Phenomenological implications of modern PDF determinations

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CERN TH Department

DIS2024 - Grenoble April 2024

Lucian's talk on Monday morning

Why do we care about PDFs?

- The LHC is a Standard Model precision machine, and PDFs are a key ingredient in this. Increasingly a limiting factor:

W mass

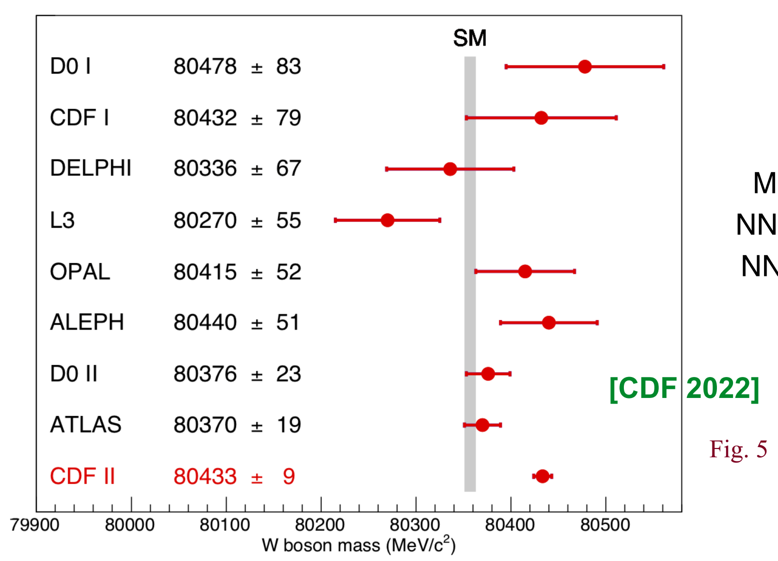


Fig. 5

SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ (PDG 2020)

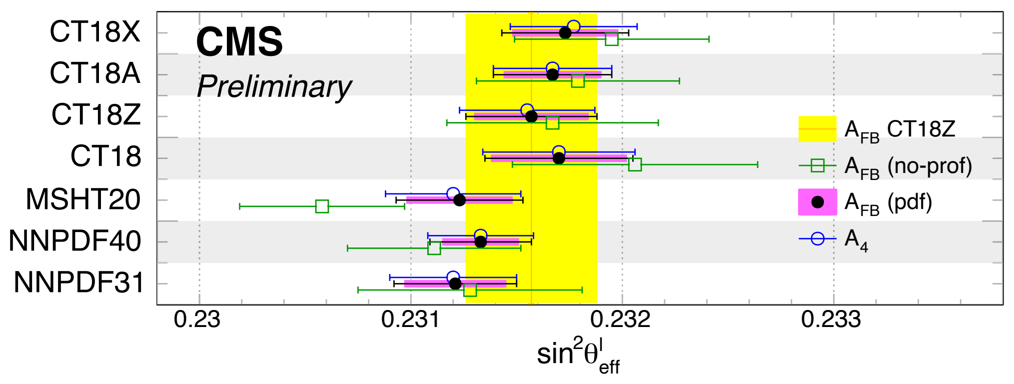
LHCb measurement : $M_W = 80{,}354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ *JHEP* 2022, 36 (2022)

PDF unc. of CDF / ATLAS / LHCb: 3.9 / 8 / 9 MeV

$\sigma_{\text{PDF}} \sim \sigma_{\text{tot}}/2$

(up to)

$\sin^2\theta^l_{\text{eff}}$

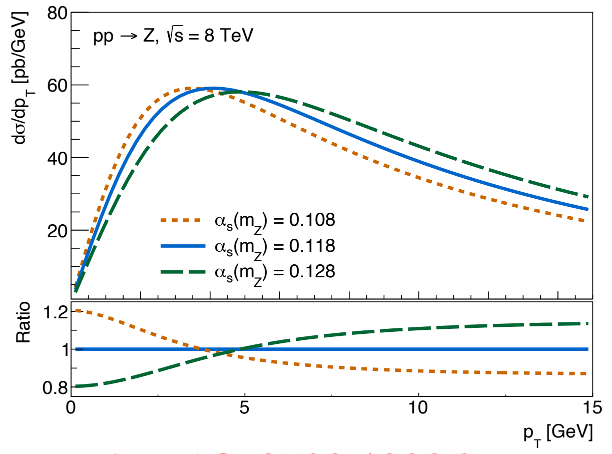


CMS PAS SMP-22-010

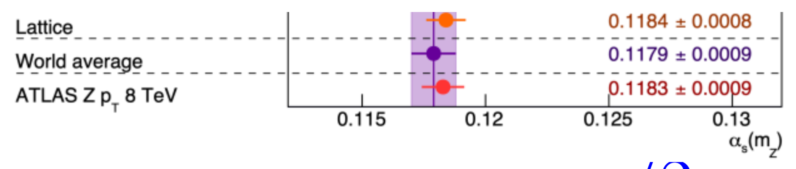
$\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00010(\text{stat}) \pm 0.00015(\text{syst}) \pm 0.00009(\text{theo}) \pm 0.00027(\text{PDF})$,

$\sigma_{\text{PDF}} \sim \sigma_{\text{tot}}$

α_S



ATLAS, 2309.12986



$\sigma_{\text{PDF}} \sim \sigma_{\text{tot}}/2$

Disclaimer: will generally refer to papers by their arxiv number, even if published.

4

Pavel's talk earlier today

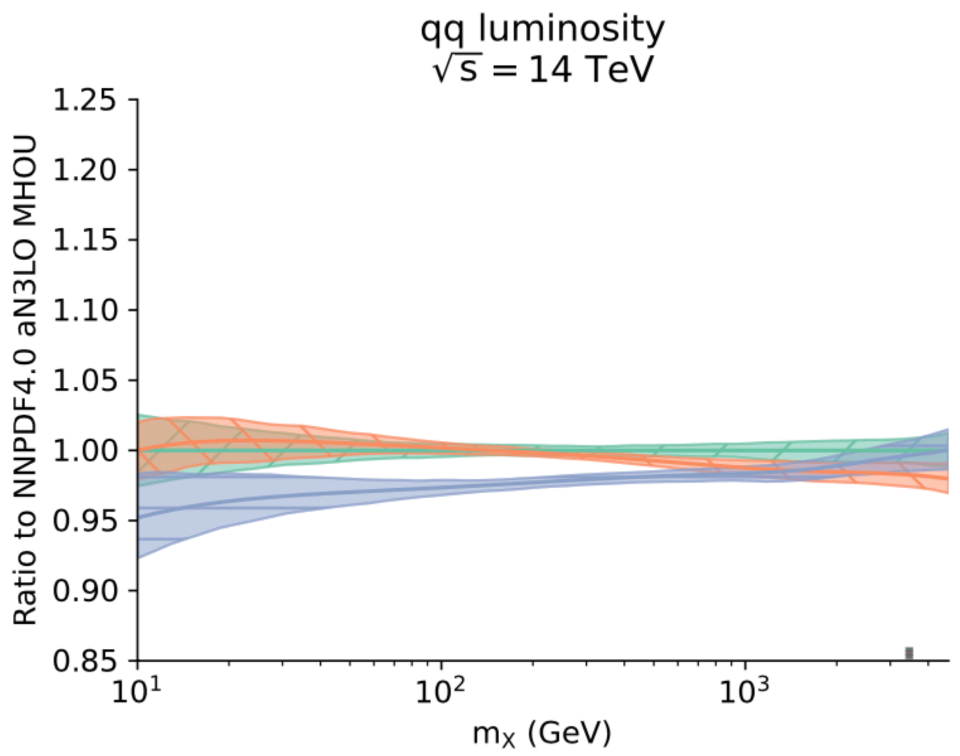
Toward a new generation of CT202X PDFs

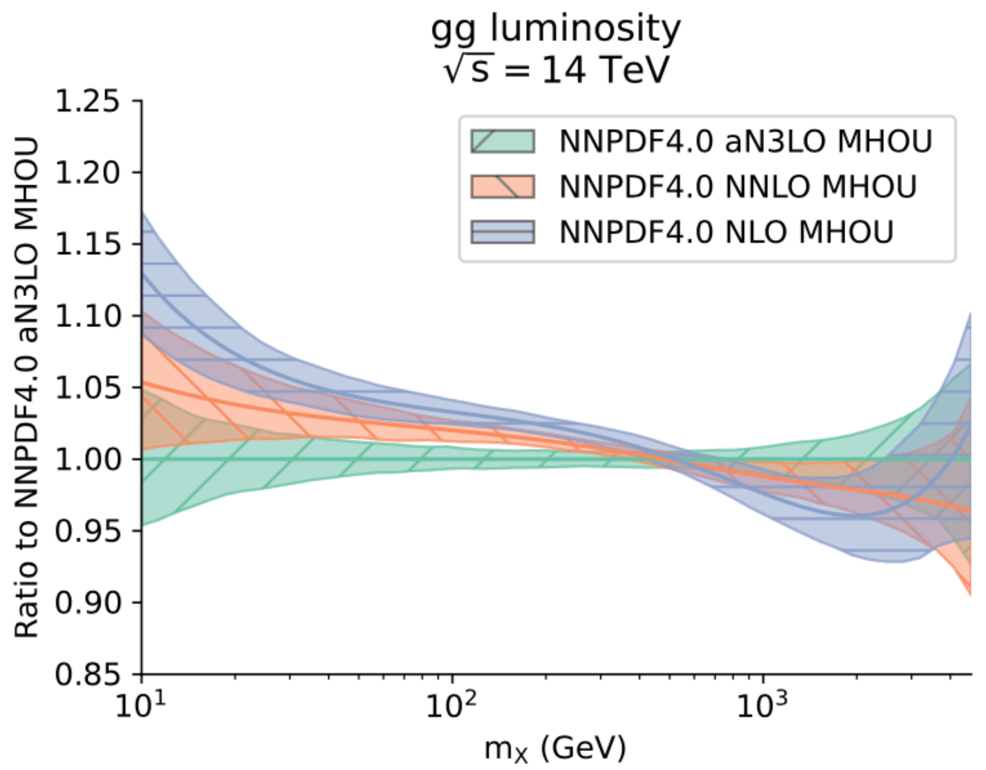
1. Multiple preliminary NNLO fits with LHC Run-2 (di)jet, vector boson, tt̄ data
   based on the selections of experiments recommended in 2305.10733, 2307.11153
2. Work on implementation of N3LO contributions
3. Next-generation PDF uncertainty quantification: Bézier curves, META combination, ML stress-testing, multi-Gaussian approaches, …
4. Physics applications
   a. QCD+QED PDFs for a neutron
   b. PDF dependence of forward-backward asymmetry
   c. An L2 sensitivity study using xFitter
   d. Pion PDFs
   e. …

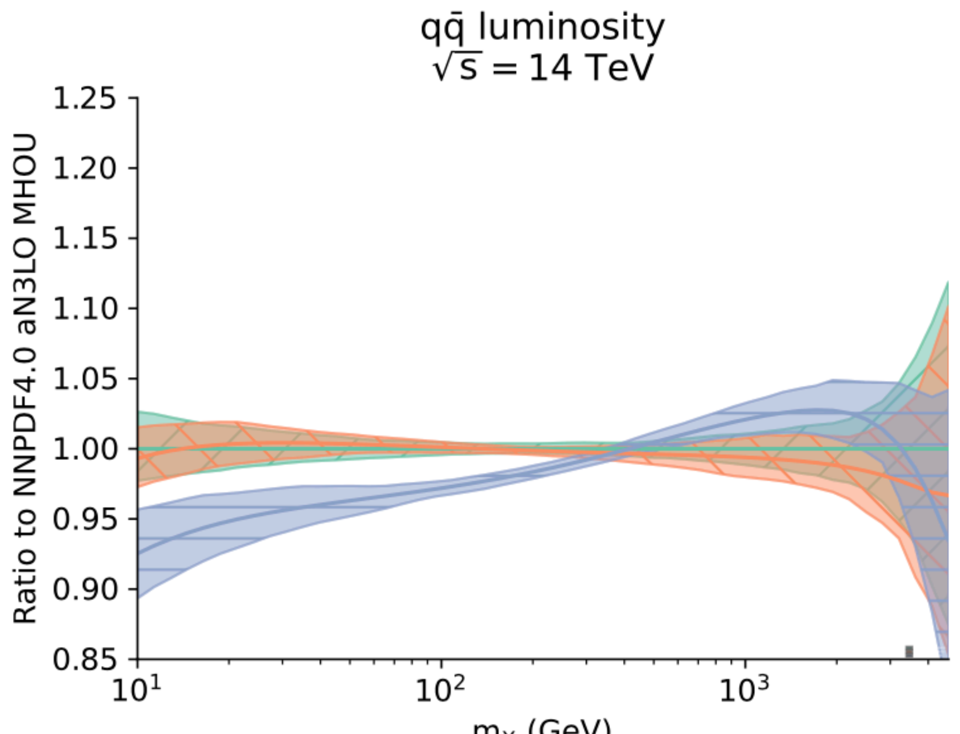
2024-04-09 P. Nadolsky, DIS 2024 3

Juan R's talk earlier today

Results: perturbative convergence







- **Good perturbative convergence**
- Impact of N³LO corrections moderate, specially for the quark luminosities
- For the gluon-gluon luminosity, NNPDF4.0 finds a **small suppression** around Higgs mass (2% effect)

Global Fit Quality at aN^{3}LO

The overall χ^2 follows the general trend one may expect from perturbation theory.

	LO	NLO	NNLO	aN^{3}LO
$\chi^2_{N_{pts}}$	2.57	1.33	1.17	1.14

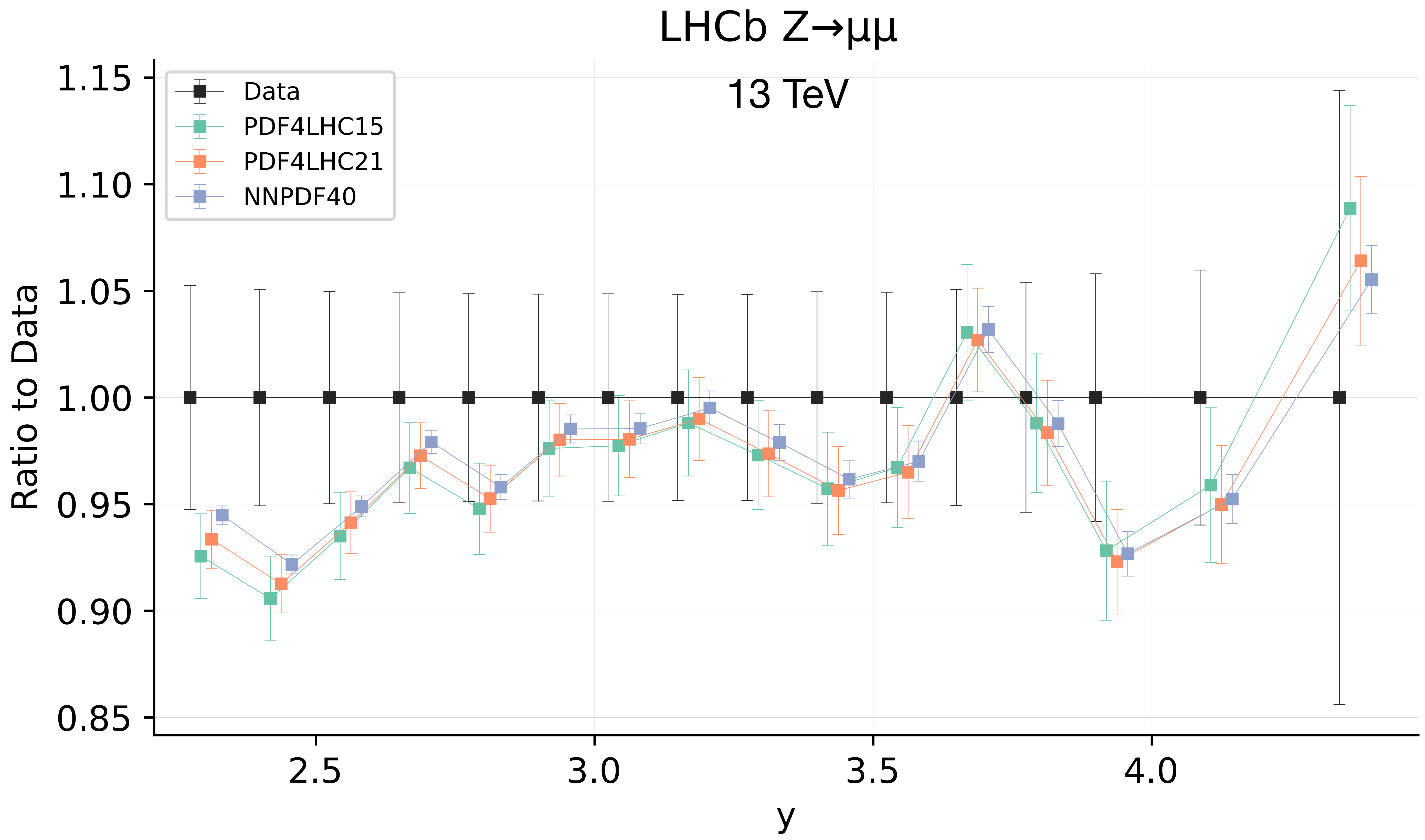
Evidence that including aN^{3}LO has reduced tensions between small and large-x.

