Hard Probes 2023, Aschaffenburg, 28.3.2023

Exclusive quarkonium photoproduction in A+A UPCs at the LHC in NLO pQCD

Kari J. Eskola

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

In collaboration with **Chris Flett, Vadim Guzey, Topi Löytäinen, Hannu Paukkunen**

Results from: Phys.Rev.C 106 (2022) 035202; 2210.16048 [hep-ph]; 2303.03007 [hep-ph]

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

AoF, CoE in Quark Matter
YoctoLHC

HELSINKI INSTITUTE OF PHYSICS

Magnus Ehrnroothin säätiö

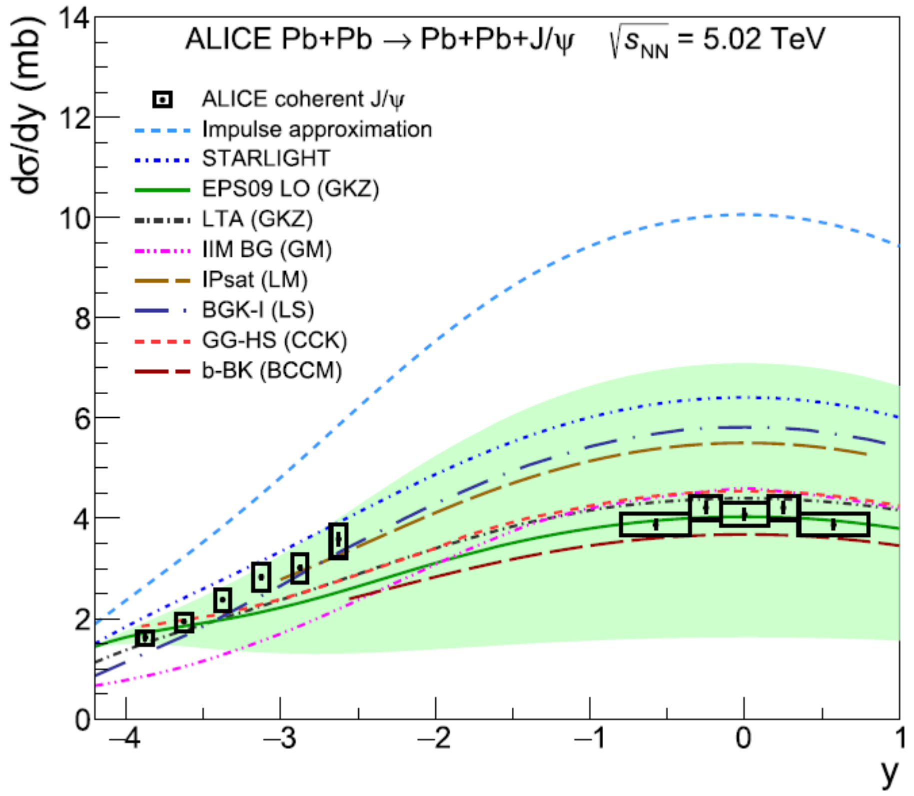
1. Motivation for NLO study

- Originally proposed by Ryskin [ZPC57(1993) 89] for $\gamma + \mathrm{p} \to J/\Psi + \mathrm{p}$ in **LO pQCD:**

$$\left(\frac{d\sigma^{\gamma^* p \to Vp}}{dt}\right)\Bigg|_{t=0} \propto \left(xg\left(x, Q^2\right)\right)^2$$

where $x = O(M^2/W^2)$ and $Q^2 = O(M^2)$

- Is exclusive coherent photoproduction of J/ψ & Υ in UPCs at the LHC, ***A+A → A+V+ A***, a good probe of collinearly factorized nuclear gluon PDFs **also in NLO?**
- Include this process as a constraint in global analyses of NLO nPDFs?
- Scale dependence, PDF-uncertainties, quark/gluon contributions, nuclear effects, real/imaginary parts of amplitude, **in NLO?**
- How does NLO match with the LHC UPC data?



ALICE, Eur. Phys. J. C 81, 712 (2021)

2. Theoretical framework

- y-differential cross section

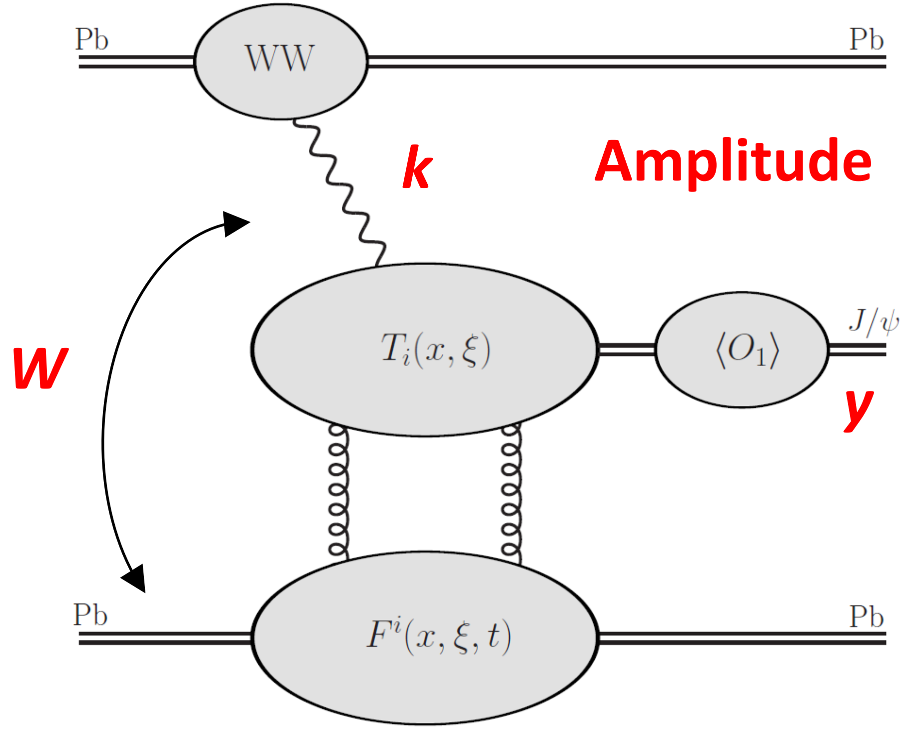
$$\frac{d\sigma^{A_1A_2\to A_1VA_2}}{dy} = \left[k\frac{dN_\gamma^{A_1}(k)}{dk}\sigma^{\gamma(k)A_2\to VA_2}\right]_{k=k^+} + \left[k\frac{dN_\gamma^{A_2}(k)}{dk}\sigma^{A_1\gamma(k)\to A_1V}\right]_{k=k^-}$$

- **WW photons** from both nuclei, energies $k^\pm \approx \frac{M_V e^{\pm y}}{2}$

- Cross section

$$\sigma^{\gamma A\to VA}(W) = \frac{d\sigma_A^{\gamma N\to VN}}{dt}\Big|_{t=0} \int_{t_{\min}=[M_V^2/(4k\gamma_L)]^2}^{\infty} dt' |F_A(-t')|^2$$

$$\frac{d\sigma_A^{\gamma N\to VN}}{dt} = \frac{\overline{|\mathcal{M}_A^{\gamma N\to VN}|^2}}{16\pi W^4}$$ at **t=0** from **pQCD+GPDs**



nuclear form factor $F_A(t) = \int d^3r \rho_A(r) e^{i\boldsymbol{q}\cdot\boldsymbol{r}}$ from WS-density $\rho_A(r) = \frac{\rho_0}{1+e^{\frac{r-R_A}{d}}}$

- **Photon flux**

  [Guzey&Zhalov JHEP 02 (2014) 046]

$$k\frac{dN_\gamma^A(k)}{dk} = \int d^2\vec{b} N_\gamma^A(k,\vec{b})\Gamma_{AA}(\vec{b})$$

number of equivalent WW photons of energy k at a transverse distance b from the center of a nucleus A with Z protons

$$N_\gamma^A(k,\vec{b}) = \frac{Z^2\alpha_{\text{QED}}}{\pi^2}\left|\int_0^\infty dk_\perp \frac{k_\perp^2 F(k_\perp^2 + k^2/\gamma_L^2)}{k_\perp^2 + k^2/\gamma_L^2} J_1(bk_\perp)\right|^2$$

require no hadronic activity

$$\Gamma_{AA}(\vec{b}) = \exp\left[-\sigma_{\text{NN}}(s)T_{AA}(\vec{b})\right]$$

$\sigma_{\text{NN}}(s)$: total pp cross section

$T_{AA}(\vec{b})$: standard nuclear overlap function

- **NLO amplitude [1]:** factorization at amplitude level [2]

GPDs, nonpert., depend on μ_F

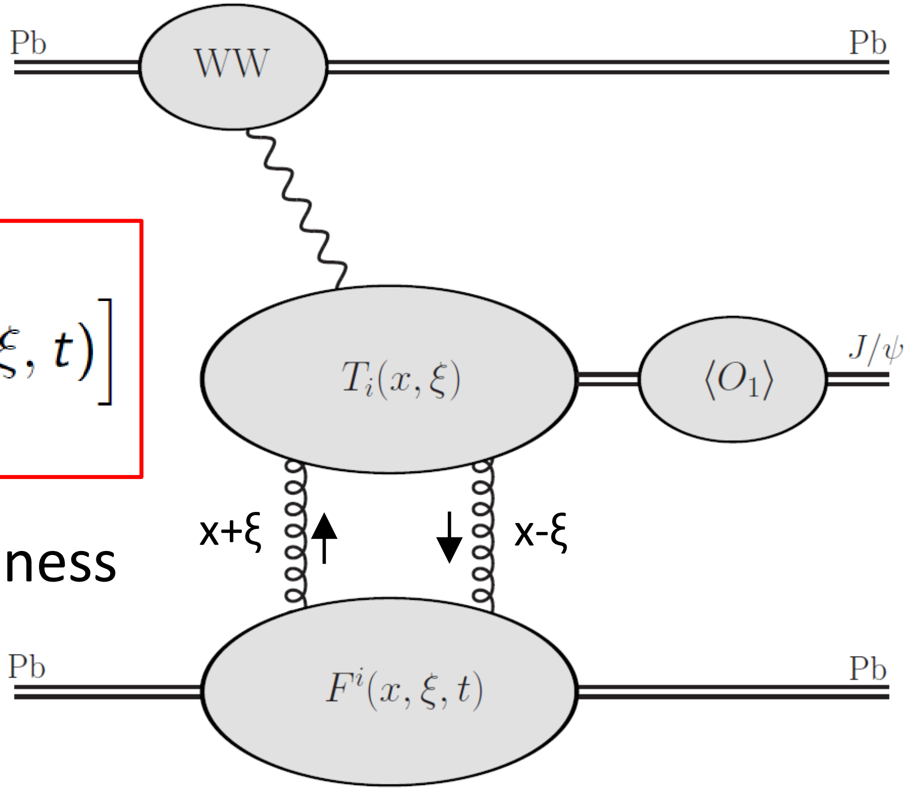
$$\mathcal{M}^{\gamma N} \propto \langle O_1 \rangle_V^{1/2} \int_{-1}^{1} dx \left[T_g(x,\xi) F^g(x,\xi,t) + T_q(x,\xi) F^{q,S}(x,\xi,t) \right]$$

Hard-scattering functions, from pQCD [1], depend on μ_F , μ_R

skewedness

NRQCD element, nonpert. obtained from

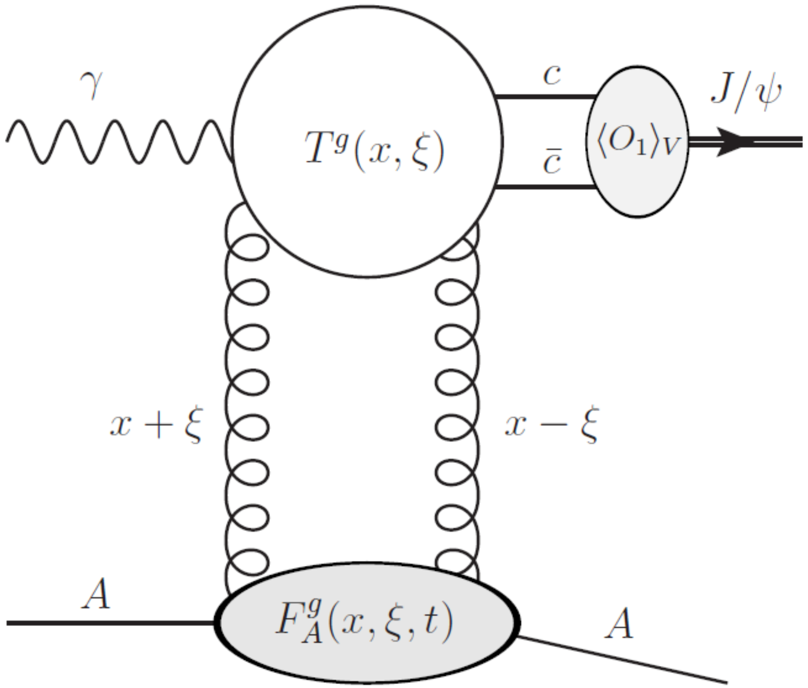
$$\Gamma(V \to l^+ l^-) = \frac{2 e_Q^2 \pi \alpha_{\rm QED}^2}{3} \frac{\langle O_1 \rangle_V}{m_Q^2} \left[1 - \frac{8 \alpha_s(\mu_R)}{3\pi} \right]^2$$

