Forward heavy flavour production

Rhorry Gauld

Heavy Flavour Production at the LHC
IPPP - 20/04/15

Science & Technology Facilities Council

Durham University

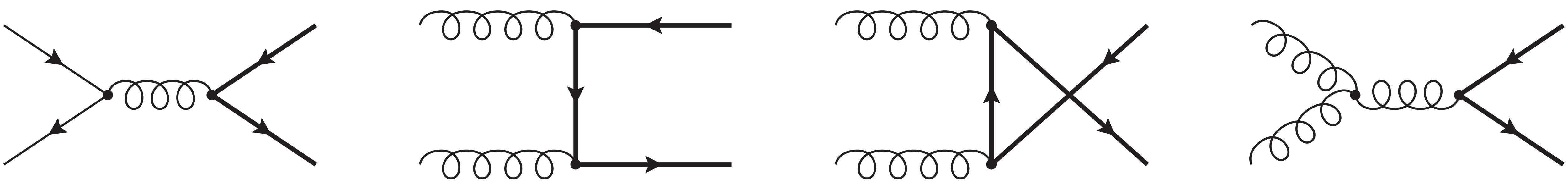
Focus is on $pp \to D + X$

- **Motivations:** benefits of forward measurements
- **Observables:** data and theoretical description
- **Results 1:** 7 TeV data and PDF reweighting
- **Results 2:** consistency with 13 TeV data

Motivations:

benefits of forward heavy flavour measurements

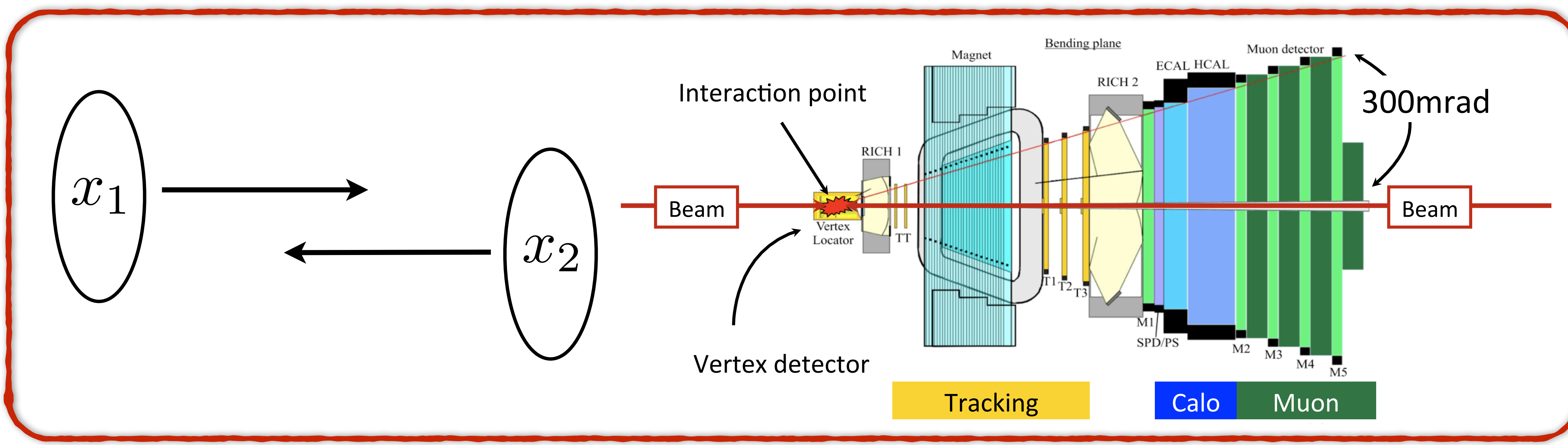
Why study forward $pp \to Q_3\bar{Q}_4 + X$?



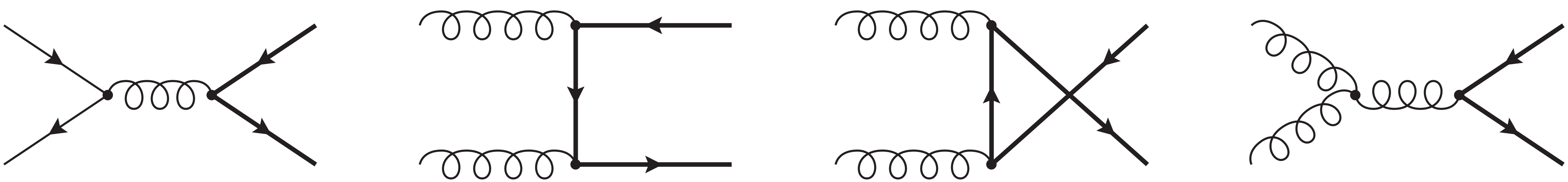
x_i : fraction of momentum
y_j : rapidity
$\sqrt{\hat{s}}$: partonic COM
m_T : transverse mass

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

LHCb acceptance: $y_D \in [2.0, 4.5]$



Why study forward $pp \to Q_3\bar{Q}_4 + X$?



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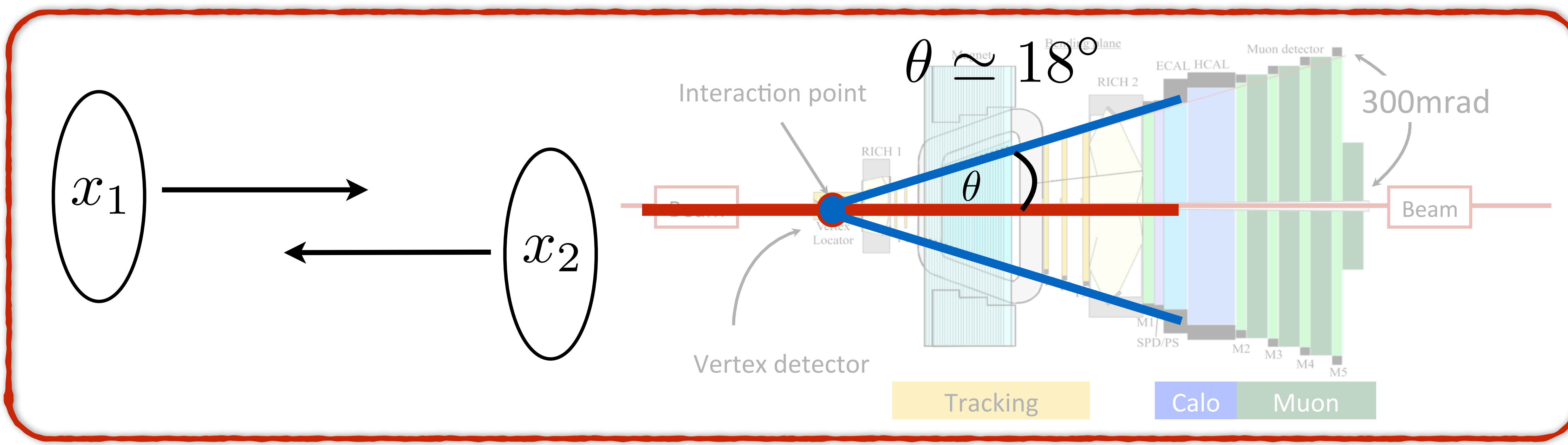


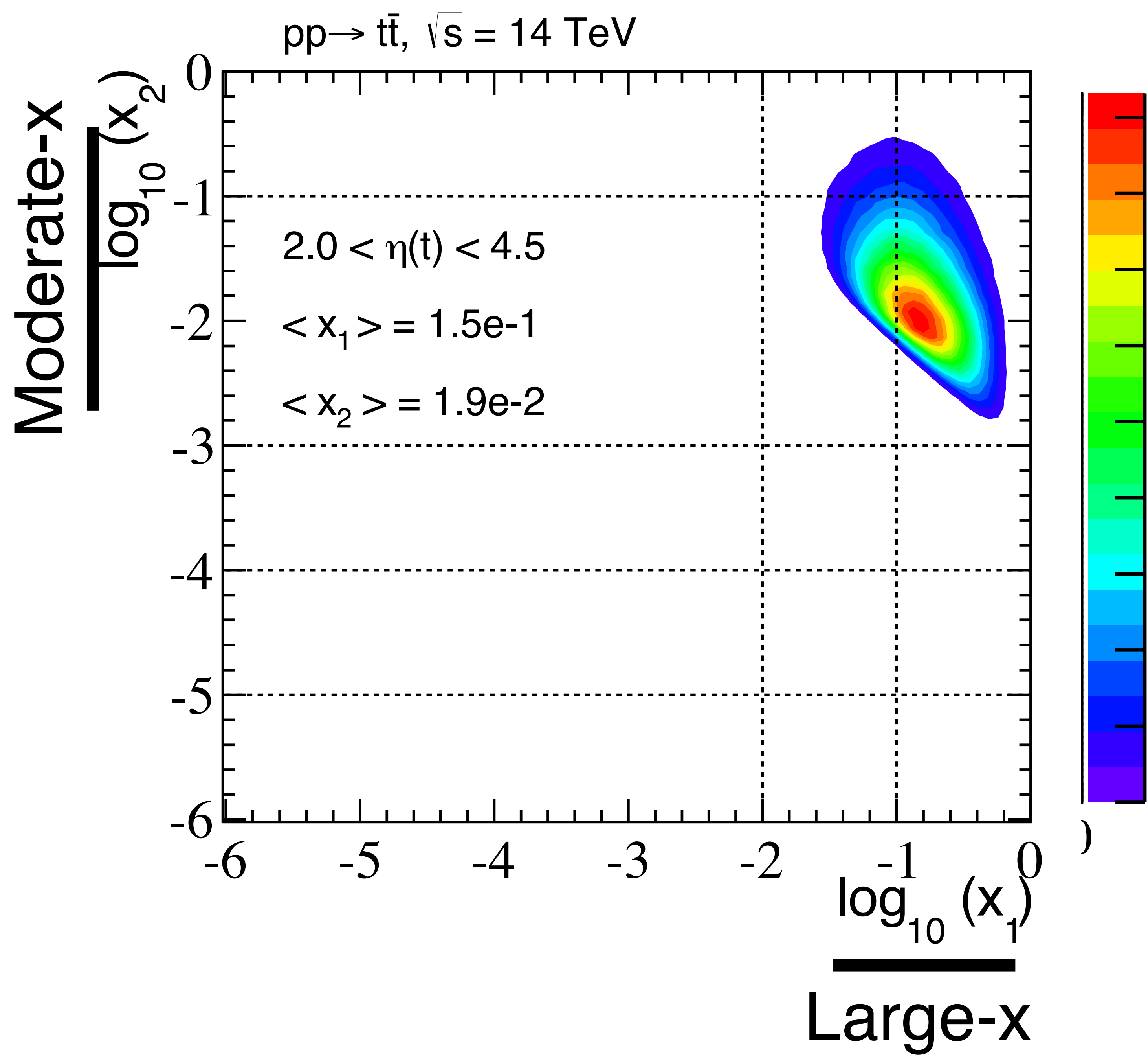
$pp \to t\bar{t}$

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

Require one of the heavy quarks within LHCb acceptance:

$$2.5 < \eta(t) < 4.5$$

$$m_t \simeq 173.0 \text{ GeV}$$



Forward top quark production discussed in:
hep-ex: LHCb observation - arXiv:1506.00903, see Will's talk (last one today)
hep-ph: Kagan et al. - arXiv:1103.3747, RG - arXiv:1311.1810, arXiv:1409.8631

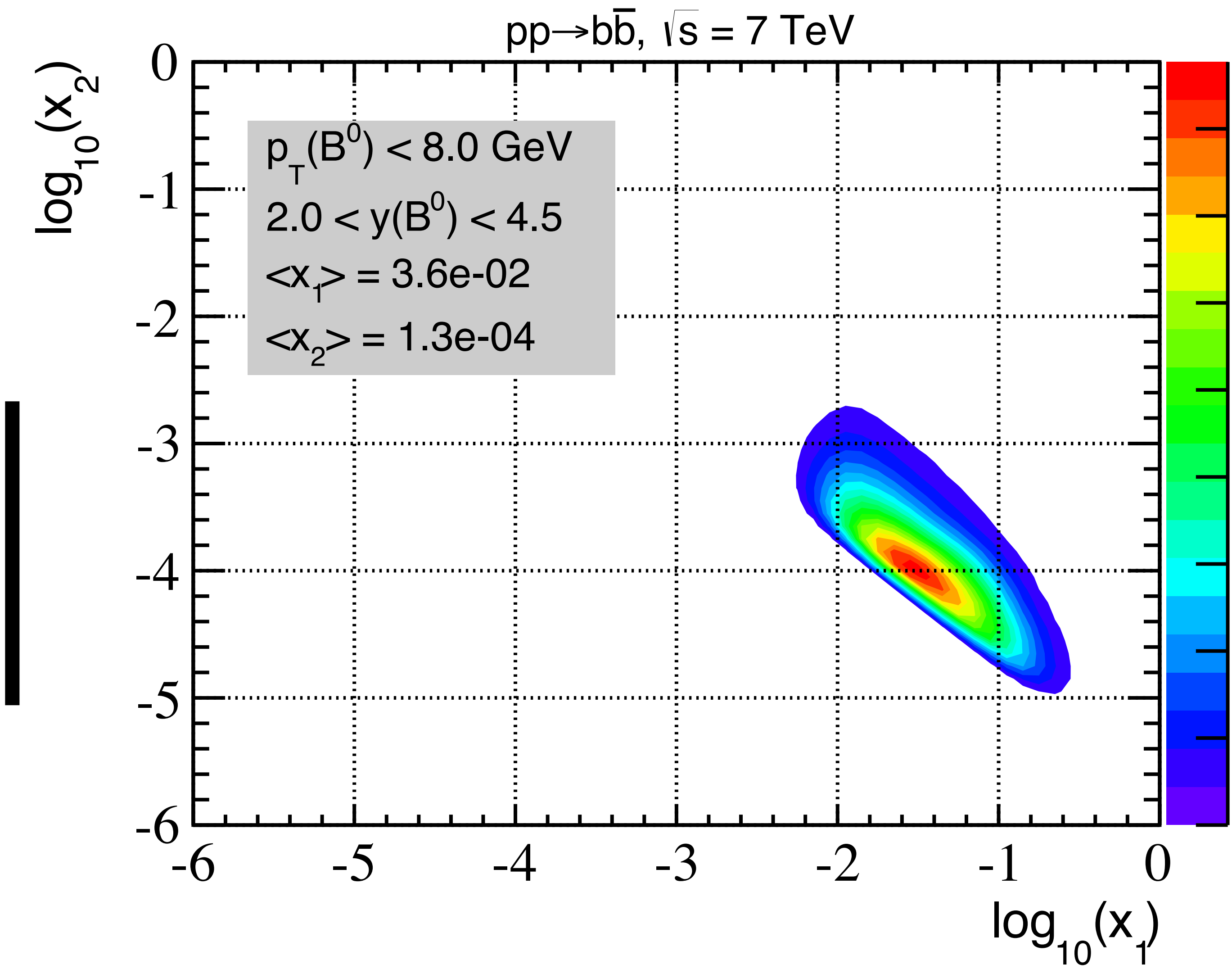
$$x_{1,(2)} = \frac{m_T}{\sqrt{\hat{s}}}(e^{(-)y_3} + e^{(-)y_4})$$

$pp \rightarrow b\bar{b}$

Require one of the B hadrons within LHCb acceptance:

$$2.0 < y(B) < 4.5$$
$$0 < p_T(B)[\text{GeV}] < 8$$
$$m_b = 4.75 \text{ GeV}$$

Low-x



Moderate-x

Forward beauty quark production discussed in:

hep-ex: LHCb B measurement (7 TeV) - arXiv:1306.3663

hep-ph: Cacciari et al. - arXiv 1205.6344, PROSA - arXiv:1503.04581

$$pp \to b\bar{b}$$

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

Require one of the B hadrons within LHCb acceptance:

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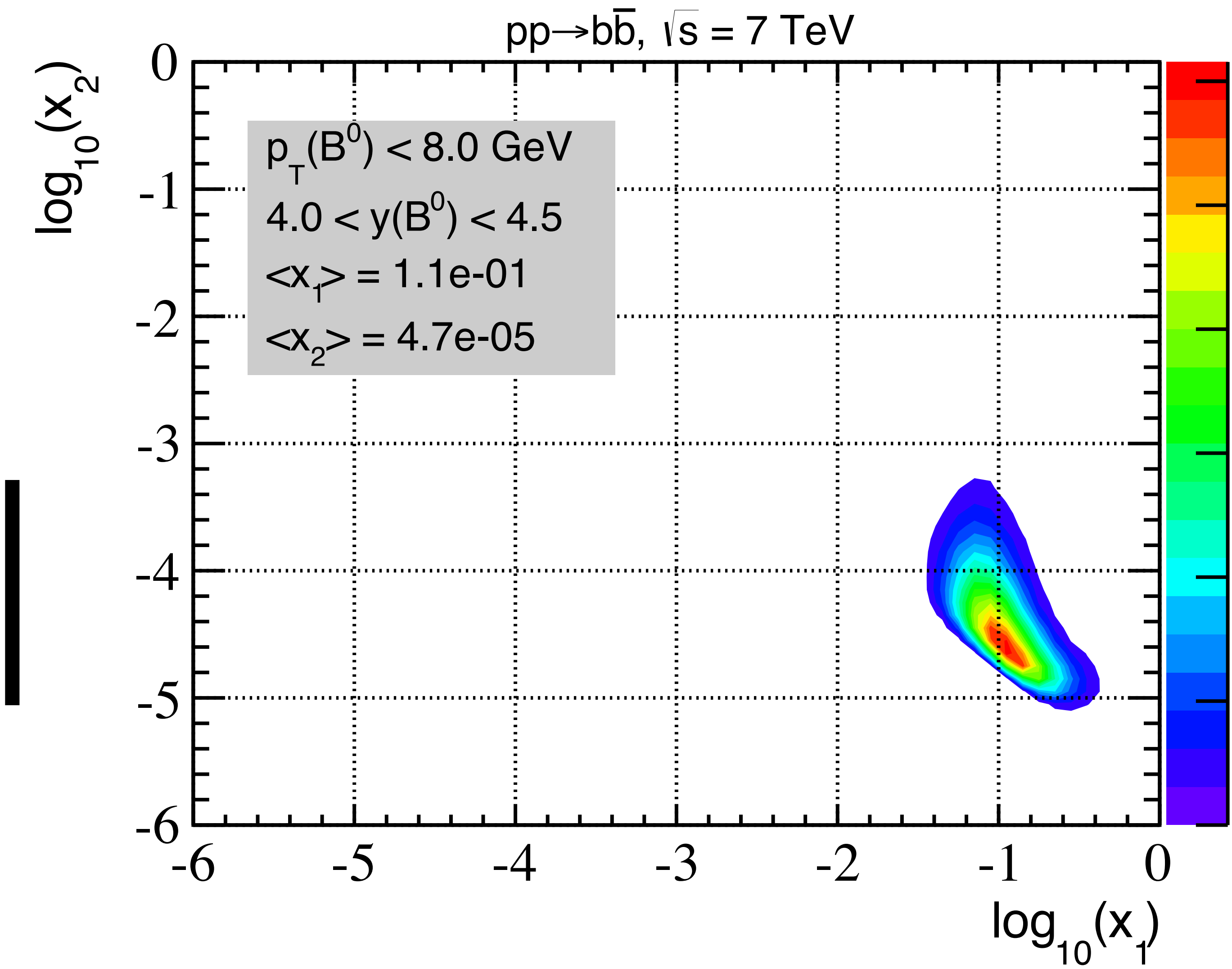
$$m_b = 4.75\ \mathrm{GeV}$$

Low-x



Moderate/Large-x

Forward beauty quark production discussed in:

hep-ex: LHCb B measurement (7 TeV) - arXiv:1306.3663

hep-ph: Cacciari et al. - arXiv 1205.6344, PROSA - arXiv:1503.04581

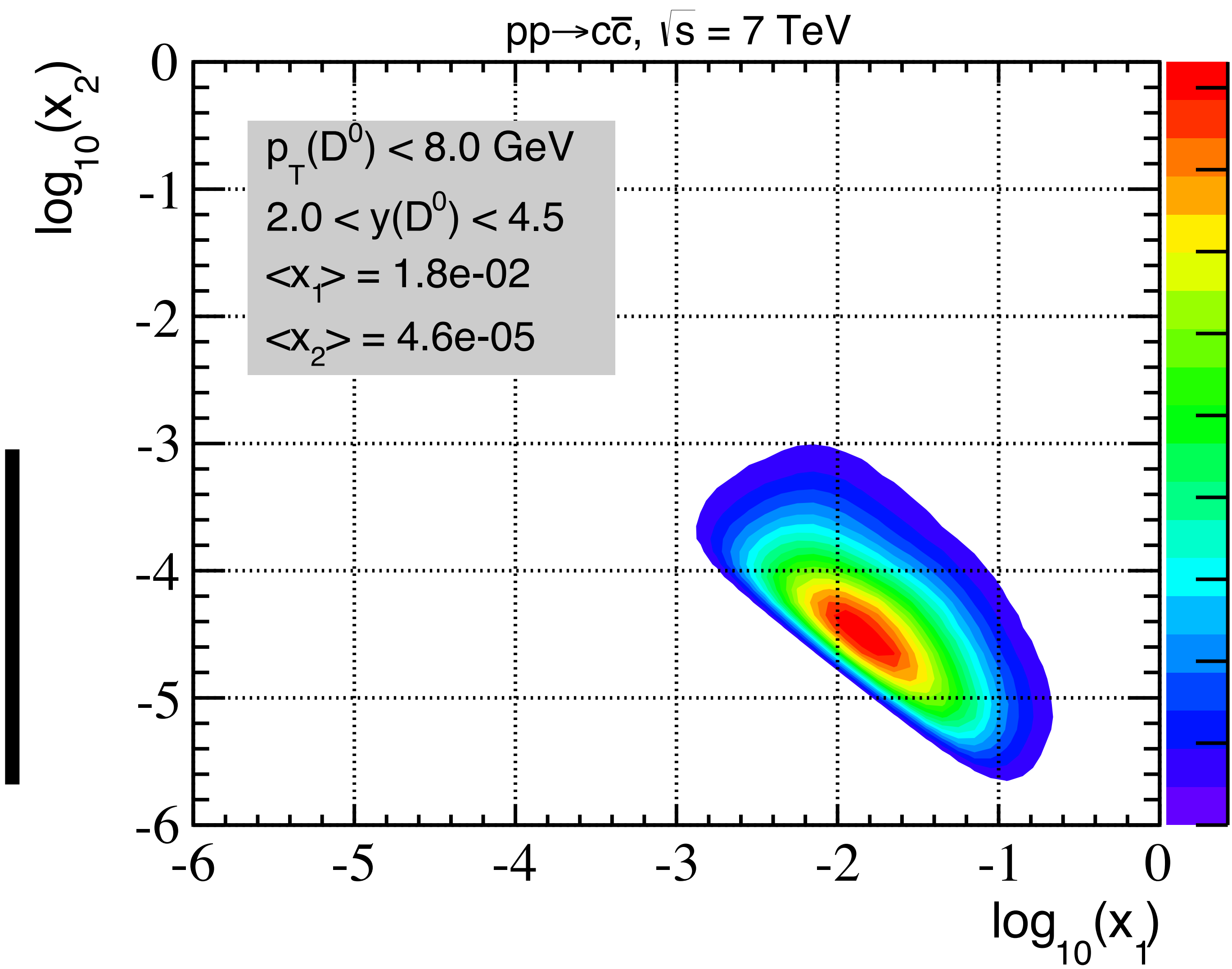
$$pp \rightarrow c\bar{c}$$

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

Require one of the D hadrons within LHCb acceptance:

$$2.0 < y(D) < 4.5$$
$$0 < p_T(D)[\text{GeV}] < 8$$
$$m_c = 1.5 \text{ GeV}$$

Low-x



Moderate-x

Forward charm quark production discussed in:
hep-ex: LHCb measurement (7/13 TeV) - arXiv:1302.2864 / 1510.01707
hep-ph: Kniehl et al. - arXiv:1202.0439, Cacciari et al. - arXiv 1205.6344, PROSA - arXiv:1503.04581, Gauld et al. - arXiv 1506.08025, Cacciari et al. - arXiv:1507.06197

$$pp \to c\bar{c}$$

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

Require one of the D hadrons within LHCb acceptance:

