Exclusive quarkonium photoproduction

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ERC adG YoctoLHC

Outline:

- UPCs as real-photon probes of nucleus and proton structure in QCD
- Coherent exclusive J/ψ photoproduction in Pb-Pb UPCs at the LHC:
  leading-twist nuclear shadowing at small x, higher Fock states in dipole picture
- Exclusive J/ψ photoproduction in p-p UPCs at the LHC:
  tamed collinear factorization and small-x gluons in proton
- Summary and Outlook

Forward Physics and QCD at the LHC and EIC, 798. WE-Heraeus-Seminar, 23-27 October, 2023, Physikzentrum, Bad Honnef, Germany

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

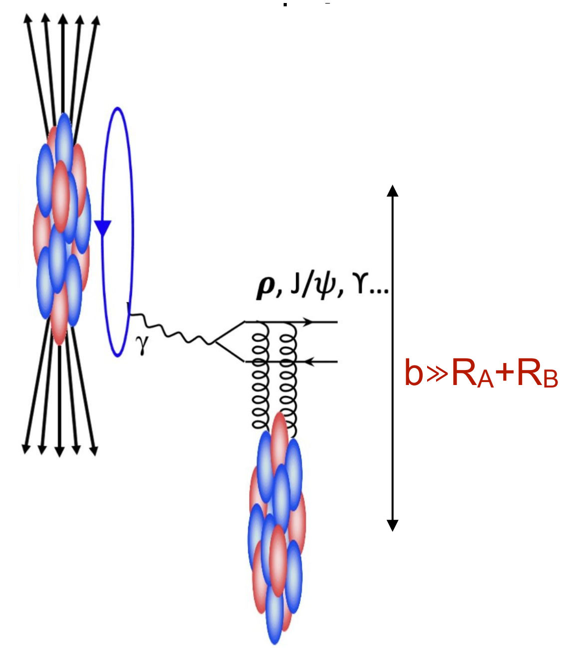


Figure credit: A. Stahl, LPCC CERN Seminar, 6.12.2022

• 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

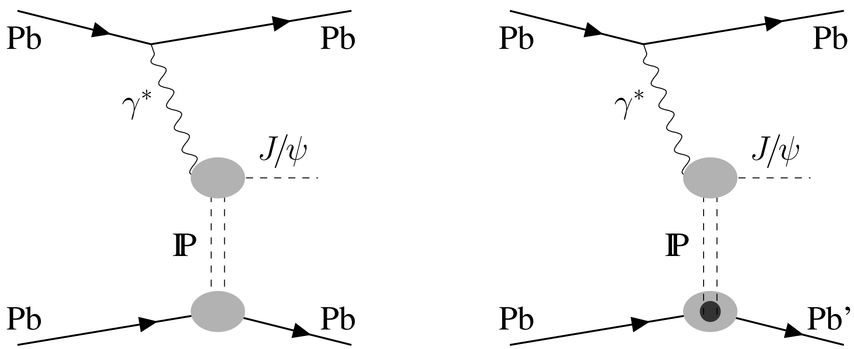
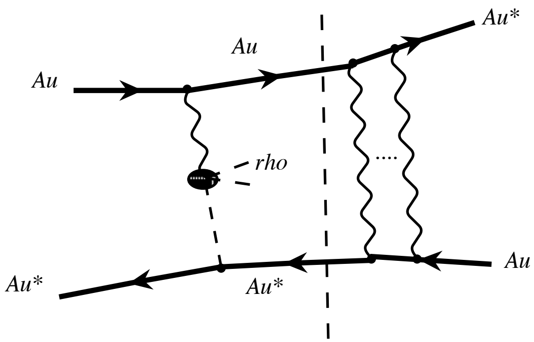


Figure credit: Aaij et al [LHCb], JHEP 07 (2022) 117

• 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

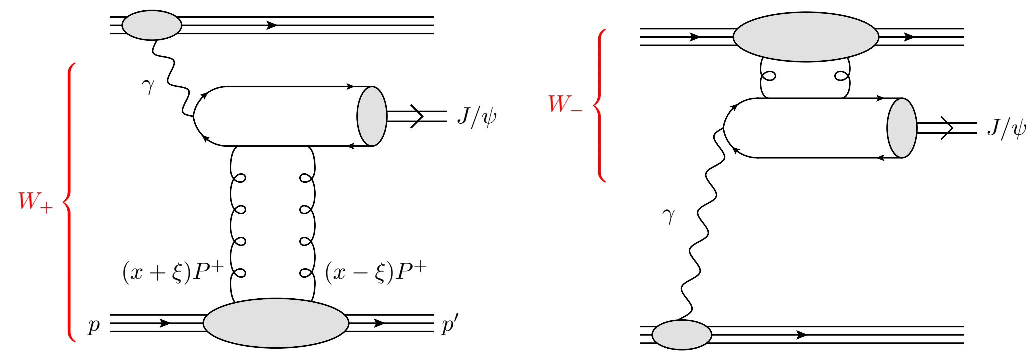


Ions de-excite by emitting neutrons detected in ZDCs

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^-):



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

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

Photoproduction cross section

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

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

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

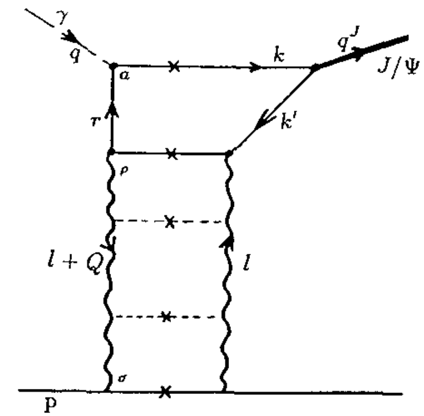
$$W^{\pm} = \sqrt{(k^{\pm}+E_A)^2}$$

- 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

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



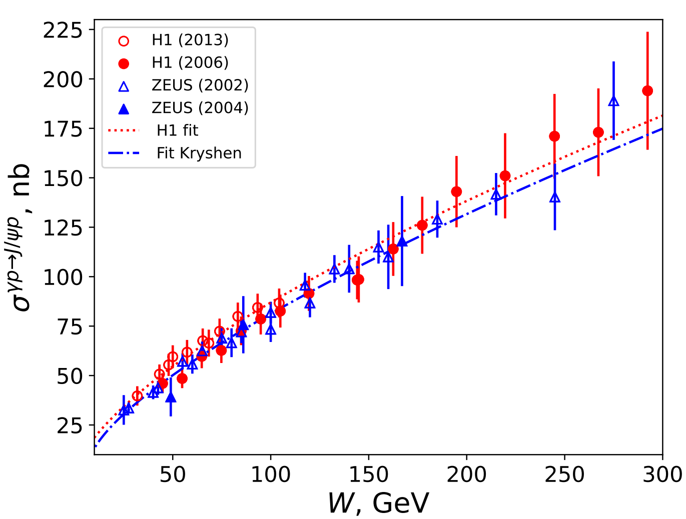
Γ_V is J/ψ leptonic decay width

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:

