Small x gluon PDF from LHCb exclusive J/psi data

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Introduction

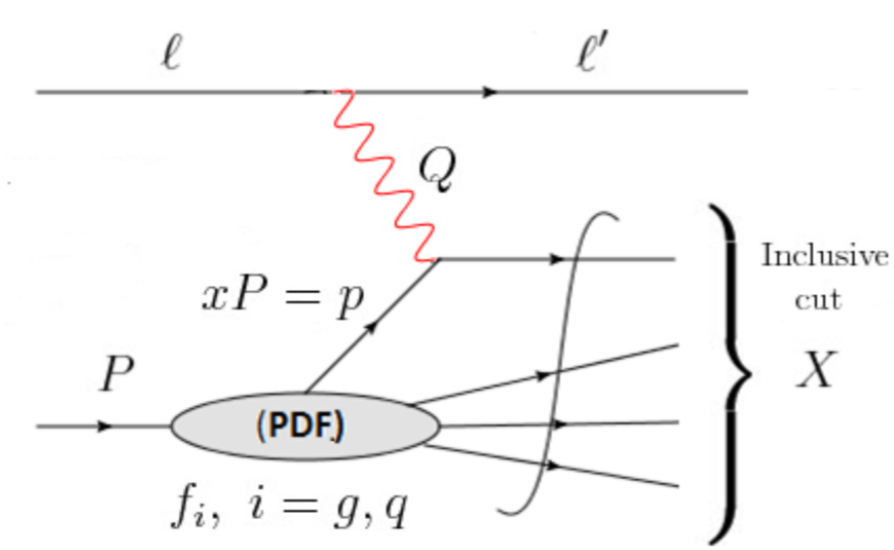
- Inclusive processes do not well constrain small x/Regge limit domain of PDFs
- Exclusive processes offer sensitive probe of this domain but as of yet not included in global analyses PDF determination - why?
    1. Off forward kinematics imply susceptibility to *GPD* over conventional PDFs
    2. Reliability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

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

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

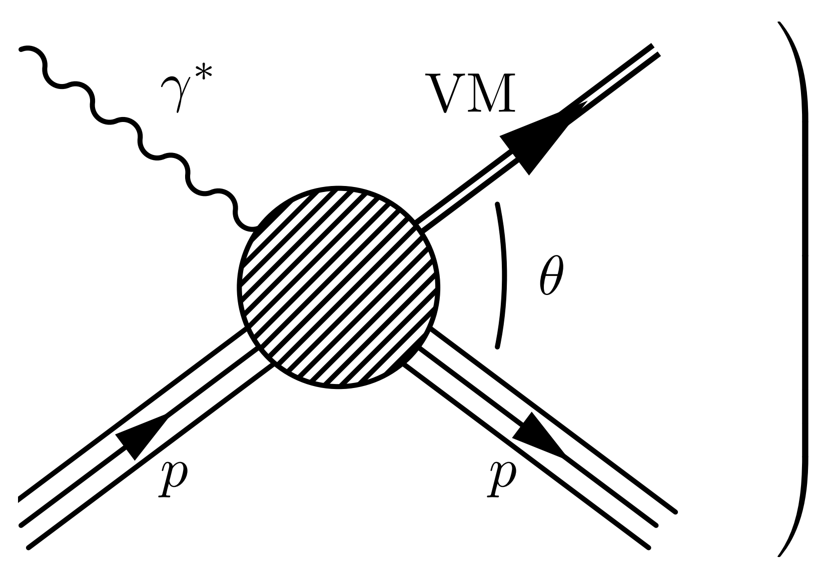
Ryskin 1993

Inclusive - included in global parton analyses



e.g. DIS

Exclusive - can we use the data?



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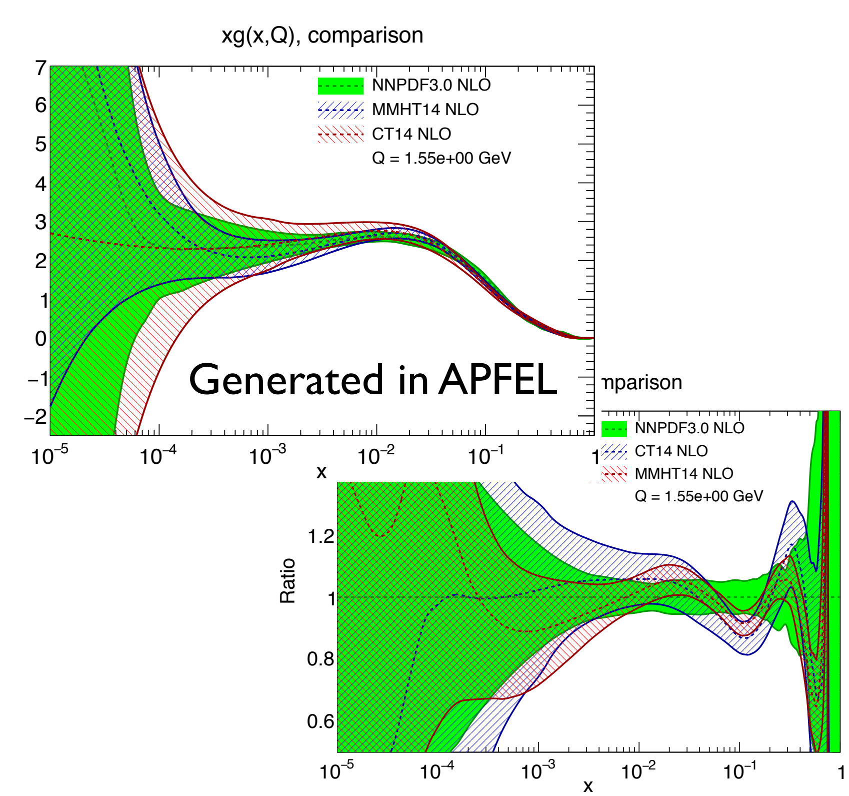
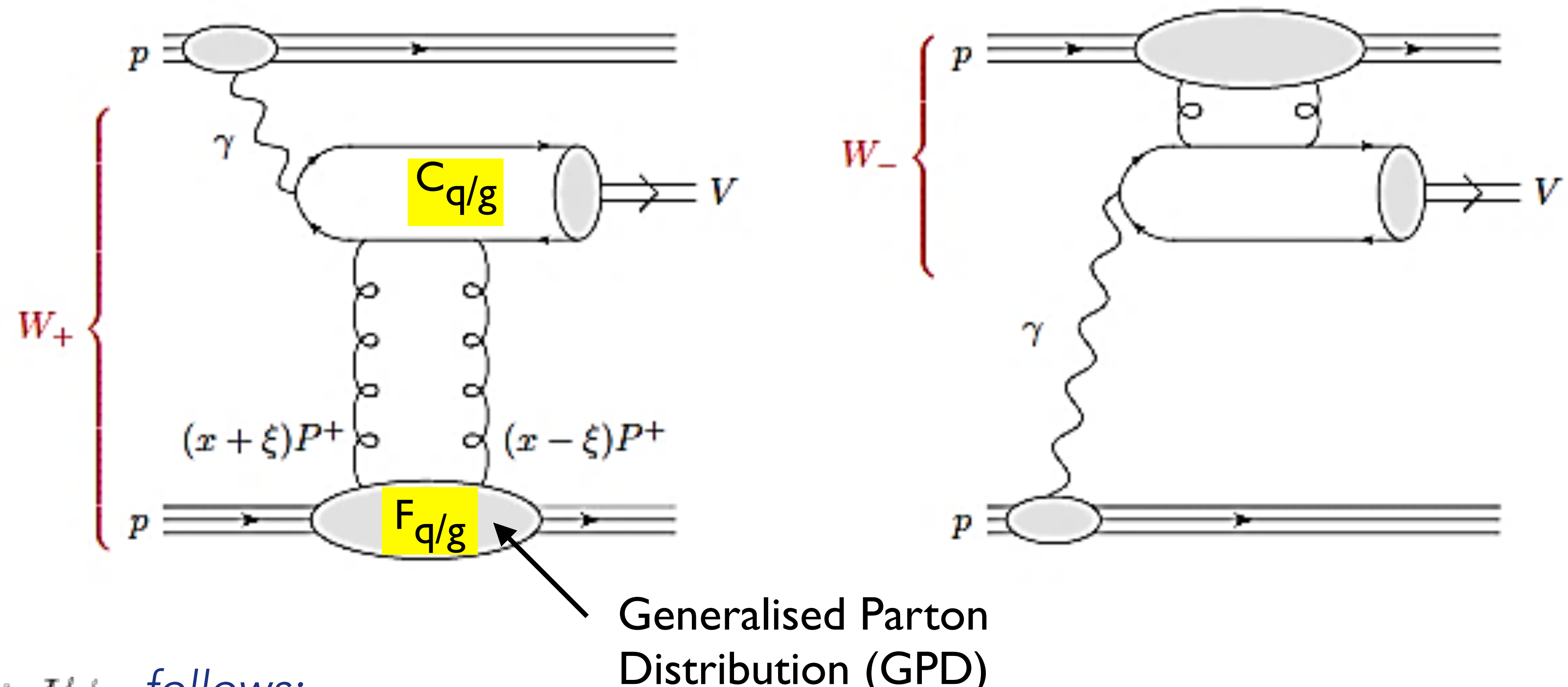


