Exclusive J/ψ photoproduction in ultraperipheral Pb+Pb collisions at the LHC to next-to-leading order perturbative QCD: Implications for ATHENA

Spencer Klein, *LBNL*

April 4, 2022

- Previous status
- Brief summary of results of calculation
- Implications

Paper is for UPCs, but conclusions apply for eA

Exclusive J/ψ photoproduction in ultraperipheral Pb+Pb collisions at the LHC to next-to-leading order perturbative QCD

K. J. Eskola,[1,2] C. A. Flett,[1,2] V. Guzey, T. Löytäinen,[1,2,*] and H. Paukkunen[1,2]

[1] *University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland*

[2] *Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland*

(Dated: March 23, 2022)

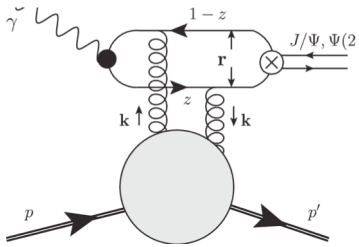
We present the first next-to-leading-order (NLO) perturbative QCD (pQCD) study of rapidity-differential cross sections of coherent exclusive photoproduction of J/ψ mesons in heavy-ion ultraperipheral collisions (UPCs) at the LHC, $d\sigma/dy(\mathrm{Pb}+\mathrm{Pb}\to\mathrm{Pb}+J/\psi+\mathrm{Pb})$. For this, we account for the photon-nucleon NLO cross sections at the forward limit, the t dependence using a standard nuclear form factor, and the photon fluxes of the colliding nuclei. Approximating the generalized parton distributions with their forward-limit parton distribution functions (PDFs), we quantify the NLO contributions in the cross sections, show that the real part of the amplitude and quark-PDF contributions must not be neglected, quantify the uncertainties arising from the scale-choice and PDFs, and compare our results with ALICE, CMS and LHCb J/ψ photoproduction data in Pb+Pb UPCs, exclusive J/ψ photoproduction data from HERA, and LHCb data in p+p. The scale dependence in $d\sigma/dy(\mathrm{Pb}+\mathrm{Pb}\to\mathrm{Pb}+J/\psi+\mathrm{Pb})$ is significant, but we can find a scale-choice that reproduces the Pb+Pb UPC data both at 2.76 and 5.02 TeV collision energies. This process has traditionally been suggested to be a direct probe of nuclear gluon distributions. We show that the situation changes rather dramatically from LO to NLO: the NLO cross sections reflect the nuclear effects of both gluons and quarks in a complicated manner where the relative signs of the LO and NLO terms in the amplitude play a significant role.

I. INTRODUCTION

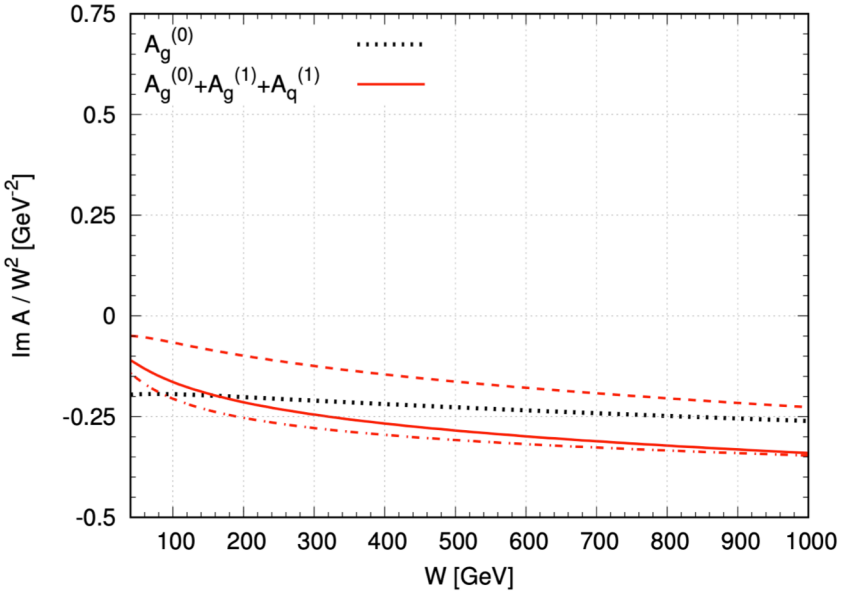
Ultraperipheral collisions (UPCs) are collisions of hadrons or nuclei which take place at large impact parameters in such a way that only the electromagnetic field of one of the colliding particles interacts with the other particle [1–3]. Coherent photoproduction of J/ψ heavy vector-mesons in UPCs of Lead nuclei at the CERN Large Hadron Collider (LHC), the exclusive process $\mathrm{Pb}+\mathrm{Pb}\to\mathrm{Pb}+J/\psi+\mathrm{Pb}$, has been suggested to be an efficient direct probe of collinear nuclear gluon distributions, $g_{\mathrm{Pb}}(x,Q^2)$, at factorization scales of the order of the vector-meson mass, $Q^2=\mathcal{O}(M_V^2)$, and small longitudinal-momentum fractions $x=\mathcal{O}(M_V^2/W^2)$, where W is the photon-nucleon center-of-momentum-system (c.m.s.) energy [4–11]. This exciting possibility derives from the fact that in such an exclusive process of no hadronic activity, one of the colliding nuclei serves as a source of equivalent real Weizsäcker-Williams photons which probe a color-singlet gluon- or quark-initiated ladder from the other becomes proportional to $[g_{\mathrm{p}}(x,Q^2)]^2$, making the process a very promising one for probing the gluon distribution. This idea has then been transferred to ultraperipheral nucleus-nucleus collisions (UPCs) in e.g. Refs. [4, 5]. Also Monte Carlo event simulations of this process in the UPCs have been developed, such as STARlight [13] and SuperChic [14]. Exclusive photoproduction of J/ψ has also been widely studied in the dipole picture, especially in the high-energy Color-Glass-Condensate approximation of QCD, see e.g. Refs. [15–25].