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



From fits to HERA data

Ratio of nucleus and proton gluon densities

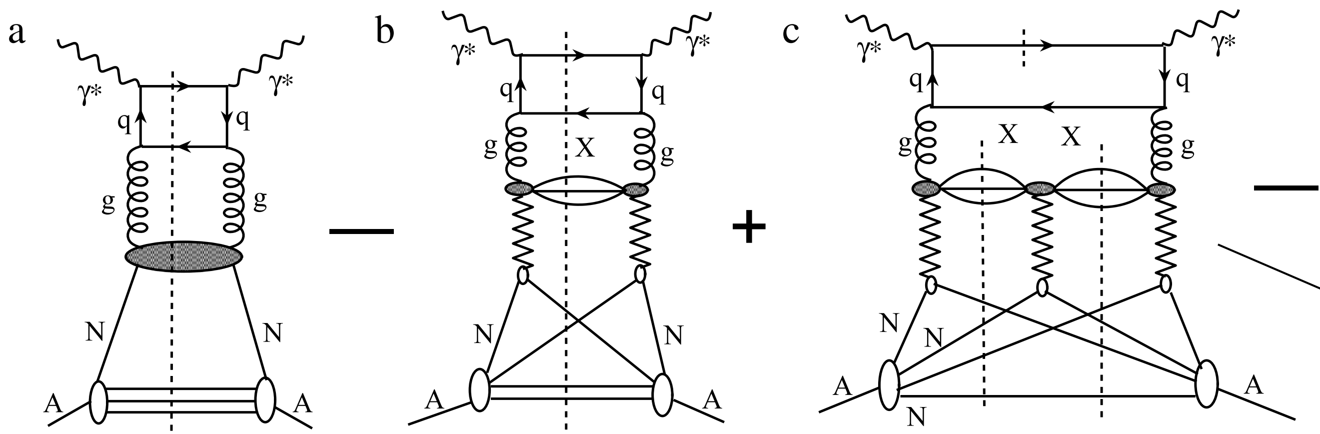
Nuclear form factor

Global QCD analyses of nPDFs, **T. Jezo talk on Monday**

Dynamical models of nuclear shadowing

Leading twist model of nuclear shadowing

- Combination of Gribov-Glauber theory with QCD factorization theorems for inclusive and diffractive DIS → prediction for small-x nPDFs at input scale Q_0,
  Frankfurt, Strikman, EPJ A5 (1999) 293; Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255



diffractive exchange

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

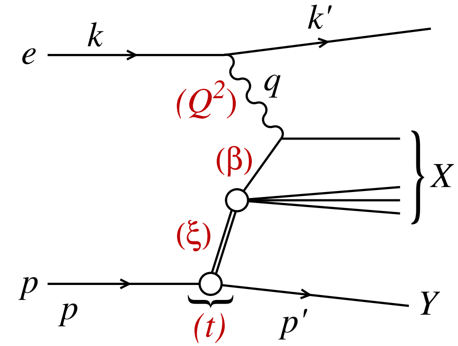
$$\times \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\,\rho_A(\vec{b}, z_1)\rho_A(\vec{b}, z_2)e^{i(z_1-z_2)x_{\mathbb{P}}m_N}\,e^{-\frac{A}{2}(1-i\eta)\sigma^j_{\text{soft}}(x,Q_0^2)\int_{z_1}^{z_2} dz'\rho_A(\vec{b},z')}$$

nuclear density

Interaction with N=2 nucleons in terms of proton diffractive PDFs from HERA

N ≥ 3 terms: model-dependent effective cross section

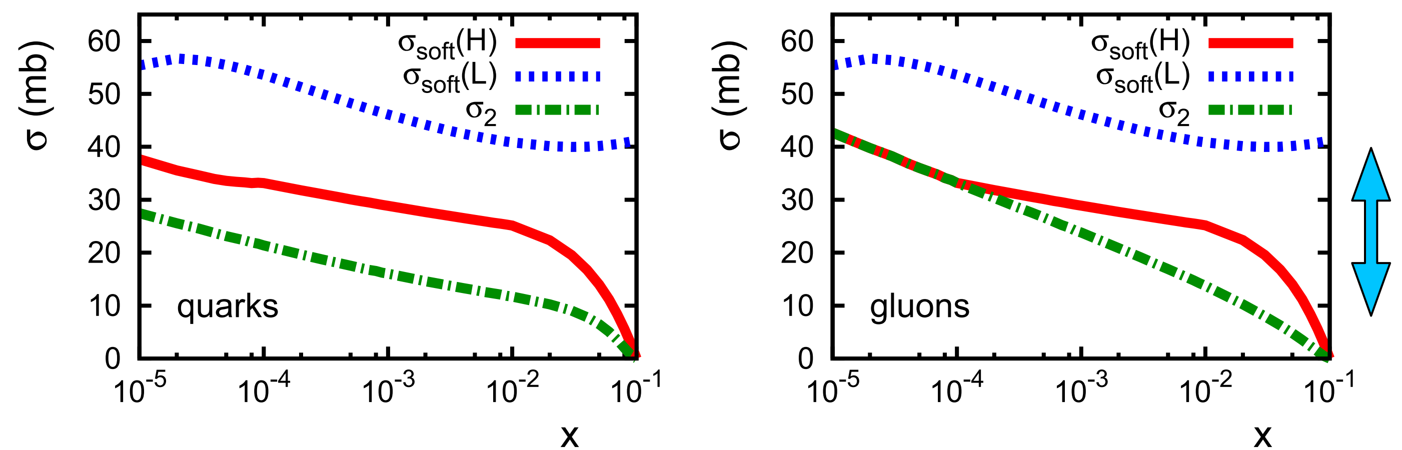
Leading twist model of nuclear shadowing (2)



- Essential input: universal, leading twist (LT) diffractive PDFs of proton, Collins, PRD 57, 3051 (1998); PRD 61, 019902 (2000)
- Extracted from HERA data on diffraction in ep DIS, Aktas et al [H1], EPJ C48, 715 (2006), EPJC 48, 749 (2006); Chekanov et al [ZEUS], NPB 831, 1 (2010)
- Interaction with 2 nucleons model-independently in terms of diffractive (Pomeron) PDFs:

$$\sigma_2^j(x, Q^2) = \frac{16\pi}{(1+\eta^2)xf_{j/N}(x,Q^2)} \int_x^{0.1} dx_{\mathbb{P}} \beta f_j^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t_{\min}).$$