General Set up and assumptions



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

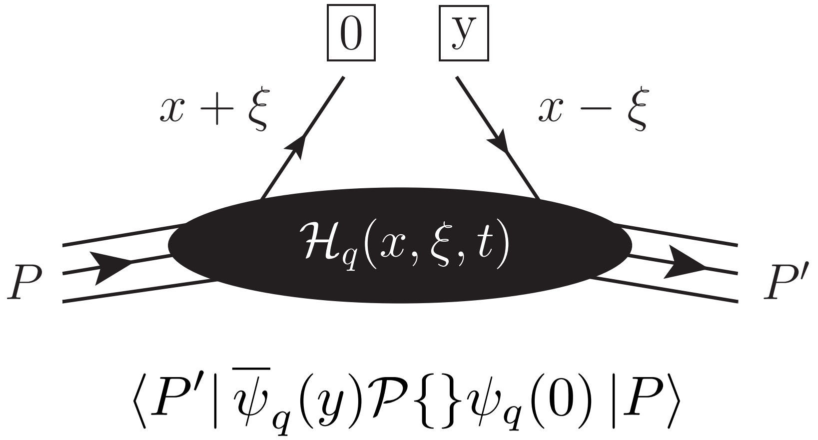
- Assume a factorisation $F_{q/g} \otimes C_{q/g} \otimes \phi^V_{Q\bar{Q}}$
- Leading zeroth order term in rel. velocity (NRQCD)
- Colour singlet exchange between hard and soft sectors

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

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

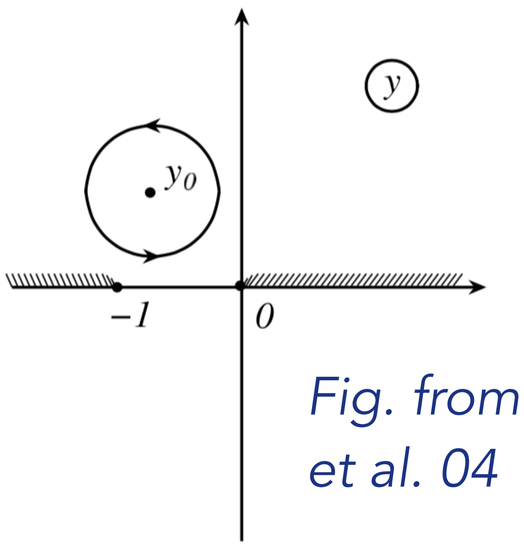


Fig. from Ivanov et al. 04

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

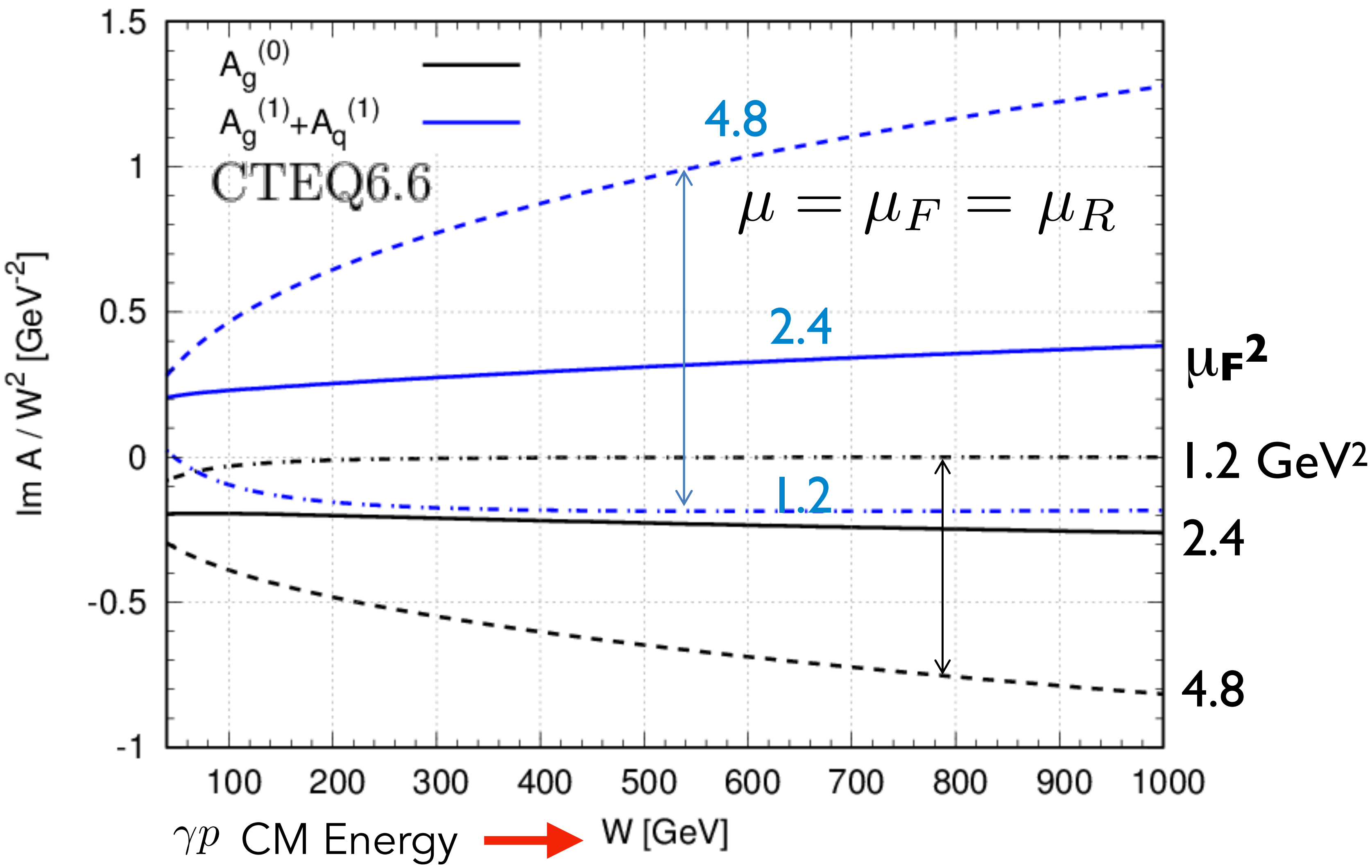
Stability of prediction I

NLO in MSbar scheme

D. Ivanov, B.Pire, L.Szymanowski, J.Wagner, hep-ph/0401131
S.P.Jones, PhD thesis, Liverpool (2014)

A. Bad perturbative convergence $|NLO_{correctn.}| > |LO|$ and opp. sign

B. Strong dependence on scale μ_F



Disclaimer: Plots generated using existing global partons. Here, CTEQ6.6

Can do better…

Stability of prediction II

'Scale Fixing'

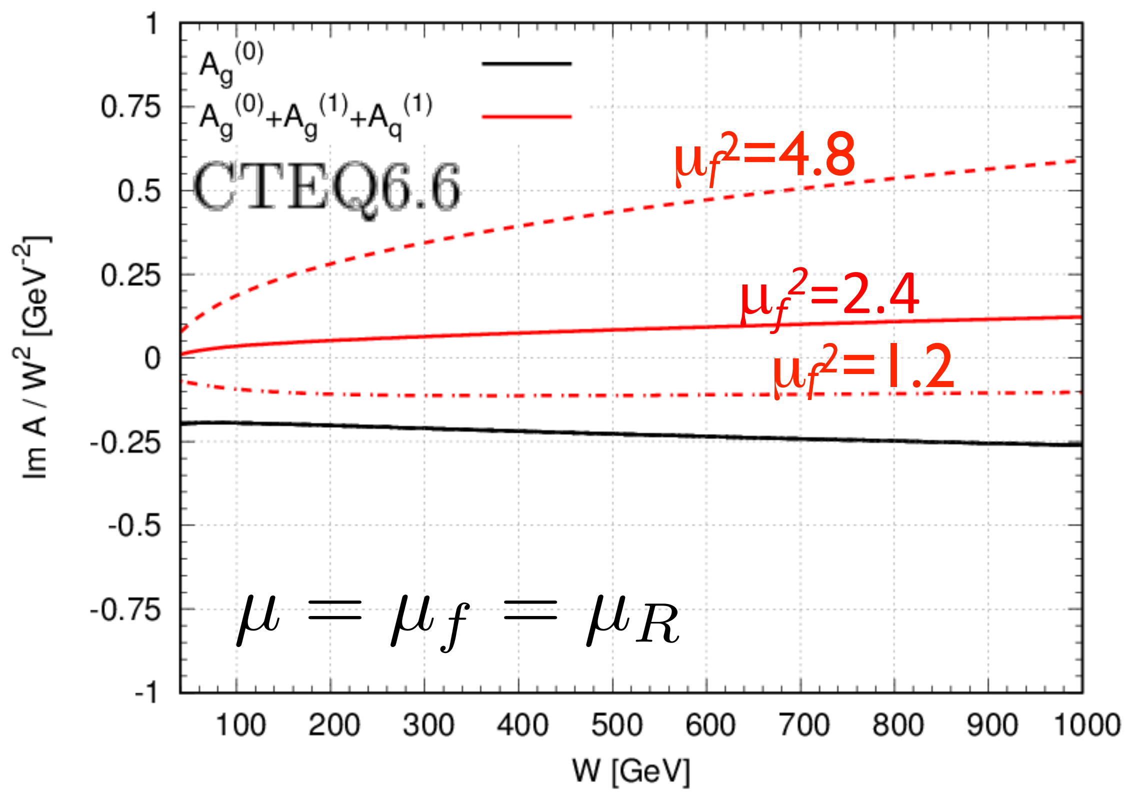
`Optimal' factorisation scale $\mu_F = m$
eliminates large logs at NLO

S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1507.06942

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

terms into LO PDF, leaving remnant
NLO coefficient
and residual, μ_f, scale dependence

