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 $\rho$ photoproduction on nuclei
- Gluon nuclear shadowing from $J/\psi$ 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
Ultraparperipheral collisions (UPCs)

- Ions can interact at large impact parameters $b >> R_A + R_B \rightarrow$ ultraperipheral collisions (UPCs) $\rightarrow$ strong interaction suppressed $\rightarrow$ interaction via quasi-real 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 $p_t$

- Coherent photoproduction of vector mesons in UPCs:

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

Photon flux: Photoproduction cross section

- Photon flux from QED:
  - high intensity $\sim Z^2$
  - large photon energies $\zeta = k(2R_A/\gamma_L)$

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

UPCs = $\gamma p$ and $\gamma A$ interactions at unprecedentedly large energies, Baltz et al., The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1
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 (\( \rho, \pi, \gamma, \gamma^*, \nu \)) of large energies (> 1 GeV)
- Explained by simultaneous interaction of projectile with target nucleons \( \rightarrow \) destructive interference among amplitudes for interaction with 1, 2, \( \ldots \) nucleons \( \rightarrow \) nucleons in rear of the nucleus “see” smaller (shadowed) flux: \( \sigma_A \sim A^{2/3} \).

\[ \text{elastic intermediate state, Glauber 1955} \quad \text{inelastic intermediate state, Gribov 1969} \]

- NS in photoproduction of light vector mesons \( \rho, \omega, \phi \):
  - dynamics of soft \( \gamma p \) and \( \gamma A \) interaction at high energies
  - validity of VMD model and role of inelastic (Gribov) shadowing
  - constraints on color dipole approach
- NS in photoproduction of heavy vector mesons \( J/\psi, \psi(2S), Y \):
  - mechanism of nuclear shadowing; leading twist vs. HT vs. saturation
  - new constraints on nuclear gluon distribution \( g_A(x, \mu^2) \) at small \( x \)
Coherent photoproduction of ρ on nuclei

• Measured with fixed targets (SLAC, $W < 6$ GeV), in Au-Au UPCs at RHIC ($W < 12$ GeV), 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 $\rho A$ scattering:

$$\sigma_{\gamma A \rightarrow \rho A}^{\text{VMD}} = \left( \frac{e}{f_\rho} \right)^2 \int d^2 b \left| 1 - e^{-\frac{1}{2} \sigma_{\rho N} T_A(b)} \right|^2$$

$\sigma_{\rho N}$ from constituent quark model/data:

Optical density:

$$T_A(b) = \int dz \rho_A(b, z)$$


• Dipole models describe data better, but strongly model-dependent, Goncalves, Machado, PRC 84 (2011) 011902

Modified vector meson dominance (mVMD) model

- At large beam energies $E_{\gamma}$, the photon can be viewed as superposition of long-lived ($l_c \sim E_{\gamma}$) fluctuations interacting with hadrons with different cross sections, Gribov, Ioffe, Pomeranchuk 1965; Good, Walker, 1960

- Convenient to realize introducing the probability distribution $P(\sigma)$, Blattel et al, 1993

\[
\int d\sigma P(\sigma) = 1 ,
\]

\[
\int d\sigma P(\sigma)\sigma = \langle \sigma \rangle , \quad \rightarrow \text{from} \quad d\sigma(\gamma p \rightarrow \rho p)/dt
\]

\[
\int d\sigma P(\sigma)\sigma^2 = \langle \sigma \rangle^2 (1 + \omega_\sigma) \quad \rightarrow \text{from measured } \gamma \text{ diffract. dissociation into large masses, Chapin 1985}
\]

- Shape like for pion, Blattel et al, 1993 + small-$\sigma$ enhancement to take into account smaller size of $\rho$ in $\gamma p \rightarrow \rho p$ than in $\sigma_{\pi N}$

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

\[
\frac{d\sigma(t=0)}{dt} , \mu b/GeV^2
\]

\[
W_{\gamma p}, \text{GeV}
\]
Photoproduction of $\rho$ on Pb in mVMD+Gribov-Glauber model

- With cross section fluctuations:
  \[ \sigma^{\text{mVMD-GGM}}_{\gamma A \rightarrow \rho A} = \left( \frac{e}{f_\rho} \right)^2 \int d^2\vec{b} \left| \int d\sigma P(\sigma) \left( 1 - e^{-\frac{\sigma}{2} T_A(b)} \right) \right|^2 \]

- “Two birds with one stone”: we describe correctly the elementary $\gamma p \rightarrow \rho p$ cross section and include inelastic Gribov shadowing in $\sigma_{\gamma A \rightarrow \rho A}$

- \( \rightarrow \) describe well normalization and W-dependence $\sigma_{\gamma A \rightarrow \rho A}$, Frankfurt, Guzey, Strikman, Zhalov, PLB 732 (2016) 51
Predictions for Run 2@LHC: $\rho$ and $\phi$ mesons

