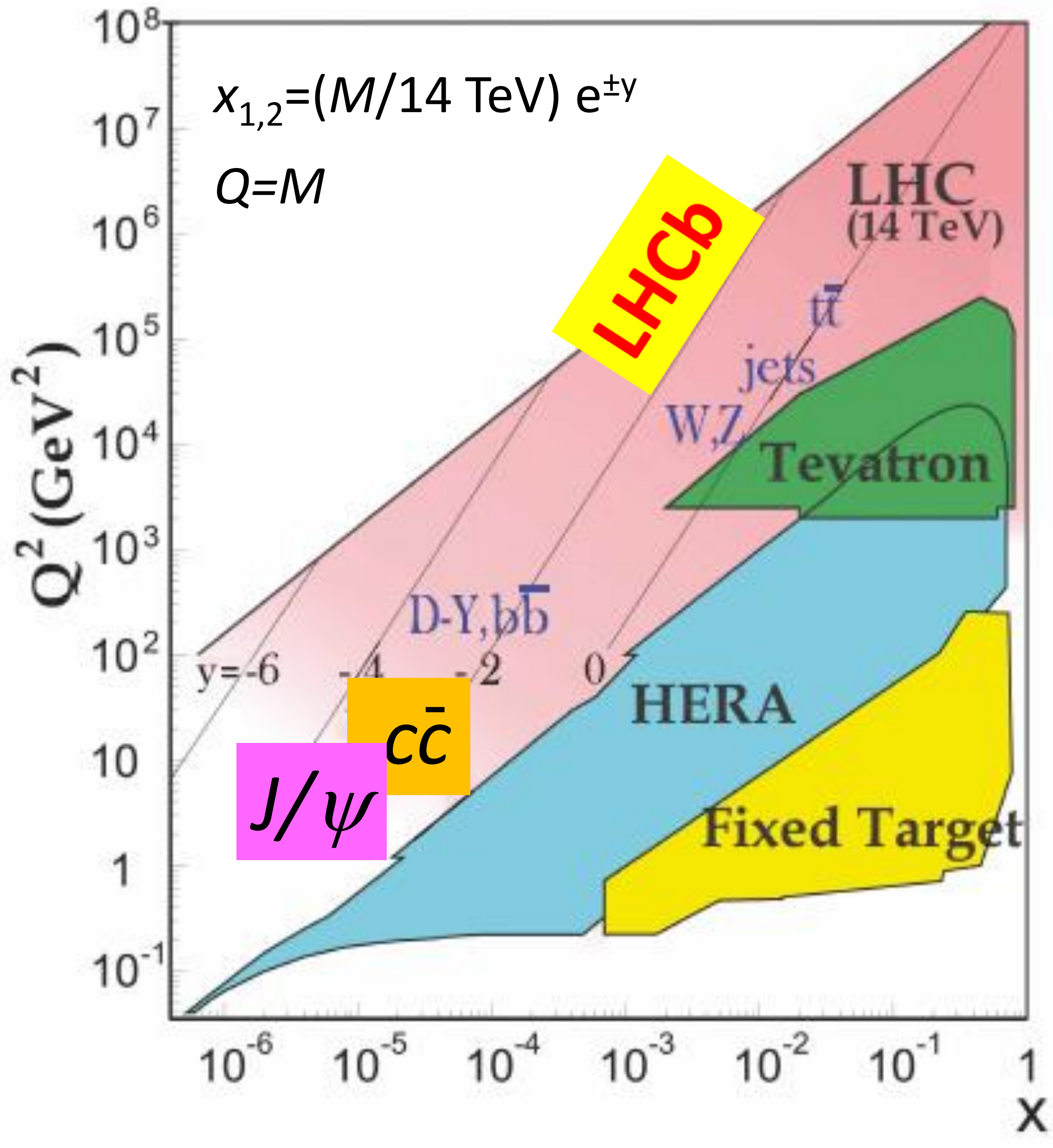
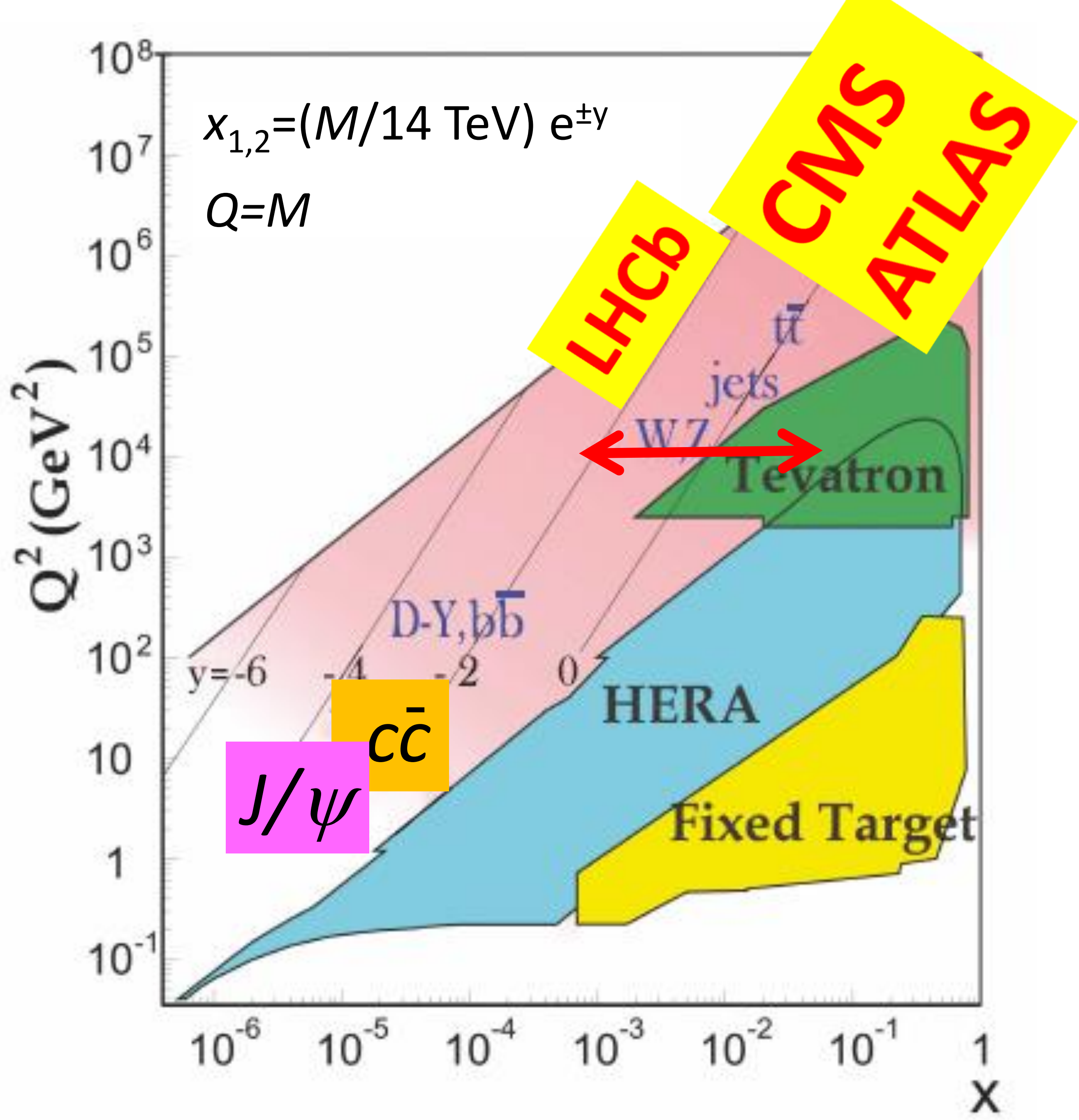
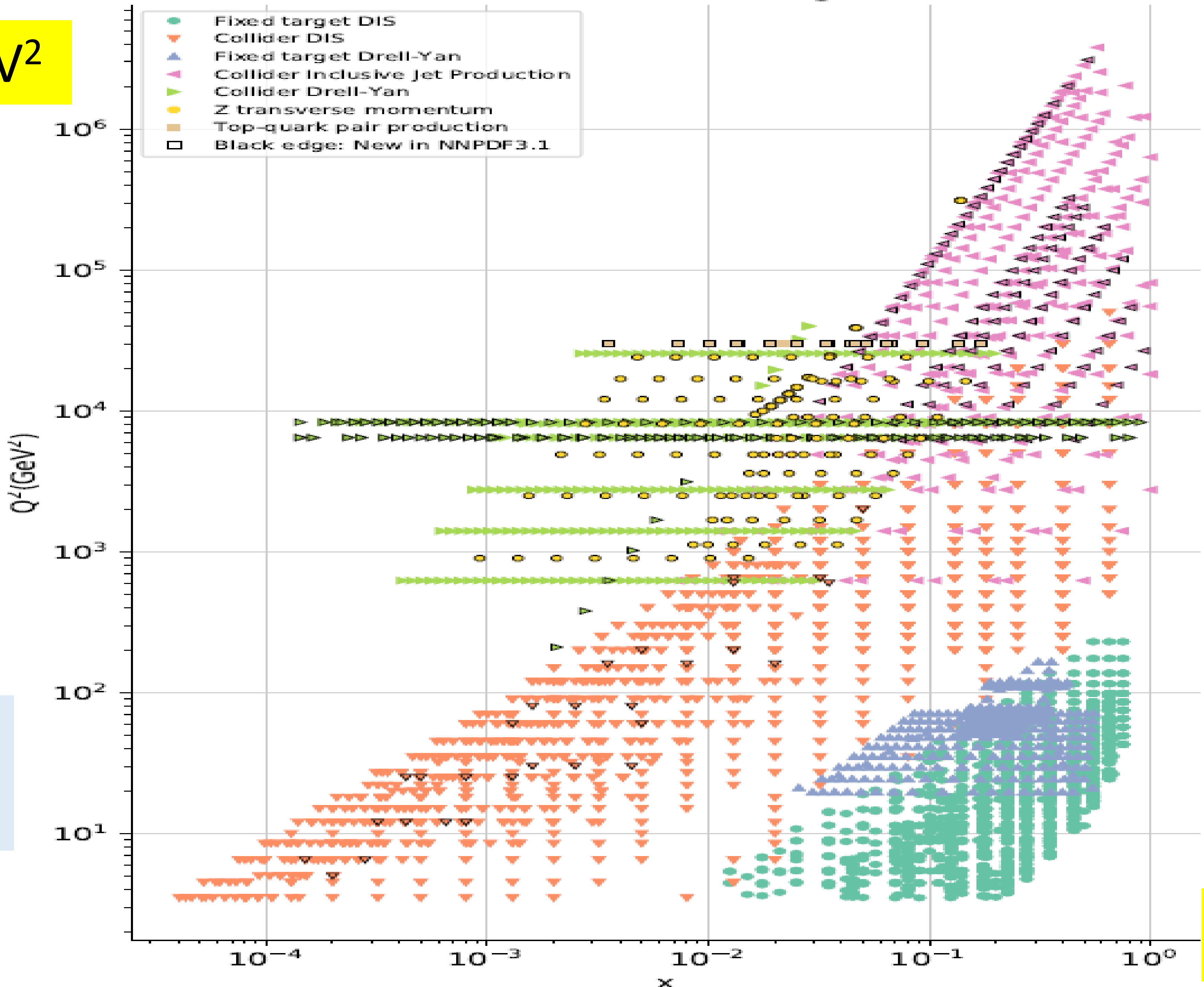


