

Implications of NNPDF4.0 for LHC physics



and beyond...

Juan M. Cruz Martínez, on behalf of
CERN TH Department

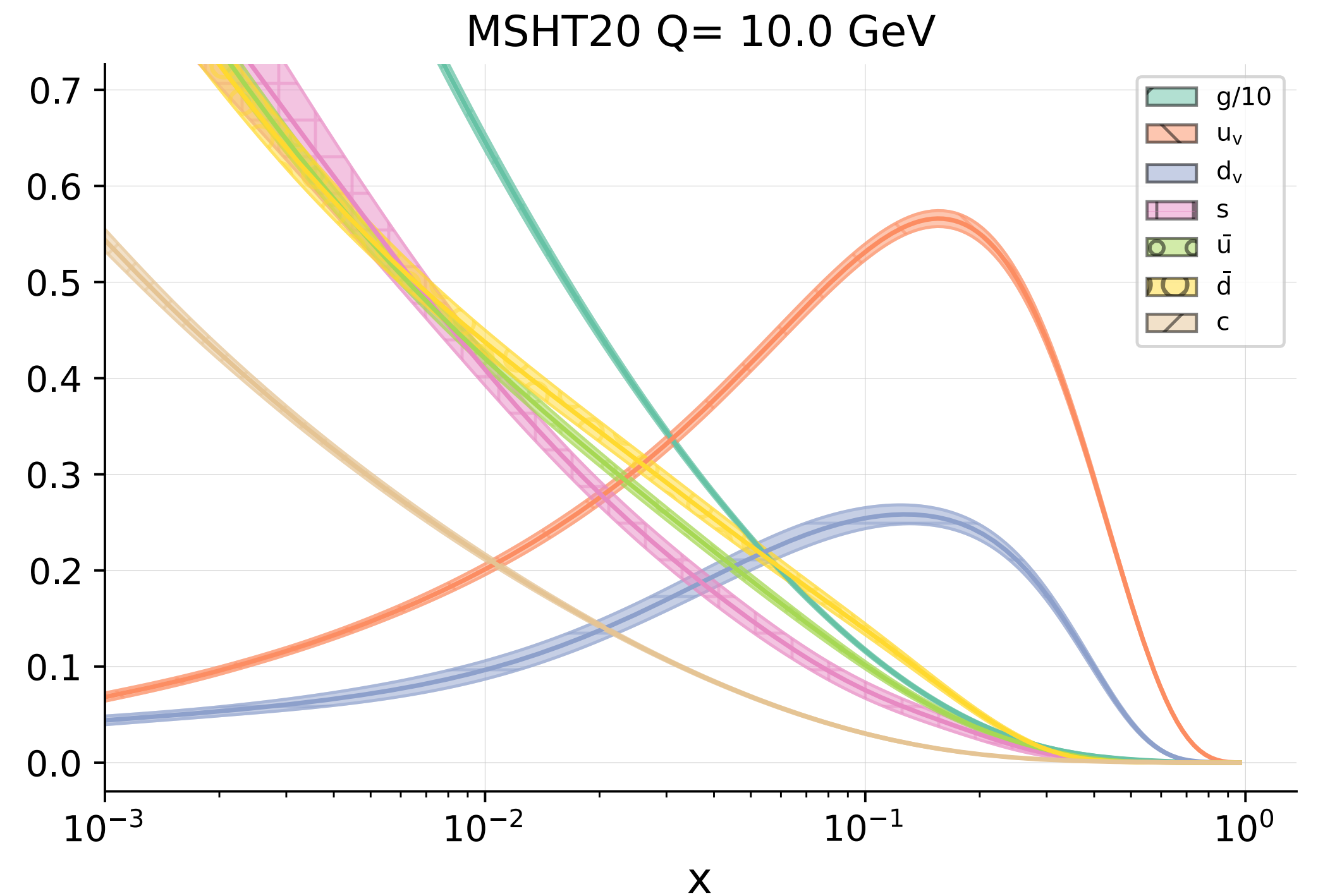
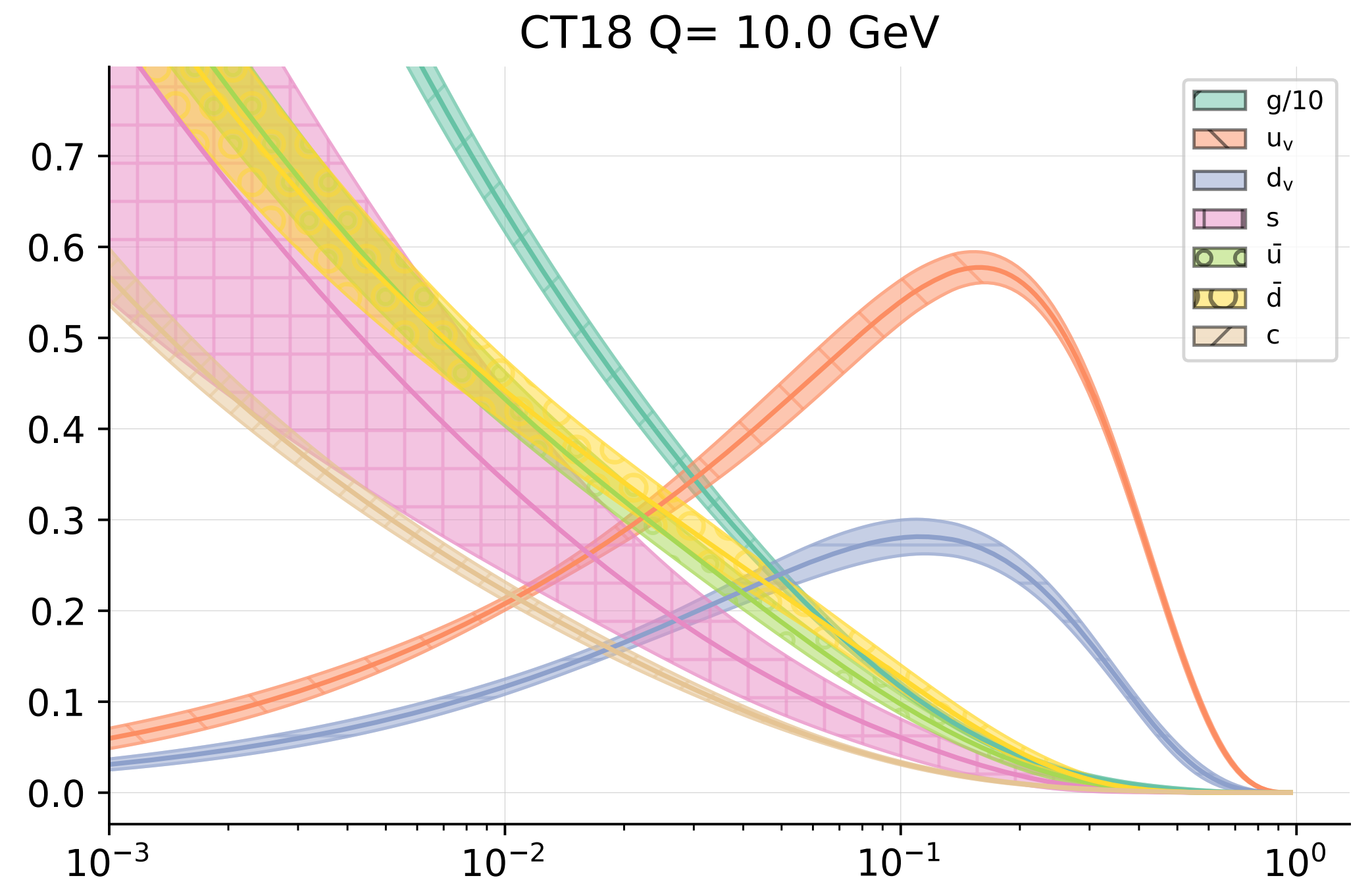
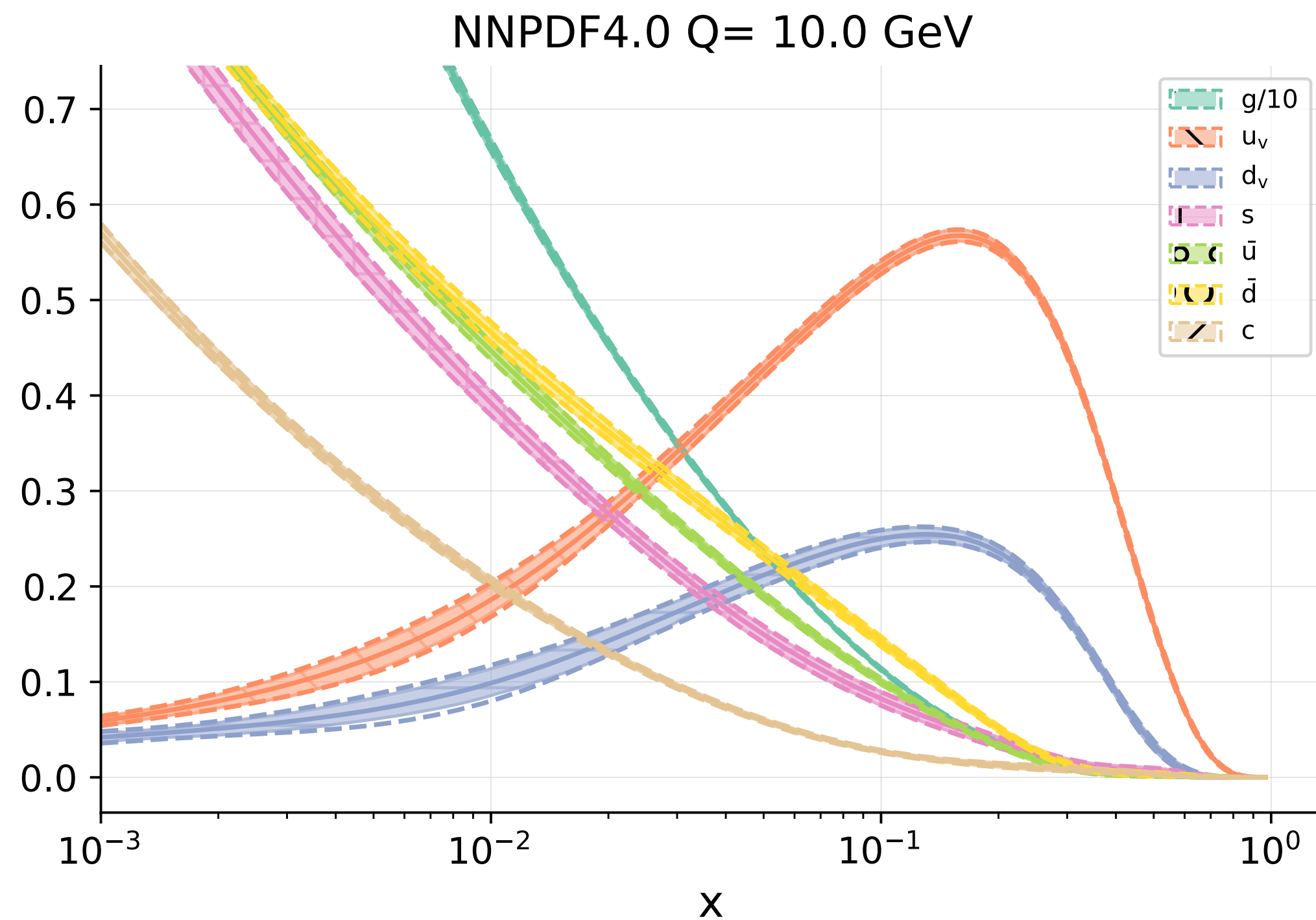


PDF4LHC - November 2023

Global NNLO PDFs

I will focus on NNPDF4.0 and the PDF4LHC21 (which includes input from NNPDF, CTEQ and MSHT). The latest releases of these three collaborations are:

- **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



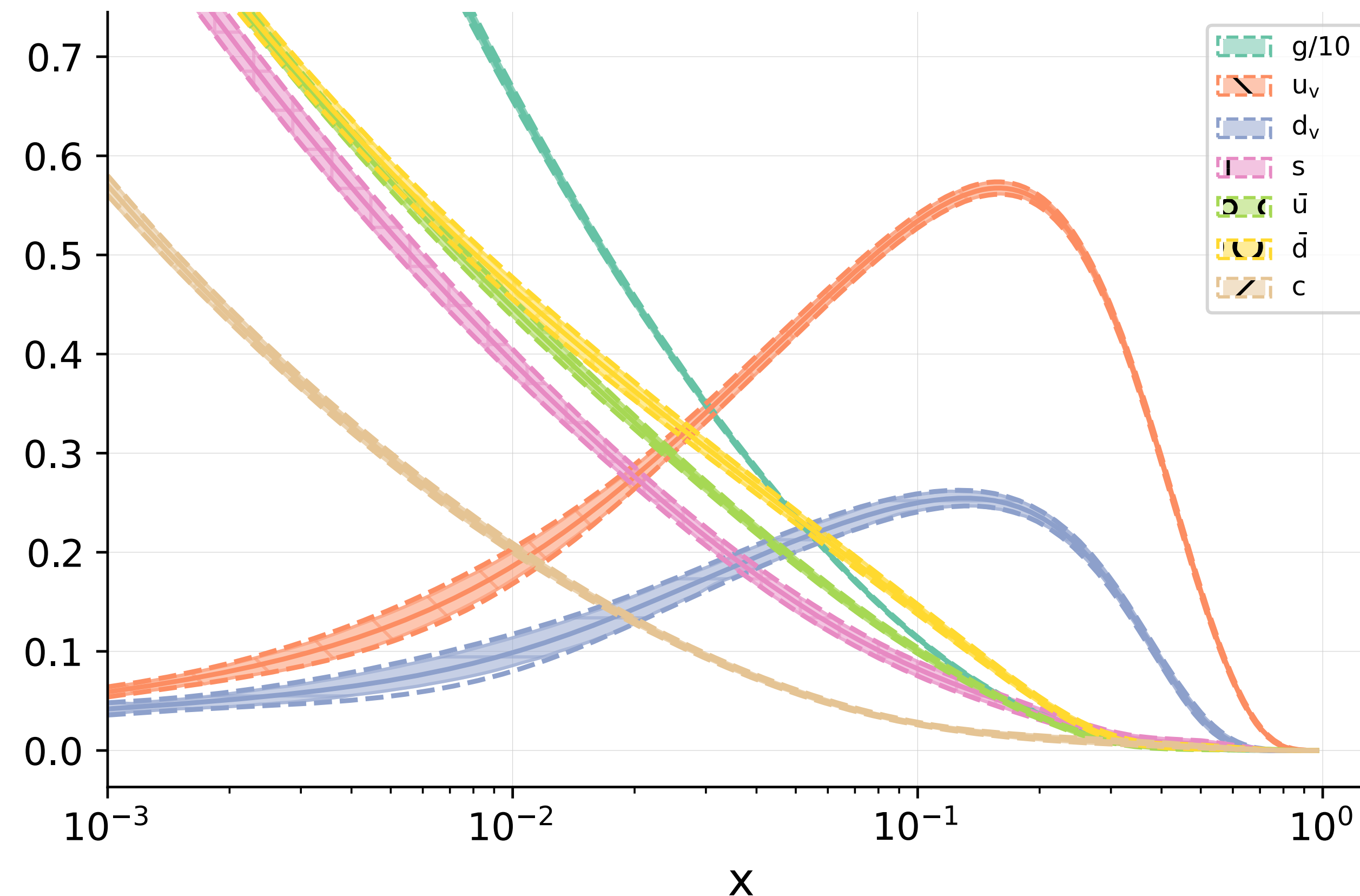
PDF4LHC21 combination - hep-ph/2203.05506

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

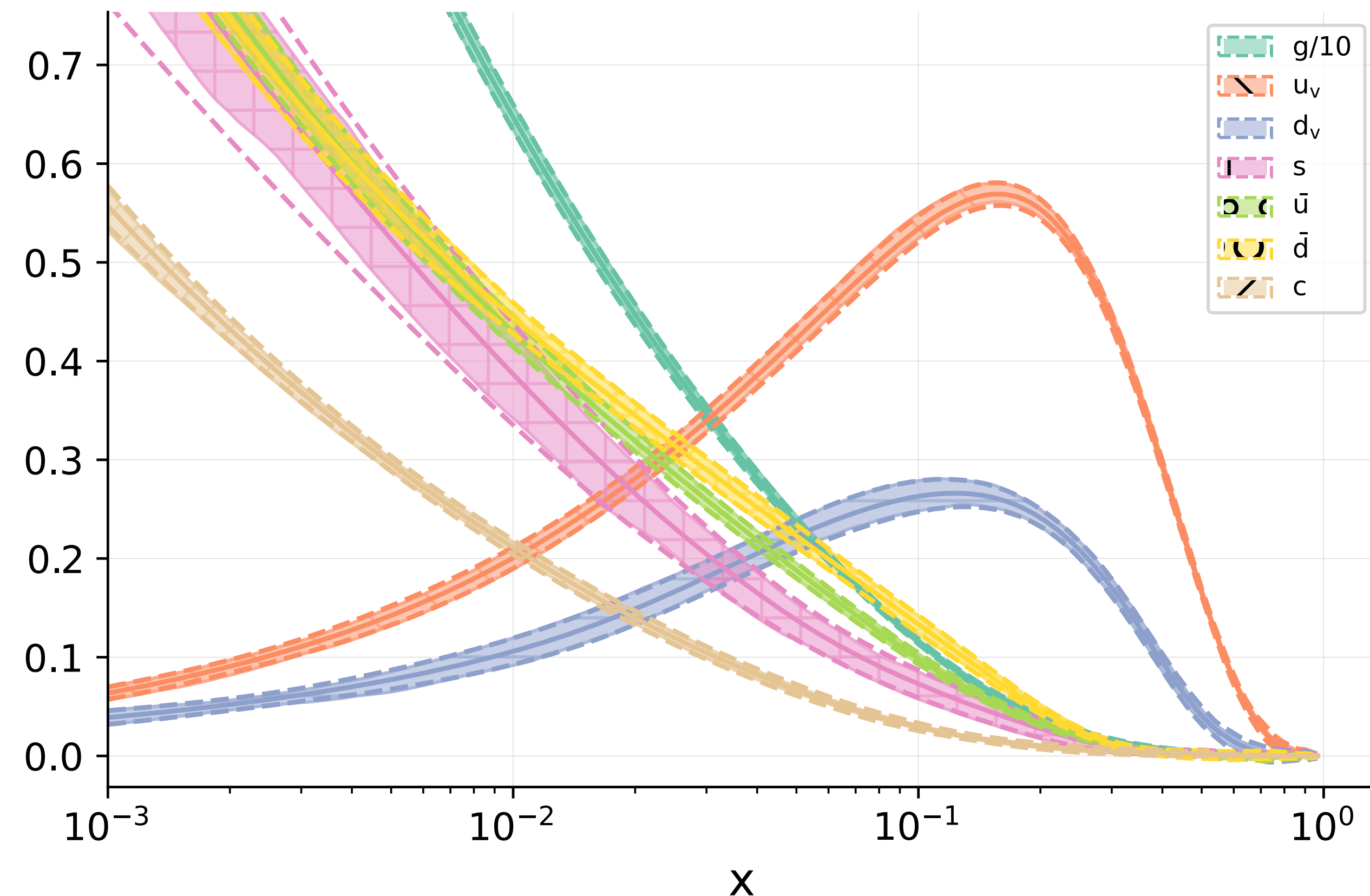
However a comparison of NNPDF4.0 and PDF4LHC21 was done in Appendix B of hep-ph/2203.05506

