

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

Orsay, 1st August 2022

Ultraperipheral collisions as photon-hadron **collider** $A_{\rm eff}$ in polynomial $\mathcal{L}_{\rm eff}$ (gluon $\mathcal{L}_{\rm eff}$

- Ultraperipheral collisions (UPCs): ions pass each other at large impact parameters b ~ $\mathcal{O}(50 \text{ fm})$ >> R_A+R_B \rightarrow strong interactions suppressed \rightarrow interaction via quasireal photons in Weizsäcker-Williams equivalent photon approximation, Budnev, Ginzburg, Meledin, Serbo, Phys. Rept. 15 (1975) 181
- Photon flux scales as Z² and photon energy as $\gamma_L \rightarrow$ $\gamma\gamma$, γ and γ A interactions at high energies.
- Pioneering studies of UPCs at RHIC, recent impetus at the LHC \rightarrow W_{yp}=5 TeV, W_{yA}=700 GeV/A, W_{yy}=4.2 TeV.

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

• 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 parant and inconarant scat in the Regge theory is referred to as pomeron (IP) [1–5]. An illustration of this process

- UPCs have very distinct experimental signatures \rightarrow two leptons from J/ decay (two pions from ρ decay) in otherwise empty detector. transfer *Q*² of about *m*² *J/ /*4, where *mJ/* is the *J/* mass [6, 7].¹ ive very distinct experimental signatures \rightarrow collisions at a nucleon-nucleon centre-of-mass energy of p*s*NN = 5 TeV collected with wo pions from p decay) in otherwise empty d Results of UPC studies have also been reported by RHIC and LHC experiments [8–15].
- The underlying photon-nucleus scattering can be coherent (target stays intact) and incoherent (target breaks up) \rightarrow 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 The forward rapidity range 2*.*0 *<y<* 4*.*5 covered by the present measurement corresponds **iderlying photon-nucleus scattering can be compared** θ nerent (target breaks up) \rightarrow dist η and companity to STARIght wome Gano, η

• 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 \rightarrow UPCs in different channels (0n0n, 0nXn, XnXn) separate W± terms → probe lower x, Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942 heavy-ion collisions. The symbol Pb' represents any final state for the nucleus inelastic scattering

Ions de-excite by emitting neutrons detected in ZDCs

Exclusive J/ 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-):

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

\nsuppression of soft strong interactions for $v < 2R_A$ (rapidity gap survival probability)

\n
$$
k dN_{\gamma/A}^{pl}(k) = \frac{2Z^2 \alpha_{e.m.}}{\pi} [\zeta K_0(\zeta) K_1(\zeta) + \frac{\zeta^2}{2} (K_0^2(\zeta) - K_1^2(\zeta)]
$$
\n
$$
k dN_{\gamma/A}^{pl}(k) = \frac{2Z^2 \alpha_{e.m.}}{\pi} [\zeta K_0(\zeta) K_1(\zeta) + \frac{\zeta^2}{2} (K_0^2(\zeta) - K_1^2(\zeta)]
$$
\n
$$
W^{\pm} = \sqrt{(k^{\pm} + E_A)^2}
$$

<mark>v</mark> to photon momentum k *y* to prioton momontum it tion for various values of the residual factorisation scale *µ^f* , namely: \rightarrow difficult to probe small x_0 since N $(k^+)\ll N$ (k^-) from the low virtuality domain *(<Q*² • Ambiguity in relating J/ ψ rapidity ${\mathsf y}$ to photon momentum ${\mathsf k} \to$ ambiguity in tribution and, moreover, reduces the scale dependence of the momentum fraction $x_A=(M_{J/\psi})^2/W^2\to$ difficult to probe small x_A since $N_\gamma(k^+)\ll N_\gamma(k^-)$

Exclusive J/ ψ **photoproduction at LO** the cross section does not depend on energy and there is ory priocoproduction binding energy of S-wave e6-quarks *J/7 J* system is small (much less than the charm quark mass \mathbf{m} *5.4. Elastic photoproduction of J/ : from HERA to LHC* The phenomenologically important case of vector meson production is elastic

