PROBING THE GLUON AT NNLO WITH TOP PAIR DIFFERENTIAL DATA

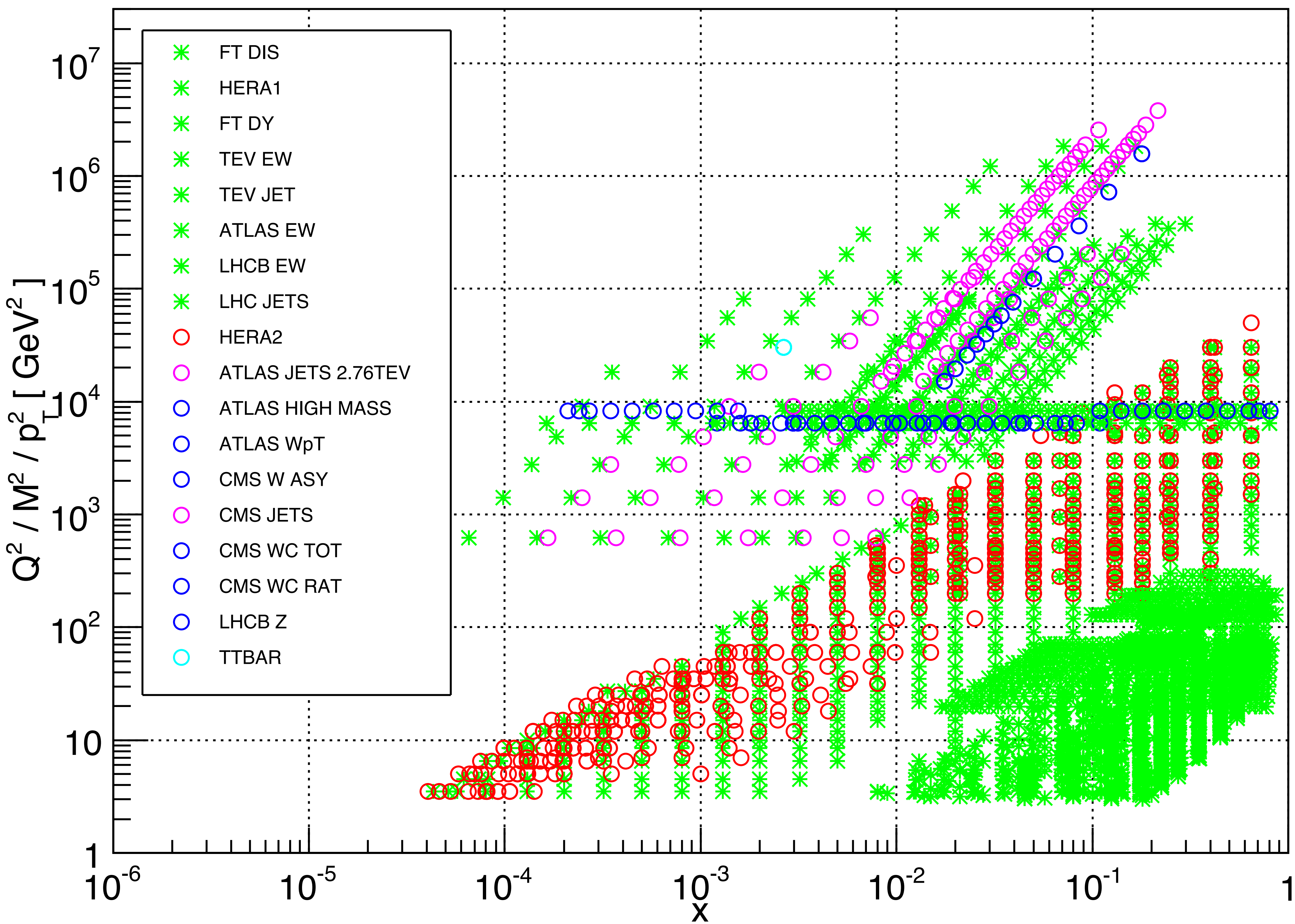
M. CZAKON, NH, A. MITOV, E. NOCERA, J. ROJO. [1611.XXXX]

Nathan Hartland
NIKHEF / Vrije Universiteit Amsterdam

HPP meeting
Nijmegen, 25/11/16

PRECISION PDFS FOR LHC PHYSICS

Modern PDF sets utilise experimental information from a wide range of sources



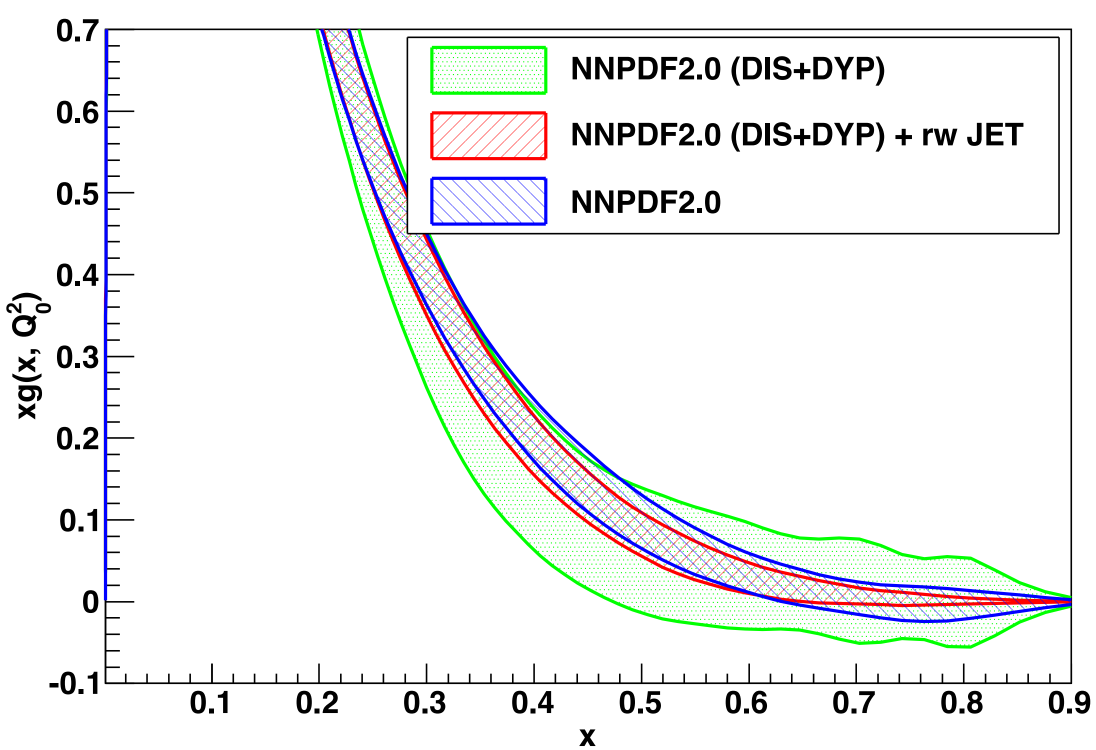
PRECISION GLUON PDF

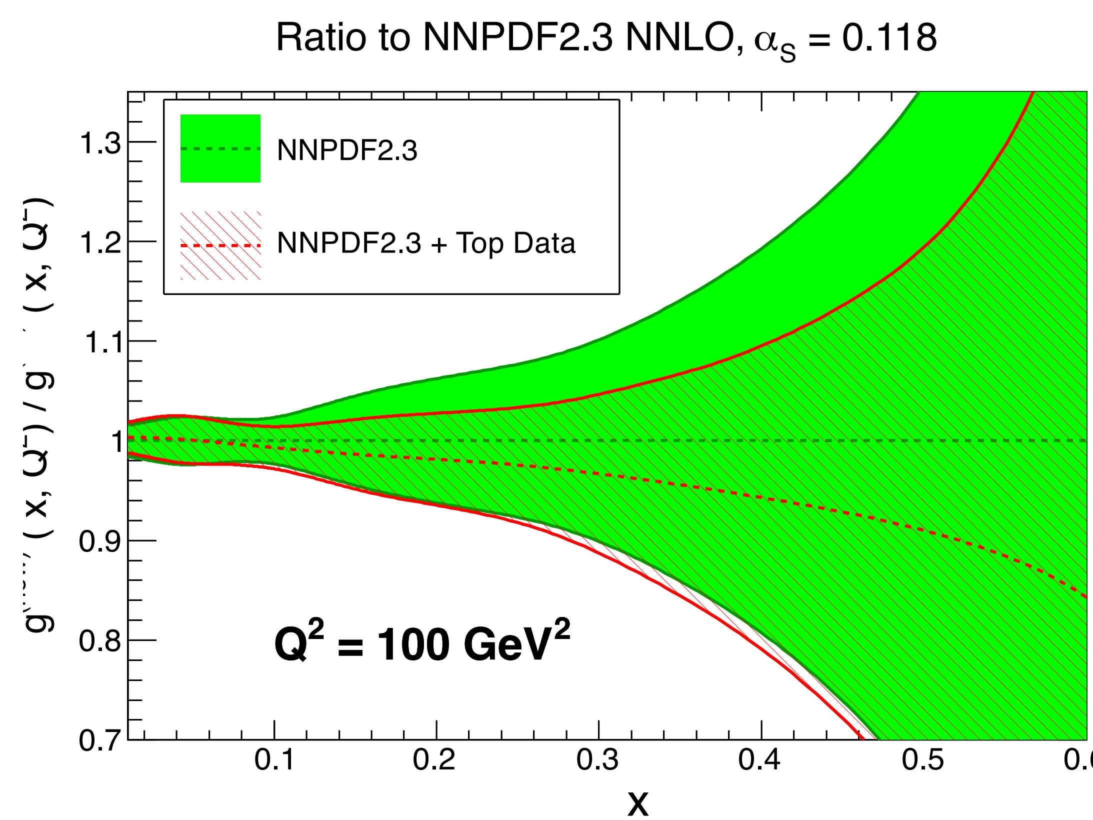
Gluon distributions are constrained by a variety of observables.

At large-x, the gluon of global PDF fits is driven by inclusive jet data.

Until recently, **Currie, Glover, Pires [1611.01460]**

Jet data could only be included in a NNLO fit with the use of some approximation





Czakon, Mangano, Mitov, Rojo [1303.721]

In recent years, the use of top quark data to constrain the large-x gluon has been explored.