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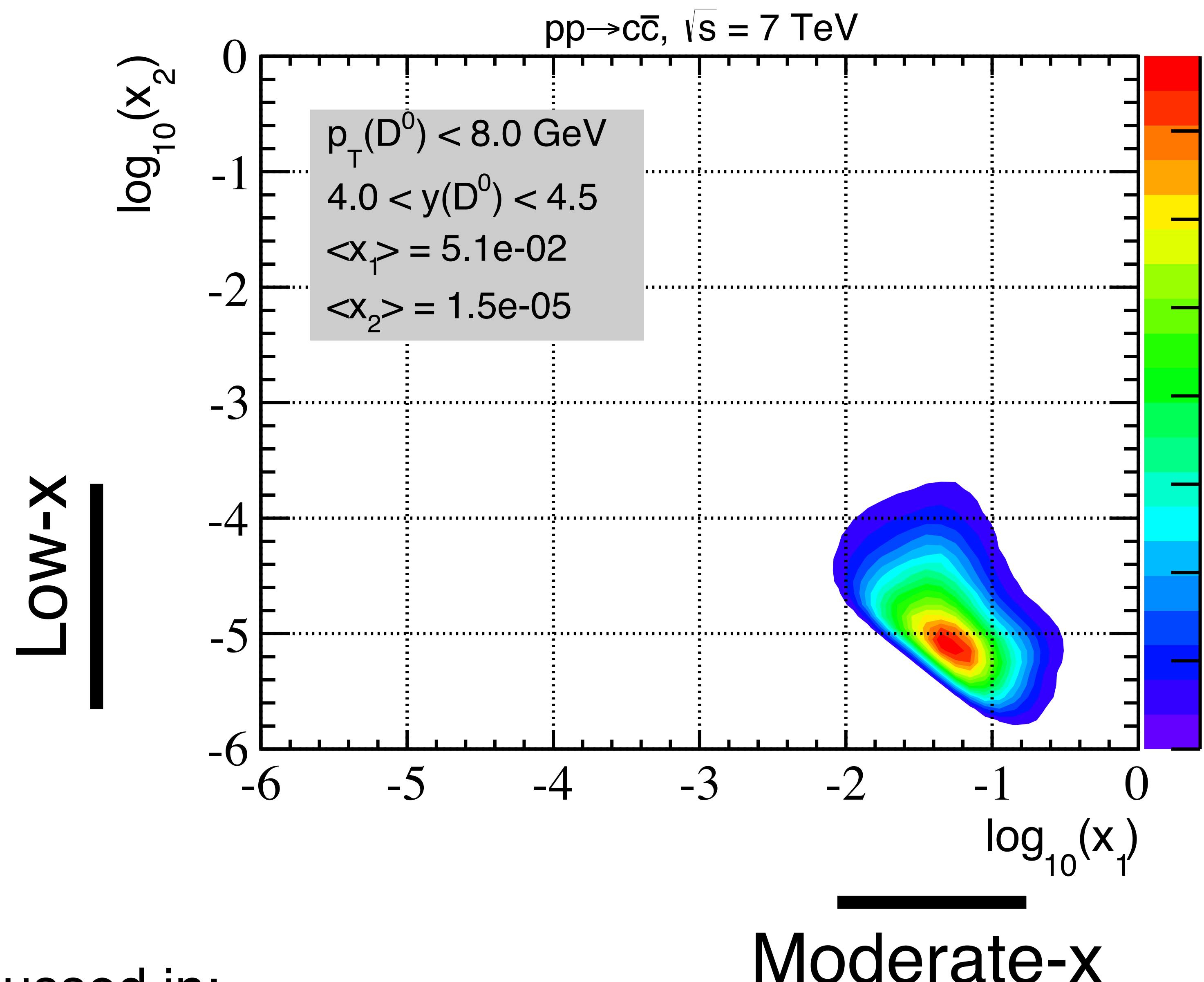

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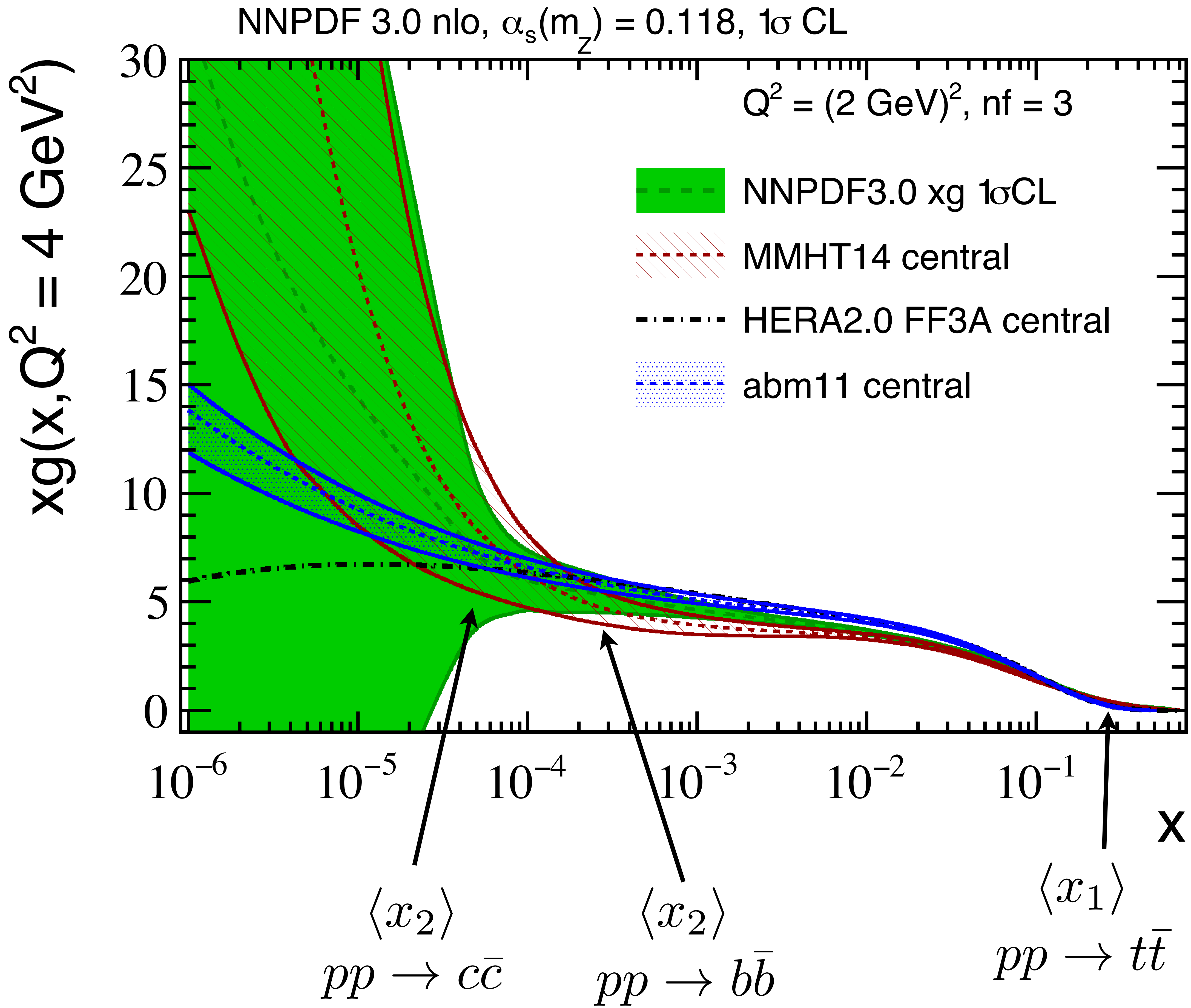
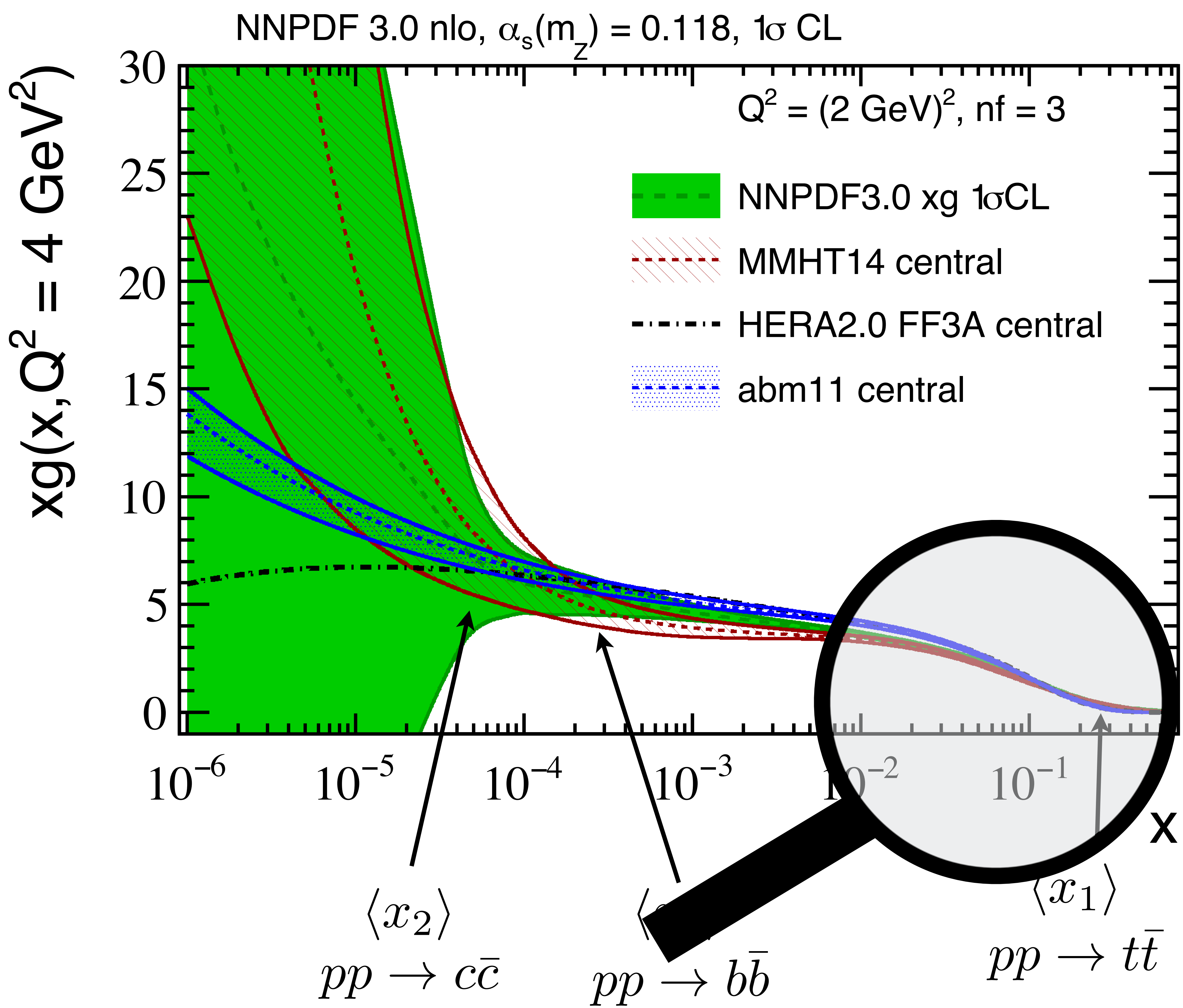

NNPDF 3.0 nlo, $\alpha_s(m_Z)$ = 0.118, 1σ CL
Q^2 = (2 GeV)^2, nf = 3
NNPDF3.0 xg 1σCL
MMHT14 central
HERA2.0 FF3A central
abm11 central
$xg(x,Q^2 = 4\ \mathrm{GeV}^2)$
x
$\langle x_2 \rangle$
$pp \to c\bar{c}$
$\langle x_2 \rangle$
$pp \to b\bar{b}$
$\langle x_1 \rangle$
$pp \to t\bar{t}$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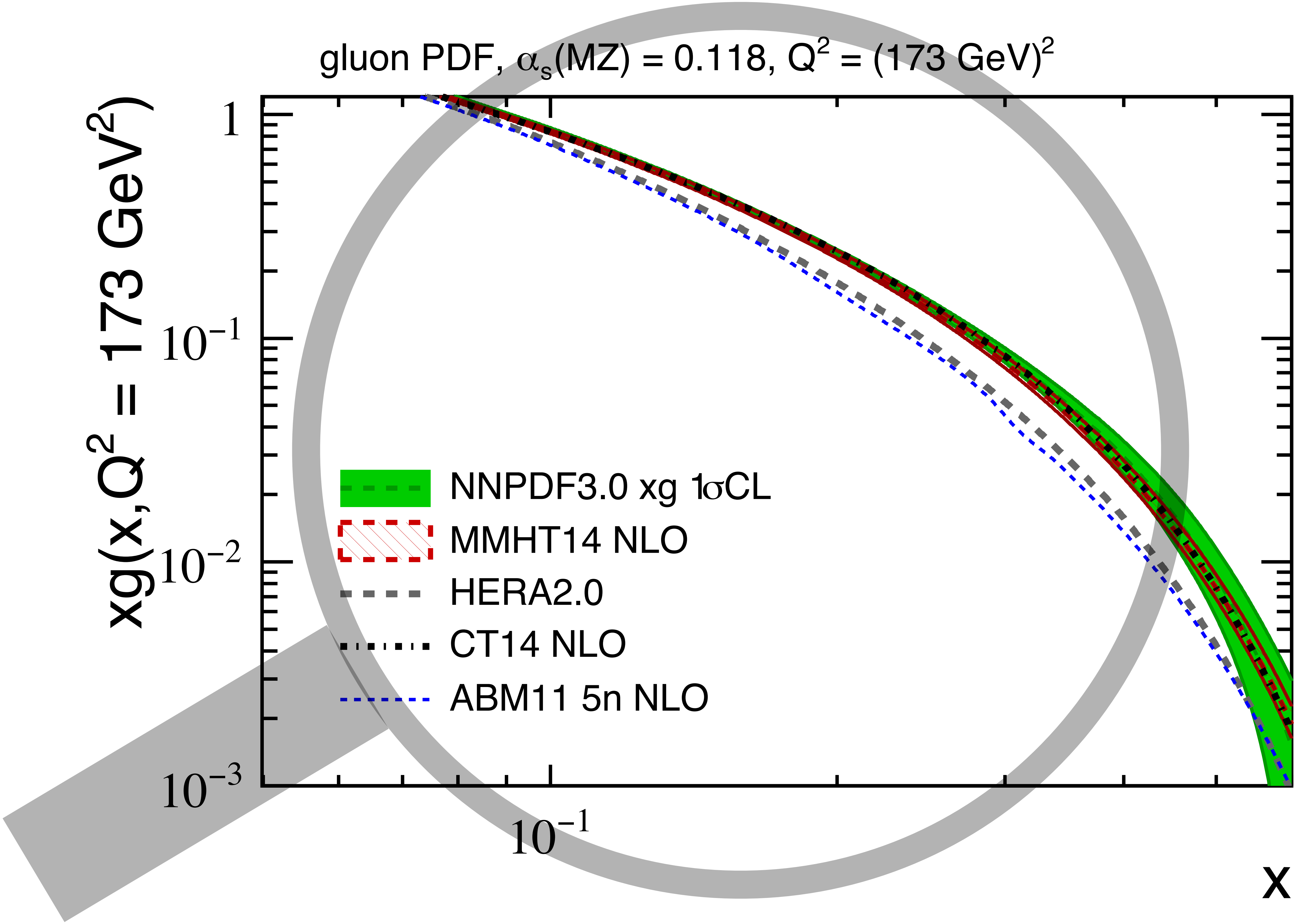
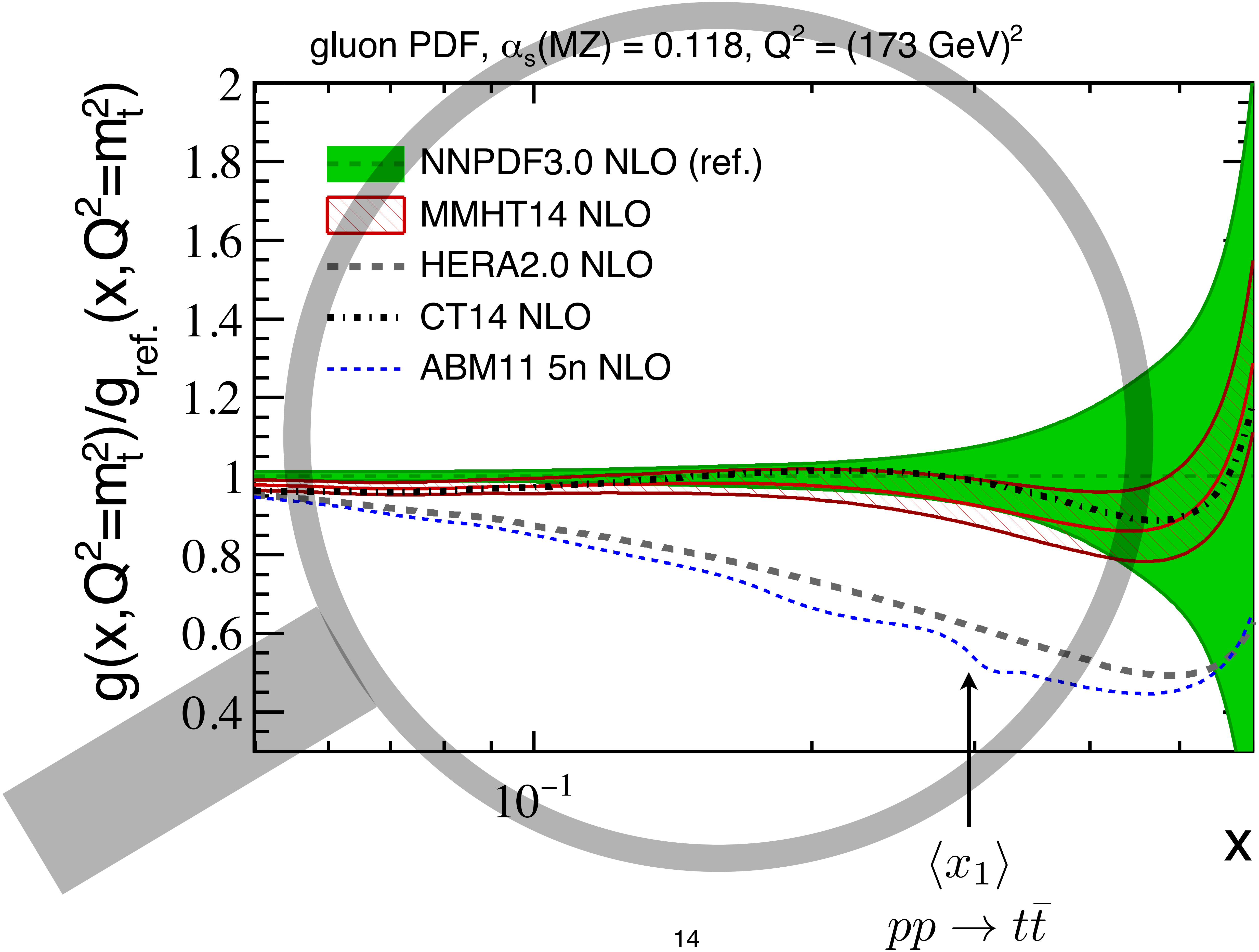
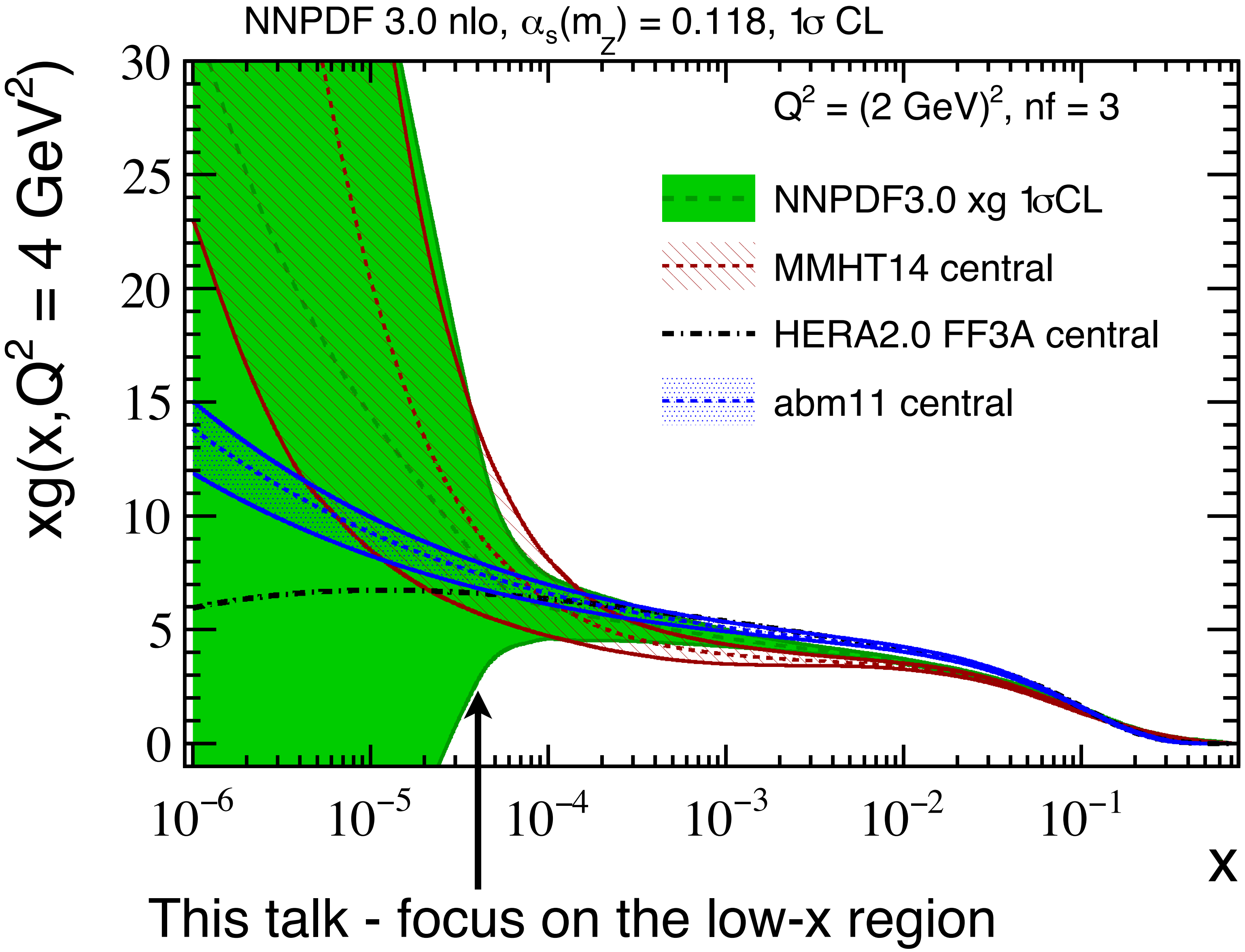

gluon PDF, α_s(MZ) = 0.118, Q^2 = (173 GeV)^2
$xg(x,Q^2 = 173\ \text{GeV}^2)$
1
10^{-1}
10^{-2}
10^{-3}
10^{-1}
x
NNPDF3.0 xg 1σCL
MMHT14 NLO
HERA2.0
CT14 NLO
ABM11 5n NLO



gluon PDF, α_s(MZ) = 0.118, Q^2 = (173 GeV)^2
$g(x,Q^2=m_t^2)/g_{ref.}(x,Q^2=m_t^2)$
NNPDF3.0 NLO (ref.)
MMHT14 NLO
HERA2.0 NLO
CT14 NLO
ABM11 5n NLO
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
10^{-1}
x
$\langle x_1 \rangle$
$pp \to t\bar{t}$