LHCb with $2 < y < 4.5$
can probe down to $x \sim 10^{-5}$



$x_{1,2}$=(M/14 TeV) $e^{\pm y}$
Q=M
LHCb
CMS
ATLAS
$t\bar{t}$
jets
W,Z
Tevatron
D-Y,$b\bar{b}$
y=-6
-4
-2
0
HERA
$c\bar{c}$
J/ψ
Fixed Target
Q^2 (GeV^2)
x

Q^2 GeV^2



Data fitted by NNPDF3.1

x

MMHT predictions and fit to new LHC data --- Thorne DIS2017

We now also fit to high rapidity W, Z data from LHCb at 7 and 8 TeV, $W + c$ jets from CMS, which constrains strange quarks, high precision CMS data on $W^{+,-}$ rapidity distributions which can also be interpreted as an asymmetry measurement, and also the final e asymmetry data from D0 (lepton, not W asymmetry).

	no. points	NLO χ^2_{pred}	NLO χ^2_{new}	NNLO χ^2_{pred}	NNLO χ^2_{new}
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS	18	19.6	20.5	14.7	15.5
LHCb 7 TeV $W + Z$	33	50.1	45.4	46.5	42.9
LHCb 8 TeV $W + Z$	34	77.0	58.9	62.6	59.0
LHCb 8TeV e	17	37.4	33.4	30.3	28.9
CMS 8 TeV W	22	32.6	18.6	34.9	20.5
CMS 7 TeV $W + c$	10	8.5	10.0	8.7	8.0
D0 e asymmetry	13	22.2	21.5	27.3	25.8
total	3738/3405	4375.9	4336.1	3741.5	3723.7

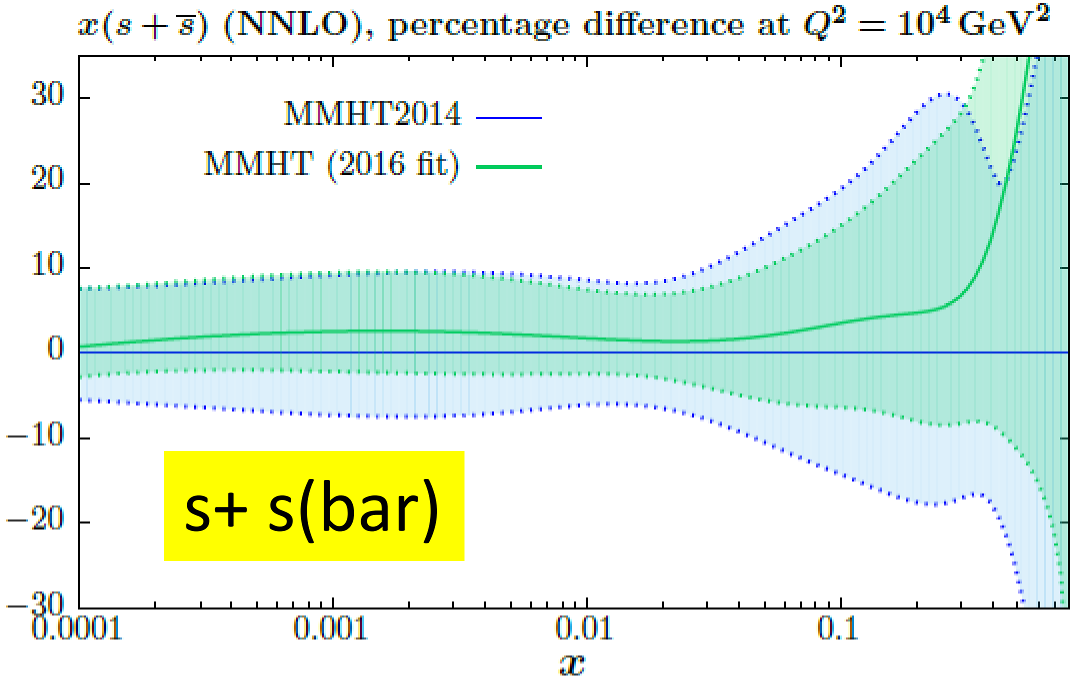
Predictions good, and no real tension with other data when refitting, i.e. changes in PDFs relatively small. Slightly (~ 10 units) better than previous report due to improvements (and one correction) in K-factors.

At NLO $\Delta\chi^2 = 9$ for the remainder of the data and at NNLO $\Delta\chi^2 = 8$.

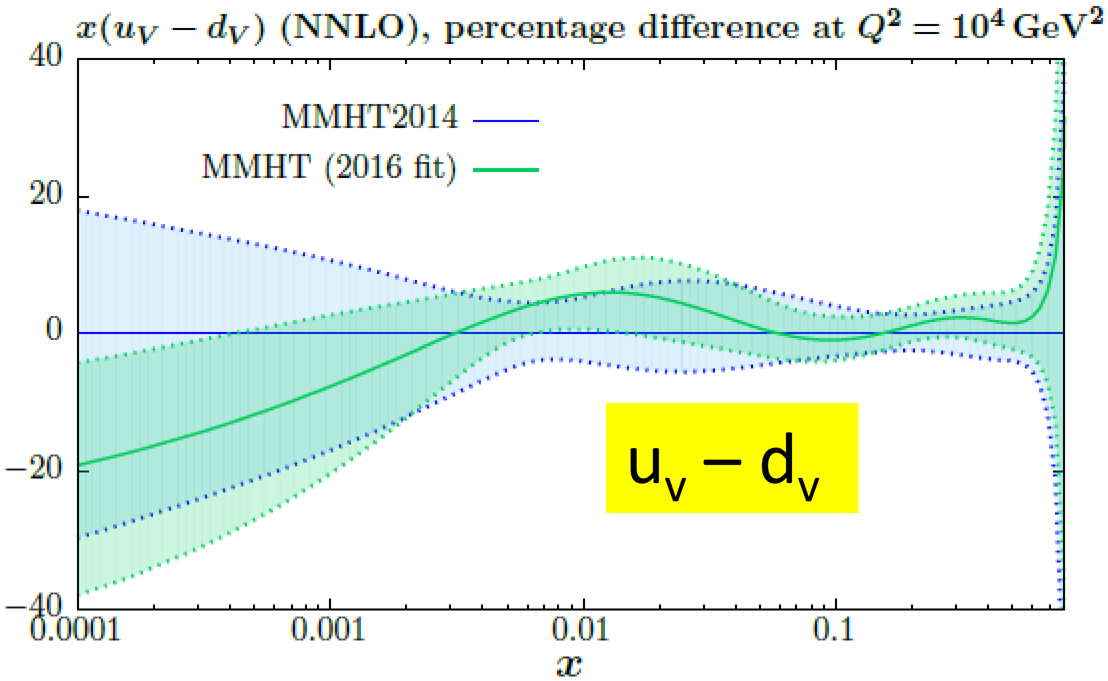
When couplings left free at NLO $\alpha_S(M_Z^2)$ stays very close to 0.120 but at NNLO $\alpha_S(M_Z^2)$ marginally above 0.118, higher than MMHT2014.

