heavy-quark production (for PDFs)

Rhorry Gauld

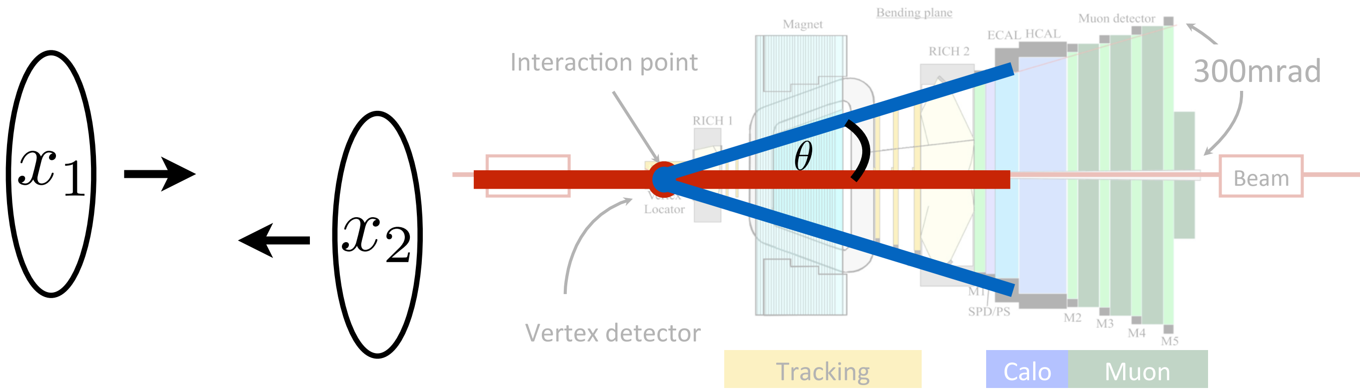
NNPDF meeting - Gargnano 2018

Netherlands Organisation for Scientific Research

Nikhef

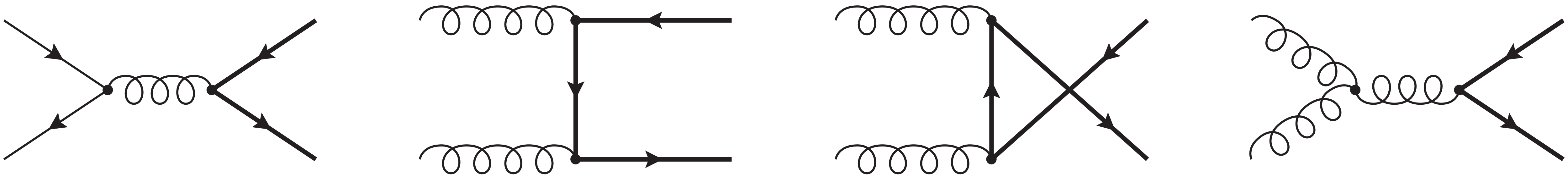
Overview

- **Introduction**
  - forward kinematics
- **Top-quark production**
  - LHCb results
  - Central results
- **D-hadron production**
  - Results from LHCb and impact on proton PDF
- **Concluding remarks**



LHCb detector

heavy-quark pair production



$$g(p_1) + g(p_2) \rightarrow Q(p_3) + \bar{Q}(p_4) + X$$

dominant subprocess at LHC

$$p_1 = \sqrt{S}/2\,(x_1, 0, 0, x_1)$$

x_i : momentum fraction

y_j : rapidity

$\sqrt{S}$: hadronic COM

m_T : transverse mass

LO PDF sampling occurs at

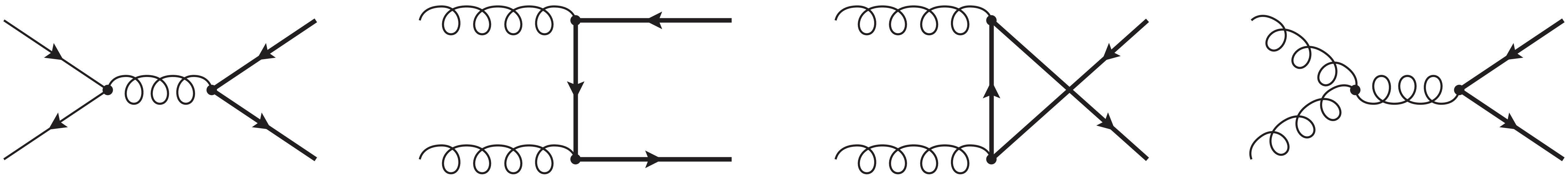
$$x_{1,(2)} = \frac{m_T}{\sqrt{S}}\left(e^{(-)y_3} + e^{(-)y_4}\right)$$

Interesting (less well constrained) region for PDFs:

Low-x, Low-Q

Large-x, Large-Q

heavy-quark pair production



$$g(p_1) + g(p_2) \to Q(p_3) + \bar{Q}(p_4) + X$$

dominant subprocess at LHC

$$p_1 = \sqrt{S}/2\,(x_1, 0, 0, x_1)$$

x_i : momentum fraction

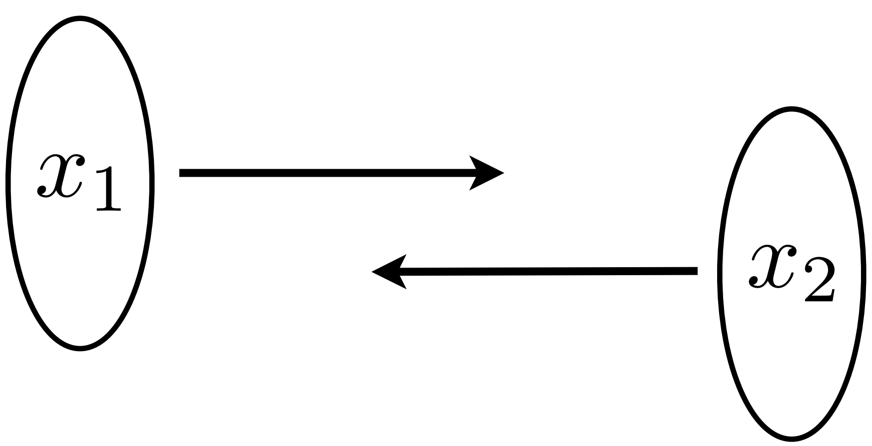
y_j : rapidity

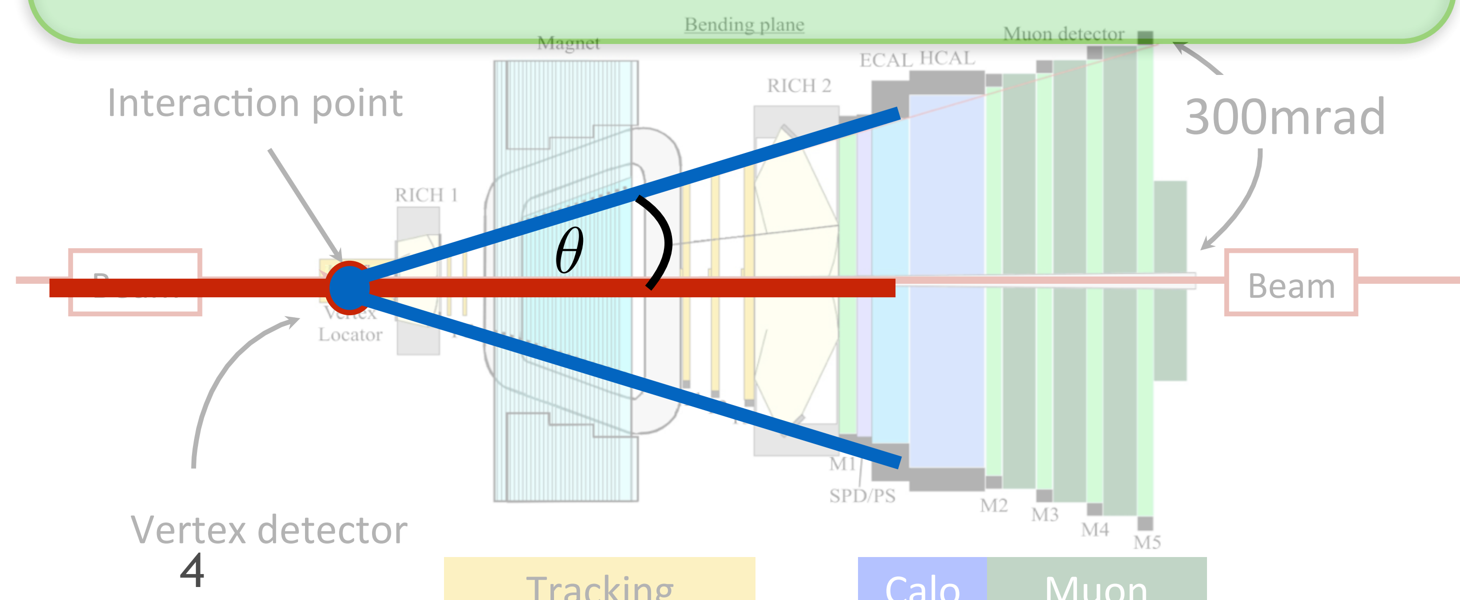
$\sqrt{S}$: hadronic COM

m_T : transverse mass

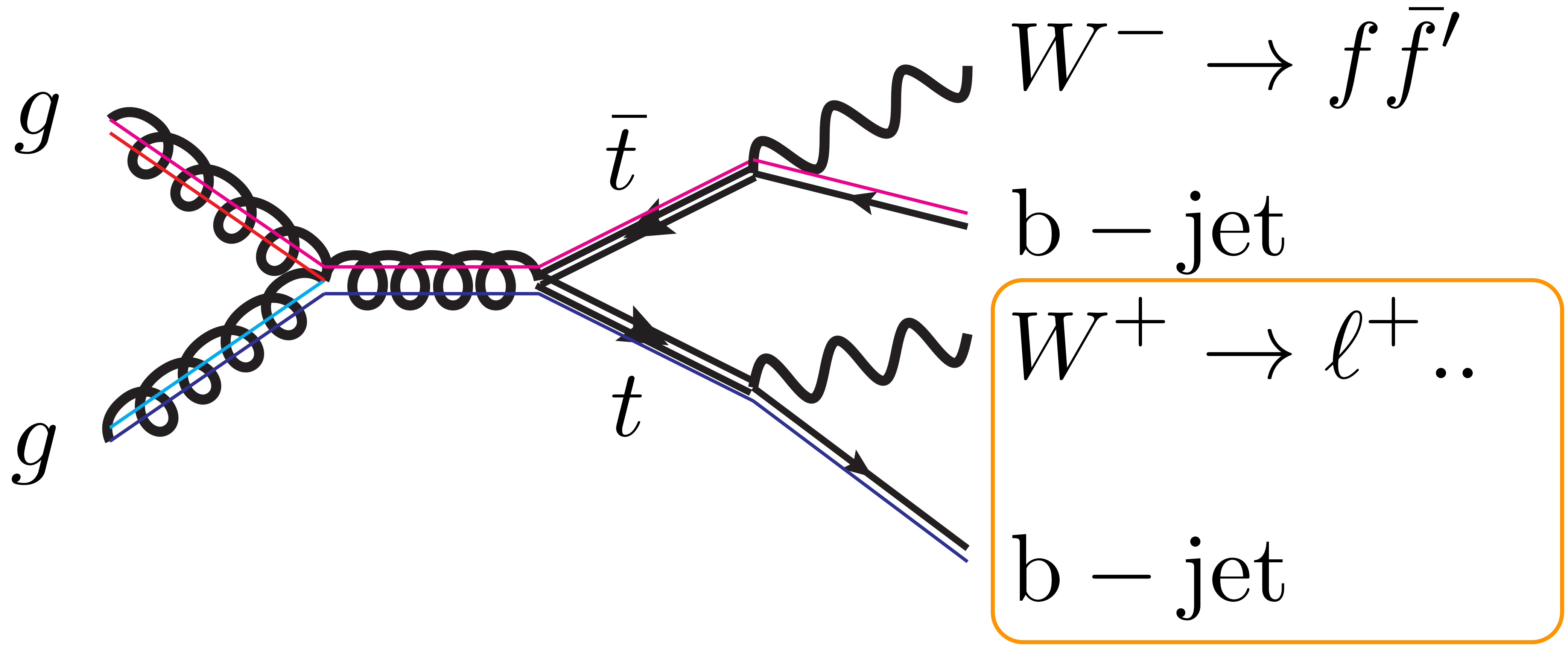
LO PDF sampling occurs at

$$x_{1,(2)} = \frac{m_T}{\sqrt{S}} \left(e^{(-)y_3} + e^{(-)y_4} \right)$$





top-quark (pair) production - LHCb

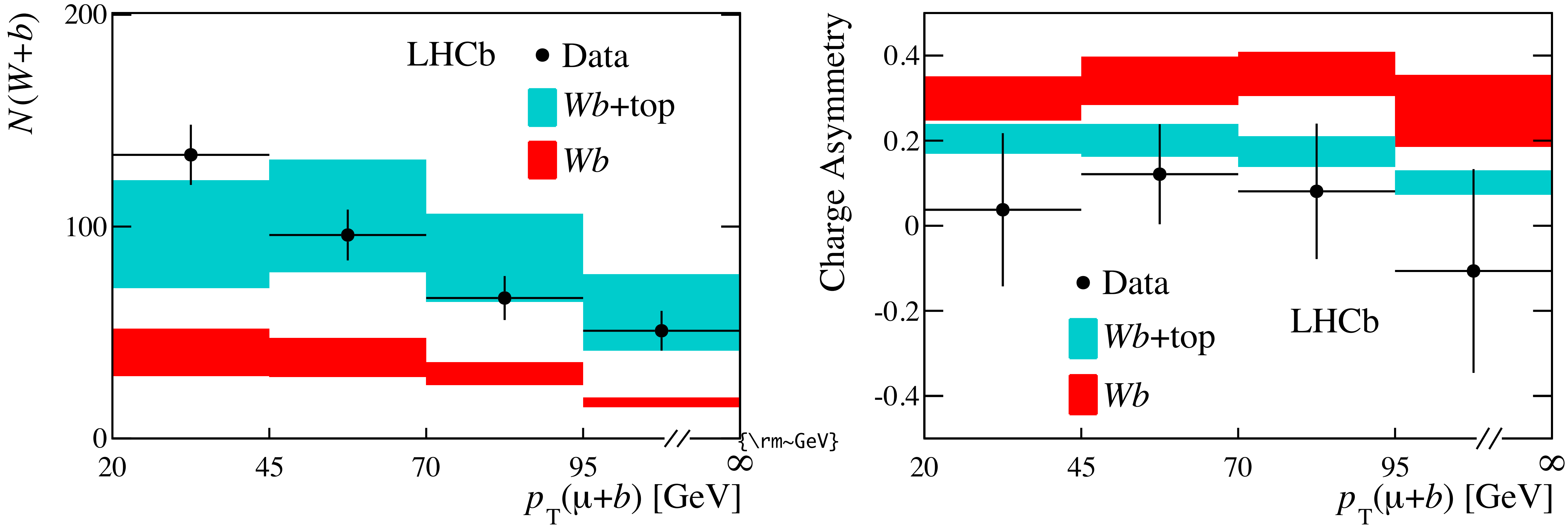


- Reconstruct all decay products: probe larger-x, smaller bkg
- Reconstruct all decay products: lower stats