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

NNPDF4.0 Q= 10.0 GeV

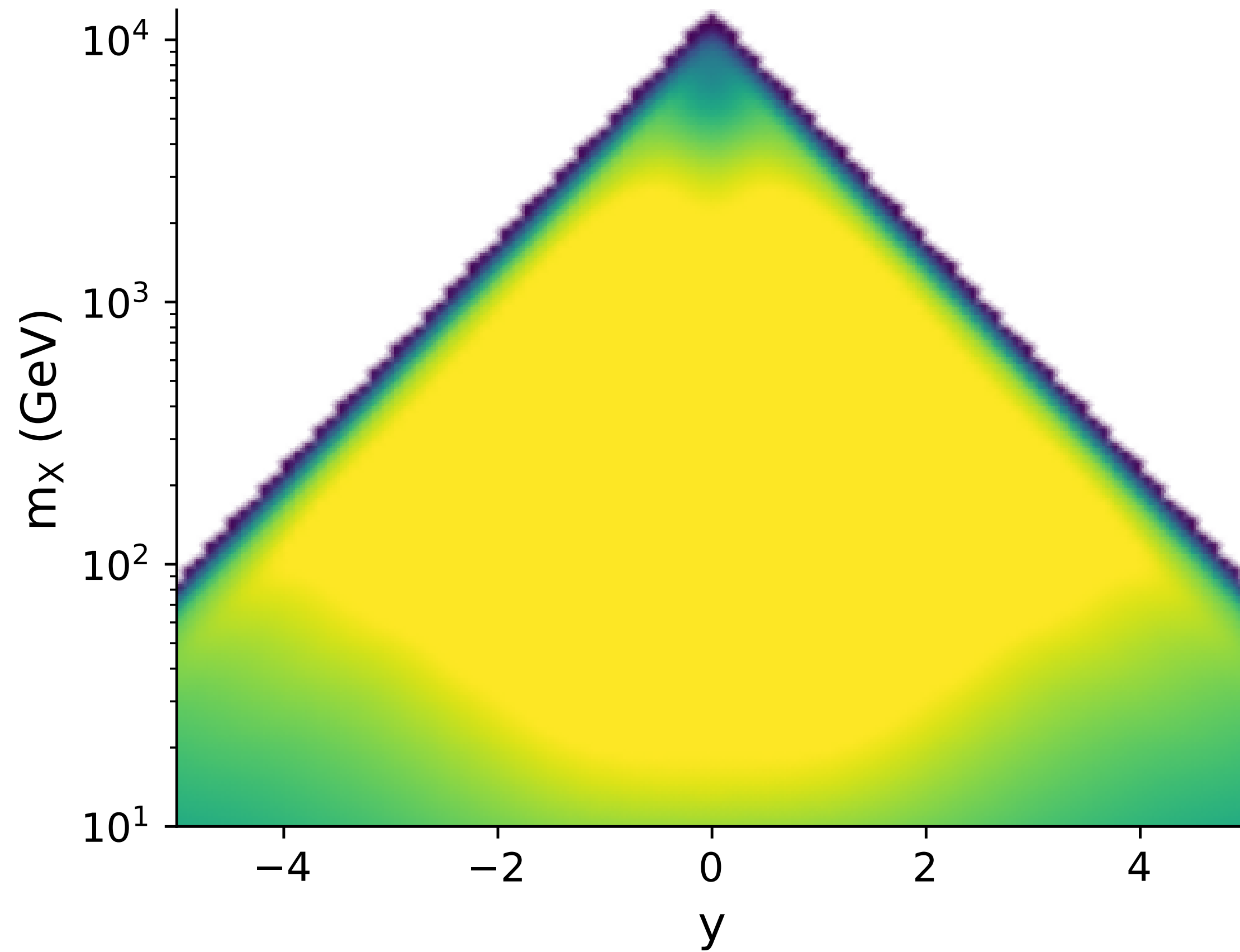


PDF4LHC21 Q= 10.0 GeV

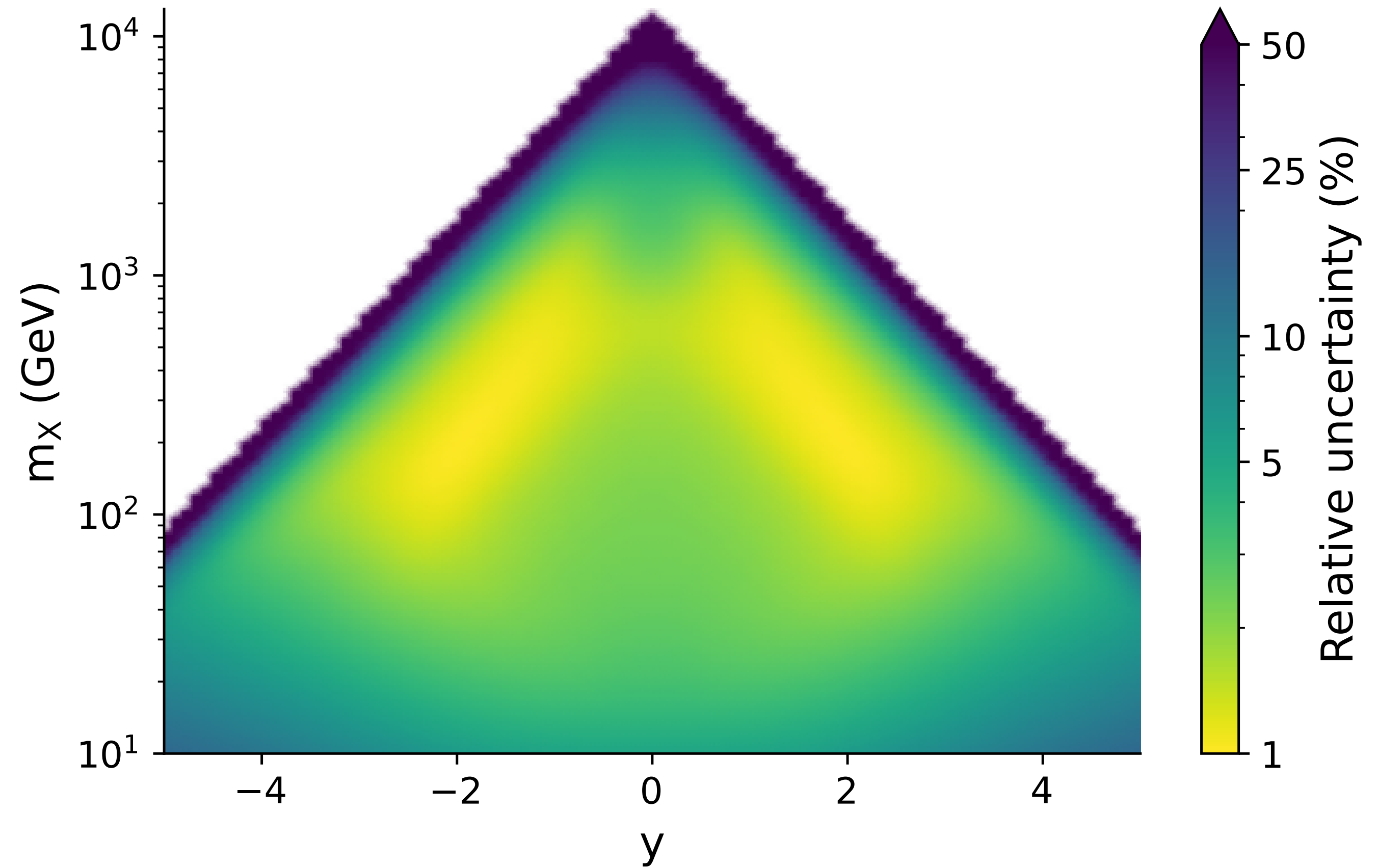


Uncertainty comparison - gq

Relative uncertainty for gq-luminosity
NNPDF4.0 - $\sqrt{s} = 13000.0$ GeV

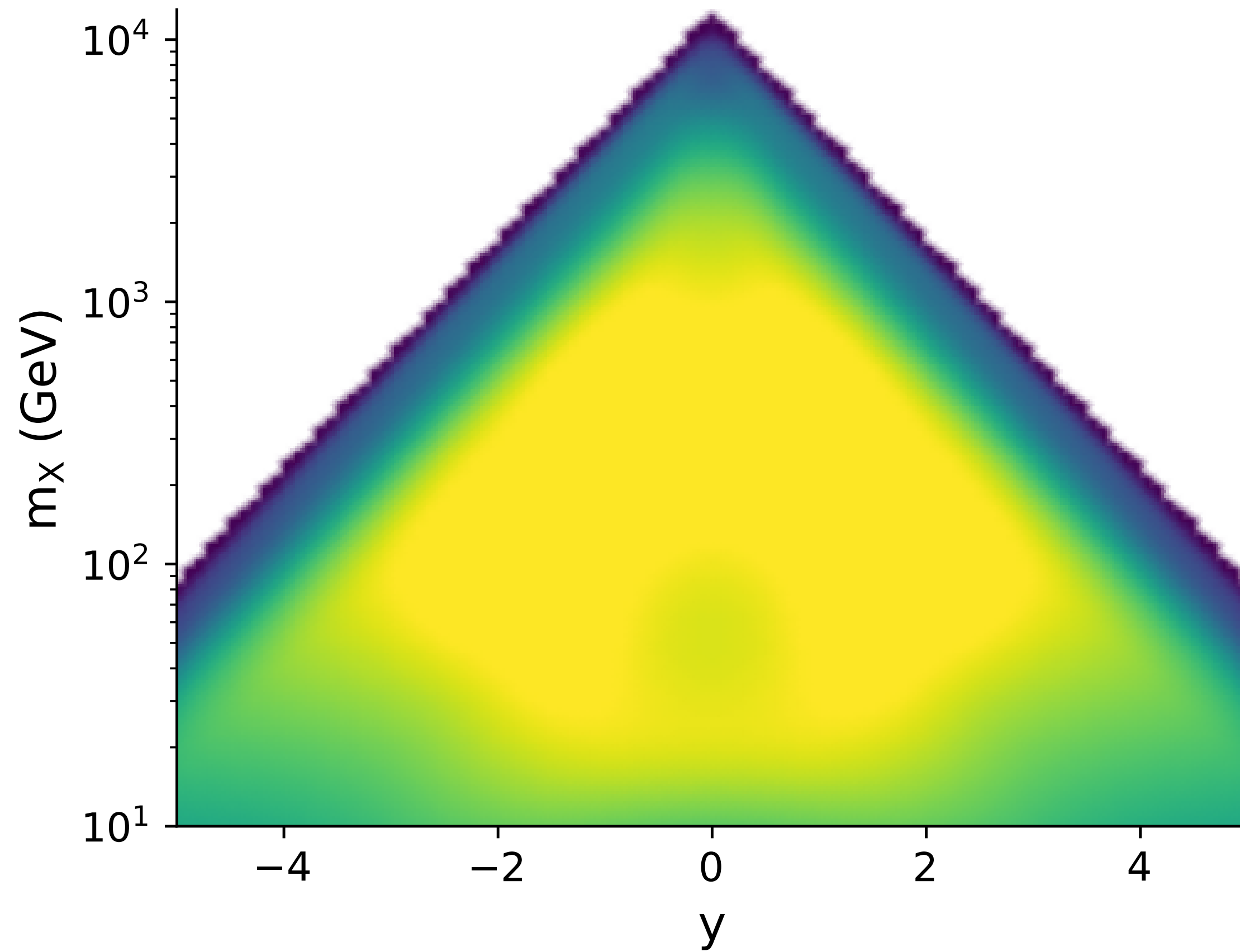


Relative uncertainty for gq-luminosity
PDF4LHC21 - $\sqrt{s} = 13000.0$ GeV

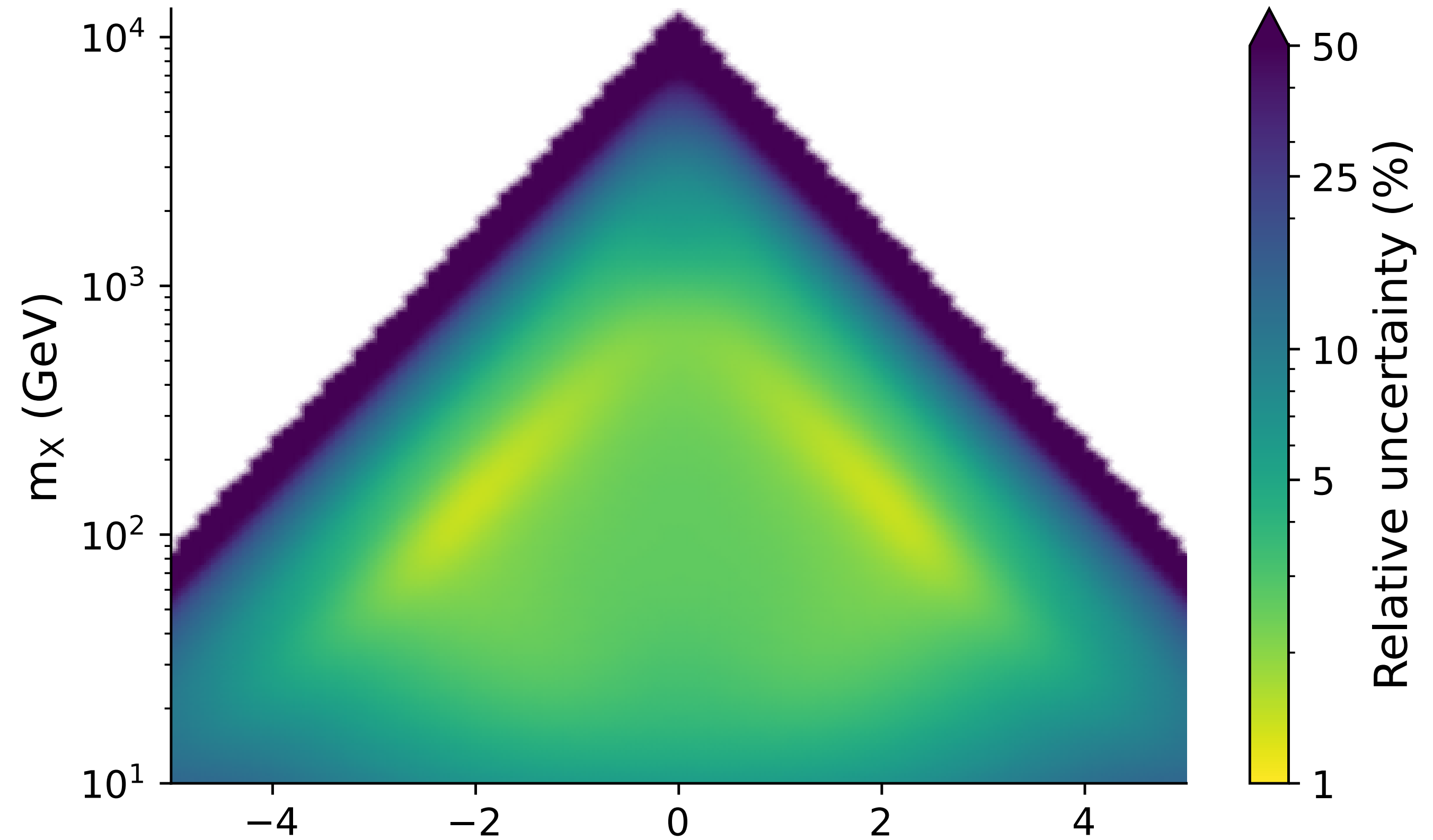


Uncertainty comparison - gg

Relative uncertainty for gg-luminosity
NNPDF4.0 - $\sqrt{s} = 13000.0$ GeV

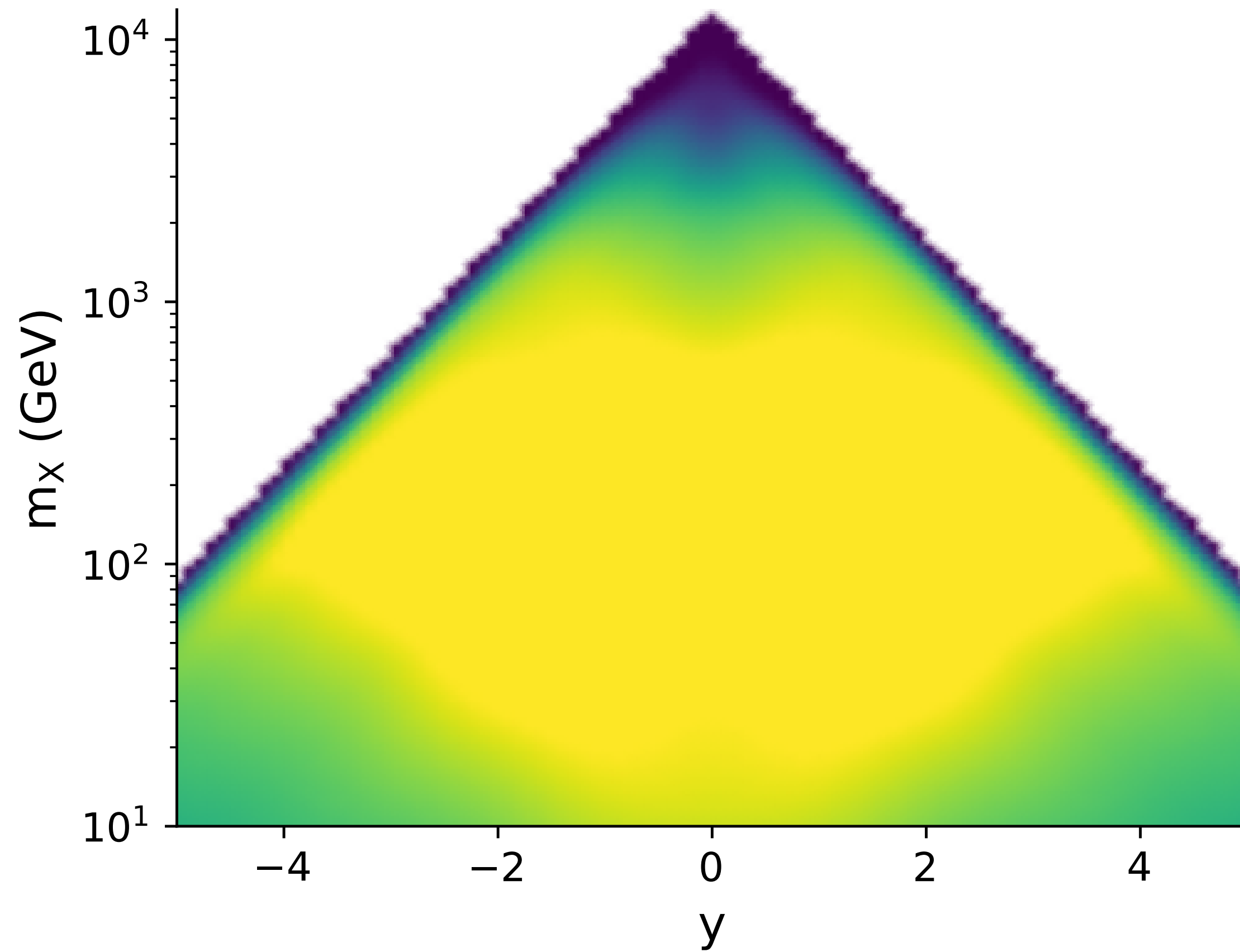


Relative uncertainty for gg-luminosity
PDF4LHC21 - $\sqrt{s} = 13000.0$ GeV

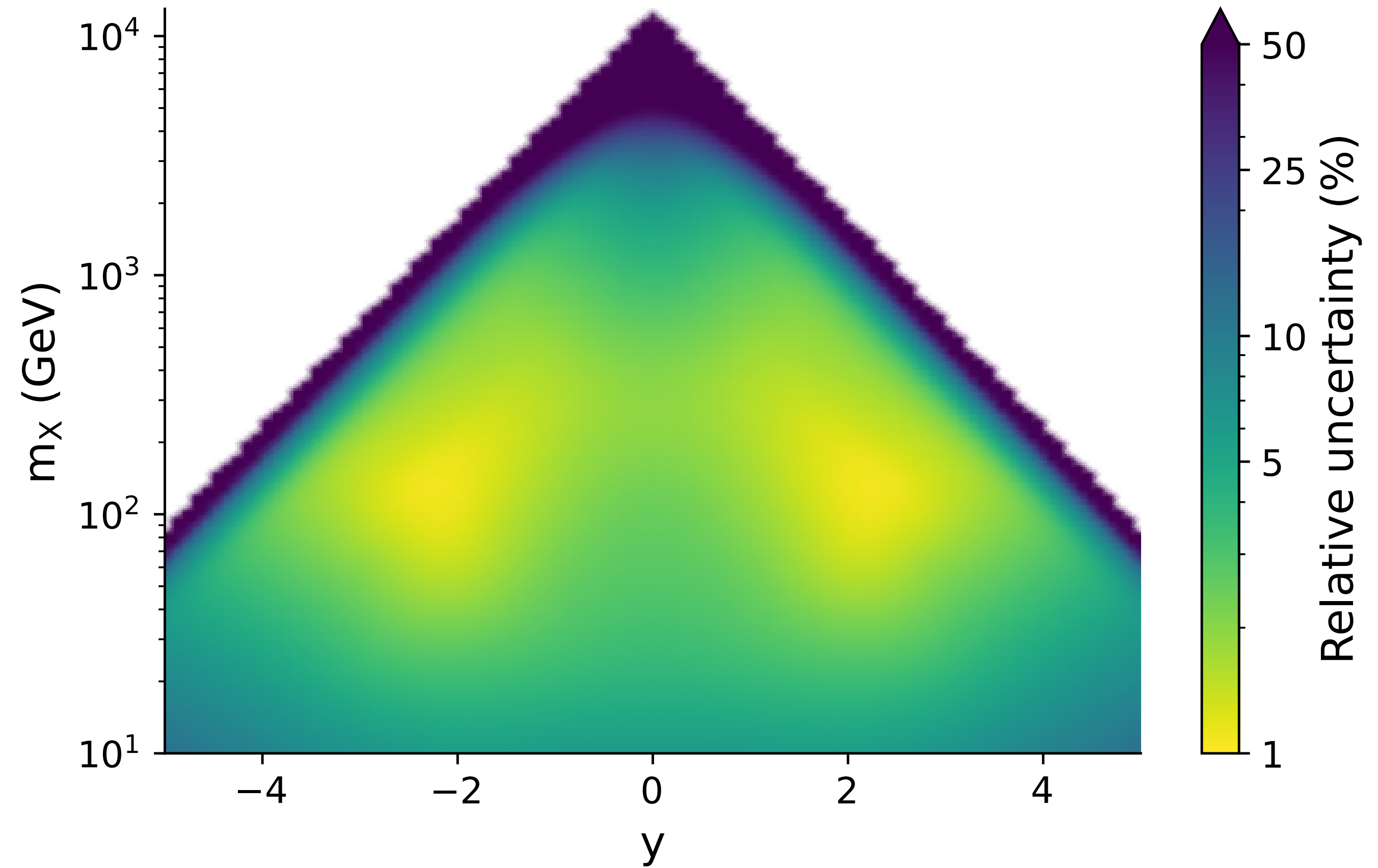


Uncertainty comparison - qqbar

Relative uncertainty for qq̄-luminosity
NNPDF4.0 - $\sqrt{s} = 13000.0$ GeV



Relative uncertainty for qq̄-luminosity
PDF4LHC21 - $\sqrt{s} = 13000.0$ GeV



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

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

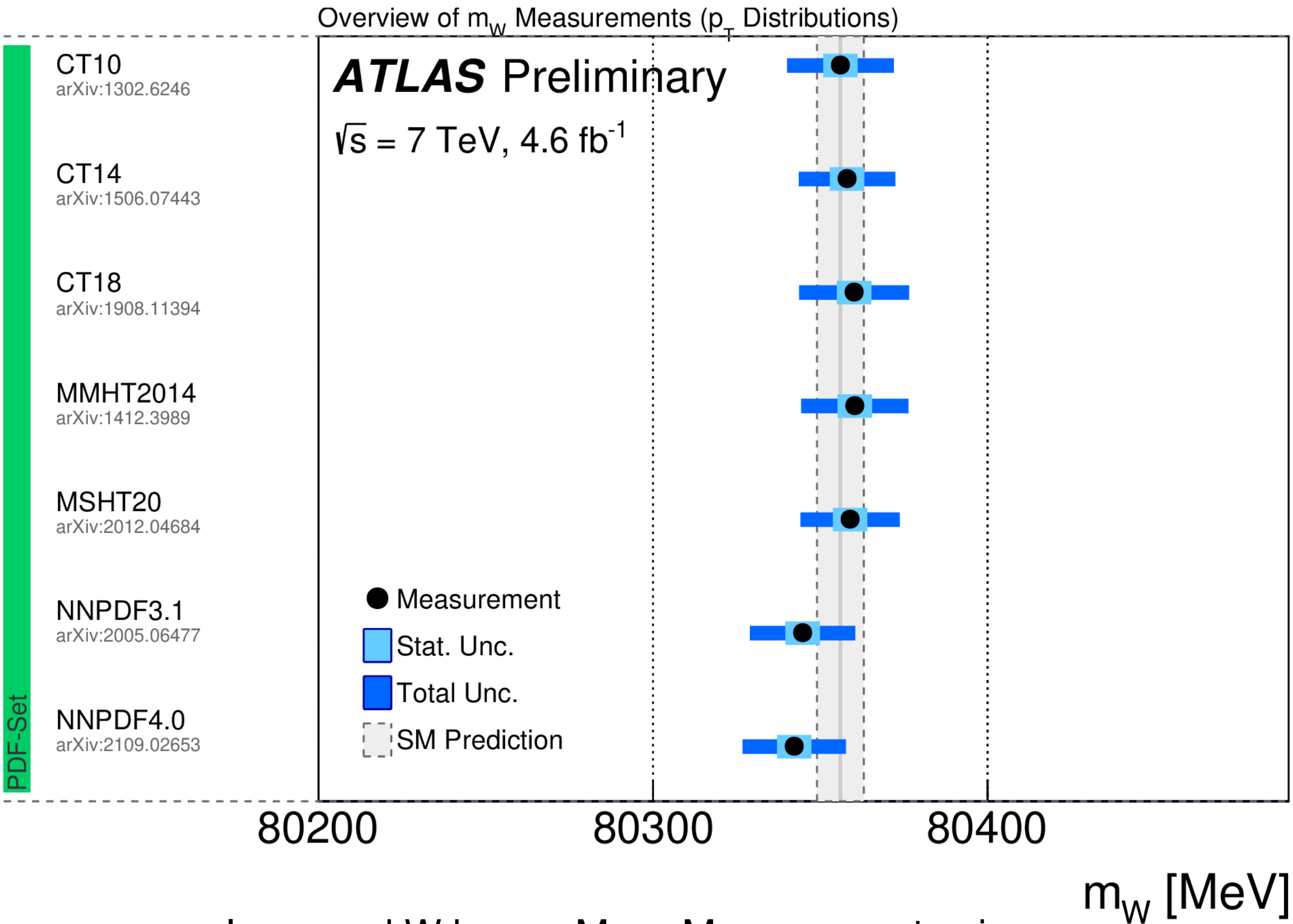
[arXiv:2309.12986](https://arxiv.org/abs/2309.12986)

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

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

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

Given these differences it is of paramount importance to validate and tests the PDF determinations against new experimental measurements!



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

How does NNPDF4.0 fare against data not included in the determination?

Process/Data set

DIS+jets (HERA)

ZEUS, $\mathcal{L} = 38.6 \text{ pb}^{-1}$, $E_p = 820 \text{ GeV}$; high Q

ZEUS, $\mathcal{L} = 81.7 \text{ pb}^{-1}$, $E_p = 920 \text{ GeV}$; high Q

ZEUS, $\mathcal{L} = 374 \text{ pb}^{-1}$, $E_p = 920 \text{ GeV}$; high Q

H1, $\mathcal{L} = 290 \text{ pb}^{-1}$, $E_p = 920 \text{ GeV}$; low Q

H1, $\mathcal{L} = 351 \text{ pb}^{-1}$, $E_p = 920 \text{ GeV}$; high Q

Inclusive jet and dijet production (LHC)

ATLAS, $\mathcal{L} = 3.2 \text{ fb}^{-1}$; $R = 0.4$; $R = 0.6$

CMS, $\mathcal{L} = 36.3 \text{ fb}^{-1}$; $R = 0.4$; $R = 0.6$

Top pair production (LHC)

ATLAS, $\mathcal{L} = 36 \text{ fb}^{-1}$, 1D and 2D diff. distr., ℓ +jets

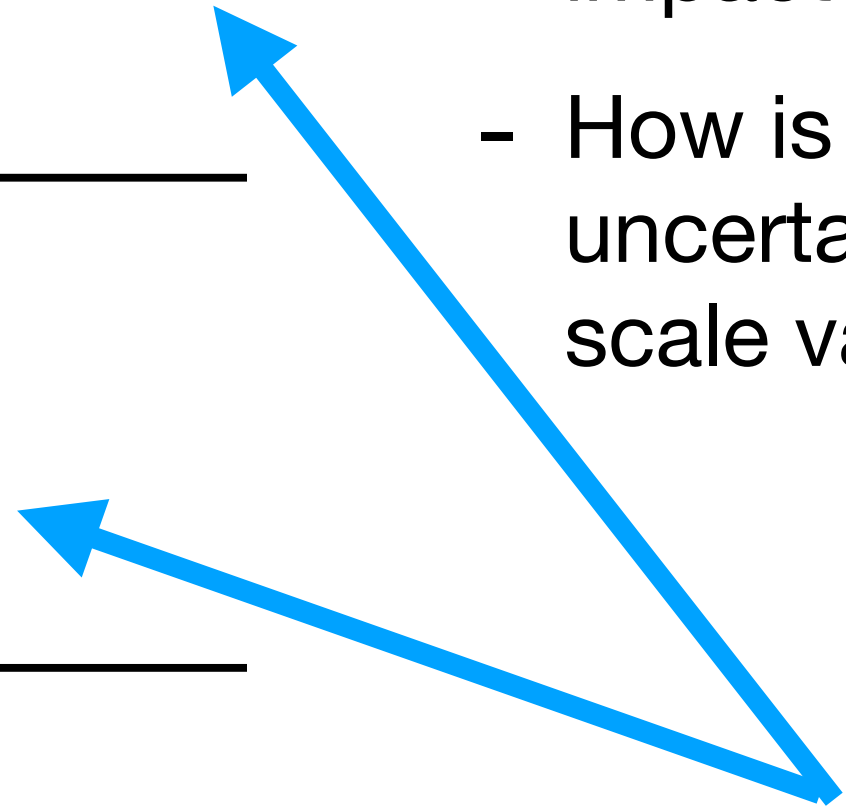
ATLAS, $\mathcal{L} = 36 \text{ fb}^{-1}$, 1D and 2D diff. distr., all hadronic

CMS, $\mathcal{L} = 137 \text{ fb}^{-1}$, 1D and 2D diff. distr., ℓ +jets

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?
- Do small uncertainties have a phenomenological impact?
- How is the agreement with the data once theory uncertainties are included in the prediction: PDF, scale variations



In this talk we'll cover some jet data (DIS+j, single inclusive and dijet production)

... all the others in preparation, we plan to publish a dedicated study for them.

How does NNPDF4.0 fare against data not included in the determination?

$Z p_T$ and $Z + \text{jet}$

ATLAS, $\mathcal{L} = 36 \text{ pb}^{-1}$, normalised cross section

ATLAS, differential cross sections ($\mathcal{L} = 139 \text{ fb}^{-1}$)

CMS, differential cross sections ($\mathcal{L} = 36 \text{ fb}^{-1}$)

Drell Yan

ATLAS $W, Z \sqrt{s} = 2.76 \text{ TeV}$ cross sections and asymmetries

ATLAS $W, Z \sqrt{s} = 5 \text{ TeV}$ differential cross sections

CMS $Z \sqrt{s} = 13 \text{ TeV}$ differential cross sections ($\mathcal{L} = 2.3 \text{ fb}^{-1}$)

CMS $Z \sqrt{s} = 13 \text{ TeV}$ A_{FB} ($\mathcal{L} = 139 \text{ fb}^{-1}$)

LHCb $Z \sqrt{s} = 13 \text{ TeV}$ forward Z production ($\mathcal{L} = 5 \text{ fb}^{-1}$)

$W + c$

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

CMS $\sqrt{s} = 8 \text{ TeV}$ differential cross sections ($\mathcal{L} = 18.4 \text{ fb}^{-1}$)

Prompt photon

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

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

Double Gauge boson production

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

Working on the implementation of these datasets as well within the NNPDF framework.

We will utilize full NNLO calculations (not kfactors) whenever we can produce grids with them:

pineappl grids now implemented in

◆ Matrix

◆ Vrap

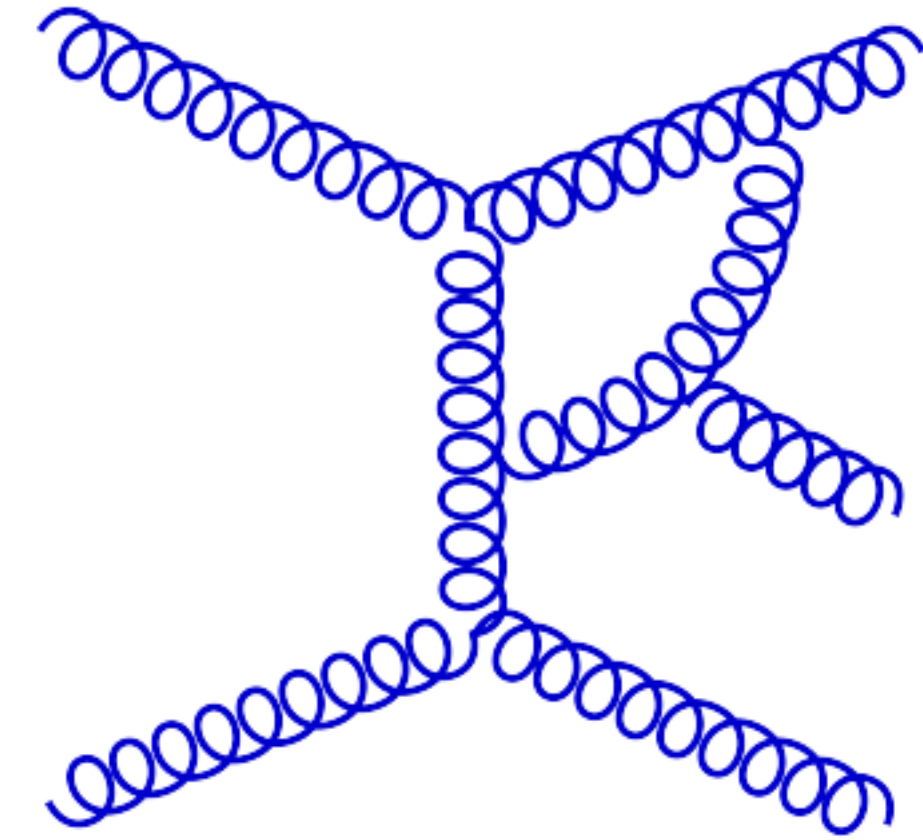
◆ NNLOJET



Some general notes:

1. The following slides include χ^2 figures and data-prediction comparison plots.
2. Using always the published NNPDF4.0 (no MHOU are included in the PDF itself)
3. Data-prediction comparisons shown are produced with PDF4LHC21 and NNPDF4.0. More general plots with other PDFs can be found in the backup
4. The data-theory comparison plot include experimental errors (black bars), and PDF uncertainties and scale variations added in quadrature.
5. The computation of the χ^2/N includes either experimental and theory uncertainties, or those two plus PDF uncertainties.

LHC jets at 13 TeV



A good description of jet and dijet data from LHC is fundamental.

