EXCLUSIVE J/ψ PRODUCTION
IN ULTRAPERIPHERAL Pb+Pb COLLISIONS
TO NLO pQCD*

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We present the first NLO pQCD study of coherent exclusive J/ψ photoproduction in ultraperipheral heavy-ion collisions (UPCs) at the LHC. Taking the generalized parton distributions (GPDs) in their forward limit, as parton distribution functions (PDFs), we quantify the NLO contributions in the rapidity-differential cross section, show that the real part of the amplitude must not be neglected, study the gluon and quark contributions, chart the scale-choice and PDF uncertainties, and compare the NLO results with LHC and HERA data. We show that the scale dependence is significant but a scale choice can be found with which we reproduce the 2.76 and 5.02 TeV UPC data. In particular, we show that the process is clearly more sensitive to the nuclear quark PDFs than thought before.

1. Introduction

It was originally proposed by Ryskin in the context of leading-order pQCD and collinear PDFs [1] that coherent exclusive J/ψ photoproduction off protons, $\gamma + p \rightarrow J/\psi + p$, is a promising probe of the gluon PDF of the proton: The forward cross section $d\sigma/dt(t = 0) \propto (xg(x, Q^2))^2$, where $x = M_{J/\psi}^2/W^2$ and $Q^2 = M_{J/\psi}^2/4$, with W the center-of-momentum-system (c.m.s.) energy and $M_{J/\psi}$ the J/ψ mass. Subsequently, coherent exclusive J/ψ photoproduction in UPCs at the LHC, Pb+Pb $\rightarrow$ Pb+J/ψ+Pb, has then been suggested to efficiently probe the nuclear gluon distributions, see *e.g.* Refs. [2, 3]. For LHC data, see Refs. [4, 5] and those in [6]. Until now, coherent J/ψ photoproduction in $A+A$ UPCs has been studied only to LO

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pQCD, although NLO studies for the $\gamma+p$ case exist [7–9]. Thus, there is an obvious need for an extension to NLO for the UPCs, the results of which we have recently presented in Ref. [6] and on which we are reporting now here.

2. Theoretical framework

In UPCs of nuclei A_1 and A_2, the coherent J/ψ photoproduction cross sections differential in the J/ψ rapidity y can be computed as

$$\frac{\mathrm{d}\sigma^{A_1 A_2 \to A_1 V A_2}}{\mathrm{d}y} = \left[k\frac{\mathrm{d}N_\gamma^{A_1}}{\mathrm{d}k}\sigma^{\gamma A_2 \to V A_2} \right]_{k=k^+} + \left[k\frac{\mathrm{d}N_\gamma^{A_2}}{\mathrm{d}k}\sigma^{A_1\gamma \to A_1 V} \right]_{k=k^-} ,$$

(1)

where $A_{1,2} = \mathrm{Pb}$, $V = J/\psi$, $k^\pm(y)$ are the energies of the photon emitted by the nucleus $A_{1,2}$, and $\mathrm{d}N_\gamma^{A_{1,2}}/\mathrm{d}k$ are the Weizsäcker–Williams photon fluxes supplemented with a requirement of having no hadronic interactions. Here,

$$\sigma^{\gamma A_2 \to V A_2} = \frac{\mathrm{d}\sigma_{A_2}^{\gamma N \to V N}}{\mathrm{d}t}\bigg|_{t=0} \int\limits_{t_{\min}}^{\infty} \mathrm{d}t' \left| F_{A_2}\left(-t'\right) \right|^2 ,$$

(2)

where t is a Mandelstam variable and the nuclear form factor F_{A_2} is obtained as a Fourier transform of the Woods–Saxon nuclear density distribution (and correspondingly for $\sigma^{A_1\gamma \to A_1 V}$). The t-differential cross section is given by the square of the collinearly factorized per-nucleon amplitude [10]

$$\mathcal{M}_A^{\gamma N \to V N} \propto \sqrt{\langle O_1 \rangle_V} \int\limits_{-1}^{1} \mathrm{d}x [T_g(x,\xi)F^g(x,\xi,t,\mu_\mathrm{F}) + T_q(x,\xi)F^{q,S}(x,\xi,t,\mu_\mathrm{F})],$$

(3)

where $\langle O_1 \rangle_V$ is the NRQCD element given by the $\mathcal{O}(\alpha_\mathrm{s}^2)$ leptonic decay width of J/ψ [7], $T_{g,q}$ are the pQCD coefficient functions calculated to $\mathcal{O}(\alpha_\mathrm{s}^2)$ in Ref. [7], ξ is the skewedness parameter, and μ_F the factorization scale. The GPDs, F^g for gluons, and $F^{q,S}$ for the quark singlet, are here taken in their forward, no-skewedness, limit,

$$\begin{aligned}
F^g(x,0,0,\mu_\mathrm{F}) &= F^g(-x,0,0,\mu_\mathrm{F}) = xg(x,\mu_\mathrm{F}), \\
F^{q,S}(x,0,0,\mu_\mathrm{F}) &= u(x,\mu_\mathrm{F}) + d(x,\mu_\mathrm{F}) + s(x,\mu_\mathrm{F}) + c(x,\mu_\mathrm{F}), \\
F^{q,S}(-x,0,0,\mu_\mathrm{F}) &= -\bar{u}(x,\mu_\mathrm{F}) - \bar{d}(x,\mu_\mathrm{F}) - \bar{s}(x,\mu_\mathrm{F}) - \bar{c}(x,\mu_\mathrm{F}),
\end{aligned}$$