Examples: $\mathrm{pp} \to \ell \mathrm{b} + X$, $\mathrm{pp} \to \mu^+ e^- \mathrm{b} + X$ $(+c.c.)$

Kagan, Kamenik, Perez, Stone - arXiv: 1103.3747
RG - arXiv: 1311.1810, 1409.8631

$pp \to \ell b + X$ - LHCb



$$\sigma(\mathrm{top})[7\ \mathrm{TeV}] = 259 \pm 53(\mathrm{stat}) \pm 38(\mathrm{sys})\ \mathrm{fb}$$

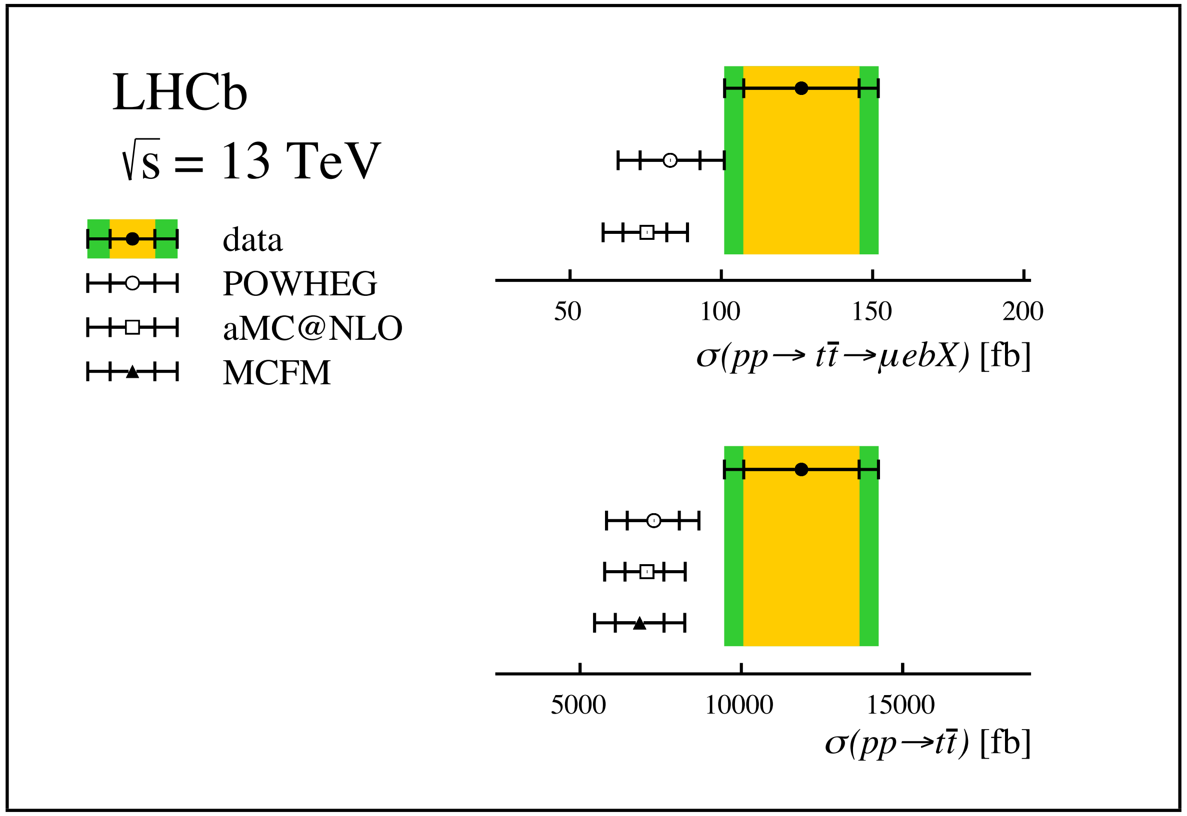
$$\sigma(\mathrm{top})[8\ \mathrm{TeV}] = 289 \pm 43(\mathrm{stat}) \pm 46(\mathrm{sys})\ \mathrm{fb}$$

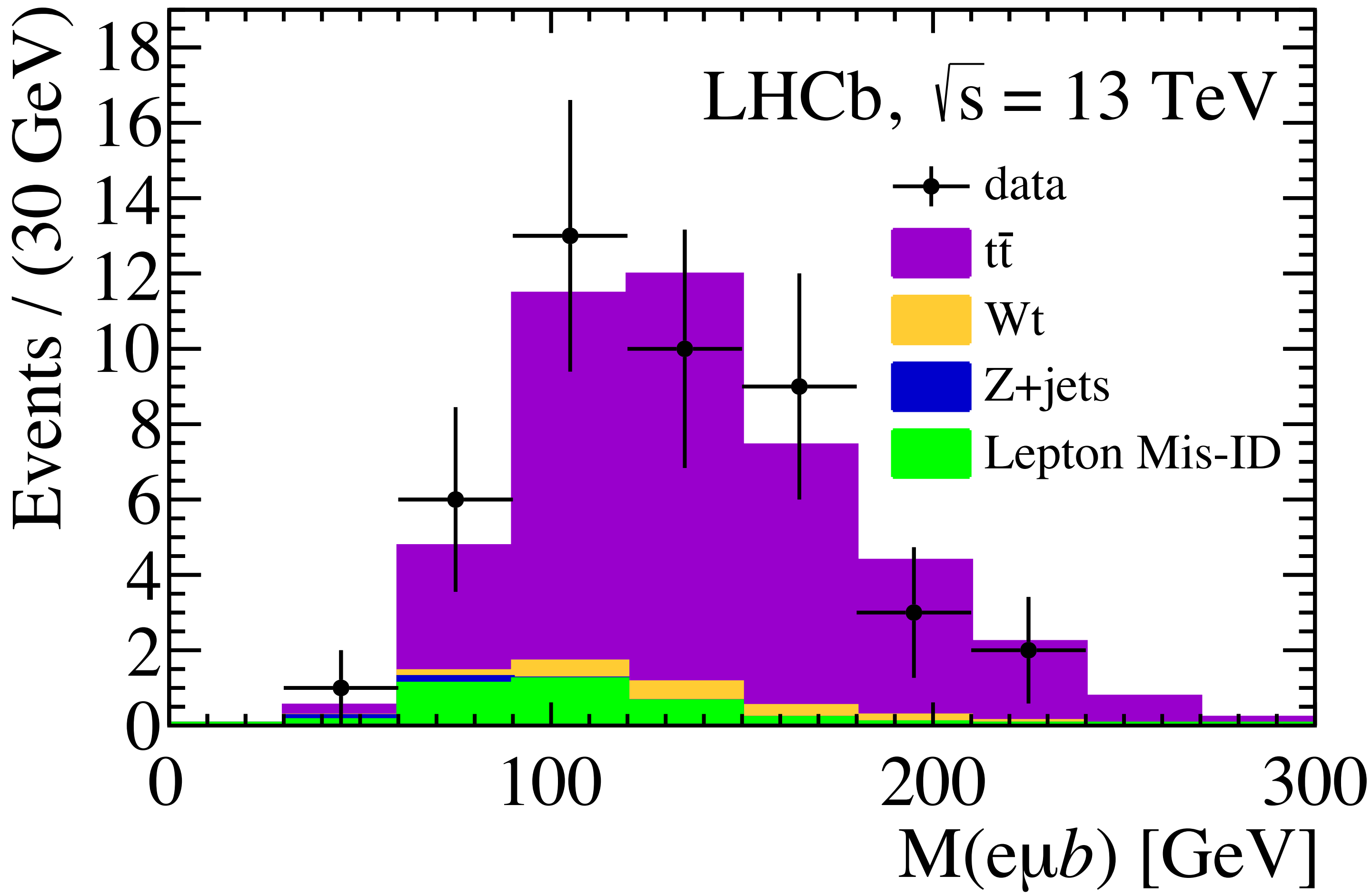
LHCb collaboration - arXiv: 1506.00903

Observation of forward top quark (ttbar and single-top) production

$$p_T^\mu > 25\ \mathrm{GeV}, \quad 2.0(2.2) < \eta^{\mu(b)} < 4.5(4.2), \quad 50 < p_T^b < 100\ \mathrm{GeV}\ldots$$

$pp \to \mu^+ e^- b + X \ (+c.c.)$ - LHCb





$$\sigma(\mu eb)[13 \ \text{TeV}] = 126 \pm 19(\text{stat}) \pm 16(\text{sys}) \pm 5(\text{lumi}) \ \text{fb}$$

