The low x gluon from LHCb data

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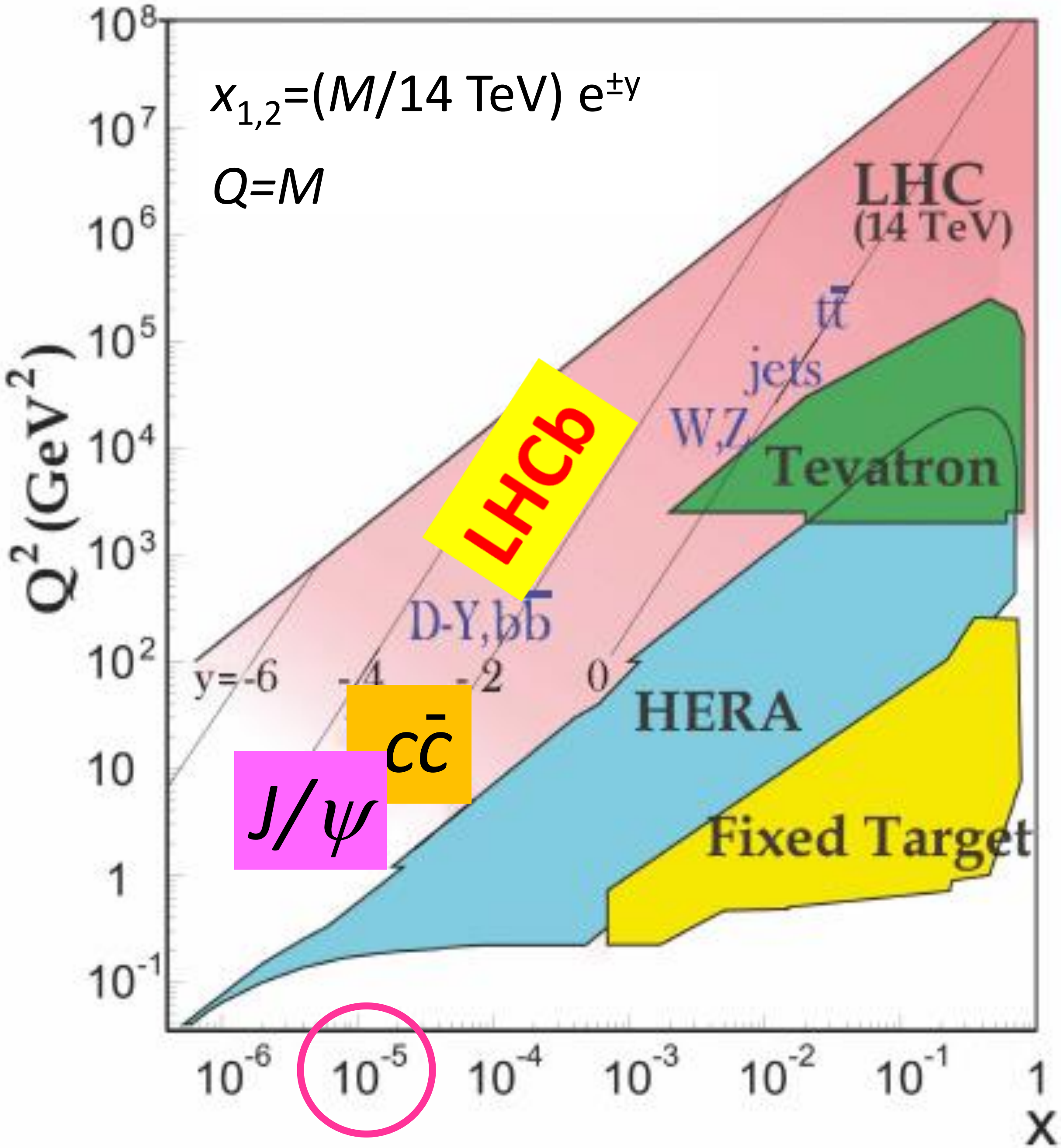
(i) Exclusive J/ψ data (+HERA J/ψ photoprod. data)
Jones, AM, Ryskin, Teubner -- 1611.03711

(ii) Open charm production
de Oliveira, AM, Ryskin -- 1705.08845

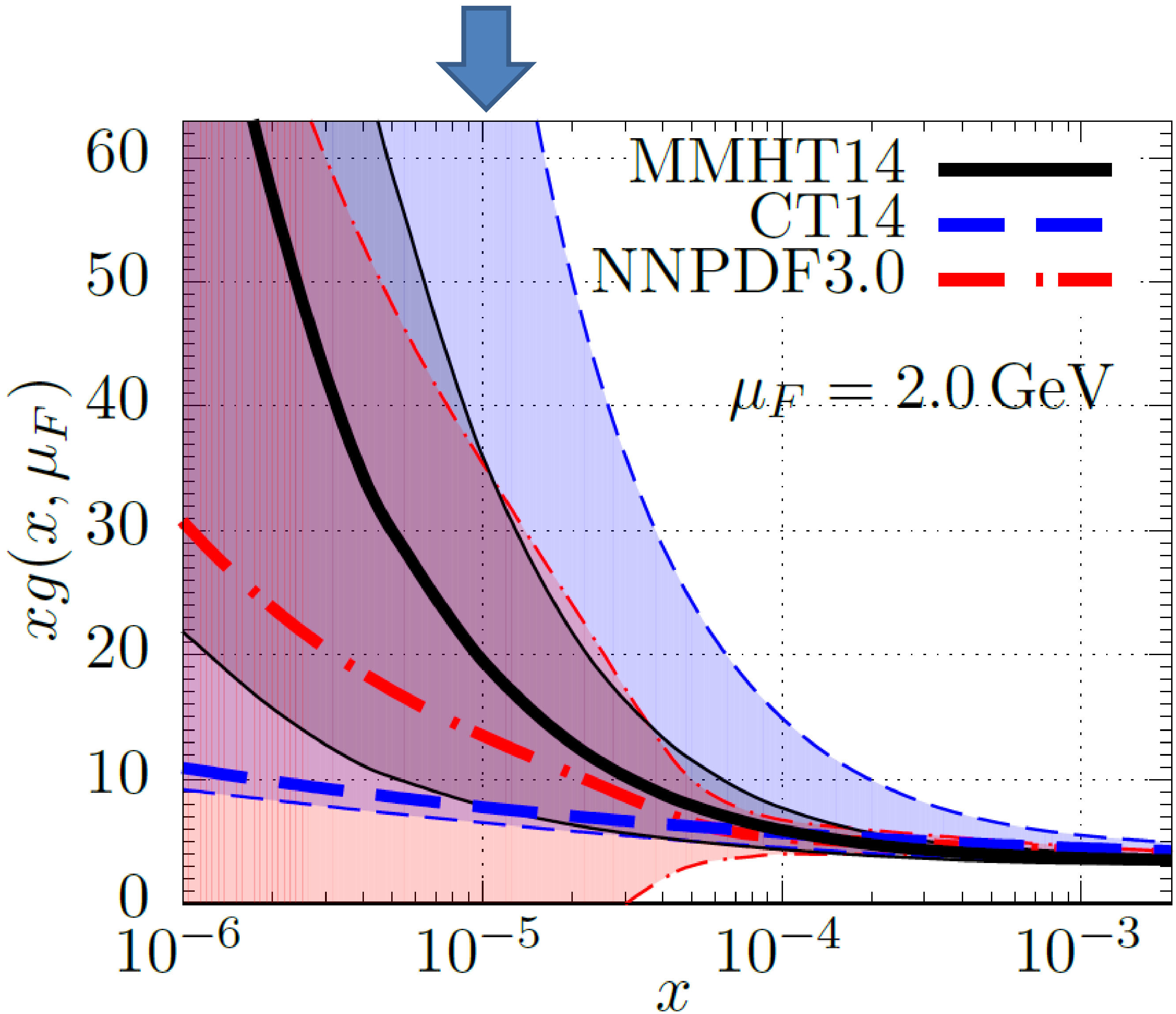
Low x meeting
Bari, Italy
June 13-17, 2017



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

exclusive J/ψ prod;
inclusive $c\bar{c}$, prod.

Gluons from global PDF analyses unknown at x ~ 10^{-5}



(i) Exclusive J/ψ production

$$pp \rightarrow p + J/\psi + p$$

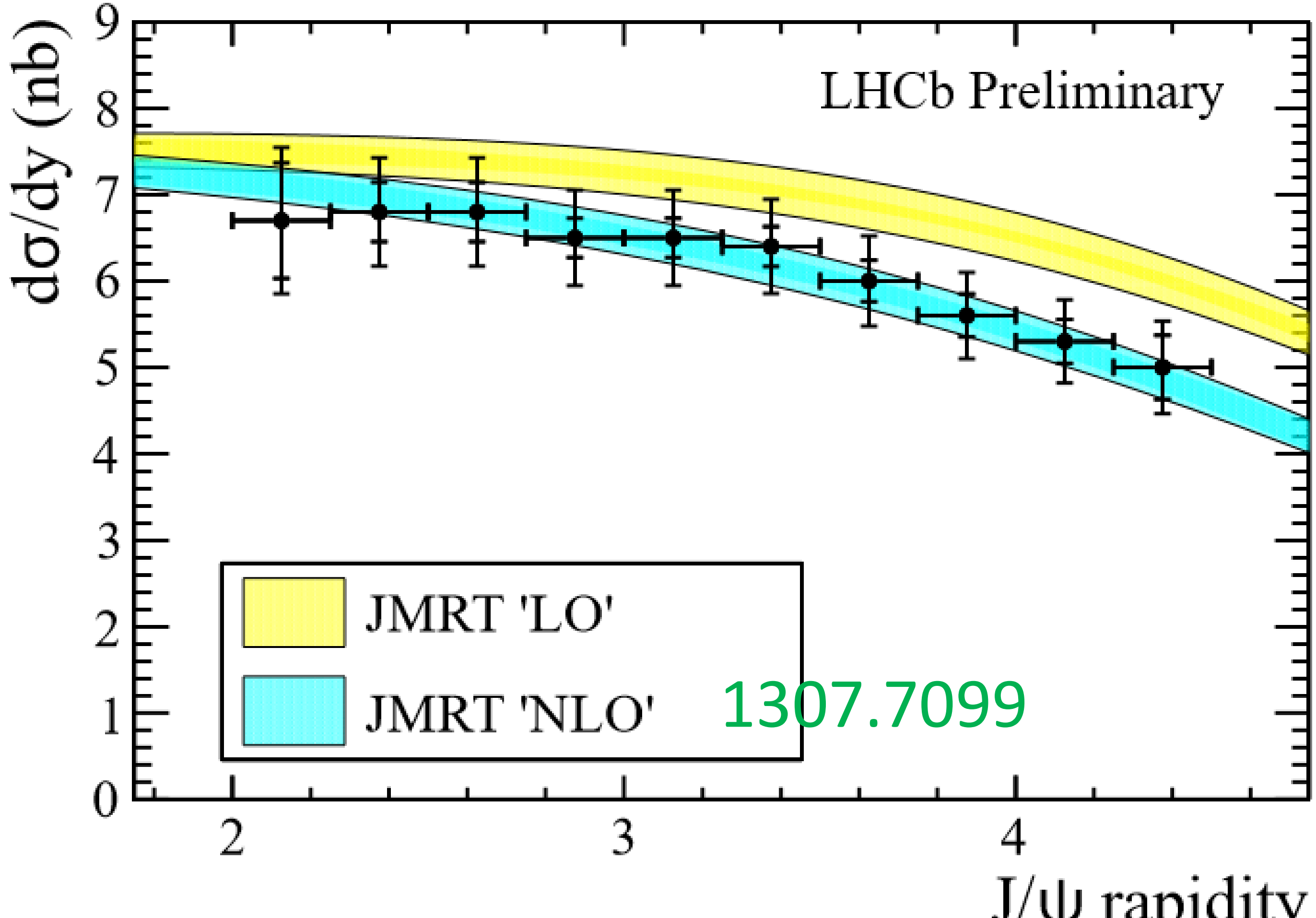
together with HERA data on $\gamma p \rightarrow J/\psi\, p$

