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

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ERC adG YoctoLHC

Based on K.J. Eskola, C.A. Flett, V. Guzey, T. Löytäinen, H. Paukkunen, PRC 106 (2022) 035202 and arXiv:2210.16048 [hep-ph]

Outline:

- Ultraperipheral collisions (UPCs) at the LHC, J/ψ photoproduction and new constraints on small-x nuclear gluon density
- Exclusive J/ψ photoproduction in Pb-Pb and O-O UPCs@LHC in NLO pQCD: strong scale dependence, uncertainties due to nPDFs, and quark dominance
- Summary and outlook

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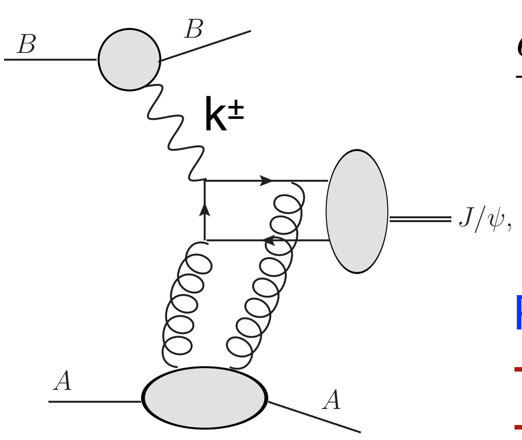
UPCs@LHC and J/ψ photoproduction

- Ultraperipheral collisions (UPCs): ions pass each other at large impact parameters $b \gg R_A+R_B$ → 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 → can be used to study open questions of proton and nucleus structure in QCD and search for new physics → **new info on quark and 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

- Most studied process is coherent J/ψ photoproduction in Pb-Pb/pp UPCs



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

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 $k^{\pm}$ from J/ψ rapidity y

Constraints on small-x gluon density in nuclei

- 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

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

Γ_V is J/ψ leptonic decay width

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

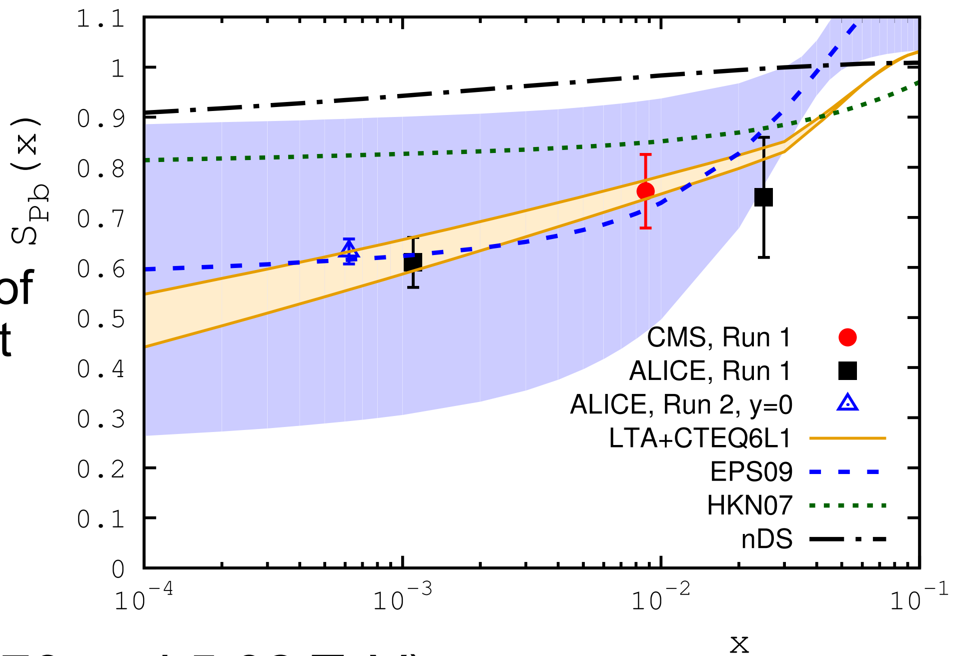
depends on details of J/ψ distribution amplitude

