Leading twist nuclear shadowing from photoproduction of charmonia in ultraperipheral collisions at the LHC

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Outline

- Gluon distribution in nuclei at small-x and ion ultraperipheral collisions (UPCs)

- Photoproduction of $J/\psi$ and $\psi(2S)$ in Pb-Pb UPCs at the LHC at $\sqrt{s_{NN}}=2.76$ TeV and constraints on leading twist nuclear shadowing of $g_A(x,\mu^2)$ at small $x$

- Summary, discussion and outlook
Gluon distribution in nuclei

- The gluon distribution in nuclei $g_A(x, \mu^2) =$ the probability (at LO) to find a gluon with the momentum fraction $x$ at the resolution scale $\mu^2$.

- Describes QCD structure of nuclei probed in hard processes.

- Important element of QCD phenomenology:
  - cold nuclear matter effects for HI collisions
  - quantitative analysis of gluon saturation in nuclei.

- $g_A(x, \mu^2)$ is determined from global QCD fits to fixed-target + RHIC data.

- Significant uncertainties due to:
  - limited kinematics
  - indirect extraction via DGLAP evolution
  - different assumptions about shape

\[
R_g(x, Q^2) = \frac{g_A(x, Q^2)}{A g_p(x, Q^2)}
\]
Gluon distribution in nuclei (2)

- **pA@LHC** data on production of W, Z, jets consistent with current nPDFs fits and give little to further constrain them, N. Armesto et al, arXiv:1512.01528

- **Notable exemption**: dijets at CMS favoring EPS09 (large) gluon antishadowing
  - similar antishadowing in leading twist nuclear shadowing model

- **EIC** will constrain $g_A(x,Q^2)$ in wide range: down to $x \approx 10^{-3}$ ($5 \times 10^{-4}$) for $Q^2 \approx 4$ GeV$^2$

**Photoproduction of charmonia ($J/\psi$, $\psi(2S)$)** in AA UPCs at the LHC probes $g_A(x,\mu^2)$ in similar kinematic point.
Ultrapерipheral collisions at the LHC

• In pp, pA and AA collisions, ions can scatter at large impact parameters $b > R_A + R_B = 10-20$ fm— ultraperipheral collisions (UPCs).

UPC events correspond to empty detector with two lepton tracks (from J/ψ decay).

• In UPCs the strong interact is suppressed and ions interact via quasi-real photons, E. Fermi (1924), C.F. von Weizsäcker; E.J. Williams (1934)

$$\frac{d\sigma_{AA \rightarrow AA J/\psi(y)}}{dy} = N_{\gamma/A}(y)\sigma_{\gamma A \rightarrow AJ/\psi(y)} + N_{\gamma/A}(-y)\sigma_{\gamma A \rightarrow AJ/\psi(-y)}$$

photon flux photoproduction cross section

$$y = \ln(2\omega/M_{J/\psi}) = \ln(W^2_{\gamma p}/(2\gamma_L m_N M_{J/\psi}))$$ is J/ψ rapidity
UPCs at the LHC (2)

- Photon flux of point-like source:

\[ N_\gamma/Z(k) = \frac{2Z^2\alpha_{em}}{\pi} \left[ \zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2} (K_1^2(\zeta) - K_0^2(\zeta)) \right] \]

- scales as \( Z^2 \) (\( Z^2 \approx 7000 \) for Pb)

- corresponds to HUGE maximal photon energy in the target rest frame due to large \( \gamma_L \):

\( \gamma_L \approx 1500 \) for Pb-Pb UPCs@2.76 TeV \( \rightarrow \omega_{\text{max}} \approx 120 \) TeV:

\[ \zeta = k(2R_A/\gamma_L) \]

Spectrum of equivalent photons in Pb-Pb UPCs in nucleus rest frame →

• UPCs give an opportunity to study \( \gamma p \) and \( \gamma A \) interactions at energies 10 larger than at HERA → new constraints on \( g_p(x,\mu^2) \) and \( g_A(x,\mu^2) \).