- Interaction with N ≥ 3 nucleons modeled using hadronic fluctuations of photon

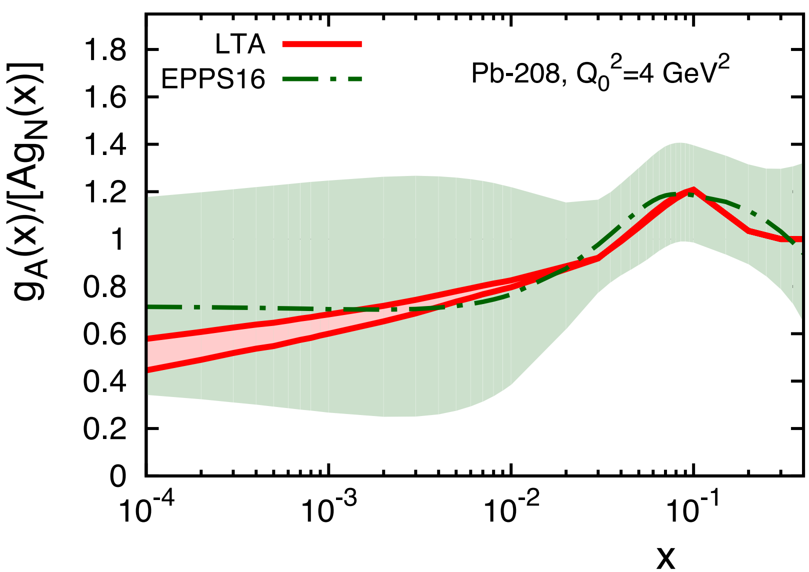


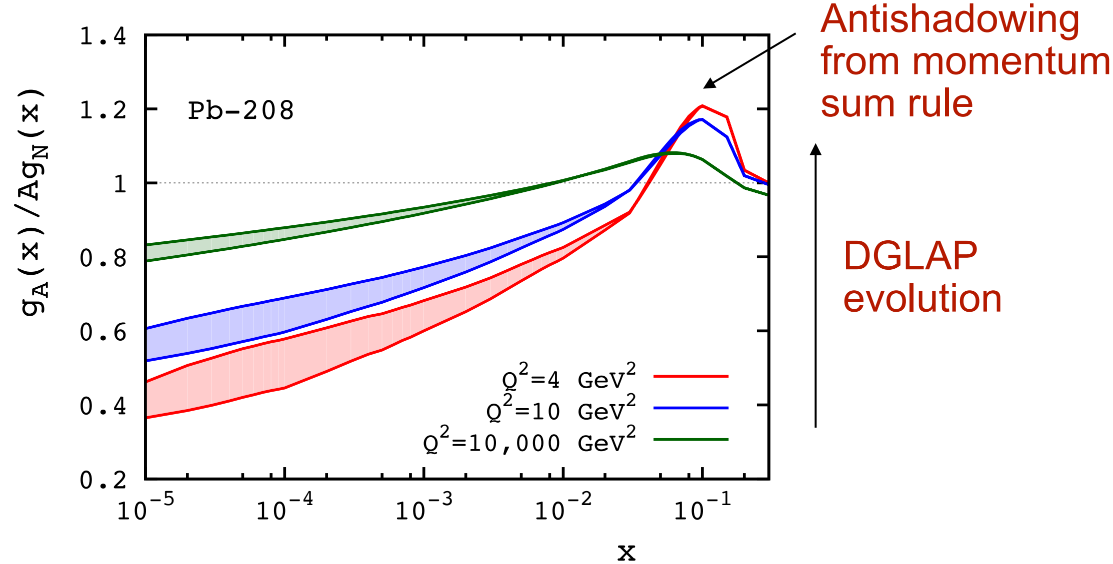
Spread in σ_{soft} → uncertainty of LTA predictions

- LT in the name comes from HERA analysis, but higher twist effects in diffraction at low Q_0 could be significant, Motyka, Sadzikowski, Slominski, PRD 86 (2012) 111501; Maktoubian, Mehraban, Khanpour, Goharipour, PRD 100 (2019) 054020.

LTA predictions for nPDFs

- HERA analysis: perturbative Pomeron is made mostly of gluons → LTA model naturally predicts large gluon nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255





- Alternative, complementary point of view: shadowing is mixture of leading and higher twist (HT) effects in dipole picture with saturation, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303, or a purely HT effect, Qiu, Vitev, PRL 93 (2004) 262301.

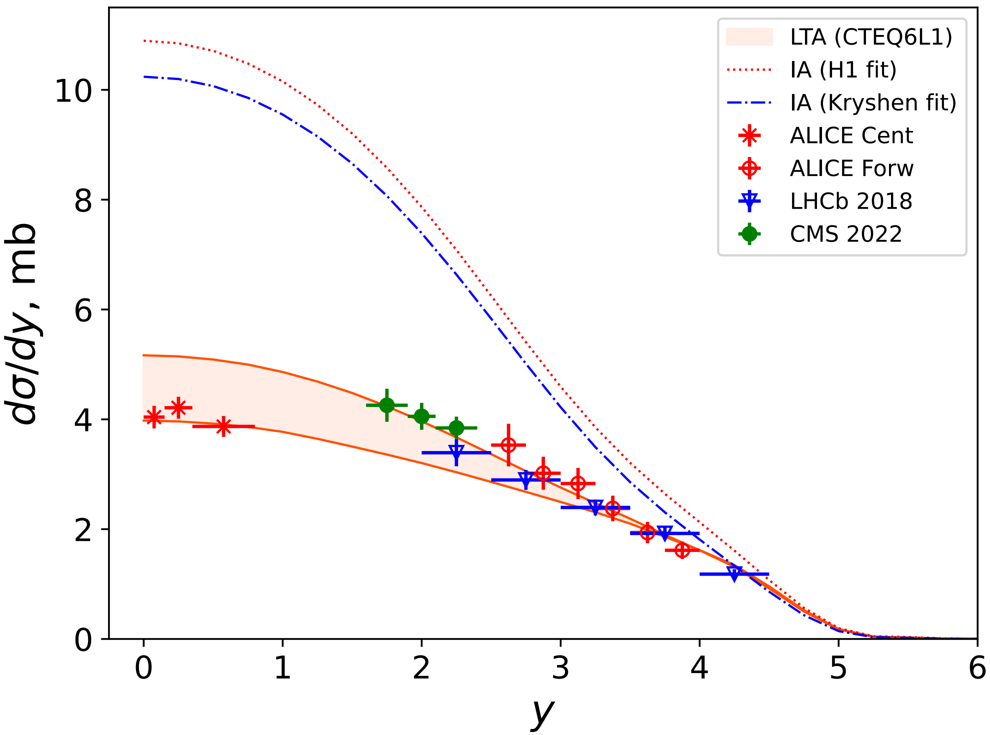
- Electron-Ion Collider has potential to discriminate models of NS due to:

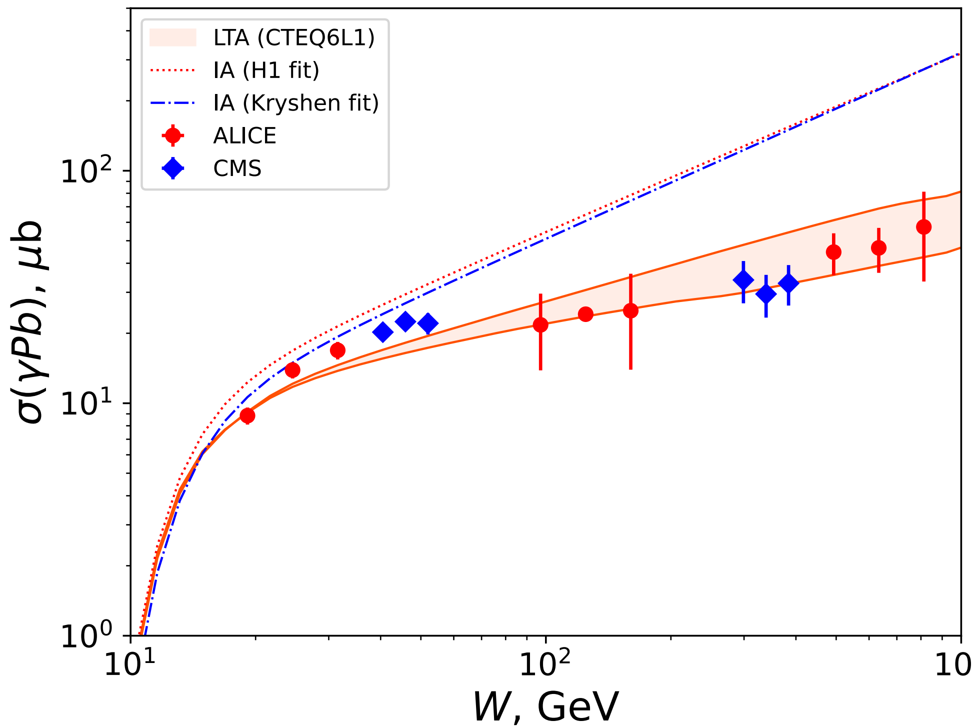
- wide x-Q^2 coverage
- measurements of the longitudinal structure function $F_L^A(x,Q^2)$ sensitive to gluons
- measurements of diffraction in eA DIS

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]; **O. Villalobos Baillie talk on Tuesday**





