Surprises and challenges in exclusive J/ψ photoproduction on nuclei

Vadim Guzey

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

HELSINKI INSTITUTE OF PHYSICS

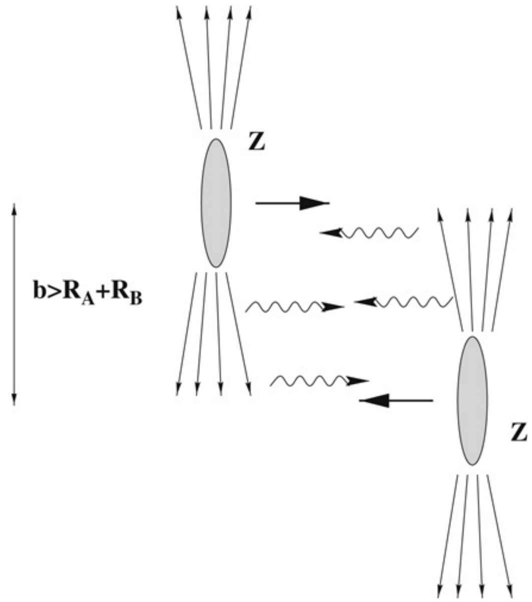
K.J. Eskola, C.A. Flett, V. Guzey, T. Löytäinen, H. Paukkunen, PRC 106 (2022) 035202 and arXiv:2210.16048 [hep-ph]

Outline:

- Exclusive J/ψ photoproduction on nuclei in ultraperipheral collisions (UPCs) at the LHC: constraints on small-x nuclear gluon density
- Exclusive J/ψ photoproduction in NLO pQCD: strong scale dependence, uncertainty due to nPDFs, and quark dominance
- Theoretical challenges: small-x resummation, non-relativistic corrections to charmonium wave function

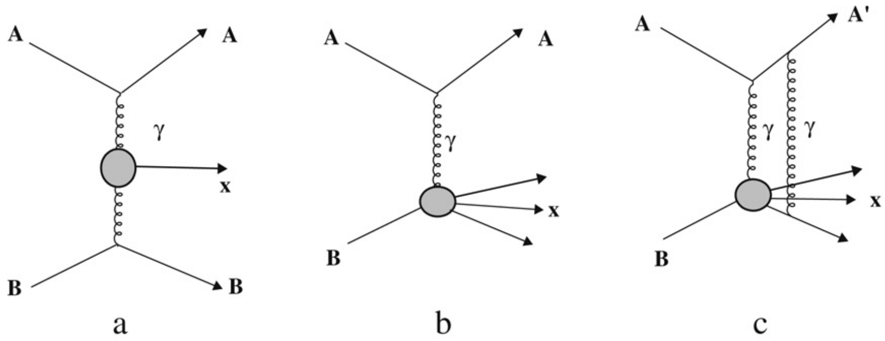
Particle Physics Day 2022, Helsinki, Nov 24, 2022

Ultraperipheral collisions at the LHC



- 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

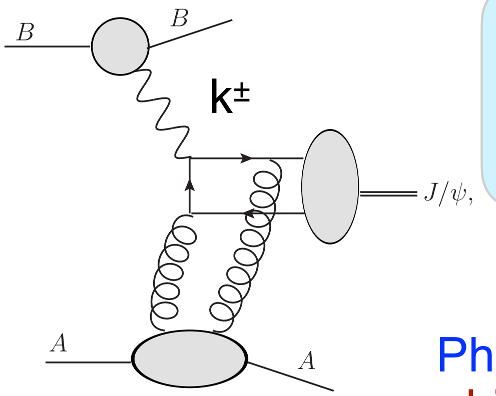


- UPCs can be used to study open questions of proton and nucleus structure in QCD and search for new physics → e.g., **new info on quark and gluon distributions in nuclei at small x**.