Robert talk earlier today

2

Getting more accurate and precise over time

slowly but surely

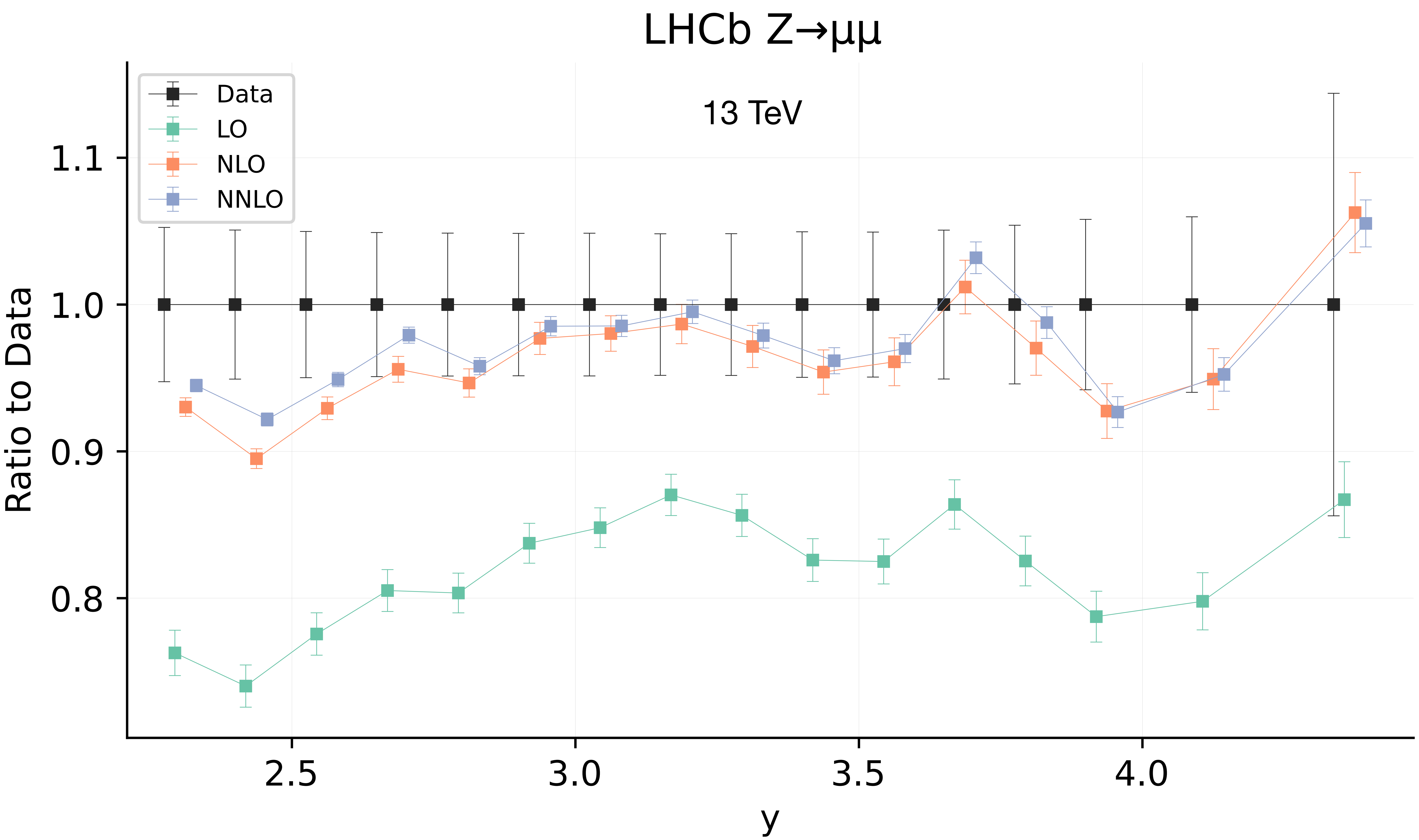


PDF4LHC15:
- **NNPDF30**
- **MMHT2014**
- **CT14**

PDF4LHC21
- **NNPDF31**
- **MSHT20**
- **CT18**

NNPDF40:
(released around the time of PDF4LHC21, more data included, such as: the distribution shown)

and over orders...



With the NNPDF40 version of the corresponding order:

- NNPDF40_nnlo_as_01180
- NNPDF40_nlo_as_01180
- NNPDF40_lo_as_01180

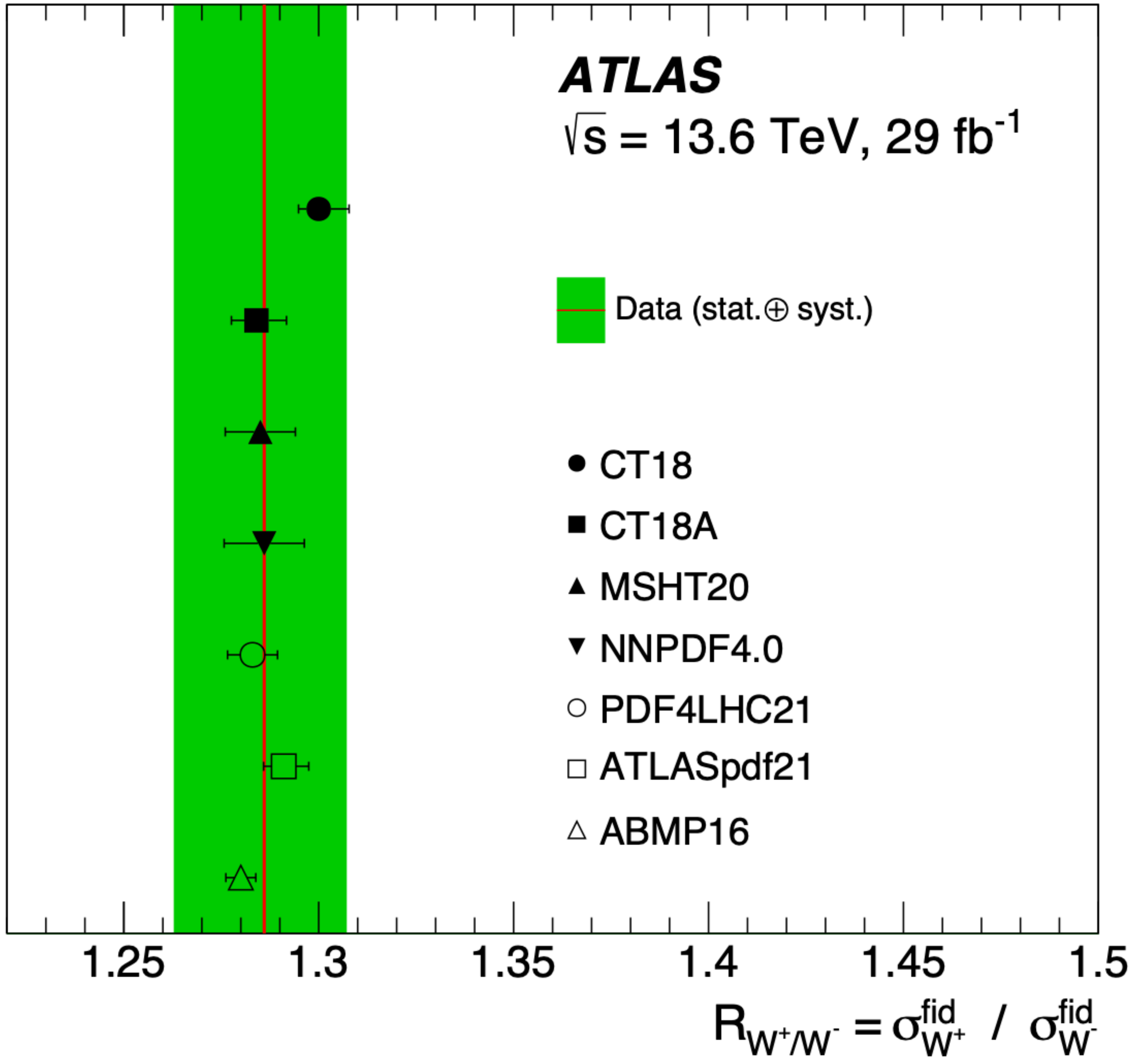
Accurate and trustworthy theory predictions are an essential ingredient of any PDF fit.

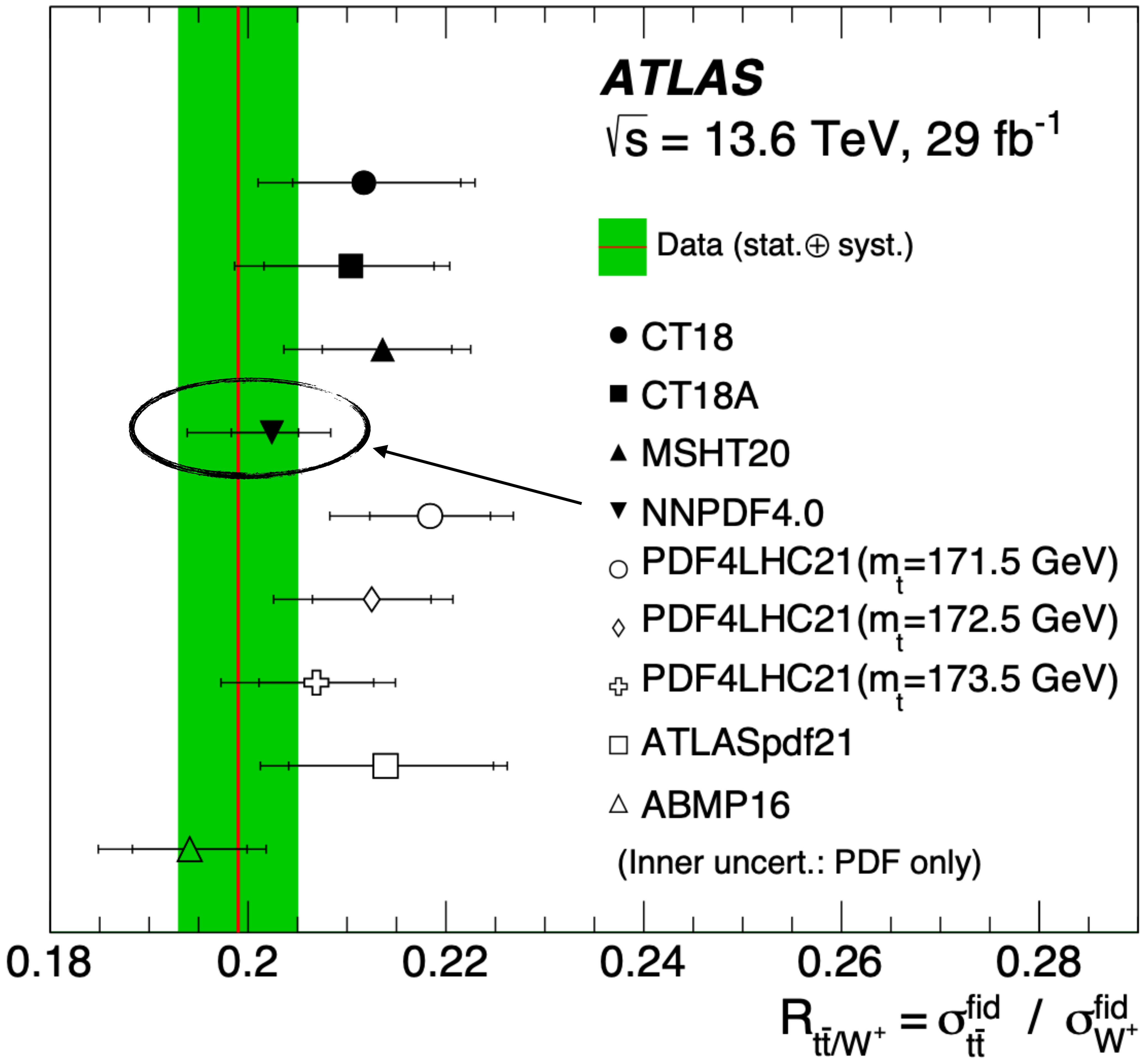
This dataset was of course included in the fit… let's look at something more recent

What's the phenomenological impact of the choice of PDF?

2403.12902

Measurement of vector boson production cross section and their ratios at $\sqrt{s} = 13.6$ with the ATLAS detector





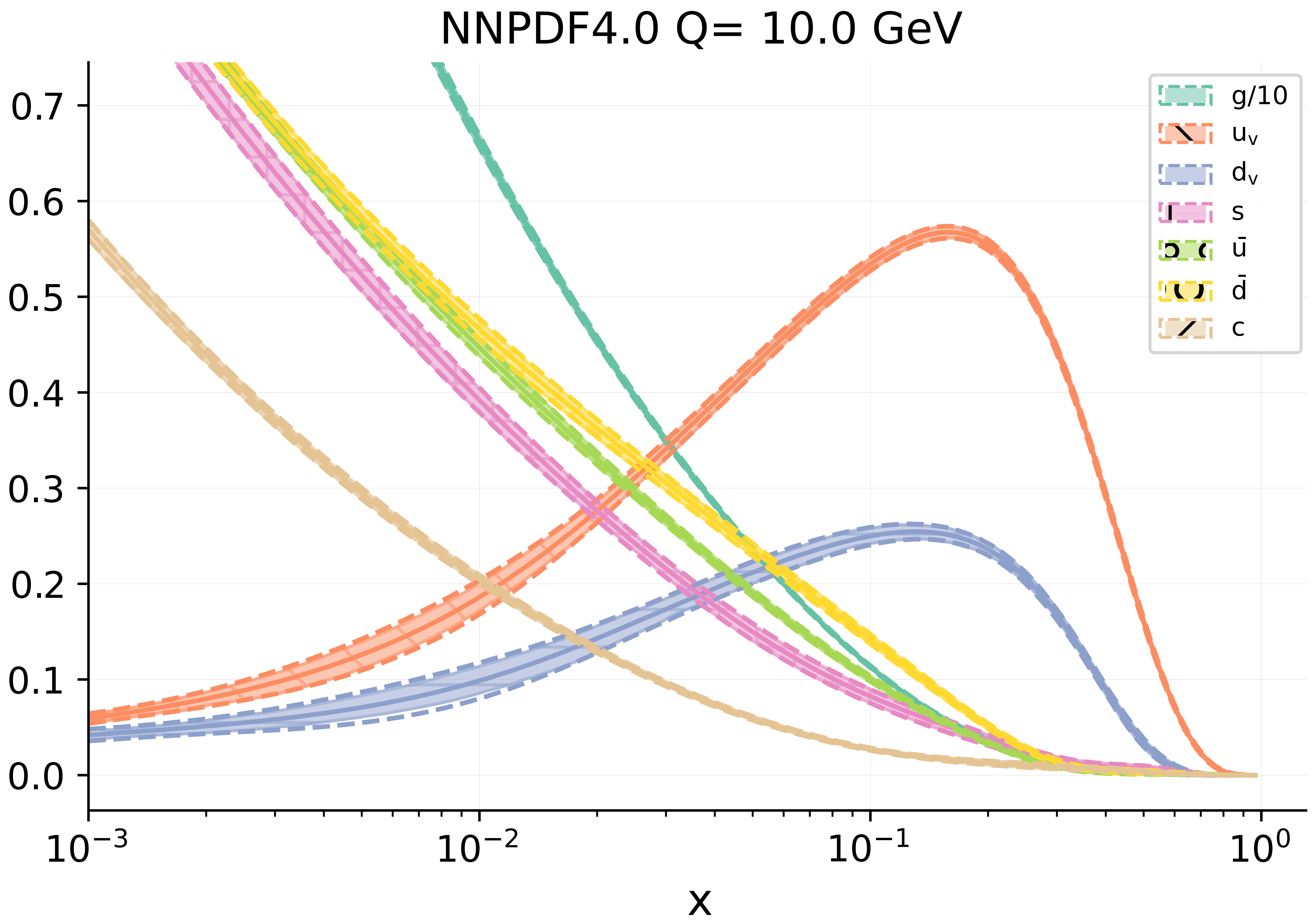
PDF4LHC21 combination - hep-ph/2203.05506

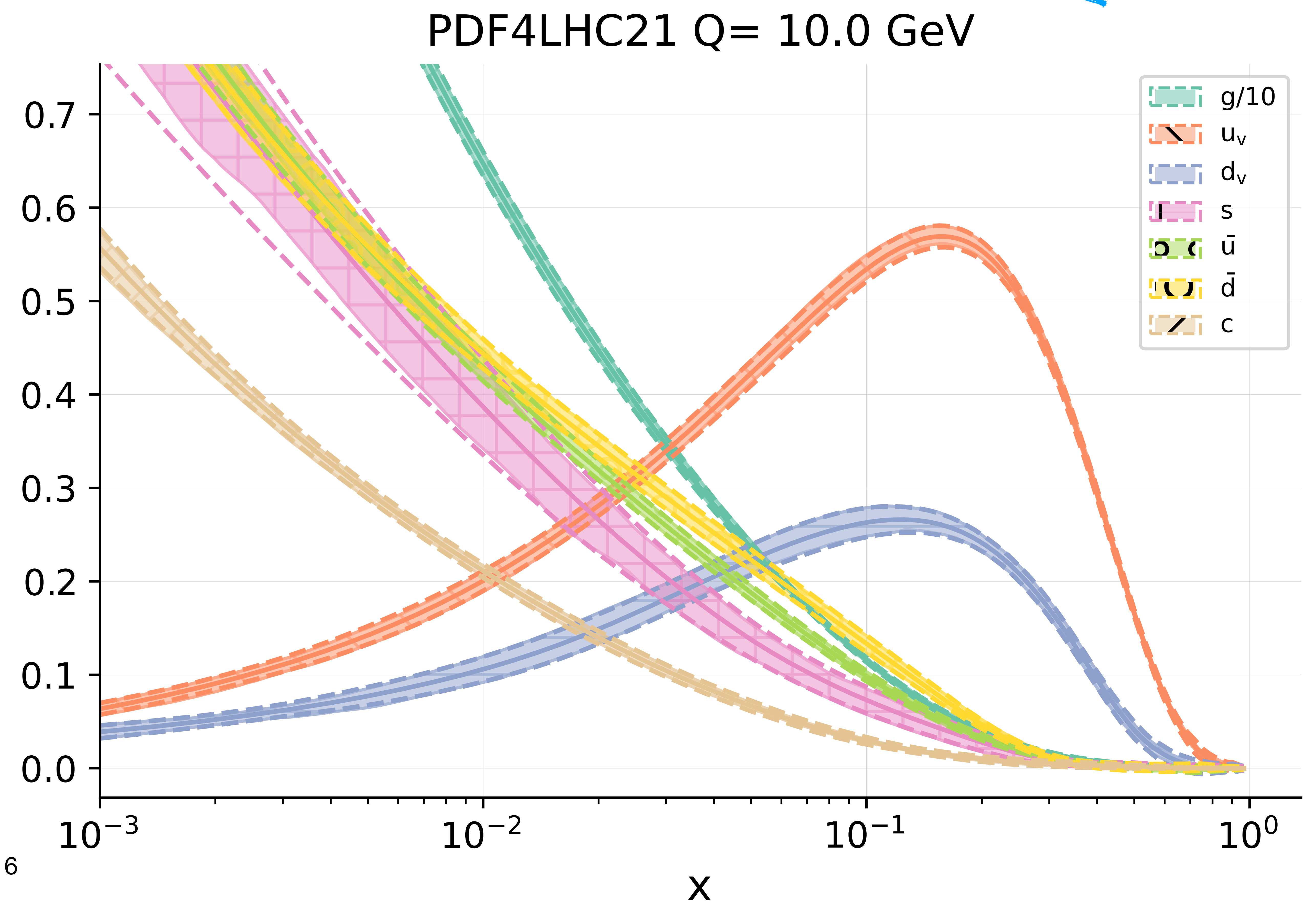
NNPDF4.0 not included in the PDF4LHC21 combination as it came out when PDF4LHC21 was already at a very advanced stage.