Thanks to **[1601.05375] Czakon, Fiedler, Heymes, Mitov** we can now study the impact of differential top-pair production data at **NNLO.**

8 TEV $t\bar{t}$ DIFFERENTIAL LHC DATA

Examine 8 TeV $l + j$ differential data from ATLAS+CMS

(Single differential data - full breakdown of experimental systematics)

Exp.	Data Set	$N_{\rm dat}$	Kinematics
ATLAS	ATLAS $d\sigma/dp_T^t$	8	$0 < p_T^t < 500$ GeV
	ATLAS $d\sigma/d\lvert y_t\rvert$	5	$0 < \lvert y_t\rvert < 2.5$
	ATLAS $d\sigma/d\lvert y_{t\bar{t}}\rvert$	5	$0 < \lvert y_{t\bar{t}}\rvert < 2.5$
	ATLAS $d\sigma/dm_{t\bar{t}}$	7	$345 < m_{t\bar{t}} < 1600$ GeV
	ATLAS $(1/\sigma)d\sigma/dp_T^t$	8	$0 < p_T^t < 500$ GeV
	ATLAS $(1/\sigma)d\sigma/d\lvert y_t\rvert$	5	$0 < \lvert y_t\rvert < 2.5$
	ATLAS $(1/\sigma)d\sigma/d\lvert y_{t\bar{t}}\rvert$	5	$0 < \lvert y_{t\bar{t}}\rvert < 2.5$
	ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	7	$345 < m_{t\bar{t}} < 1600$ GeV
CMS	CMS $d\sigma/dp_T^t$	8	$0 < p_T^t < 500$ GeV
	CMS $d\sigma/dy_t$	10	$-2.5 < y_t < 2.5$
	CMS $d\sigma/dy_{t\bar{t}}$	10	$-2.5 < y_{t\bar{t}} < 2.5$
	CMS $d\sigma/dm_{t\bar{t}}$	7	$345 < m_{t\bar{t}} < 1600$ GeV
	CMS $(1/\sigma)d\sigma/dp_T^t$	8	$0 < p_T^t < 500$ GeV
	CMS $(1/\sigma)d\sigma/dy_t$	10	$-2.5 < y_t < 2.5$
	CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$	10	$-2.5 < y_{t\bar{t}} < 2.5$
	CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	7	$345 < m_{t\bar{t}} < 1600$ GeV

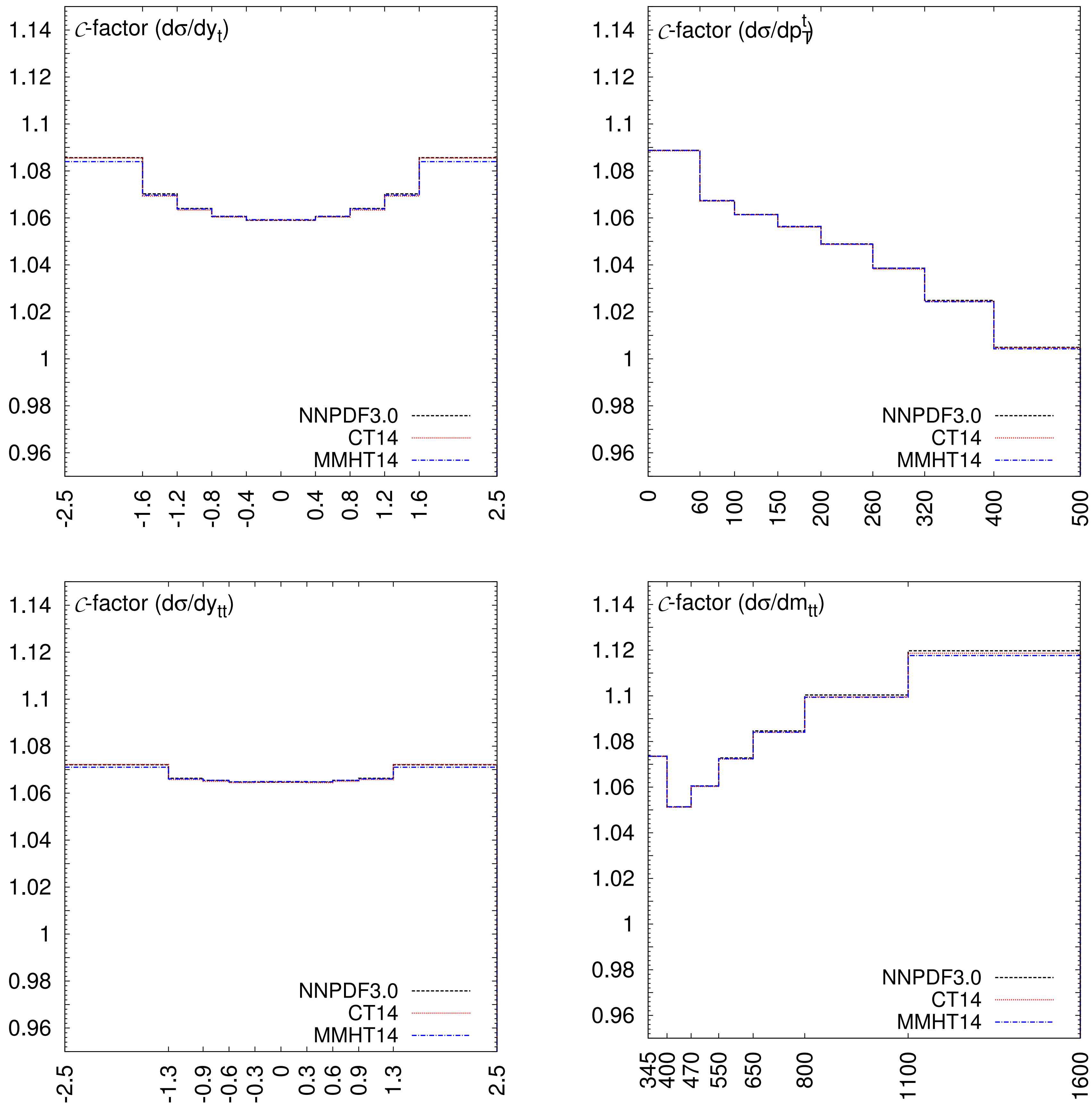
***Normalised** and **absolute** data is provided for ATLAS.*

*CMS provides **normalised** data. Absolute data is reconstructed from inclusive cross-section.*

Questions

- *Are the data compatible?*
- *What level of PDF constraint?*
- *Is normalising beneficial?*
- *Which combination is best?*

THEORY CONFIGURATION: NNLO C-FACTORS



Full NNLO calculation remains prohibitively expensive for inclusion in a PDF fit

$$\mathcal{C} = \frac{\tilde{\sigma}^{\mathrm{nnlo}} \otimes \mathcal{L}^{\mathrm{nnlo}}}{\tilde{\sigma}^{\mathrm{nlo}} \otimes \mathcal{L}^{\mathrm{nnlo}}}$$

Bin-by-bin C-factors are computed with identical settings as for the NLO.

Results are stable under variation of applied PDF

THEORY CONFIGURATION: NLO CALCULATION

For NLO, use interpolated partonic cross-section tables (**APPLgrid/FK**)

- Matrix elements: (**Sherpa** x **Openloops**) via **MCgrid**

Strong coupling set as per PDF set, e.g $\alpha_S(M_Z) = 0.118,\ 0.113$ for ABM

$m_t = 173.3$ as per PDG average.

For perturbative scales, we follow the lead of **Czakon, Heymes, Mitov [1606.0335]**

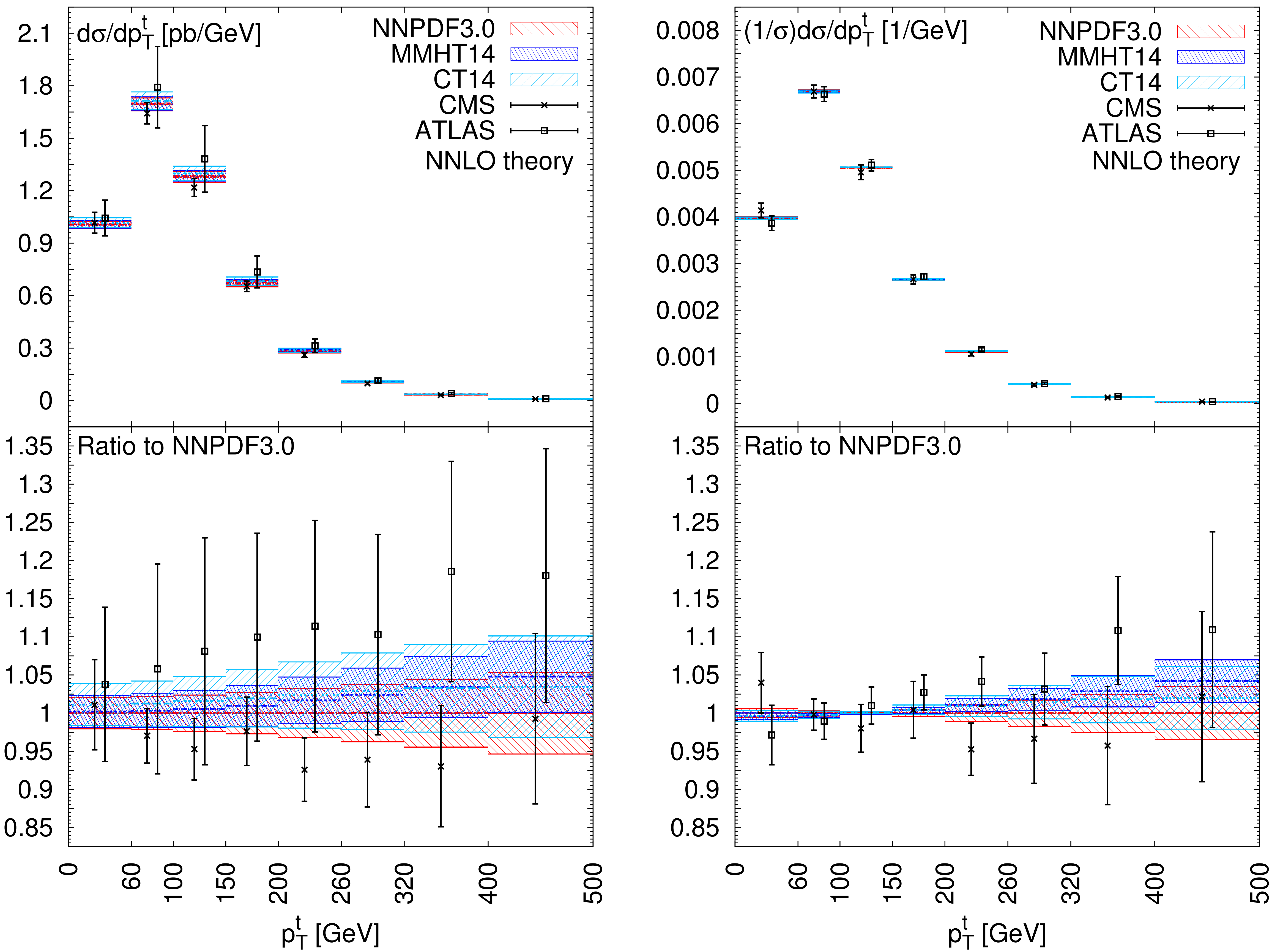
$$\boxed{y_t,\ y_{tt},\ m_{tt}: \quad \mu_R = \mu_F = \frac{1}{4}\sqrt{m_t^2 + \left(p_T^t\right)^2} + \frac{1}{4}\sqrt{m_t^2 + \left(p_T^{\bar{t}}\right)^2}}$$