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

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

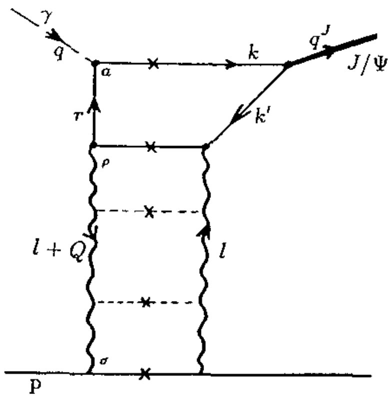
Photoproduction cross section

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

Photon momentum from J/ψ rapidity y

- 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_{eff}^2=2.5-3 GeV^2

depends on details of charmonium distribution amplitude

Constraints on small-x gluon density in nuclei

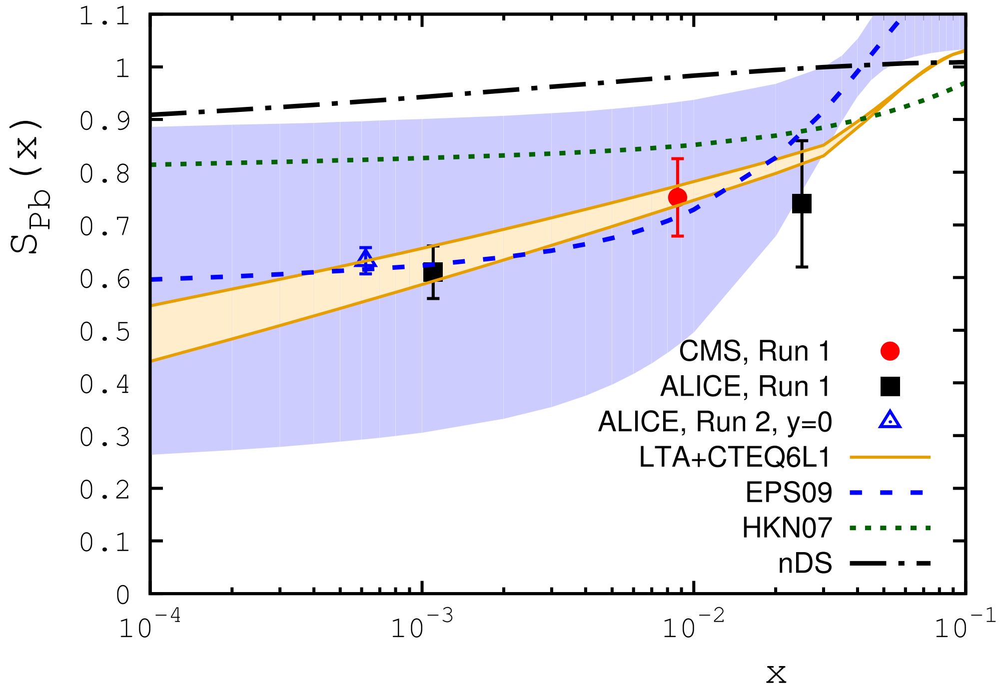
- Ratio of nucleus and proton cross sections → nuclear suppression factor S

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

Model-independently using data on Pb-Pb UPCs at the 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



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), 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

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

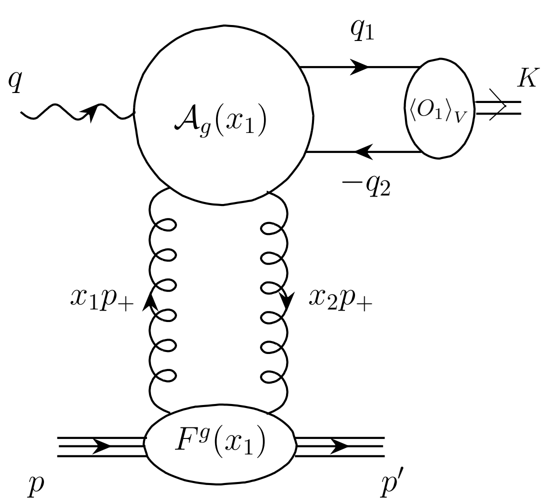
NRQCD matrix element from J/ψ leptonic decay

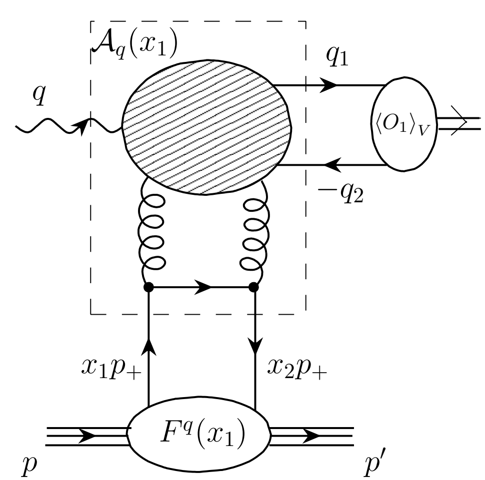
pQCD coeficient function

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 ξ=(1/2)($M_{J/\psi}$)^2/$W^2 \ll 1$

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

→ 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.