- $\rho$: $P(\sigma)$ from data
- $\phi$: $P(\sigma)$ from $\sigma_{\phi N}$

(Donnachie, Landshoff, 1995) + constituent quark $\omega^\phi = \frac{\sigma_{NN}}{\sigma_{\phi N}} \omega^\phi$

- "Ears" for $\rho$: effect of Reggeon in $\sigma_{\rho N}$
- Change of shape for 0nXn-channel due to large $W_{\gamma p}$ enhancement of photon flux

0nXn-channel: e.m. excitation of either of nuclei with forward emission > 1 neutron in ZDC

Guzey, Kryshen, Zhalov, PRC 93 (2016) 055206
News from QM2017 on $\rho$ photoproduction on nuclei in Pb-Pb UPCs in Run 2

- Preliminary ALICE result on Pb-Pb UPCs at $\sqrt{s_{NN}}$=5.02 TeV: cross section is almost 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

- $d\sigma/dy = (448 \pm 2\text{ (stat)}^{+38}_{-75}\text{ (syst)})\text{ [mb]}$
- 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

- Gluon nuclear shadowing: \( g_A(x, \mu^2) < A g_N(x, \mu^2) \) for small \( x < 0.005 \).
- 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
- At small \( x \), \( g_A(x, \mu^2) \) is known with large uncertainties →
- Option right now: Charmonium photoproduction in Pb-Pb UPCs@LHC

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

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

\[
\frac{d\sigma_{\gamma T \rightarrow J/\psi T}(W, t = 0)}{dt} = C' (\mu^2) \left[ x G_T(x, \mu^2) \right]^2
\]

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

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

- Application to nuclear targets:

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

- Small correction $k_{A/N} \approx 0.90-95$
- From HERA and LHCb
- Gluon shadow, $R_g$
- From nuclear form factor $\Phi_A(t_{\text{min}}) = \int_{-\infty}^{t_{\text{min}}} dt |F_A(t)|^2$

- Nuclear suppression factor $S \rightarrow$ direct access to $R_g$

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

- Impulse approx.

Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290
Leading twist nuclear shadowing model

- Combination of Gribov-Glauber NS model with QCD factorization theorems for inclusive and diffractive DIS → shadowing for individual partons j, Frankfurt, Strikman (1999)

Interaction with 2 nucleons:
model-indep via diffractive PDFs:

\[
\sigma^j_2(x) = \frac{16\pi}{xf_{j/N}(x, \mu^2)} \int_0^{0.1} dxP(\beta f_{j/N}^{D(4)}(x, \mu^2, x_P, t = 0))
\]

Interaction with ≥ 3 nucleons: via soft hadronic fluctuations of γ*:

\[
\sigma_{\text{soft}}(x) = \frac{\int d\sigma P_{\gamma}(\sigma)\sigma^3}{\int d\sigma P_{\gamma}(\sigma)\sigma^2}
\]

P(σ) probability to interact with cross section σ


\[
xf_{j/A}(x, \mu^2) = Af_{j/N}(x, \mu^2) - \frac{2\sigma^j_2f_{j/N}(x, \mu^2)}{[\sigma^j_{\text{soft}}(x)]^2} \int d^2b \left( e^{-\frac{1}{2}\sigma^j_{\text{soft}}(x)TA(b)} - 1 + \frac{\sigma^j_{\text{soft}}(x)}{2}TA(b) \right)
\]
Leading twist nuclear shadowing model (2)

- Model gives nuclear PDFs at $\mu^2=3-4$ GeV$^2$ for subsequent DGLAP evolution.

- Name “leading twist” since diffractive structure functions/PDFs measured at HERA scale with $Q^2$.

- Gluon diffractive PDFs are large, ZEUS, H1 2006 → predict large shadowing for $g_A(x,\mu^2)$, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

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 $J/\psi$ photoproduction in Pb-Pb UPCs@2.76 TeV → first direct evidence of large gluon NS, $R_g(x=0.001) \approx 0.6$.

- 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.


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

Abelev et al. [ALICE], PLB718 (2013) 1273;
Abbas et al. [ALICE], EPJ C 73 (2013) 2617;
CMS Collab., arXiv:1605.06966
3D nuclear gluon distribution

- 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 dependent nPDF $g_A(x,b,Q^2)$

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

predicted by LT shadowing model

extracted/guessed in EPS09s, Helenius et al, JHEP 1207 (2012) 073

- 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)

- 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

![Graphs showing cross-section fluctuations](image1.png)

![Graphs showing cross-section fluctuations](image2.png)
Q1: Incoherent J/ψ photoproduction in Pb-Pb UPCs@LHC

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

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

• ... and predicts too much shadowing

• One possible source of discrepancy: contribution of nucleon dissociation \( \gamma + N \rightarrow J/\psi + Y \) → singled out by different t-dep.