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

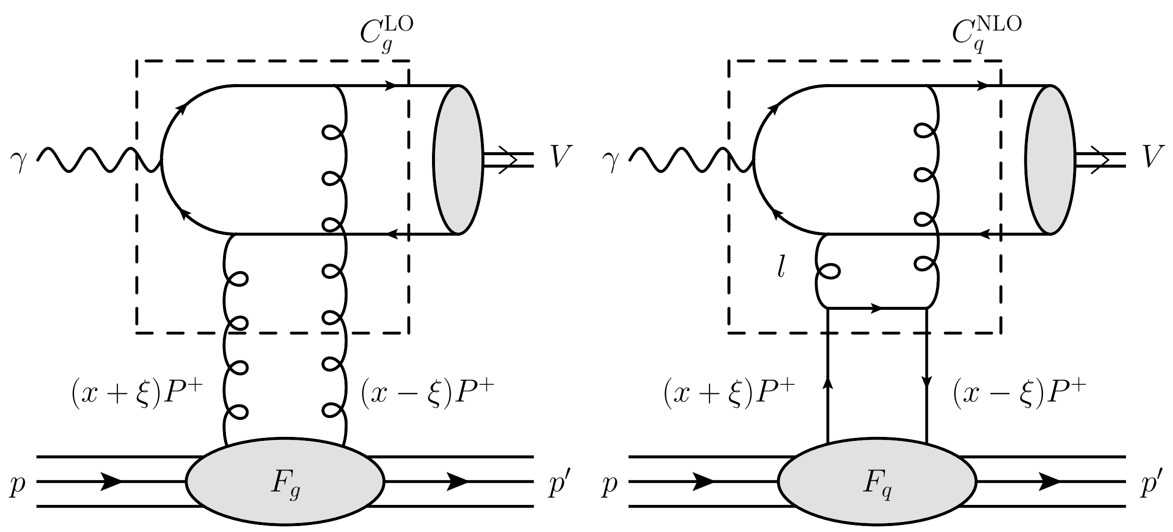


$$A(\mu_f) = C^{LO} \times GPD(\mu_F) + C^{NLO}(\mu_F) \times GPD(\mu_f)$$

Look for another sizeable correction that can reduce variations further
-> implementation of a **`Q0'** cut

Stability of prediction III

`Q0' cut   S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1610.02272



Subtract DGLAP contribution

NLO (| ℓ^2 | < Q_0^2)

from known NLO MSbar coefficient function to avoid a double count with input GPD at Q_0.

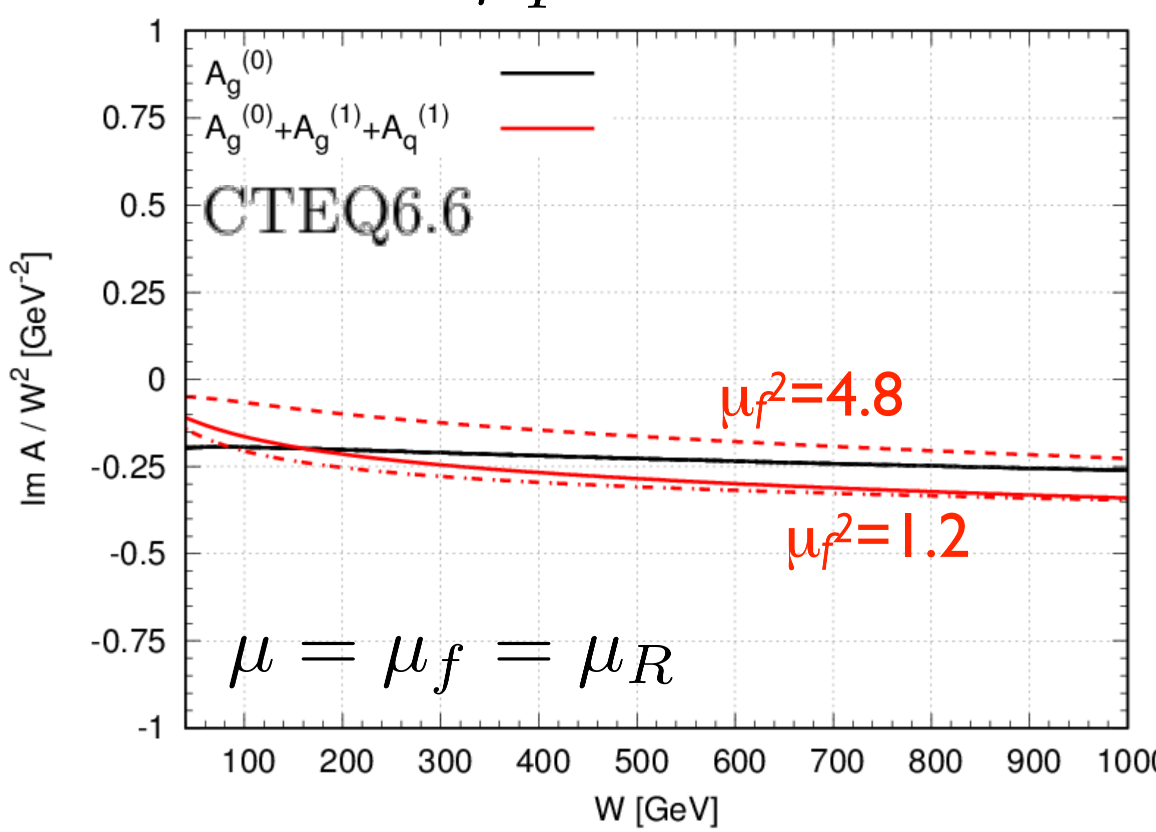
Typically power suppressed, but sizeable here

$$\mathcal{O}(Q_0^2/m_c^2)$$

→

How do these predictions compare with the data at HERA and LHCb?

