UPCs as probes of partonic structure — exclusive and inclusive processes

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AoF CoE in Quark Matter

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Outline:

- Brief introduction to ultraperipheral collisions (UPCs)
- Exclusive J/ψ and Υ photoproduction in UPCs@LHC:
  - collinear factorization and NLO pQCD
  - dipole picture
- Inclusive dijet photoproduction in Pb-Pb UPCs@LHC
- Summary and Outlook

11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Aschaffenburg, Germany, 26-31 March, 2023

Ultraperipheral collisions as photon-hadron collider

- Important part of physics program at the LHC and RHIC.

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

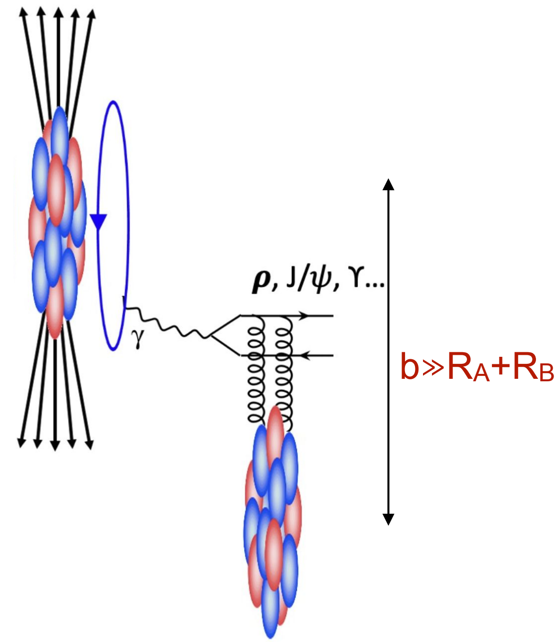


Figure credit: A. Stahl, LPCC CERN Seminar, 6.12.2022

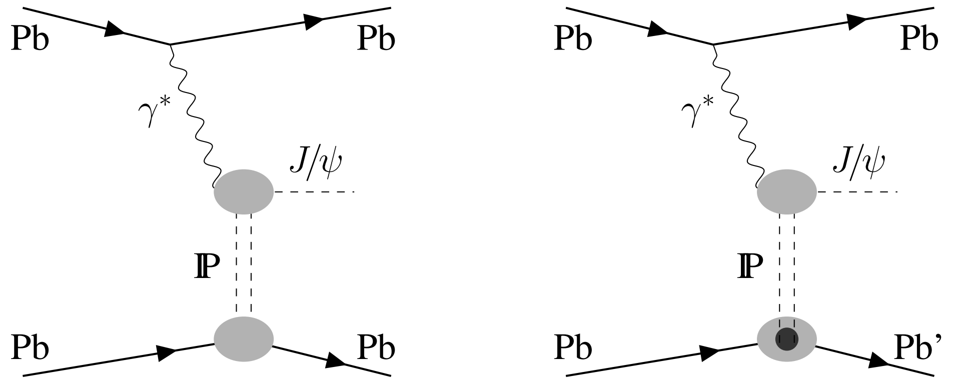
- Photon flux ~ Z^2 and photon energy $k \sim \gamma_L$ → $\gamma\gamma$, γp, γA scattering at high energies → $W_{\gamma p}$=5 TeV, $W_{\gamma A}$=700 GeV/A, $W_{\gamma\gamma}$=4.2 TeV at the LHC.

- Real photons in UPCs are probes of nucleus and proton partonic structure and strong interaction dynamics in small-x QCD.

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

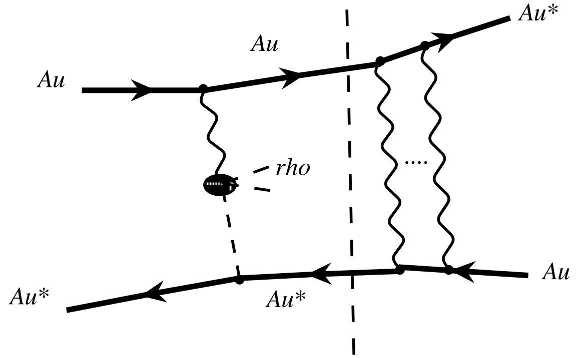
Coherent and incoherent scattering in UPCs

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



UPCs have distinct experimental signatures → two leptons from J/ψ decay in otherwise empty detector.

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



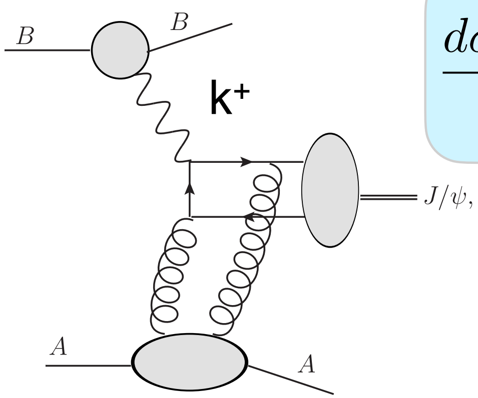
Ions de-excite by emitting neutrons detected in ZDCs

• Coherent and incoherent scattering can be accompanied by mutual e.m. excitation of ions followed by forward neutron emission, Pshenichnov et al, PRD 64 (2001) 1; Baltz, Klein, Nystrand, PRL 89 (2002) 01230.

• UPCs in different channels (0n0n, 0nXn, XnXn) allow one probe lower x, Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942; CMS PAS HIN-22-002; Kryshen, Strikman, Zhalov, 2303.12052 [hep-ph]; **R. Lavicka talk 28.03.2023, W. Li talk 29.03.2023**

Exclusive J/ψ photoproduction in UPCs

- Cross section of exclusive, coherent J/ψ photoproduction in AA UPCs → two terms corresponding to high photon energy k^+ (low-x_A) and low k^- (high-x_A) → ambiguity in relating J/ψ rapidity y to gluon momentum fraction x_A.



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

Photon flux from QED+Glauber-model suppression for b<2R_A

Photoproduction cross section

$$k^{\pm} = \frac{M_{J/\psi}}{2}e^{\pm y}$$

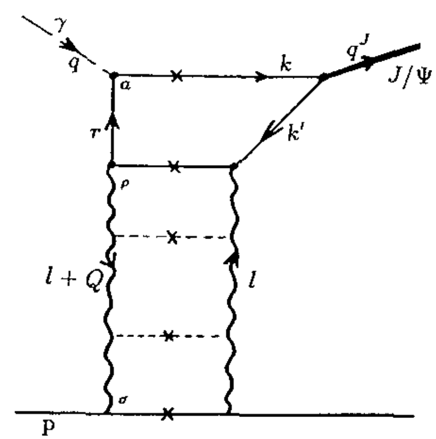
- In leading $\ln(Q^2)\ln(1/x)$ double logarithmic approximation of perturbative QCD and non-relativistic approximation for J/ψ wave function, Ryskin, Z. Phys. C57 (1993) 89

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

Γ_V is J/$\psi \to \ell^+\ell^-$ leptonic decay width

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

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



Constraints on small-x gluon shadowing

• Application to nuclear targets:

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

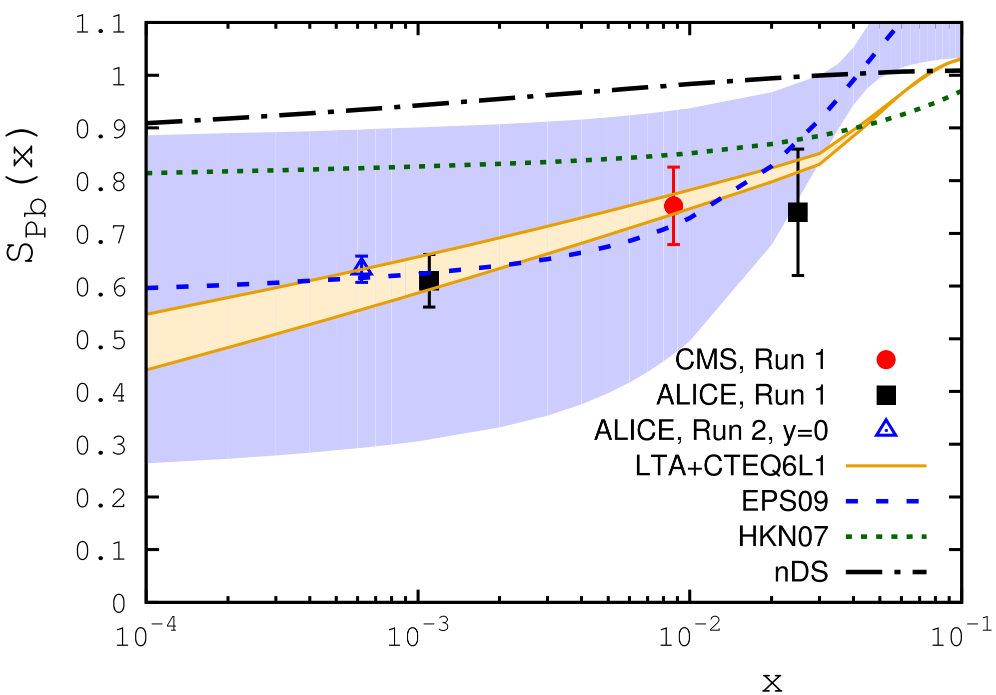
From fit to HERA and pp/pA UPC data

Ratio of nucleus and proton gluon densities

Nuclear form factor

• Well-defined impulse approximation (IA) → nuclear suppression factor S_{Pb},
Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290; Guzey, Zhalov, JHEP 1310 (2013) 207

$$\sigma_{\rm IA}^{\gamma A\to J/\psi A}(W) = \frac{d\sigma^{\gamma p\to J/\psi p}(W,t=0)}{dt}\int_{|t_{\min}|}^{\infty} dt|F_A(t)|^2 \longrightarrow S_{Pb}(W) = \left[\frac{\sigma^{\gamma A\to J/\psi A}(W)}{\sigma_{\rm IA}^{\gamma A\to J/\psi A}(W)}\right]^{1/2} = \frac{g_A(x,\mu^2)}{Ag_p(x,\mu^2)}$$



• Model-independent* extraction of S_{Pb} from UPC@LHC data, 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], EPJC 81 (2021) 8, 712

• Direct evidence of significant gluon shadowing, $R_g(x=6\times10^{-4} - 0.001) \approx 0.6$ in agreement with LTA model, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255 and EPS09, EPPS16 and nCTEQ15 nPDFs.