1) Improve understanding of the structure of the low-x gluon PDF
2) Study the application of pQCD to forward D-hadron production (useful to have predictive rates for D/B for rare decays etc.)
3) Important input for modelling of soft QCD at the LHC
4) Input for neutrino astronomy - the `prompt neutrino flux’

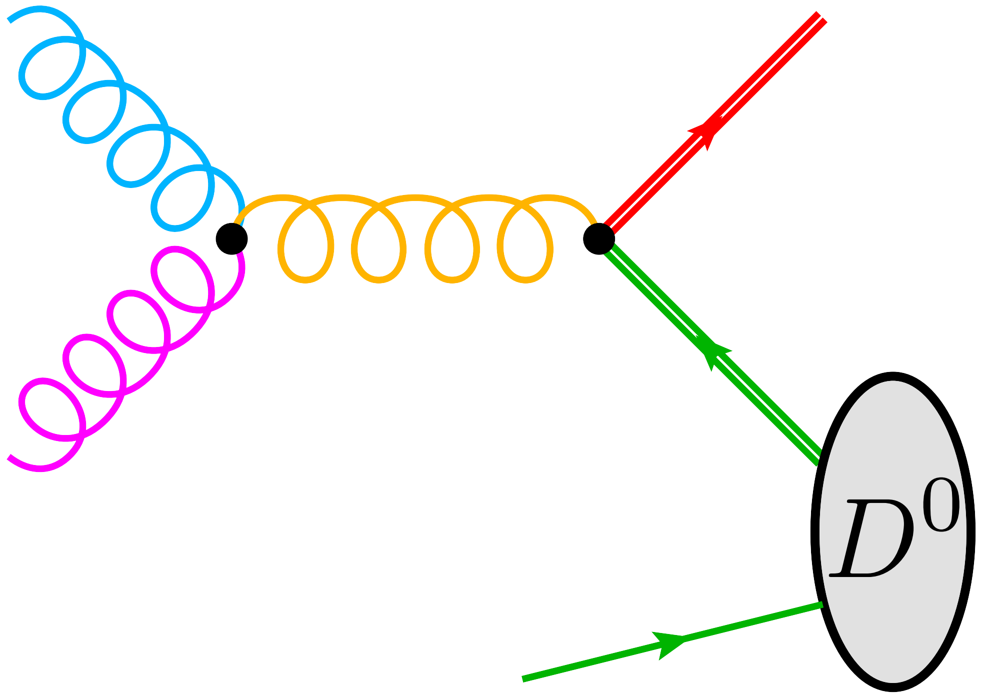
Observables:

data and theoretical description

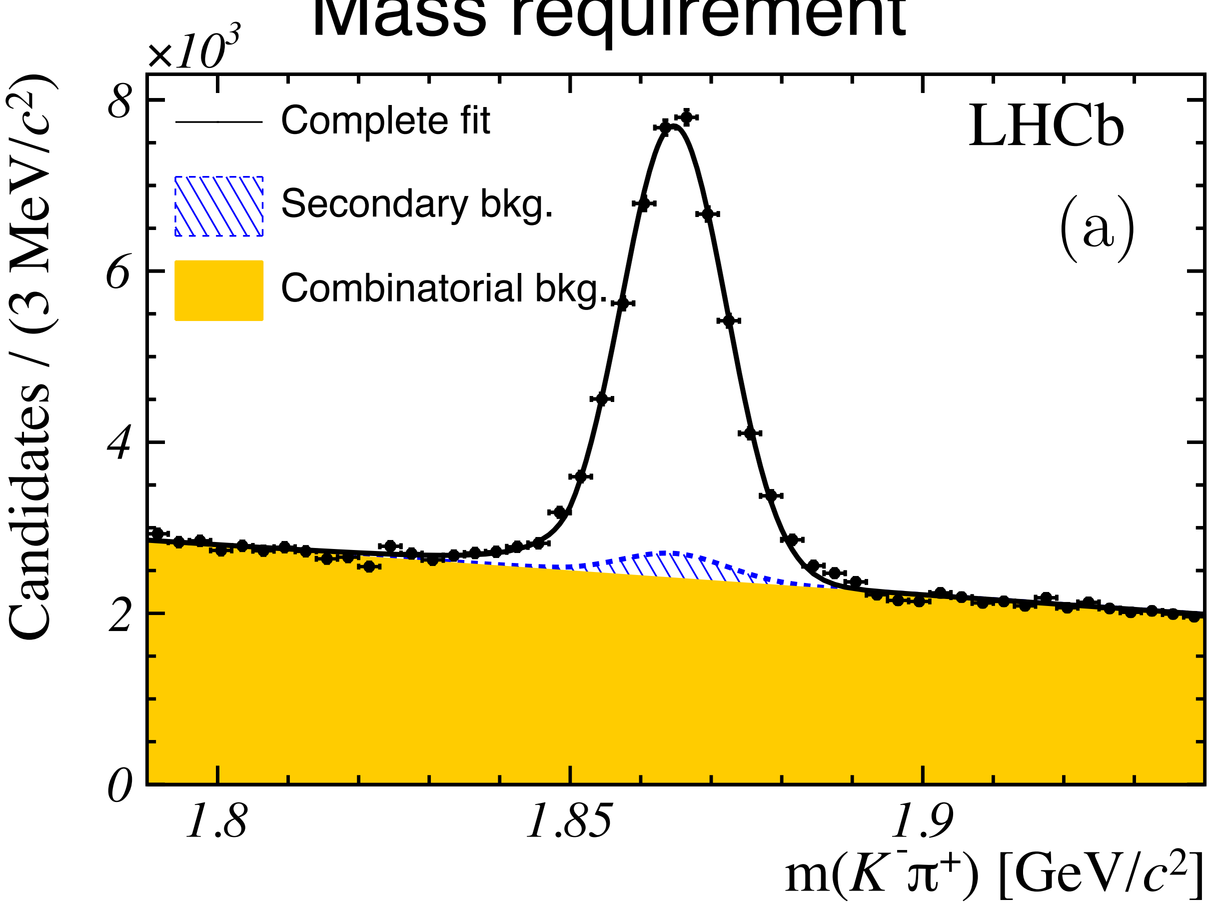
(I’m focussing on charm)

Prompt D measurement at LHCb

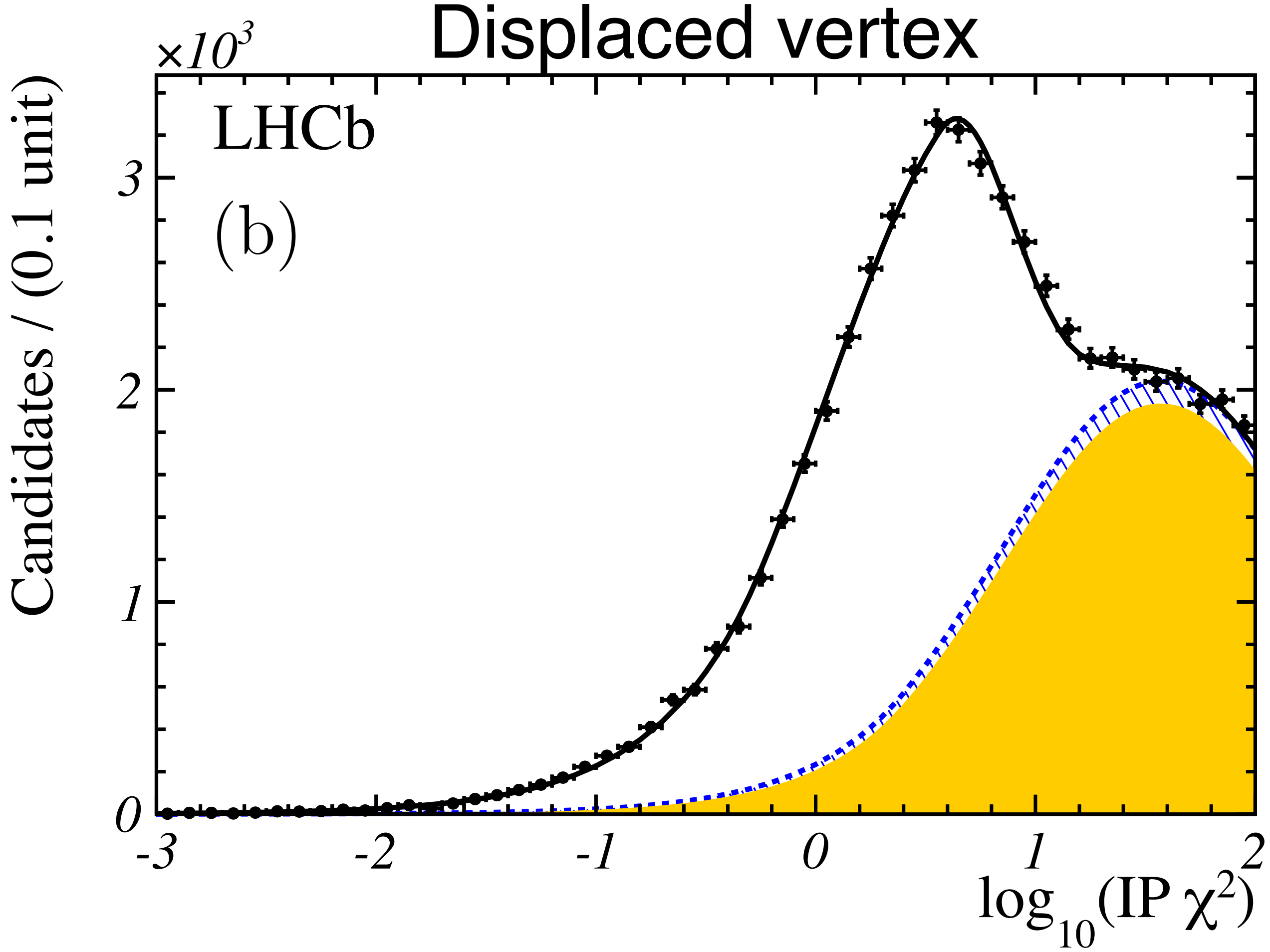
$$pp \to D + X$$
$$2.0 < y_D < 4.5$$
$$p_T^D < 8.0 \text{ GeV}$$



Mass requirement



Displaced vertex



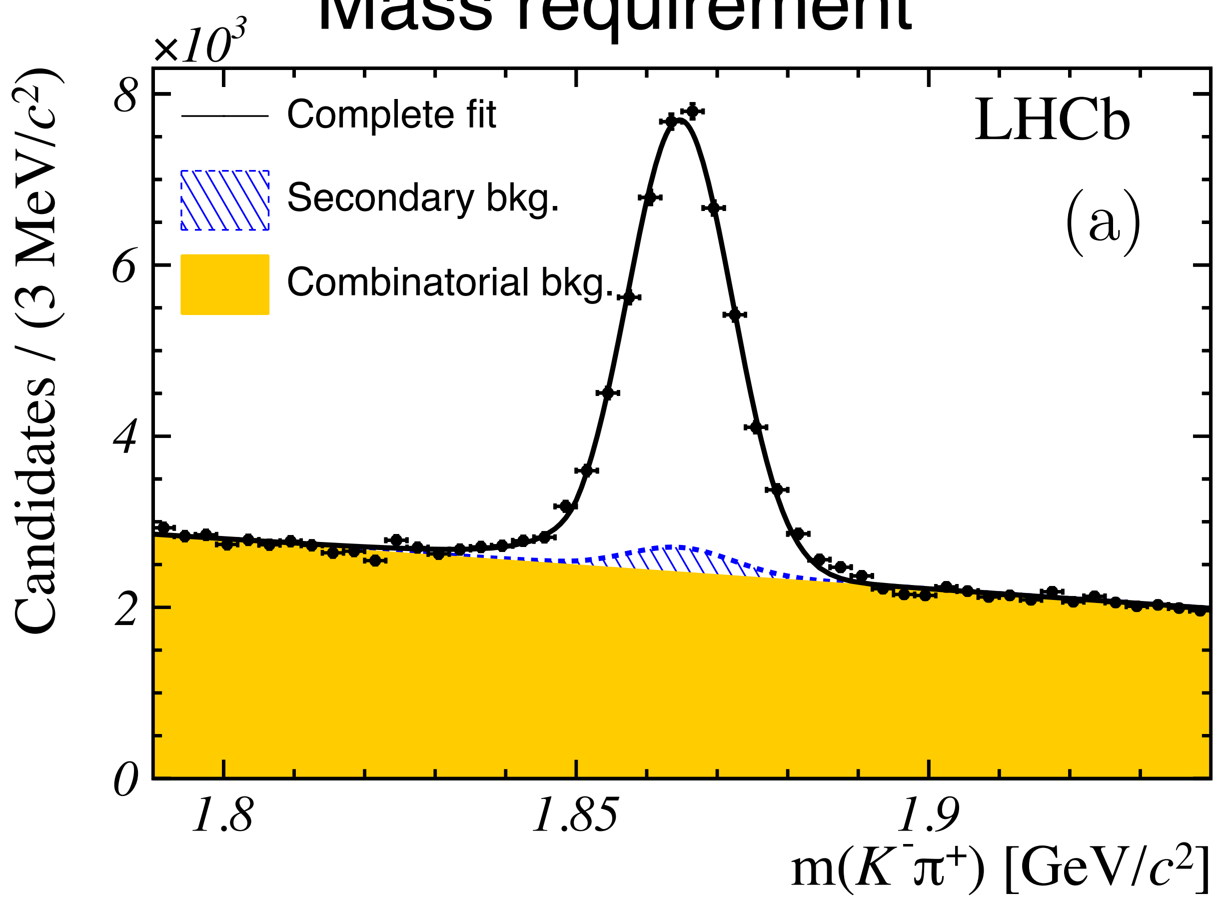
Prompt D measurement at LHCb

$$pp \to D + X$$
$$2.0 < y_D < 4.5$$
$$p_T^D < 8.0 \text{ GeV}$$

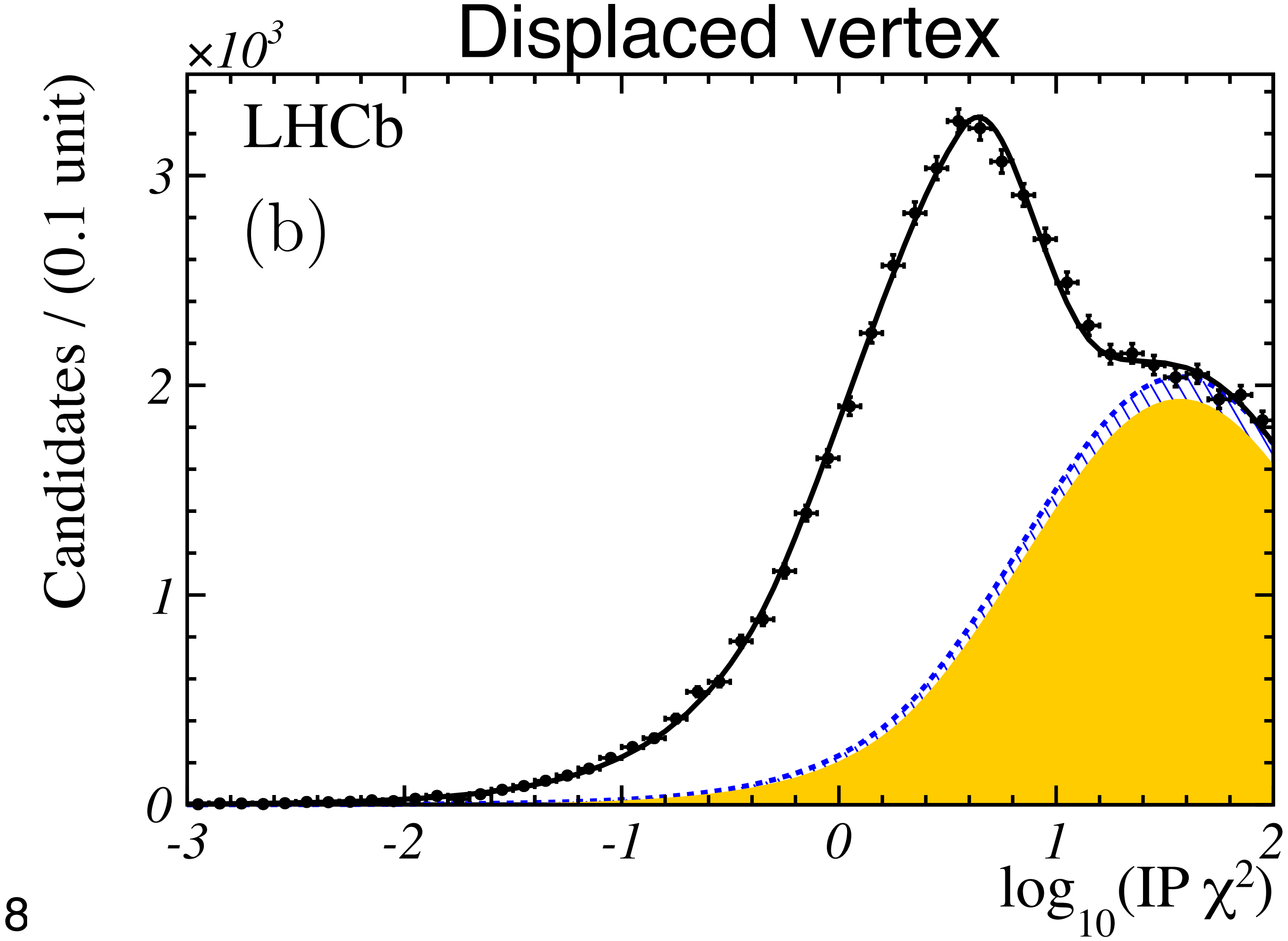
$$\frac{d^2\sigma^D(p_T, y)}{dp_T\, dy}$$

Measurement performed double differentially in: p_T, y

Mass requirement



Displaced vertex



Theoretical description

Differential D-hadron production

$$p_T^D < 8.0 \text{ GeV}$$
$$2.0 < y^D < 4.5$$

Public tools (NLO QCD accuracy):
HVQMNR (Mangano,Nason,Ridolfi) - Fixed-Order

FONLL (Cacciari, et al.) - Fixed-Order + $\mathcal{O}\left(\alpha_s^3(\alpha_s \log\left[p_T/m_Q\right])^k\right)$

NLO+PS - POWHEG (Frixione,Nason,Ridolfi), MC@NLO (Frixione, Nason, Webber),

HERWIG, SHERPA, aMC@NLO

Fixed-Order calculations:
1) nf = 3 (Charm massive), Input PDFs nf = 3 and corresponding PDF alphas running

2) quark mass = pole mass - Generally converted from accurate MSbar extractions

$$m_c^{\text{pole}} = 1.5 \pm 0.2 \text{ GeV}$$

Alternatively:
1) Use nf = 4, nf = 5 VFNS Input PDFs and corresponding PDF alphas running

$$\delta\alpha_s = -\hat{\sigma}_{ij}^{(0)} \frac{2T_F \alpha_s(\mu_R^2)}{3\pi} \text{Log}\left[\frac{\mu_R^2}{m_Q^2}\right]$$

$$\delta\text{PDF} = +\hat{\sigma}_{gg}^{(0)} \frac{2T_F \alpha_s(\mu_R^2)}{3\pi} \text{Log}\left[\frac{\mu_F^2}{m_Q^2}\right]$$

Theoretical description

What I'll show:
a) Fixed-Order predictions (using FONLL framework, thanks to Matteo Cacciari)

b) POWHEG+Pythia8 (** Monash Tune, turning off nf=4,5 splittings in shower **)

Input PDF set: NNPDF3.0 NLO as(mz) = 0.118 VFNS (100/1000 replica set)

Fragmentation fractions: taken from LHCb measurement arXiv:1302.2864

$$f(c \to D^{\pm}) = 0.246\,, \quad f(c \to D^0) = 0.565\,, \quad f(c \to D_s) = 0.080\,, \quad f(c \to D^*) = 0.224$$