With the experimental data being released from the LHC, the situation is becoming ever more interesting. Firstly, the exclusive coherent J/ψ photoproduction cross sections involving real photons have been measured in electron-proton collisions at the DESY-HERA collider by the H1 [26] and ZEUS [27] collaborations, and extracted also from the LHCb measurements of the process $\mathrm{p}+\mathrm{p}\to\mathrm{p}+J/\psi+\mathrm{p}$ at the LHC [28, 29]. For detailed NLO pQCD studies of these, see e.g. Refs. [30–35]. From the viewpoint of the UPCs, these data sets

Previously….



- LO (2-gluon) + partial NLO calculations
- Many complications & technical issues
  - Setting renormalization scale $\mu_R=\mu_F$ reduces uncertainties
    - μ_F is factorization scale
  - Skewed distributions ($x_1 \neq x_2$)
  - GPDs vs. PDFs
  - Double-counting of low Q^2 range (for partial NLO)



S. P. Jones *et al.*,
Eur. Phys. J. C76, 633 (2016)

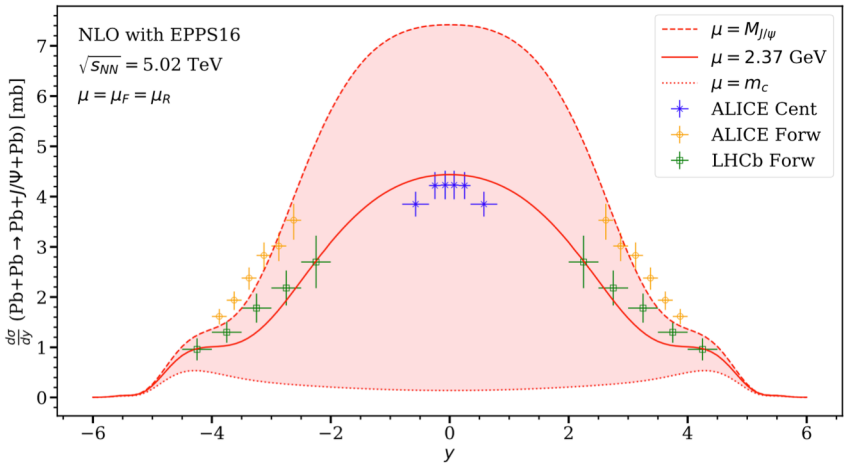
Figure 4: The predictions for the LO and NLO contributions to the imaginary part of the J/ψ photoproduction amplitude calculated exactly as in Fig. 2 except that now the Q_0 cut is imposed.