Exclusive J/ψ photoproduction in NLO pQCD

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

• γA → 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

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

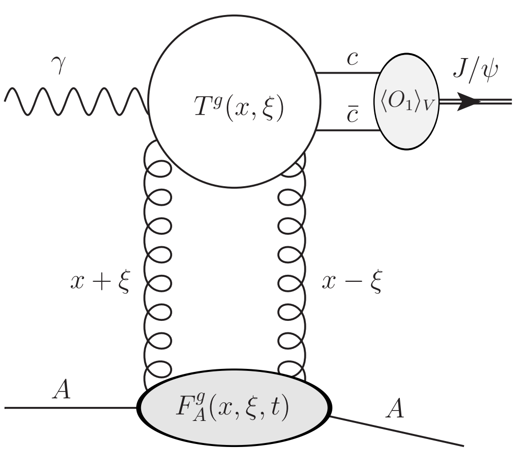
NRQCD matrix element from J/ψ leptonic decay

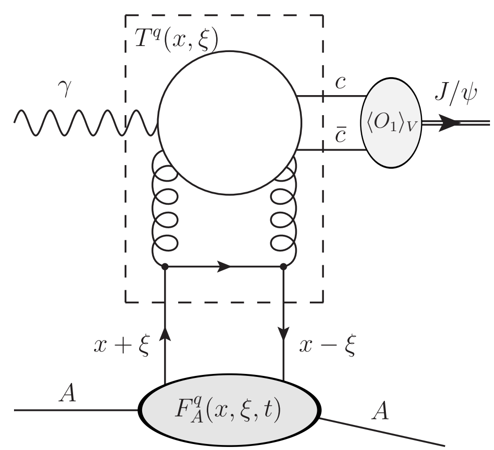
pQCD coeficient function

Gluon GPD

Quark contribution

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





$$\xi \approx \frac{M_{J/\psi}^2}{2W^2} \ll 1$$

GPDs at small ξ ≈ PDFs

- GPDs are hybrid distributions interpolating between usual PDFs, distribution amplitudes and form factors → depend on momentum fractions x and ξ, mom. transfer t, and scale μ → connection to PDFs and is model-dependent.

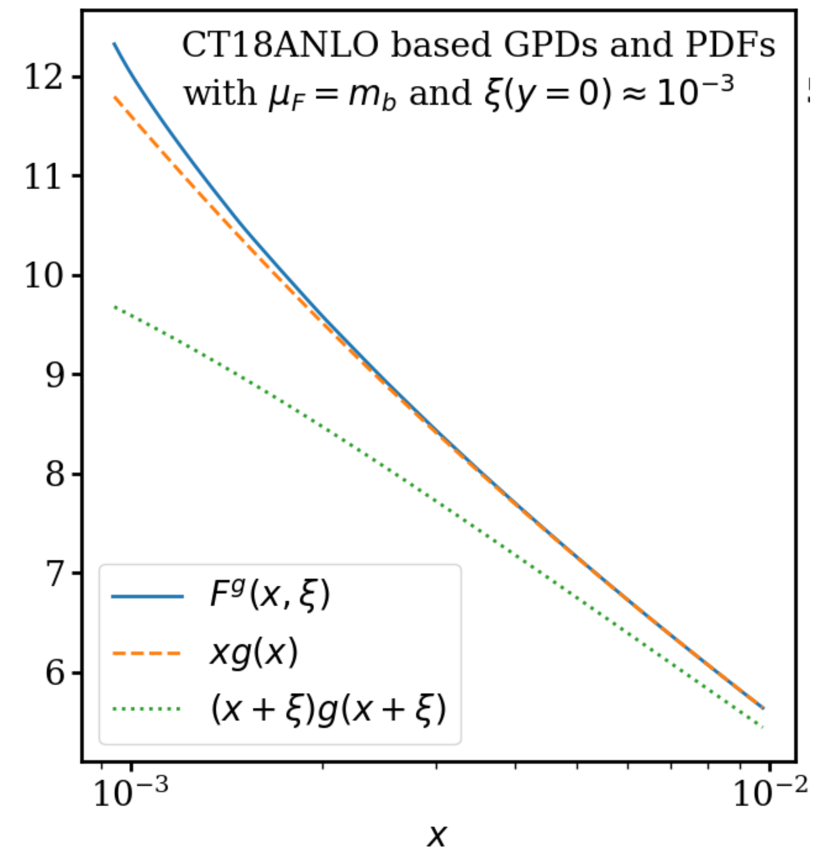
- However, at small ξ, GPDs can be expressed in terms of PDFs because μ^2 evolution washes out information on ξ-dependence, Shuvaev, Golec-Biernat, Martin, Ryskin, PRD 60 (1999) 014015; Dutrieux, Winn, Bertone, arXiv:2302.07861 [hep-ph].

- Numerically, with a few % accuracy, one can use for nuclear GPDs, Eskola, Flett, Guzey, Löytäinen, Paukkunen, arXiv:2303.03007 [hep-ph]

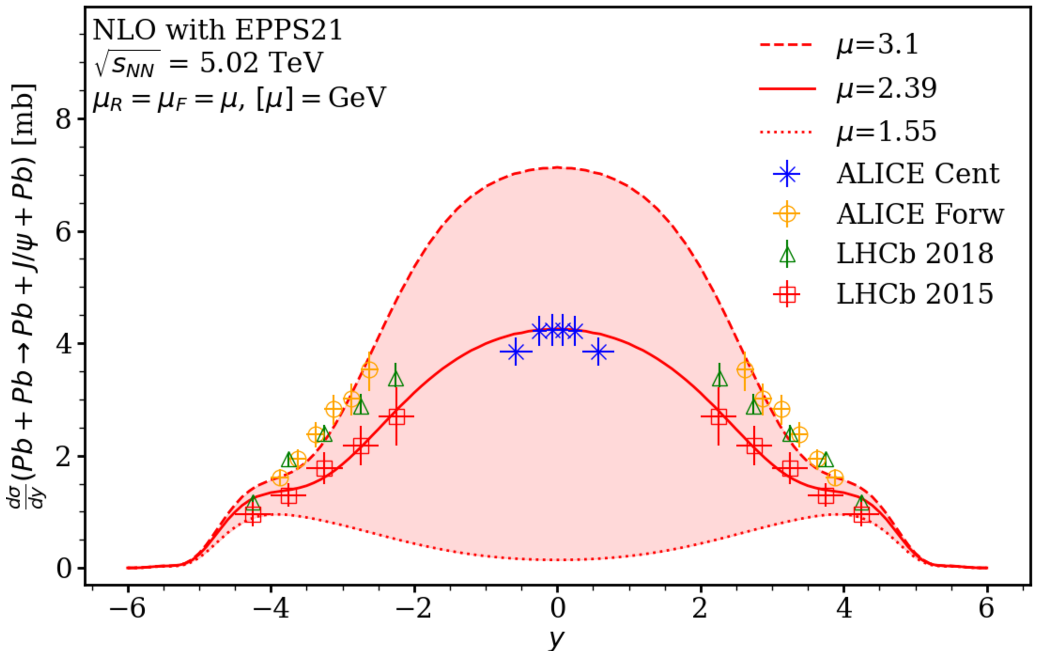
$$F_A^g(x,\xi,t,\mu_F) = x g_A(x,\mu_F) F_A(t)$$