probe gluon at $x < 10^{-5}$

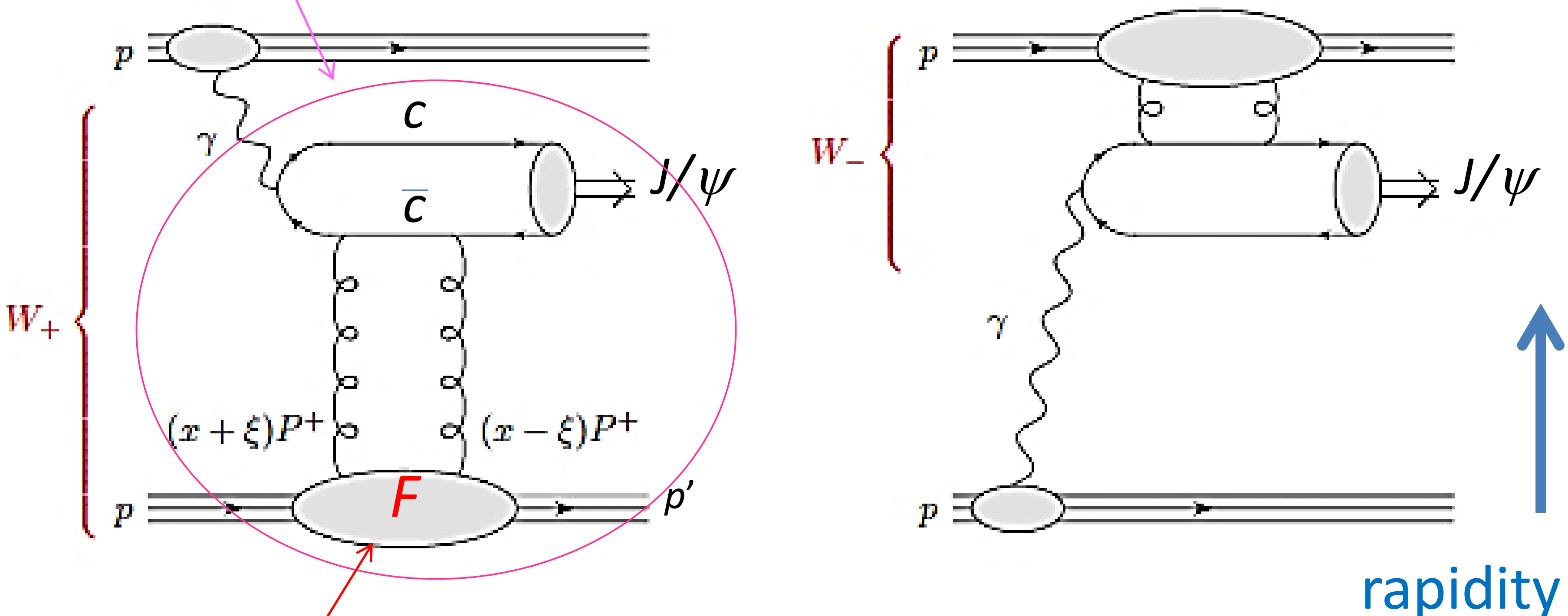
LHCb data for pp → p + J/ψ + p at 13 TeV

with new HERSCHEL forward shower counters to improve the exclusivity of the events

LHCb-CONF-2016-007



$\gamma^* p \rightarrow J/\psi + p$ is the quasi-elastic process which drives the LHC data for $pp \rightarrow p + J/\psi + p$



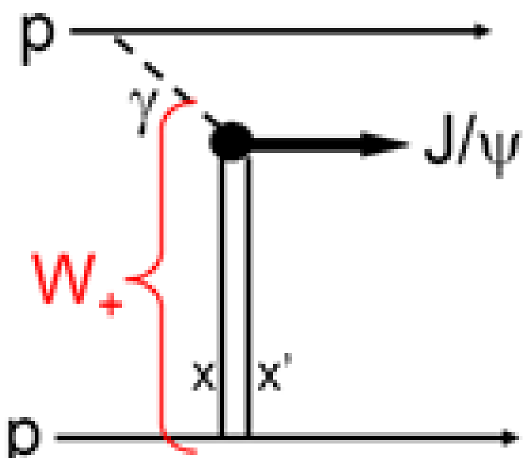
GPD: $F(x, \xi, \mu_F^2)$

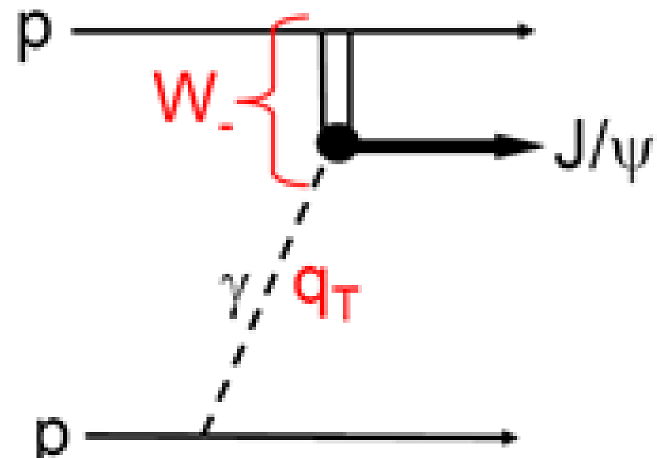
$(p' - p = \xi(p + p'))$

pp → p + J/ψ + p   at the LHC

$$W_\pm^2 = M_{J/\psi}\sqrt{s}\; e^{\pm|y|}$$

γp,   pγ   ambiguity





|y|=4

$x \sim M_{J/\psi}\exp(-|y|)\;/\sqrt{s} < 10^{-5}$

$x \sim M_{J/\psi}\exp(|y|)\;/\sqrt{s} \sim 0.02$

from fit to LHCb

Show W+

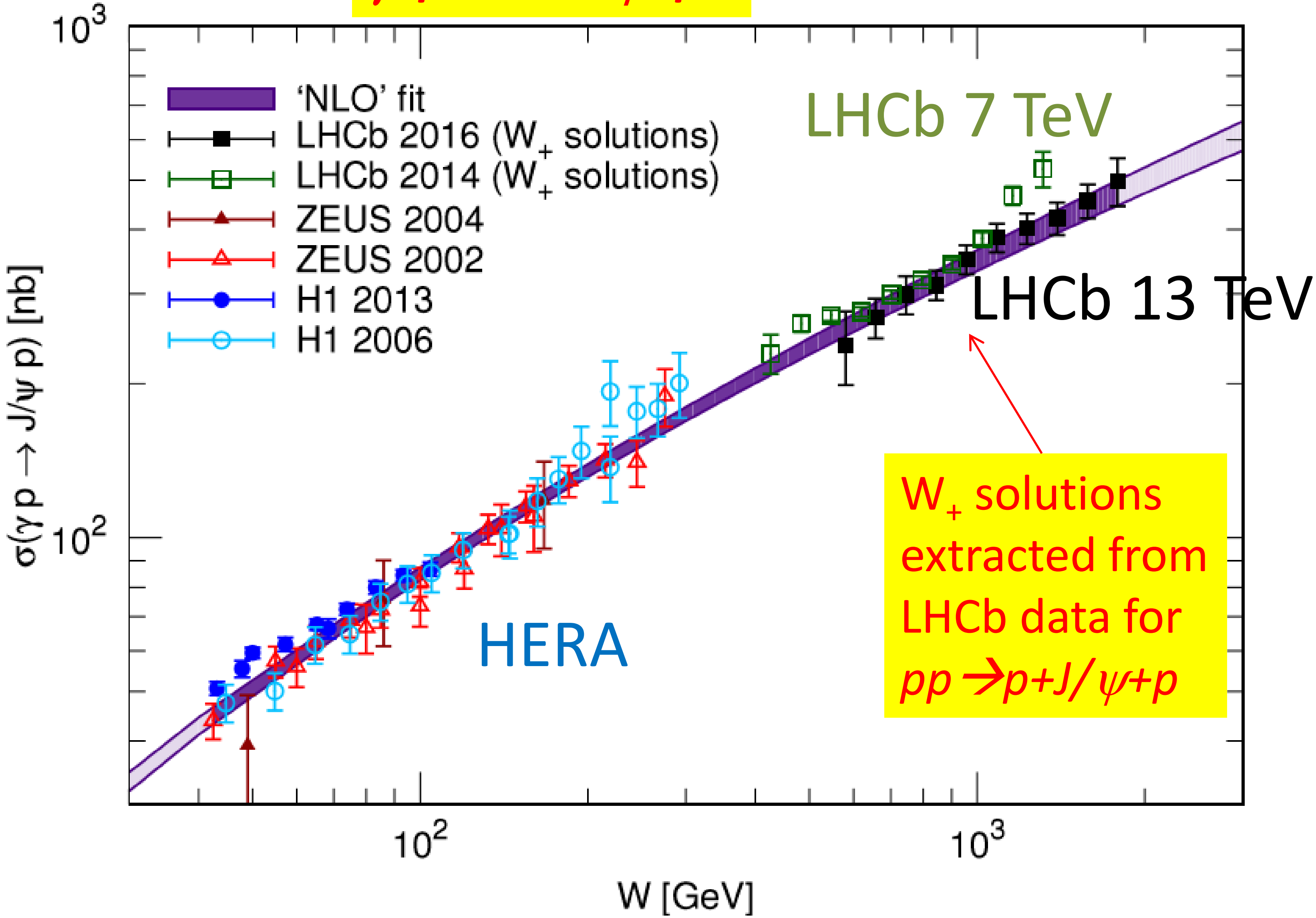
known from HERA

$$\frac{\mathrm{d}\sigma^{\mathrm{th}}(pp)}{\mathrm{d}y} = S^2(W_+)\left(k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\right)\sigma_+^{\mathrm{th}}(\gamma p) + S^2(W_-)\left(k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\right)\sigma_-^{\mathrm{th}}(\gamma p)$$

where (...) is photon flux for photon energy $k_\pm$

and S^2 are survival probabilities of LRG

$\gamma p \to J/\psi\, p$



Why was JMRT "NLO" prediction of 13 TeV so reasonable?