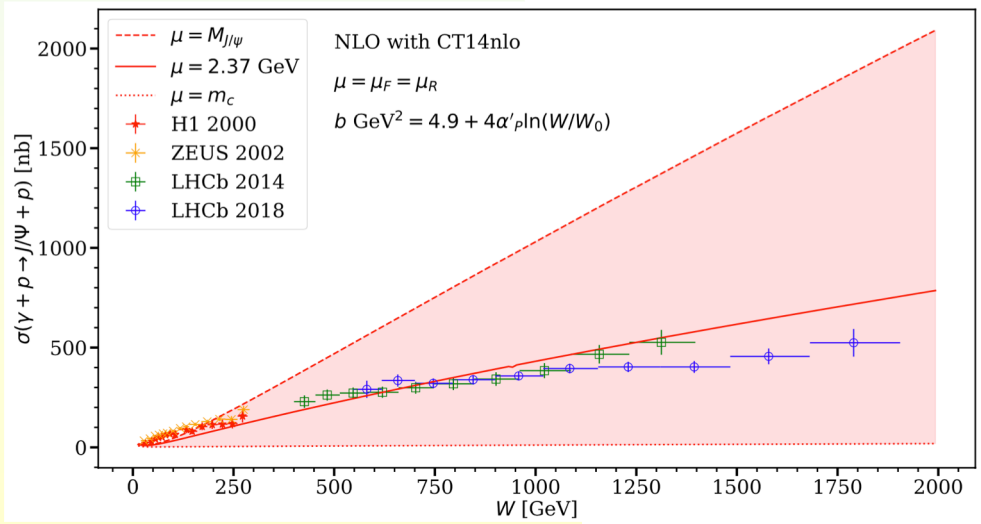
Full NLO calculation

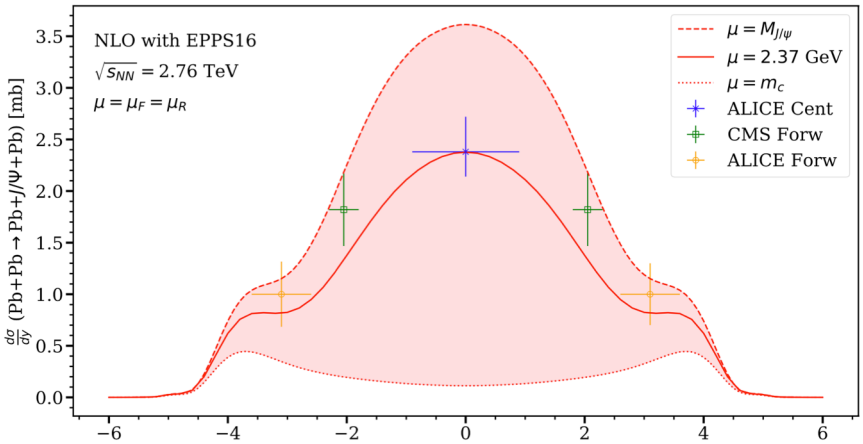
- Important to consider real and imaginary parts of amplitudes
  - Contrary to expectations, real parts are important
- Quark contributions are also significant
- 3 PDF combos: EPPS16, and CT14NLO with both nCTEQ15 and nNNPDF2.0 nuclear modifications
- Done for γp at HERA and γA in LHC ultra-peripheral collisions
  - In UPCs, there is a bidirectional photon flux
    - Rapidity maps to photon flux, with an exp(±y) scale ambiguity
  - Photon flux calculations appear standard
    - Woods-Saxon form factor, photon flux for $b>2R_A$ etc.

Scale uncertainty

- Is huge for both proton and lead targets
- μ=2.37 GeV fits the data well
  - What do we learn? What is the uncertainty?







NLO vs. LO apples-to-apples

- Note y-axis scale
- σ_{NLO} ~55-70% below σ_{LO}
  - Big change in magnitude; smaller change in shape
- Scale variation is a factor of 20 at LO; factor of 50 at NLO
- Hints that this is better for heavier mesons, like Υ