- Ratio of nucleus and IA cross sections → nuclear suppression factor $S_{Pb}(x)$

$$S_{Pb}(x) = \left[\frac{\sigma_{\gamma Pb\to J/\psi Pb}}{\sigma^{\rm IA}_{\gamma Pb\to J/\psi Pb}}\right]^{1/2} = \kappa_{A/N}\frac{g_A(x,\mu^2)}{Ag_N(x,\mu^2)}$$

Model-independently using data on Pb-Pb UPCs@LHC, 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 of nPDFs or leading twist nuclear shadowing model, Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290; Guzey, Zhalov, JHEP 1310 (2013) 207



- Good agreement with ALICE data at y=0 (2.76 and 5.02 TeV)

→ direct evidence of large gluon shadowing, $R_g(x=6\times10^{-4} - 0.001) \approx 0.6$

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), Ji, PRD 55 (1997) 7114; Radyushkin PRD 56 (1997) 5524; Diehl, Phys. Rept. 388 (2003) 41

- 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

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

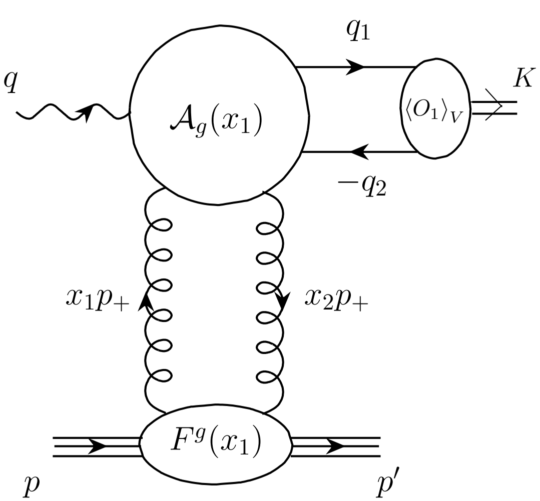
NRQCD matrix element from J/ψ leptonic decay

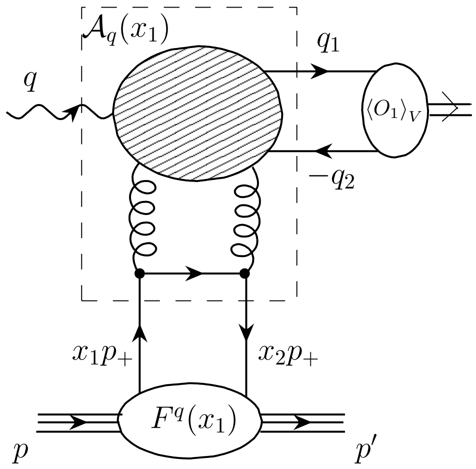
pQCD coeficient function

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 limit of high W corresponding to small $\xi=(1/2)(M_{J/\psi})^2/W^2 \ll 1$

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

→ helps to qualitatively understand the features of our numerical calculations.

• GPDs are hybrid distributions interpolating between usual PDFs and form factors → depend on momentum fractions x and ξ and momentum transfer t.