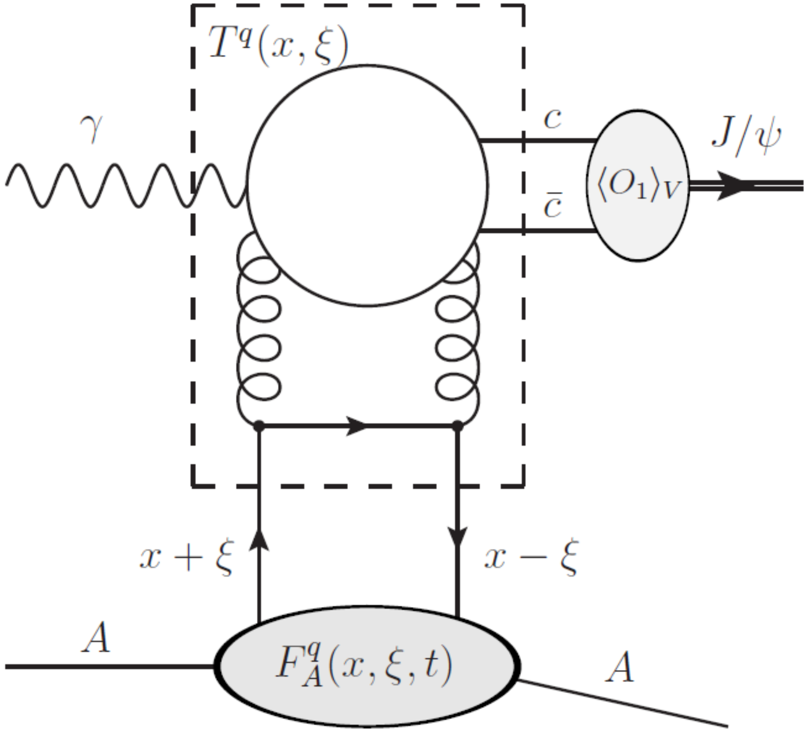


[1] D. Y. Ivanov, A. Schafer, L. Szymanowski, G. Krasnikov, Eur. Phys. J. C 34 (2004) no. 3, 297 [Erratum: Eur.Phys.J.C 75, 75 (2015)]
[2] J. C. Collins, L. Frankfurt and M. Strikman, Phys. Rev. D 56 (1997) 2982

LO: only gluon GPDs contribute, no quarks here

NLO: both gluon and quark GPDs contribute





- 6 graphs at LO
- At NLO, add one internal gluon anywhere
  → Many gluon graphs at NLO

- Full NLO calculation done in
  [Ivanov et al., Eur. Phys. J. C 34 (2004) no. 3, 297],
  → we apply these results

[Figs. from VadimG, 2303.12630 [hep-ph]]

- First, take GPDs at their forward limit (t=0, ξ=0), where they become PDFs (x>0 below)

$$F^g(x,0,0) = F^g(-x,0,0) = xg(x),$$
$$F^{q,S}(x,0,0) = u(x) + d(x) + s(x) + c(x)$$
$$F^{q,S}(-x,0,0) = -\bar{u}(x) - \bar{d}(x) - \bar{s}(x) - \bar{c}(x)$$

→ Entering the calculation of *M*: $\int_0^1 dx \left[2xg(x,\mu_F)T_g(x,\xi) + T_q(x,\xi)\sum_q \left[q(x,\mu_F) + \bar{q}(x,\mu_F)\right]\right]$

- Nuclear PDFs studied here: EPPS16/21, nCTEQ15/WZSIH, nNNPDF2.0/3.0

- Complex-valued T_g, T_q from [Ivanov et al, Eur. Phys. J. C 34 (2004) no. 3, 297]

$$T_g(x,\xi) = \frac{\xi}{(x-\xi+i\epsilon)(x+\xi-i\epsilon)}\left[\alpha_s(\mu_R) + \frac{\alpha_s^2(\mu_R)}{4\pi} f_g\left(\frac{x-\xi+i\epsilon}{2\xi}\right)\right]$$

LO **NLO**

$$T_q(x,\xi) = \frac{2\alpha_s^2(\mu_R)}{3\pi} f_q\left(\frac{x-\xi+i\epsilon}{2\xi}\right)$$ **NLO**

- We solve the complex integrals numerically, bringing ε → 0 in the end & check the numerics using another method [Flett:2021xsl]

3. Results for J/ψ

A. Scale sensitivity

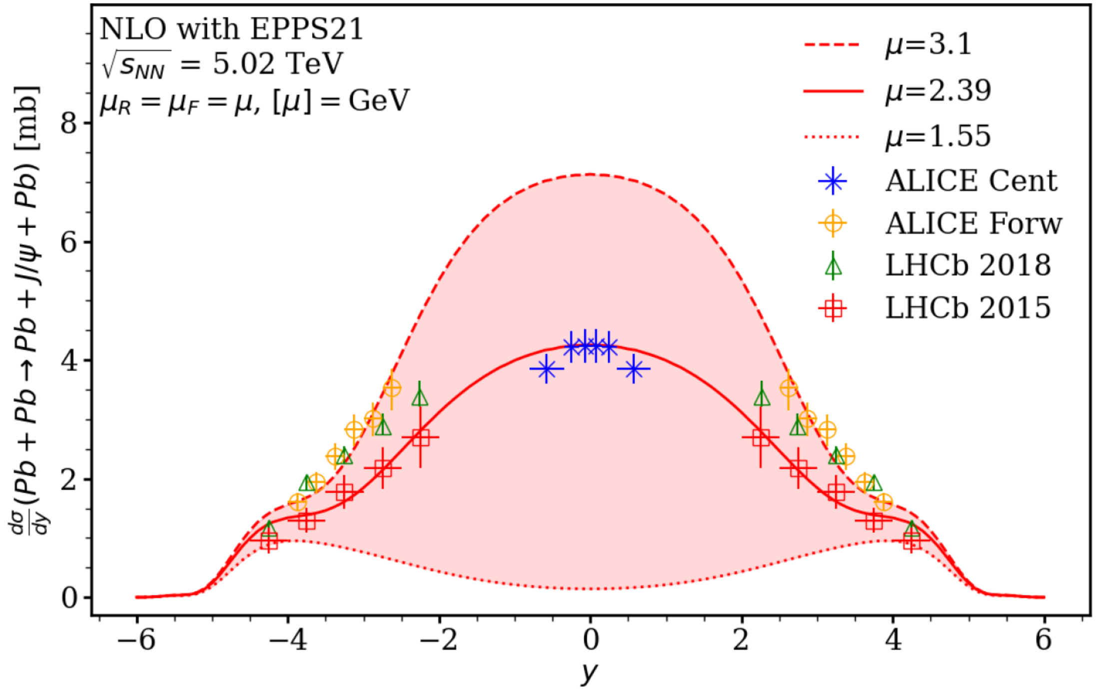
- Set $\mu_F = \mu_R = \mu$, vary μ from $M_{J/\psi}/2 = m_c$ to $M_{J/\psi} = 2m_c$

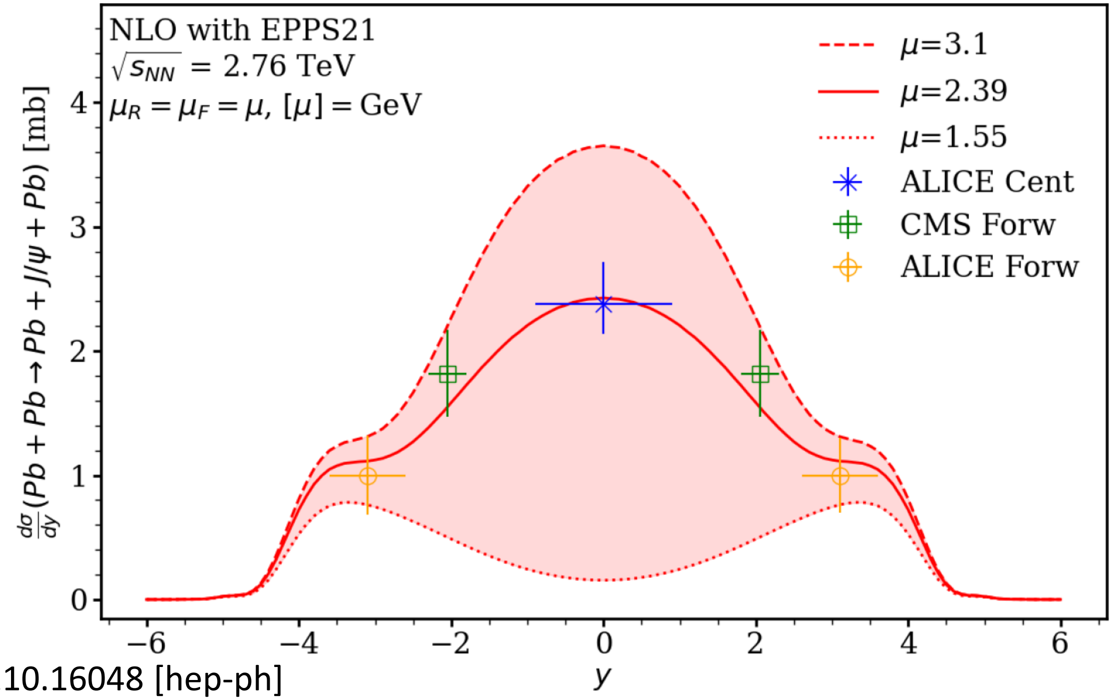
→ **Scale dependence considerable**

- **"Optimal" scale $\mu = 0.77\, M_{J/\psi}$ can be found** which ~reproduces ALICE central, CMS and 2015 LHCb data

- Also at NLO difficult to reproduce simultaneously fwd&central data (2018 LHCb data closer to ALICE fwd)

