Exclusive heavy vector meson photoproduction on nuclei in NLO QCD

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AoF CoE in Quark Matter

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:

- Heavy vector meson (J/ψ) photoproduction at the LHC and 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
- Open questions and Summary

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Ultraperipheral collisions at LHC as photon-nucleus collider

• 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: $W_{\gamma p}$=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**.

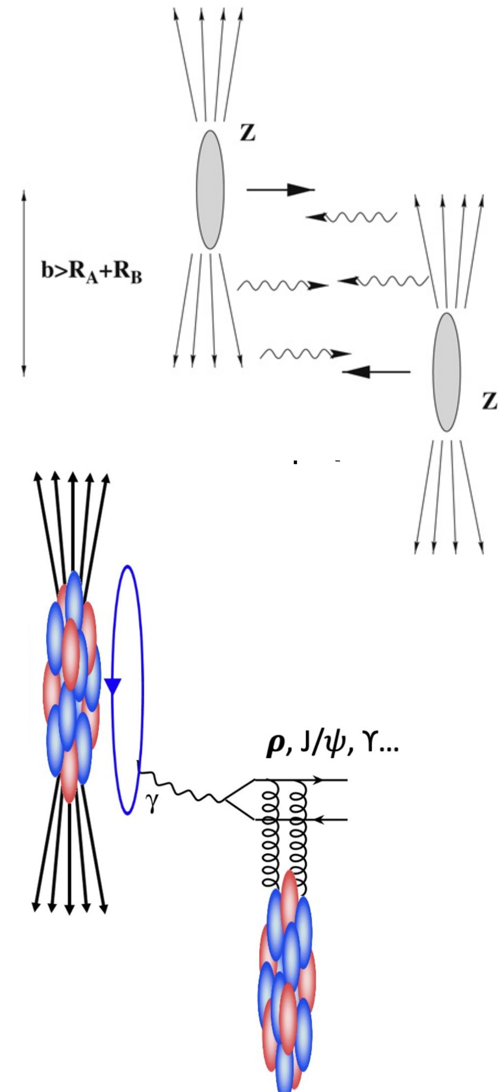
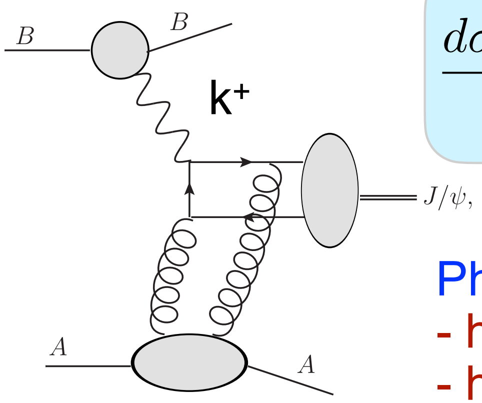


Figure credit: A. Stahl, LPCC CERN Seminar, 06.12.2022

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 AA UPCs → two terms corresponding to high photon momentum k^+ (low-x_A) and low k^- (high-x_A) → ambiguity in relating J/ψ rapidity y to gluon momentum fraction x_A.



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

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

Photoproduction cross section

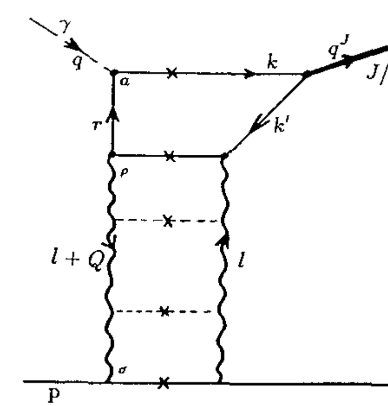
$$k^{\pm} = \frac{M_{J/\psi}}{2}e^{\pm y}$$

Photon momentum $k^{\pm}$ and $(W_{\pm})^2=(k^{\pm}+E_A)^2$ from J/ψ rapidity y

• In leading logarithmic approximation (LLA) of pQCD (in practice, leading double $\ln(Q^2)\ln(1/x)$ approximation),

Ryskin, Z. Phys. C57 (1993) 89; Brodsky, Frankfurt, Gunion, Mueller, Strikman, PRD 50 (1994) 3134

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



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 charmonium distribution amplitude; $C(Q^2=0)=1$ in NR limit.

Constraints on small-x gluon shadowing

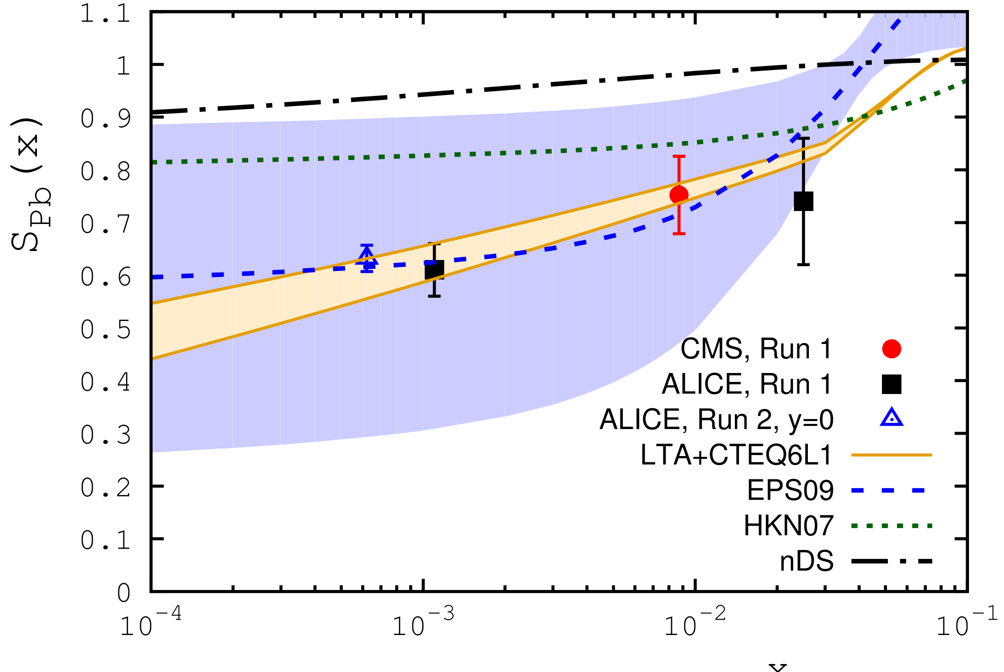
• Ratio of nucleus and proton UPC cross sections → nuclear suppression factor S(x) → works only for y=0 and large |y|, where there is no ambiguity