Obtain top p_T as average over $t/\bar{t}$ with scales set as:

$$\boxed{p_T^t: \quad \mu_R = \mu_F = \frac{1}{2}\sqrt{m_t^2 + \left(p_T^t\right)^2}}$$

DATA-THEORY COMPARISON - TOP TRANSVERSE MOMENTA

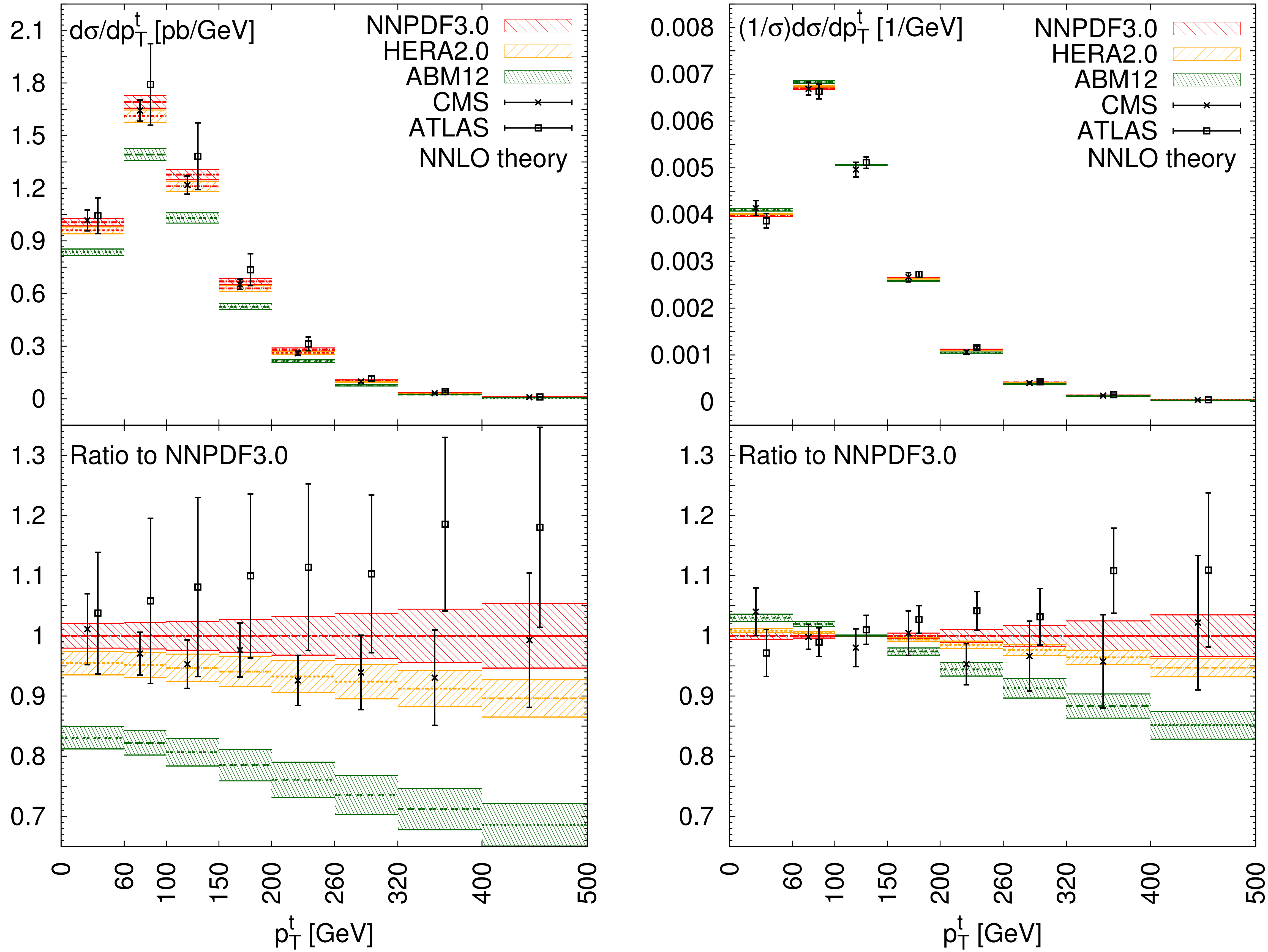
ABSOLUTE | **NORMALISED**



DATA-THEORY COMPARISON - TOP TRANSVERSE MOMENTA

ABSOLUTE

NORMALISED



DATA–THEORY COMPARISON – TOP TRANSVERSE MOMENTA

ABSOLUTE