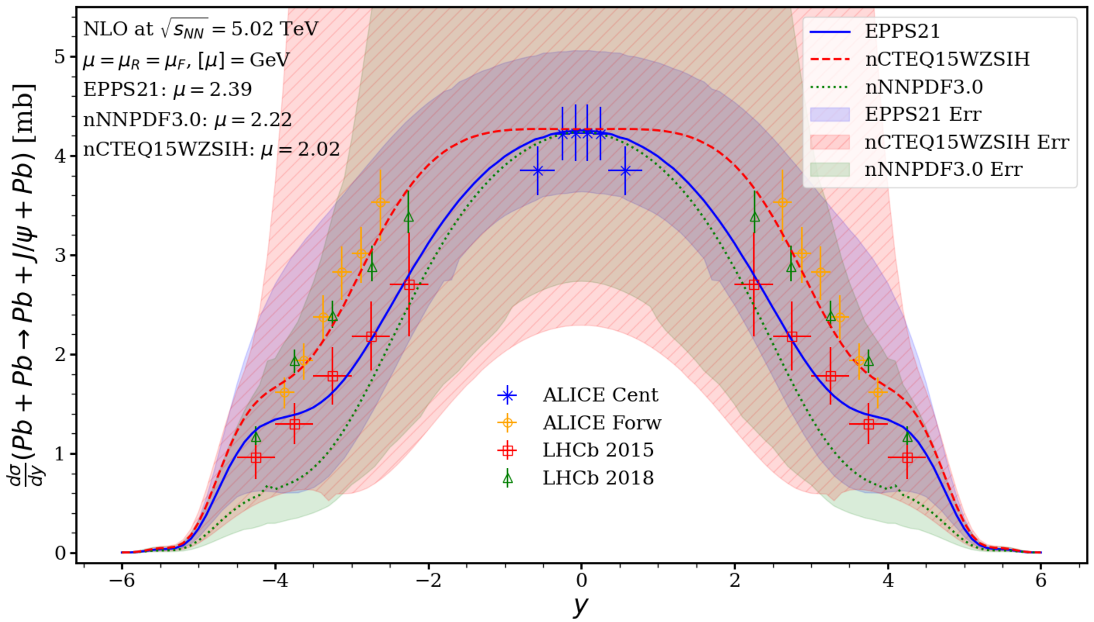
↙ Nuclear PDFs (EPPS16, EPPS21, nCTEQ15 nNNPDF3.0)

↘ Nucleus form factor (Woods-Saxon)



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





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

- 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.

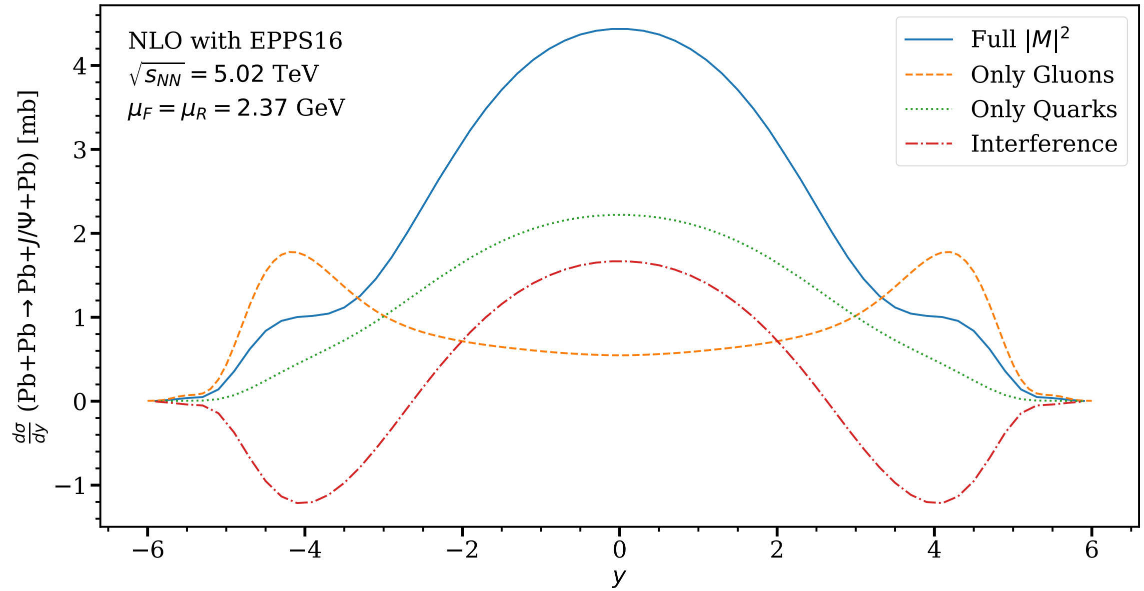
- Uncertainties due nPDFs are quite significant → opportunity to reduce them using these data.

Eskola, Flett, Guzey, Löytäinen, Paukkunen, PRC 106 (2022) 3, 035202 and arXiv:2210.16048 [hep-ph]

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

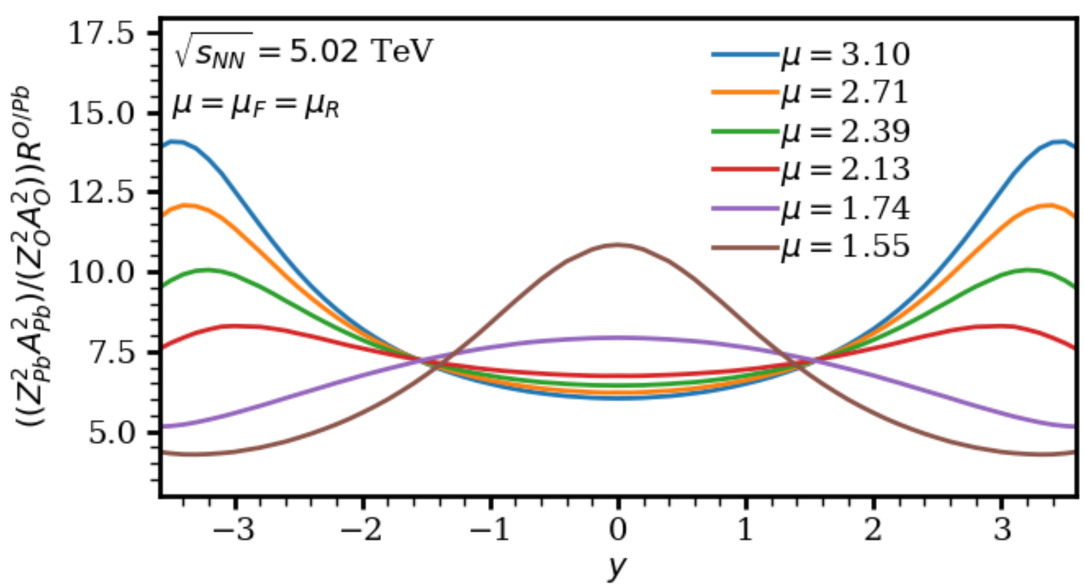
- Consequence of very large NLO corrections → dominance of quark contribution for |y|<2 due to strong cancellations between LO and NLO gluons, Eskola, Flett, Guzey, Löytäinen, Paukkunen, PRC 106 (2022) 3, 035202



- At face value, this complicates interpretation of the 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:

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



Eskola, Flett, Guzey, Löytäinen, Paukkunen, arXiv:2210.16048 [hep-ph]

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 cross section, GPD modeling benefits from longer μ^2 evolution up to bottom quark mass $\mu=m_b$, relativistic effects smaller.

• 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.

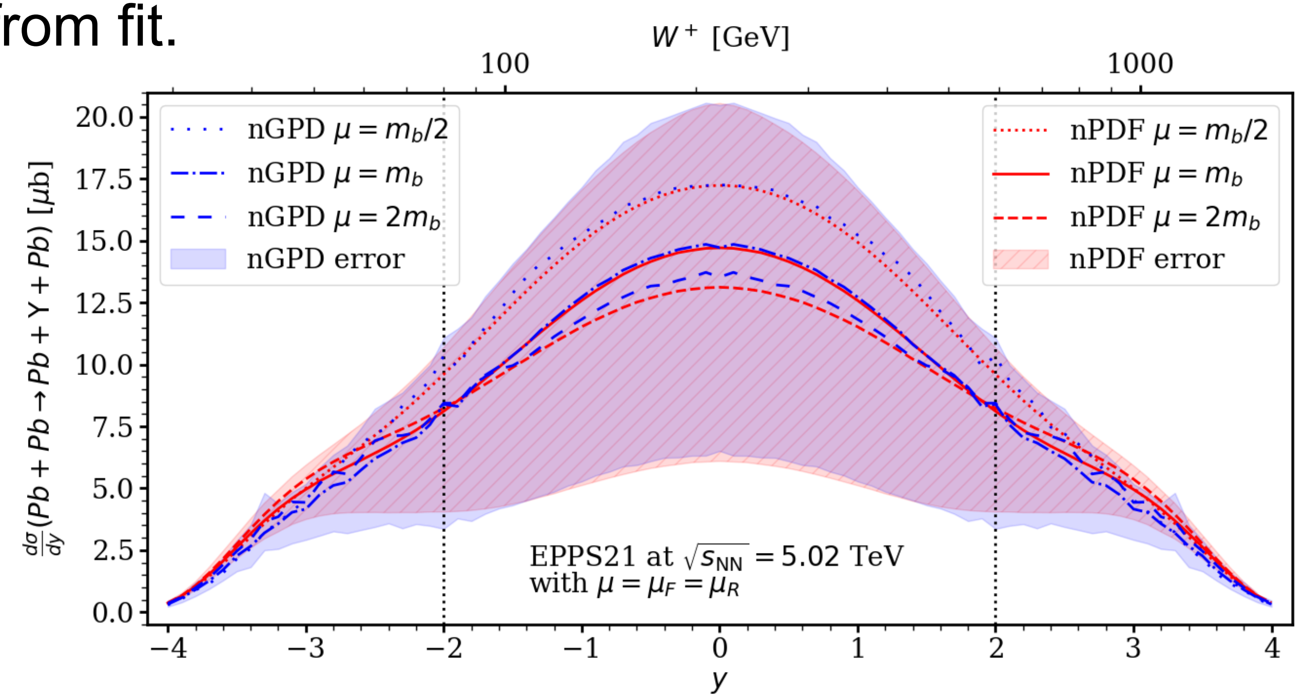
• Data-driven approach: NLO pQCD for the ratio of nucleus and proton cross sections + proton cross sect. from fit.