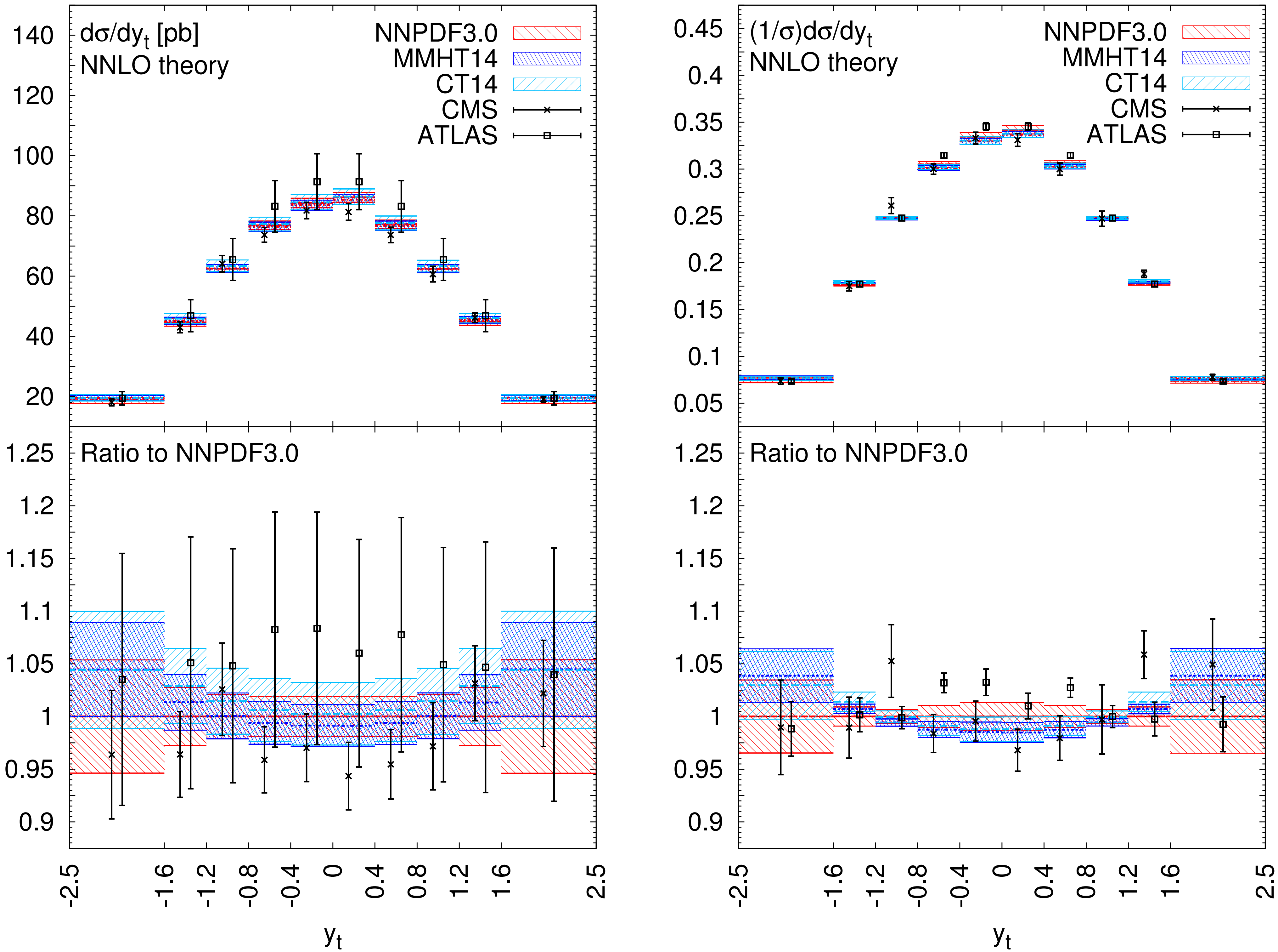
LHCb collaboration - arXiv: 1803.05188

$$p_T^\ell > 20 \ \text{GeV}, \quad 2.0 < \eta^\ell < 4.5$$

$$p_T^b > 20 \ \text{GeV}, \quad 2.2 < \eta^b < 4.2$$

Expect at least 20 times more data... work on systematics $(< 10\%)$

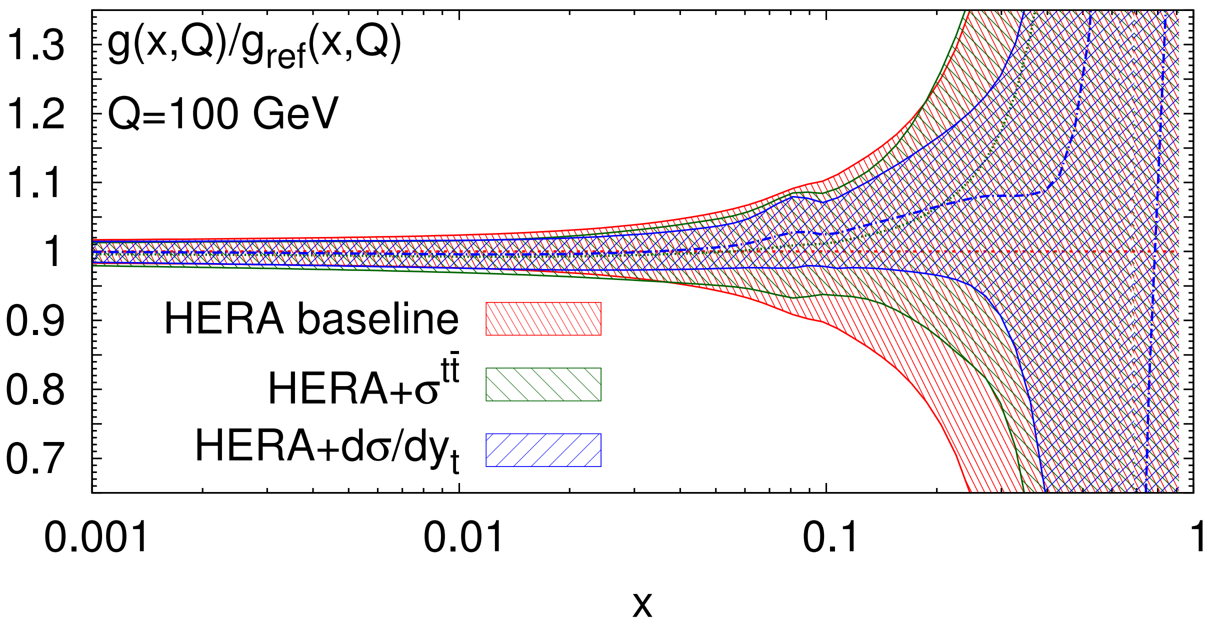
top-quark pair production - central

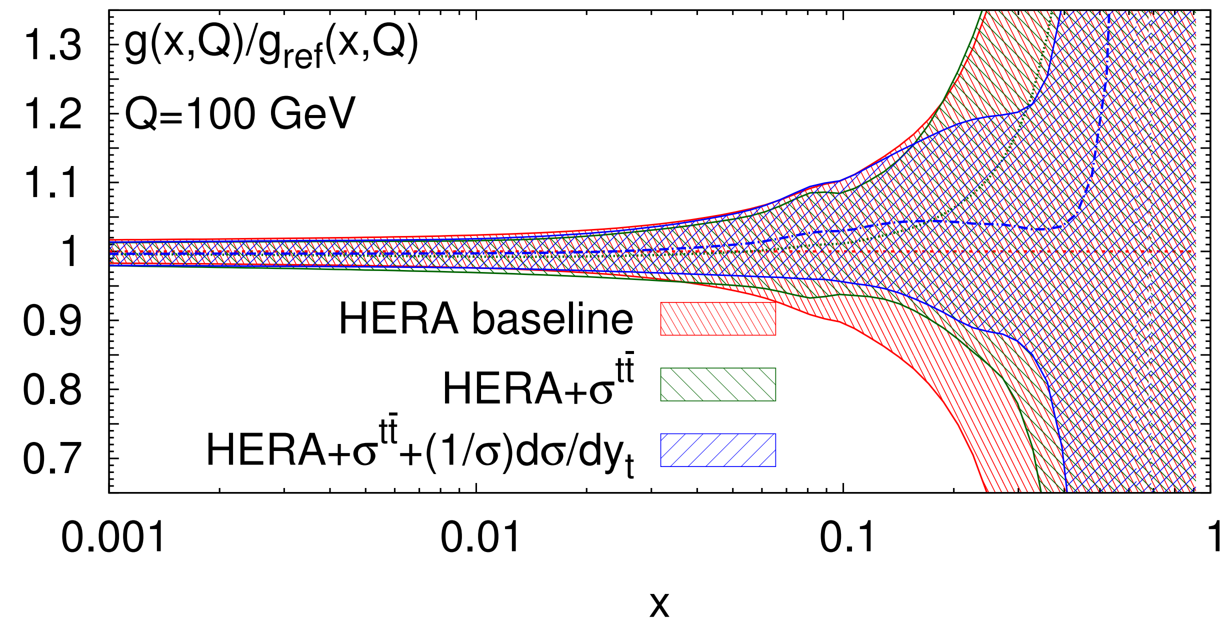


Comparison between NNLO and ATLAS/CMS 8 TeV data

Czakon et al - arXiv: 1611.08609

top-quark pair production - central





PDF fit - HERA + top quark rapidity distributions

Czakon et al - arXiv: 1611.08609

(In)consistency of ATLAS and CMS rapidity distributions:

ATLAS $d\sigma/dy_t$

NNPDF3.0	0.73	(0.28)
CT14	1.28	(0.20)
MMHT14	1.36	(0.29)
HERA2.0	0.72	(0.99)
ABM12	5.32	(1.45)

CMS $d\sigma/dy_t$

NNPDF3.0	3.04	(1.05)
CT14	2.23	(1.47)
MMHT14	2.12	(0.98)
HERA2.0	3.65	(1.49)
ABM12	22.1	(9.78)

LHCb can provide forward data for $\ell b(\approx y_t)$ as well as $e\mu b(\approx y_{t\bar{t}})$

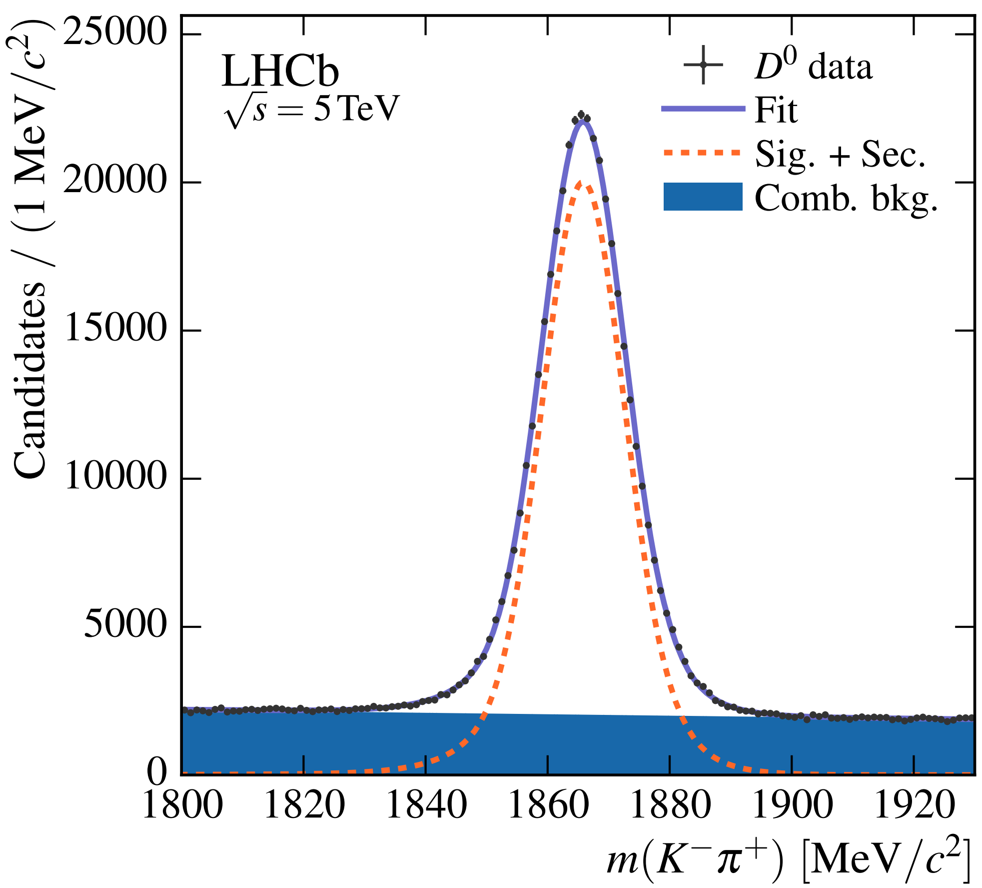
charm-quark (pair) production - LHCb

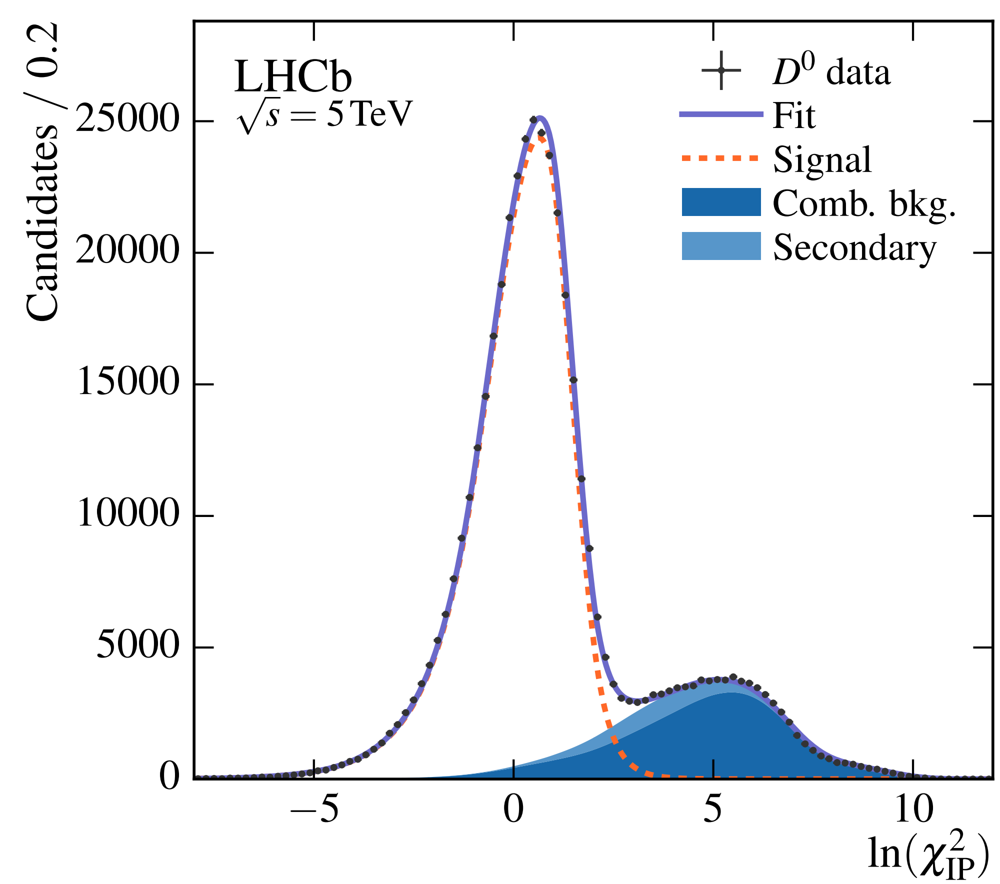
$$pp \rightarrow D^0 + X$$
$$D^0 \hookrightarrow K^- \pi^+$$

Exclusively reconstruct D-hadrons within experimental acceptance

For example, LHCb fiducial region:

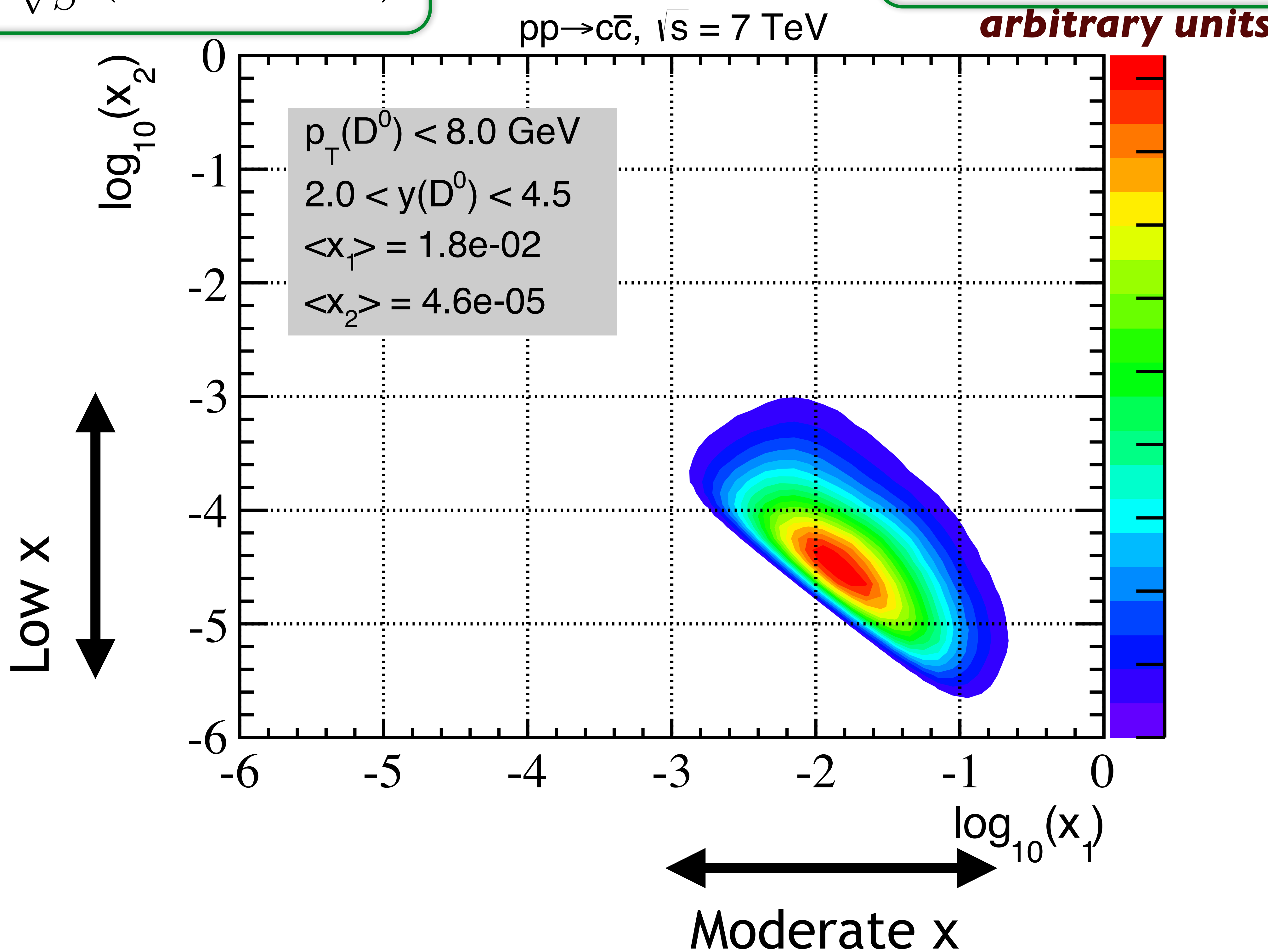
$$p_T^D < 8 \text{ GeV}$$
$$2.0 < y^D < 4.5$$