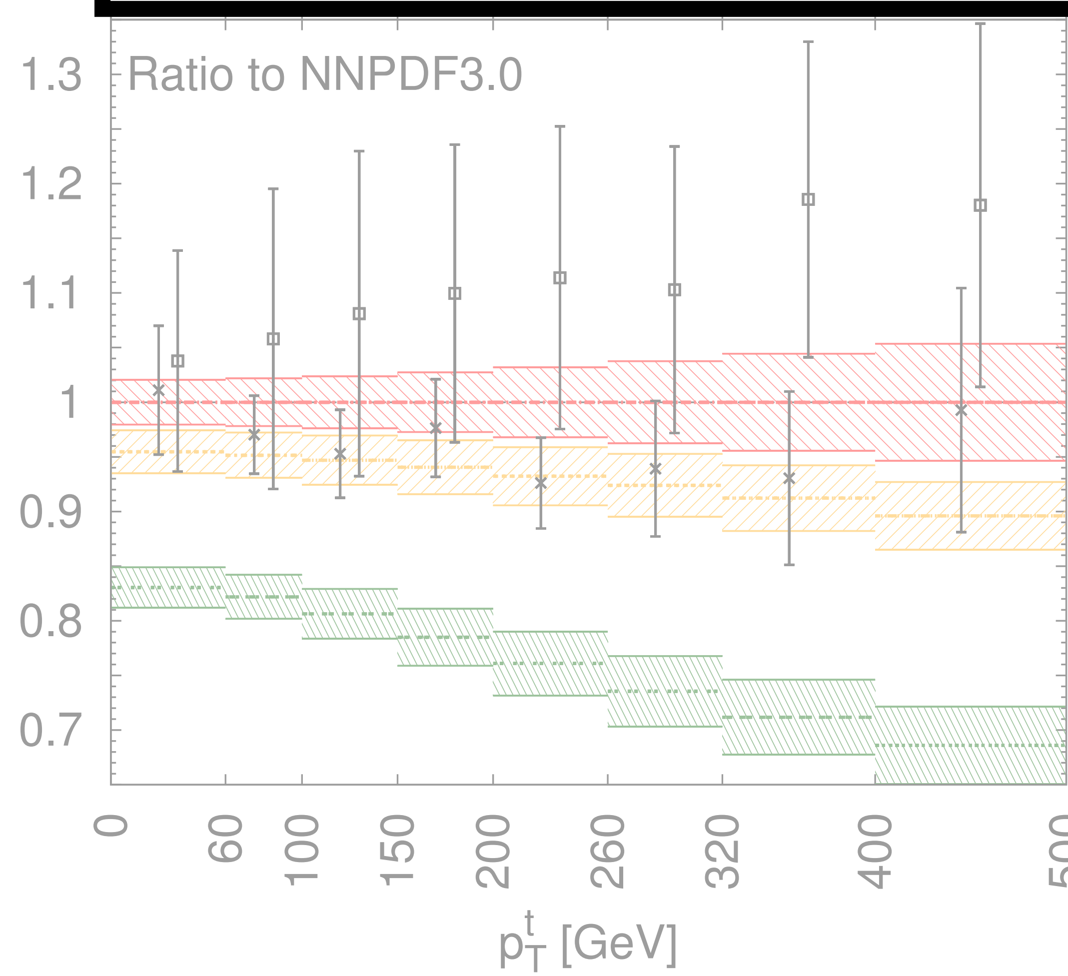
NORMALISED

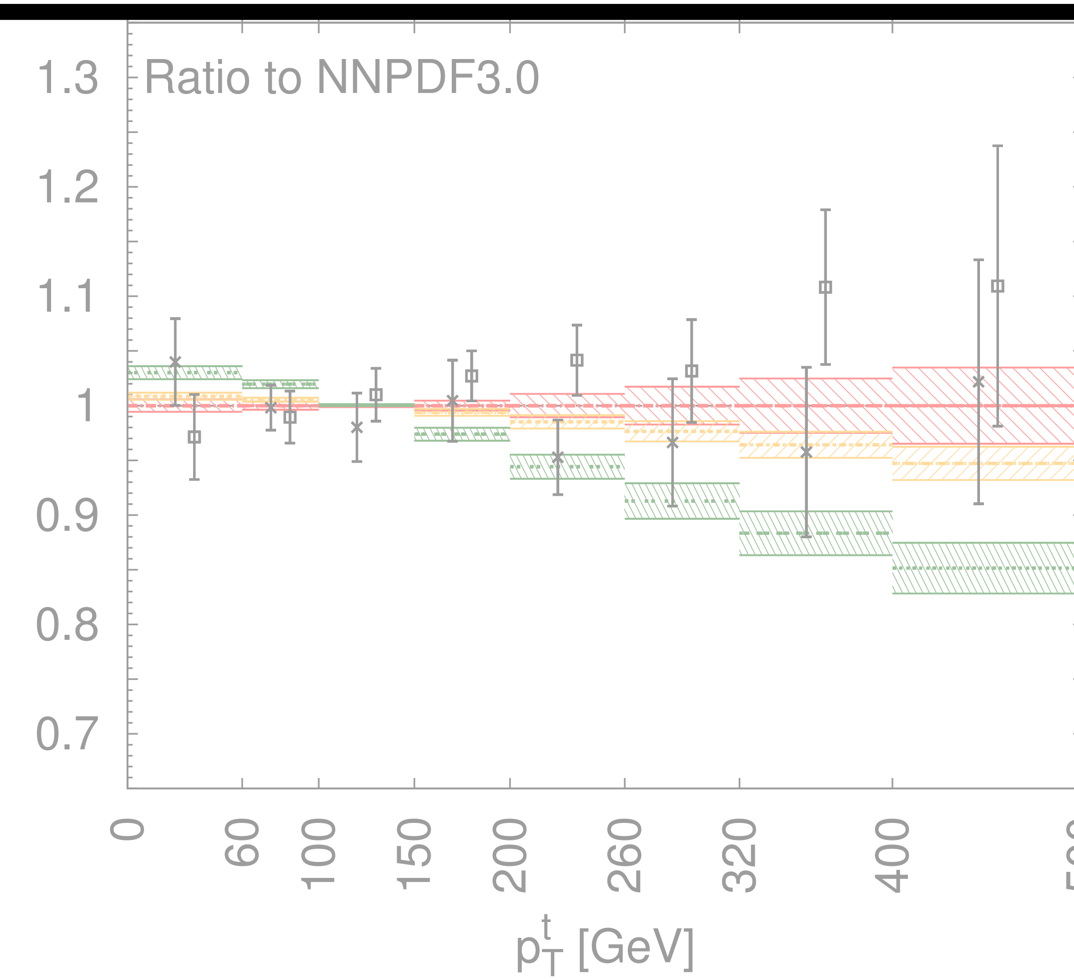
2.1 1.8 1.5 1.2 0.9 0.6 0.3 0

Absolute distribution χ^2

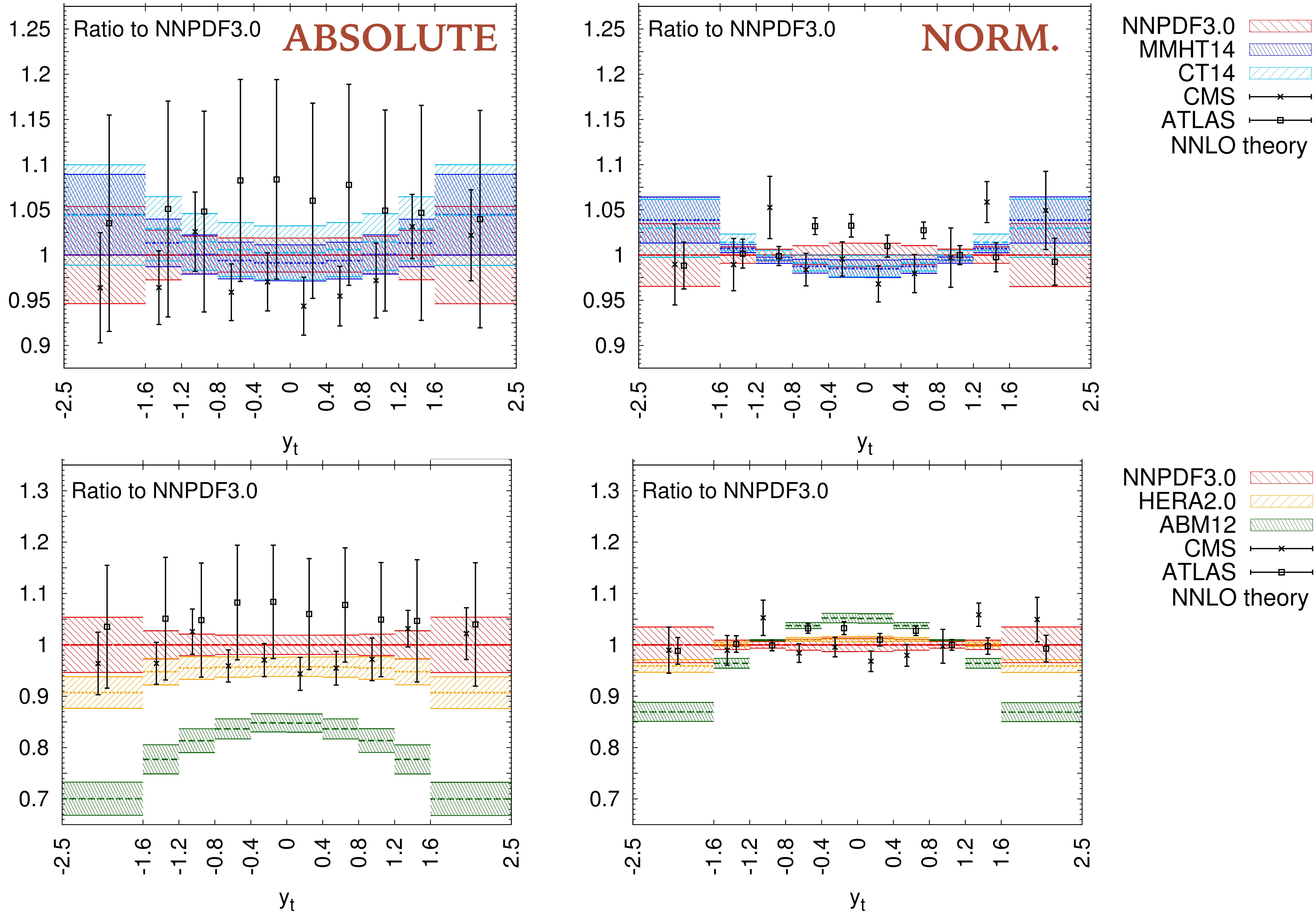
Dataset	PDF set	
ATLAS $d\sigma/dp_T^t$		
	NNPDF3.0	0.84
	CT14	0.76
	MMHT14	0.63
	HERA2.0	1.13
	ABM12	6.23

Dataset	PDF set	
CMS $d\sigma/dp_T^t$		
	NNPDF3.0	1.24
	CT14	1.67
	MMHT14	1.54
	HERA2.0	0.69
	ABM12	12.5