For these tests we are using NNLO grids from Ploughshare: <https://ploughshare.web.cern.ch/ploughshare/>

The datasets we are looking at are:

1. Atlas jet and dijet data, 13 TeV 3.2fb^{-1} , $0.1 < p_T < 3.5 \text{ TeV}$; $|y| < 3$

data from: hepdata / 1634970 (two alternative correlation scenarios considered for single jet)

2. CMS jet data for $R=0.4$ and $R=0.7$, 13 TeV 36.6fb^{-1} , $0.1 < p_T < 3.1 \text{ TeV}$; $|y| < 2$

data from: hepdata / 1972986

Note: the experimental covariance matrix is regularized using the recipe from EPJ C82 (2022) 956

Atlas jets, χ^2/N with only experimental and theory uncertainties

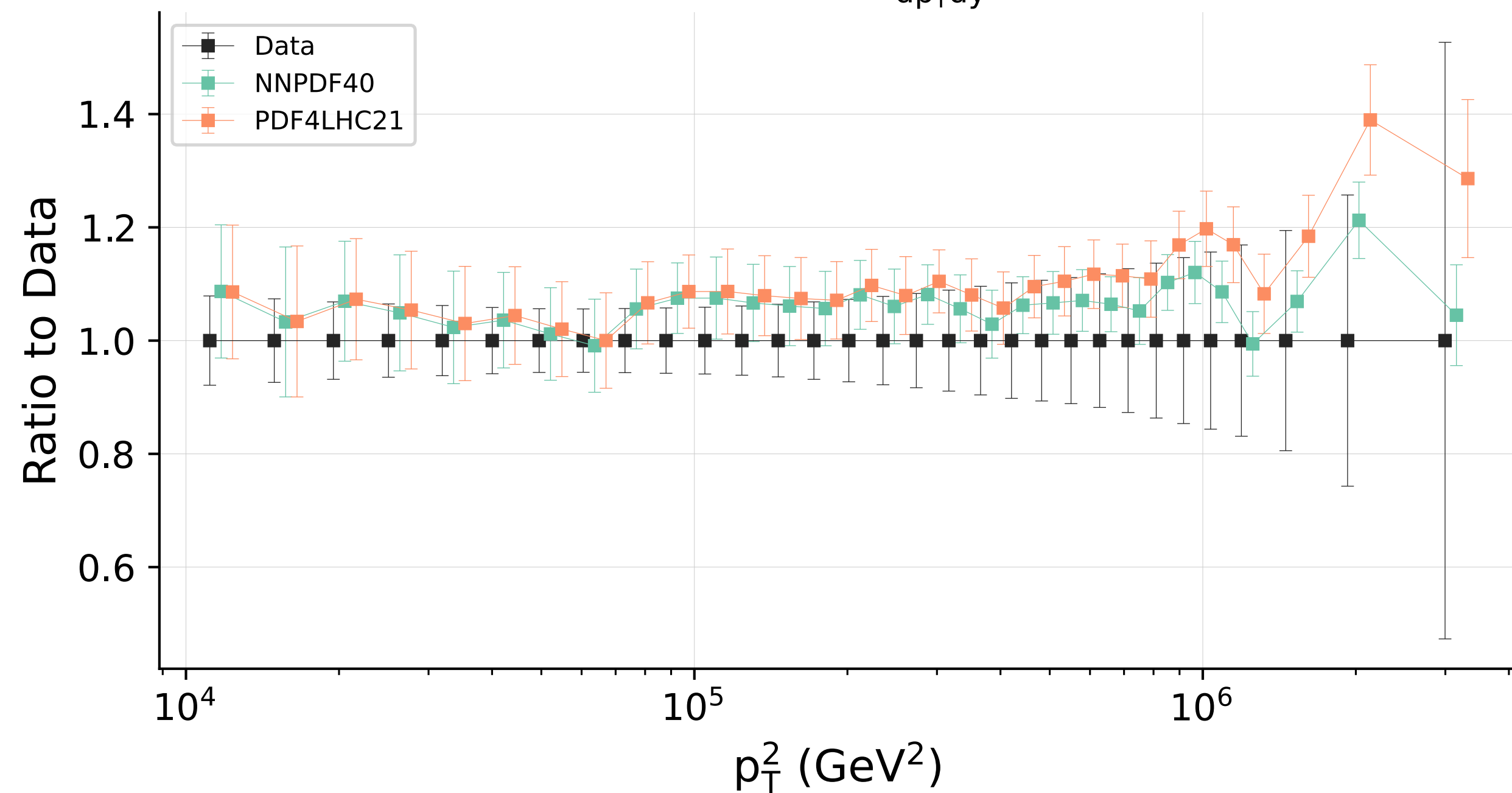
Single inclusive jets

Single inclusive jets
(alternative correlation model)

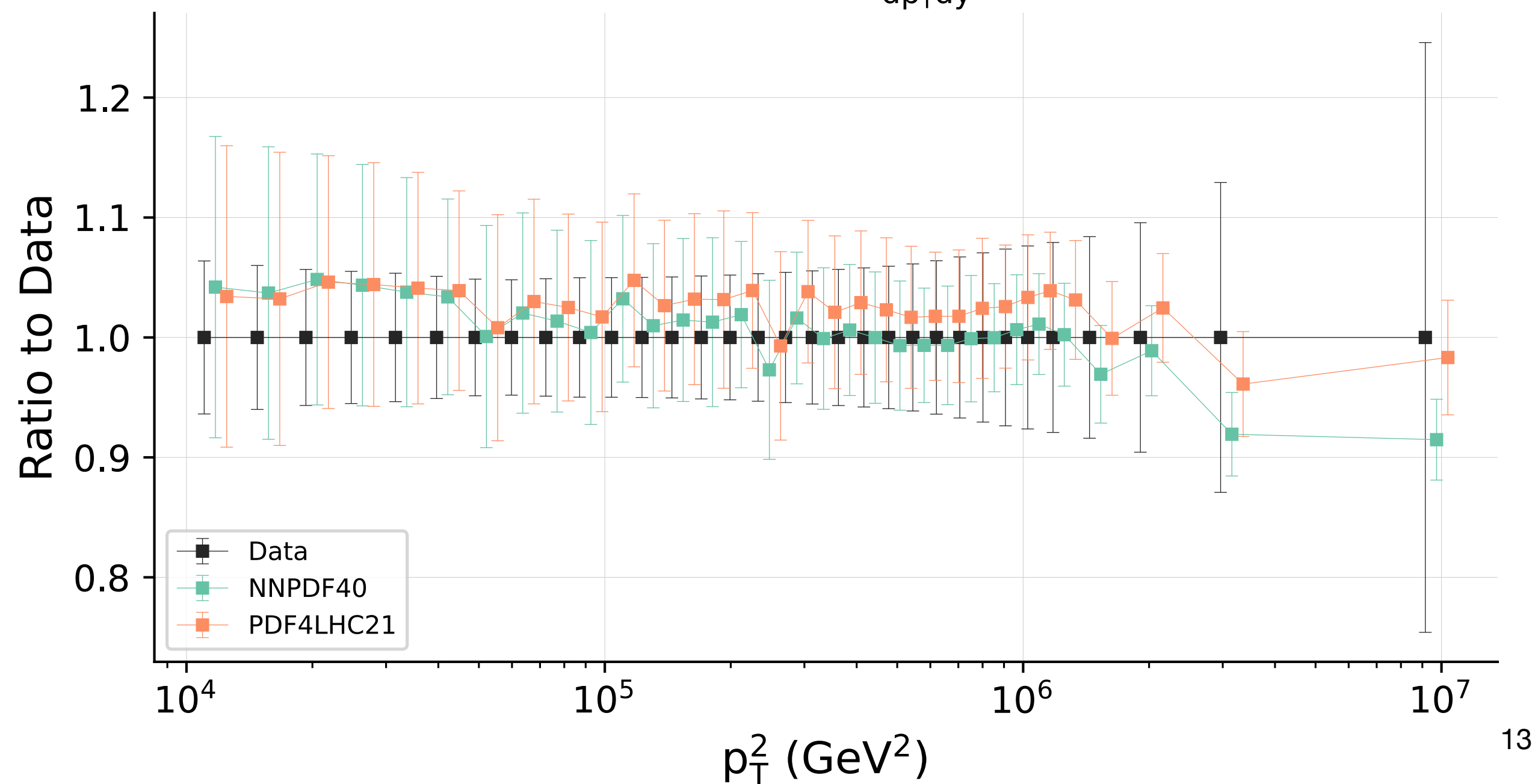


Atlas single jets

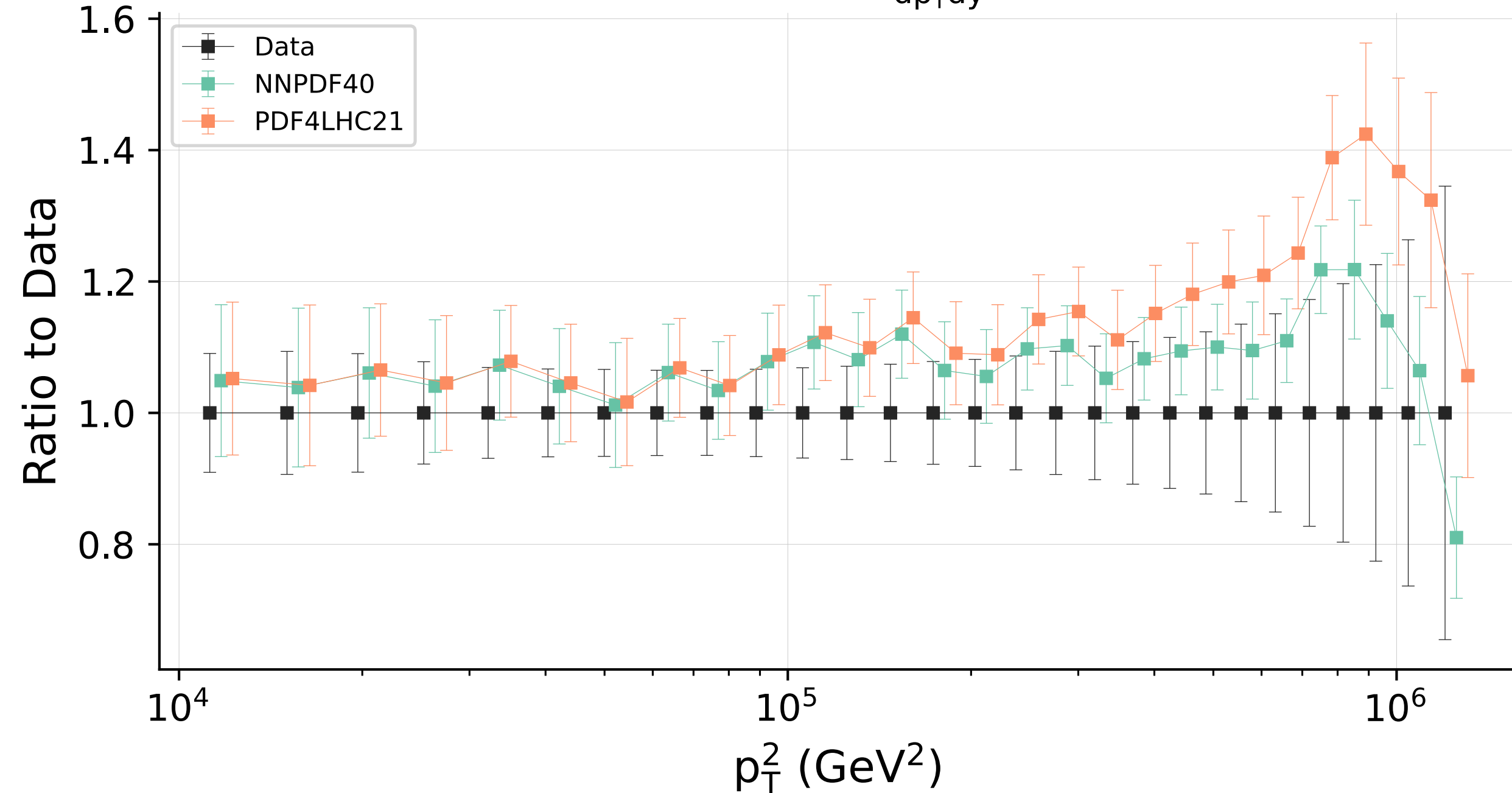
ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 1.75$



ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 0.75$

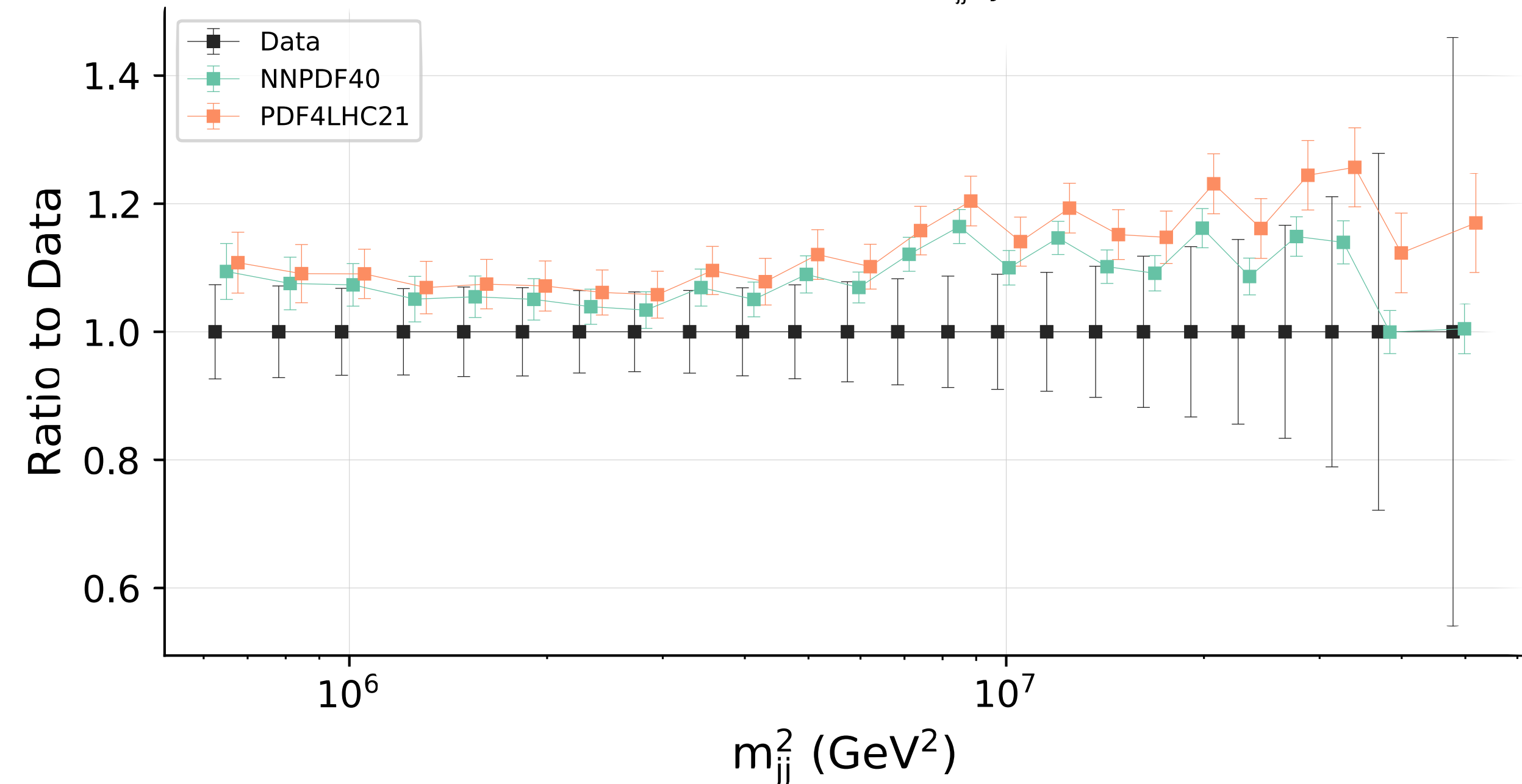


ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 2.25$

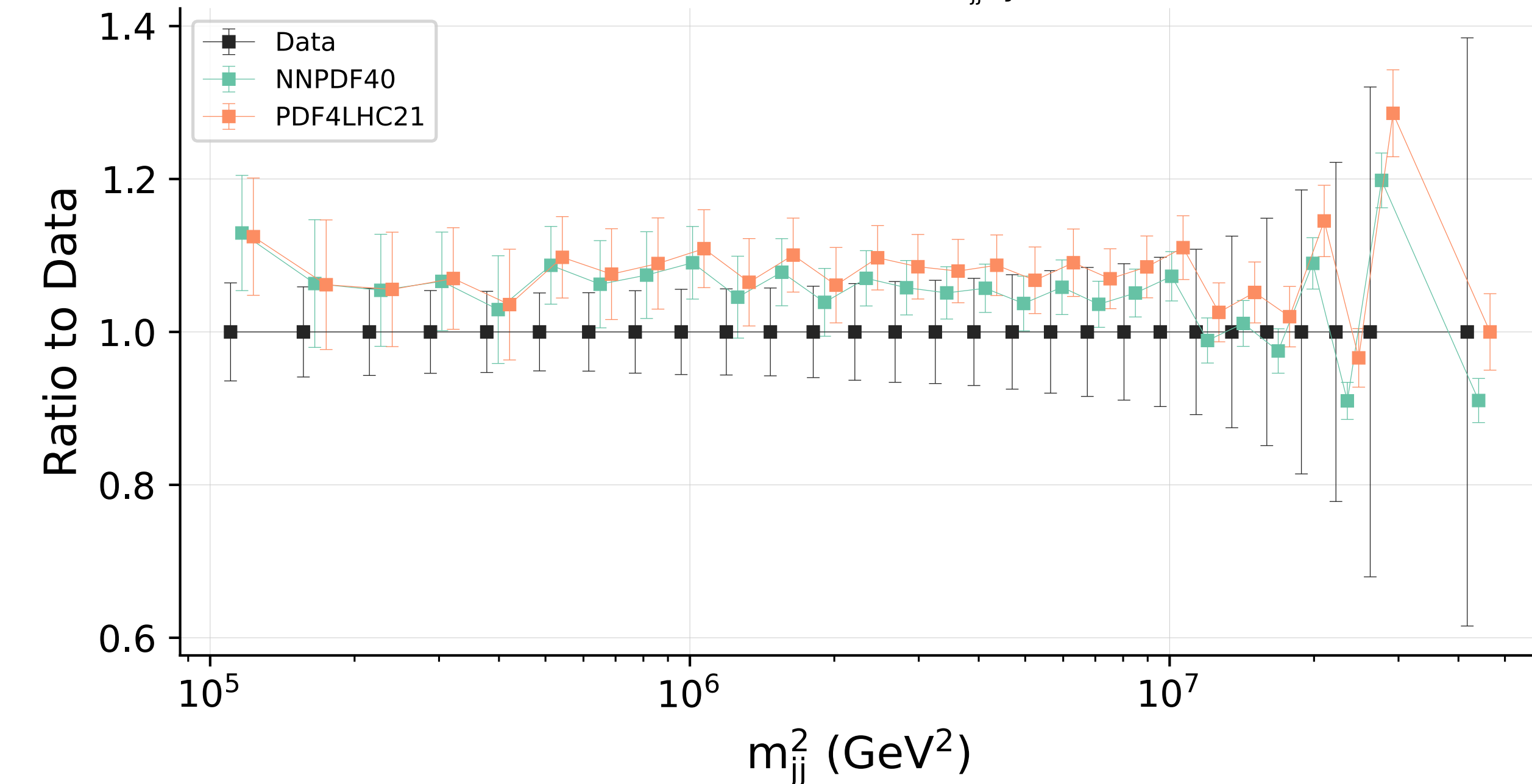


Atlas dijets

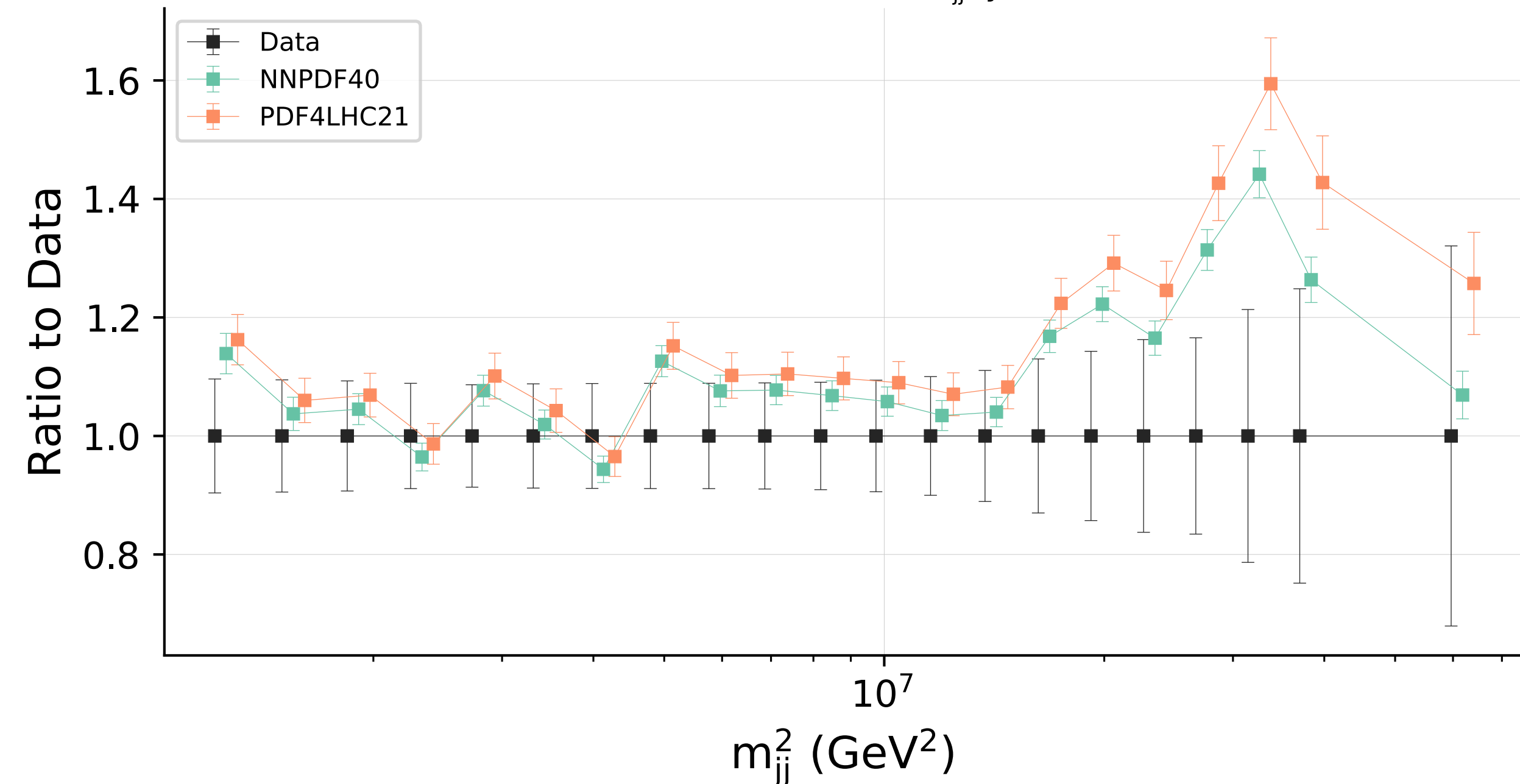
ATLAS Dijet 13 TeV: $\frac{d^2\sigma}{dm_{jj}dy} y^* = 1.75$



ATLAS Dijet 13 TeV: $\frac{d^2\sigma}{dm_{jj}dy} y^* = 0.75$



ATLAS Dijet 13 TeV: $\frac{d^2\sigma}{dm_{jj}dy} y^* = 2.25$

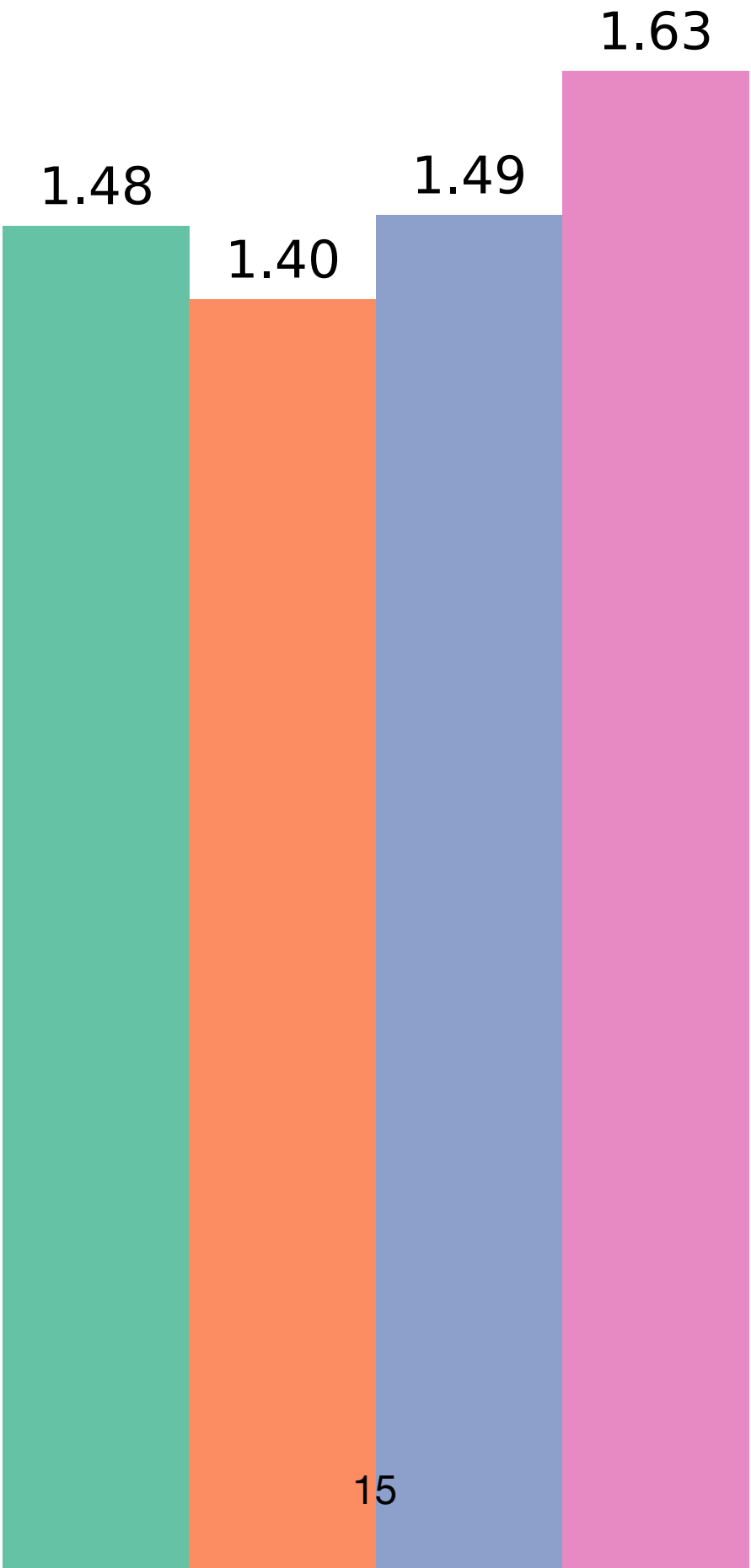
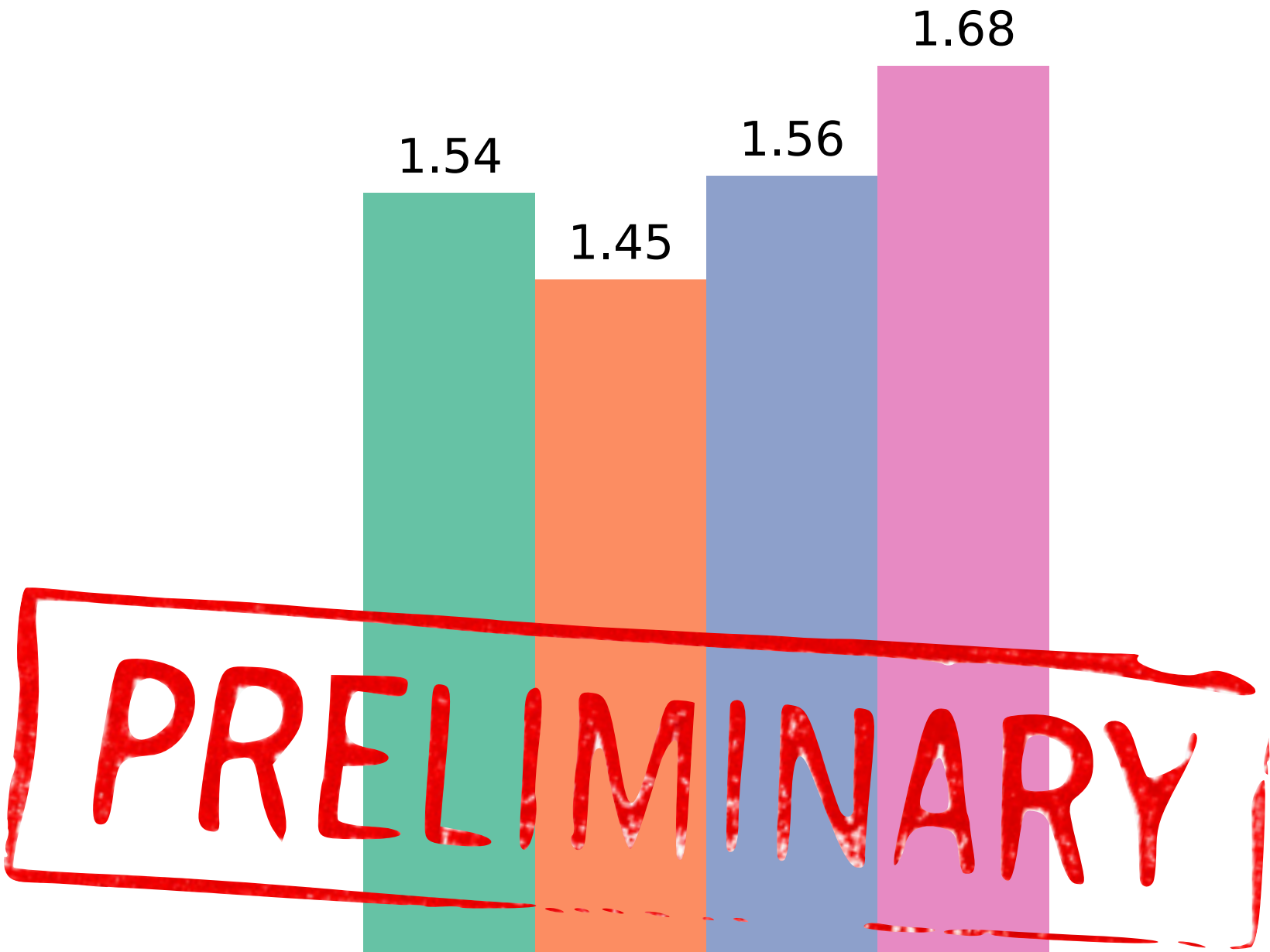
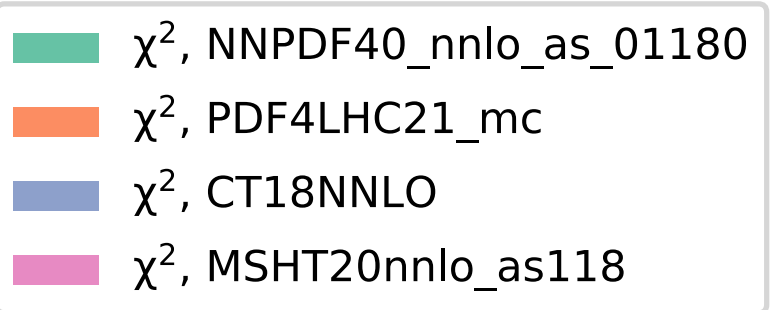


Atlas jets, total χ^2/N (with exp + PDF + scale variations)

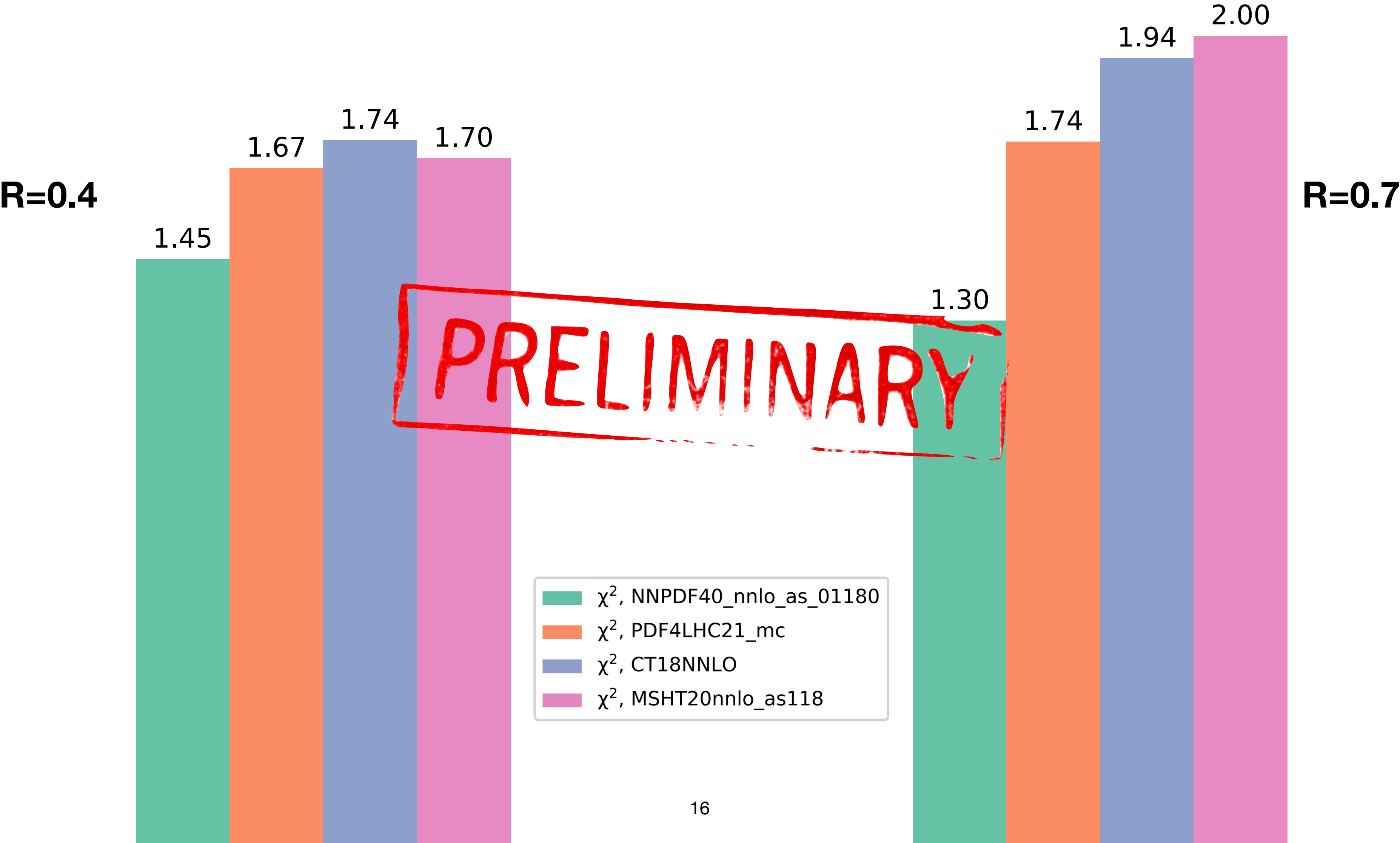
Single inclusive jets

Single inclusive jets
(alternative correlations)