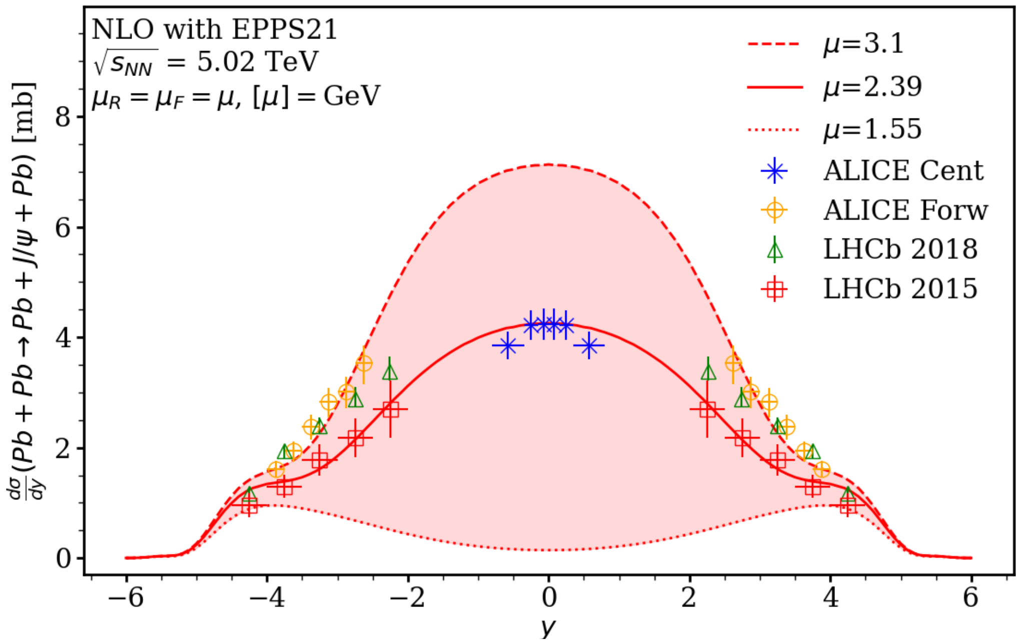
• Connection between GPDs is necessarily model-dependent. In our analysis, we neglect dependence of GPDs on ξ and used the forward model, Freund, McDermott, Strikman, PRD 67 (2003) 036001. For gluons (quarks are similar):

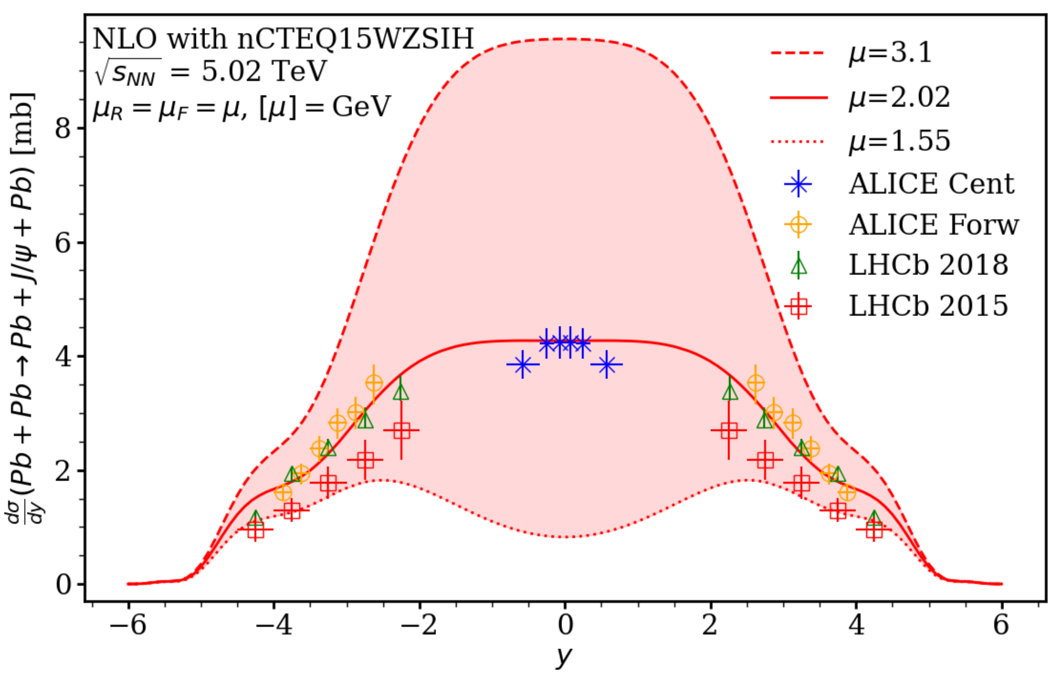
$$F_A^g(x,\xi,t,\mu_F)=xg_A(x,\mu_F)F_A(t)$$