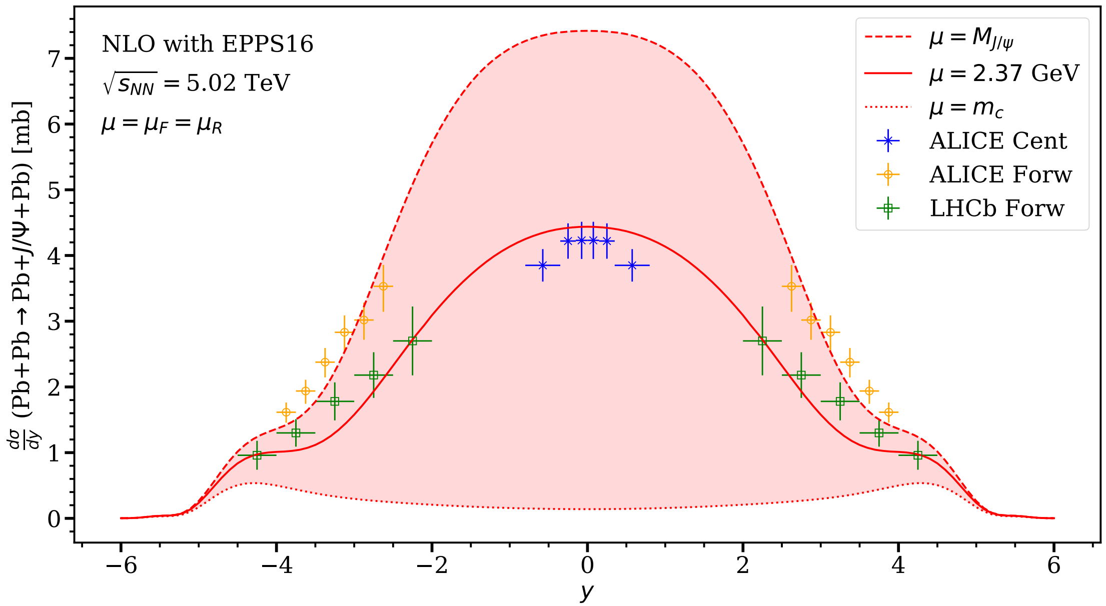
- Connection between GPDs is necessarily model-dependent. In our analysis, we neglect dependence of GPDs on ξ and used the forward model, Freund, McDermott, Strikman, PRD 67 (2003) 036001. For gluons (quarks are similar):

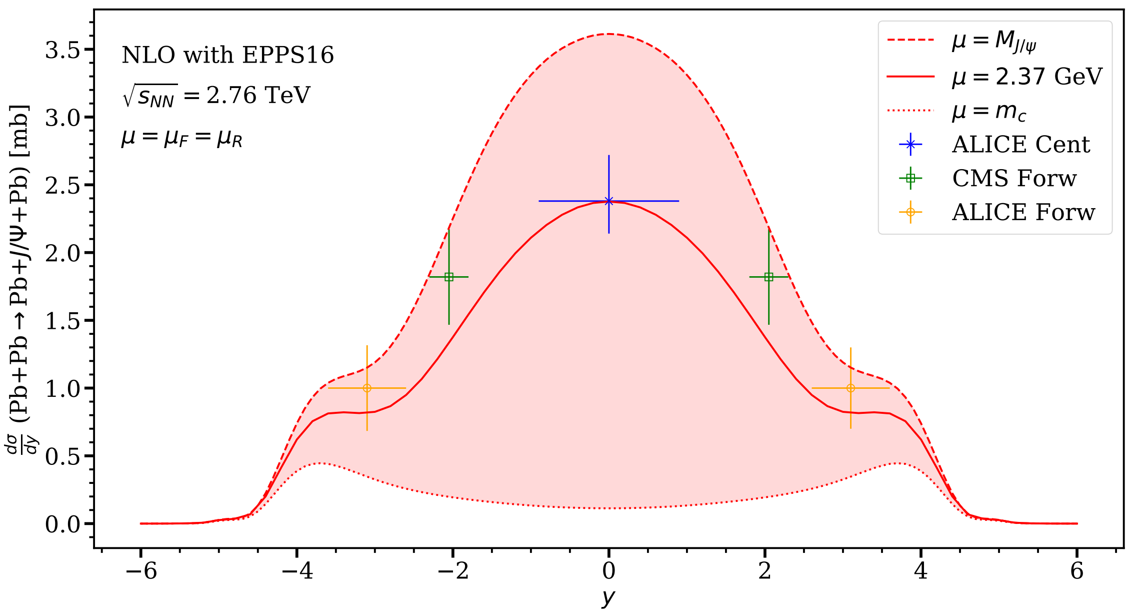
$$F_A^g(x,\xi,t,\mu_F)=xg_A(x,\mu_F)F_A(t)$$