Problems of using exclusive J/ψ data in global PDF fits?

1. Process described by GPD's

→ however not a problem for $\xi < |x| << 1$

GPD(ξ, x) = PDF(x') ⊗ Shuvaev(ξ, x, x') hep-ph/9902410

2. Bad convergence of LO, NLO,... pert. series using collinear factorization at low ξ and low scales

additional gluons = $\langle n \rangle \simeq \frac{\alpha_s N_C}{\pi} \ln(1/\xi)\, \Delta \ln \mu_F^2$ ~ 5

whereas **NLO** allows the addition of only 1 gluon !

So why is the JMRT "NLO" prediction so reasonable?

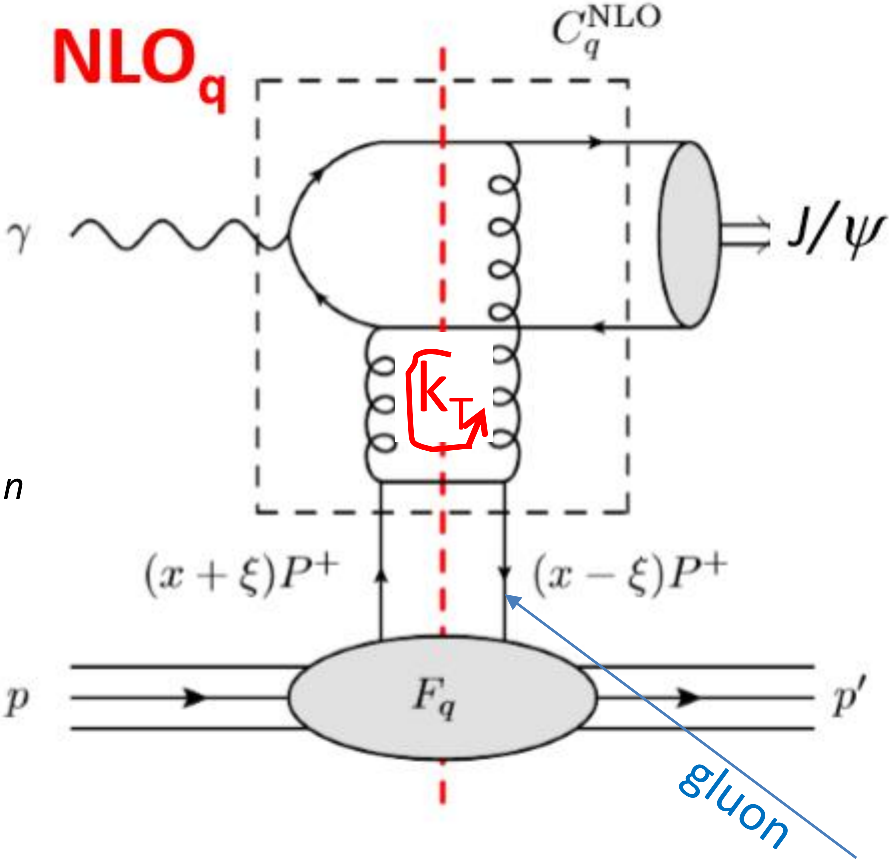
1307.7099

It uses **k_T fact^n** scheme and resums the ln(1/ξ) diagrams

k_T fact^n procedure

Obtain approx NLO corr^{ns} to coeff. fns by performing explicit k_T integration in the last step of evolution, and using an input PDF with resummed $(\ln(1/\xi)\ln\mu_F^2)^n$ terms arising from ladder diag^s.

Not the complete NLO, but includes most important diagrams at low x and low μ_F^2



also NLO$_g$ coeff. fn.

Need gluon PDF unintegrated over k_T

$$f(x,k_T^2) = \partial\left[xg(x,k_T^2)T(k_T^2,\mu^2)\right]/\partial\ln k_T^2$$

known Sudakov factor T so no additional gluons > k_T emitted

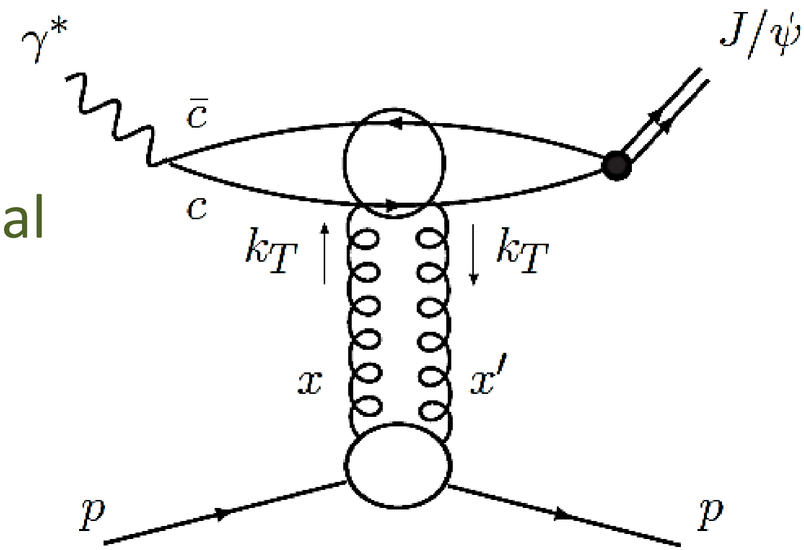
“NLO” formula for $\gamma^*p \rightarrow J/\psi + p$

Start with LO formula

Ryskin 1993

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

$$\begin{aligned} x &= (Q^2+M^2_{J/\psi})/(W^2+Q^2) \\ \bar{Q}^2 &= (Q^2+M^2_{J/\psi})/4 \end{aligned}$$



Allow for skewing (x≠x’) a la Shuvaev et al

Allow for real part

Mimic NLO by including $k_T{}^2$ integration in last step of evol^n (a la Kimber at al)

$$\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4}xg(x,\bar{Q}^2)\right] \longrightarrow \int_{Q_0^2}^{(W^2-M^2_{J/\psi})/4}\frac{\mathrm{d}k_T^2\,\alpha_s(\mu^2)}{\bar{Q}^2(\bar{Q}^2+k_T^2)}\frac{\partial\left[xg(x,k_T^2)\sqrt{T(k_T^2,\mu^2)}\right]}{\partial k_T^2}$$

