Theory overview of vector meson photoproduction on nuclei in UPCs at the LHC

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Outline:

- Introduction: UPCs and nuclear shadowing
- Inelastic nuclear shadowing and coherent ρ photoproduction on nuclei
- Gluon nuclear shadowing from J/ψ photoproduction on nuclei at the LHC
- Open questions, topics for discussion, outlook and summary

Workshop INT-17-65W "Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the Path to EIC", INT, Seattle, Feb 13-17, 2017

Ultraperipheral collisions (UPCs)

• Ions can interact at large impact parameters $b \geq R_A+R_B \rightarrow$ ultraperipheral collisions (UPCs) \rightarrow strong interaction suppressed \rightarrow interaction via quasireal photons, Fermi (1924), von Weizsäcker; Williams (1934)

- UPCs correspond to empty detector with only two lepton/pion tracks
- Nuclear coherence by veto on neutron production by Zero Degree Calorimeters and selection of small pt
- Coherent photoproduction of vector mesons in UPCs:

$$
\frac{d\sigma_{AA \to AAJ/\psi}(y)}{dy} = N_{\gamma/A}(y)\sigma_{\gamma A \to AJ/\psi}(y) + N_{\gamma/A}(-y)\sigma_{\gamma A \to AJ/\psi}(-y)
$$
\nPhoton flux:

\nPhoton flux from QED:

\nhigh intensity ~ Z²

\n– high intensity ~ Z²

\n– large photon energies
$$
\zeta = k(2R_A/\gamma_L)
$$

 B ² Paltz et al. The Phy Baltz *et al.*, The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1 UPCs = γ p and γ A interactions at unprecedentedly large energies,

Nuclear shadowing

- Nuclear shadowing (NS) = suppression of cross section on a nucleus compared to sum of cross sections on individual nucleons: $\sigma_A < A \sigma_N$.
- Observed for various beams (p, π , γ , γ^* , v) of large energies (> 1 GeV)
- Explained by simultaneous interaction of projectile with target nucleons \rightarrow destructive interference among amplitudes for interaction with 1, 2, …nucleons \rightarrow nucleons in rear of the nucleus "see" smaller (shadowed) flux: σ_Α~Α^{2/3}. $\frac{2}{10}$, $\frac{11}{2}$ $\frac{100}{2}$

- NS in photoproduction of light vector mesons ρ, ω, φ *2.3. Comparison of the Gribov and Glauber results for nuclear shadowing*
	- dynamics of soft γp and γA interaction at high energies t eigenstates of the strong Hamiltonian, contains both the original hadron (elastic scattering) as well as well as t
- validity of VMD model and role of inelastic (Gribov) shadowing $\frac{1}{2}$ excited states (coherent diffraction). The Gribov approach is essentially field-theoretical and the creation of particles in intermediate state is properly taken into account, see Figs. 2 and 5. Hence, although the final answer for nuclear shadowing in the Glauber and Gribov approaches is expressed through topologically different diagrams, it has the structure of the sum
- constraints on color dipole approach The corresponding expression for the total pion–deuteron cross section reads [113]:
	- NS in photoproduction of heavy vector mesons J/ψ, ψ(2S), Y: ⇡*^N* tot ² \mathbf{r} *r*2 *D* production of heavy vector mesons $\vert \psi \rangle$ $\vert \psi \rangle$ (2) $\vert \psi \rangle$ η io ui ψ , ψ (ϵ U), interactions of the deuteron. The deuteron. The deuteron. The deuteron of this interactions of the deuteron. The deuteron of the deuteron. The deuteron of the deuteron. The deuteron of the deut
- mechanism of nuclear shadowing; leading twist vs. HT vs. saturation *d*
2 **111**
2 111 to the scattering and the overlapping integral between the final state and projection the final state and projec
Integral between the final state and projection wave and projection was and projection to final state and pro $\mathsf{SL}(V\mathsf{S},\,\Pi\mathsf{T})$ the section of diffraction $\mathsf{SL}(V\mathsf{S})$
- new constraints on nuclear gluon distribution $g_A(x,\mu^2)$ at small x with $\overline{}$ r_{11} _{$\left(111\right)$} ot omelly $\mathsf{SA}(\wedge,\mathsf{M}_{\geq})$.