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

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

• Dependence on modeling of nuclear GPDs is eliminated → important for nPDF phenomenology.

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



Tamed collinear factorization: gluons in proton

- Stability of perturbation series for exclusive J/ψ photoproduction in NLO pQCD can be improved by "resummation" of $\ln(m_c^2/\mu_F^2)\ln(1/\xi)$ terms and Q_0 subtraction, Jones, Martin, Ryskin, Teubner, J. Phys. G 43 (3) (2016) 035002 and EPJC 76 (2016) 633.

- Restores the gluon dominance and allows for sensible comparison to HERA and UPC data on $\gamma+p\to J/\psi+p$, Flett, Jones, Martin, Ryskin, Teubner, PRD 101 (2020) 9, 094011.

- Allows to use the data to extract gluon PDF at small x, Flett, Martin, Ryskin, Teubner, PRD 102 (2020) 114021

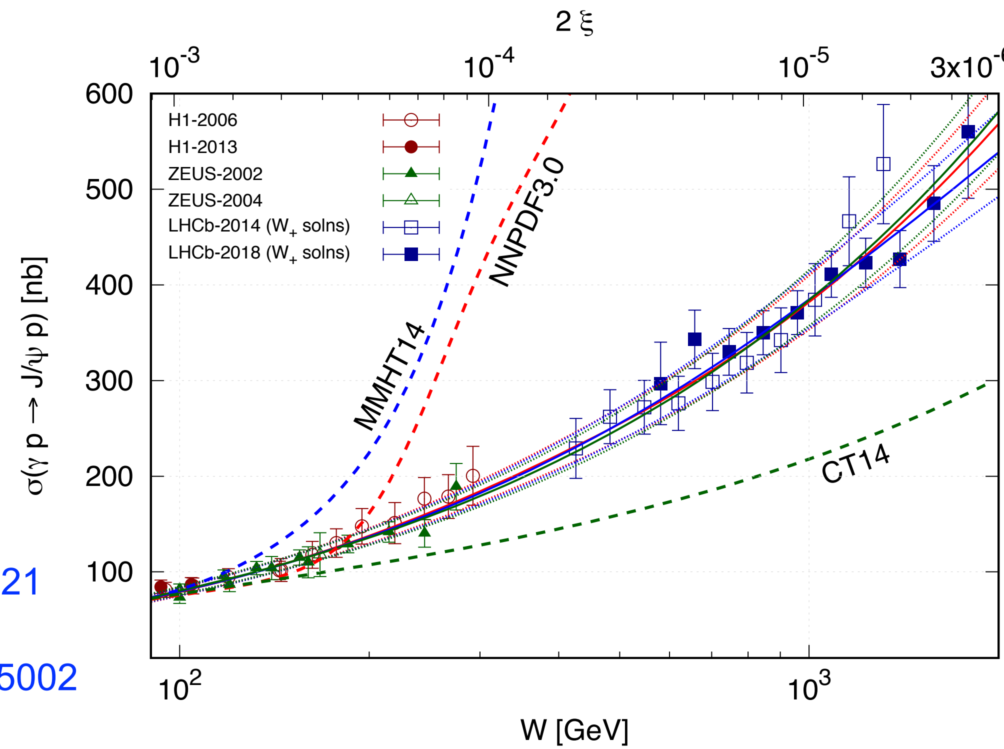
$$xg(x,\mu_0^2) \;=\; C\; xg^{\rm global}(x,\mu_0^2) \;+\; (1-C)\; xg^{\rm new}(x,\mu_0^2)$$

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

- Constraints on xg_p for $3\times10^{-6}<x<10^{-3}$

- No signs of saturation

- Predictions for Υ, Flett, Jones, Martin, Ryskin, Teubner, PRD 105 (2022) 3, 034008; PRD 106 (2022) 7, 074021

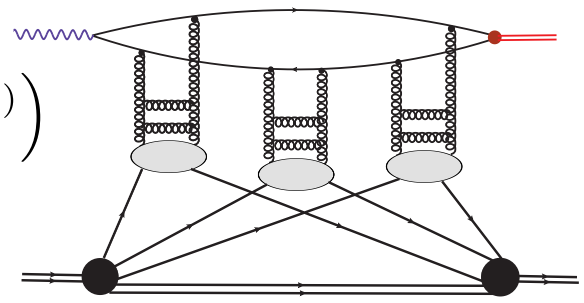


Shown LHCb data: Aaij et al [LHCb], J. Phys. G41 (2014) 055002 and JHEP 1810 (2018) 167.

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:



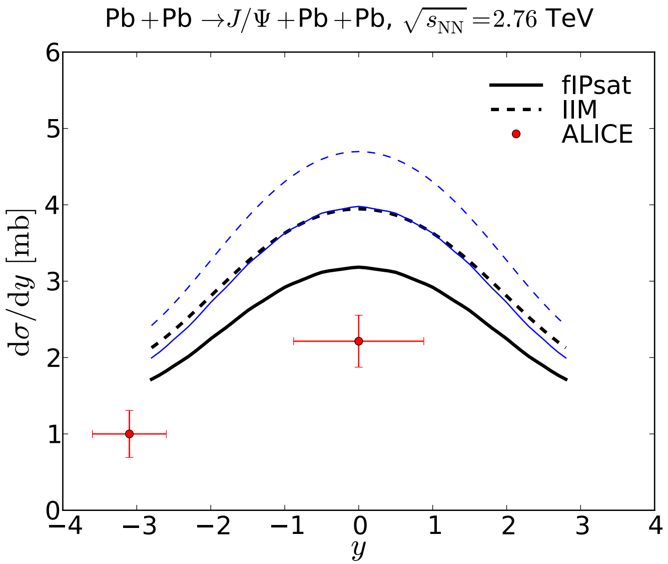
$$\mathcal{M}^{\gamma A\to J/\psi A} = \int d^2\mathbf{r}_T \int \frac{dz}{4\pi} \int d^2\mathbf{b}_T [\Psi^*_{J/\psi}\Phi_\gamma] 2\left(1 - e^{-\frac{1}{2}\sigma_{\rm dip}(\mathbf{r}_T)T_A(\mathbf{b}_T)}\right)$$

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

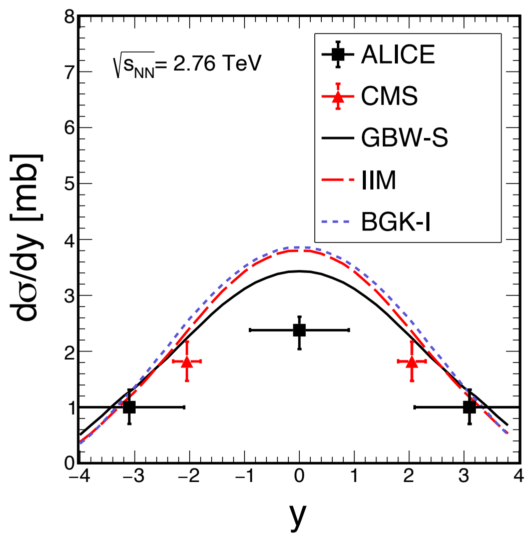
Dipole cross section from fits to HERA

Nuclear density

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



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



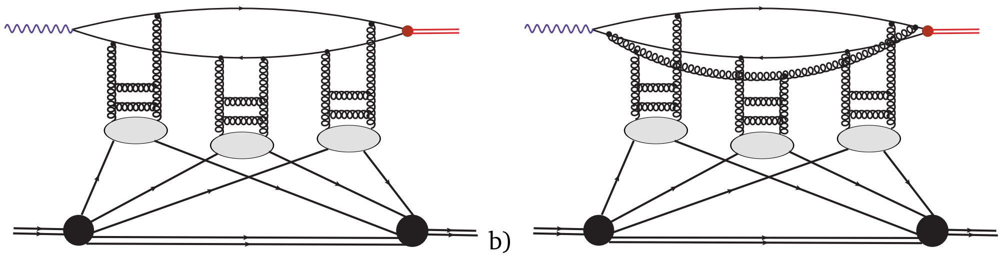
• This implementation over-predicts the data at y=0 → nuclear shadowing due to rescattering of small dipoles with $\langle r_T \rangle \sim 0.3$ fm is too weak.