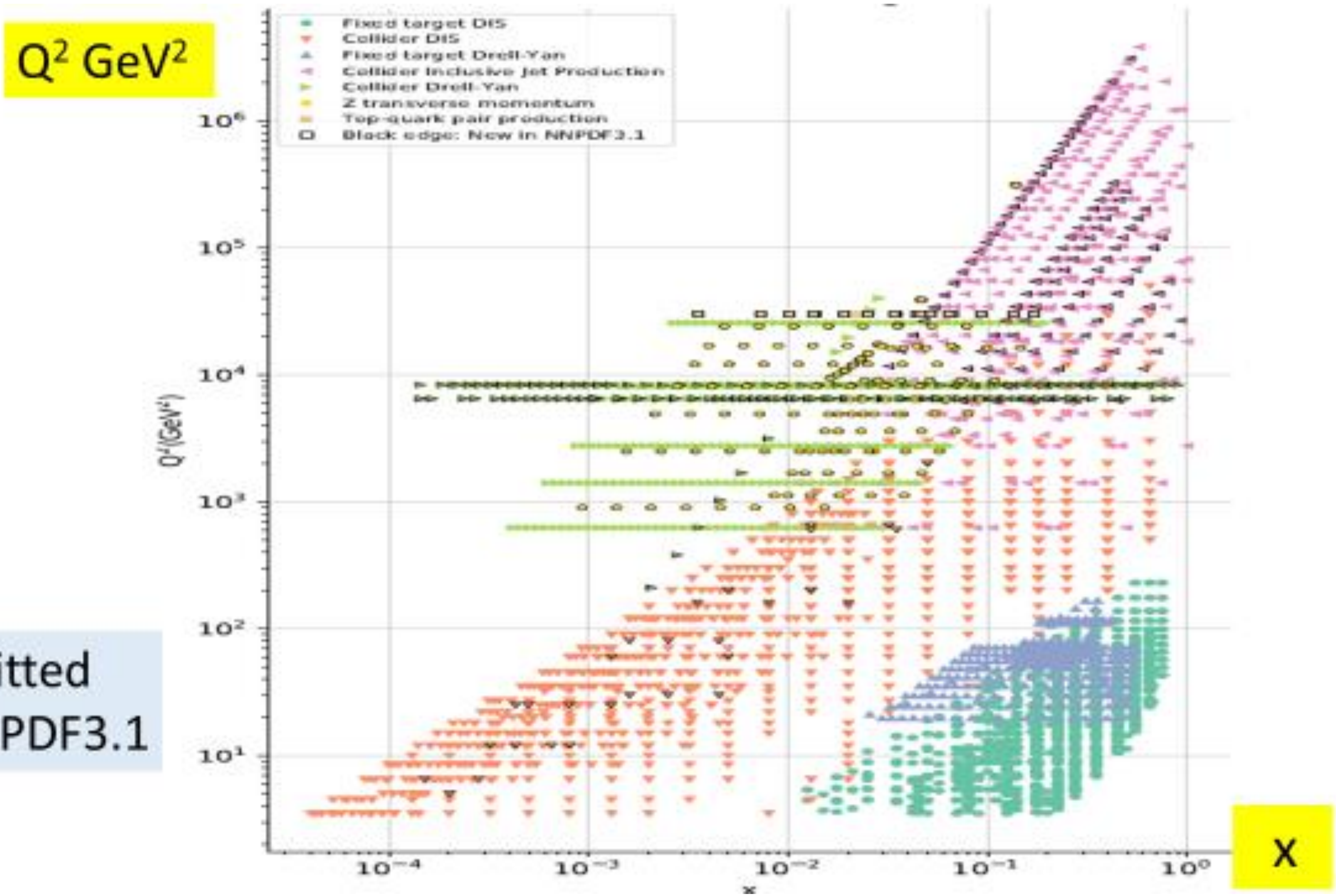
Effect on PDFs

Large reduction in the $s + \bar{s}$ uncertainty, but little change in central value. Due to $W + c$ jets data.



A significant change in $u_v - d_v$, and reduction in the uncertainty, from (effective) CMS asymmetry data.



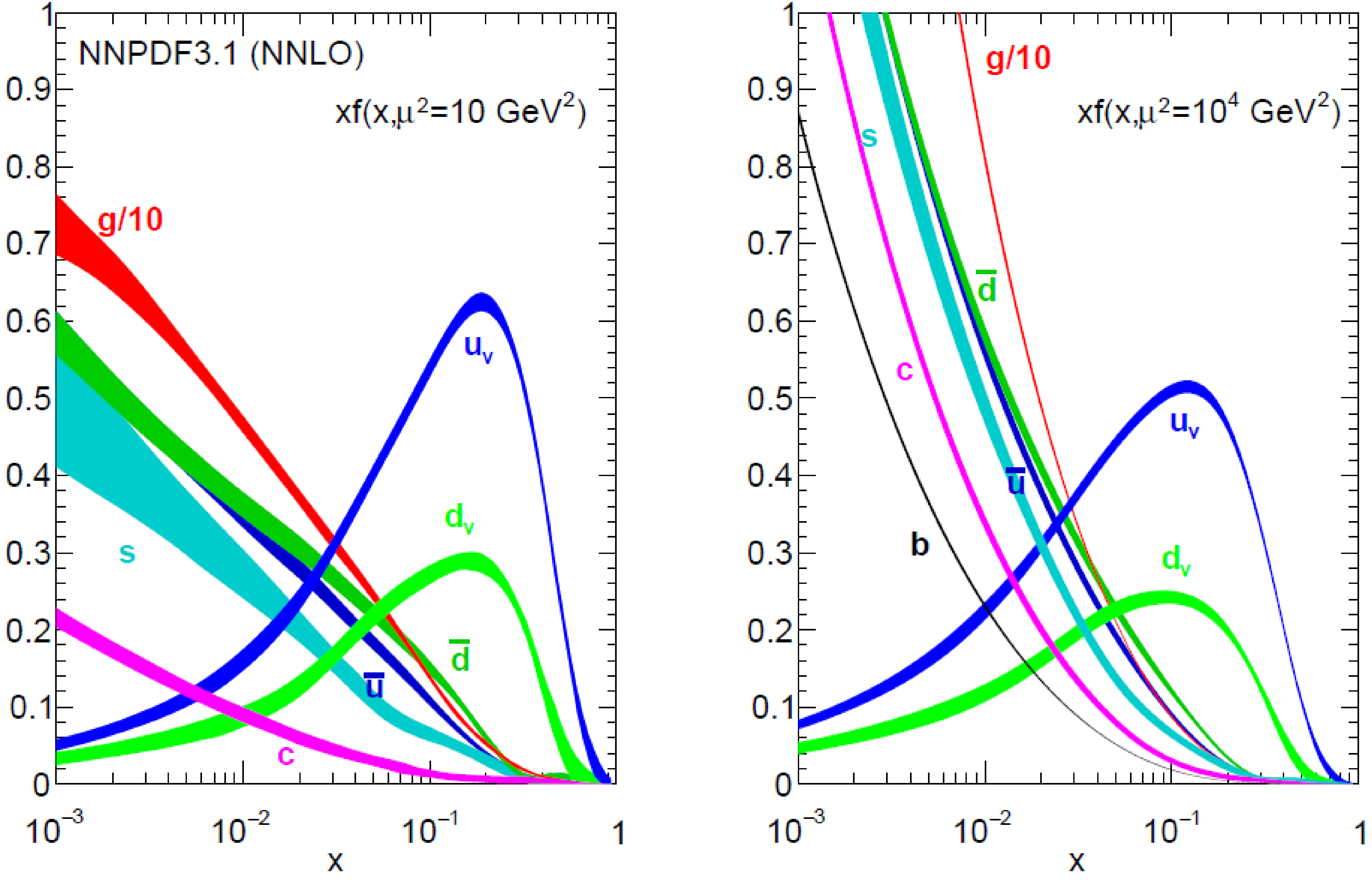


Data fitted
By NNPDF3.1

NNPDF3.1 1706.00428

Include in the fit all LHC data at 7, 8 TeV
W, Z, tt(bar), jets…..

Parametrize charm PDF and no longer assume that it is perturbatively fixed by *gg* → *cc(bar)*



NNPDF3.1 (NNLO)
xf(x,μ²=10 GeV²)
g/10
u_v
d_v
s
c
d̄
ū
x
xf(x,μ²=10⁴ GeV²)
b

gluon best determined parton (except for $x < 10^{-3}$ at low scales)