Coherent photoproduction of ρ on nuclei

- Measured with fixed targets (SLAC, W < 6 GeV), in Au-Au UPCs at RHIC (W < 12 Гэ B), and Pb-Pb UPCs at the LHC $@2.76$ TeV (W=46 GeV).
- For W < 10 GeV, explained by the vector meson dominance (VMD) model for $\gamma \rightarrow \rho$ transition and Glauber model for shadowing in ρA scattering:

$\sigma_{\gamma A \to \rho A}$	ϵ	ϵ	
$\sigma_{\gamma A \to \rho A}$	ϵ	ϵ	ϵ
$\sigma_{\rho N}$ from constituent quark model/data:	$\sigma_{\rho N}$	Optical density:	
$\sigma_{\rho N}$ from constituent quark model/data:	$T_A(b) = \int dz \rho_A(b, z)$		
\bullet ... but fails to describe large-W RHIC (STAR), Adder, et al, Phys. Rev. Lett. 89 (2002) 272302; Abelev et al., Phys. Rev. C 77 (2008) 034910; Agakishiev, et al., Phys. Rev. C 85 (2012) 014910 and ALICE data by factor ~1.5, Adam et al (ALICE), JHEP 1509			
\bullet Dinole models describe data better but strongly	auxu-AuAu		

- Dipole models describe data better, but strongly model-dependent, Goncalves, Machado, PRC 84 (2011) 011902
- Best description by STARlight despite approximate treatment of Glauber model, Klein and Nystrand, PRC60 (1999) 014903.

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50 100 150 200 250 W_{NIM}, GeV

Modified vector meson dominance (mVMD) model y) model

• At large beam energies E_{γ} , the photon can be viewed as superposition of long-lived ($I_c \sim E_\gamma$) fluctuations interacting with hadrons with different cross Sections, Gribov, Ioffe, Pomeranchuk 1965; Good, Walker, 1960 \cdot At large beam energies $\mathsf{L} \gamma$, the photo $\frac{1}{2}$ long-lived ($\frac{1}{2} \sim F_{\nu}$) fluctuations interacting with hadrons with dif constant that the *π γ note that the misrast* **SECIIONS, Gribov, loffe, Pomeranchuk 1965; Good, Wal** η e beam energies E_{x.} the photon can be viewed as sup coherent superposition of the superposition of the scattering of the scatterin UTIO, GINOV, IONE, I UNIEI ANCHUR 1900, GOOD, VVAINEI, 1900 does not contain ρ. The inelastic final state *X* is selected experbsition of nt cross **MX**

• Convenient to realize introducing the probability distribution $P(\sigma)$, of *^P(*σ = ⁰*)* ̸= 0 and also *^P(*σ → ∞*)* → 0. The free parameters *^C*, **Convenient to realize introducing the probability distribution** $P(0)$ **, Blattel et al, 1993** ϵ Convenient to realize introducing the • Convenient to realize introducing the probability distribution $P(\sigma)$, Blattel et al, 1993 state interactions with nucleus according to the target nucleus according to the target nucleus according to \mathbf{r}_{max}

cross sections calculated in the Glauber model with the available data. Bottom: The $→$ talk by **L. Frankfurt** tions with the DL94 model for σπ *^N* are compared to the available data. \rightarrow talk by **L. Frankfurt**

$$
\int d\sigma P(\sigma) = 1,
$$
\n
$$
\int d\sigma P(\sigma) \sigma = \langle \sigma \rangle, \rightarrow \text{from} \quad d\sigma (\gamma p \rightarrow \rho p) / dt
$$
\n
$$
\int d\sigma P(\sigma) \sigma^2 = \langle \sigma \rangle^2 (1 + \omega_{\sigma}) \rightarrow \text{from measured } \gamma
$$
\n
$$
\text{different. dissociation into large } \sum_{i=1}^{\infty} 120
$$
\n
$$
\text{masses, Chapin 1985} \qquad \sum_{i=1}^{\infty} 120
$$

 \mathbf{r}

our calculations with the STAR data.