• Hard scale by charm quark mass $m_c \rightarrow in$ 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 \bullet Hard scale by charm quark mass ${\sf m}_{\sf c} \to$ in leading ${\sf In}({\sf Q}^2)$ ln $(1/{\sf x})$ double ${\sf J}/\psi$ ${\sf VETEX},\,$ Ryskin, Z. Phys. C57 (1993) 89 ovimation for rest-framing approximation of perturbative pQCD and static approximation for and static approximation for **~7**

vector meson dominance and pomeron exchange was considered • Application to nuclear targets:

$$
\sigma^{\gamma A \to J/\psi A}(W) = \frac{d\sigma^{\gamma p \to J/\psi p}(W, t=0)}{dt} \begin{bmatrix} x g_A(x, Q_{\text{eff}}^2) \\ \frac{225}{200} \left[\frac{1}{2} \arccos \frac{1}{2} \arccos
$$

Leading twist mone for nuclear shadowing **AUTHORY PERSONAL PROPERTY**

• Combination of Gribox-Glauber theory with QCD factory ation theorems for inclusive and diffractive DIS \rightarrow prediction for small-x nPDFs at input scale Q₀, Frankfurt, Strikman, EPJ A5 (1999) 293; Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Leading twist model of nuclear shadowing (2) Rep. Prog. Phys. **85** (2022) 126301 Review Eq. (51) is valid at high energies (small *x*), when the effect of the finite coherence length (the coherence length is proportional to the fluctuations \mathbf{u} is unimportant. In this case, all factors associated with the space–time space–t

- Essential input: universal, leading twist (LT) diffractive $e^{\frac{k}{(a^2)^2q}}$ $\text{PDFs of proton, Collins, PRO 57, 3051 (1998); PRO 61, 019902 (2000)}$ 051 (1998); PRD 61, 019902 (2000) (β) (3) $\left\{\right\}$
- 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) $P \rightarrow Q \rightarrow (t)$ $P' \rightarrow (t)$ after *ei(z*1*z*2*)mN ^x*^P is set to unity in Eq. (48). (Note that we take into account the effect of the finite coherence length in our Final expression below, $\frac{1}{2}$ as follows from the following fluctuation fluctuation fluctuations, the second moment momentum \mathcal{A}

 $\frac{1}{10^{-2}}$

 x

 10^{-3}

•Interaction with 2 nucleons modelindependently in terms of diffractive $\sigma_2(x, \mathbb{Q}^2) = \frac{1}{10}$ (Pomeron) PDFs: اب
L:، ... hi*^j*

quarks

 10^{-4}

60

50

 Ω

 10^{-5}

 σ (mb)

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

)<*e(*¹ *ⁱ*⌘*)*

collinear approximation. For the purpose that purpose they introduced they introduced they introduced they introduce $\frac{1}{\sqrt{2\pi}}$ the fracture functions which contain the informations which contain the information the information $\frac{1}{\sqrt{2\pi}}$ α about the structure function of a given target hadron once α it has fragmented into another given !nal state hadron. The state hadron. The state hadron. The state hadron. \bigwedge can be classified as a special case of \bigwedge $\left\{\begin{matrix} 1 \\ 1 \end{matrix}\right\}$ Spread in $\sigma_{\text{soft}} \rightarrow$ where it was demonstrated that they can be described within The last term in Eq. (51) describes the interaction with three and more nucleons of the target. It corresponds to graph c uncertainty of LTA \sim $\sqrt{7}$ predictions diffractive proof, provided by \mathcal{O} . The factorization proof, proof, presented by \mathcal{O} $\frac{1}{2}$, essentially followed that of the inclusive case. Note that of the inclusive case. Note that of the inclusive case. Note that $\frac{1}{2}$ 10^{-2} and 10^{-1} $\mathsf X$ in diffractive $\mathsf X$

and in Figs. 10 and 11. Denoting the contribution of the contribution of the contribution of the last term in Eq. (51) \sim (51) $\$

 \mathbf{k}'

 $\dot{\mathbf{m}}$ fluctuations of photon is t_{t} the target fragmentation region, can be described with $\frac{1}{2}$ *L.* Aucleons modeled using hadronic fluctuations of ph Ironic fluctuations of photon • Interaction with $N \geq 3$ nucleons modeled using hadronic fluctuations of photon

60

40

 Ω

 $\frac{0}{10^{-5}}$

) = *xfj/^N (x, ^Q*²

 $\frac{1}{1}$ coincides with the second term in Eq. (51).