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

Nucleus form factor (Woods-Saxon form)

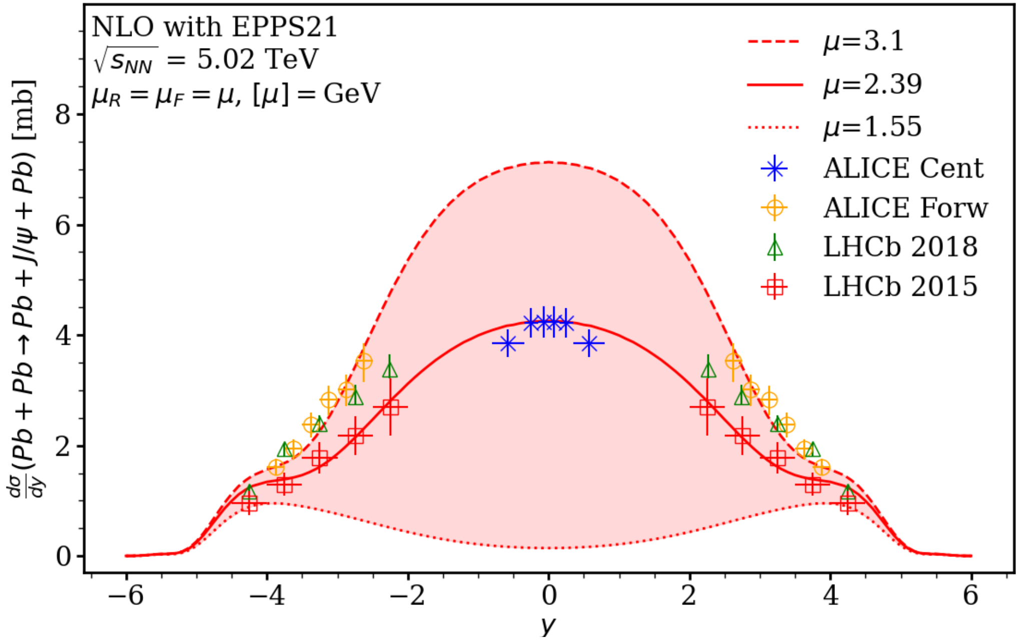
Scale dependence and comparison to data on J/ψ photoproduction in Pb-Pb UPCs (Runs 1&2)