→ Room for GPD effects (GPDs≠PDFs), NRQCD corrections, NNLO corrections

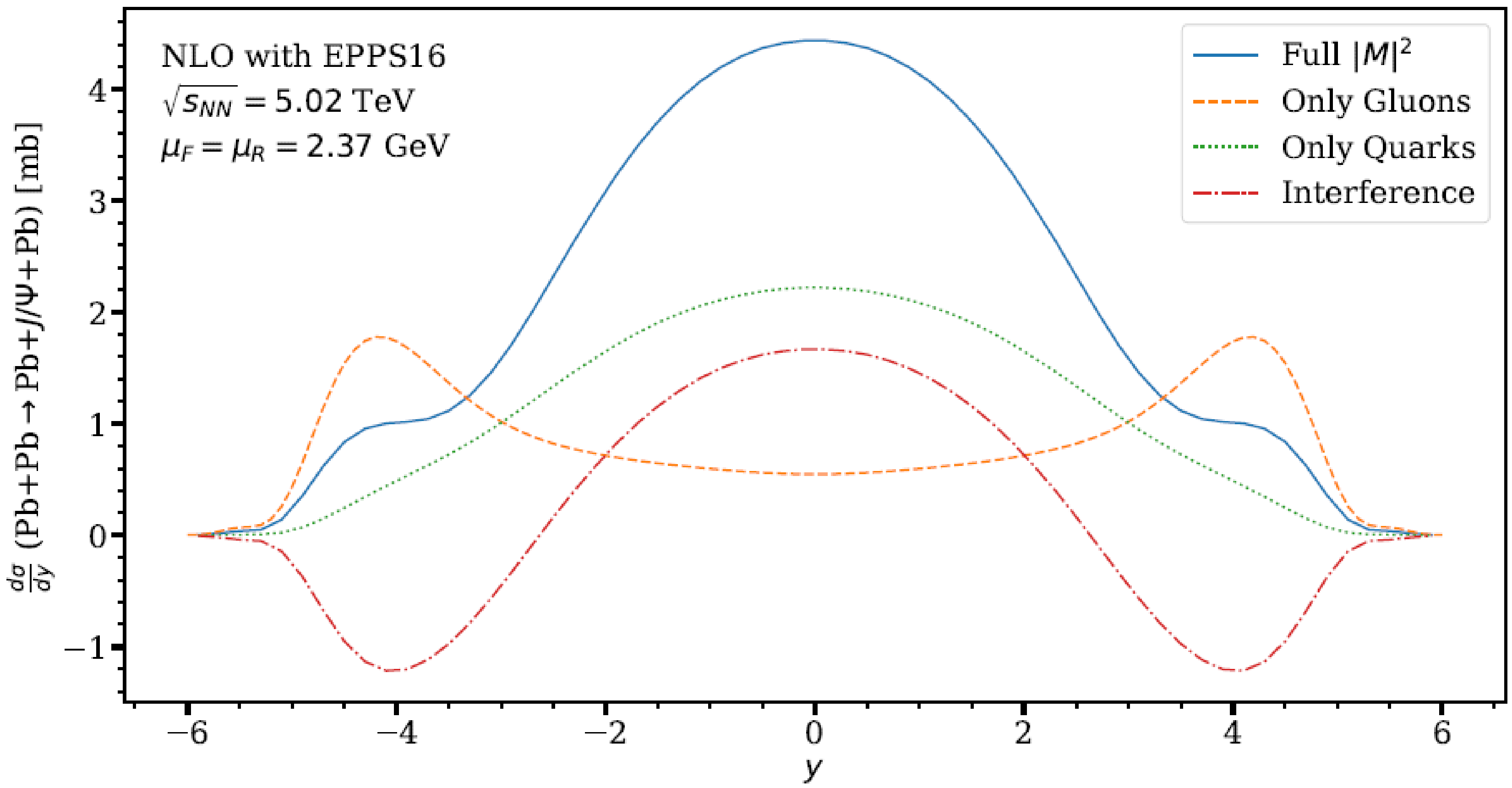




Phys.Rev.C 106 (2022) 035202, Figs. from 2210.16048 [hep-ph]

B. Surprise: Quarks important at NLO

Phys.Rev.C 106 (2022) 035202



$$\mathcal{M} = \mathcal{M}_G^{\mathrm{LO}} + \mathcal{M}_G^{\mathrm{NLO}} + \mathcal{M}_Q^{\mathrm{NLO}}$$

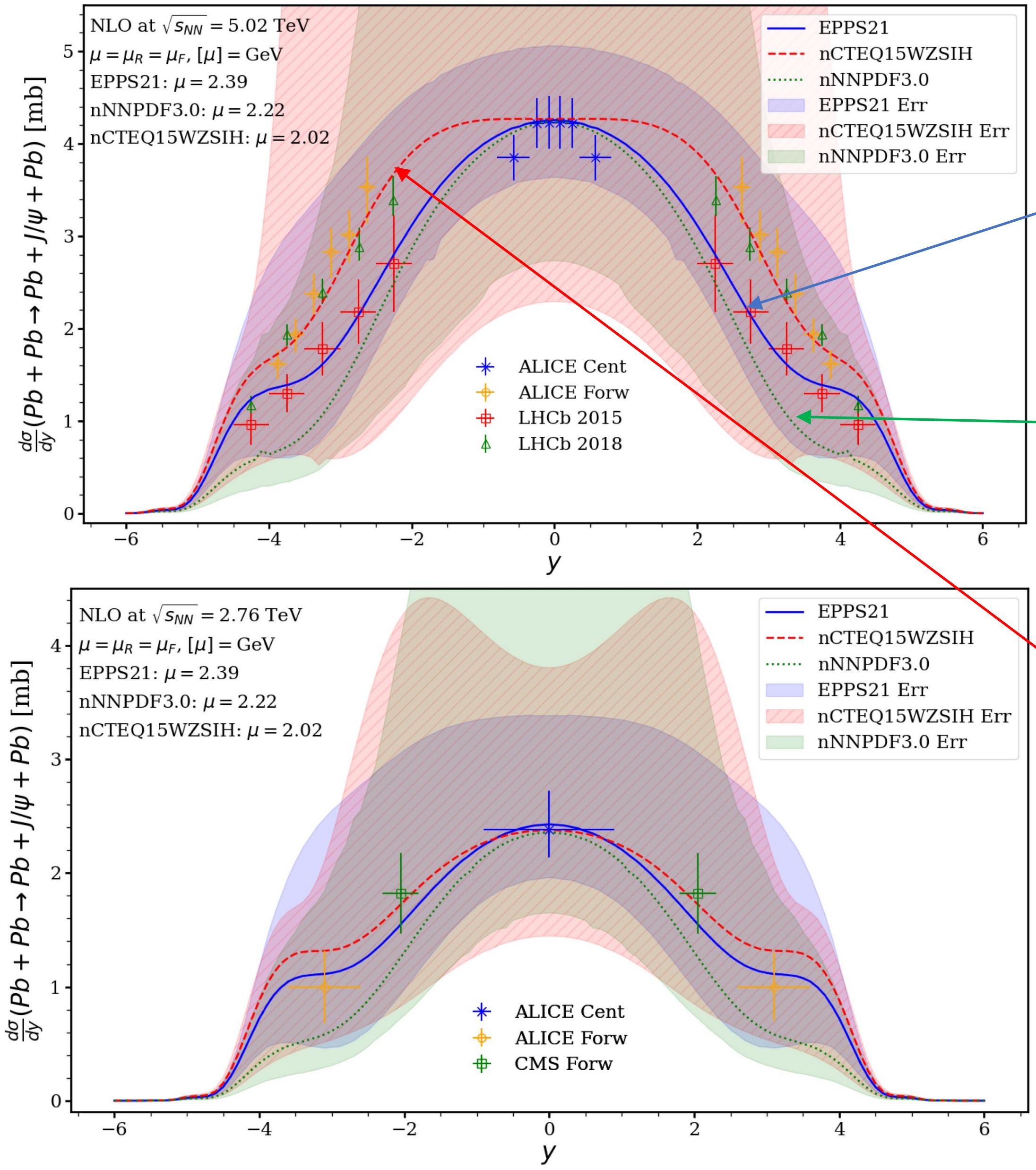
Only gluons — Only quarks

$$|\mathcal{M}|^2 = |\mathcal{M}_G^{\mathrm{LO}} + \mathcal{M}_G^{\mathrm{NLO}}|^2 + |\mathcal{M}_Q^{\mathrm{NLO}}|^2 + 2\Big[\mathrm{Re}(\mathcal{M}_G^{\mathrm{LO}} + \mathcal{M}_G^{\mathrm{NLO}})\mathrm{Re}(\mathcal{M}_Q^{\mathrm{NLO}}) + \mathrm{Im}(\mathcal{M}_G^{\mathrm{LO}} + \mathcal{M}_G^{\mathrm{NLO}})\mathrm{Im}(\mathcal{M}_Q^{\mathrm{NLO}})\Big].$$

Interference

- At NLO: at y = 0 **quarks(!)** dominate & at bkwd-/fwd-most y gluons dominate
- Very different from LO!
- The reason: LO and NLO gluon amplitudes tend to cancel
  → XSs reflect PDF shadowing in very nontrivial way – **not** $\sim(R_g(\xi))^2$ as in LO

C. Propagation of PDF uncertainties



2210.16048 [hep-ph]

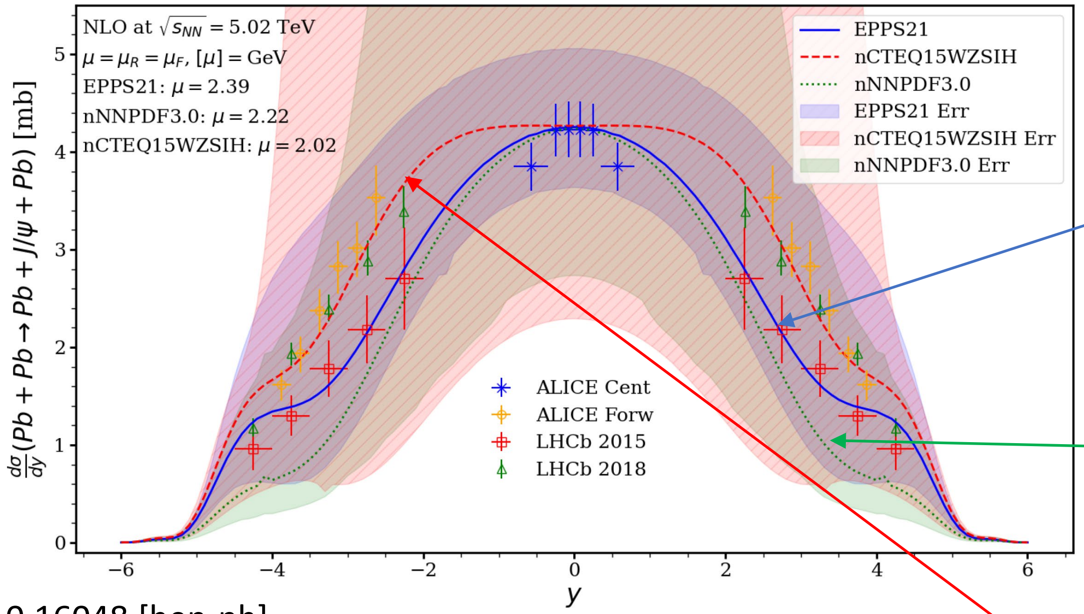
EPPS21: nuclear + CT18A uncertainties
- **all** PDF uncertainties are moderate;
- PDF uncertainties larger than data errors
- Consistent w. data within PDF uncertainties
- Tension: ALICE fwd and new LHCb data are above the EPPS21 central-set result

nNNPDF3.0: nuclear + free p uncertainties
- Consistent w. data, larger uncertainties
- Central-set result: narrower y-shape than in data

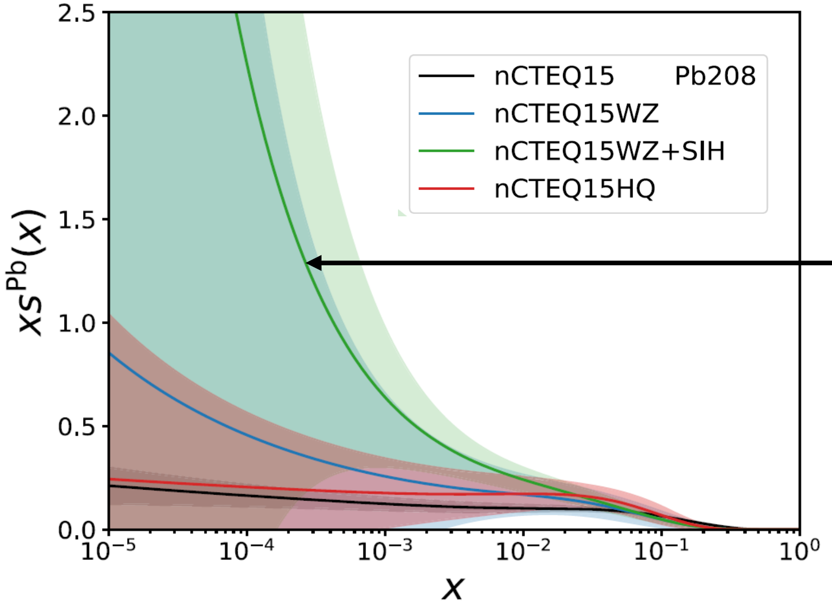
nCTEQ15WZSIH: only nuclear uncertainties
- Consistent w. data, larger uncertainties
- Enhanced s-quarks → Central-set result fits fwd data better → **s-quark probe!?**

EPPS21, Eur.Phys.J.C 82 (2022) 5, 413
nNNPDF3.0, Eur.Phys.J.C 82 (2022) 6, 507
nCTEQ15WZSIH, Phys.Rev.D 104 (2021) 094005

C. Propagation of PDF uncertainties



2210.16048 [hep-ph]



