Exclusive J/ψ photoproduction in Pb-Pb UPCs at the LHC in NLO QCD

Vadim Guzey

University of Jyväskylä & Helsinki Institute of Physics,
University of Helsinki, Finland

K.J. Eskola, C.A. Flett, V. Guzey, T. Löytäinen, H. Paukkunen, PRC 106 (2022) 035202

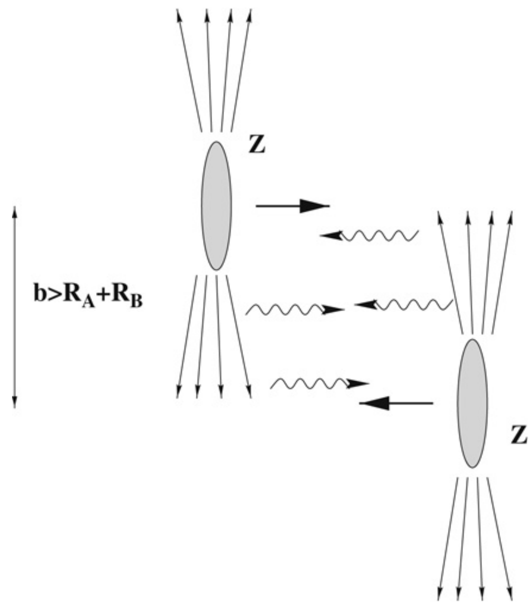
Outline:

- Ultraperipheral collisions (UPCs) at the Large Hadron Collider (LHC)
- Exclusive J/ψ photoproduction in Pb-Pb UPCs@LHC in LLA: constraints on small-x gluon nuclear shadowing
- Exclusive J/ψ photoproduction in Pb-Pb UPCs@LHC in NLO pQCD: strong scale dependence, uncertainty due to nPDFs, and quark dominance
- Summary and Outlook

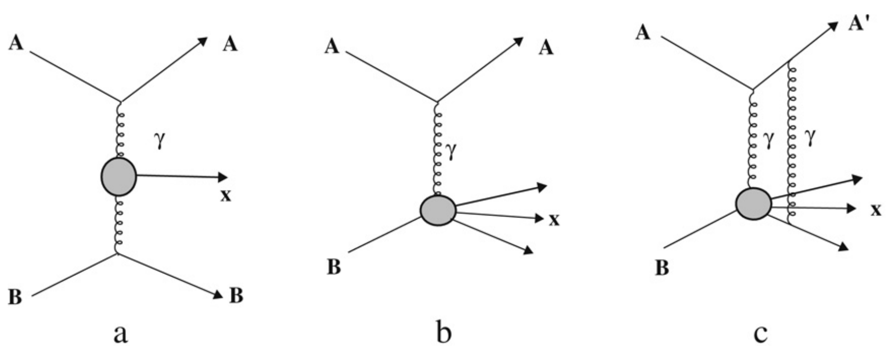
QWG 2022 - The 15th International Workshop on Heavy Quarkonium, GSI Darmstadt, Sep 26-30, 2022

Ultraperipheral collisions

• Ultraperipheral collisions (UPCs): ions interact at large impact parameters $b >> R_A+R_B$ → strong interactions suppressed → interaction via quasi-real photons in Weizsäcker-Williams equivalent photon approximation, Budnev, Ginzburg, Meledin, Serbo, Phys. Rept. 15 (1975) 181



• UPCs@LHC allow one to study $\gamma\gamma$, γp and γA interactions at unprecedentedly high energies (energy frontier) reaching: $W_{\gamma p}$=5 TeV, $W_{\gamma A}$=700 GeV/A, $W_{\gamma\gamma}$=4.2 TeV

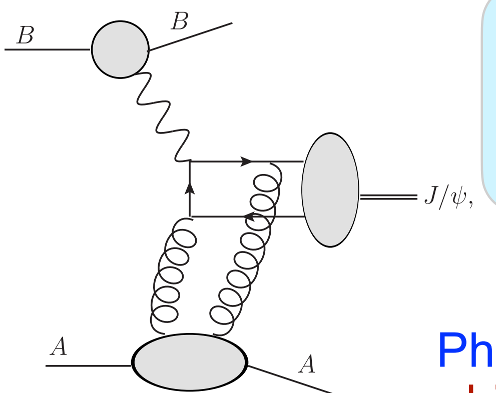


• UPCs can be used to study open questions of proton and nucleus structure in QCD and search for new physics → e.g., **new info on gluon distributions in nuclei at small x**.

