal{N}_{\rm BK}(\mathbf{r}_T, \mathbf{b}_T, x)$$

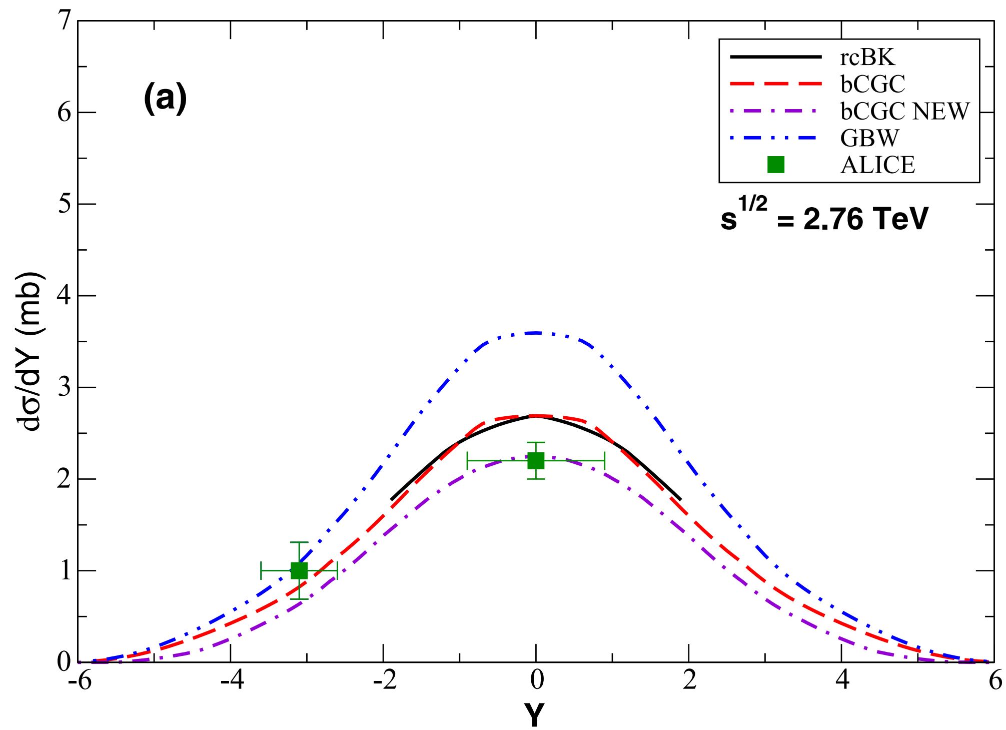
• Should be taken with grain of salt → predictions strongly depend on models for the dipole cross section and J/ψ wave function.

Bendova, Cepila, Contreras, Matas, PLB 817 (2021) 136306



Shown Run 2 data: Acharya et al [ALICE], EPJC 81 (2021) no.8, 712 and PLB 798 (2019) 134926; Aaij et al [LHCb], JHEP 07 (2022) 117

Goncalves, Moreira, Navarra, PRC 90 (2014) 015203



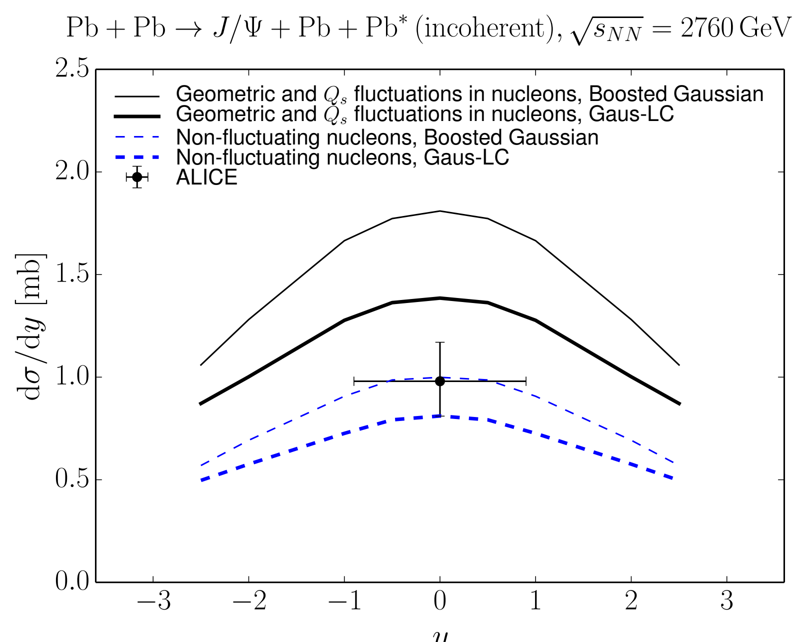
Shown Run 1 data: Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE]