 10^{-4}

) u
σ

 $\frac{1}{10^{-3}}$

4

t^{(L}

²*(x, ^Q*²

*^j/^A (x, ^Q*²

xf (b)

 10^{-1}

LTA predictions for nPDFs

• HERA analysis: perturbative Pomeron is made mostly of gluons \rightarrow 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-Q2 coverage
- measurements of the longitudinal structure function $F_LA(x,Q²)$ sensitive to gluons
- measurements of diffraction in eA DIS

LTA shadowing vs. Run 2 LHC data

FICT TO OT OS At OTZ TOV, Adilaya et al. [ALICE], EP3O 61 (2021) 110.6, 712 and PLD 796 (2019), 134
Aaij *et al*. [LHCb], JHEP 06 (2023), 146; Tumasyan *et al.* [CMS], arXiv:2303.16984 [nucl-ex] ions with forward neutron emission. • 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;

• 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

 $\sum_{i=1}^{\infty}$

Nuclear suppression factor

• Nuclear suppression factor $S_{Pb}(x)$ from UPC data \rightarrow 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

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

Exclusive J/ ψ **photoproduction in NLO pQCD**

- Collinear factorization for hard exclusive processes, Collins, Frankfurt, Strikman, PRD 56 (1997) 2982
- $\cdot \gamma A \rightarrow J/\psi A$ 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
- 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

$$
\mathcal{M}^{\gamma A \to J/\psi A} \propto \sqrt{\langle O_1 \rangle_{J/\psi}} \int_{-1}^1 dx \left[T_g(x,\xi) F_A^g(x,\xi,t,\mu_F) + T_q(x,\xi) F_A^g(x,\xi,t,\mu_F) \right]
$$
\n
$$
\downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow
$$
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$$
\text{NRQCD matrix element from}
$$
\n
$$
\text{J/\psi leptonic decay}
$$
\n
$$
\text{function}
$$
\n
$$
\text{Gluon GPD}
$$
\n
$$
\text{Quark contribution}
$$

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

Exclusive J/ photoproduction in NLO pQCD (2)

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

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

 \rightarrow helps to qualitatively understand the features of our numerical calculations.

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

• Connection between GPDs is necessarily model-dependent. However, at small ξ , Q² evolution washes out information on input GPDs \rightarrow 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** 6 T The error bands in the predictions for T_1 **EXPRESS SHOWN IN FIGURE 15-18 WERE NOT CALCULATED CORPOR** lower one was somewhat underestimated. Note that the predictions made with the central values of the nNNPDF3.0 n Port as with EPPS² $T_{\rm eff}$ of our paper is shown in Fig. 1 of our paper is shown in Fig. 1 below. In addition to the corrected n

• Scale dependence for $m_c \le \mu \le 2m_c$ 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 \rightarrow note that $\gamma+p\rightarrow J/\psi+p$ proton data is somewhat overestimated.

• Uncertainties due nPDFs are quite significant \rightarrow 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 Pommanoc or quarts

Fig. 3. *Upper panel:* Breakdown of the NLO cross section in the upper panel of • 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. $U\psi$ priotoproduction in Heavy-Pon

• Perturbative stability of NLO pQCD improves for scaled ratio of oxygen and lead UPC cross secs: pe. Distribution solid ratio of

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

Eskola, Flett, Guzey, Löytäinen, Paukkunen, remove the e↵ects of the *Z*² scaling of the photon flux PRC 107 (2023) 4, 044912

Exclusive J/ ψ **photoproduction in dipole picture** into account the multiple scattering of the *c*¯*c*-dipole on the constituent protons and neutrons of the nucleus.

- Space-time picture of strong interaction at high energies in target rest frame \rightarrow photon is a superposition of long-lived $q\bar{q}$, $q\bar{q}g,...$ dipoles. will be satisfied not only by the *companies*
- Dipoles successively, elastically scatter on target nucleons \rightarrow high-energy factorization for $\gamma+A\rightarrow J/\psi+A$ amplitude: to the *c*¯*c g* component.