• Shape like for pion, Blattel et al, 1993 + small- σ \equiv $\frac{1}{2}$ enhancement to take into account smaller $\widehat{\mathbb{C}}$ 80 $\left\{ \begin{array}{c} \bigcup_{i=1}^{n} A_i \cup A_i \end{array} \right\}$ $\frac{1}{2}$ on the photon discociation, in particular, the factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-factor-fac σ of pin γ pion diameter γ • Shape like for pion, Blattel et al, 1993 + small- $\sigma = \frac{1}{2}$ in $\sigma = \frac{1}{2}$ $t_{\rm eff}$ measurements. This means that the reasons of the disagreesize of *ρ* in γ *p*→*pp* than in $\sigma_{\pi N} \rightarrow$ π *^N* → π *^N* one):

$$
P(\sigma) = C \frac{1}{1 + (\sigma/\sigma_0)^2} e^{-(\sigma/\sigma_0 - 1)^2/\Omega^2}
$$

Photoproduction of ρ on Pb in mVMD+Gribov-Glauber model dissociation of protons, neutrons and pions on hydrogen and nucleid and in muclear shadowing in hadron-nucleus total cross sections [50]. applying this formalism to the property \mathbf{r}

• With cross section fluctuations:

$$
\sigma_{\gamma A \to \rho A}^{\text{mVMD-GGM}} = \left(\frac{e}{f_{\rho}}\right)^2 \int d^2 \vec{b} \left| \int d\sigma P(\sigma) \left(1 - e^{-\frac{\sigma}{2} T_A(b)}\right) \right|^2
$$

- "Two birds with one stone": we describe correctly the elementary γ p \rightarrow pp $\frac{1}{2}$ cross section and include inelastic Gribov shadowing in σ_{γ A→ρA
- 56 *L. Frankfurt et al. / Physics Letters B 752 (2016) 51–58* Zhalov, PLB 732 (2016) 51coherent superposition of eigenstates of the scattering operator, which is a scattering operat • \rightarrow describe well normalization and W-dependence $\sigma_{\gamma A\rightarrow\rho A}$, Frankfurt, Guzey, Strikman,

Predictions for Run 2@LHC: ρ and ɸ mesons

• Combination of mVMD and Gribov-Glauber models:

News from QM2017 on ρ photoproduction on *Fig. 9: Invariant mass distribution of unlike-sign pion pairs with different fit* **nuclei in Pb-Pb UPCs in Run 2** *Fig. 6: Topological trigger in SPD contributions*

- Preliminary ALICE result on Pb-Pb UPCs at $\sqrt{s_{NN}}$ =5.02 TeV: cross section is almost the same as in Run 1 $\overline{}$ $\overline{\$
	- the same as in Run 1
• Cannot be described by our mVMD-GG approach and color dipole models
		- Excellent description by STARlight

Different theoretical approaches predicts very different shapes of rapidity dependence.

> D. Horak (ALICE), poster at conference "Quark Matter 2017", Feb 6-11, 2017

- $d\sigma/dy = (448 \pm 2(\text{stat})^{+38}_{-75}(\text{syst}))$ [mb]
- Predictions by **STARLIGHT** [2], Gonçalves and Machado using Color Dipole Model (**CDM**) [3,4] and Guzey, Kryshen, Zhalov (**GKZ**) [5] reported
- Result compatible with STARLIGHT model

Nuclear shadowing in nuclear gluon distribution aoroar graon aroanoaron t

- Gluon nuclear shadowing: $g_A(x, \mu^2) < A g_N(x, \mu^2)$ for small $x < 0.005$. α
- Important for QCD phenomenology of hard processes with nuclei: cold nuclear matter effects (RHIC, LHC), gluon saturation (RHIC, LHC, EIC)
- $g_A(x,\mu^2)$ is determined from global QCD fits to data on fixed-target DIS, hard processes in dA (RHIC) and pA (LHC) → talks by **R. Vogt, F. Olness, S. Kumano** are considered (Fig.15). An
Considered in Ref. 19.10 in Ref. 19.10 in Ref. [18] . Above the parameter of Parameter Scale And Scale Art 2.1
- At small x, $g_A(x,\mu^2)$ is known with large uncertainties →
- pA@LHC data can help little, Armesto et al, arXiv:1512.01528; Eskola et al, JHEP 1310 (2013) 213, Eskola et al, arXiv:1612.075 (EPPS16 nPDFs)
- Future: Electron-Ion Collider in the US, Accardi et al, ArXiv:1212.1701; LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001 → talks by **E. Aschenauer, C. Weiss**