Duwentäster et al, Phys.Rev.D 105 (2022) 114043

EPPS21: nuclear + CT18A uncertainties

- **all** PDF uncertainties are moderate;
- PDF uncertainties larger than data errors
- Consistent w. data within PDF uncertainties
- Tension: ALICE fwd and new LHCb data are above the EPPS21 central-set result

nNNPDF3.0: nuclear + free p uncertainties

- Consistent w. data, larger uncertainties
- Central-set result: narrower y-shape than in data

nCTEQ15WZSIH: only nuclear uncertainties

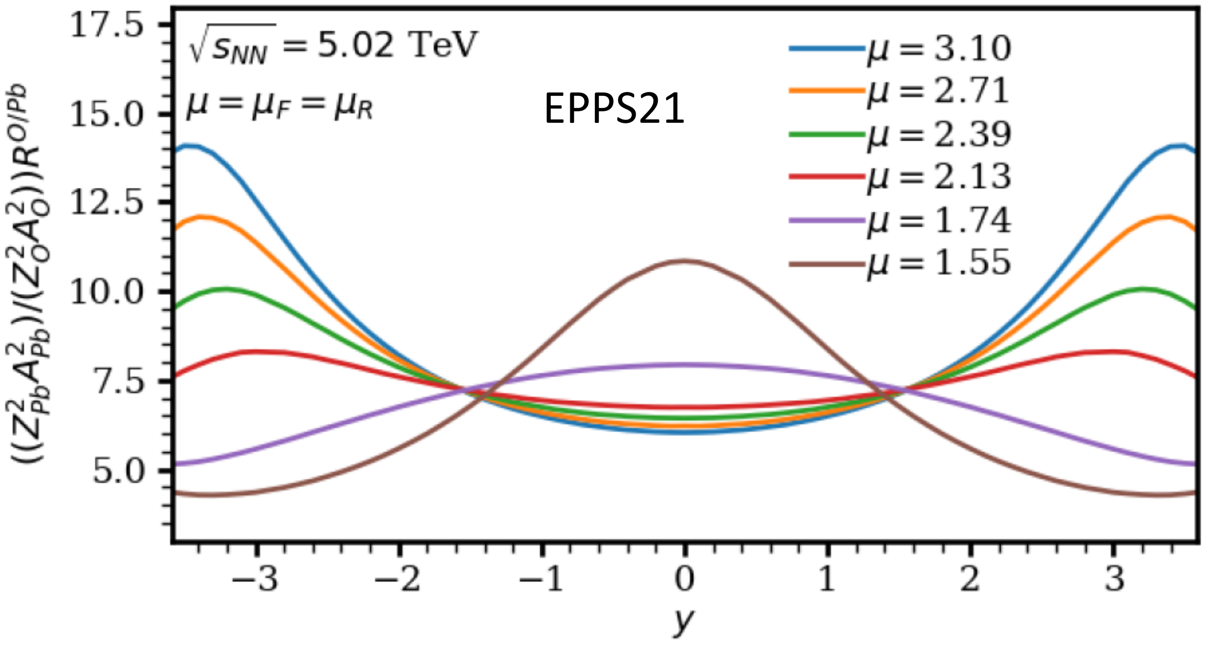
- Consistent w. data, larger uncertainties
- Enhanced s-quarks → Central-set result fits fwd data better → **s-quark probe!?**

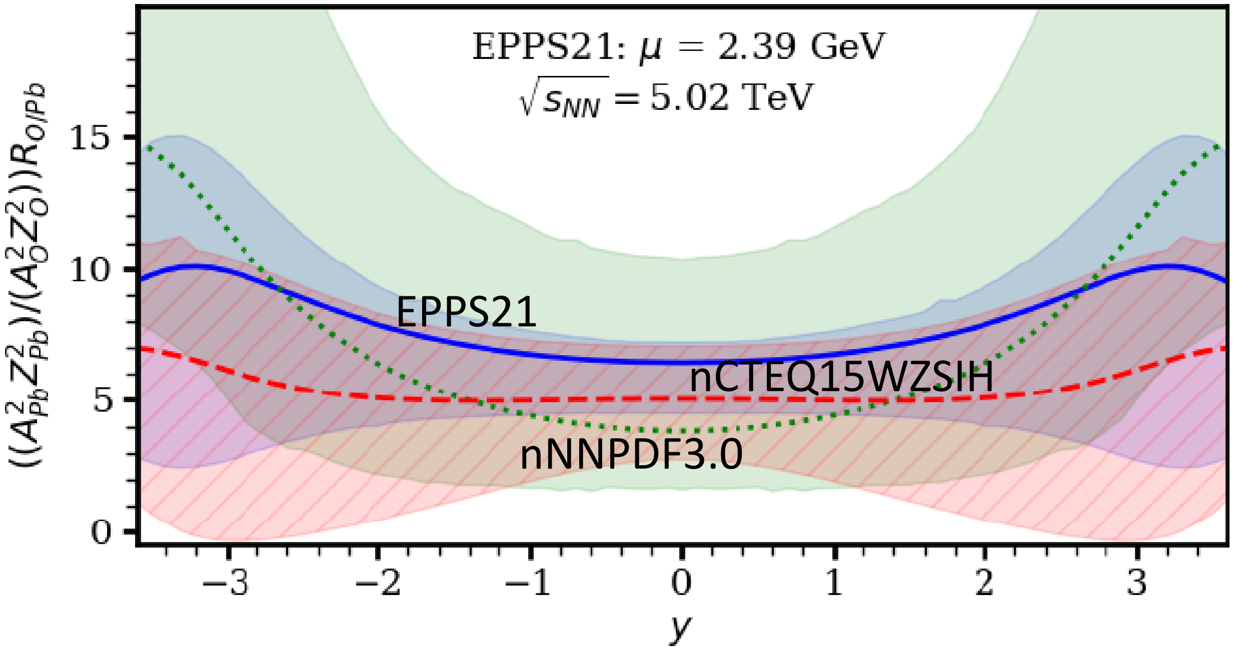
EPPS21, Eur.Phys.J.C 82 (2022) 5, 413
nNNPDF3.0, Eur.Phys.J.C 82 (2022) 6, 507
nCTEQ15WZSIH, Phys.Rev.D 104 (2021) 094005

D. Taming the scale dependence

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

2210.16048 [hep-ph]

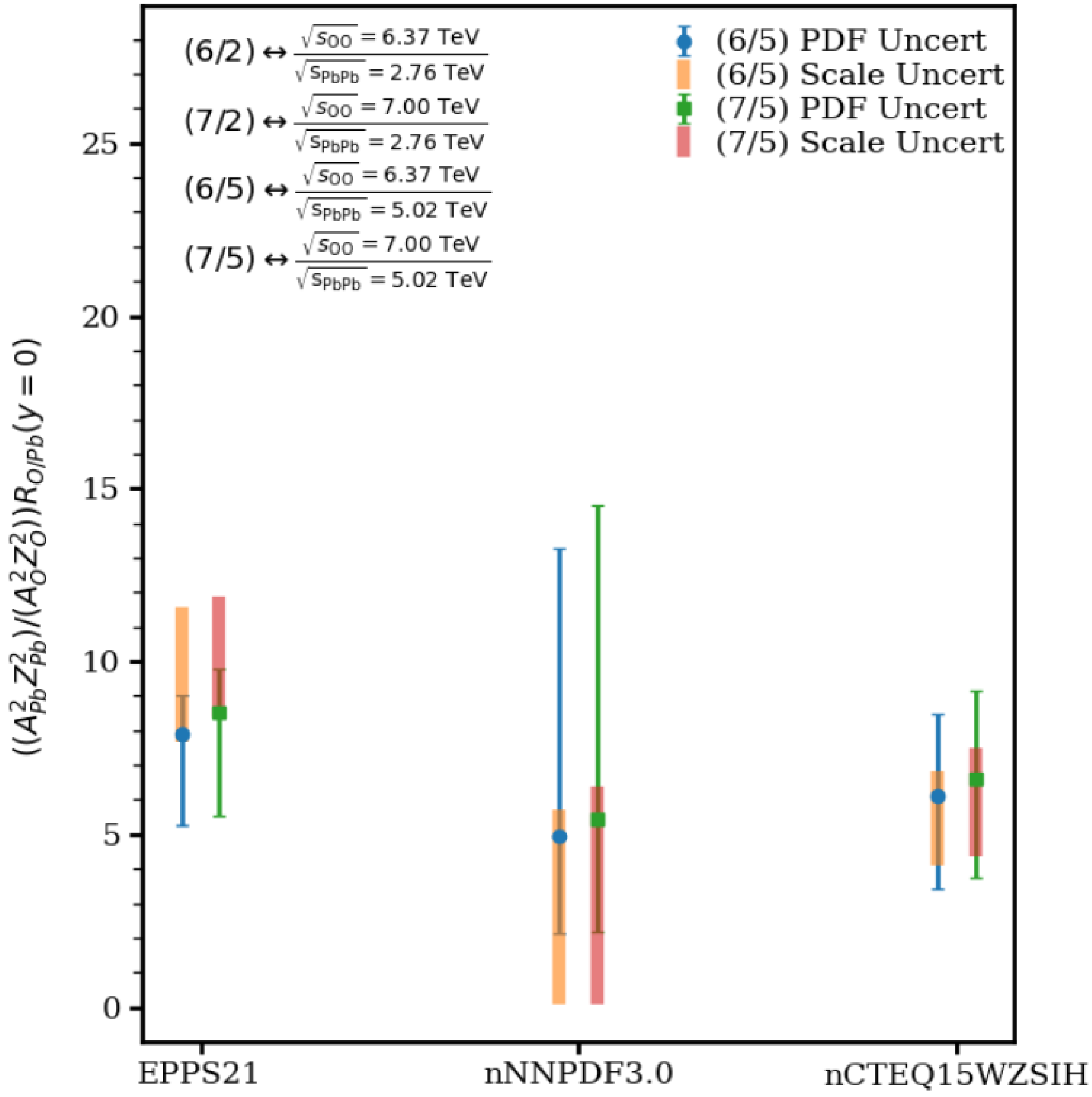




At y≈0, in the ratios, the scale dependence is considerably reduced…

… while these ratios remain conveniently sensitive to the nPDF uncertainties

2210.16048 [hep-ph]



Studied possible different-energy O+O/Pb+Pb ratios

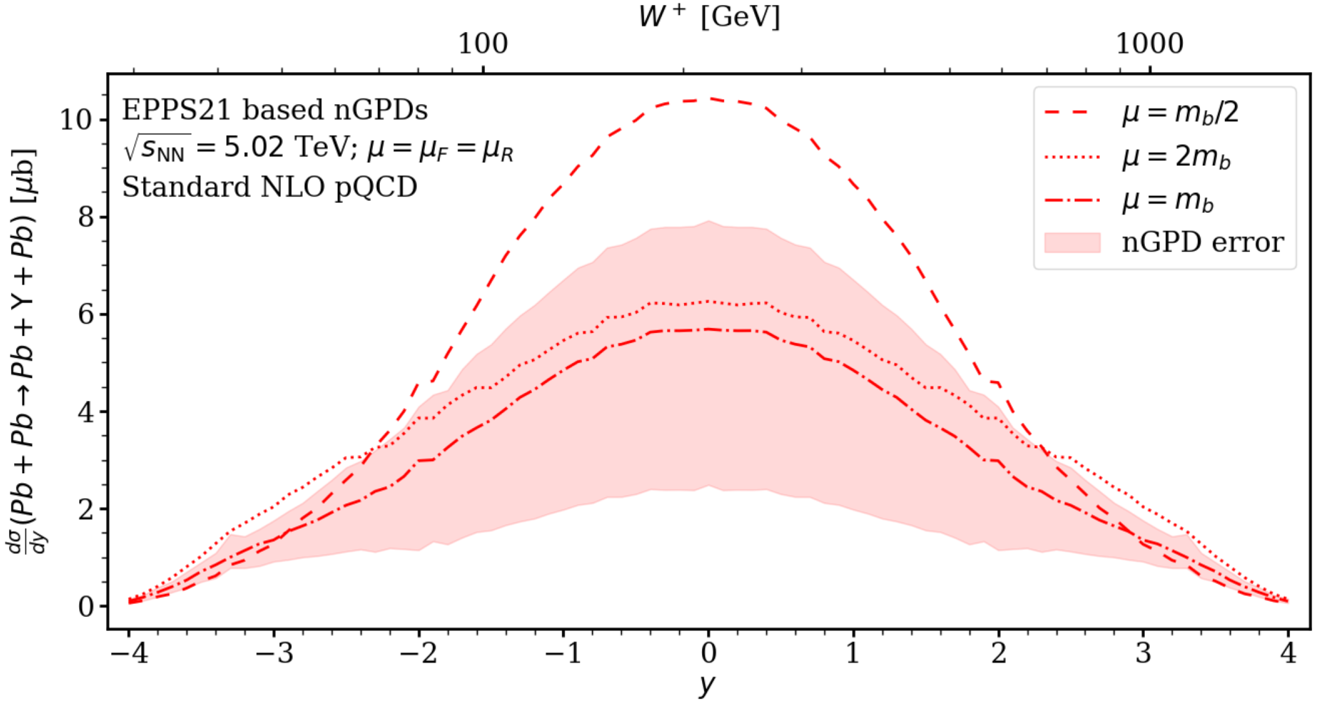
$$\left(\frac{208 Z_{\mathrm{Pb}}}{16 Z_{\mathrm{O}}}\right)^2 \frac{d\sigma(\mathrm{O}+\mathrm{O} \to \mathrm{O}+J/\psi+\mathrm{O})/dy}{d\sigma(\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb}+J/\psi+\mathrm{Pb})/dy}$$