Dipole picture: Hot spots in proton and incoherent J/ψ photoproduction on nuclei

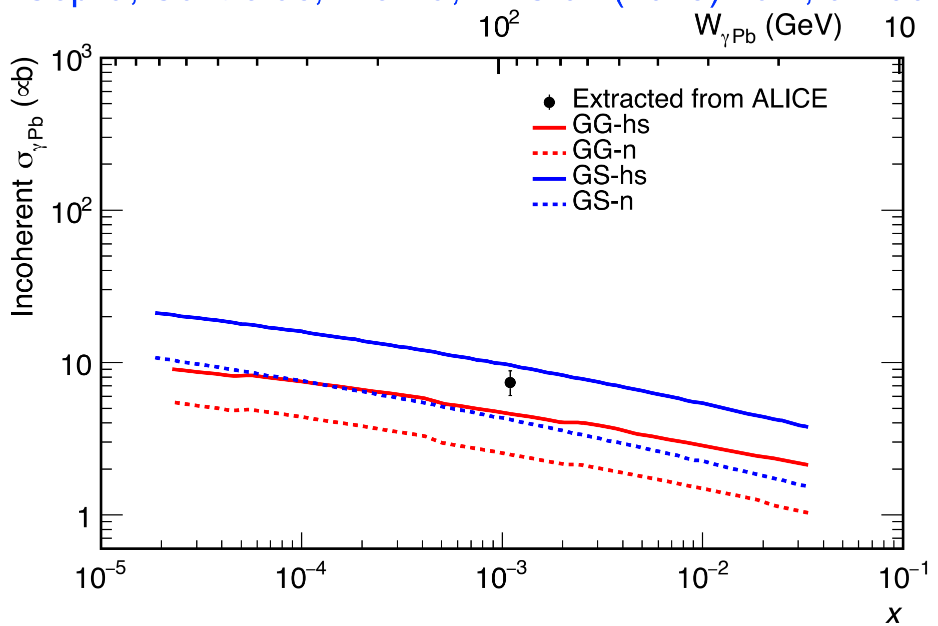
- Description of incoherent diffraction γ+p→J/ψ+p* on the proton requires a new subnucleon scale → gluonic "hot spots" and geometric fluctuations of the proton,
Mäntysaari, Schenke, PRL 117 (2016) 052301; Cepila, Contreras, Tapia-Takaki, PLB 766 (2017) 186

- Can be applied to incoherent J/ψ photoproduction in Pb+Pb→Pb+J/ψ+Pb* UPC

Mäntysaari, Schenke, PLB 772 (2017) 832



Cepila, Contreras, Krelina, PRC 97 (2018) no.2, 024901



- Increases ×2 incoherent cross section, affects weakly coherent cross section, describes well incoh/coh ratio.
- Alternative description: leading twist gluon nuclear shadowing, Guzey, Strikman, Zhalov, PRC 99 (2019) 1, 015201.