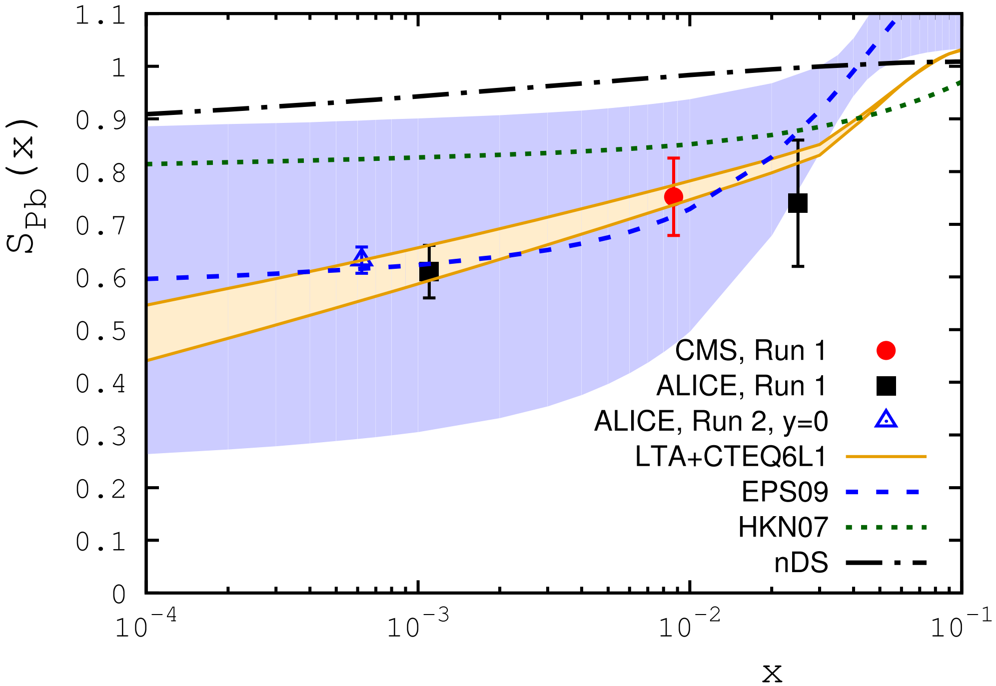
- Small-x nuclear shadowing down to $x\sim10^{-5}$ is captured by LTA model.
- → also good description by EPPS21, nCTEQ15 down to $x\sim10^{-3}$.

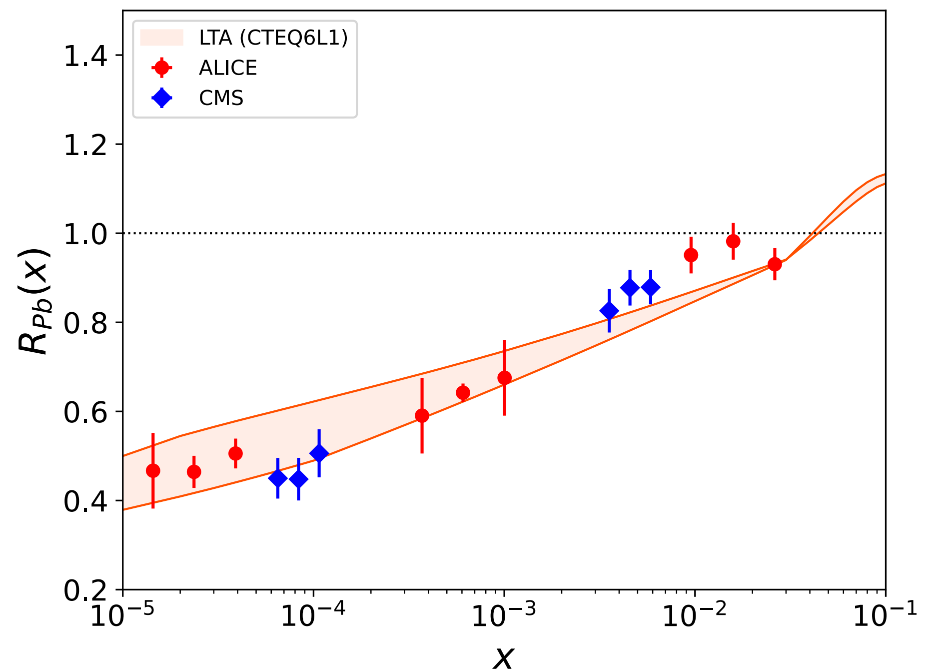
Nuclear suppression factor

- 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

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

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





- 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 $x{\sim}10^{-5}$ → 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 $\to$ 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

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

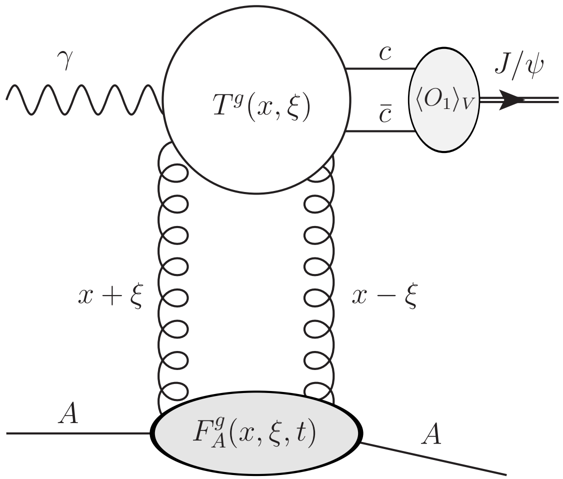
NRQCD matrix element from J/ψ leptonic decay

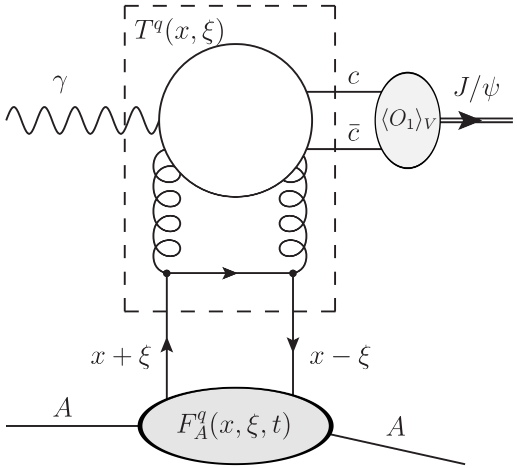
pQCD coeficient function

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

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

+ 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.

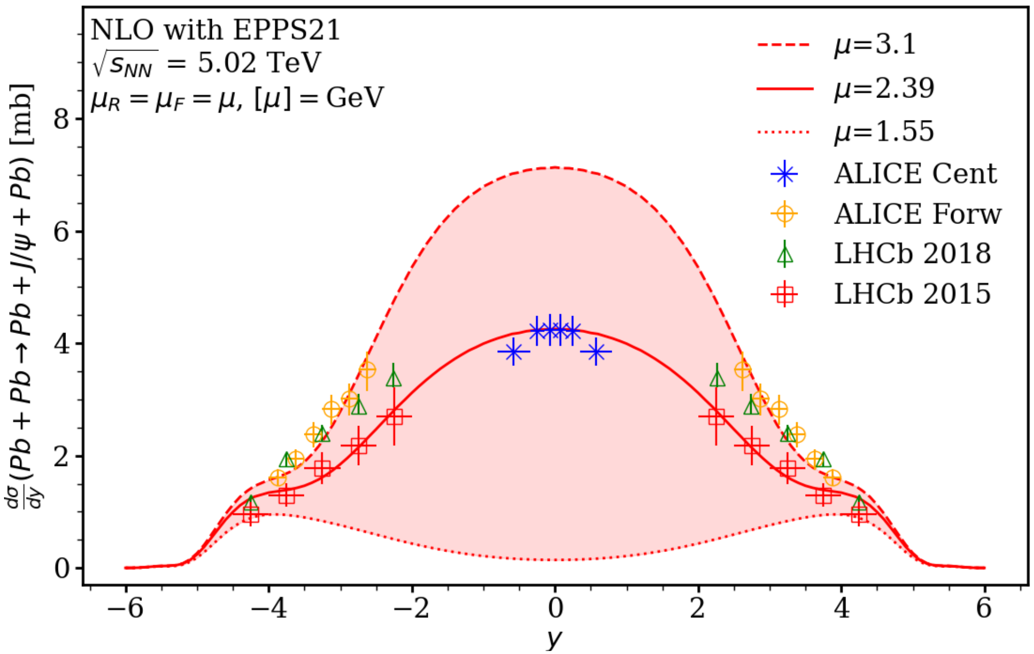
- Connection between GPDs is necessarily model-dependent. However, at small ξ, Q^2 evolution washes out information on input GPDs → GPDs in terms of PDFs, Shuvaev, Golec-Biernat, Martin, Ryskin, PRD 60 (1999) 014015; Dutrieux, Winn, Bertone, PRD 107 (2023) 11, 114019