$$x_{1,(2)} = \frac{m_T}{\sqrt{S}} \left(e^{(-)y_3} + e^{(-)y_4} \right)$$

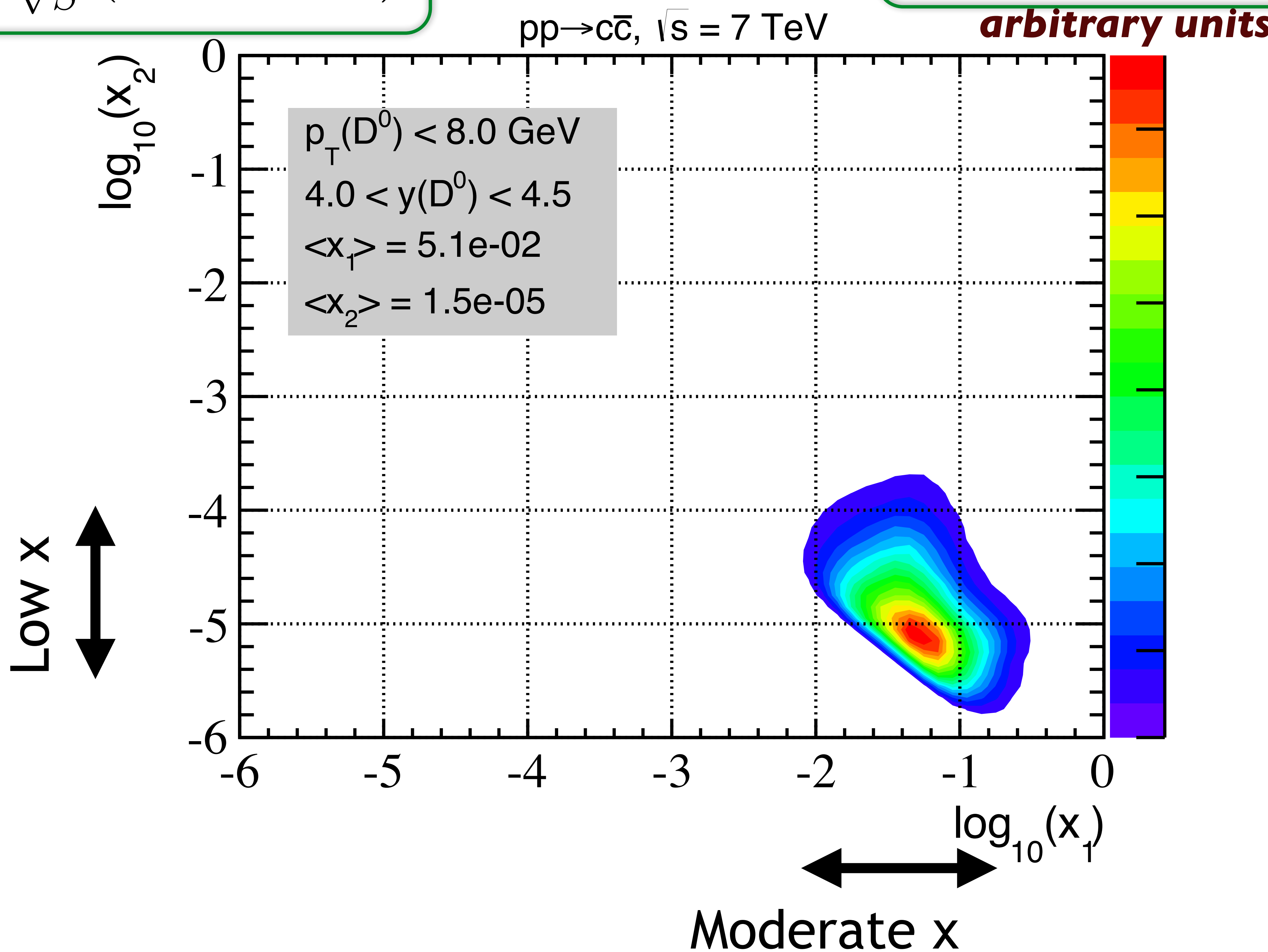
$$\sqrt{\hat{s}} = \sqrt{x_1\, x_2\, S} \geq 2m_c$$



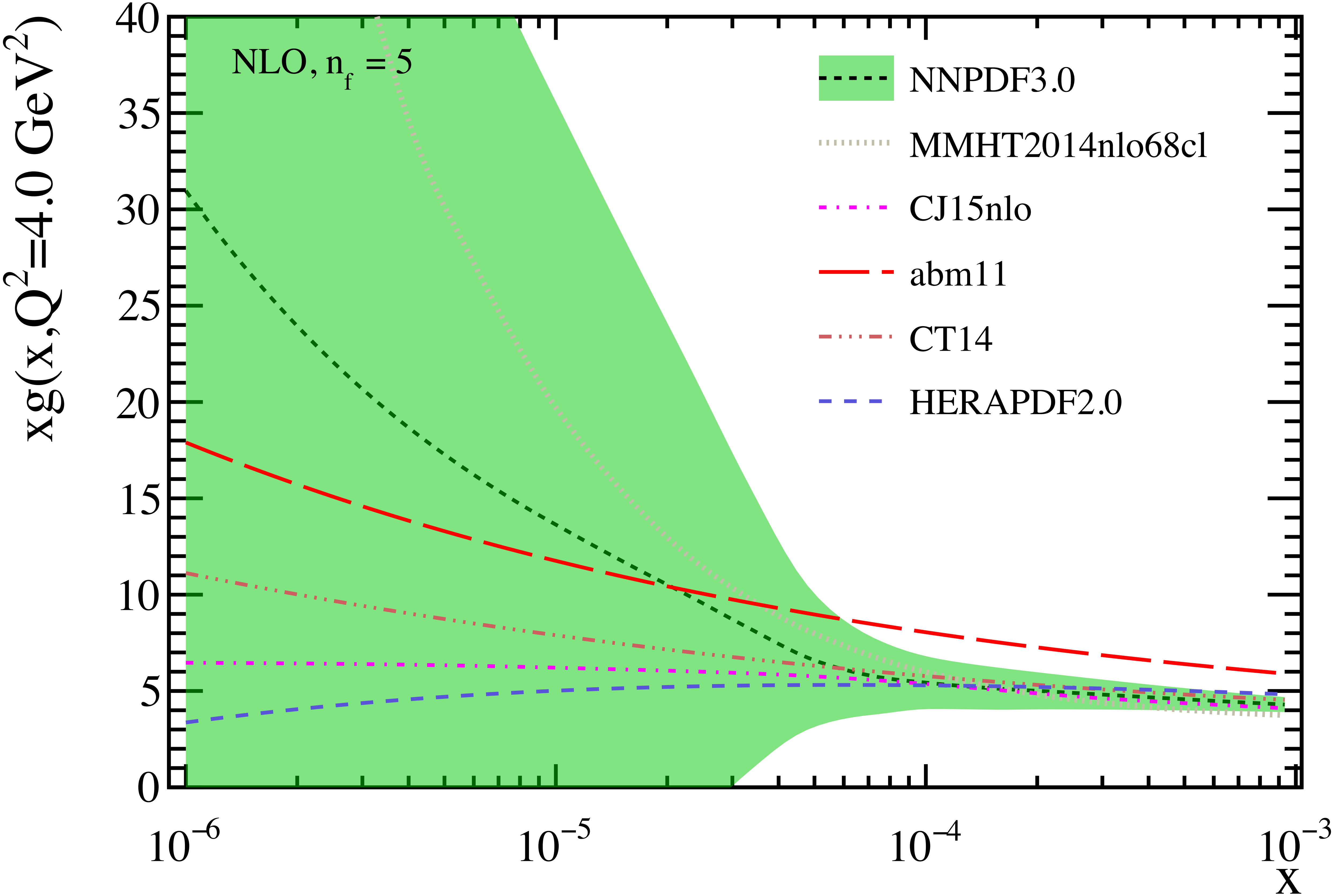
Require a D hadron within LHCb acceptance at 7 TeV

$$x_{1,(2)} = \frac{m_T}{\sqrt{S}}\left(e^{(-)y_3} + e^{(-)y_4}\right)$$

$$\sqrt{\hat{s}} = \sqrt{x_1\, x_2\, S} \geq 2m_c$$



Require a D hadron within LHCb acceptance at 7 TeV



NLO, n_f = 5
NNPDF3.0
MMHT2014nlo68cl
CJ15nlo
abm11
CT14
HERAPDF2.0
$xg(x,Q^2=4.0\ GeV^2)$
0
5
10
15
20
25
30
35
40
10^{-6}
10^{-5}
10^{-4}
10^{-3}
x

What exactly is measured?

$$pp \to D + X$$

$\curvearrowright$ $D^0,\ D^+,\ D_s,\ D^{*+}\ (+c.c.)$

Number of events

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T^D \mathrm{d}y^D} = \frac{1}{\Delta p_T^D \Delta y^D} \cdot \frac{N_i(D \to f + c.c.)}{\epsilon_i(D \to f)\mathcal{B}(D \to f)\kappa\mathcal{L}_{\rm int}}$$

lumi

bins

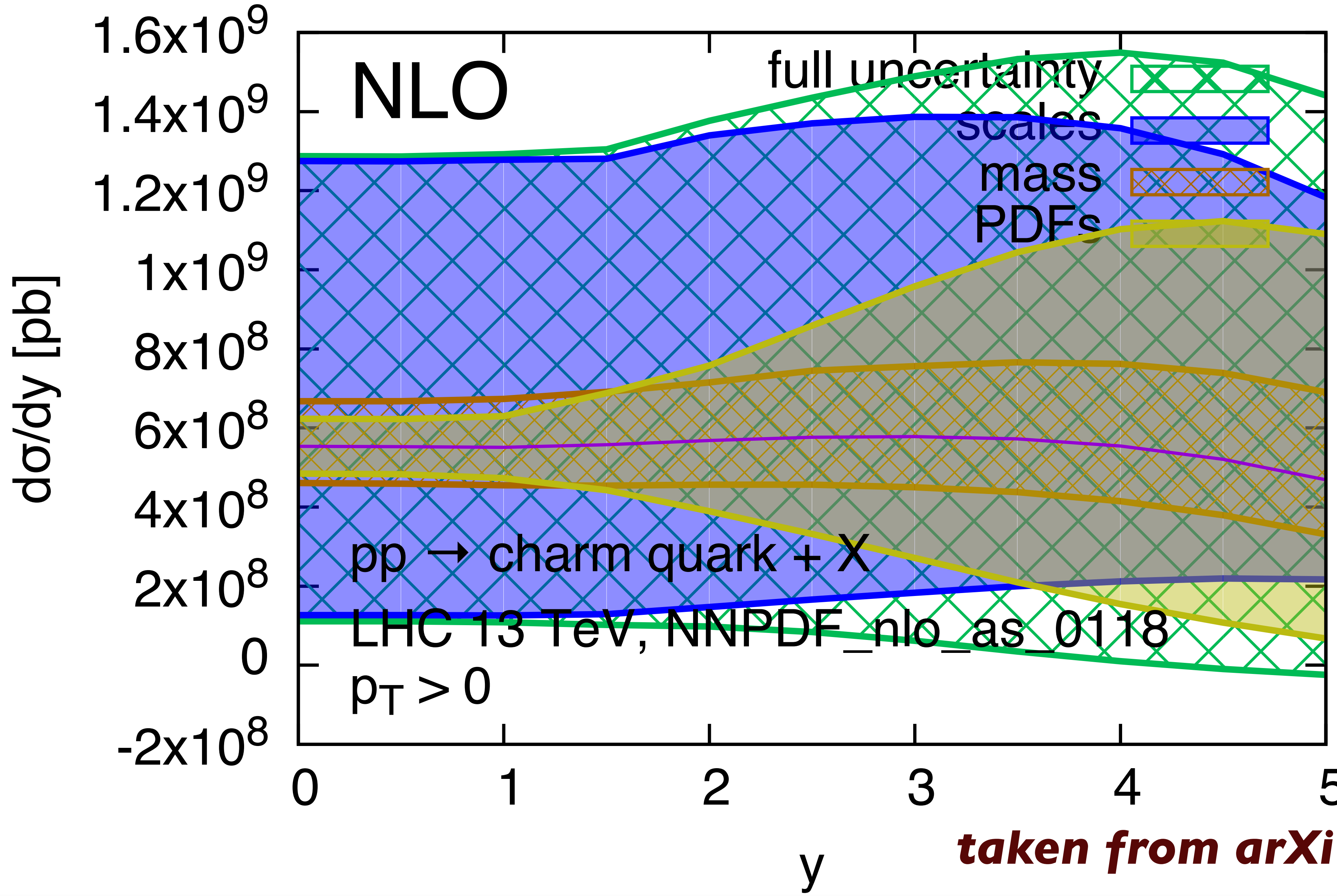
efficiency to measure f

branching fraction to f

hardware efficiency

- Measurements performed at 3 CoM Energies (5, 7, 13 TeV)
- 8 bins within $p_T^D < 8.0\ \mathrm{GeV}$, 5 bins within $2.0 < y^D < 4.5$ (40 total)

In total approximately 480 data points



taken from arXiv 1507.06197

$$\hat{\sigma}_{ij}(\beta, m, \mu_F) = \frac{\alpha_s^2(\mu_R)}{m_Q^2}\left(\sigma_{ij}^{(0)} + \alpha_s(\mu_R)\left[\sigma_{ij}^{(1)} + \overline{\sigma}_{ij}^{(1)}(\mu_F, \mu_R)\right] + ...\right)$$

Scale uncertainties at low energy scales overwhelming

$$\mu \sim \sqrt{m_Q^2 + p_{T,Q}^2} \sim 2.2\,\mathrm{GeV} \qquad \alpha_s(2.2\,\mathrm{GeV}) \sim 0.3$$

Measurements performed double differentially in p_T^D and y_D

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

Measurements performed at multiple hadronic CoM values

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

$$x_{1,(2)} = \frac{m_T}{\sqrt{S}} \left(e^{(-)y_3} + e^{(-)y_4} \right)$$

Hadronic CoM Energy

Measurements performed double differentially in p_T^D and y_D

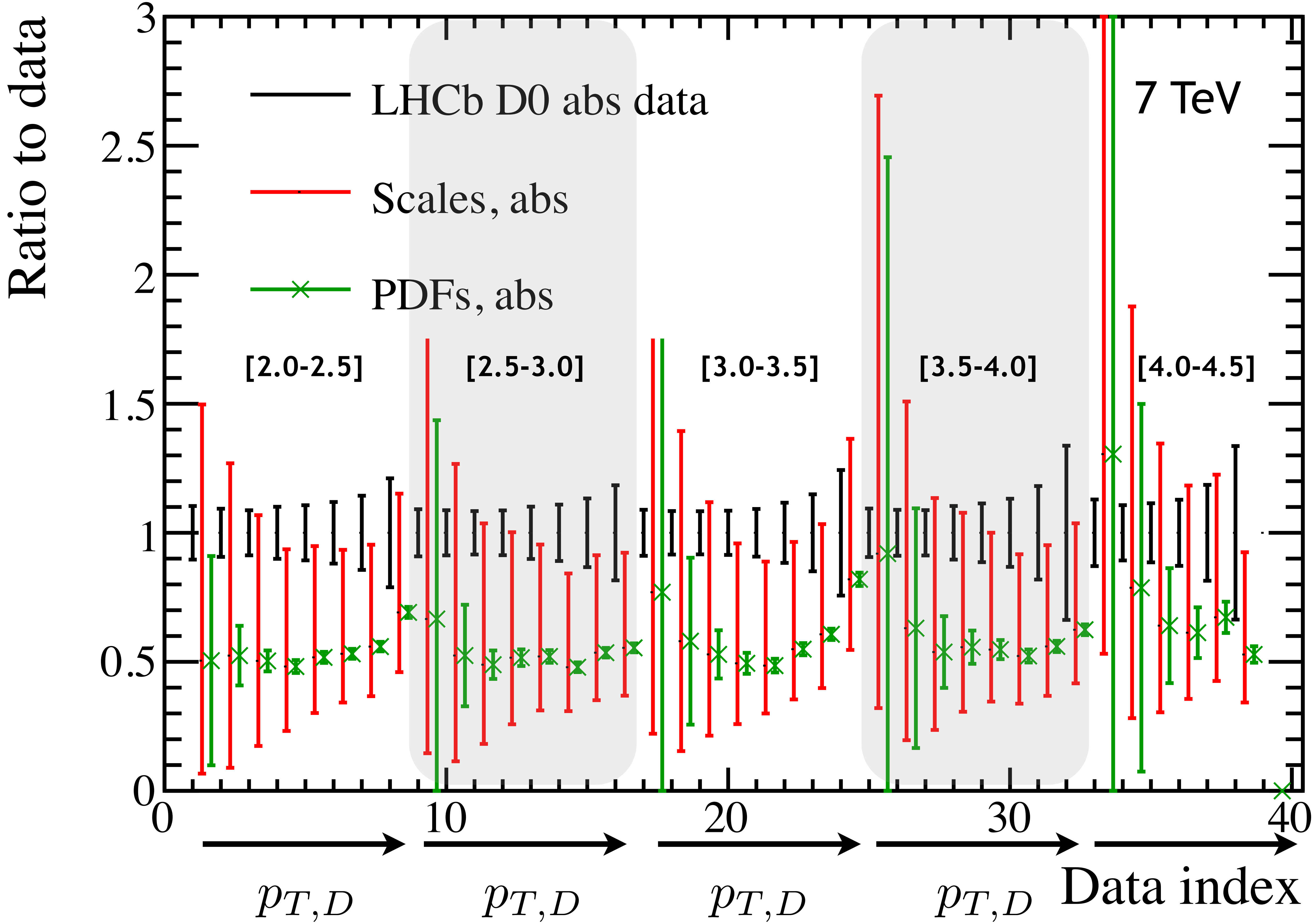
$$N_X^{ij} = \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} \Bigg/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{ref}}^D d(p_T^D)_j}$$