A comparison of NNPDF4.0 and PDF4LHC21 was done in Appendix B of hep-ph/2203.05506

- NNPDF31' (changes to m_c and dataset)
- CT18' (changes to m_c)
- MSHT20

We see smaller uncertainties (~1% in some regions) for NNPDF4.0 when comparing, i.e., to PDF4LHC21

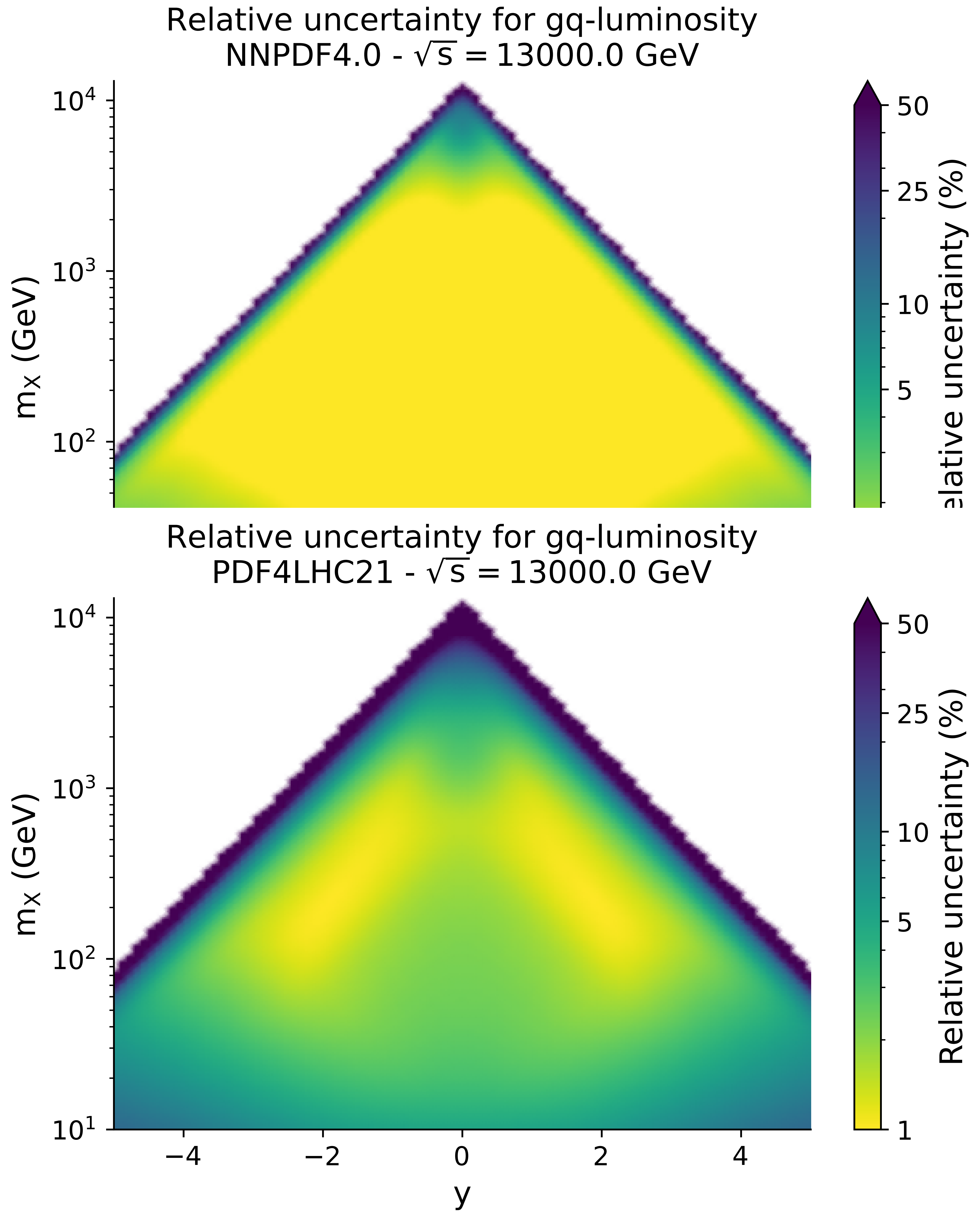




Do the NNPDF4.0 uncertainties have a sizeable effect when comparing against data not included in the determination?

We will systematically study the impact of the PDF choice in the agreement between theory and data for datasets not included in the NNPDF4.0 analysis.

Process/Data set
DIS+jets (HERA)
ZEUS, $\mathcal{L} = 38.6$ pb^{-1}, $E_p = 820$ GeV; high Q
ZEUS, $\mathcal{L} = 81.7$ pb^{-1}, $E_p = 920$ GeV; high Q
ZEUS, $\mathcal{L} = 374$ pb^{-1}, $E_p = 920$ GeV; high Q
H1, $\mathcal{L} = 290$ pb^{-1}, $E_p = 920$ GeV; low Q
H1, $\mathcal{L} = 351$ pb^{-1}, $E_p = 920$ GeV; high Q
Inclusive jet and dijet production (LHC)
ATLAS, $\mathcal{L} = 3.2$ fb^{-1};
CMS, $\mathcal{L} = 36.3$ fb^{-1};
Top pair production (LHC)
ATLAS, $\mathcal{L} = 36$ fb^{-1}, 1D and 2D diff. distr., ℓ+jets
ATLAS, $\mathcal{L} = 36$ fb^{-1}, 1D and 2D diff. distr., all had
CMS, $\mathcal{L} = 137$ fb^{-1}, 1D and 2D diff. distr., ℓ+jets



all results are preliminary

PRELIMINARY

Some general notes:

1. All results are NNLO (no k-factor approximation). The program used in each case are mentioned in the corresponding slides.

2. Baseline NNPDF4.0 (no MHOU or N3LO corrections)

3. Comparisons are shown for NNPDF4.0 and PDF4LHC21 to avoid cluttering the plots. More information (comparisons to other sets) in the backup

4. The plot include: absolute comparison, normalized and the size of the PDF (solid) and dashed (theory) uncertainties compared to the data uncertainty. The shaded band includes theory and PDF uncertainties added in quadrature

5. The computation of the χ^2/N is always shown considering as uncertainties either (exp + theory) or (exp + theory + pdf) and over the entire dataset / hepdata entry.

PineAPPL

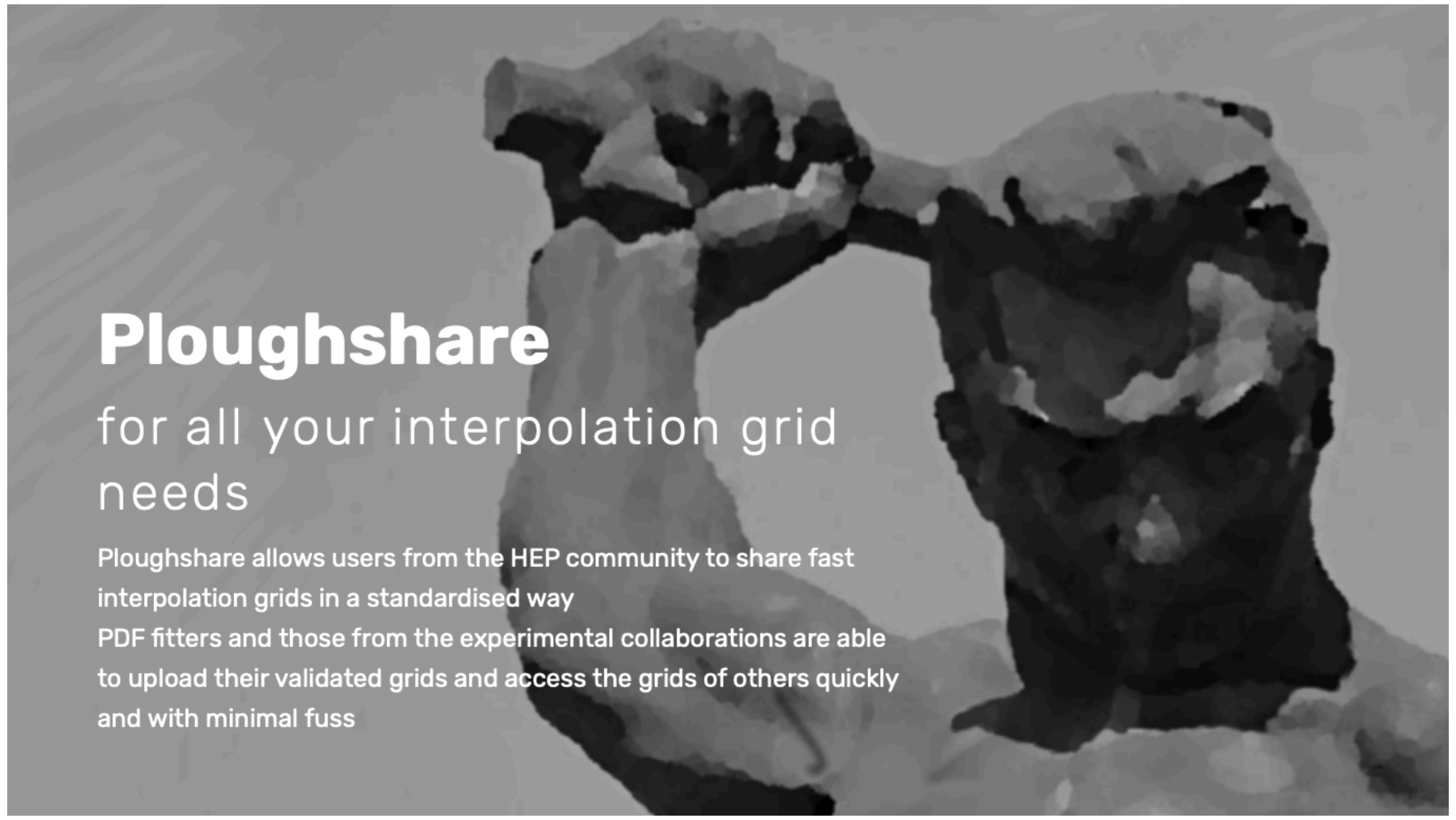
JHEP 12 (2020) 108 - 2008.12789 [hep-ph]
https://nnpdf.github.io/pineappl/

MATRIX

Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
Automates qT-subtraction and Resummation to Integrate X-sections

Eur.Phys.J.C 78 (2018) 7, 537 - 1711.06631 [hep-ph]
https://arxiv.org/abs/1711.06631

NNLOJET



https://ploughshare.web.cern.ch/ploughshare/

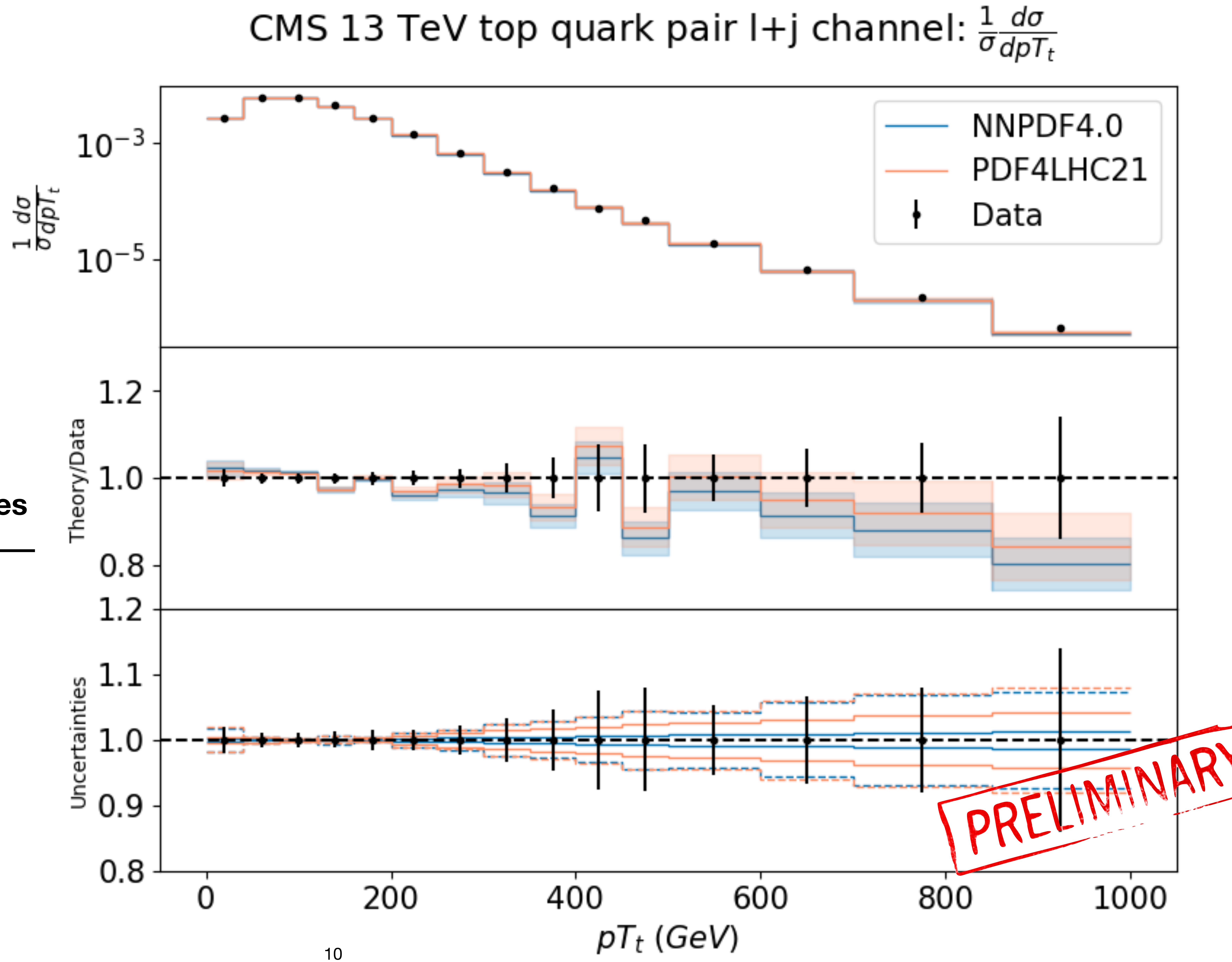
As usual, all code, data, etc will be available at https://nnpdf.mi.infn.it/nnpdf-open-source-code/

CMS TTB

Differential $t\bar{t}$ production at $\sqrt{s} = 13$ TeV

Predictions: MATRIX
Hepdata: 10.17182/hepdata.102956

χ^2/N	Only exp. and th. unc.	All uncertainties
PDF4LHC21	0.658	0.647
NNPDF40	0.817	0.811