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

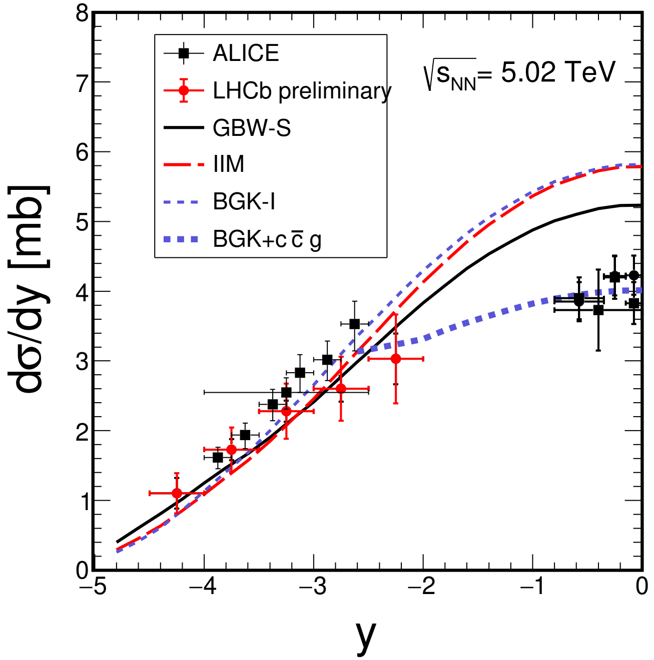
• Small-<r_T> $q\bar{q}$ dipoles provide higher-twist contribution to γ+A→J/ψ+A as well as to other nuclear observables, e.g. longitudinal structure function $F_L^A(x,Q^2)$,

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

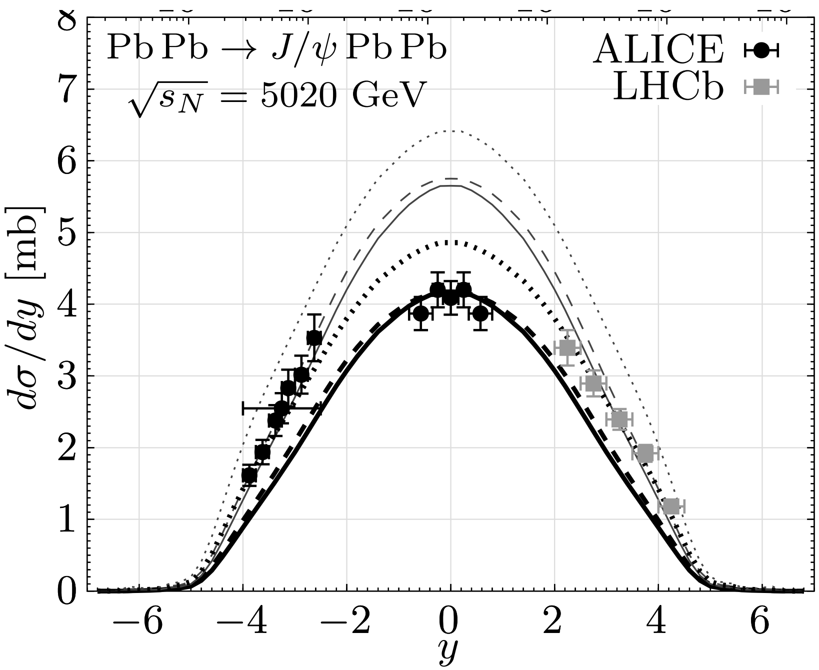
• Need to include higher $q\bar{q}g$ Fock states → 3-body "dipole" cross section and wave function.



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



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



• Good description of data → includes elastic and inelastic nuclear shadowing.

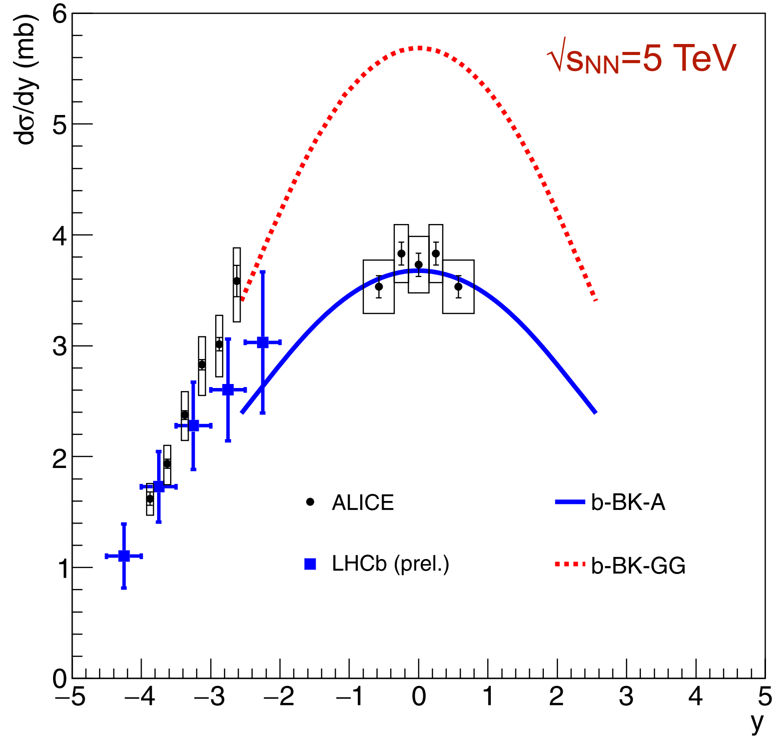
Dipole picture: saturation in nuclei

• Nuclear geometry in initial condition for Balitsky-Kovchegov equation → saturation in nuclei, but not necessarily in nucleons → good agreement with data.

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

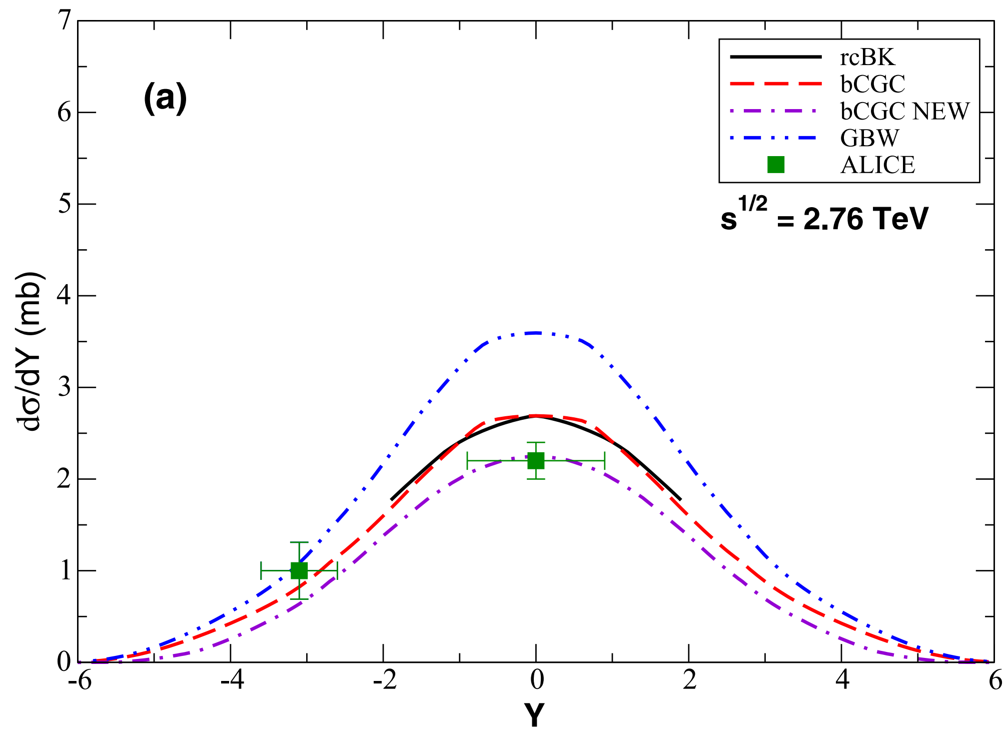
• Should be taken with grain of salt → predictions strongly depend on models for the dipole cross section and J/ψ wave function.

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

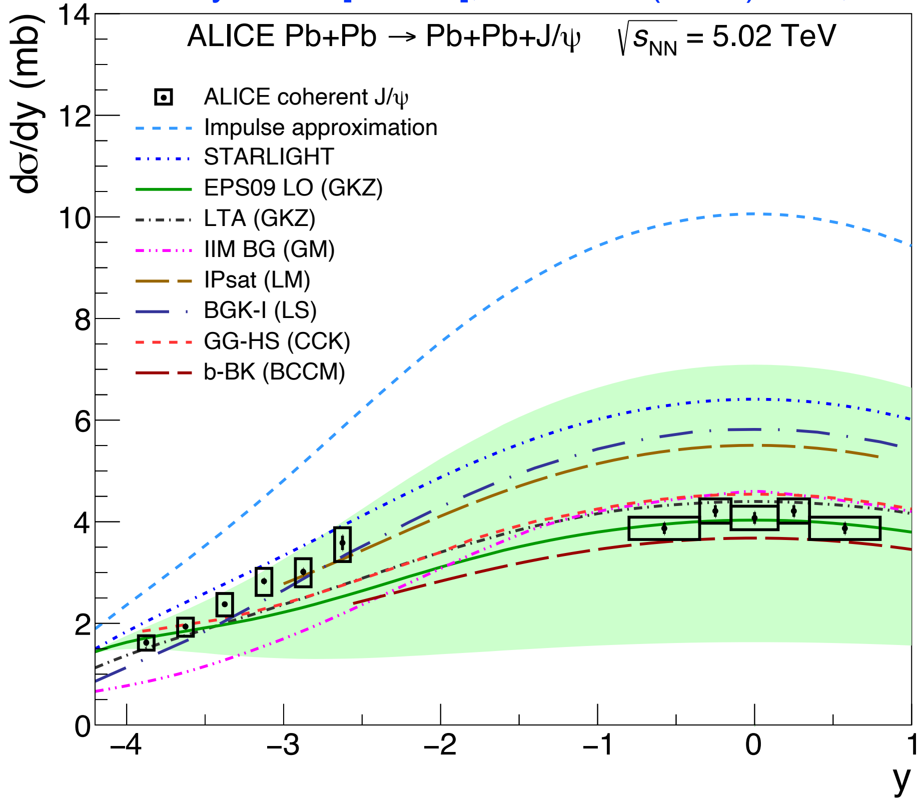
Goncalves, Moreira, Navarra, PRC 90 (2014) 015203