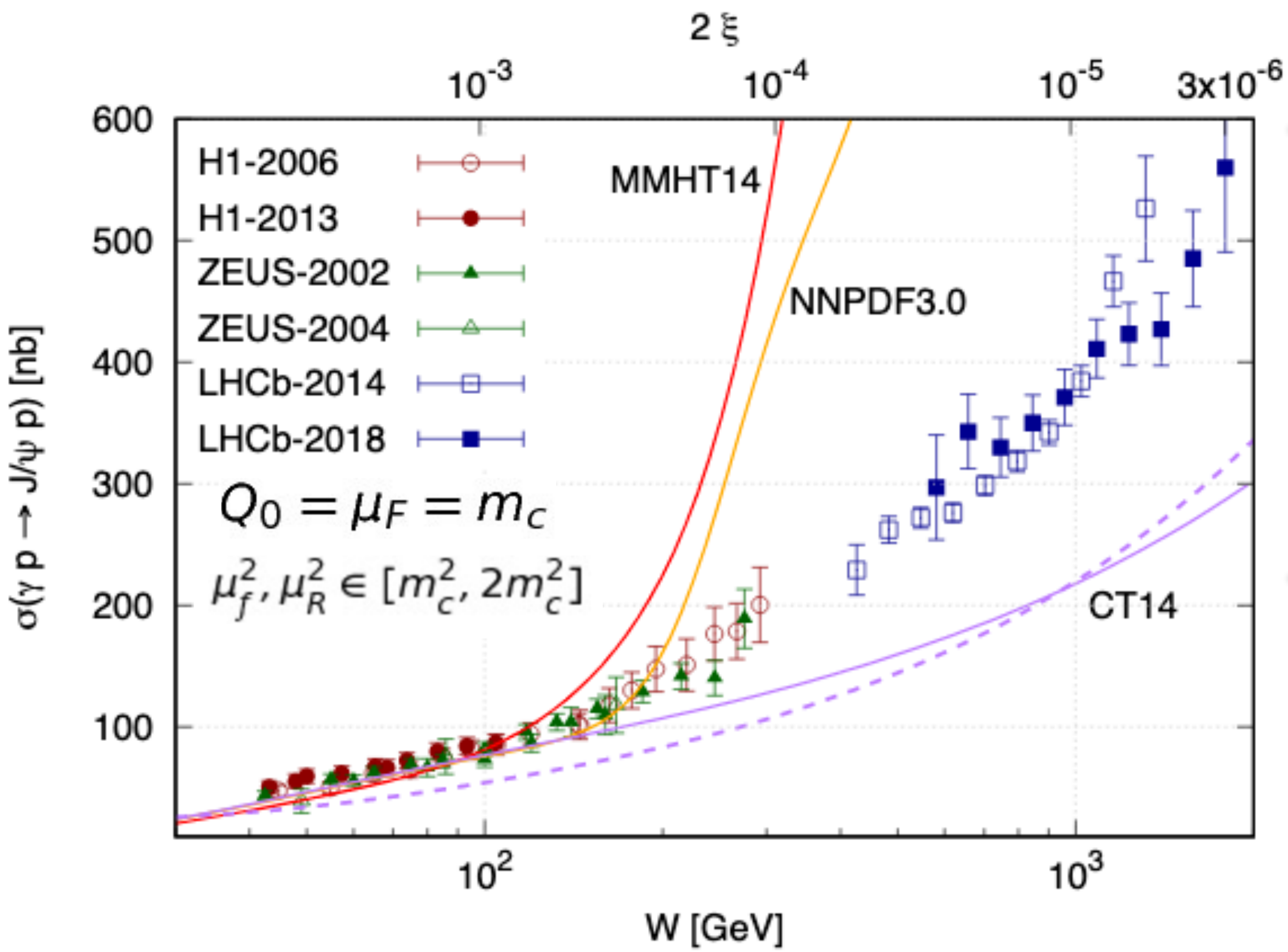
Fix: $\mu_F^2 = 2.4 \text{ GeV}^2$



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

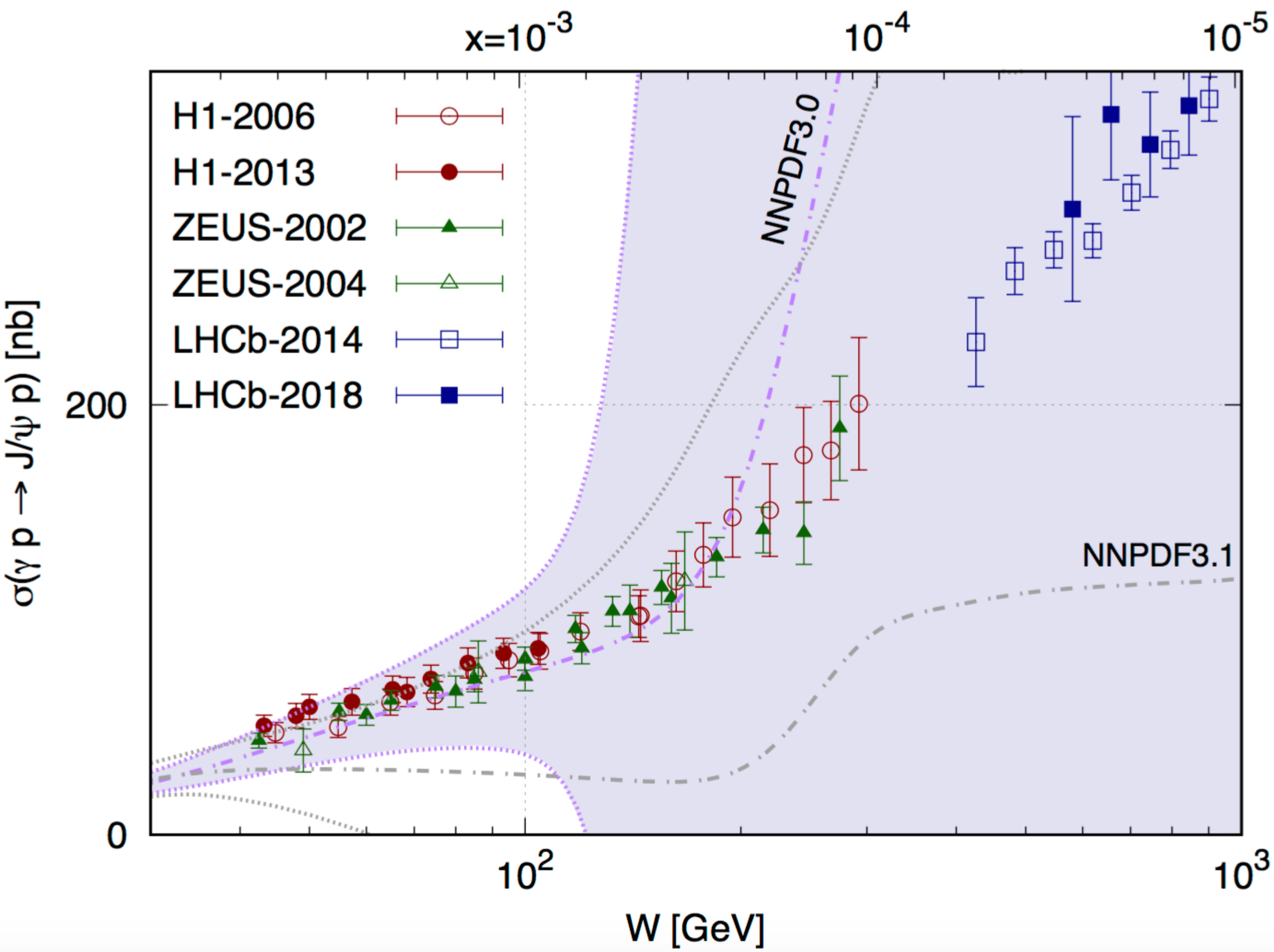
Repeat Disclaimer:

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

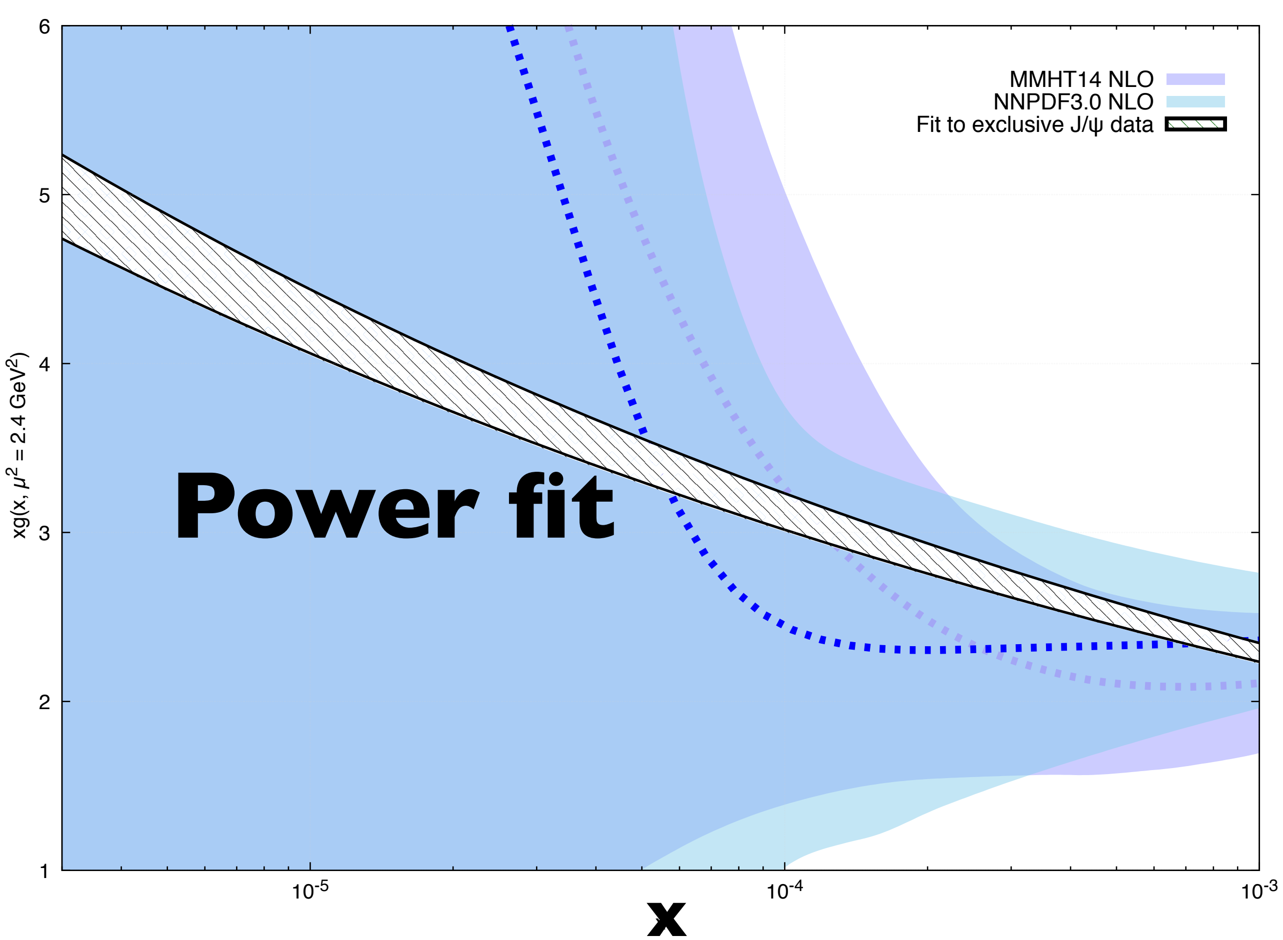
$$xg^{\rm new}(x,\mu_0^2) \;=\; nN_0\,(1-x)\,x^{-\lambda}$$