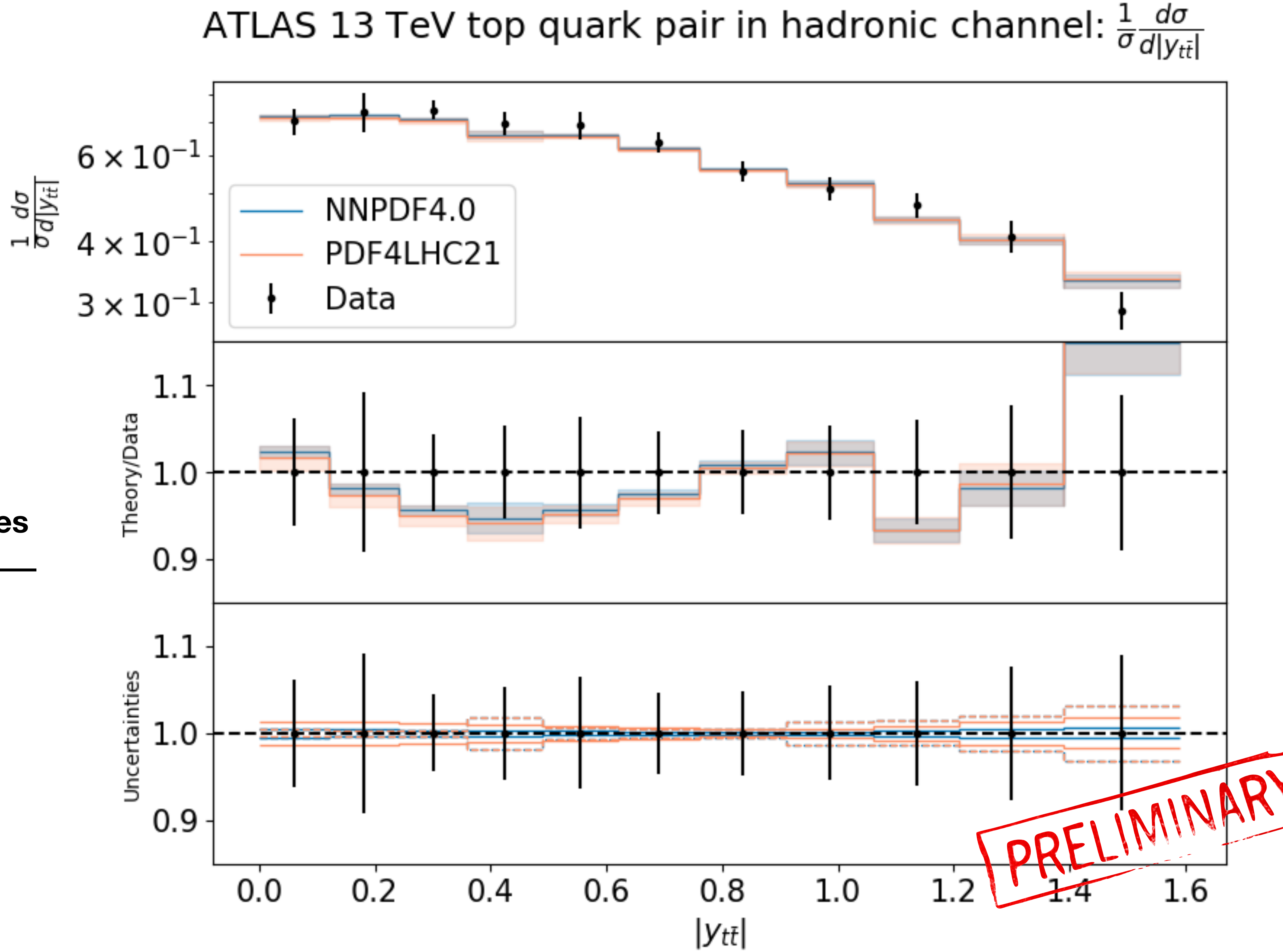


ATLAS TTB

Differential $t\bar{t}$ production at $\sqrt{s} = 13$ TeV

Predictions: MATRIX
Hepdata: 10.17182/hepdata.95758

χ^2/N	Only exp. and th. unc.	All uncertainties
PDF4LHC21	0.772	0.750
NNPDF40	0.713	0.711

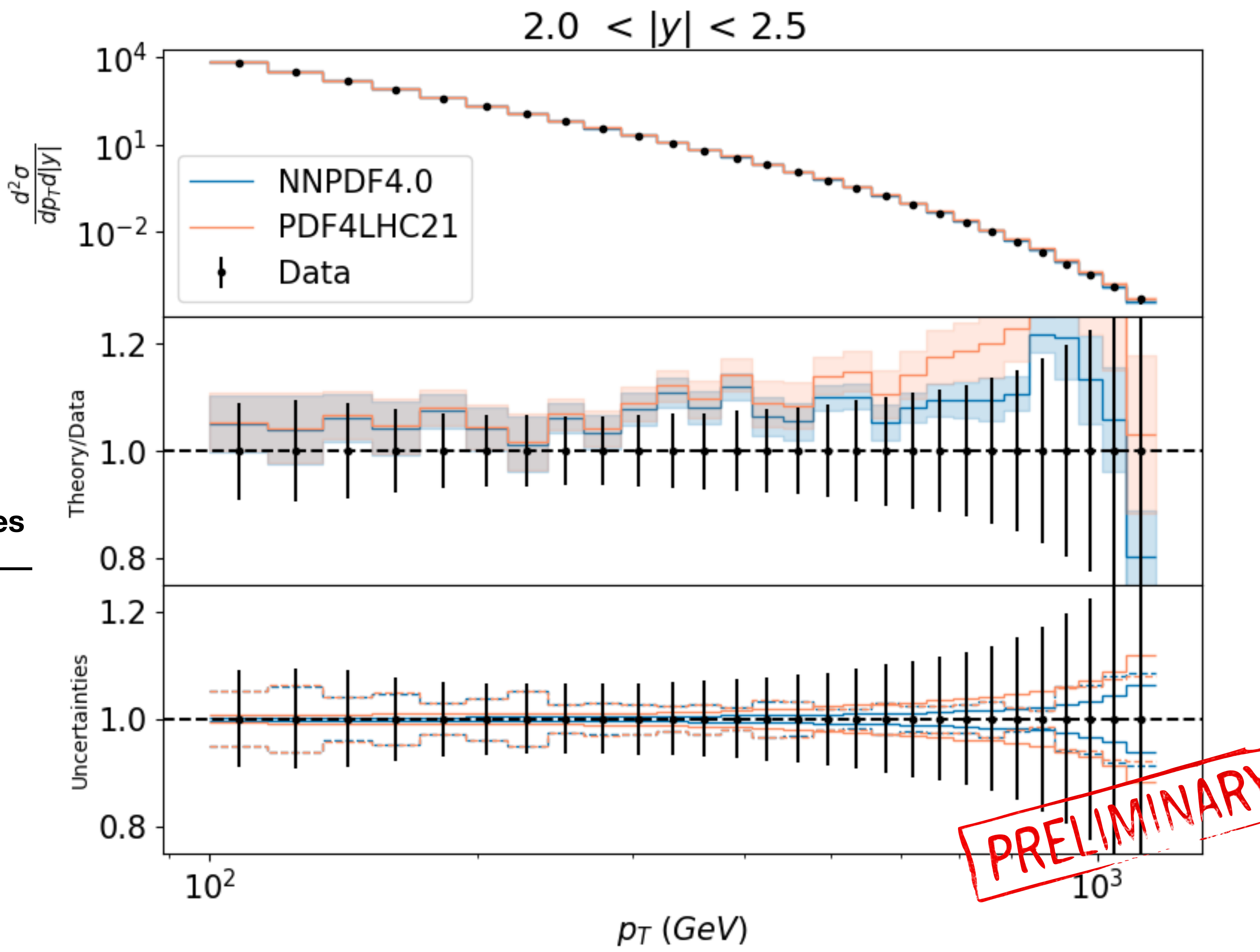


Atlas 1jet

Inclusive jet cross-sections at $\sqrt{s} = 13$ TeV. Dataset with 3.2fb-1 2015.
Leading color NNLO correction

Predictions: NNLOJET (plougshare)
Hepdata: 10.17182/hepdata.79952

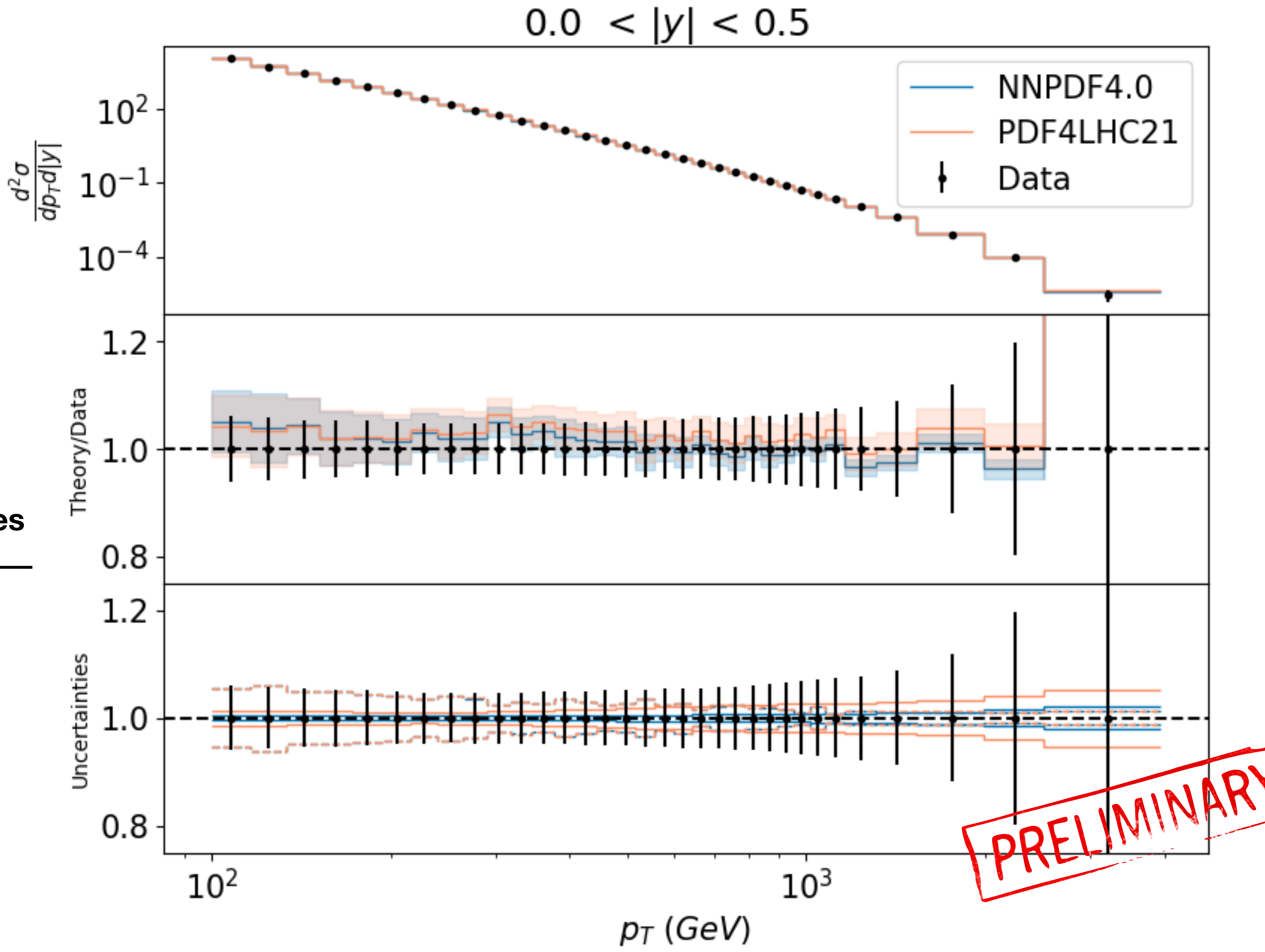
χ^2/N	Only exp. and th. unc.	All uncertainties
PDF4LHC21	4.62	3.93
NNPDF40	4.78	4.59



Atlas 1jet

We find a score of Z = 16.87, which points to instabilities in the covariance matrix. Indeed, when we regularize with the recipe from EPJ C82 (2022) 956 the χ^2 looks a bit better.

χ^2/N	**Only exp. and th. unc.**	**All uncertainties**
PDF4LHC21	1.88	1.58
NNPDF40	1.83	1.74

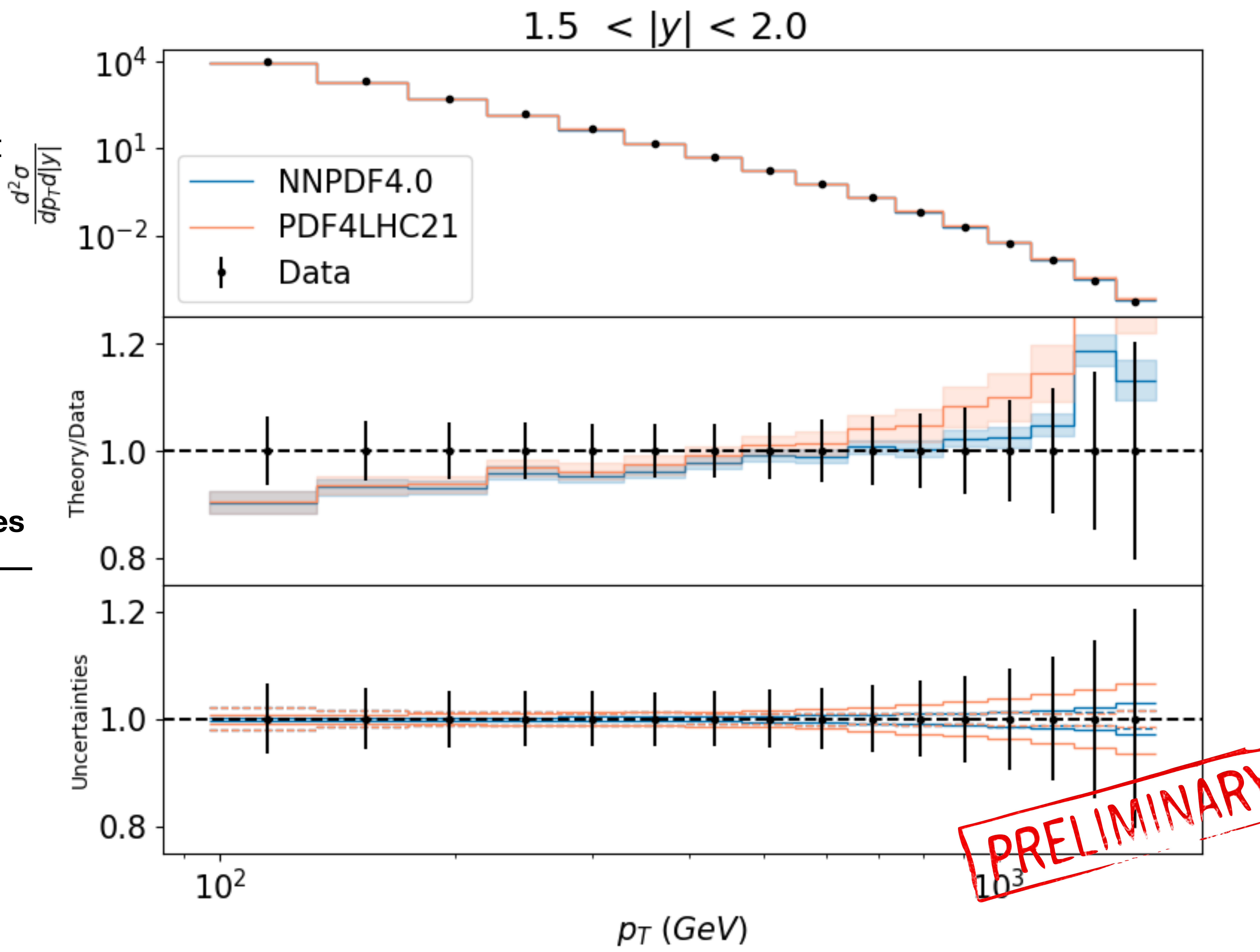


CMS 1jet

Inclusive jet cross-sections at $\sqrt{s} = 13$ TeV. Dataset with 33.5fb-1 (data for anti-kT radius of 0.7)
Leading color NNLO correction