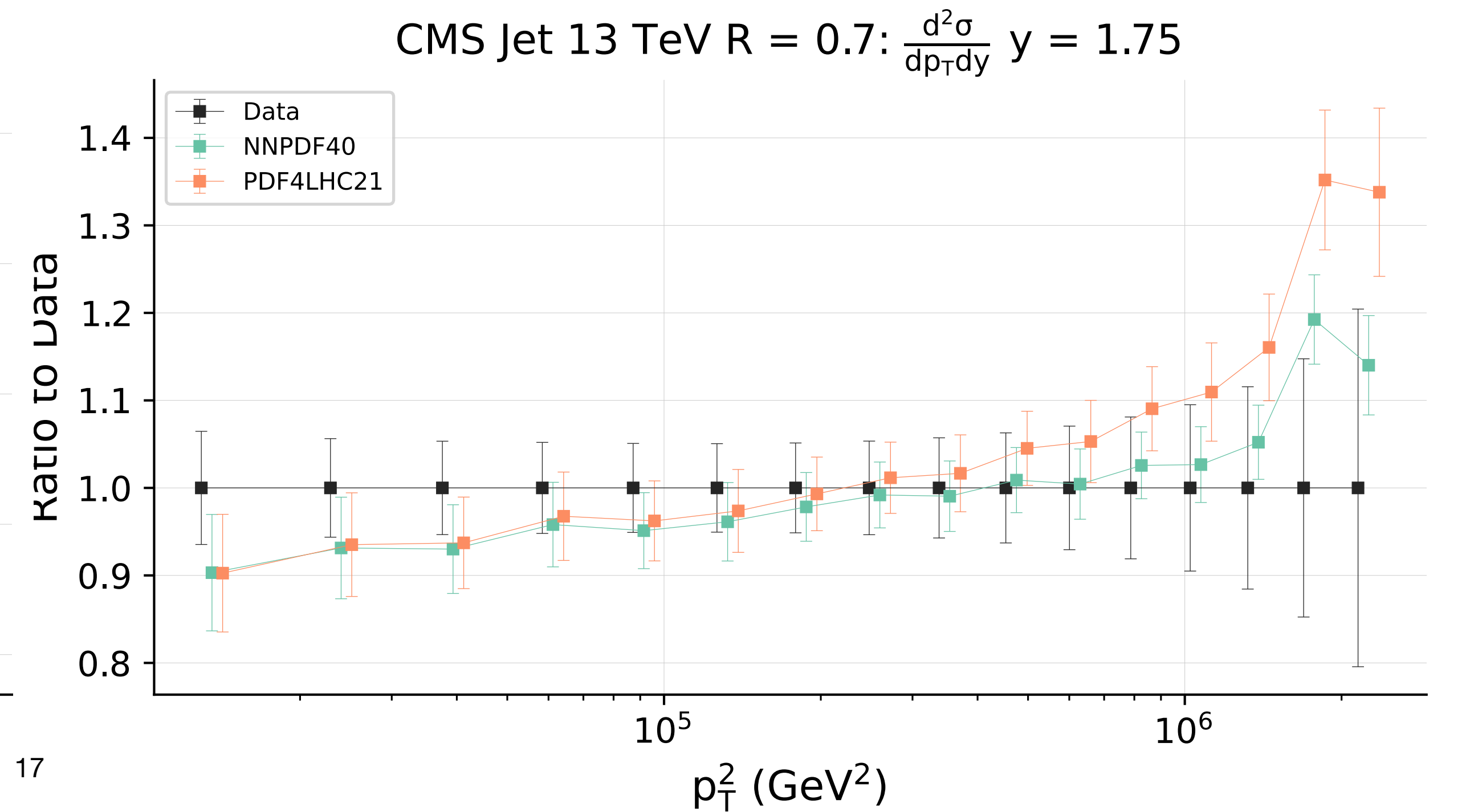
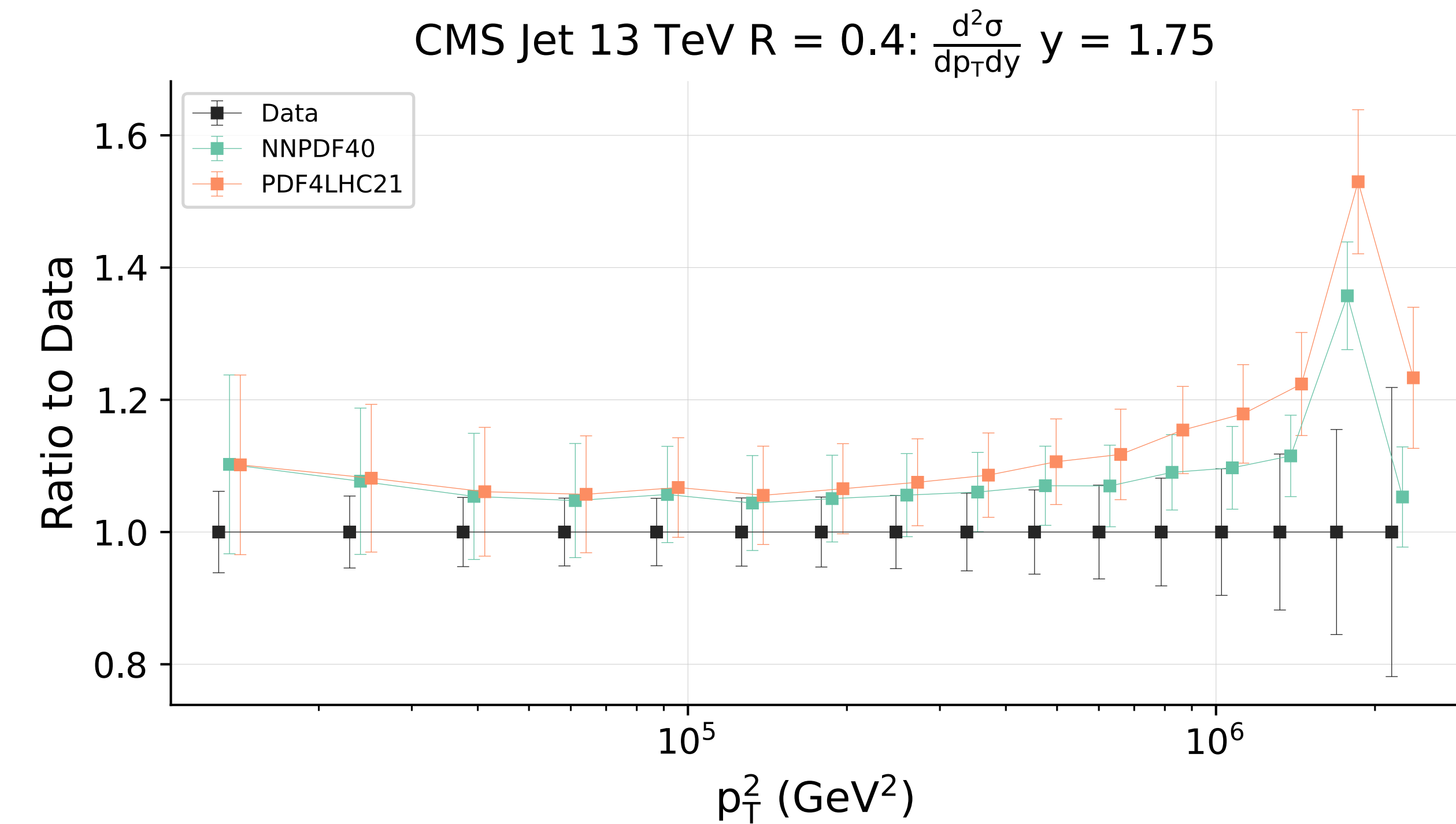
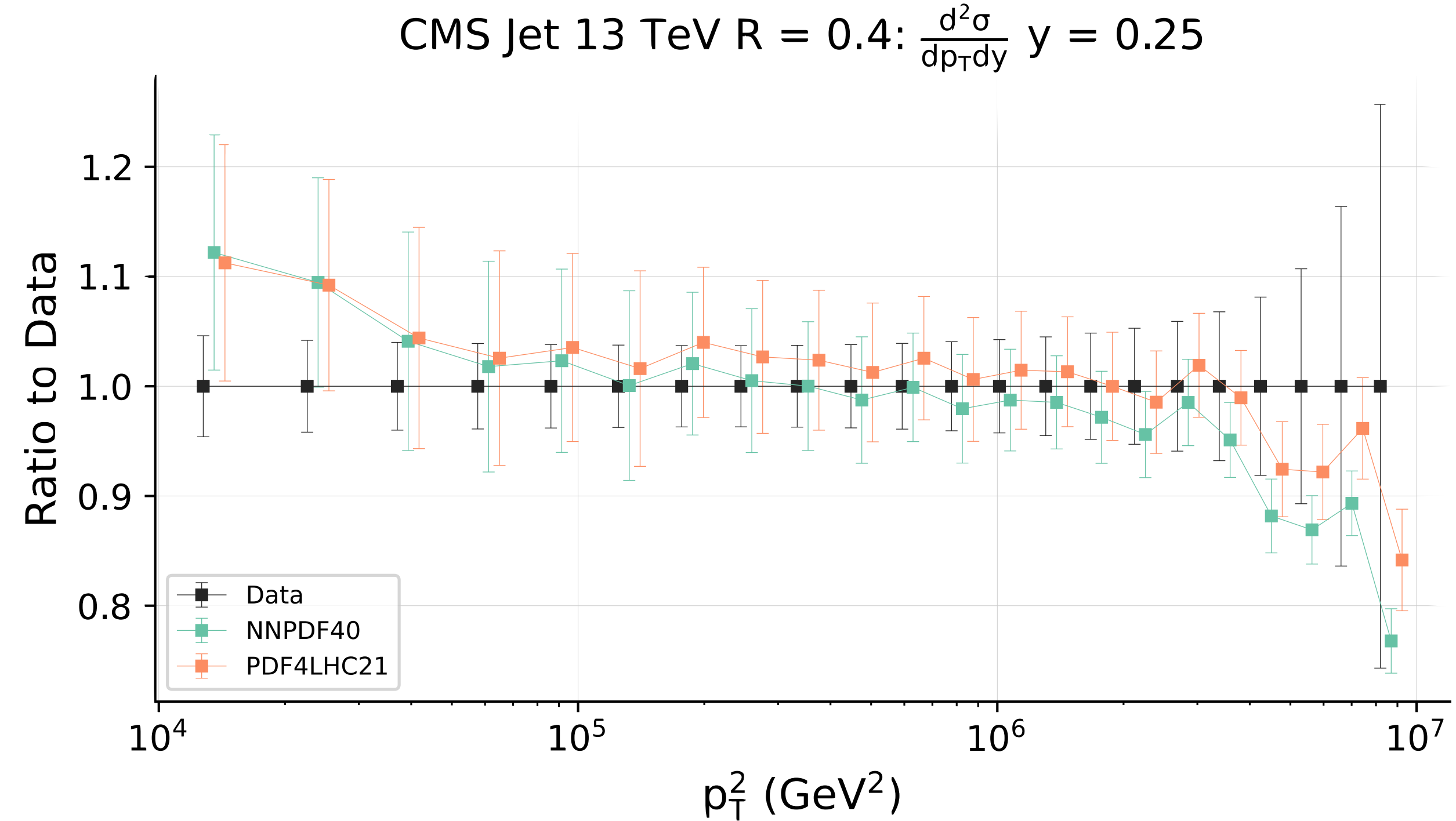
Dijets



CMS single inclusive jets, χ^2/N with only experimental and theory uncertainties



CMS single inclusive jets

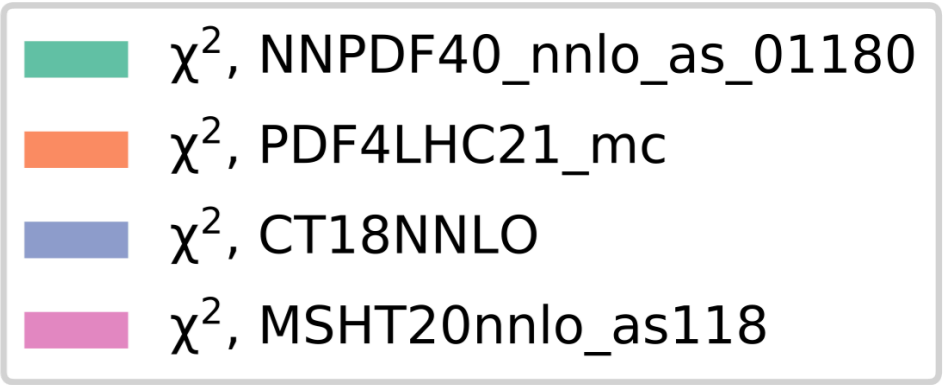
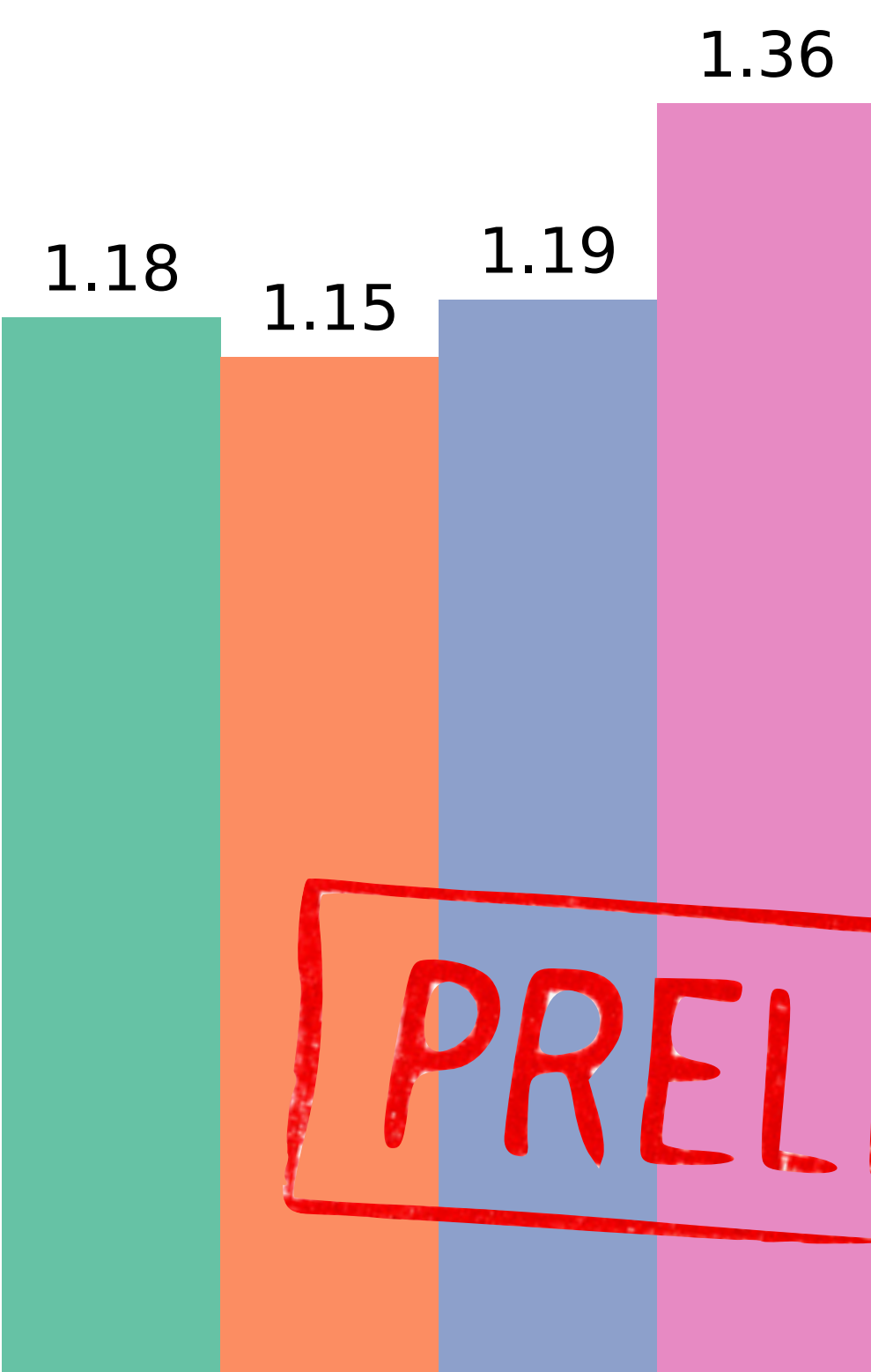


CMS single inclusive jets, total χ^2/N (with exp + PDF + scale variations)

R=0.4



R=0.7



PRELIMINARY

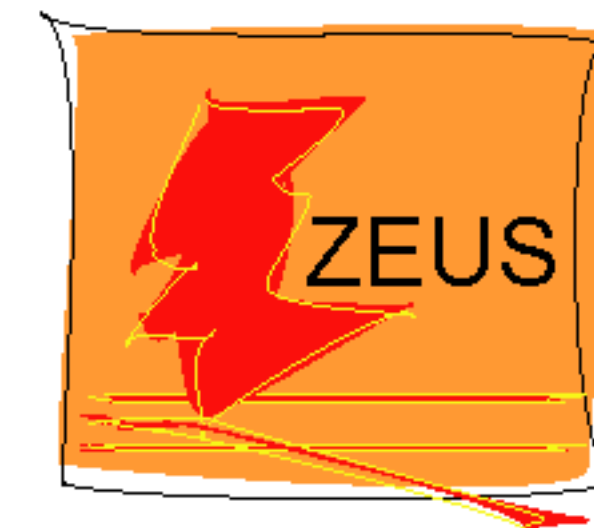
There's more than the LHC... Hera

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)

For these tests we are using NNLO grids from Ploughshare: <https://ploughshare.web.cern.ch/ploughshare/>

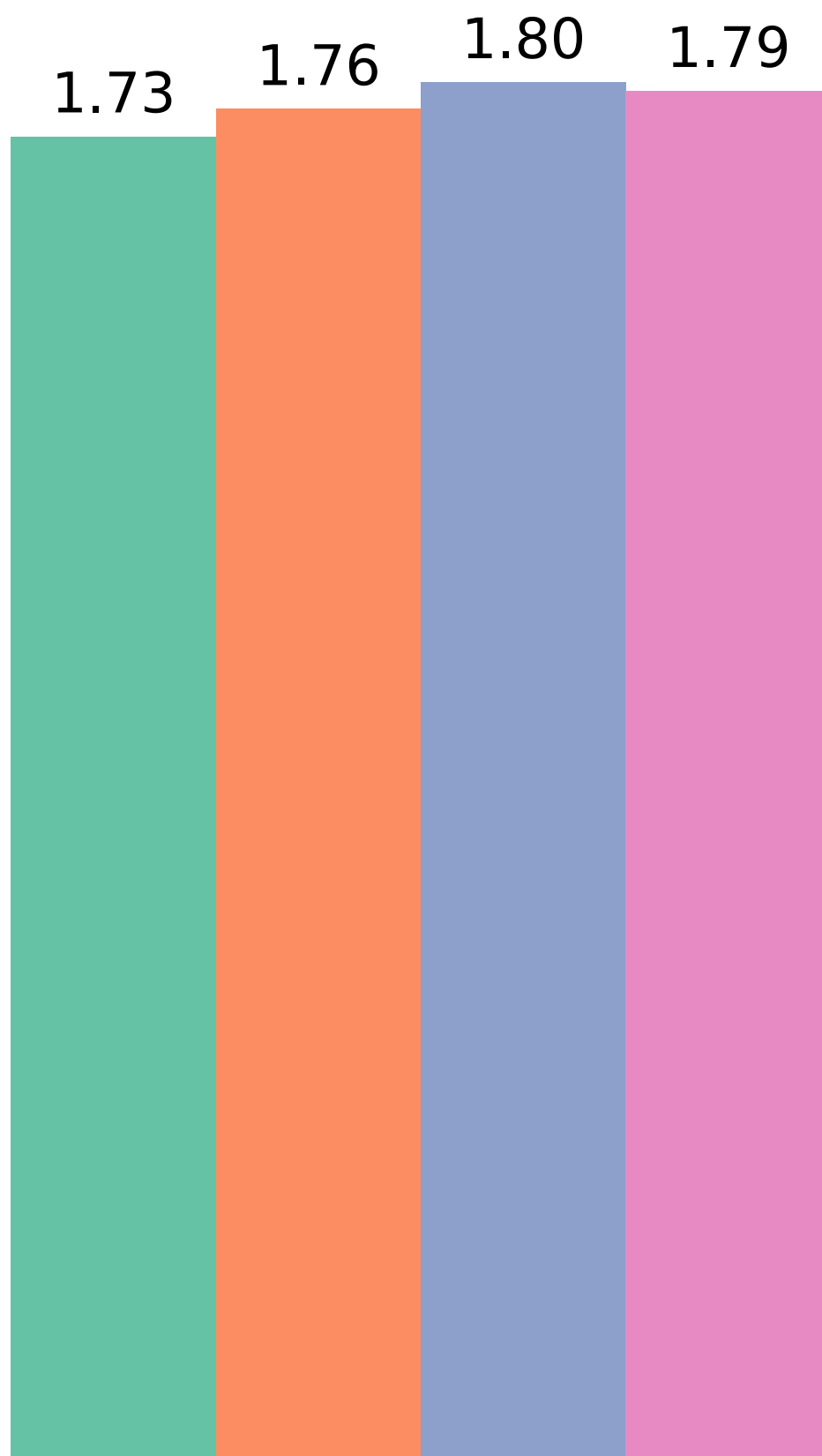
The datasets we are looking at are:

1. H1 jet and dijet production, 290pb^{-1} , $5.5 < Q^2 < 80 \text{ GeV}^2$; $0.2 < y < 0.6$ hepdata / 1496981
2. H1 jet and dijet production, 391pb^{-1} , $150 < Q^2 < 15000 \text{ GeV}^2$ hepdata / 1301218
3. Zeus inclusive jet production, 38.6pb^{-1} , $125 < Q \text{ GeV}$ hepdata / 593409
4. Zeus inclusive jet production, 82pb^{-1} , $125 < Q \text{ GeV}$ hepdata / 724050
5. Zeus dijet production, 374pb^{-1} , $125 < Q \text{ GeV}$ hepdata / 875006

