Exclusive J/ψ production in ultraperipheral Pb+Pb collisions to NLO pQCD

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Magnus Ehrnroothin säätiö

AoF, CoE in Quark Matter
YoctoLHC

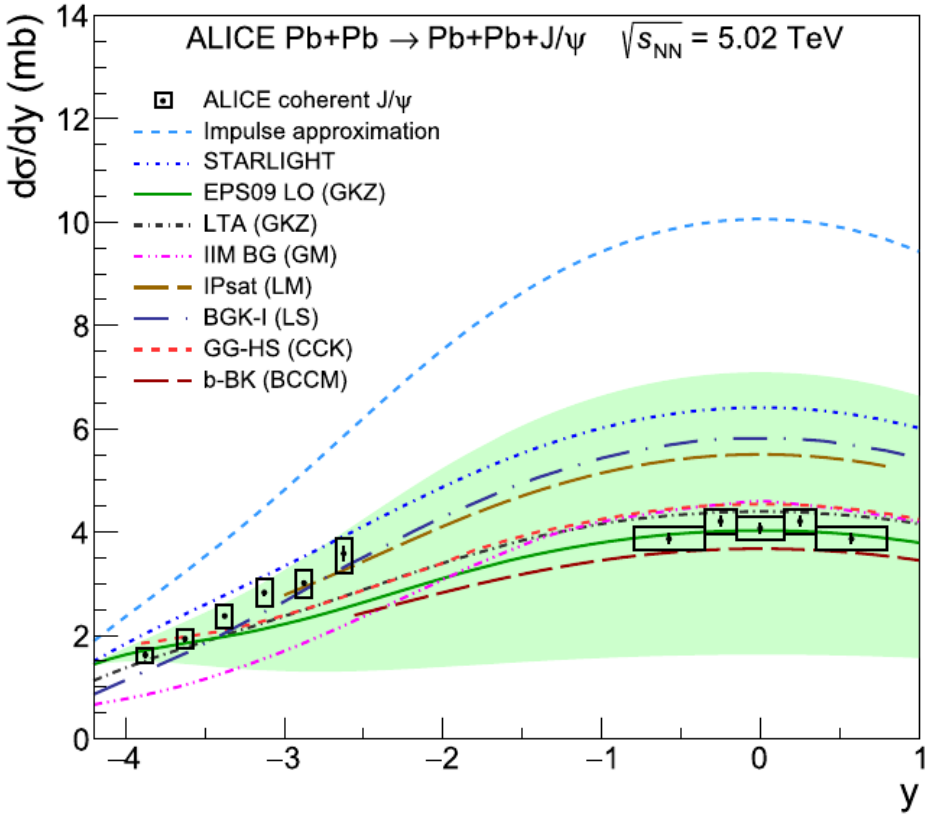
Motivation

- Is exclusive J/ψ photoproduction in UPCs, A+A→A+J/ψ+A, a good probe of collinear nuclear gluon distributions?
- Originally proposed by Ryskin[1] in the context of electroproduction

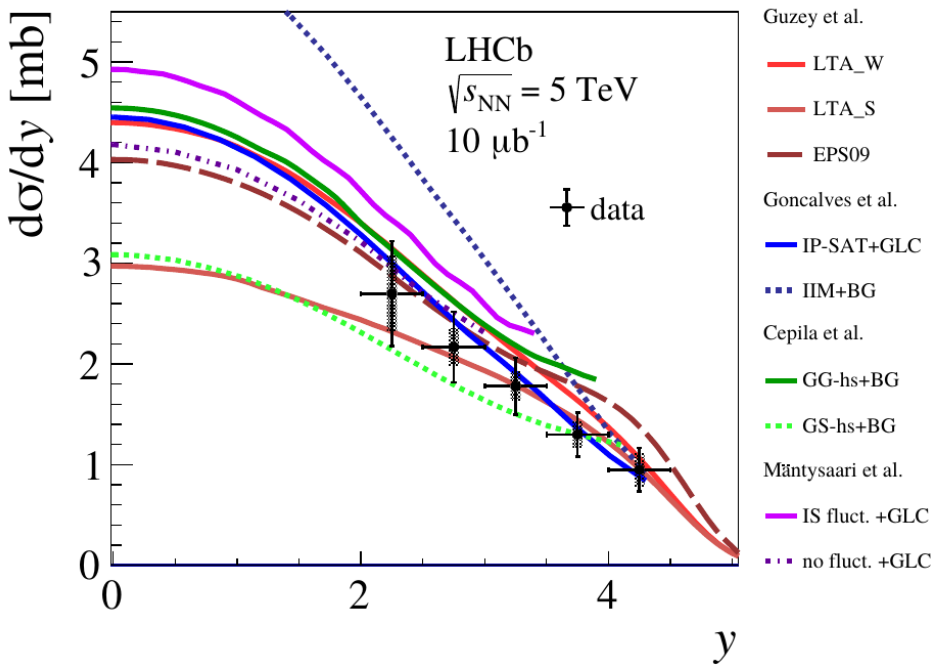
$$\left(\frac{d\sigma^{\gamma^* p \to Vp}}{dt}\right)\Bigg|_{t=0} \propto \left(xg\left(x, Q^2\right)\right)^2.$$

- Until now, only LO calculations for A+A UPCs. Need for NLO!
- Scale dependence, PDF-uncertainties, quark/gluon contributions, nuclear effects, real/imaginary parts of amplitude?
- How does NLO match with the LHC data?

[1] *Z.Phys.C 57 (1993) 89-92*



- Earlier calculations compared to ALICE data. Figure from Eur. Phys. J. C 81, 712 (2021).



- Earlier calculations compared to LHCb data. Figure from arXiv:2107.03223 [hep-ex].

The Framework

- Rapidity differential cross section:

$$\frac{d\sigma^{AA\to AVA}}{dy} = \left[k\frac{dN_\gamma^A(k)}{dk}\sigma^{\gamma A\to VA}(k)\right]_{k^-} + \left[k\frac{dN_\gamma^A(k)}{dk}\sigma^{A\gamma\to AV}(k)\right]_{k^+}$$

  V is the vector meson and $k^{+/-}$ are the photon energies.
- Photon flux dN_γ^A/dk in Weizsäcker-Williams (WW) approximation, require no hadronic activity.
- Cross section through the product:

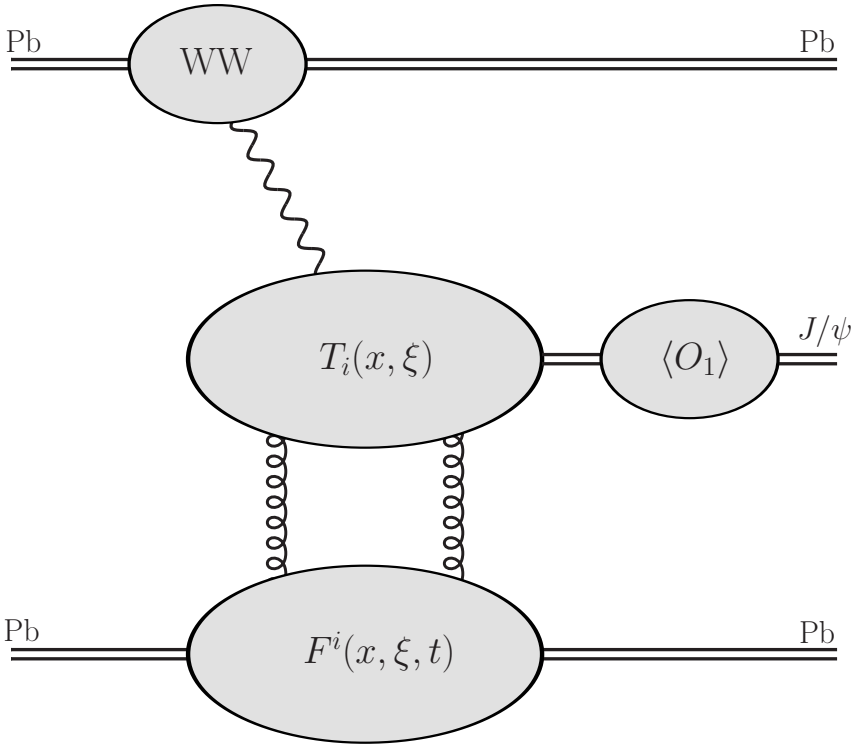
$$\sigma^{\gamma A\to VA} = \frac{d\sigma^{\gamma N\to VN}}{dt}\bigg|_{t=0}\int_{t_{min}}^{\infty} dt' \; |F_A(-t')|^2$$

  $F_A(t)$ is the form factor.

- NLO amplitude[2], factorization at amplitude level[3]:

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

- NRQCD element $\langle O_1 \rangle_V$.
- Hard-scattering functions T_i.
- GPDs F^i.
- No quarks in LO.



[2] Ivanov et al. *Eur.Phys.J.C 34 (2004) 3, 297-316 and 75 (2015) 2*
[3] Collins, *Phys.Rev.D 56 (1997) 2982-3006*

- $\langle O_1 \rangle_V$ from the leptonic decay width in the leading NRQCD approximation.