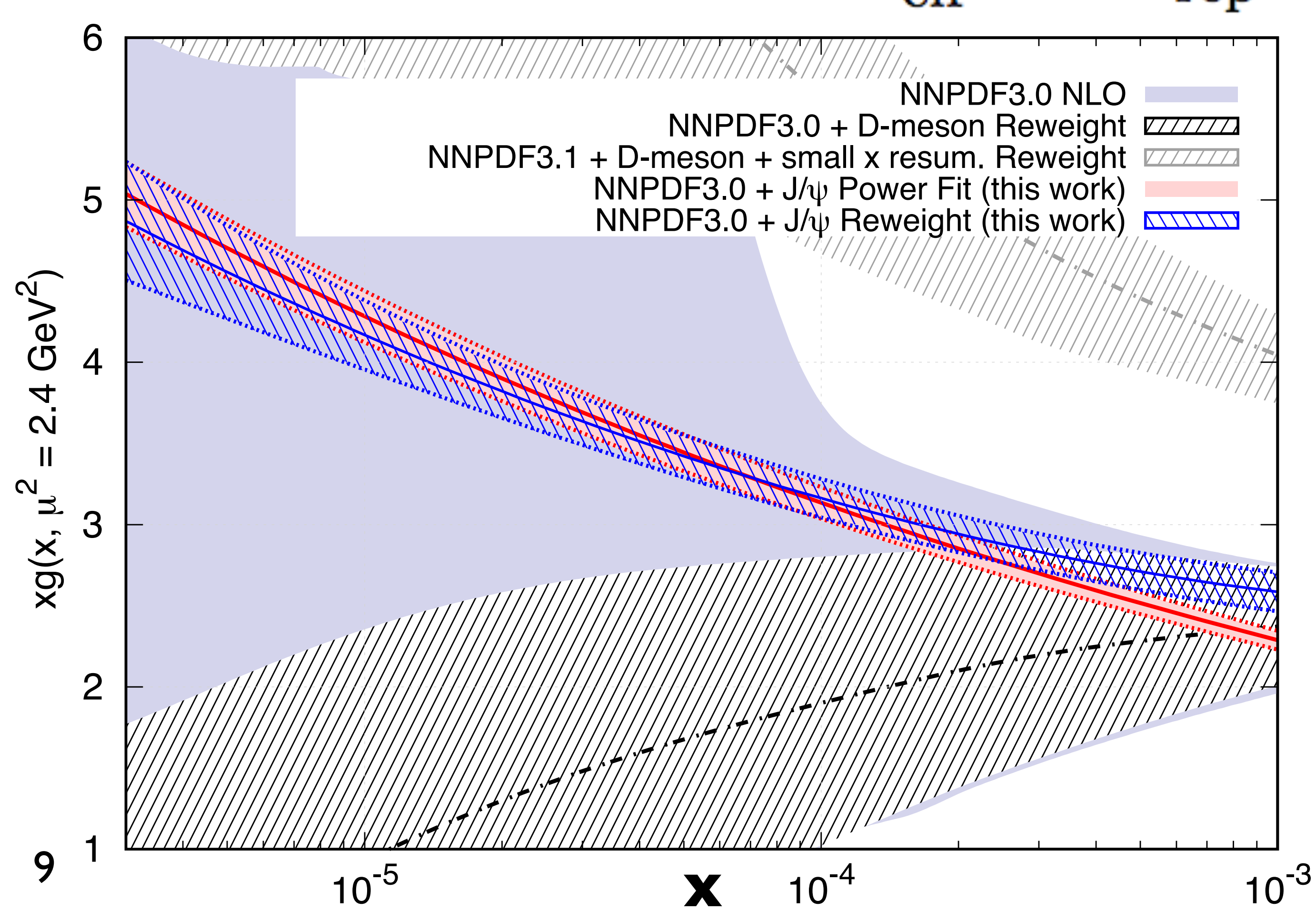
lambda = 0.136 +/- 0.006

n = 0.966 +/- 0.025

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

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



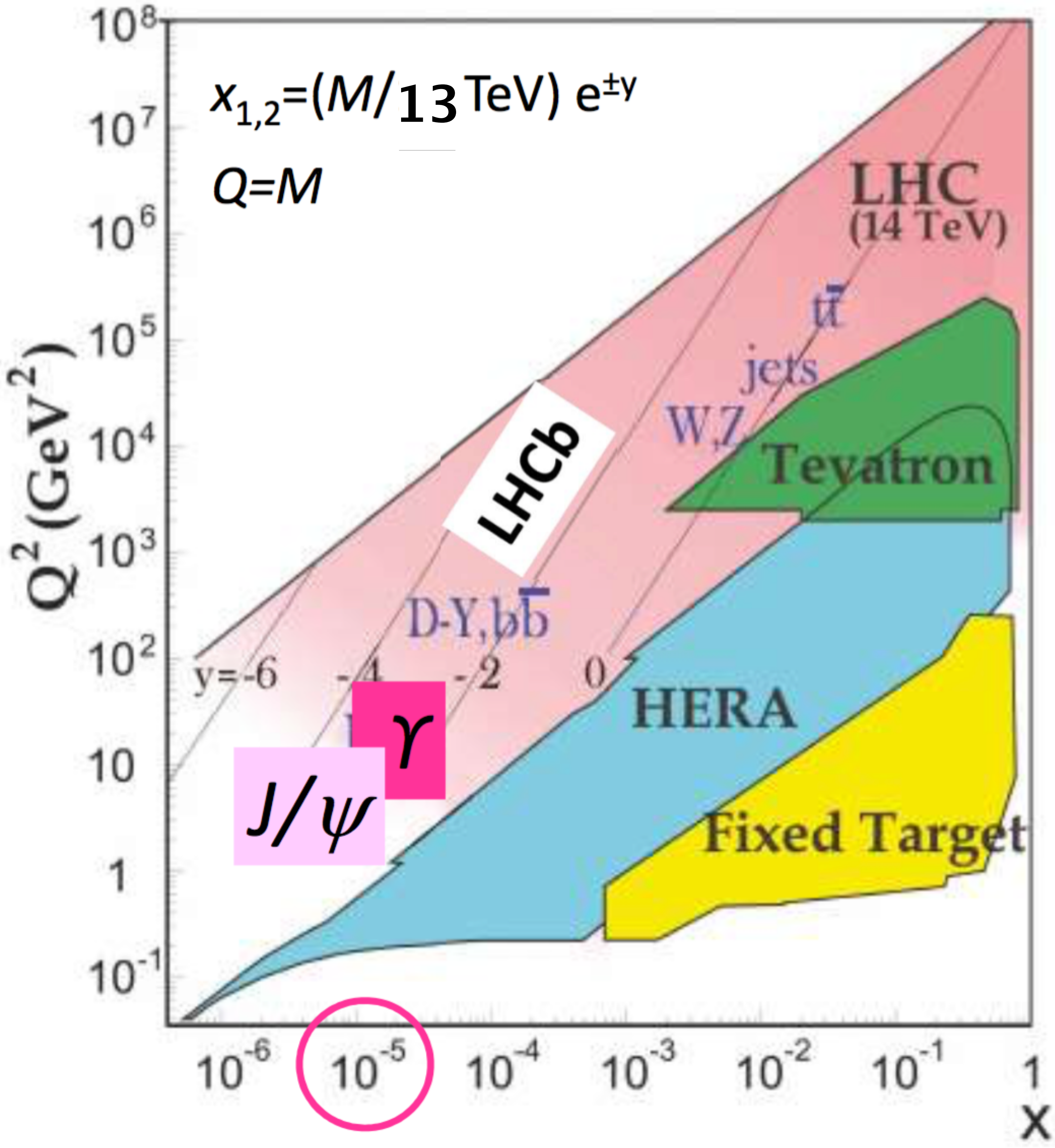


Summary

- Conventional MSbar NLO coll. fact. result unreliable and unstable
- Systematic taming via 'Q0' cut and resummation of large logarithmic contributions collectively reduce wild scale variations
- Predictions at cross section level exhibit good scale stability and central values in agreement of data within 1sigma error bands
- MMHT14' and NNPDF3.0 largely overshooting data in LHCb regime
- Impossible to describe growth of J/psi cross section with energy, observed by the LHCb, using gluons obtained from fit to open charm (decreasing with decreasing x). Tension observed between extracted gluons from exclusive and inclusive sector through J/psi and D channels resp.
- Inconsistencies in the D sector from the experimental side? (see backup slides)
- Upshot: In a position to finally use exclusive J/psi data (easier to collect and theory result now improved) in a global fitter framework

Thank you

Kinematic coverage

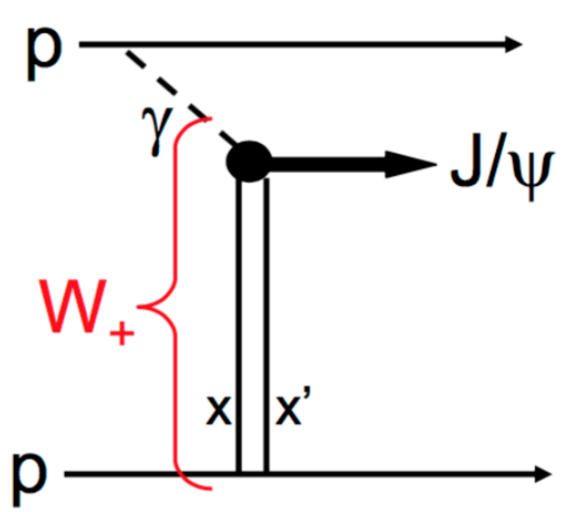


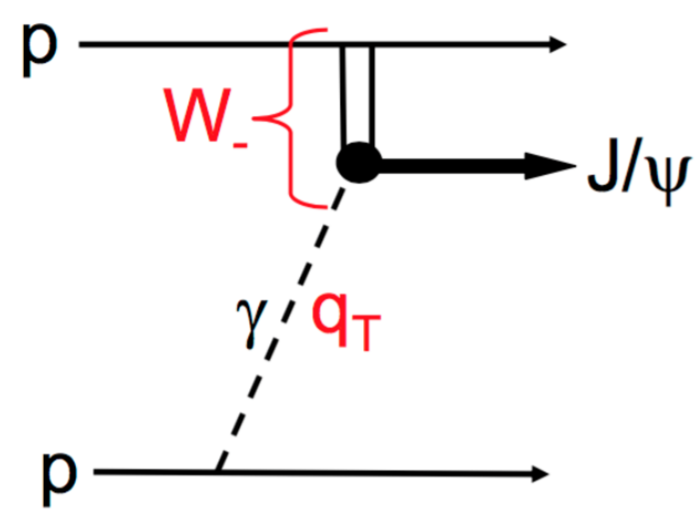
LHCb with $2 < y < 4.5$ can probe gluon down to $x \sim 10^{-5}$

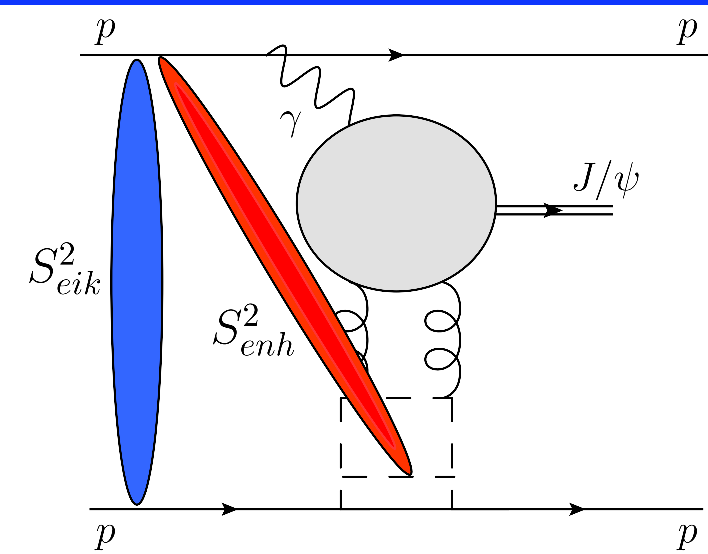
exclusive J/ψ, Υ
[Q=M_V/2 (scale)]

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-

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

Shuvaev Transform

Full Transform:

$$\mathcal{H}_q(x,\xi) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi} \mathrm{Im} \int_0^1 \frac{\mathrm{d}s}{y(s)\sqrt{1-y(s)x'}} \right] \frac{\mathrm{d}}{\mathrm{d}x'} \left(\frac{q(x')}{|x'|} \right),$$

$$\mathcal{H}_g(x,\xi) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi} \mathrm{Im} \int_0^1 \frac{\mathrm{d}s(x+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}} \right] \frac{\mathrm{d}}{\mathrm{d}x'} \left(\frac{g(x')}{|x'|} \right),$$

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

[Shuvaev et. al 1999]

Shuvaev Transform cont.

