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Exclusive J/ψ photoproduction in Pb+Pb UPC collisions to NLO pQCD

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Based on arXiv:2203.11613

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Introduction

- Inclusive processes do not well constrain small x/Regge limit domain of PDFs
- Exclusive processes offer sensitive probe of this domain but as of yet not included in global analyses PDF determination - why?
    1. Off forward kinematics imply susceptibility to *GPD* over conventional PDFs
    2. Reliability and stability of theoretical predictions

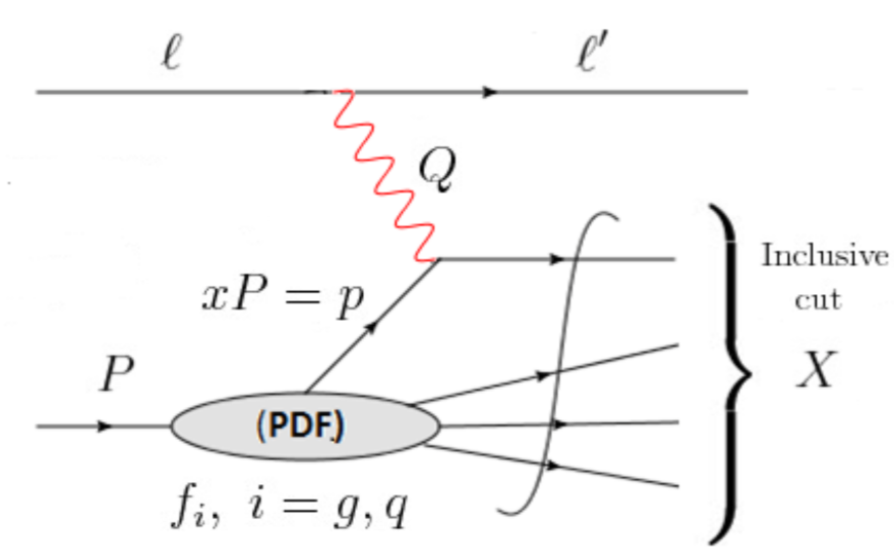
- As higher CM energies are realised at LHC, pushed towards small x domain, W ~ 1/x

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma^* p)\Big|_{t=0} = \frac{\Gamma_{ee}^{J/\psi} M_{J/\psi}^3 \pi^3}{48\alpha_{\mathrm{em}}} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} R_g x g(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

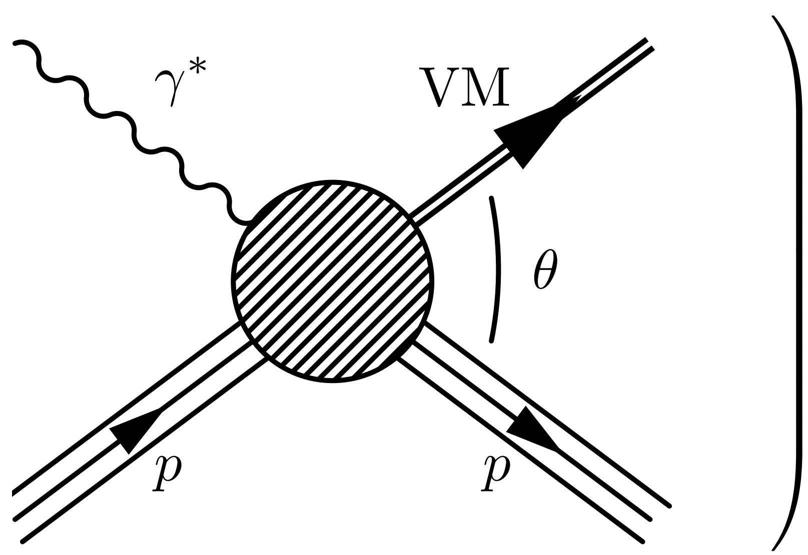
Ryskin 1993

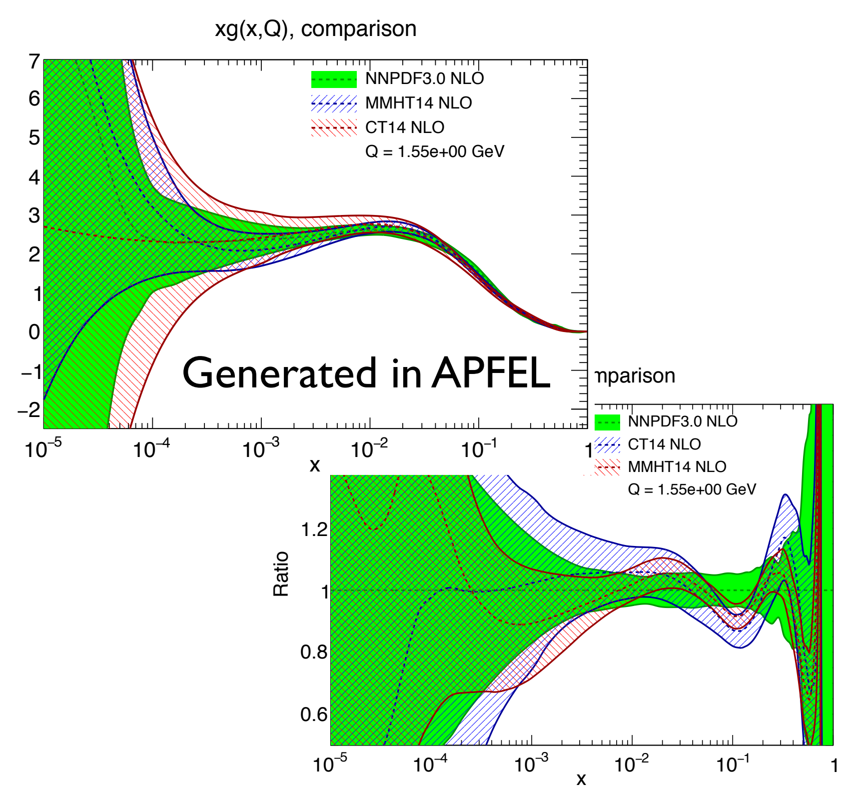
Inclusive - included in global parton analyses

Exclusive - can we use the data?



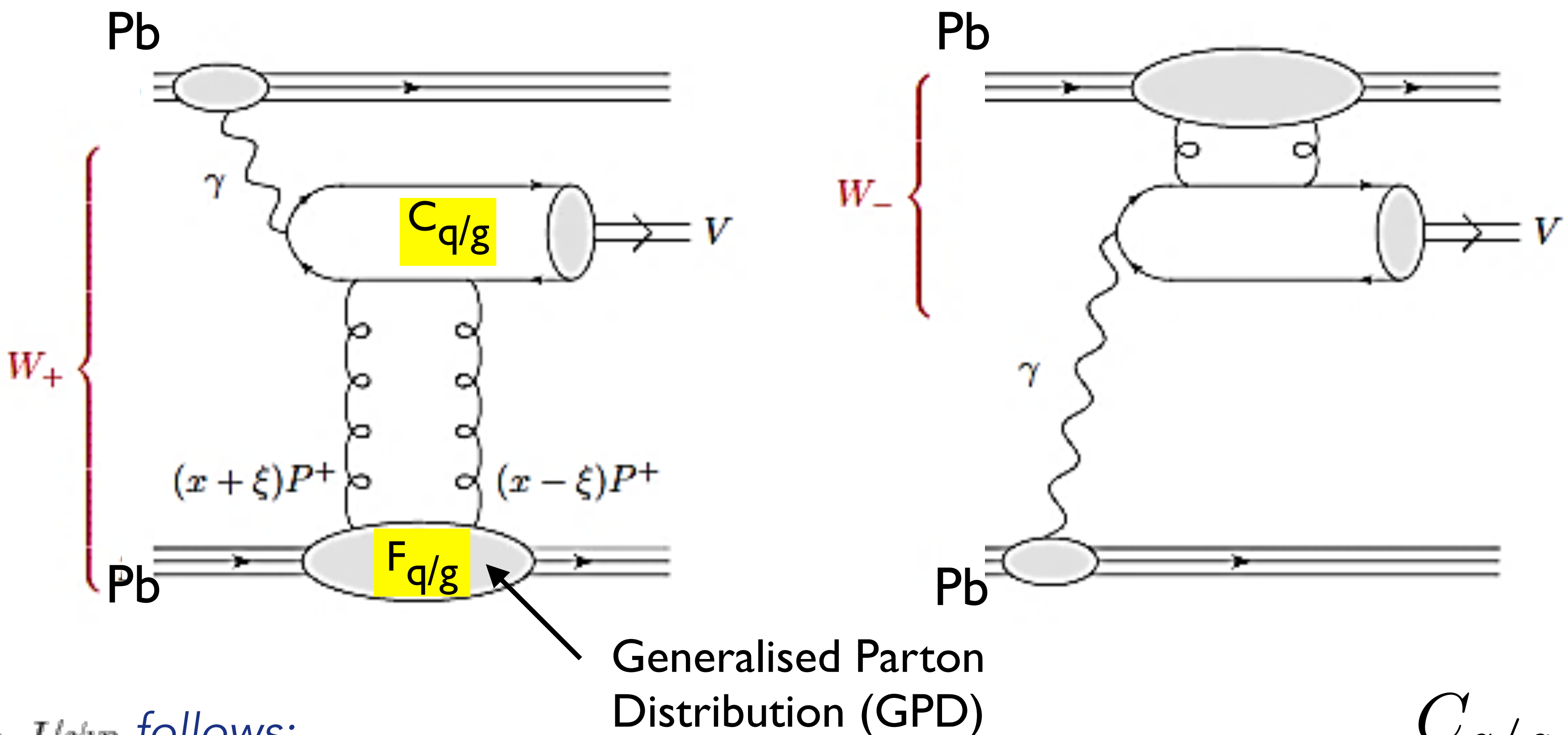
e.g. DIS





General Set up and assumptions

Exclusive J/psi production in Pb+Pb UPC collisions in *conventional* collinear factorisation



Setup for $\gamma p \to J/\psi p$ follows:
Ivanov, Schäfer, Szymanowski, Krasnikov, 04

$C_{q/g}$

Photoproduction:
- hep-ph/0401131

Electroproduction:
- arXiv:1903.00171
- arXiv:2105.07657

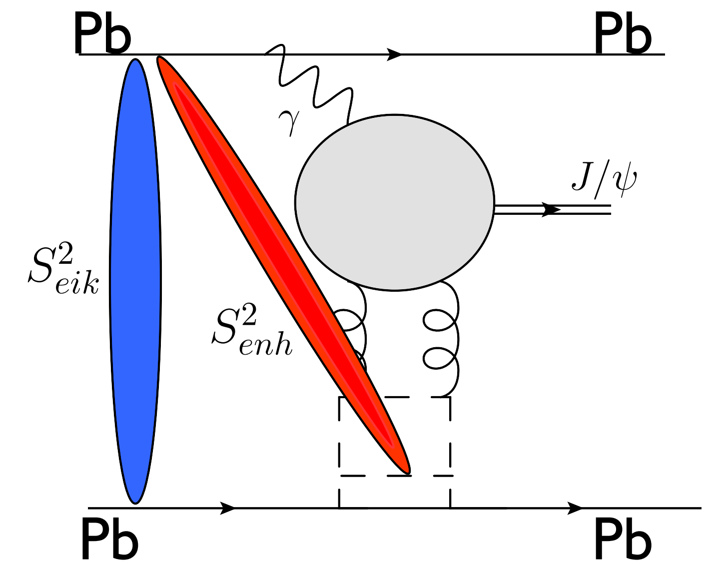
- Assume a factorisation $\quad F_{q/g} \otimes C_{q/g} \otimes \phi^V_{Q\bar{Q}}$
- Leading zeroth order term in rel. velocity (NRQCD)
- Colour singlet exchange between hard and soft sectors

$$A \propto \int_{-1}^{1} \mathrm{d}x \left[C_g(x,\xi) F_g(x,\xi) + \sum_{q=u,d,s} C_q(x,\xi) F_q(x,\xi) \right]$$