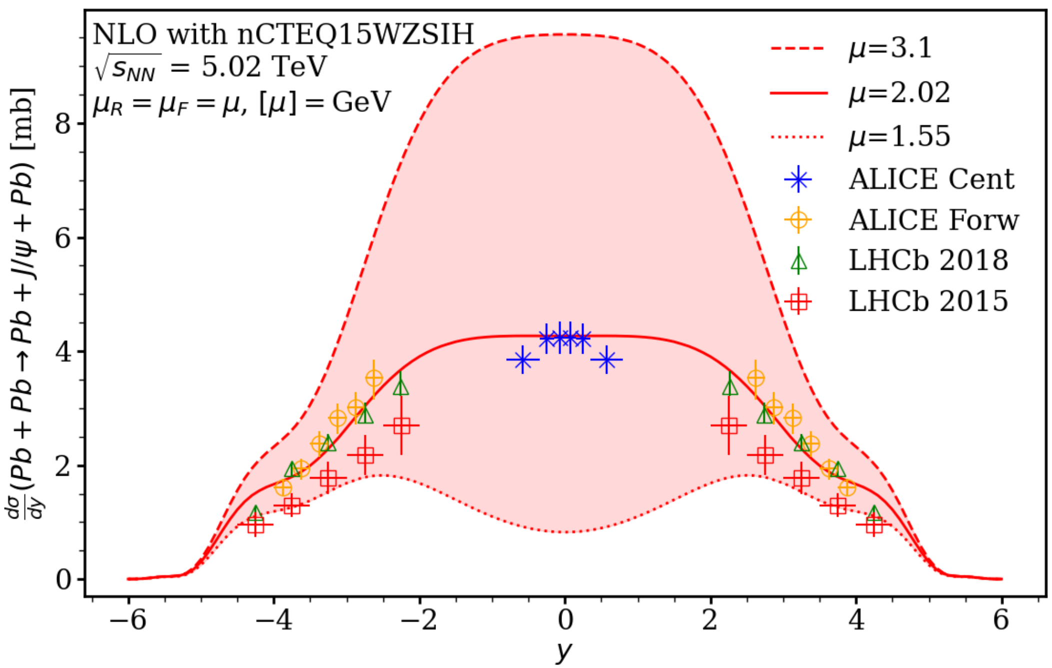




- Scale dependence of our NLO pQCD results for $m_c \leq \mu_F \leq M_{J/\psi}$ is very strong.
- One can find an "optimal scale" giving simultaneous good description of Run 1&2 UPC data.
- With this choice of scale, the γ+p→J/ψ+p proton data is somewhat overestimated, but within large scale uncertainties.

Scale dependence and comparison to data on J/ψ photoproduction in Pb-Pb UPCs: update



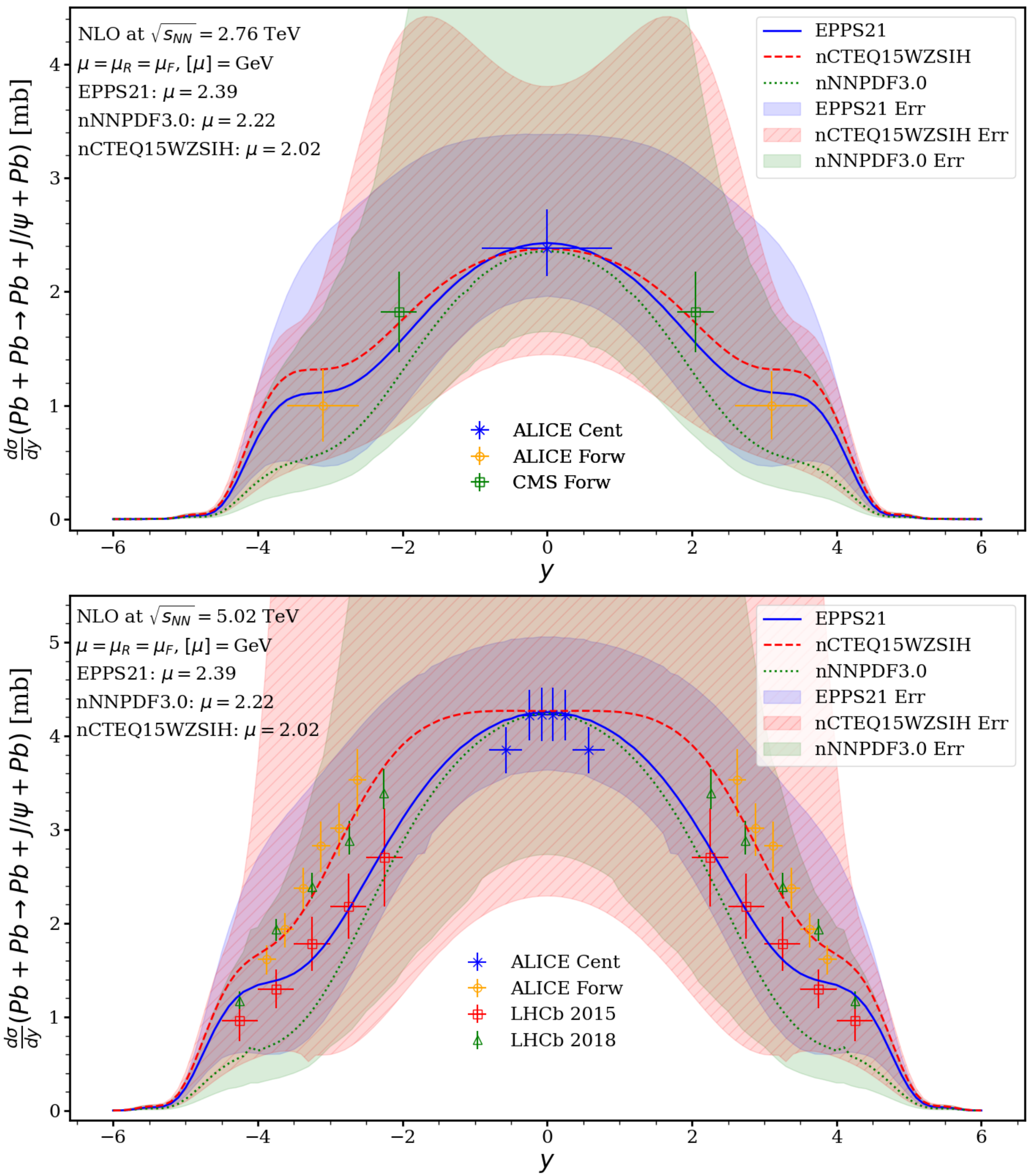


- Repeated our calculations using state-of-the-art EPPS21, nNNPDF3.0 and nCTEQ15WZSIH nPDFs.