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

Nucleus form factor (Woods-Saxon form)

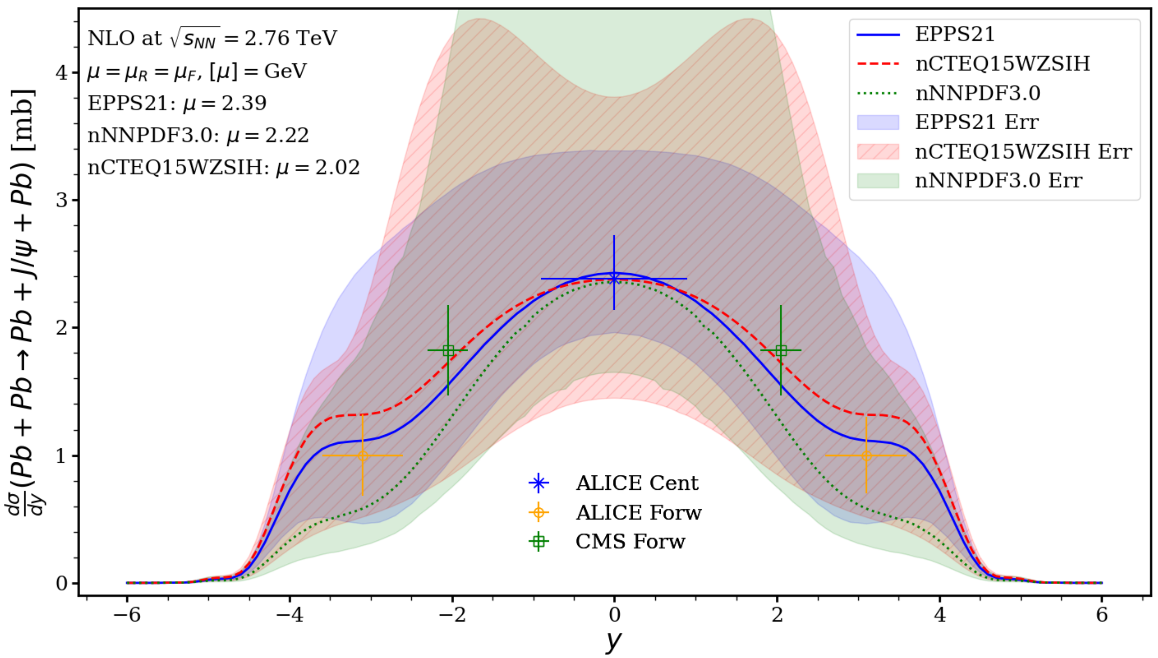
Scale dependence and comparison to data on J/ψ photoproduction in Pb-Pb UPCs (Runs 1&2)