• Option right now: Charmonium photoproduction in Pb-Pb UPCs@LHC

Coherent charmonium photoproduction no flavour exchange. Strictly speaking, this is not a true din dirolopiodu da a consequence, the inclusive *J/qJ* cross section ~zz ~const. (much less than the charm quark mass me= m), one can fion \blacksquare \blacksquare

• In leading logarithmic approximation of perturbative QCD and non-relativistic approximation for charmonium wave function (J/ ψ , $\psi(2{\rm S})$): are portains and ∞ of photons Tower (ψ , ψ (ω)). over the relative momenta of c6^quarks k=k' in *J/7 J* rest-frame system) in the form *g(k+m)Tu.* The constant **~7** *qJ k*

$$
\frac{d\sigma_{\gamma T \to J/\psi T}(W, t=0)}{dt} = C(\mu^2) \left[x G_T(x, \mu^2) \right]^2 \quad \text{M. Ryskin (1993)}
$$
\n
$$
x = \frac{M_{J/\psi}^2}{W^2}, \qquad \mu^2 = M_{J/\psi}^2 / 4 = 2.4 \text{ GeV}^2 \quad C(\mu^2) = M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s(\mu^2) / (48 \alpha_{em} \mu^8) \quad \text{M. Ryskin (1993)}
$$

- Corrections on quark and gluon k_T , non-forward kinematics, real part of amplitude \rightarrow corrections to $C(\mu^2)$ and μ^2 , Ryskin, Roberts, Martin, Levin, Z. Phys. (1997); Frankfurt, Koepf, Strikman (1997)
- Application to nuclear targets:

Impulse approx.

$$
\sigma_{\gamma A \to J/\psi A}(W_{\gamma p}) = \frac{(1 + \eta_A^2)R_{g,A}^2}{(1 + \eta^2)R_g^2} \frac{d\sigma_{\gamma p \to J/\psi p}(W_{\gamma p}, t = 0)}{dt} \left[\frac{G_A(x, \mu^2)}{AG_N(x, \mu^2)} \right]^2 \Phi_A(t_{\text{min}})
$$
\nSmall correction $k_{AN} \approx 0.0.90$ -95 From HERA and LHCb Gluon shadow. Rg From nuclear form factor

\n• Nuclear suppression factor $S \to$ direct access to Rg

\n
$$
S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb \to J/\psi Pb}}{\sigma_{\gamma Pb \to J/\psi Pb}^{IA}} \right]^{1/2} = \kappa_{A/N} \frac{G_A(x, \mu^2)}{AG_N(x, \mu^2)} = \kappa_{A/N} R_g
$$

Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290

• Combination of Gribov-Glauber NS model with QCD factorization theorems for inclusive and diffractive $DIS \rightarrow$ shadowing for individual partons j, Frankfurt, Strikman (1999) σ and dimatuve $D\cup\rightarrow$ shadowing for mu

• Interaction with 2 nucleons:

Interaction with 2 nucleons:
$$
\sigma_2^j(x) = \frac{16\pi}{x f_{j/N}(x,\mu^2)} \int_x^{0.1} dx_P \beta f_{j/N}^{D(4)}(x,\mu^2, x_P, t=0)
$$

• Interaction with ≥ 3 nucleons: via 2. idronic fluctuations of γ : the substantial for $d\sigma P_{\alpha}(\sigma)\sigma^2$, with cross sec soft hadronic fluctuations of γ^* :

 \mathcal{L} and σ in the derivation of our master equation for σ of the σ is the use of the σ $\int \frac{d\omega}{\omega}$ *x*^{γ} (ω *)* \in $\sigma_{\rm soft}(x) = % \begin{cases} f(x) \; x \leq \frac{1}{\sqrt{2\pi}} \sqrt{2\pi} \sqrt{2\pi} & \text{for } x < \infty, \ \frac{f(x)}{2\sqrt{2\pi}} \sqrt{2\pi} & \text{for } x < \infty. \end{cases}$ $\int d\sigma P_{\gamma}(\sigma) \sigma^3$ $\int d\sigma P_{\gamma}(\sigma) \sigma^2$

