Nuclear shadowing in exclusive processes

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Outline:

- Nuclear PDFs at small-x and UPCs
- Gluon nuclear shadowing from coherent $J/\psi$ photoproduction on nuclei
- Theoretical issues in pQCD studies of coherent $J/\psi$ photoproduction
- Imaging of nuclear gluons at small $x$

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Nuclear shadowing and nPDFs at small-x

- Nuclear shadowing: suppression \( f_A(x, \mu^2) < A f_N(x, \mu^2) \) for small \( x < 0.005 \).
- Important for QCD phenomenology of hard processes with nuclei: cold nuclear matter effects, gluon saturation (RHIC, LHC, EIC, LHeC/FCC)
- \( f_A(x, \mu^2) \) are determined from global QCD fits to data on fixed-target DIS, hard processes in \( dA \) (RHIC) and \( pA \) (LHC) \( \to f_A(x, \mu^2) \) with significant uncertainties

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

Paukunen, NPA 926 (2014) 24

- \( pA@LHC \) data help little, EPPS16, Eskola, Paakkinen, Paukunen, Salgado EPJ C77 (2017) 163

Gluon nuclear shadowing at EIC and LHeC

• In the future, gluon nuclear shadowing will be further constrained at EIC, Accardi et al, EPJ A52 (2016) no.9, 268; LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001 due to wide $Q^2$-x kinematic coverage, $F_L^A(x,Q^2)$ and $F_2^{\text{charm}}(x,Q^2)$ measurements:
Ultraperipheral collisions

- Ultraperipheral collisions (UPCs): ions interact at large impact parameters $b >> R_A+R_B$ → strong interaction suppressed → interaction via quasi-real photons, Fermi (1924), von Weizsäcker; Williams (1934)

- UPCs correspond to empty detector with only two lepton/pion tracks from vector meson decay
- Nuclear coherence by veto on neutron production by Zero Degree Calorimeters (ZDCs) and selection of small pt

• Coherent photoproduction of vector mesons in UPCs:

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

Photon flux from QED:
- high intensity $\sim Z^2$
- high photon energy $\sim \gamma_L$

Photoproduction cross section

$$y = \ln\left[\frac{W^2}{2\gamma_L m_N M_V}\right]$$

= $J/\psi$ rapidity

UPCs@LHC = $\gamma p$ and $\gamma A$ interactions at unprecedentedly large energies, Baltz et al., The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1
**UPCs at the LHC**

- To probe partonic structure of (nuclear) targets, one selects UPC processes with a hard scale → heavy vector meson mass or jet $p_T$

  - **Run1:** photoproduction of quarkonia $J/\psi, \psi(2S)$ in:
    - p-Pb UPCs, [ALICE] Abelev et al., PRL 113 (2014) 232504,


  - Also photoproduction of $\rho$, [ALICE] Adam et al. JHEP 1509 (2015) 095 → soft nuclear shadowing


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### Exclusive $J/\psi$ photoproduction

- **Direct photon**
  - Nucleus intact
  - No neutrons

- **Resolved photon**
  - Nucleus breaks up
  - Multiple neutrons

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### Inclusive dijet photoproduction

- **Direct photon**
  - Nucleus intact
  - No neutrons

- **Resolved photon**
  - Nucleus breaks up
  - Multiple neutrons

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Exclusive charmonium photoproduction

- In leading logarithmic approximation (LLA) of pQCD and non-relativistic approximation for charmonium wave function (J/ψ, ψ(2S)), Ryskin, Z. Phys. C57 (1993) 89

\[ \frac{d\sigma}{dt} = C(\mu^2) \left[ xG_T(x, \mu^2) \right]^2 \]

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

- Beyond LLA and NR approximation for charmonium:
  - **kT-factorization**, Ryskin, Roberts, Martin, Levin, Z. Phys. C76 (1997) 231; Martin, Nockles, Ryskin, Teubner, PLB 662 (2008) 252; Jones, Martin, Ryskin, Teubner, JHEP 1311 (2013) 085: gluon and quark kT → additional suppression by factor 1/2; some NLO effects using unintegrated g(x,k_T) reducing to NLO g(x,μ^2) + skewness factor to relate GPDs and PDFs → successful LO and NLO pQCD description of HERA and LHCb data on charmonium photoproduction
  - **kT-factorization**, Cisek, Schafer, Szczurek, JHEP 1504 (2014) 159: unintegrated gluon distribution with saturation seems to be somewhat preferred by LHCb data on J/ψ photoproduction
  - **color dipole model framework**, Frankfurt, Koepf, Strikman (1998): relativistic effects in charmonium wf are very important; gluon virtualities are much higher than in NR case; Goncalves, Machado 2008-present; Lappi, Mäntysaari (2013): dipole cross section with/without saturation; large dependence on charmonium wf; phenomenological description of HERA and UPC data for proton. For Pb targets, nuclear suppression due to shadowing is generally underestimated.
  - **Collinear factorization at NLO**, Ivanov, Schaefer, Szymanowski, Krasnikov (2015); Jones, Martin, Ryskin, Teuber (2015): large ~200% NLO corrections and scale dependence
Coherent charmonium photoproduction on nuclei