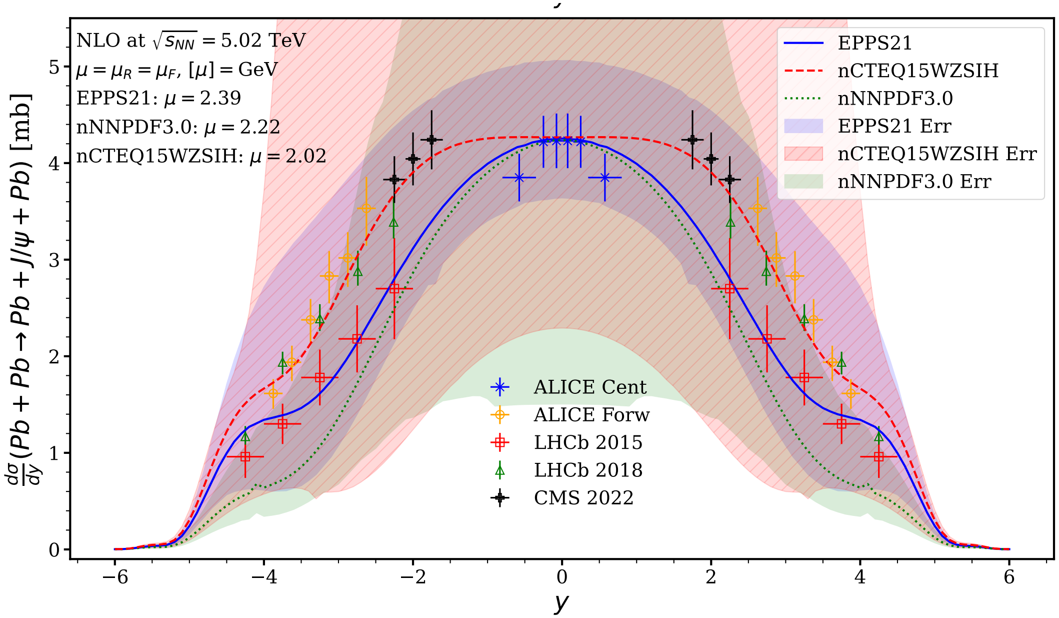
$$F_A^g(x,\xi,t,\mu_F)=xg_A(x,\mu_F)F_A(t)$$

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.

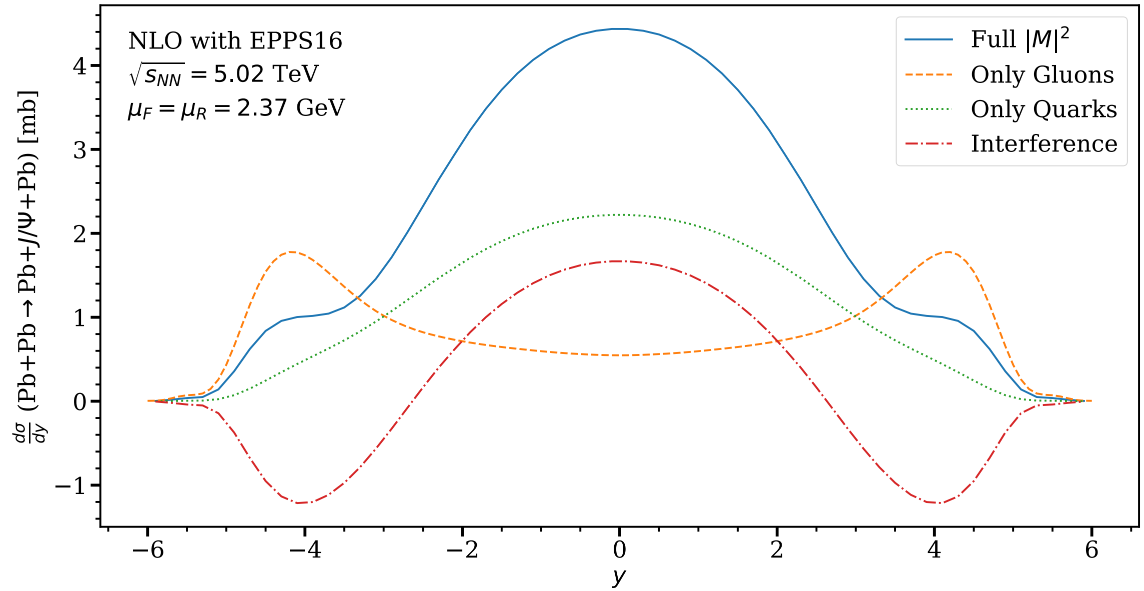
- Uncertainties due nPDFs are quite significant → opportunity to reduce them using these data.

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

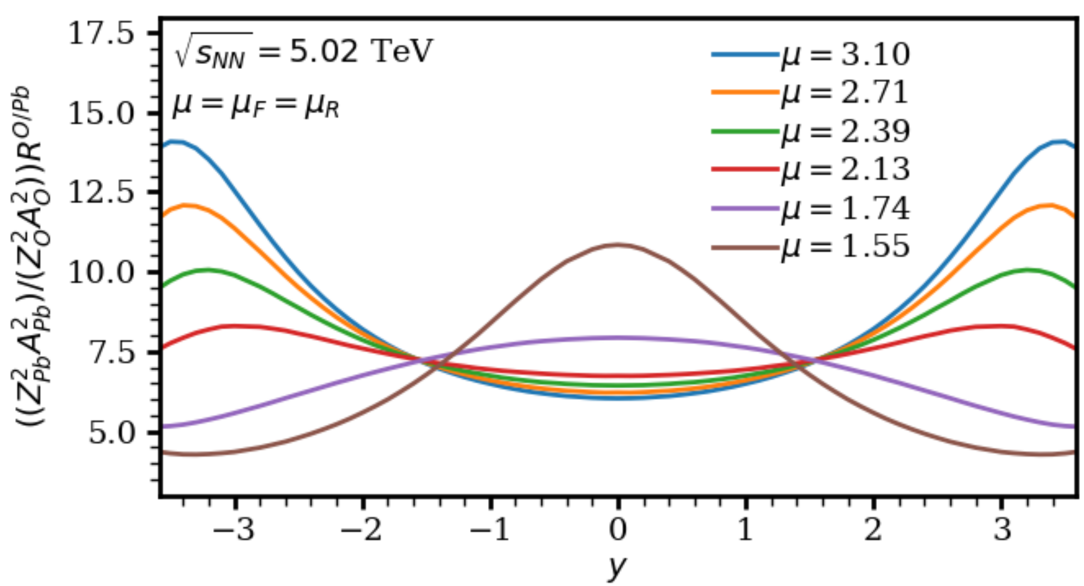
- Consequence of very large NLO corrections → dominance of quark contribution for |y|<2 due to strong cancellations between LO and NLO gluons, Eskola, Flett, Guzey, Löytäinen, Paukkunen, PRC 106 (2022) 3, 035202



- 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:

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

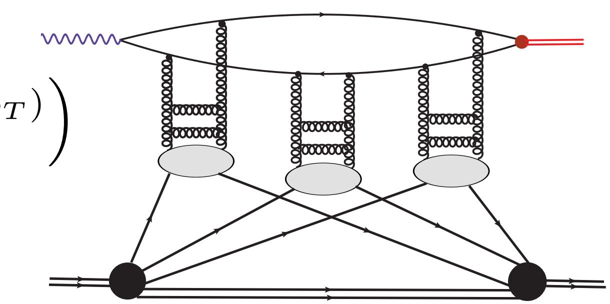


Eskola, Flett, Guzey, Löytäinen, Paukkunen, PRC 107 (2023) 4, 044912

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:



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

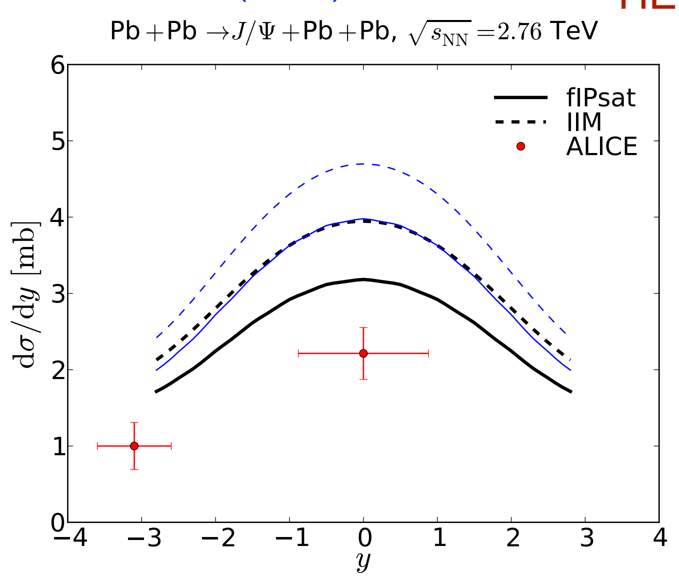
Overlap of photon (QED) and J/ψ (model) wf's

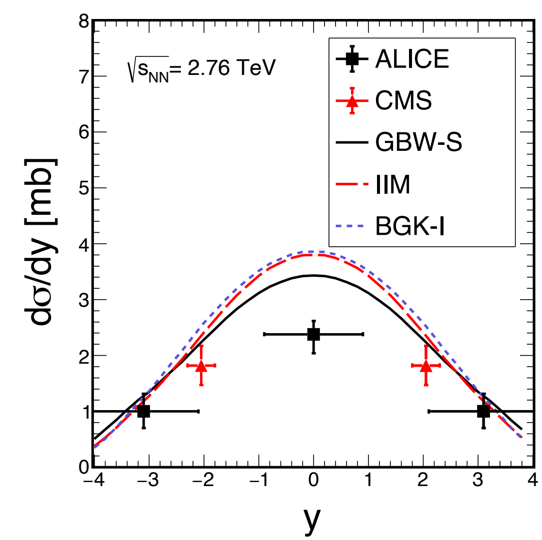
Dipole cross section from fits to HERA

Nuclear density

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

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





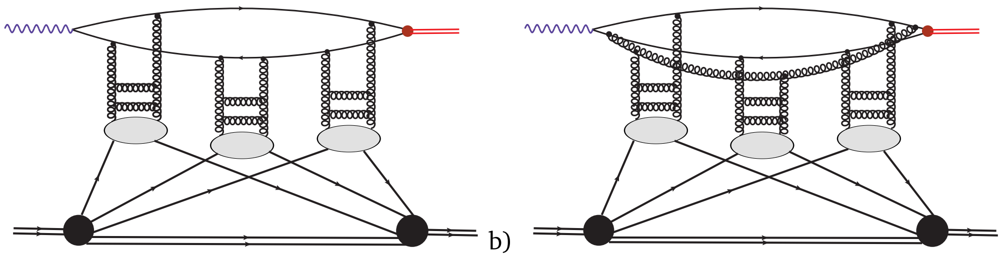
- This implementation over-predicts the data at y=0 since nuclear shadowing due to rescattering of small dipoles with $\langle r_T\rangle \sim 0.3$ fm is too weak.

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

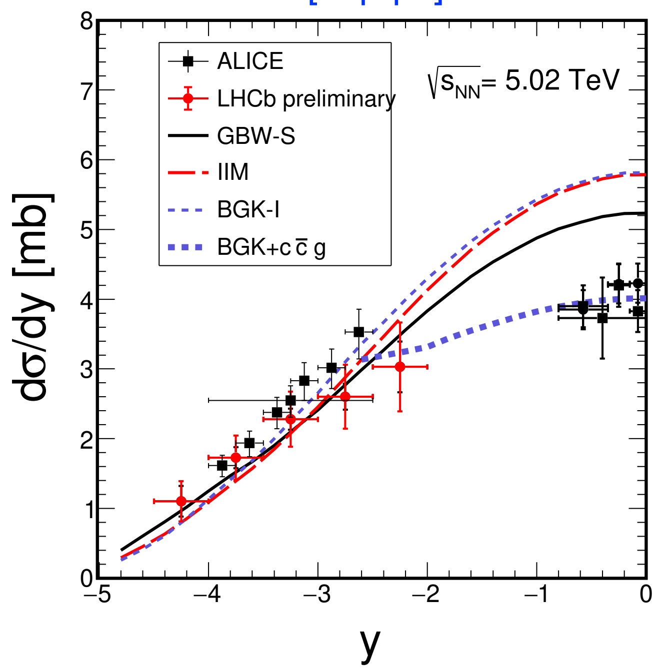
• Small-<r_T> $q\bar{q}$ dipoles provide higher-twist contribution to γ+A→J/ψ+A as well as to other nuclear observables, e.g. longitudinal structure function $F_L^A(x,Q^2)$,

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

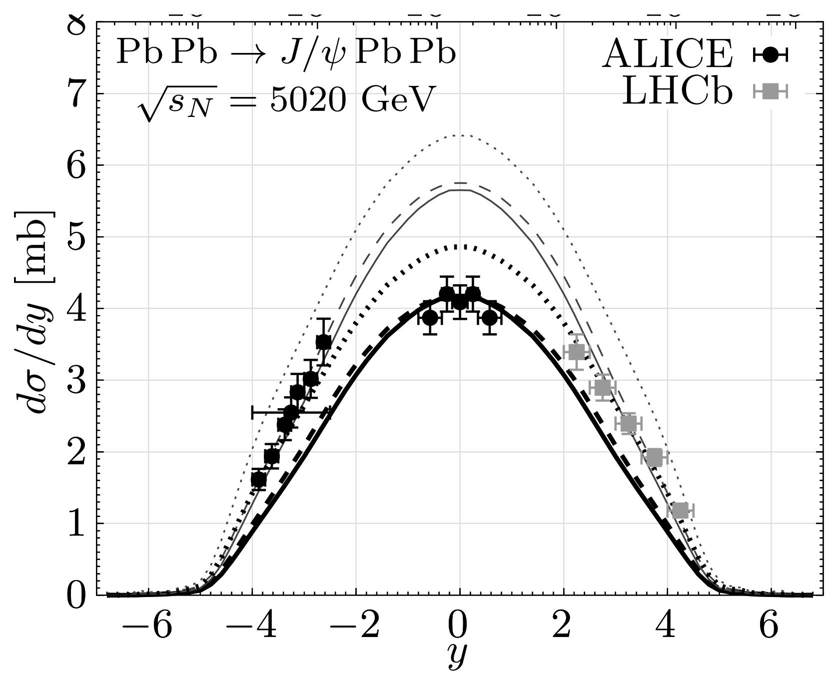
• Need to include higher $q\bar{q}g$ Fock states → modeling of 3-body "dipole" cross section and wave function.



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.