+ Q_0 contribution

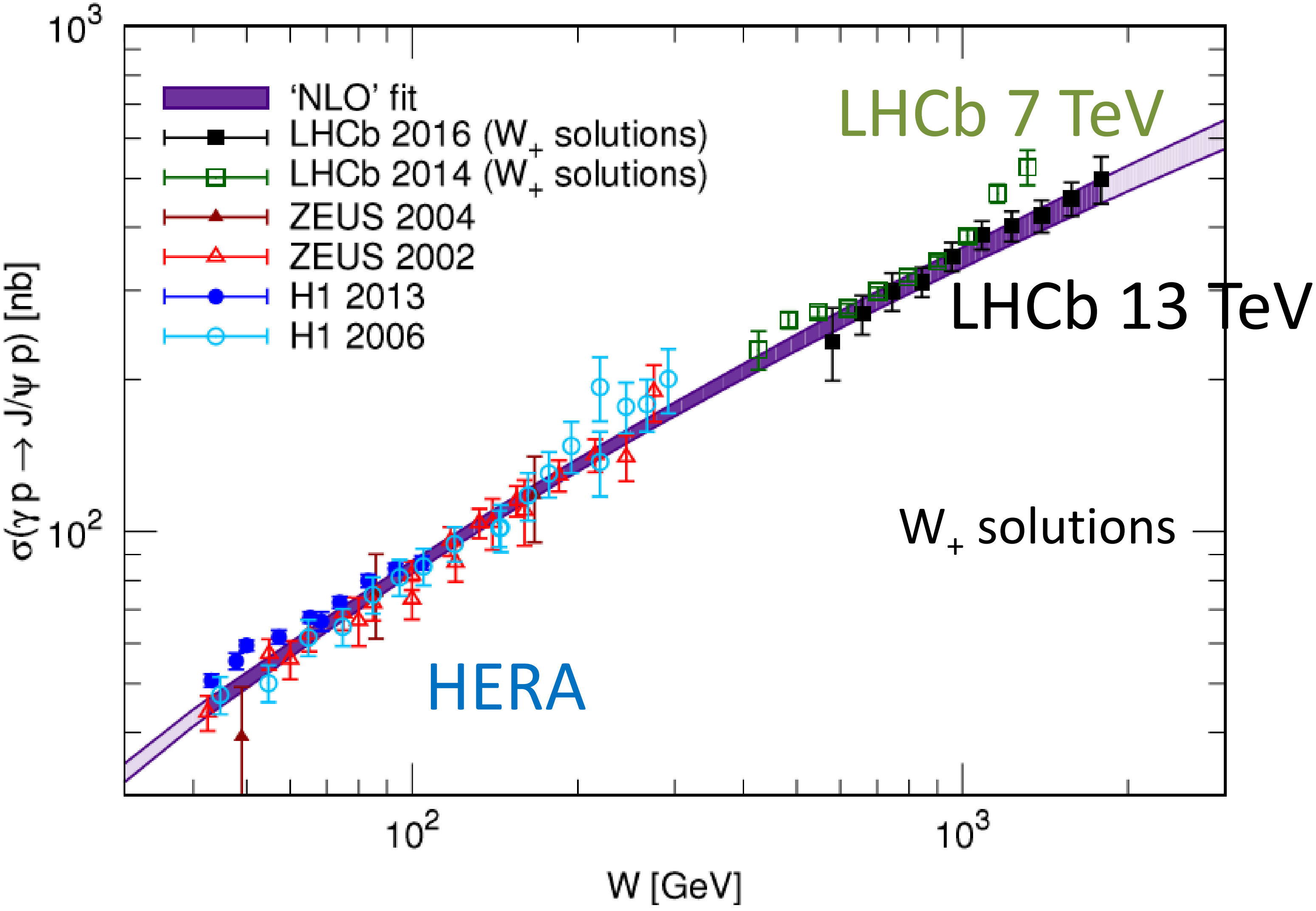
Parametrization of gluon *(N, a, b)*

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

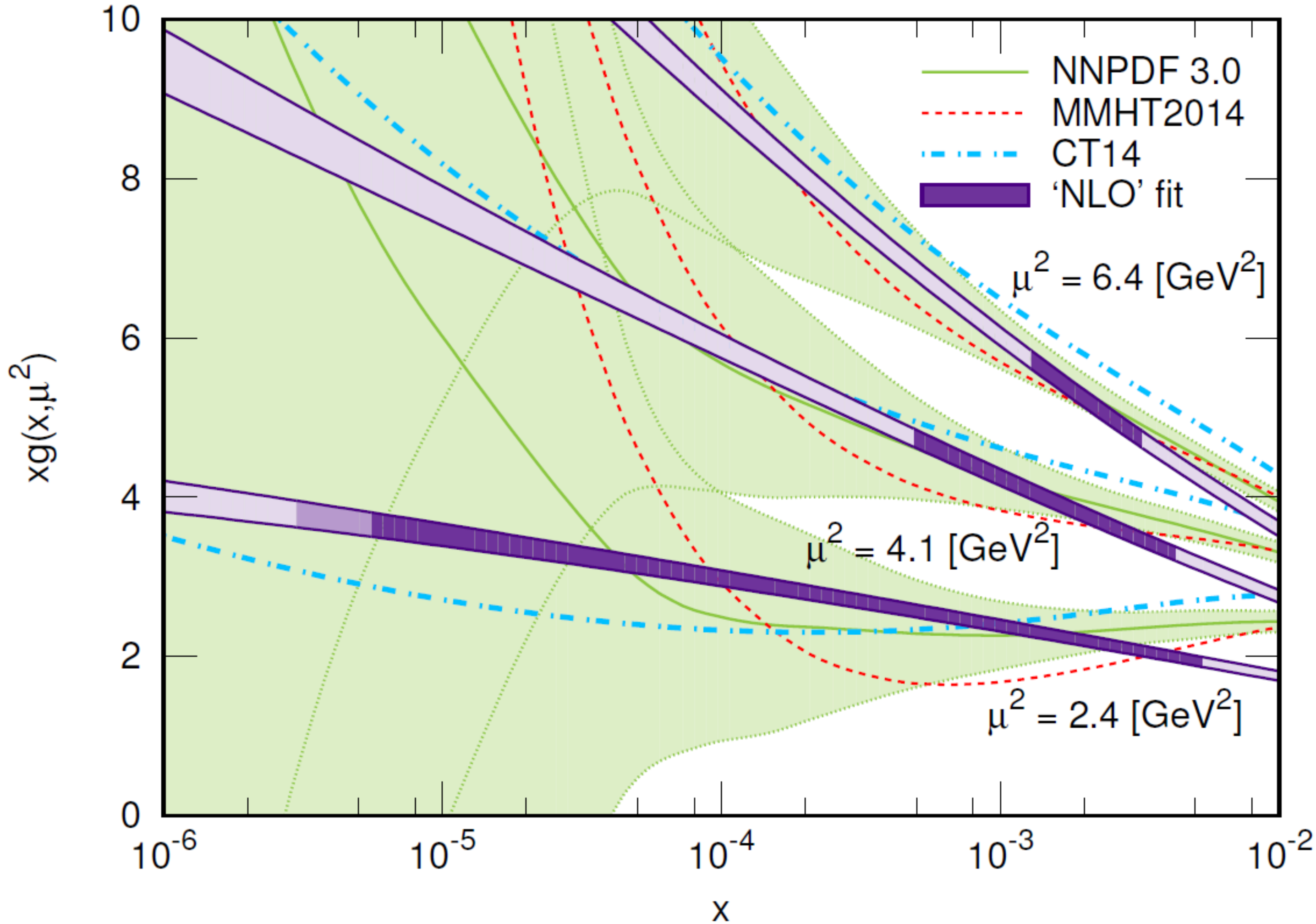
$$\text{with} \quad G = \frac{\ln(\mu^2/\Lambda^2_{\rm QCD})}{\ln(Q_0^2/\Lambda^2_{\rm QCD})}$$

resummation of D.Log terms, $(..\alpha_s \ln(1/x)\ln\mu^2)^n$, written explicitly, while summation of single logs accounted for by powers *a,b*

Form checked to be consistent with NLO DGLAP in low *x* region of interest,



JMRT refit (1611.03711) but find parameters *N,a,b* same as in 2013 fit using only 7 TeV LHCb data



J/ψ "NLO" gluon PDF compared to gluons of global PDF sets

but.... physical k_T fact^n scheme

collinear MS(bar) scheme

Problems of using exclusive J/ψ data in global PDF fits?

1. Process described by GPD's

→ however not a problem for $\xi < |x| << 1$

$$\mathrm{GPD}(\xi, x) = \mathrm{PDF}(x') \otimes \mathrm{Shuvaev}(\xi, x, x')$$ hep-ph/9902410

2. Bad convergence of LO, NLO,... pert. series using collinear factorization at low ξ and low scales

additional gluons = $\langle n \rangle \simeq \frac{\alpha_s N_C}{\pi} \ln(1/\xi) \, \Delta \ln \mu_F^2$ ~ 5

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1307.7099

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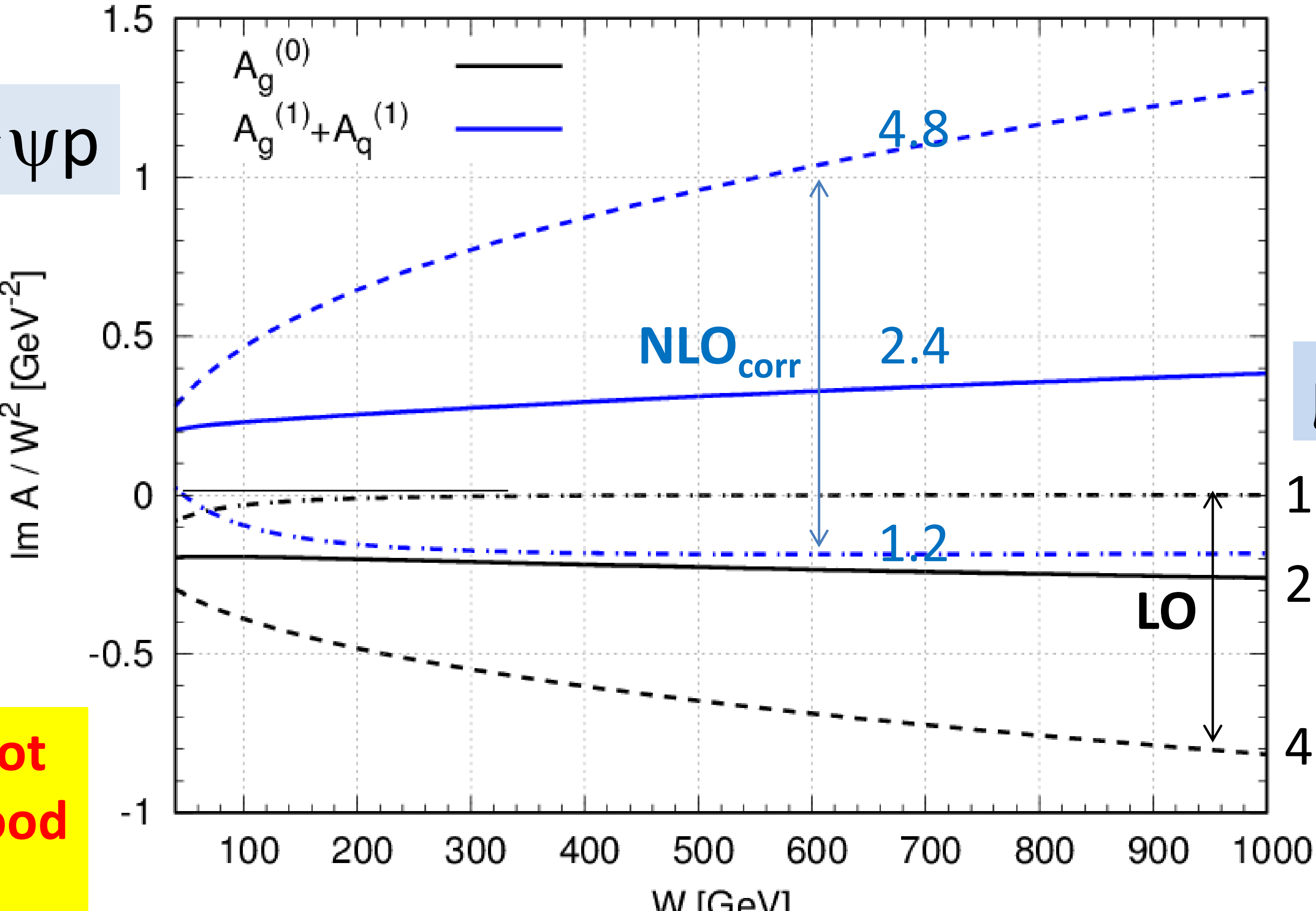
NLO known in MS(bar) scheme, but problems:

D. Ivanov, B.Pire, L.Szymanowski, J.Wagner, 1411.3750
S.P.Jones, A.D.Martin, M.Ryskin, T.Teubner, 1507.06942

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

B. **Strong dependence on scale** μ_F

$\gamma p \to \psi p$



μ_F^2

1.2 GeV²

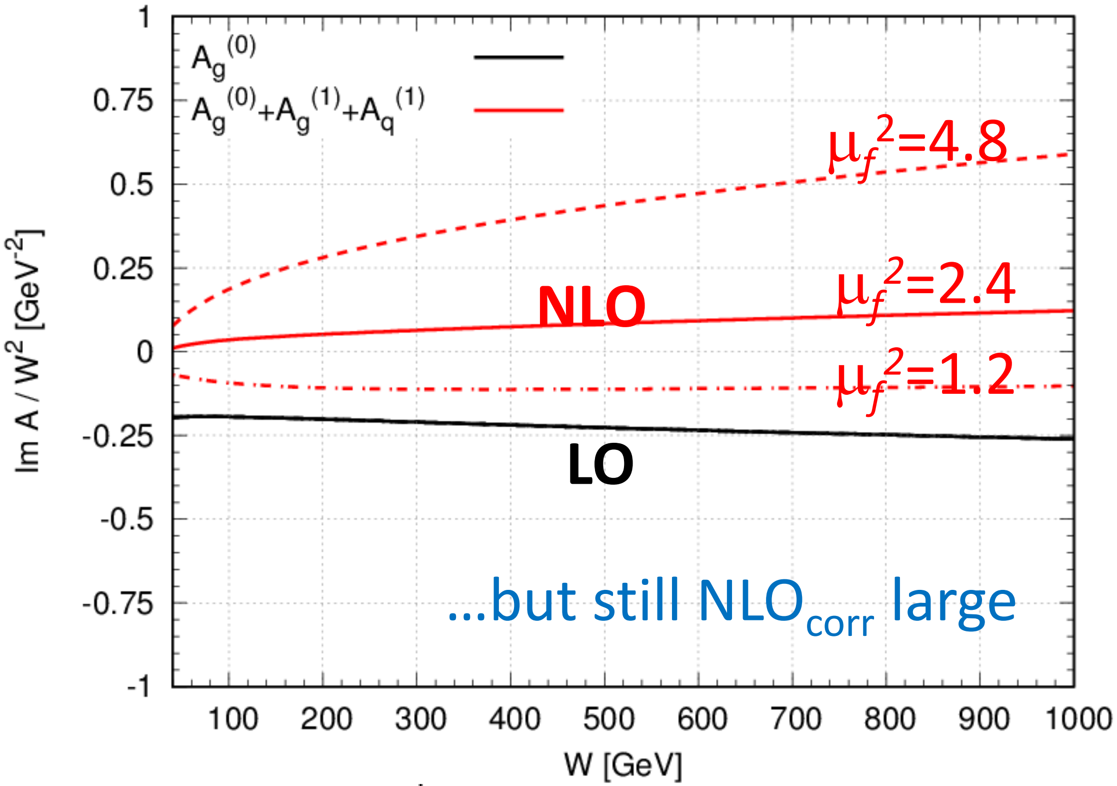
2.4

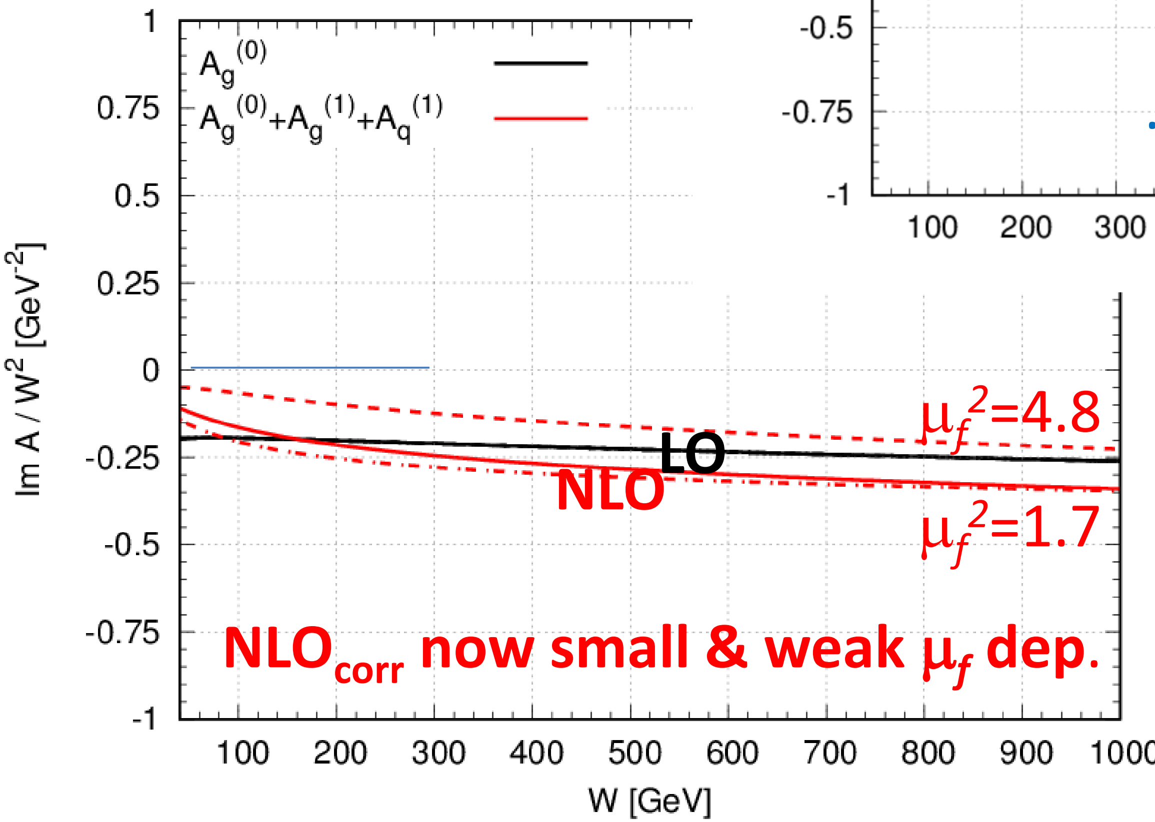
4.8

Does not look good but.....

Can resum $(\alpha_s \ln(1/\xi) \ln\mu^2)^n$ terms, & move into LO PDF leaving small remaining NLO coeff.fn.

1507.06942





Subtract double counting NLO ($|q^2|<Q_0^2$) contrib^n

1610.02272

(ii) Open charm production

$$pp \rightarrow c\bar{c}\,X$$

LHCb data determine the gluon

$$10^{-5} \lesssim x \lesssim 10^{-4}$$

(ii) LHCb $pp \rightarrow c\bar{c}X$ data (via observing D mesons)

at 7, 13, 5 TeV; we use recently corrected 13, 5 data

Process mainly driven by gg fusion. We work at NLO

OMR: 1705.088451

$$\frac{d^2\sigma}{dp_{t,D}\;dy} = \mathrm{PDF}(x_1, \mu_F) \otimes |\mathcal{M}|^2 \otimes \mathrm{PDF}(x_2, \mu_F) \otimes D(z)$$

4 bins: $1<p_t<5$ GeV

5 bins: $2<y<4.5$

$x_2 \sim 10^{-5}$

xg ?

$c \rightarrow D$ frag. f^{ns} use Cacciari,Nason,Oleari

$D^+ + D^-$	$D^0 + \bar{D}^0$	$D_s + \Lambda_c$
0.246	1.1(0.565)	0.133

scale $\mu_F = 0.85\, m_T$
$= 0.85\, \sqrt{(m_c^{\,2} + p_{t,c}^{\,2})}$
see 1610.06034

$x_1 > 10^{-3}$

Use global PDFs

2x3x5=30 data at

$D \;\; E \;\; y \qquad$ each p_t

(A) gluons at fixed μ_F with simple 2-parameter fits

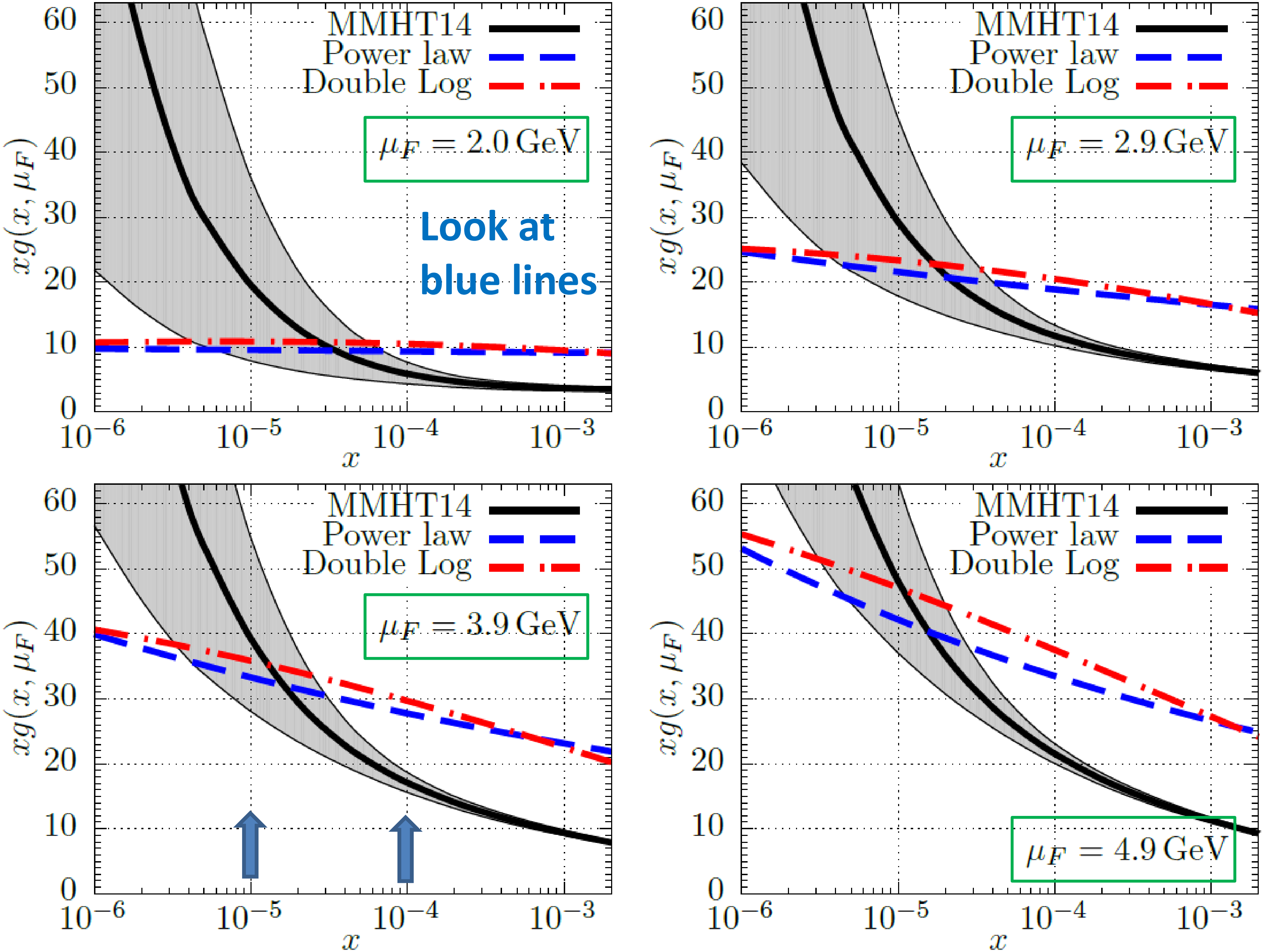
$xg(x,\mu_F)=\mathbf{N}(x/10^{-5})^{-\lambda}$

$p_{t,D}$	μ_F	N	λ	χ^2_{all}	χ^2_5	χ^2_7	χ^2_{13}
1.5	2.0	9.6 ± 0.6	-0.01 ± 0.02	52	18	6	28
2.5	2.9	21.6 ± 1.6	0.06 ± 0.03	31	12	6	13
3.5	3.9	33.3 ± 2.9	0.08 ± 0.03	27	7	12	8
4.5	4.9	42.1 ± 4.1	0.10 ± 0.03	30	4	15	11