- Note that updated LHCb data have moved up worsening the agreement with EPPS21.

- However, the agreement is restored by using nCTEQ15WZSIH nPDFs, which are 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.

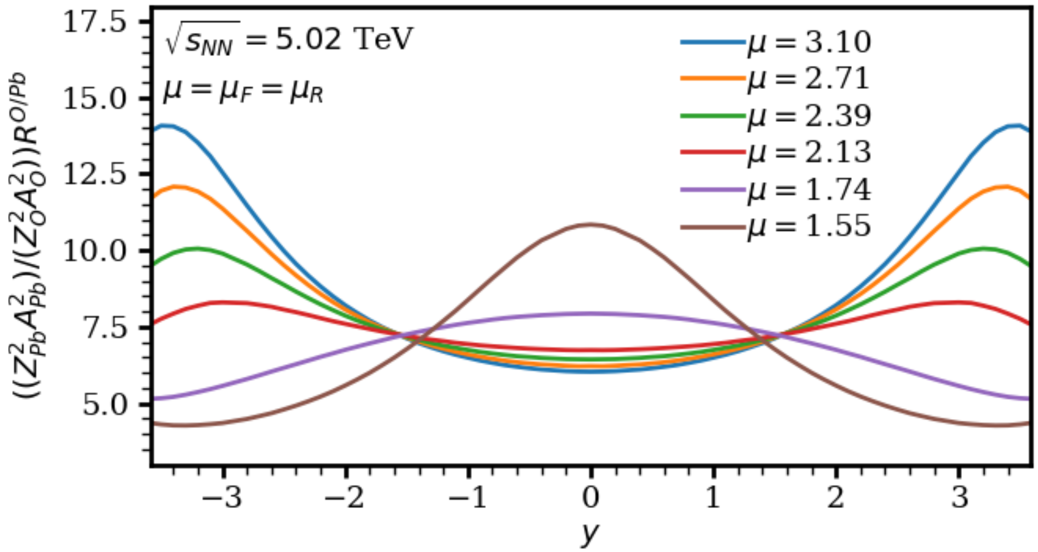
- The nNNPDF3.0 nPDFs correspond to much less constrained fit → large uncertainties.

Reduction of uncertainties using O/Pb ratio

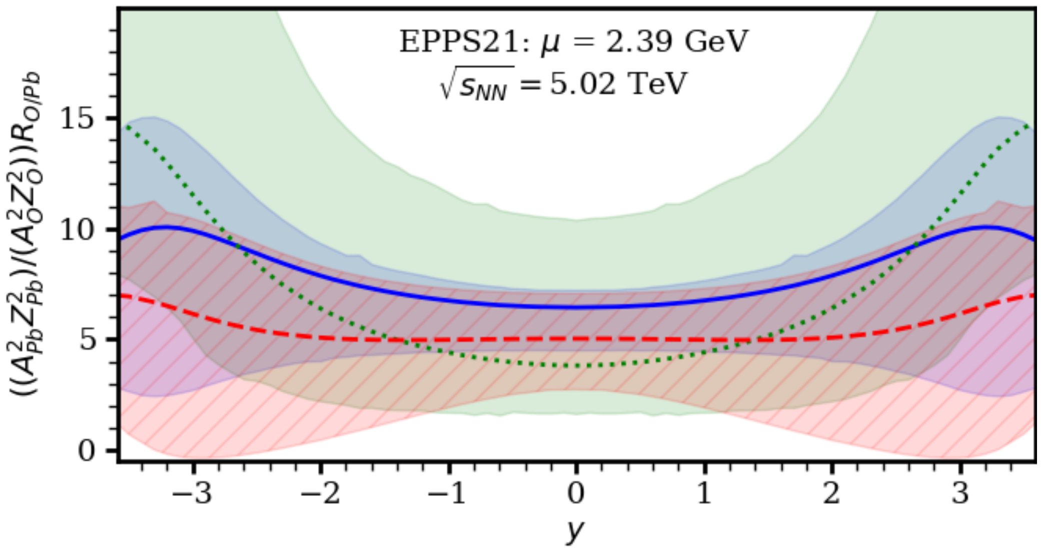
- One can reduce the significant scale μ_F and nPDF uncertainties by considering the ratio of oxygen to lead UPC cross sections:

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

Scale uncertainty of R



nPDF uncertainty of R

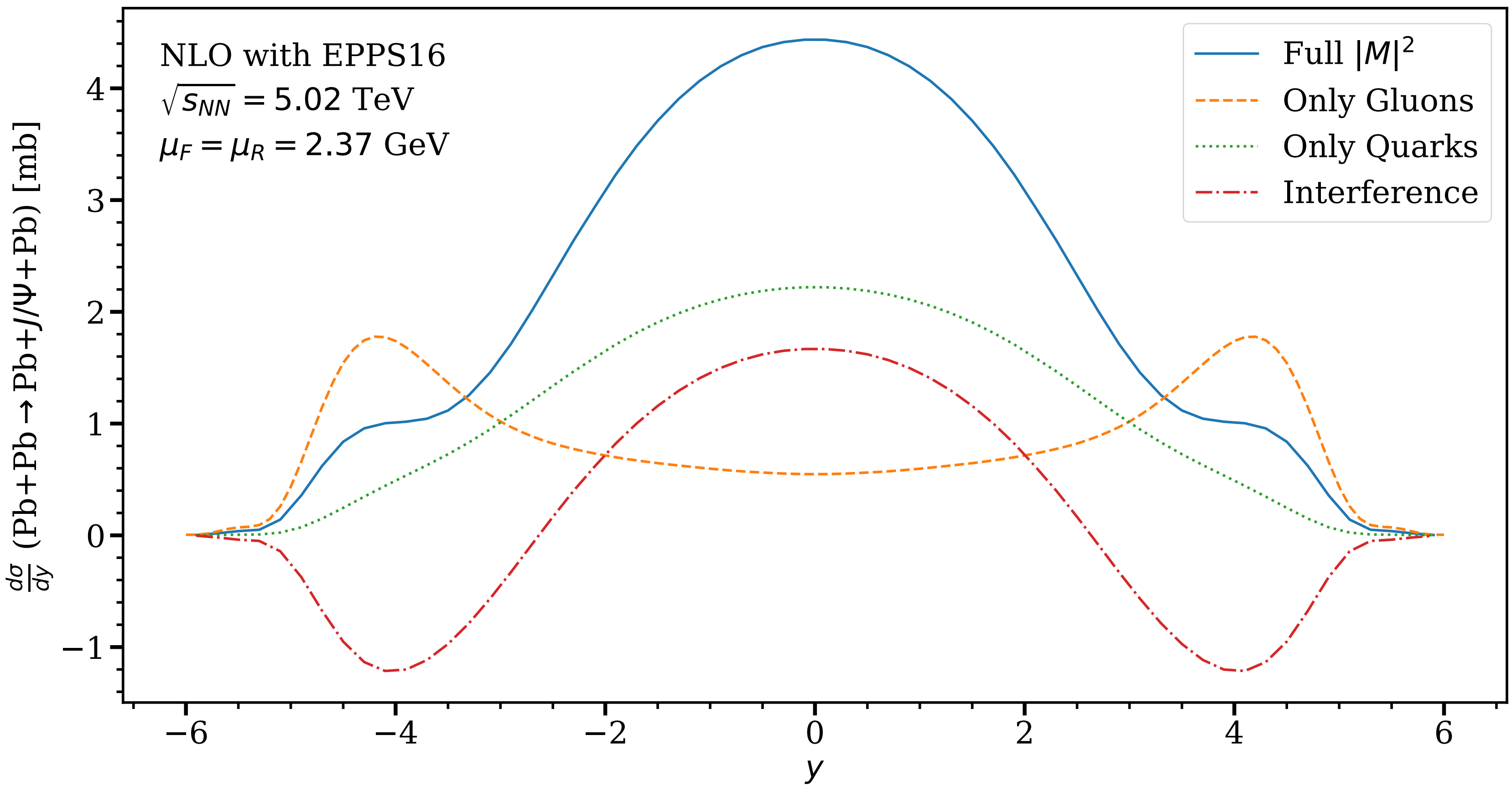


- Hard scattering coefficient functions for O and Pb are the same → the scale dependence comes from nPDFs → reduced by factor of 10 compared to individual UPC cross sections.

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

Surprise: 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 → but this requires overcoming certain theoretical challenges.

Exclusive J/ψ photoproduction in NLO pQCD.

