NLO pQCD predictions for exclusive J/Psi and Upsilon photoproduction in A+A UPCs at the LHC

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AoF, CoE in Quark Matter YoctoLHC





1. Motivation for NLO study

• Originally proposed by Ryskin [ZPC57(1993) 89] for $\gamma + p \rightarrow J/\Psi + p$ in LO pQCD:

 $\left(\frac{d\sigma^{\gamma^* p \to Vp}}{dt}\right)\Big|_{t=0} \propto \left(xg\left(x, Q^2\right)\right)^2 \quad \text{where } x = O(M^2/W^2) \text{ and } Q^2 = O(M^2)$

- Is exclusive coherent photoproduction of $J/\psi \& \Upsilon$ in UPCs at the LHC, $A+A \rightarrow A+V+A$, a good probe of collinearly factorized nuclear gluon PDFs also in NLO?
- Include these processes as a constraint in global analyses of NLO nPDFs?
- Scale dependence, PDF-uncertainties, quark/gluon contributions, nuclear effects, real/imaginary parts of amplitude, in NLO?
- How does NLO match with the LHC UPC data?



2. Theoretical framework

• y-differential cross section for coherent photoproduction of V in A+A UPCs



• Photon flux

[Guzey&Zhalov JHEP 02 (2014) 046]

$$k\frac{dN_{\gamma}^{A}(k)}{dk} = \int d^{2}\vec{b}N_{\gamma}^{A}(k,\vec{b})\Gamma_{AA}(\vec{b})$$

number of equivalent WW photons of energy k at a transverse distance b from the center of a nucleus A with Z protons [Vidovic et al, Phys. Rev. C 47 (1993) 2308]

$$N_{\gamma}^{A}(k,\vec{b}) = \frac{Z^{2}\alpha_{\text{QED}}}{\pi^{2}} \left| \int_{0}^{\infty} dk_{\perp} \frac{k_{\perp}^{2}F(k_{\perp}^{2}+k^{2}/\gamma_{L}^{2})}{k_{\perp}^{2}+k^{2}/\gamma_{L}^{2}} J_{1}(bk_{\perp}) \right|^{2}$$

 Require no hadronic activity I
 → integration over b without a cut-off

$$\Gamma_{AA}(\vec{b}) = \exp\left[-\sigma_{\rm NN}(s)T_{AA}(\vec{b})\right]$$

total pp cross section

standard nuclear overlap function

• NLO amplitude [1]: factorization at amplitude level [2]



[1] D. Y. Ivanov, A. Schafer, L. Szymanowski, G. Krasnikov, Eur. Phys. J. C 34 (2004) no. 3, 297 [Erratum: Eur.Phys.J.C 75, 75 (2015)]
 [2] J. C. Collins, L. Frankfurt and M. Strikman, Phys. Rev. D 56 (1997) 2982

LO: only gluon GPDs contribute, no quarks here



- 6 graphs at LO
- At NLO, add one internal gluon anywhere
 → Many gluon graphs at NLO

NLO: both gluon and quark GPDs contribute



Full NLO calculation done in
 [Ivanov et al., Eur. Phys. J. C 34 (2004) no. 3, 297]

 → we apply these results

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• First, take GPDs at their forward limit (t=0, ξ =0), where they become PDFs (x>0 below)

$$F^{g}(x,0,0) = F^{g}(-x,0,0) = xg(x),$$

$$F^{q,S}(x,0,0) = u(x) + d(x) + s(x) + c(x)$$

$$F^{q,S}(-x,0,0) = -\bar{u}(x) - \bar{d}(x) - \bar{s}(x) - \bar{c}(x)$$

$$\Rightarrow \text{ Entering the calculation of } M: \int_{0}^{1} dx \Big[2xg(x,\mu_{F})T_{g}(x,\xi) + T_{q}(x,\xi) \sum_{q} \Big[q(x,\mu_{F}) + \bar{q}(x,\mu_{F}) \Big] \Big]$$

- Nuclear PDFs studied here: EPPS16/21, nCTEQ15/WZSIH, nNNPDF2.0/3.0
- Complex-valued T_g, T_q from [Ivanov et al, Eur. Phys. J. C 34 (2004) no. 3, 297]

$$\begin{split} T_g(x,\xi) &= \frac{\xi}{(x-\xi+i\epsilon)(x+\xi-i\epsilon)} \begin{bmatrix} \alpha_s(\mu_R) + \frac{\alpha_s^2(\mu_R)}{4\pi} f_g\left(\frac{x-\xi+i\epsilon}{2\xi}\right) \end{bmatrix} \\ & \text{LO} \\ T_q(x,\xi) &= \frac{2\alpha_s^2(\mu_R)}{3\pi} f_q\left(\frac{x-\xi+i\epsilon}{2\xi}\right) \text{ NLO} \end{split}$$