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

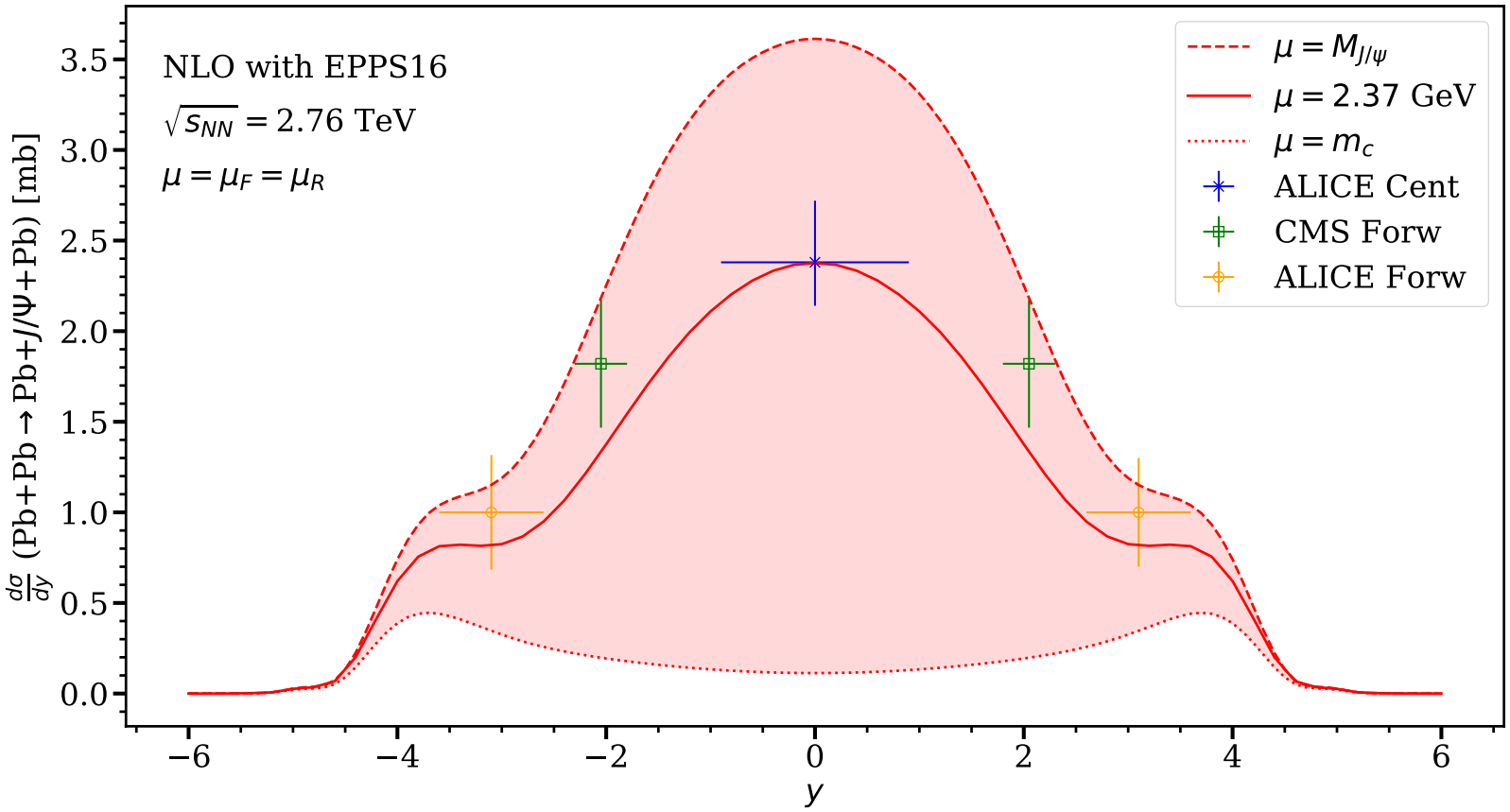
- The GPDs taken here in their forward limit ($x > 0$):

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

- Nuclear corrections for the bound nucleons from EPPS16[4], nCTEQ15[5], nNNPDF2.0[6].
- Numerical results checked with two different methods.

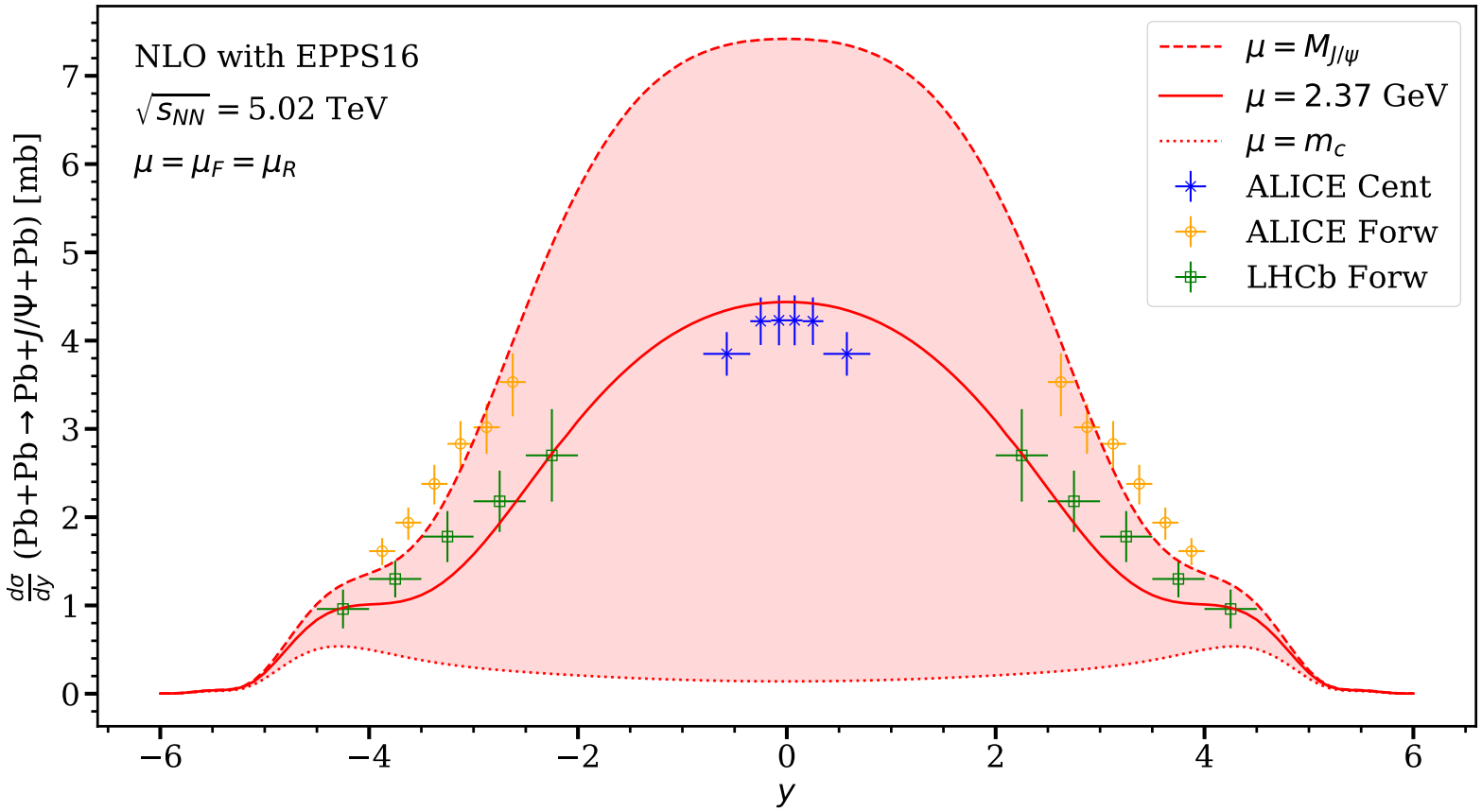
[4] Eskola et al. *Eur.Phys.J. C77 (2017) no.3, 163*
[5] Kovarik et al. *Phys.Rev.D 93 (2016) 8, 085037*
[6] Khalek et al. *JHEP 09 (2020) 183*

Results: LHC Run 1 data



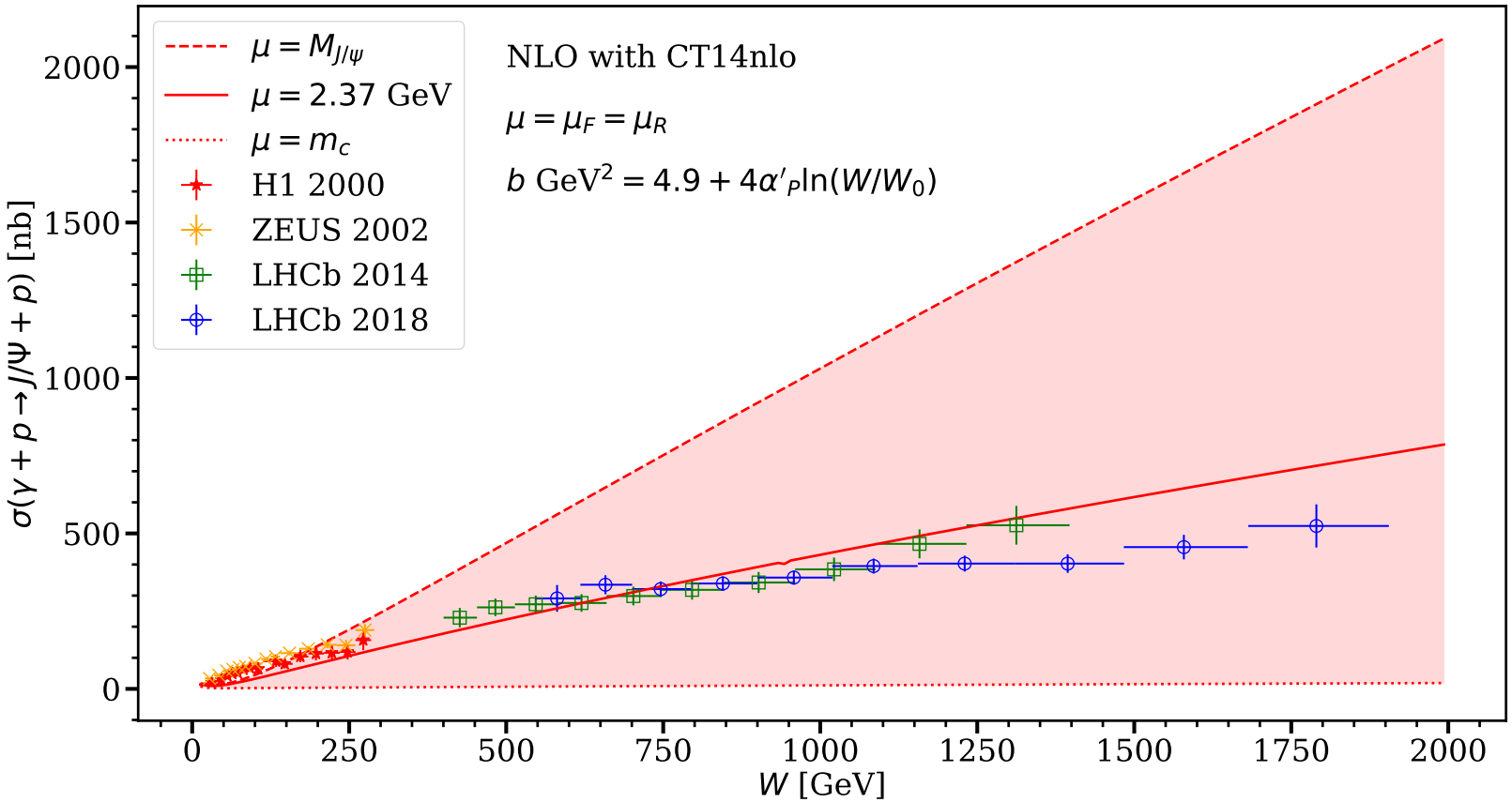
- Scale dependence considerable but an "optimal" scale can be found.