Measurements performed at multiple hadronic CoM values

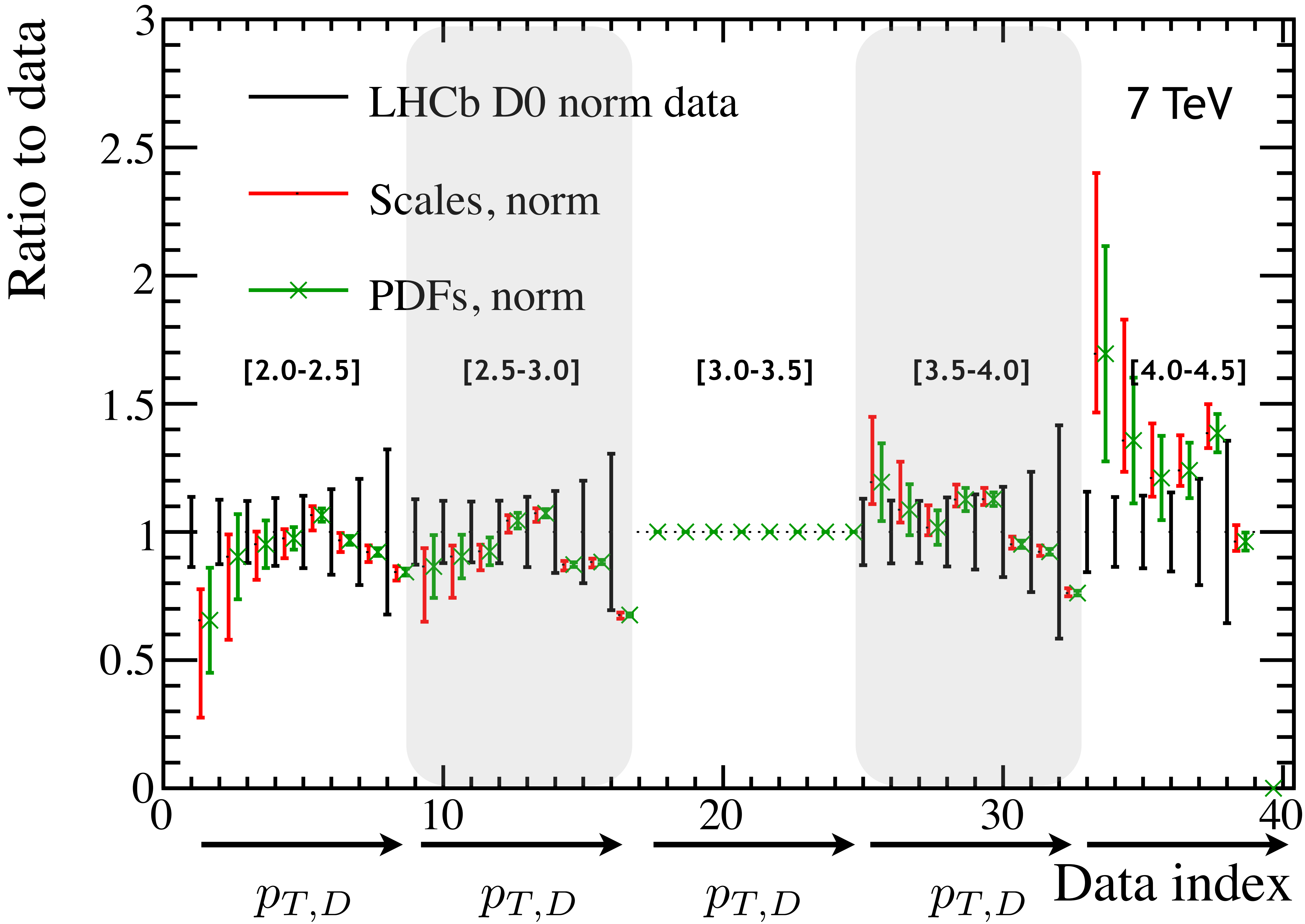
$$R_{13/X}^{ij} = \frac{d^2\sigma(13\ \mathrm{TeV})}{dy_i^D d(p_T^D)_j} \Bigg/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{i}}^D d(p_T^D)_j}$$

pros: theoretical (and experimental) uncertainties highly correlated

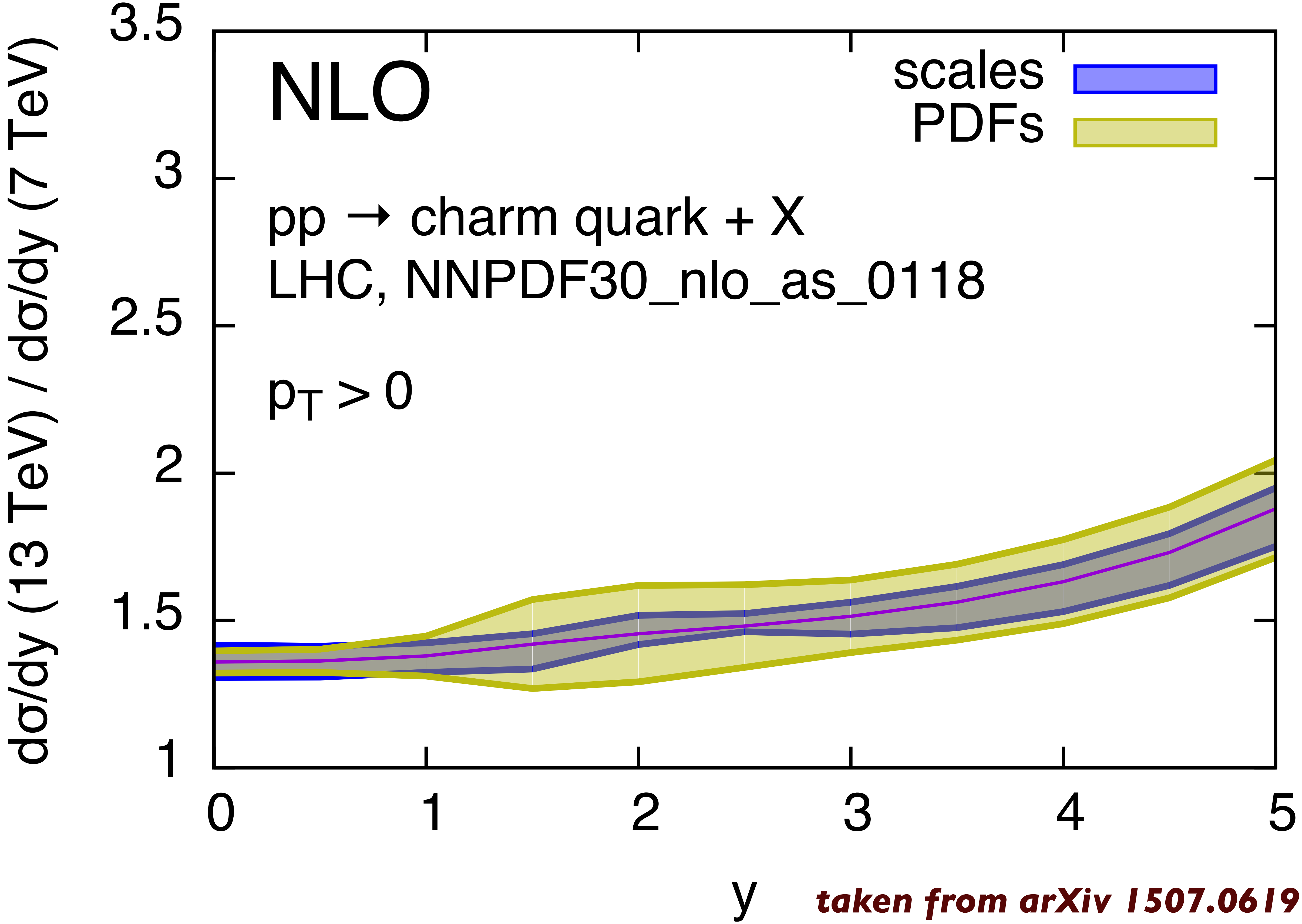
cons: PDF uncertainties **also** correlated (lose sensitivity to PDFs)



Absolute cross-section

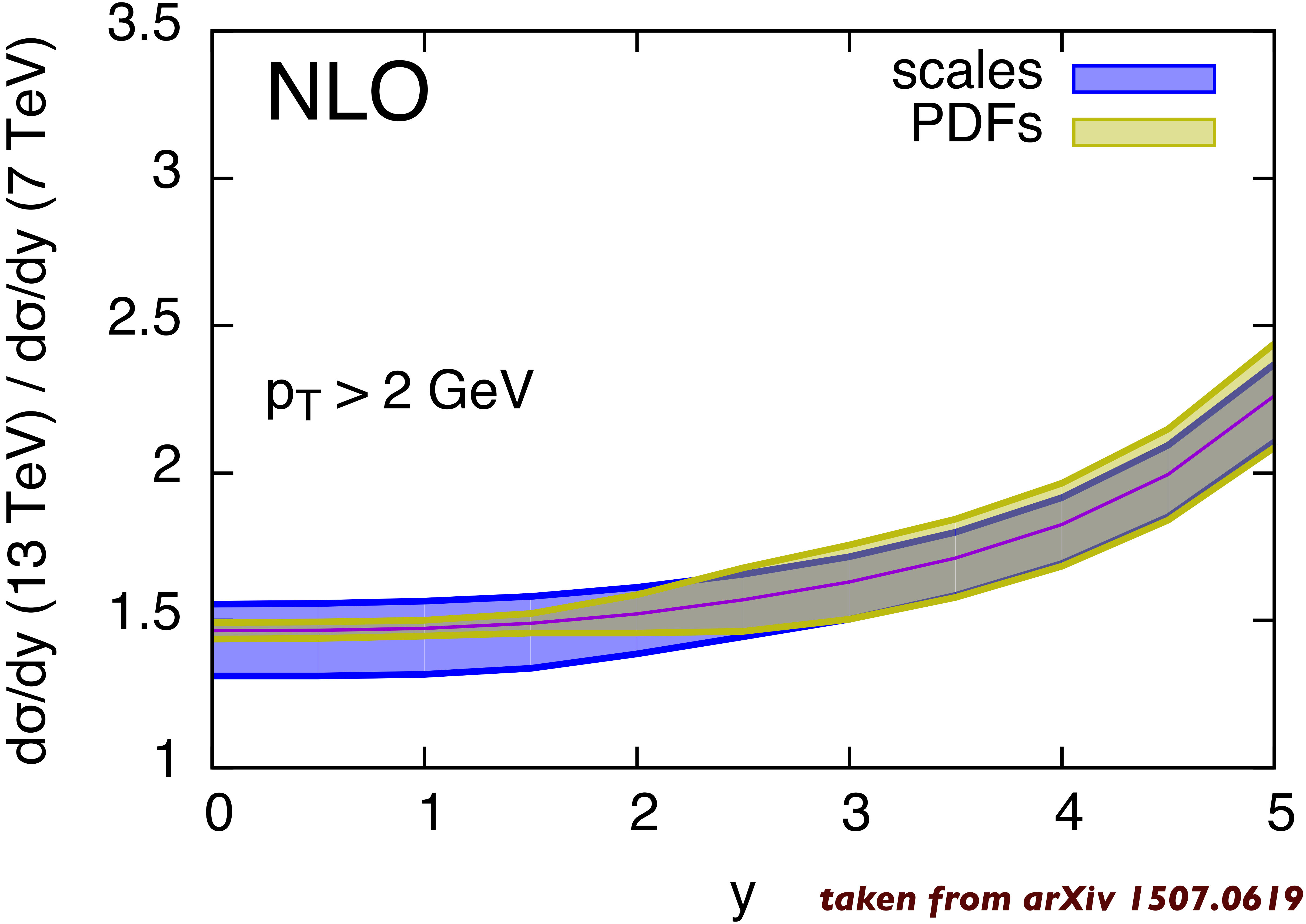


Normalised cross-section



taken from arXiv 1507.06197

Ratio of cross-sections



taken from arXiv 1507.06197

Ratio of cross-sections

Summary of LHCb data

Prompt charm production at 13 TeV (and 13/7 ratio), arXiv:1510.01707

Erratum: September 2016

Erratum: May 2017

Prompt charm production at 5 TeV (and 13/5 ratio), arXiv:1610.02230

Erratum: May 2017

Prompt charm production at 7 TeV, arXiv:1302.2864

Prompt B production at 13 TeV (and 13/7 ratio), arXiv:1612.05150

Erratum: September 2017

Prompt B production at 7 TeV, arXiv:1306.3663

Summary of PDF analyses (reweighting or fits)