P(σ) probability to interact with cross section σ

Cj with the parton distribution functions of the target *fj* (*j* is the parton flavor): Z ¹ ✓*x* ◆ • In quasi-eikonal approximation in low-x limit, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

$$
xf_{j/A}(x,\mu^2) = Af_{j/N}(x,\mu^2) - \frac{2\sigma_2^j f_{j/N}(x,\mu^2)}{[\sigma_{\text{soft}}^j(x)]^2} \int d^2b \left(e^{-\frac{1}{2}\sigma_{\text{soft}}^j(x)T_A(b)} - 1 + \frac{\sigma_{\text{soft}}^j(x)}{2}T_A(b) \right)
$$

Leading twist nuclear shadowing model (2)

- Model gives nuclear PDFs at μ^2 =3-4 GeV² for subsequent DGLAP evolution.
- Name "leading twist" since diffractive structure functions/PDFs measured at HERA scale with Q2.
- Gluon diffractive PDFs are large, $z \in U$ s, $H1 2006 \rightarrow$ predict large shadowing for $g_A(x,\mu^2)$, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Results of DGLAP evolution: from $Q^2=4$

For quarks, the agreement between LTA and EPS09 is much better.

Comparison to S_{Pb} from ALICE and CMS UPC data

- Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV \rightarrow first direct evidence of large gluon NS, Rg(x=0.001) ≈ 0.6.
- Similarly good description using central value of EPS09+CTEQ6L, large uncertainty.
- Qualitatively similar large nuclear suppression is predicted in kT-factorization approach, Cisek, Schafer, Szczurek, PRC86 (2012) 014905.

• Dipole model cannot (Goncalves, Machado PRC84 (2011) 011902; Lappi, Mantysaari, PRC 87 (2013) 032201), but sometimes can (Goncalves, Moreira, Navarra, PRC90(2014) 015203; G. Chen et al, arXiv:1610.04945) describe the data → talks by **G. Chen, W. Schaefer, B. Gay Ducati, H. Mantysaari**

3D nuclear gluon distribution \mathbf{r} IISTrik

• Large LT nuclear shadowing does not only suppress $\gamma A \rightarrow J/\psi A$ cross section, but also shifts its t-dependence towards smaller $|t| \rightarrow$ access to impact parameter $\frac{1}{2}$ dependent nPDF g_A(x,b,Q²) V. GUZEY, M. STRIKMAN, AND M. ZHALOV PHYSICAL REVIEW C **00**, 005200 (2017) $\mathcal{G}(\lambda,\mu)$ corresponds to the upper limit on the shadowing effect for *J/*ψ ²⁷⁷ • Large LT nuclear shadowing does not only suppress $\gamma A \rightarrow J/\psi A$ cross section, but -dependence towards smaller $|t| \rightarrow$ access to impact part $\overline{1}$ $\mathsf{P}\mathsf{D}\mathsf{P} \mathsf{D} \mathsf{P} \mathsf{C} \mathsf{B}(\mathsf{X},\mathsf{D},\mathsf{Q}^2)$ predicted by I

\n
$$
\frac{d\sigma_{\gamma A \to J/\psi A}}{dt} = \frac{d\sigma_{\gamma p \to J/\psi p}(t=0)}{dt} \left(\frac{R_{g,A}}{R_{g,p}} \right)^2 \left[\frac{\int d^2b \, e^{i\vec{q}_\perp \vec{b}} g_A(x, b, \mu^2)}{A g_p(x, \mu^2)} \right]^2
$$
\n

\n\n e. Dcsulting shift can be interpreted as 5-11%. The proof approach is important in important, the use of a function, which is the following method.\n

predicted by LT $\frac{p}{2}$ reducted by Li M $\overline{\mathcal{C}}$

- extracted/guessed in EPS09s, Helenius et al, **ET SOSS, HEIGHIUS Et al.**
JHEP 1207 (2012) 073 $\begin{bmatrix} 1 & \cdots & 1 \end{bmatrix}$. In the property case of $\begin{bmatrix} 1 & \cdots & 1 \end{bmatrix}$ acted/g
- Resulting shift can be interpreted as 5-11% broadening in impact parameter space of gluon nPDF, Guzey, Strikman, Zhalov, arXiv:1611.05471 (accepted to PRC) <mark>.</mark>
የ $k = \frac{1}{20}$ J I