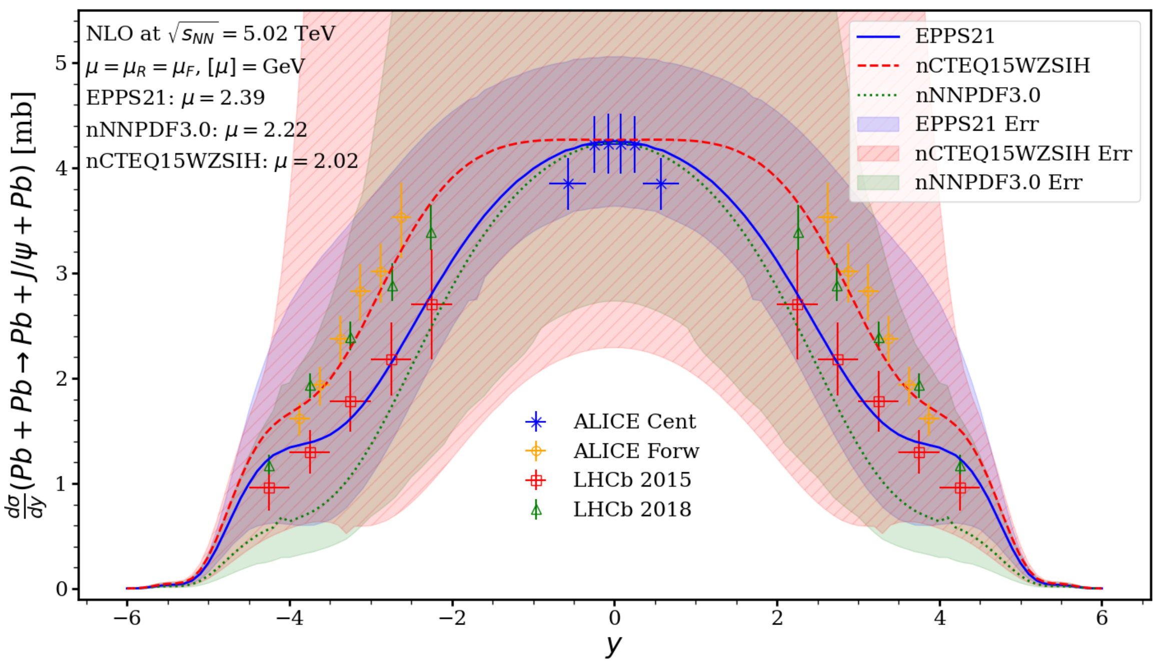




- Scale dependence of our NLO pQCD results for $m_c \leq \mu_F \leq M_{J/\psi}$ is very strong.
- One can find an "optimal scale" μ_F=2.39 GeV (EPPS21) giving simultaneous good description of Run 1&2 UPC data → note that γ+p→J/ψ+p proton data is somewhat overestimated.
- Note that updated LHCb data have moved up worsening the agreement with EPPS21.
- The agreement is restored by using nCTEQ15WZSIH nPDFs characterized by large strange quark density → sensitivity to strange quarks in nuclei?