LHC Run 2 data



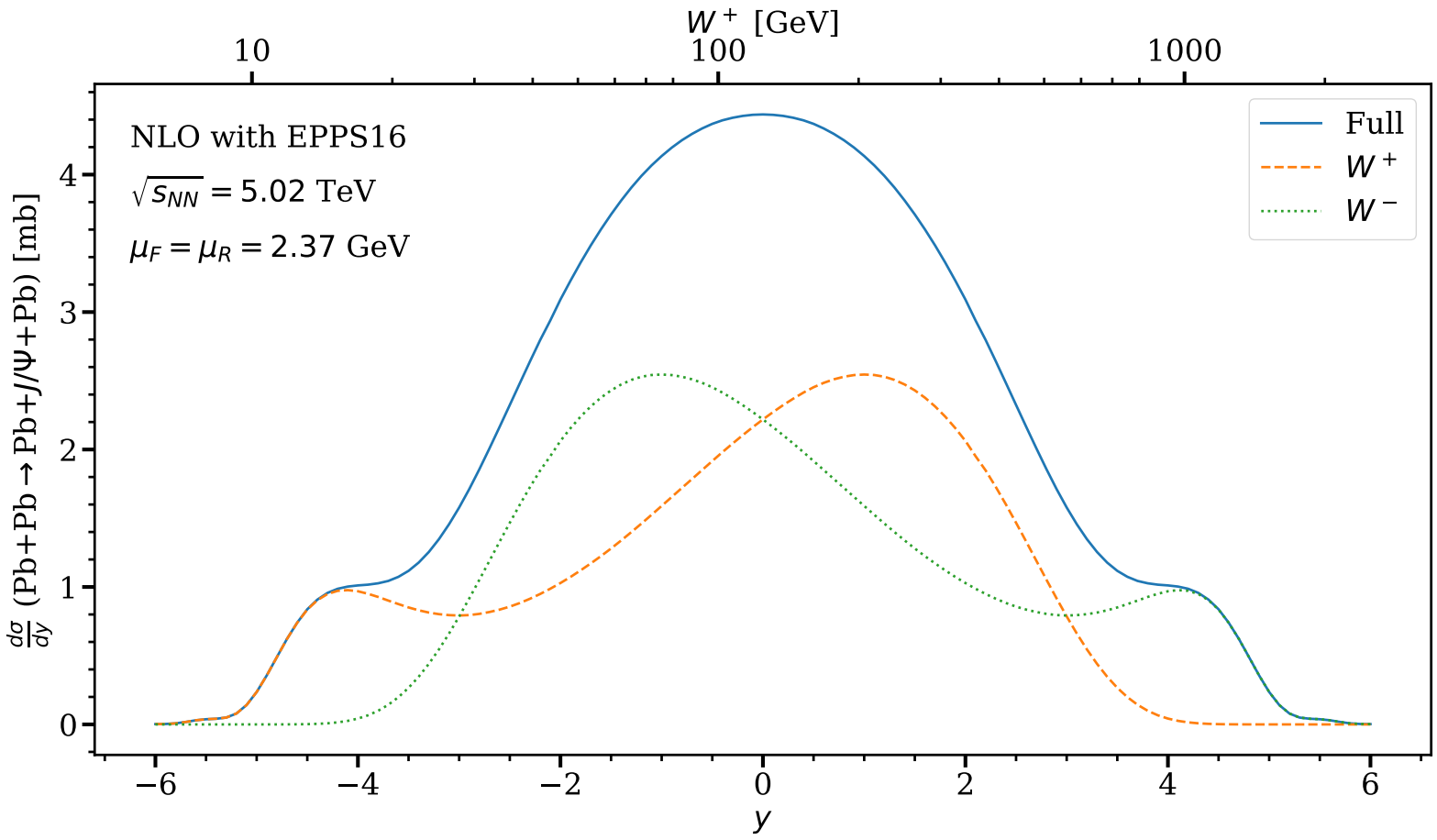
- Scale dependence considerable but an "optimal" scale can be found.

γp baseline



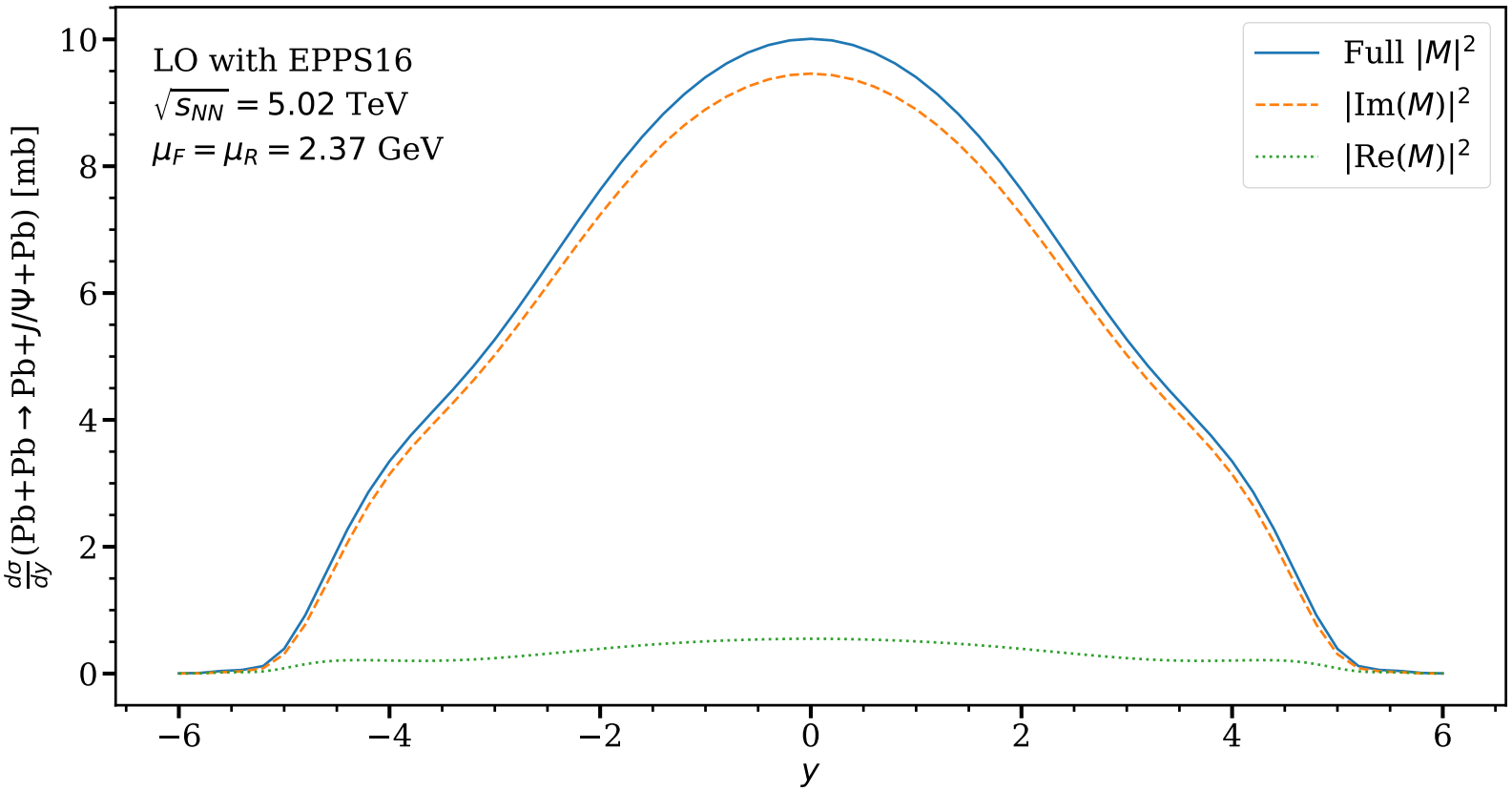
- The optimal scale works reasonably well also for the γp baseline.

W breakdown



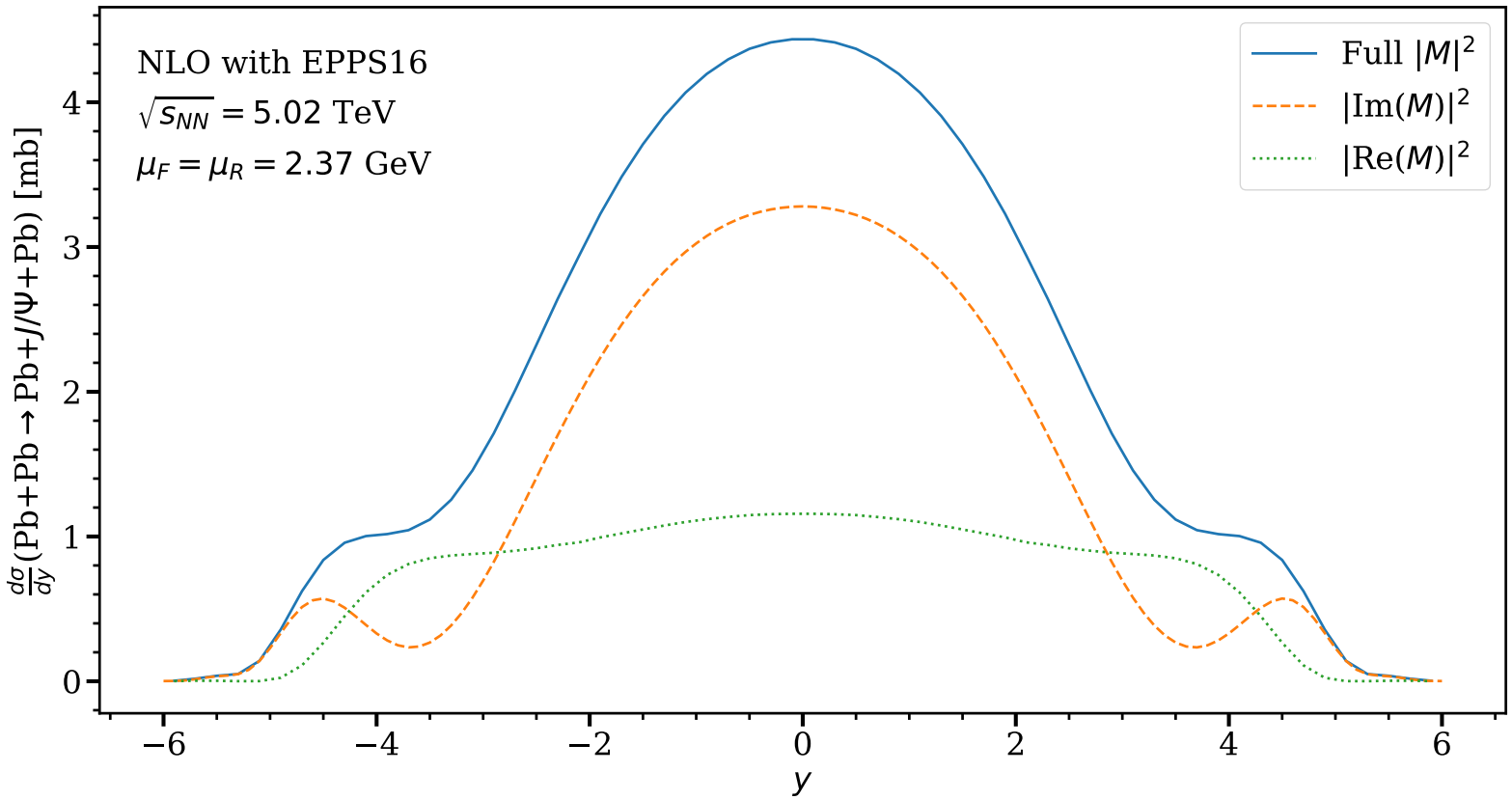
- W-contributions symmetric w.r.t. $y = 0$. Shoulders arise in NLO: interplay of cross section, photon flux and form factor.