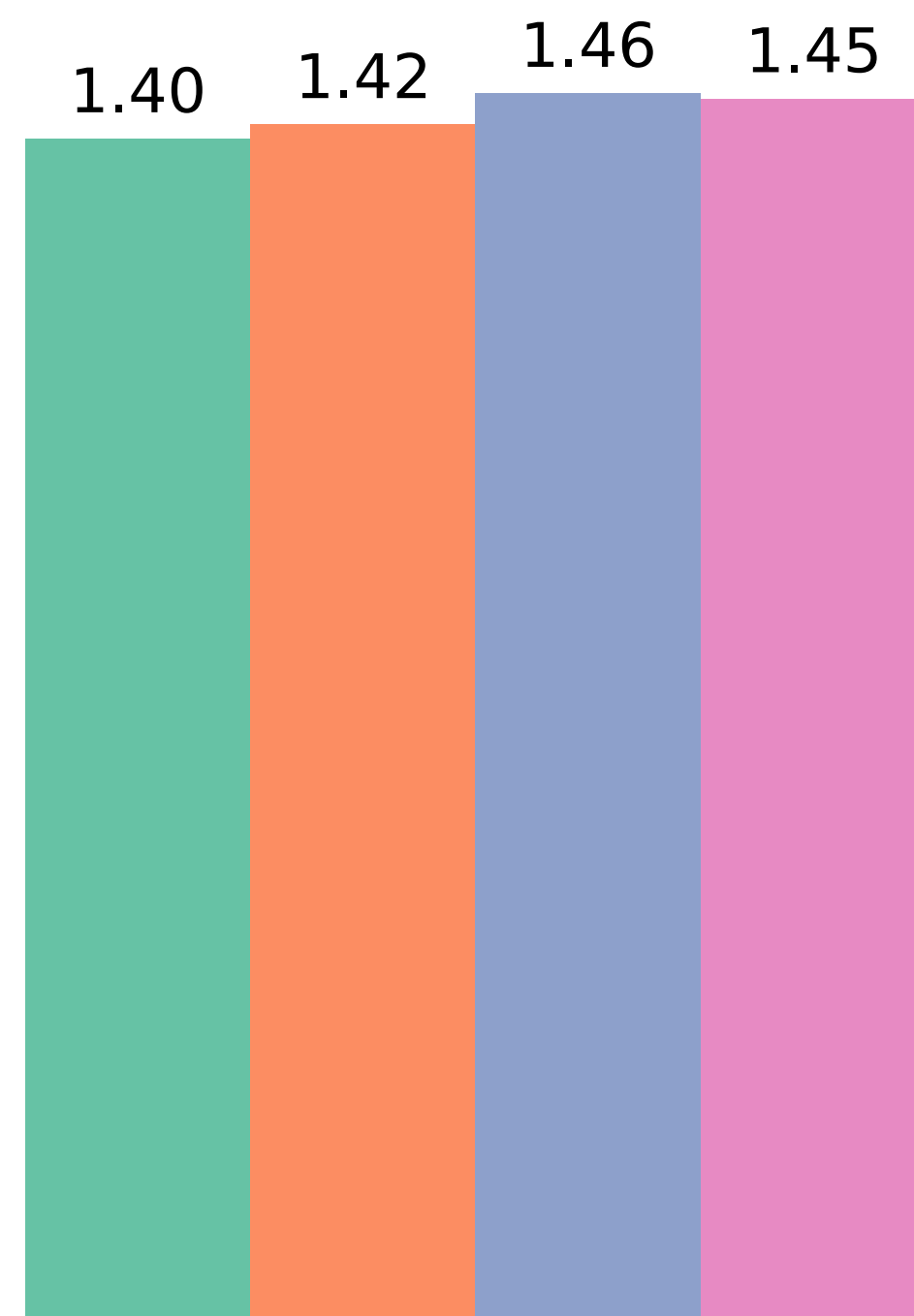


H1, χ^2/N with only experimental and theory uncertainties

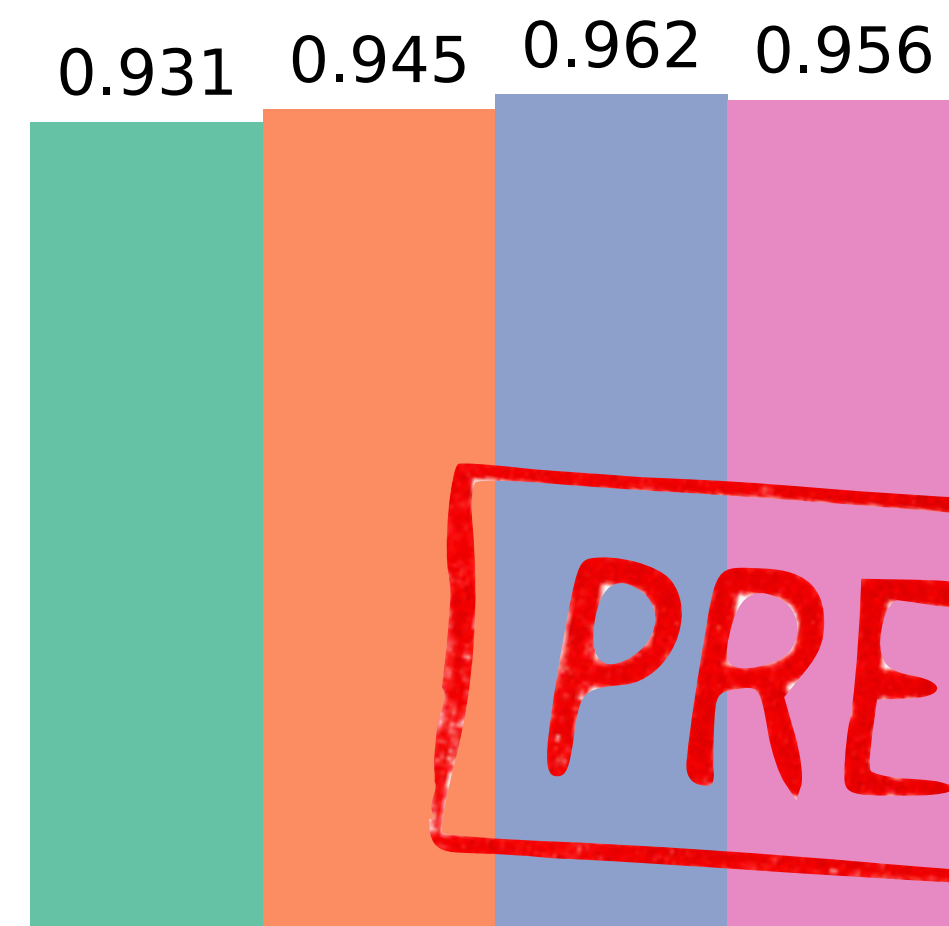
H1 1j 290pb⁻¹



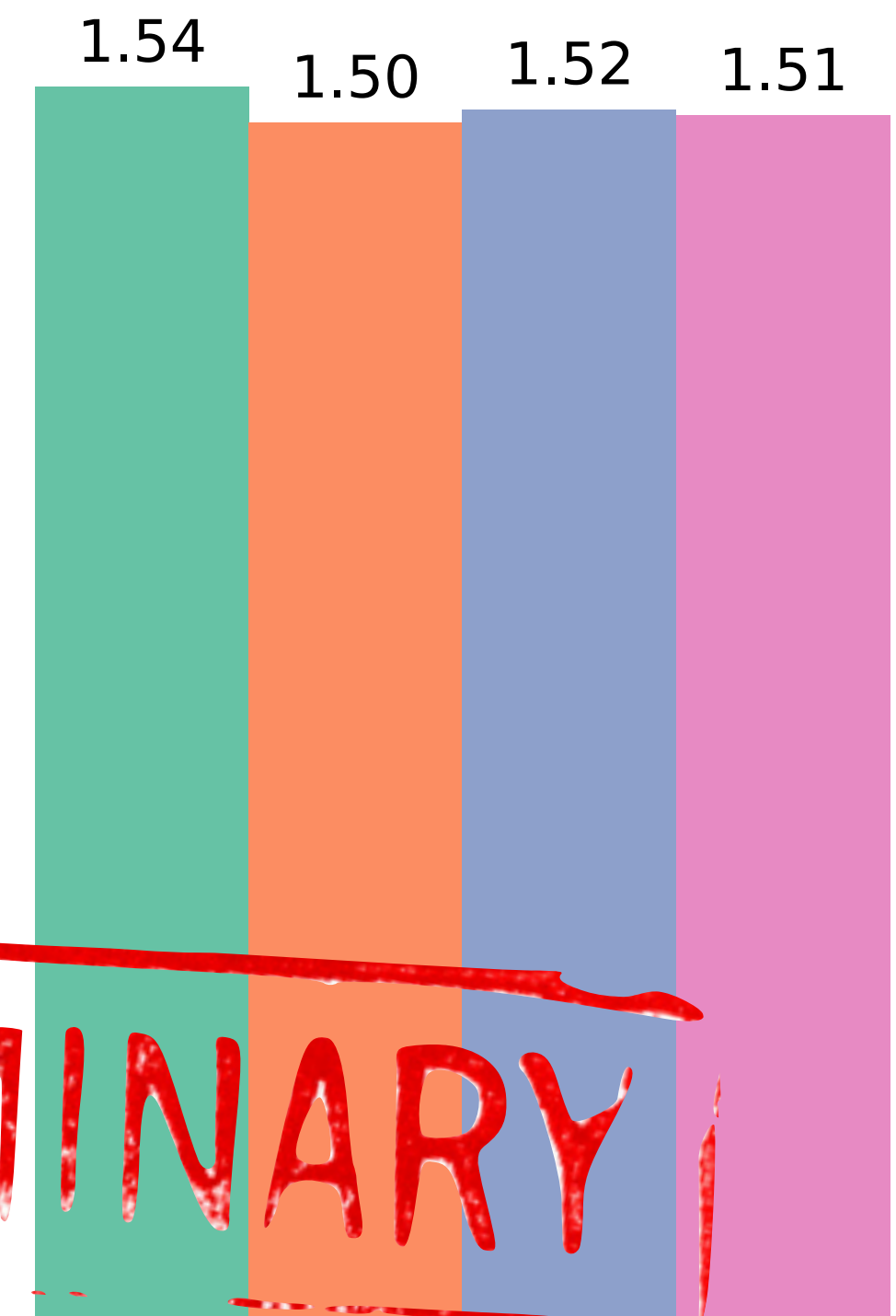
H1 1j 351pb⁻¹



H1 2j 290pb⁻¹

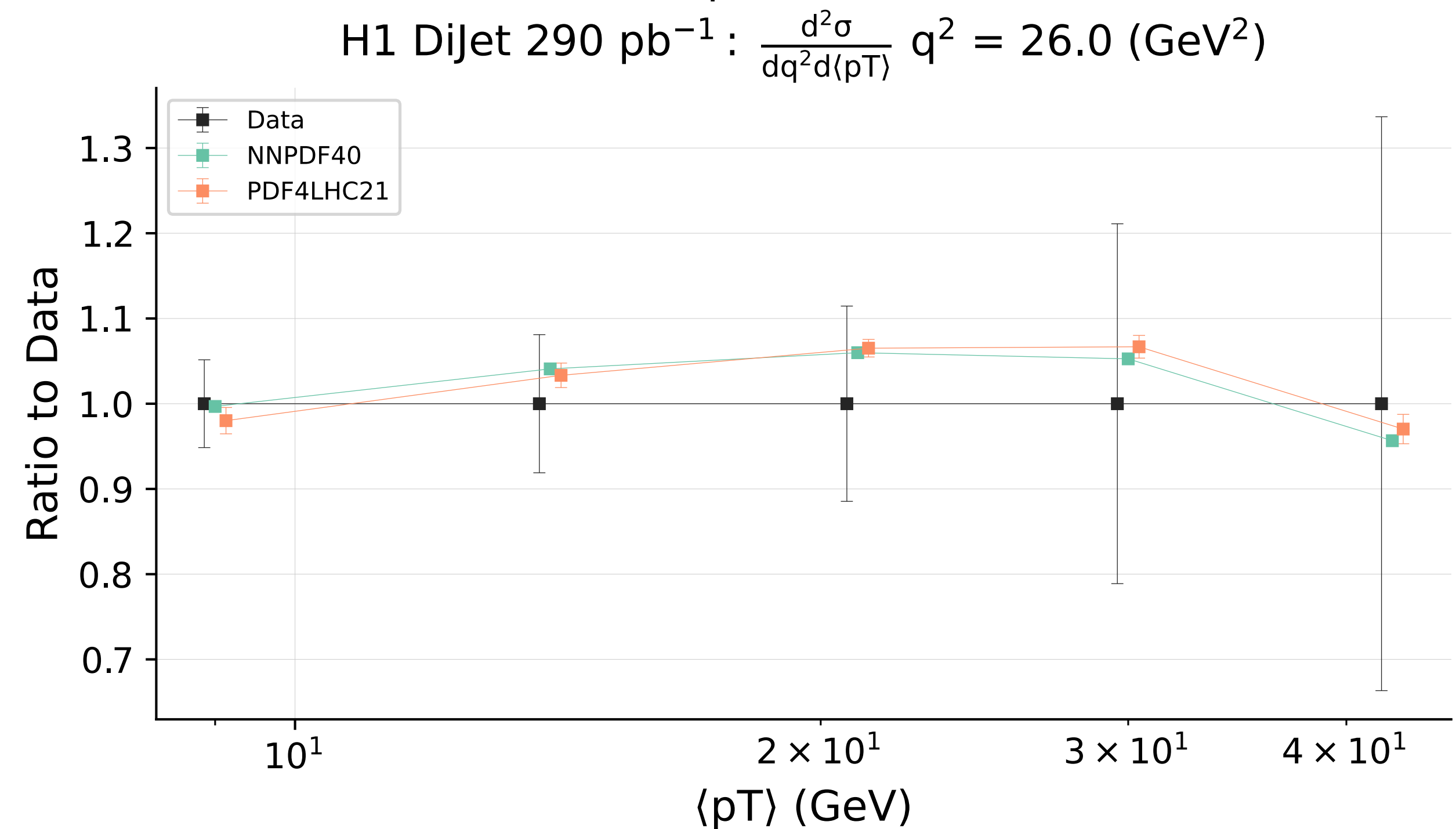
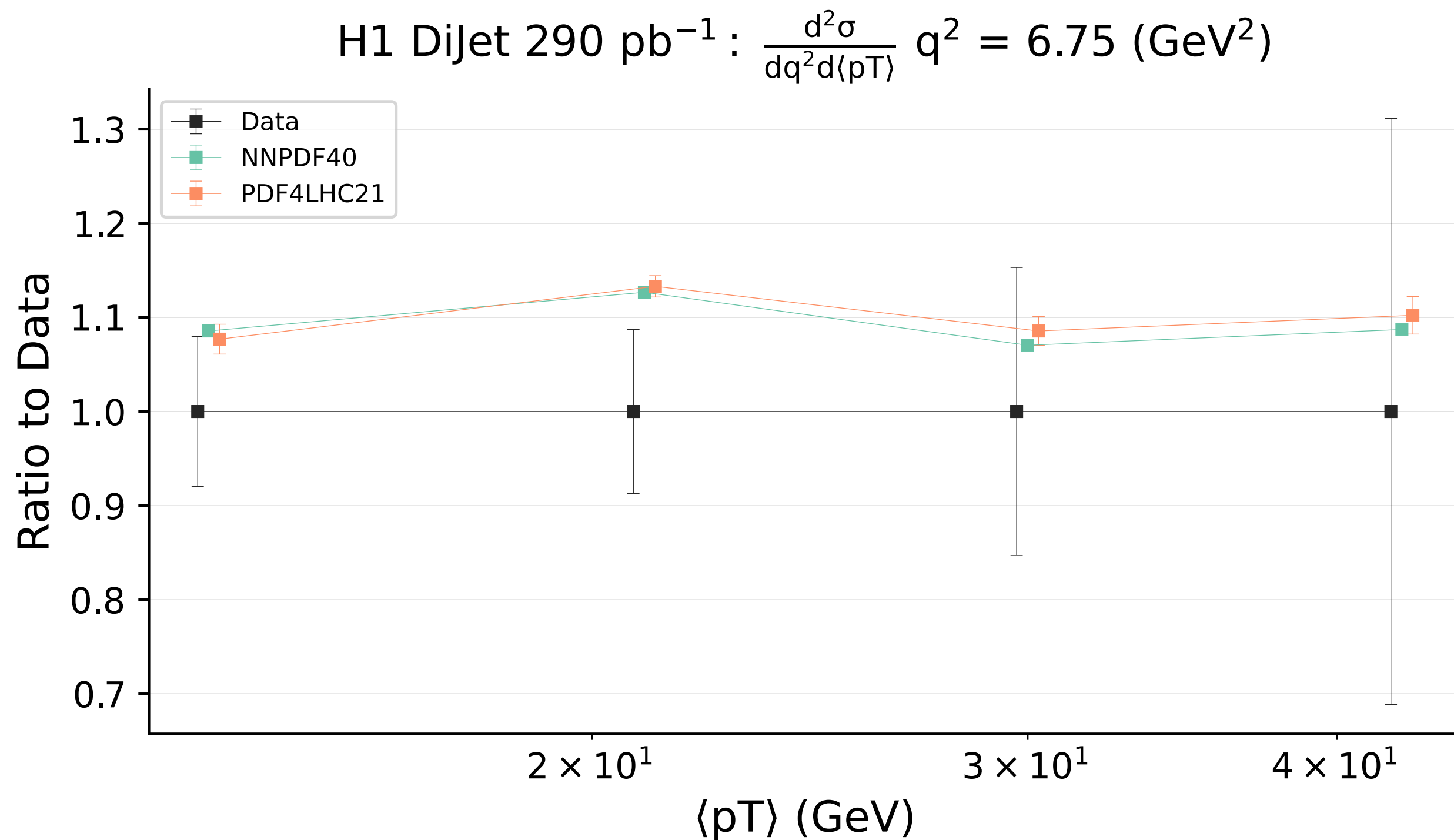
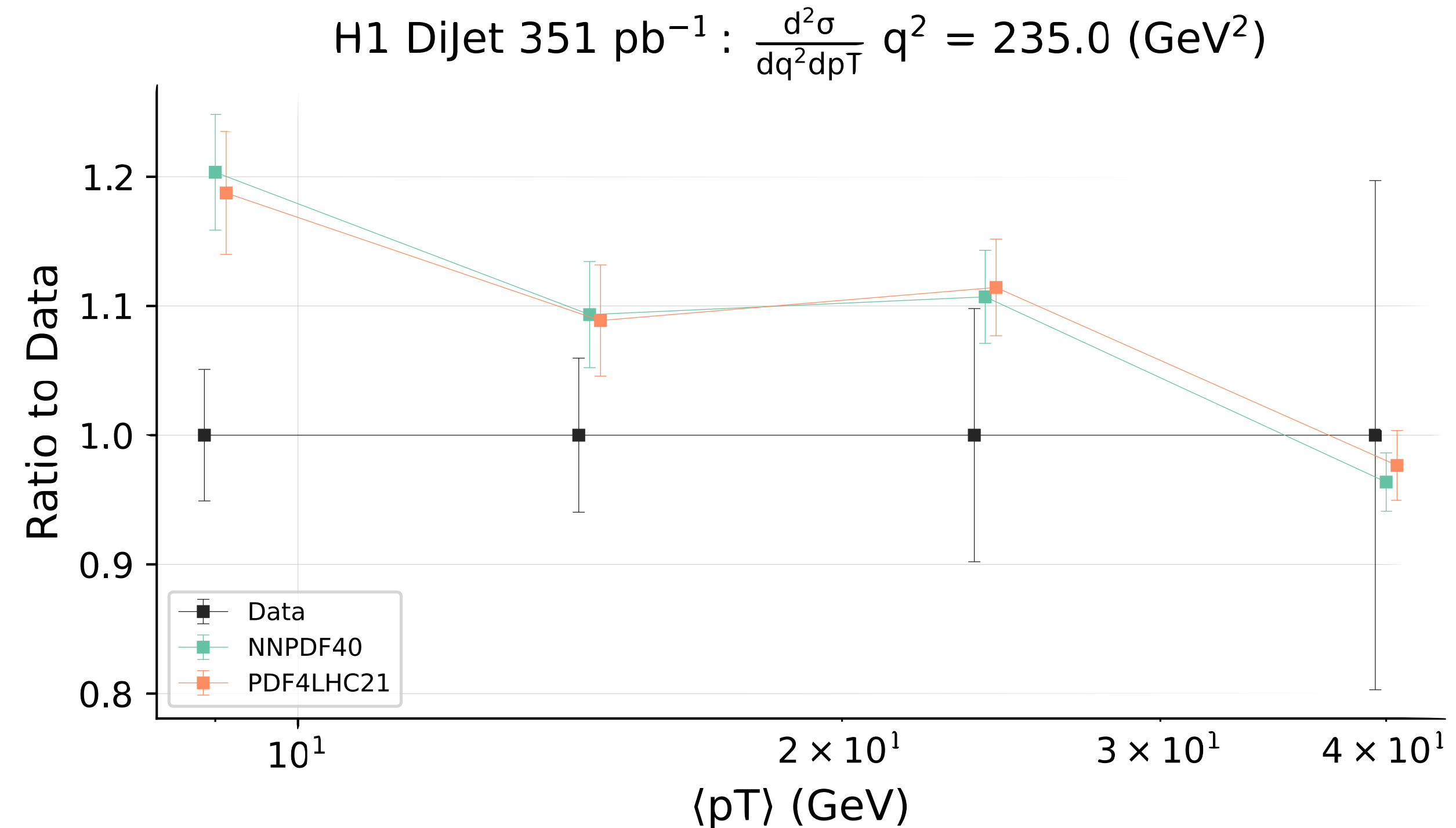


H1 2j 351pb⁻¹



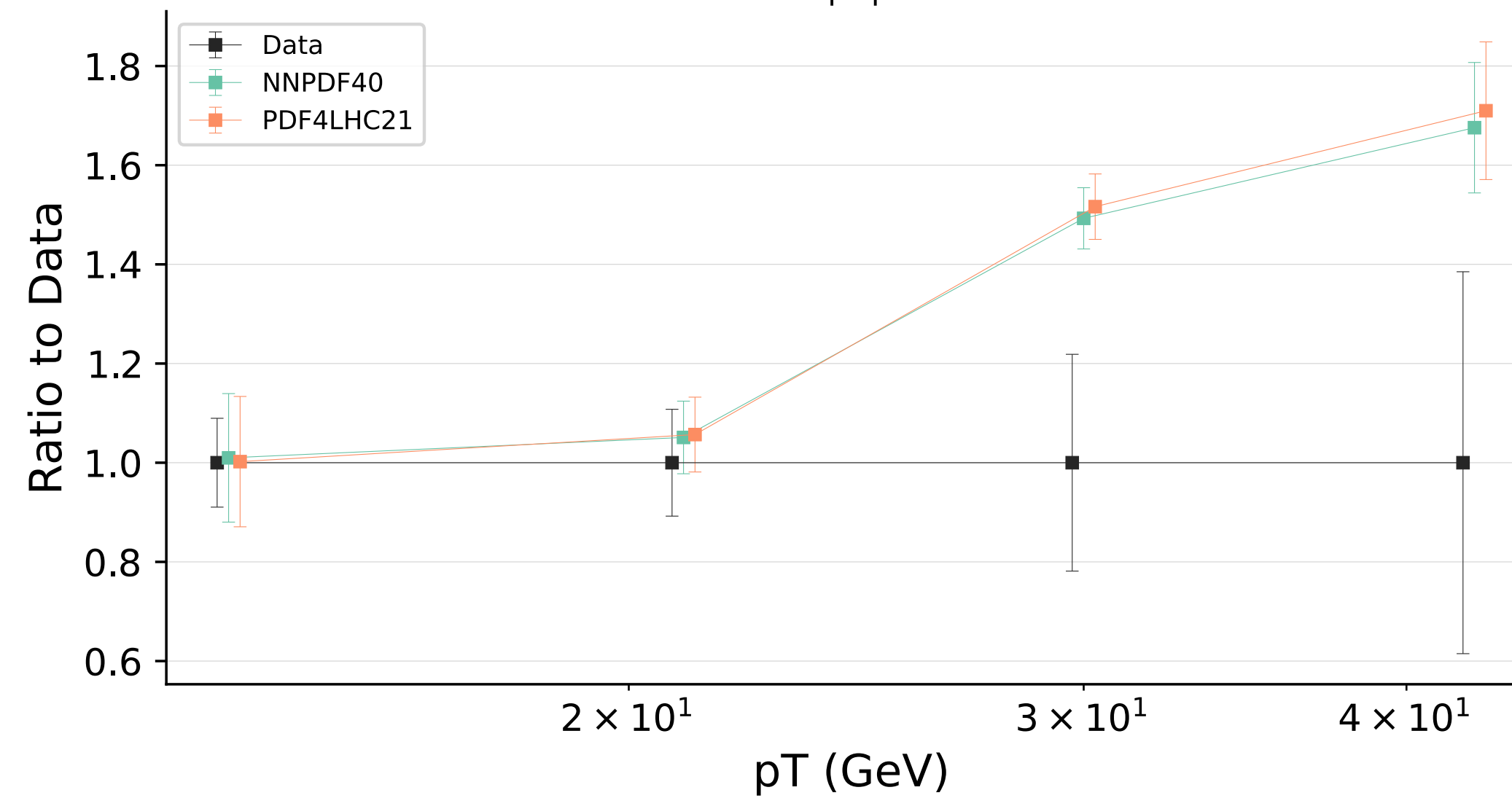
PRELIMINARY

H1 dijets

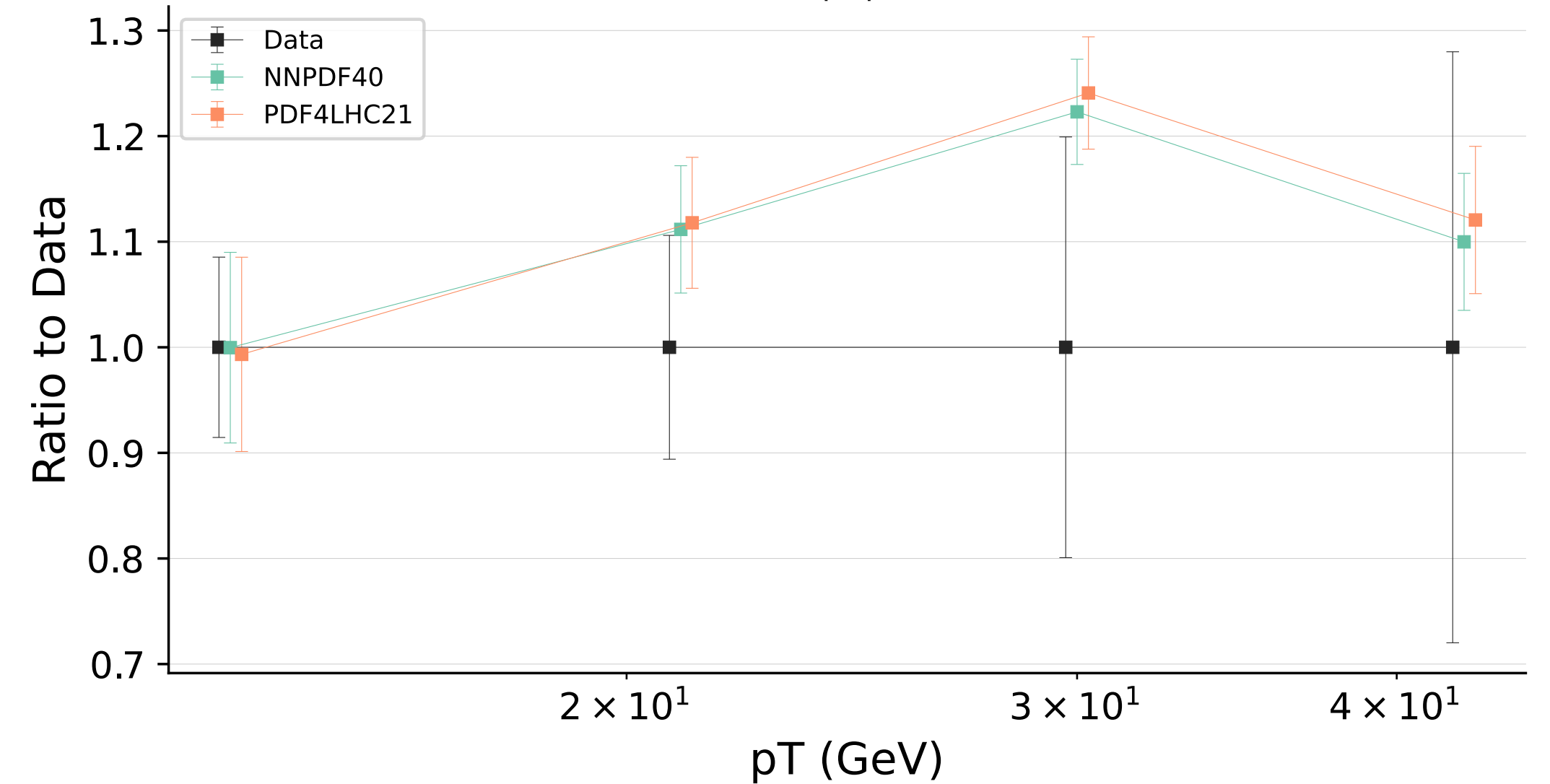


H1 single inclusive jets

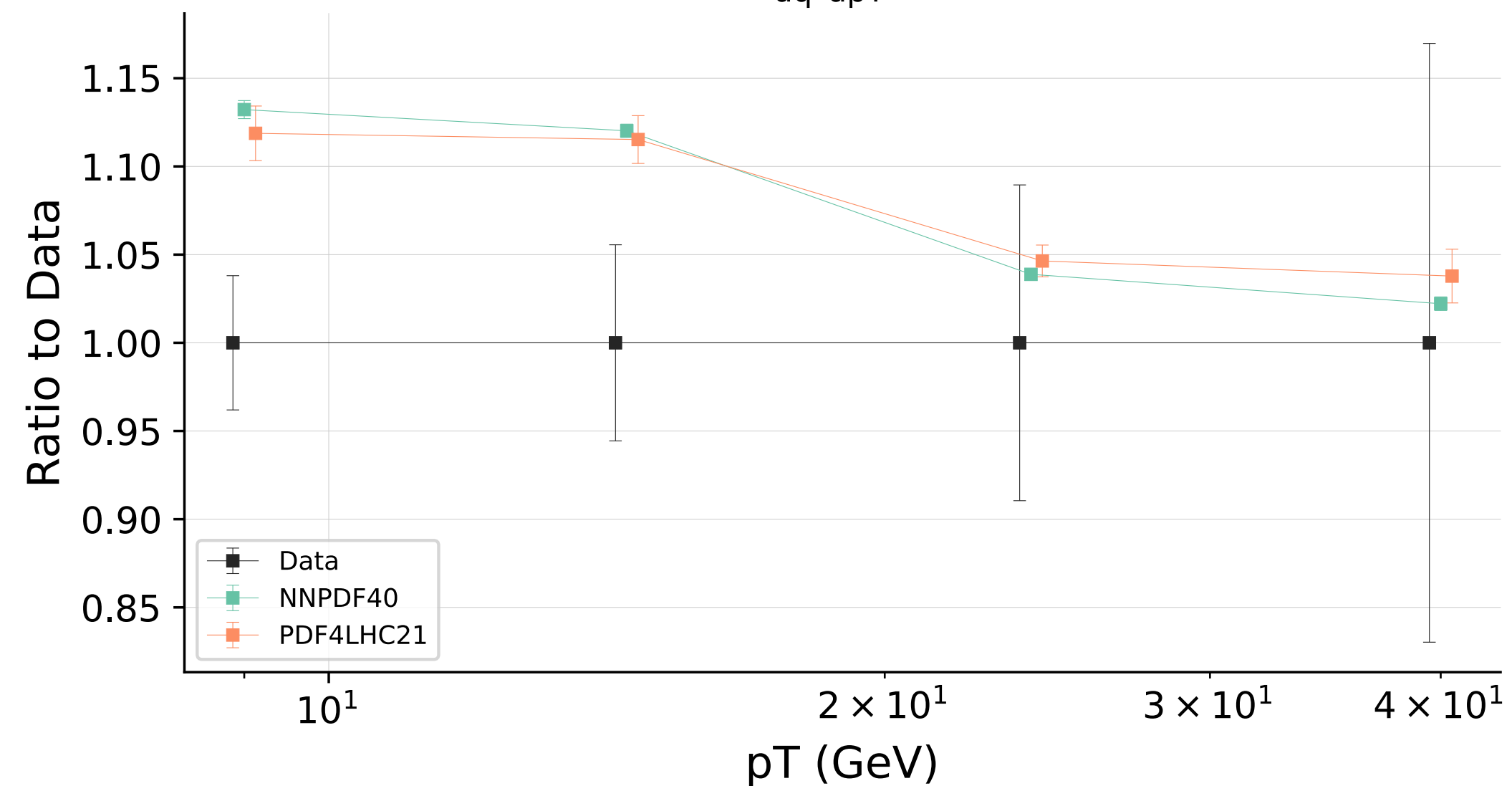
H1 Jet 290 pb⁻¹ : $\frac{d^2\sigma}{dq^2 dp_T}$ $q^2 = 6.75$ (GeV²)



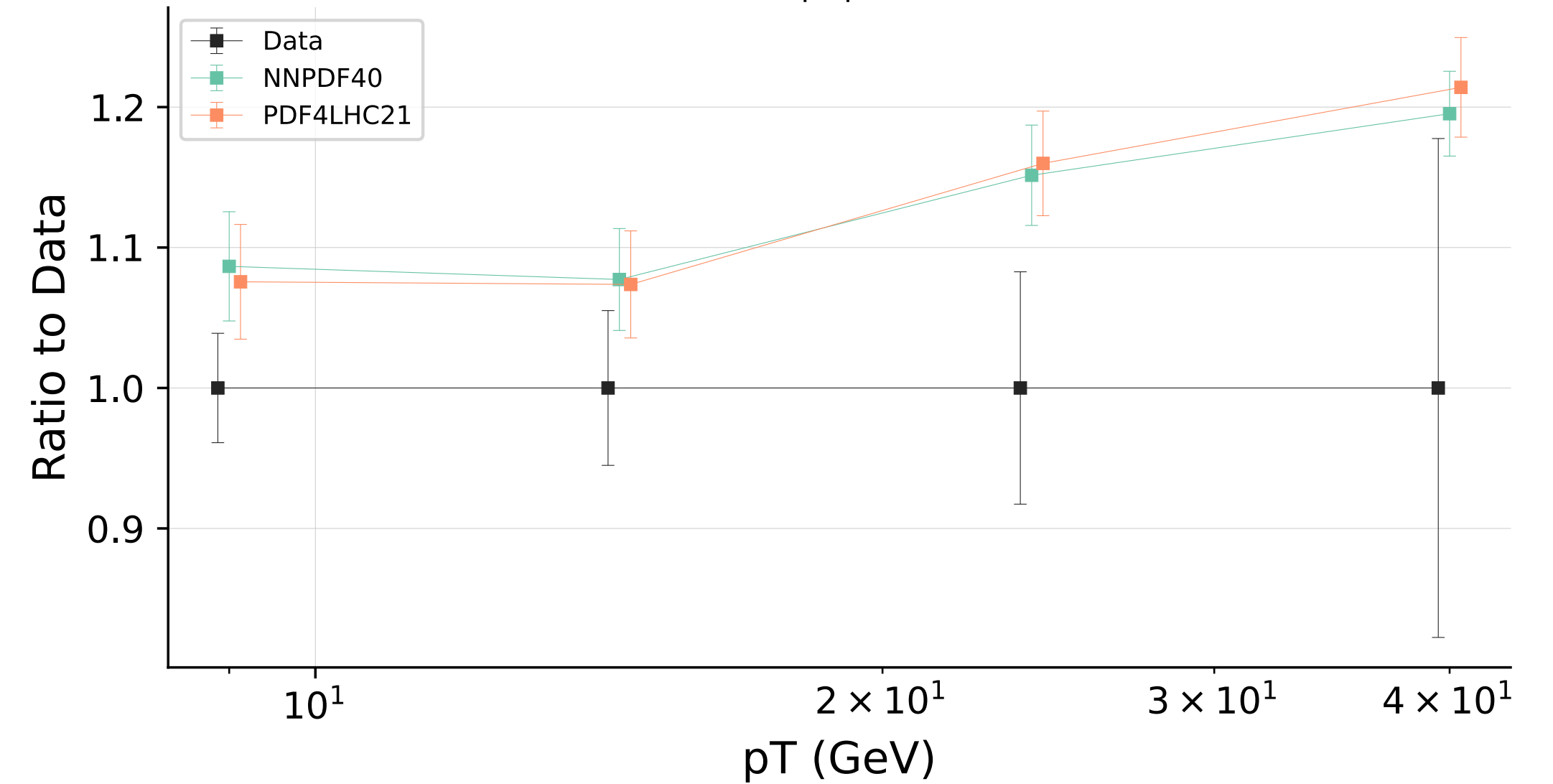
H1 Jet 290 pb⁻¹ : $\frac{d^2\sigma}{dq^2 dp_T}$ $q^2 = 13.5$ (GeV²)