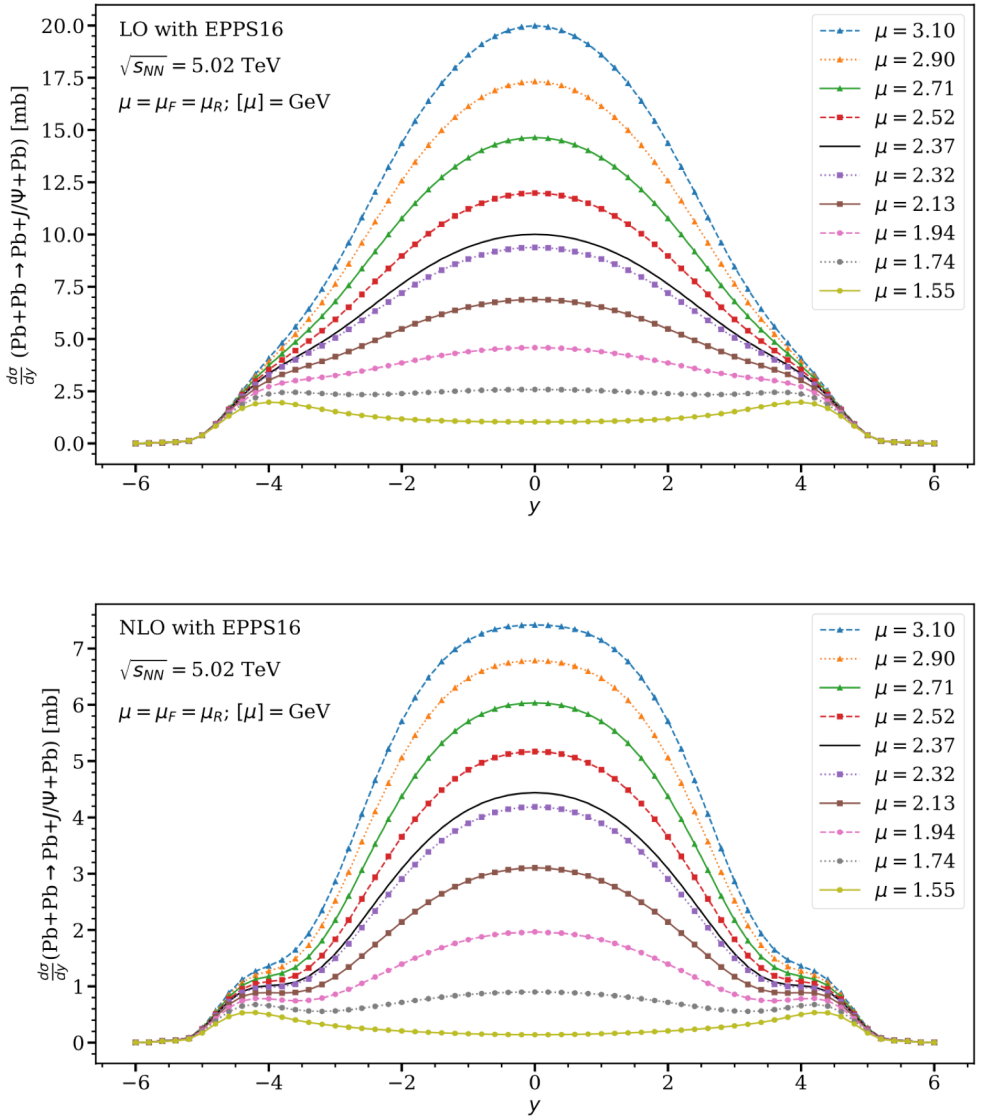