• Similar effect is predicted to be caused by saturation, but magnitude is smaller, Cisek, Schafer, Szczurek, PRC86 (2012) 014905; Lappi, Mantysaari, PRC 87 (2013) 032201; Toll, Ullrich, PRC87 (2013) 024913; Goncalves, Navarra, Spiering, arXiv:1701.04340 .
با با سال effect is predicted to be caused b One can see from the figure that nuclear shadowing ²⁸⁶ **uration, but magnitude is smaller,** Cisek,
27.(2013) 022201: Tell Hilrich, BBC27 (2013) 024012; |*t*| [GeV2 11 CI
87 \sim \sim \sim \sim \sim \sim

Q1: Incoherent J/w photoproduction in Pb-Pb UPCs@LHC upper limit on the predicted nuclear shadowing. $J_{\rm eff}$ is included in the ALICE does not to include in the ALICE does not to include the ALICE does

• LT nuclear shadowing model makes predictions for incoherent J/ ψ photoproduct. on nuclei without additional parameters, Guzey, Strikman, Zhalov, EPJ C 74 (2014) 2942 on nuclei without additional parameters, Guzey, Strikman, Zhalov, EPJ C 74 (2014) 2942

$$
S_{\rm incoh}(W_{\gamma p}) \equiv \frac{d\sigma_{\gamma A \to J/\psi A'}^{\rm pQCD}(W_{\gamma p})/dt}{Ad\sigma_{\gamma p \to J/\psi p}^{\rm pQCD}(W_{\gamma p})/dt} = \frac{1}{A} \int d^2 \vec{b} \, T_A(b) \left[1 - \frac{\sigma_2}{\sigma_3} + \frac{\sigma_2}{\sigma_3} e^{-\sigma_3/2T_A(b)}\right]^2
$$

• ... and predicts too much shadowing \bullet and predicts too much shadowing

 $\frac{d}{dt}$ contribution of puckage dissociation $\frac{d}{dt}$ is $\frac{d}{dt}$ and $\frac{d}{dt}$ cantribution of puckage dissociation • One possible source of discrepancy: contribution of nucleon dissociation $\gamma + N \rightarrow J/\psi + Y$

 $\theta \rightarrow$ singled out by different t-dep.

 $\text{area} \left[\begin{array}{cc} -\frac{1}{2} & -\frac{1}{2} \ -\frac{1}{2} & -\frac{1}{2} \ \end{array} \right]$ $\text{phase} \left[\begin{array}{cc} -\frac{1}{2} & \frac{1}{2} \ -\frac{1}{2} & \frac{1}{2} \ \end{array} \right]$ (2013) 032201; Gay Ducati, Griep, $\frac{1}{6}$ • Dipole models with typically weaker shadowing **RG = 1 LHC 2.76 TeV** data, Lappi, Mantysaari, PRC 87 Machado, PRC88 (2013) 014910 are clo **Property**

Q2: ψ(2S) photoproduction in Pb-Pb UPCs@LHC 2: ψ(2S) photoproduction in tion in Pb-Pb UP

• Our LTA approach naturally predicts similar suppression for J/ ψ and $\psi(2S)$ \rightarrow tension with ALICE data on $\psi(2{\rm S})$ photoproduction in Pb-Pb UPCs at y=0 $^+$ indicating less shadowing, Adam et al. [ALICE], PLB751 (2015) 358 . .u..
otin $\overline{1}$ $\overline{}$ 51 (2 -9.6 sup $\overline{}$

 $\overline{}$ versions of the dinole $\bm{\mathsf{re}}$ asonable well for coherent $\psi(\textsf{2S})$, Gay Ducati, Griep, Machado, PRC88 (2013) 014910. UL
V • The versions of the dipole model, which do not describe coherent J/ ψ data, work

incoherent J/ ψ and coherent $\psi(2S)$ photoproduction in Pb-Pb UPCs. ψ(2S) meson photoproduction at √s = 2.76 TeV in PbPb \rightarrow challenge to reconcile theoretical description of data on coherent and \mid

Q3: Impact on global QCD fits of nPDFs nact on dional (JCI). ticular relevant provesses behavior of the ~conventional! diagonal partons which is is of newles. We then the attractive the attractive the attractive the attractive the attractive the attractiv \bullet of \bullet in \bullet \bullet