A. Baltz et al., The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1
Exclusive photoproduction of charmonium

- In leading logarithmic approximation of perturbative QCD and non-relativistic limit for charmonium (J/ψ, ψ(2S)) wave function:

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

\[
x = \frac{M_{J/\psi}^2}{W^2}, \quad \mu^2 = M_{J/\psi}^2/4 = 2.4 \text{ GeV}^2, \quad C(\mu^2) = M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s(\mu^2) / (48\alpha_{em}\mu^8)
\]

- Relativistic corrections (k_T-formalism), skewed kinematics, real part:

\[
C(\mu^2) \to (1 + \eta^2) R_g^2 F^2(\mu) C(\mu^2) \to 1.5 F^2(\mu) C(\mu^2)
\]

- Our phenomenological approach:
  - use freedom in \(\mu^2\) and choose it to describe W-dependence of HERA data
  - fix normalization \(C(\mu^2)\) using the \(W=100\) GeV HERA data point

- Our results:
  - J/ψ: \(\mu^2 \approx 3\) GeV\(^2\), \(F^2(\mu^2) \approx 0.5\), Guzey, Zhalov JHEP 1310 (2013) 207
  - ψ(2S): \(\mu^2 \approx 4\) GeV\(^2\), \(F^2(\mu^2)\) from \(\sigma_{\gamma p \to \psi(2S)p} = 0.17\sigma_{\gamma p \to J/\psi p}\) Guzey, Zhalov, arXiv:1405.7529
Coherent charmonium photoproduction on nuclei and gluon nuclear shadowing

- Applying to coherent charmonium photoproduction on nuclei:

\[
\sigma_{\gamma A \rightarrow J/\psi A}(W_{\gamma p}) = \frac{(1 + \eta_A^2) R_{g,A}^2}{(1 + \eta^2) R_g^2} \int \frac{d\sigma_{\gamma p \rightarrow J/\psi p}(W_{\gamma p}, t = 0)}{dt} \left[ \frac{G_A(x, \mu^2)}{AG_N(x, \mu^2)} \right]^2 \Phi_A(t_{\min})
\]

Small correction \( \kappa_{A/N} \approx 0.95 \)

From HERA and LHCb

- Comparing to theoretically-defined impulse approximation (IA):

\[
\sigma_{\gamma Pb \rightarrow J/\psi Pb}(W_{\gamma p}) = \int \frac{d\sigma_{\gamma p \rightarrow J/\psi p}(W_{\gamma p}, t = 0)}{dt} \Phi_A(t_{\min})
\]

Nuclear suppression factor:

\[
S(W_{\gamma p}) = \left[ \frac{\sigma_{\gamma Pb \rightarrow J/\psi Pb}(W_{\gamma p})}{\sigma_{\gamma Pb \rightarrow J/\psi Pb}(W_{\gamma p})} \right]^{1/2}
\]

- \( S(W_{\gamma p}) = \kappa_{A/N} \frac{G_A(x, \mu^2)}{AG_N(x, \mu^2)} = \kappa_{A/N} R_g(x, \mu^2) \)

\( S \) gives direct measure of gluon shadowing ratio \( R_g(x, \mu^2) \).
Model of leading twist nuclear shadowing

- Based on generalization of the Gribov-Glauber theory of nuclear shadowing and QCD factorization theorems:

\[ x f_{j/A}(x, Q_0^2) = A x f_{j/N}(x, Q_0^2) - 8\pi A(A-1) \operatorname{Re} \frac{(1 - i\eta)^2}{1 + \eta^2} B_{\text{diff}} \int_0^{0.1} dx_P \beta f_j^{D(3)}(\beta, Q_0^2, x_P) \]
\[ \times \left( \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\hat{b}, z_1) \rho_A(\hat{b}, z_2) e^{i(z_1-z_2) x_P m_N} e^{-\frac{A}{2} (1-i\eta) \sigma_{\text{soft}}(x, Q_0^2) \int_{z_1}^{z_2} dz' \rho_A(\hat{b}, z')} \right) \]

Nuclear part from Glauber model

- Input:
  - proton diffractive PDFs \( f_j^{D(3)} \)
  - diffractive slope \( B_{\text{diff}} \)
  - model-dep. effective cross section \( \sigma_{\text{soft}} \)

Shadowing in eA DIS is driven by diffraction in ep DIS!
Model of leading twist nuclear shadowing (2)

- Characteristic feature — large nuclear gluon shadowing due to large gluon diffractive PDF of the proton as measured in ep diffraction in DIS at HERA.