Framework

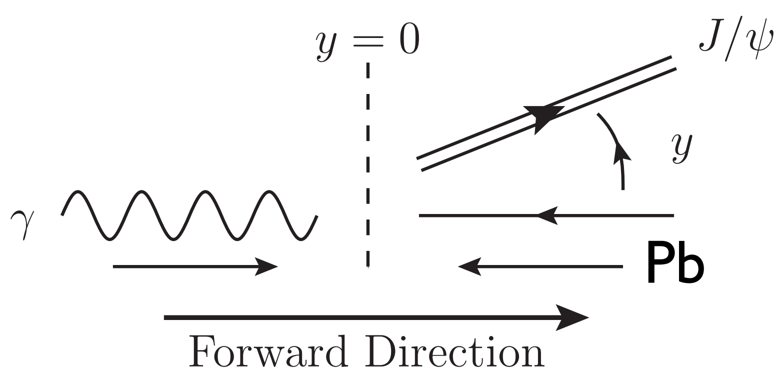
Rapidity differential cross section:

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

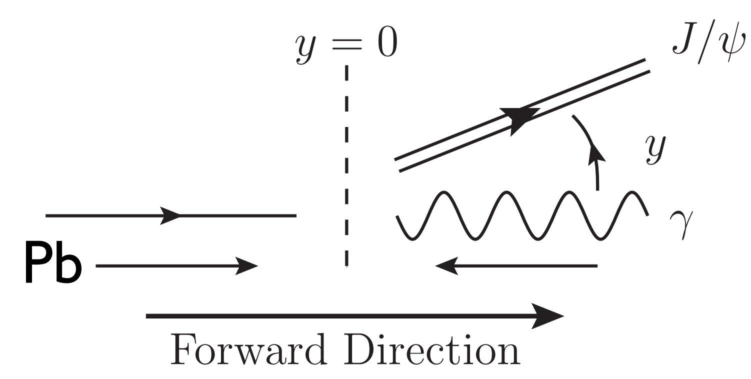


Photon flux / survival factor

For a given rapidity y, have photons of energy $k_\pm = \frac{M_{J/\psi}}{2}\exp(\pm y)$ in configuration $W_\pm$



W_+



W_-

Hard scattering cross section:

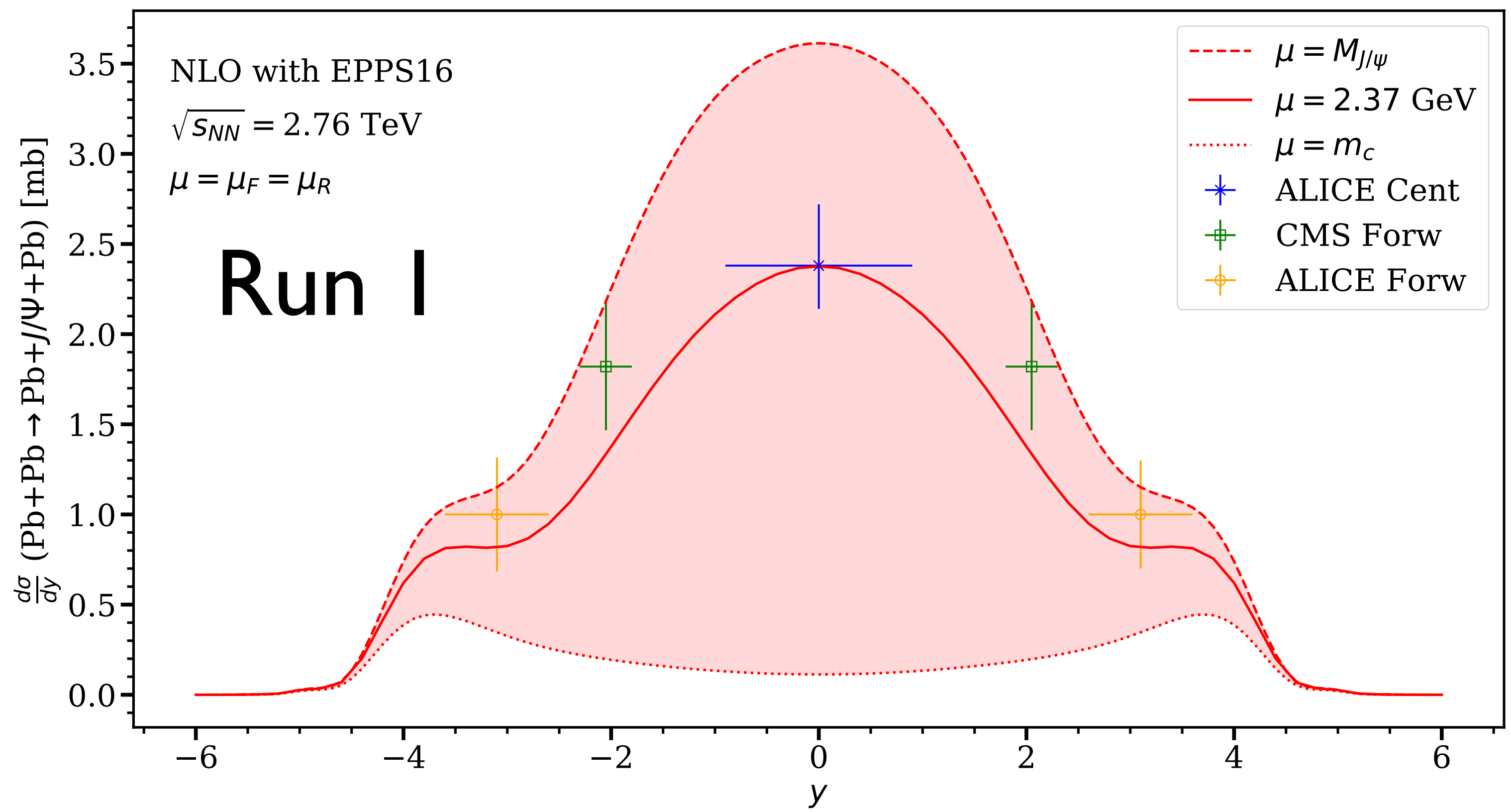
$$\sigma^{\gamma A\to VA} = \left.\frac{d\sigma^{\gamma N\to VN}}{dt}\right|_{t=0}\int_{t_{min}}^{\infty} dt'\ |F_A(-t')|^2$$