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

$\kappa_{A/N} \approx 1$ is a correction due to skewness (Shuvaev transform)

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 of nPDFs or leading twist (LTA) nuclear shadowing model Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290, Guzey, Zhalov, JHEP 1310 (2013) 207

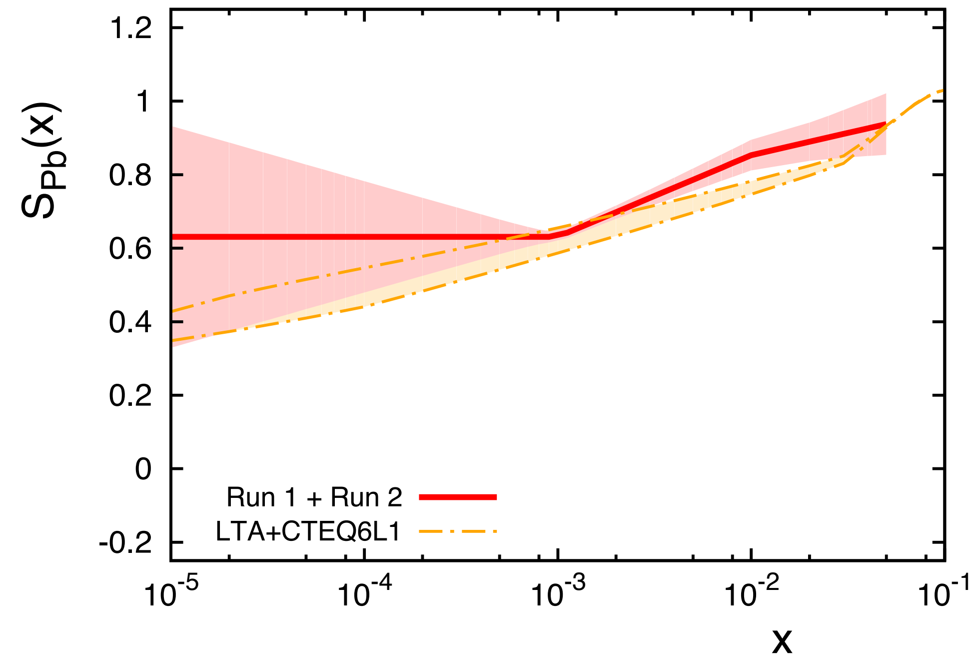


LTA: Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028

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

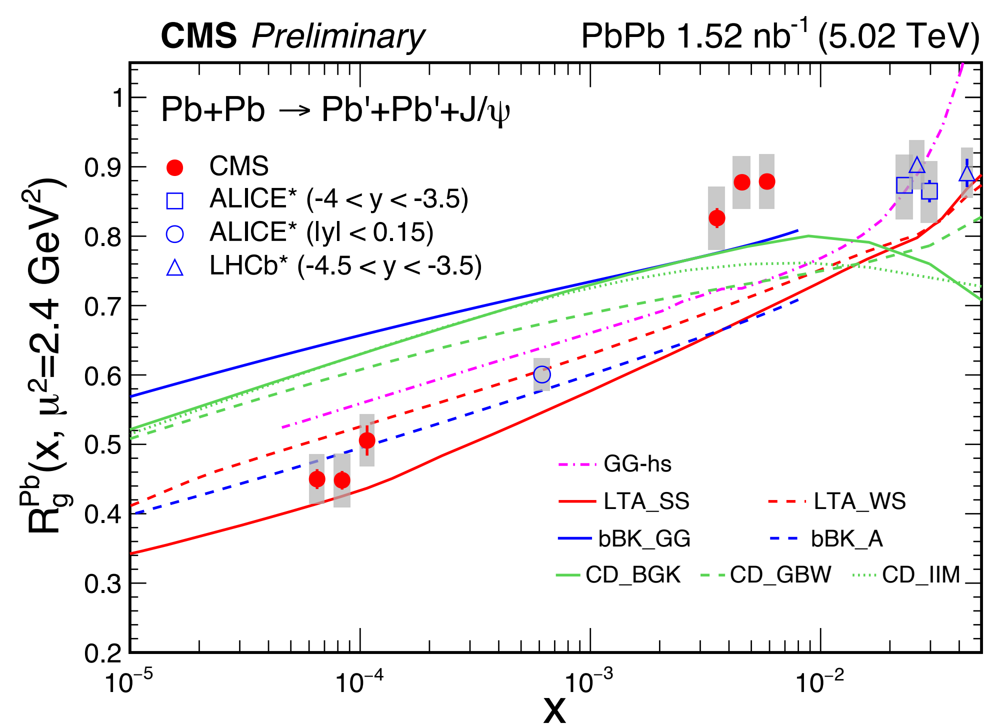
Constraints on small-x gluon shadowing (2)