LO decomposition to Real and Imaginary parts



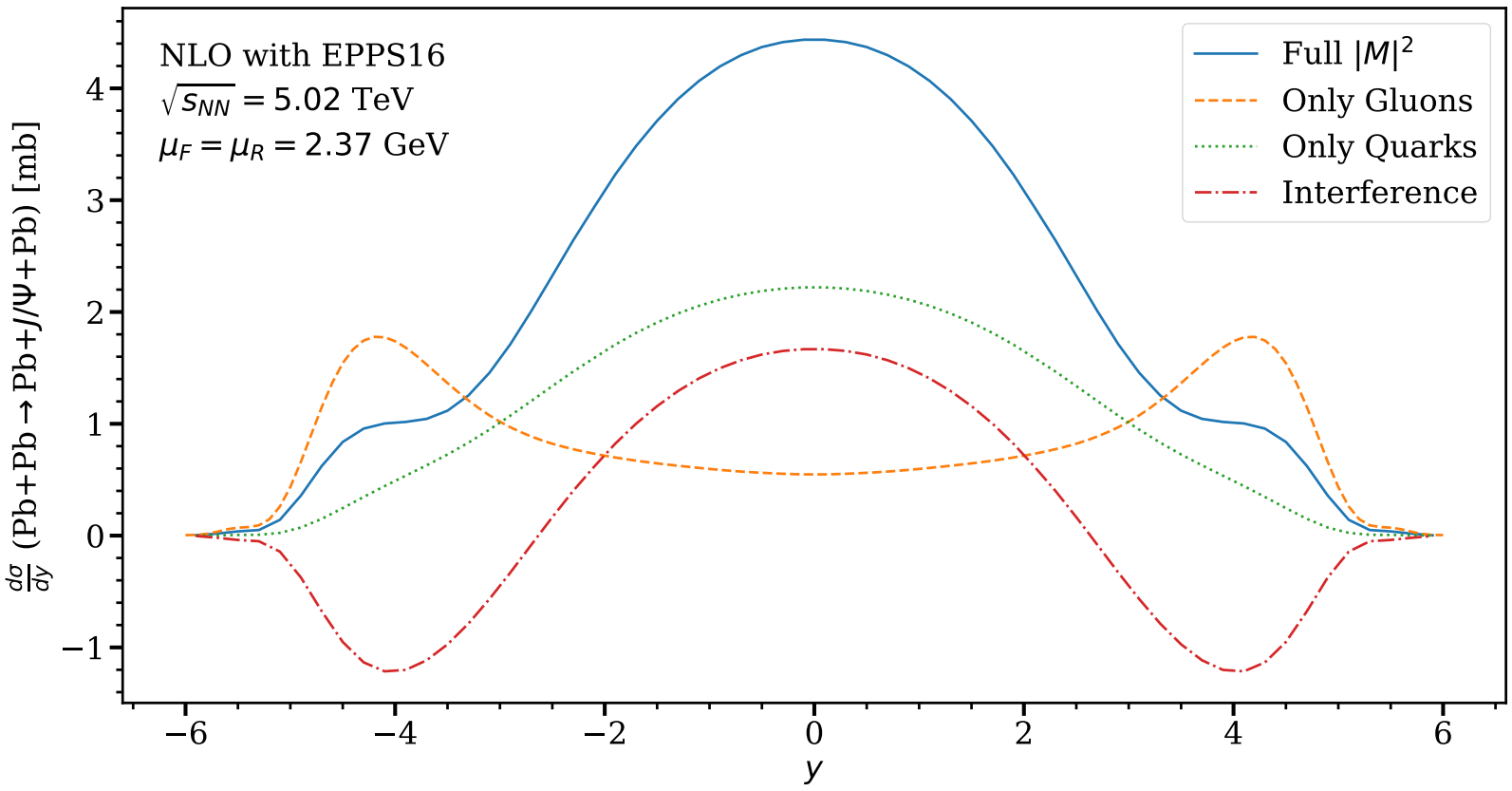
- In LO imaginary part clearly dominates.

NLO decomposition to Real and Imaginary parts



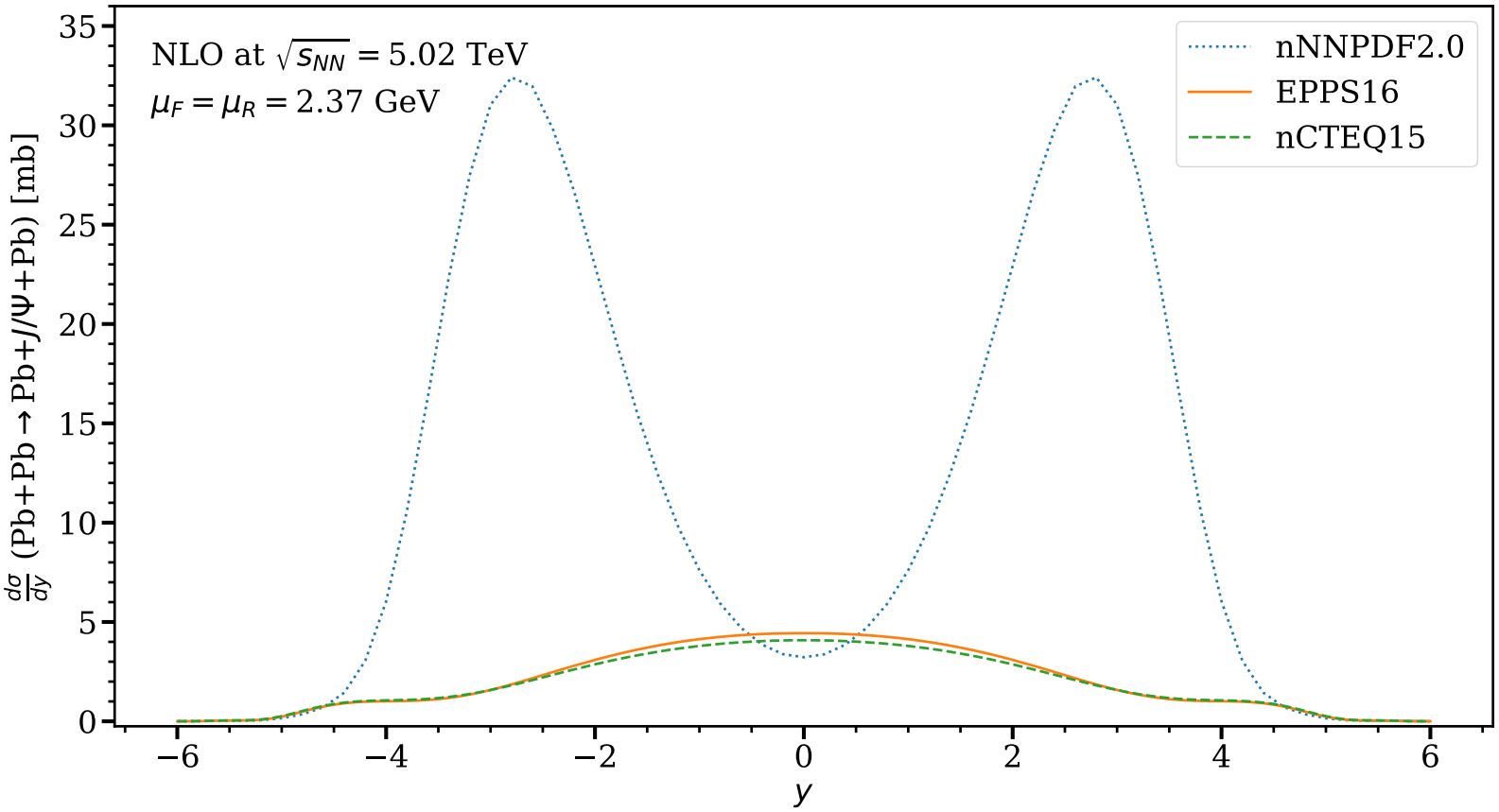
- In NLO the situation is more involved. Real part cannot be neglected.