The conformal moments H_i^N of the GPDs are given by

$$H_i^N \equiv \int_{-1}^{1} \mathrm{d}x R_{N,i}(x_1, x_2) H_i(x, \xi), \qquad i = q, g,$$

Ohrndorf, 82

The conformal moments are polynomials in even powers of ξ,

$$H_i^N = \sum_{k=0}^{\lfloor (N+1)/2 \rfloor} c_{k,i}^N \xi^{2k} = c_{0,i}^N + c_{1,i}^N \xi^2 + c_{2,i}^N \xi^4 + \ldots, \qquad , \; c_{0,i}^N = f_i^N$$

Leading term is Mellin moment of PDF

- Provided inverse exists then can relate GPDs to PDFs with suppression of order xi (i.e. good low x approx)

Shuvaev Transform cont.

Widely debated, certain conditions needing upheld, e.g lack of singularities in Re N > 1 plane

e.g Diehl, Kugler, 08

Regge theory considerations => condition met Martin, Nockles, Ryskin, Teubner, 09

- Can check in physically motivated ansatz, e.g MSTW2008 global partons input parametrisation

Martin, Stirling,Thorne, Watt, 09

$$xg(x,Q_0^2) = A_g x^{\delta_g}(1-x)^{\eta_g}(1+\epsilon_g\sqrt{x}+\gamma_g x) + A_{g'}x^{\delta_{g'}}(1-x)^{\eta_{g'}}.$$

Expand about x ~ 0

$$xg(x,Q_0^2) = A_g x^{\delta_g} + A_{g'}x^{\delta_{g'}} + \ldots,$$

Mellin transform:

$$xg^N(Q_0^2) = \int_0^1 \mathrm{d}x x^{N-1}(A_g x^{\delta_g} + A_{g'}x^{\delta_{g'}}) + \ldots$$
$$= \frac{A_g}{N+\delta_g} + \frac{A_{g'}}{N+\delta_{g'}} + \ldots,$$

Fits to data (including 1sig. errors) suggest $\delta_g > -1$ and $\delta_{g'} > -1$

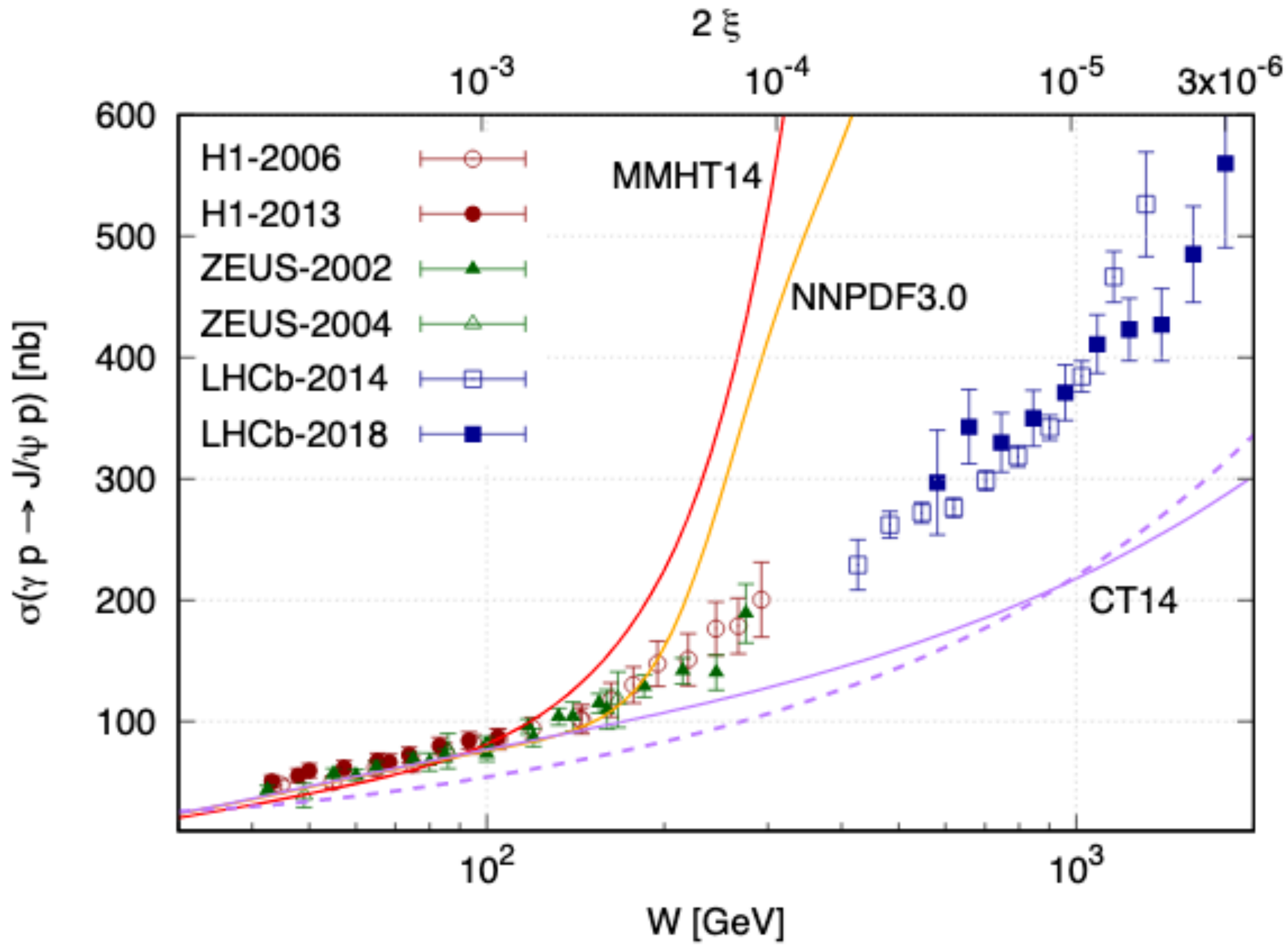
- Shuvaev transform describes HVM and GDVCS data well

Kumericki, Muller, 10

Cross section stability

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

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



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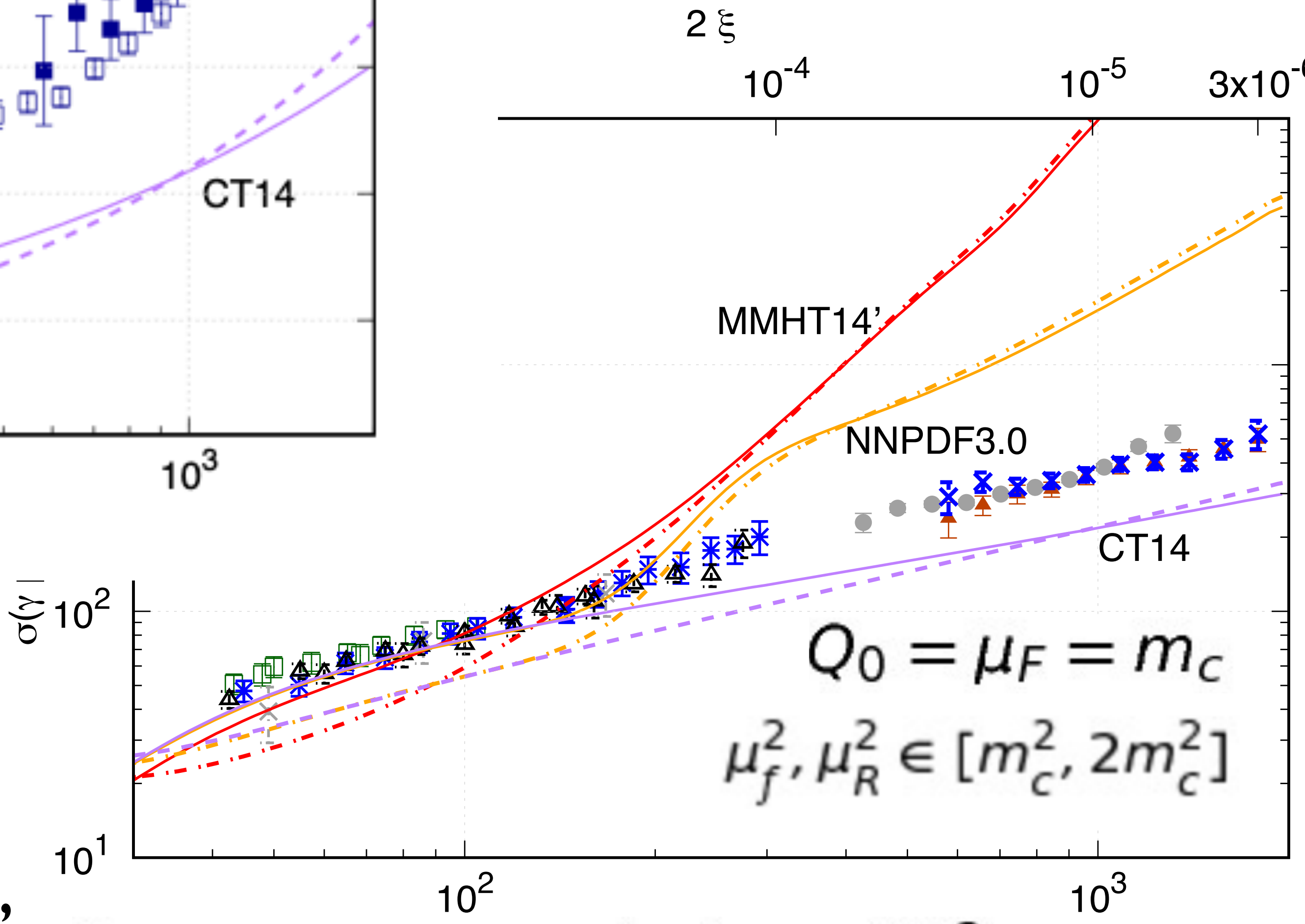