Scale uncertainties:

$$\mu_{\rm cen.} = \sqrt{m_c^2 + p_T^2}\,, \qquad \mu_{\rm alt.} = \sqrt{4m_c^2 + p_T^2}$$

Factorisation and Renormalisation scales varied independently by factor of two

Observables:

$$\frac{d^2\sigma^D}{dp_T\,dy}$$

$$\frac{d^2\sigma^D}{dp_T\,dy} \Big/ \frac{d^2\sigma^D_{\rm ref}}{dp_T\,dy}$$

Normalised 7 TeV

$$\frac{d^2\sigma^D_{13}}{dp_T\,dy} \Big/ \frac{d^2\sigma^D_{7}}{dp_T\,dy}$$

Ratio 13 / 7 TeV

Theoretical description

$$\frac{d^2\sigma^D}{dp_T\, dy}$$

Subject to strong scale uncertainties:

$$\alpha_s(Q = 1.275\mathrm{GeV}) \simeq 0.37$$

$$\frac{d^2\sigma^D}{dp_T\, dy} \Big/ \frac{d^2\sigma^D_{\mathrm{ref}}}{dp_T\, dy}$$

Normalised 7 TeV

Logarithmic dependence on regularisation scale partially cancels (provided bin kinematics are similar)

Suitable if 13/7 TeV not available

$$\frac{d^2\sigma^D_{13}}{dp_T\, dy} \Big/ \frac{d^2\sigma^D_{7}}{dp_T\, dy}$$

Ratio 13 / 7 TeV

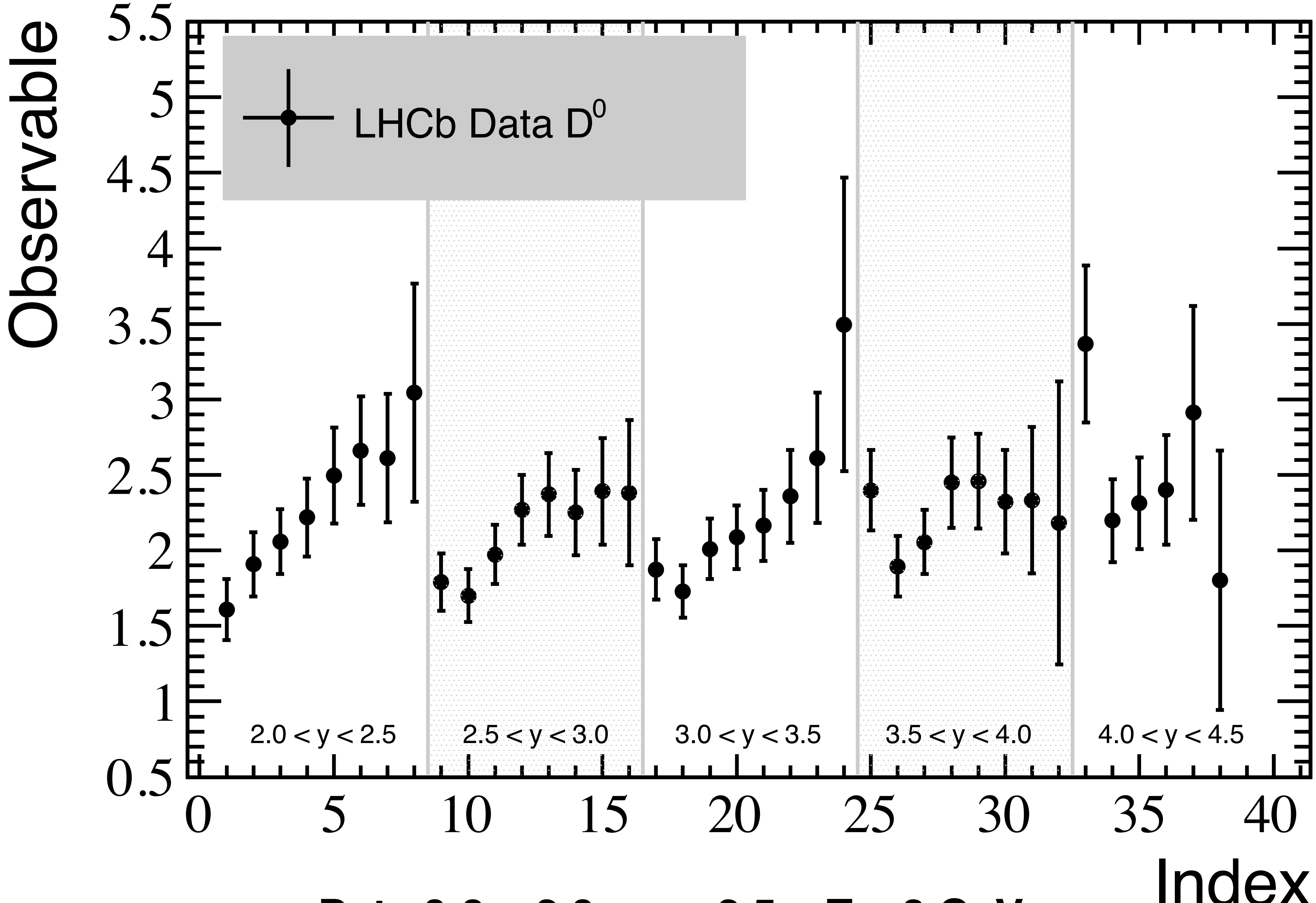
Logarithmic dependence on regularisation scale cancels (independent of beam energy)

see discussion: 1206.3557 1507.06197

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

Results 1:

7 TeV data and PDF reweighting

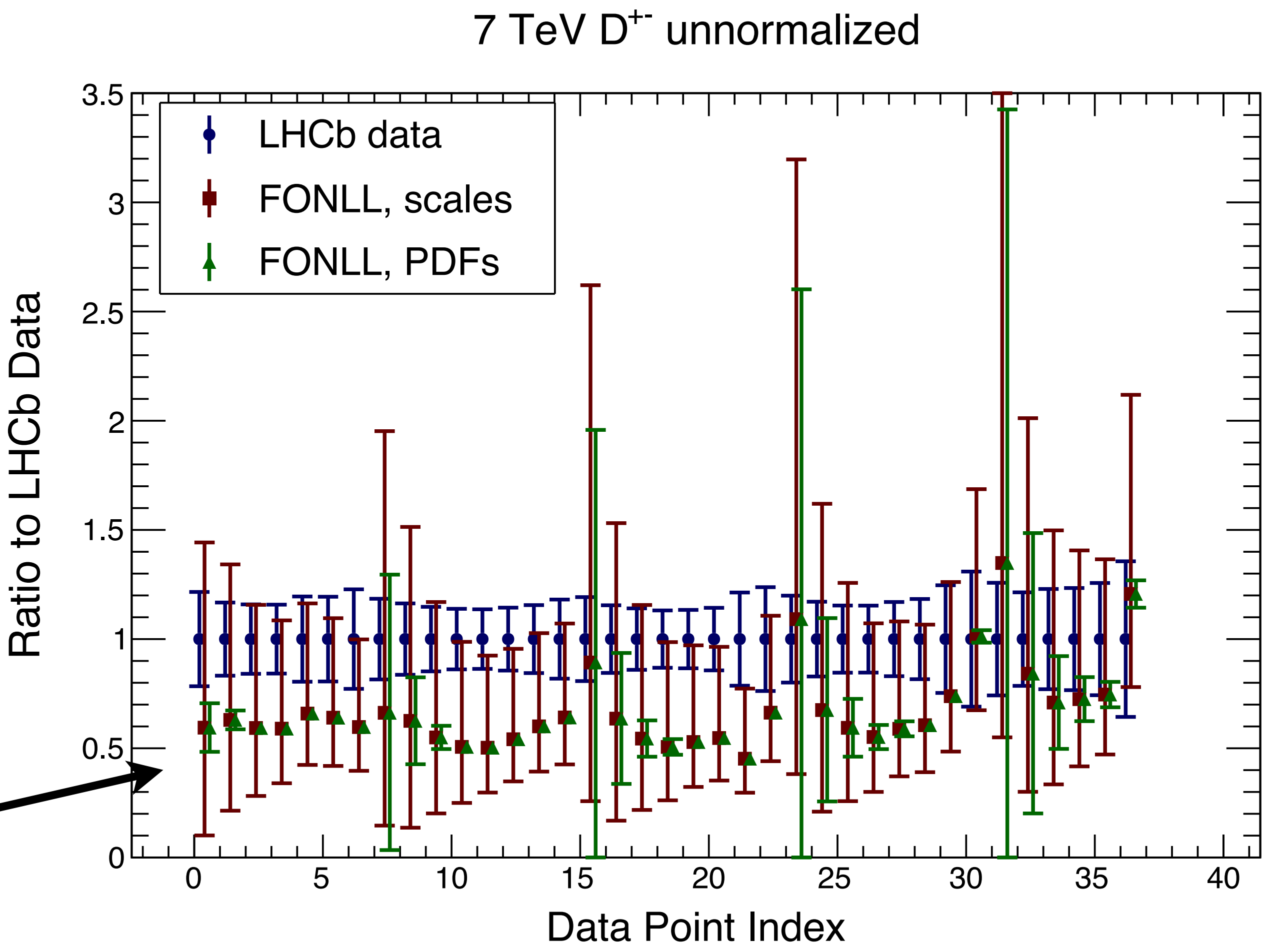


Data 0-8 : 2.0 < y < 2.5, pT < 8 GeV
Data 9-16: 2.5 < y < 3.0, pT < 8 GeV

$$\frac{d^2\sigma^D}{dp_T\, dy}$$

Data 0-8 : 2.0 < y < 2.5, pT < 8 GeV
Data 9-16: 2.5 < y < 3.0, pT < 8 GeV
….
Showing Theory/Data for observable

Theory on low-side

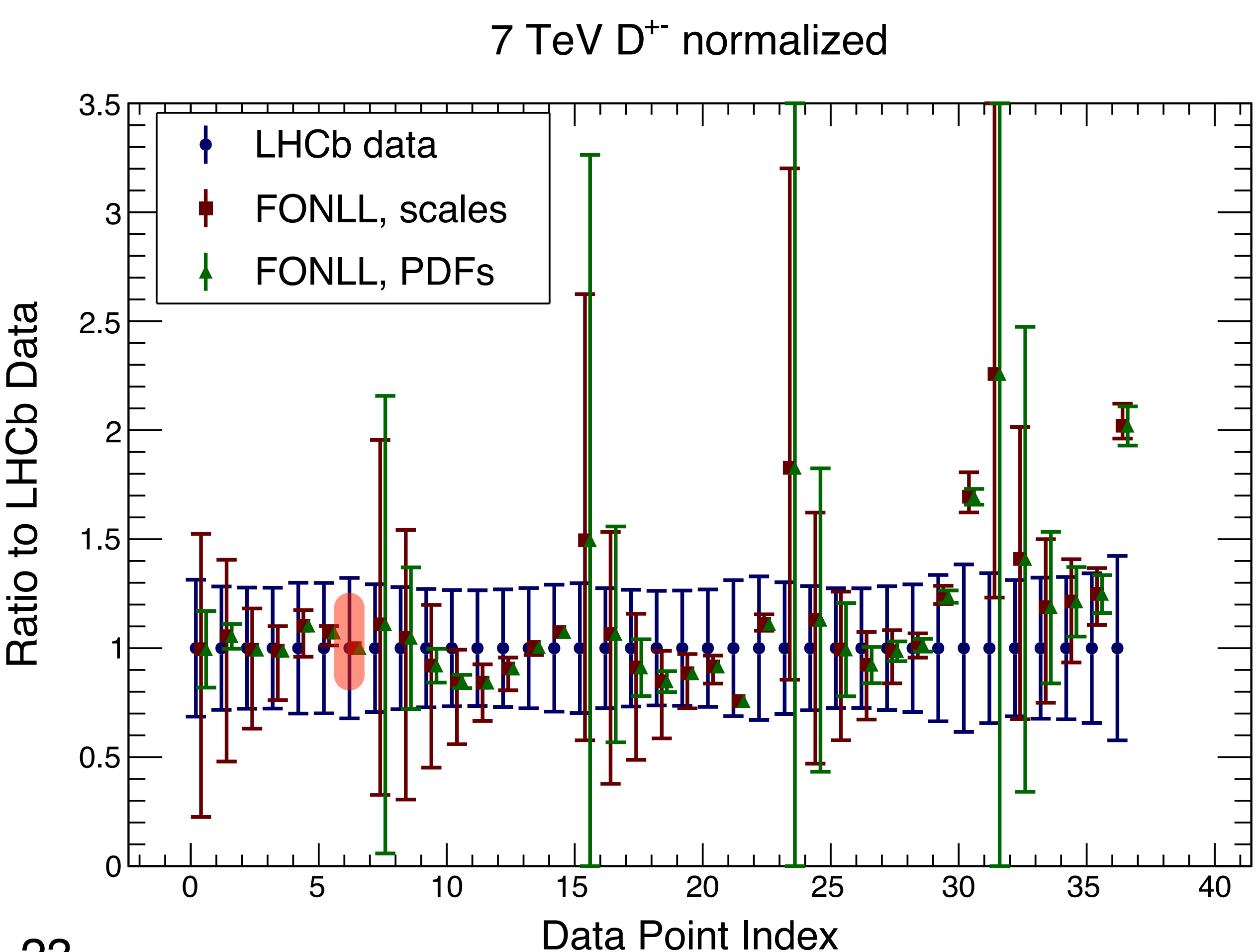


$$\frac{d^2\sigma^D}{dp_T\, dy} \Big/ \frac{d^2\sigma^D_{\rm ref}}{dp_T\, dy}$$

Normalised to Data 8

Data 0-8 : 2.0 < y < 2.5, pT < 8 GeV
Data 9-16: 2.5 < y < 3.0, pT < 8 GeV
….
Description already rather good!

$$\chi^2/N_{\rm dat}(D^0) = 39/37$$

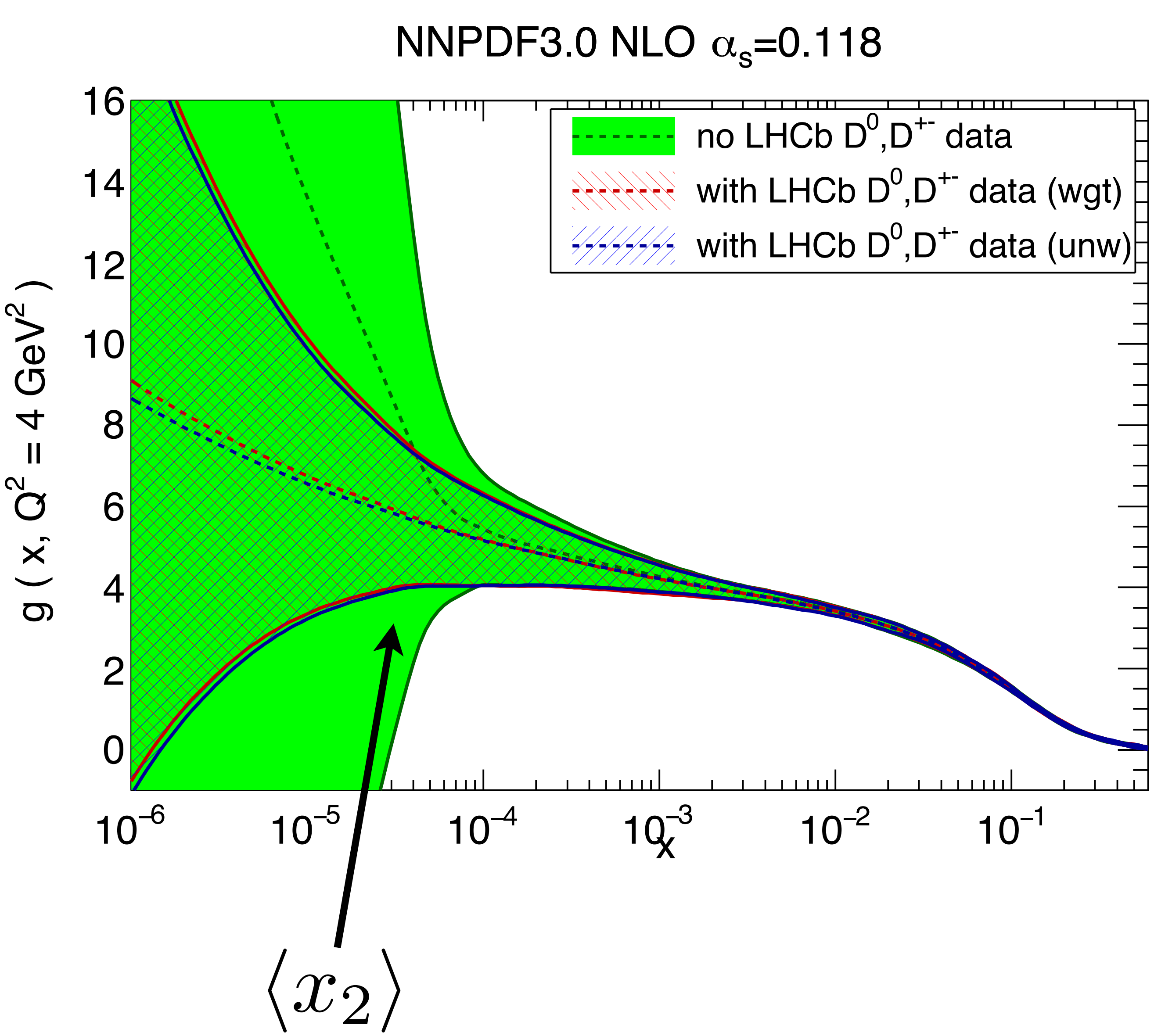


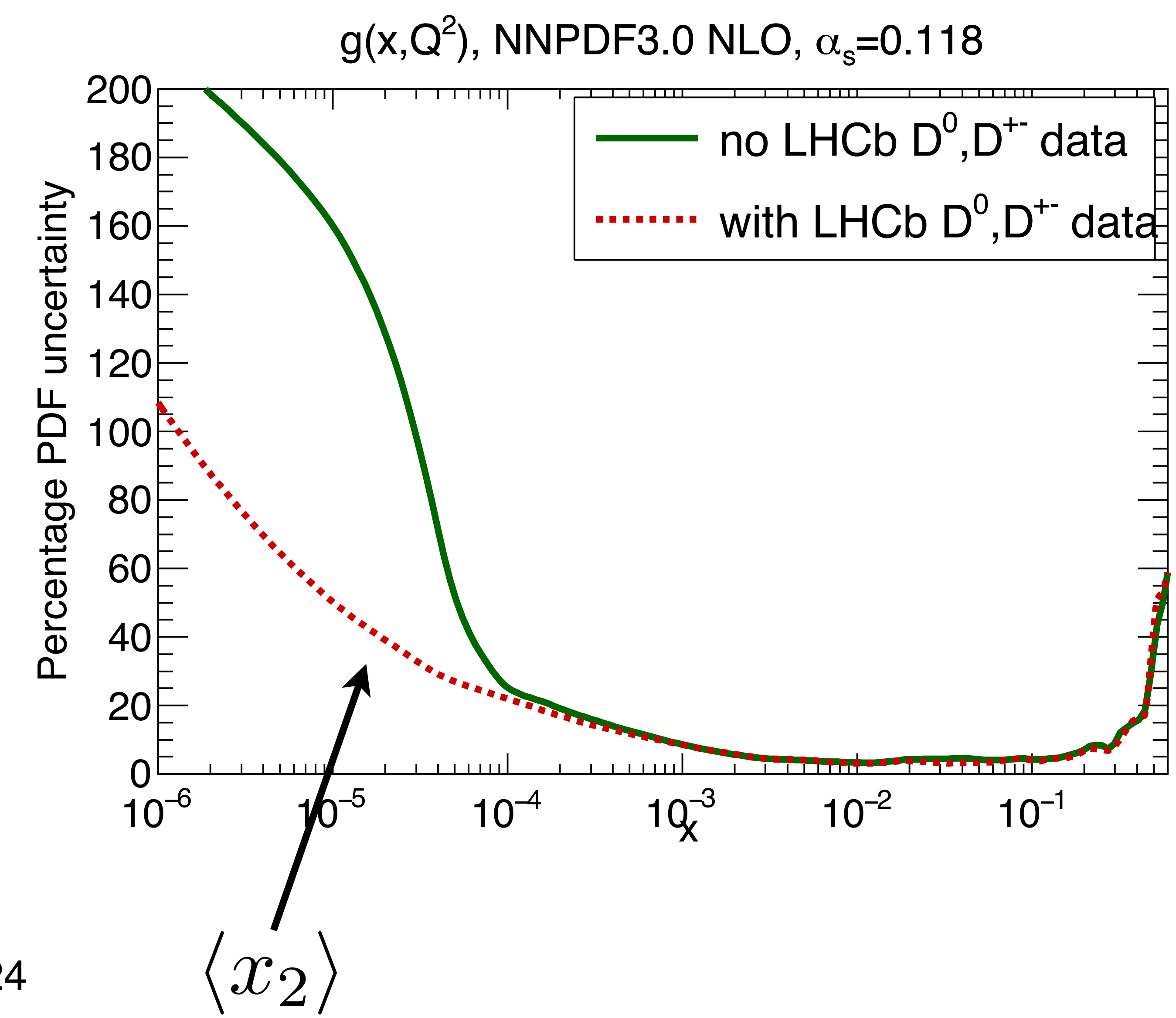
Reweighting NNPDF3.0

RG, J. Rojo, L. Rottoli, J. Talbert - arXiv:1506.08025

1) Normalise LHCb differential charm data to **high-pt**, **low-y** bin
2) Reweight the 100 replicas based on compatibility with LHCb data (here we use the FONLL predictions provided by Matteo)

$$\chi^2/N_{\rm dat}(D^0 + D^+ + h.c.) = 56/75$$



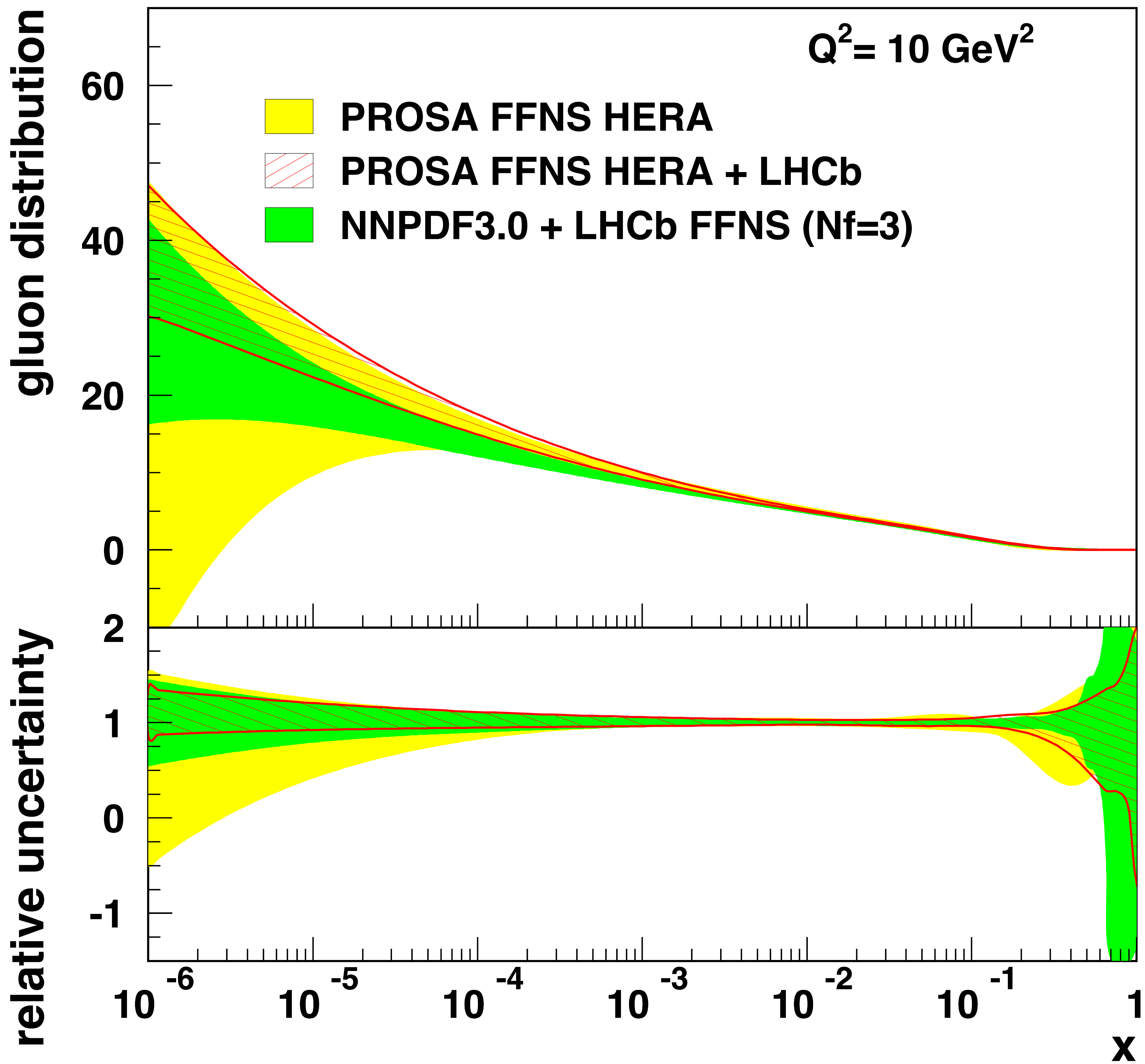


Comparison of our result?