• Dipole models with typically weaker shadowing are closer to the incoherent data, Lappi, Mantysaari, PRC 87 (2013) 032201; Gay Ducati, Griep, Machado, PRC88 (2013) 014910
**Q2: ψ(2S) photoproduction in Pb-Pb UPCs@LHC**

- Our LTA approach naturally predicts similar suppression for $J/\psi$ and $\psi(2S)$ → tension with ALICE data on $\psi(2S)$ photoproduction in Pb-Pb UPCs at $y=0$ indicating less shadowing, Adam et al. [ALICE], PLB751 (2015) 358

- The versions of the dipole model, which do not describe coherent $J/\psi$ data, work reasonable well for coherent $\psi(2S)$, Gay Ducati, Griep, Machado, PRC88 (2013) 014910.

→ challenge to reconcile theoretical description of data on coherent and incoherent $J/\psi$ and coherent $\psi(2S)$ photoproduction in Pb-Pb UPCs.
Q3: Impact on global QCD fits of nPDFs

- In our approach, we use

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

- We fix $\mu^2$ and $C(\mu^2)$ using $W$-dependence of cross section on proton measured at HERA:
  - $\mu^2 \approx 3 \text{ GeV}^2$ for $J/\psi$, Guzey, Zhalov JHEP 1310 (2013) 207
  - $\mu^2 \approx 4 \text{ GeV}^2$ for $\psi(2S)$, Guzey, Zhalov, arXiv:1405.7529

- In LO of collinear factorization for exclusive processes and NR expansion for $J/\psi$ distribution amplitude (wave function), cross section is in terms of gluon GPD:

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

- At high energies (small $\xi$) and LO, GPDs can be connected to PDFs in a weakly model-dependent way:
  - At low $\mu_0$, $x_{1,2} \gg \xi \rightarrow$ skewness can be neglected
  - All skewness at $\mu > \mu_0$ due to evolution, Frankfurt, Freund, Guzey, Strikman, PLB 418 (1998) 345; Shuvaev et al., RPD 60 (1999) 014015

\[
H^g(\xi, \xi, t = 0, \mu^2) = R_g xg(x_B, \mu^2)
\]

\[
R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + 5/2)}{\Gamma(4 + \lambda)} \approx 1.2, \text{ for } xg \sim 1/x^\lambda \text{ with } \lambda \approx 0.2
\]
Q3: Impact on global QCD fits of nPDFs (2)


- However, in the nuclear suppression factor $S_{Pb}$ many complications (skewness, NLO and higher-twist corrections) are likely minimized → use $S_{Pb}$ in global QCD fits of nPDFs.

![Graph showing nuclear suppression factor $S_{Pb}$ versus $x$ for CMS, ALICE, LTA+CTEQ6L1, EPS09, HKN07, nDS]
Q4: Leading twist vs. dipole model vs. saturation

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

Triple-Pomeron coupling to 2 nucleons

Separate Pomeron couplings to 2 nucleons

→ higher twist (HT) for small dipoles

- 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
  - cross section of $J/\psi$ photoproduction on nuclei in UPCs@LHC

- As soon as dipole model includes q-\overline{q}-bar-g, q-\overline{q}-bar-2g, etc. dipoles → correctly models diffraction → reproduces large inelastic Gribov shadowing.

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:

![Graph showing photoproduction cross-section results for various experiments](image-url)

**Legend:**
- LHCb (\(\sqrt{s} = 13\) TeV)
- LHCb (\(\sqrt{s} = 7\) TeV)
- ALICE
- H1
- ZEUS
- Fixed target experiments
- Power law fit to H1 data
- JMRT NLO prediction

**Figure 7:** Comparison of photoproduction cross-sections for various experiments. The results are in better agreement with the JMRT 'NLO' prediction compared to the previous measurement at 

\[ \left( \frac{d\sigma}{dy} \right) \text{nb} \]

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

• Very interesting recent data: enhanced J/ψ yield in AA \textit{peripheral} collisions at small \( p_T \).

J. Adam et al [ALICE], PRL 116 (2016) 222301

\begin{align*}
\text{Possible interpretation: coherent photoproduction on nucleus fragment(s).}
\end{align*}
Outlook: other UPC processes

- **Photoproduction of Y:**
  - will allows one to study $\mu^2$ dependence of shadowing suppression and $g_A(x,\mu^2)$ at small $x$
  - 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 $\mu^2$, 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

• 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 $\rho$ and $\phi$ on nuclei tests the roles of hadronic fluctuations of the photon and inelastic nuclear shadowing.

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

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

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