Bertulani, Klein, Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271; Baltz et al, Phys. Rept. 480 (2008) 1; Contreras and Tapia-Takaki, Int. J. Mod. Phys. A 30 (2015) 1542012; Snowmass LoI, Klein et al, arXiv:2009.03838

Exclusive J/ψ photoproduction in UPCs

- Cross section of exclusive, coherent J/ψ photoproduction in Pb-Pb UPCs → two terms corresponding to high photon mom. k^+ (low x) and low k^- (high x)



$$\frac{d\sigma^{AB\to AJ/\psi B}}{dy} = \left[k\frac{dN_{\gamma/B}}{dk}\sigma^{\gamma A\to J/\psi A}\right]_{k=k^+} + \left[k\frac{dN_{\gamma/A}}{dk}\sigma^{\gamma B\to J/\psi B}\right]_{k=k^-}$$

Photon flux from QED:
- high intensity ~ Z^2
- high photon energy ~ γ_L

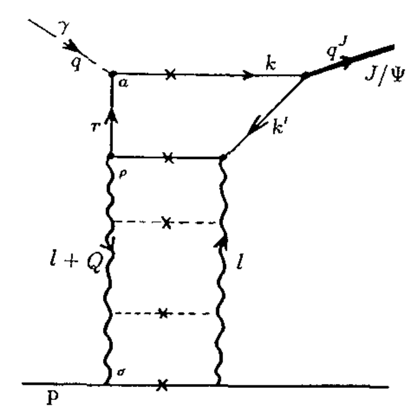
Photoproduction cross section

$$k^{\pm} = \frac{M_{J/\psi}}{2}e^{\pm y}$$

Photon momentum from J/ψ rapidity

- In leading logarithmic approximation (LLA) of pQCD, Ryskin, Z. Phys. C57 (1993) 89; Frankfurt, Koepf, Strikman, PRD 57 (1998) 512; Frankfurt, McDermott, Strikman, JHEP 03 (2001) 045

$$\frac{d\sigma^{\gamma p\to J/\psi p}(t=0)}{dt} = \frac{12\pi^3}{\alpha_{\mathrm{e.m.}}}\frac{\Gamma_V M_V^3}{(4m_c^2)^4}\left[\alpha_s(Q^2_{\mathrm{eff}})xg(x,Q^2_{\mathrm{eff}})\right]^2 C(Q^2=0)$$