HERA down to 10^{-3}

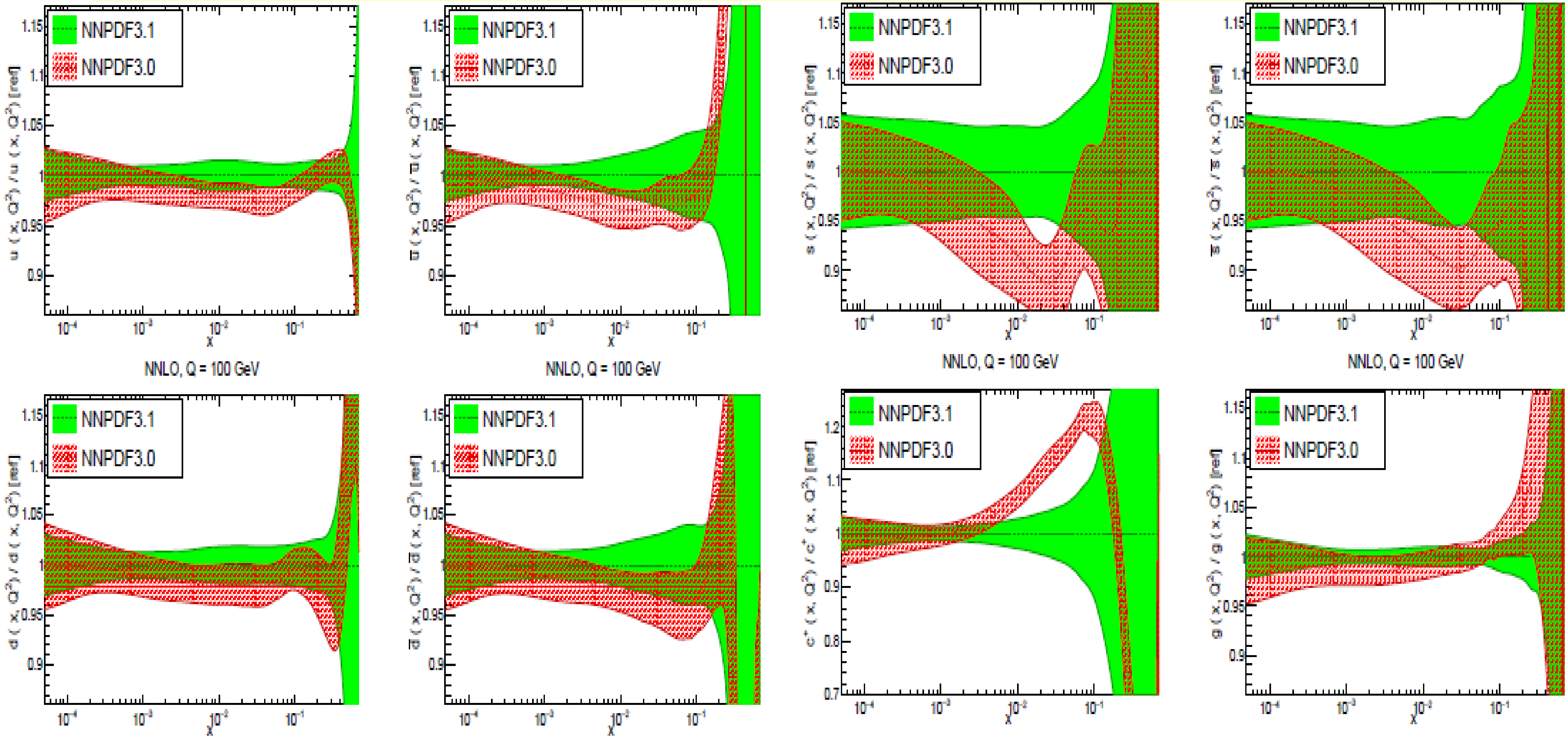
$Z(p_T)$ at LHC 10^{-3} - 10^{-1}

double dist. low mass D-Y at LHC 10^{-3} - 10^{-1}

tt(bar) + jets at LHC up to $x \sim 0.5$

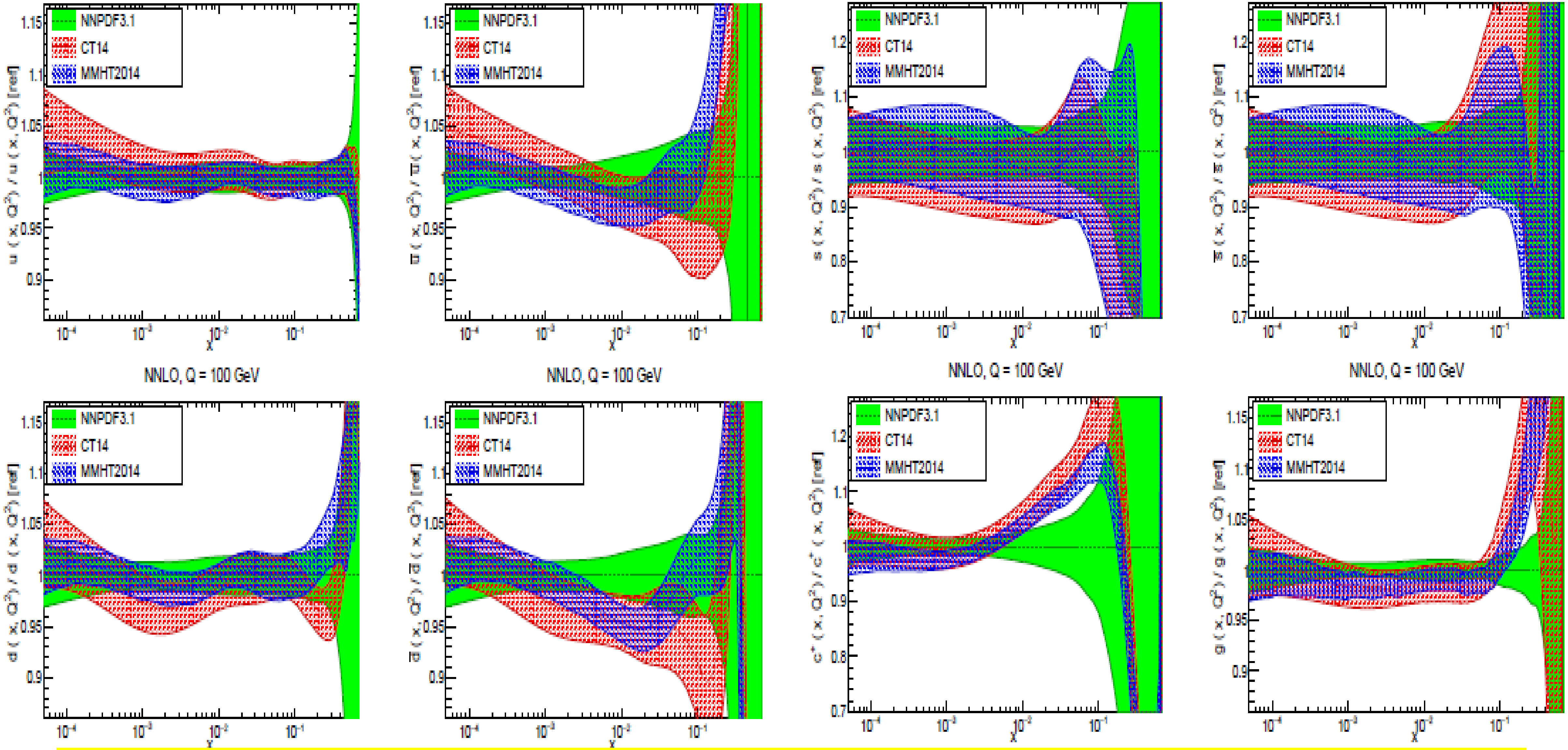
J/ψ, cc(bar) at LHCb

u u(bar) s s(bar)



d d(bar) c g

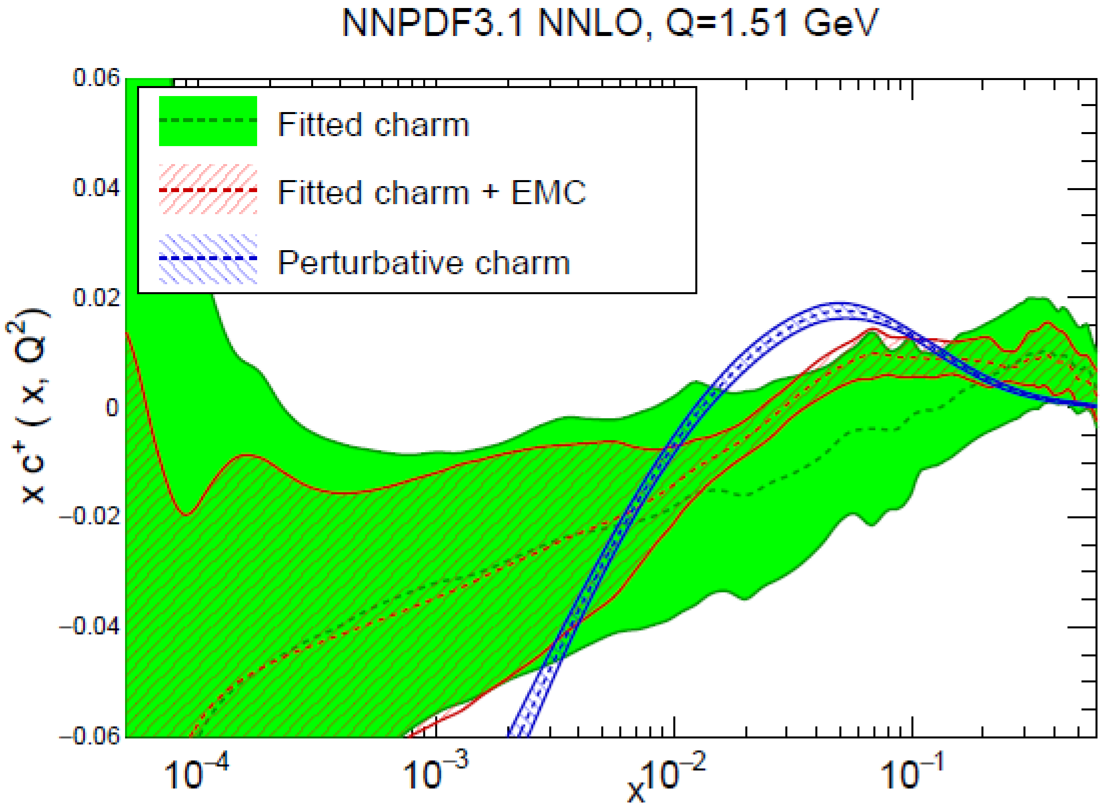
u u(bar) s s(bar)



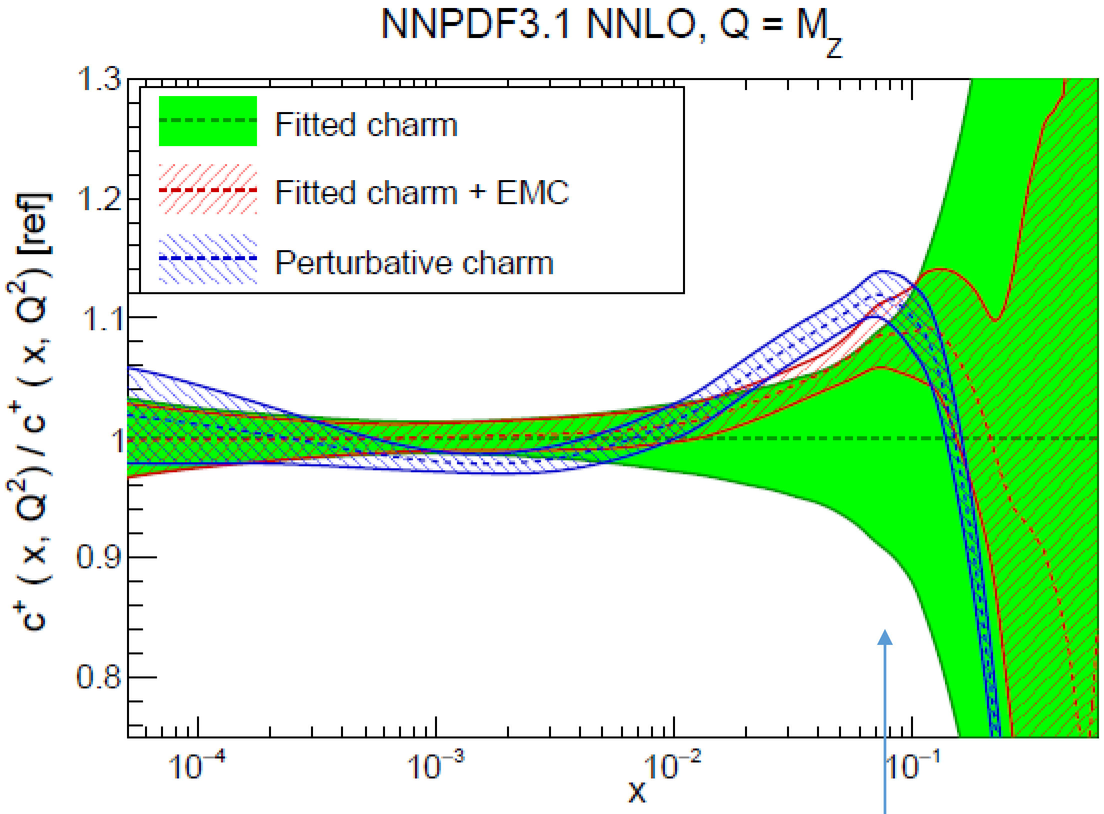
d d(bar) c g

xc(x,Q)