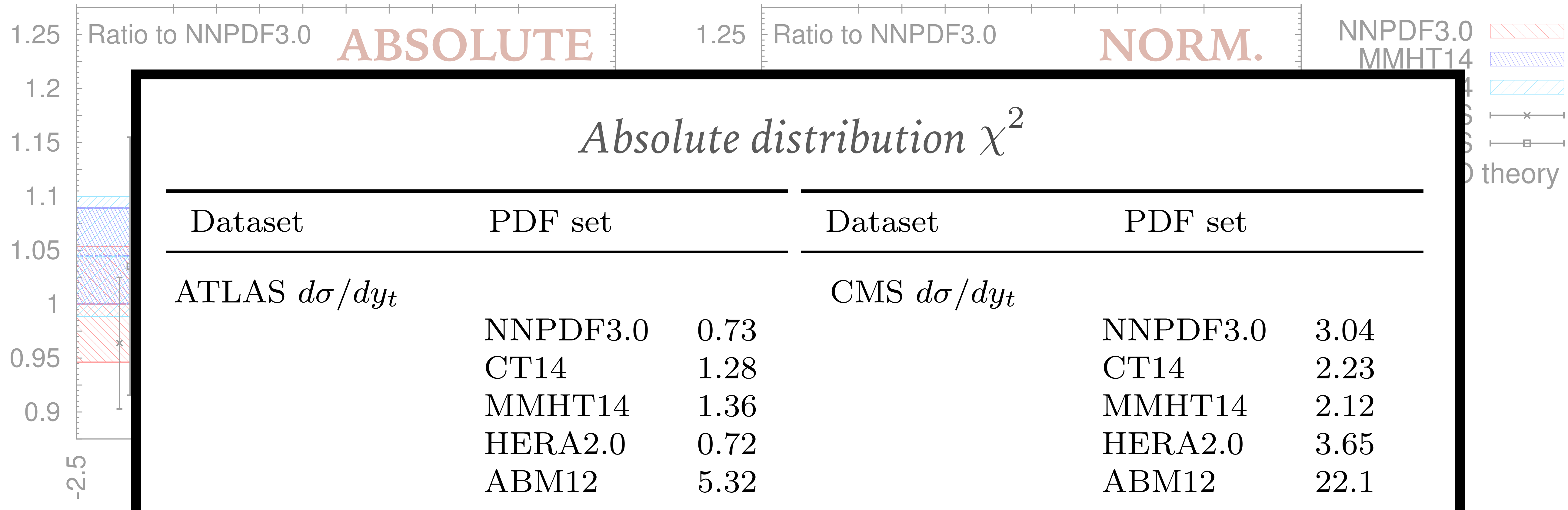




DATA-THEORY COMPARISON - TOP RAPIDITY



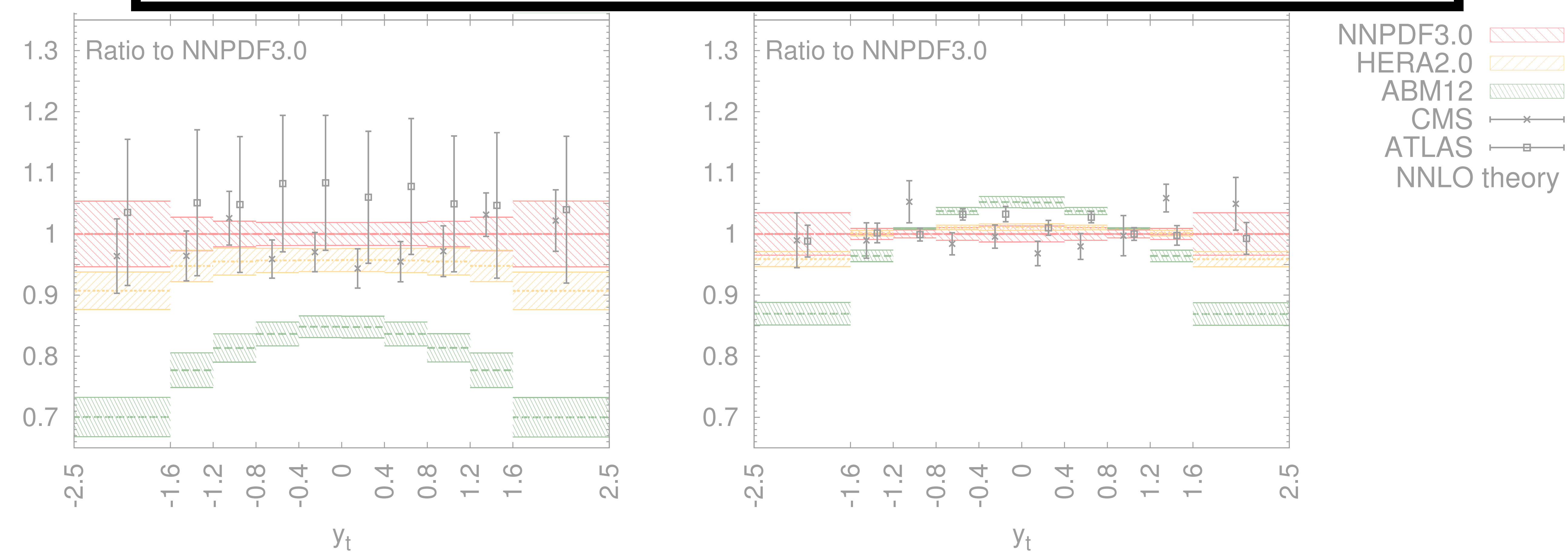
DATA-THEORY COMPARISON - TOP RAPIDITY



Absolute distribution χ^2

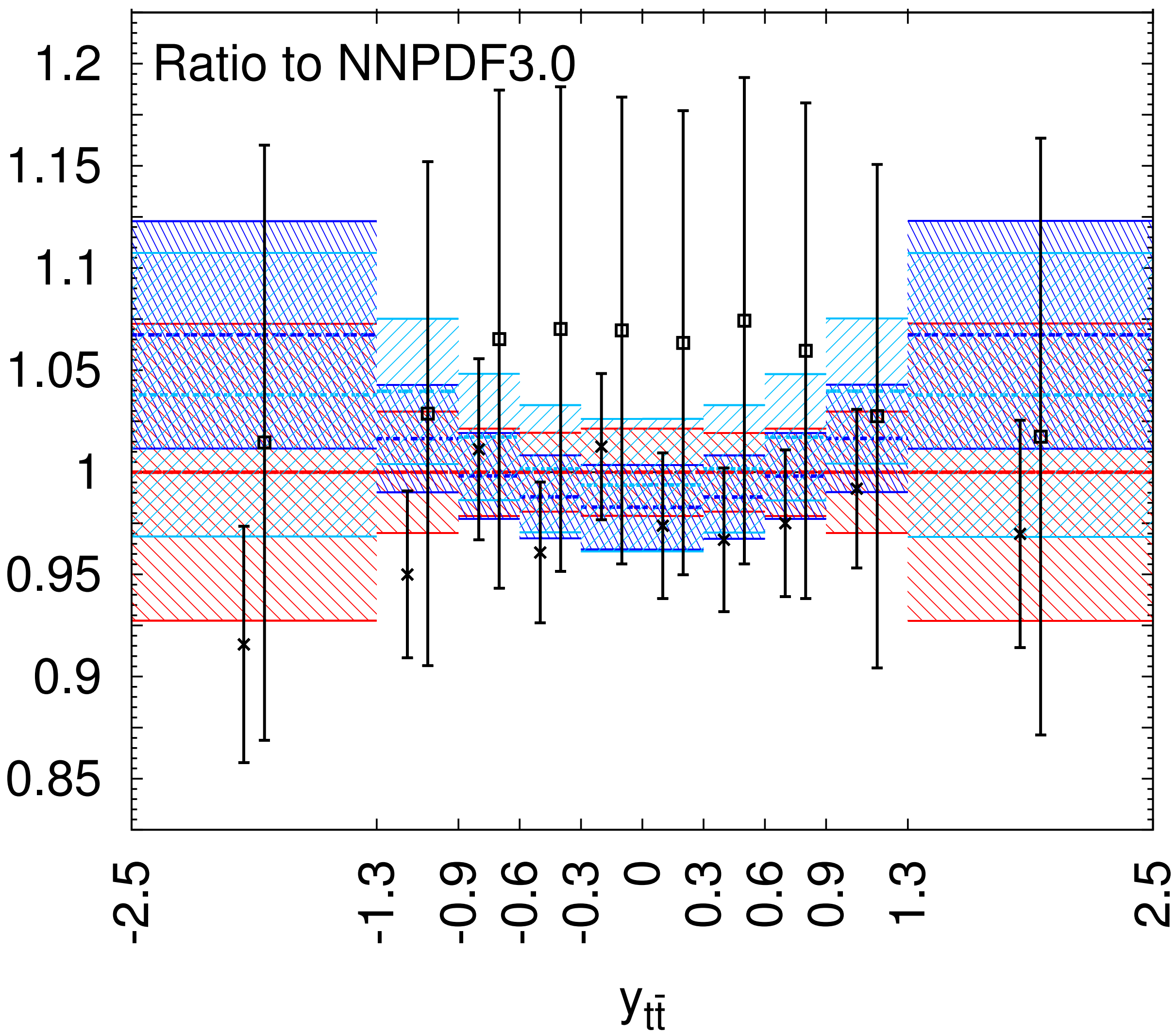
Dataset	PDF set	
ATLAS $d\sigma/dy_t$		
	NNPDF3.0	0.73
	CT14	1.28
	MMHT14	1.36
	HERA2.0	0.72
	ABM12	5.32

Dataset	PDF set	
CMS $d\sigma/dy_t$		
	NNPDF3.0	3.04
	CT14	2.23
	MMHT14	2.12
	HERA2.0	3.65
	ABM12	22.1

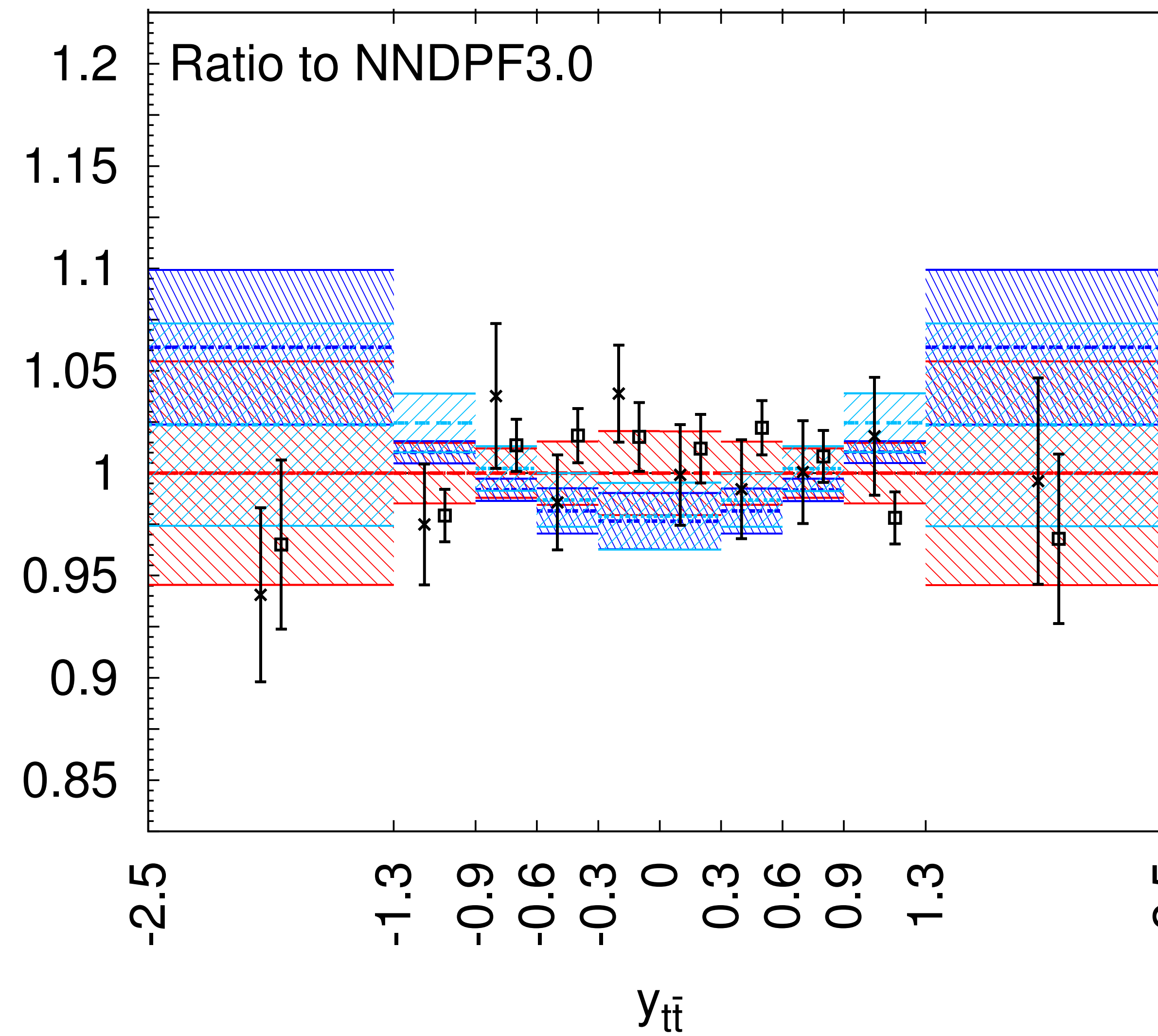


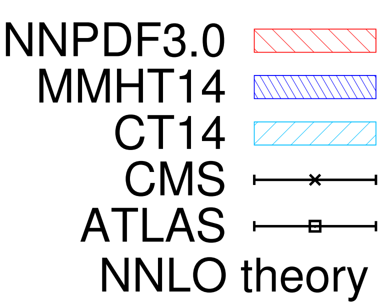
DATA-THEORY COMPARISON - TOP PAIR RAPIDITY