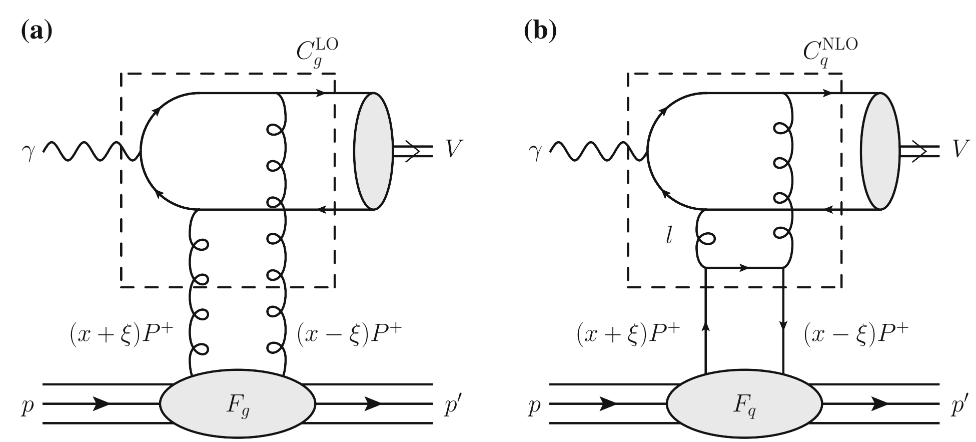
Tamed collinear factorization

• Stability of perturbation series for exclusive J/ψ photoproduction in NLO pQCD can be improved in 2 steps:

- Choose factorization scale $\mu_F=\mu_c$ to transfer $\ln(m_c^2/\mu_F^2)\ln(1/\xi)$ terms of NLO coefficient function to LO GPDs → resummation in spirit of DGLAP → residual μ_f dependence is weak, Jones, Martin, Ryskin, Teubner, J. Phys. G 43 (3) (2016) 035002

$$A^{(0)}(\mu_f) + A^{(1)}(\mu_f) \;=\; C^{(0)} \otimes F(\mu_F) + \alpha_s C^{(1)}_{\rm rem}(\mu_F) \otimes F(\mu_f)$$

- Subtraction of $l_T < Q_0 \sim m_C$ contribution from NLO coefficient functions to avoid double counting (included in LO gluons) → Q_0 subtraction method, Jones, Martin, Ryskin, Teubner, EPJC 76 (2016) 633

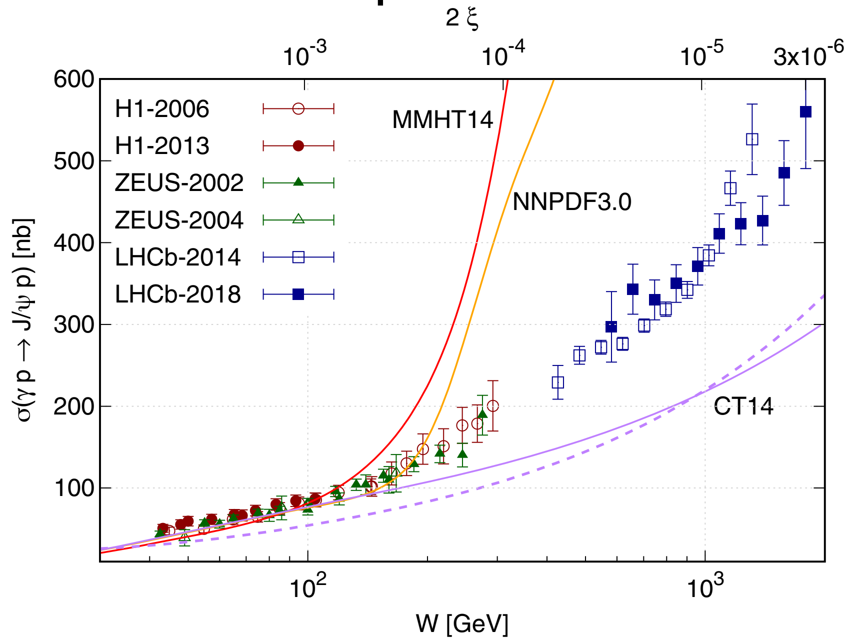


• Q_0-subtraction addresses $\mathcal{O}(Q_0^2/m_c^2)$ power suppressed terms → numerically important for J/ψ and much less important for DIS with $\mathcal{O}(Q_0^2/Q^2)$.

Tamed collinear factorization: gluons in proton

- Restores the gluon dominance and allows for sensible comparison to data.