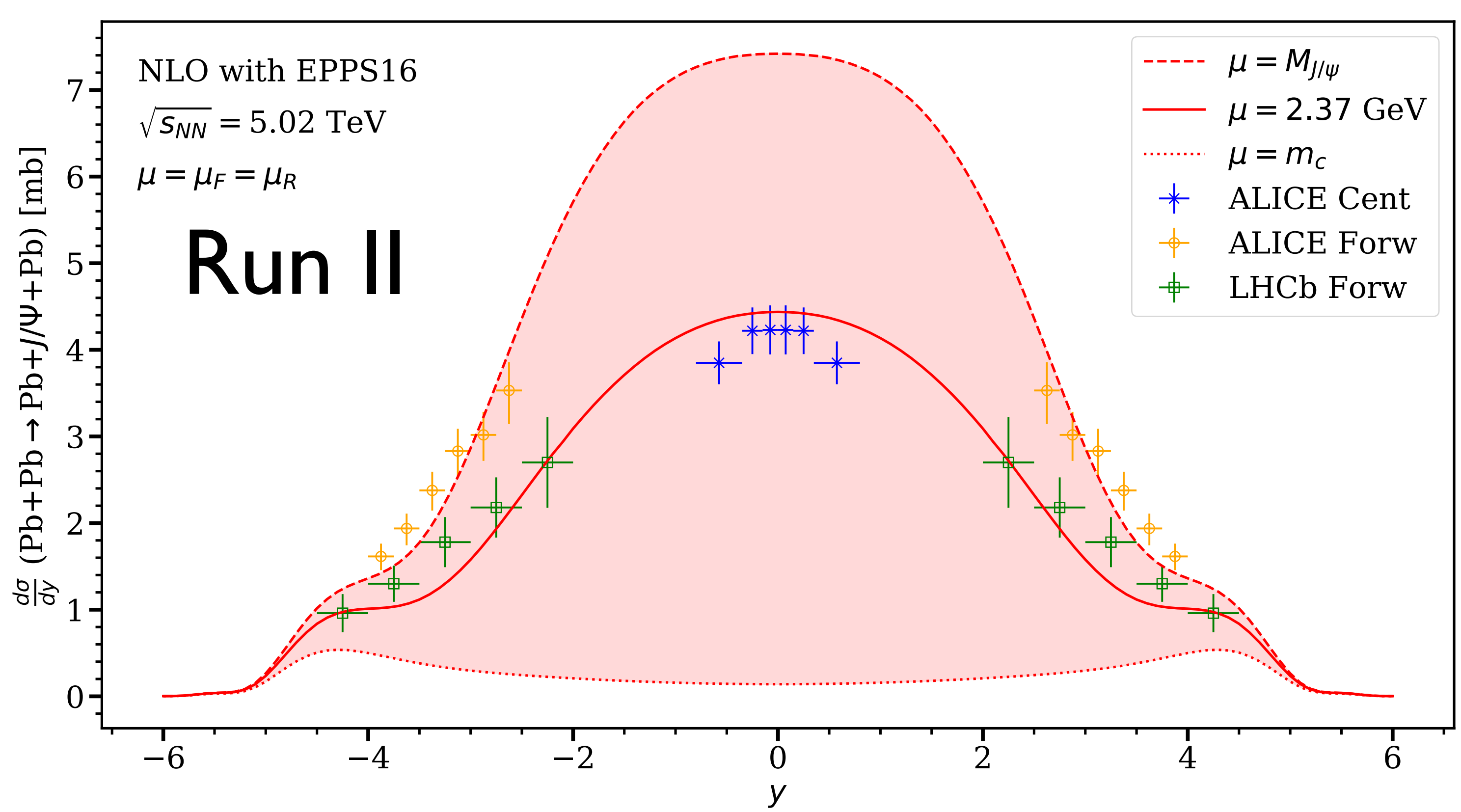
Nuclear form factor

Baseline: GPDs in forward limit

Numerical results checked in two different ways

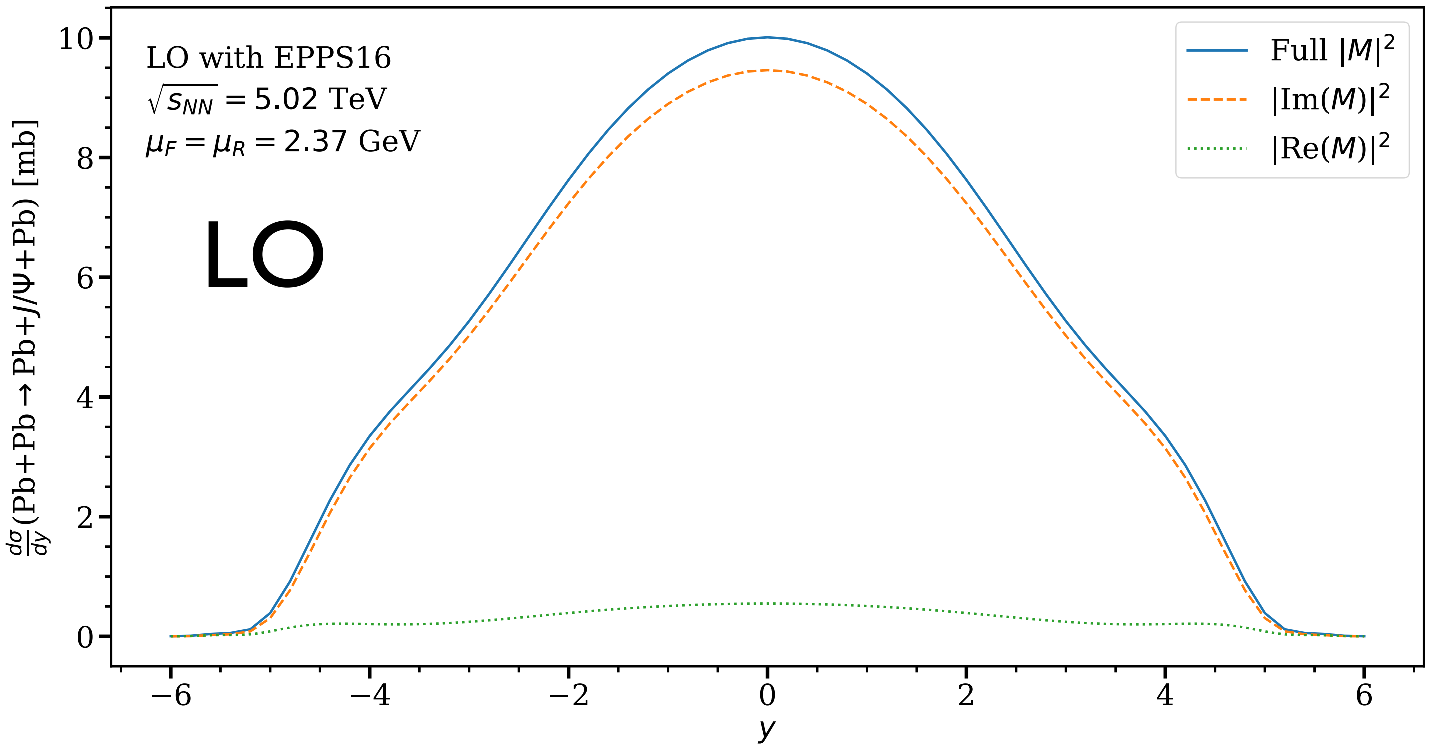
Scale dependence at NLO



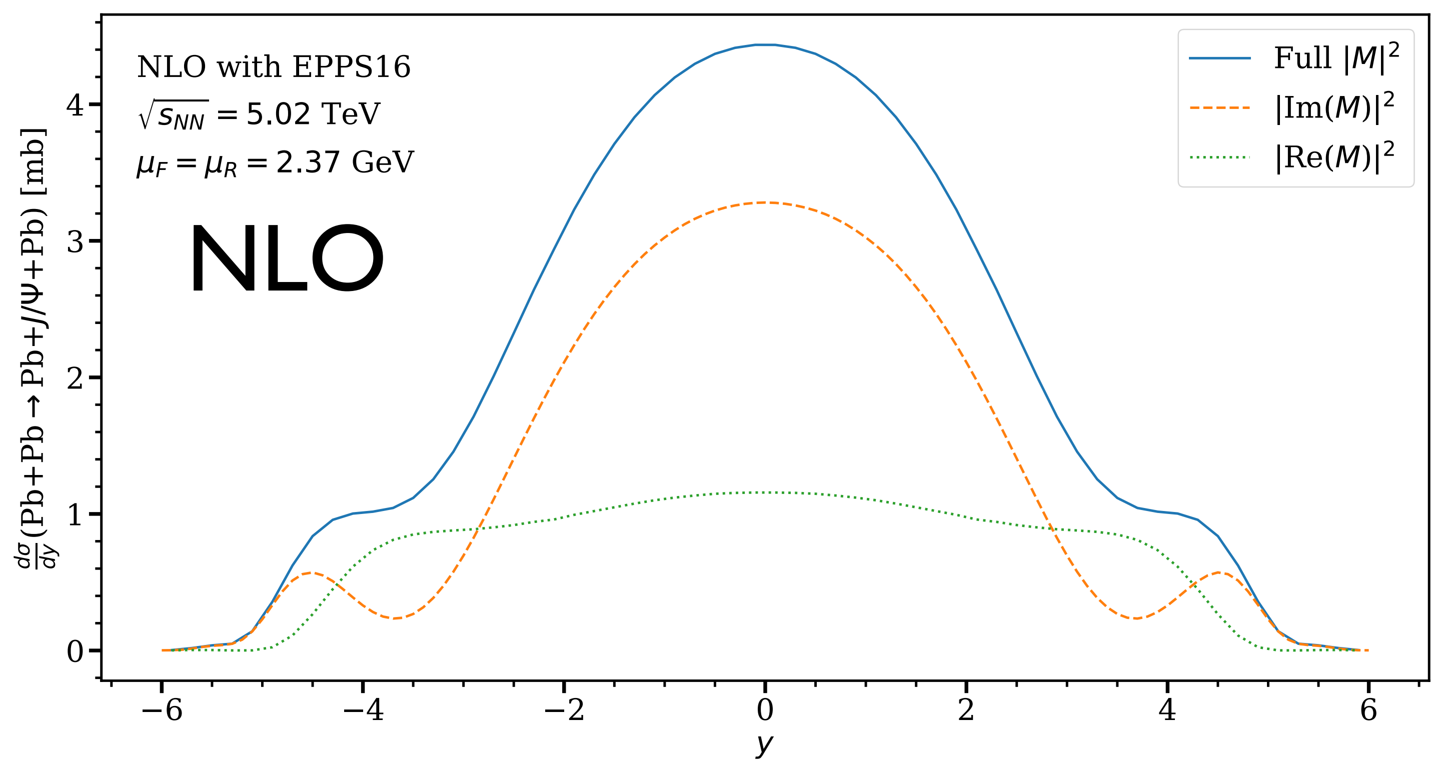


- Scale dependence large (!)
- ‘Optimal scale’: fitted to reproduce the data at both Run I and Run II energies
- Large scale variation consistent with results in hep-ph/0401131