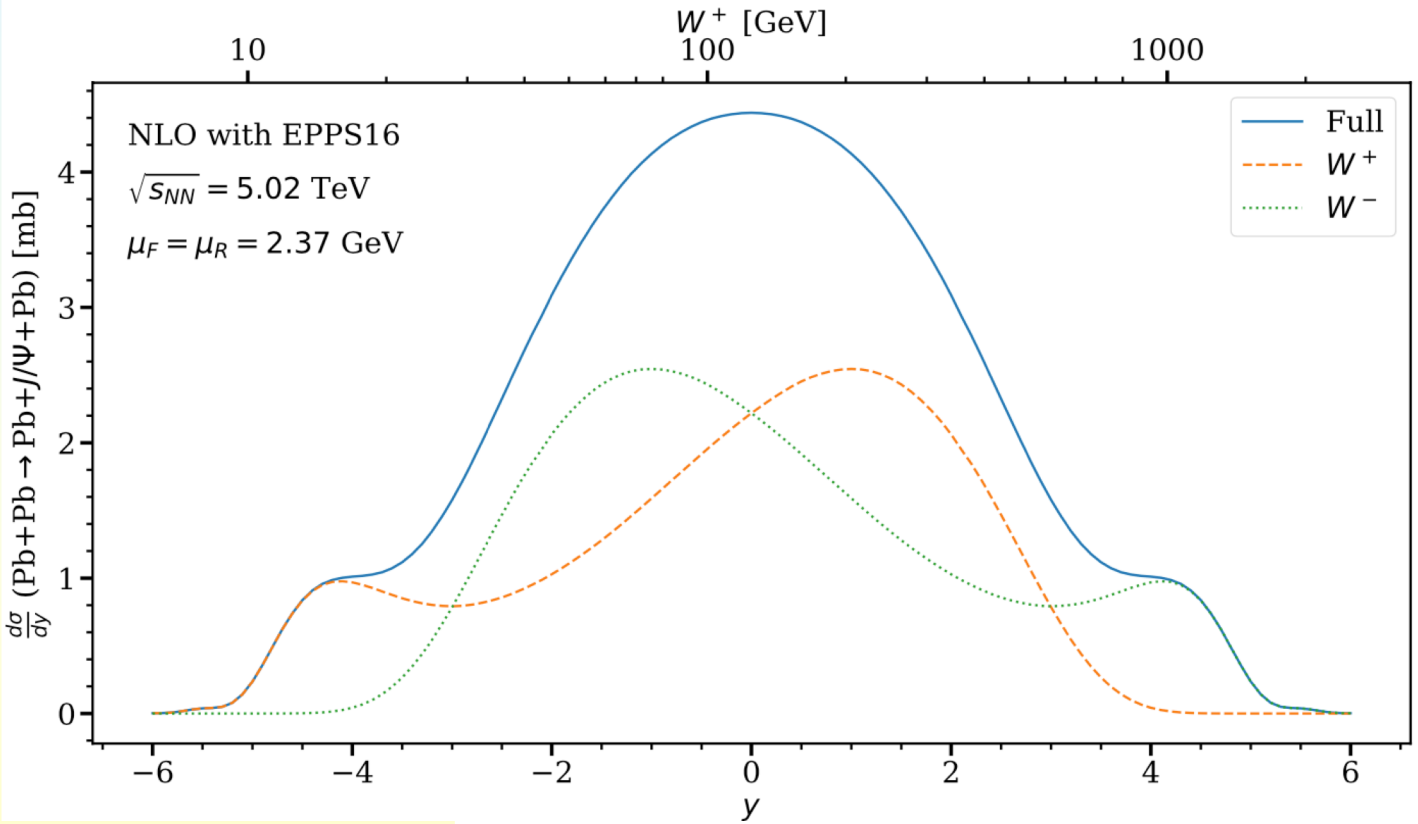