- One can attempt to utilize all available ALICE, CMS and LHCb data (17 points) by performing a χ^2 fit assuming a piece-wise form of S(x), Guzey, Kryshen, Strikman, Zhalov, PLB 861 (2021) 136202 + see Refs. to LHC experimental data



- Alternatively, to separate W^+ and W^- contributions at y≠0, one can study UPCs accompanied by forward neutron emission in different classes (0n0n, 0nXn, XnXn), Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942

- CMS Physics Analysis Summary using |y|≈2 data, CMS PAS HIN-22-002



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

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

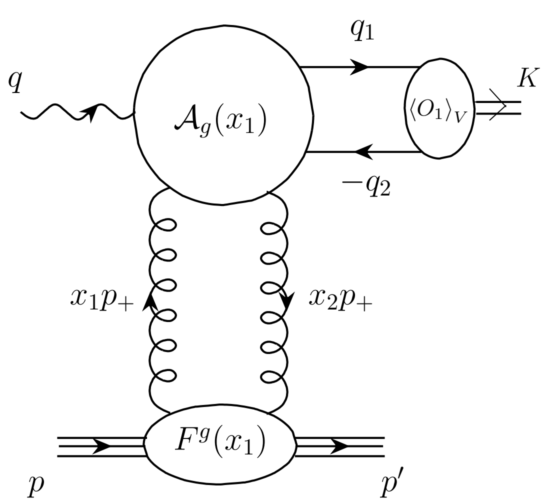
NRQCD matrix element from J/ψ leptonic decay

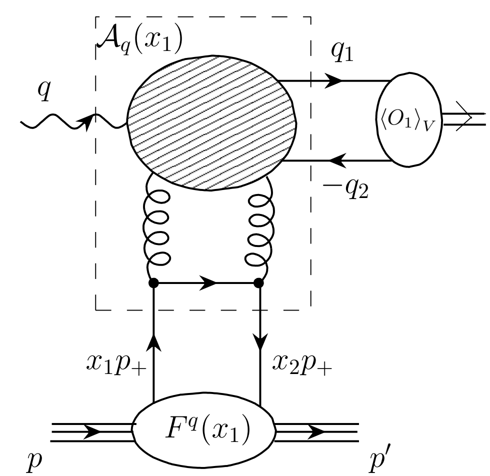
pQCD coeficient function

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 $\xi=(1/2)(M_{J/\psi})^2/W^2 \ll 1$

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

+ less singular and non-log terms

→ 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.

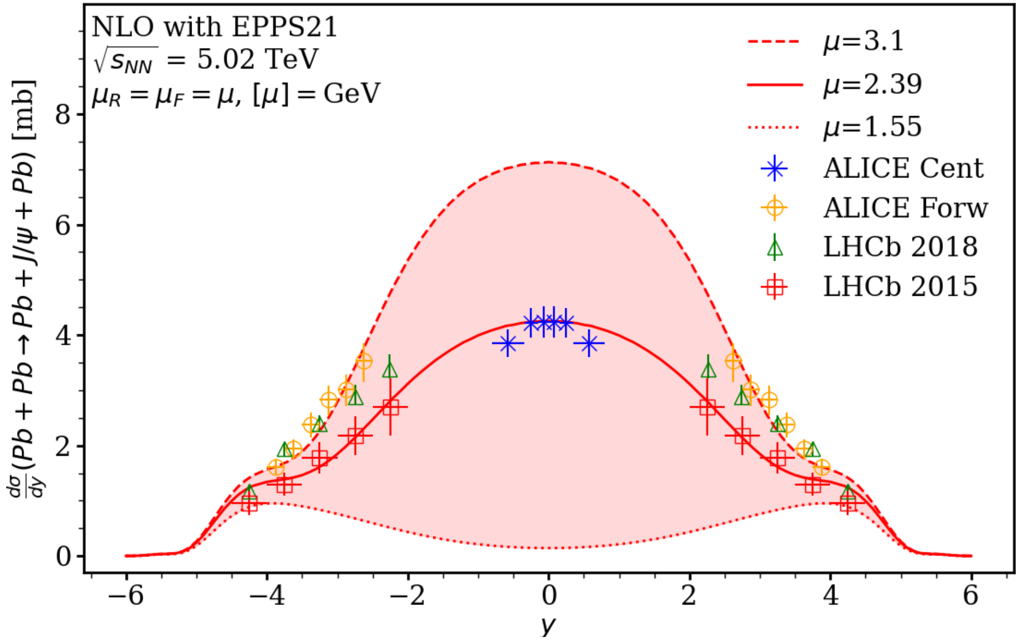
- Connection between GPDs is necessarily model-dependent. In our analysis, we neglect dependence of GPDs on ξ and used the forward model, Freund, McDermott, Strikman, PRD 67 (2003) 036001. For gluons (quarks are similar):