• In our approach, we use

$$
\text{JSE} \quad \left[\frac{d\sigma_{\gamma T \to J/\psi T}(W, t=0)}{dt} = C(\mu^2) \left[x G_T(x, \mu^2) \right]^2 \right]
$$

• We fix μ^2 and $C(\mu^2)$ using W-dependence of cross section on proton measured at HERA: **Jusing vv-dependence of cross s** In terms of the operator product expansion ~OPE! the evo- μ uon on proton measured at μ

- $-\mu^2 \approx 3$ GeV² for J/ ψ , Guzey, Zhalov JHEP 1310 (2013) 207 Guzey, Zhalov JHEP 1310 (2013) 207
- $-\mu^2 \approx 4$ GeV² for $\psi(2S)$, Guzey, Zhalov, arXiv:1405.7529 **b** \int , Guzey, Zhalov, arXiv:1405.7529

 \bullet In LO of collinear factorization for exclusive processes and NR expansion for J/ ψ distribution amplitude (wave function), cross section is in terms of gluon GPD: evolution. In the limit ^j!0 the distributions reduce to the f unction), cross se 2*¯* where \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} and right and right

$$
\frac{d\sigma_{\gamma T \to J/\psi T}(W,t=0)}{dt} = \frac{16\pi^3 \Gamma_{ee}}{3\alpha_{\rm e.m.}M_V^5} \Big[\alpha_S(\mu^2)H^g(\xi,\xi,t=0,\mu^2)\Big]^2
$$

• At high energies (small ξ) and LO, GPDs can be connected to PDFs in a weakly model-dependent way: controlled by the non-perturbative starting \mathcal{L} tion at some low scale ^m25*Q*⁰

explore the possibility that, in the small *x*,j!1 region, the - At low μ_0 , $x_{1,2} \gg \xi \rightarrow$ skewness can be neglected $x_i = x + \xi$ $-$ All skewness at μ > μ_0 due to evolution, Frankfurt, Freund, Guzey, ϵ the due to evolution. Expectual to be the case of the case o x_i' Strikman, PLB 418 (1998) 345; Shuvaev et al., RPD 60 (1999) 014015 ciently large @i.e. ln(*Q*² $\widehat{H^{g}}(\xi, \xi, t=0, \mu^{2}) = R_{g}xg(x_{B}, \mu^{2})$ $\frac{1}{2}$ (*n*) = *R* $ra(r_B \mu^2)$

$$
R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+5/2)}{\Gamma(4+\lambda)} \approx 1.2, \text{ for } xg \sim 1/x^{\lambda} \text{ with } \lambda \approx 0.2
$$

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Q3: Impact on global QCD fits of nPDFs (2)

- NLO corrections are very large, Ivanov, Schafer, Szymanowski, Krasninov, EPJ C 75 (2015) 2, 75; Jones, Martin, Ryskin, Teubner, J. Phys. G43 (2015) 035002, but can be tamed by choice of factorization scale $\mu = m_c$ and other tricks, Jones et al, Eur. Phys. J. C76 (2016) 633.
- However, in the nuclear suppression factor S_{Pb} many complications (skewness, NLO and higher-twist corrections) are likely minimized \rightarrow use S_{Pb} in global QCD fits of nPDFs.

Q4: Leading twist vs. dipole model vs. saturation

• Principal difference between our LTA and dipole model: Frankfurt, Guzey, McDermott, Strikman 2002

 $\mathcal{L}_{\mathcal{A}}$

Triple-Pomeron coupling to 2 nucleons

vs.