Similar analysis first performed by PROSA collaboration: arXiv: 1503.04581

- HERA+LHCb Data PDF fit
- FFS, NF=3
- Normalise to 'middle' rapidity bin for each pT
- HERAfitter framework

Results very consistent!



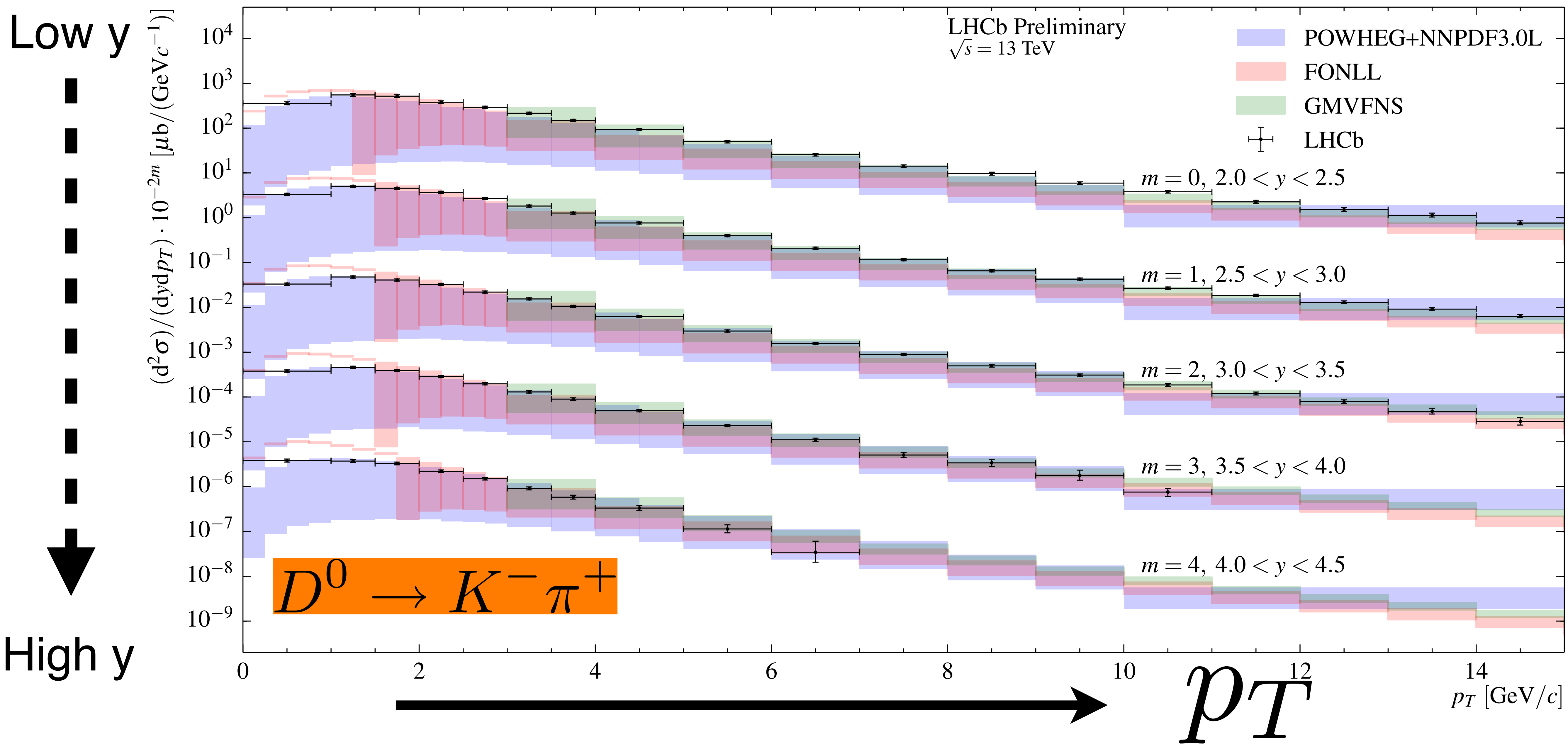
Results 2:

Consistency with 13 TeV data

13 TeV Differential cross section (D0)

Data: LHCb measurement (13 TeV) - arXiv:1510.01707

Theory: POWHEG+NNPDF3.0 reweighted with LHCb 7 TeV data arXiv:1506.08025
FONLL+NNPDF3.0, Cacciari, Mangano, Nason arXiv:1507.06197
GMVFNS - Kniehl et al. arXiv:1202.0439

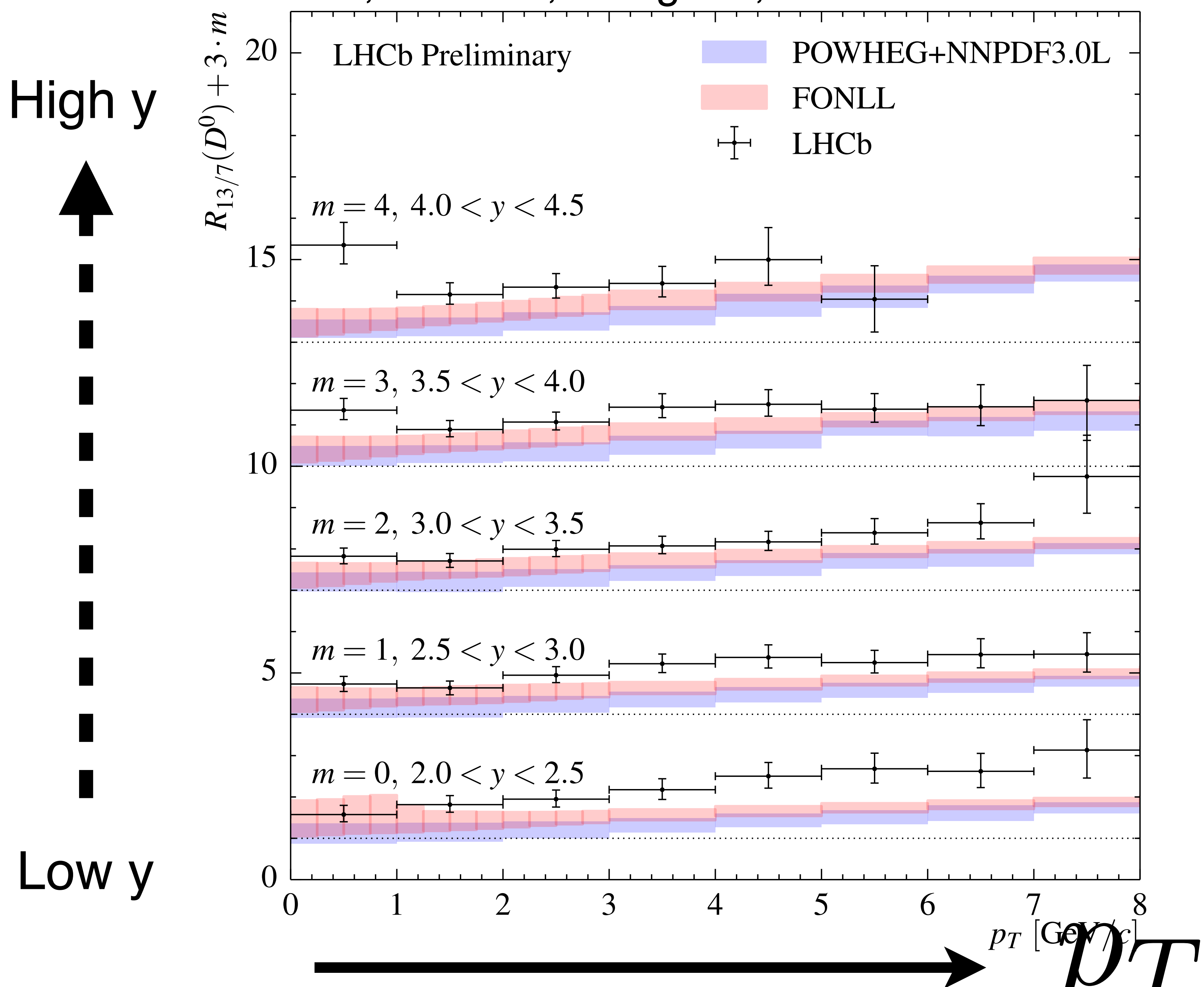


13 TeV / 7 TeV Ratio (D0)

Data: LHCb measurement (13 TeV) - arXiv:1510.01707

Theory: POWHEG+NNPDF3.0 reweighted with LHCb 7 TeV data arXiv:1506.08025

FONLL+NNPDF3.0, Cacciari, Mangano, Nason arXiv:1507.06197



13 TeV / 7 TeV Ratio (D0)

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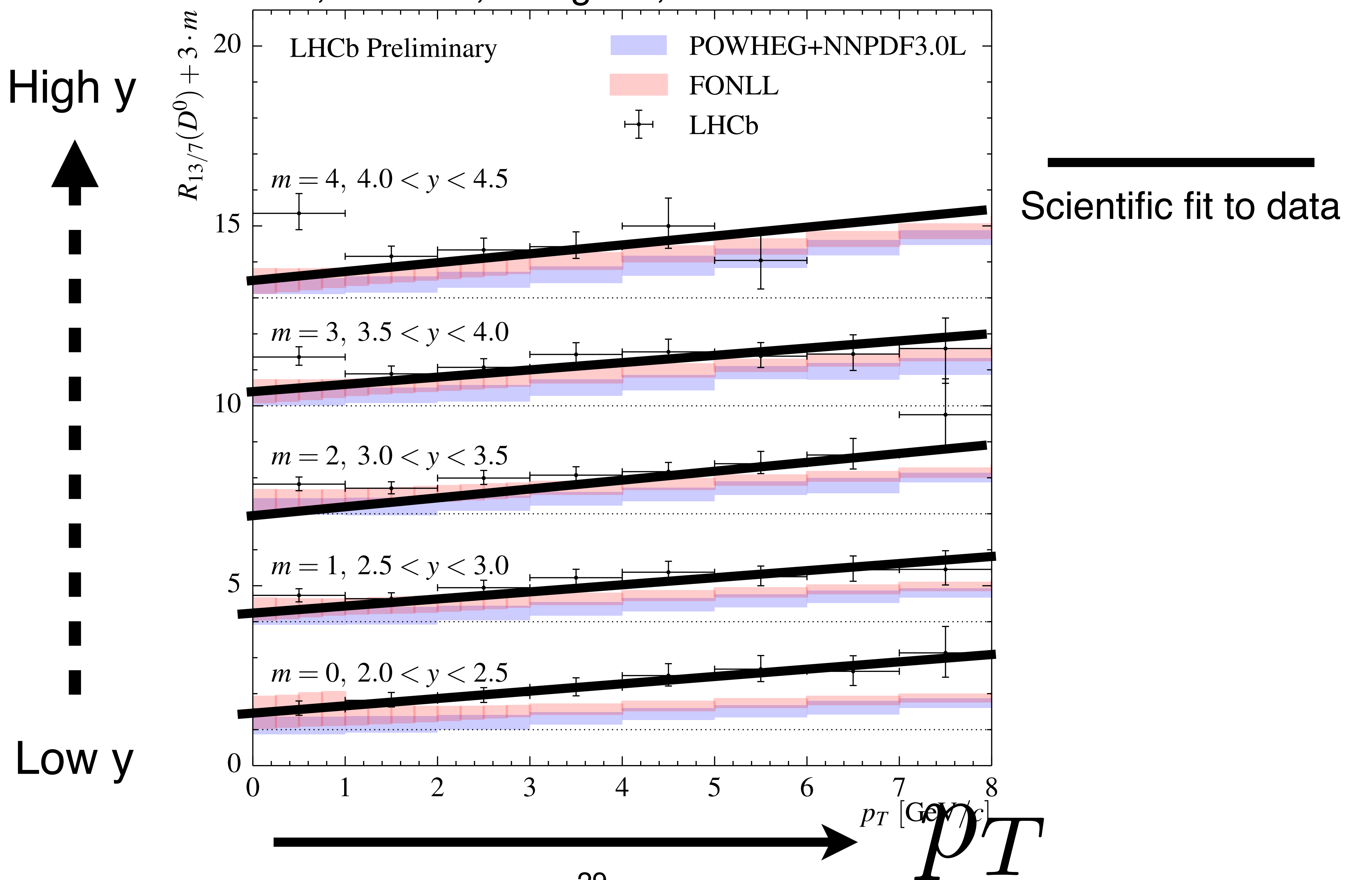
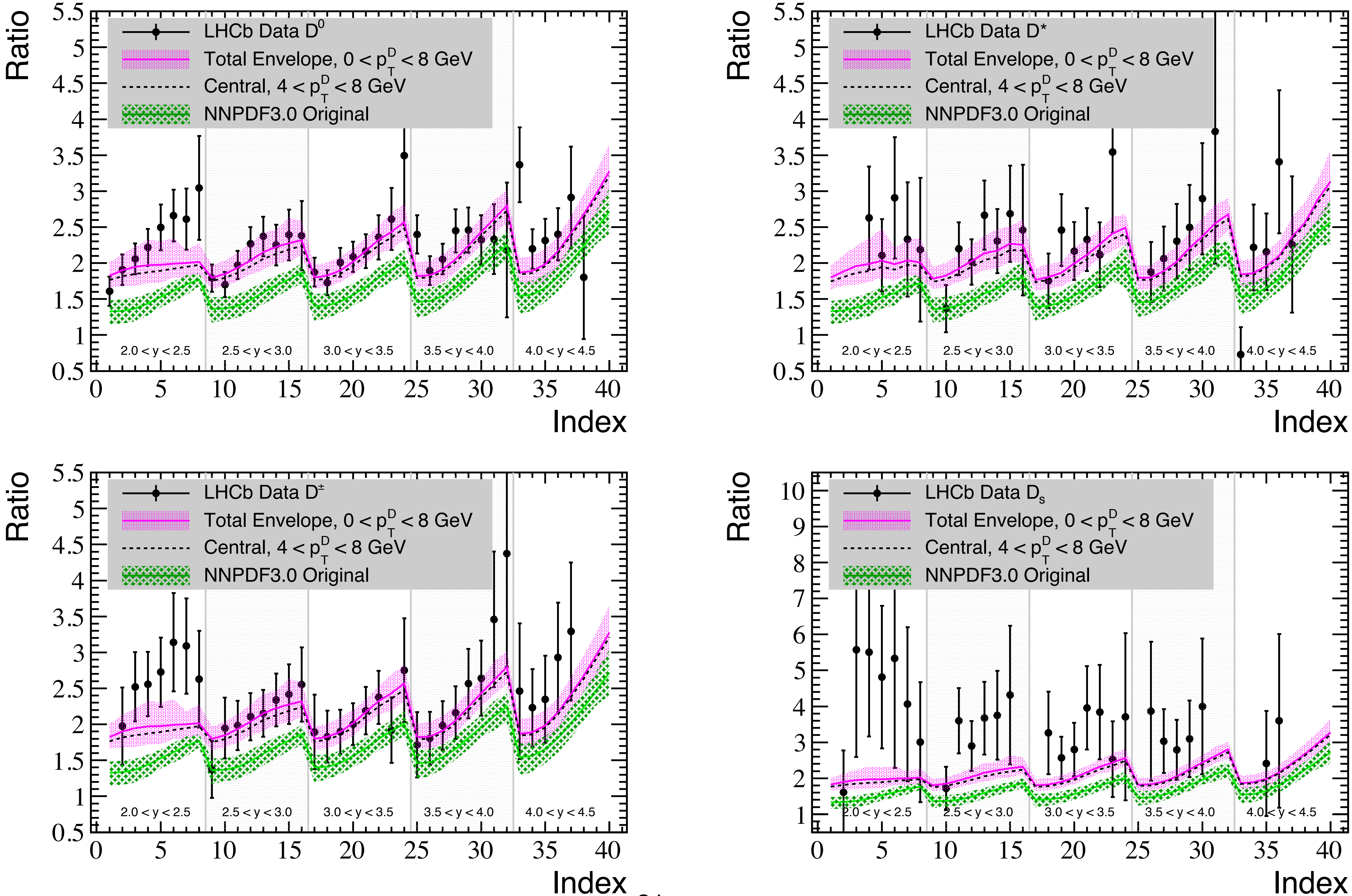


Preliminary Results…..

13 TeV / 7 TeV Ratio

$$\chi^2_{\rm orig}/N_{\rm dat} = 420/131$$
$$\chi^2_{\rm rwgt}/N_{\rm dat} = 114/131$$



Resultant gluon PDF

Include ratio data into original NNPDF fit

Using 1000 PDF Replica set

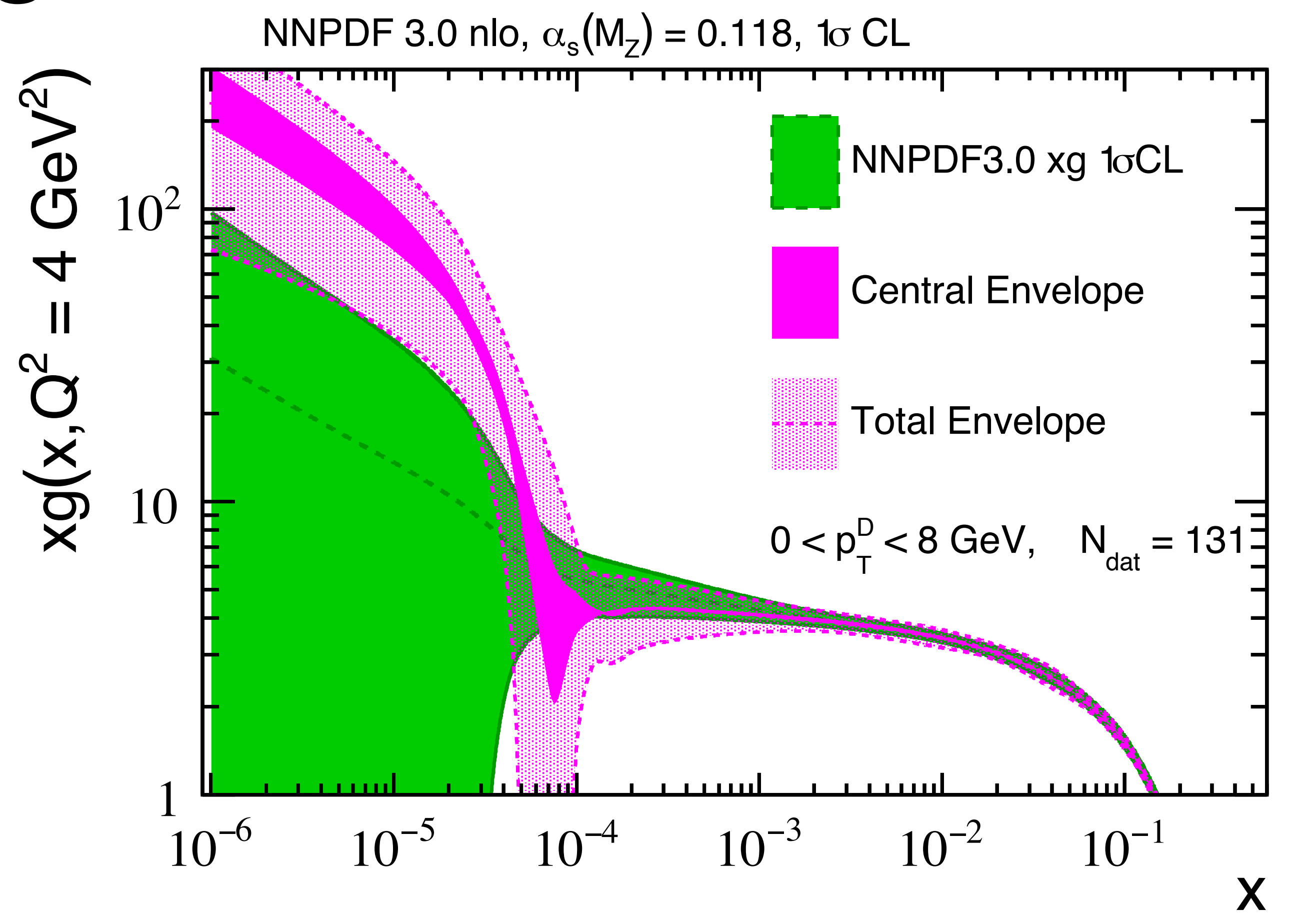
Perform Reweighting 6 times:

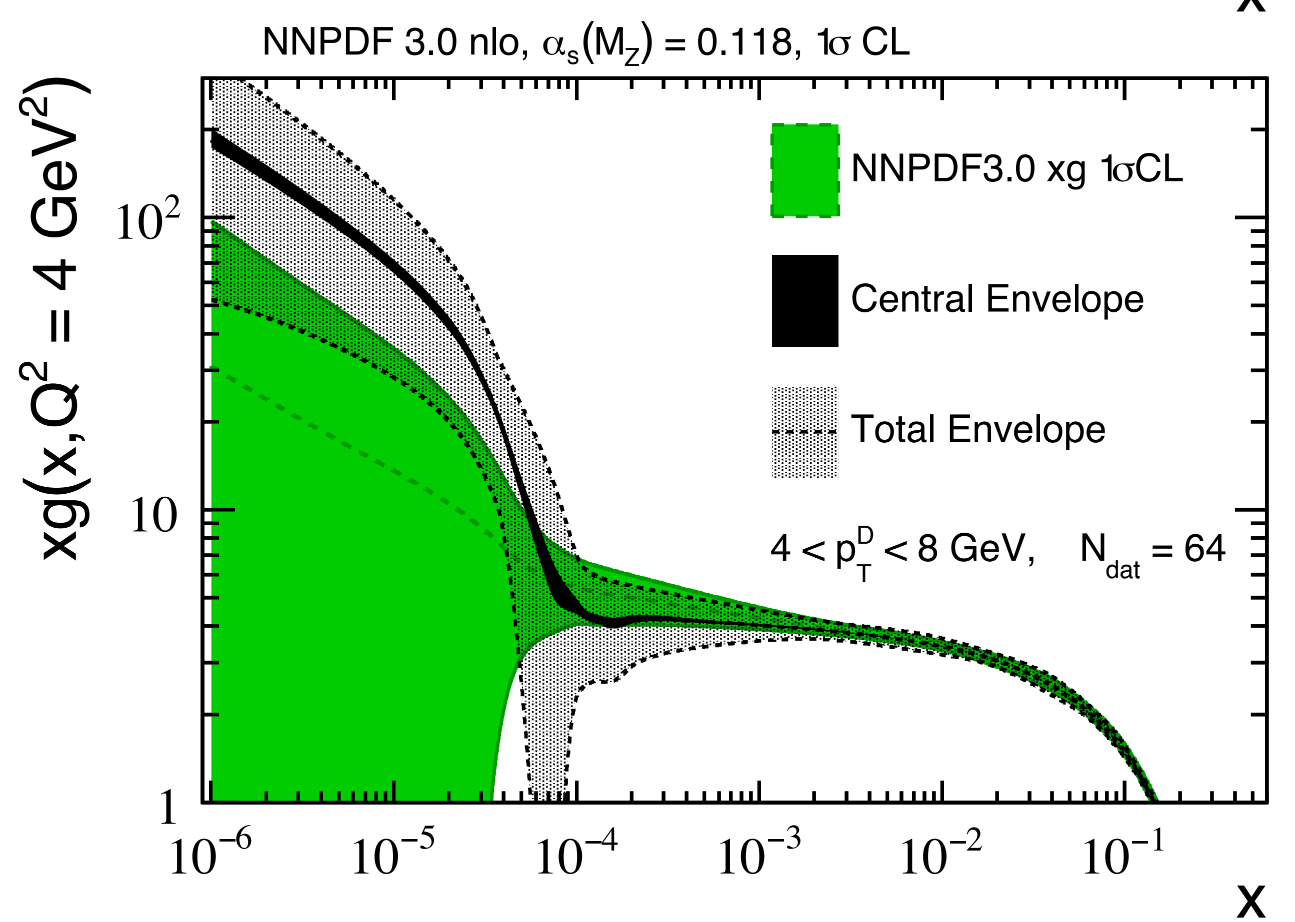
$$\mu_{\text{cen}} = \sqrt{m_c^2 + P_T^2}$$

$$\mu_{\text{alt}} = \sqrt{4m_c^2 + P_T^2}$$

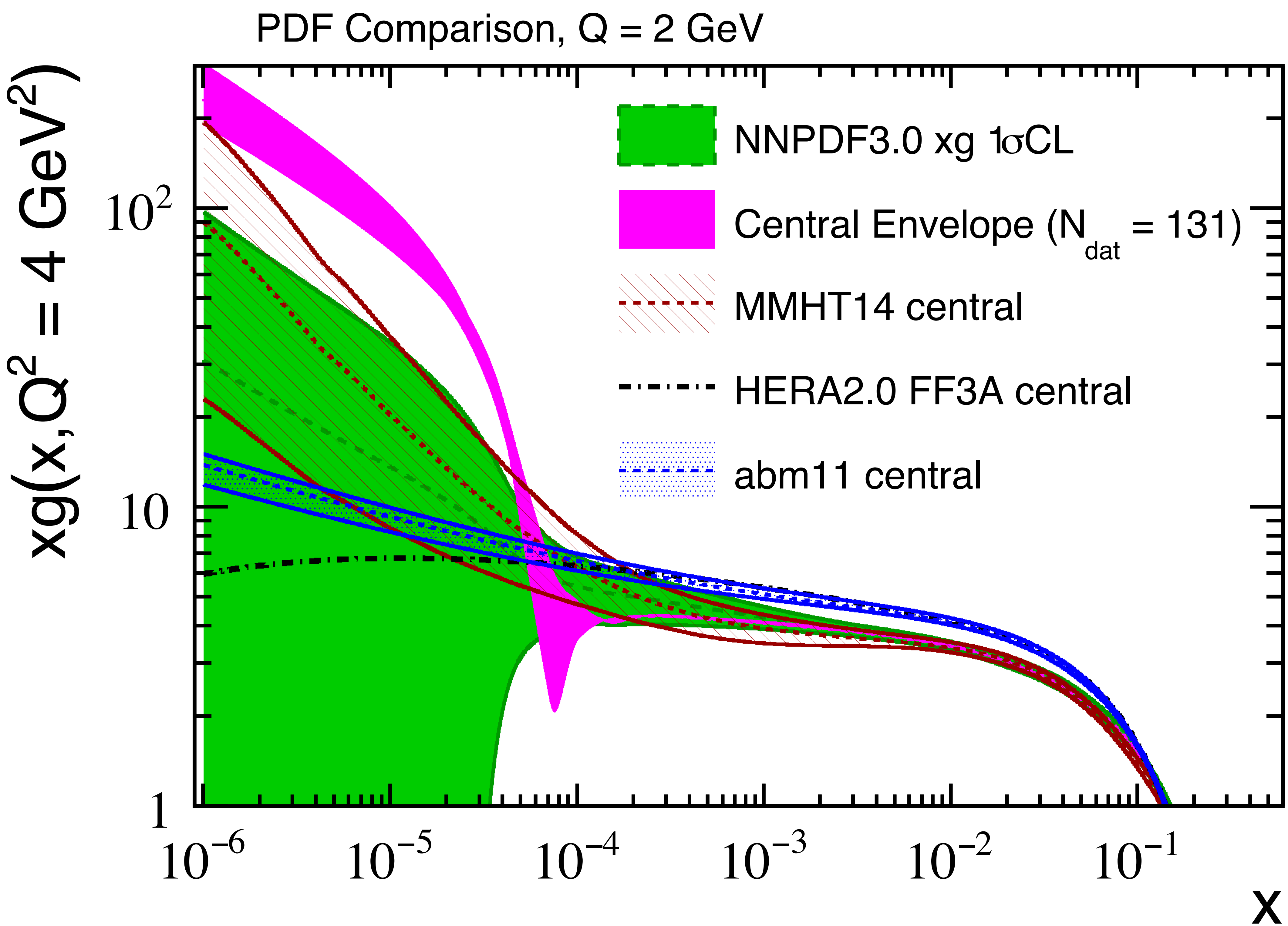
$$m_c^{\text{pole}} \in \{1.3, 1.5, 1.7\}\ \text{GeV}$$

1) Take envelope of central result
2) Take total envelope of uncertainties
3) Include all data (131) high pT data(64)





Resultant gluon PDF



Summary

1) First attempts to include D data in PDF fits with normalised 7 TeV data seemed successful

    i) Description of normalised distributions good at NLO

    ii) Little dependence on choice of bin for normalisation

2) The 13 TeV data does not have same behaviour

    Normalised cross section

    i) Description quite poor (reweighted and original PDF set)

    ii) Dependence on choice of bin, and input theory settings (mc, reference scale) stronger

    Ratio of 13/7 TeV

    i) Can describe data well after reweighting

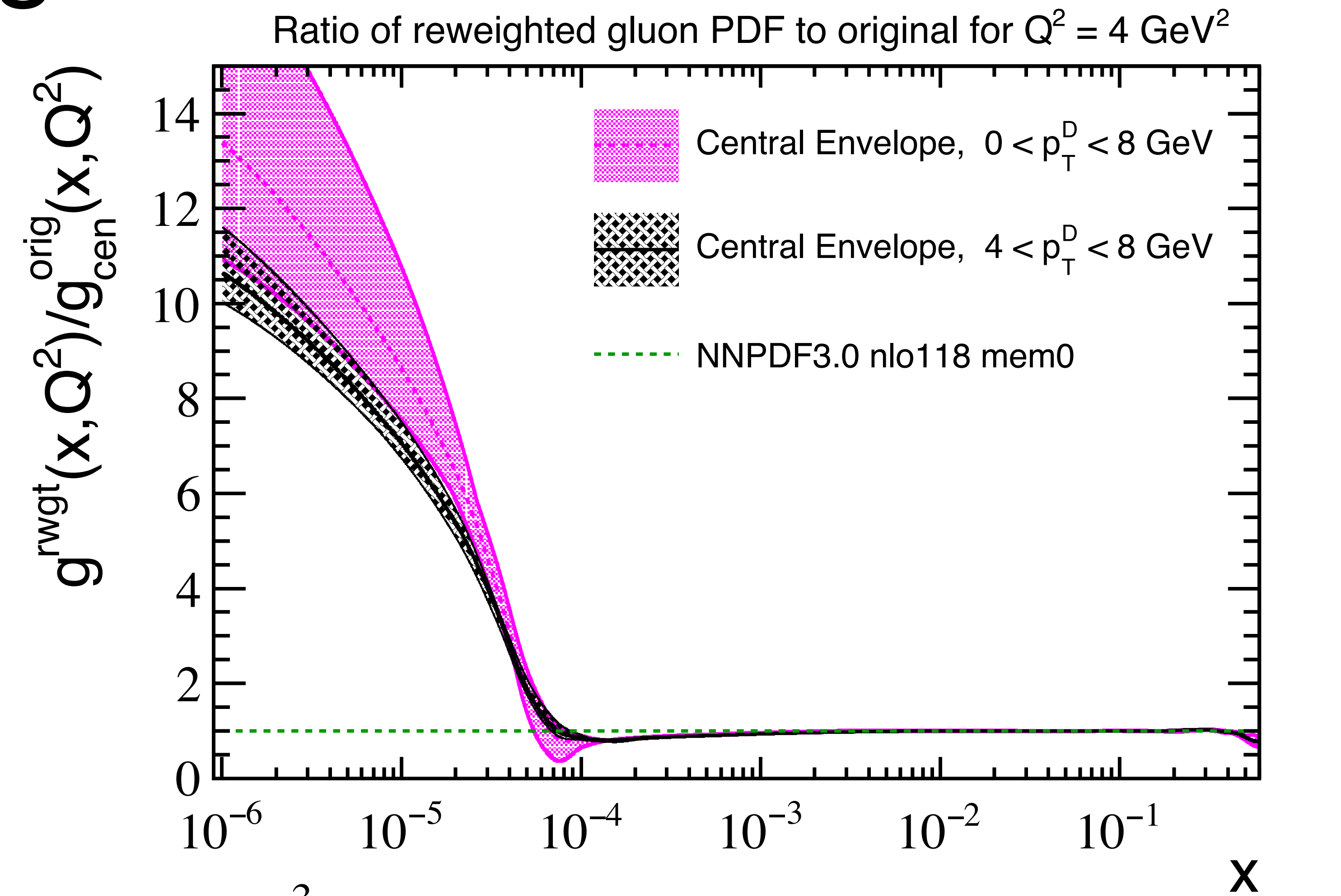
    iii) Very little dependence on input theory settings

    iv) Requires a steeply rising low-x gluon PDF

***Not dicussed: Onia/top production at LHCb or any Pb-p results**

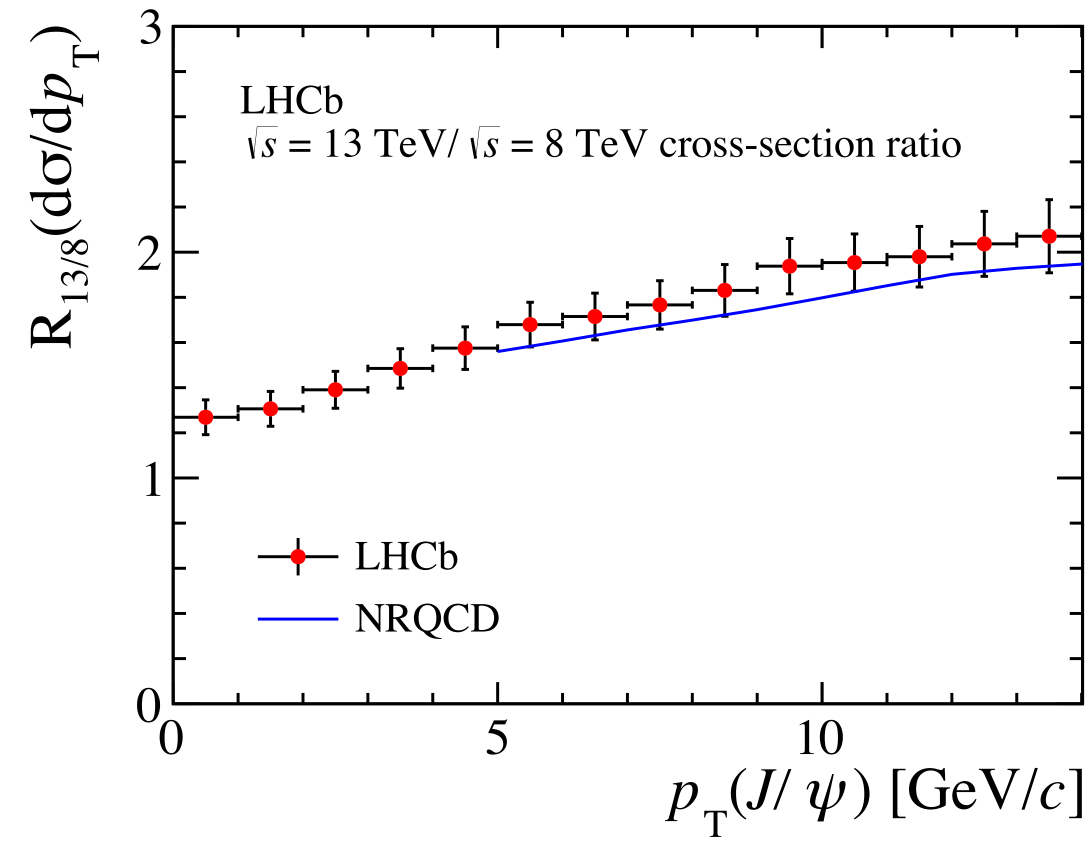
Ratio to original NNPDF3.0

Ratio to original gluon PDF



Similar behaviour in LHCb J/Psi data
arXiv:1509.00771

Ratio of 13/8 TeV:
data exhibits larger gradient

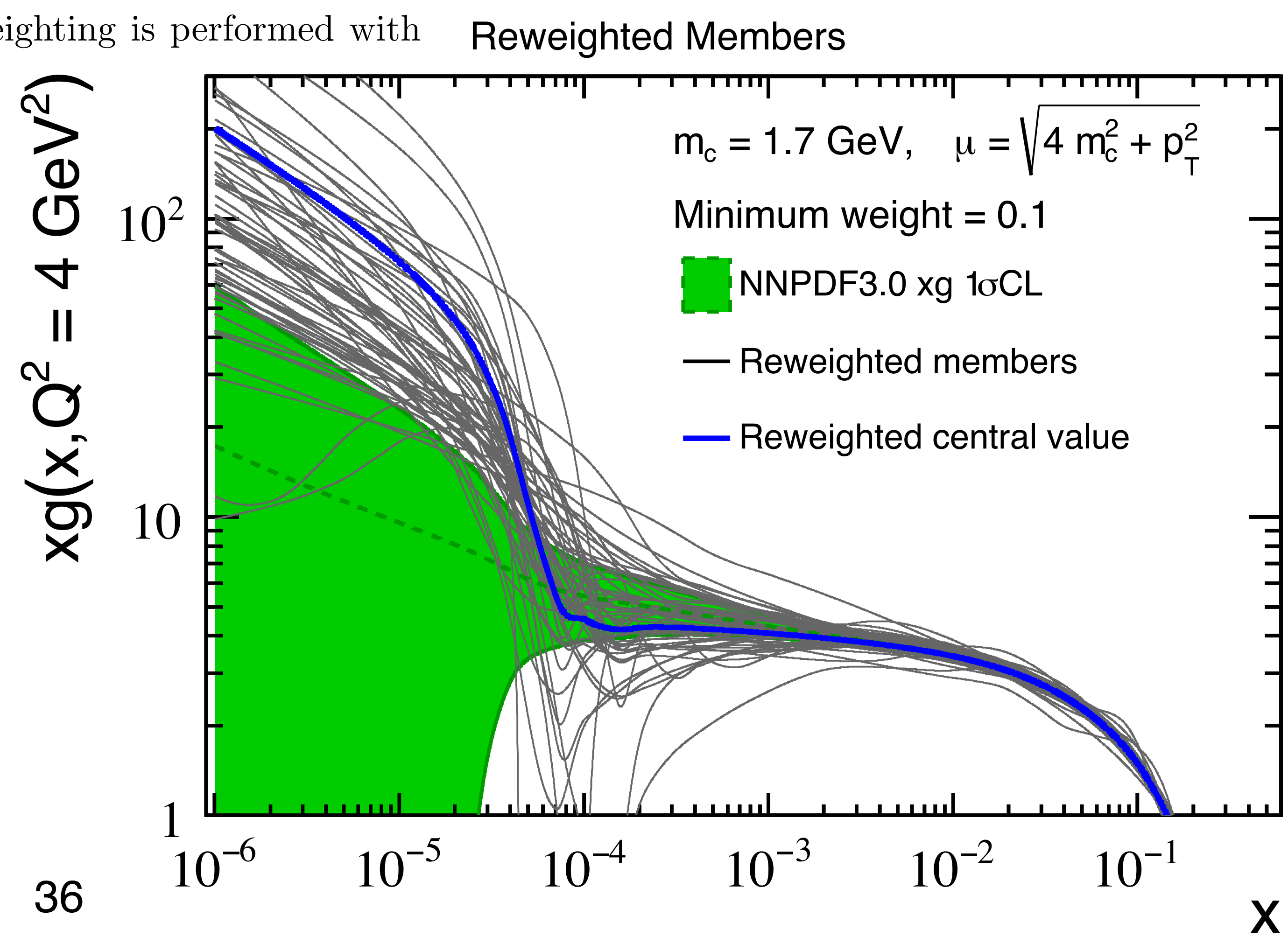


		$D^0, D^\pm$		$D^0, D^\pm, D^*$		$D^0, D^\pm, D^*, D_s$	
Settings	P_T range (GeV)	$\chi^2/\mathrm{N_{dat}}$	$\mathrm{N_{eff}}$	$\chi^2/\mathrm{N_{dat}}$	$\mathrm{N_{eff}}$	$\chi^2/\mathrm{N_{dat}}$	$\mathrm{N_{eff}}$
$m_c = 1.3$ GeV	$0 < p_T < 8$	338/75	9	400/104	10	460/131	8
μ_{low}	$4 < p_T < 8$	124/36	19	151/51	20	177/64	19
$m_c = 1.3$ GeV	$0 < p_T < 8$	284/75	18	339/104	18	395/131	17
μ_{high}	$4 < p_T < 8$	109/36	23	132/51	25	157/64	23
$m_c = 1.5$ GeV	$0 < p_T < 8$	306/75	18	364/104	18	422/131	17
μ_{low}	$4 < p_T < 8$	113/36	23	138/51	25	163/64	23
$m_c = 1.5$ GeV	$0 < p_T < 8$	253/75	22	303/104	23	357/131	21
μ_{high}	$4 < p_T < 8$	99/36	27	121/51	31	145/64	28
$m_c = 1.7$ GeV	$0 < p_T < 8$	280/75	20	334/104	21	390/131	20
μ_{low}	$4 < p_T < 8$	107/36	25	131/51	28	155/64	26
$m_c = 1.7$ GeV	$0 < p_T < 8$	230/75	22	278/104	22	330/131	21
μ_{high}	$4 < p_T < 8$	93/36	29	114/51	36	137/64	32

Table 1. The $\chi^2/\mathrm{N_{dat}}$ and number of effective replicas when performing a reweighting of the LHCb ratio data. The results are provided for the full data set, as well as that of a limited p_T range, and for different combinations of D hadron flavours. In each case, the reweighting is performed with different theoretical inputs.