FIG. 3. **Upper panel:** Rapidity-differential exclusive J/ψ photoproduction cross sections in Pb+Pb UPCs at $\sqrt{s_{\rm NN}}$ = 5.02 TeV, as a function of the rapidity y, computed at LO pQCD with the EPPS16 nPDFs at various fixed scales μ. The lowest- and highest-scale results here give the envelope shown in Fig. 1. The result with our "optimal" scale is shown by the solid curve. **Lower panel:** The same but at NLO pQCD.

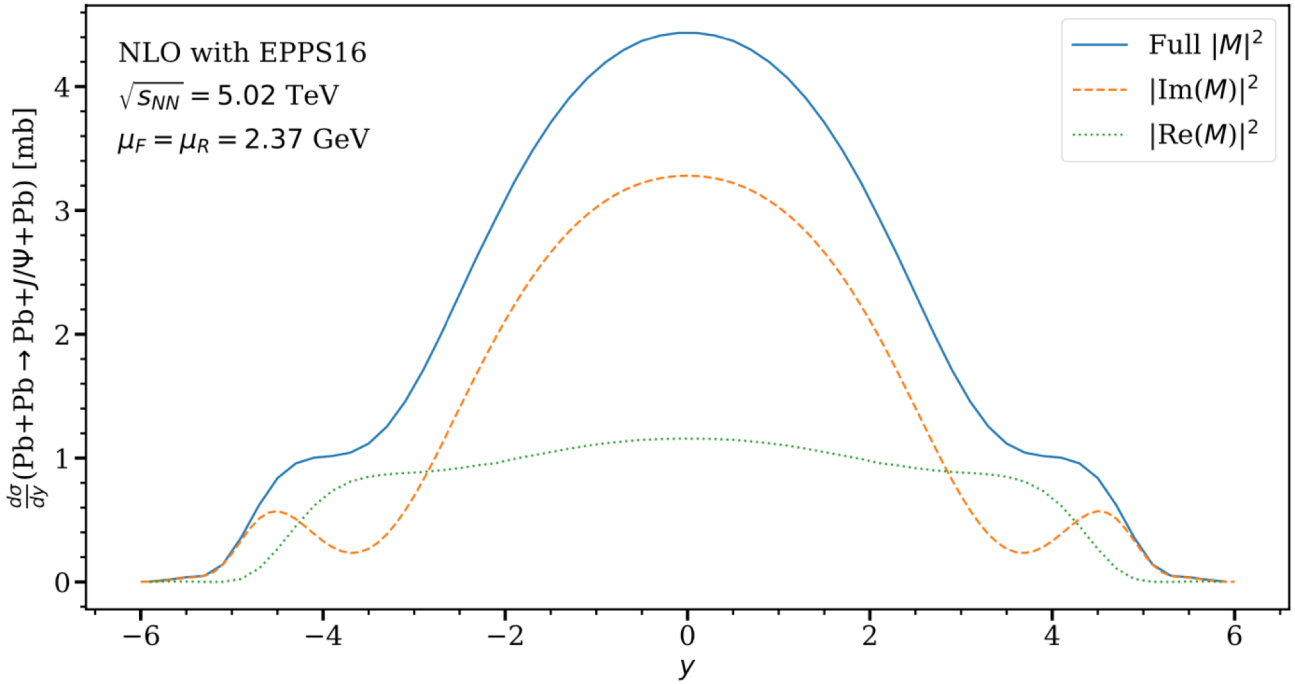
Contributions from two directions

- Two peaks in dσ/dy for each direction
  - In paper, explained as competition between decrease in photon flux and increase in γA cross-section with increasing energy



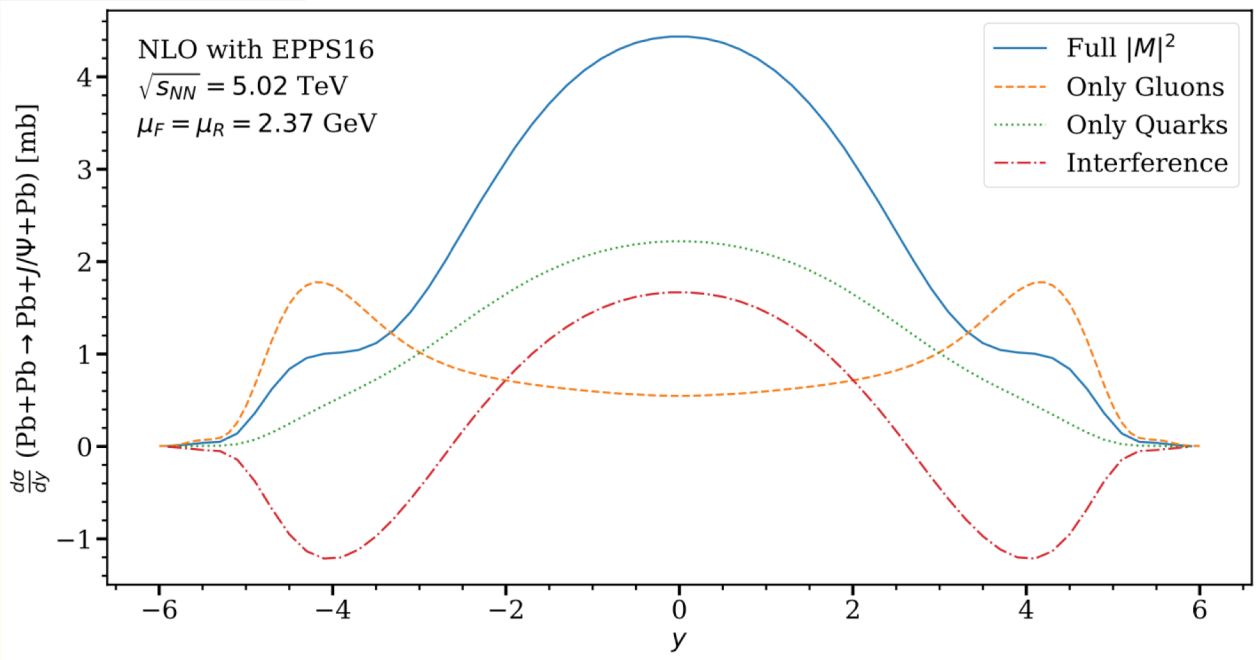
Real part of the cross-section

- In conventional paradigm, Pomeron represents absorptive part of the cross-section, so is almost purely imaginary
  - Not so for the J/ψ because σ rises sharply with energy
- These calculations confirm that it is not.
- Real part is largest near threshold (as expected)
- Implications for interference with γγ->ll or other channels?