Uncertainties due to nuclear PDFs



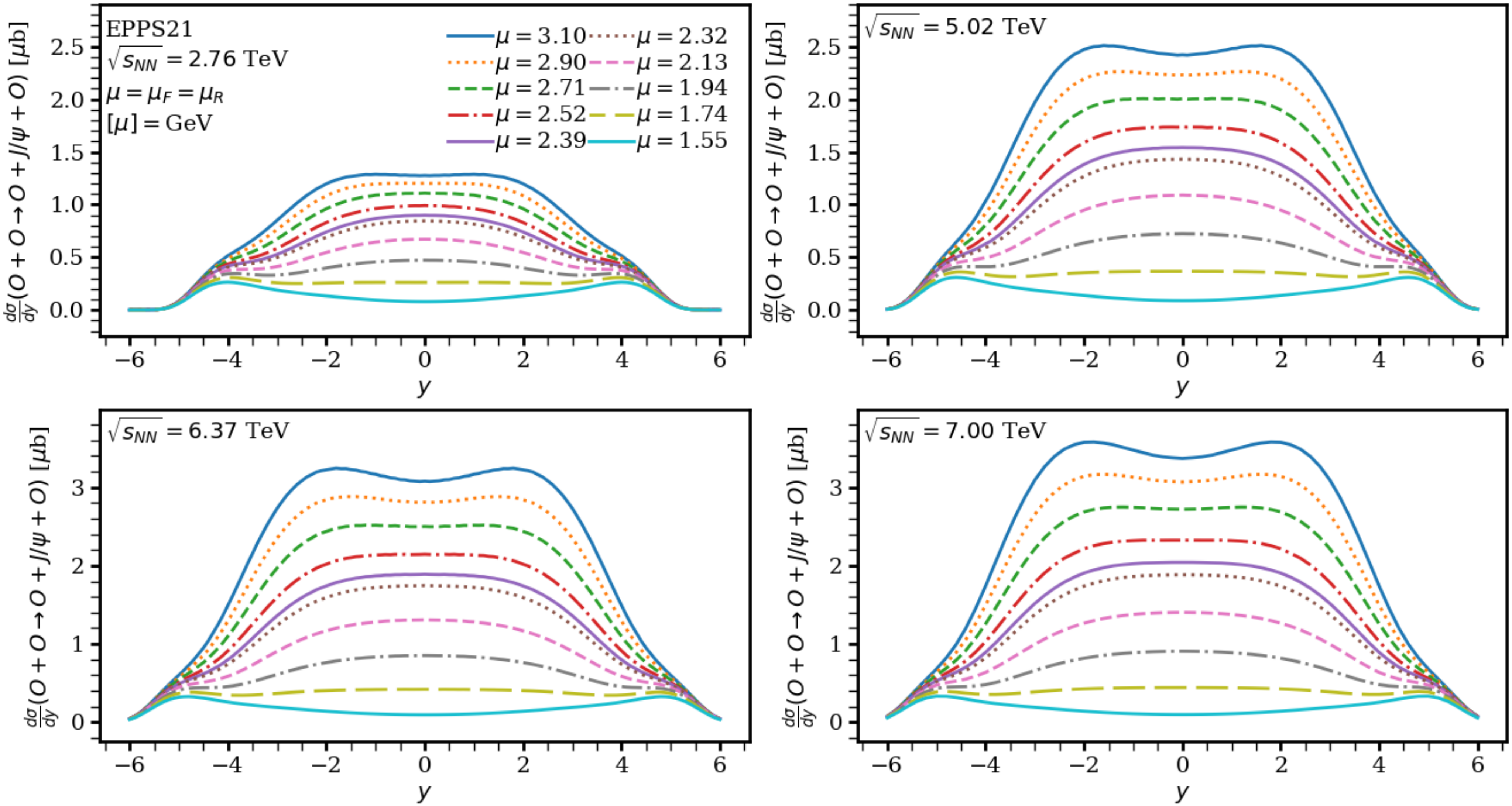


- Uncertainties due nPDFs are quite significant → opportunity to reduce them using the data on J/ψ photoproduction in AA UPCs.

- Compared to our original calculations, abnormally large uncertainty associated with EPPS16 disappears when using more recent EPPS21.

- The nNNPDF3.0 nPDFs correspond to much less constrained fit → large uncertainties.

NLO pQCD predictions for O-O UPCs



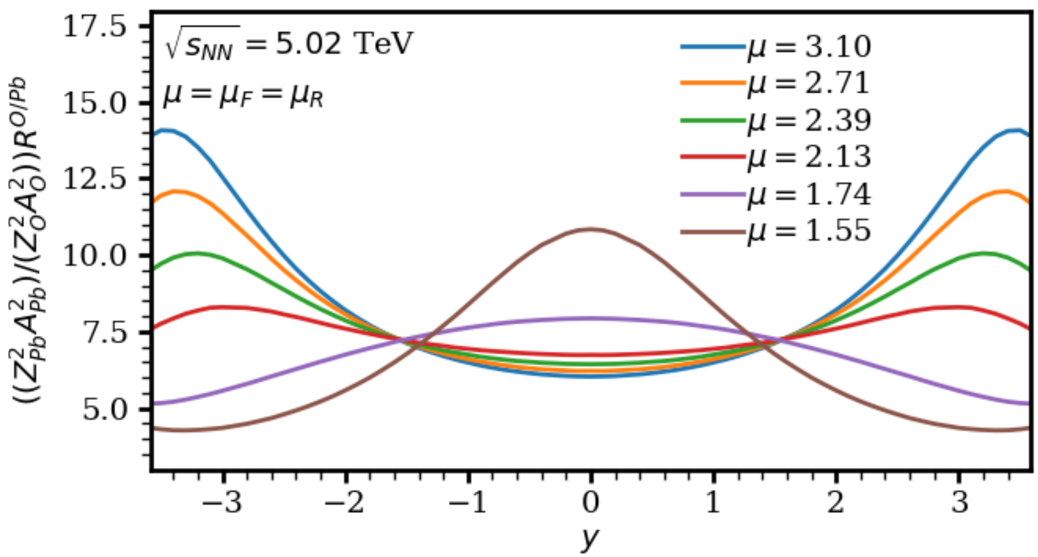
• NLO pQCD predictions for anticipated O-O run with 4 options for $\sqrt{s_{NN}}$ → similar trends as for Pb-Pb UPCs → large scale and nuclear PDF uncertainties.