Breakdown to gluon and quark contributions



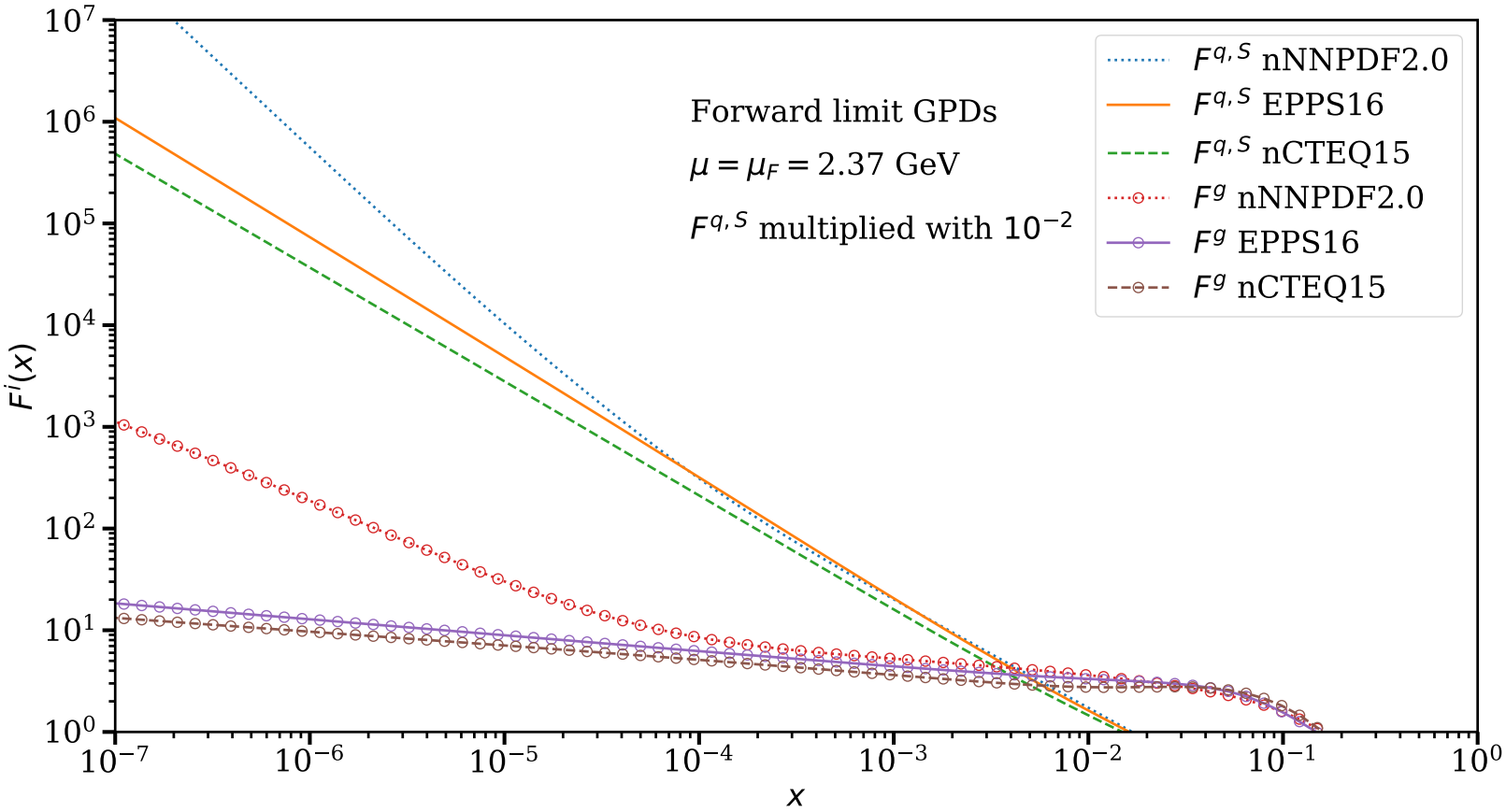
- Now, at $y = 0$ *quark* contribution dominates. Different from LO! Reason: LO and NLO gluon amplitudes cancel.

Different nPDF groups



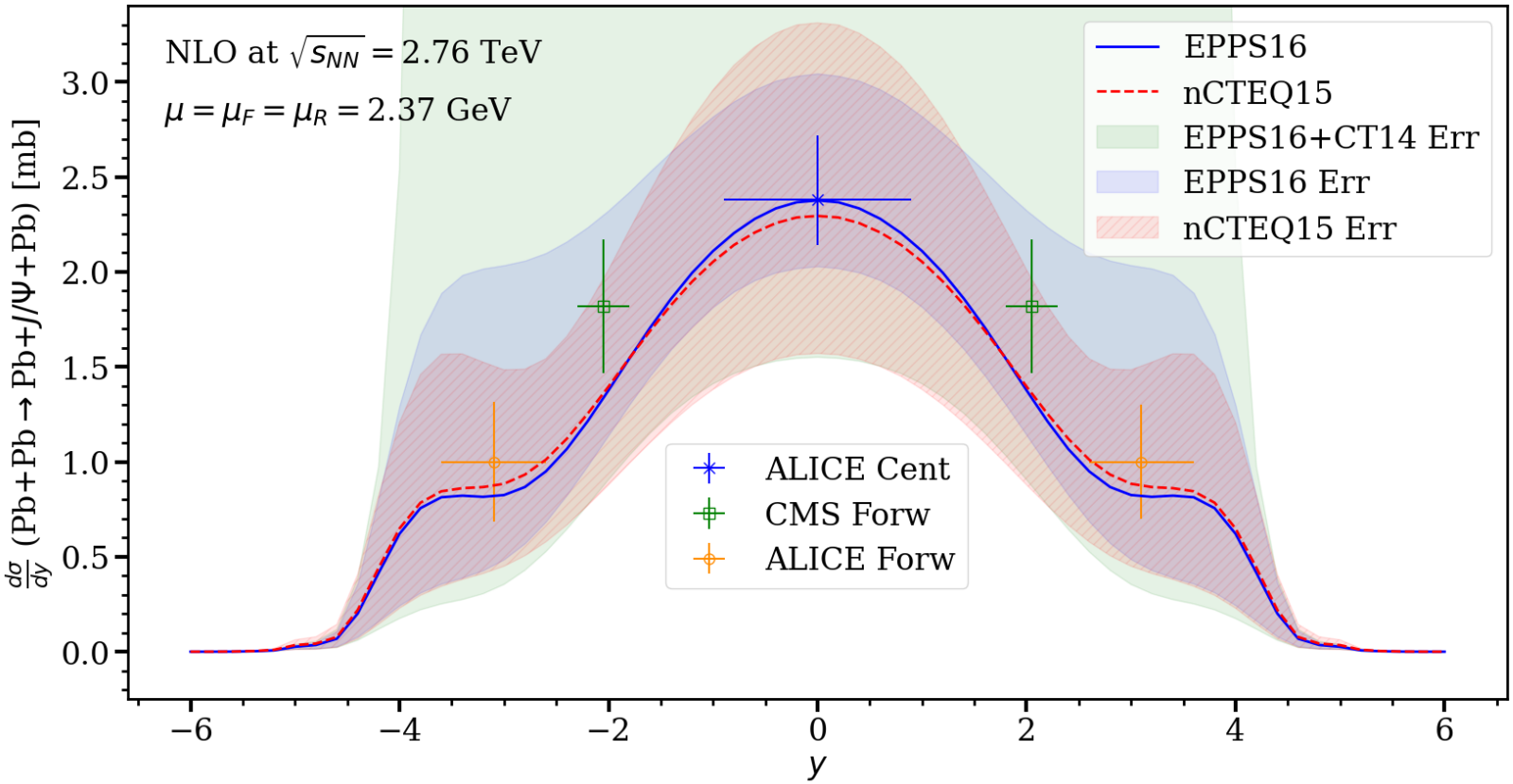
- nCTEQ15 agrees with EPPS16 but nNNPDF2.0 does not...

Underlying nPDF sets



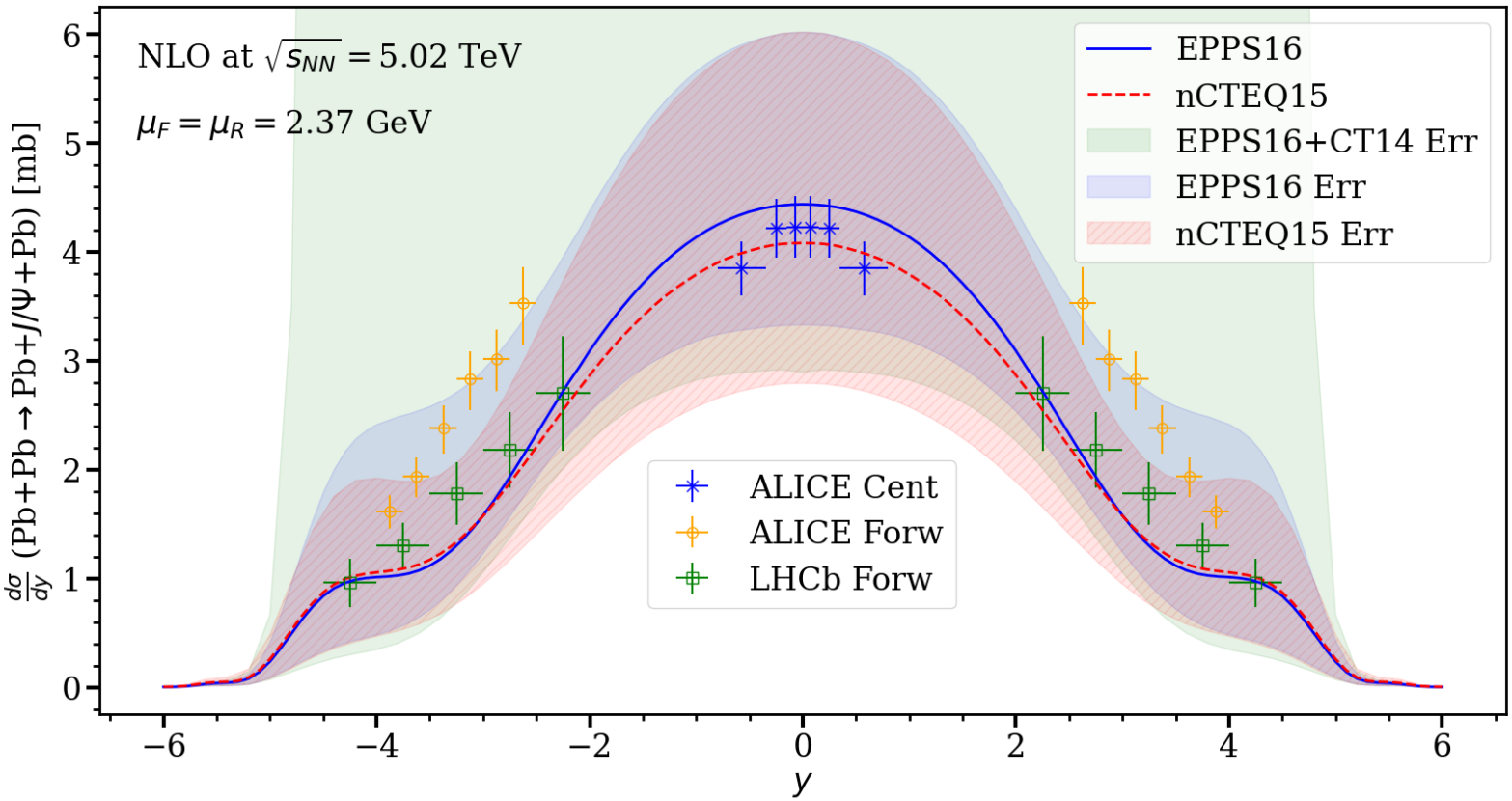
- ... due to different behaviour of the gluon distribution.

Run 1 data and propagation of PDF errors



- Nuclear uncertainties moderate. Large free proton uncertainties dominated by single error set.