Γ_V=J/ψ leptonic decay width

gluon density at $x=(M_{J/\psi})^2/W^2$ and Q_{eff}^2=2.5-3 GeV^2

depends on details of charmonium distribution amplitude

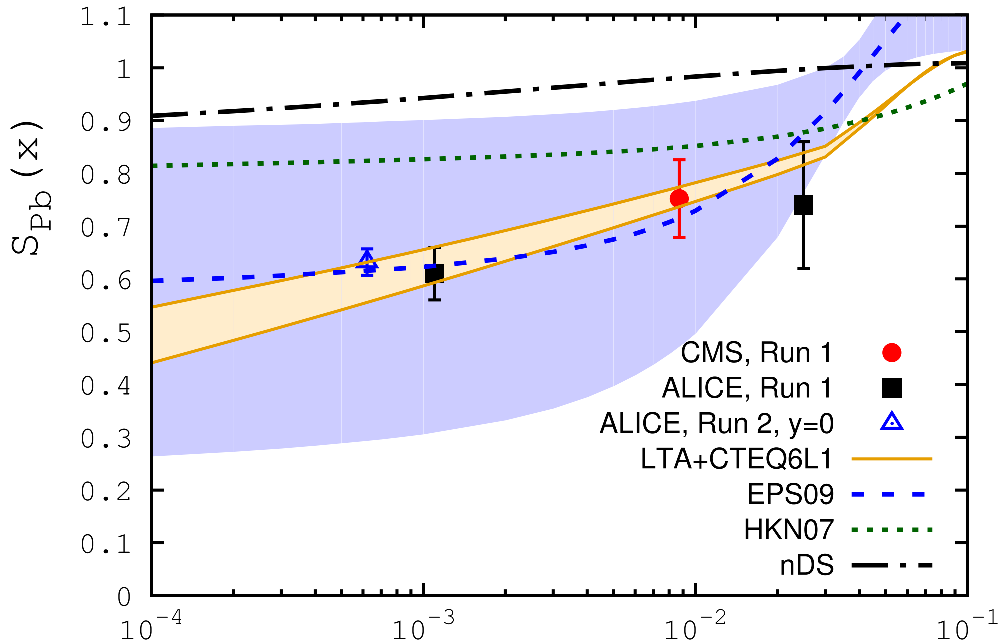
Constraints on small-x gluon shadowing

- Ratio of nucleus and proton cross sections → nuclear suppression factor S

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

Model-independently* using data on UPCs and on γp at HERA, Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489; Acharya et al [ALICE], arXiv:2101:04577 [nucl-ex]

From global QCD fits or leading twist nuclear shadowing model
Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290;
Guzey, Zhalov, JHEP 1310 (2013) 207



LTA: Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028

- Good agreement with ALICE data at y=0 (2.76 and 5.02 TeV) → direct evidence of large gluon shadowing, $R_g(x=6\times10^{-4} - 0.001) \approx 0.6$ → nicely agrees with LTA model and EPS09, EPPS16 nuclear parton distribution functions (nPDFs).

Exclusive J/ψ photoproduction in NLO pQCD

- Collinear factorization for hard exclusive processes, Collins, Frankfurt, Strikman, PRD 56 (1997) 2982: γA $\rightarrow$ J/ψA amplitude in terms of generalized parton distribution functions (GPDs).

- To next-to-leading order (NLO) of perturbative QCD, Ivanov, Schafer, Szymanowski, Krasnikov, EPJ C 34 (2004) 297, 75 (2015) 75 (Erratum); Jones, Martin, Ryskin, Teubner, J. Phys. G: Nucl. Part. Phys. 43 (2016) 035002

$$\mathcal{M}^{\gamma A \to J/\psi A} \propto \sqrt{\langle O_1 \rangle_{J/\psi}} \int_{-1}^{1} dx \left[T_g(x,\xi) F_A^g(x,\xi,t,\mu_F) + T_q(x,\xi) F_A^q(x,\xi,t,\mu_F) \right]$$

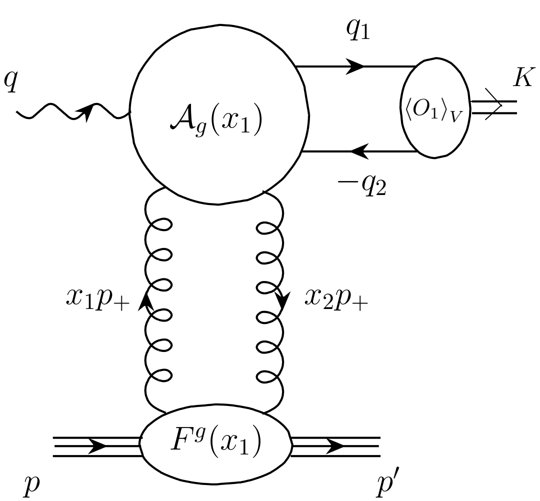
NRQCD matrix element from J/ψ leptonic decay

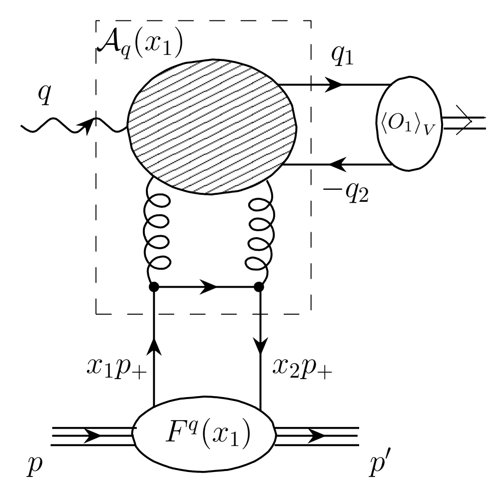
pQCD coeficient function

Gluon GPD

Quark contribution

- To leading order (LO), only gluons; both quarks and gluons at NLO.