H1 Jet 351 pb⁻¹ : $\frac{d^2\sigma}{dq^2 dp_T}$ $q^2 = 235.0$ (GeV²)



H1 Jet 351 pb⁻¹ : $\frac{d^2\sigma}{dq^2 dp_T}$ $q^2 = 335.0$ (GeV²)

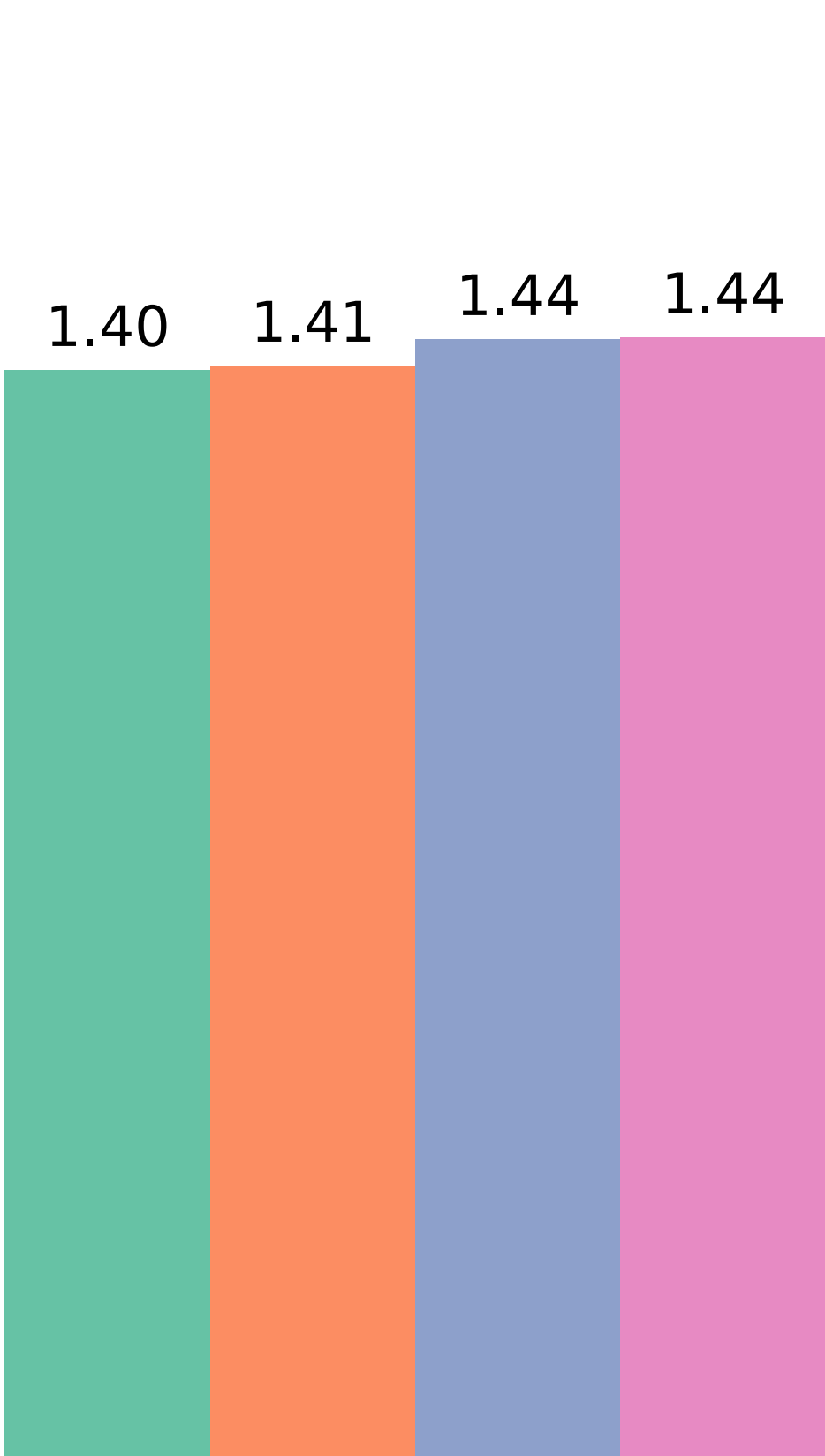


H1, total χ^2/N (with exp + PDF + scale variations)

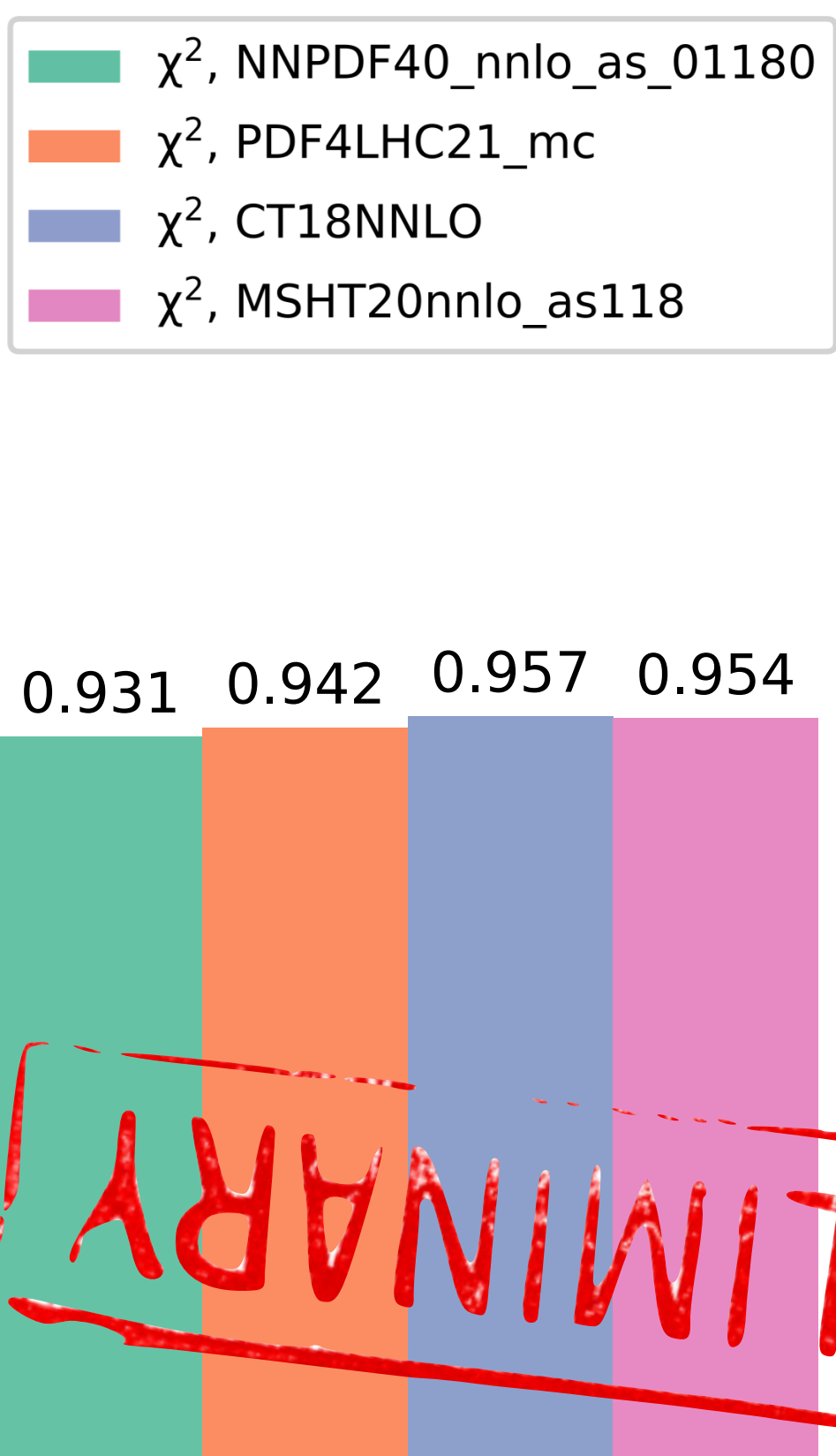
H1 1j 290pb⁻¹



H1 1j 351pb⁻¹



H1 2j 290pb⁻¹

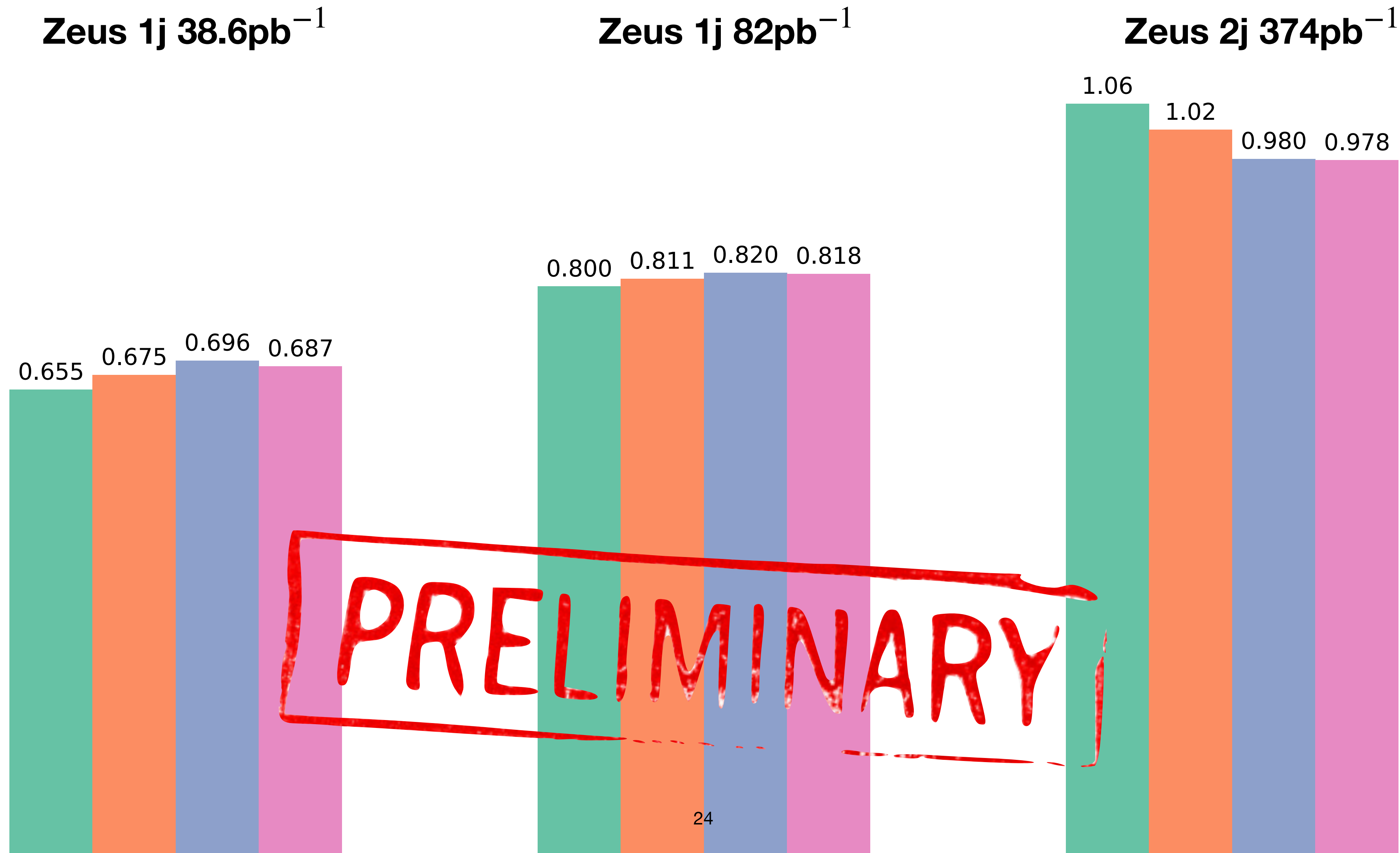


H1 2j 351pb⁻¹

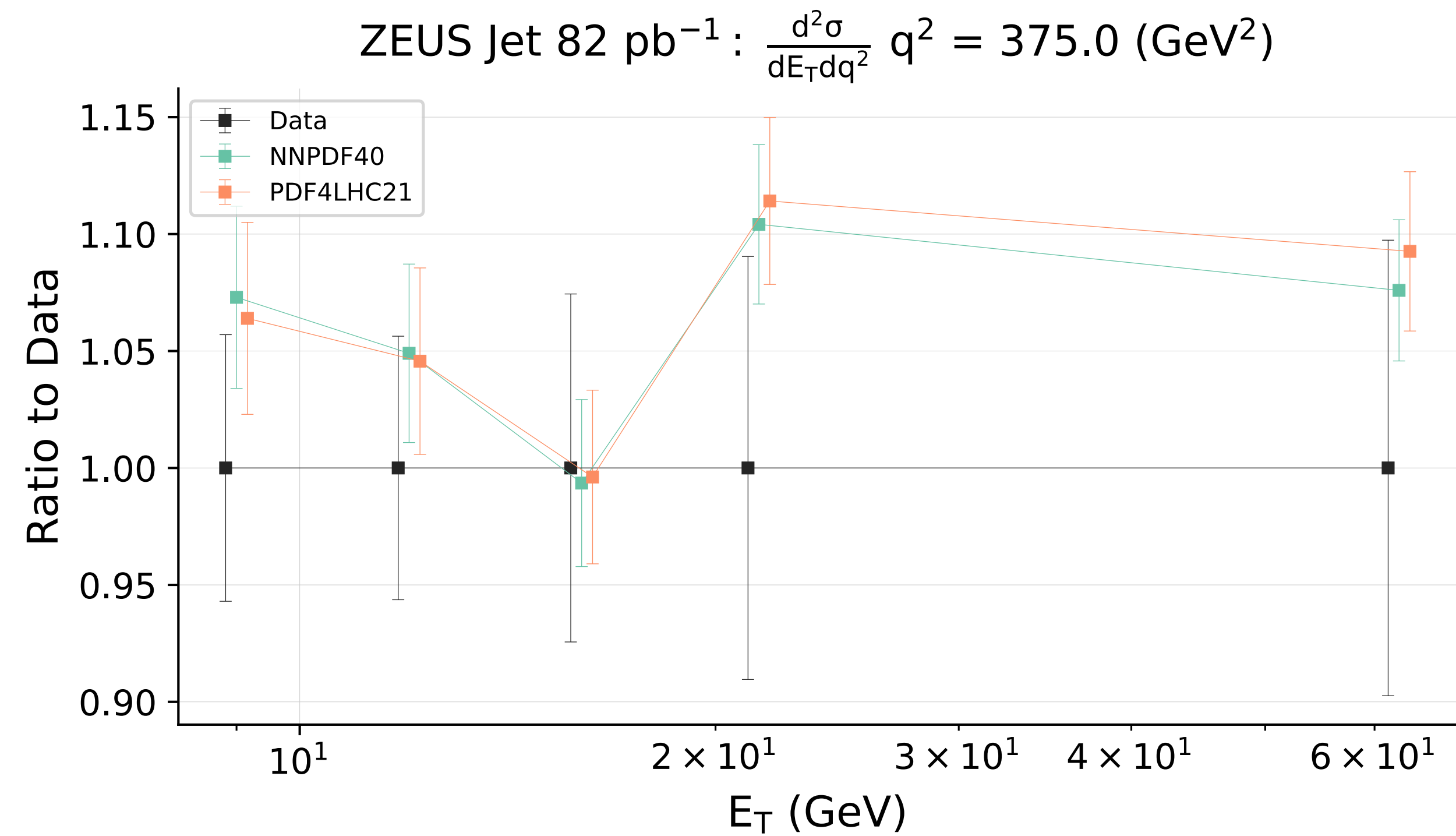
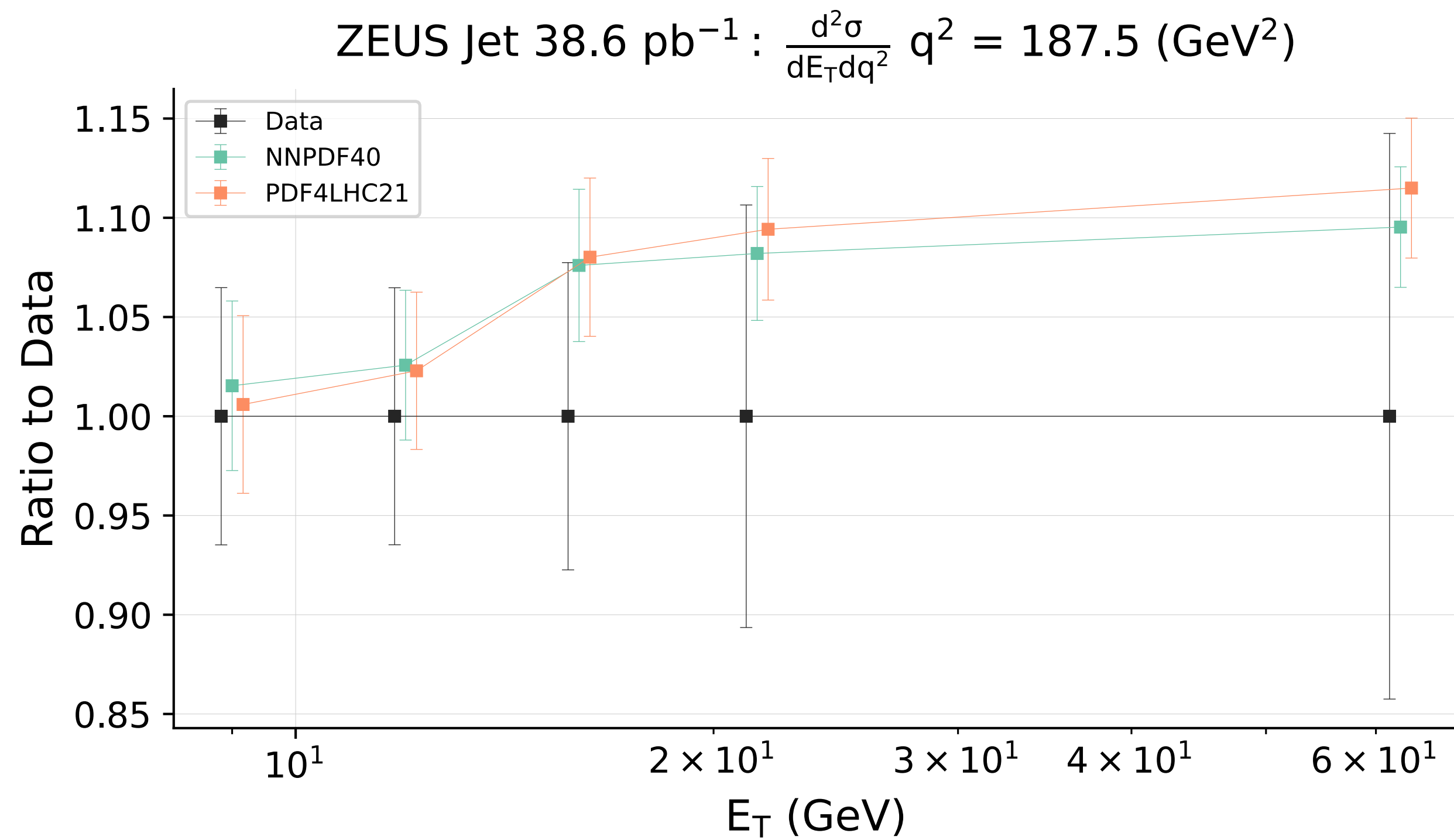


PRELIMINARY

Zeus, χ^2/N with only experimental and theory uncertainties

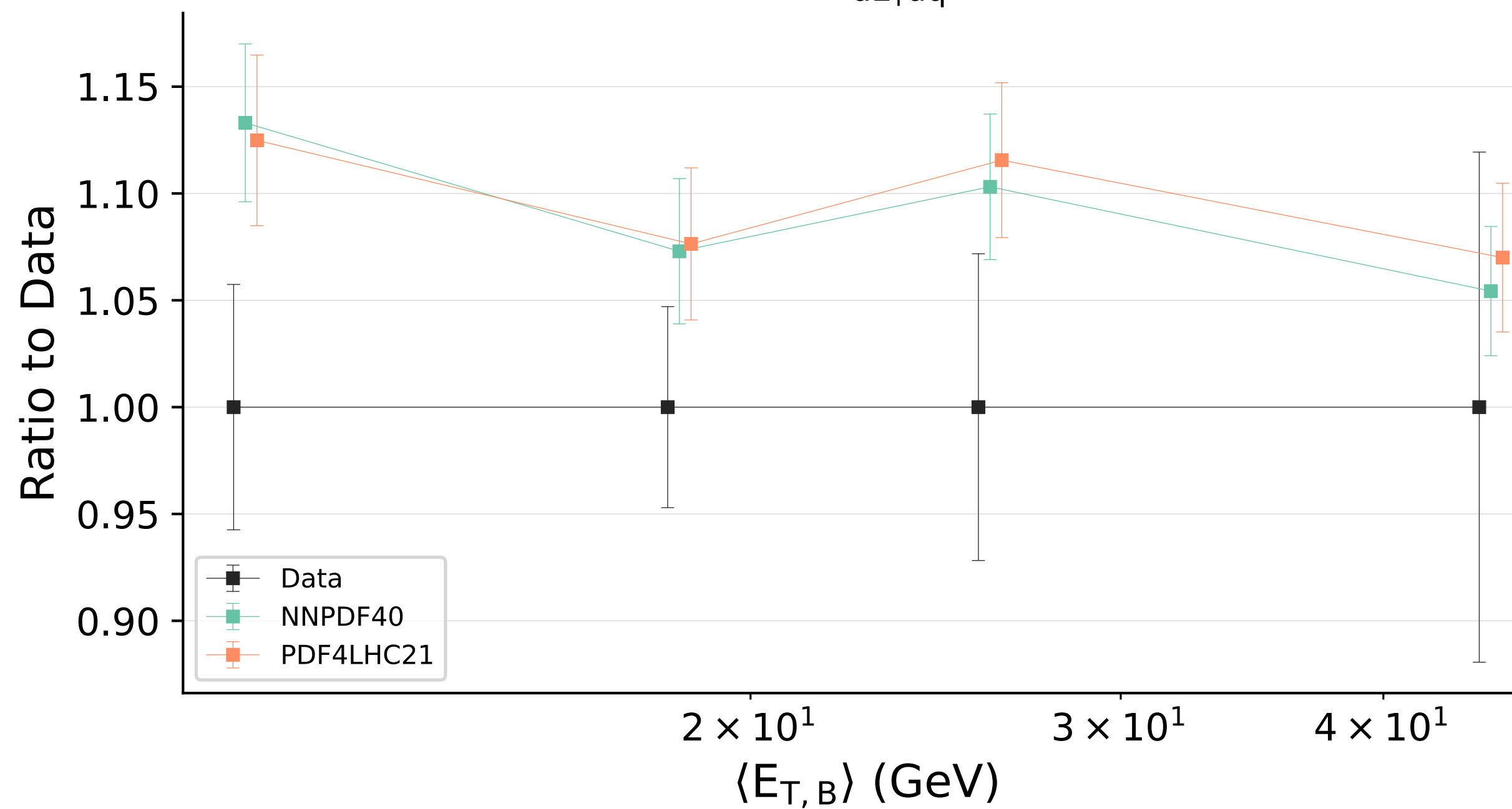


Zeus inclusive jet production

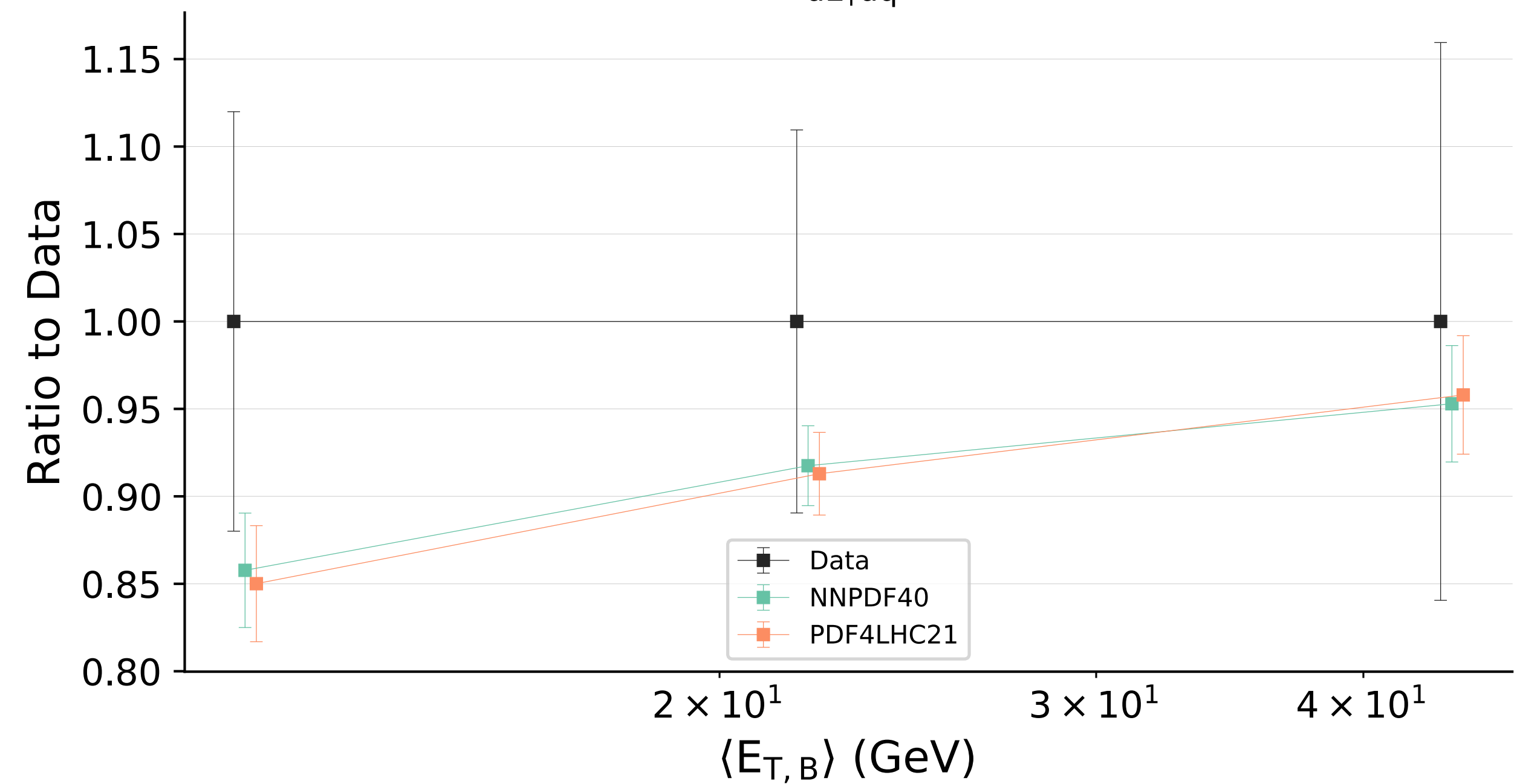


Zeus dijet, 374pb^{-1}

ZEUS Dijet 374 pb^{-1} : $\frac{d^2\sigma}{dE_T dq^2} q^2 = 375.0\text{ (GeV}^2\text{)}$



ZEUS Dijet 374 pb^{-1} : $\frac{d^2\sigma}{dE_T dq^2} q^2 = 12500.0\text{ (GeV}^2\text{)}$



Zeus, total χ^2/N (with exp + PDF + scale variations)