NLO analysis, HERA + LHCb B/D 7 TeV data, arXiv:1503.04581

Prosa Collaboration

NNPDF3.0 NLO Global fit + LHCb D 7 TeV data, arXiv:1506.08025

RG, Rojo, Rottoli, Talbert

NNPDF3.0 NLO Global fit + LHCb D 13, 7, 5 TeV data, arXiv:1610.09373

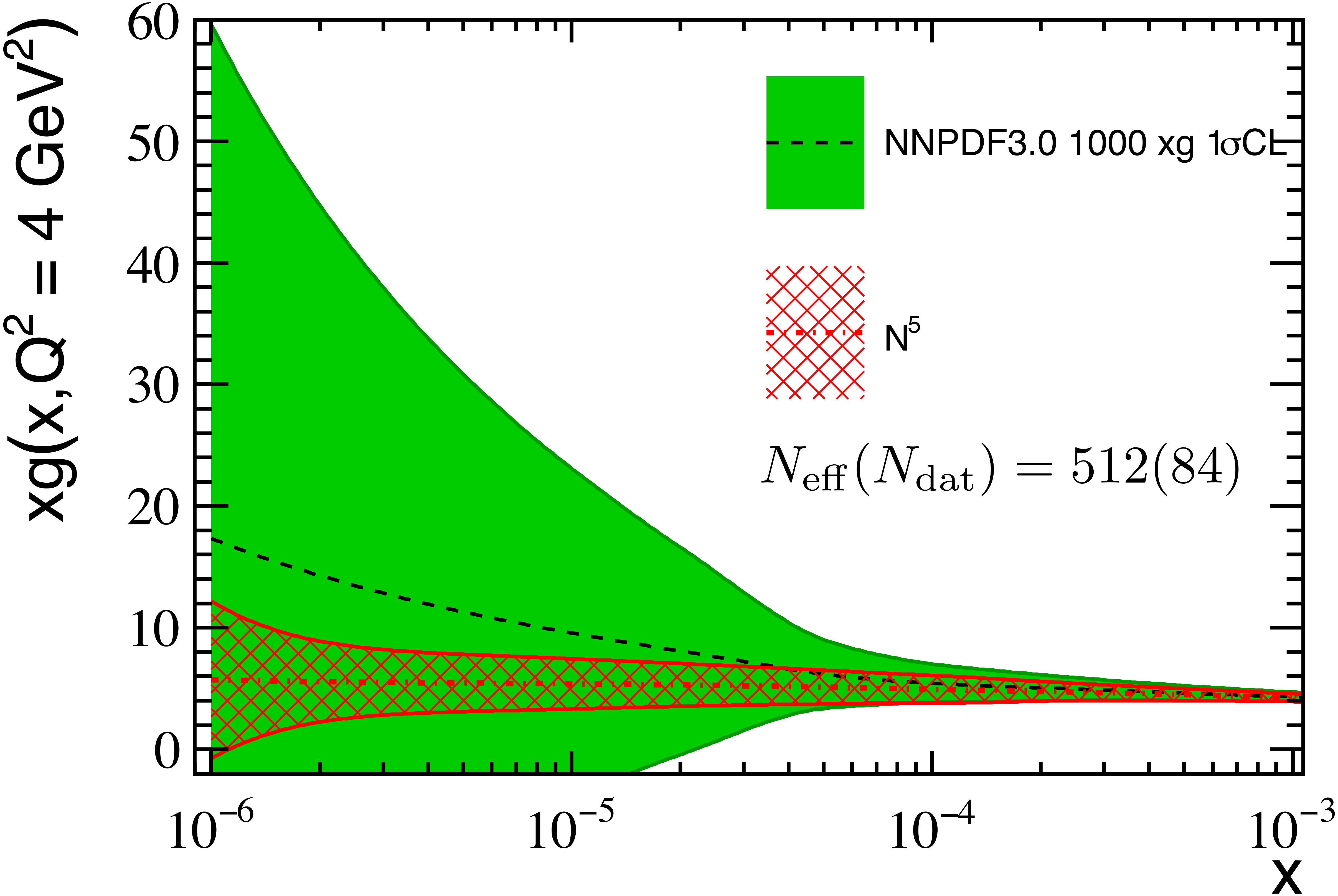
RG, Rojo (updated May 2017)

The LHCb B and D hadron data is wrong paper, arXiv:1703.03636

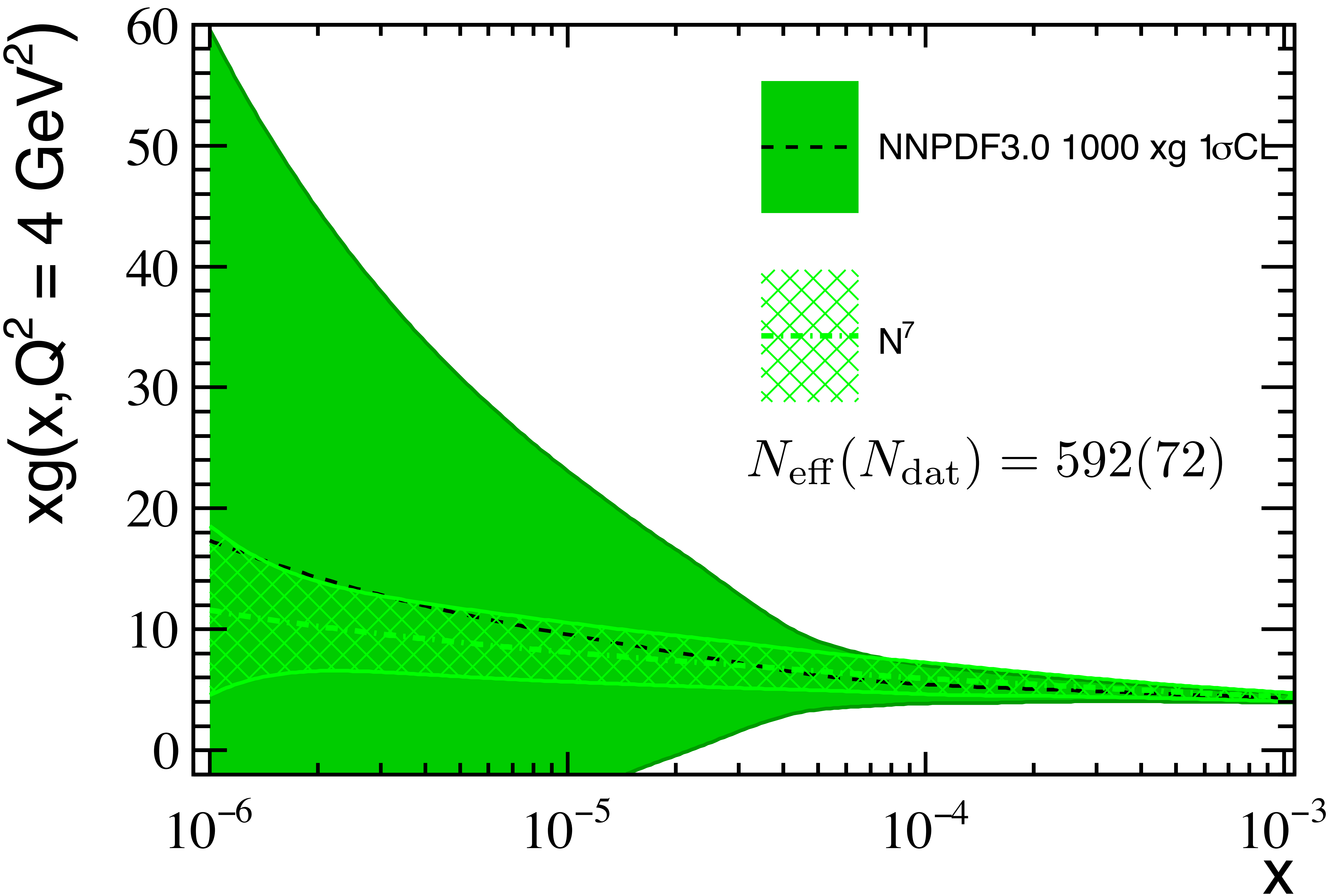
RG

Analyses of absolute D cross section data, arXiv:1705.08845

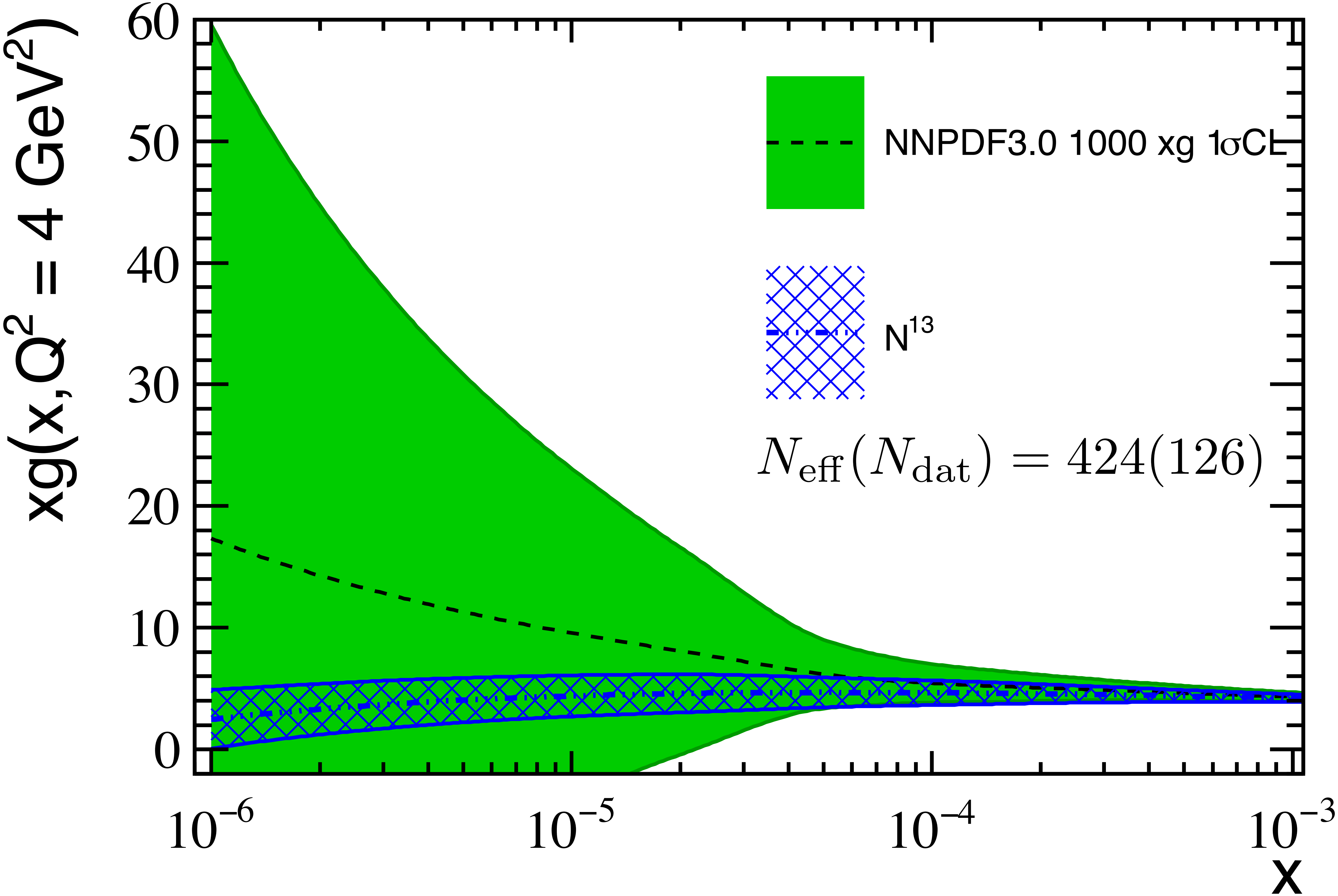
Martin, Oliviera, Ryskin



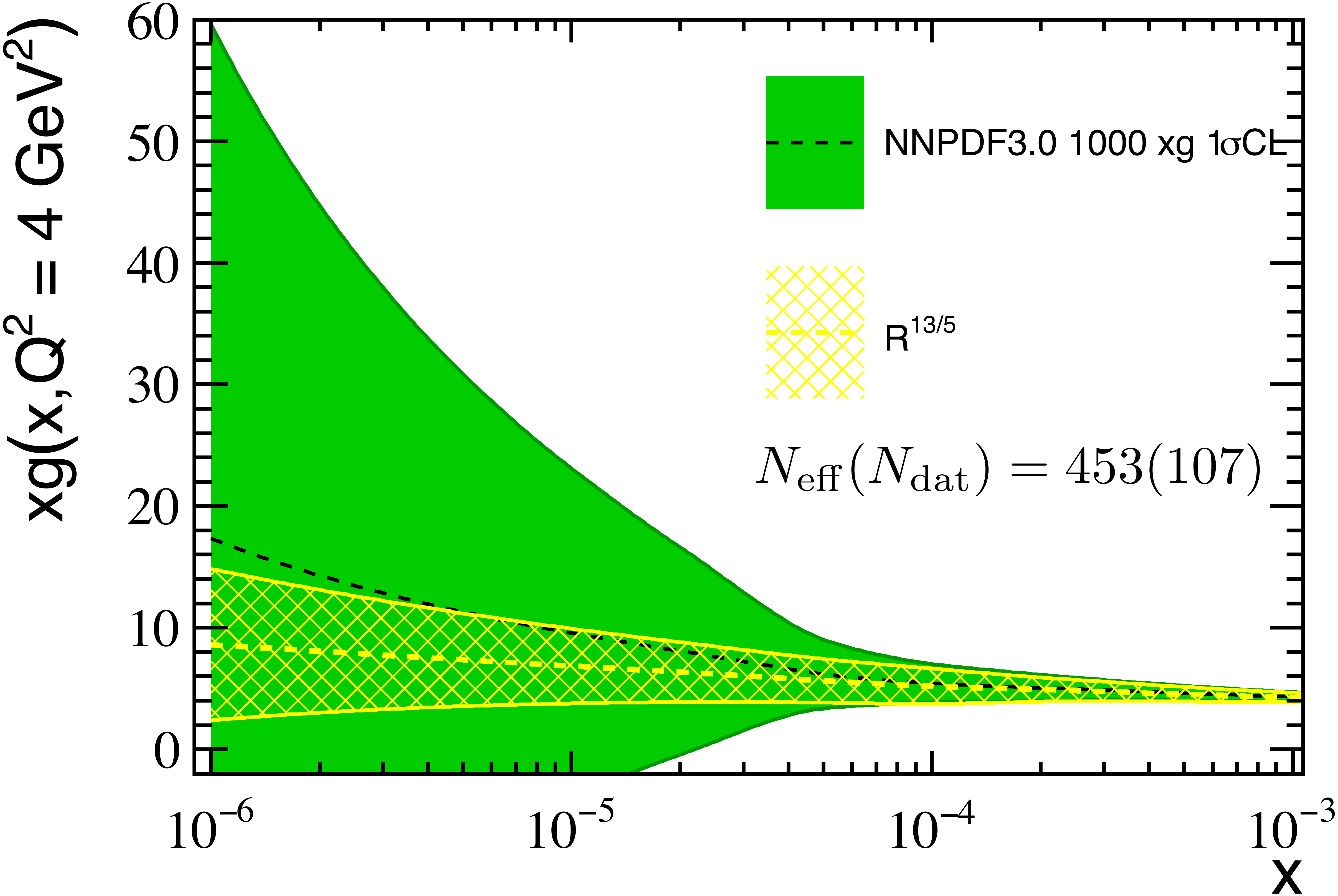
$xg(x,Q^2 = 4\ GeV^2)$
60
50
40
30
20
10
0
NNPDF3.0 1000 xg 1σCL
N^5
$N_{\rm eff}(N_{\rm dat}) = 512(84)$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
x