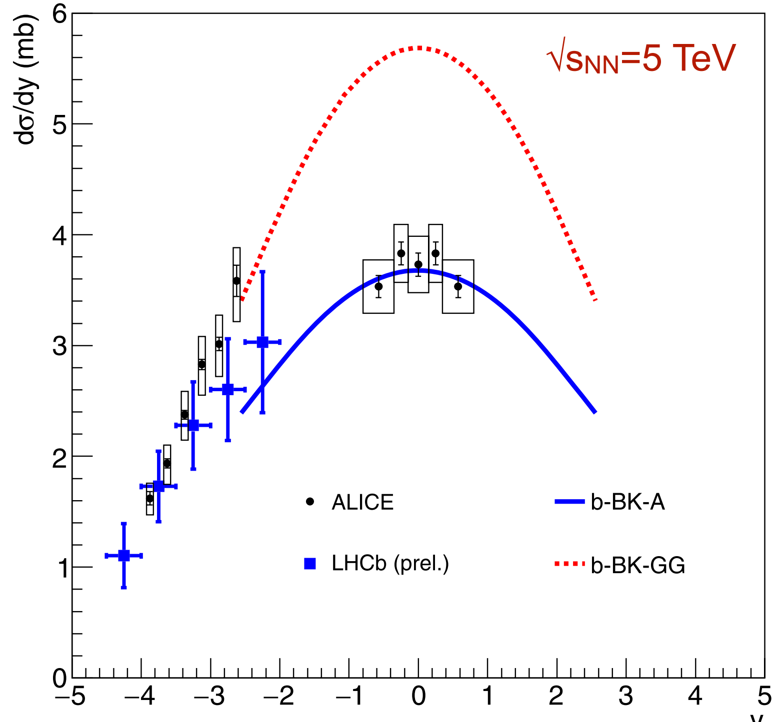
Dipole picture: saturation in nuclei

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

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

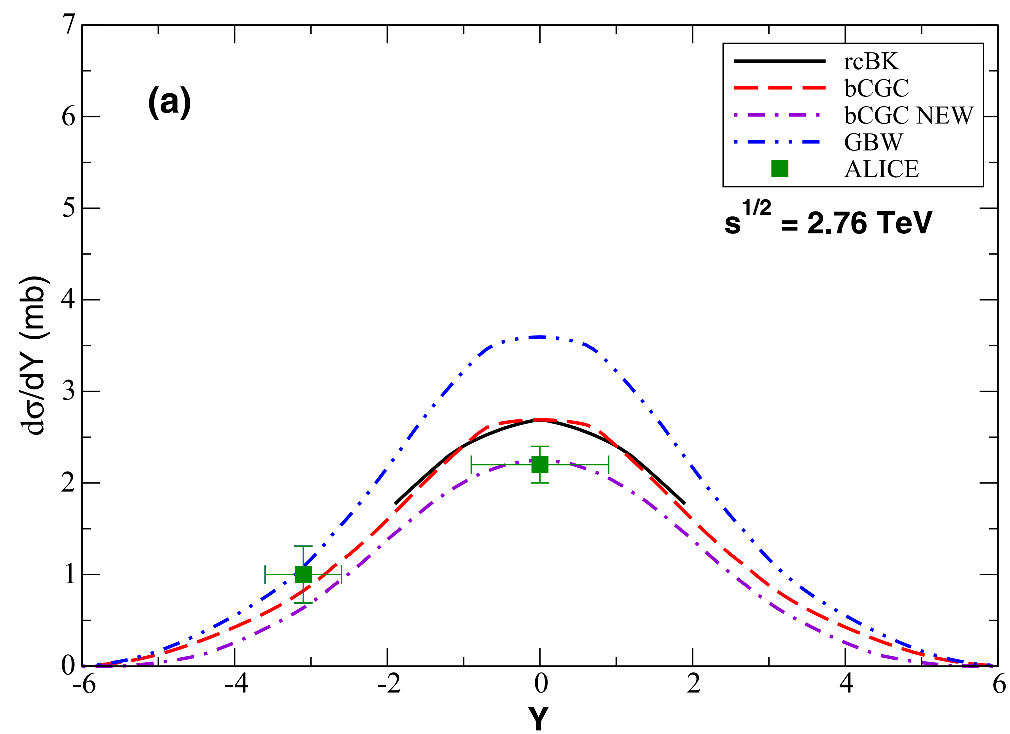
- Should be taken with grain of salt → predictions strongly depend on models for the dipole cross section and J/ψ wave function.

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

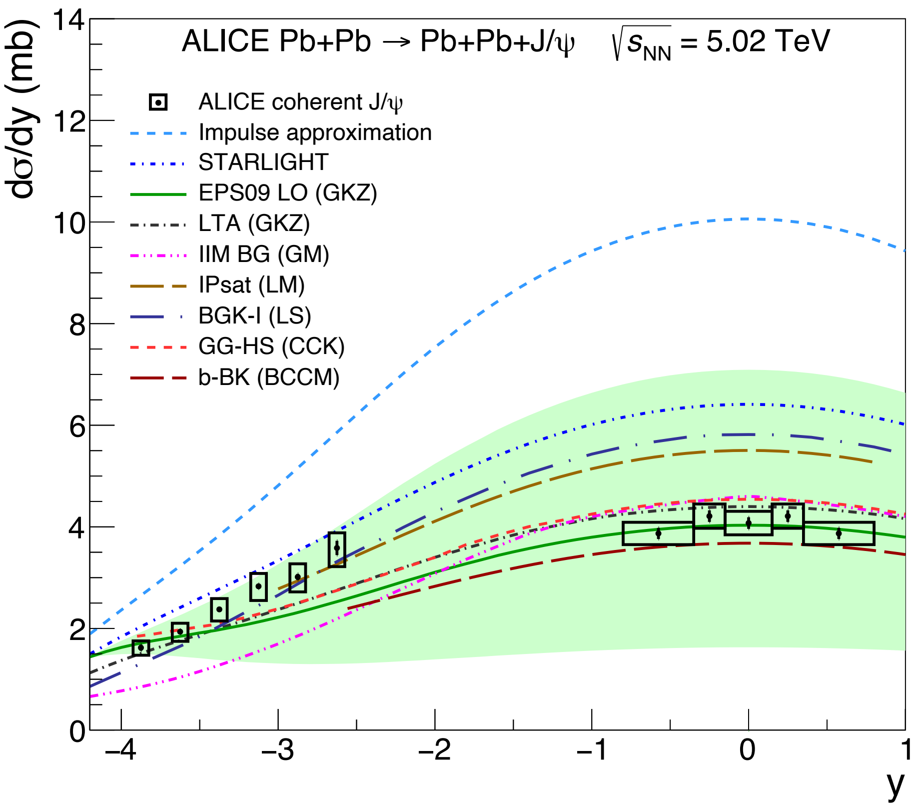


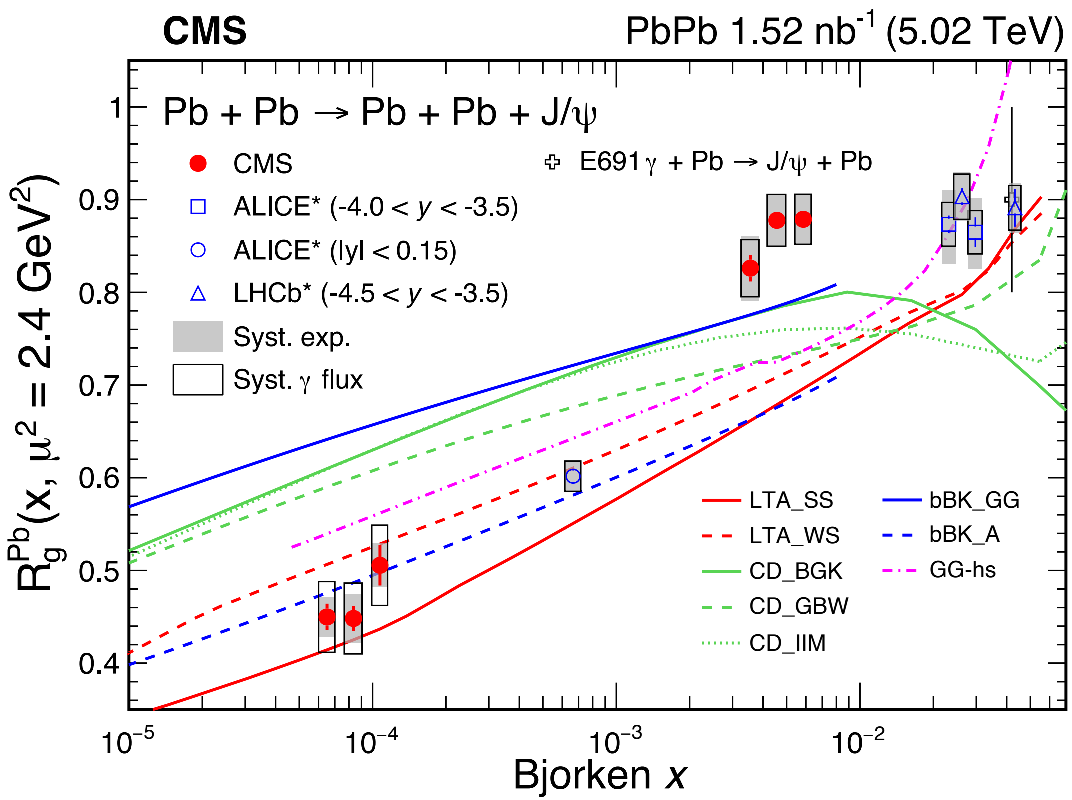
Shown Run 1 data: Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE]