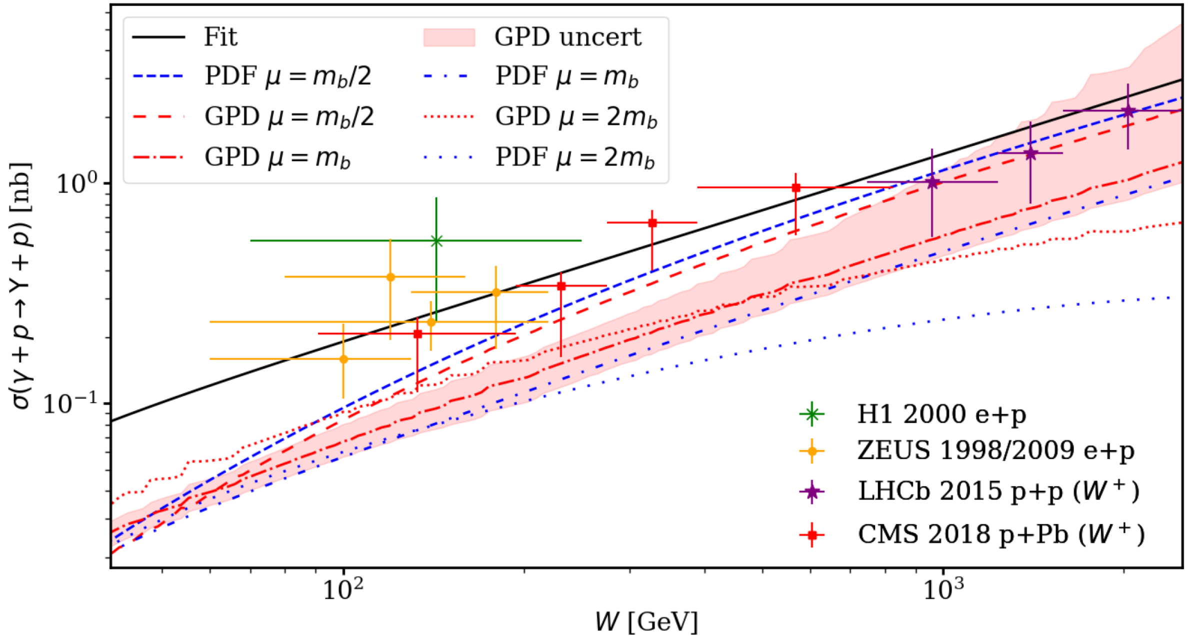
At y=0, scale uncertainty does not anymore dominate over the PDF uncertainty

→ improved quality as a nPDF constraint

4. Pb+Pb UPC Predictions for Upsilon

2303.03007 [hep-ph]





- Added nGPD modeling to our NLO pQCD framework: Shuvaev-transformed nPDFs

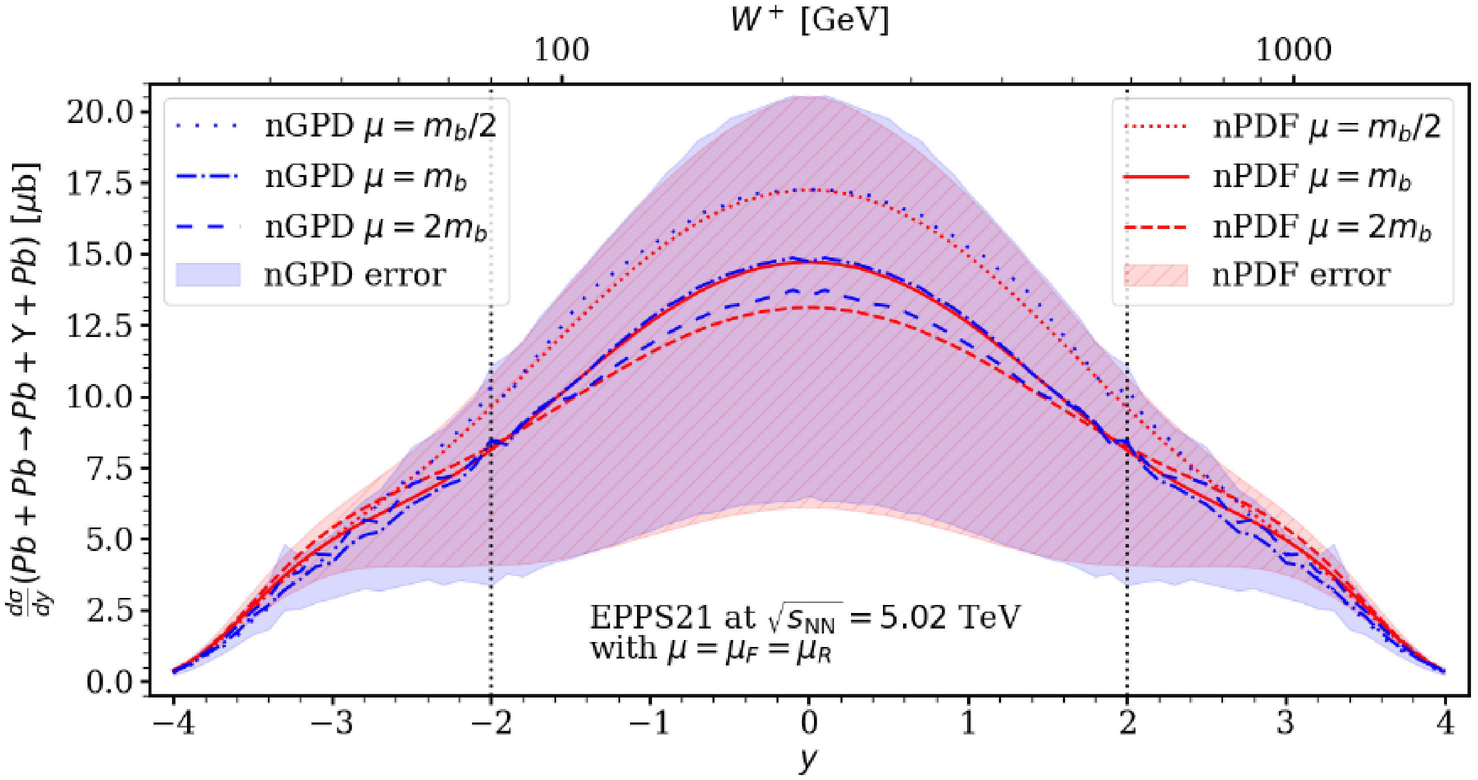
  [Flett et al, Phys.Rev.D 102 (2020) 114021, Phys.Rev.D 101 (2020) 9, 094011]

  → GPD effects in ϒ XSs are small
- Larger-scale process → weaker scale dependence
- Gluons dominate, unlike for J/ψ
- No A+A UPC data to guide us
  → exploit e+p/p+p/p+Pb results?

- NLO pQCD underpredicts HERA e+p/LHC data
  → NRQCD corrections? NNLO corrections?
- Make use of the data?
  → Data-driven method for $\sigma^{\gamma\text{Pb}\to\Upsilon\text{Pb}}(W)$
  - nuclear effects from the NLO calculation
  - overall normalization from HERA-data fit

$$\sigma^{\gamma\text{Pb}\to\Upsilon\text{Pb}}(W) = \left[\frac{\sigma^{\gamma\text{Pb}\to\Upsilon\text{Pb}}(W)}{\sigma^{\gamma p\to\Upsilon p}(W)}\right]_{\text{pQCD}} \sigma_{\text{fit}}^{\gamma p\to\Upsilon p}(W)$$

2303.03007 [hep-ph]

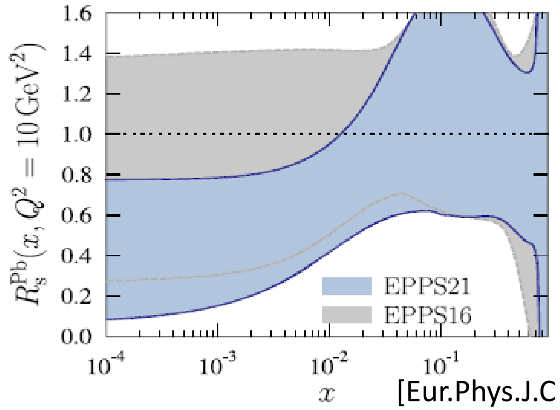


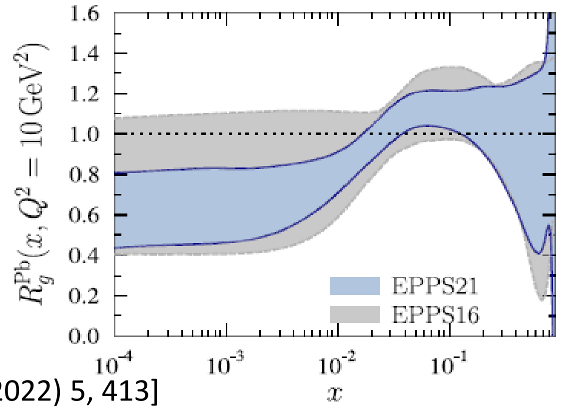
Data-driven prediction for exclusive photoroduction of ϒ in Pb+Pb UPCs:

- scale uncertainties tend to cancel in the pQCD ratio $\left[\frac{\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W)}{\sigma^{\gamma p \to \Upsilon p}(W)}\right]_{\mathrm{pQCD}}$
  → scale uncertainties become smaller than the PDF uncertainties
- GPD effects become negligible in the pQCD ratio
- Probe of gluon shadowing

5. Conclusions & Outlook

- First implementation of collinearly factorized NLO pQCD cross sections of coherent exclusive photoproduction of J/ψ and ϒ in A+A UPCs
- Scale dependence in NLO is considerable for J/ψ but an "optimal" scale can be found
  - reproduce the J/ψ Run1 & Run2 data at y=0, and within PDF uncertainties at all y
- Still tension between central-PDF-set NLO results and J/ψ UPC LHC data at fwd/bkwd y
  - room for NRQCD corrections, NNLO corrections, more detailed GPD modeling,...
- LO and NLO gluon amplitudes for J/ψ tend to cancel
  - at y = 0 quarks(!) dominate — different from LO!
  - J/ψ process may turn out to be a probe of s-quark (!) PDFs
    = currently the worst known piece in global nPDF fits
  - what happens in NNLO??