- Tamed NLO pQCD predictions using existing proton PDFs vs. HERA and LHCb pp UPC data on γ+p→J/ψ+p, Flett, Jones, Martin, Ryskin, Teubner, PRD 101 (2020) 9, 094011

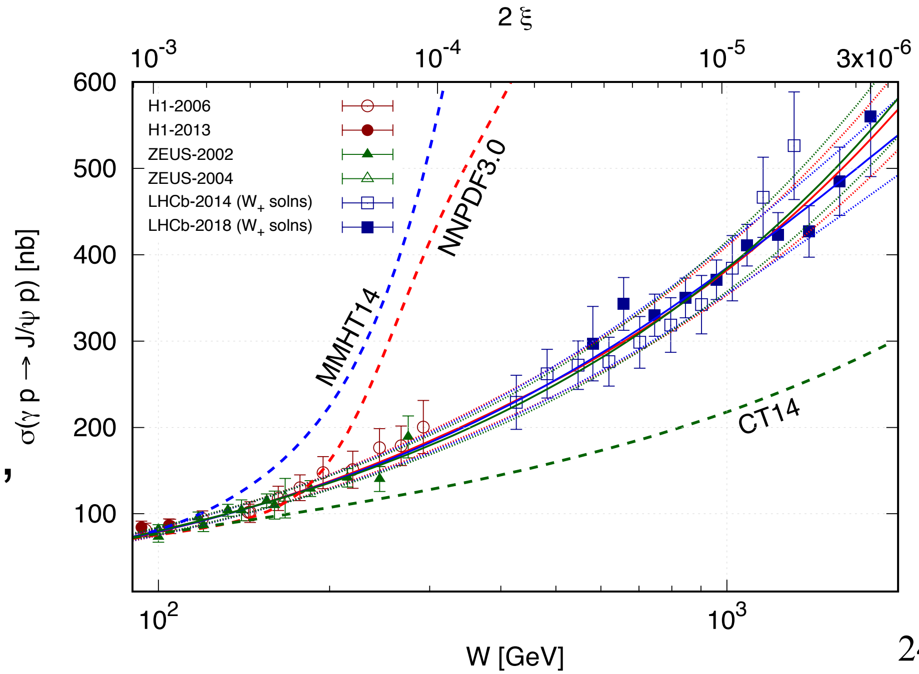


- Predictions are stable, but description of LHCb data is poor.

- Extraction of gluon PDF for $x< 10^{-3}$ using global analysis of data on γ+p→J/ψ+p, Flett, Martin, Ryskin, Teubner, PRD 102 (2020) 114021

$$xg(x,\mu_0^2) \;=\; C\;xg^{\rm global}(x,\mu_0^2) \;+\; (1-C)\;xg^{\rm new}(x,\mu_0^2)$$

$$xg^{\rm new}(x,\mu_0^2) \;=\; nN_0\;(1-x)\;x^{-\lambda}$$



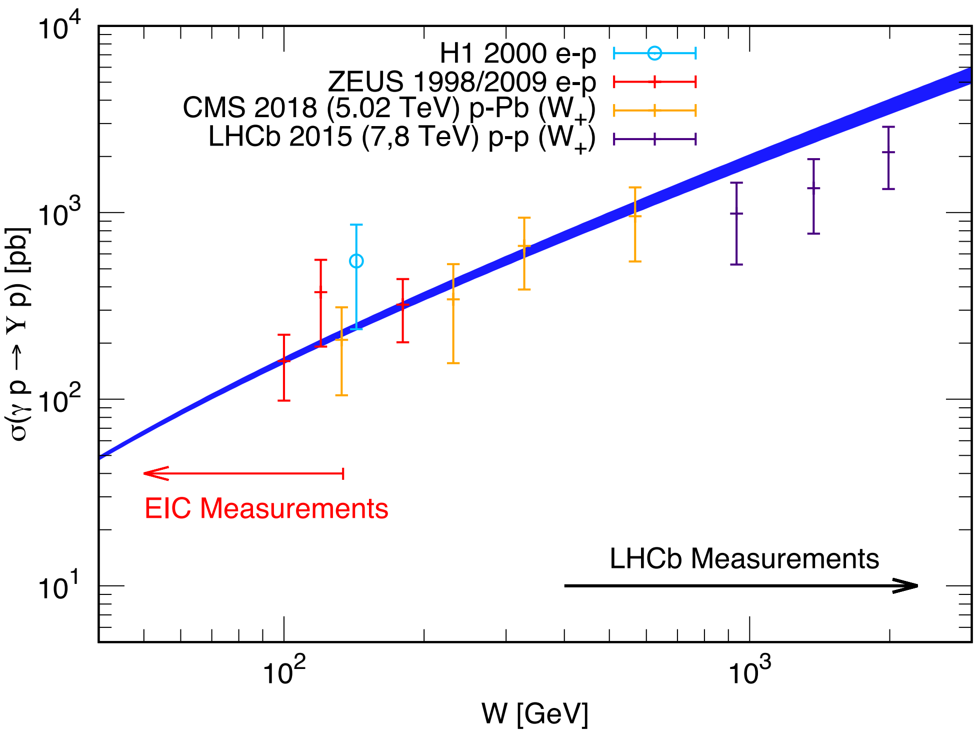
- Constraints on $xg_p(x,\mu)$ for $3\times10^{-6} < x<10^{-3}$, no signs of saturation.