Zeus 1j 38.6pb⁻¹

0.654 0.672 0.690 0.685

Zeus 1j 82pb⁻¹

0.800 0.810 0.816 0.816

1.05 Zeus 2j 374pb⁻¹

0.952 0.914 0.957

PRELIMINARY

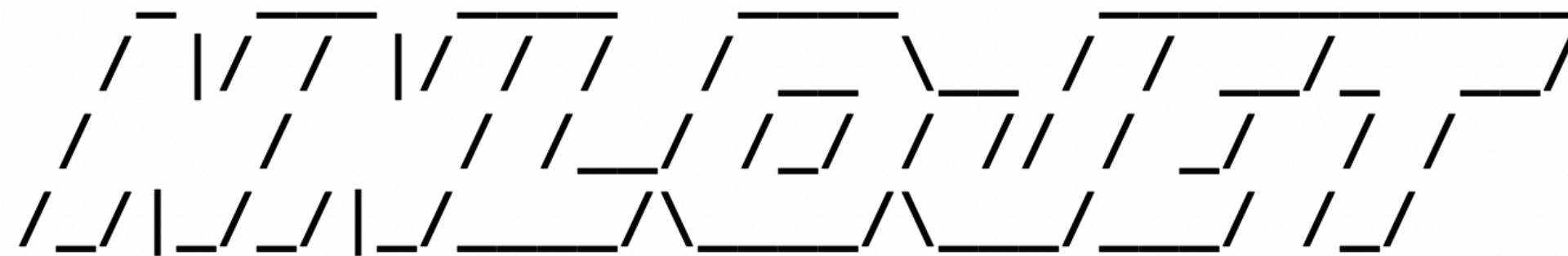
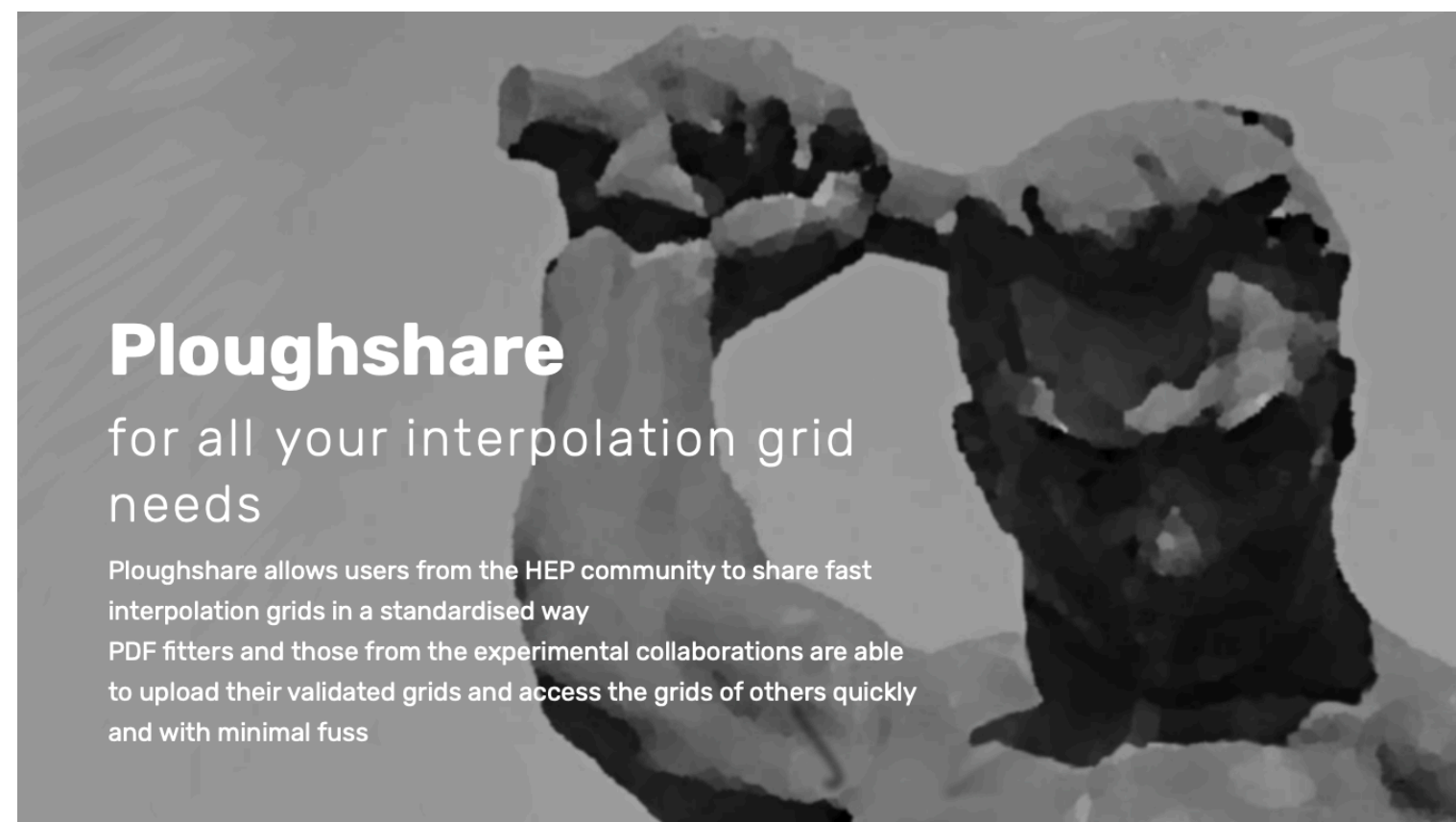
Thanks!

All fast-kernel tables, data implementation, treatment of uncertainties, computation of χ^2 , even plotting scripts and runcards necessary to reproduce all published results and plots are available, as usual, at: <https://github.com/NNPDF> - <http://nnpdf.science/nnpdf-open-source-code/>



pineappl

Special thanks to code, grids and utilities from:



fastNLO



HEPData

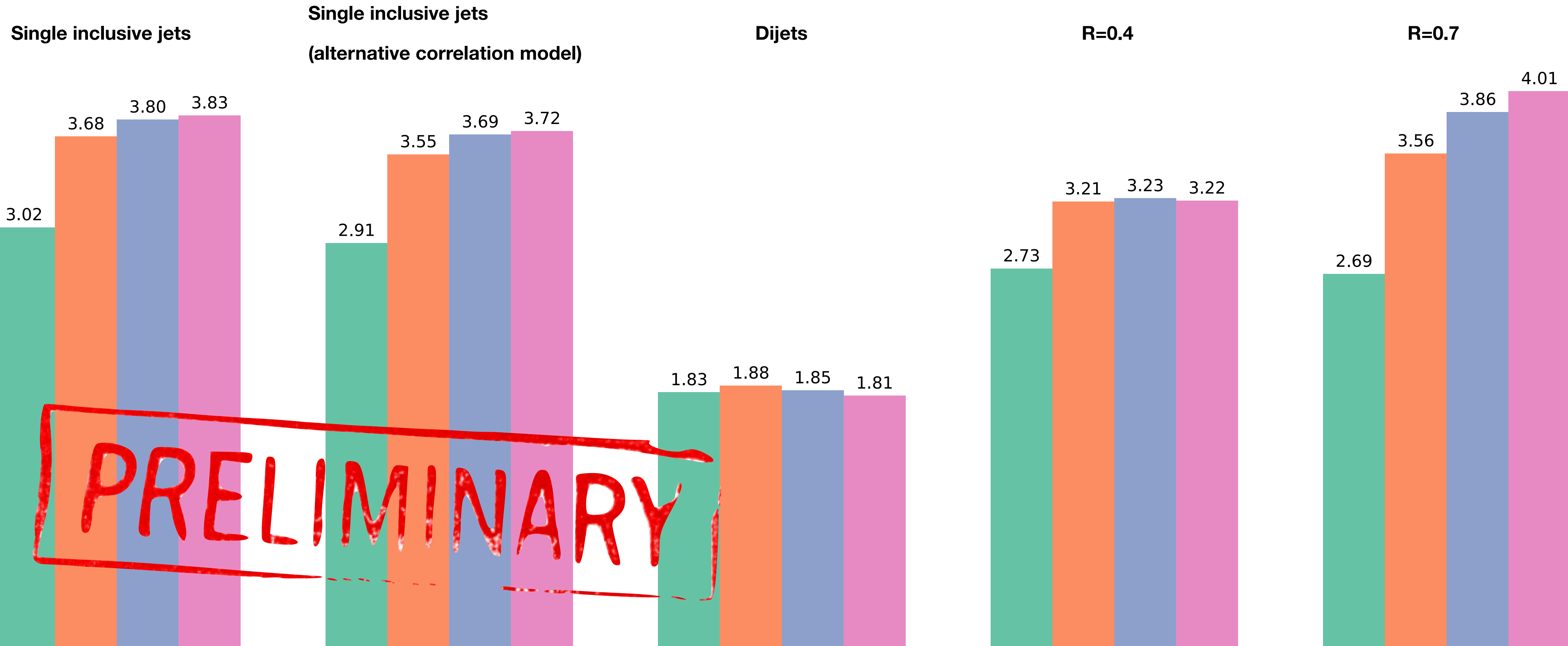
Backup

χ^2/N for ATLAS and CMS without regularizing the covariance matrix

experimental and scale uncertainties only

ATLAS

CMS



χ^2/N for ATLAS and CMS without regularizing the covariance matrix

all uncertainties

ATLAS

CMS

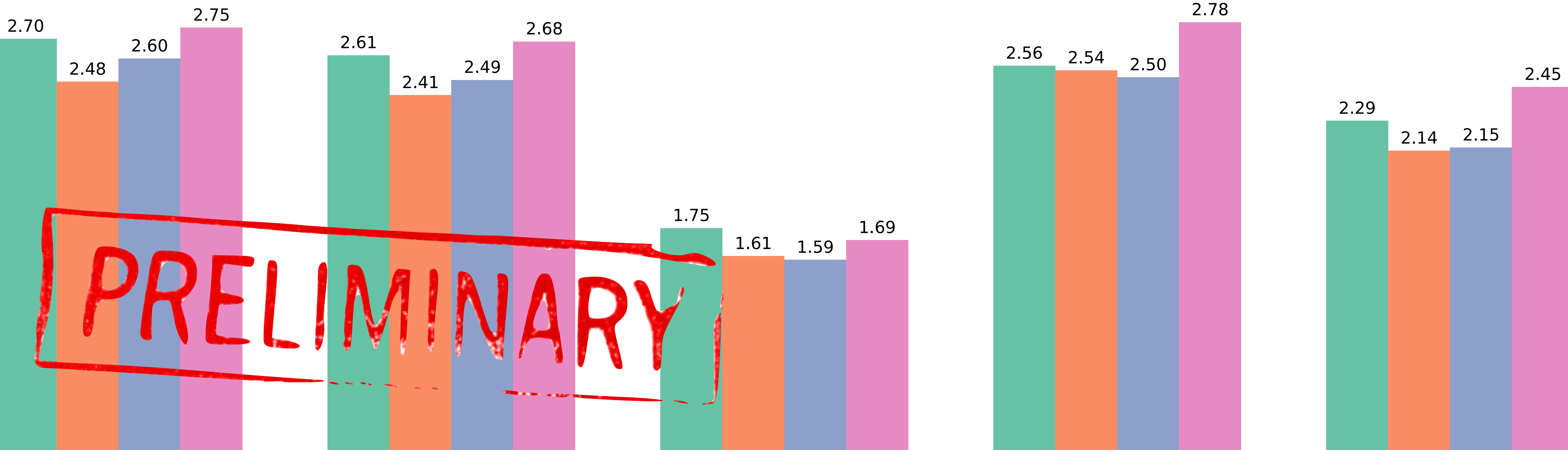
Single inclusive jets

Single inclusive jets
(alternative correlation model)

Dijets

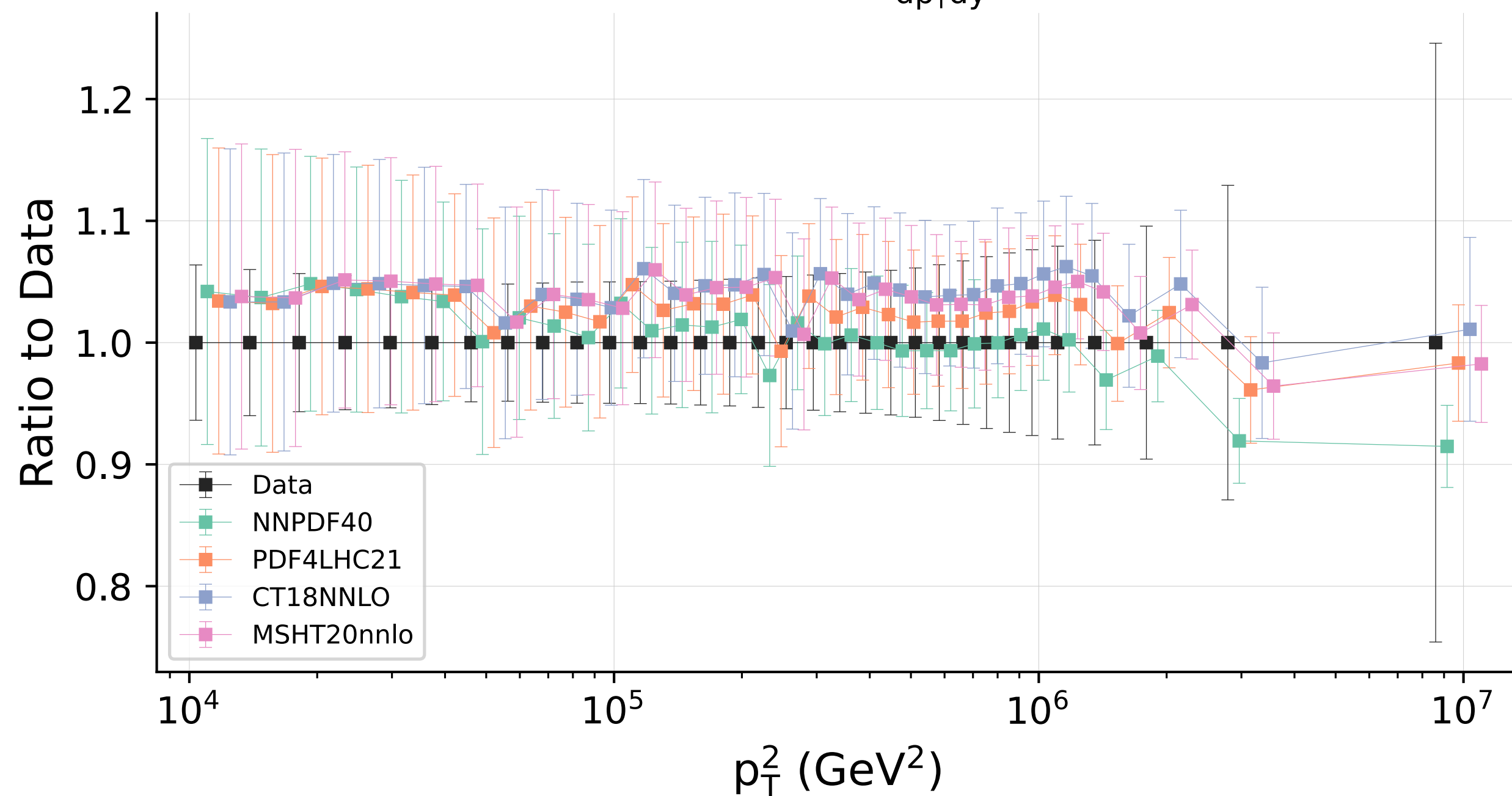
R=0.4

R=0.7

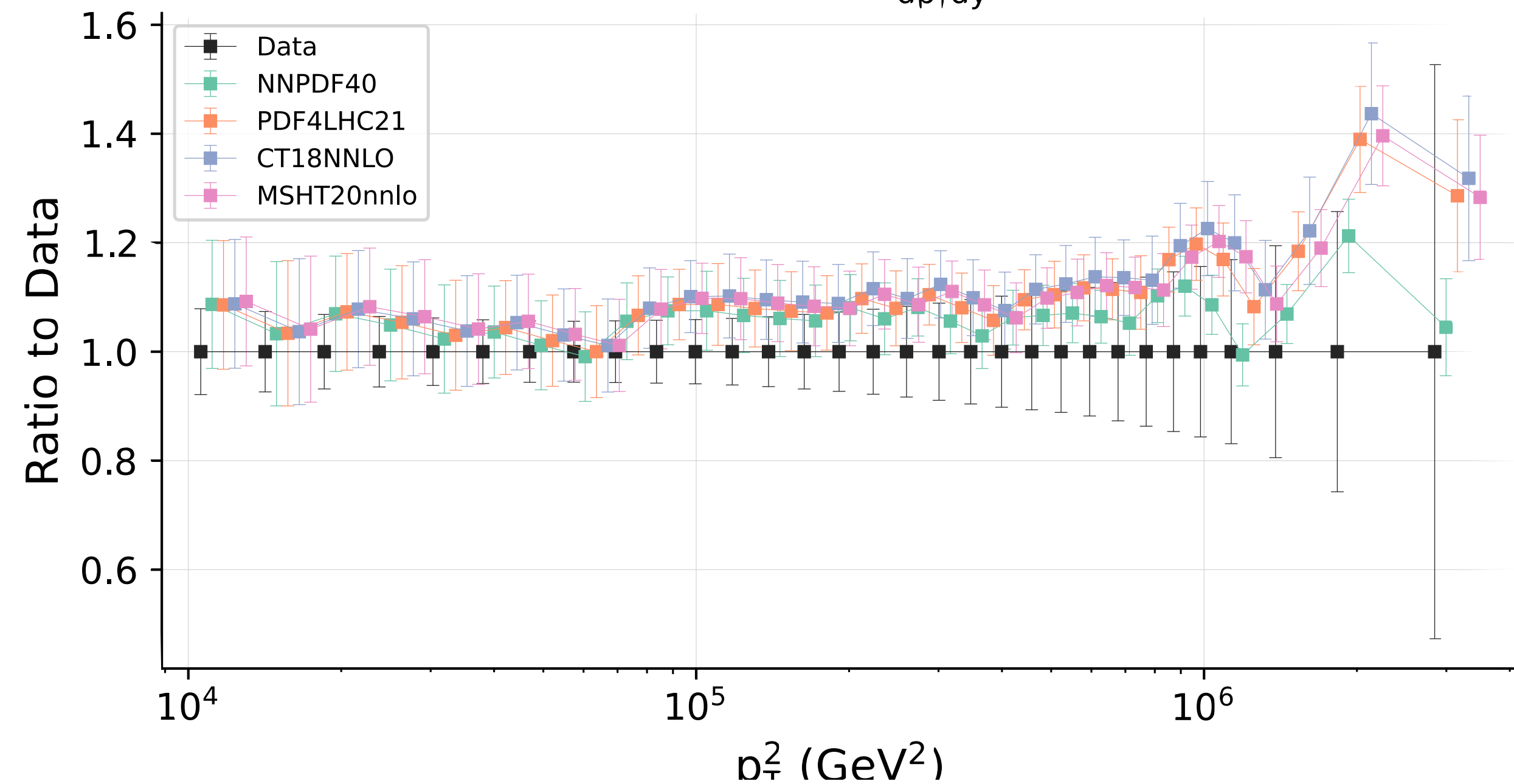


Atlas single jets

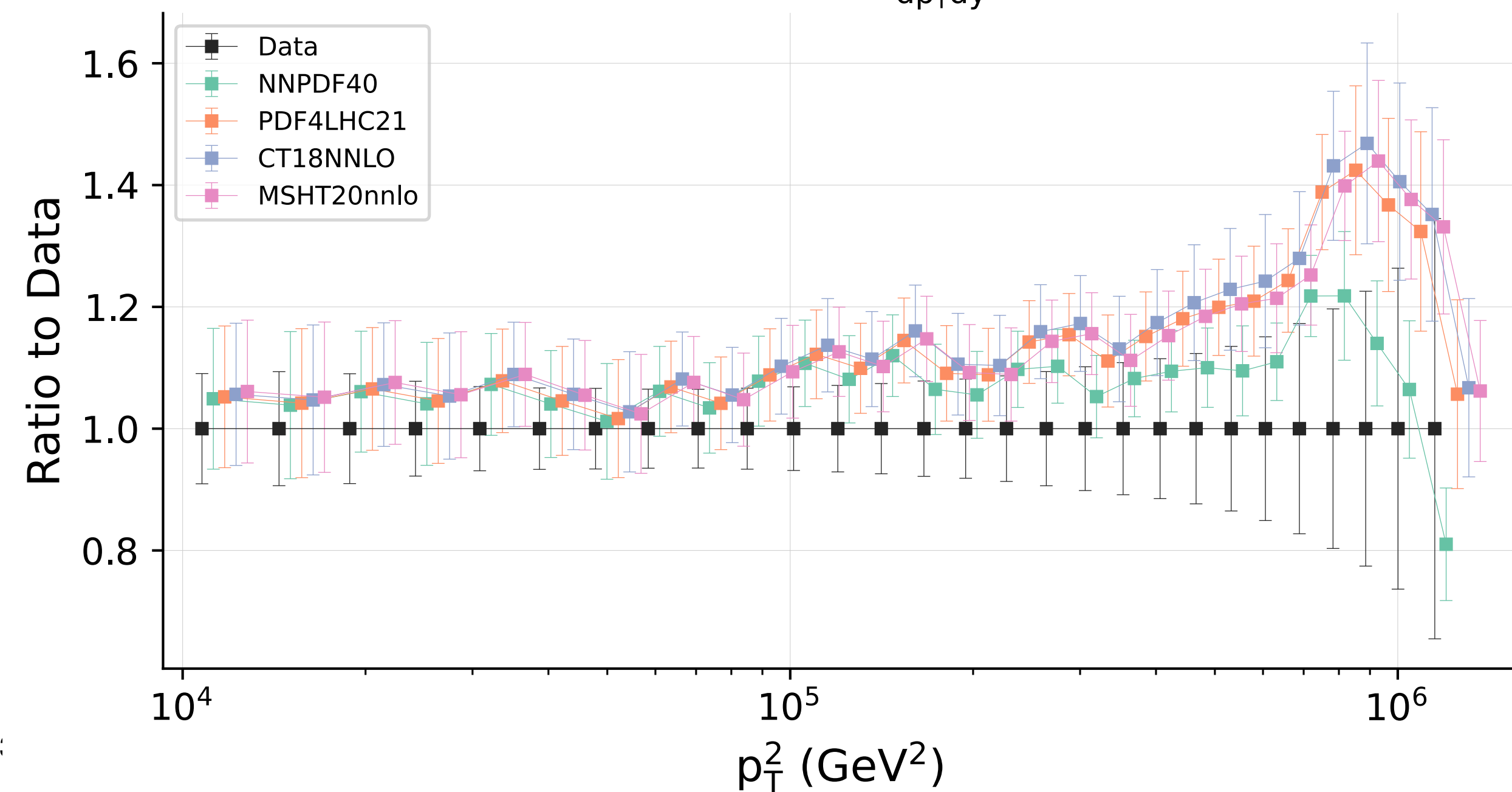
ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 0.75$



ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 1.75$

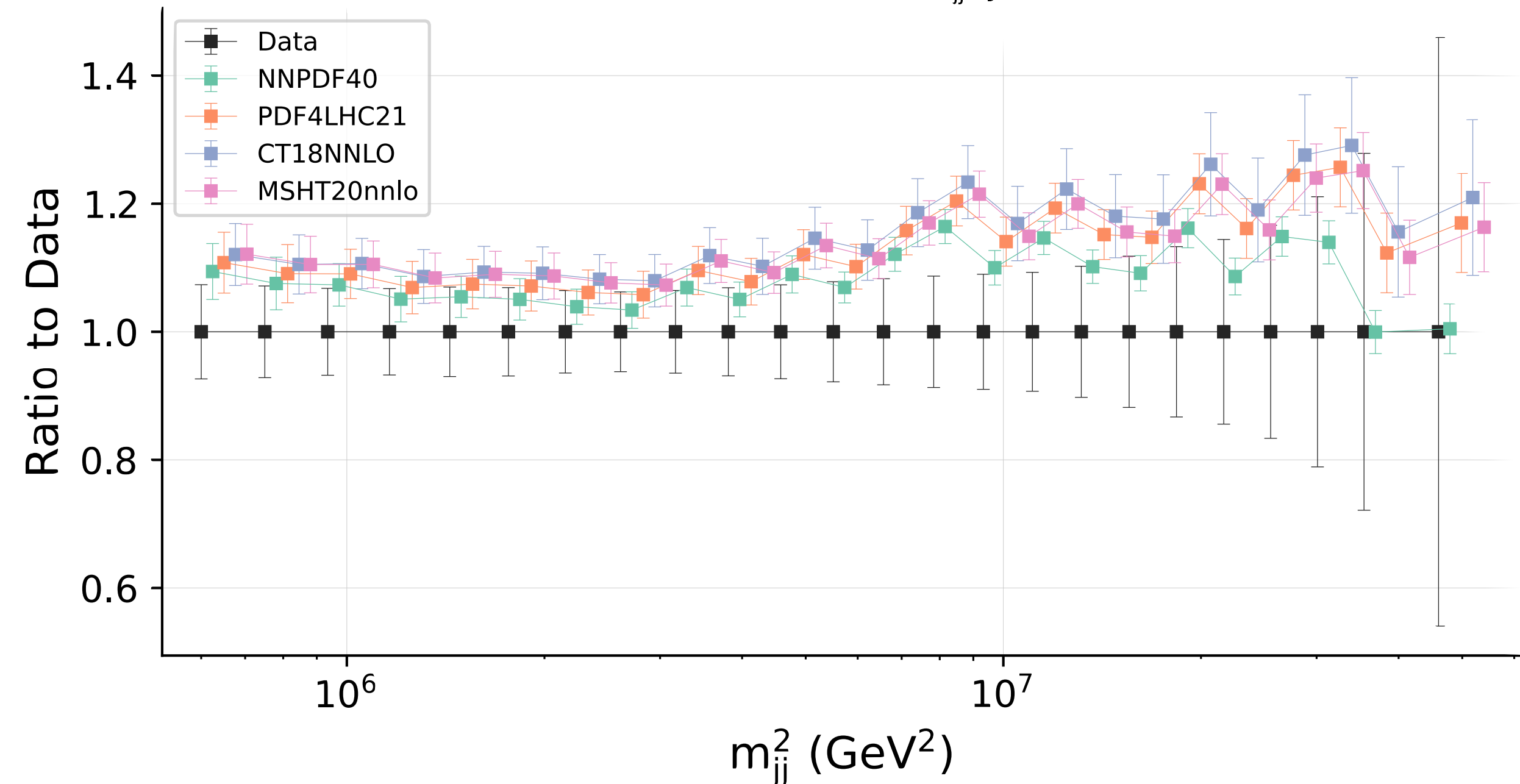


ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 2.25$

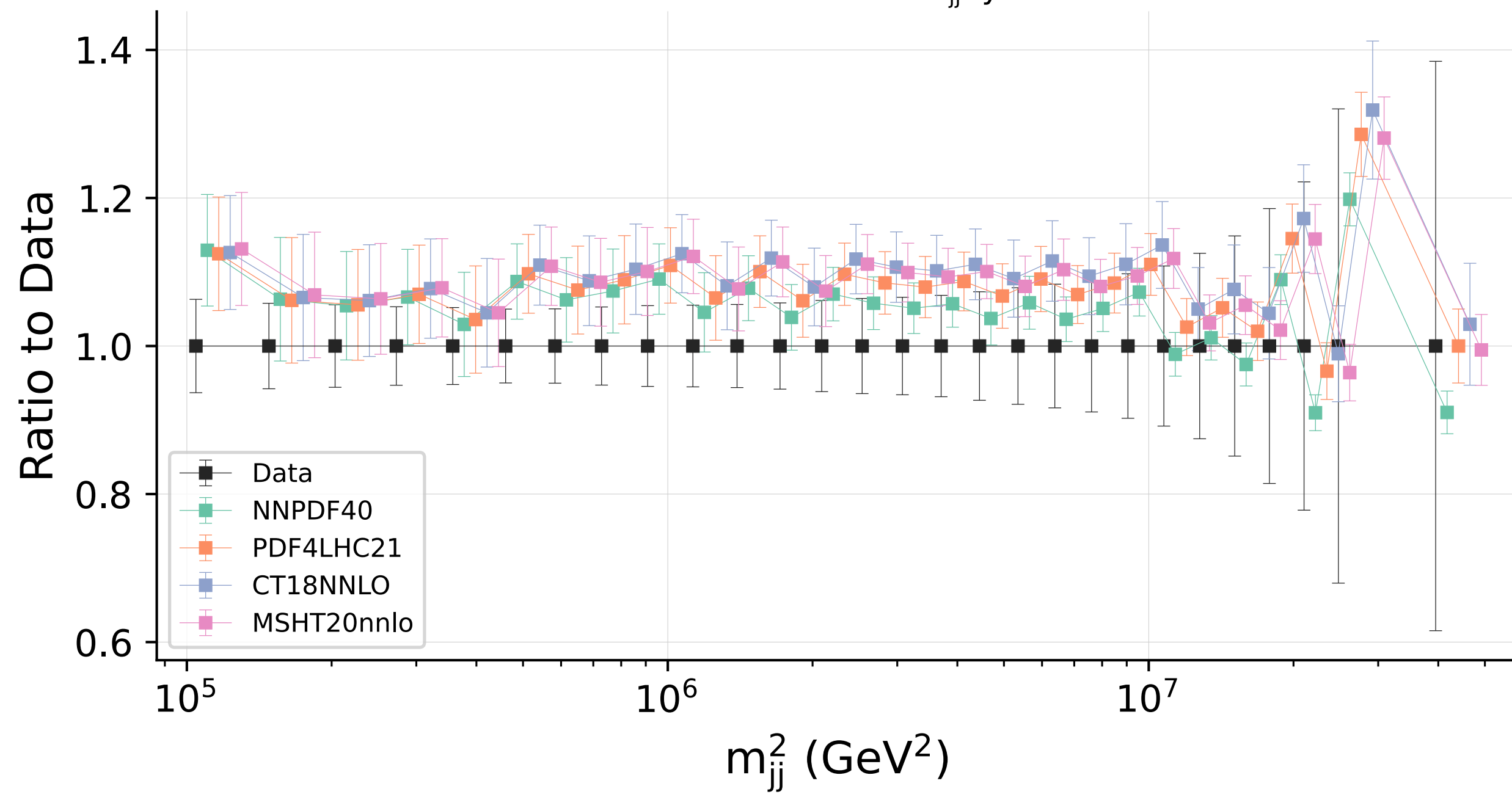


Atlas dijets

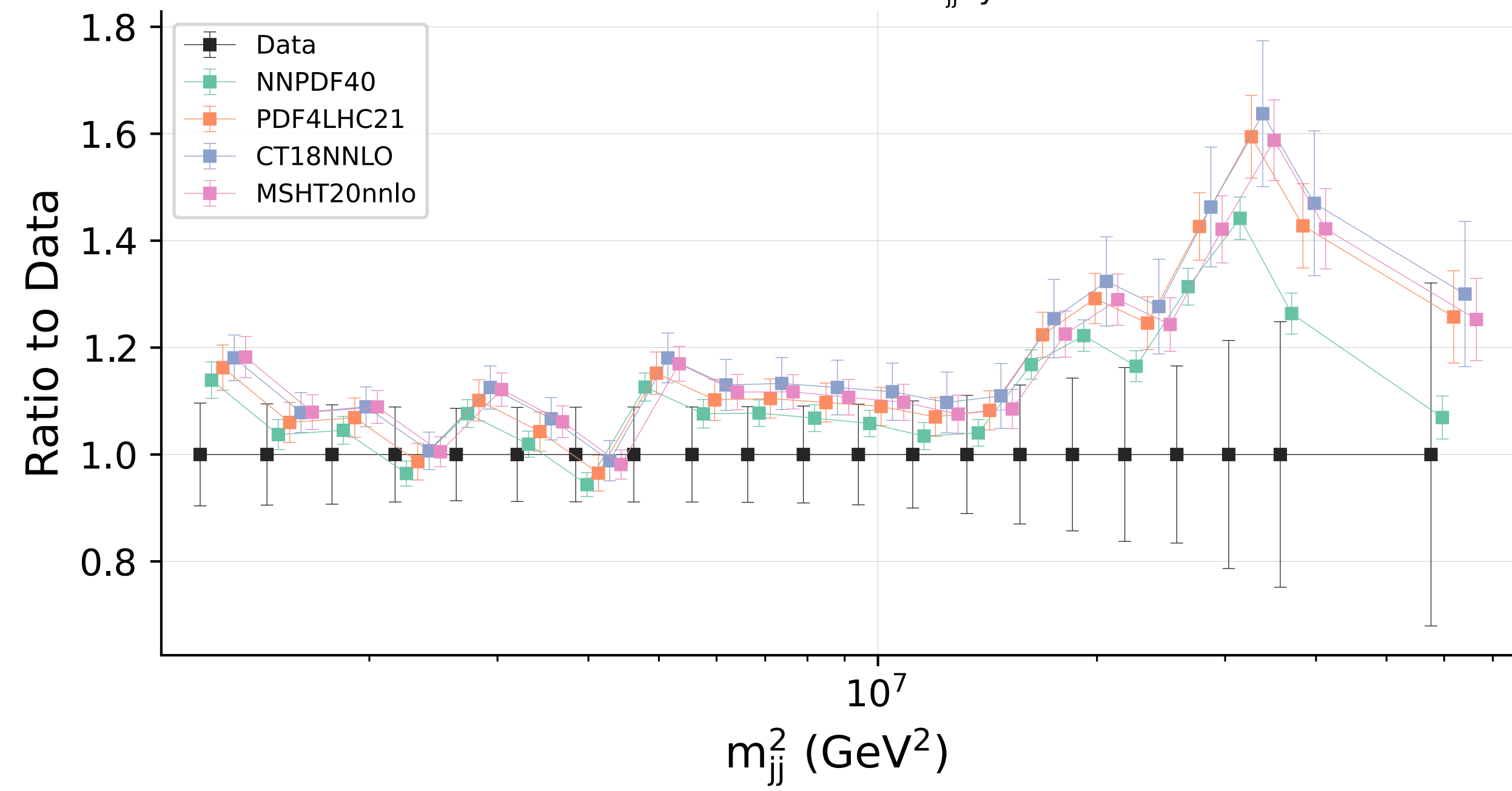
ATLAS Dijet 13 TeV: $\frac{d^2\sigma}{dm_{jj}dy} y^* = 1.75$