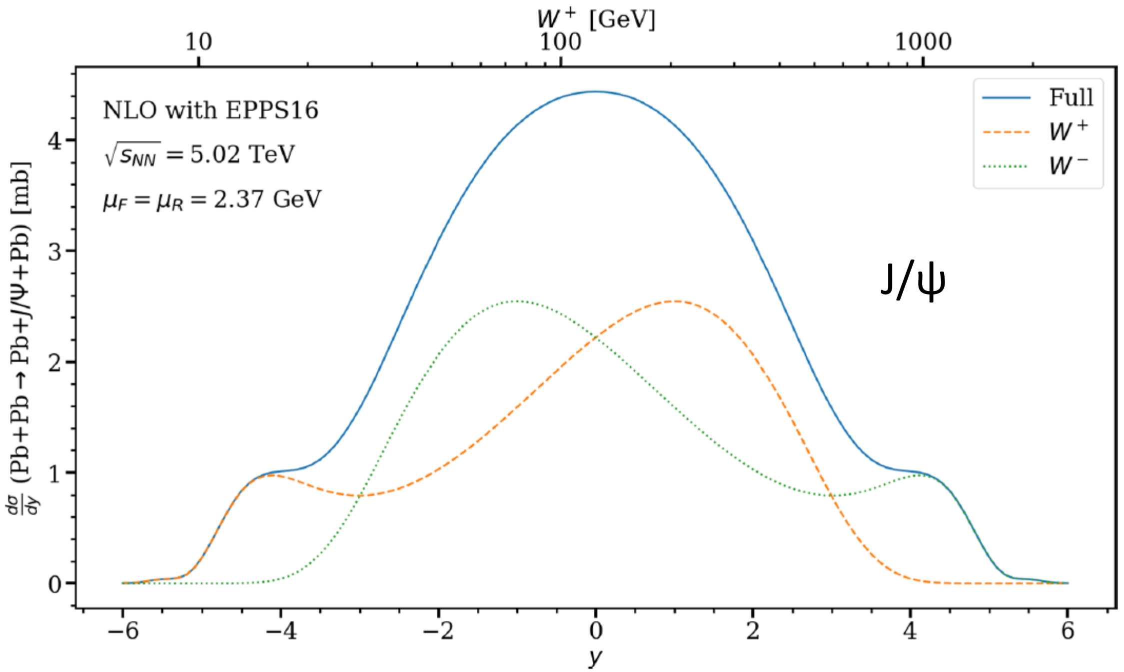




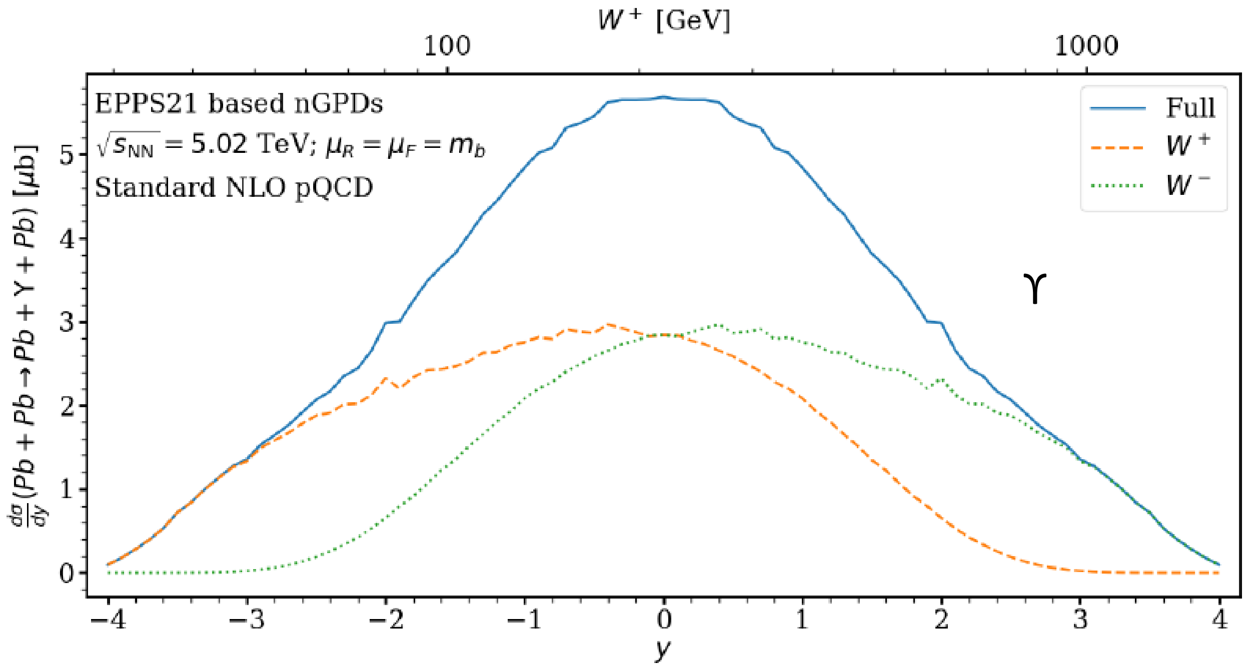
[Eur.Phys.J.C 82 (2022) 5, 413]

- Nuclear + free-proton PDF uncertainties now start to be moderate (EPPS21)
  - free-proton uncertainties must be accounted for in absolute cross sections
  - PDF/GPD uncertainties for J/ψ larger than Pb+Pb UPC data errors
    → Constraining power from data
- Reduce the large scale-dependence with nuclear ratios, e.g. O+O/Pb+Pb for J/ψ?
  → seems possible, at least at y=0 !
- Made NLO pQCD predictions for exclusive photoproduction of ϒ
  in Pb+Pb UPCs at the LHC, using also HERA data:
  - reduced scale dependence relative to the J/ψ case
  - GPD effects via Shuvaev transform turned out to be small
  - gluons dominate → ϒ more direct probe of gluon shadowing than J/ψ

Extra slides



Phys.Rev.C 106 (2022) 035202

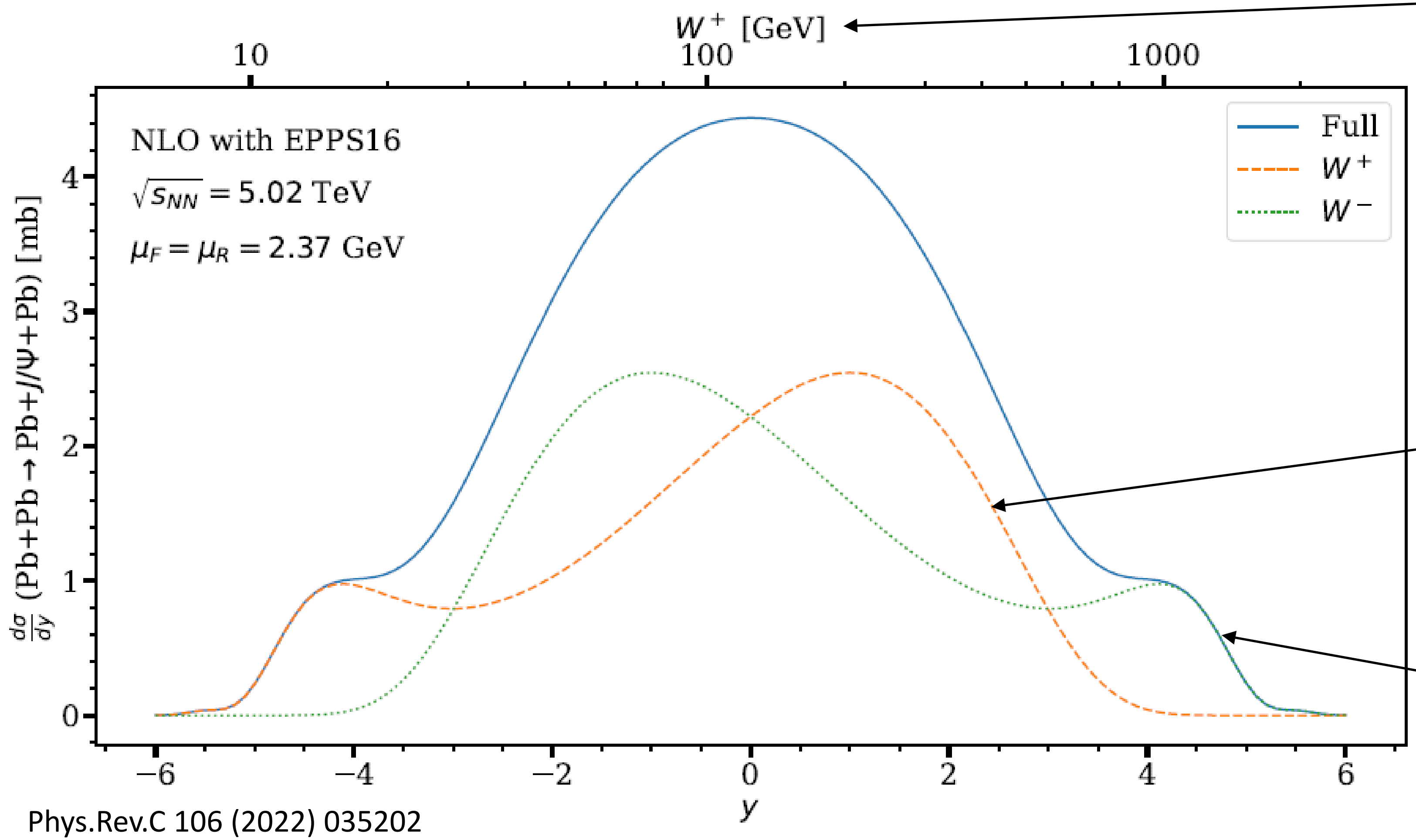


2303.03007 [hep-ph]

The two photon components contributing to coherent exclusive photoproduction XSs of J/ψ and ϒ in Pb+Pb UPCs at the LHC

Symmetric W^+ and W^- contributions in Pb+Pb UPCs

Photon energy $k^{\pm} \approx \frac{M_V e^{\pm y}}{2}$



Phys.Rev.C 106 (2022) 035202

- W^+ (k^+) grows to the right, W^- (k^-) grows to the left
- $(W^{\pm})^2 = M \sqrt{s_{NN}}\, e^{\pm y}$, probed x decreases with incr. $W^{\pm}$: $x \sim \xi \approx M^2/(2(W^{\pm})^2) = Me^{-(\pm y)}/(2\sqrt{s_{NN}})$

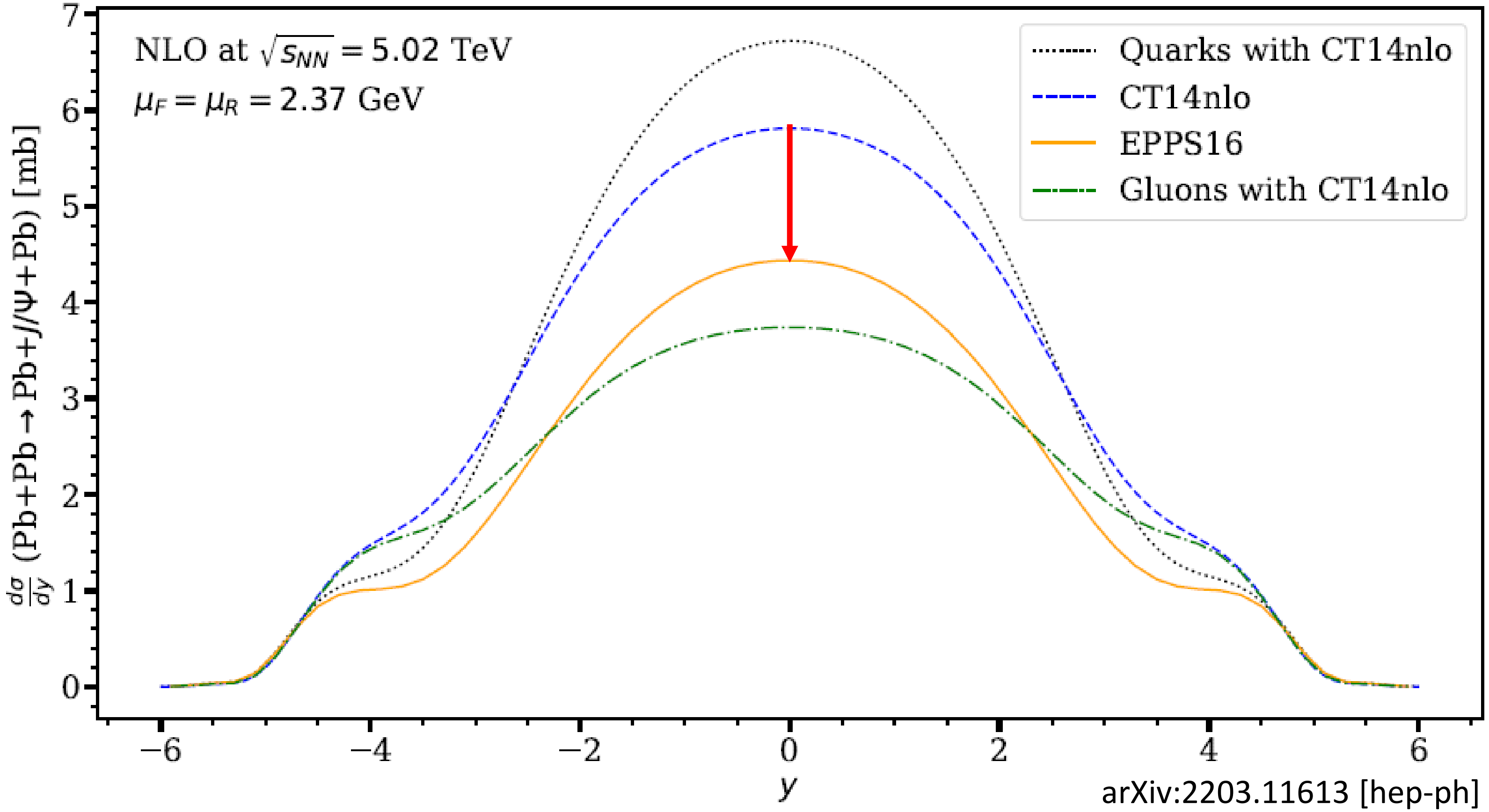
With increasing W^+ :