Shown LHCb data: Aaij et al [LHCb], J. Phys. G41 (2014) 055002 and JHEP 1810 (2018) 167.

Tamed collinear factorization for exclusive Υ photoproduction on the proton

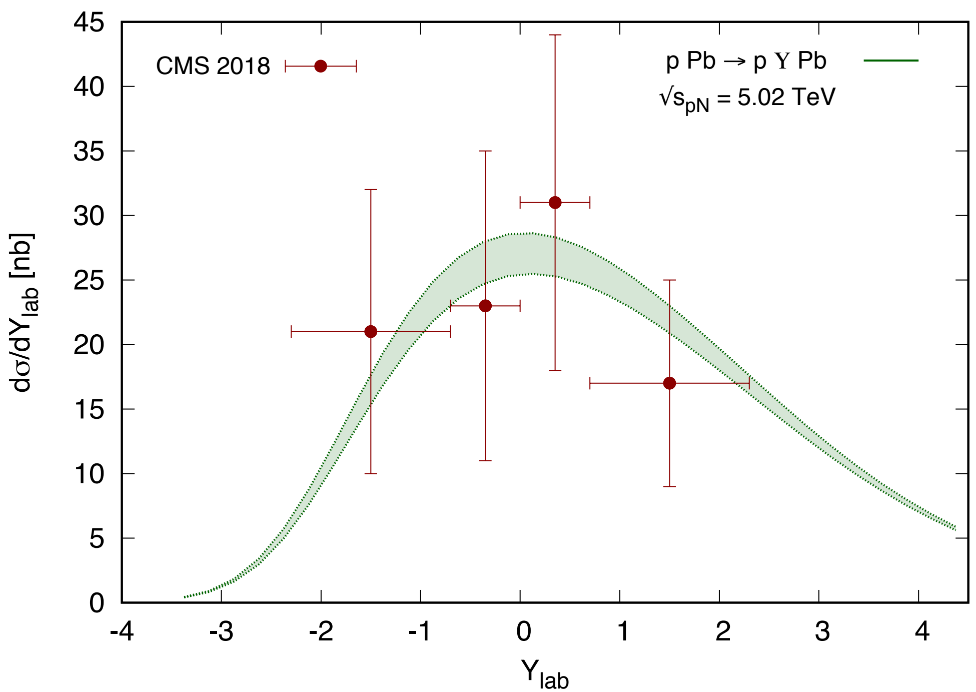
- The gluon distribution from J/ψ data can be used for model-free predictions for exclusive Υ photoproduction on the proton → good description of data.

- NLO pQCD vs. HERA and LHC UPC data on γ+p→Υ+p, Flett, Jones, Martin, Ryskin, Teubner, PRD 105 (2022) 3, 034008



Shown UPC data: Aaij et al. [LHCb], JHEP 09 (2015) 84; Sirunyan et al [CMS], EPJC 79 (2019) 3, 277

- NLO pQCD vs. CMS pA UPC data, Flett, Jones, Martin, Ryskin, Teubner, PRD 106 (2022) 7, 074021



Shown UPC data: Sirunyan et al. [CMS], EPJC 79 (2019) 3, 277

NLO pQCD predictions for ϒ photoproduction in Pb-Pb UPCs at LHC

• These issues are much milder for ϒ photoproduction: NLO corrections are moderate, the gluons dominate the UPC cross section, GPD modeling benefits from longer μ^2 evolution up to the bottom quark mass $\mu=m_b$.