ATLAS Dijet 13 TeV: $\frac{d^2\sigma}{dm_{jj}dy} y^* = 0.75$

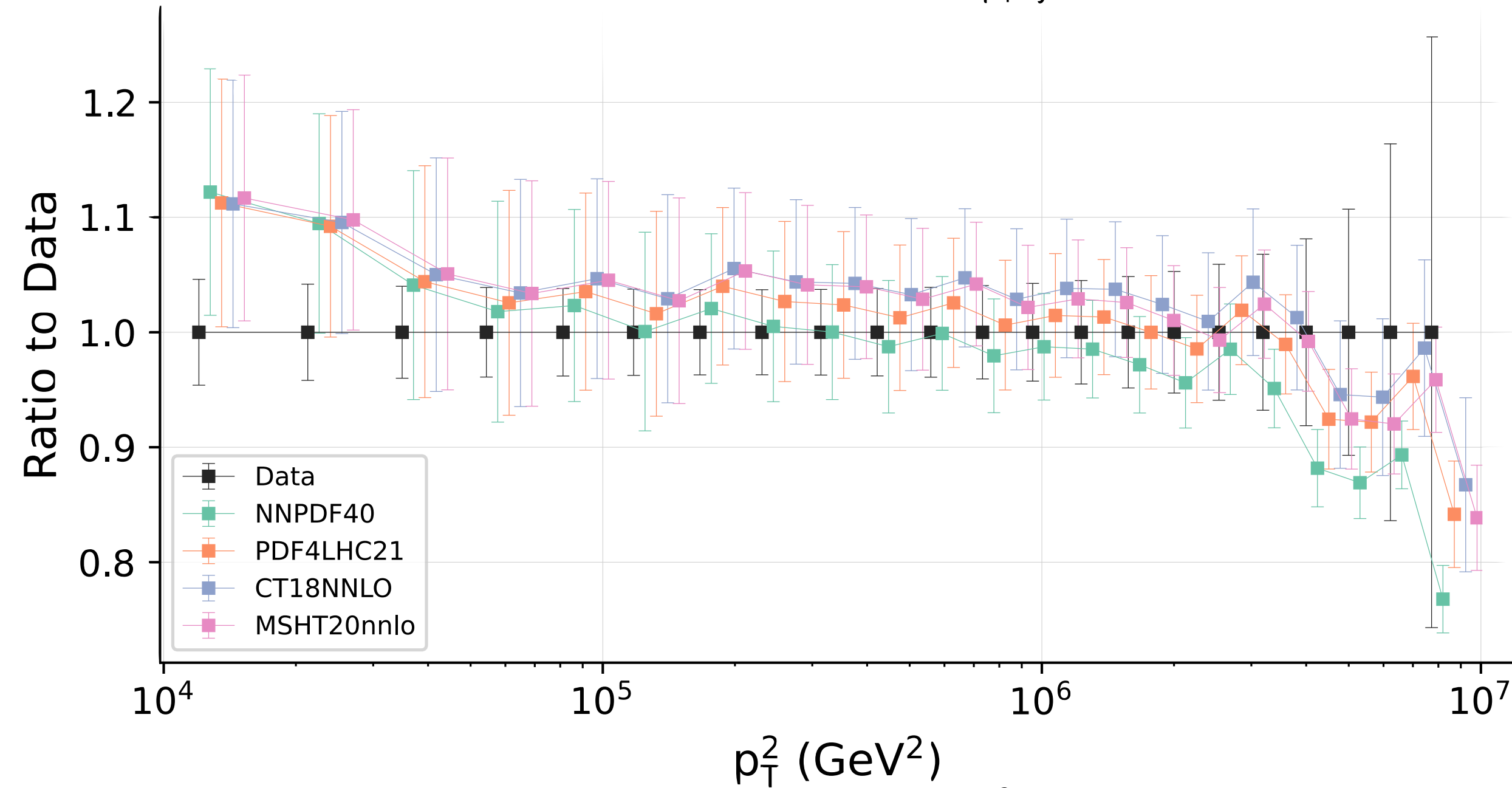


ATLAS Dijet 13 TeV: $\frac{d^2\sigma}{dm_{jj}dy} y^* = 2.25$

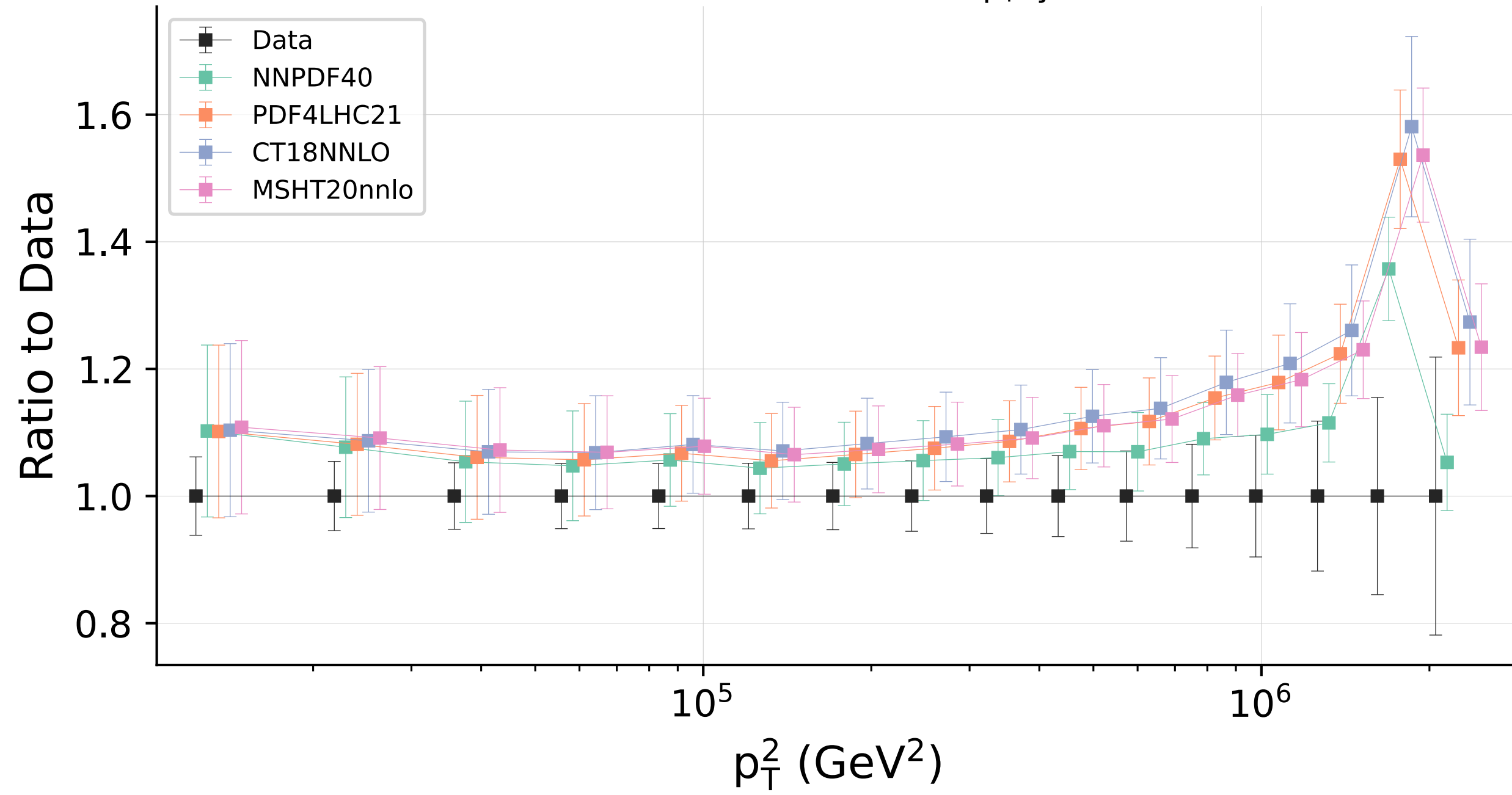


CMS single inclusive jets

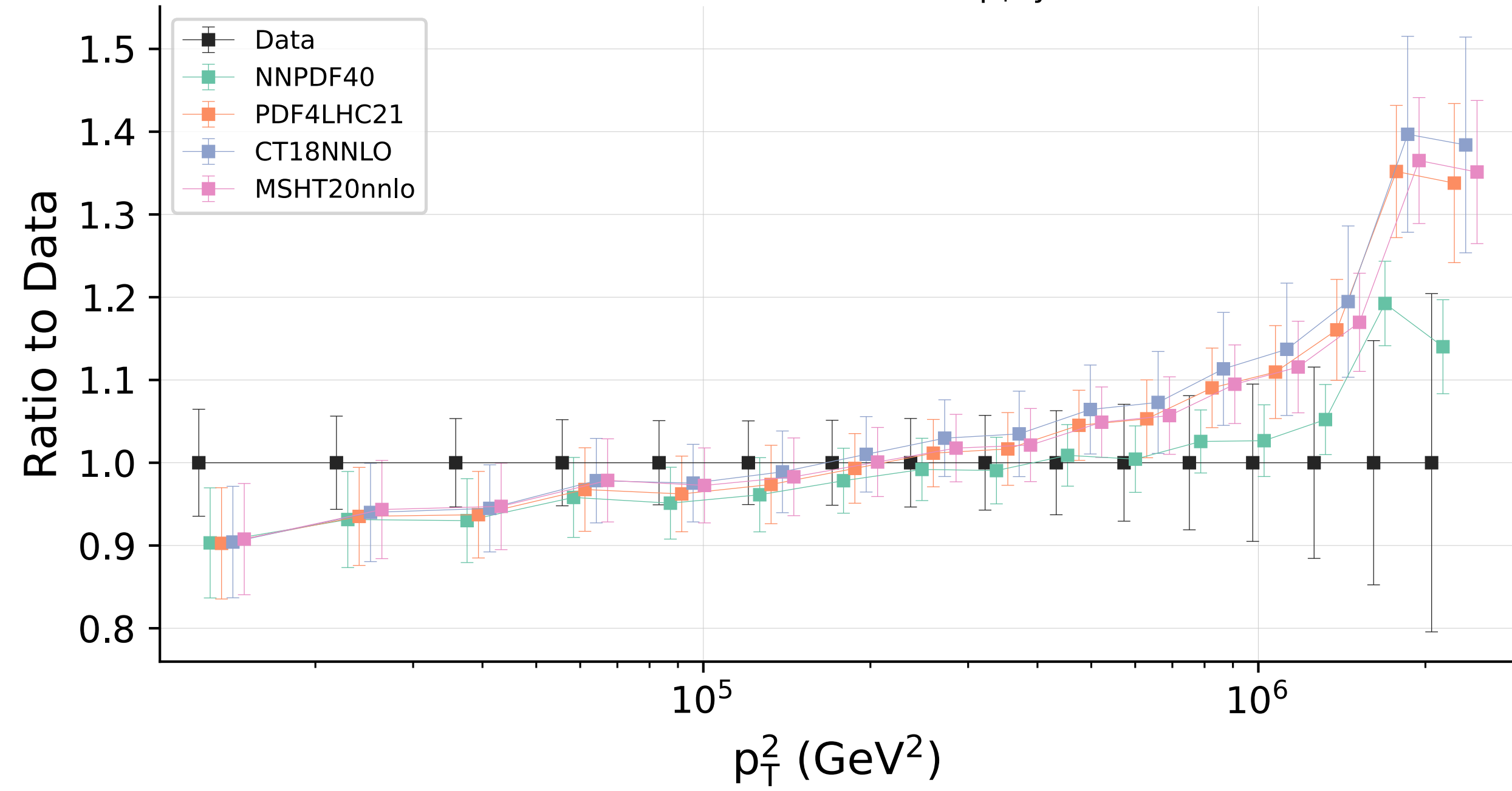
CMS Jet 13 TeV $R = 0.4$: $\frac{d^2\sigma}{dp_T dy}$ $y = 0.25$



CMS Jet 13 TeV $R = 0.4$: $\frac{d^2\sigma}{dp_T dy}$ $y = 1.75$



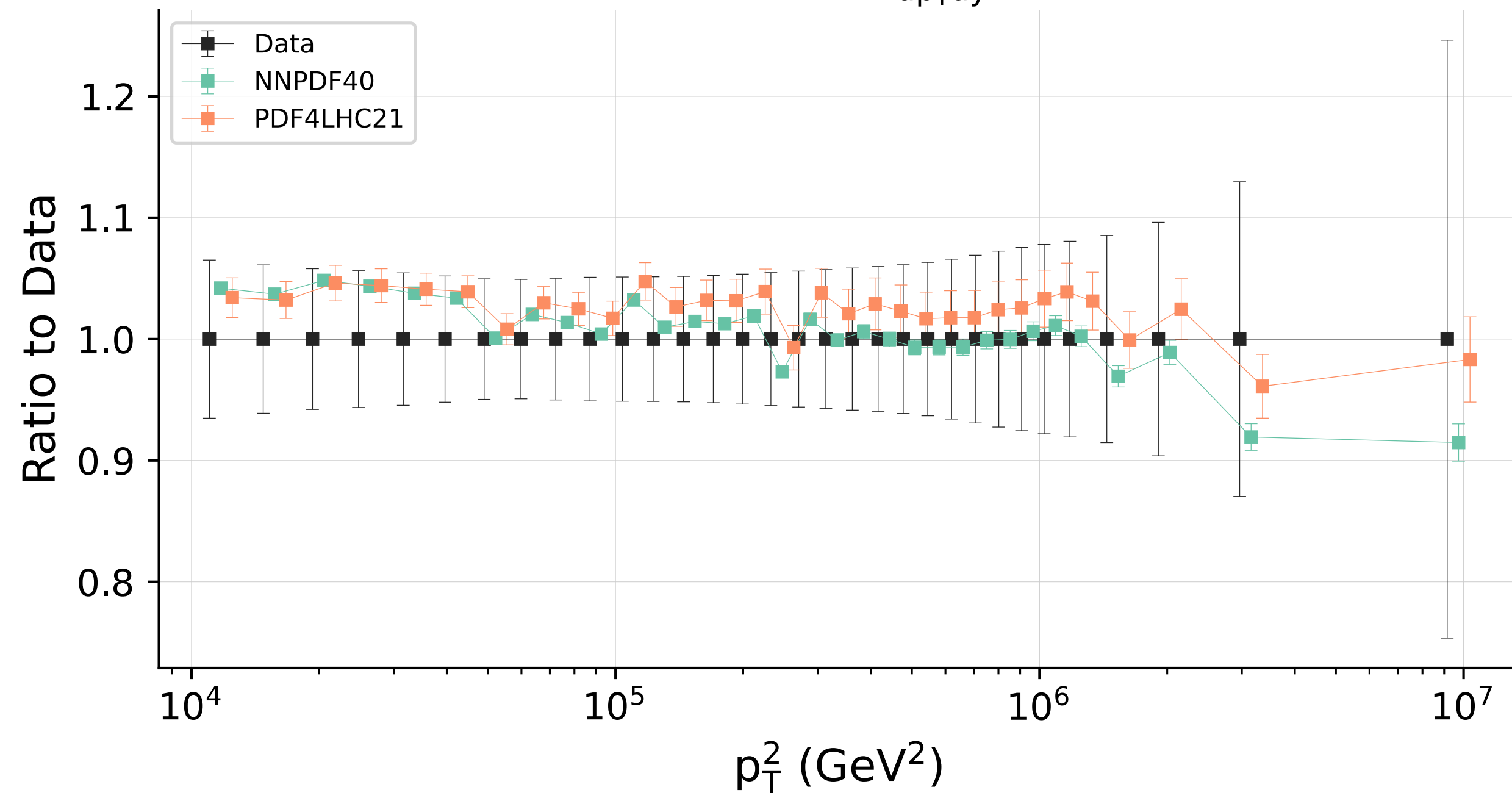
CMS Jet 13 TeV $R = 0.7$: $\frac{d^2\sigma}{dp_T dy}$ $y = 1.75$



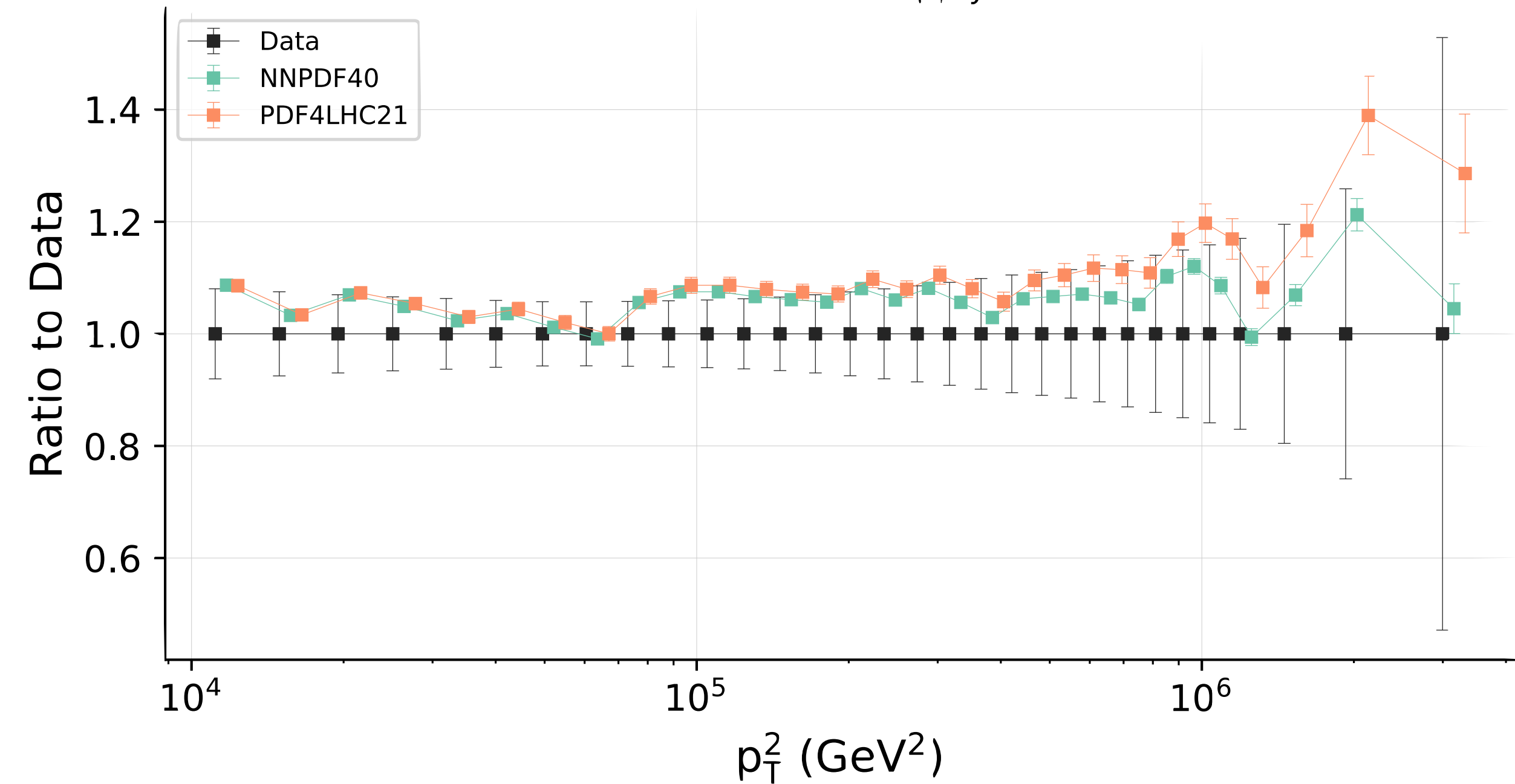
Atlas single jets

results with no scale uncertainties
for reference

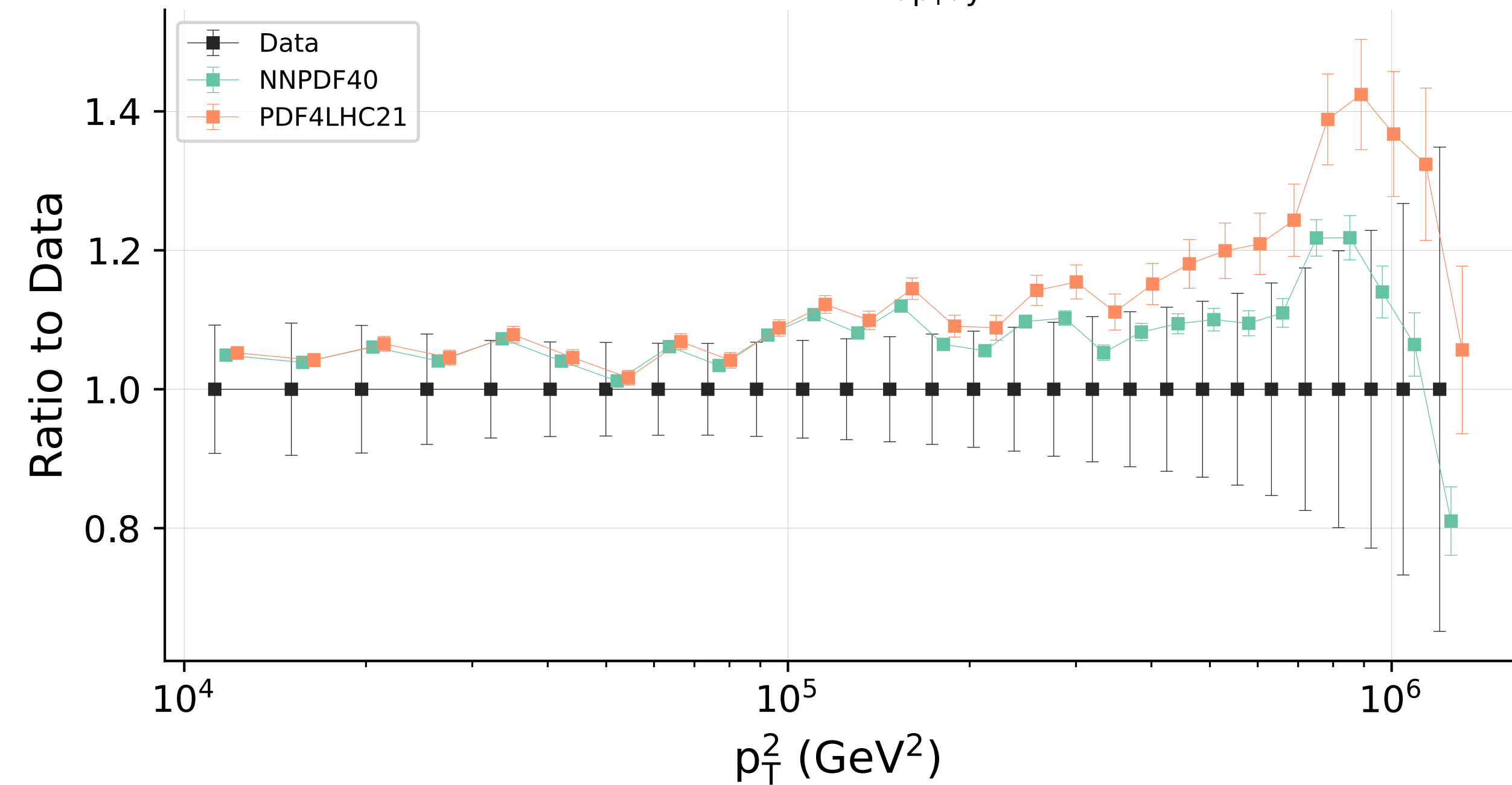
ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 0.75$



ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 1.75$



ATLAS Jet 13 TeV: $\frac{d^2\sigma}{dp_T dy}$ $y = 2.25$



DATA-THEORY AGREEMENT

17/33

Dataset	NNPDF31	NNPDF40	MMHT14	MSHT20	CT18NNLO	ABMP16
CDF Z rapidity	24 28 / 28	28 30 / 28	30 31 / 28	32 32 / 28	27 27 / 28	31 31 / 28
CDF W asymmetry	11 57 / 13	14 17 / 13	12 13 / 13	28 27 / 13	11 35 / 13	21 43 / 13
D0 Z rapidity	22 22 / 28	23 23 / 28	23 23 / 28	24 23 / 28	22 22 / 28	22 22 / 28
D0 $W e \nu$ lepton asymmetry	22 32 / 13	23 29 / 13	52 51 / 13	42 40 / 13	19 32 / 13	26 24 / 13
D0 $W \mu \nu$ lepton asymmetry	12 14 / 10	12 16 / 10	11 14 / 10	11 13 / 10	12 13 / 10	11 12 / 10
ATLAS peak CC Z rapidity	13 18 / 12	13 17 / 12	58 89 / 12	17 19 / 12	11 77 / 12	18 32 / 12
ATLAS W^- lepton rapidity	12 18 / 11	12 15 / 11	33 33 / 11	16 17 / 11	9.9 28 / 11	14 17 / 11
ATLAS W^+ lepton rapidity	8.9 13 / 11	8.6 11 / 11	15 21 / 11	12 13 / 11	9.4 16 / 11	10 12 / 11
Correlated χ^2	76 110	63 83	212 236	91 102	43 251	86 108
Log penalty χ^2	-0.62 -0.62	-0.58 -0.58	-1.62 -1.62	-2.89 -2.89	-1.68 -1.68	-2.72 -2.72
Total χ^2 / dof	200 312 / 126	195 242 / 126	445 509 / 126	270 283 / 126	163 499 / 126	236 300 / 126
χ^2 p-value	0.00	0.00	0.00	0.00	0.02	0.00

NNPDF4.0 and MSHT20 best data-theory agreement
(without PDF uncertainty in the χ^2 computation)

CT18 and NNPDF4.0 best data-theory agreement
(with PDF uncertainty in the χ^2 computation)

CERN-LPCC-2022-06 ; FERMILAB-TM-2779-V