Run 2 data and propagation of PDF errors



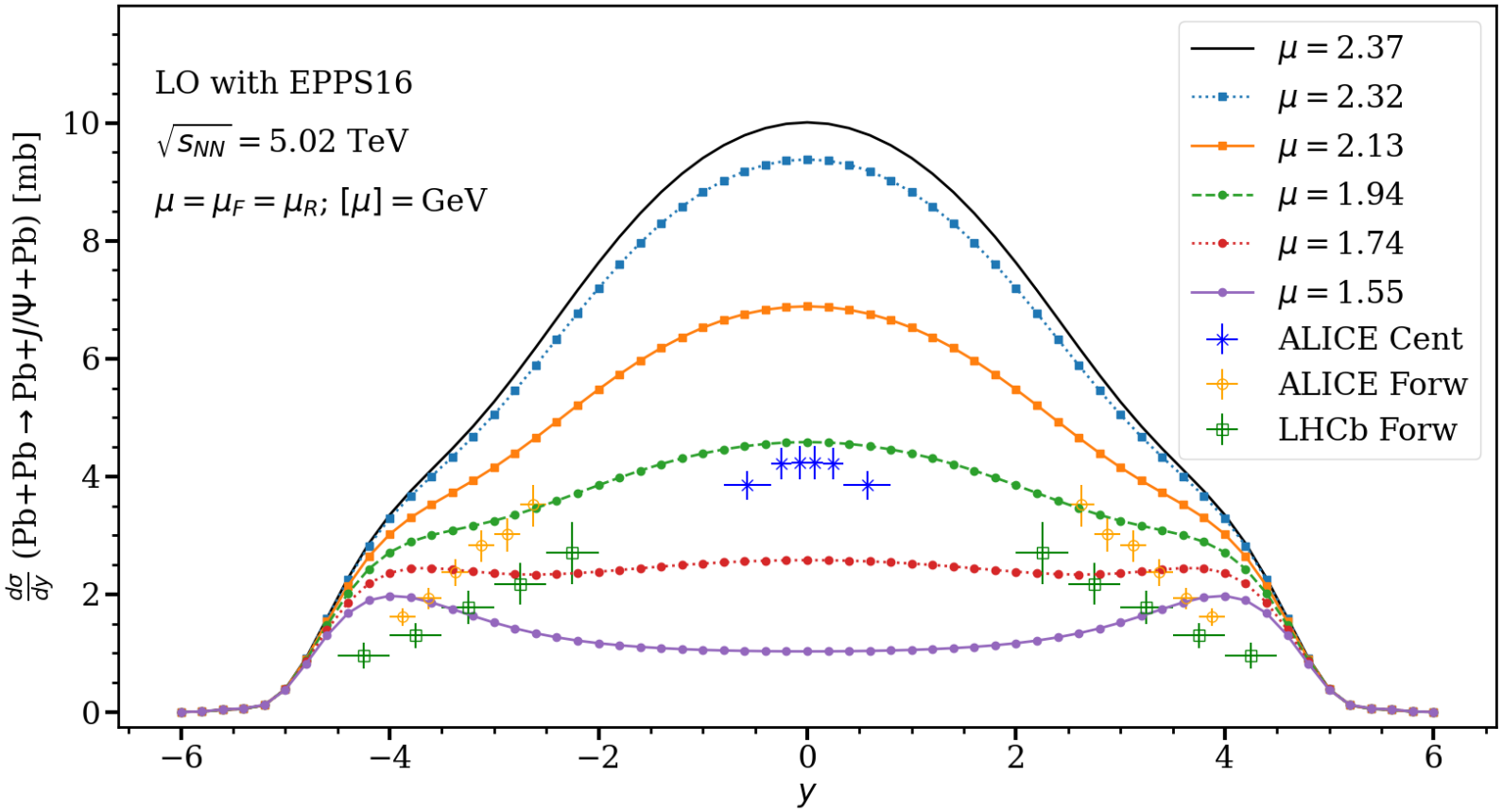
- Nuclear uncertainties moderate. Large free proton uncertainties dominated by single error set.

Summary

- First implementation of NLO pQCD y-differential cross section of exclusive photoproduction of J/ψ in Pb+Pb UPCs.
- Scale dependence in NLO is considerable but an "optimal" scale can be found for EPPS16/nCTEQ15 on the basis of the UPC data.
- In NLO, must account also for Re($\mathcal{M}$).
- LO and NLO gluon amplitudes cancel. At $y = 0$ quarks dominate. Different from LO!
- Nuclear PDF errors are moderate, free proton uncertainties need to be taken into account.
- Next step: more detailed GPD modeling.

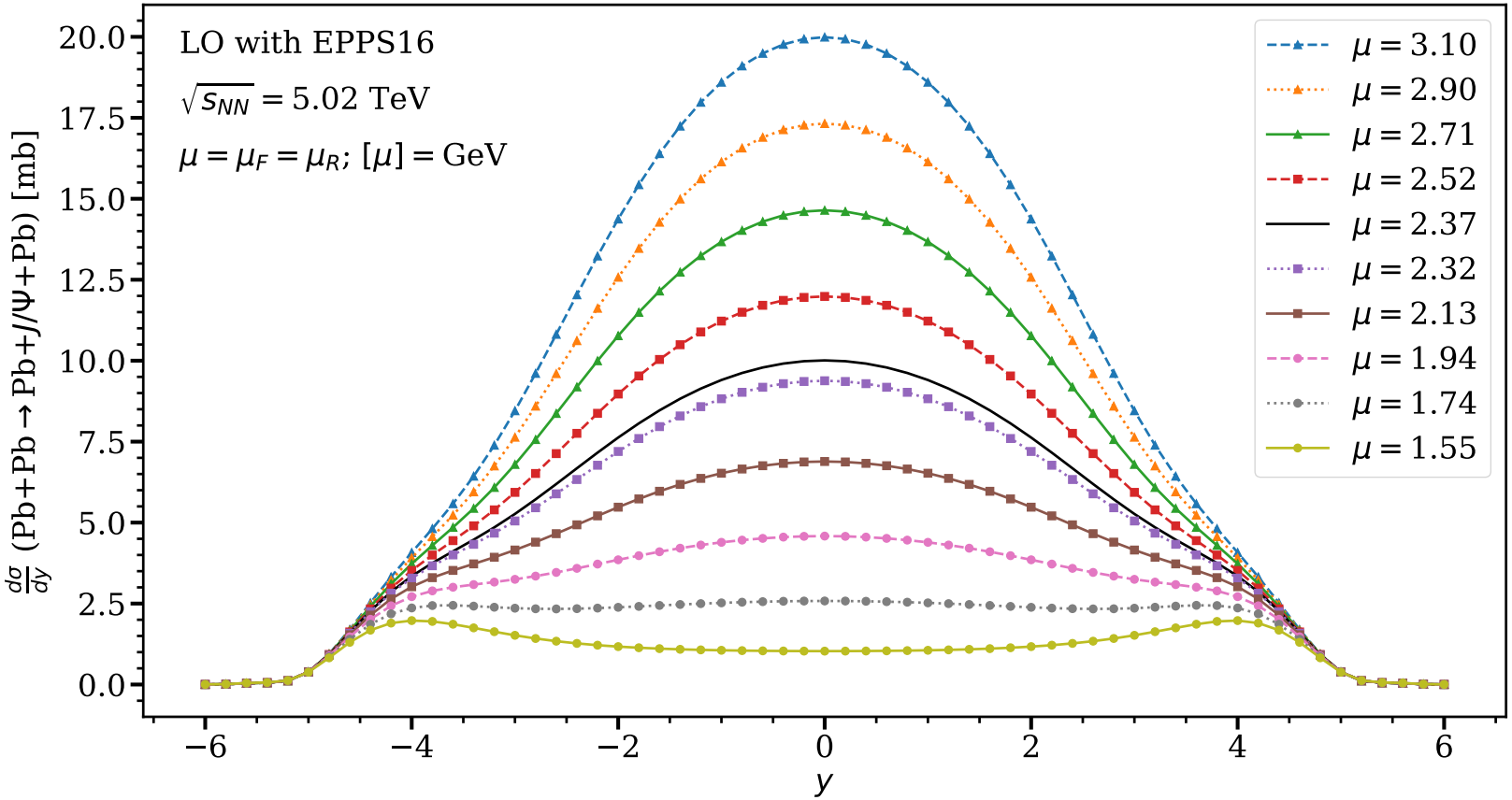
Backup

LO comparison to Data



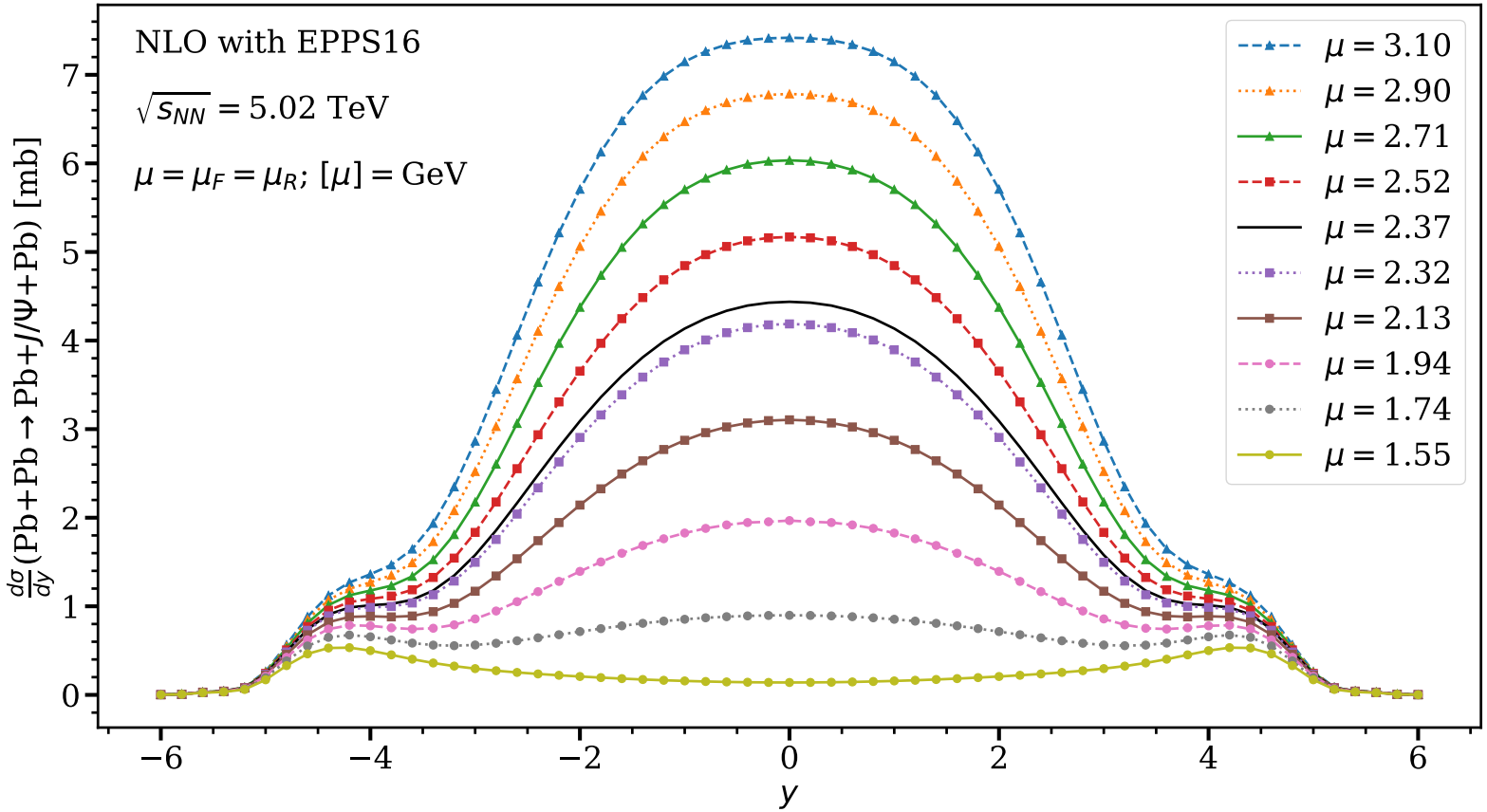
- Hard to reproduce the experimental data with LO.