GeV

$\mu_F = 0.85\sqrt{(m_c^2+p_{t,c}^2)}$
with $p_{t,c} \sim p_{t,D}/0.8$

2x3x5=30 data at
D E y each p_t



MMHT14
Power law
Double Log
$\mu_F = 2.0\,\mathrm{GeV}$
$\mu_F = 2.9\,\mathrm{GeV}$
$\mu_F = 3.9\,\mathrm{GeV}$
$\mu_F = 4.9\,\mathrm{GeV}$
Look at
blue lines
$xg(x, \mu_F)$
x
60
50
40
30
20
10
0
10^{-6}
10^{-5}
10^{-4}
10^{-3}

(B) Fit to all 120 data with Double Log parametrization

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

The resummation of DL terms, $(\alpha_s \ln(1/x)\ln\mu^2)^n$, is written explicitly while the remaining single logs are accounted for by powers *a, b.*

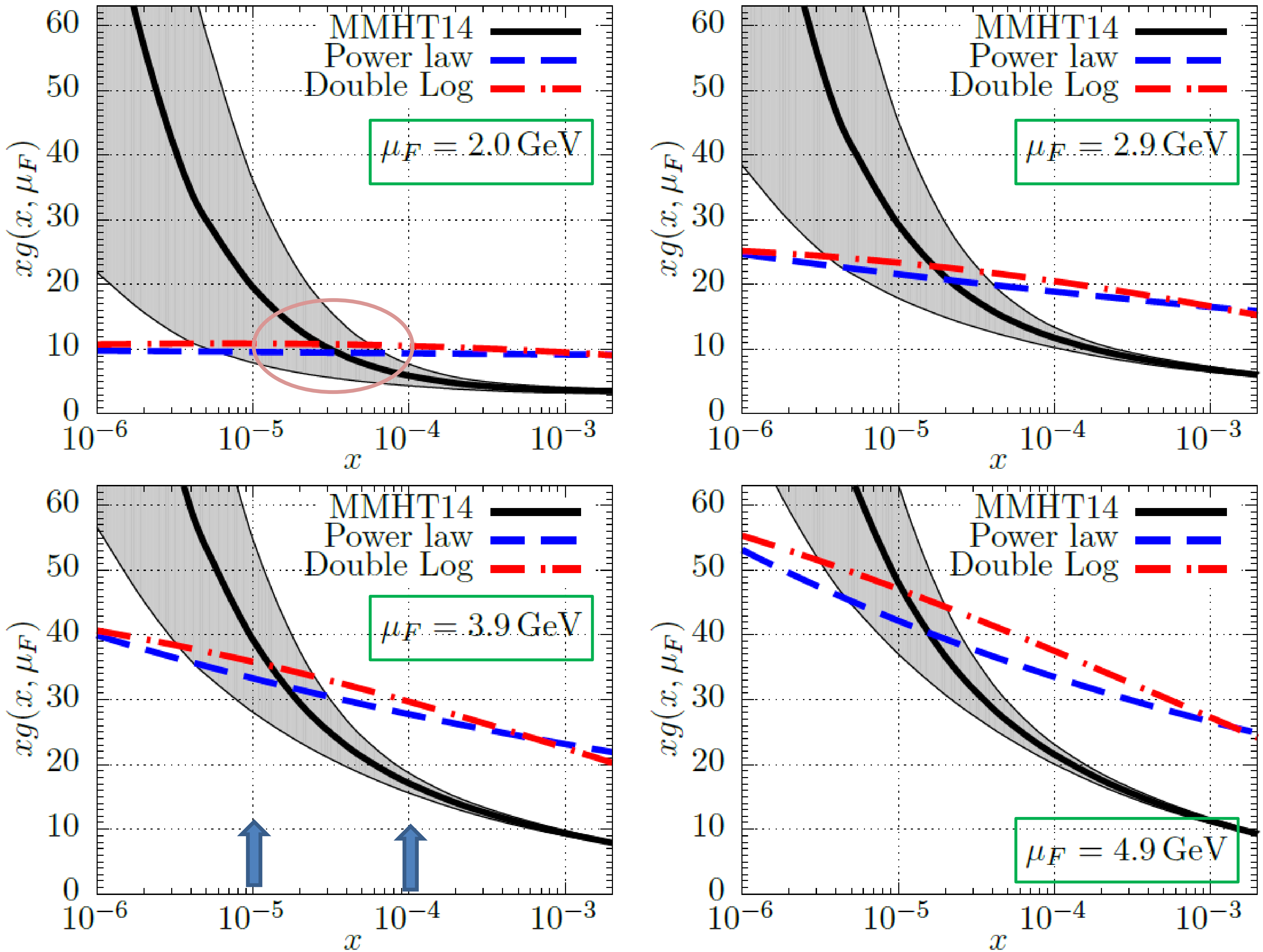
$$G=\frac{\ln(\mu^2/\Lambda^2_{\rm QCD})}{\ln(Q_0^2/\Lambda^2_{\rm QCD})}$$

$N_c=3$, $\beta_0=9$, $Q_0=1$ GeV, $\Lambda_{QCD}=200$ MeV

Such a form shown consistent with NLO DGLAP evolution with b=0.2 in exclusive J/ψ paper 1611.03711

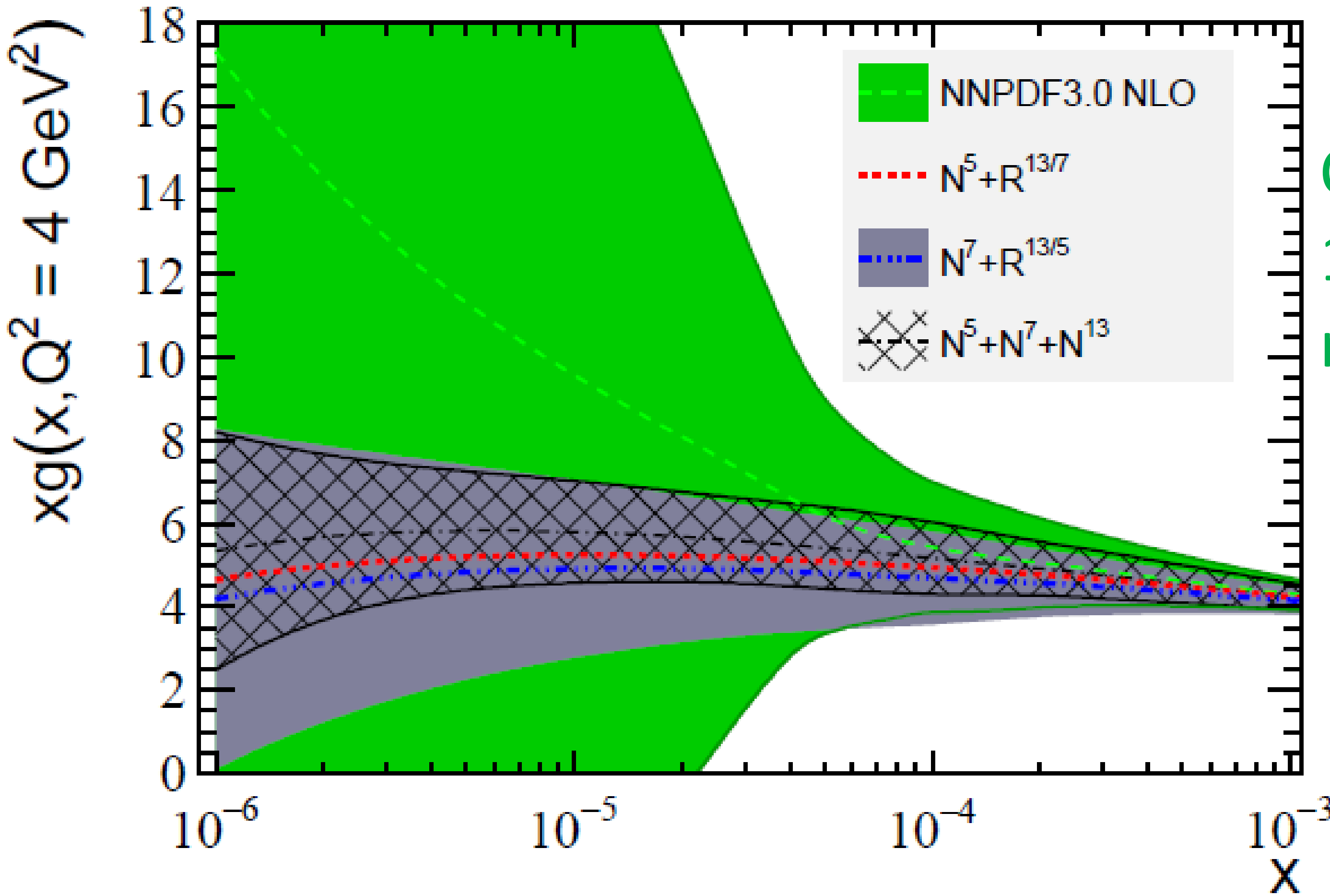
	$N^{\rm DL}$	a	b (fixed)	χ^2	χ^2_5	χ^2_7	χ^2_{13}
Fit to $c\bar{c}$ data	0.13 ± 0.01	-0.20 ± 0.01	-0.2	141	43	39	59
Fit[17] to J/ψ data	0.092 ± 0.009	-0.10 ± 0.01	-0.2				

fixed



MMHT14
Power law
Double Log
$\mu_F = 2.0\,\mathrm{GeV}$
$\mu_F = 2.9\,\mathrm{GeV}$
$\mu_F = 3.9\,\mathrm{GeV}$
$\mu_F = 4.9\,\mathrm{GeV}$
$xg(x, \mu_F)$
x

Comparison with Gauld, Rojo determination 1610.09373



Corrected 13, 5 TeV data not available

Only fit ratios (N = data(y)/data(3.25)) so normal^n not fixed.
Ratios agree rather flat x dep., but normal twice as small

Conclusions for determination of low x gluons

LHCb pp → p+J/ψ+p data determine NLO g(PDF) for $x < 10^{-5}$

(i) LHCb data well decribed by 3-parameter NLO gluon form in the k_T factorization scheme.

(ii) Can include data in global PDF fit in MS(bar) scheme
if (a) the scale is fixed to resum the DL and
(b) a Q_0 cut is used to avoid double counting.

LHCb pp → $c\bar{c}X$ data probe g(PDF) for $10^{-5} < x < 10^{-4}$. Find similar size, or little larger, to global g(x) extrapolated into this unexplored domain. However, we find direct measurements have a much weaker x dependence. Higher statistics forward charm data will be valuable to resolve the dilemma.

