Exclusive $J/\psi$ production in ultraperipheral Pb+Pb collisions to NLO pQCD

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arXiv:2203.11613

AoF, CoE in Quark Matter
YoctoLHC
Motivation

- Is exclusive $J/\psi$ photoproduction in UPCs, $A+A \rightarrow A+J/\psi+A$, a good probe of collinear nuclear gluon distributions?
- Originally proposed by Ryskin\(^1\) in the context of electroproduction

\[
\left( \frac{d\sigma_{\gamma^* p \rightarrow V p}}{dt} \right) \bigg|_{t=0} \propto (xg(x, Q^2))^2.
\]

- Until now, only LO calculations for A+A UPCs. Need for NLO!
- Scale dependence, PDF-uncertainties, quark/gluon contributions, nuclear effects, real/imaginary parts of amplitude?
- How does NLO match with the LHC data?

\(^1\) Z.Phys.C 57 (1993) 89-92
Earlier calculations compared to ALICE data. Figure from Eur. Phys. J. C 81, 712 (2021).

Earlier calculations compared to LHCb data. Figure from arXiv:2107.03223 [hep-ex].
Rapidity differential cross section:

\[
\frac{d\sigma^{AA\rightarrow AVA}}{dy} = \left[ k \frac{dN^A_\gamma(k)}{dk} \sigma^{\gamma A\rightarrow VA}(k) \right]_{k^-} + \left[ k \frac{dN^A_\gamma(k)}{dk} \sigma^{A\gamma\rightarrow AV}(k) \right]_{k^+}
\]

\(V\) is the vector meson and \(k^+/−\) are the photon energies.

Photon flux \(dN^A_\gamma/dk\) in Weizsäcker-Williams (WW) approximation, require no hadronic activity.

Cross section through the product:

\[
\sigma^{\gamma A\rightarrow VA} = \left. \frac{d\sigma^{\gamma N\rightarrow VN}}{dt} \right|_{t=0}^{t=t_{\text{min}}} \int_{t_{\text{min}}}^{\infty} dt' \ |F_A(-t')|^2
\]

\(F_A(t)\) is the form factor.
NLO amplitude\(^2\), factorization at amplitude level\(^3\):

\[
\mathcal{M}^{\gamma N} \propto \langle O_1 \rangle^{1/2}\int_{-1}^{1} dx \left[ T_g(x, \xi) F^g(x, \xi, t) + T_q(x, \xi) F^{q,S}(x, \xi, t) \right].
\]

- NRQCD element \(\langle O_1 \rangle\).
- Hard-scattering functions \(T_i\).
- GPDs \(F^i\).
- No quarks in LO.


\(^3\)Collins, Phys.Rev.D 56 (1997) 2982-3006
\( \langle O_1 \rangle_V \) from the leptonic decay width in the leading NRQCD approximation.

\[
\Gamma(V \to l^+ l^-) = \frac{2e_Q^2 \pi \alpha_{\text{QED}}^2 \langle O_1 \rangle_V}{3 m_Q^2} \left[ 1 - \frac{8\alpha_s}{3\pi} \right]^2
\]

The GPDs taken here in their forward limit \((x > 0)\):

\[
F^g(x, 0, 0) = F^g(-x, 0, 0) = x g(x),
\]

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

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

Nuclear corrections for the bound nucleons from EPPS16\(^4\), nCTEQ15\(^5\), nNNPDF2.0\(^6\).

Numerical results checked with two different methods.

\(^5\) Kovarik et al. *Phys.Rev.D* 93 (2016) 8, 085037
\(^6\) Khalek et al. *JHEP 09* (2020) 183
Scale dependence considerable but an "optimal" scale can be found.
Scale dependence considerable but an "optimal" scale can be found.
The optimal scale works reasonably well also for the $\gamma p$ baseline.
$W$-contributions symmetric w.r.t. $y = 0$. Shoulders arise in NLO: interplay of cross section, photon flux and form factor.
LO decomposition to Real and Imaginary parts

In LO imaginary part clearly dominates.
In NLO the situation is more involved. Real part cannot be neglected.
Breakdown to gluon and quark contributions

Now, at $y = 0$ quark contribution dominates. Different from LO! Reason: LO and NLO gluon amplitudes cancel.
Different nPDF groups

- \( n_{\text{CTEQ15}} \) agrees with \( \text{EPPS16} \) but \( n_{\text{NNPDF2.0}} \) does not...

\[
\text{NLO at } \sqrt{s_{NN}} = 5.02 \text{ TeV} \\
\mu_F = \mu_R = 2.37 \text{ GeV}
\]
Underlying nPDF sets

Forward limit GPDs
\[ \mu = \mu_F = 2.37 \, \text{GeV} \]
\[ F^{q, S} \text{ multiplied with } 10^{-2} \]

- due to different behaviour of the gluon distribution.
Nuclear uncertainties moderate. Large free proton uncertainties dominated by single error set.
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First implementation of NLO pQCD $y$-differential cross section of exclusive photoproduction of $J/\psi$ in Pb+Pb UPCs.

Scale dependence in NLO is considerable but an "optimal" scale can be found for EPPS16/nCTEQ15 on the basis of the UPC data.

In NLO, must account also for Re($\mathcal{M}$).

LO and NLO gluon amplitudes cancel. At $y = 0$ quarks dominate. Different from LO!

Nuclear PDF errors are moderate, free proton uncertainties need to be taken into account.

Next step: more detailed GPD modeling.
Backup
LO comparison to Data

LO with EPPS16
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ \mu = \mu_F = \mu_R; [\mu] = \text{GeV} \]

- Hard to reproduce the experimental data with LO.
At $y = 0$ difference between lowest/highest scale about a factor of 20.
At $y = 0$ difference between lowest/highest scale about a factor of 50.
NLO scale dependence vs LO depends on $y$. 
One error set in CT14NLO stands out from the rest.
Nuclear corrections come from the shadowing region. Effect of quark-gluon interference non-trivial.
Real part of photoproduction amplitude

- LO and NLO gluons tend to cancel.
Imaginary part of photoproduction amplitude

- LO and NLO gluons tend to cancel.