• We solve the complex integrals numerically, bringing $\varepsilon \rightarrow 0$ in the end & checked the numerics using another method [Flett:2021xsl]

3. Results for J/ ψ in Pb+Pb UPCs at LHC

A. Scale sensitivity

- Set $\mu_F = \mu_R = \mu$, vary μ from $M_{J/\psi}/2 = m_c$ to $M_{J/\psi} = 2m_c$
- \rightarrow Scale dependence considerable
- "Optimal" scale μ = 0.77 M_{J/ψ} can be found which ~reproduces ALICE central, CMS and 2015 LHCb data
- Also at NLO difficult to reproduce simultaneously fwd¢ral data (2018 LHCb data closer to ALICE fwd)
- → Room for GPD effects (GPDs≠PDFs), NRQCD corrections, NNLO corrections,...



B. Surprise: Quarks important at NLO, for J/Psi

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- At NLO: at y = 0 quarks(!) dominate & at bkwd-/fwd-most y gluons dominate
- Very different from LO!
- The reason: LO and NLO gluon amplitudes tend to cancel
 → XSs reflect PDF shadowing in very nontrivial way not ~(R_g(ξ))² as in LO

C. Propagation of PDF uncertainties



EPPS21: nuclear + CT18A uncertaintiesall PDF uncertainties are moderate;

- PDF uncertainties larger than data errors
- Consistent w. data within PDF uncertainties
- Tension: ALICE fwd and new LHCb data are above the EPPS21 central-set result

nNNPDF3.0: nuclear + free p uncertainties

- Consistent w. data, larger uncertainties
- Central-set result: narrower y-shape than in data

nCTEQ15WZSIH: only nuclear uncertainties

- Consistent w. data, larger uncertainties
- Enhanced s-quarks → Central-set result fits fwd data better → s-quark probe!?

EPPS21, Eur.Phys.J.C 82 (2022) 5, 413 nNNPDF3.0, Eur.Phys.J.C 82 (2022) 6, 507 nCTEQ15WZSIH, Phys.Rev.D 104 (2021) 094005

C. Propagation of PDF uncertainties



D. Tame the scale dependence?

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

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At y≈0, in the ratios, the scale dependence is considerably reduced...

... while these ratios remain conveniently sensitive to the nPDF uncertainties

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Studied possible different-energy O+O/Pb+Pb ratios

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

At y=0, scale uncertainty does not anymore dominate over the PDF uncertainty
→ improved quality as a nPDF constraint

4. NLO predictions for coherent photoproduction of Upsilon in Pb+Pb UPCs



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 Added nGPD modeling to our NLO pQCD framework via Shuvaev-transformed nPDFs

[Shuvaev, Phys.Rev. D60 (1999) 116005, Flett et al, Phys.Rev. D 102 (2020) 114021; Phys. Rev. D 101 (2020) 094011] \rightarrow GPD effects in Υ XSs small, << scale&nPDF uncertainties

- Larger-scale process \rightarrow weaker scale dependence than for J/ ψ
- Gluons dominate, unlike for J/ψ
 → Υ more direct gluon probe than J/ψ
 (at least in NLO...)



- No A+A UPC data to guide us \rightarrow exploit e+p/p+p/p+Pb data?
- NLO pQCD underpredicts HERA e+p/LHC data → NRQCD corrections? NNLO corrections?
- Make use of these data?

 \rightarrow Data-driven method for $\sigma^{\gamma Pb \rightarrow \gamma Pb}(W)$

- nuclear effects from the NLO calculation
- overall normalization from HERA-data fit

$$\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W) = \left[\frac{\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W)}{\sigma^{\gamma p \to \Upsilon p}(W)}\right]_{\mathrm{pQCD}} \sigma_{\mathrm{fit}}^{\gamma p \to \Upsilon p}(W)$$



Data-driven prediction for coherent photoroduction of Y in Pb+Pb UPCs:

- scale uncertainties tend to cancel in the pQCD ratio $\left[\frac{\sigma^{\gamma^{Pb} \rightarrow \gamma^{Pb}(W)}}{\sigma^{\gamma p \rightarrow \gamma_{p}(W)}}\right]_{pQCD}$ \rightarrow scale uncertainties become smaller than the PDF uncertainties
- GPD effects become negligible in the pQCD ratio
- Probe of gluon shadowing