Diversity in prediction -> important message

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

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

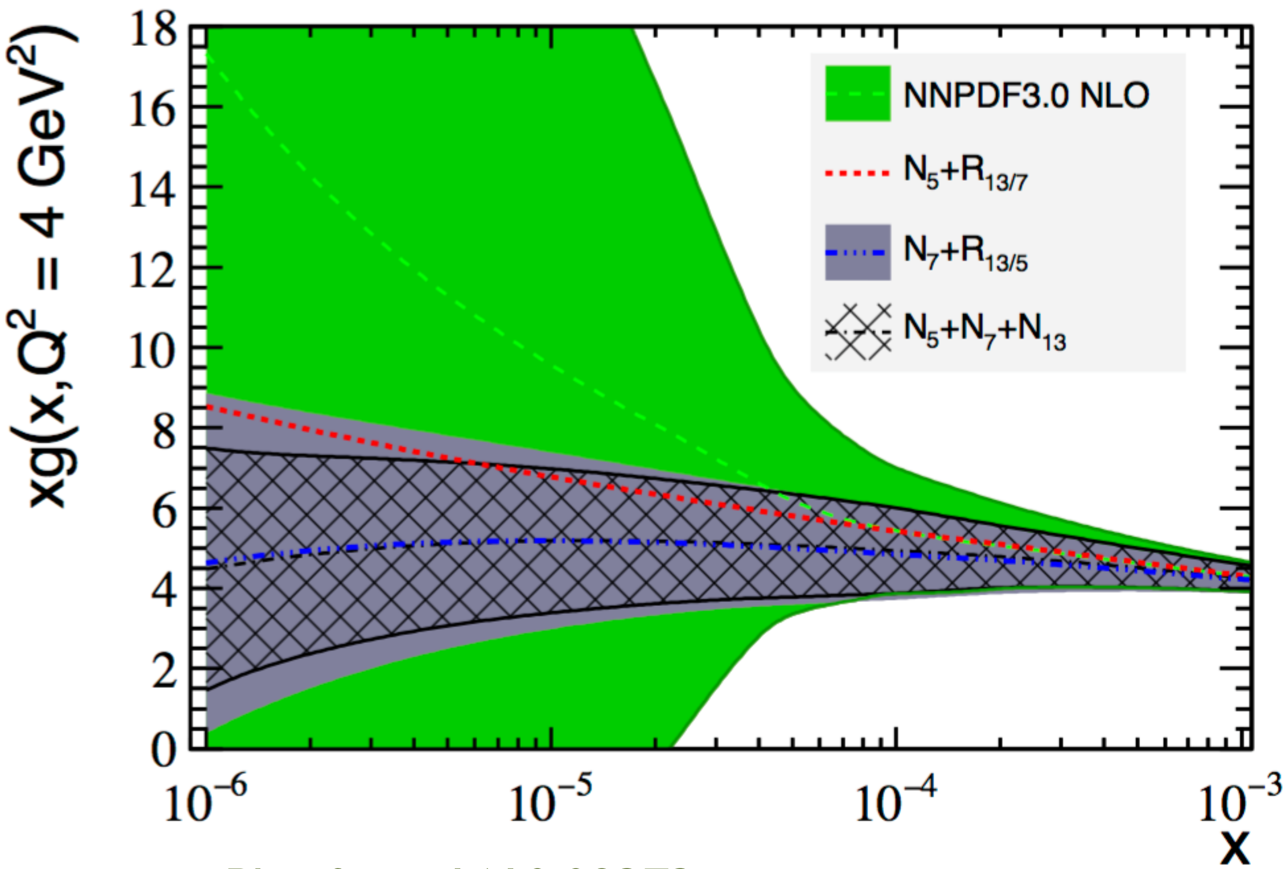
Constraints from inclusive D meson production data

Idea: Construct ratios of observables in y and p_t bins to combat various uncertainties

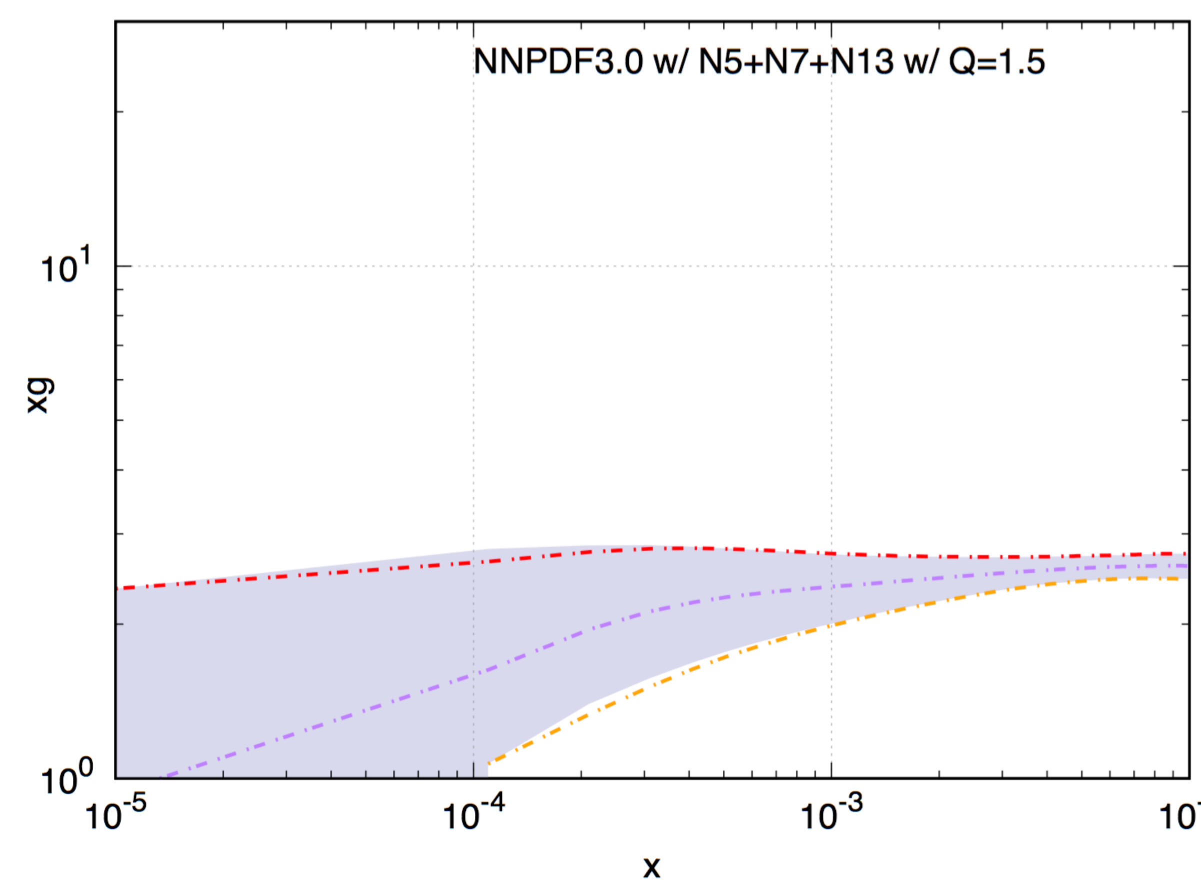
$$N_X^{ij} = \frac{d^2\sigma(\text{X TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\text{X TeV})}{dy_{\text{ref}}^D d(p_T^D)_j}$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(\text{13 TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\text{X TeV})}{dy_{\text{i}}^D d(p_T^D)_j}$$