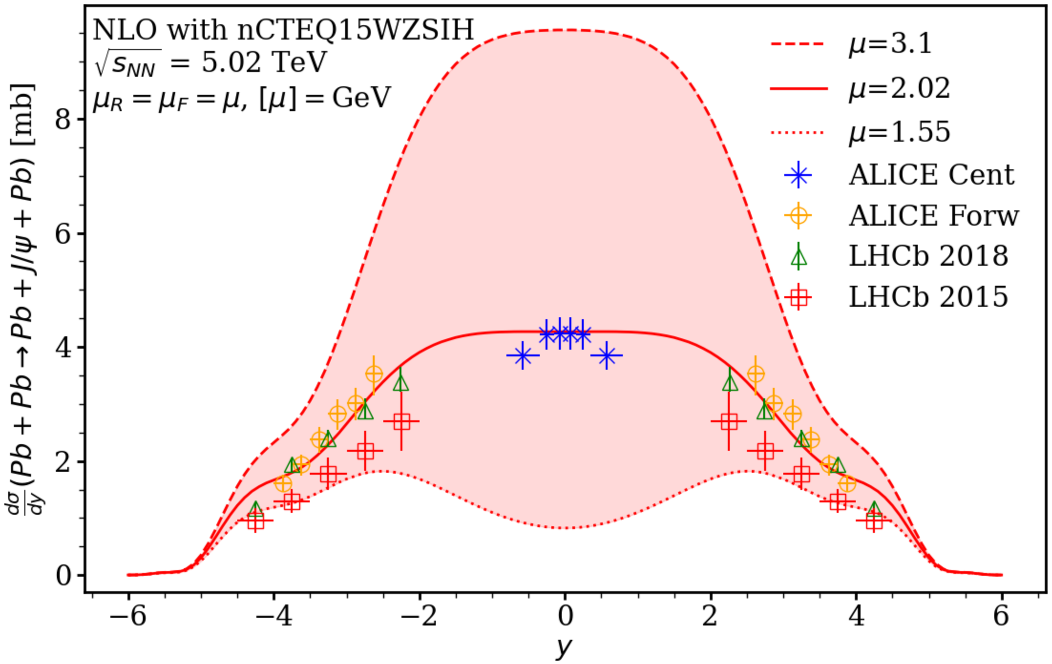
$$F_A^g(x,\xi,t,\mu_F) = xg_A(x,\mu_F)F_A(t)$$

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)





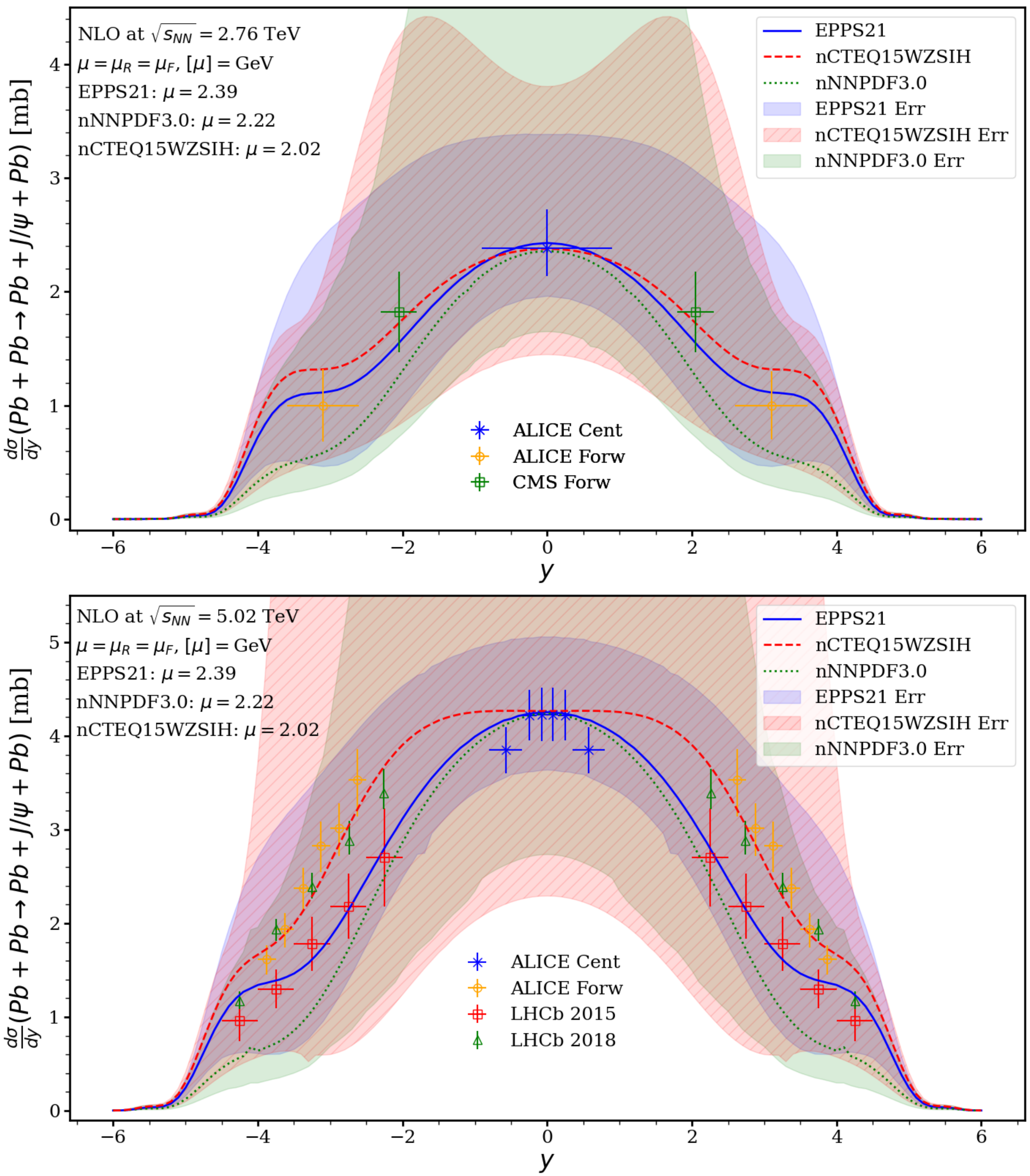
- Scale dependence of our NLO pQCD results for $m_c \leq \mu_F \leq M_{J/\psi}$ is very strong.