- photon-Pb XS increases
- photon flux decreases fast

- Smallest $W^{\pm}$s: Form factor t-integral runs out of PS

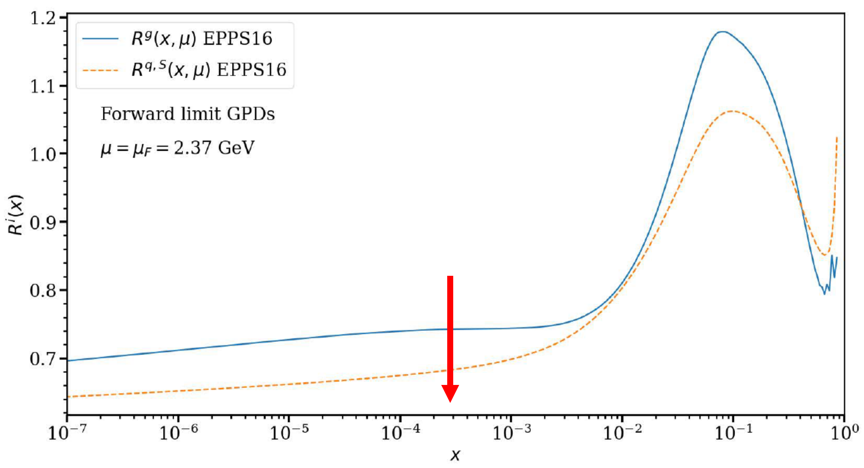
- Interplay of $W^{\pm}$ components, QCD cross section, photon flux and form-factor integral

Q&G shadowing in the cross section – a further surprise



arXiv:2203.11613 [hep-ph]

EPPS16 nuclear effects

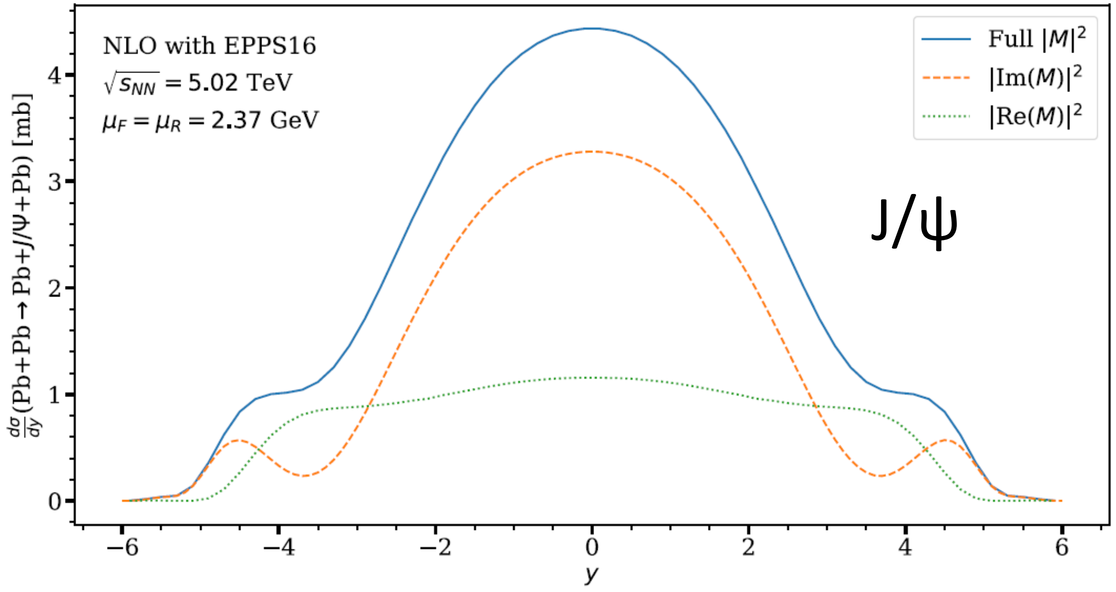


$R_{q,g}(x) \sim 0.7$ (shadowing)

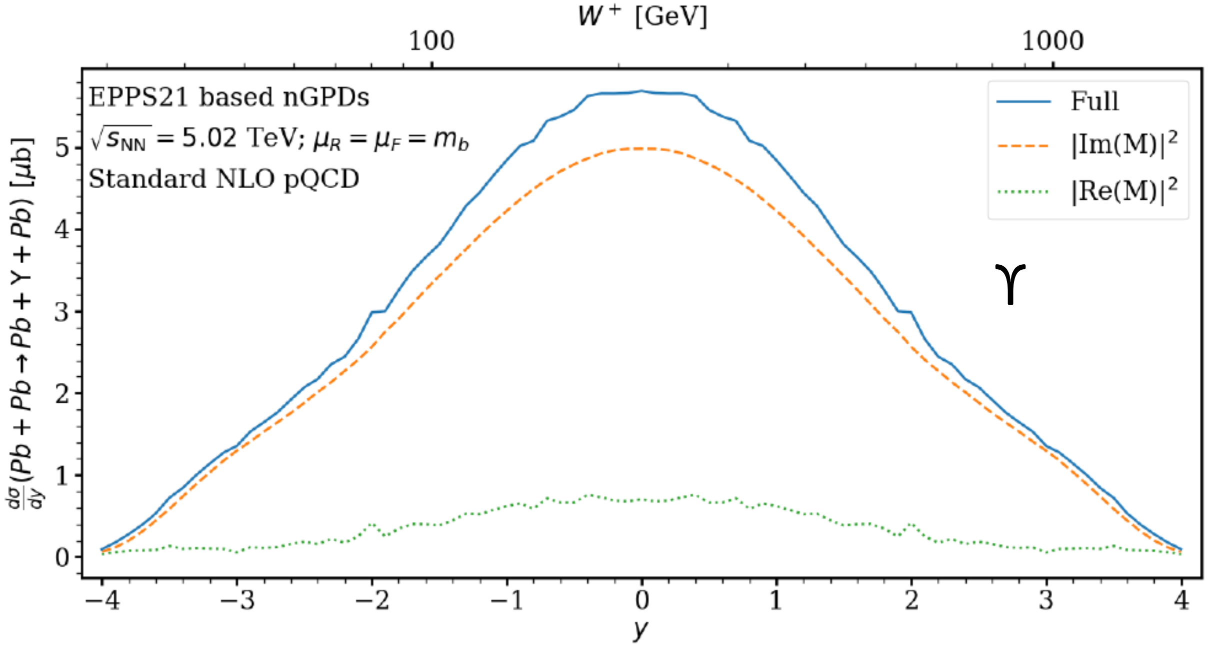
→ expect the XS at y=0 to be reduced by a factor $(R_{q,g}(x))^2 \sim 0.7^2 \sim$ 0.5

Reduction from CT14NLO (no nuclear effects) to EPPS16 (w. nuclear effects) XS is only a factor ~0.76 — **Why?**

- integration over x in M weakens the dependence on nuclear effects somewhat but the main reason is again the degree of cancellation of M_G^{LO} and M_G^{NLO}



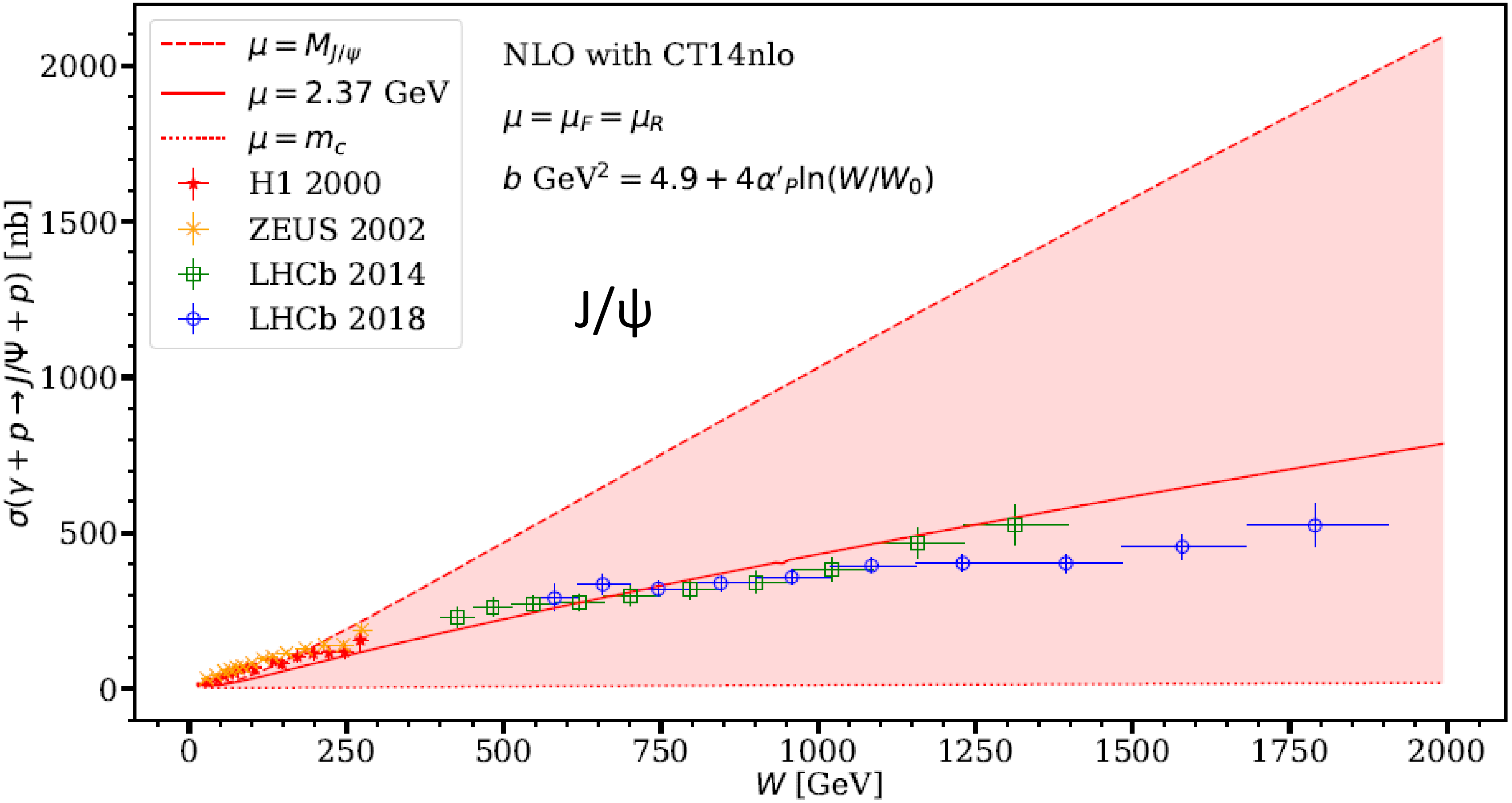
Phys.Rev.C 106 (2022) 035202



2303.03007 [hep-ph]

Decomposition of the XSs to contributions from the real and imaginary parts of the amplitude.