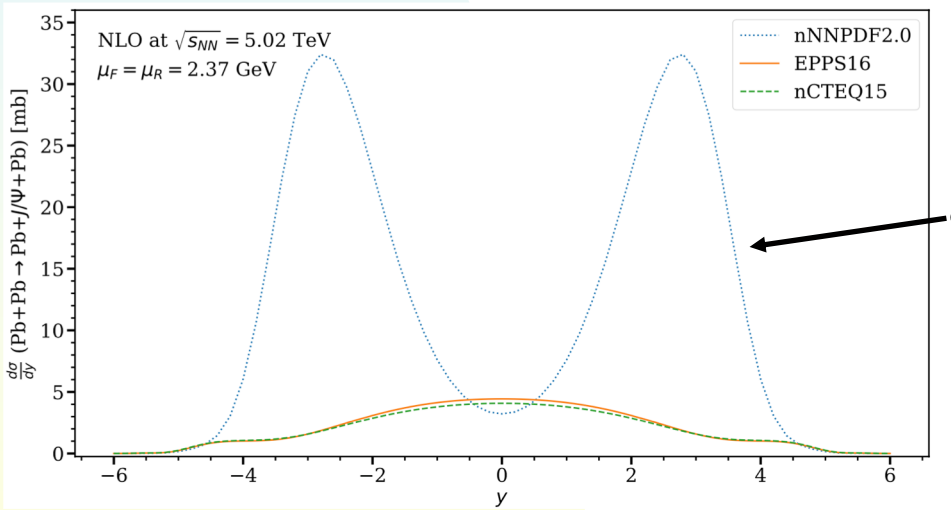
Quarks and gluons

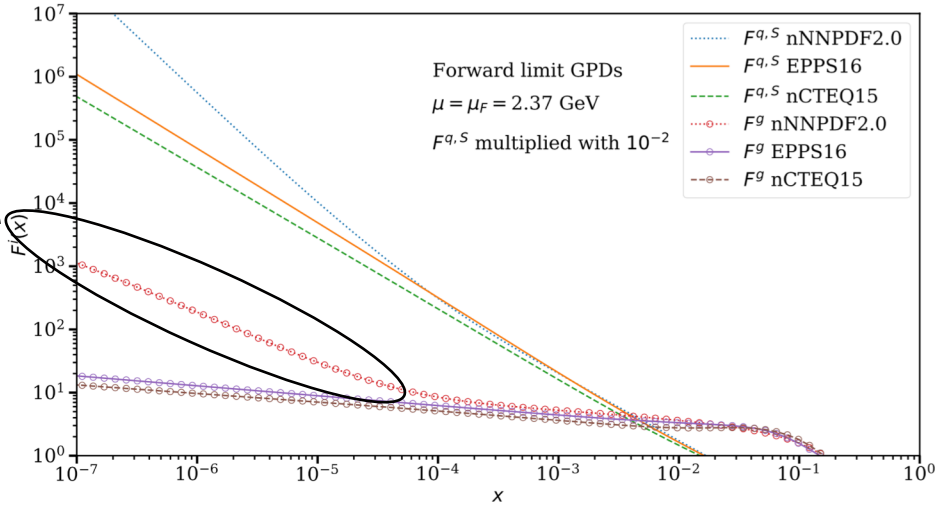
- LO and NLO gluon contributions have opposite sign, so significantly cancel
- Quarks matter
  - $\sigma \sim g^2(x)$ does not hold
  - Except a large W ($|y| \sim 4$)
- Complex energy/rapidity behavior because of interference ?
- Is this partly because we are using PDFs that underestimate the gluon contribution and overestimate the quarks?