Decomposition LO and NLO Re and Im

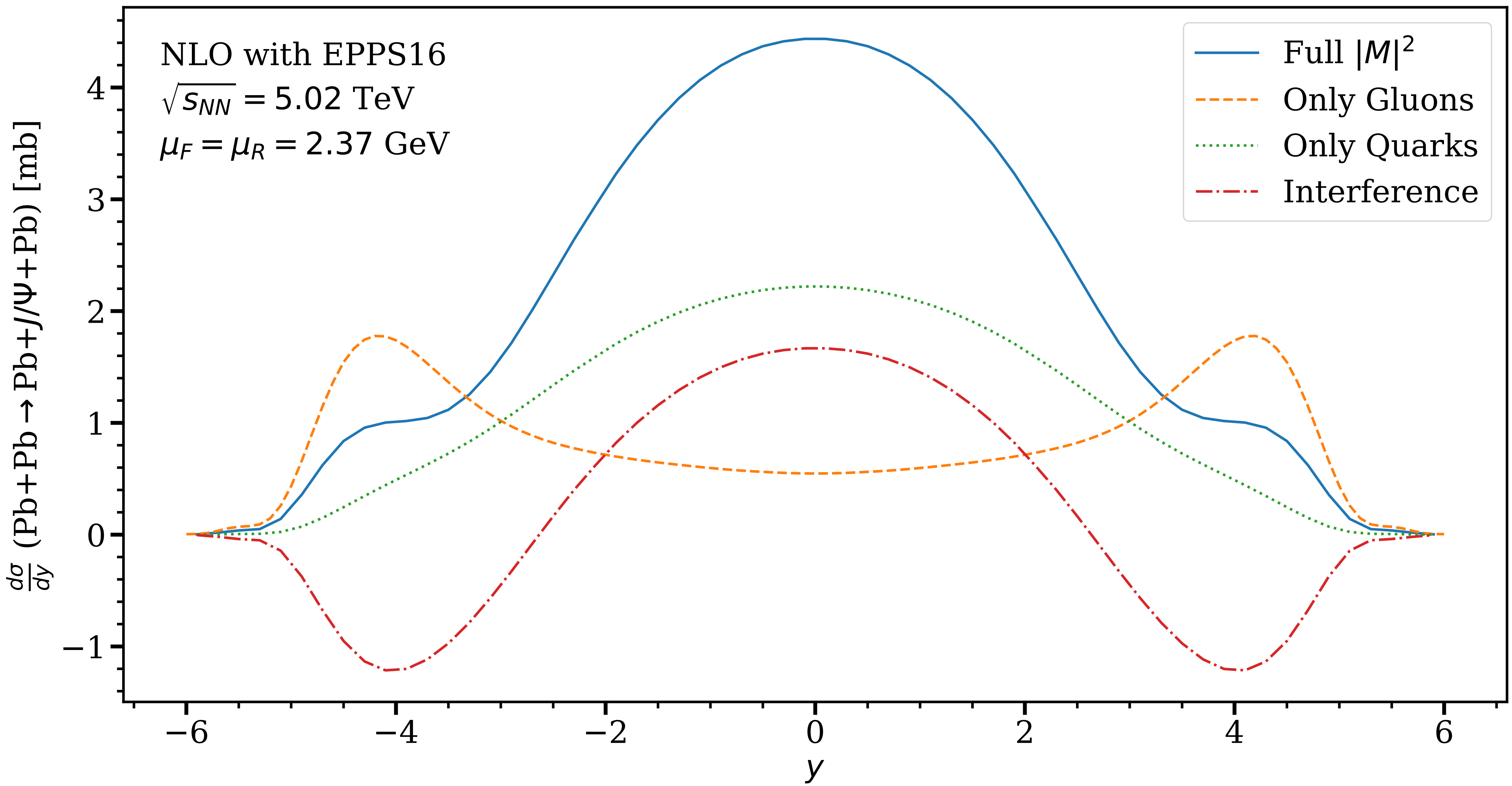


- At LO imaginary part of amplitude dominates



- At NLO, real part not negligible
- See also hep-ph/0401131

Interplay of quark and gluon at NLO

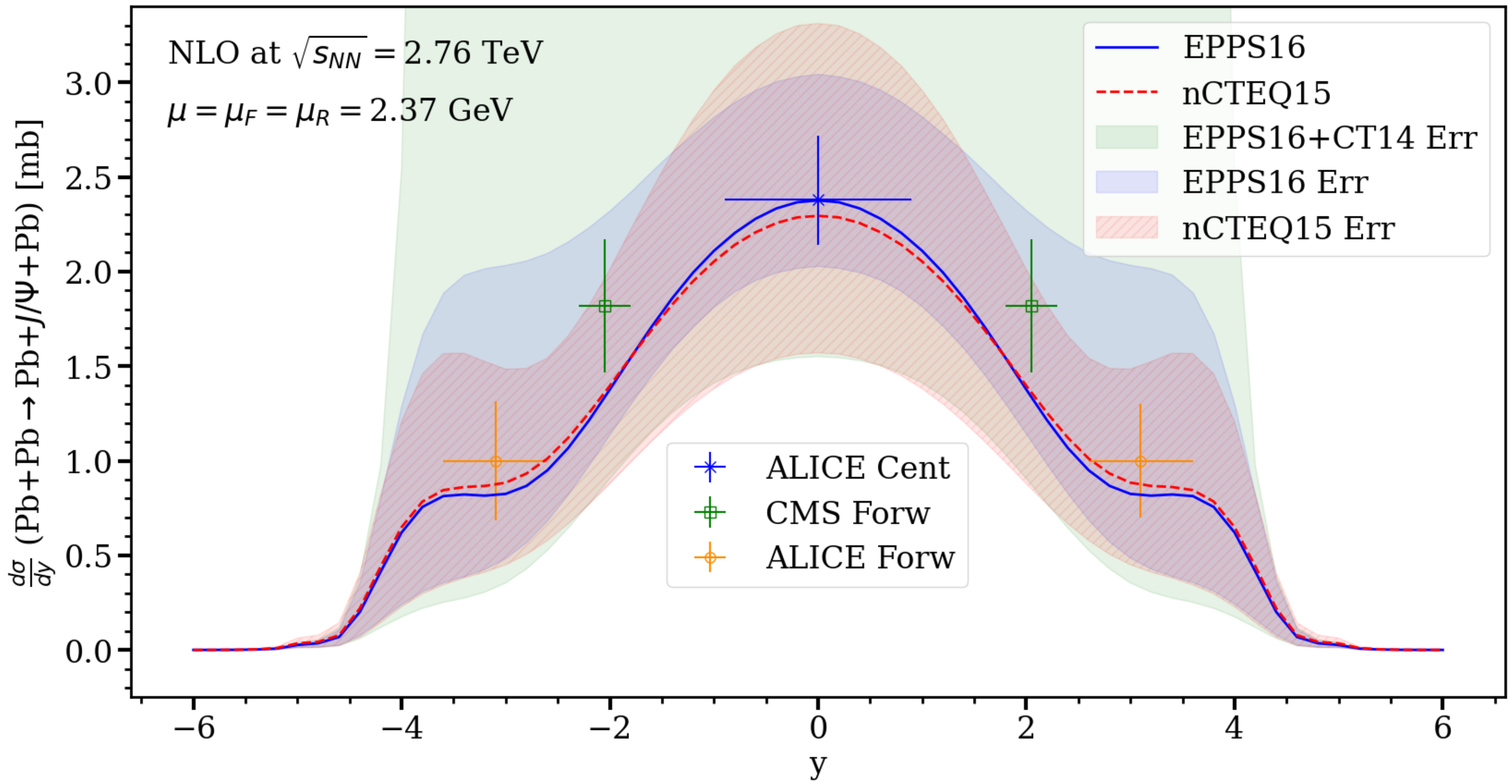


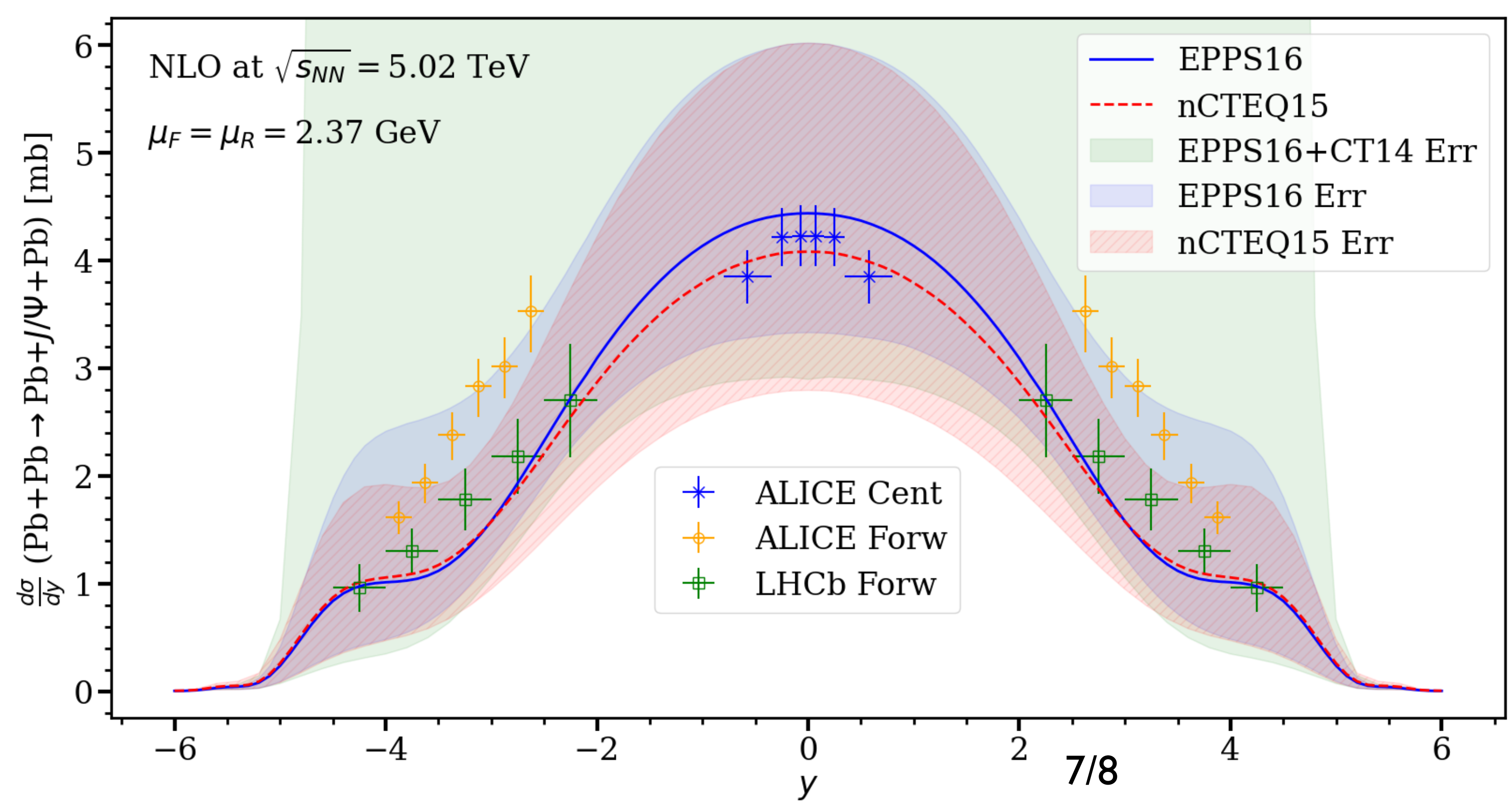
Quark contribution dominant at mid-rapidity (!)

Structure of amplitude detailed, interplaying between photoproduction cross section, photon flux, form factor and $W_{\pm}$ components

Key: Cancellation of LO and NLO gluon amplitudes due to opp. signs

Comparison with data





- Nuclear uncertainties encompass available data both at Run I and Run II energies nicely
- Free proton uncertainties large and dominated by single error set
- Tension between Run II ALICE and LHCb data at forward rapidities

Conclusions and Outlook

- Implementation of NLO collinear factorisation to exclusive photoproduction of J/psi in PbPb UPCs

Noteworthy features:

-*Large* scale dependence

-Quarks dominate at mid rapidity at NLO

→ Discouraging… what use?

- Exclusive J/psi production in a *tamed* collinear factorisation

-Q_0 subtraction and resummation

→ Upshot: all hope not lost!

-*Mild* scale dependence

-Quark contribution small (~0)

See plots →

Framework: Tamed collinear factorisation + Shuvaev(PDF) + NRQCD

-Allowed for a meaningful comparison of new and improved theory prediction with data in pp UPCs and therefore extraction of low x gluon PDF

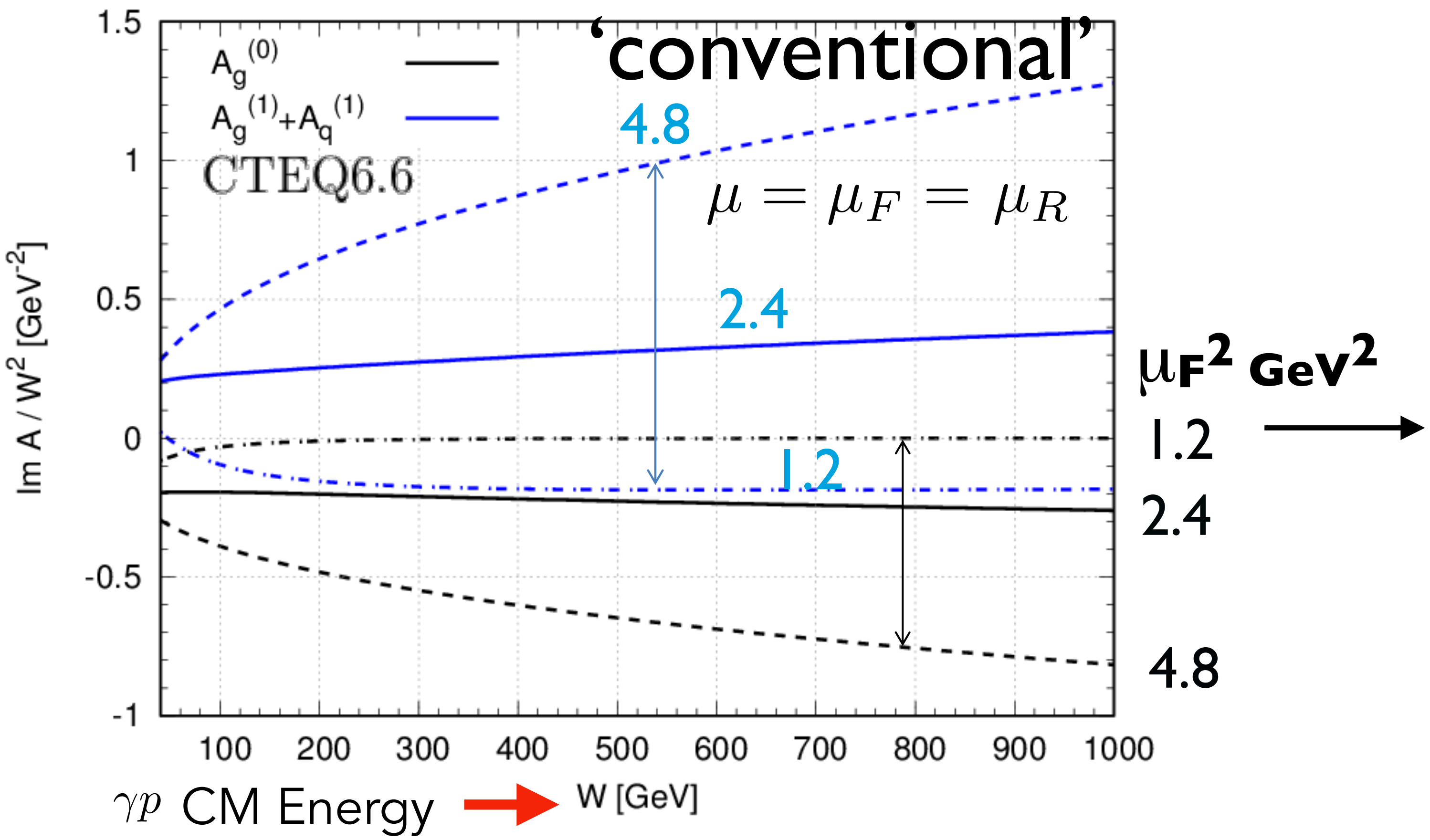
arXiv: 1908.08398

arXiv: 2006.13857

-Extend refined framework built originally for p+p to Pb+Pb

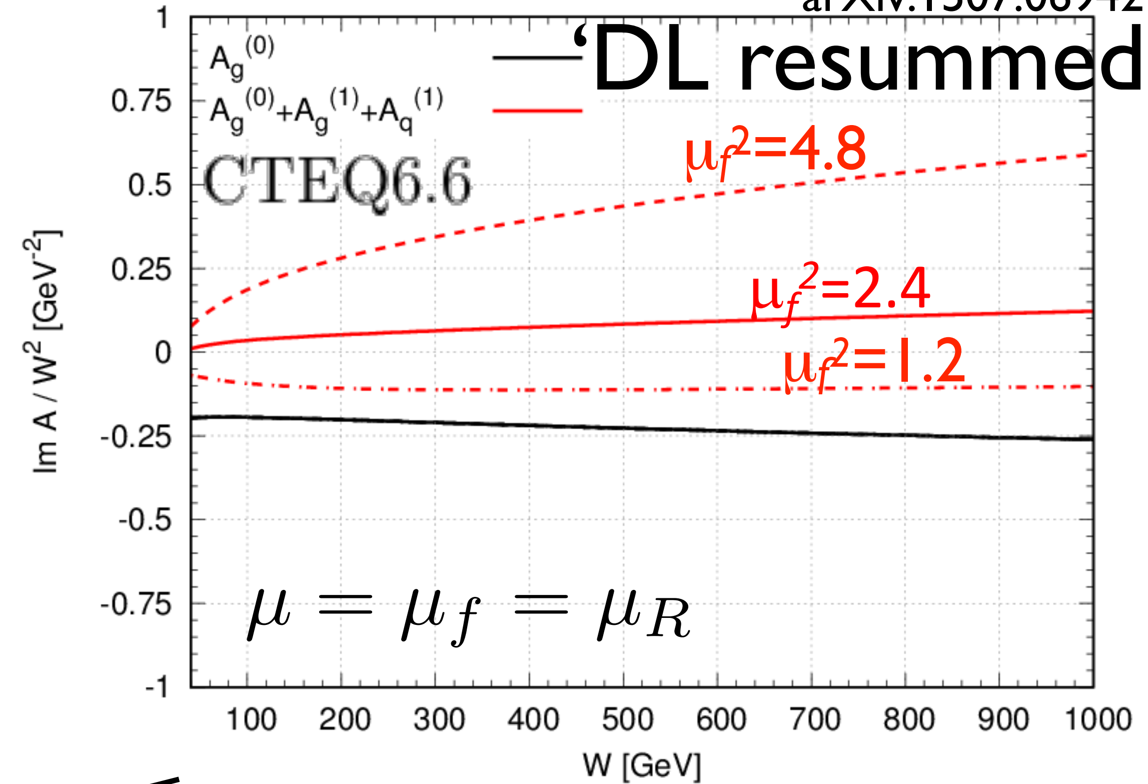
…extension to p+Pb in this framework, *in preparation*