Reduction of uncertainties using O/Pb ratio

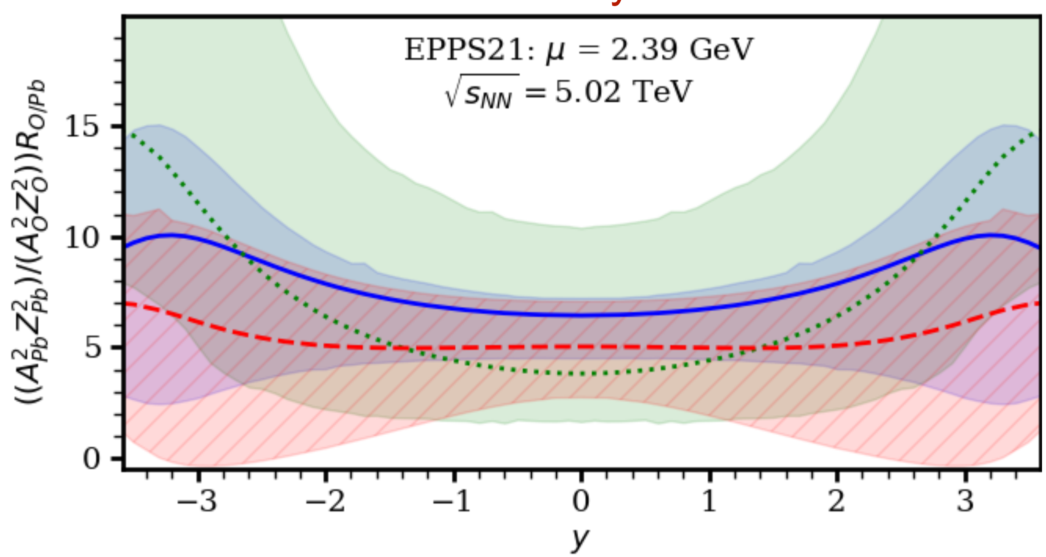
- One can reduce the significant scale μ_F and nPDF uncertainties by considering the ratio of oxygen to lead UPC cross sections:

$$R^{\mathrm{O/Pb}} = \left(\frac{208 Z_{\mathrm{Pb}}}{16 Z_{\mathrm{O}}}\right)^2 \frac{d\sigma(\mathrm{O}+\mathrm{O} \to \mathrm{O} + J/\psi + \mathrm{O})/dy}{d\sigma(\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb} + J/\psi + \mathrm{Pb})/dy}$$