- One can find an "optimal scale" μ_F=2.39 GeV (EPPS21) giving simultaneously 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

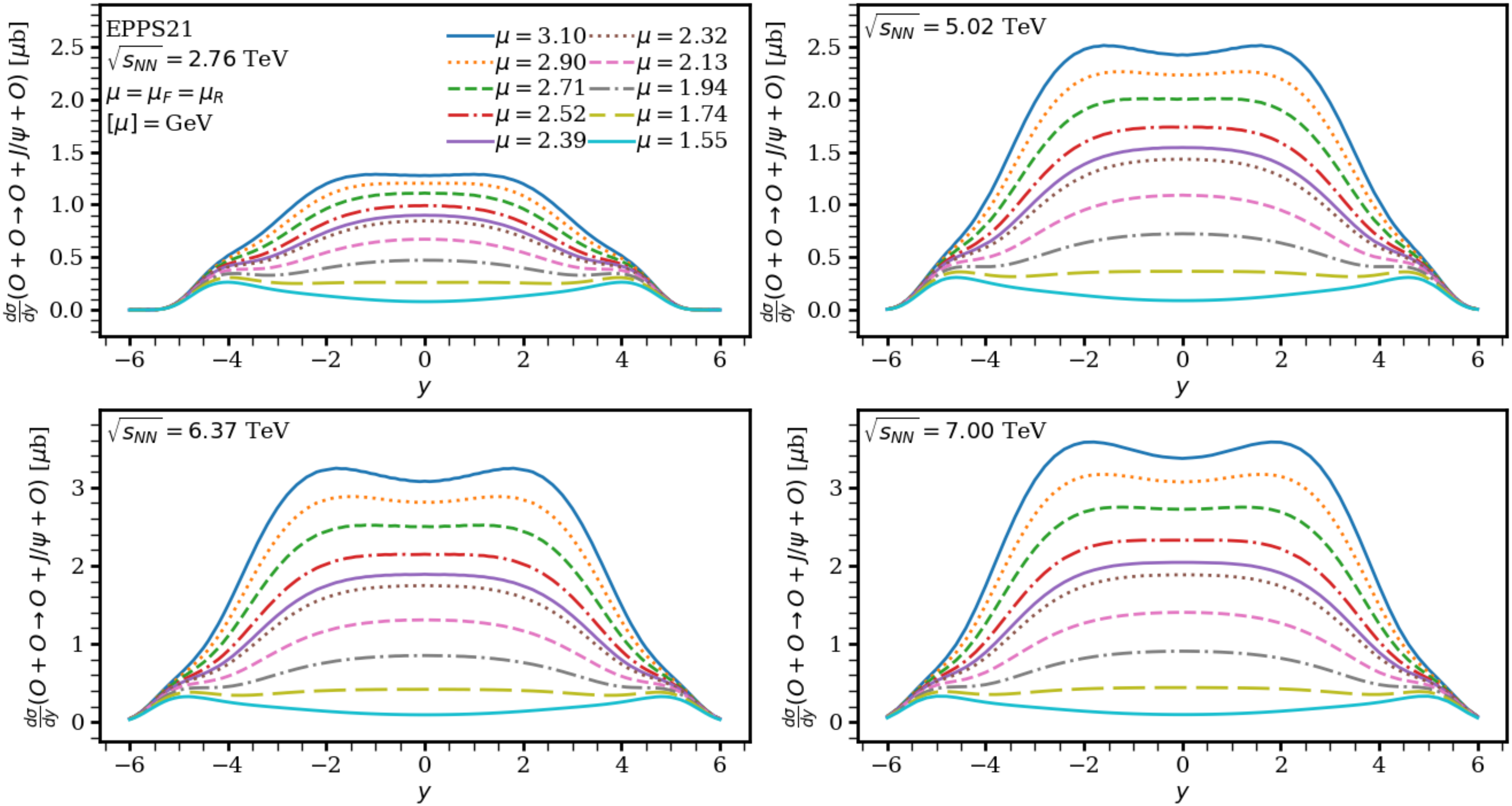


- Uncertainties due nPDFs are quite significant → opportunity to reduce them using the data on J/ψ photoproduction in AA UPCs.