Stability of prediction



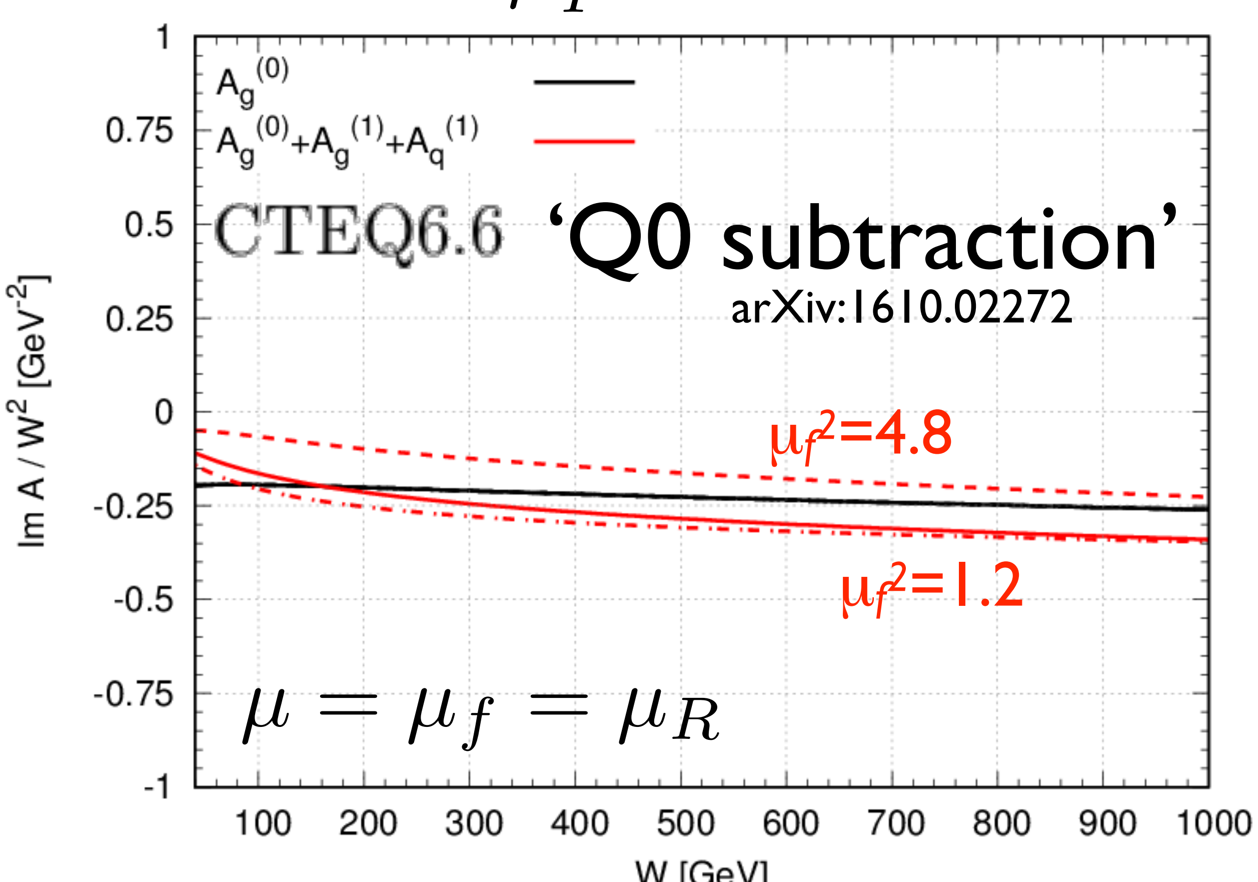
Fix: $\mu_F^2 = 2.4\ \mathrm{GeV}^2$

arXiv:1507.06942



$\sim(\alpha_s \ln(1/\xi) \ln(\mu_F/m))^n$

Fix: $\mu_F^2 = 2.4\ \mathrm{GeV}^2$

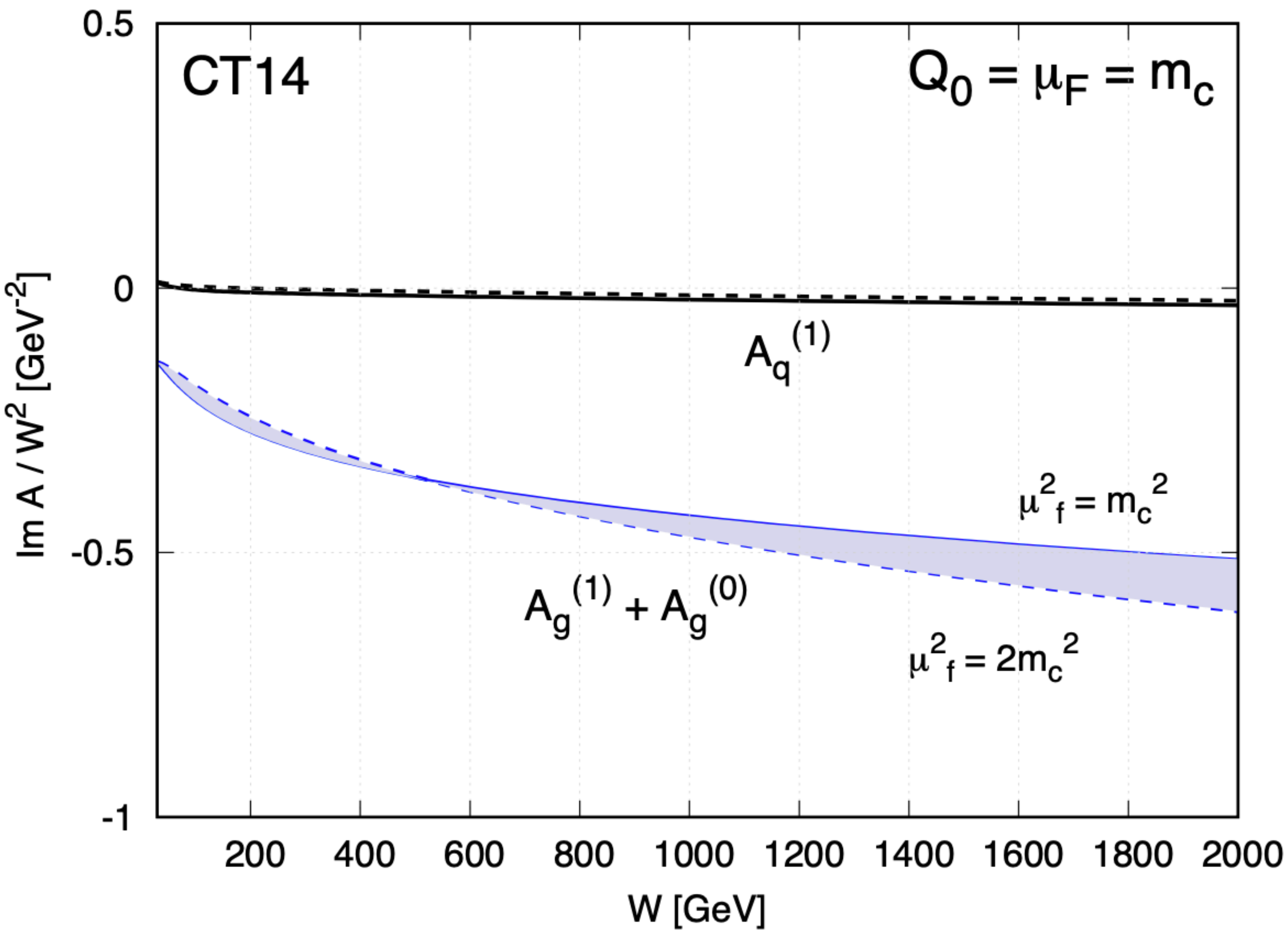


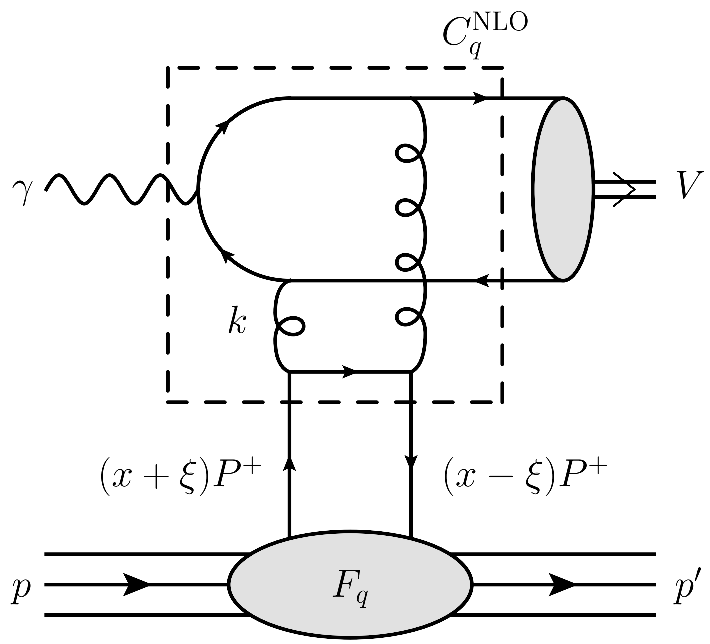
Subtract DGLAP contribution
NLO ($|\ell^2| < Q_0^2$)
from known NLO MSbar coefficient function to avoid a double count with input GPD at Q_0.

Typically power suppressed, but sizeable here: $\mathcal{O}(Q_0^2/M_{J/\psi}^2)$

Interplay of quark and gluons at NLO

After Q_0 subtraction:





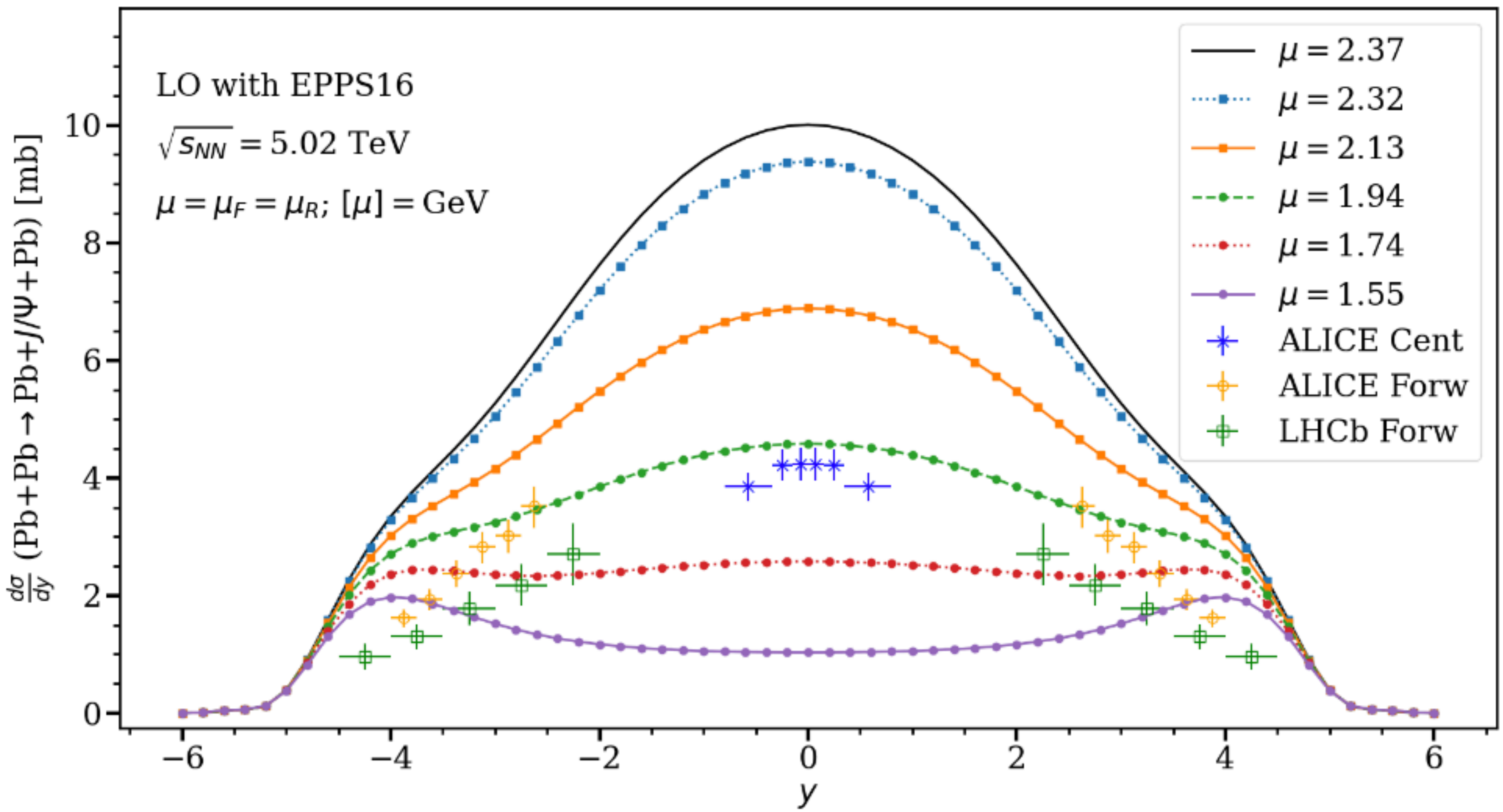
arXiv: 1908.08398

Quark contribution separated from hard scattering by at least *one* step of DGLAP evolution and is therefore removed after imposition of Q_0 subtraction