Chi-squared for performing reweighting for different theoretical inputs

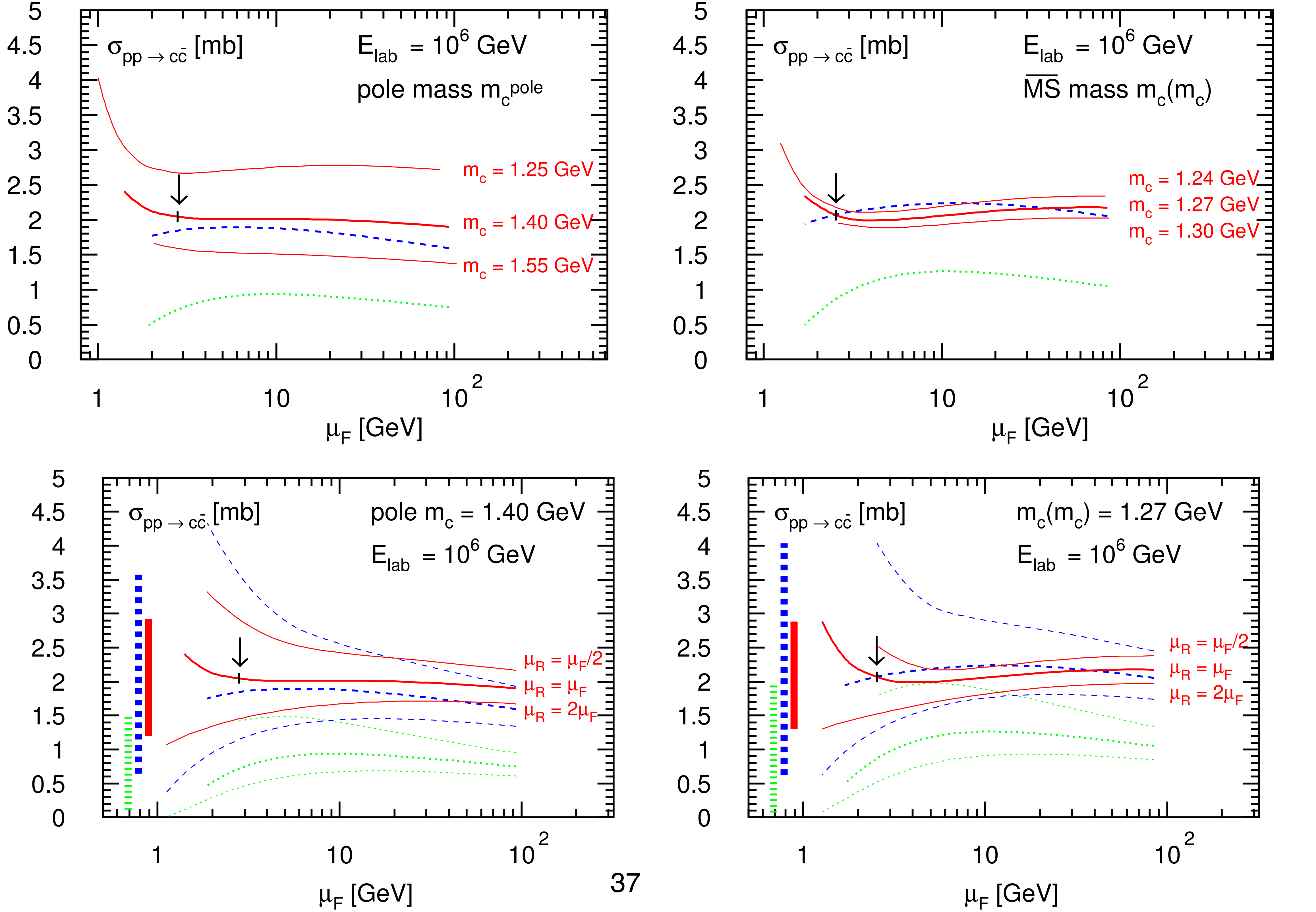
Surviving replicas with large weights



Theoretical uncertainty, $pp \rightarrow Q_3\bar{Q}_4 + X$

Ren/Fac/Mass/Scheme dependence examined in 1507.01570 (Garzelli et al)

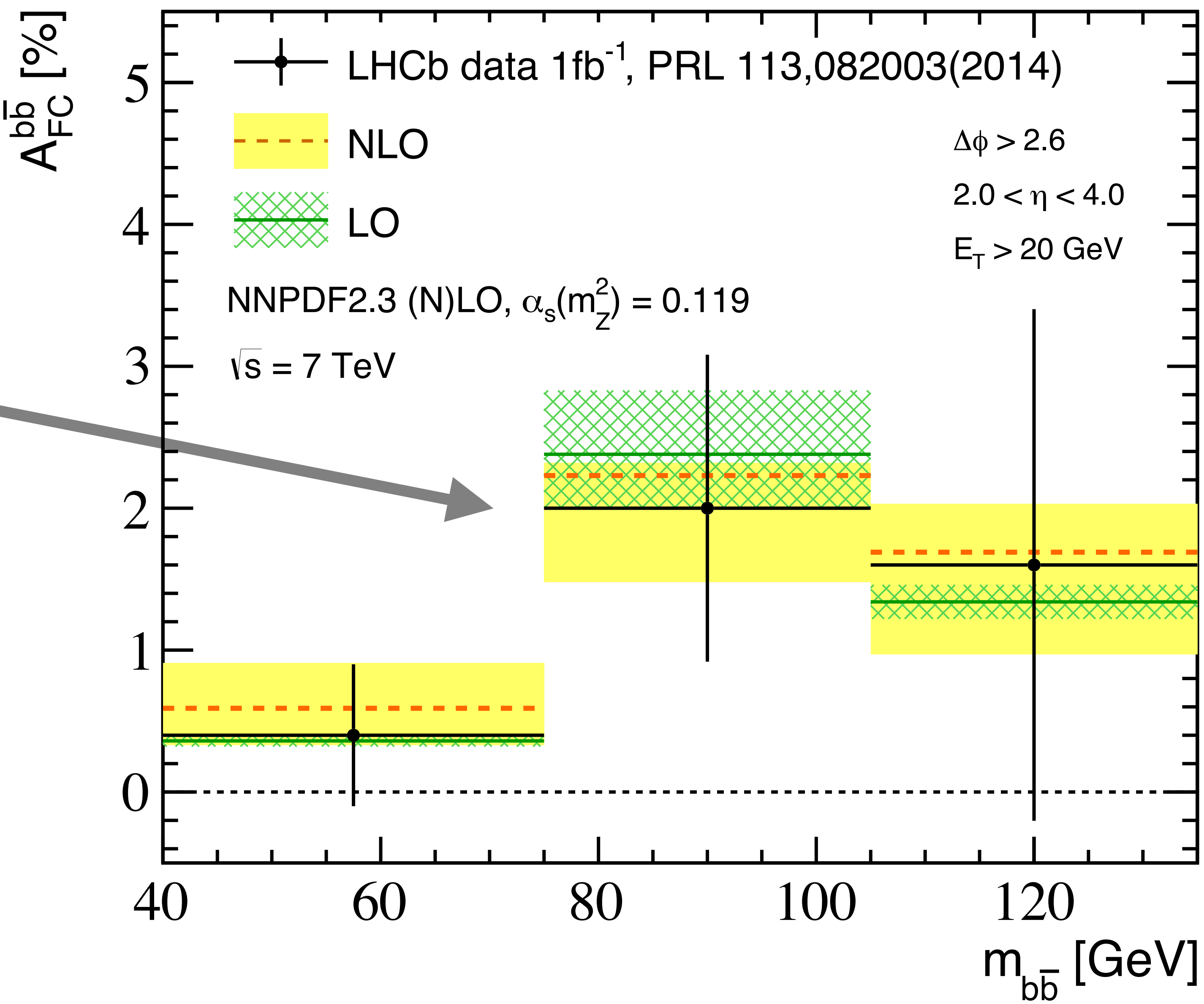
$$\sqrt{s} = 1.4 \quad TeV$$



b-quark forward-backward asymmetry

EW dominates

QCD dominates



$$A_{\rm FC}^{Q\bar{Q}} = \frac{\alpha_s^3 \sigma_a^{s(0)} + \alpha_s^2 \alpha \, \sigma_a^{se(0)} + \alpha^2 \left(\sigma_a^{e(0)} + \alpha_s \sigma_a^{e(1)} \right)}{\alpha_s^2 \left(\sigma_s^{s(0)} + \alpha_s \sigma_s^{s(1)} \right) + \alpha^2 \left(\sigma_s^{e(0)} + \alpha_s \sigma_s^{e(1)} \right)} \, .$$

RG, Ulrich Haisch, Ben D. Pecjak, Emanuele Re, arXiv:1505.02429

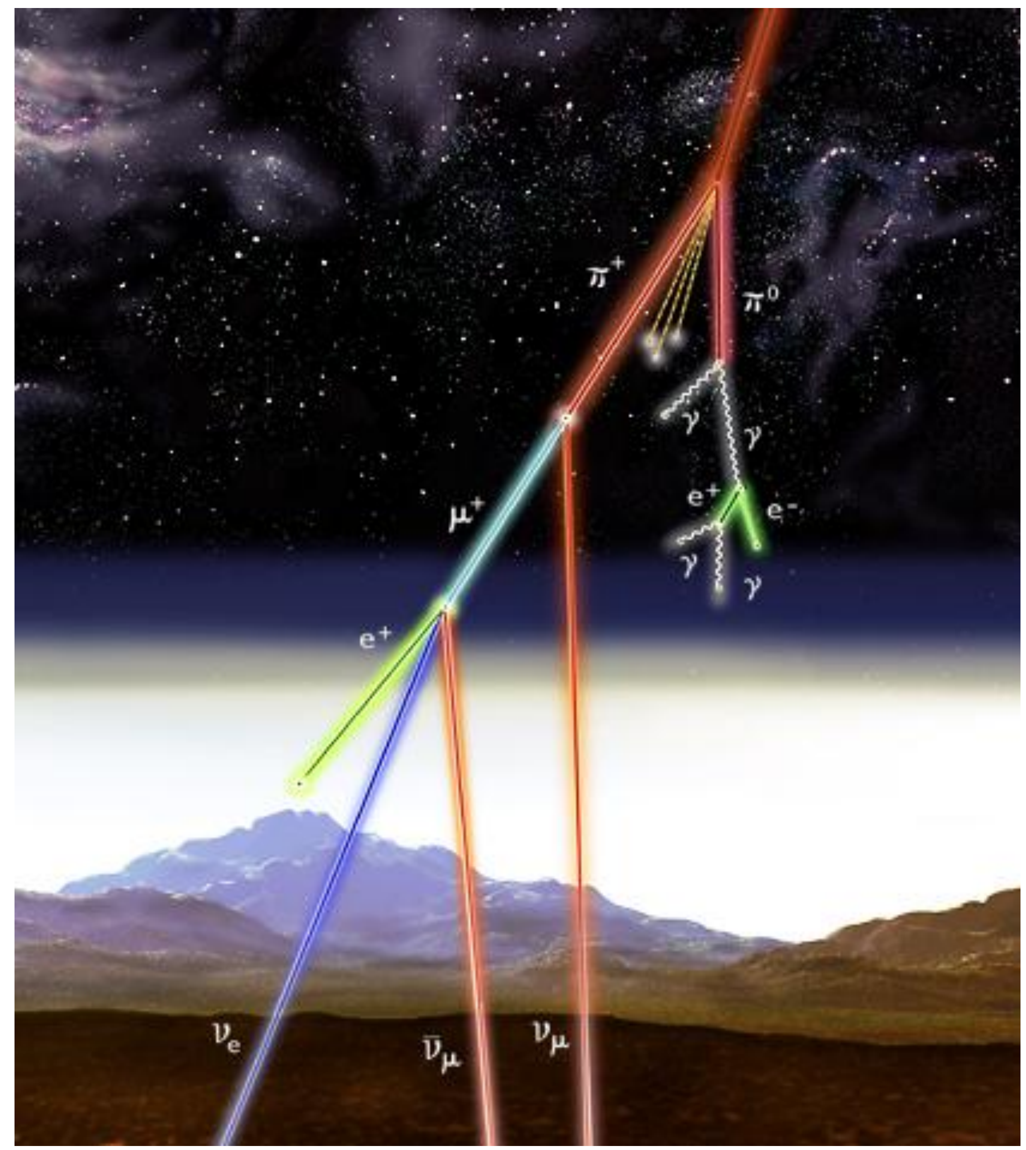
Neutrino aside

RG, J. Rojo, L. Rottoli, S. Sarkar, J. Talbert - arXiv:1511.06346

Atmospheric hadroproduction

- **Cosmic rays** colliding with atmospheric nuclei incite a 'cascade' of particle production and decay.
- Hadrons, including **pions**, **kaons**, **B** and **D** mesons, are formed in the initial collisions.
- While propagating through the atmosphere, these hadrons both re-interact with atmospheric nuclei and also decay leptonically, producing a **flux of atmospheric leptons**…

$$NA \to hY \to lX$$



INFN-Notizie No. 1 June 1999

Slide, courtesy of J. Talbert

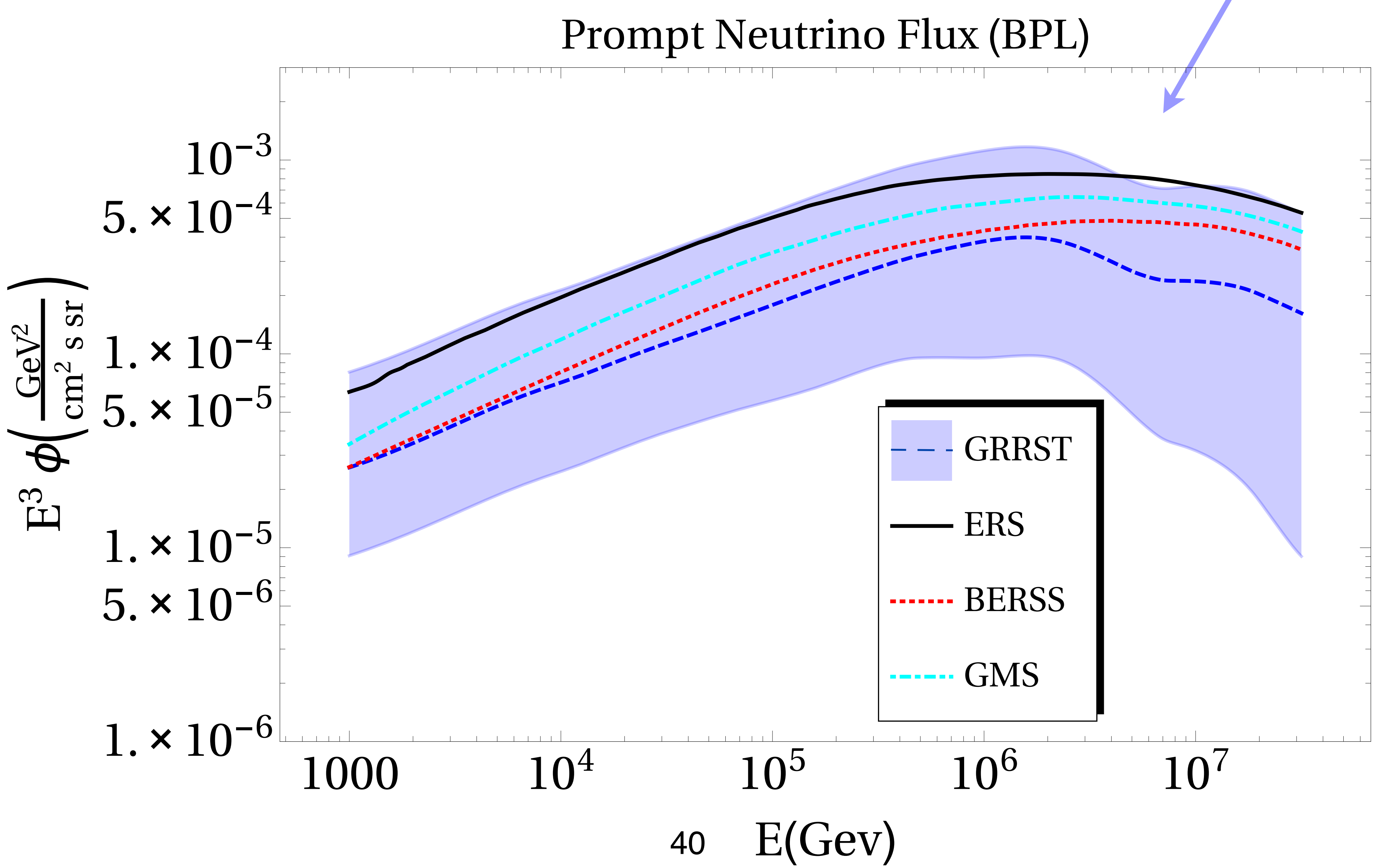
Neutrino aside

RG, J. Rojo, L. Rottoli, S. Sarkar, J. Talbert - arXiv:1511.06346

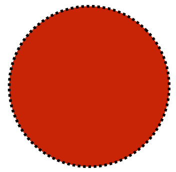
prompt neutrino flux background to extraterrestrial neutrinos

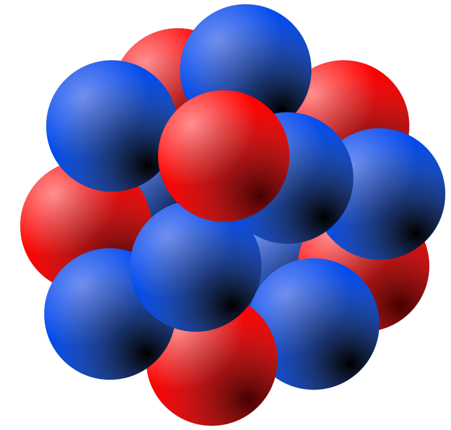
$$nA \to (D \to \nu_l X) + Y$$

Our result blue!



How do p-Pb differ from pp?





$${}^{1}_{1}H$$

$${}^{208}_{82}Pb$$

$$E_p = 4\ TeV$$

$$E_n = Z/A \cdot 4\ TeV$$
$$= 1.58\ TeV$$

$$\sqrt{s_{pn}} \simeq 5\ TeV$$

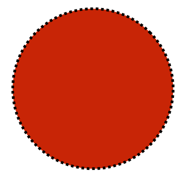
Lab frame is not Centre-of-Mass frame!

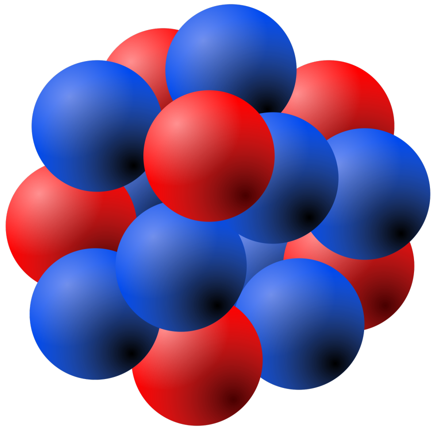
$$\beta_p = \frac{|\vec{p}_p|}{E_p}$$

$$y_p = \frac{1}{2}\mathrm{Log}\left[\frac{1+\beta_p}{1-\beta_p}\right]$$

$$\Delta_y = y_p - y_n$$
$$= 0.465$$

How do p-Pb differ from pp?



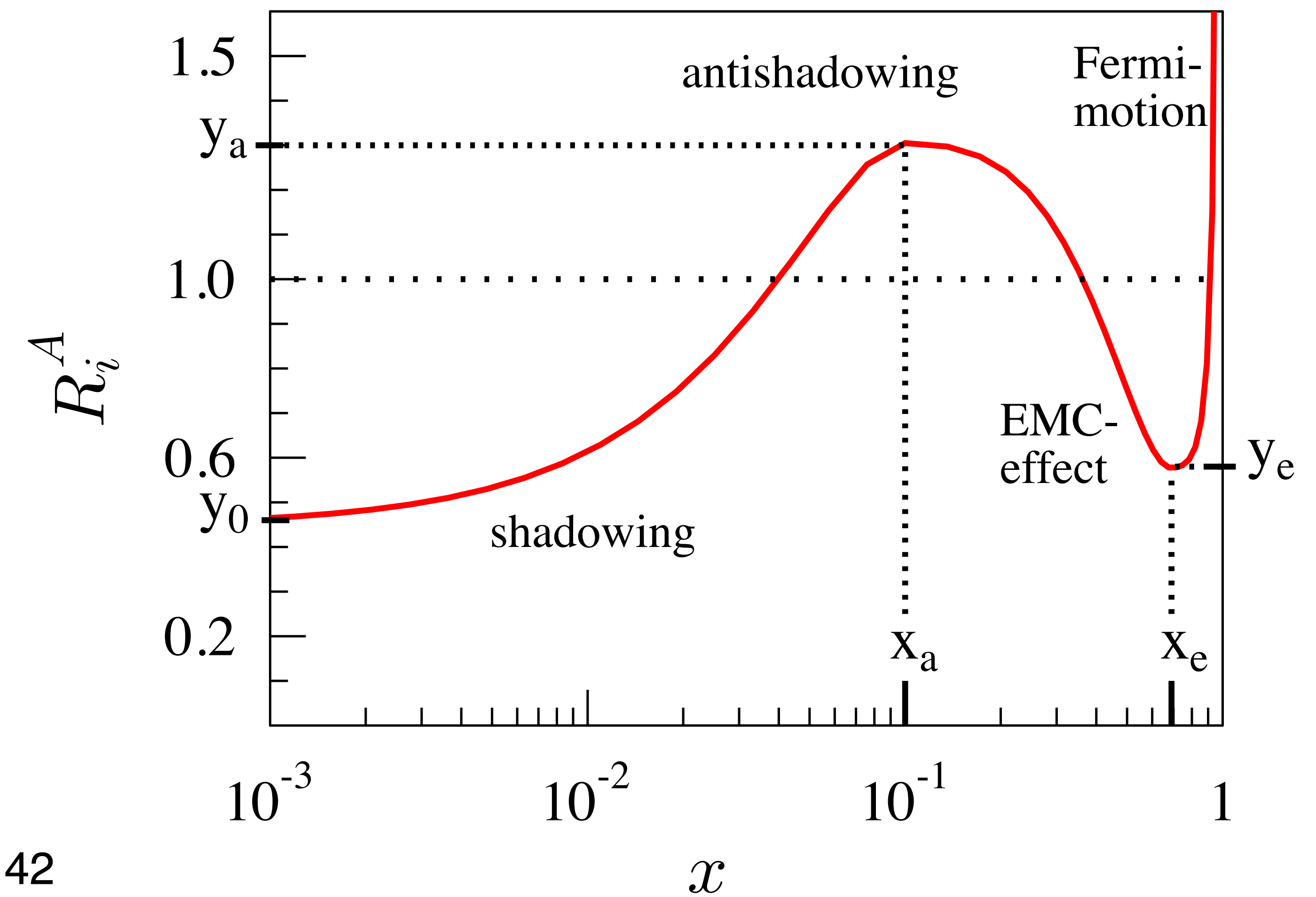


Is the distribution of partons the same in bound and free nuclei?