LO scale dependence



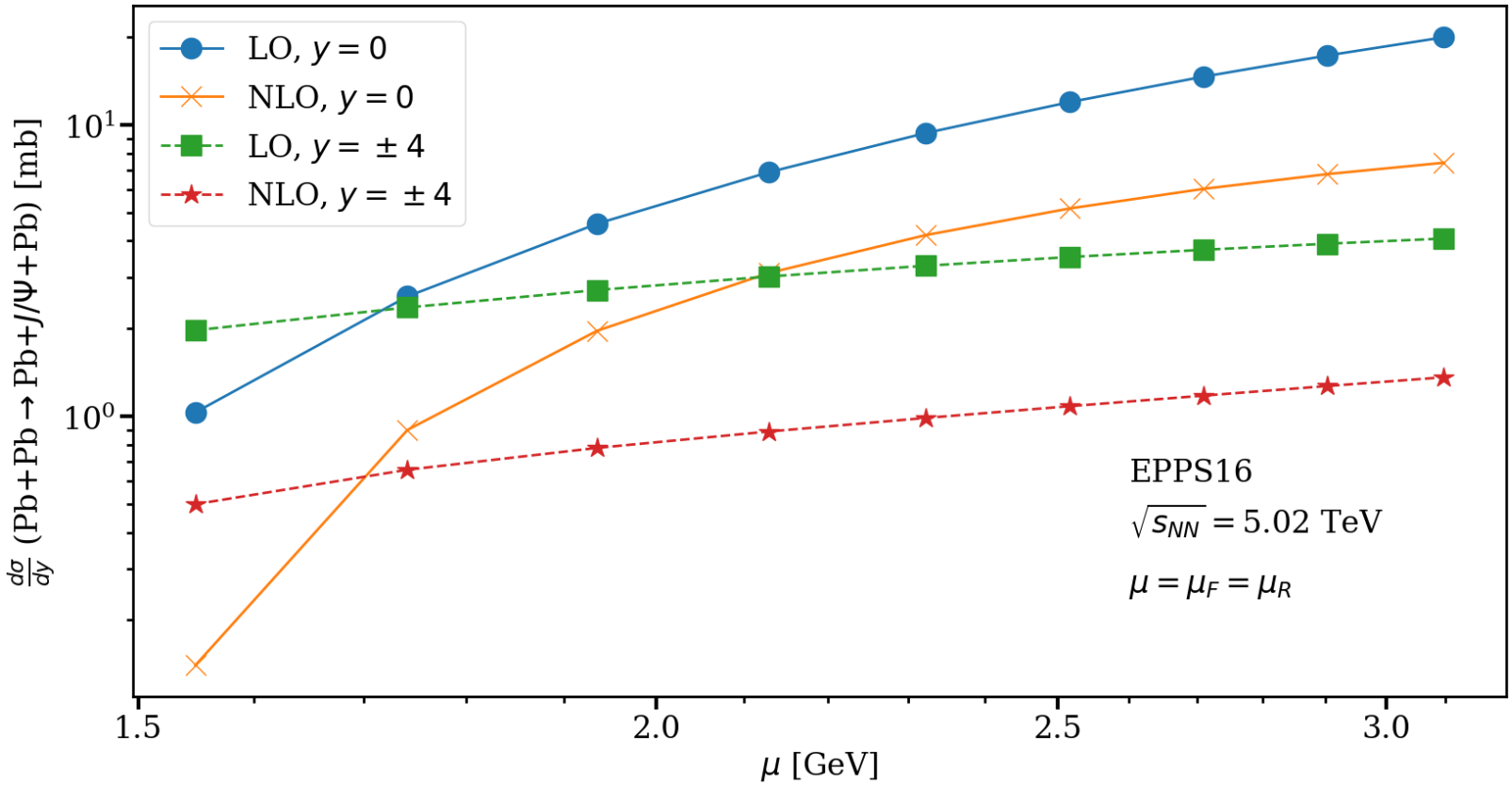
- At $y = 0$ difference between lowest/highest scale about a factor of 20.

NLO scale dependence



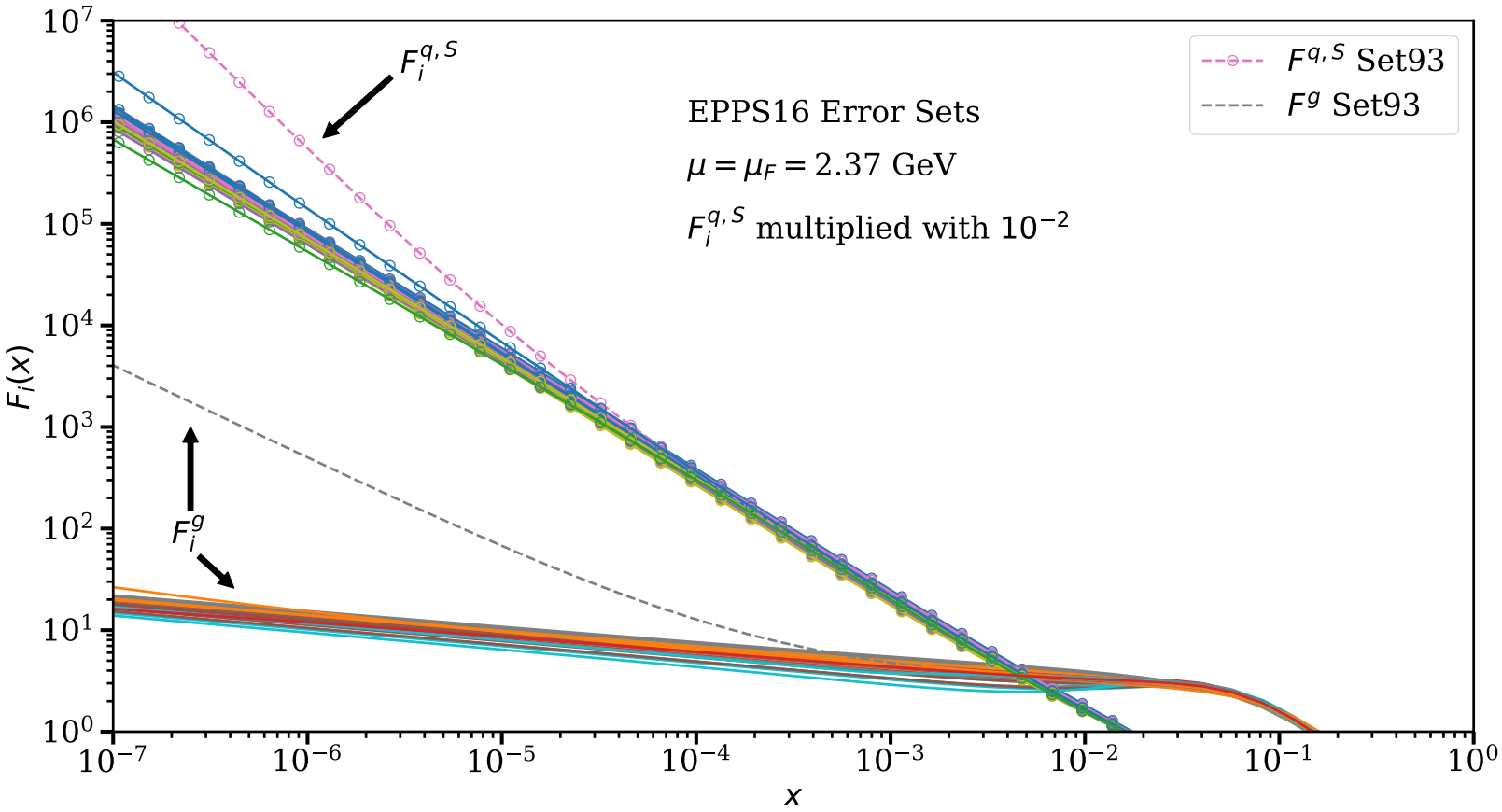
- At $y = 0$ difference between lowest/highest scale about a factor of 50.