- Shadowing due to interaction with two nucleons is driven by:

\[
\frac{\langle \sigma^2 \rangle}{\langle \sigma \rangle} \equiv \sigma_2(x, \mu^2) = \frac{16\pi B_{\text{diff}}}{(1 + \eta^2)xG_N(x, \mu^2)} \int_x^{0.1} dx' P_\beta G_N^{D(3)}(\beta, \mu^2, x')
\]

- Interaction with N ≥ 3 nucleons modeled using eikonal app. with σ_{soft}=σ_3=30-50 mb.

- Predictions for the gluon nuclear shadowing:

\[
R_g(x, Q^2) = \frac{g_A(x, Q^2)}{A g_p(x, Q^2)}
\]

![Similar to EPS09 nuclear PDFs](image-url)
Coherent photoproduction of charmonia at LHC

• ALICE measured J/ψ, ψ(2S) photoproduct in Pb-Pb UPCs at √sNN=2.76 TeV

Abelev et al. [ALICE], PLB718 (2013) 1273; Abbas et al. [ALICE], EPJ C 73 (2013) 2617

Adam et al. [ALICE], PLB751 (2025) 358

"Consistent with models incorporating moderate nuclear gluon shadowing at x ≈10^{-3}"

"Disfavors models implementing strong nuclear gluon shadowing"
Comparison to nuclear suppression extracted from ALICE data

- Very good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs at 2.76 TeV → first direct evidence of large nuclear gluon shadowing at x=0.001.

- Theory predicts similar nuclear suppression in J/ψ and ψ(2S) cases → contradicts ALICE data on ψ(2S) photoproduction in Pb-Pb UPCs at central rapidity → may be resolved with more statistics in Run 2.
Coherent photoproduction of $J/\psi$ in Pb-Pb UPCs accompanied by neutron emission

- UPCs can be accompanied by mutual e.m. excitation of nuclei followed by forward neutron emission:
  
  Baltz, Klein, Nystrand, PRL 89 (2002) 012301

- CMS measurement in (Xn,0n)-channel (prel.) nicely agrees with our predictions of large nuclear gluon shadowing, CMS Note, CMS PAS HIN-12-99
Summary, discussion and outlook

• The gluon distribution in nuclei $g_A(x,\mu^2)$ for small $x$, $x < 0.005$, is poorly constrained.

• LHC pA data provide modest improvement, which possible exception of antishadowing. EIC should pin down $g_A(x,\mu^2)$ down to $x \approx 10^{-3}$ ($5 \times 10^{-4}$) for $\mu^2 \approx 4$ GeV$^2$.

• ALICE data on coherent $J/\psi$ photoproduction in Pb-Pb UPCs at 2.76 TeV gives first direct evidence of large nuclear gluon shadowing at $x=10^{-3}$ and $\mu^2 \approx 3$ GeV$^2$ which agrees with predictions of leading twist nuclear shadowing model and EPS09 fit.

• At the same time, there is discrepancy between models with large gluon shadowing and ALICE data on coherent $\psi(2S)$ photoproduction in Pb-Pb UPCs at the LHC at 2.76 TeV $\rightarrow$ Run 2 data may resolve this.

• Our leading twist approach overestimates nuclear suppression of incoherent $J/\psi$ photoproduction in Pb-Pb UPCs at 2.76 TeV $\rightarrow$ account of nucleon dissociation $\gamma N \rightarrow J/\psi$ $X$ may help to decrease the discrepancy.
Summary, discussion and outlook (2)

- Main competitor to pQCD description of considered processes — color dipole model. Since charmonium wf selects small-size dipoles, nuclear shadowing due to multiple rescattering on target nucleons is generically small, Lappi, Mantysaari, PRC 87 (2013) 032201; Goncalves, Machado, PRC 84 (2011) 011902.


- The UPC program at LHC will continue in Run 2 with measurements of light ($\rho, \phi$) and heavy ($J/\psi, \psi(2S), \Upsilon$) vector mesons photoproduction in Pb-Pb UPCs at $\sqrt{s_{NN}}=5.02$ TeV.

- UPCs with e.m. excitations of the colliding ions followed by forward neutron emission and detection in ZDCs allow one to separate low-W and high-W terms in UPC cross section → access to lower $x < 10^{-3}$ in $g_A(x, \mu^2)$.

- New UPC processes for Run 2 at the LHC: diffractive photoproduction of dijets to address factorization breaking and measure nuclear diffractive PDFs.