- 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



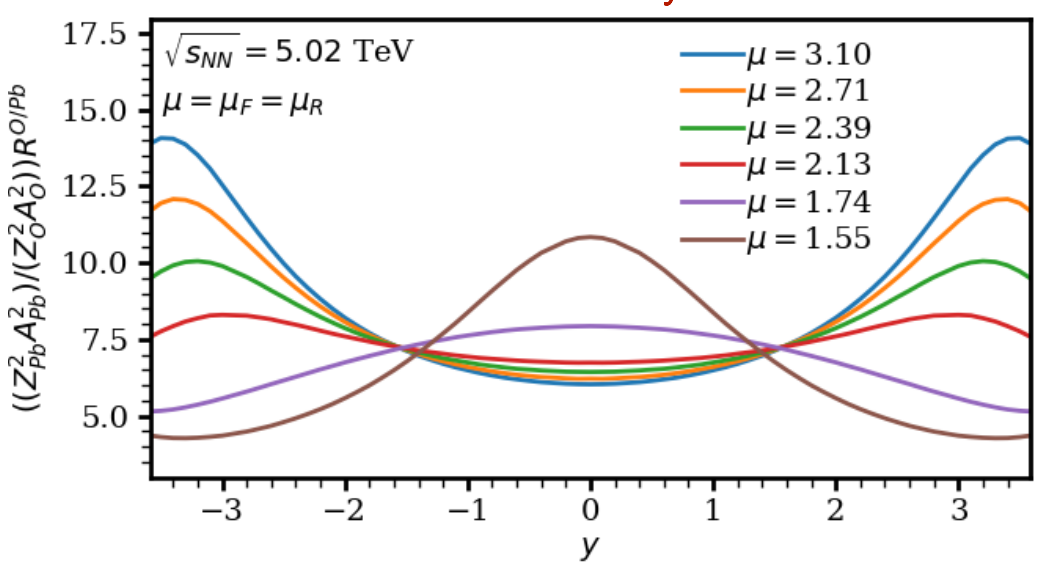
• NLO pQCD predictions for anticipated O-O run with 4 options for $\sqrt{s_{NN}}$ → similar trends as for Pb-Pb UPCs → large scale and nuclear PDF uncertainties.

Reduction of uncertainties using O/Pb ratio

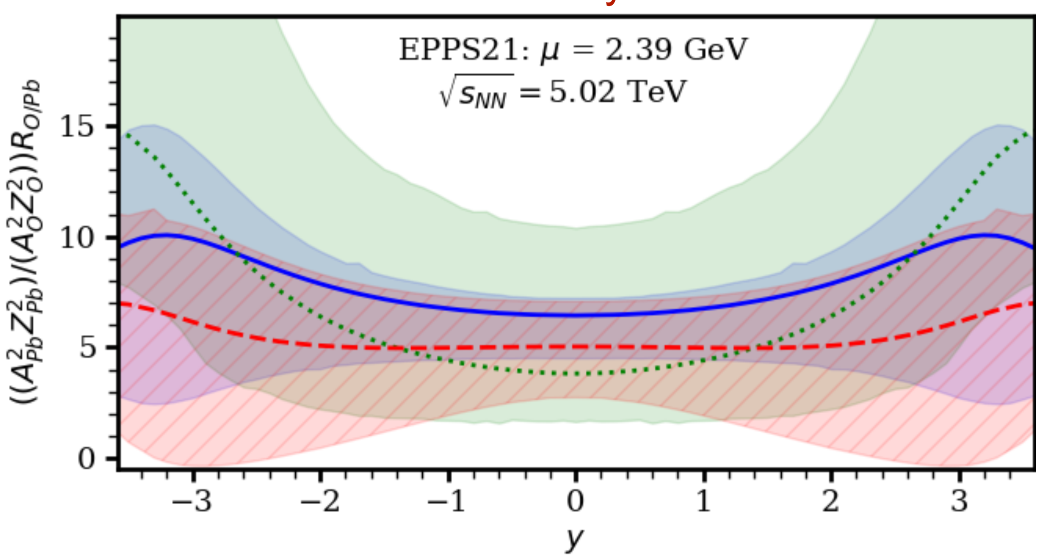
- One can reduce the significant scale μ_F and nPDF uncertainties by considering the ratio of oxygen to lead UPC cross sections:

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

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



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

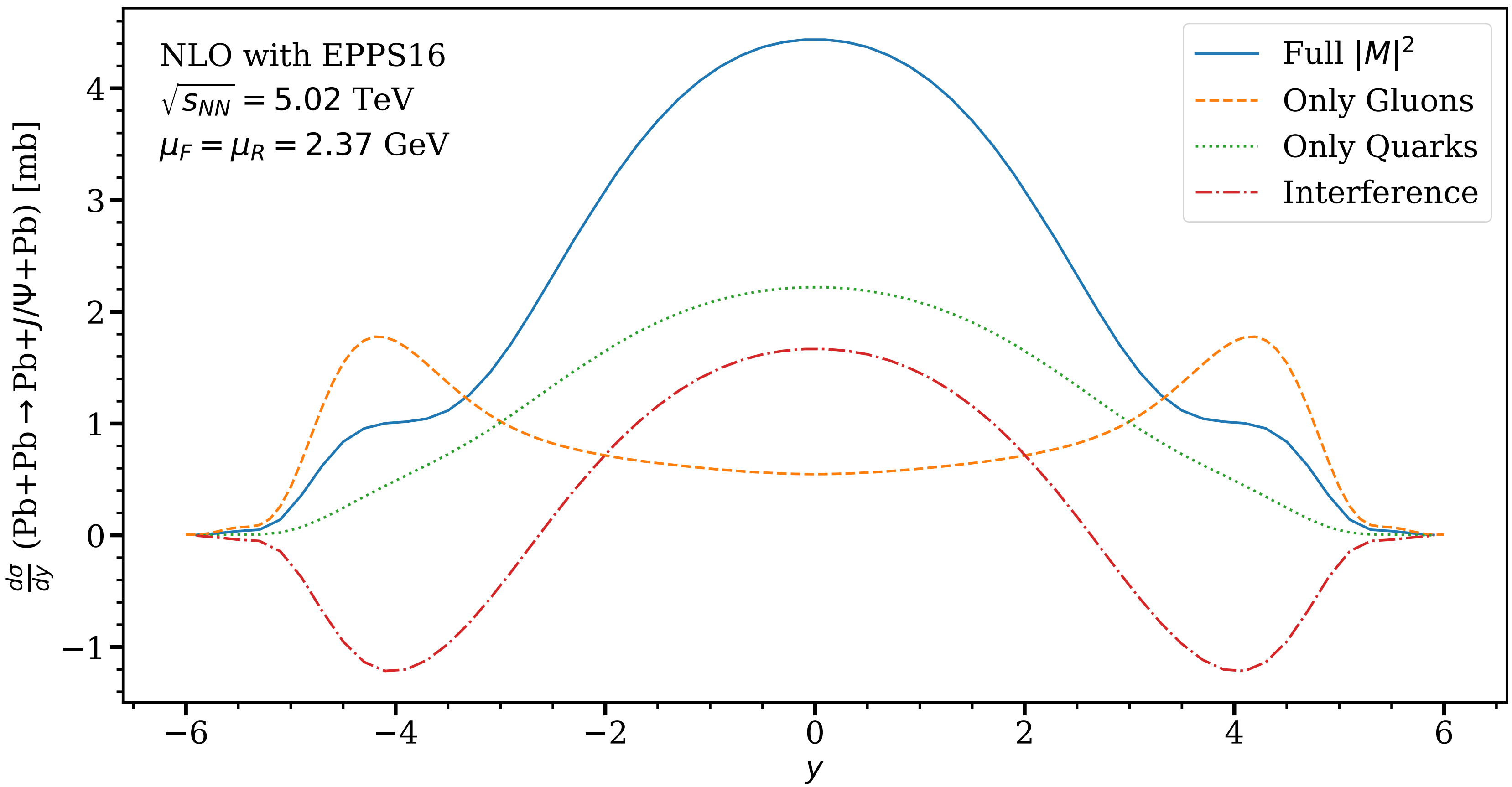


- Hard scattering coefficient functions for O and Pb are the same → differences come from O and Pb nPDFs → scale dependence reduced by factor of 10 compared to individual UPC cross sections.

- 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.

Open question 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 $2\xi \approx (M_{J/\psi})^2/W^2 \ll 1$

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

- Possible solution: resummation of $\alpha_S \ln(Q^2)\ln(1/\xi)$ terms by choosing $\mu_F=\mu_c$ and subtracting $k_T < Q_0 \sim m_C$ contribution from NLO coefficient functions (Q_0 subtraction), Jones, Martin, Ryskin, Teubner, EPJC 76 (2016) 11, 633; Flett, Jones, Martin, Ryskin, Teubner, PRD 101 (2020) 9, 094011 → leads to stable NLO predictions for the proton.

- However, this does not resum large $\alpha_S \ln(1/\xi)$ terms → one needs high energy (BFKL-type) resummation, Ivanov, arXiv:0712.31983 [hep-ph]; Ivanov, Pire, Szymanowki, Wagner, EPJ Web. Conf. 112 (2016) 01020

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

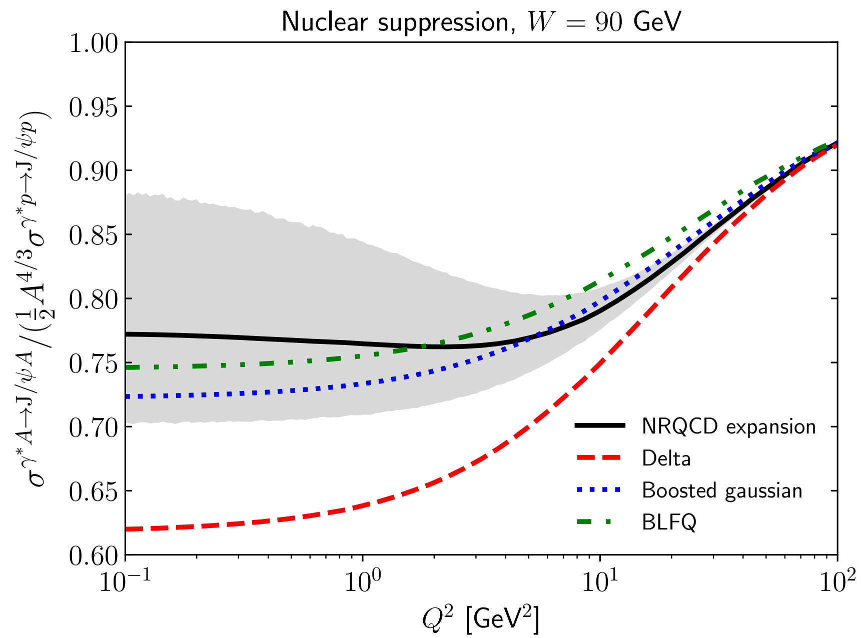
where $L = \ln(M_V^2/\mu_F^2)$

Open question 2: non-relativistic effects in charmonium wave function

• Our analysis assumes a static (non-relativistic) limit for J/ψ vertex → transition of J/ψ to c-cbar in terms of LO non-relativistic QCD matrix element.