Different PDFs matter

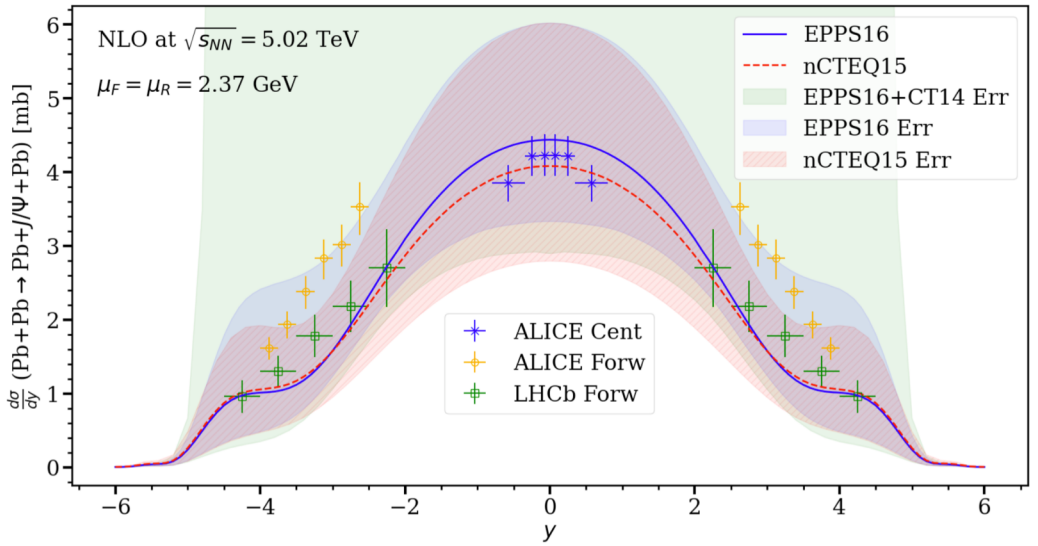
- nNNPDF2.0 is very different
  - Due to rapid growth in real part of LO gluon amplitude with decreasing x.
  - Less cancellation between LO and NLO gluon component

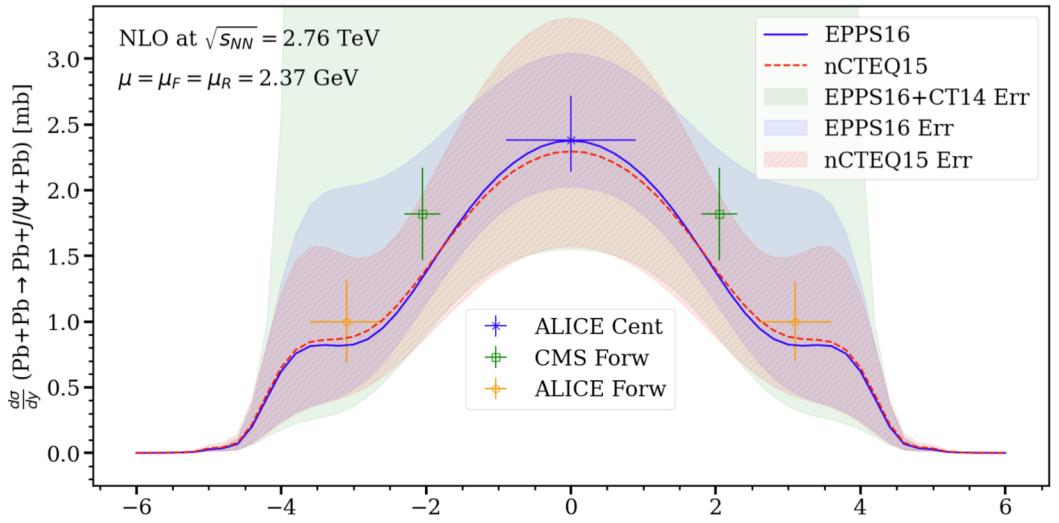




PDF uncertainties

- Even with scale problems, J/y might give marginally useful constraints
- If scale problem can be fixed, then these data can provide important constraints





Conclusions

- The first full NLO calculation of J/ψ photoproduction has appeared, with some surprises
  - There is a very large scale uncertainty
  - σ_{NLO} is a factor of 2-3 below σ_{LO}
  - There are cancellations (interference) between LO and NLO gluon components, so quark PDFs are important in the calculation
  - NNPDF2.0 makes very different predictions for ds/dy than other PDFs
- Can we still use J/ψ data to probe gluon distributions in nuclei?
  - How much does the scale factor uncertainty cancel out when comparing proton and lead targets?
    - Can one fix the scale from low-energy data, and use that scale at higher energies?
  - Can current fits use J/ψ data, with its mix of quarks and gluons?
- What about studies of transverse position dependence (GPDs)?
- What about the Υ? The higher mass might lead to less scale dependence