ABSOLUTE



NORMALISED



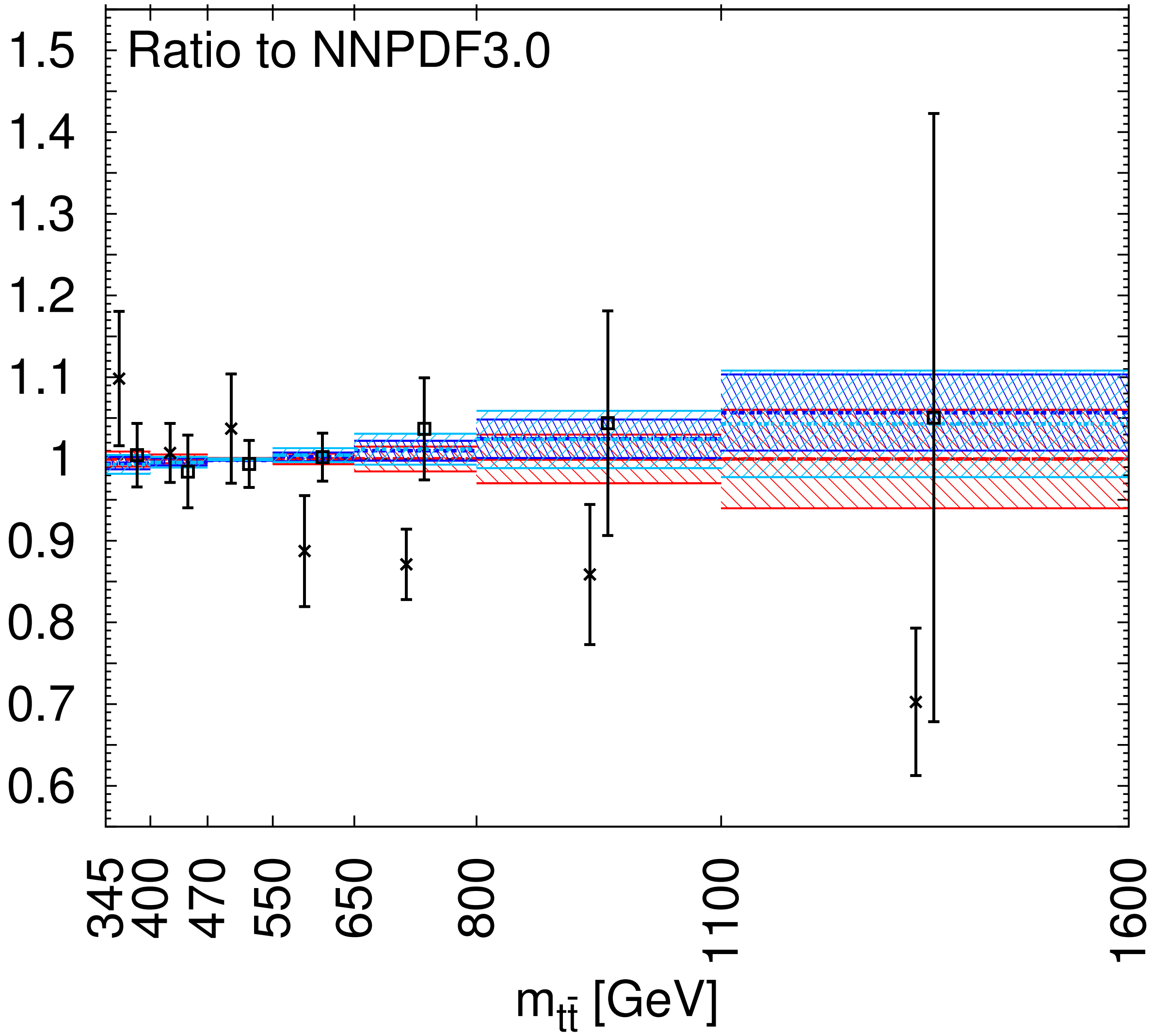


Dataset	PDF set	
ATLAS $d\sigma/dy_{t\bar{t}}$		
	NNPDF3.0	0.84
	CT14	2.69
	MMHT14	2.36
	HERA2.0	0.53
	ABM12	4.04

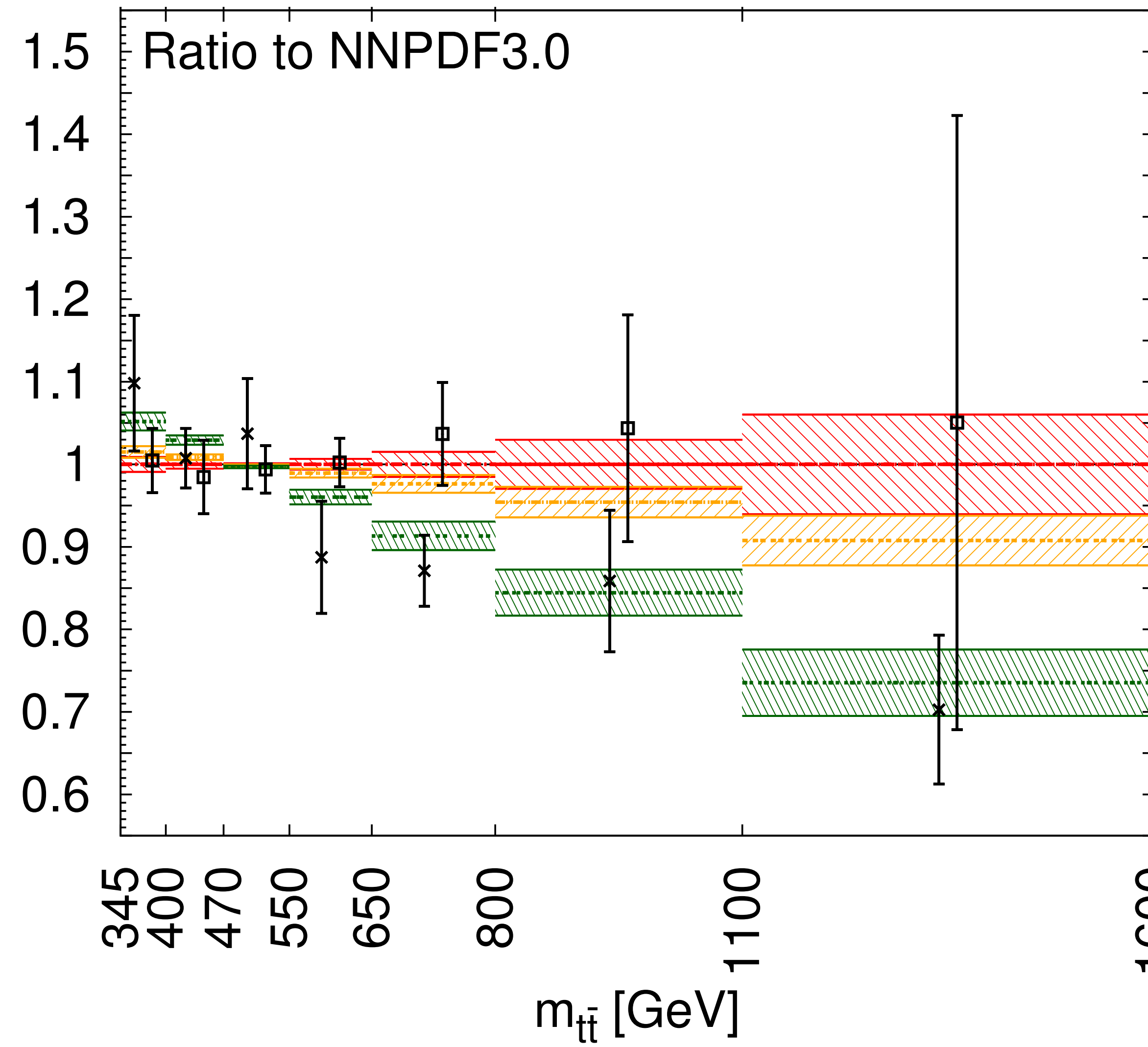
Dataset	PDF set	
CMS $d\sigma/dy_{t\bar{t}}$		
	NNPDF3.0	0.99
	CT14	1.88
	MMHT14	2.27
	HERA2.0	1.02
	ABM12	18.0

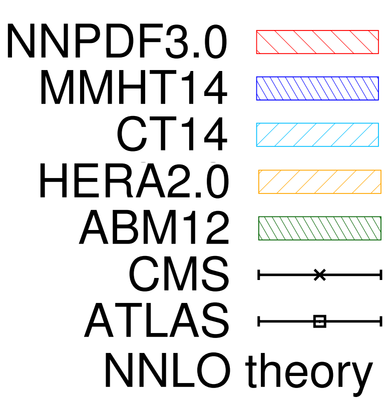
DATA–THEORY COMPARISON – TOP PAIR MASS

NORMALISED



NORMALISED



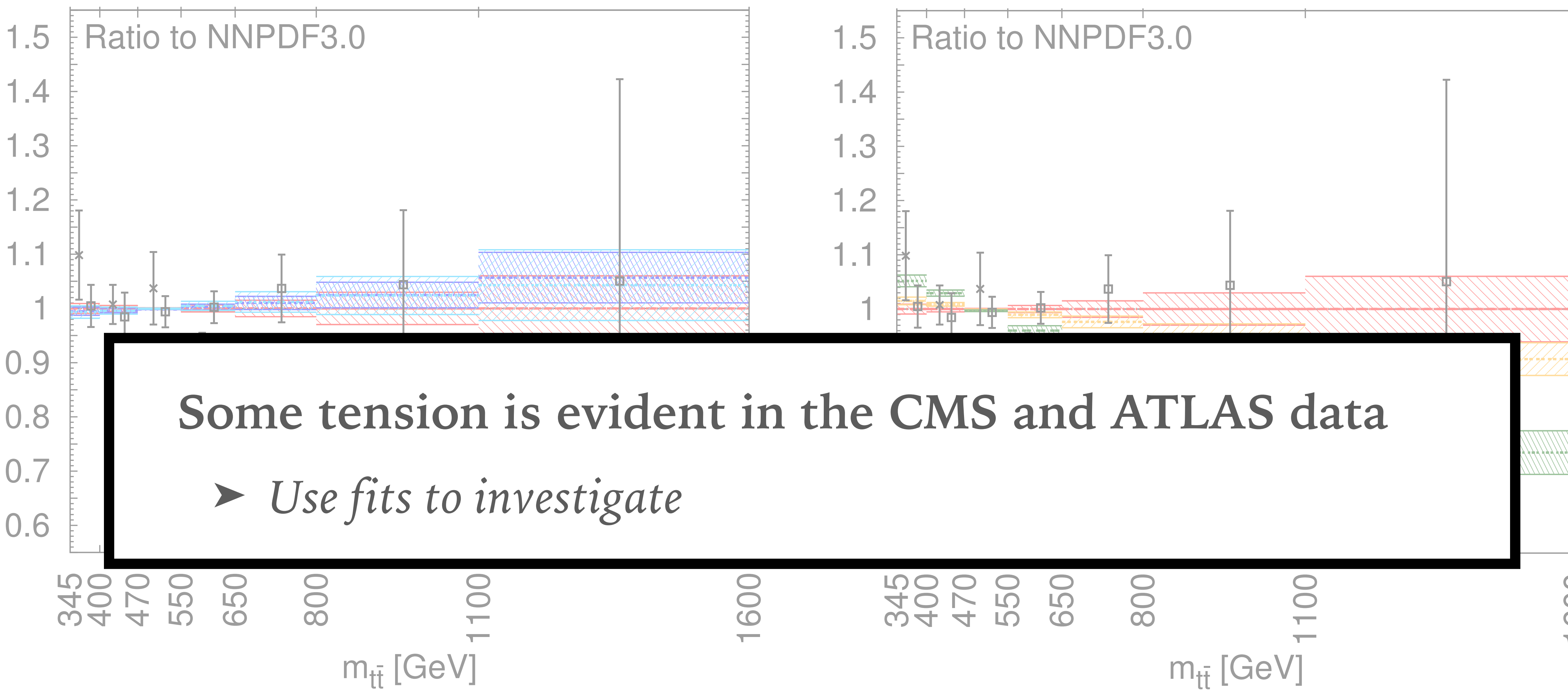


Dataset	PDF set	
ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$		
	NNPDF3.0	1.57
	CT14	1.09
	MMHT14	1.01
	HERA2.0	4.36
	ABM12	21.1