• Standard lore: relativistic corrections are small, Hoodbhoy, PRD 56 (1997) 388

• Recent analyses have shown that relativistic v/m_C corrections are sizable, Eskobedo, Lappi, PRD 101 (2020) 3, 034030; Lappi, Mantysaari, Penttala, PRD 102 (2020) 5, 054020 → wave function dependence does not cancel in nucleus/proton ratio → affects 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

• Consistent description in pQCD requires J/ψ light-cone distribution amplitude → no smooth connection to NR wf, Brodsky, Frankfurt, Gunion, Mueller, Strikman, PRD 50 (1994) 3134

Open question 3: pre-asymptotic effects

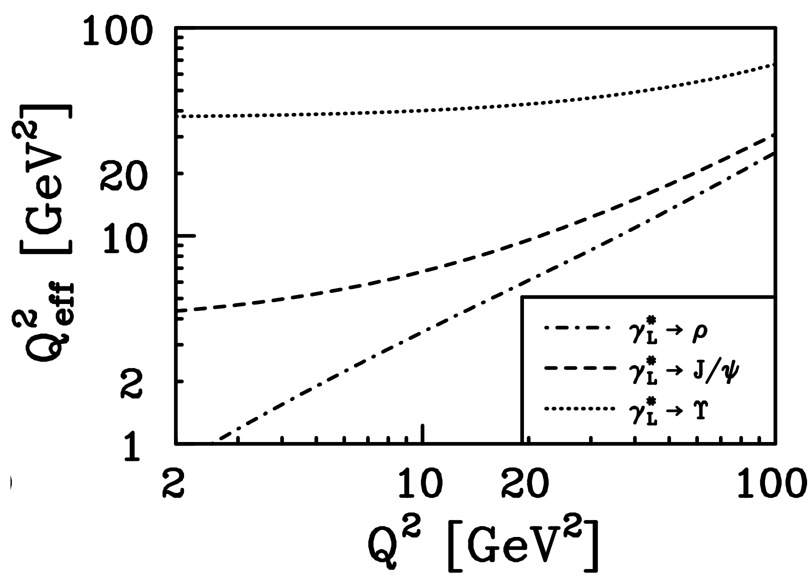
- Charm quark mass m_c does not provide sufficiently high scale → asymptotic pQCD expressions receive large corrections, Frankfurt, Koepf, Strikman, PRD 57 (1998) 512

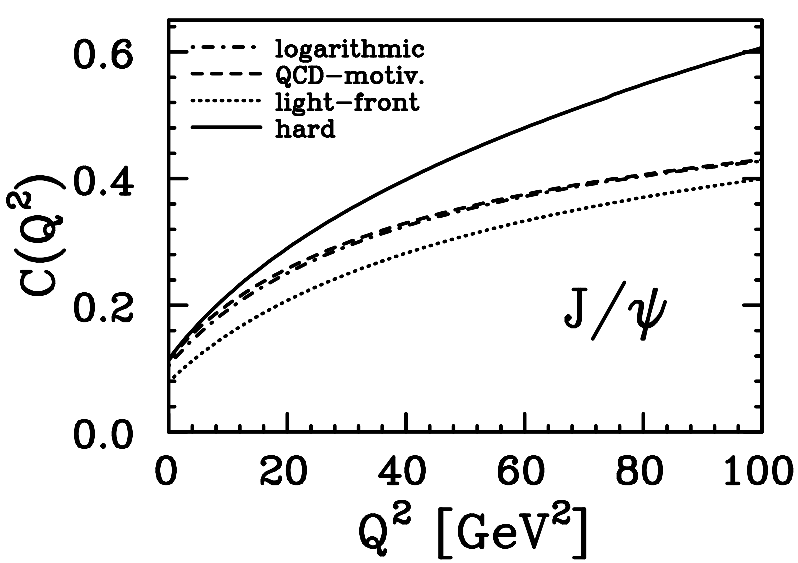
- Can be quantified by factor $C(Q^2)$ taking into account quark motion in J/ψ

$$\mathcal{C}(0) \propto \left[\frac{\int \frac{dz}{z^2(1-z)^2} \int d^2k_t \; \phi_V(z,k_t) \; \Delta_t \; \phi_\gamma(z,k_t)}{\int \frac{dz}{z(1-z)} \int d^2k_t \; \phi_V(z,k_t)} \right]^2$$

- Cross section: $$\left.\frac{d\sigma_{\gamma^{(*)}N\to VN}}{dt}\right|_{t=0} = \frac{12\pi^3\Gamma_V M_V^3}{\alpha_{EM}(Q^2+4m^2)^4} \left|\alpha_s(Q^2_{eff})\,(1+i\beta)\,xG_N(x,Q^2_{eff})\right|^2 \left(1+\epsilon\frac{Q^2}{M_V^2}\right) \mathcal{C}(Q^2)$$

- → leads to an increase of effective scale $Q_{eff}^2 > (Q^2+M_V^2)/4$ and significant suppression of the cross section → agrees with fixed-target and HERA data on J/ψ photoproduction on the proton (circa 1998).





Summary

• There is growing interest in using heavy-ion UPCs at the LHC to obtain new constraints on proton and nucleus PDFs.

• 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 by using in global QCD fits.

• In the present form, this is challenging and more work is required on small-x resummation, non-relativistic corrections, and pre-asymptotic effects.

• Probably the best way forward is to consider ratio of AA/pp UPC cross sections, where most of complications (scale dependence, uncertainties of nPDFs, details of GPD modeling, relativistic corrections) should partially cancel → our activity in Jyvaskyla.

Studies of hadron structure in QCD using UPCs@LHC is a precursor of an EIC, which would provide high precision, variation of Q^2 and a range of target nuclei.