Exclusive J/ψ photoproduction in NLO pQCD (2)

- In the high W (small x) limit:

$$\mathcal{M}^{\gamma A \to J/\psi A} \propto i\sqrt{\langle O_1 \rangle_{J/\psi}} \Big[F_A^g(\xi, \xi, t, \mu_F) + \frac{\alpha_s N_c}{\pi} \ln\left(\frac{m_c^2}{\mu_F^2}\right) \int_\xi^1 \frac{dx}{x} F^g(x, \xi, t)$$
$$+ \frac{\alpha_s C_F}{\pi} \ln\left(\frac{m_c^2}{\mu_F^2}\right) \int_\xi^1 \frac{dx}{x} \left(F^{q,S}(x, \xi, t) - F^{q,S}(-x, \xi, t)\right) \Big]$$

$\rightarrow$ helps to qualitatively understand the features of our numerical calculations.

- In our analysis, we neglect dependence GPDs on $\xi \approx (1/2)(M_{J/\psi})^2/W^2 \ll 1$.

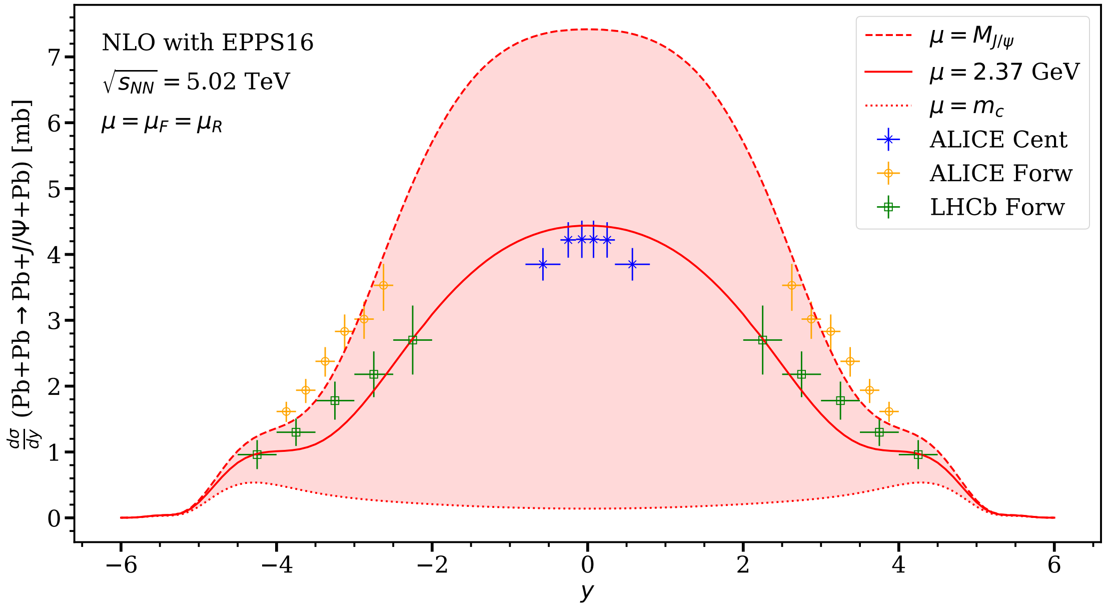
For gluons (quarks are similar):