Scale uncertainty of $R^{\mathrm{O/Pb}}$



nPDF uncertainty of $R^{\mathrm{O/Pb}}$

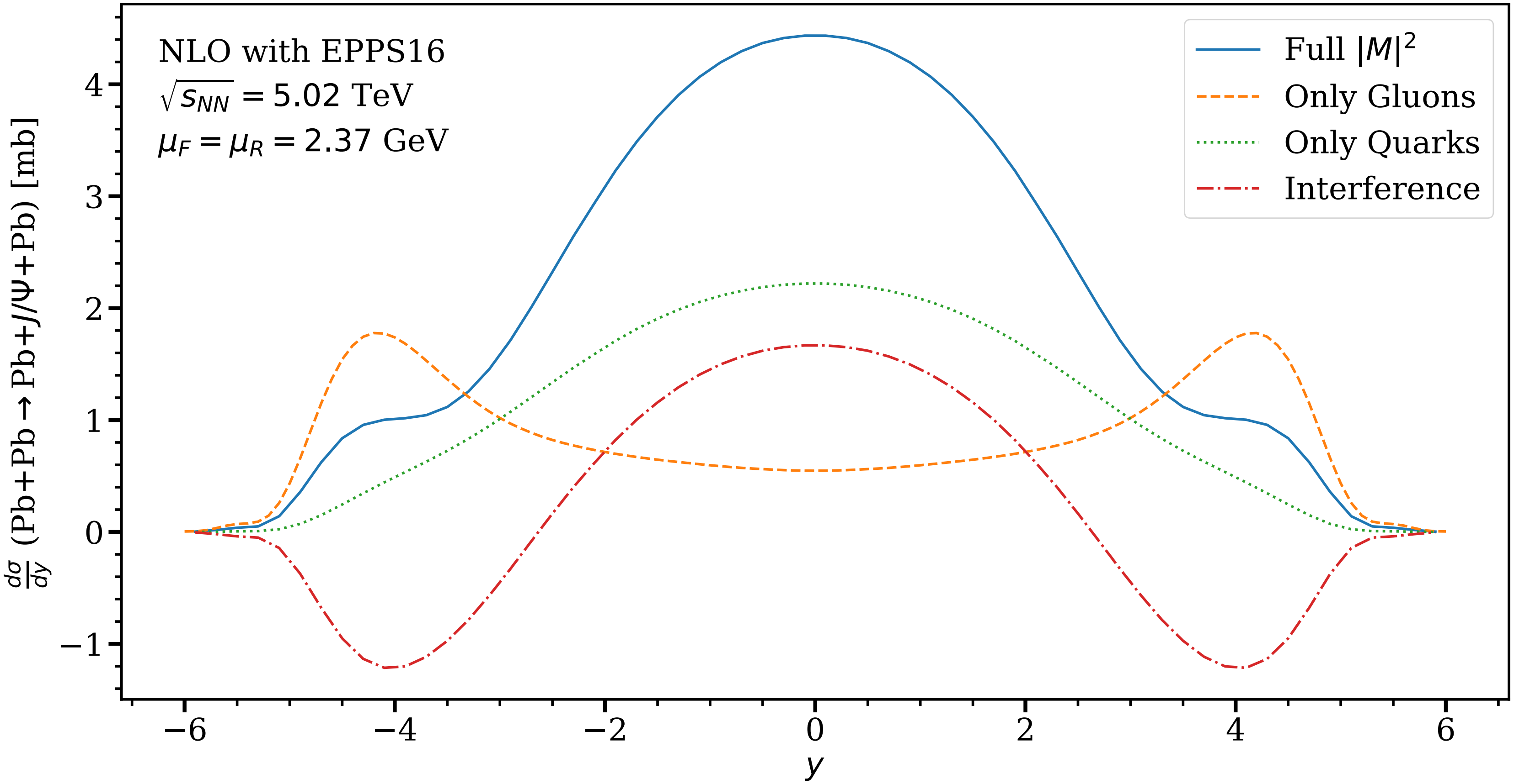


- Hard scattering coefficient functions for O and Pb are the same → differences come from O and Pb nPDFs → scale dependence reduced by factor of 10 compared to individual UPC cross sections.

- Reduction of nPDF uncertainties is also large due to additional partial cancellation of uncertainties associated with proton PDFs.

Dominance of quark contribution

- The most striking result is strong cancellations between LO and NLO gluons → 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 and O-O 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 these UPC data in global QCD fits.

• In the present form, this is challenging. Possible solutions:

- Consider ratio of AA to OO/pp UPC cross sections, where most of complications (scale dependence, uncertainties of nPDFs, details of GPD modeling and its Q^2 evolution, relativistic corrections to the charmonium wave function) partially cancel.
- Even in the case of the UPC cross section ratios, non-relativistic corrections to charmonium wave function do not cancel exactly and should be taken into account, Eskobedo, Lappi, PRD 101 (2020) 3, 034030; Lappi, Mantysaari, Penttala, PRD 102 (2020) 5, 054020