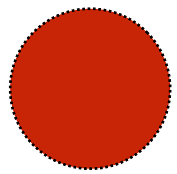
$$f_i^A(x, \mu_F^2) = R_i^A(x, \mu_F^2) \otimes f_i^{\mathrm{free}}(x, \mu_F^2)$$

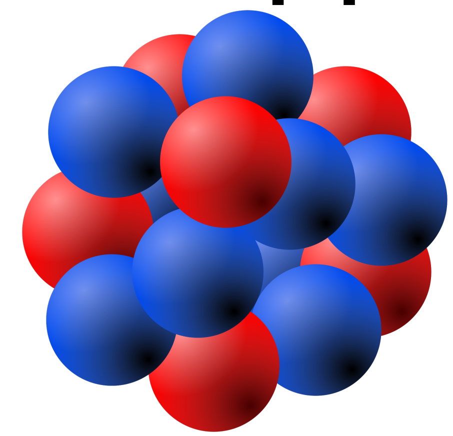
Nuclear modification of PDFs, extracted from data! e.g.:

nCTEQ15 - arXiv 1509.00792
EPS09 - arXiv 0902.4154
DSSZ - arXiv 1112.6324
HKN07 - arXiv 0709.3038



How do p-Pb differ from pp?





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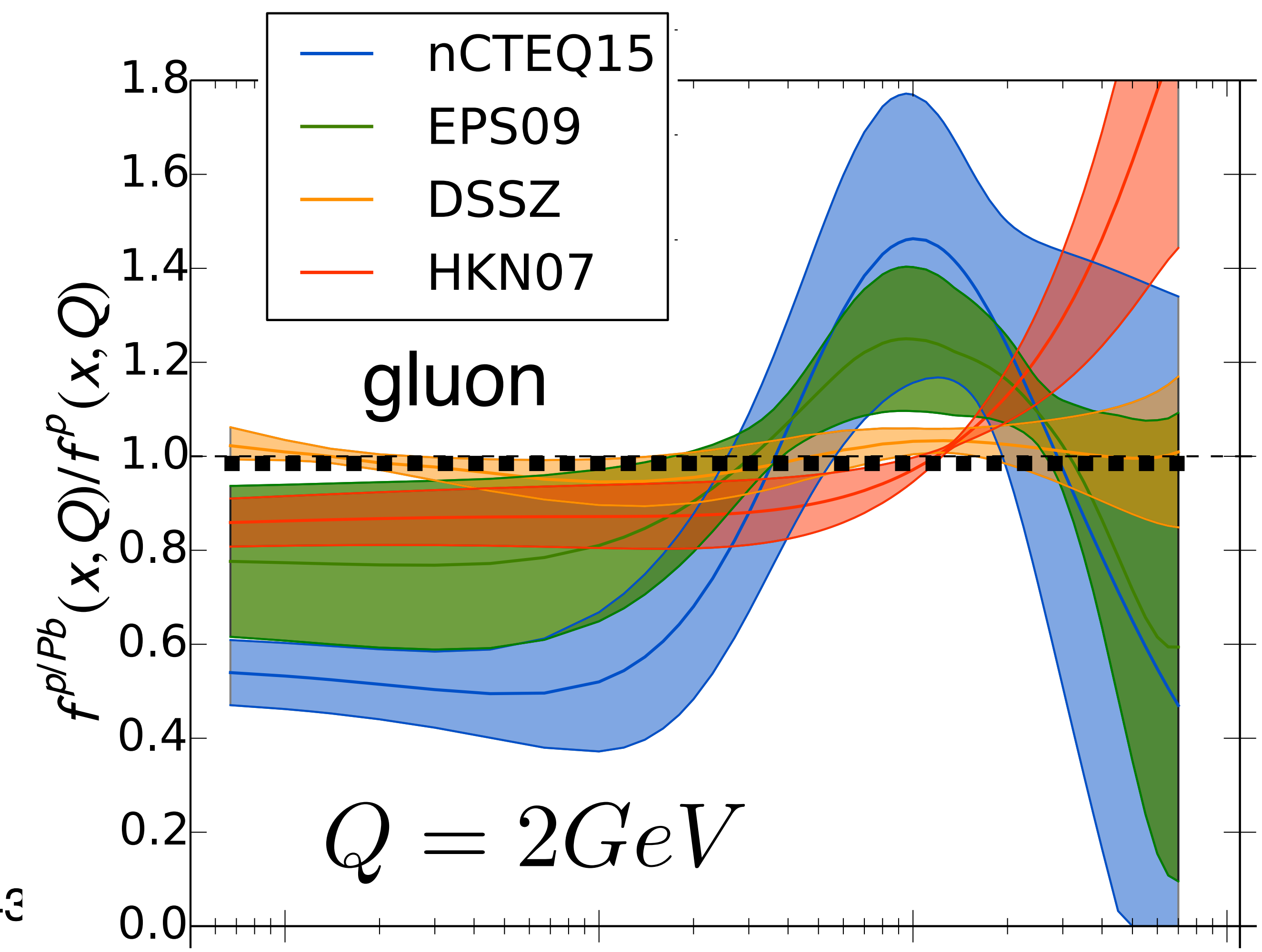


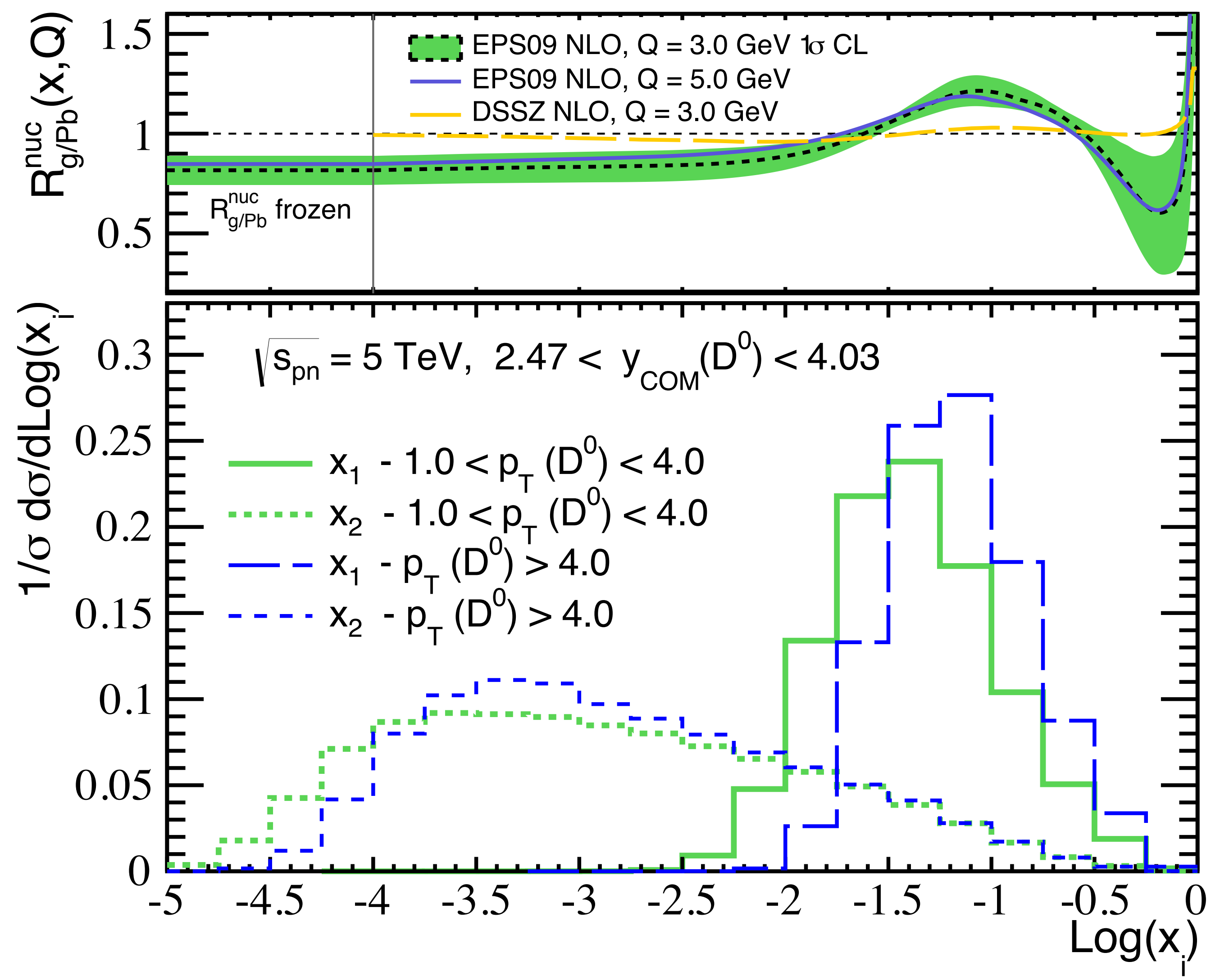
LHCb kinematics

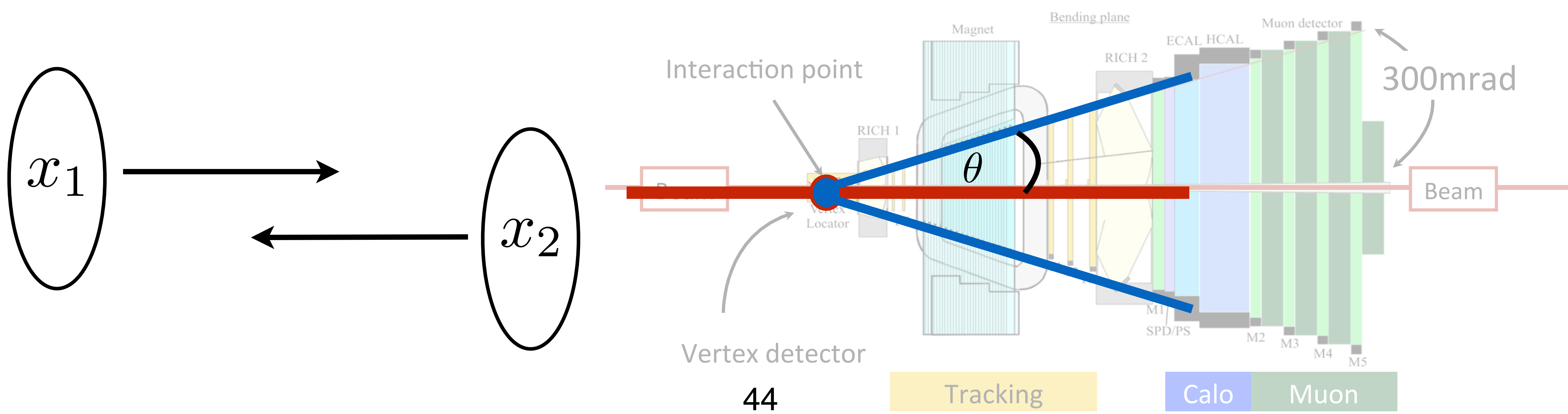
p-Pb probe shadowing (low-x)

Pb-p probe anti-shadowing (x~0.05)

Rfb simultaneously sensitive to these effects

Increasing D pT gains sensitivity to anti-shadowing regime!





Cross section and Rfb predictions for Pb-p

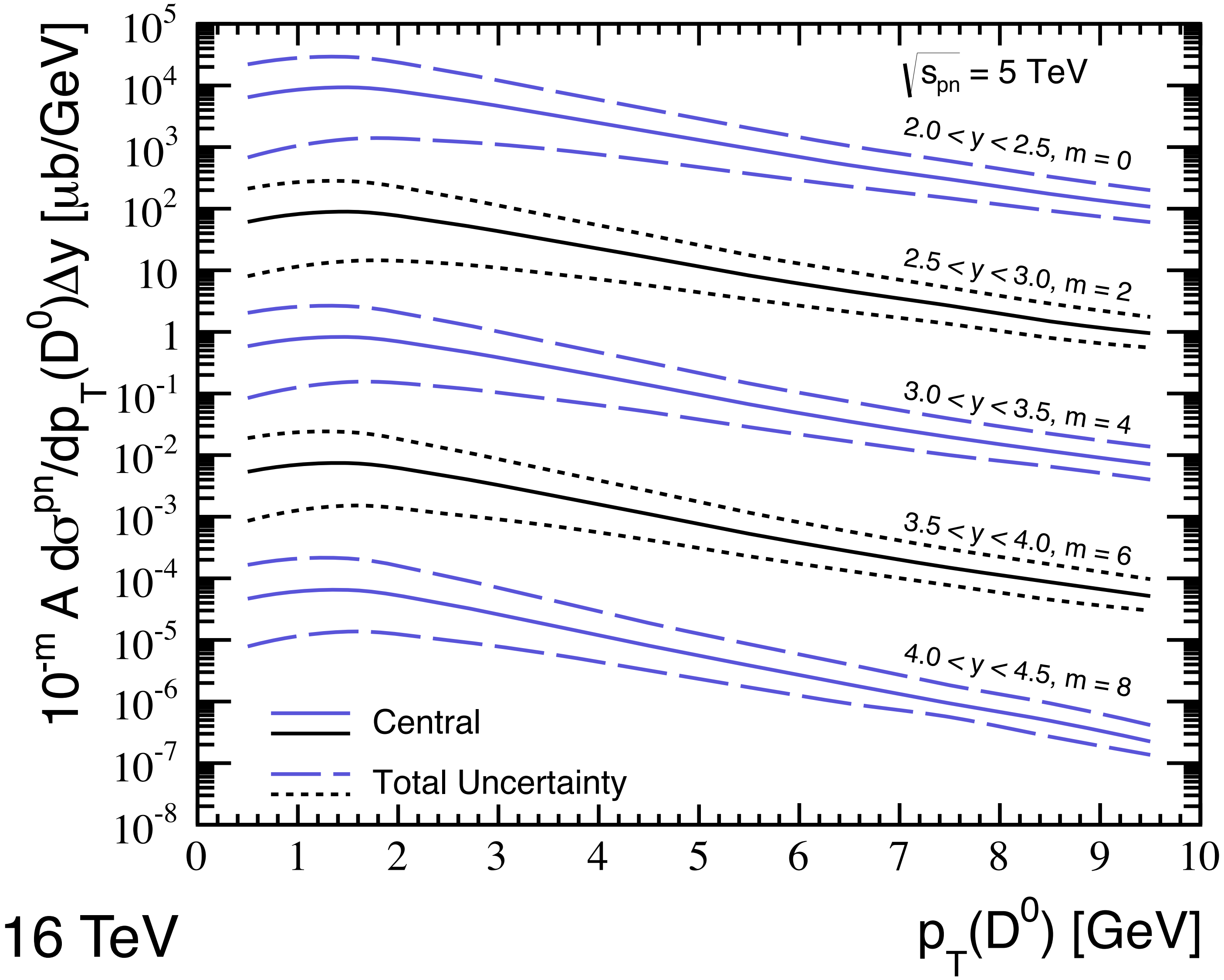
More details provided in arXiv: 1508.07629 RG

Double differential cross sections predictions provided

POWHEG+Pythia8
NNPDF3.0LHCb + EPS09

+compensation terms for VFNS

All 5 and 8 TeV predictions can be provided on request.



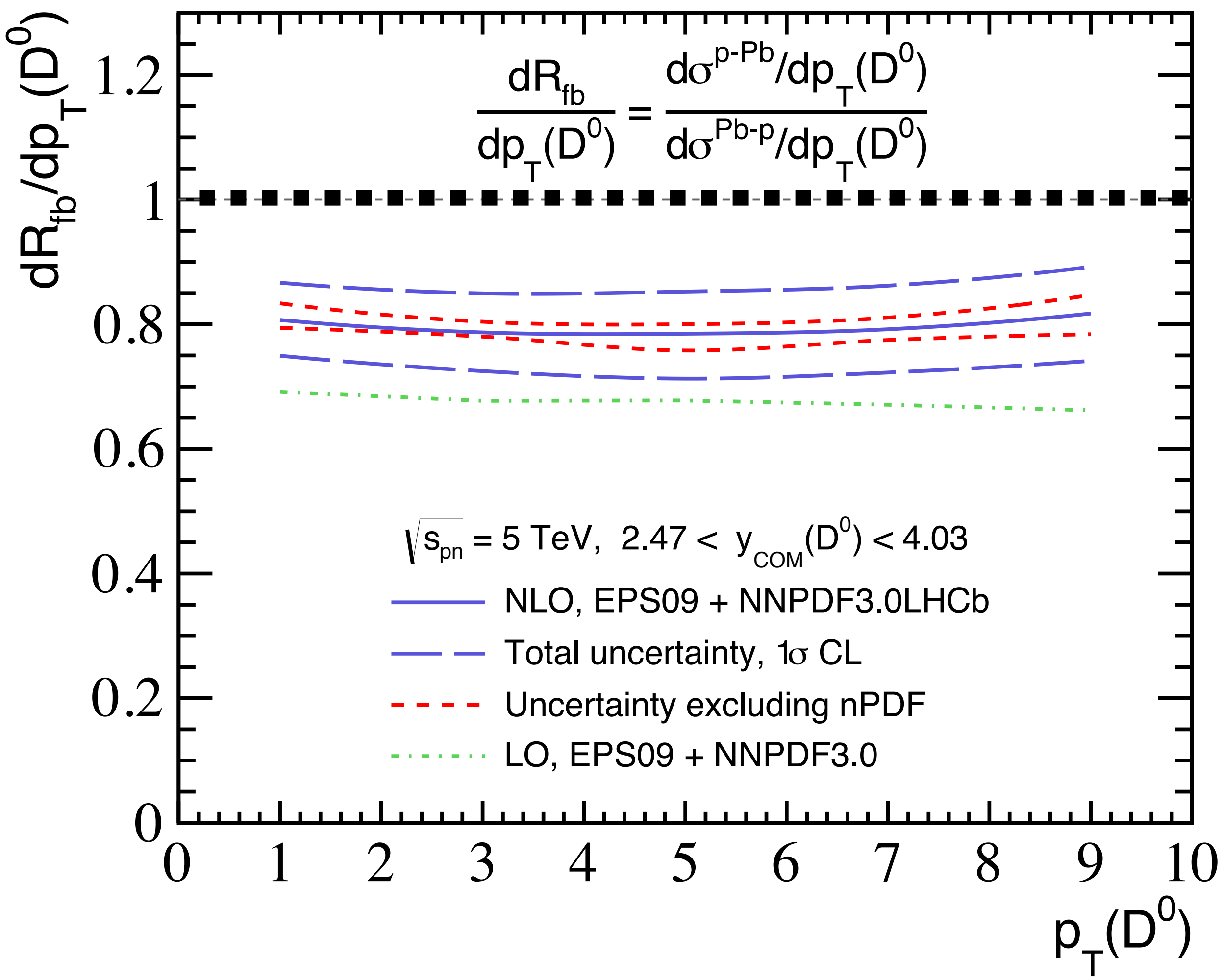
In run-II p-Pb collisions at 8.16 TeV

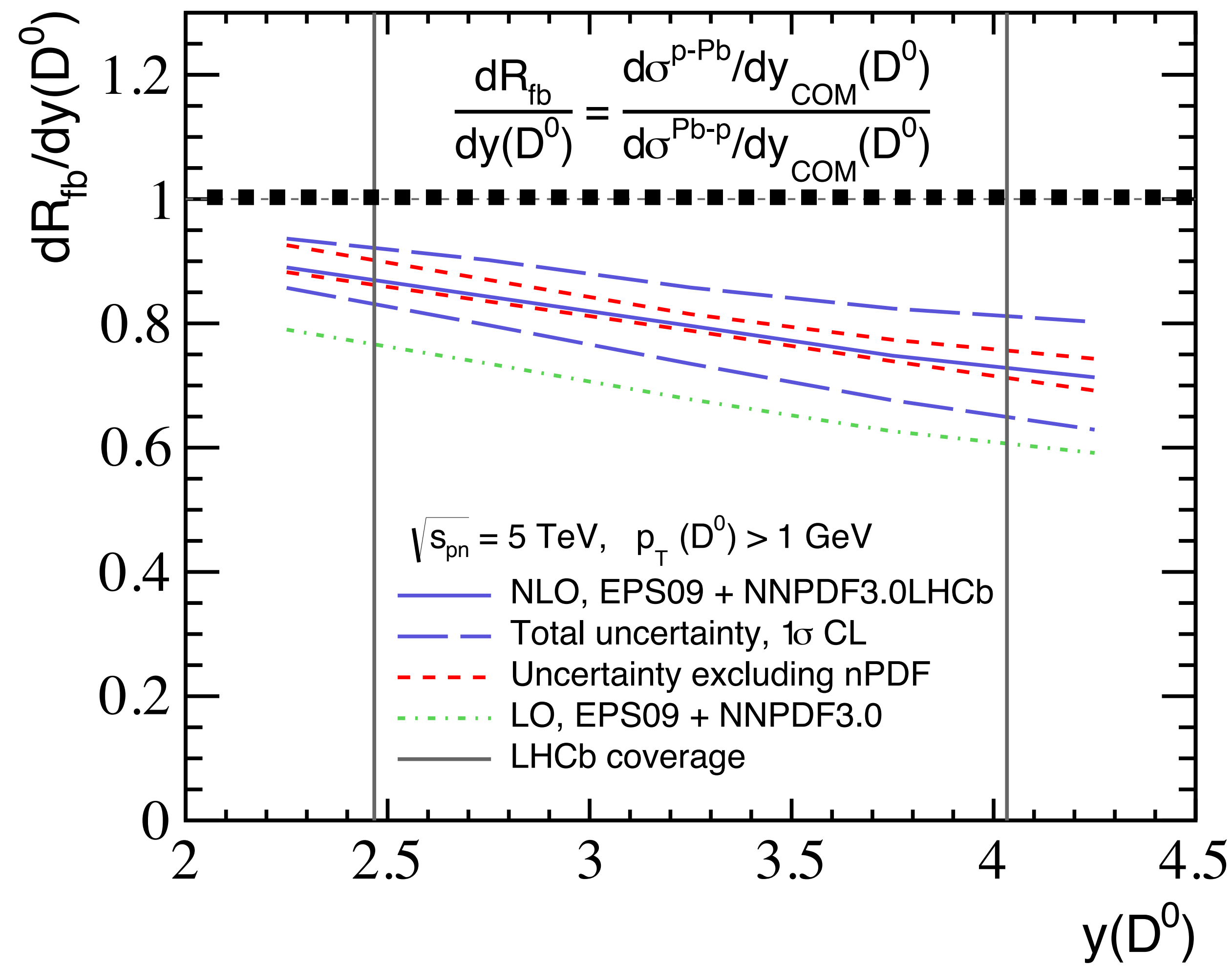
Could also measure:
$$\frac{d^2\sigma}{dy\,dp_T}\Big|_{5TeV} \Big/ \frac{d^2\sigma}{dy\,dp_T}\Big|_{8TeV}$$

nPDF effects ~ cancel for p-Pb / p-Pb

Cross section and Rfb predictions

More details provided in arXiv: RG 1508.07629





$$\frac{dR_{fb}}{dx} \equiv \frac{d\sigma^{pPb}(x)}{dx} \bigg/ \frac{d\sigma^{Pbp}(x)}{dx}$$

1) D predictions better understood than J/psi
2) Higher stats, and better systematics?