Scale dependence at fixed y



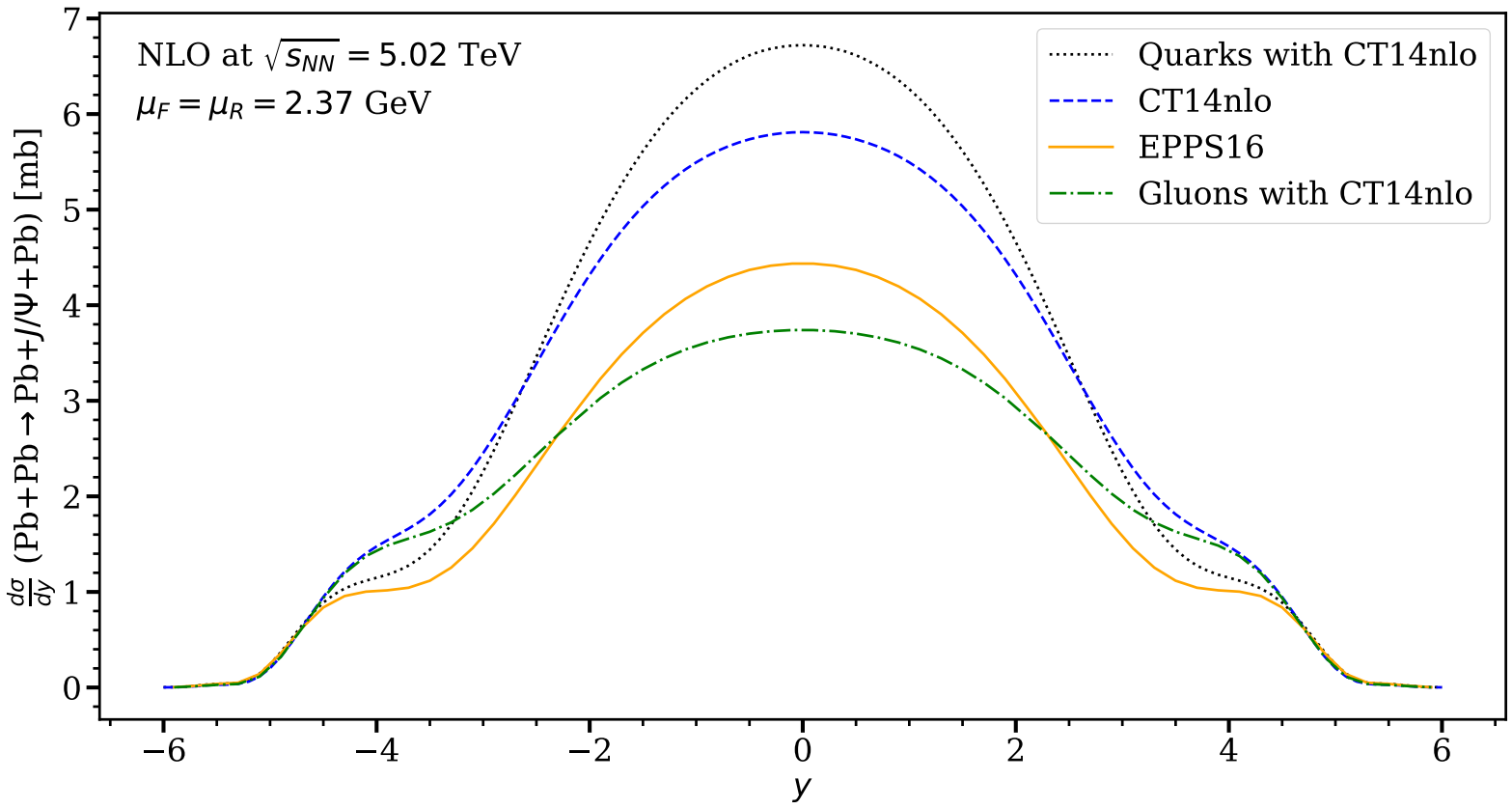
- NLO scale dependence vs LO depends on y.

EPPS16+CT14NLO Error sets



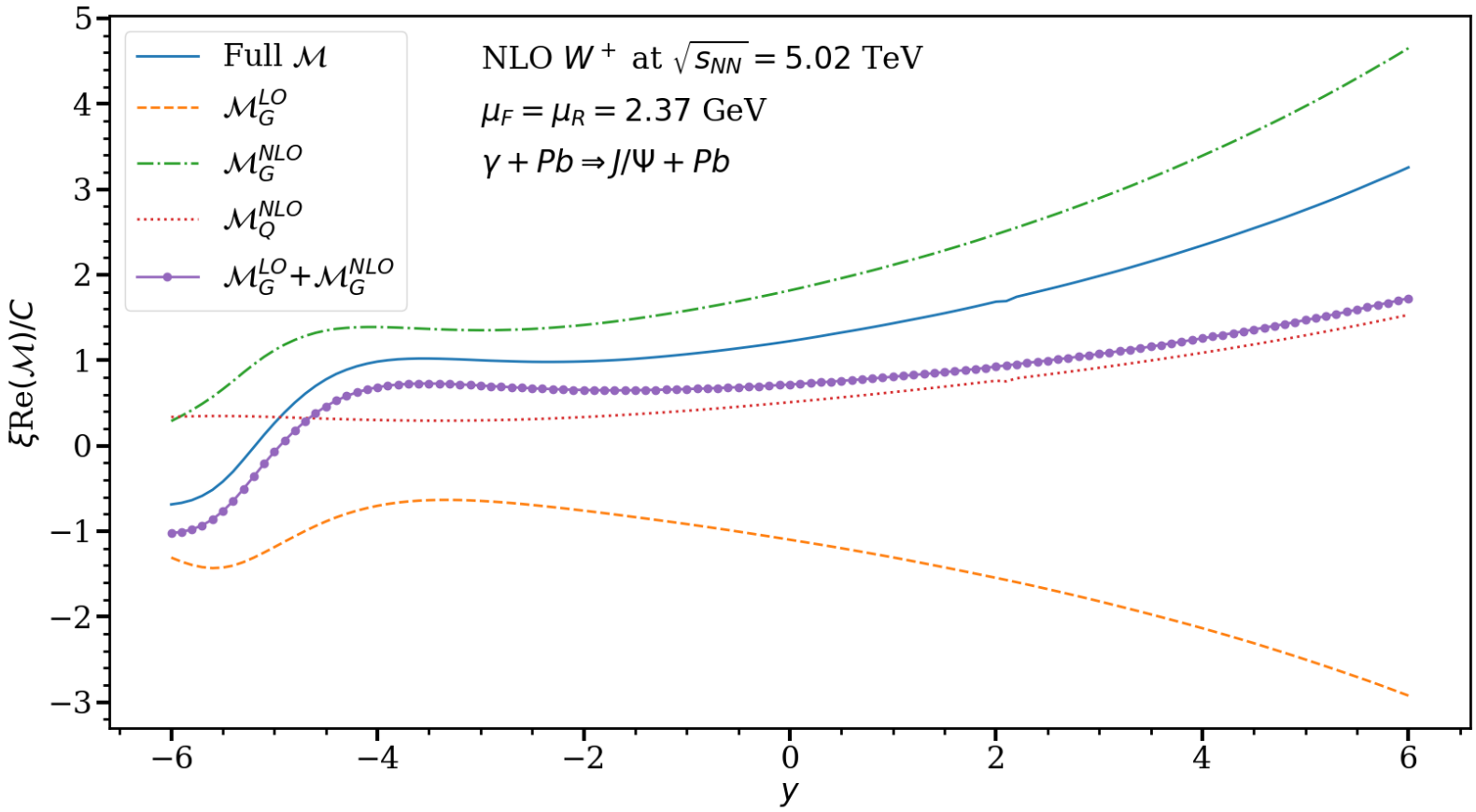
- One error set in CT14NLO stands out from the rest.

Sensitivity to nuclear corrections



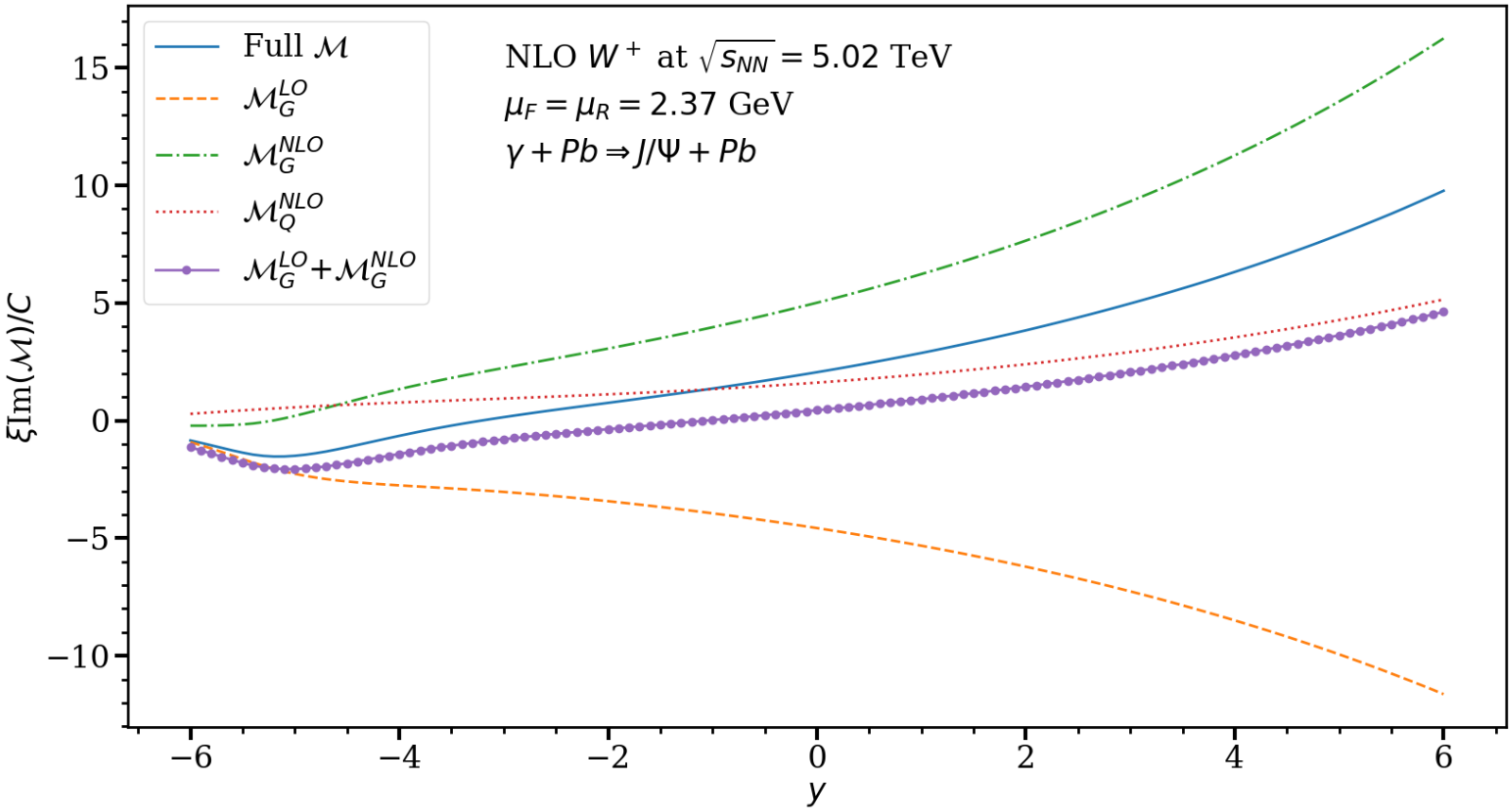
- Nuclear corrections come from the shadowing region. Effect of quark-gluon interference non-trivial.

Real part of photoproduction amplitude



- LO and NLO gluons tend to cancel.

Imaginary part of photoproduction amplitude



- LO and NLO gluons tend to cancel.