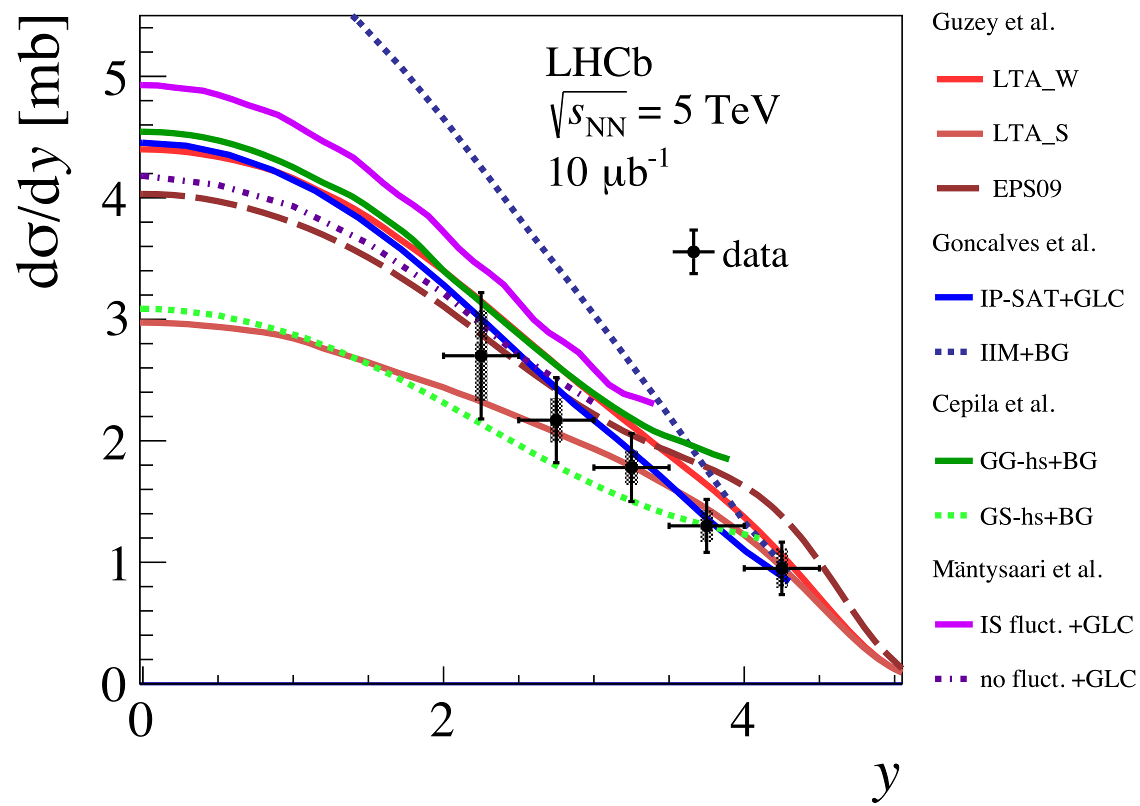
Shown Run 1 data: Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE]

Coherent J/ψ photoproduction in Pb-Pb UPCs

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



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



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

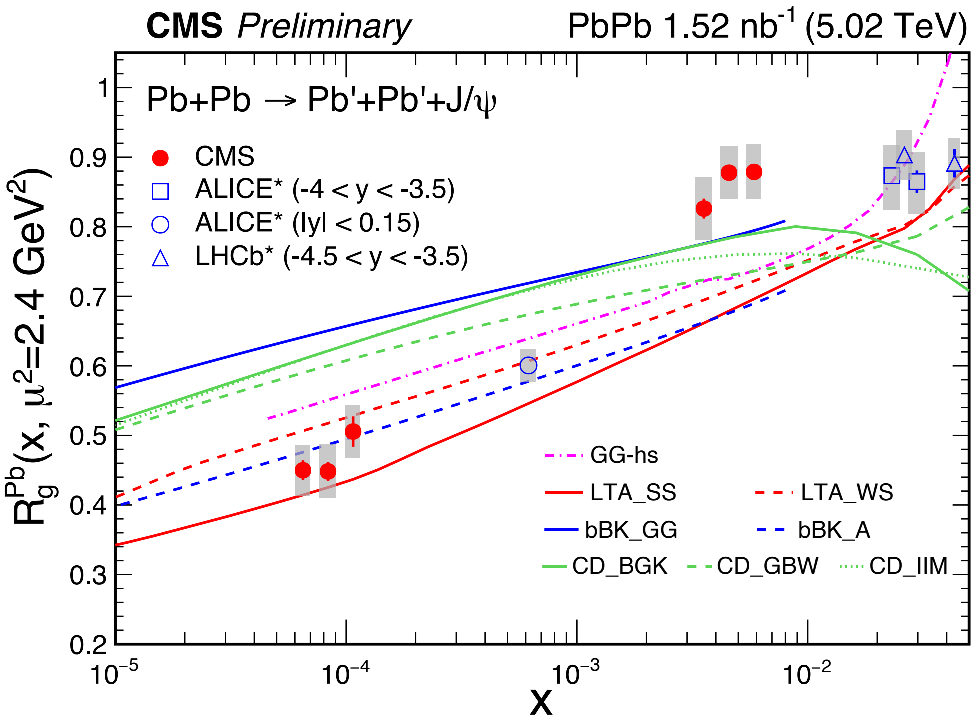
- Suppression at y=0 → strong leading-twist gluon/quark shadowing at small x, role of qq̄g dipoles, or a sign of saturation in nuclei.

- Behavior at large |y| → shadowing is small and models converge, while being at the border of their applicability.

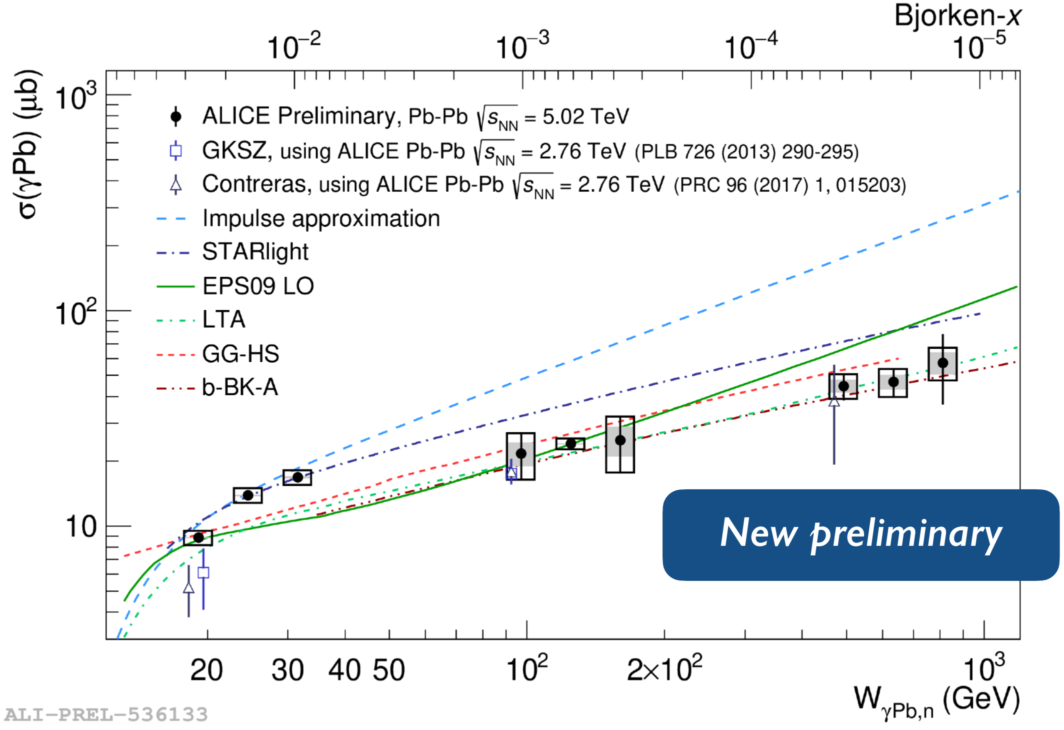
Coherent J/ψ photoproduction in Pb-Pb UPCs with neutron emission

• Measurements of UPCs with neutron emission in any 2 channels (0n0n, 0nXn) allow one to separate W^+ and W^- contributions to UPC cross section → probe nuclear gluons down to $x{\sim}10^{-5}$!