Predictions: NNLOJET (plougshare)
Hepdata: 10.17182/hepdata.115022.v2

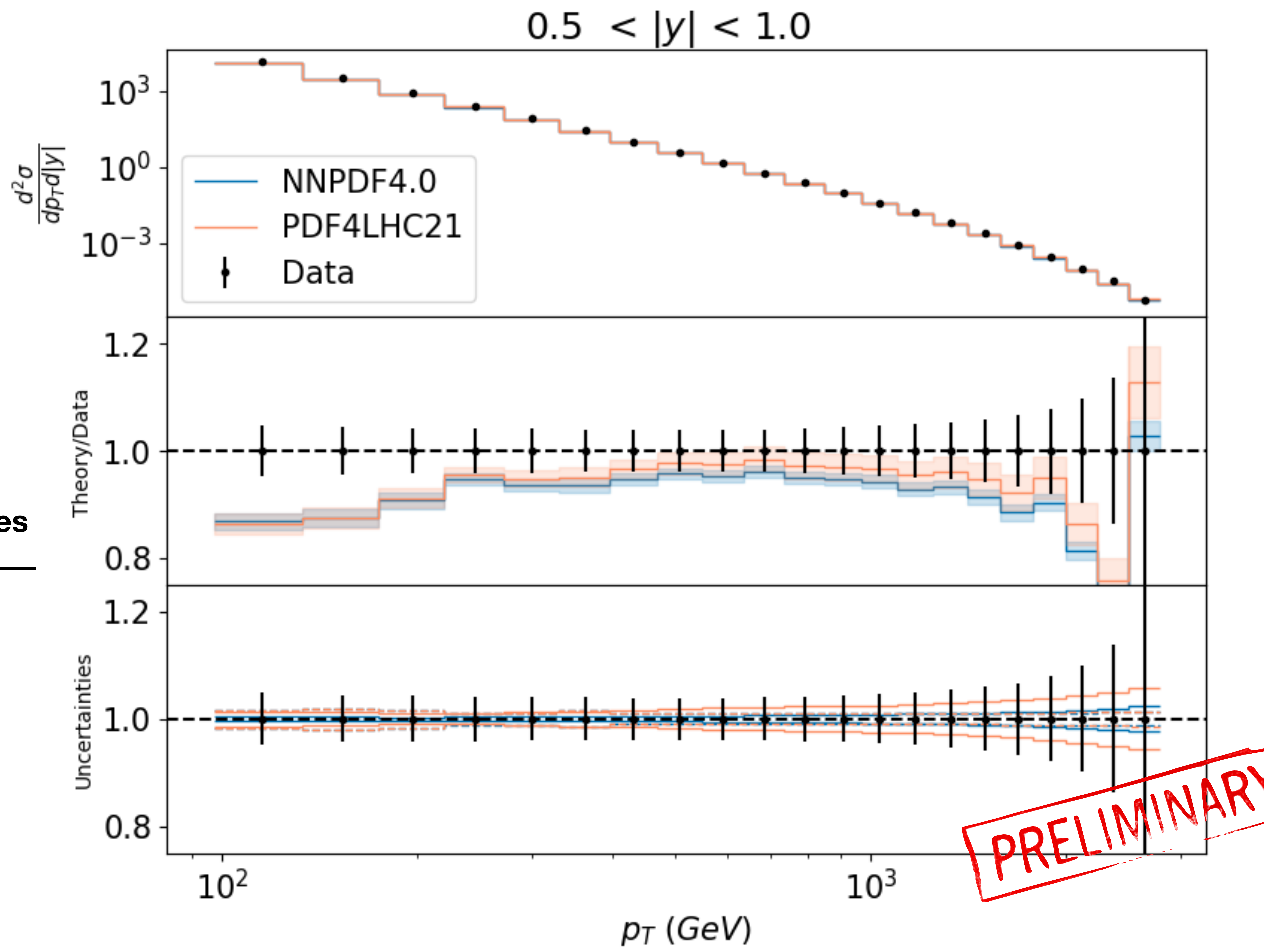
χ^2/N	Only exp. and th. unc.	All uncertainties
PDF4LHC21	4.76	2.85
NNPDF40	3.81	3.23



CMS 1jet

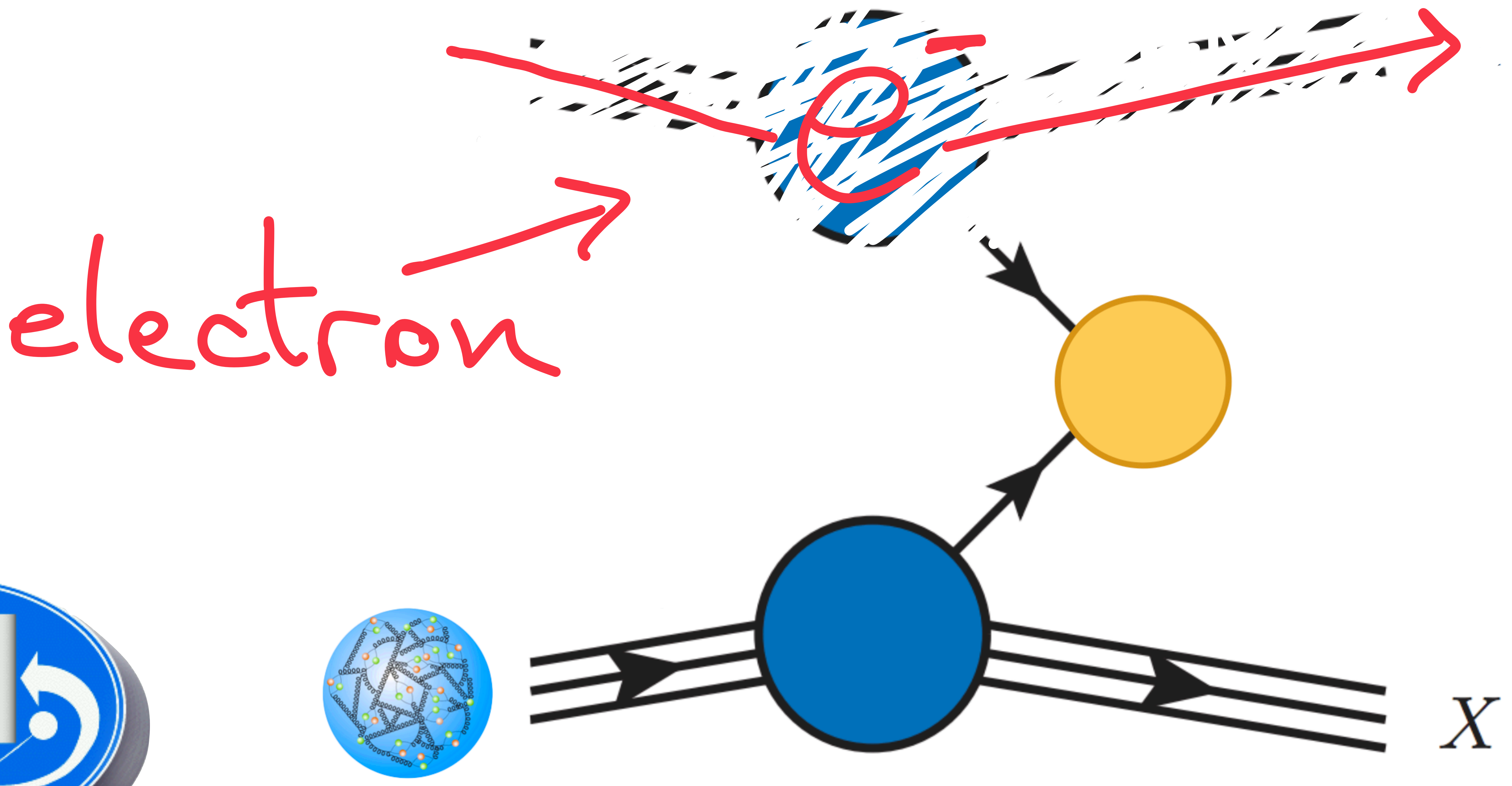
Similar issues with the covariance matrix were found, Z = 14.81

χ^2/N	**Only exp. and th. unc.**	**All uncertainties**
PDF4LHC21	2.15	1.37
NNPDF40	1.69	1.51



Let's not forget where we are…

…because we don't always have 2 protons



Note: The DIS + j data from HERA is not included in the NNPDF fits (although its possible impact was already assessed in the release paper of 4.0 hep-ph/2109.02653)

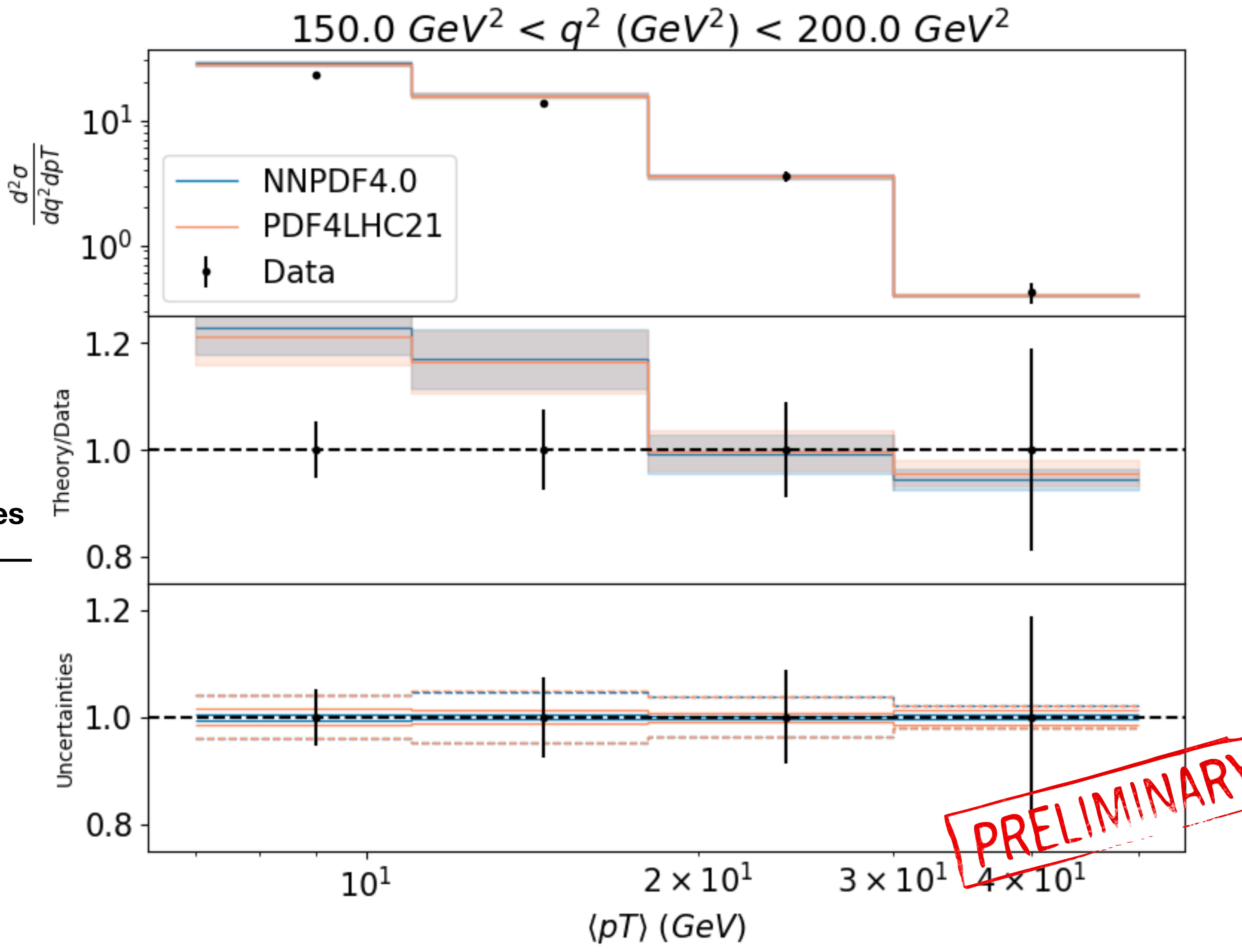
H1 dijet

Data taken from 2003 to 2007, integrated luminosity of 351pb-1

Predictions: NNLOJET (plougshare)

Hepdata: 10.17182/hepdata.64353

χ^2/N	Only exp. and th. unc.	All uncertainties
PDF4LHC21	1.50	1.49
NNPDF40	1.54	1.50

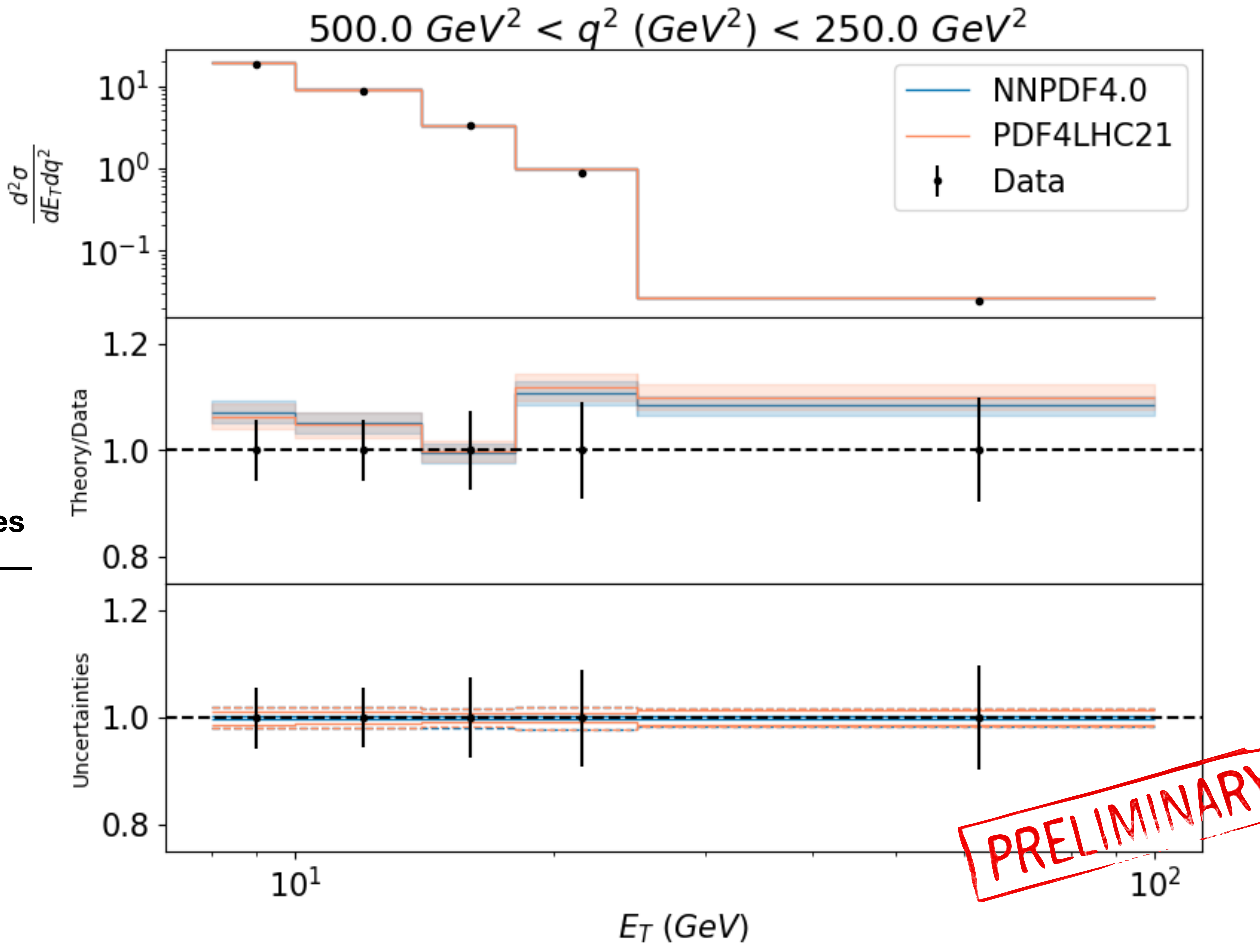


Zeus 1jet

Inclusive jet differential cross section, integrated luminosity of 82pb-1

Predictions: NNLOJET (plougshare)
Hepdata: 10.17182/hepdata.45641

χ^2/N	Only exp. and th. unc.	All uncertainties
PDF4LHC21	0.819	0.817
NNPDF40	0.813	0.813



Conclusions:

In this talk we have seen several examples by comparing NNPDF4.0 to PDF4LHC21 (as a proxy for NNPDF3.1, CT18, MSHT20) and the following trends emerge:

- While PDF uncertainties are smaller, the data-theory description in terms of χ^2/N is similar to that of PDF4LHC21.
- When comparing to data not included in the fit, predictions for NNPDF4.0 seem to fall close the data -> hinting that the improvement in precision (smaller uncertainties than 3.1) came with an improvement in accuracy
- Oscillations far from the data can have big scale uncertainties, luckily the era of N3LO PDFs is starting now!

Thanks!