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, importance of $q\bar{q}g$ dipoles, or a sign of saturation in nuclei.

- 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,…

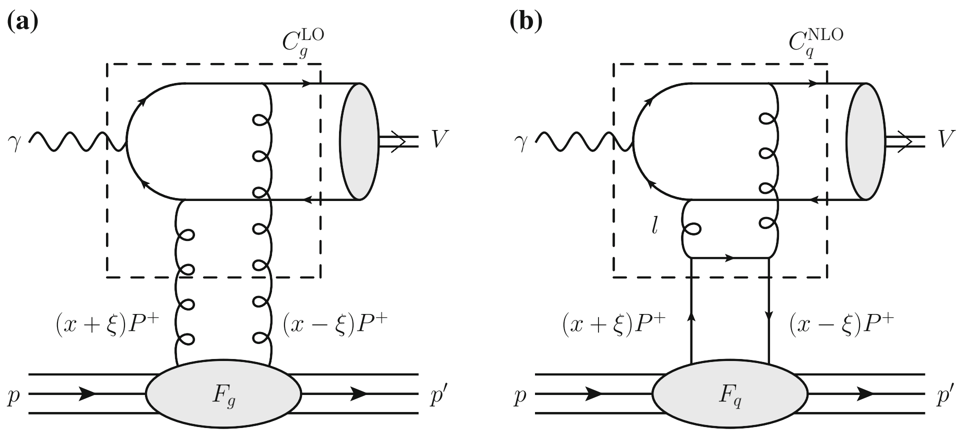
Tamed collinear factorization

- 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

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

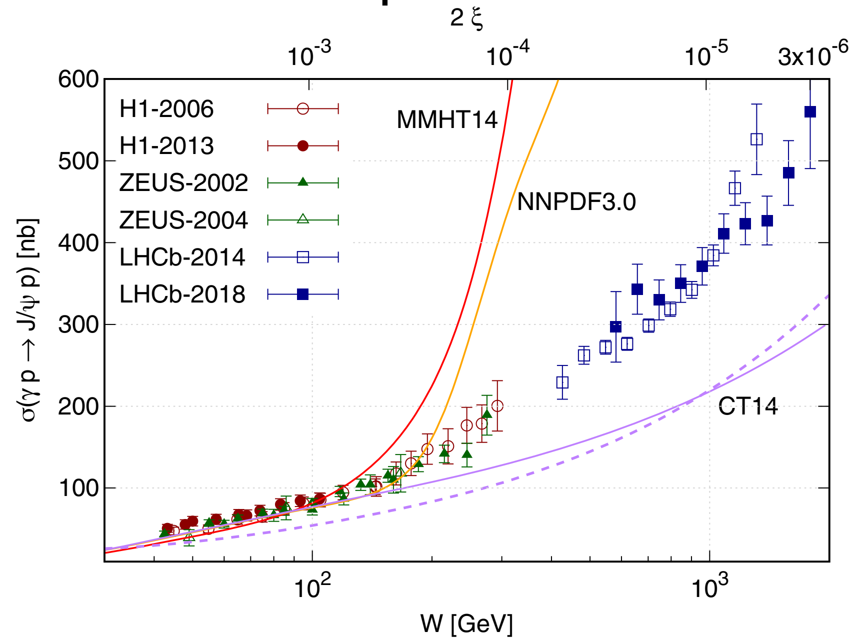
- Subtraction of $l_T < Q_0 \sim m_C$ contribution from NLO coefficient functions to avoid double counting (included in LO gluons) → Q_0 subtraction method, Jones, Martin, Ryskin, Teubner, EPJC 76 (2016) 633



- 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

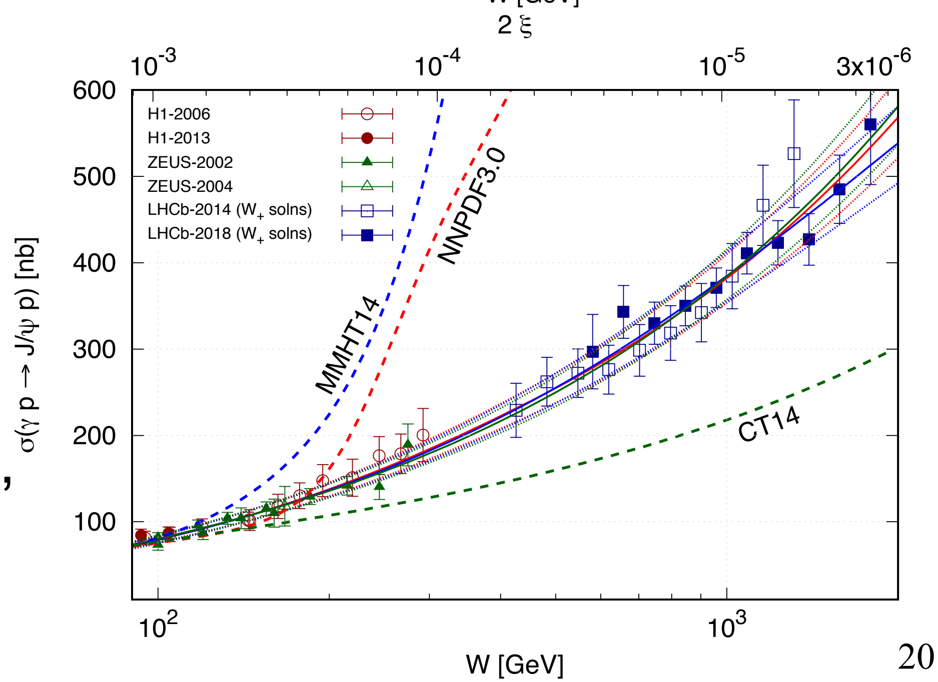
- Predictions are stable, but description of LHCb data is poor.

- 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.

Summary and Outlook

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

• The data challenges both collinear factorization and dipole model frameworks.

• Strong nuclear suppression of coherent J/ψ photoproduction in Pb-Pb UPC → large gluon shadowing at small x, $q\bar{q}g$ dipoles, or a sign of saturation in nuclei → important to test in ϒ photoproduction, where theory predictions are cleaner.

• J/ψ photoproduction in pp UPCs constrains $g_p(x,Q^2)$ down to x~10^{-6}.

• Extraction of nuclear PDFs is feasible using ratios of AA/pp UPCs cross sections, where strong scale dependence, modeling of GPDs, and relativistic corrections partially cancel.

• The outstanding challenges are the consistent treatment of J/psi vertex in NRQCD ($q\bar{q}$ and $q\bar{q}g$ distribution amplitudes) and taming of small-ξ behavior of NLO coefficient functions.

• I didn't have time to cover t-dependence and incoherent J/ψ photoproduction in Pb-Pb UPCs → complement. constraints on shadowing in LT and dipole pictures.