→ higher twist (HT) for small dipoles Separate Pomeron couplings to 2 nucleons

- **Fig. 9. Graphs for the total photon–nucleus cross section,** *A. Graph* **a give the shadowing approximation; graphs b and c give the shadowing the shadowing the shadowing the shadowing the shadowing the shadowing the sha** . The difference should manifest itself in observables dominated by small-size dipoles:
	- nuclear longitudinal structure function $F_{L}^{A}(x,Q^{2})$ at LHeC/EIC - nuclear longitudinal structure function F∟^A(x,Q²) at LHeC/EIC
- arget at the same intervention at the same instance, for the nucleus of $\frac{1}{2}$ *-* cross section or *J/* ψ photoproduction on nuclei in UPUS@LHG *)* = *AF*2*^N (x, ^Q*² - cross section of J/ ψ photoproduction on nuclei in UPCs@LHC
- Λ widely differential the strength of the target: the fluctuations of a small transverse size corresponding to Λ \cdot As soon as dipole model includes q-qbar-g, t argenting strength but the small phase volume. A parameter α parameter α phase volume α q-qbar-2g, etc. dipoles \rightarrow correctly models diffraction \rightarrow reproduces large inelastic Gribov $\begin{array}{ccc} \circ & \circ & \circ \\ \circ & \circ & \end{array}$ non-perturbative QCD phenomenon complicated by the leading twist *Q*² evolution. At extremely small *x*, perturbative QCD $\mathsf{\mathsf{shadowing}}\mathsf{.}$ diffraction → reproduces large inelastic Gribov दे अस्ति ।
shadoving denoted by the two-gluon exchange in Fig. 55.

 $\text{Gay Ducati, Griep, Machado, PRC88 (2013) } 014910; \quad 10 \leftarrow \text{Peri} \right)$ longitude recentributions from the Graphs Cisek, Schafer, Szczurek, PRC86 (2012) 014905 scattering and taking the imaginary part of the graphs in Fig. 9 (presented by the vertical dashed lines), one obtains in Fig. 9 (presented by the vertical dashed lines), one obtains in Fig. 9 (presented by the vertical d Gay Ducati, Griep, Machado, PRC88 (2013) 014910; 1.0 and Tanara

Q4: Leading twist vs. dipole model vs. saturation (2)

- Saturation of dipole cross section is part of dynamics of color dipole models.
- Since dipoles models have large theoretical uncertainties and non-perturbative contributions, *in my opinion*, LHC data on vector meson photoproduction in UPCs has not allowed so far to unambiguously establish necessity of saturation.
- All the data can also be described in collinear factorization and kt-factorization frameworks.
- Example: J/ ψ photoproduction in pp UPCs measured by LHCb in Run 1 and 2:

Q5: Peripheral production of J/ ψ in Pb-Pb collisions

• Very interesting recent data: enhanced J/ ψ yield in AA *peripheral* collisions at small pT.

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Possible interpretation: coherent photoproduction on nucleus fragment(s).

Outlook: other UPC processes

- Photoproduction of Y:
	- will allows one to study μ^2 dependence of shadowing suppression and $g_A(x,\mu^2)$ at small x
	- NLO and HT corrections are smaller, Ivanov, Schafer, Szymanowski, Krasninov, EPJ C 75 (2015) 2,

75; Jones, Martin, Ryskin, Teubner, J. Phys. G43 (2015) 035002

- Dipole models have still large uncertainty, Goncalves, Moreira, Navarra, arXiv:1408.1344.
- UPCs accompanied by forward neutron emission: possibility to probe smaller x, Guzey, Strikman, Zhalov, EPJ C (2014) 74: 2942
- Photoproduction of dijets in AA UPCs: complimentary probe of $g_A(x,\mu^2)$ at small x and large µ² , Strikman, Vogt, White, PRL 96 (2006) 082001 → **talks by A. Angerami, P. Kotko**
- *Diffractive* photoproduction of dijets in UPCs, Guzey, Klasen JHEP 1604 (2016) 158.
- access to nuclear diffractive PDFs at small x
- probe of mechanism of QCD factorization breaking: global suppression vs. resolved-only suppression →

Summary

 \cdot Coherent photoproduction of vector mesons on nuclei in UPCs@LHC allows one to study nuclear shadowing in soft and hard processes at unprecedentedly high energies.

• Photoproduction of ρ and ϕ on nuclei tests the roles of hadronic fluctuations of the photon and inelastic nuclear shadowing.

• Photoproduction of J/ ψ , ψ' and Y on nuclei gives direct access to the nuclear gluon distribution $g_A(x,\mu^2)$ down to $x \approx 10^{-3}$ (5×10⁻⁴) at $\mu^2 \approx 3$ -4 GeV² and allows one to study its μ^2 dependence; direct evidence of large gluon nuclear shadowing $Rg(x=0.001) = 0.6$.

• Apart from several mentioned problem, the available UPC data can be described by competing theoretical approaches — collinear factorization, ktfactorization, dipole models with/out saturation.

• Hopefully, new Run 2 UPC data on photoproduction of VM and jets will help to clarify the situation.