→ find decreasing gluon at the lowest x they may probe



Plot from 1610.09373

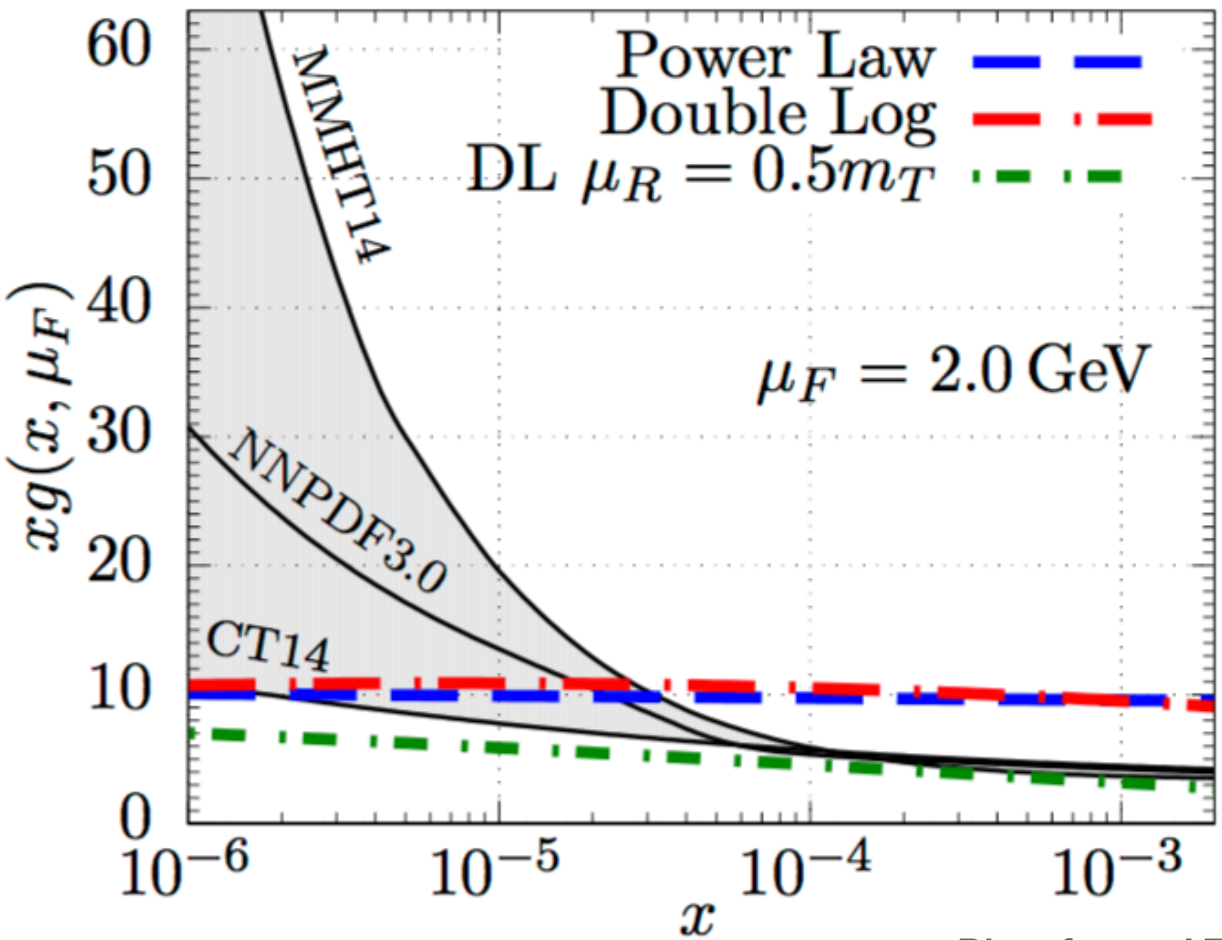


Tension with the J/psi data

We need a much harder gluon at low x to describe the exclusive J/psi LHCb data.

What's the reconciliation?

Indications of **inconsistencies** in the inclusive D experimental measurement

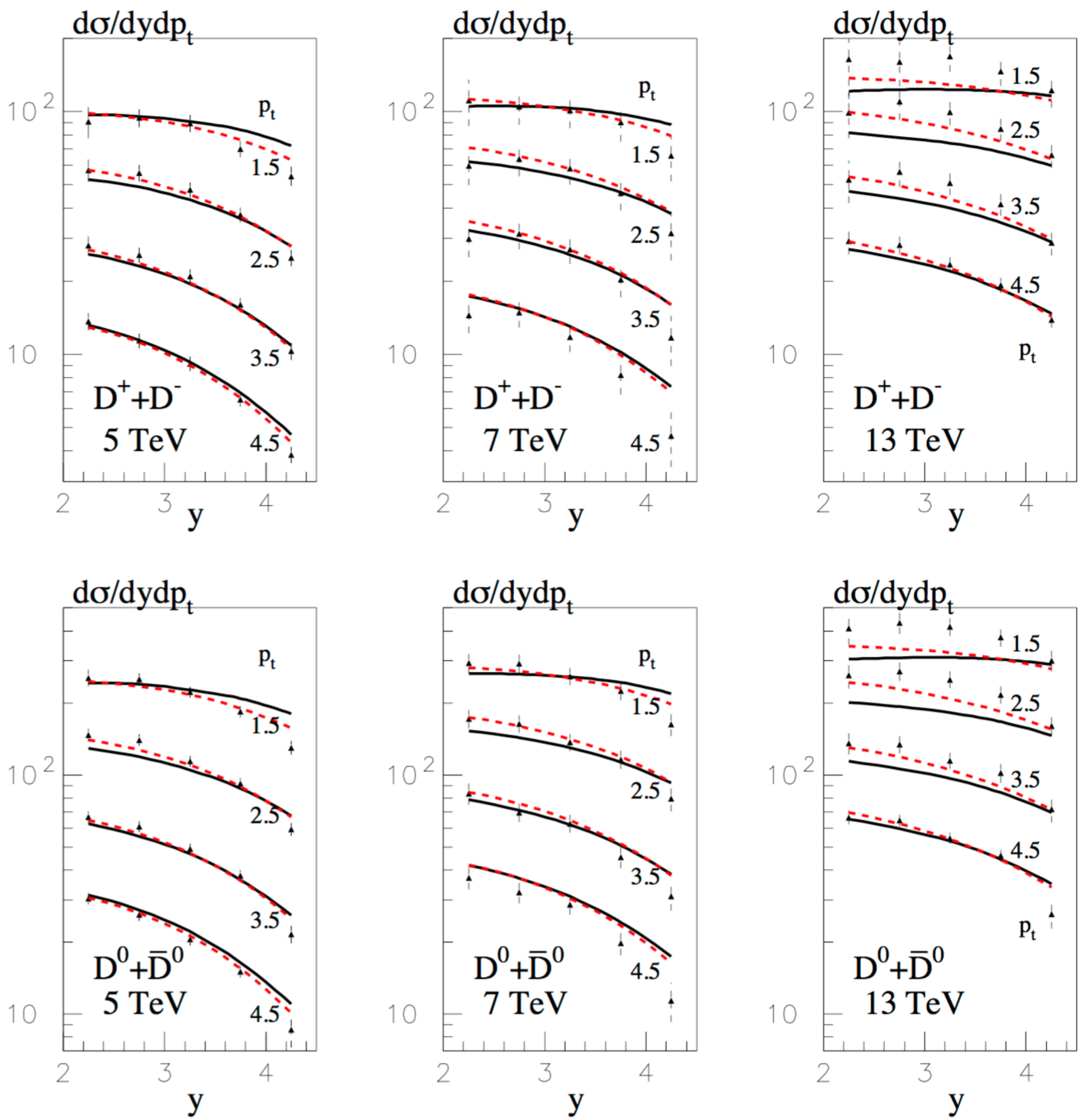


Plot from 1712.06834

$$xg(x) = N\left(\frac{x}{x_0}\right)^{-\lambda}$$

$$xg(x,\mu^2) \;=\; N^{\mathrm{DL}}\left(\frac{x}{x_0}\right)^{-a}\left(\frac{\mu^2}{Q_0^2}\right)^{b}\exp\left[\sqrt{16(N_c/\beta_0)\ln(1/x)\ln(G)}\right]$$

Rapidity and energy dependence of open charm cross section



Plot from 1712.06834

- Need *slower* increasing gluon with decreasing x to describe rapidity dependence
- Need *faster* increasing gluon with decreasing x to describe energy dependence

y ~ ln(1/x) !!

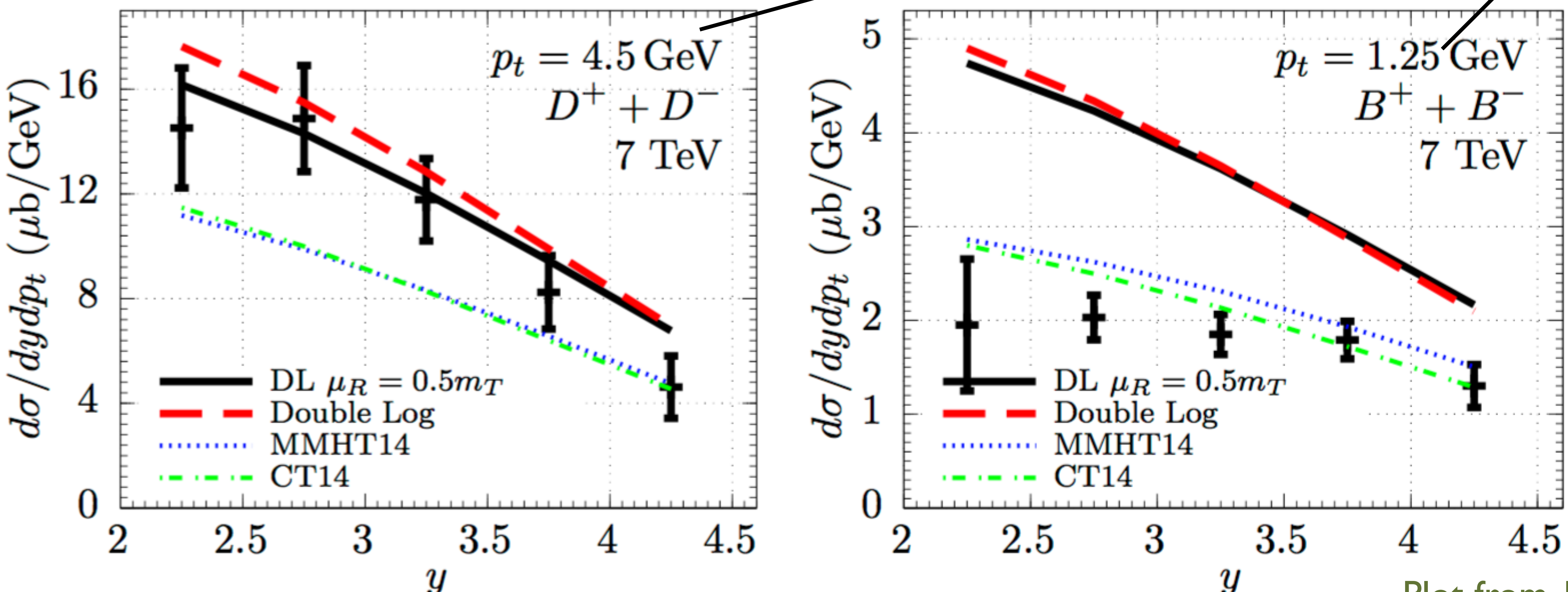
dash Q_0=1 GeV and $\mu_F = \mu_R = 0.85 m_T$

solid $\mu_f = \mu_R = 0.5 m_T$ and Q_0=0.5 GeV

Open beauty results

B sector has something to say…

p_t chosen to sample gluon at same factorisation scale and x



Plot from 1712.06834

Gluon found through fit to D meson data fails to describe the B meson distribution

Should we really trust the decreasing nature of the low scale, low x gluon obtained via fit to LHCb open charm data?