⟶ Gluon driven again like at LO

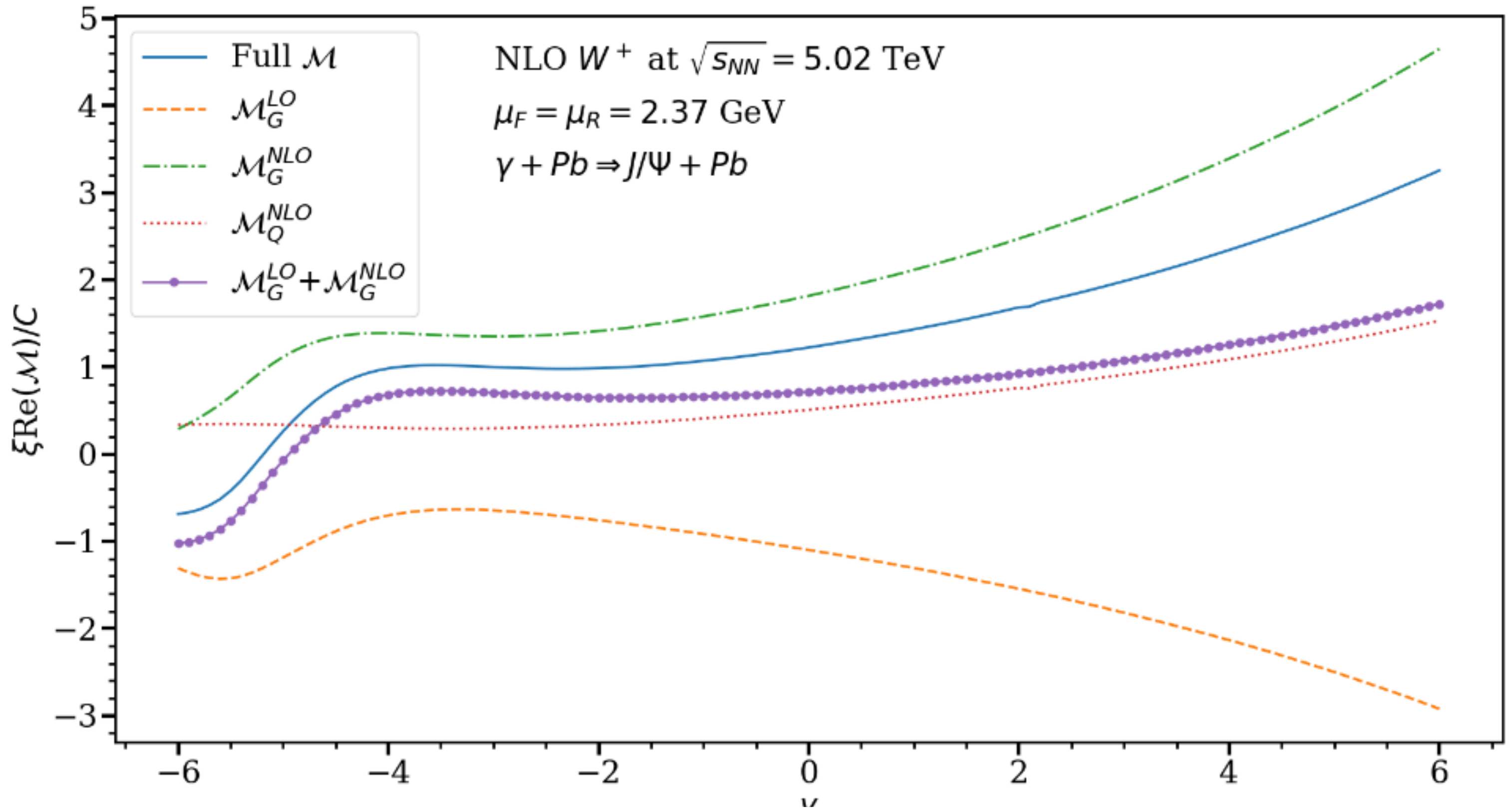
Backups

LO Scale dependence & comparison to data

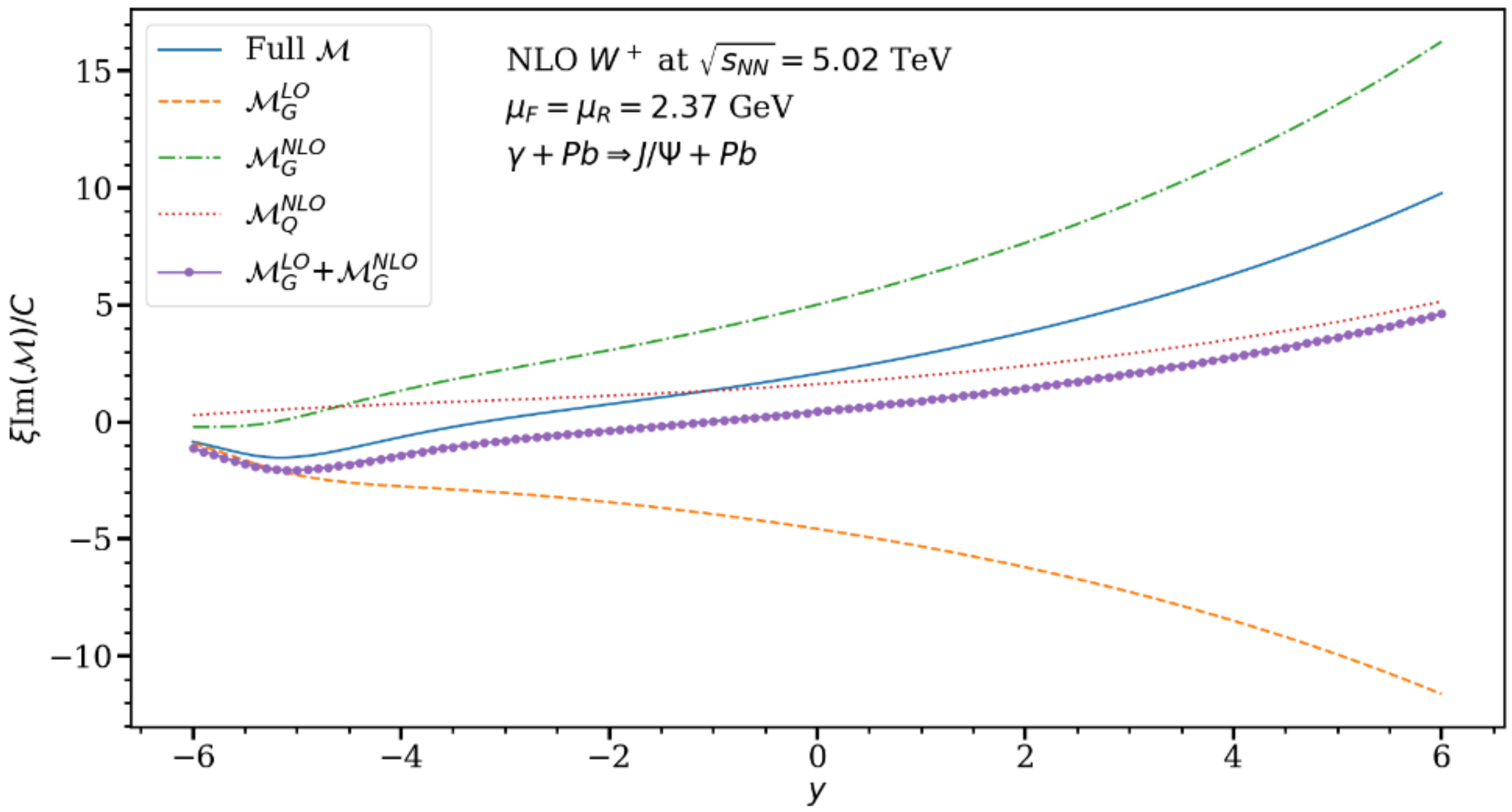


LO and NLO amplitudes

Re:



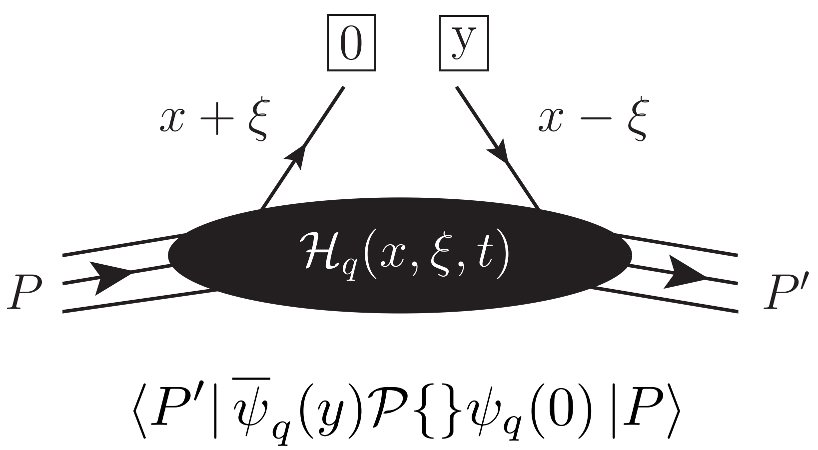
Im:



GPDs and the Shuvaev transform

GPDs generalise PDFs: outgoing/incoming partons carry different momentum fractions

Müller 94; Radyushkin 97; Ji 97



Shuvaev: Relates GPDs to PDFs at small x under physically motivated assumptions c.f analyticity