We saw why it is a problem at low ξ

gluons emitted = $\langle n \rangle \simeq \dfrac{\alpha_s N_C}{\pi} \ln(1/\xi)\, \Delta \ln \mu_F^2$ ~ 5

for ξ << 1 and reasonable variation of μ_F

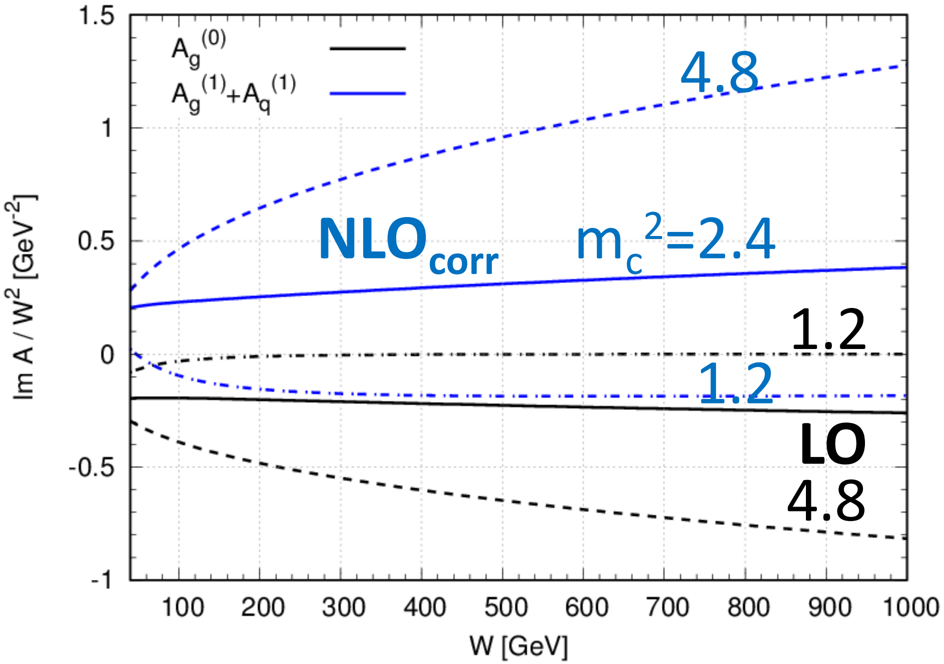
whereas NLO only allows emission of one gluon !

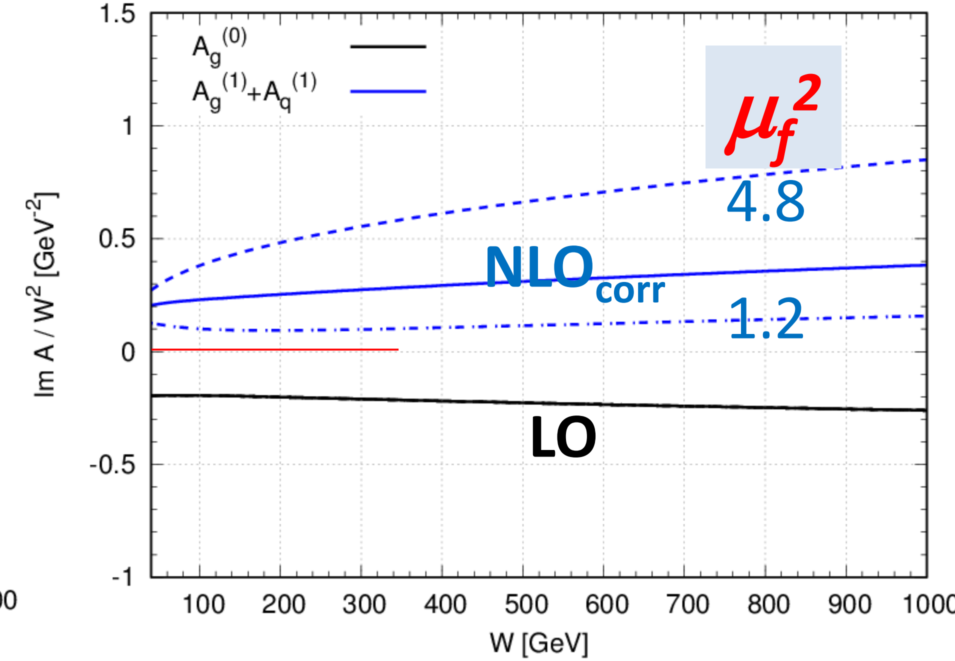
however can resum $(\alpha_s \ln(1/\xi)\ \ln\mu_F^2)^n$ terms and move into LO contrib. by choosing $\mu_F = m_c$ (see JMRT, 1507.06942)

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

Use explicit NLO to calculate small remainder C_{rem}.
Residual dependence on scale μ_f is small

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





scale dependence now weaker

A. But still have very bad perturbative convergence

NLO$_{correction}$ ~ LO and opposite sign

Have we missed something? **YES.** Effect of important Q_0 cut

Q_0^2/μ_F^2 power corr^{ns}.

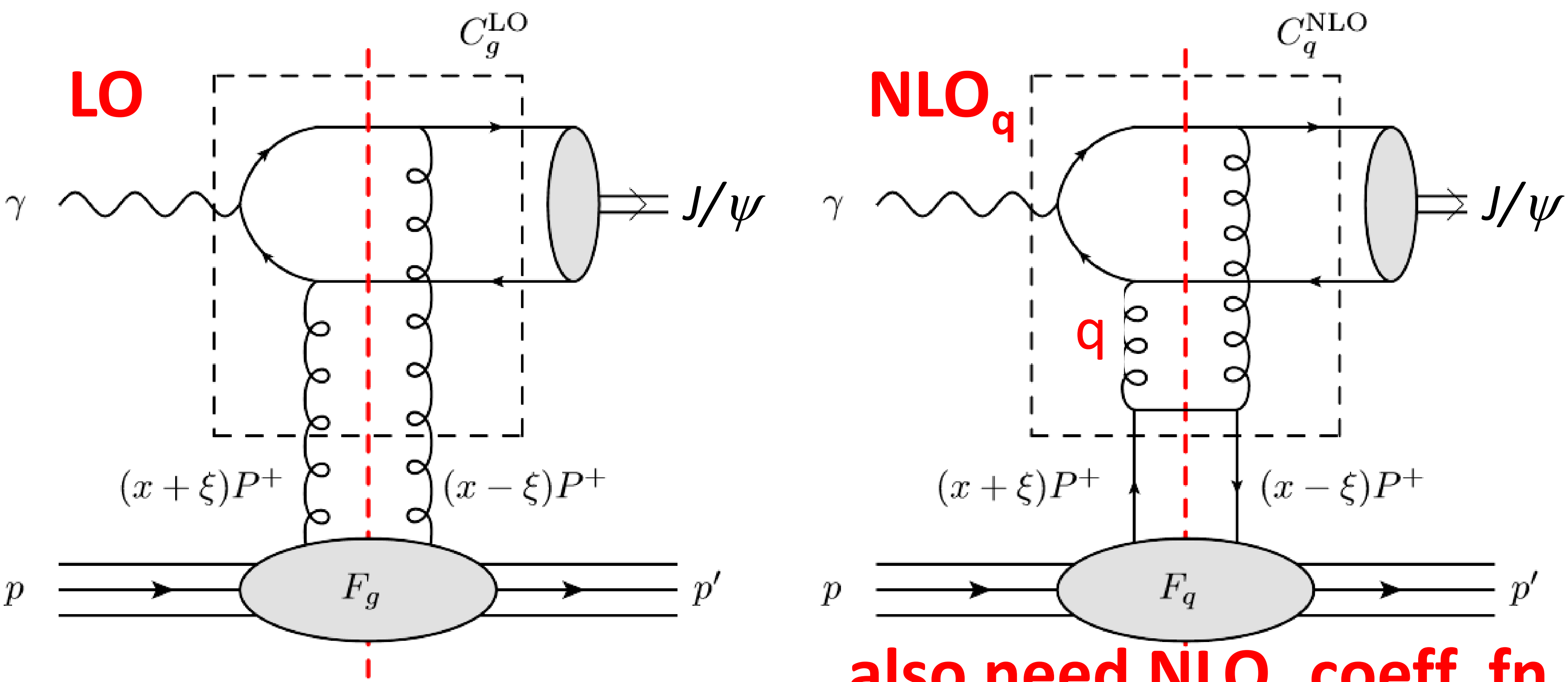
Start DGLAP evol. at Q_0

At LO everything below Q_0 is included in input PDF(Q_0)

At NLO the contrib^n from $|q^2| < Q_0^2$ is double counting

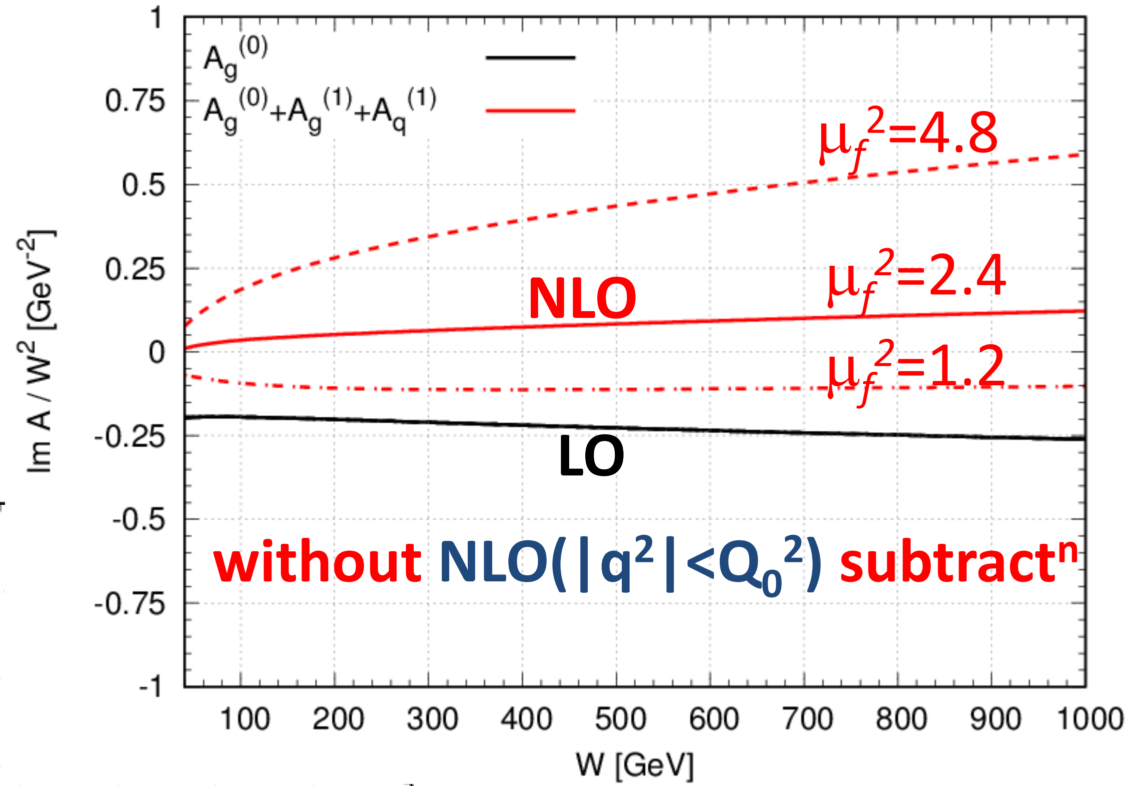
Need to subtract NLO($|q^2|<Q_0^2$) contrib^n for both q & g