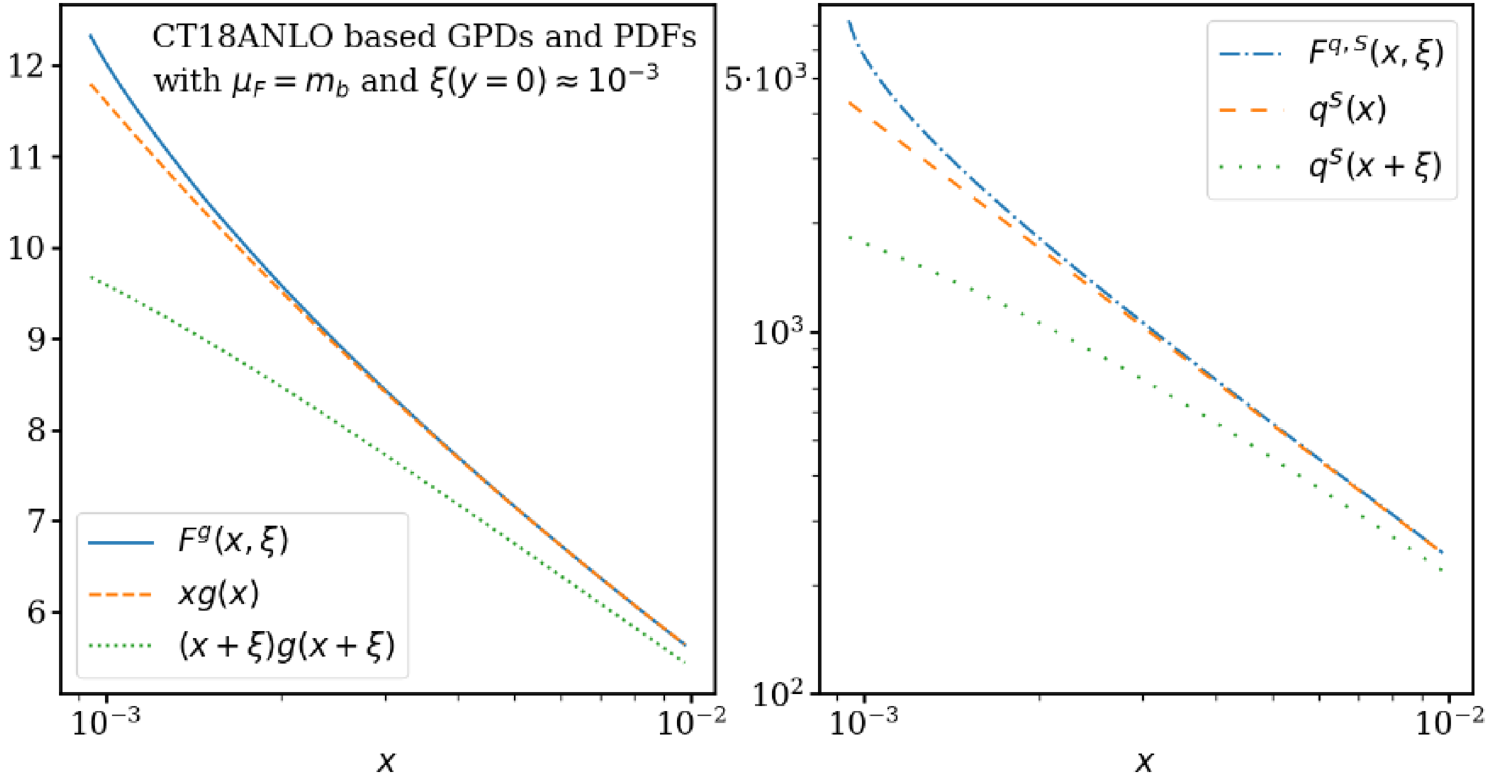
B. Photon-proton baseline (here independent from UPC)



Phys.Rev.C 106 (2022) 035202

- Our UPC "optimal" scale works also reasonably well here, but…
- Room for GPD effects (GPDs≠PDFs), NRQCD corrections, NNLO corrections,…

2303.03007 [hep-ph]



GPDs via Shuvaev transform

[A. Shuvaev, Phys. Rev. D 60 (1999), 116005]

$$H^q(x,\xi,t=0,\mu_F) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\Im m \int_0^1 \frac{\mathrm{d}s}{y(s)\sqrt{1-y(s)x'}}\right] \frac{\mathrm{d}}{\mathrm{d}x'}\frac{q(x',\mu_F)}{|x'|}$$

$$H^g(x,\xi,t=0,\mu_F) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\Im m \int_0^1 \frac{\mathrm{d}s\ (x+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}}\right] \frac{\mathrm{d}}{\mathrm{d}x'}\frac{g(x',\mu_F)}{|x'|}$$

where the kernel of the transform is

$$y(s) = \frac{4s(1-s)}{x+\xi(1-2s)}\,.$$

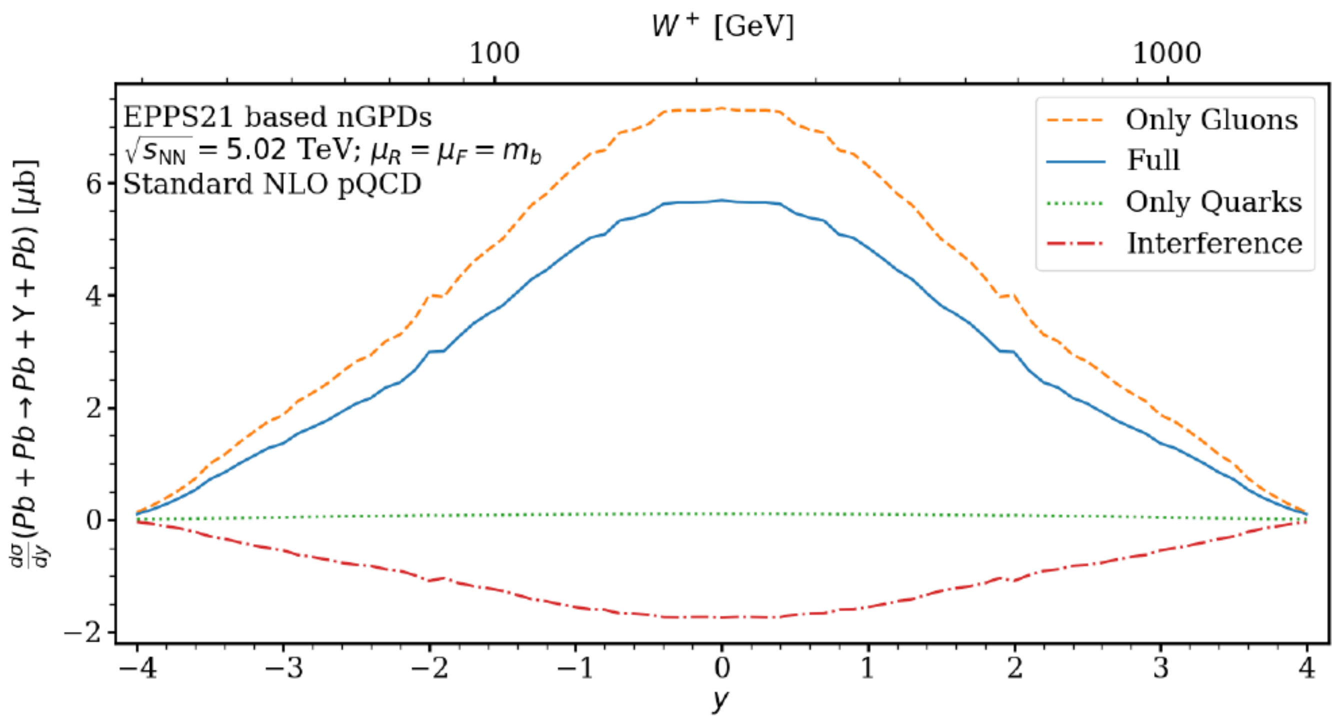
GPD effects relative to PDFs at the Upsilon mass scale are rather small, and still smaller at the J/Psi mass scale

With GPDs via Shuvaev tr., restore Re(M) via the dispersion relation

[M.G. Ryskin, et al., Z. Phys. C 76 (1997) 231]

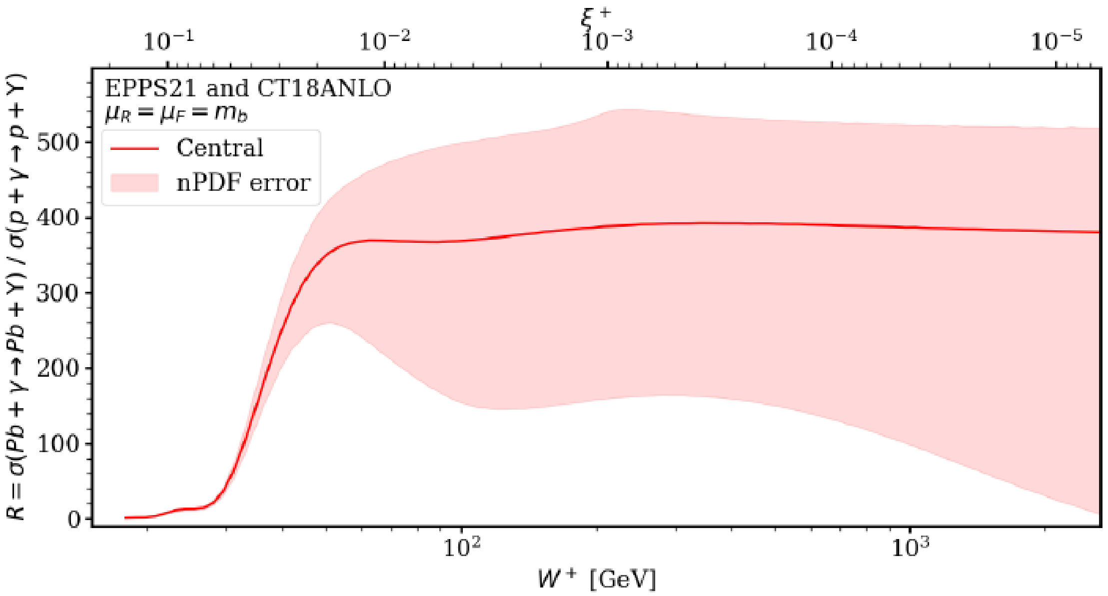
$$\frac{\Re e\mathcal{M}_A^{\gamma N\to\Upsilon N}(\xi,t=0)}{\Im m\mathcal{M}_A^{\gamma N\to\Upsilon N}(\xi,t=0)} = \tan\left(\frac{\pi}{2}\,\frac{\partial\ln(\Im m\mathcal{M}_A^{\gamma N\to\Upsilon N}(\xi,t=0)/(1/\xi))}{\partial\ln(1/\xi)}\right)$$

2303.03007 [hep-ph]



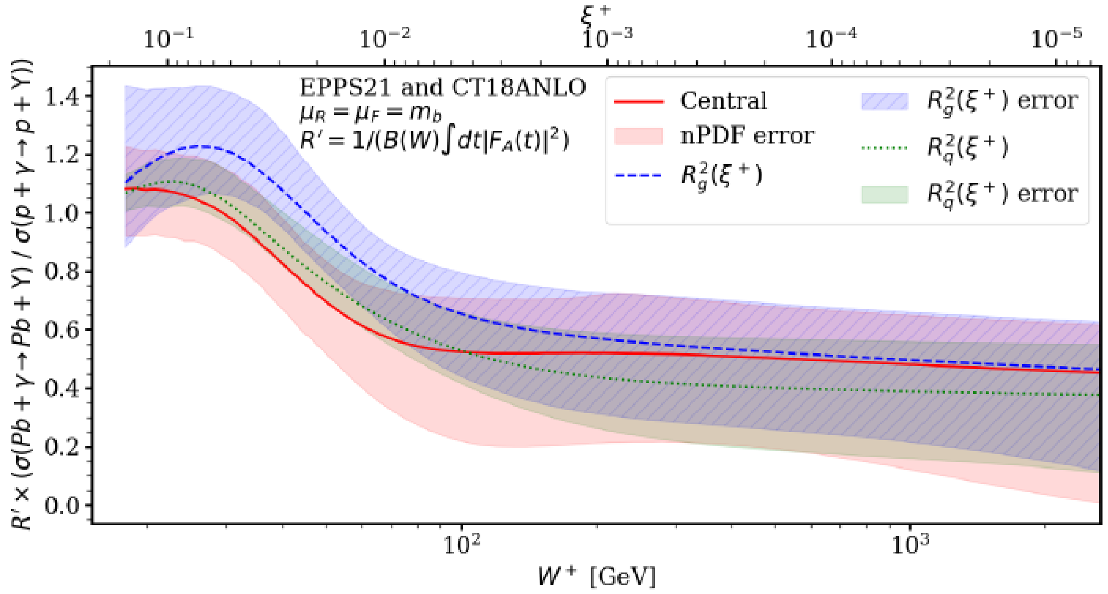
Coherent Upsilon photoproduction in Pb+Pb UPCs at the LHC: gluons dominate

2303.03007 [hep-ph]



pQCD ratio $\left[\frac{\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W)}{\sigma^{\gamma p \to \Upsilon p}(W)}\right]_{\mathrm{pQCD}}$

unscaled, contains the form factors



Nuclear effects in the pQCD ratio $\left[\frac{\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W)}{\sigma^{\gamma p \to \Upsilon p}(W)}\right]_{\mathrm{pQCD}}$
with the form factors scaled away
-- sensitive to (gluon shadowing)^2