Q=1.51 GeV



$Q = M_Z$

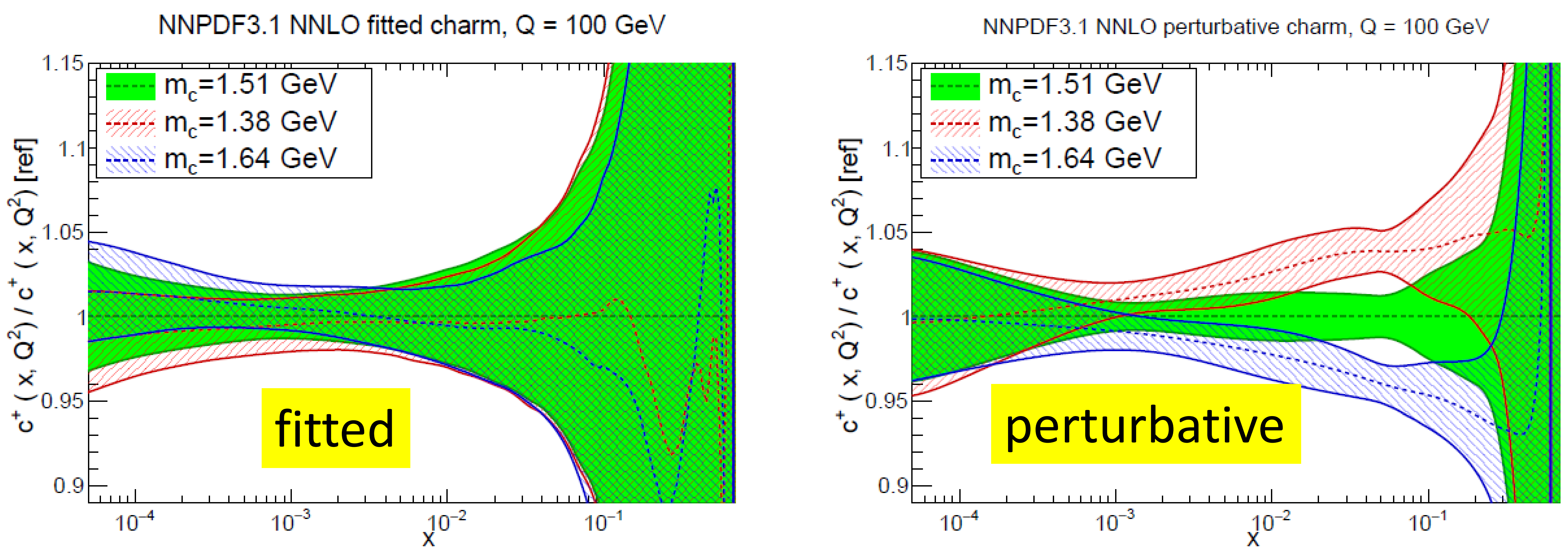


intrinsic = fitted – perturbative ?

negative

Claim fraction of charm mom^n compt. = 0.16 +/- 0.14 %

charm at $Q^2=10^4$ GeV



strangeness

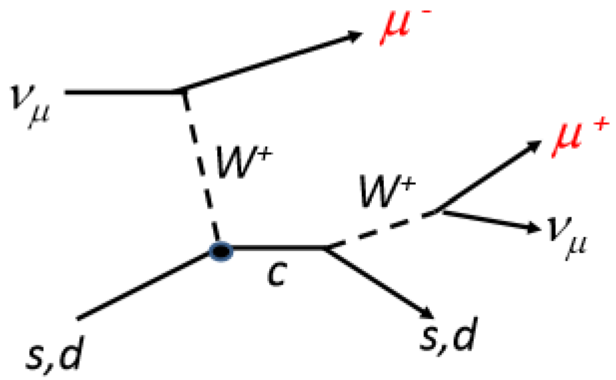
$$K_s(Q^2) = \frac{\int_0^1 dx\, x\, \left(s(x,Q^2) + \bar{s}(x,Q^2)\right)}{\int_0^1 dx\, x\, \left(\bar{u}(x,Q^2) + \bar{d}(x,Q^2)\right)}$$

Global PDF fitter's often found $K_s \sim 0.5$

High precision ATLAS W,Z data challenge this result

---- their data suggested $K_s \sim 1$ 1612.03016

MMHT +
ATLAS W, Z data



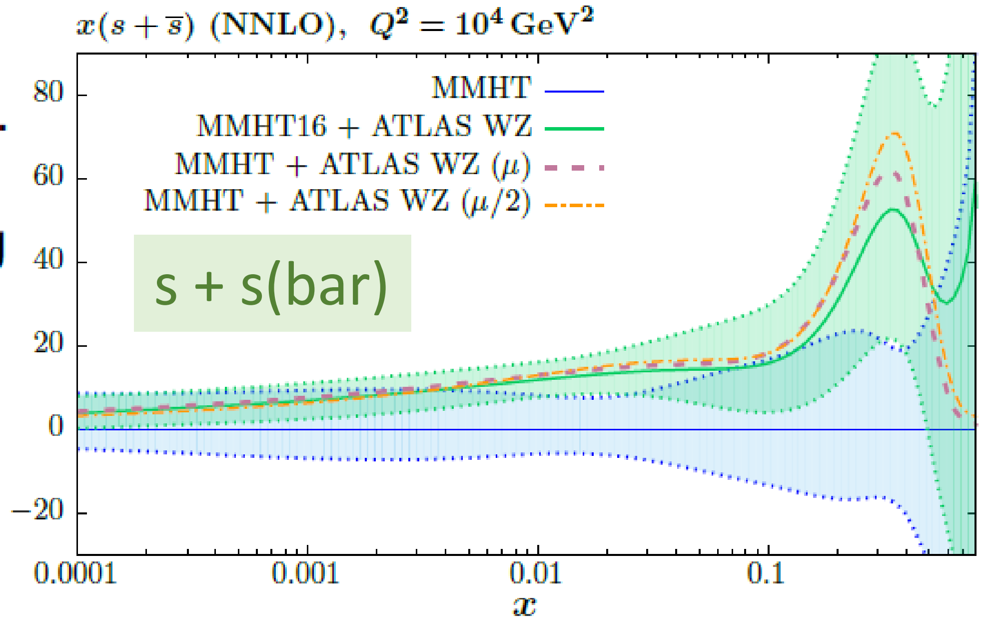
B(D→μ) =
(0.085-0.091)+/-15%

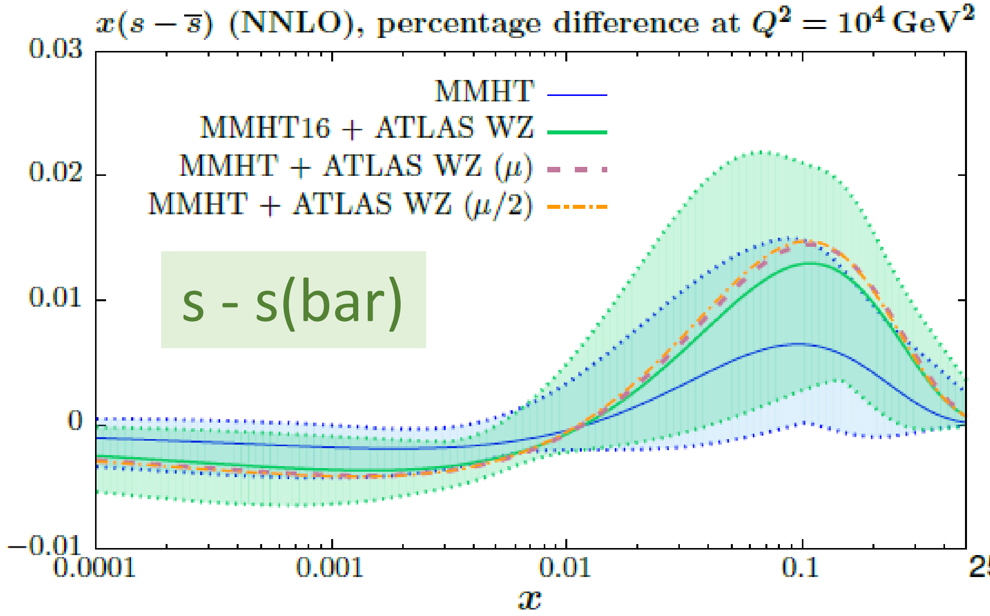
Large increase in $s + \bar{s}$ and decrease in uncertainty. Correlation with fit to dimuon data (lower branching ratio) leads to increase at high x.