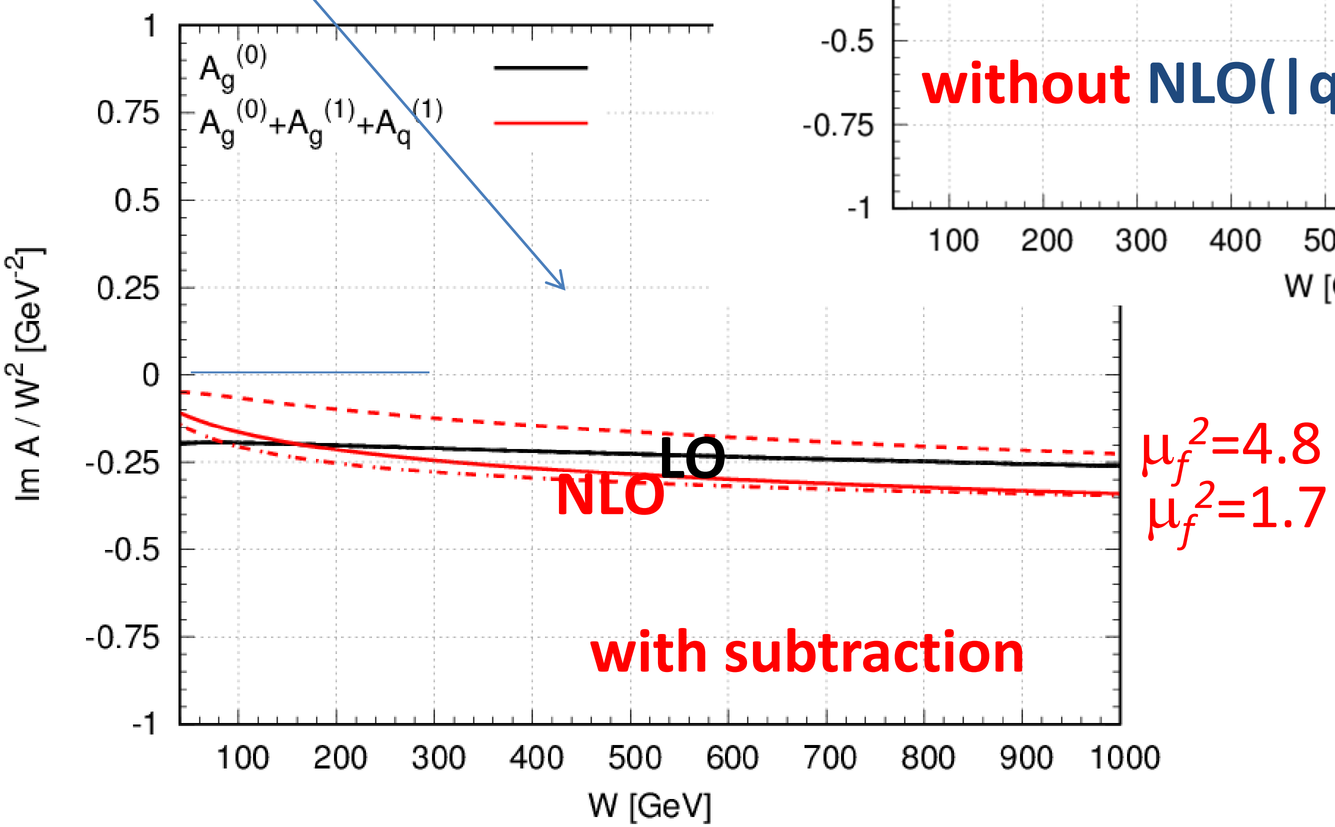
See appendix of 1610.02272



also need NLO$_g$ coeff. fn

$\mathbf{NLO_{corr}}$ is (i) now **small** and (ii) much less dependent on choice of (residual) factⁿ scale μ_f





Aside: choice of renormalization scale

Choose $\mu_R = \mu_F$.   Two reasons:

1. Corresponds to BLM prescription --- eliminates
   NLO $\beta_0 \ln(\mu_R/\mu_F)$ term
2. New q loop in g propagator appears twice:
   (a) part for scales $\mu<\mu_F$ by virtual comp^t of LO splitting in DGLAP evolution.
   (b) part for scales $\mu>\mu_R$ from running α_S behaviour after regular^n of UV divergence.

Not to miss part and/or to avoid double counting take

$$\mu_R = \mu_F$$

Single inclusive open $c\bar{c}$ (and $b\bar{b}$) prod^n

Oliveira, M, Ryskin
1610.06034

We find optimum scale to resum $(\alpha_s \ln \mu_F^2 \ln(1/x))^n$ terms is

$$\mu_F^2 = 0.72\,(p_T^2 + m_c^2)$$

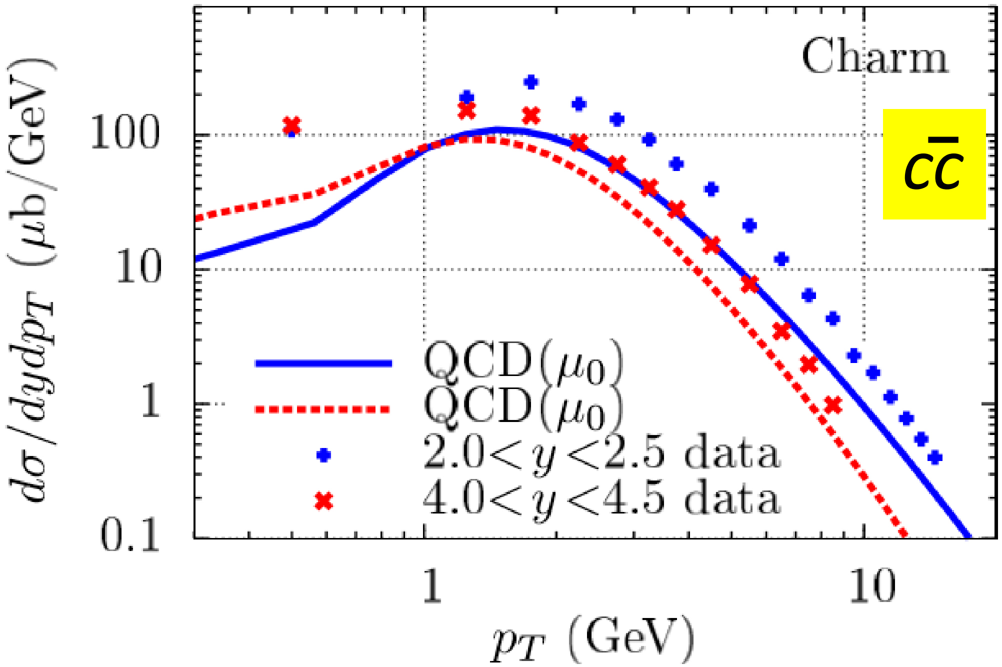
Though reduced, we find still rather strong scale dependence coming from numerically large 2→2 ($gg \rightarrow c\bar{c}$) terms at NLO and higher orders

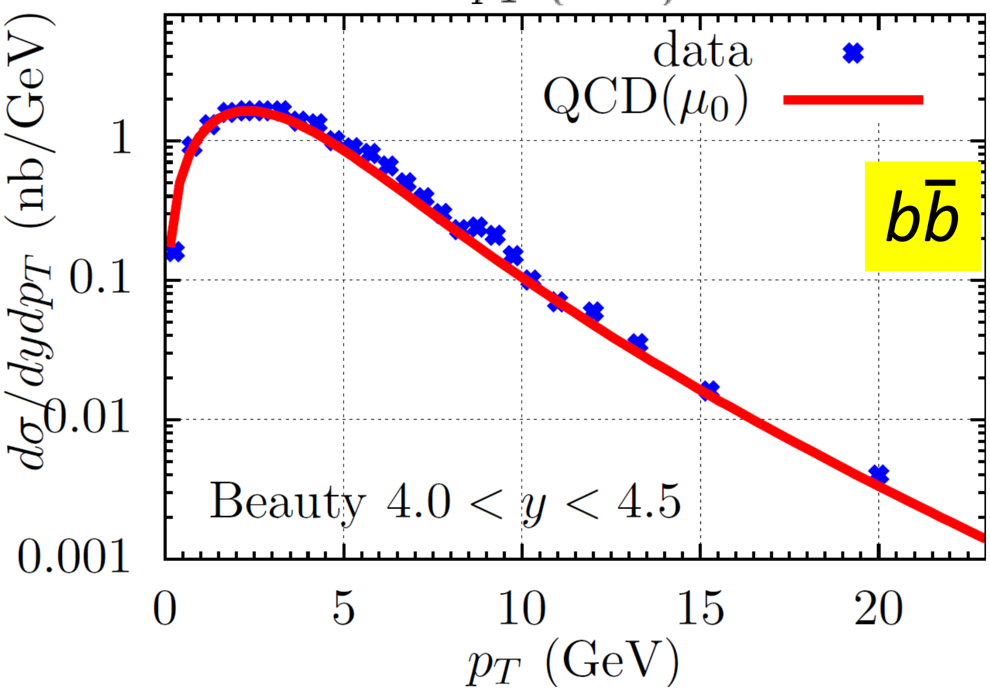
We discuss the optimum scale to resum 2→2 these effects

We then compare with LHCb data using MCFM and FONLL

taking Prob ($c \rightarrow D^+$) = 0.25 and $p_D \sim 0.75\, p_c$

Prob ($b \rightarrow B^+$) = 0.4 and $p_B \sim 0.9\, p_b$





Conclusion for $c\bar{c}$, $b\bar{b}$

QCD predictions undershoot the LHCb $c\bar{c}$ data indicating input low x gluon of CT14 NLO PDF should be larger.

Similar for other global PDFs.

Has implications for the flux of prompt atmospheric ν's, recall Anna Stasto's talk

LO approximation uses non-relativistic J/ψ wave fn.

Hoodbhoy (hep-ph/9611207) shows that the relativistic corrections, written in terms of the experimentally measured J/ψ width Γ_{ee}, are small, ~O(4%).

Suppose input *g(x)*=0, then only have NLO *q* term

But gluons cannot be smaller than density of gluons emitted before evol^n starts, so have opposite sign LO term

Input gluons cannot be freely parametrised in global fits, *g(x)* needs to be sufficiently positive

Pure global fits should take account of absorptive corrections which occur at low x, low Q^2.
Opposite sign NLO term mimics this effect in *g(x)*.

So much for conventional MS(bar) global PDFs at low x and low Q^2