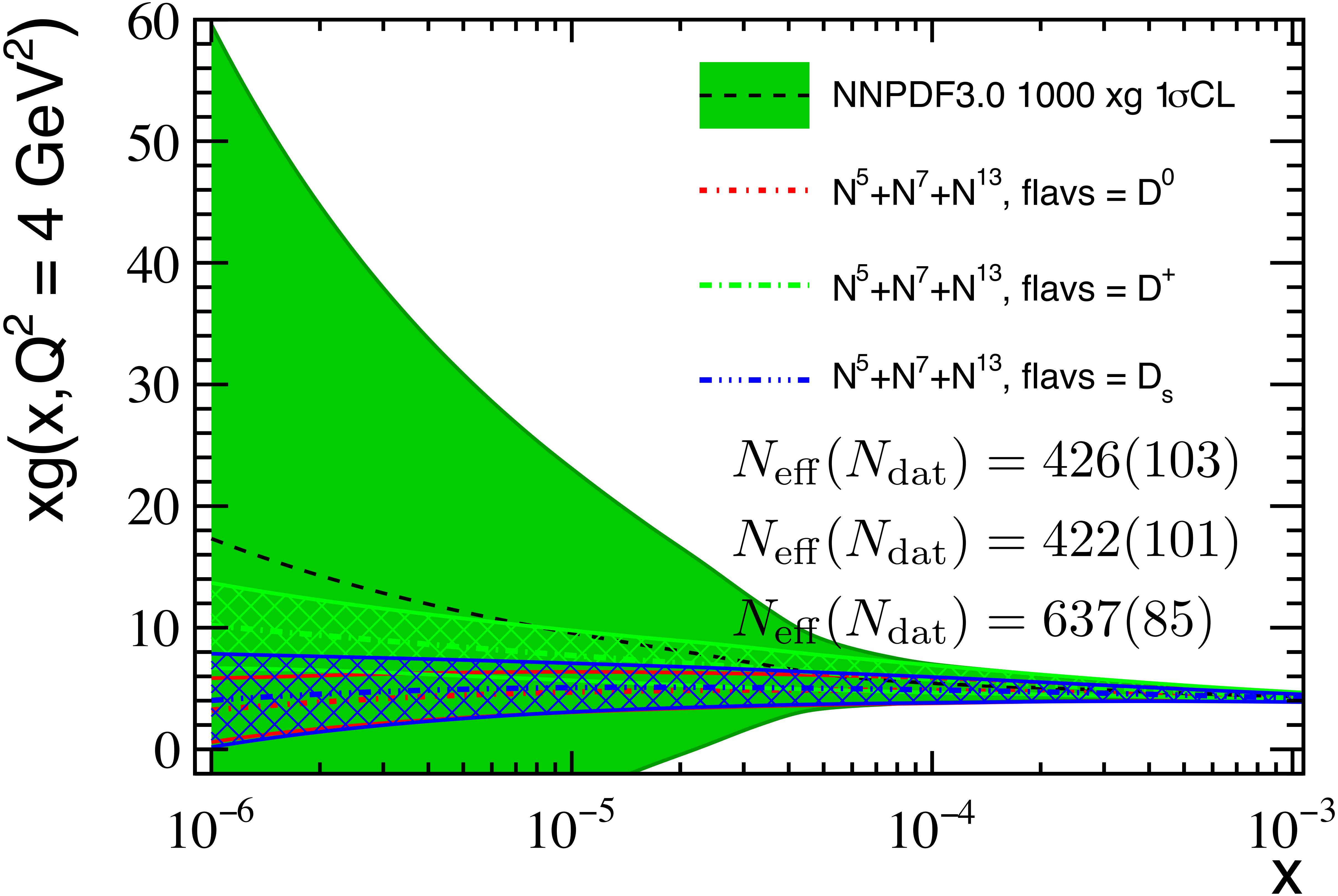
60
50
40
30
20
10
0
$xg(x,Q^2 = 4\ GeV^2)$
NNPDF3.0 1000 xg 1σCL
N^7
$N_{\rm eff}(N_{\rm dat}) = 592(72)$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
x



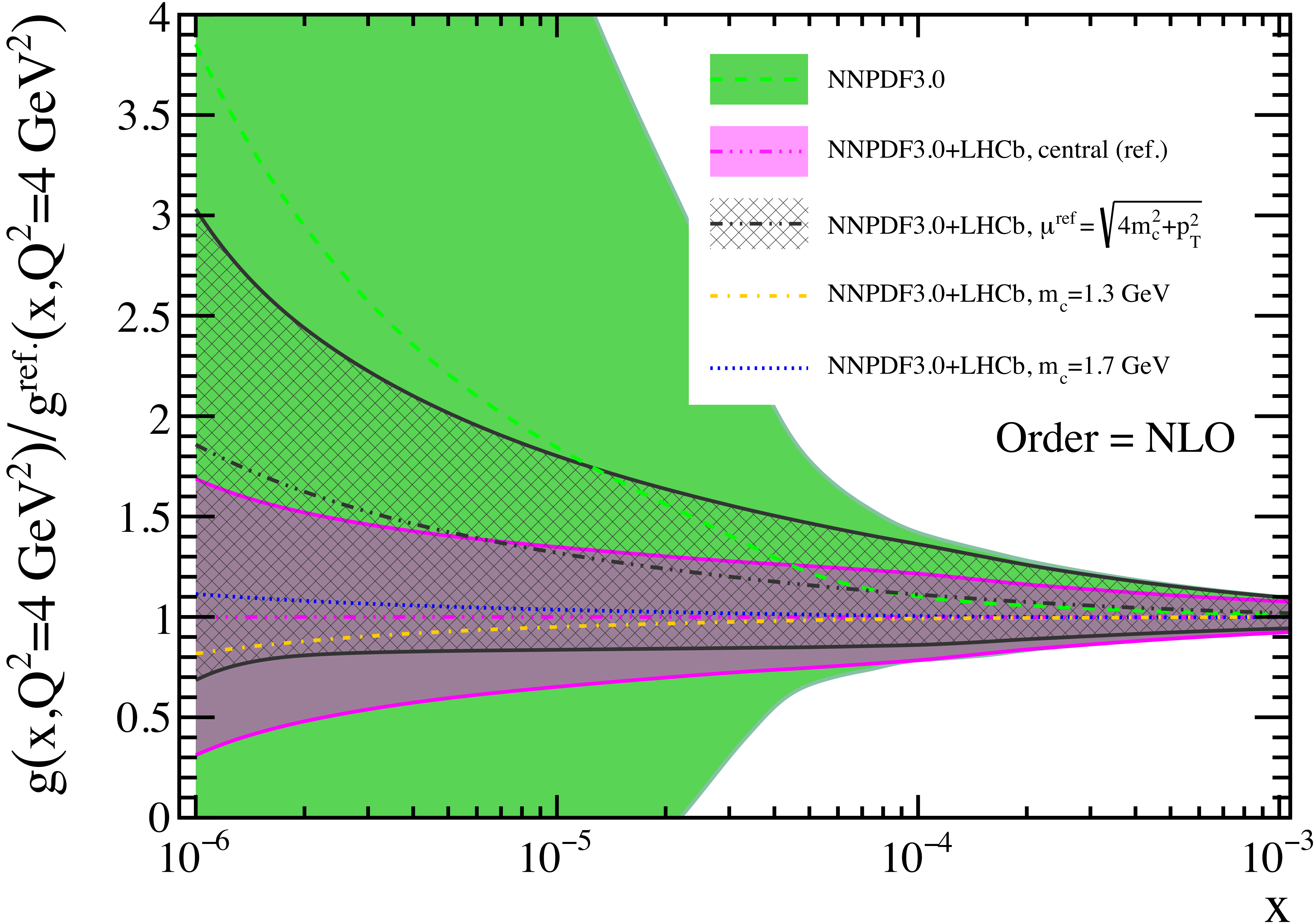
60
50
40
30
20
10
0
$xg(x,Q^2 = 4\ GeV^2)$
NNPDF3.0 1000 xg 1σCL
N^{13}
$N_{\rm eff}(N_{\rm dat}) = 424(126)$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
x



60
50
40
30
20
10
0
$xg(x, Q^2 = 4\ GeV^2)$
NNPDF3.0 1000 xg 1σCL
$R^{13/5}$
$N_{\rm eff}(N_{\rm dat}) = 453(107)$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
x



xg(x,Q^2 = 4 GeV^2)
60
50
40
30
20
10
0
10^-6
10^-5
10^-4
10^-3
x
NNPDF3.0 1000 xg 1σCL
N^5+N^7+N^13, flavs = D^0
N^5+N^7+N^13, flavs = D^+
N^5+N^7+N^13, flavs = D_s
$N_{\rm eff}(N_{\rm dat}) = 426(103)$
$N_{\rm eff}(N_{\rm dat}) = 422(101)$
$N_{\rm eff}(N_{\rm dat}) = 637(85)$



NNPDF3.0
NNPDF3.0+LHCb, central (ref.)
NNPDF3.0+LHCb, $\mu^{ref}=\sqrt{4m_c^2+p_T^2}$
NNPDF3.0+LHCb, m_c=1.3 GeV
NNPDF3.0+LHCb, m_c=1.7 GeV
Order = NLO
$g(x,Q^2=4\ GeV^2)/g^{ref.}(x,Q^2=4\ GeV^2)$
x
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0
0.5
1
1.5
2
2.5
3
3.5
4

Observable → Number of data points

$N_5(84)$	$N_7(79)$	$N_{13}(126)$	$R_{13/5}(107)$	$R_{13/7}(102)$
1.97	1.21	2.36	1.36	0.80
0.86	0.72	1.14	1.35	0.81
1.31	**0.91**	1.58	1.36	0.82
0.74	0.66	**1.01**	1.38	0.80
1.08	0.81	1.27	**1.29**	0.80
1.53	0.99	1.73	1.30	**0.81**
1.07	0.81	1.34	1.35	**0.81**
0.82	**0.70**	1.07	**1.35**	0.81
0.84	**0.71**	**1.10**	1.36	0.81

$$\chi^2/N_{\rm dat} = \sum_{i,j}(O_i - T_i)\sigma_{ij}^{-1}(O_j - T_j)$$

Summary of D-hadron data

- The LHCb data leads to constraints: $x \sim 10^{-6}, Q \sim 3 \text{ GeV}$
  - theory predictions based on normalised NLO observables
  - very specific applications (neutrino astronomy)

- Theoretical improvements not expected imminently:
  - numerical stability issues in secdec NNLO top production
  - needs extension to include convolution with FF

- Also an interest to study D-production in p-Pb collisions:
  - Rfb observable highly sensitive to nuclear shadowing

Kusina et al. - arXiv 1712.07024

Back-up slides

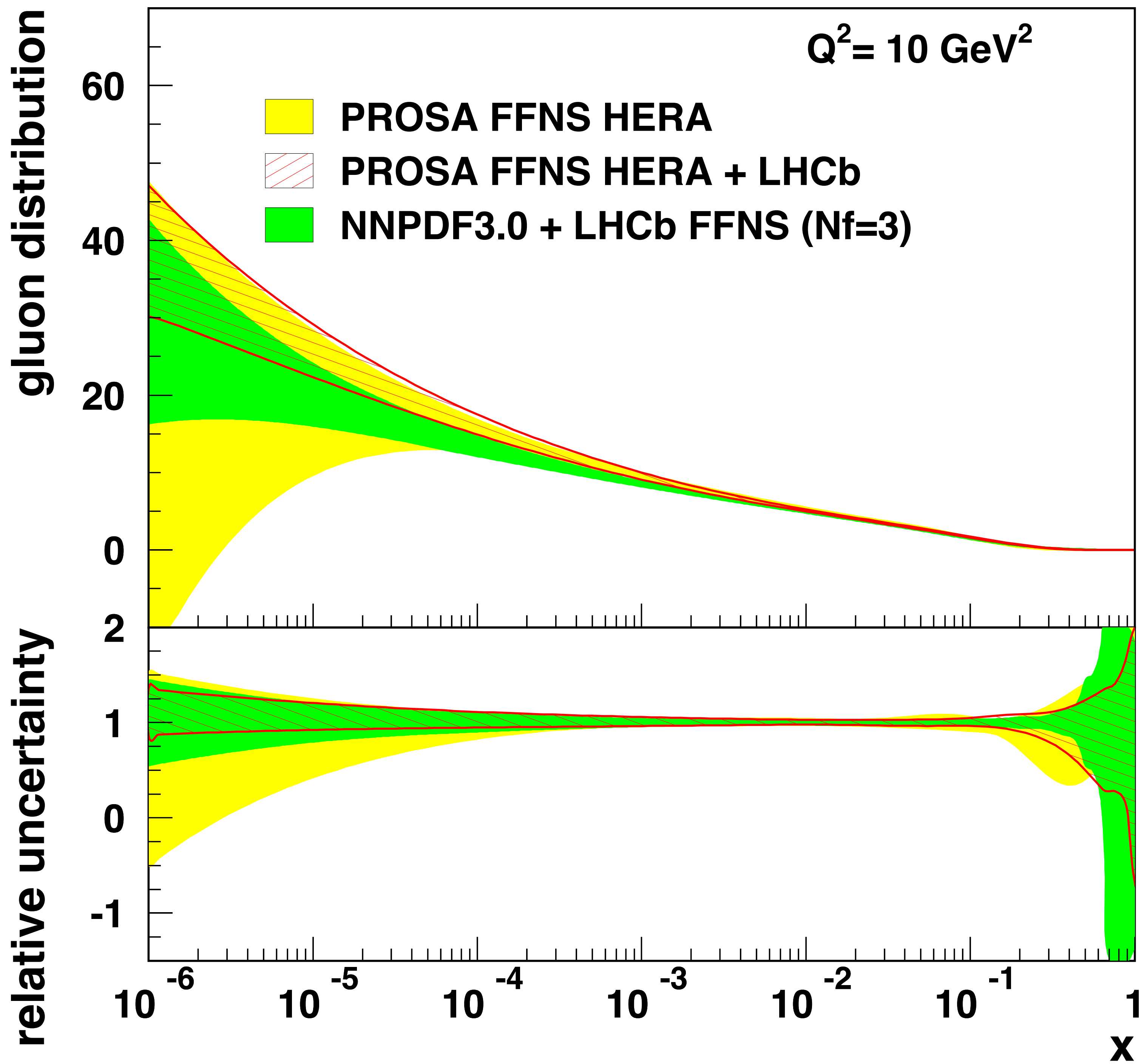
Gluon PDF extraction at 7 TeV

PROSA results:

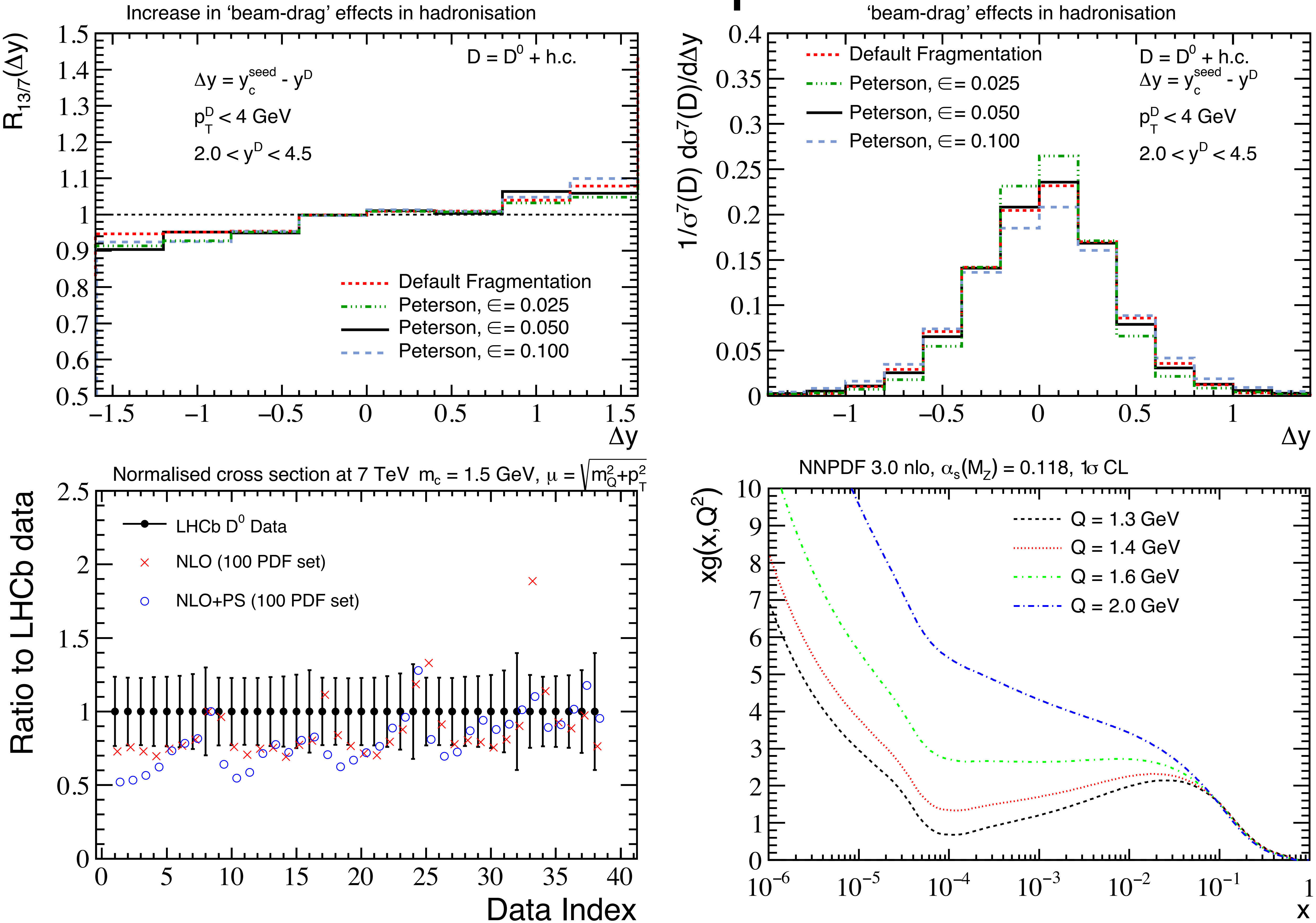
- HERA+LHCb Data PDF fit
- FFS, NF=3
- Normalise to ‘middle’ rapidity bin for each pT
- HERAfitter framework
- Also LHCb B data

GRRT results:

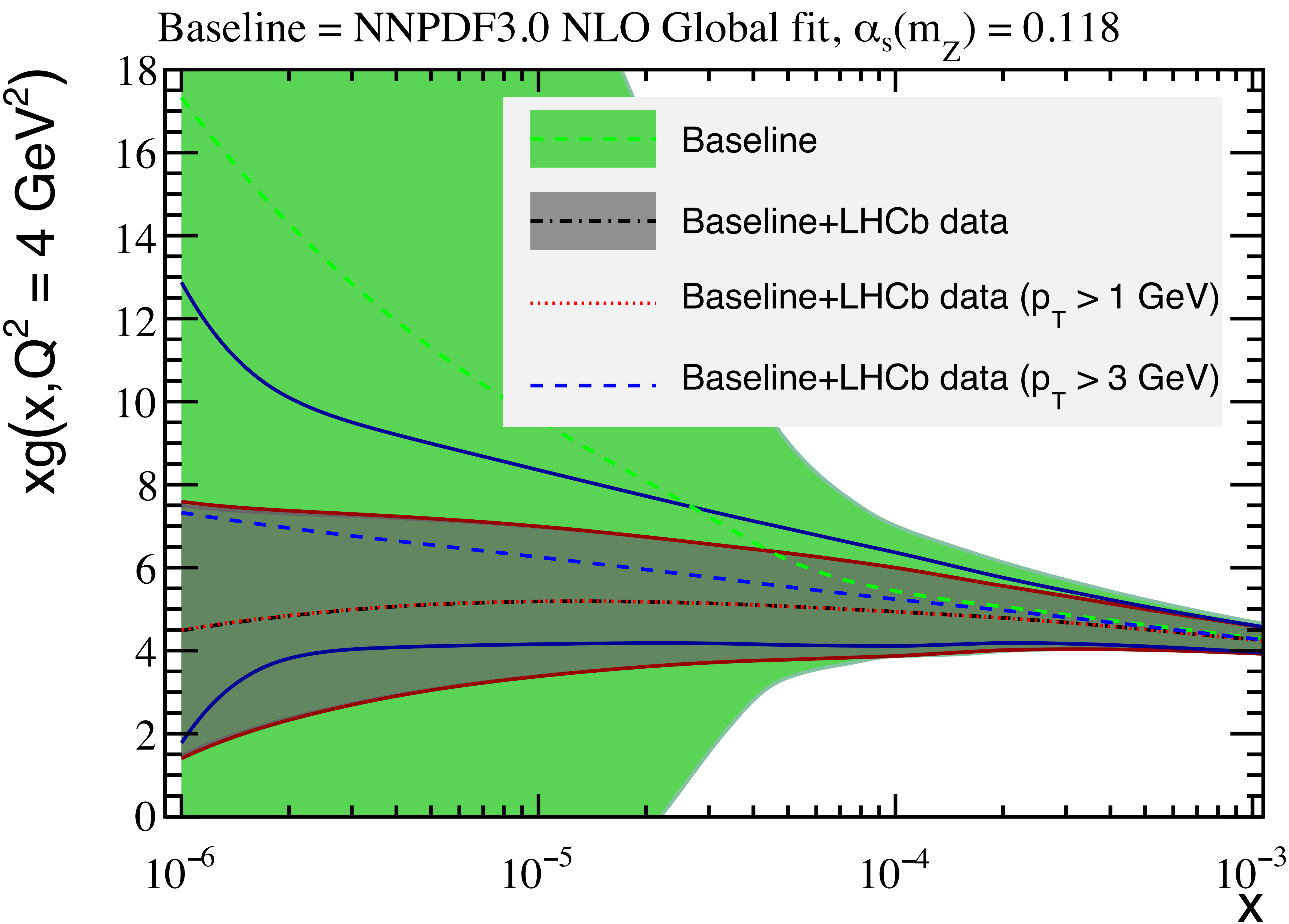
- NNPDF3.0 Global fit
- input set is VFNS
- Normalise to max pT / min rapidity bin
- Bayesian Reweighting



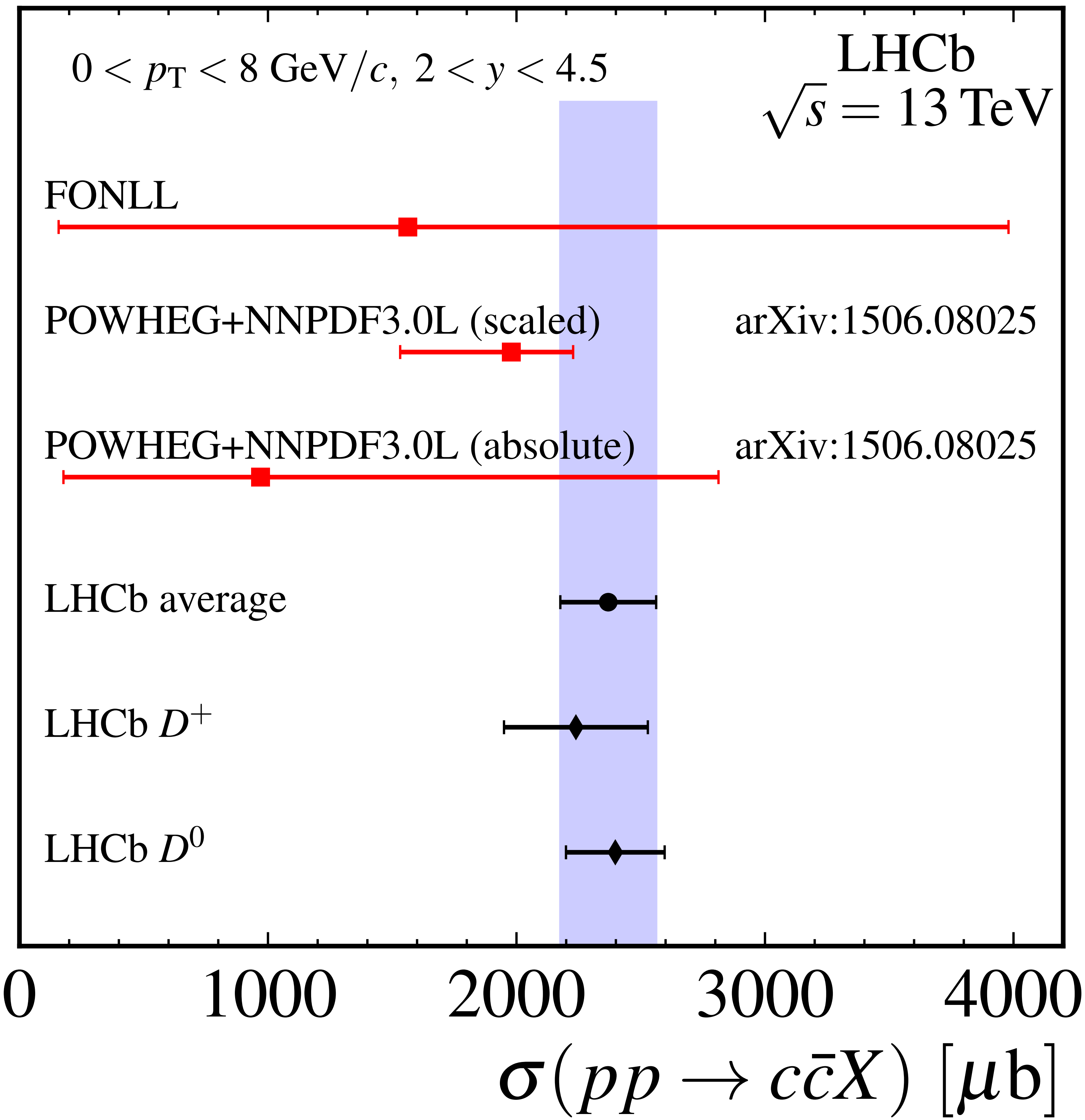
Useful plots



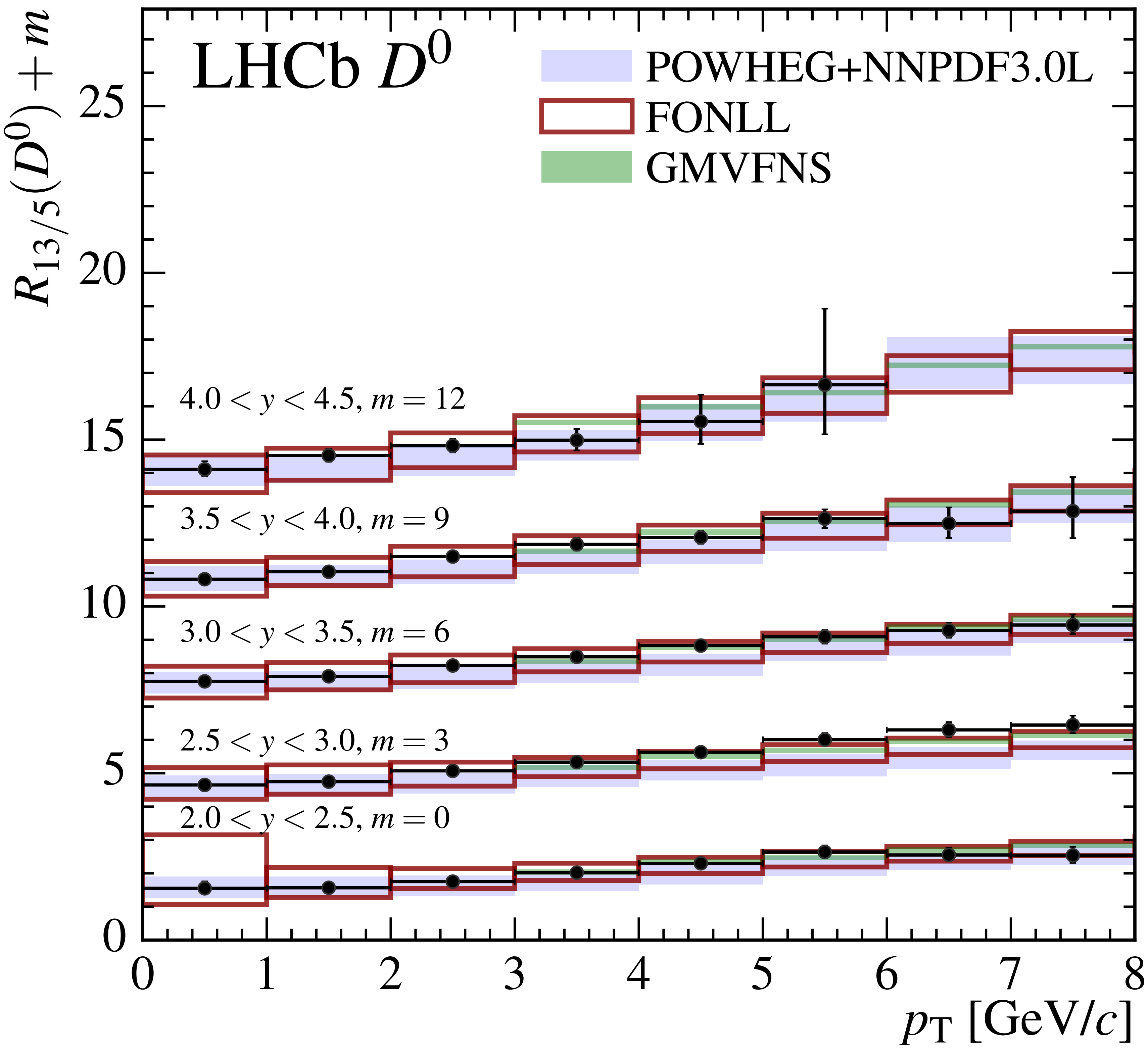
pT cut dependence



How do the data actually look?



How do the data actually look?



How do the data actually look?