Shuvaev 99 Martin et al. 09

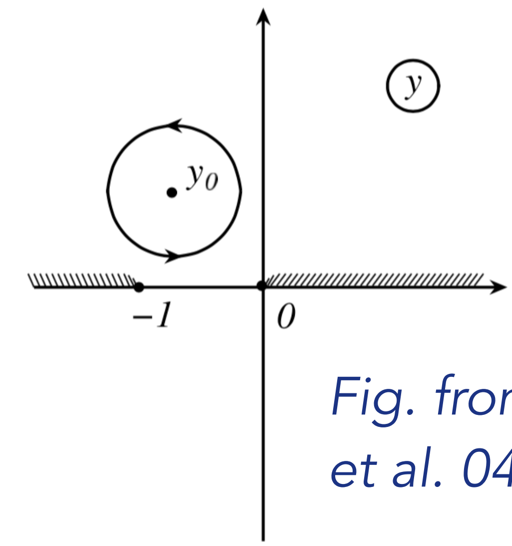


Fig. from Ivanov et al. 04

Idea: Conformal moments of GPDs = Mellin moments of PDFs

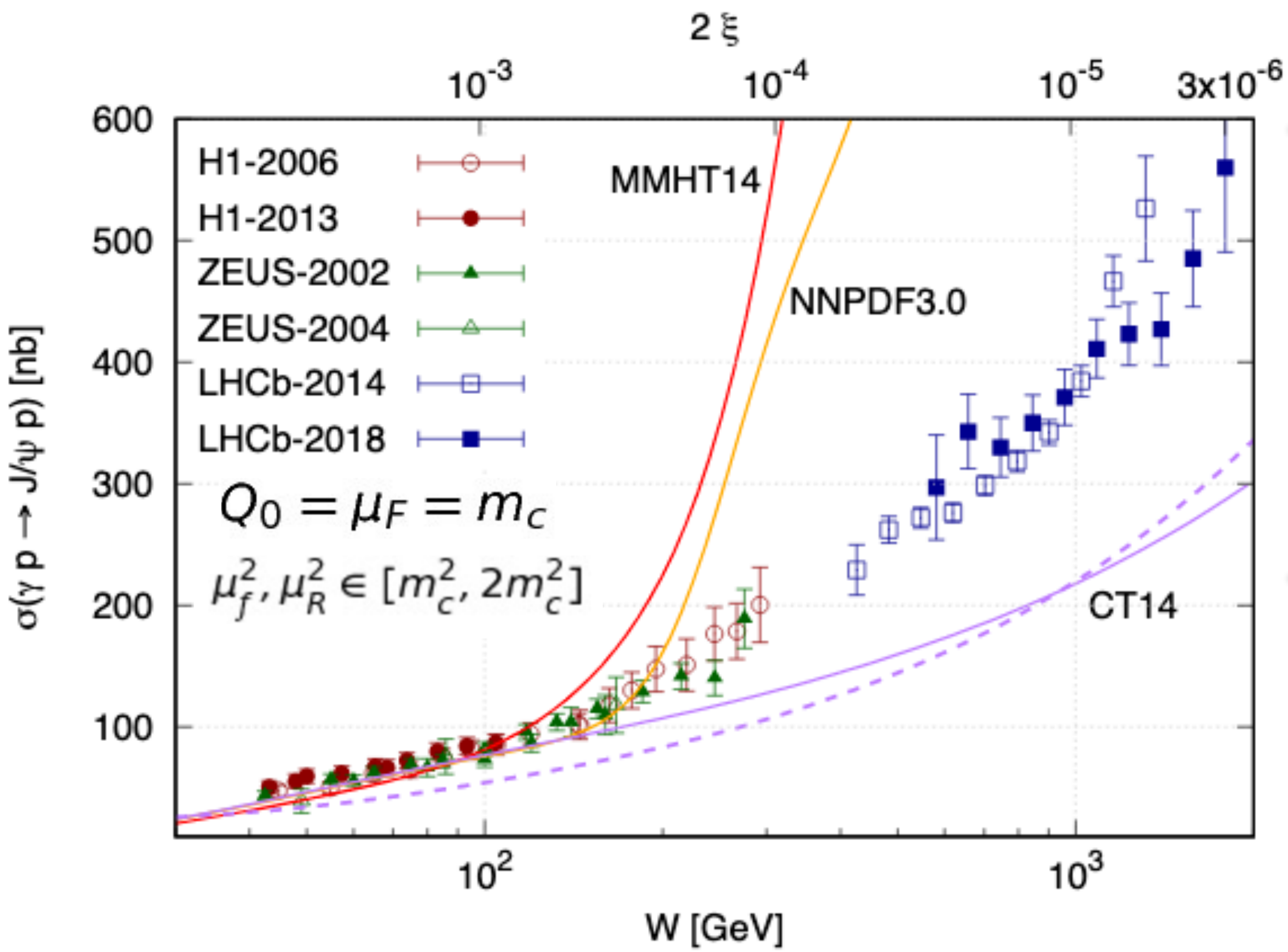
(up to corrections of order xi^2)

- Construct GPD grids in multidimensional parameter space x,xi/x,qsq with forward PDFs from LHAPDF
- Costly computationally due to slowly converging double integral transform
- Regge theory considerations => Shuvaev transform valid in space like (DGLAP) region only. In time like (ERBL) region imaginary part of coefficient is zero

Towards the bigger picture

Plot demonstrates good scale stability of our NLO predictions in LHCb regime

Predictions at optimal scale (solid) agree better with HERA data



CAF, S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1907.06471 & 1908.08398

Diversity between predictions based on current global PDFs in unconstrained phase space -> important message

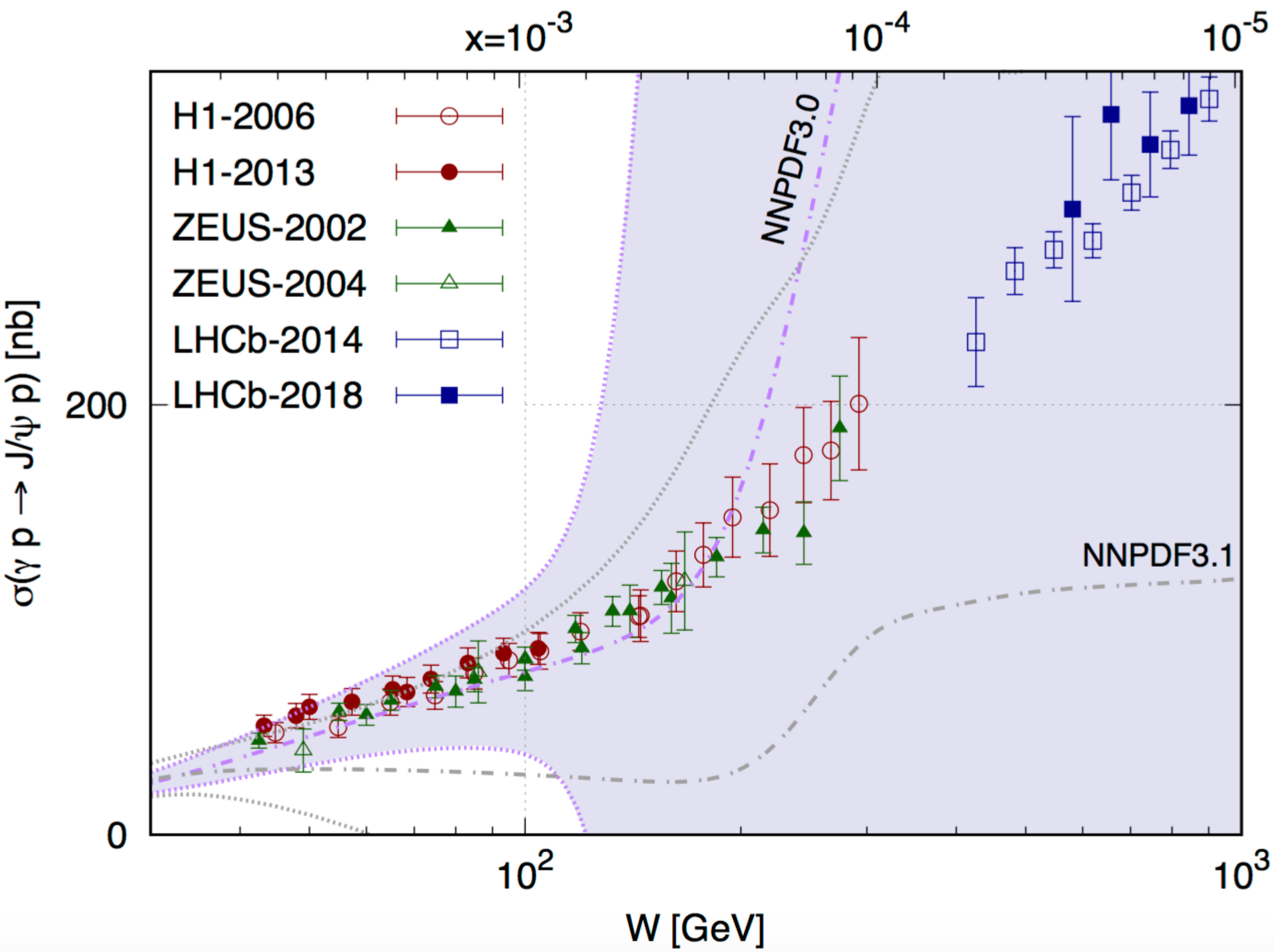
Repeat Disclaimer:

Convoluting with existing global partons. Here, MMHT14, NNPDF3.0 & CT14

$$\frac{\mathrm{Re}\mathcal{M}}{\mathrm{Im}\mathcal{M}} \sim \frac{\pi}{2}\lambda = \frac{\pi}{2}\frac{\partial \ln \mathrm{Im}\mathcal{M}/W^2}{\partial \ln W^2} \quad \text{with} \quad \mathcal{M} \sim x^{-\lambda}$$

Error budgets: errors due to parameter variations in global fits >> experimental uncertainty and scale variations in the theoretical result

…… exclusive data now in a position to readily improve global analyses



Exclusive LHCb data will constrain small x growth whilst *exclusive* HERA data will improve determination of partons in regime with data constraints already from diffractive DIS HERA data

CAF, S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1907.06471, 1908.08398

Extraction of low x gluon PDF via exclusive J/psi

Left
Approach 1: Fit a low x gluon PDF ansatz to the data

Right
Approach 2: Bayesian reweight current global PDF analyses

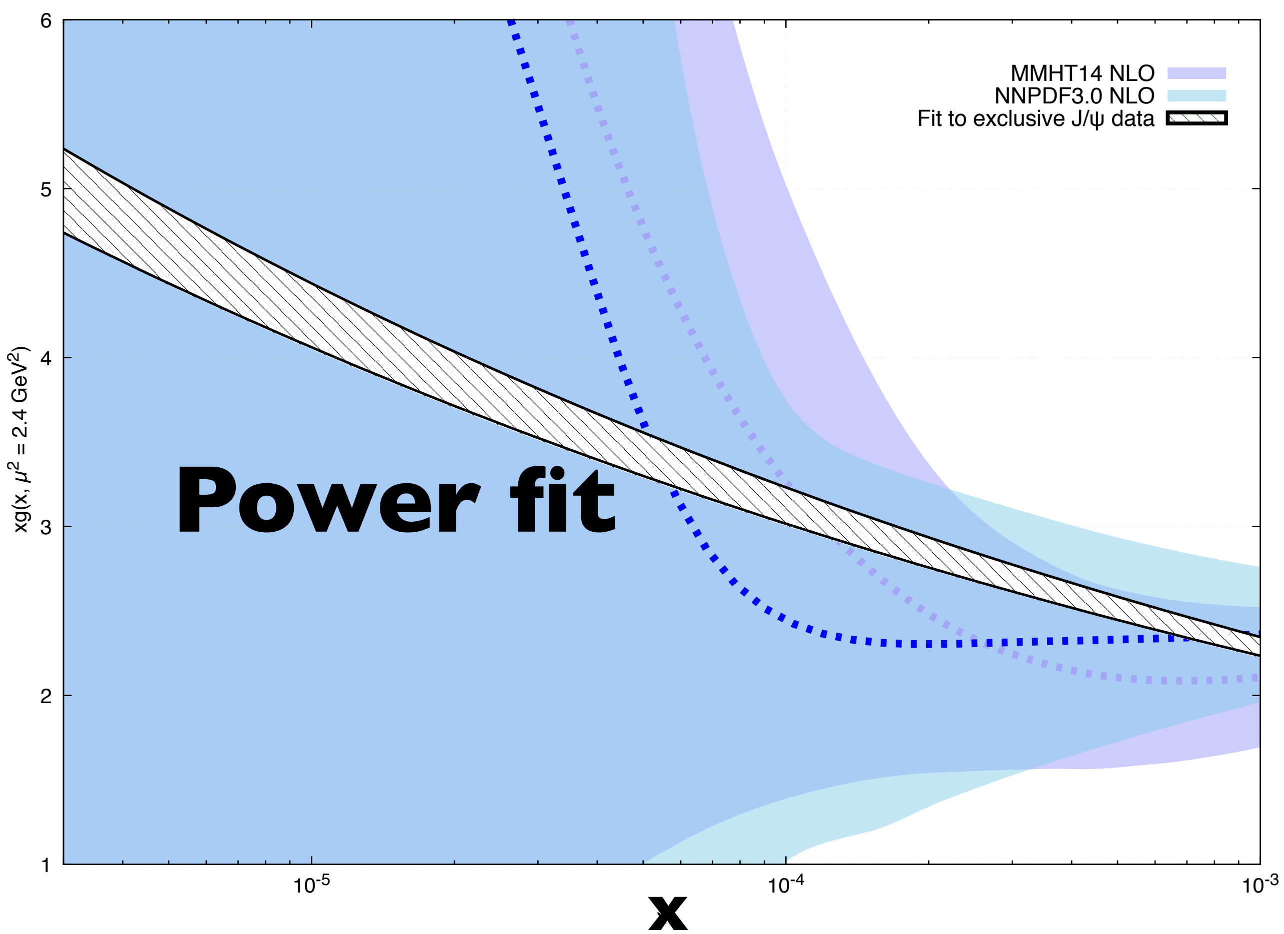
	λ	n	$\chi^2_{\rm min}$	$\chi^2_{\rm min}$/d.o.f
NNPDF3.0	0.136	0.966	44.51	1.04
MMHT14	0.136	1.082	47.00	1.09
CT14	0.132	0.946	48.25	1.12