5. Conclusions & Outlook

- First implementation of collinearly factorized NLO pQCD cross sections of coherent exclusive photoproduction of J/ ψ and Y in A+A UPCs
- Scale dependence in NLO is considerable for J/ ψ but an "optimal" scale can be found - reproduce the J/ ψ Run1 & Run2 data at y=0, and within PDF uncertainties at all y
- Still tension between central-PDF-set NLO results and J/ψ UPC LHC data at fwd/bkwd y

 room for NRQCD corrections, NNLO corrections, more detailed GPD modeling,...
- LO and NLO gluon amplitudes for J/ψ tend to cancel
 - at y = 0 quarks(!) dominate different from LO!
 - J/ ψ process may turn out to be a probe of s-quark (!) PDFs
 - = currently the worst known piece in global nPDF fits
 - what happens in NNLO??



- Nuclear + free-proton PDF uncertainties now start to be moderate (EPPS21)
 - free-proton uncertainties must be accounted for in absolute cross sections
 - PDF/GPD uncertainties for J/ $\psi\,$ larger than Pb+Pb UPC data errors
 - \rightarrow Constraining power from data
- Reduce the large scale-dependence with nuclear ratios, e.g. O+O/Pb+Pb for J/ ψ ? \rightarrow seems possible, at least at y=0 !
- Made NLO pQCD predictions for exclusive photoproduction of Υ in Pb+Pb UPCs at the LHC, using also HERA data:
 - reduced scale dependence relative to the J/ ψ case
 - GPD effects via Shuvaev transform turned out to be small
 - gluons dominate $\rightarrow \Upsilon$ more direct probe of gluon shadowing than J/ ψ

Extra slides

B. Photon-proton baseline (here independent from UPC)



- Our UPC "optimal" scale works also reasonably well here, but...
 - Room for GPD effects (GPDs≠PDFs), NRQCD corrections, NNLO corrections,...

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The two photon components contributing to coherent exclusive photoproduction XSs of J/ ψ and Υ in Pb+Pb UPCs at the LHC



• Interplay of W[±] components, QCD cross section, photon flux and form-factor integral

Q&G shadowing in the cross section – a further surprise



Reduction from CT14NLO (no nuclear effects) to

EPPS16 (w. nuclear effects) XS is only a factor ~0.76 — Why?

- integration over x in M weakens the dependence on nuclear effects somewhat but the main reason is again the degree of **cancellation of M_G^{LO} and M_G^{NLO}** Decomposition of the XSs to contributions from the real and imaginary parts of the amplitude.





GPD effects relative to PDFs at the Upsilon mass scale are rather small, and still smaller at the J/Psi mass scale

With GPDs via Shuvaev tr., restore Re(M) via the dispersion relation [M.G. Ryskin, et al., Z. Phys. C 76 (1997) 231]

GPDs via Shuvaev transform [A. Shuvaev, Phys. Rev. D 60 (1999) 116005]

$$\begin{aligned} H^{q}(x,\xi,t=0,\mu_{F}) &= \\ \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\Im m \int_{0}^{1} \frac{\mathrm{d}s}{y(s)\sqrt{1-y(s)x'}}\right] \frac{\mathrm{d}}{\mathrm{d}x'} \frac{q(x',\mu_{F})}{|x'|} \\ H^{g}(x,\xi,t=0,\mu_{F}) &= \\ \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\Im m \int_{0}^{1} \frac{\mathrm{d}s \ (x+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}}\right] \frac{\mathrm{d}}{\mathrm{d}x'} \frac{g(x',\mu_{F})}{|x'|} \end{aligned}$$

where the kernel of the transform is

$$y(s) = \frac{4s(1-s)}{x+\xi(1-2s)}.$$

$$\frac{\Re e \mathcal{M}_A^{\gamma N \to \Upsilon N}(\xi, t=0)}{\Im m \mathcal{M}_A^{\gamma N \to \Upsilon N}(\xi, t=0)}$$
$$= \tan\left(\frac{\pi}{2} \frac{\partial \ln(\Im m \mathcal{M}_A^{\gamma N \to \Upsilon N}(\xi, t=0)/(1/\xi))}{\partial \ln(1/\xi)}\right)$$



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Nuclear effects in the pQCD ratio with the form factors scaled away -- sensitive to ~(gluon shadowing)²