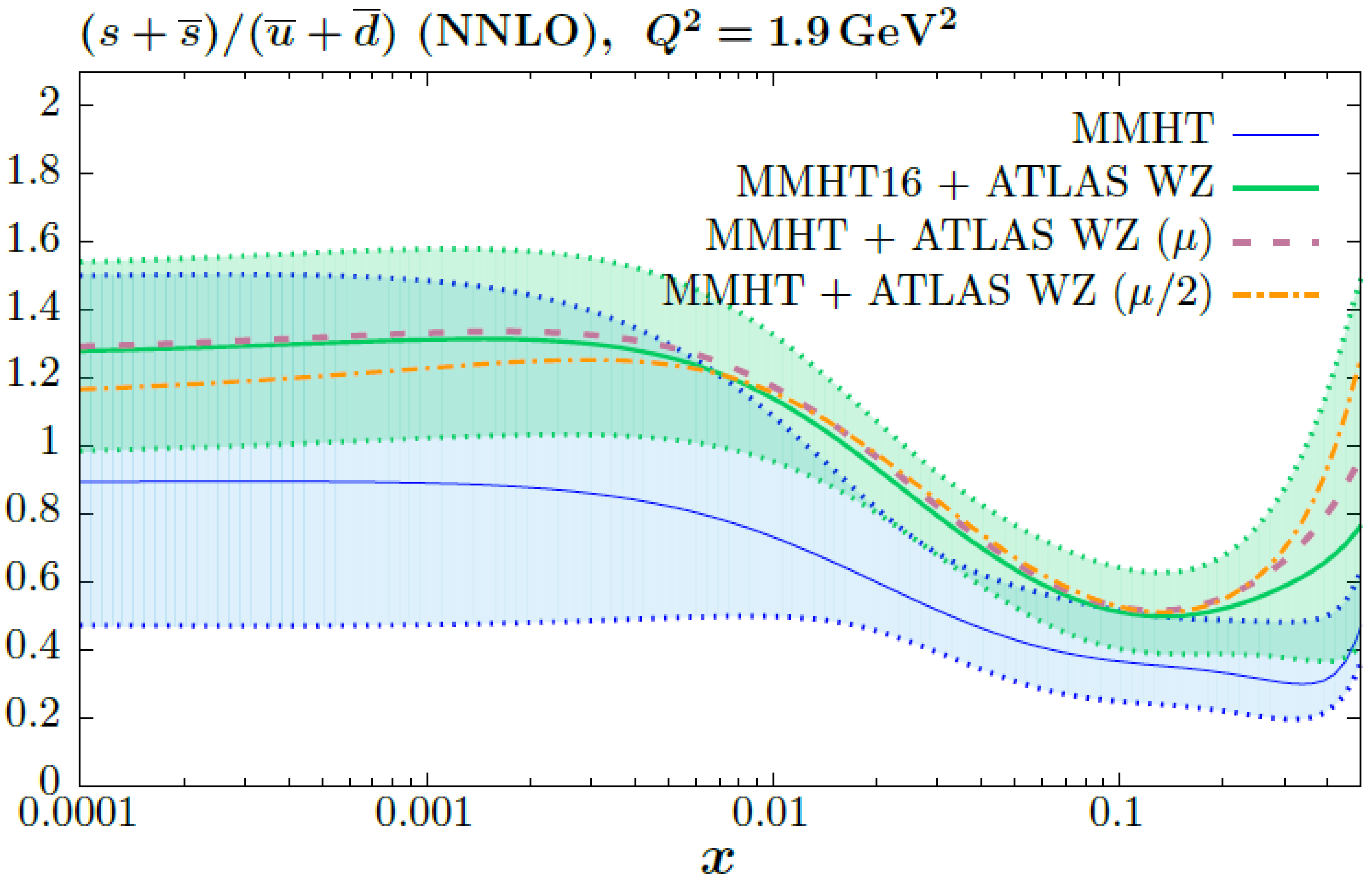
Thorne DIS2017

Larger for $x > 0.1$ due to significant down quark contribution in this region despite Cabibbo suppression.

There is impact on $s - \bar{s}$ uncertainty, from the change in branching ratio.







Ratio of $(s+\bar{s})$ to $\bar{u}+\bar{d}$, i.e. R_s at $Q^2 = 1.9\ \mathrm{GeV}^2$.

At $x = 0.023$ $R_s \sim 0.83 \pm 0.15$. Compare to ATLAS with $R_s = 1.13^{+0.08}_{-0.13}$

R_s exceeds unity at lower x, but essentially an extrapolation. Comfortably consistent with unity.

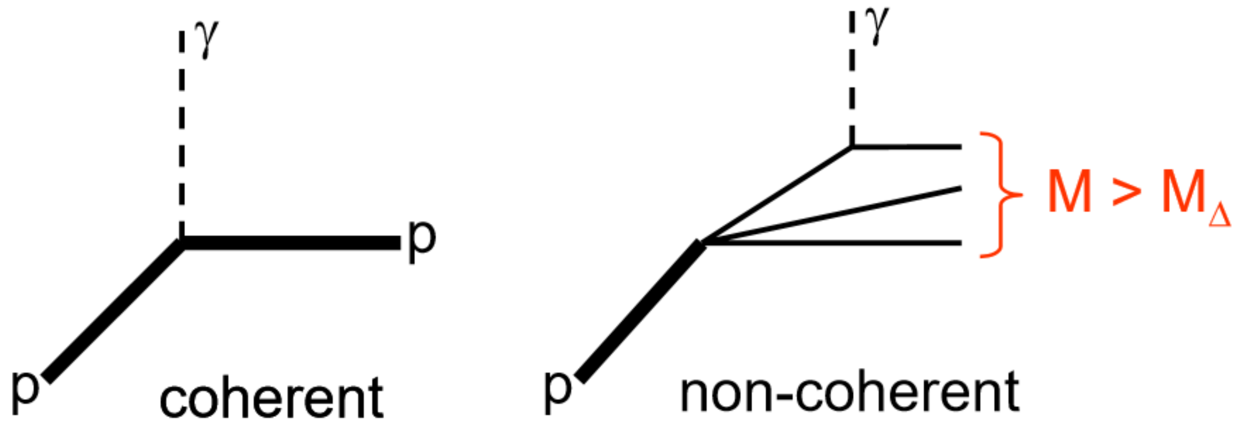
Photon PDF

$$\frac{\partial\gamma(x,Q^2)}{\partial \log Q^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left(P_{\gamma\gamma}\otimes\gamma + \sum_1 e_i^2 P_{\gamma q}\otimes q_i\right)$$

Choice of iput: MRST(1995) used photon emission off valence quarks

$$\gamma^p(x,Q_0^2) \;=\; \frac{\alpha}{2\pi}\int\frac{dz}{z}\left[\frac{4}{9}\log\left(\frac{Q_0^2}{m_u^2}\right)u_0\left(\frac{x}{z}\right)+\frac{1}{9}\log\left(\frac{Q_0^2}{m_d^2}\right)d_0\left(\frac{x}{x}\right)\right]\frac{1+(1-z)^2}{z}$$

$$\gamma^N(x,Q_0^2) = \gamma^N_{\rm coh} + \gamma^N_{\rm incoh}$$

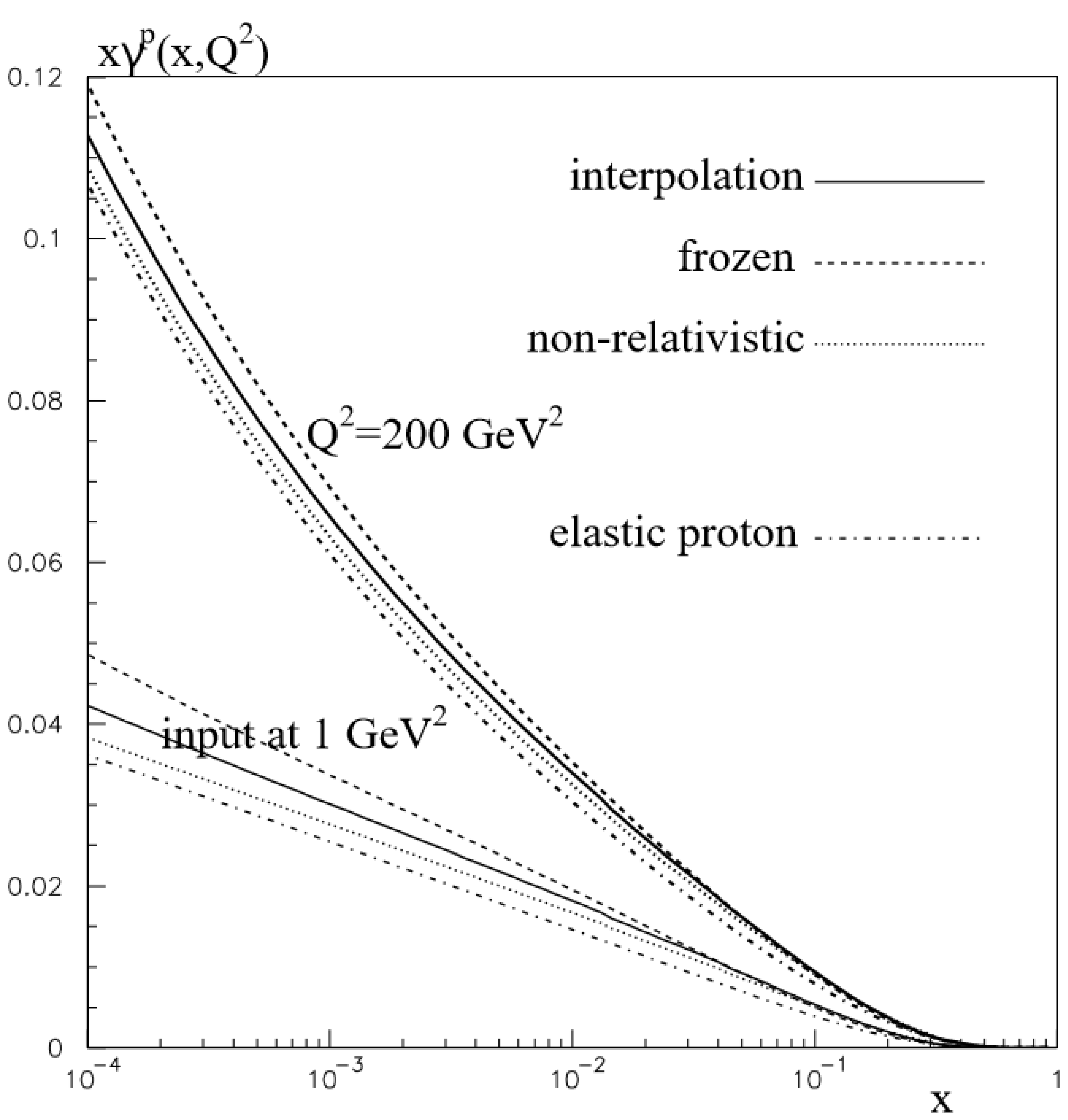


$$\gamma^p_{\rm coh}(x,Q_0^2) = \frac{\alpha^{\rm QED}}{2\pi}\,\frac{[1+(1-x)^2]}{x}\int_0^{|t|<Q_0^2} dq_t^2 \frac{q_t^2}{(q_t^2+x^2m_p^2)^2}F_1^2(t)$$