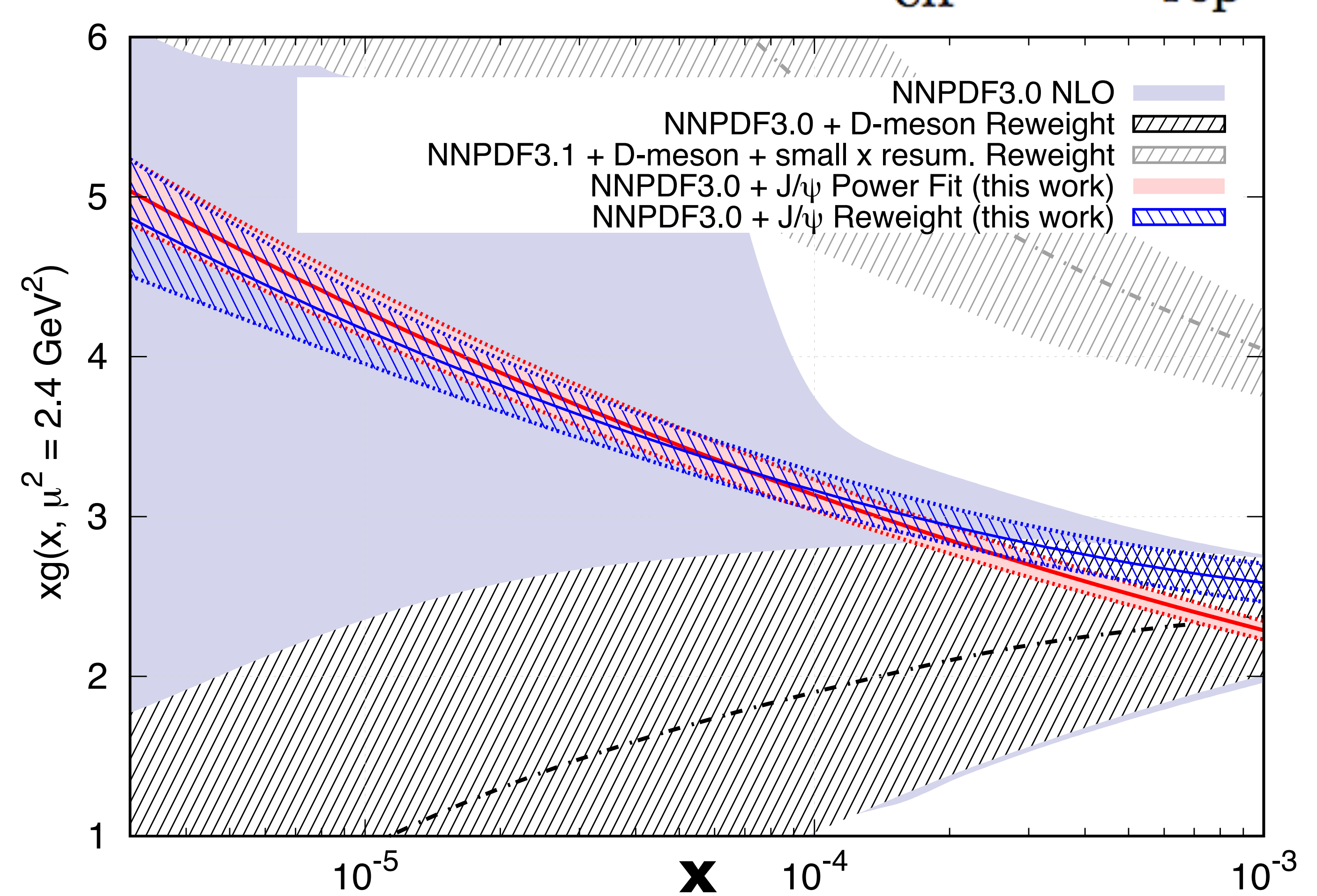
$$xg^{\rm new}(x,\mu_0^2) = nN_0\,(1-x)\,x^{-\lambda}$$

lambda = 0.136 +/- 0.006
n = 0.966 +/- 0.025

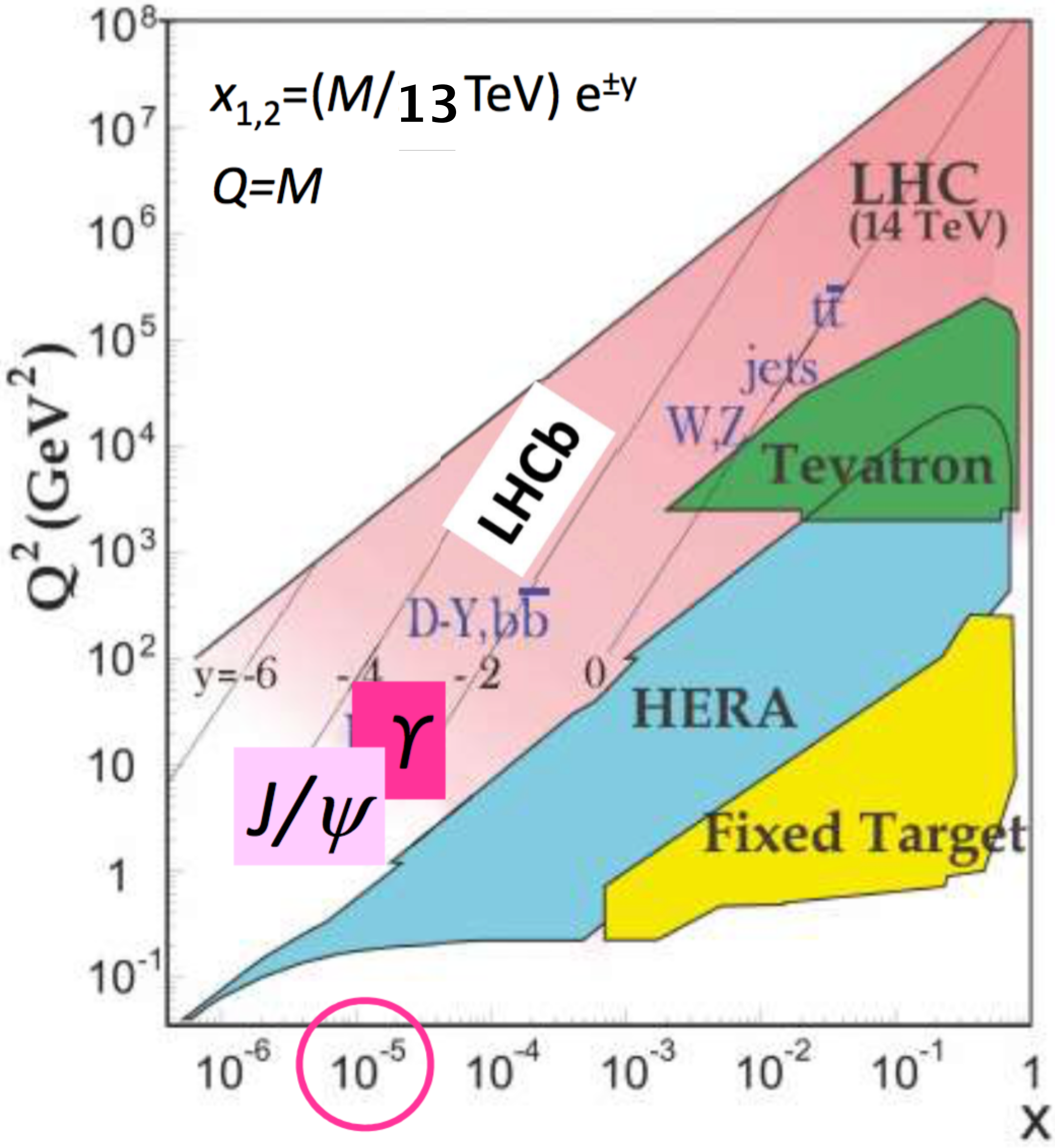
CAF, A.D.Martin, M.G.Ryskin, T.Teubner, 2006.13857

$N_{\rm eff} \ll N_{\rm rep}$





Kinematic coverage

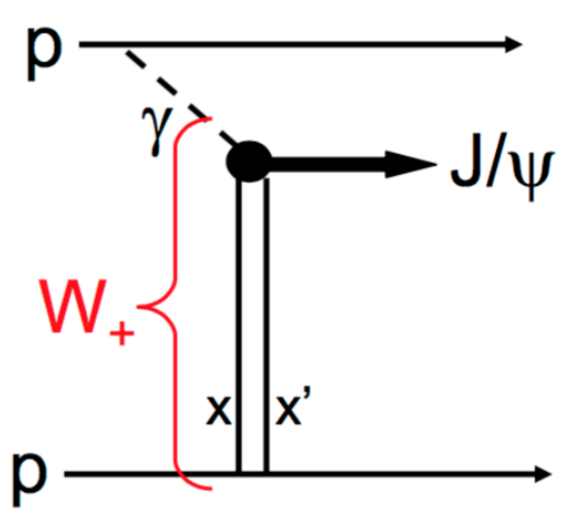


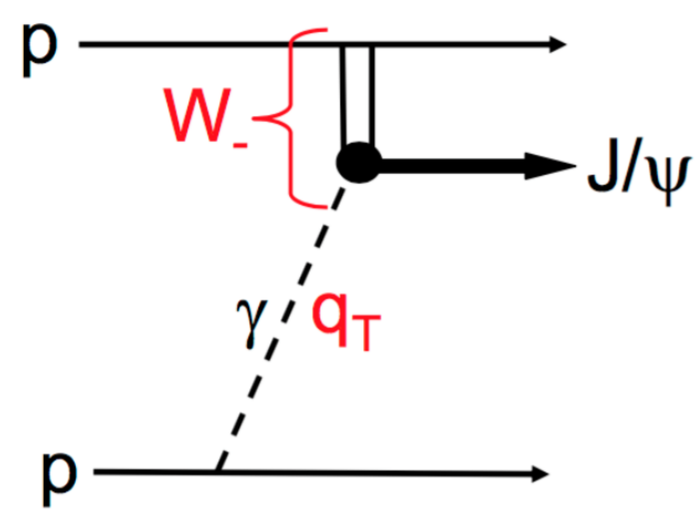
LHCb with $2 < y < 4.5$ can probe gluon down to $x \sim 10^{-5}$

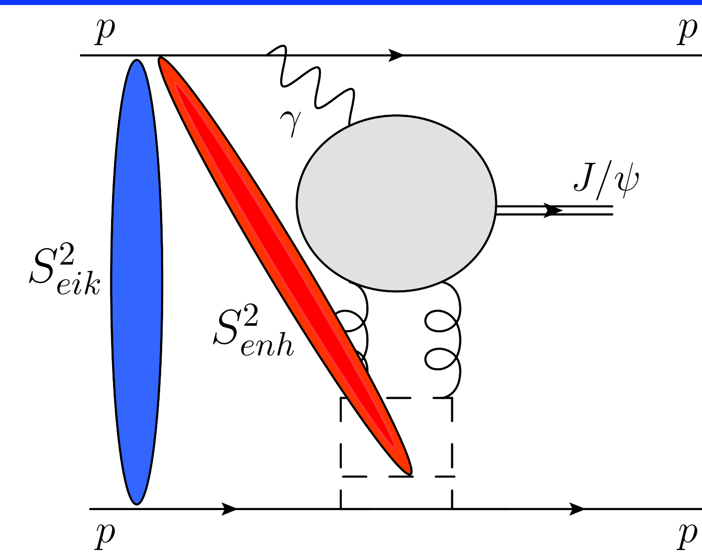
exclusive J/ψ, Υ
[$Q=M_V/2$ (scale)]

Why are these LHCb data not used in global PDF fits ??

General Set up and assumptions







LHCb data

$$\frac{d\sigma(pp)}{dy} = S^2(W_+)\left(k_+\frac{dn}{dk_+}\right)\sigma_+(\gamma p) + S^2(W_-)\left(k_-\frac{dn}{dk_-}\right)\sigma_-(\gamma p)$$

survival probability factors

LHCb 'data'

photon flux

HERA gives W-

$$W_\pm^2 = M_{J/\psi}\sqrt{s}e^{\pm|y|} \quad \Rightarrow x_\pm = \begin{cases} 10^{-5} \\ 0.02 \end{cases} \quad \text{at } y=4,\ \sqrt{s}{=}13 \text{ TeV}$$