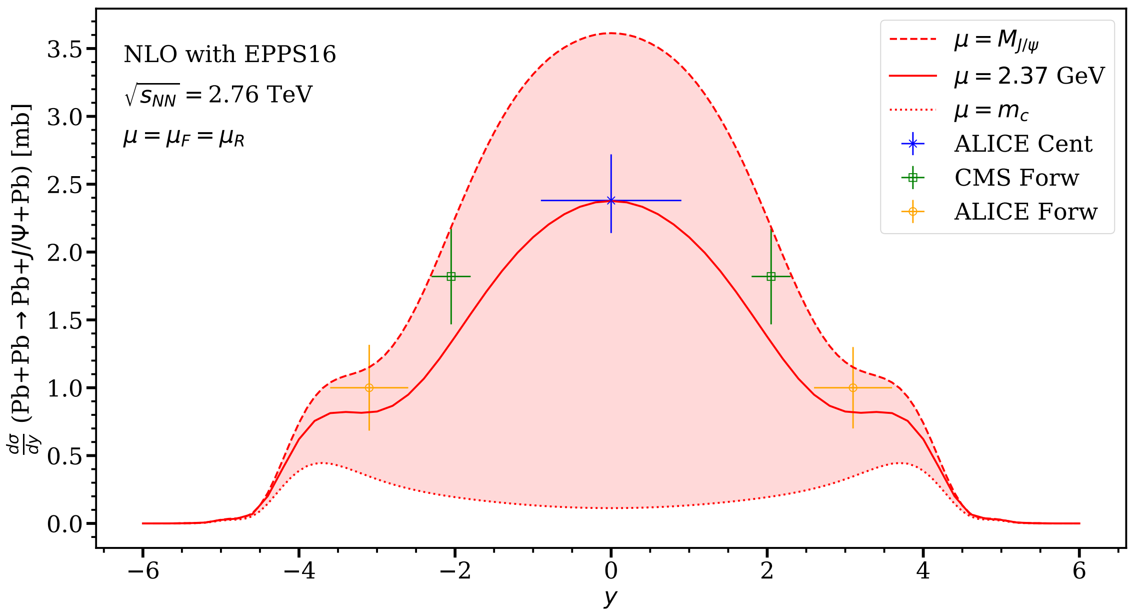
$$F_A^g(x, \xi, t, \mu_F) = x g_A(x, \mu_F) F_A(t)$$

Nuclear PDFs: EPPS16, nCTEQ15, nNNPDF2.0 + update with EPPS21, nCTEQ15WZSIH, nNNPDF3.0

Nucleus form factor (Woods-Saxon form)

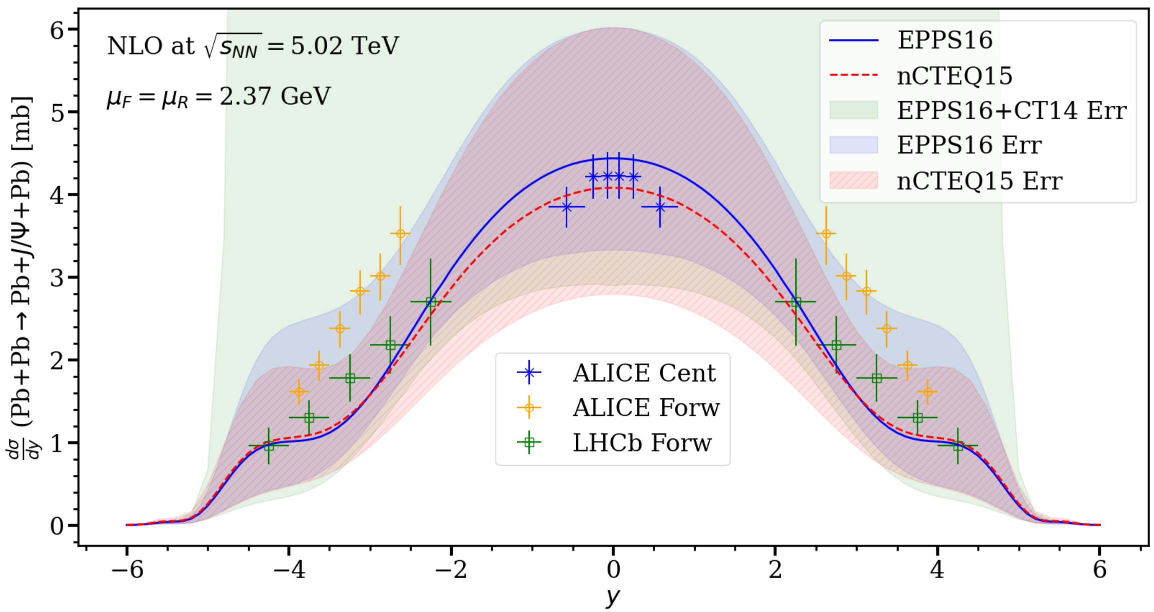
Scale dependence and comparison to data on J/ψ photoproduction in Pb-Pb UPCs (Runs 1&2)