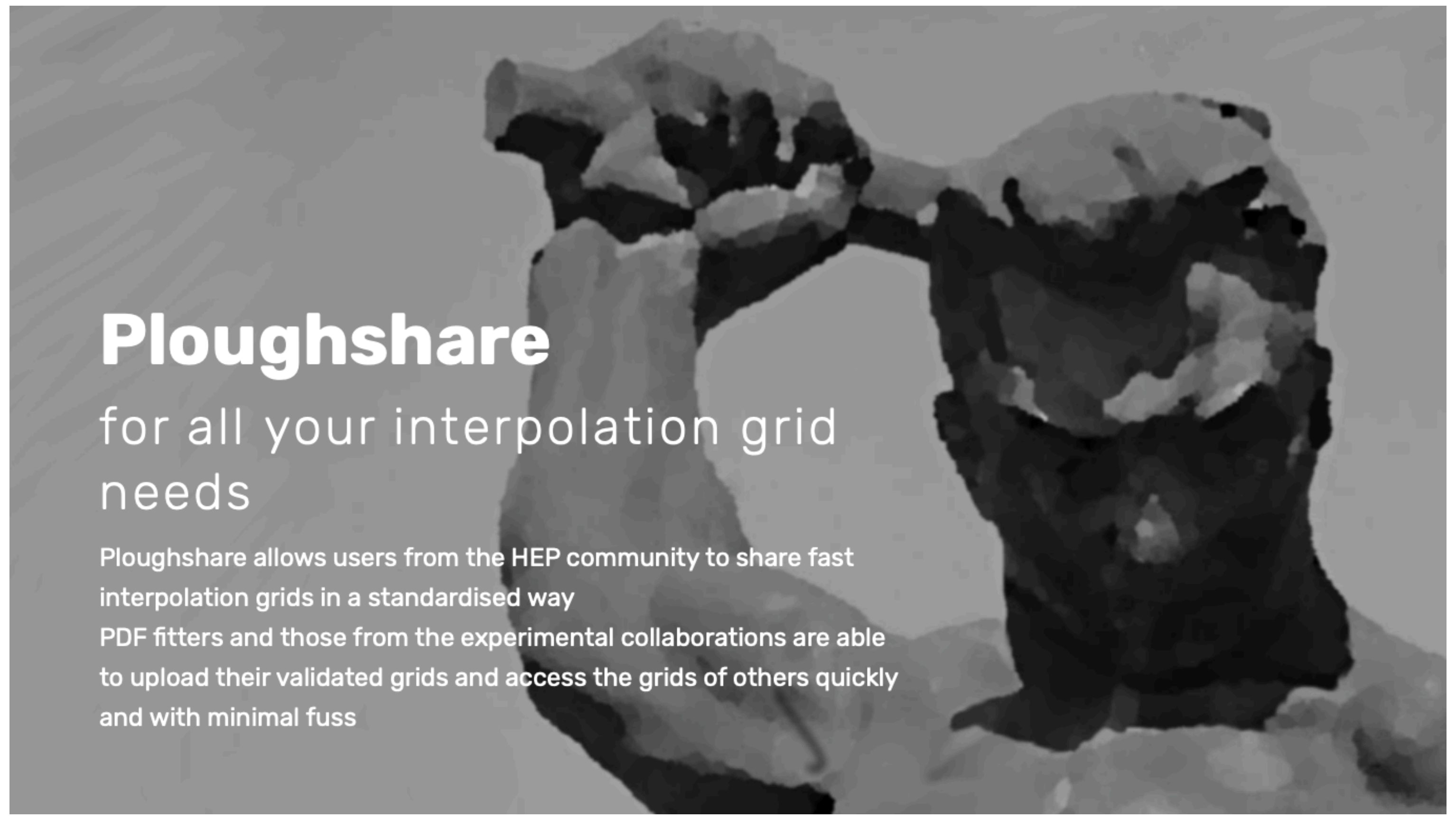
and special thanks to:

PineAPPL

the APPLgrid project

MATRIX

Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
Automates qT-subtraction and Resummation to Integrate X-sections



fastNLO

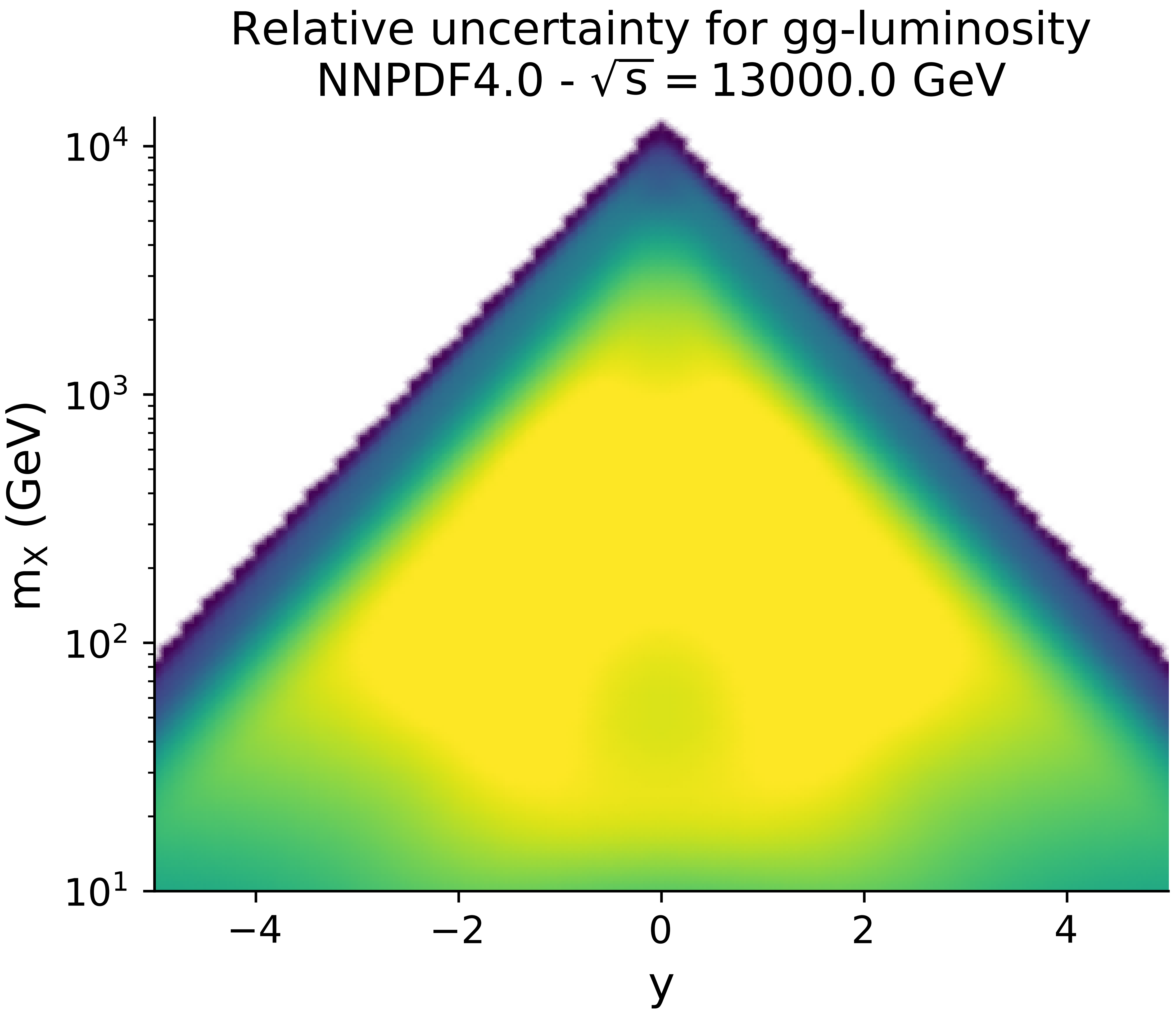
NNLOJET

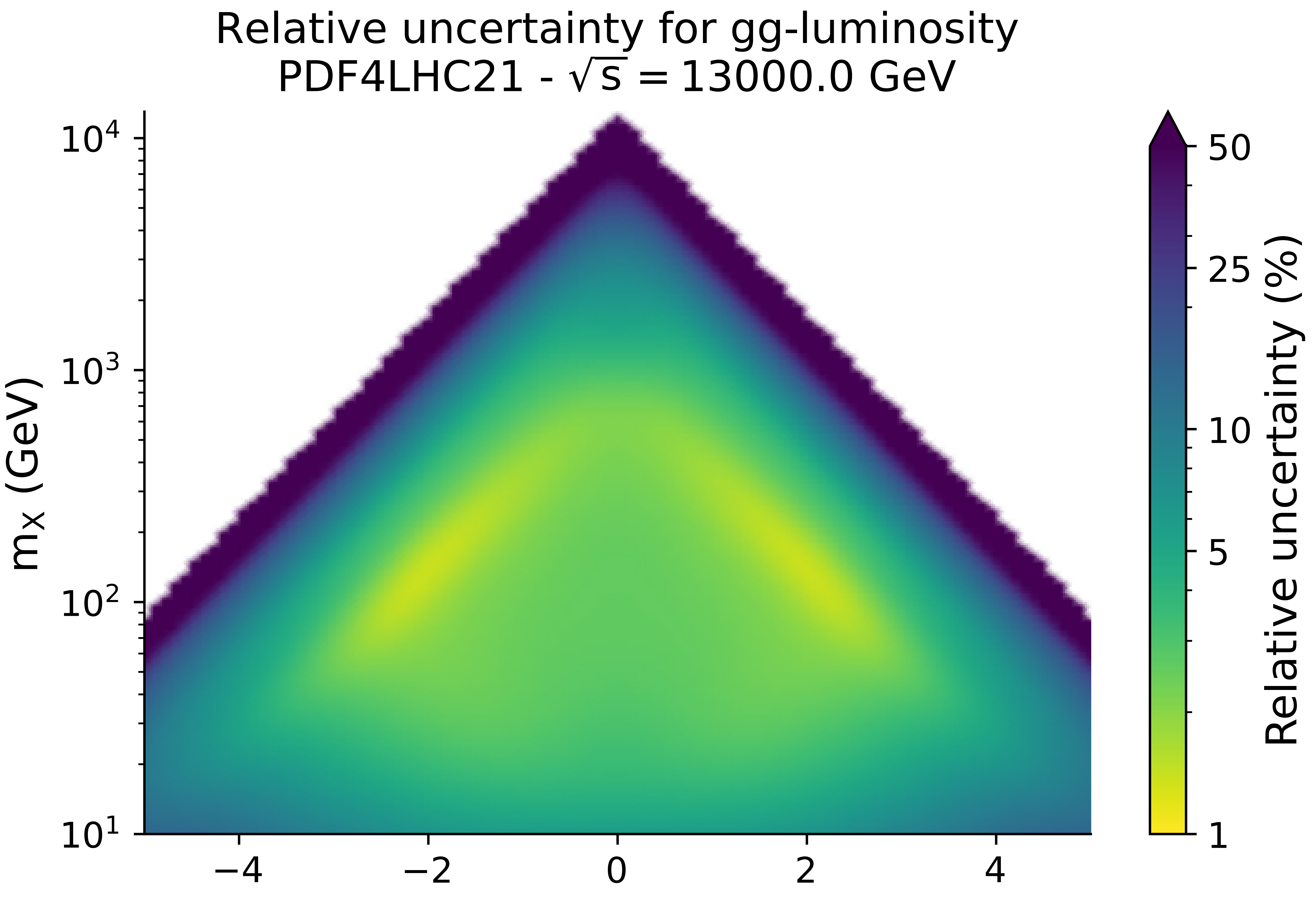
HEPData

Backup

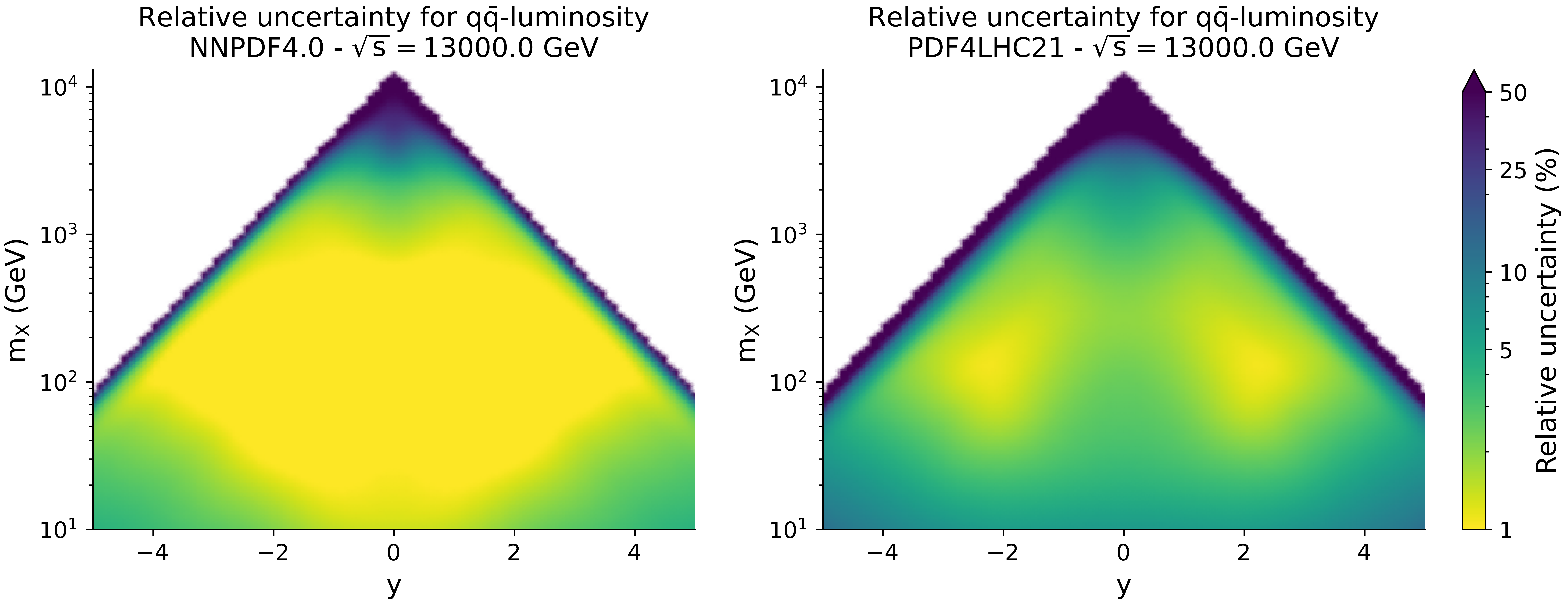
Uncertainty comparison - gq

Uncertainty comparison - gg





Uncertainty comparison - qqbar



More datasets under consideration

Z p_T and Z+jet
ATLAS, $\mathcal{L} = 36$ pb^{-1}, normalised cross section
ATLAS, differential cross sections ($\mathcal{L} = 139$ fb^{-1})
CMS, differential cross sections ($\mathcal{L} = 36$ fb^{-1})

Drell Yan
ATLAS W, Z $\sqrt{s} = 2.76$ TeV cross sections and asymmetries
ATLAS W, Z $\sqrt{s} = 5$ TeV differential cross sections
CMS Z $\sqrt{s} = 13$ TeV differential cross sections ($\mathcal{L} = 2.3$ fb^{-1})
CMS Z $\sqrt{s} = 13$ TeV A_{FB} ($\mathcal{L} = 139$ fb^{-1})
LHCb Z $\sqrt{s} = 13$ TeV forward Z production ($\mathcal{L} = 5$ fb^{-1})

$W + c$
ATLAS $\sqrt{s} = 13$ TeV differential cross sections ($\mathcal{L} = 139$ fb^{-1})
CMS $\sqrt{s} = 8$ TeV differential cross sections ($\mathcal{L} = 18.4$ fb^{-1})

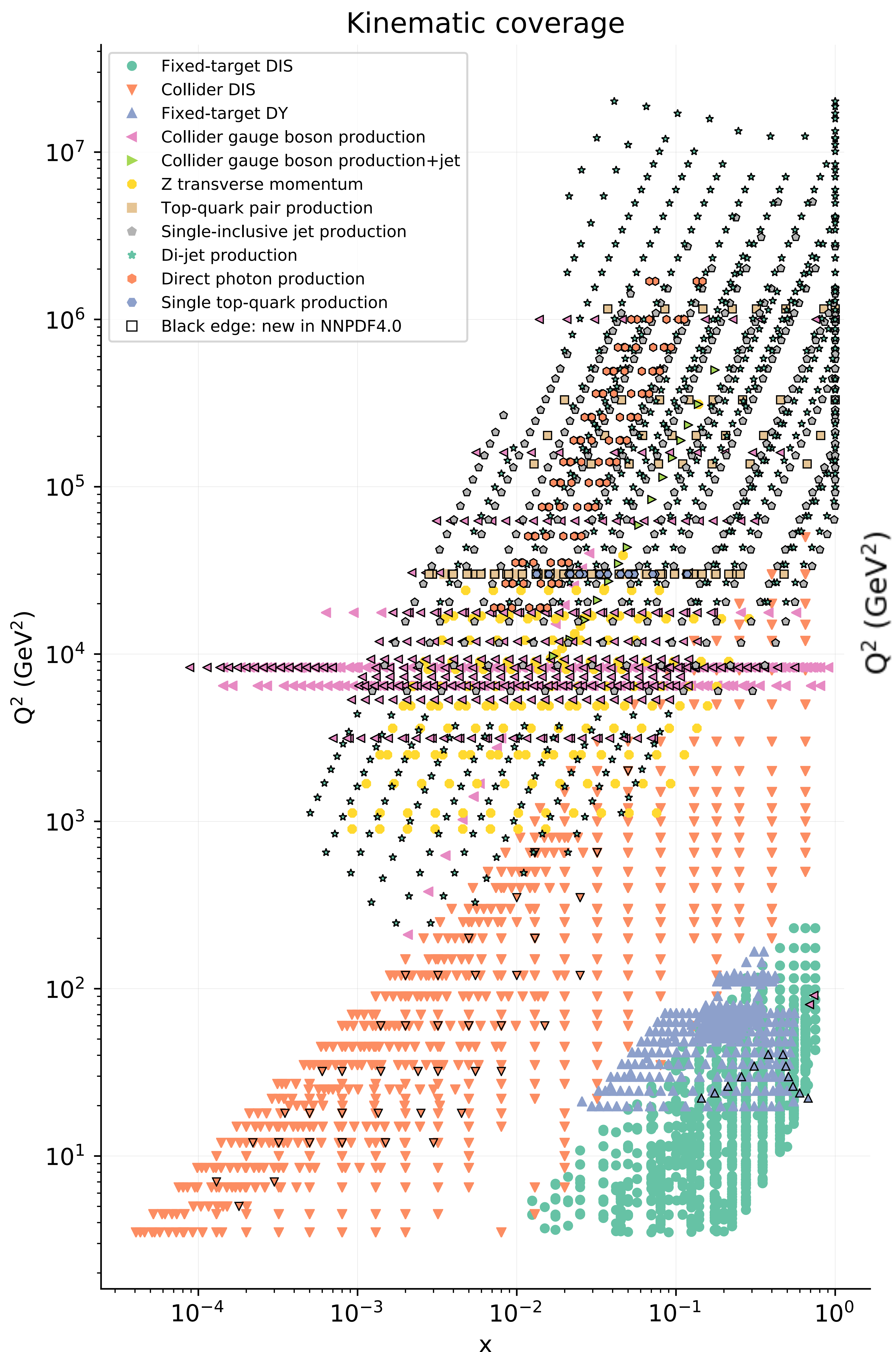
Prompt photon
ATLAS $\sqrt{s} = 13$ TeV differential cross sections ($\mathcal{L} = 139$ fb^{-1})
CMS $\sqrt{s} = 13$ TeV differential cross sections ($\mathcal{L} = 2.3$ fb^{-1})