Dataset	PDF set	
CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$		
	NNPDF3.0	10.6
	CT14	13.5
	MMHT14	13.5
	HERA2.0	5.96
	ABM12	1.24

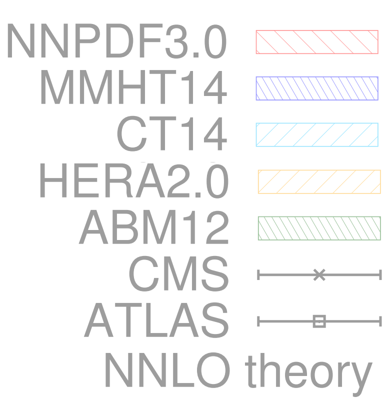
DATA–THEORY COMPARISON – TOP PAIR MASS

NORMALISED | NORMALISED



Some tension is evident in the CMS and ATLAS data

- *Use fits to investigate*



Dataset	PDF set	
ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$		
	NNPDF3.0	1.57
	CT14	1.09
	MMHT14	1.01
	HERA2.0	4.36
	ABM12	21.1

Dataset	PDF set	
CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$		
	NNPDF3.0	10.6
	CT14	13.5
	MMHT14	13.5
	HERA2.0	5.96
	ABM12	1.24

FIT SETUP

Fits are performed in the NNPDF 3.XX framework

- *Now using HERA legacy combination dataset for inclusive structure functions*
- *Inclusive top pair production data excluded from baseline*
- *Jet production measurements excluded - consistent NNLO fit*

The statistical correlations between distributions is not provided by the experiments: only one distribution per experiment can be fit simultaneously

*To investigate, we perform fits with **pairs** of the same distribution from ATLAS/CMS*

Total of eight investigatory fits

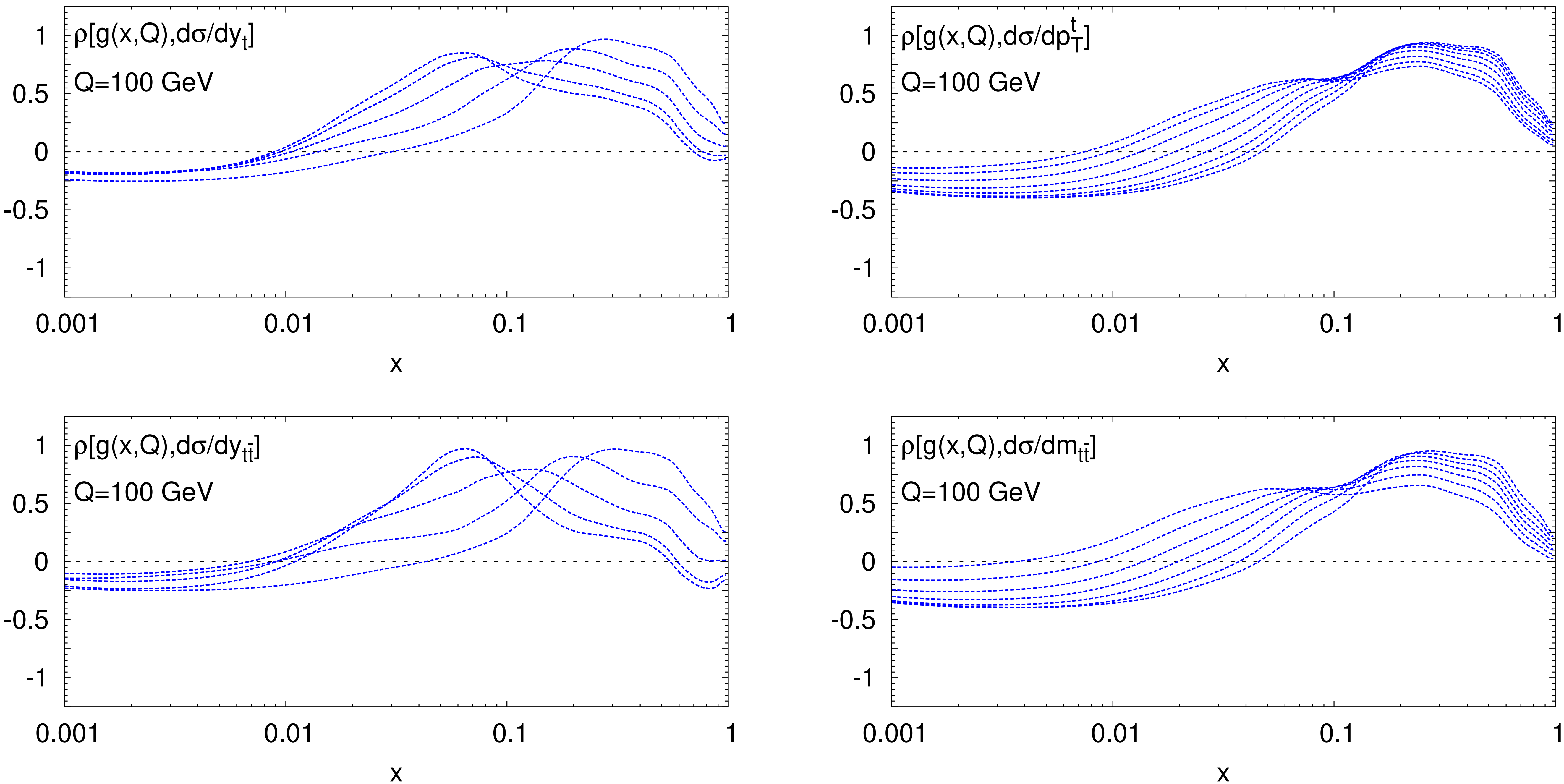
$d\sigma/dp_T^t$	$(1/\sigma)d\sigma/dp_T^t$
$d\sigma/d\lvert y_t\rvert$	$(1/\sigma)d\sigma/d\lvert y_t\rvert$
$d\sigma/d\lvert y_{t\bar{t}}\rvert$	$(1/\sigma)d\sigma/d\lvert y_{t\bar{t}}\rvert$
$d\sigma/dm_{t\bar{t}}$	$(1/\sigma)d\sigma/dm_{t\bar{t}}$

Fits of normalised distributions *include* total cross-section data

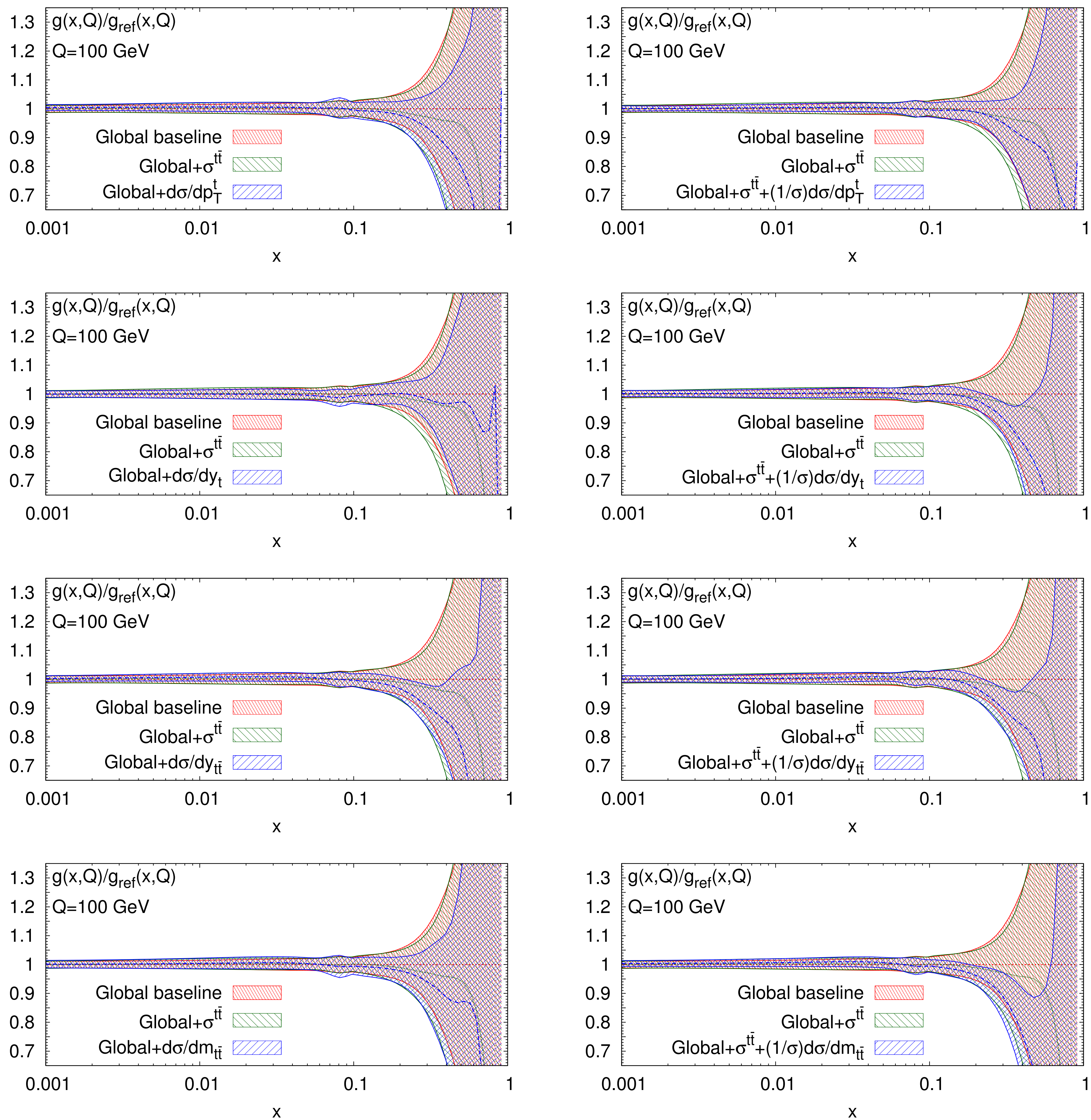
WHAT SHOULD WE EXPECT FROM THE FIT?

$$\rho[A, B] = \frac{\langle AB \rangle_{\text{rep}} - \langle A \rangle_{\text{rep}} \langle B \rangle_{\text{rep}}}{\sigma_A \sigma_B}$$

Plot correlation coefficients of gluon PDF with cross-sections



IMPACT OF TOP DATA ON LARGE-X GLUON



- Significant reduction in the gluon uncertainty at large-x
- Fits show remarkable consistency across dataset choices
- Normalised distributions appear to have a greater impact upon uncertainties

NNLO FIT QUALITY

χ^2 to datasets *after* the associated fit

Fit	ATLAS	CMS
p_T^t	**1.99** (2.37)	**2.60** (3.50)
y_t	**1.09** (0.93)	**2.66** (3.48)
$y_{t\bar{t}}$	**1.32** (2.44)	**0.89** (1.36)
$m_{t\bar{t}}$	**4.02** (4.27)	**5.11** (7.07)
$(1/\sigma)\ p_T^t$	**2.96** (2.93)	**3.56** (4.31)
$(1/\sigma)\ y_t$	**1.68** (5.00)	**4.76** (3.66)
$(1/\sigma)\ y_{t\bar{t}}$	**2.17** (9.69)	**1.05** (1.59)
$(1/\sigma)\ m_{t\bar{t}}$	**2.98** (2.30)	**7.27** (12.0)

(Values in brackets are those of the baseline)

Good χ^2 values achievable, but not for all distributions

Some tension in simultaneous fit

Good description of pair rapidity

Difficulties fitting both experiments

Large improvements in fit quality

Significant disagreement

What is the origin of this tension?