Challenge 1: small-x resummation

- NLO corrections and, hence, the scale dependence are very large → large theoretical uncertainties in phenomenological applications.
- The reason is well understood → large $\ln(Q^2)\ln(1/\xi)$ terms for $2\xi \approx (M_{J/\psi})^2/W^2 \ll 1$

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

- Possible solution: so-called Q_0 subtraction based on subtraction of $k_T < Q_0 \sim m_C$ contribution from NLO coefficient functions, Jones, Martin, Ryskin, Teubner, EPJC 76 (2016) 11, 633; Flett, Jones, Martin, Ryskin, Teubner, PRD 101 (2020) 9, 094011
- Other (related) option to tame small-x behavior: BFKL resummation, Ivanov, arXiv:0712.31983 [hep-ph]; Ivanov, Pire, Szymanowki, Wagner, EPJ Web. Conf. 112 (2016) 01020

$$\mathcal{I}m\mathcal{M}^g \sim H^g(\xi,\xi) + \int_\xi^1 \frac{dx}{x}H^g(x,\xi)\sum_{n=1} C_n(L)\frac{\bar{\alpha}_s^n}{(n-1)!}\log^{n-1}\frac{x}{\xi}$$

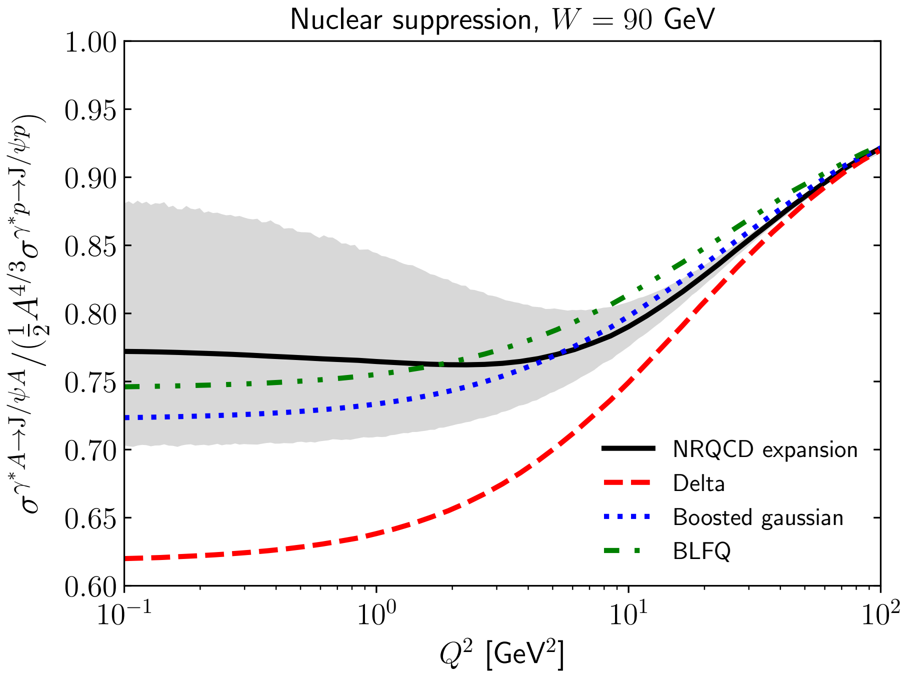
where $L = \ln(M_V^2/\mu_F^2)$

→ Need to calculate $C_n(L)$ and include in our NLO pQCD analysis.

Exclusive J/ψ photoproduction in NLO pQCD.
Challenge 2: non-relativistic corrections to charmonium wf

- Our analysis assumes a static (non-relativistic) limit for J/ψ vertex.

  - Recent analyses have shown that relativistic v/mC corrections are sizable, Eskobedo, Lappi, PRD 101 (2020) 3, 034030; Lappi, Mantysaari, Penttala, PRD 102 (2020) 5, 054020 → affect interpretation of nuclear suppression in AA UPCs@LHC.



  - There is also a related issue of D-wave (spin rotation) of the charmonium wave function, Krelina, Nemchik, Pasechnik, EPJ C 80 (2020) 2, 92

Need to couple non-relativistic v/mC corrections to our NLO pQCD calculations.

Summary

- 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 data to obtain new information on nuclear PDFs at small x, e.g., by using the 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, relativistic corrections to the charmonium wave function) partially cancel.
    - Small-x BFKL resummation and Q_0 subtraction to tame the large scale dependence.
    - Even in the case of the UPC cross section ratios, nonrelativistic corrections to charmonium wf do not cancel exactly and should be taken into account.