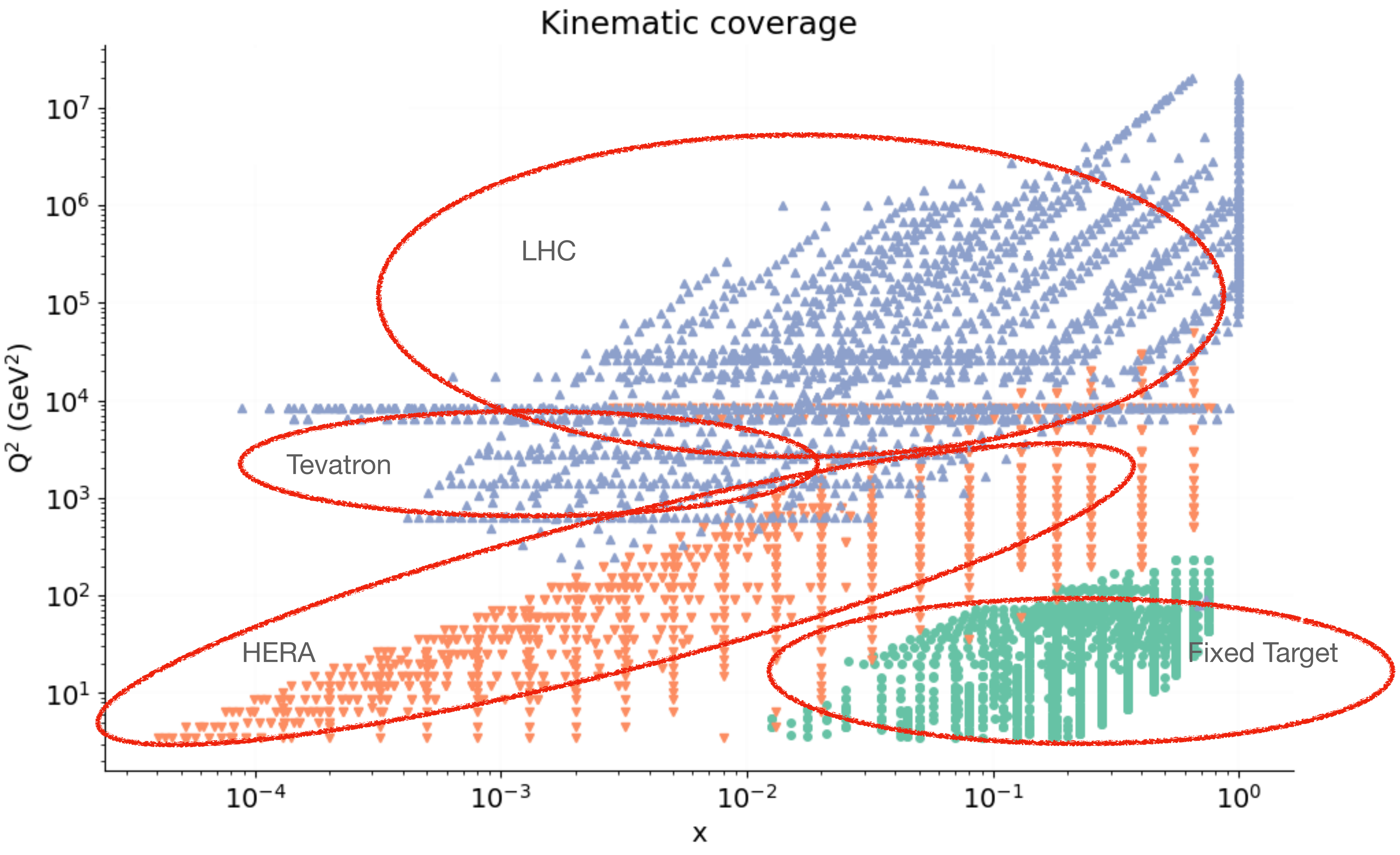
Double Gauge boson production
ATLAS WW $\sqrt{s} = 13$ TeV diff. cross sections ($\mathcal{L} = 2.3$ fb^{-1})

We want to perform a systematic theory-data comparison for datasets that were not included in the determination of NNPDF4.0.

We are particularly interested in the phenomenological impact:

- Is the prediction of the PDFs compatible with the experimental measurements?
- How is the agreement with the data once theory uncertainties are included in the prediction: PDF, scale variations



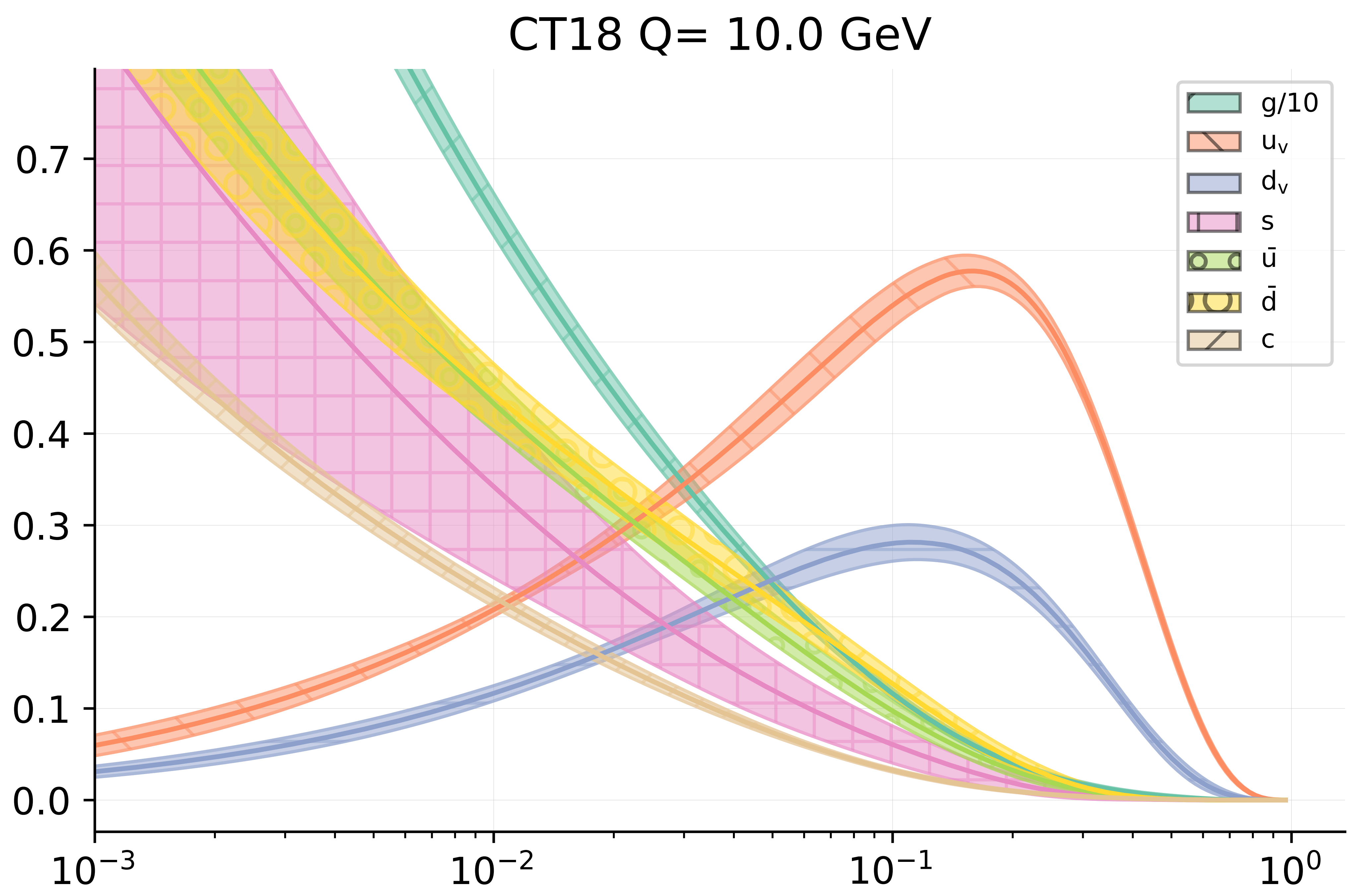


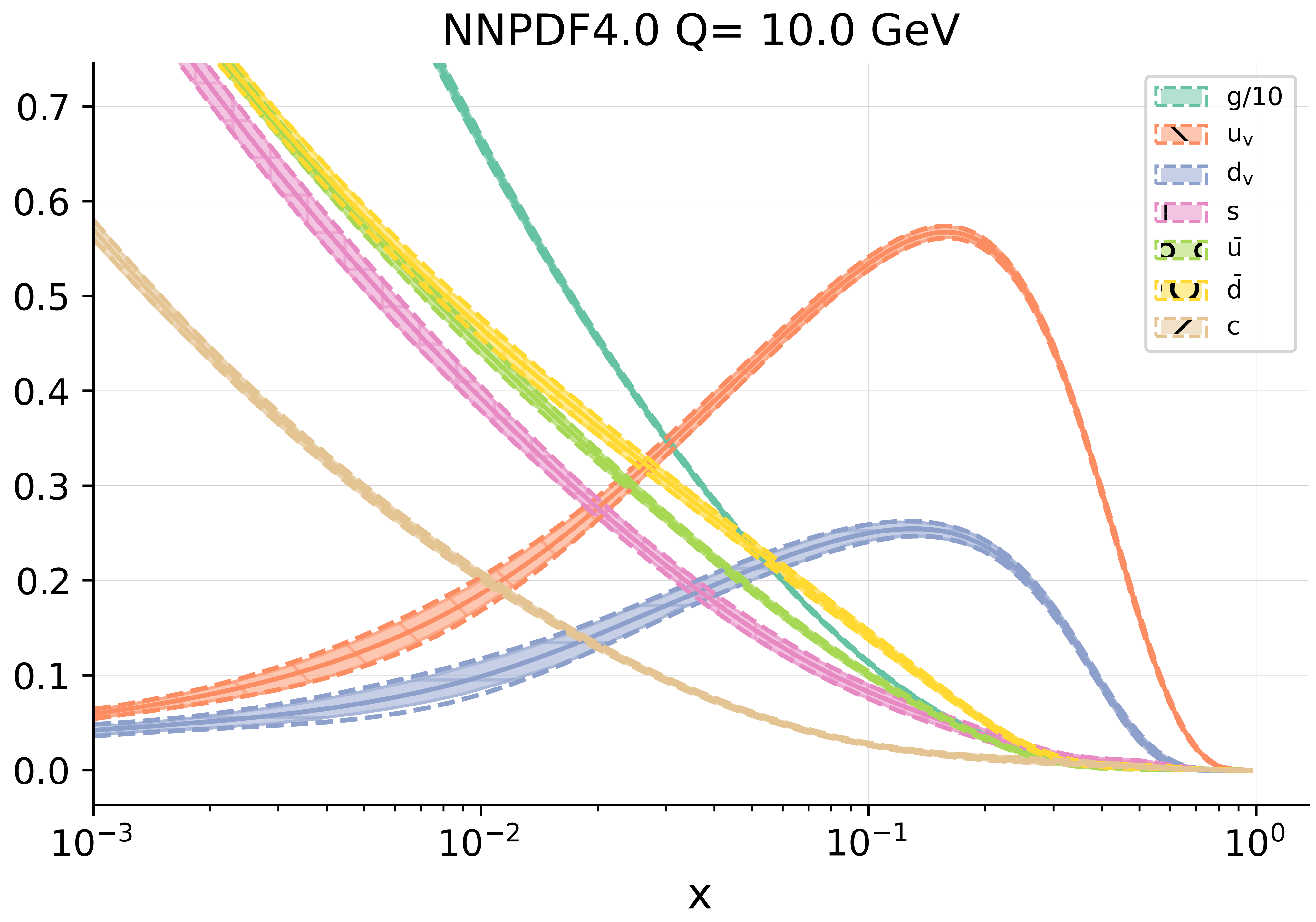
Full list of datasets in this plot can be checked in Appendix B of the NNPDF4.0 paper: link

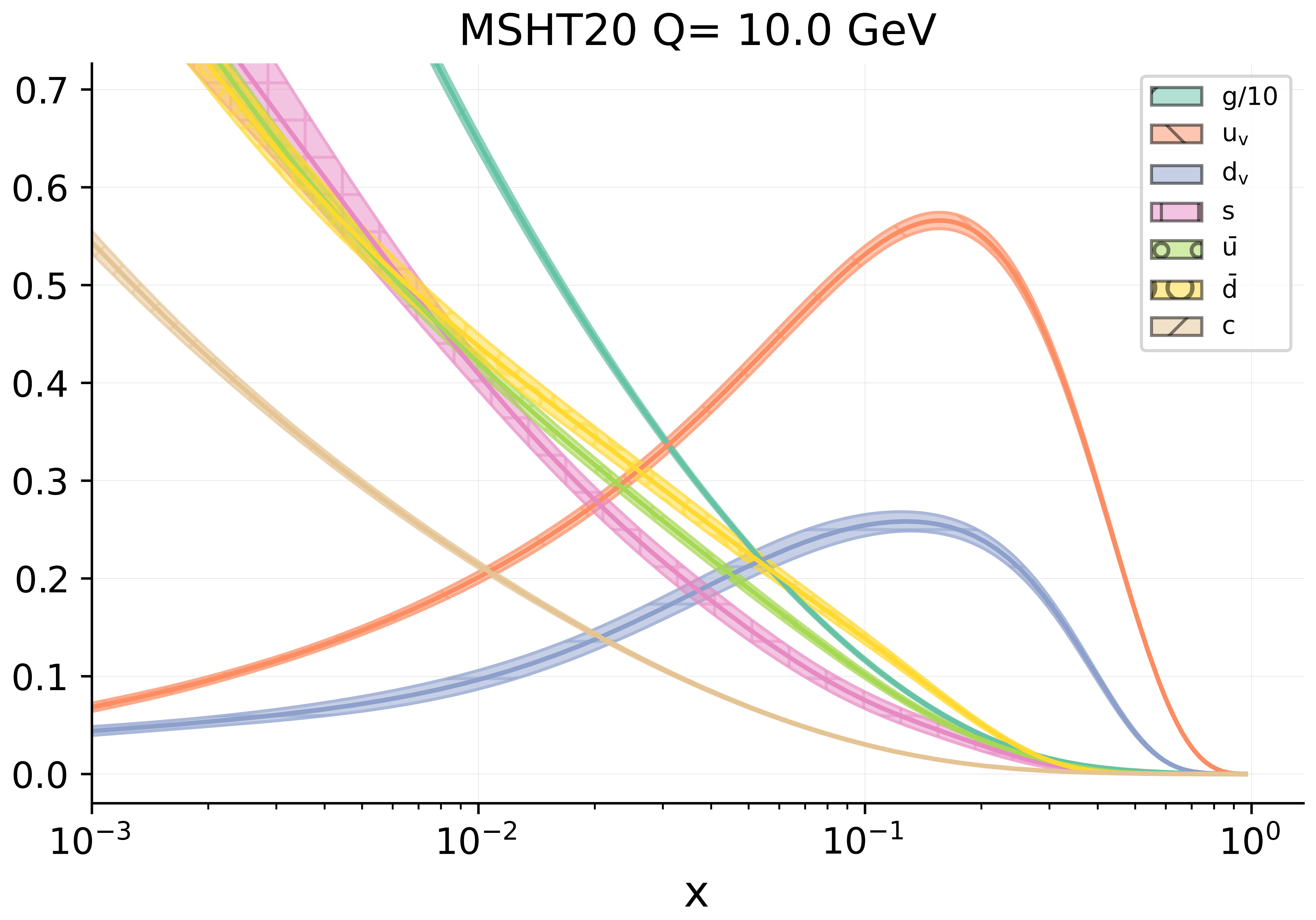
Global NNLO PDFs

Some differences between the global NNLO PDF groups included in PDF4LHC21

- **CT18** [hep-ph] 1912.10053
  -> perturbative charm, hessian, tolerance
- **MSHT20** [hep-ph] 2012.04684
  -> perturbative charm, hessian, dynamic tolerance
- **NNPDF4.0** [hep-ph] 2109.02653
  -> fitted (intrinsic) charm, monte carlo