- Application to nuclear targets:

\[ \sigma_{\gamma A \rightarrow J/\psi A}(W_{\gamma p}) = \kappa_{A/N}^2 \frac{d\sigma_{\gamma p \rightarrow J/\psi p}(W_{\gamma p}, t = 0)}{dt} \frac{G_A(x, \mu^2)}{AG_N(x, \mu^2)}^2 \Phi_A(t_{\text{min}}) \]

Small correction \( k_{A/N} \approx 0.90-95 \) due to different skewnesses of nuclear and nucleon GPDs

From HERA and LHCb

Nucleus/proton gluon ratio \( R_g \)

From nuclear form factor

- Well-defined impulse approximation (IA):

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

- Nuclear suppression factor \( S \) (like \( R_{pA} \) or \( R_{AA} \)) \( \rightarrow \) direct access to \( R_g \)

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

Model-independently from data on UPC@LHC (ALICE, CMS) and HERA, LHCb Abelev et al. [ALICE], PLB718 (2013) 1273; Abbas et al. [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489

From global QCD fits of nPDFs or leading twist nuclear shadowing model

$S_{\text{Pb}}$ from ALICE and CMS UPC data vs. theory

- $J/\psi$ photoproduction in Pb-Pb UPCs at LHC, Abelev et al. [ALICE], PLB 718 (2013) 1273; Abbas et al. [ALICE], EPJ C 73 (2013) 2617; CMS Collab., PLB 772 (2017) 489 → suppression factor $S_{\text{Pb}}$

- Good agreement with ALICE data on coherent $J/\psi$ photoproduction in Pb-Pb UPCs at LHC, $\mu^2=3$ GeV$^2$ → direct evidence of large gluon NS, $R_g(x=0.001) \approx 0.6$.

- Also good description using central value of EPS09, EPPS16, large uncertainty.

- Color dipole models generally give too little suppression, Goncalves, Machado (2011); Lappi, Mäntysaari, 2013, but proton shape fluctuations help, Mäntysaari, Schenke, PLB 772 (2017) 681

LTA: Guzey, Zhalov JHEP 1310 (2013) 207
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028
Recent results on exclusive J/ψ photoproduction in Pb-Pb UPCs from LHCb

- Good agreement with LTA, EPS09, and certain versions of the dipole model with proton shape fluctuations.
Theoretical issues: collinear factorization

- Ryskin’s formula is derived in leading $\alpha_s \ln(1/x) \ln Q^2$ approx. + NR approx. for charmonium wf (charm quarks have $k_T=0, z=1/2, J/\psi$ via its $J/\psi \rightarrow e^+e^-$ decay)

- Electroproduction of $J/\psi$ in leading $\alpha_s \ln(1/x) \ln Q^2$ approx., Brodsky, Frankfurt, Gunion, Mueller, Strikman, PRD 50 (1994) 3134: answer in terms of $xg(x,\mu^2)$ and $J/\psi$ distribution amplitude


\[ \mathcal{M} = \left( \frac{\langle O_1 \rangle_V}{m} \right)^{1/2} \sum_{p=g,q,\bar{q}} \int_0^1 dx_1 \ A_{H}^{p}(x_1, \mu_F^2) \ F^{p}_{\zeta}(x_1, t, \mu_F^2) \]

- Amplitude = convolution of generalized parton distributions (GPDs) with hard coefficients
- Information on $J/\psi$ via NR matrix element

- NLO corrections and scale dependence are very large, $\sim 200\%$ in HERA kinematics $\rightarrow$ problematic to build successful phenomenology, Ivanov, Schaefer, Szymanowski, Krasnikov, EPJ C 75 (2015) 75
Our phenomenological approach

• In our approach, Guzey, Zhalov, JHEP 1310 (2013) 207, we took Ryskin’s formula at face value, chose $\mu^2=3$ GeV$^2$ to fit $W$-dependence of HERA data on $\gamma+p \to J/\psi+p$, and corrected it by skewness and real part → describe well $W$-dependence of HERA, LHCb data, but overestimate normalization by factor of two.