(4)

where $x > 0$. Note that quarks contribute only at NLO here. For the nuclear PDFs (nPDFs), we use EPPS16 [11], nCTEQ15 [12], and nNNPDF2.0 [13]. Throughout this work, we set the renormalization scale μ_R to be equal to μ_F. We have also cross-checked our numerical results with two different methods for doing the complex integrations. For more details, see [6, 7].

3. Results

The main results from our NLO study are collected in Figs. 1–5. Figure 1 shows that the scale dependence is considerable but an "optimal" scale $\mu = 0.76 M_{J/\psi}$ can be found with which the LHC data are well reproduced. The
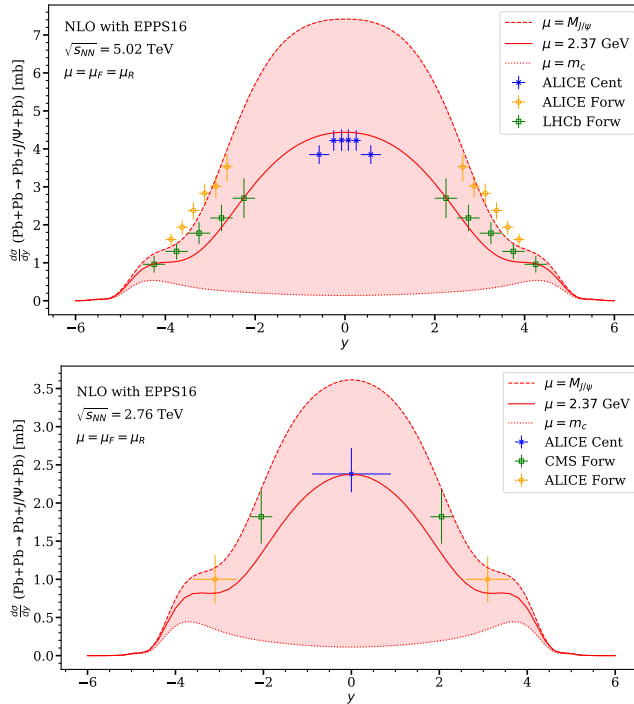

Fig. 1. Rapidity-differential coherent exclusive J/ψ photoproduction cross section *vs.* rapidity in Pb+Pb UPCs at $\sqrt{s_{NN}} = 5.02$ TeV (upper panel) and 2.76 TeV (lower panel), computed with EPPS16 nPDFs and scales $\mu = M_{J/\psi}/2$, $0.76 M_{J/\psi}$, and $M_{J/\psi}$. For the references to the LHC data shown, see [6]. Figure from [6].

same "optimal" scale works reasonably well also for the $\gamma + p$ baseline, as seen in Fig. 2. Figure 3 demonstrates the complex structure of the NLO cross section which in Pb+Pb UPCs results from an interplay between the pQCD cross section, photon fluxes from both nuclei, and the nuclear form factor. The upper panel shows that unlike in LO where the imaginary part of the amplitude clearly dominates, in NLO the situation becomes more involved and the real part cannot be neglected. The lower panel shows that in NLO, the *quark* contribution dominates at $y = 0$ — perhaps the most striking result of this study. This follows from the canceling LO and NLO gluon amplitudes, as analysed in detail in Ref. [6]. The "shoulders" in the full NLO
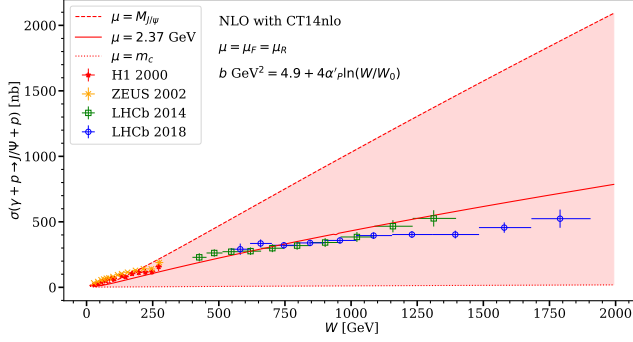
Fig. 2. Exclusive J/ψ photoproduction cross section in $\gamma + p$ collisions *vs.* c.m.s. energy W, computed with CT14NLO PDFs [14] and scales $\mu/M_{J/\psi} = 2$, 0.76, and 1. For the references to the HERA and LHC data shown, see [6]. From [6].
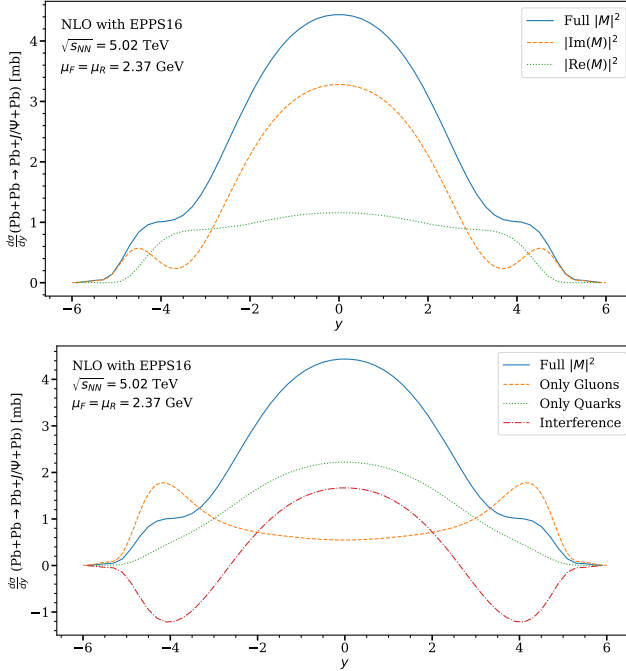