known & dominant

$$\gamma^p_{\rm incoh}(x,Q_0^2) = \frac{\alpha}{2\pi}\int_x^1 \frac{dz}{z}\left[\frac{4}{9}u_0(\frac{x}{z}) + \frac{1}{9}d_0(\frac{x}{z})\right]\,\frac{1+(1-z)^2}{z}\int_{|t_{\rm min}|}^{Q_0^2}\frac{dt}{t-m_q^2}\,\left(1-F_1^2(t)\right)$$

1406.2118



$x\gamma^p(x,Q^2)$
0.12
0.1
0.08
0.06
0.04
0.02
0
interpolation
frozen
non-relativistic
elastic proton
Q^2=200 GeV^2
input at 1 GeV^2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

Inclusive jet production at NNLO

NNLO formalism just available after many years work by Glover et al.

However, choice of factorization scale a problem. Ambiguous.
Have up to 4 jets in final state. Moreover jet cone size.

Each devours many days of computing.

There is a way to fix the scale (1702.01663) but data collection not set up to implement it.

$b\bar{b}$ production at NLO at fac^{n} scale μ_f

1610.06034

μ_f dep. of $C^{(1)}$ occurs, -- need to subtract part of NLO diag generated by LO evolution

$$\sigma^{(0)}(\mu_f) + \sigma^{(1)}(\mu_f) \;=\; \alpha_s^2\,[\mathrm{PDF}(\mu_f)\otimes C^{(0)}\otimes \mathrm{PDF}(\mu_f) + \mathrm{PDF}(\mu_f)\otimes \alpha_s C^{(1)}(\mu_f)\otimes \mathrm{PDF}(\mu_f)]$$

Free to evaluate LO term at diff.scale μ_F since it can be compensated by changes in $C^{(1)}$

$$\sigma^{(0)}(\mu_f)+\sigma^{(1)}(\mu_f) \;=\; \alpha_s^2\,[\mathrm{PDF}(\mu_F)\otimes C^{(0)}\otimes \mathrm{PDF}(\mu_F) + \mathrm{PDF}(\mu_f)\otimes \alpha_s C^{(1)}_{\mathrm{rem}}(\mu_F)\otimes \mathrm{PDF}(\mu_f)]$$

$$\alpha_s^2\,\mathrm{PDF}(\mu_f)\otimes\left(C^{(0)} + \frac{\alpha_s}{2\pi}\ln\left(\frac{\mu_F^2}{\mu_f^2}\right)(P_{\mathrm{left}}\otimes C^{(0)} + C^{(0)}\otimes P_{\mathrm{right}})\right)\otimes \mathrm{PDF}(\mu_f)$$

LO DGLAP evolution

The idea is to use known NLO coeff fn $C^{(1)}(\mu_f)$ to choose μ_F so that $C_{\mathrm{rem}}^{(1)}(\mu_F)$ is a minimum

$$C^{(1)}_{\mathrm{rem}}(\mu_F) \;=\; C^{(1)}(\mu_f) - \frac{\alpha_s}{2\pi}\ln\left(\frac{\mu_F^2}{\mu_f^2}\right)(P_{\mathrm{left}}\otimes C^{(0)} + C^{(0)}\otimes P_{\mathrm{right}})$$

change due to compensation

full NLO coeff.fn

part moved to LO PDFs

$$\sigma^{(0)}(\mu_f)+\sigma^{(1)}(\mu_f) \;=\; \alpha_s^2\left[\mathrm{PDF}(\mu_f)\otimes C^{(0)}\otimes \mathrm{PDF}(\mu_f)+\mathrm{PDF}(\mu_f)\otimes \alpha_s C^{(1)}(\mu_f)\otimes \mathrm{PDF}(\mu_f)\right]$$

Free to evaluate LO term at diff.scale μ_F since it can be compensated by changes in $C^{(1)}$

$$\sigma^{(0)}(\mu_f)+\sigma^{(1)}(\mu_f) \;=\; \alpha_s^2\left[\mathrm{PDF}(\mu_F)\otimes C^{(0)}\otimes \mathrm{PDF}(\mu_F)+\mathrm{PDF}(\mu_f)\otimes \alpha_s C^{(1)}_{\mathrm{rem}}(\mu_F)\otimes \mathrm{PDF}(\mu_f)\right]$$

$$\boxed{\alpha_s^2\,\mathrm{PDF}(\mu_f)\otimes\left(C^{(0)}+\frac{\alpha_s}{2\pi}\ln\left(\frac{\mu_F^2}{\mu_f^2}\right)(P_{\mathrm{left}}\otimes C^{(0)}+C^{(0)}\otimes P_{\mathrm{right}})\right)\otimes \mathrm{PDF}(\mu_f)}$$

LO DGLAP evolution

The idea is to use known $C^{(1)}(\mu_f)$ to choose μ_F so that $C_{rem}^{(1)}(\mu_F)$ is a minimum

$$\boxed{C^{(1)}_{\mathrm{rem}}(\mu_F) \;=\; C^{(1)}(\mu_f)-\frac{\alpha_s}{2\pi}\ln\left(\frac{\mu_F^2}{\mu_f^2}\right)(P_{\mathrm{left}}\otimes C^{(0)}+C^{(0)}\otimes P_{\mathrm{right}})}$$

change due to compensation

That is, μ_F is fixed so that the residual NLO coeff. f^n excludes $\alpha_s \log\mu_F^2 \log(1/x)$ contrib^{ns} moving them to the LO PDFs where they are resummed to all orders by DGLAP evolution

The residual fac^n scale, μ_f, dependence is optimized (reduced) for low x. Note that $C^{(1)}_{rem}(\mu_F)$ does not depend on μ_f --- the μ_f dependence occurs only in the PDFs in the NLO correction

Physical understanding of optimal scale

The log integration $\int \frac{dk^2}{k^2}$ over incoming parton virtuality k^2, hidden in DGLAP,

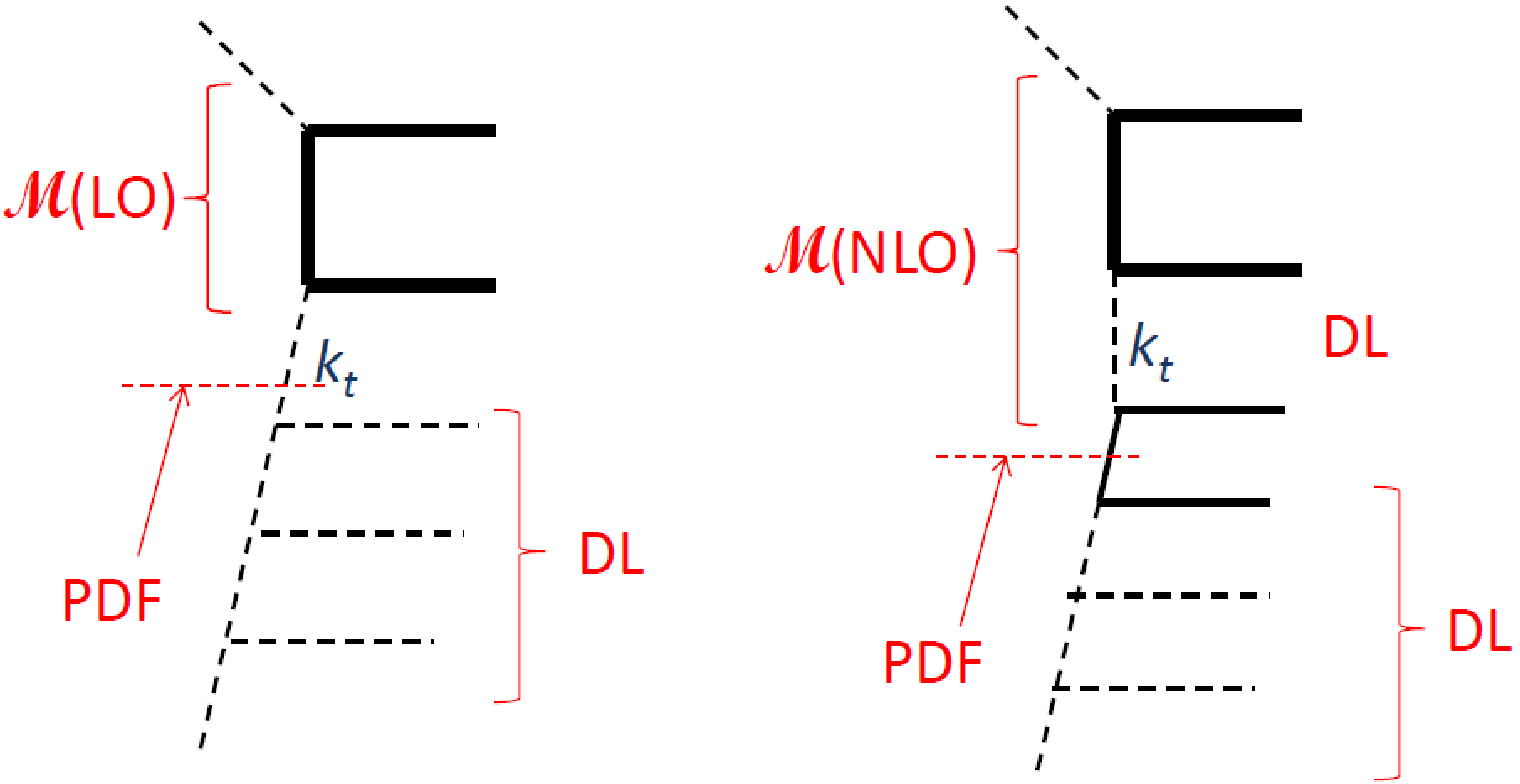
does not extend to ∞, and is limited by off-shell matrix element $\mathcal{M}^{\mathrm{LO}}(k^2)$