CMS PAS HIN-22-002, W. Li talk 29.03.2023



R. Lavicka, talk 28.03.2023



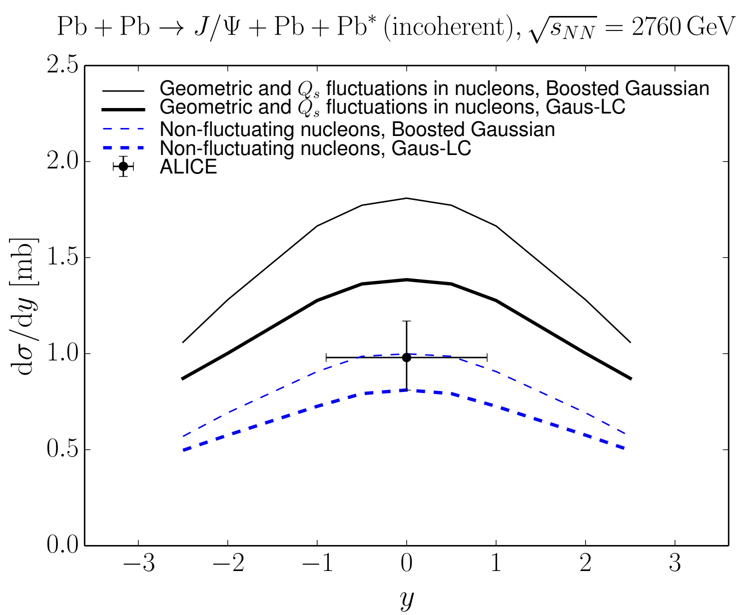
• The data indicates a continuous increase of nuclear shadowing at small x in agreement with leading twist model (LTA) and nuclear saturation (bBK-A).

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

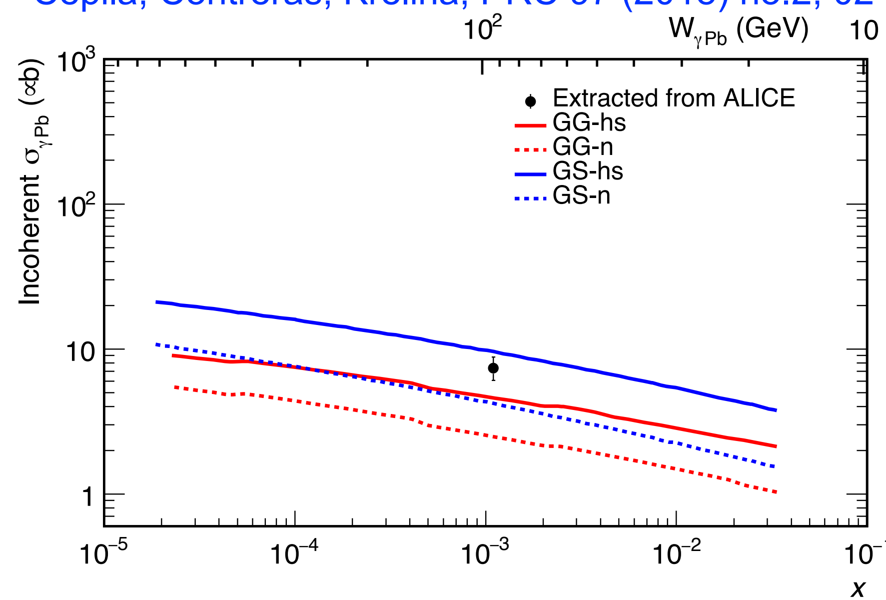
• Description of incoherent diffraction γ+p→J/ψ+p* on the proton requires a new sub-nucleon scale → gluonic "hot spots" and geometric fluctuations of the proton,
Mäntysaari, Schenke, PRL 117 (2016) 052301; Cepila, Contreras, Tapia-Takaki, PLB 766 (2017) 186

• 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

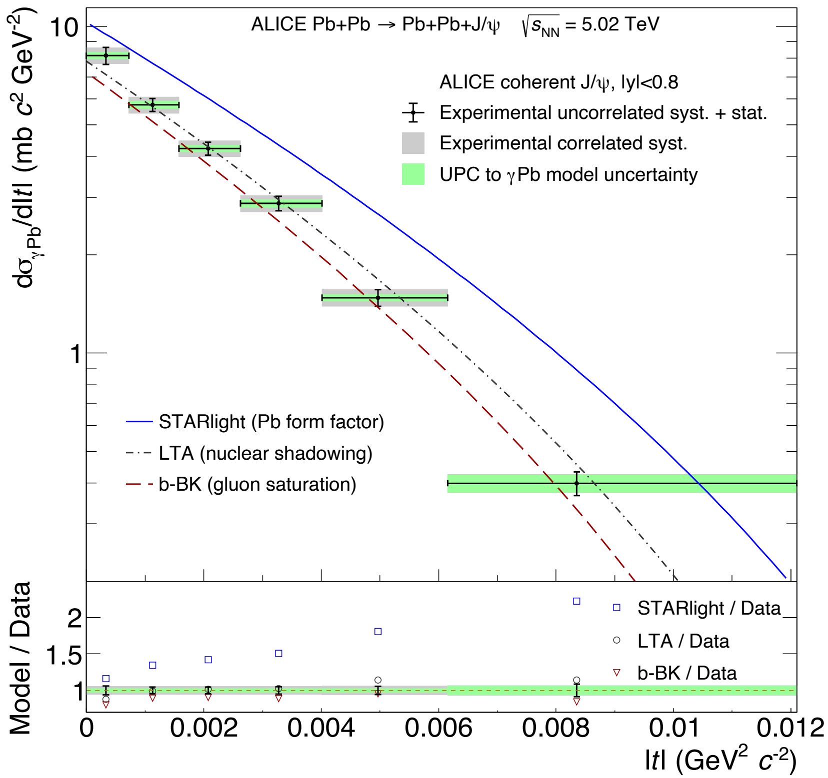


• Increases ×2 incoherent cross section, weakly affects coherent cross section, describes well incoh/coh ratio.

• Alternative description of incoherent data: leading twist model (LTA), Guzey, Strikman, Zhalov, PRC 99 (2019) 1, 015201; Kryshen, Strikman, Zhalov, 2303.12052 [hep-ph]

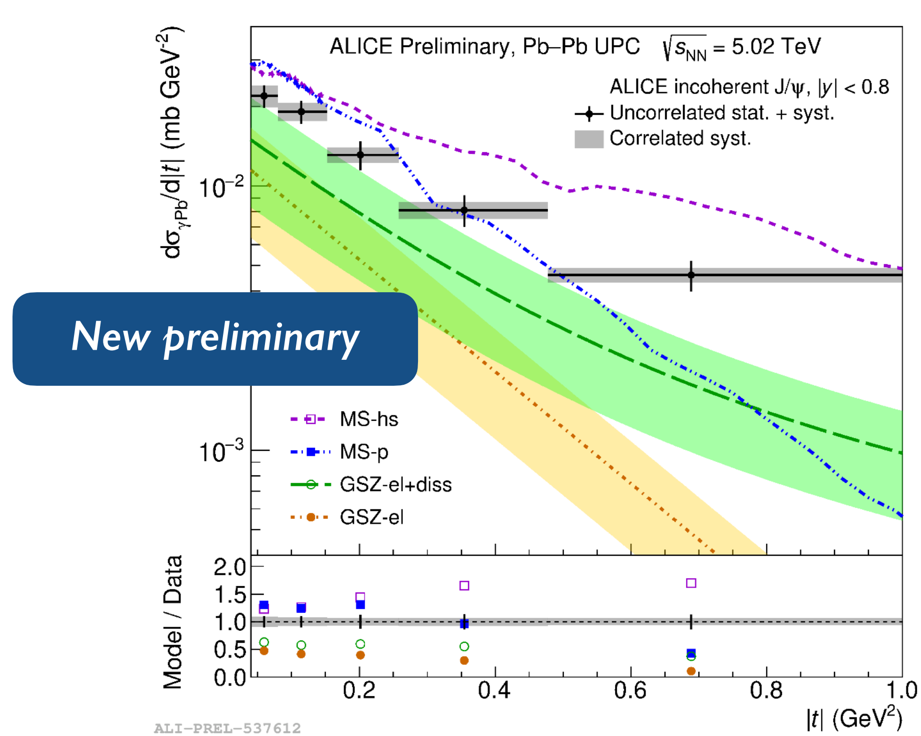
t-dependence of coherent and incoherent J/ψ photonuclear cross section