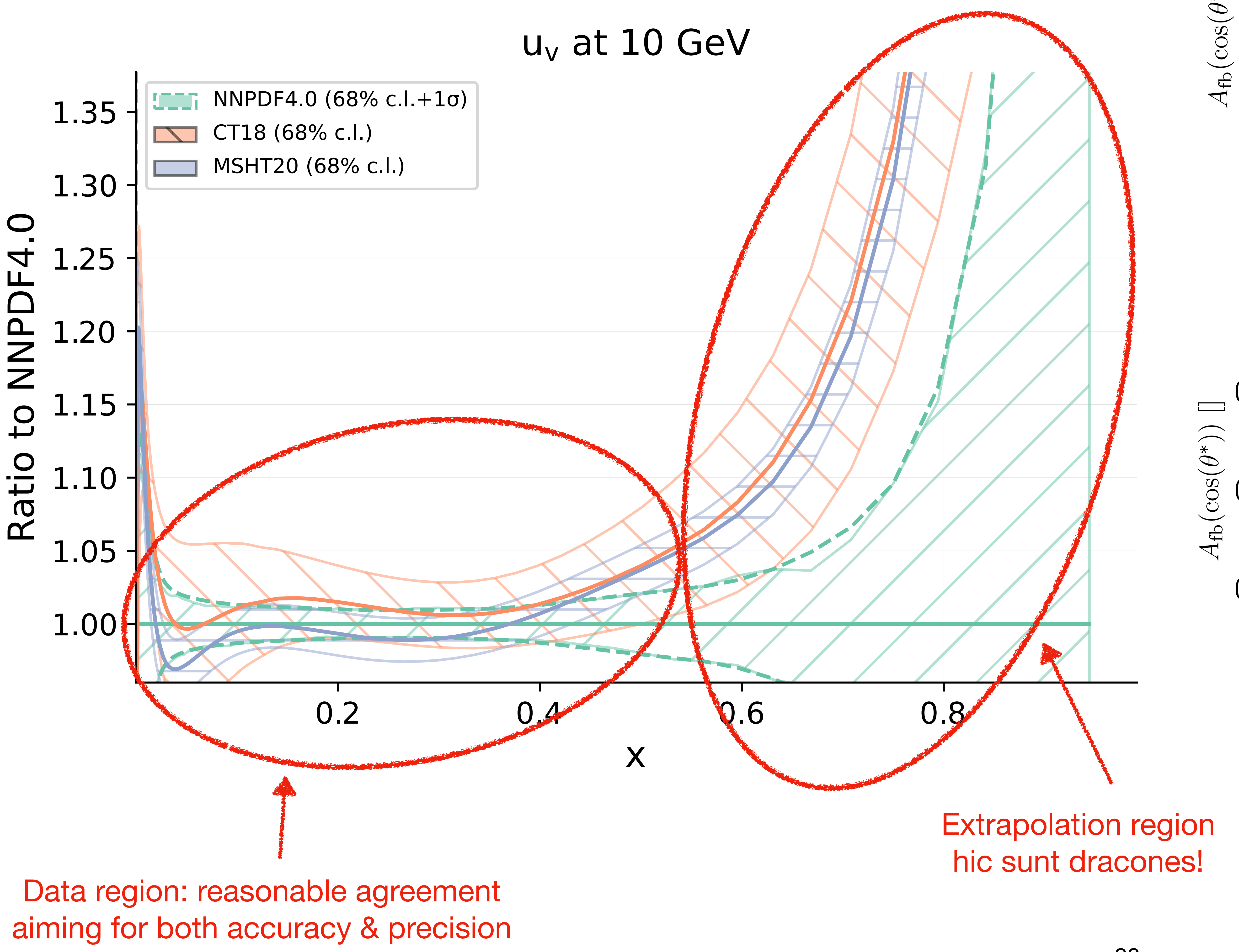


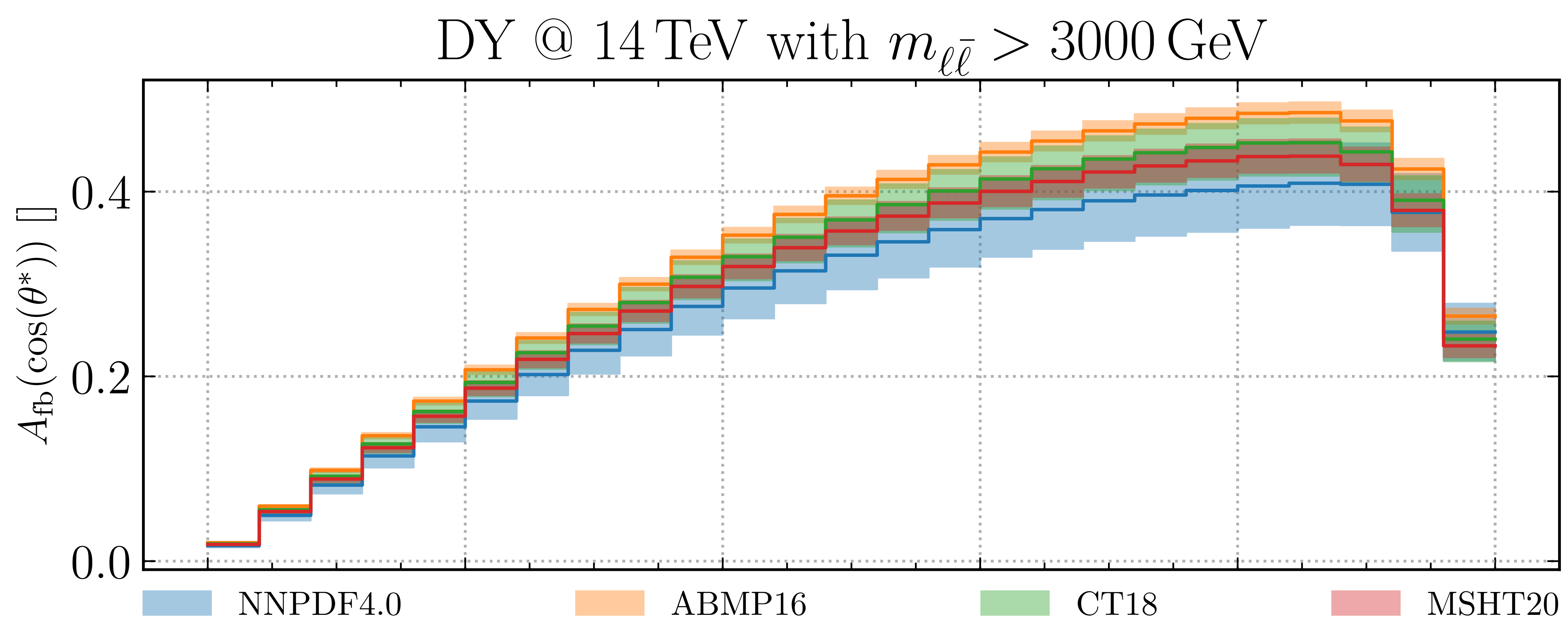


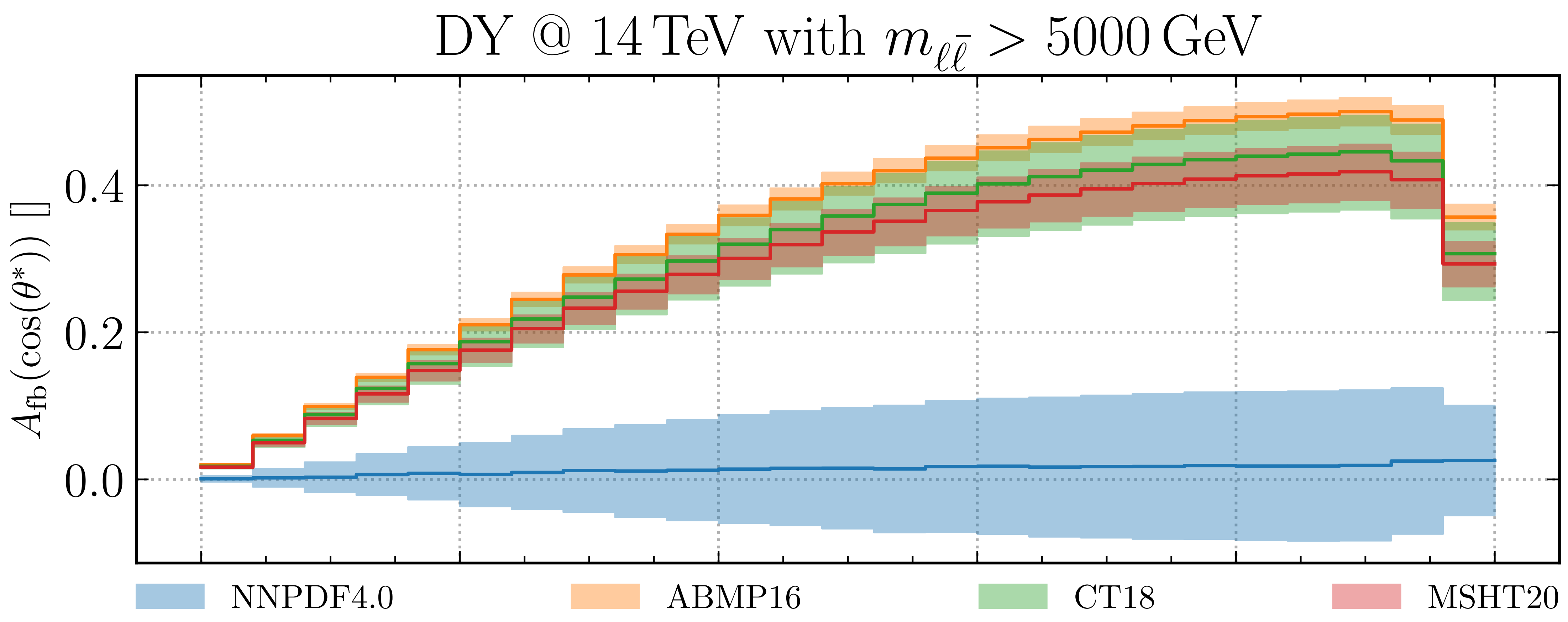
The precision follows the data

based on

Not all regions are equally well determined, for PDFs the “data region” ends at around x~0.5







In hep-ph/2209.08115 it was demonstrated how a too restrictive parametrization can lead to extrapolation behaviour not justified by the available data!

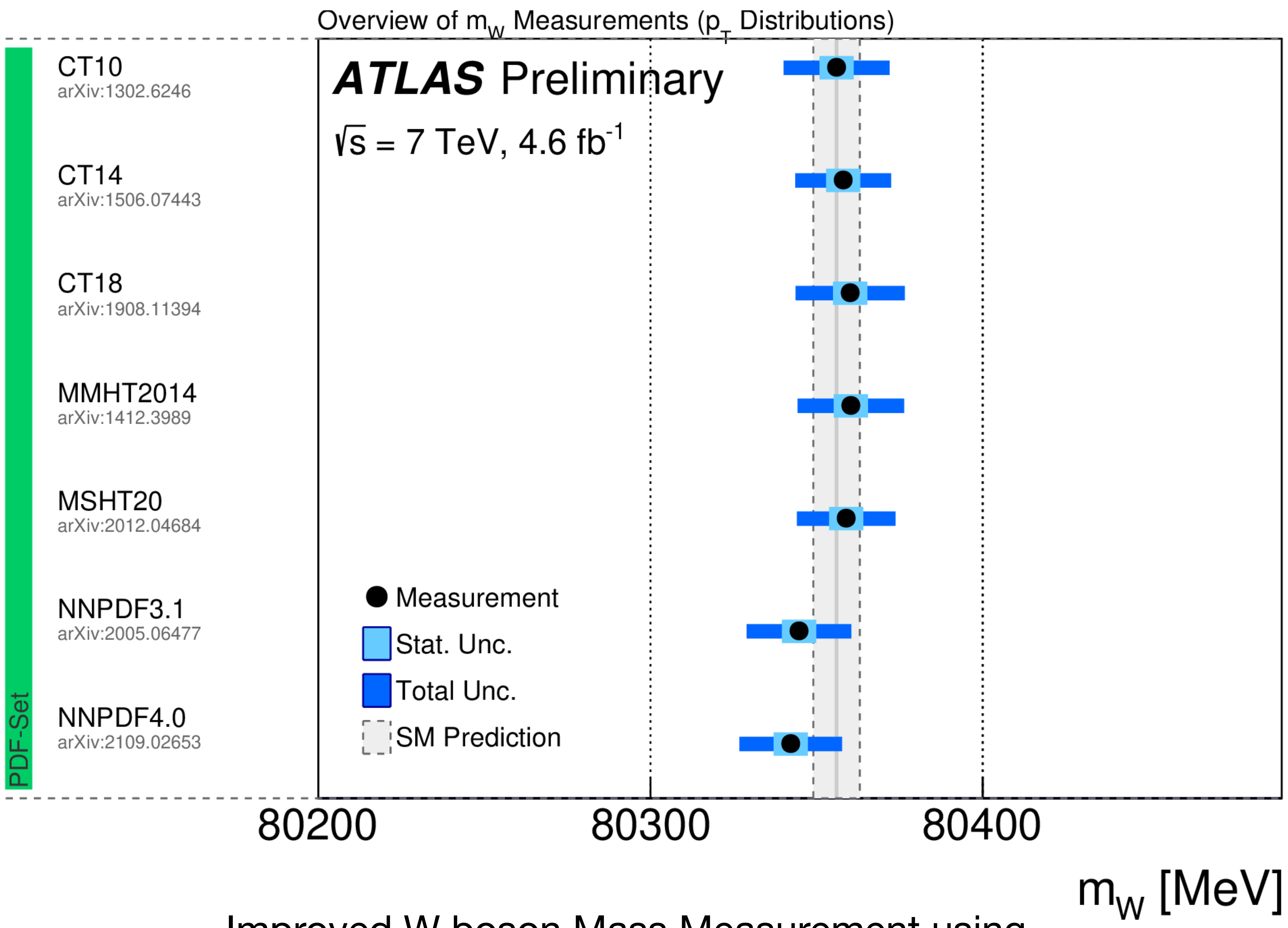
A precise determination of the strong-coupling from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s} = 8$ TeV

arXiv:2309.12986

PDF set	$\alpha_s(m_Z)$	PDF uncertainty
MSHT20 [37]	0.11839	0.00040
NNPDF4.0 [84]	0.11779	0.00024
CT18A [29]	0.11982	0.00050
HERAPDF2.0 [65]	0.11890	0.00027

$$\Delta_{\text{PDF}}\left(\text{MSHT20 only}\right) = 0.34\,\%$$

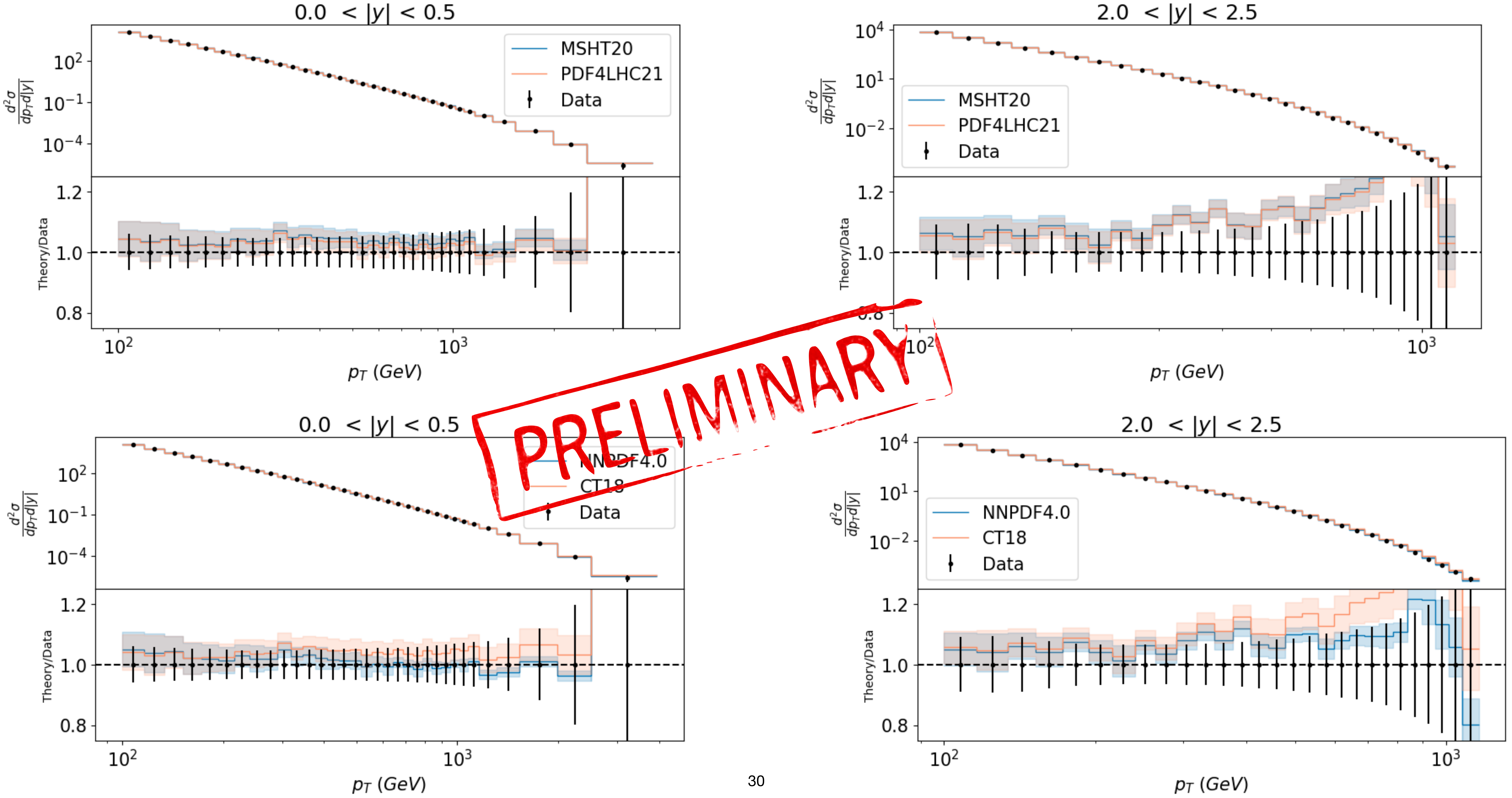
$$\Delta_{\text{PDF}}\left(\text{NNPDF4.0} - \text{CT18A}\right) = 1.6\,\%$$



Improved W boson Mass Measurement using $\sqrt{s} = 7$ TeV pp Collisions with the ATLAS Detector

ATLAS-CONF-2023-004

More PDF sets: ATLAS 1jet



More PDF sets: ATLAS TTB