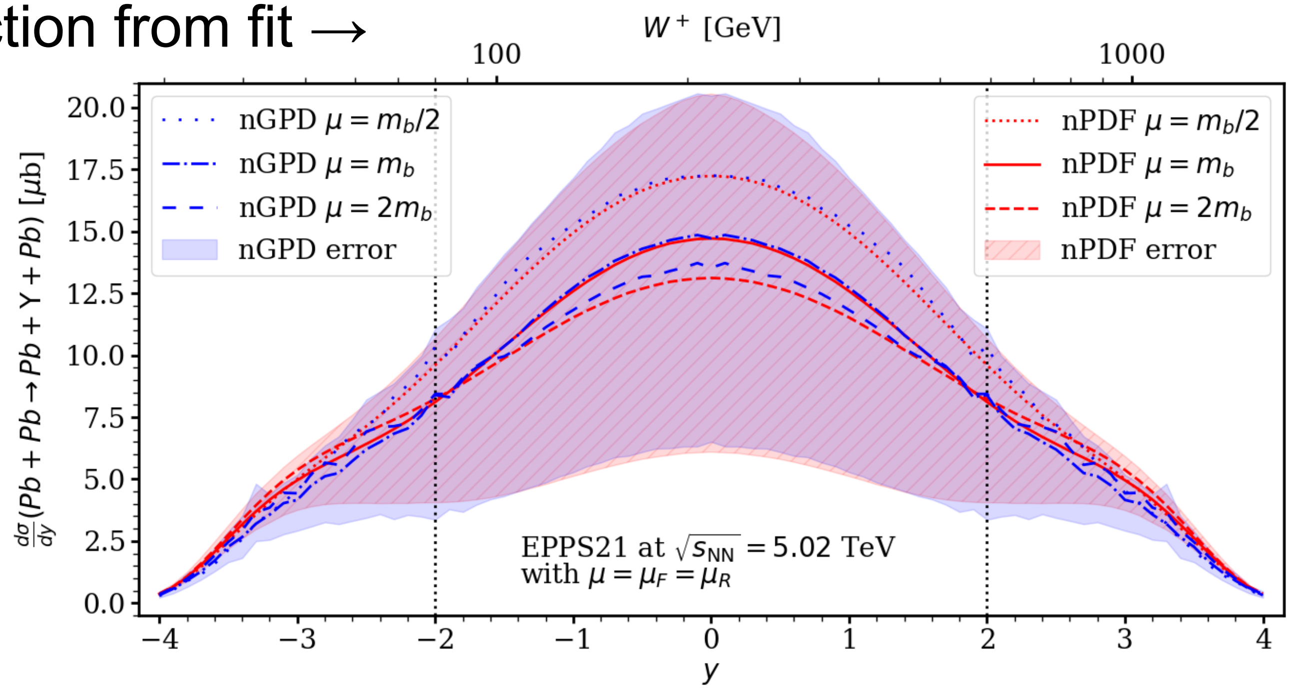
• Nevertheless, NLO pQCD under-predicts by factor ~2 the γ+p→ϒ+p cross section measured at HERA and in p-p and p-Pb UPCs at the LHC.

• Data-driven approach: NLO pQCD only for the ratio of nucleus and proton cross sections, the proton cross section from fit →

$$\sigma^{\gamma \mathrm{Pb}\to \Upsilon \mathrm{Pb}}(W) = \left[\frac{\sigma^{\gamma \mathrm{Pb}\to \Upsilon \mathrm{Pb}}(W)}{\sigma^{\gamma p\to \Upsilon p}(W)}\right]_{\mathrm{pQCD}} \sigma_{\mathrm{fit}}^{\gamma p\to \Upsilon p}(W)$$

• Scale uncertainty is reduced → smaller than propagated errors of nPDFs.

• Sensitivity to nuclear GPDs is essentially eliminated → important for nPDF phenomenology.



Eskola, Flett, Guzey, Löytäinen, Paukkunen, arXiv:2303.03007 [hep-ph]