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



R. Lavicka, talk 28.03.2023

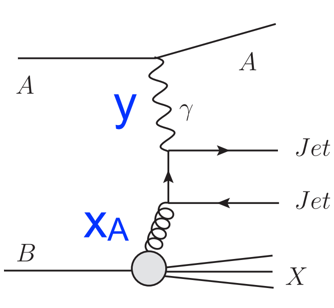
Incoherent: t distribution



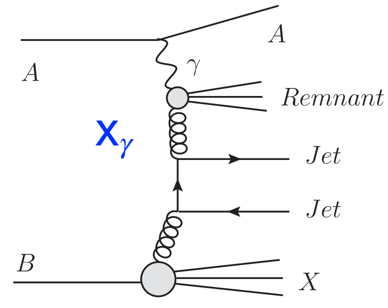
- LTA model predicts stronger shadowing at nucleus center → 5-11% broadening of gluon distribution in impact parameter space → shift of diffractive minima, Guzey, Strikman, Zhalov, PRC 95 (2017) 025204
- Similar effect is caused by saturation in dipole picture, Bendova, Cepila, Contreras, Matas, PLB 817 (2021) 136306
- Strong sensitivity to sub-nucleon fluctuations 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 (a)



resolved photon (b)

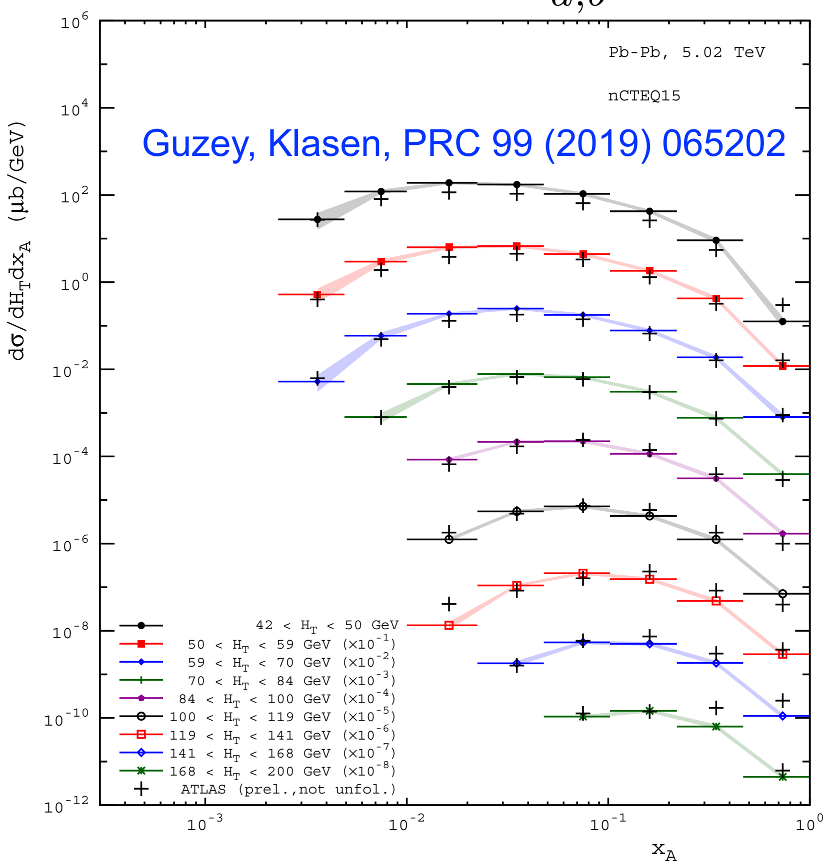
$$d\sigma^{AA\to A+2\text{jets}+X} = \sum_{a,b}\int dy \int dx_\gamma \int dx_A f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma,\mu^2) f_{b/A}(x_A,\mu^2)\hat{\sigma}_{ab\to\text{jets}}$$

Photon flux

Photon PDFs for resolved case

Nuclear PDFs (nCTEQ15, EPPS16)

Hard parton cross section



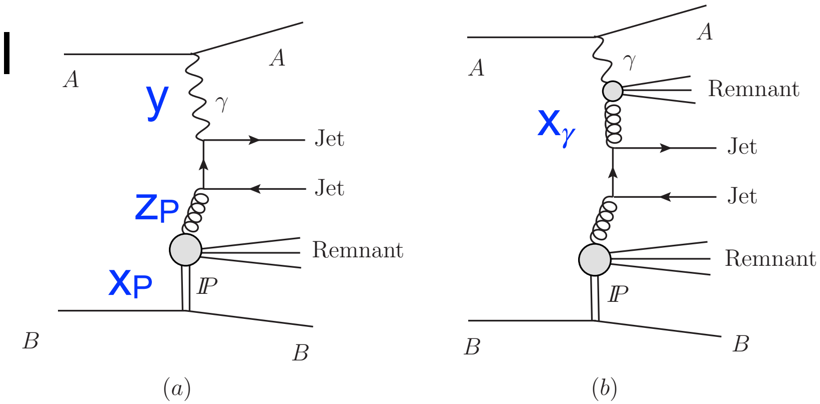
- NLO pQCD describes shape and normalization of ATLAS data, ATLAS-CONF-2017-011

- Sensitivity to nuclear modifications of PDFs at 10-20% level → can be used to reduce uncertainty of gluon density by factor 2 at $x_A=10^{-3}$, 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

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:



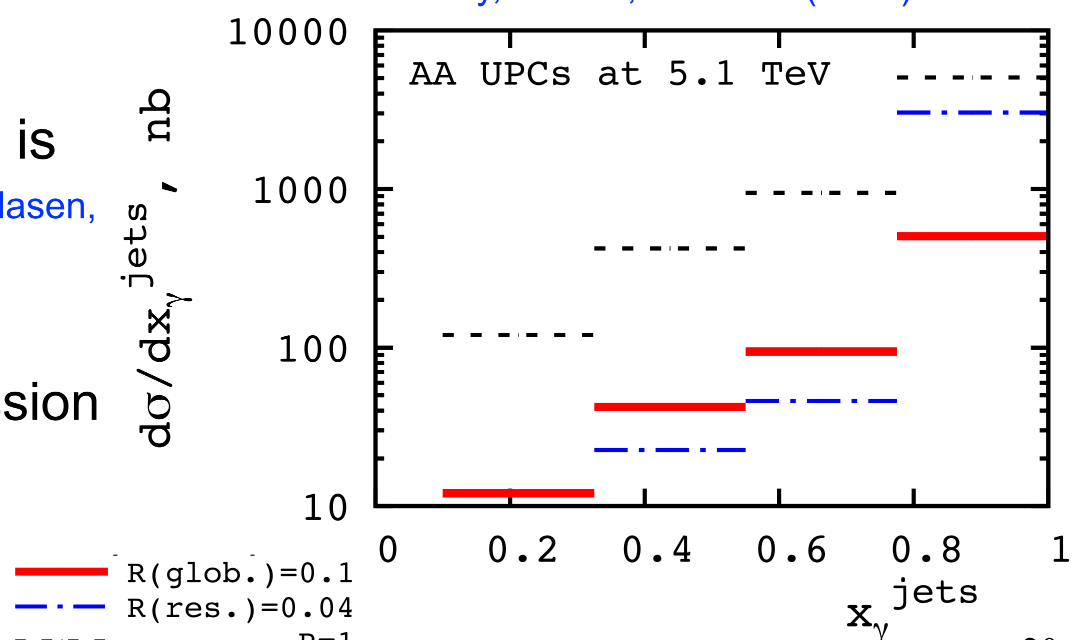
$$d\sigma(AA \to A + 2\text{jets} + X + A)^{(+)} =$$

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

Nuclear diffractive PDFs

- 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.

Guzey, Klasen, JHEP 04 (2016) 158



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 at y=0 → large gluon/quark shadowing at small x, 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 theoretical complications cancel.

• Outstanding challenges are the treatment of J/psi vertex in NLO pQCD beyond NRQCD and small-x resummation of NLO coefficient functions.

• In the dipole picture, significant progress in calculations exclusive vector meson photoprodiction at NLO, Mäntysaari, Penttala, JHEP 08 (2022) 247 → applications to AA UPCs

• New avenue is AA peripheral, I.-C. Arsene, talk 29.03.2023 and UPCs with neutron emission providing an access to very small $x{\sim}10^{-5}$ both in coherent and incoherent cases, Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942.

Dipole picture: relativistic effects in J/ψ wave function

• Standard lore: relativistic effects are small provided LO matrix element normalized to J/$\psi \to l^+ l^-$ decay width, Hoodbhoy, PRD 56 (1997) 388

• However, it was shown that relativistic v_c/m_C corrections are sizable, Eskobedo, Lappi, PRD 101 (2020) 3, 034030; Lappi, Mäntysaari, Penttala, PRD 102 (2020) 5, 054020
→ J/ψ wave function dependence does not cancel in nucleus/proton ratio → affects interpretation of nuclear suppression in AA UPCs@LHC and not included in shown dipole results.

• There is also a related issue of D-wave (spin rotation) of the charmonium wave function, Krelina, Nemchik, Pasechnik, EPJ C 80 (2020) 2, 92

• Charm quark mass m_c does not provide sufficiently high scale → asymptotic pQCD expressions receive large k_T/m_c corrections depending on J/ψ wf, Frankfurt, Koepf, Strikman, PRD 57 (1998) 512; Frankfurt, McDermott, Strikman, JHEP 02 (1999) 02 and JHEP 03 (2001) 045
→ dramatic ($C(Q^2=0)\sim 0.1$) suppression for J/ψ and moderate for Y.

• Consistent description in pQCD requires J/ψ light-cone distribution amplitude → no smooth connection to NR wf, Brodsky, Frankfurt, Gunion, Mueller, Strikman, PRD 50 (1994) 3134