V](*r*⁰ *, Q*²*, z*⁰) FIG. 1: The coherent di↵ractive *J/* photoproduction (*Q*² = rescattering of small dipoles **** Tev computed using fIPs and IIM parameters and IIM parameters and IIM parameters and IIM parameters and IIM para • This implementation over-predicts the data at y=0 since nuclear shadowing F_1 F_2 F_3 F_4 F_5 F_6 in F_7 in F_7 in F_8 due to rescattering of small dipoles with < r_T > ~0.3 fm is too weak.

into all poles picture: role of qq̃g dipoles the nucleus. In the midrapidity region the maximum of the *A*-cm energy accessible in the collision is obtained. Roughly we have there *W* ⇠ 100 GeV. With increasing energy, the coherency condition *lc RA*

 $200 \, \text{C}$ 200 200 1140 C $r - 50$ W [GeV] ີ• S້rmall 14 " $r_{\overline{1}}$, 50 q̄ dipoles provide higher-twist contribution to γ +A→J/ ψ +A as well as to other nuclear observables, e.g. longitudinal structure function $F_{L}A(x,Q^2)$, will be satisfied not only by the *c*¯*c*-state, but also by higher *c*¯*c g* states shown in in Fig. 1b. In the vist contribution to γ +A \rightarrow J/ γ +A as well Initudinal structure tunction F_1 A(y \bigcap 2) to the *c*¯*c g* component.

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

nucleus. The data points are taken from Ref. [20]. cross section and wave function. • Need to include higher qqq Fock states \rightarrow modeling of 3-body "dipole"

• Includes elastic and inelastic nuclear shadowing \rightarrow good description of data. *RHIC collision energy* p*s^N* = 200 *GeV (top panels) and at LHC energies* p*s^N* = 2*.*76 *TeV (middle panels) and* p*s^N* = 5*.*02 *TeV*

Dipole picture: saturation in nuclei

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

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

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

Coherent J/ ψ **photoproduction in Pb-Pb UPCs** ifoduction in Ph.Ph LIPCs. \blacksquare cross section will reach the unitarity limit while the gluon density can continue increasing.

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

• None of the approaches describe the data in the entire range of J/ ψ rapidity y. α doto in the entire renge of $\frac{1}{2}$ repidity α $\bm{\theta}$ data in the entire range of J/ $\bm{\psi}$ rapidity y. periments are displayed for specific rapidity regions, where the two-way ambiguity effect

- Suppression at $y=0 \rightarrow$ strong leading-twist gluon shadowing at small x, importance of qq̄g dipoles, or a sign of saturation in nuclei. ment *aluen. Shadowing at small x* values are evalued at the corresponding and corresponding α $\frac{1}{2}$ ranges. The vertical bars and shaded and shaded and open boxes represent the statistical, experiment the statistical, experiment the statistical, experiment the statistical, experiment the statistical, experimen
- Behavior at large $|y|$ and $x_A > 0.01 \rightarrow$ all approaches close to the border of applicability \rightarrow require refinements: e.g., earlier onset of antishadowing,... tension with the J*/*y data at semi-forward rapidity in the range 2*.*5 *< |y| <* 3*.*5, indicating that the nupresented over a broad energy range. In a coherent process, the J/*y* is produced by the photon

Tamed collinear factorization

• Stability of perturbation series for exclusive J/ ψ photoproduction in NLO pQCD can be improved in 2 steps: where the Figure the Figure the Coefficient function μ on the coefficient μ

- 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 µf dependence is weak, Jones, Martin, Ryskin, Teubner, J. Phys. G 43 (3) (2016) 035002

$$
A^{(0)}(\mu_f) + A^{(1)}(\mu_f) = C^{(0)} \otimes F(\mu_F) + \alpha_s C_{\text{rem}}^{(1)}(\mu_F) \otimes F(\mu_f)
$$

from NLO coefficient functions to avoid $\frac{1000113}{x}$ $\frac{1}{x}$ $\frac{1}{x}$ do $\frac{1}{x}$ at $\frac{1}{x}$ for the fillow, Jones, $\frac{(x+\xi)P^+}{x}$ $\frac{1}{x}$ $\frac{(x-\xi)P^+}{x}$ $\frac{(x-\xi)P^+}{x}$ gluons) \rightarrow Q₀ subtraction method, Jones, \sim contributio lines and couplings of the gluon ווטו וא נט מ \ln lo

 $\frac{1}{2}$ • Q_0 -subtraction addresses $\mathcal{O}(Q_0^2/m_c^2)$ power suppressed terms \rightarrow numerically important for J/ ψ and much less important for DIS with $\mathcal{O}(\mathsf{Q_0}^2/\mathsf{Q^2})$. $\frac{1}{2}$ (a) $\frac{1}{2}$ or $\frac{1}{2}$ power suppr important for J/ ψ and much less important for DIS with $\mathcal{O}(\mathsf{Q_0}^2/\mathsf{Q^2})$. \mathbf{I} $\overline{1}$ ferma • Q₀-subtraction addresses $\mathcal{O}(Q_0^2/m_c^2)$ power suppressed terms \rightarrow numerically