• Our approach is equivalent to collinear factorization at LO:

$$\mathcal{M} = -\frac{8\pi\alpha_s e_c g(e^*_V \cdot e_\gamma)}{m_c} \int_{-1}^{1} dx \frac{F^g(x, \xi, t, \mu^2)}{(x-\xi+i\epsilon)(x+\xi-i\epsilon)}$$

At LO, the imaginary part probes the most skewed situation, when GPDs are far from PDFs. The connection is model-dependent and based on forward input for DGLAP evolution for GPDs, Shuvaev, Golec-Biernat, Martin, Ryskin, PRD 60 (1999) 014015

$$R = \frac{H(\xi,\xi)}{H(2\xi,0)} = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+5/2)}{\Gamma(\lambda+3+p)}$$

where $xg(x) \sim (1/x)^\lambda$
Implications for gluon nPDF at small x

• Taking nucleus/proton ratio, one might hope that most corrections cancel and $S_{Pb}$ represents gluon shadowing at LO with small correction due to different skewness for nucleus and proton GPDs:

$$S(W_p) = \left[ \frac{\sigma_{\gamma Pb \rightarrow J/\psi Pb}}{\sigma_{IA \gamma Pb \rightarrow J/\psi Pb}} \right]^{1/2} = \kappa_{A/N} \frac{G_A(x, \mu^2)}{A G_N(x, \mu^2)} = \kappa_{A/N} R_g$$

\[ k_{A/N} = R_A / R_N \]

• One needs to check further (LO and NLO):
  - cancellation of GPD/PDF connection in ratio $S_{Pb}$
  - to what extent corrections beyond collinear approximation cancel in $S_{Pb}$
  - useful guide to estimate the magnitude of these corrections is provided by the dipole model, Frankfurt, Koepf, Strikman 1996,1998

• Open questions:
  - relativistic corrections to $J/\psi$ distribution amplitude
  - resummation to reduce the large scale dependence at NLO
  - connection between collinear factorization (GPDs) and $k_T$ factorization/dipole models; leading twist vs. all-twist nuclear shadowing
Imaging of nuclear gluons at small $x$

- In case of large nuclear shadowing, $\gamma A \rightarrow J/\psi A$ cross section should be generalized:

$$\frac{d\sigma_{\gamma A \rightarrow J/\psi A}}{dt} = \frac{d\sigma_{\gamma p \rightarrow J/\psi p}(t = 0)}{dt} \left( \frac{R_{g,A}}{R_{g,p}} \right)^2 \left( \frac{g_A(x, \mu^2)}{A g_p(x, \mu^2)} \right)^2 F_A^2(t)$$

$$\frac{d\sigma_{\gamma A \rightarrow J/\psi A}}{dt} = \frac{d\sigma_{\gamma p \rightarrow J/\psi p}(t = 0)}{dt} \left( \frac{R_{g,A}}{R_{g,p}} \right)^2 \left( \frac{g_A(x, t, \mu^2)}{A g_p(x, \mu^2)} \right)^2$$

- Answer in terms of nuclear GPD in the $x_1=x_2$ limit $\rightarrow$ FT $\rightarrow$ impact-parameter-dependent nPDF $f_{j/A}(x,Q_0^2,b)$, Guzey, Strikman, Zhalov, PRC 95 (2017) 025204

$$xf_{j/A}(x, Q_0^2, b) = A T_A(b) xf_{j/N}(x, Q_0^2) - 8\pi A(A - 1) B_{\text{diff}} \Re e \left( \frac{1 - i\eta)^2}{1 + \eta^2} \int_0^1 dx_{\perp} \beta f_j^{D(3)}(\beta, Q_0^2, x_{\perp}) \right.$$  

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

Correlations between impact parameter \( b \) and \( x \) (shadowing is stronger in nucleus center) → shift of t-dependence of \( \gamma A \rightarrow J/\psi A \) cross section in UPCs:

\[
\frac{(d\sigma/dt)}{[d\sigma/dt(t_{\text{min}})]} \quad \text{as a function of } t_{\min}
\]

- Resulting shift = **5-11% broadening** in impact parameter space of gluon nPDF
- Similar effect is predicted to be caused by saturation, Cisek, Schafer, Szczurek, PRC86 (2012) 014905; Lippi, Mäntysaari, PRC 87 (2013) 032201; Toll, Ullrich, PRC87 (2013) 024913; Goncalves, Navarra, Spiering, arXiv:1701.04340
- Oscillations of beam-spin nuclear DVCS asymmetry at EIC and LHeC.
Summary

- Small-x nPDFs — especially gluon nPDFs — are poorly constrained by available fixed-target nuclear DIS and pA LHC data. Additional processes and Run 2 data may help.

- Photoproduction of J/ψ in Pb-Pb UPCs at the LHC gives direct evidence of large gluon nuclear shadowing $R_g(x=0.001, \mu^2 \approx 3 \text{ GeV}^2) = 0.6$.

- Theoretical challenge and open question: include UPC data on exclusive J/ψ in global QCD fits of nPDFs.

- Heavy quarkonia photoproduction in UPCs gives access to transverse imaging of (nuclear) gluon distribution at small x.