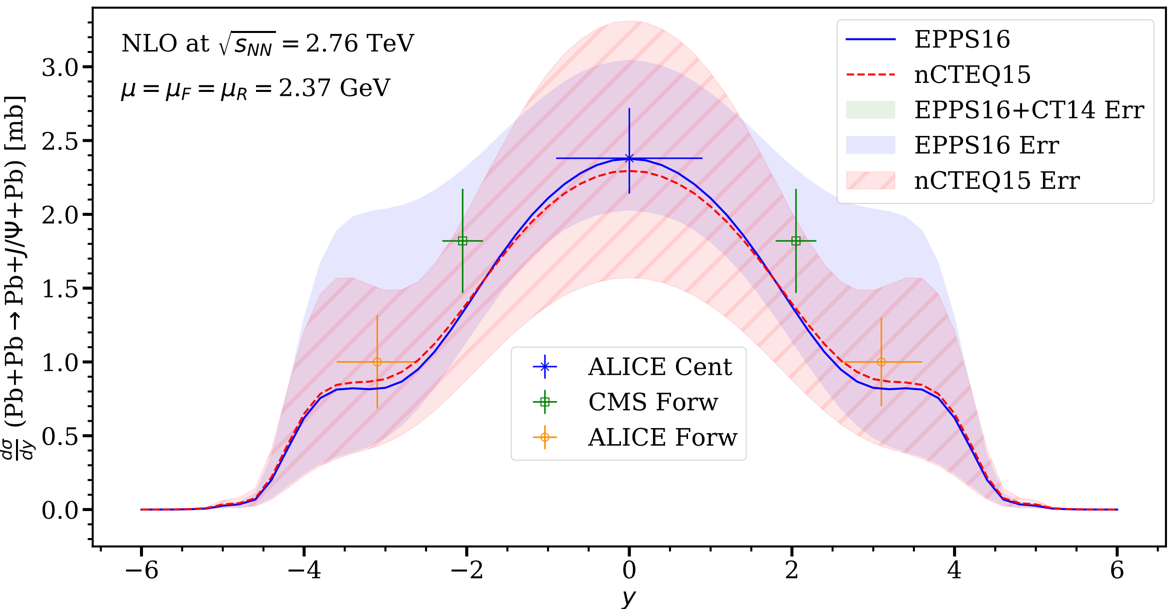




- Scale dependence of NLO pQCD results for $m_c \leq \mu \leq M_{J/\psi}$ is very strong.
- One can find an "optimal scale" giving simultaneous good description of Run 1&2 UPC data.
- Note that updated LHCb data have moved up worsening the agreement → restored by using nCTEQ15WZSIH nPDFs.
- With this choice of scale, the γ+p→J/ψ+p proton data is somewhat overestimated, but within large scale uncertainties.