Fig. 3. Upper panel: Breakdown of the NLO cross section in the upper panel of Fig. 1 into contributions from the imaginary and real parts of the amplitude. Lower panel: Contributions without quarks, without gluons, and from the quark–gluon interference terms alone. Figures from [6].

result arise because the NLO terms weaken the W dependence of the pQCD cross section at small values of W. Figure 4 shows the NLO cross sections computed with different nPDFs. While nCTEQ15 gives very similar results as EPPS16, nNNPDF2.0 deviates from them considerably. This is due to the very rapidly growing small-x gluon distributions in nNNPDF2.0. Finally,
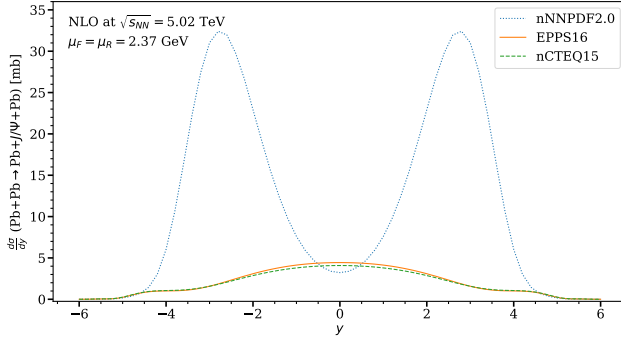

Fig. 4. As Fig. 1 upper panel, but computed with three different nPDFs using the same "optimal" scale. Figure from [6].
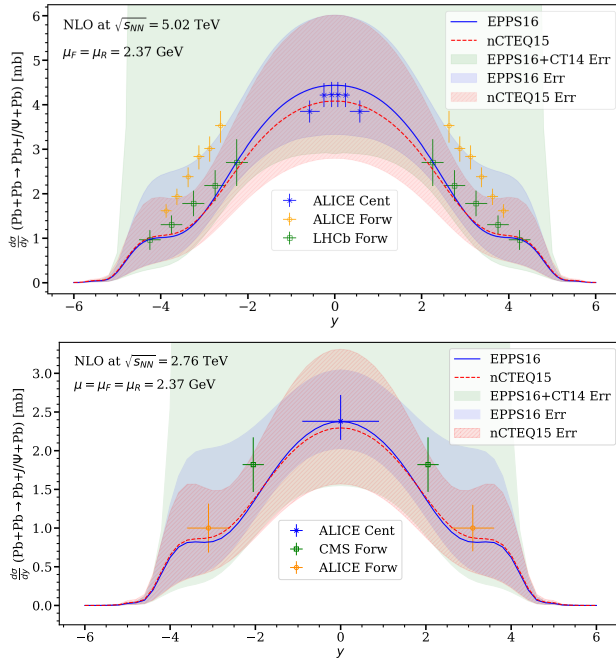

Fig. 5. As Fig. 1 but with PDF uncertainties at the "optimal" scale. From [6].

the propagation of the PDF uncertainties is shown in Fig. 5. The EPPS16 and nCTEQ15 nPDF uncertainties remain moderate, while the CT14NLO error bands are large and dominated by one error set where again the small-x gluons rise very rapidly.

4. Summary

We have presented the first implementation of the NLO pQCD cross section of exclusive J/ψ photoproduction in Pb+Pb UPCs [6][1]. In spite of the large scale-dependence envelope, there seems to be an "optimal" scale with which we can, with EPPS16 and nCTEQ15, reproduce the LHC data well. We have shown that at NLO, the real part of the amplitude must not be neglected, and that the canceling of LO and NLO gluon amplitudes makes quarks contribute much more than what was traditionally expected. Thus, the picture changes rather dramatically at NLO. We have also charted how the PDF uncertainties propagate into the computed cross sections. In this exploratory study, we assumed the forward limit for the GPDs. In the future, it will be interesting to study the effects of GPD modeling.

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