NNLO FIT QUALITY

1. **Perform fits to ATLAS and CMS data separately**
   Study whether the tension is between the two experiments

2. **Perform the same fits, but with a HERA-only baseline**
   (Essentially) unconstrained large-x gluon should reduce tension w.r.t global dataset

ATLAS	COMBINED	SEP.	SEP. HERA.
$(1/\sigma)\ y_t$	1.68	1.1	0.8
$(1/\sigma)\ m_{t\bar{t}}$	2.98	1.8	0.6

CMS	COMBINED	SEP.	SEP. HERA.
$(1/\sigma)\ y_t$	4.76	2.6	1.7
$(1/\sigma)\ m_{t\bar{t}}$	7.27	4.1	0.9

Good description is possible

- *NNLO theory is sufficient*
- *Datasets appear to be internally consistent*

Poor fit quality of some dists. due to tension between datasets

PROCEDURAL SUGGESTION

While some distributions exhibit tension, some appear perfectly compatible.

- Impact of data upon PDFs appears relatively insensitive of dist. choice.

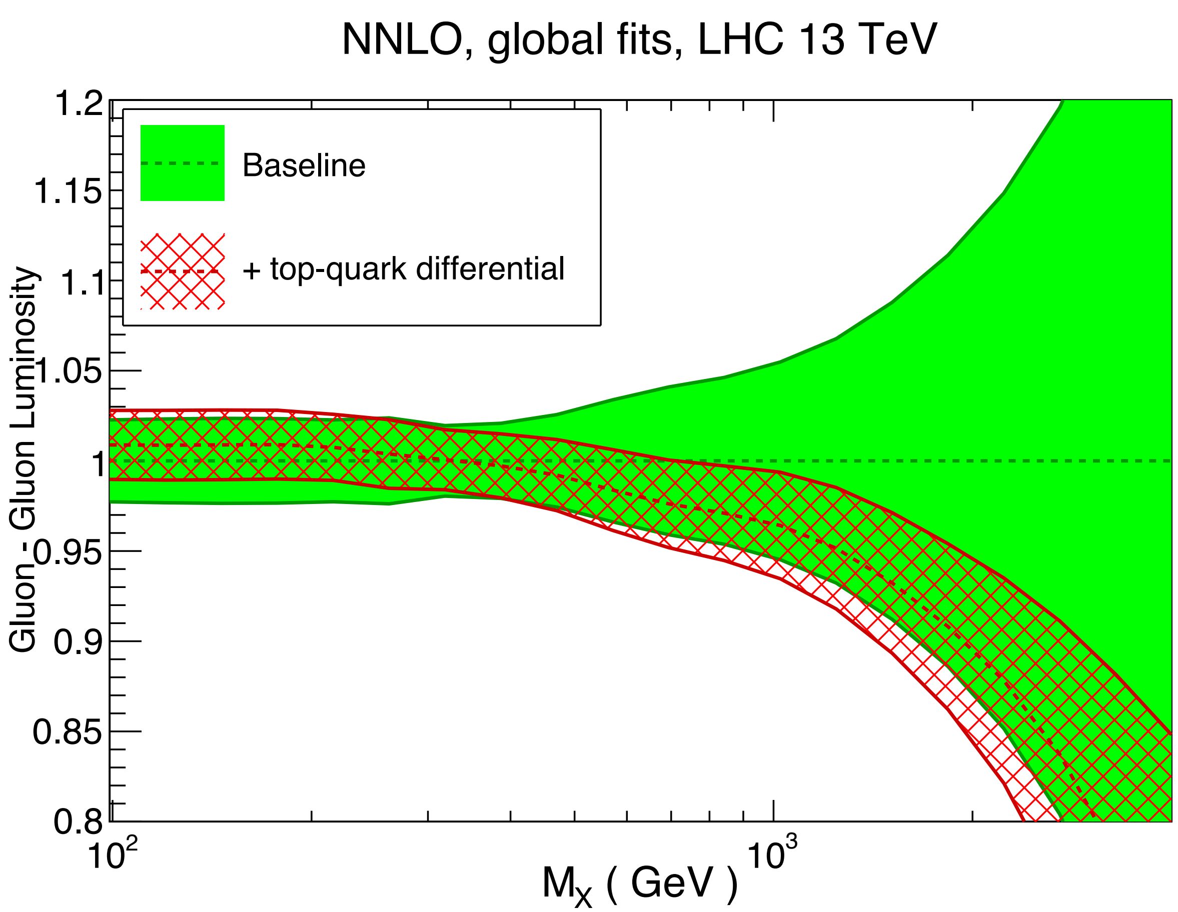
***Our fitting dataset recommendation**: (while stat. correlations are unavailable)*

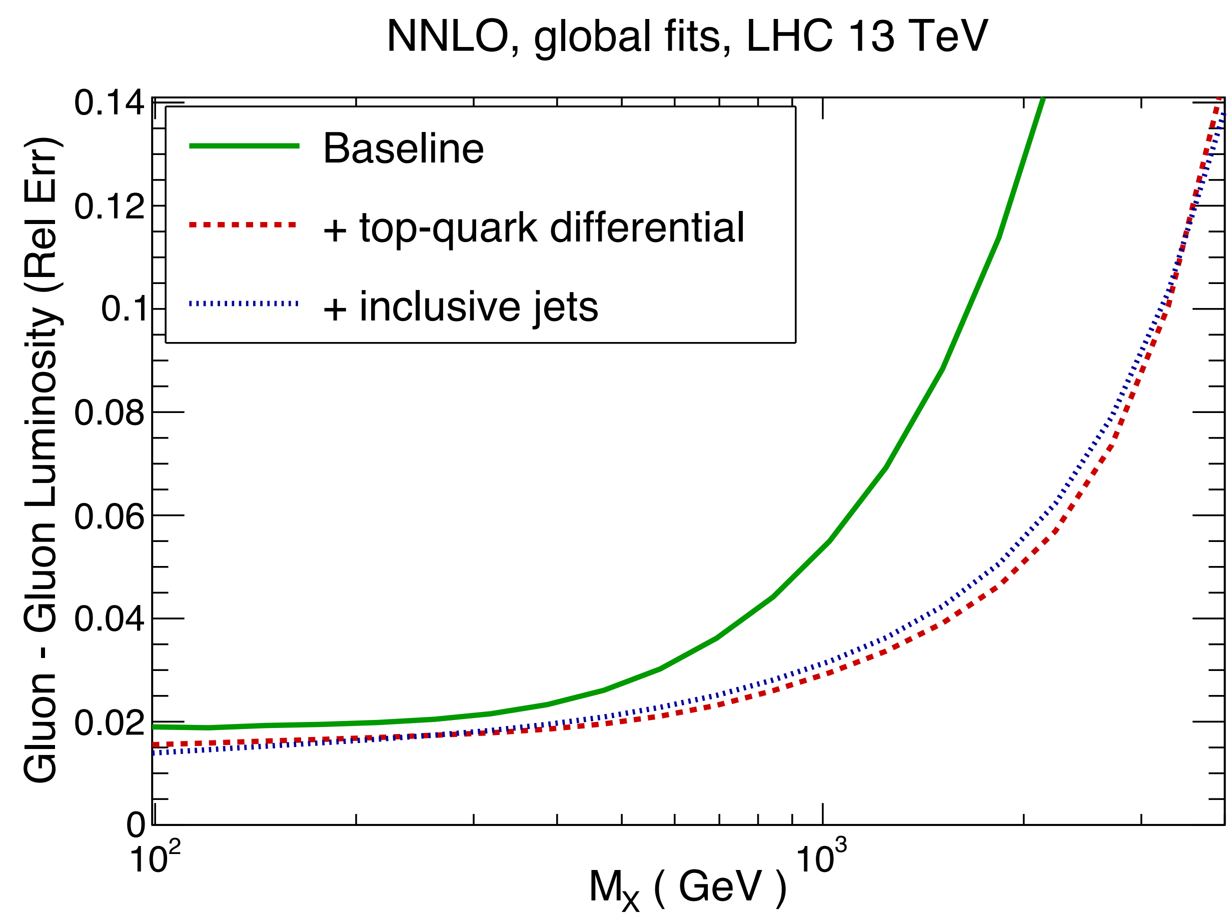
- *ATLAS normalised top-quark rapidity distributions* $(1/\sigma)\, d\sigma/dy_t$
- *CMS normalised top-quark pair rapidity distributions* $(1/\sigma)\, d\sigma/dy_{t\bar{t}}$

Selection minimises	**Balanced against**
- *Tension between ATLAS/CMS*	- *PDF constraining power*
- *Tension with existing data*	- *Varied kinematic coverage*

IMPACT UPON LARGE-X GLUON

What is the practical impact of fitting our recommended distributions?





- *Significant reduction of gg luminosity uncertainties at ≳ TeV invariant masses*
- *Impact upon gluon uncertainties equivalent to that of incl. jet data*

Precision determination of the gluon at large-x now possible at NNLO

Situation should only improve further with the recent NNLO incl. jets calculation!

SUMMARY

A combination of theoretical and experimental advances are shedding light on the gluon.

Precise constraints upon the gluon at NNLO are now available from LHC top-pair differential data - complementing incl. jet constraints.

LHC 8 TeV differential top data has its mysteries

- Tension between ATLAS and CMS in some distributions
- Tension with some data in a global PDF dataset

Recent data at 13TeV should help in understanding the origin of tensions

- *However, data shows excellent consistency in the pull upon gluon PDFs*
- *Reduction in uncertainties comparable to the constraining power of incl. jets*
- *Provide precise predictions for (B)SM process in the crucial large* M_X

Thank you for listening!