Uncertainties due to nuclear PDFs



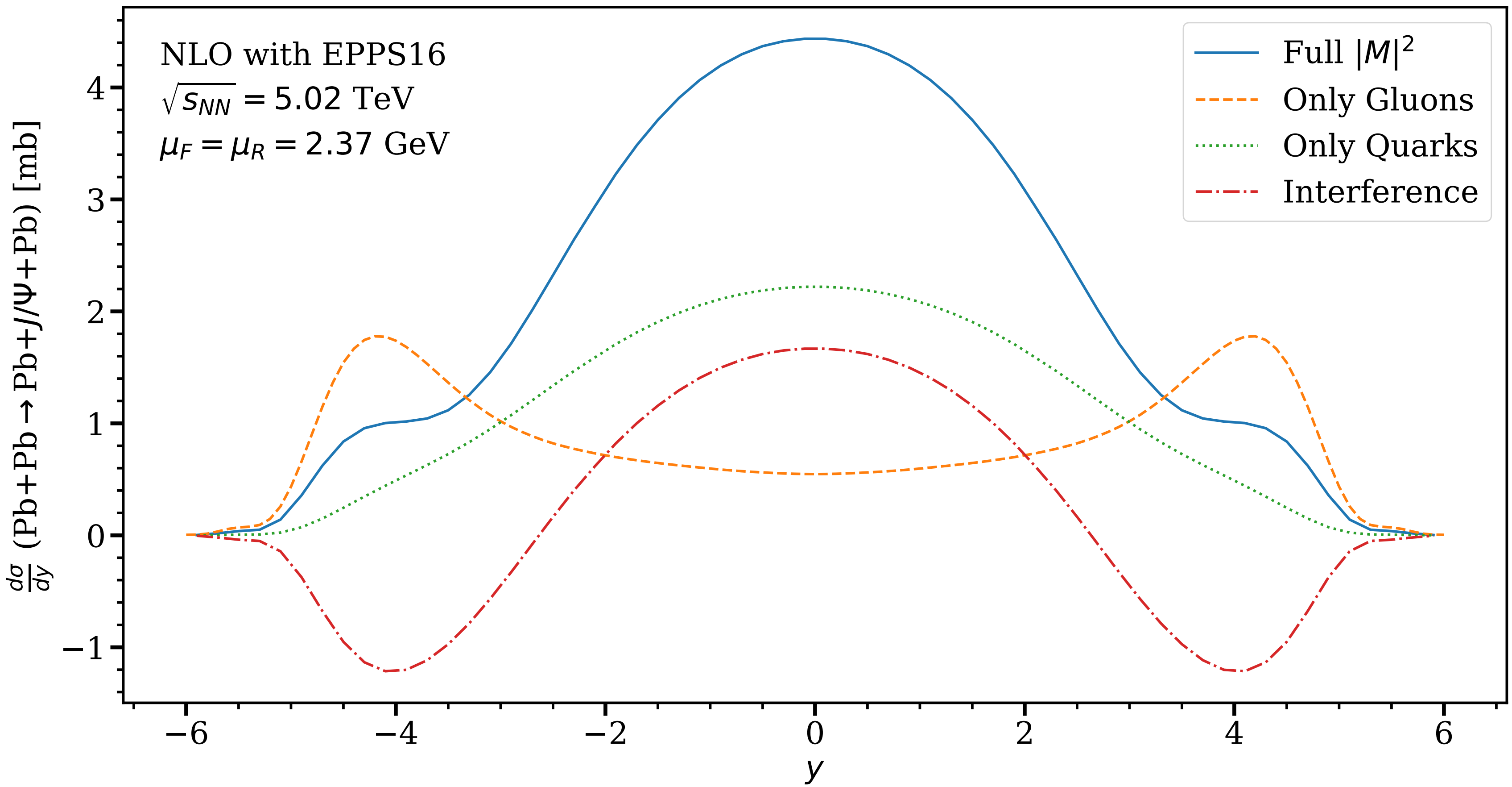


- Uncertainties due nPDFs are quite significant → opportunity to reduce them using the data on J/ψ photoprod. in AA UPCs.

- Abnormally large uncertainty for EPPS16 disappears when using more recent EPPS21.

Dominance of quark contribution

- The most striking result is strong cancellations between LO and NLO gluons $\rightarrow$ dominance of quark contribution at central rapidities.



- At the face value, this totally changes the interpretation of data on coherent J/ψ photoproduction in heavy-ion UPCs as a probe of small-x nuclear gluons.

Summary and Outlook

- First NLO pQCD calculation of exclusive J/ψ photoproduction in Pb-Pb UPCs@LHC in the framework of collinear factorization.

- Our analysis confirmed strong scale dependence noticed earlier, quantified uncertainty due to nuclear PDFs, observed the dominance of the quark contribution, and provided simultaneous description of Run 1&2 LHC data.

- From phenomenology point of view, the ultimate goal is to use this data to obtain new information on nuclear PDFs, e.g., by using it in global QCD fits.

- In the present form, this is problematic. Possible solutions:

  - Consider ratio of AA to pp UPC cross sections, where most of complications (scale dependence, uncertainties of proton PDFs, details of GPD modeling, relativistic corrections to the charmonium wave function) should largely cancel.

  - Note that even in the ratio, NR corrections do not cancel exactly, Eskobedo, Lappi, PRD 101 (2020) no. 3, 034030; Lappi, Mantysaari, Penttala, PRD 102 (2021) no. 5, 054020

  - To tame the large scale dependence, use the so-called Q_0 subtraction, Flett, Jones, Martin, Ryskin, Teubner, PRD 101 (2020) 9, 094011