Tamed collinear factorization: gluons in proton *x x* $\boldsymbol{\mathcal{A}}$ $\boldsymbol{\mathcal{$

→ J/ψ p) [nb]

- Restores the gluon dominance and allows for sensible comparison to data. we determine the low *x* gluon directly from the data. In Section 4, we compare the results • Restores the gluon dominance and allows for sen
- Tamed NLO pQCD predictions using \sim \sim \sim existing proton PDFs vs. HERA and LHCb $\frac{1}{2}$ on $\frac{1}{10}$ the Nuction substitutions in the value of $\frac{1}{10}$ pp UPC data on γ +p→J/ ψ +p, Flett, Jones, Martin, $\frac{d}{d\alpha}$ Ryskin, Teubner, PRD 101 (2020) 9, 094011 via the exclusive *J/* data and compare and contrast this with the gluon obtained from the above alternative approach and conclusions are being a summarized in Section 6. \bullet Tamed NI O nOCD predictions using describe the LHCb data, we e↵ectively need the gluon in the region of low *x* ' *X* + ⇠ only. So
- in the leading order part of the amplitude \mathcal{F}_{in} • Predictions are stable, but description of LHCb data is poor. S pool. Parton Distribution Distribution Distribution with *X* **100**, $\frac{1}{100}$ had a smooth analytical behaviour with the property that *g*(*x*) ! 0 as *x* ! 1. In order to \bullet Predictions are stable, but description of ⁰) + (1 *^C*) *xg*new(*x, µ*²
- α of aluen DDE for $v < 10-3$ using • Extraction of gluon PDF for $x < 10^{-3}$ using 10^{-3} global analysis of data on _γ+p→J/ψ+p, _{Flett,} $\begin{array}{cc} \cdot & 1 & 1 \\ \cdot & \cdot & \cdot \end{array}$ Martin, Ryskin, Teubner, PRD 102 (2020) 114021

₅₀₀ over the whole *x <* 1 interval. Moreover, the transform was derived assuming that the gluon gioual analysis of data bit $\gamma^{+}P \rightarrow J/\psi^{+}P$, Fiett, $\sum_{H1, 200}$ raction or giuo
al analvsis of d \overline{u} udi \overline{a} ∂ ON ν +D \rightarrow J/ ν +D, Flett, 600 and where $\frac{1}{2}$ is the gluon PDF obtained in a global PDF obtained in a global PDF analysis. The set of the global PDF analysis in a global PDF analysis. The value of $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$

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

\n
$$
x g^{\text{new}}(x, \mu_0^2) = n N_0 (1 - x) x^{-\lambda}
$$

\n
$$
\stackrel{\text{g}}{\underset{\text{p}}{\rightleftharpoons}} 300
$$

\n
$$
\stackrel{\text{g}}{\underset{\text{p}}{\rightleftharpoons}} 300
$$

 (x_{II}) for $3x10-6$ $\frac{1}{2}$ $r_{\rm gal}$ reas for this are as follows. First, this corresponds to $r_{\rm gal}$ σ(γ p • Constraints on $xg_p(x,\mu)$ for $3\times10^{-6} < x < 10^{-3}$, $\frac{1}{5}$ 200 no signs of saturation.² simplest low *x* form for the gluon would be

 \sim Apii et al II HCh1 \pm Dhus $CA4$ (2014) 055002 <u>Shown LHCb data</u>: Aaij et al [LHCb], J. Phys. G41 (2014) 055002
and JHEP 1810 (2018) 167. R=μ² from the NLO terms in \mathcal{L} terms in Eq. (3.95) of \mathcal{L} *xg*new(*x, µ*² and JHEP 1810 (2018) 167.**167.** \overline{a}

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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 \rightarrow large gluon shadowing at small x, qq̃g dipoles, or a sign of saturation in nuclei \rightarrow 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 $x \sim 10^{-6}$.
- 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 (qq and qqq distribution amplitudes) and taming of small- ξ behavior of NLO coefficient functions.
- Pb-Pb UPCs \rightarrow complement. constraints on shadowing in LT and dipole pictures $_{_{21}}$ • I didn't have time to cover t-dependence and incoherent J/ψ photoproduction in