Optimal choice of μ_F is such that value of DGLAP integral up to μ_F equals the value of the convergent integral :

$$\int_{Q_0^2}^{\infty} \frac{dk^2}{k^2} |\mathcal{M}^{\mathrm{LO}}(k^2)|^2 = \int_{Q_0^2}^{\mu_F^2} \frac{dk^2}{k^2} |\mathcal{M}^{\mathrm{LO}}(k^2=0)|^2 = |\mathcal{M}^{\mathrm{LO}}(k^2=0)|^2 \ln\frac{\mu_F^2}{Q_0^2}$$

So part of NLO correction, which has same DGLAP structure,
is moved to the LO term --- this minimizes the NLO correction

Physical understanding continued



Double Log (DL) integral in NLO matrix elem. is the same as in the gluon cell below the LO matrix elem.

Now consider jet production

Summary of NLO b$\bar{\text{b}}$ prod. to determine optimal fac. scale μ_F

$$\sigma^{(0)}(\mu_f)+\sigma^{(1)}(\mu_f) = \alpha_s^2 \left[\mathrm{PDF}(\mu_F)\otimes C^{(0)} \otimes \mathrm{PDF}(\mu_F) + \mathrm{PDF}(\mu_f)\otimes \alpha_s C^{(1)}_{\mathrm{rem}}(\mu_F)\otimes \mathrm{PDF}(\mu_f)\right]$$

LO term

small residual NLO correction

$$\boxed{\alpha_s^2\,\mathrm{PDF}(\mu_f)\otimes\left(C^{(0)}+\frac{\alpha_s}{2\pi}\ln\left(\frac{\mu_F^2}{\mu_f^2}\right)\left(P_{\mathrm{left}}\otimes C^{(0)}+C^{(0)}\otimes P_{\mathrm{right}}\right)\right)\otimes\mathrm{PDF}(\mu_f)}$$

P's are LO DGLAP splitting fns.

Generalise to jet production – but now three scales μ_-, μ_+, μ_D

jet frag. fn.

$$\left[\alpha_s^2\,\mathrm{PDF}(\mu_-)\otimes\left(C^{(0)}+\frac{\alpha_s}{2\pi}\left[\ln\left(\frac{\mu_F^2}{\mu_-^2}\right)P_{\mathrm{left}}\otimes C^{0)}+\ln\left(\frac{\mu_F^2}{\mu_+^2}\right)C^{(0)}\otimes P_{\mathrm{right}}\right]\right)\otimes\mathrm{PDF}(\mu_+) \otimes\left(1+\frac{\alpha_s}{2\pi}\ln\left(\frac{\mu_F^2}{\mu_D^2}\right)P_D\right)\otimes D(z,\mu_D)\right]$$

LO term

$$+\ \ldots\ldots\ C^{(1)}_{\mathrm{rem}}(\mu_-,\mu_+,\mu_D)\ \ldots\ldots$$

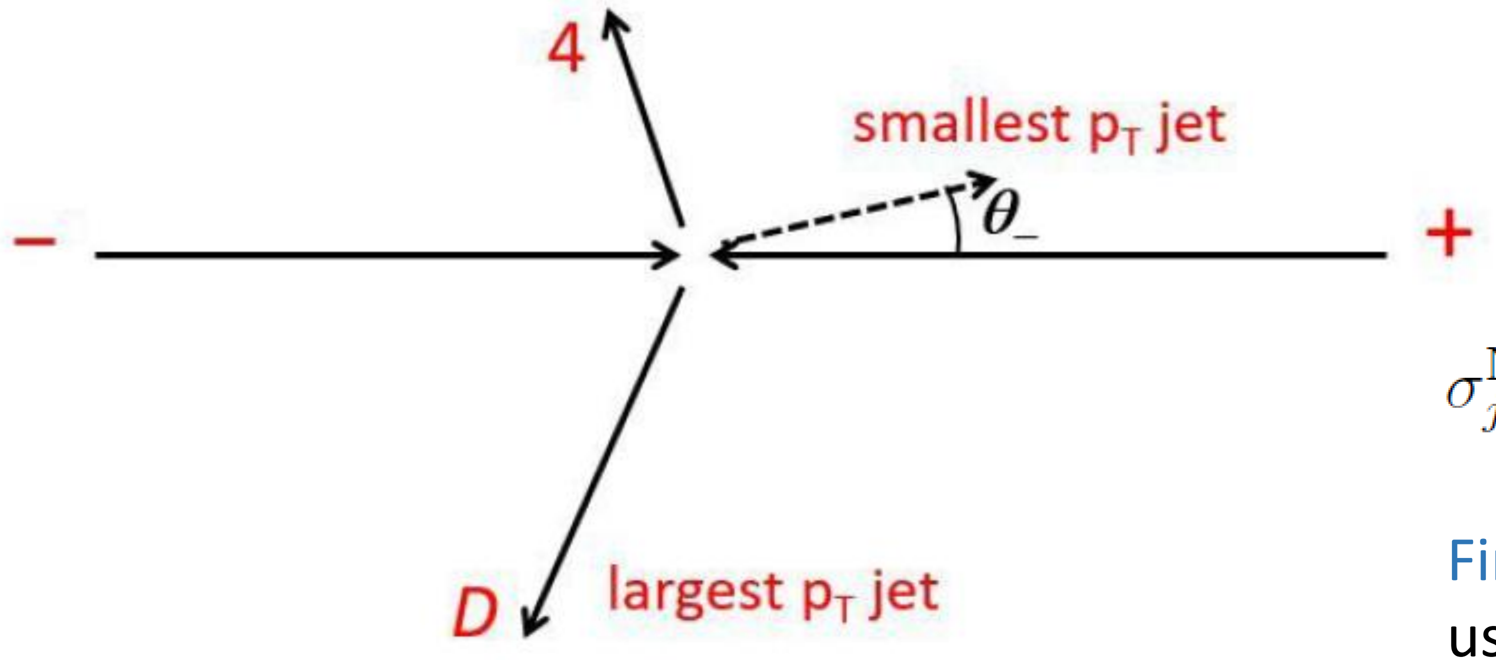
small residual NLO correction

The optimum value of μ_D is driven by the jet cone size ΔR

Since DGLAP evolution is written in terms of collinear factorization --- it is most convenient to order the contributions to the **jet process in terms of angles.**

To obtain the optimal LO description we study the 2→3 NLO subprocess.

First calculate the angles θ_i of the 4 partons relative to lowest p_T outgoing parton



Next, divide $\sigma_{2\to3}$ into 4 parts corresponding to the smallest θ_i's

$$\sigma^{\rm NLO}_{j=+,-,D,4} \;=\; \sigma_{2\to3}\ \Pi_{i\neq j}\ \Theta(\theta_i - \theta_j)$$

Finally, determine 3 optimal scales μ_j using 3 coupled eqs. each of the form :

j=+,-,D

$$\boxed{\sigma^{\rm NLO}_j(\mu_0) \;=\; |\mathcal{M}^{\rm LO}(k^2=0)|^2 \otimes {\rm PDF}_{i\neq j}(\mu_0) \otimes D_{i\neq j}(\mu_0) \otimes {\rm PDF}_j(\mu_0) \otimes P^{\rm real}(z)\ \ln\frac{\mu_j^2}{\mu_0^2}}$$

(μ_0 is a low dummy scale. Iterate with μ_0 replaced by new μ_j in turn)

see boxed eq.
3 slides previous

$\hat{P}^{+}_{\rm LO}$ means sp.fn acts on PDF(μ_+)

That is, the 3 optimal scales are fixed to make residual NLO coefficient function as small as possible ; namely

$$C^{(1)}_{\rm rem}(\mu_-,\mu_+,\mu_D) \;=\; C^{(1)}(\mu_f) - \sum_{j=+,-,D} C^{(0)}\,\frac{\alpha_s}{2\pi}\ln\left(\frac{\mu_j^2}{\mu_f^2}\right)\hat{P}^{j}_{\rm LO} \quad ,$$

NLO coeff.fn

part moved to LO PDFs, *D* fn.

by absorbing (and resumming) in the LO term as much as possible of the NLO correction. In this way the dependence on the residual factorization scale, μ_f, is reduced to a minimum.

The procedure can be extended in a straightforward way to NNLO. We fix the scales in the NLO correction by dividing up the real 2→4 NNLO contribution into 5 parts in terms of angles. Only three parts, those collinear to the +, - and *D* directions, are relevant.

Power Corrections

Tendency to overshoot HERA neutral current data at highest *y* and low *x* and Q^2

Phenomenology: $F_L \rightarrow F_L\,(1 + a/Q^2)$ $a = 4.3\ \mathrm{GeV}^2$

F_2 does not seem to need correction

MMHT 1601.03413
Mandy & collaborators

Physical origin of corrections:

1. Absorptive corrections
2. Confinement
3. Q_0 cut to avoid double counting in Coeff. Fns