

# Top-quark pair production in global QCD analyses: updates from CTEQ

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with

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**Michigan State University**



**KENNESAW STATE  
UNIVERSITY**

# Main Goals

Work is going on towards the upcoming release of CTEQ PDFs: CT2X ( $X>2$ ).

- Efforts are being put into:
  1. selecting the most sensitive data from recent high-precision measurements at the LHC.
  2. understanding uncertainties and their intricacies in a multitude of scattering processes entering the global analysis (e.g., scale uncertainties).
- This talk: focuses on eligible  $t\bar{t}$  production measurements at the LHC 13 TeV and their impact on the gluon PDF at large  $x$  from an optimal baseline selection of measurements of 1D absolute differential Xsec.

# Motivations

- Assess the impact of new  $t\bar{t}$  production 1D diff. Xsec measurements on unpol. coll. PDFs
- Improve PDF uncertainties in global QCD analyses (in particular,  $g(x)$  at large  $x$ )
- Explore QCD dynamics and interplay between jet and  $t\bar{t}$  production in PDFs at large  $x$

Important for: precision BSM searches, precise and accurate theory predictions (pQCD),...

## Heavy-flavor treatment in theory predictions (GMVFN schemes):

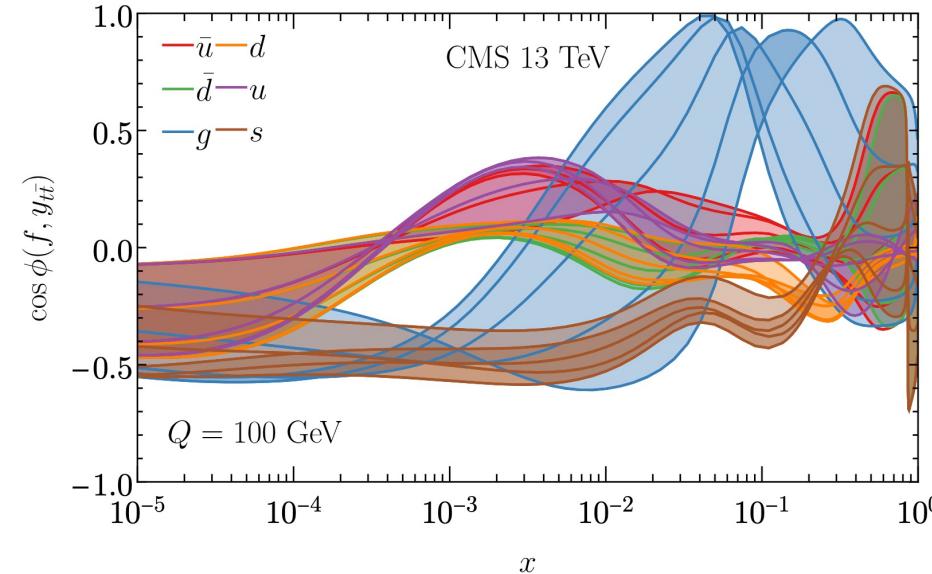
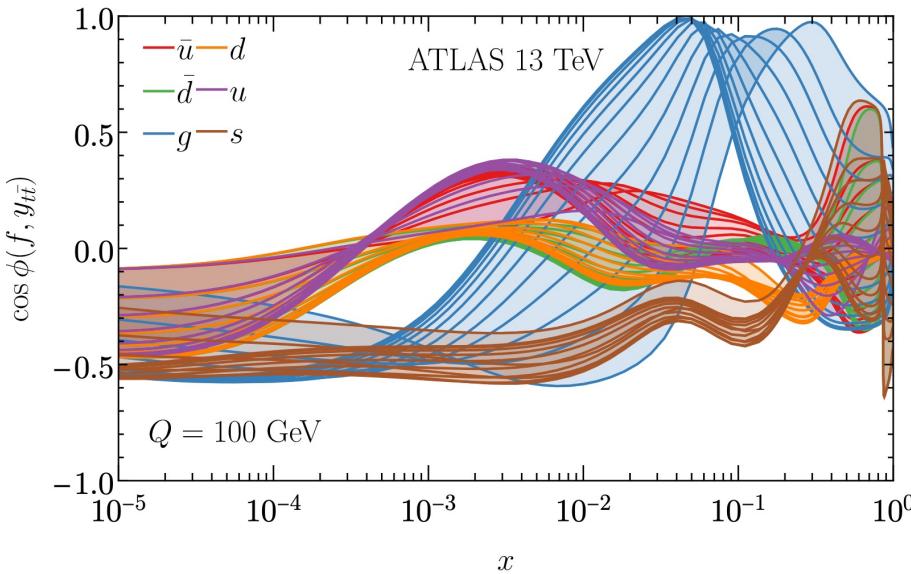
- DIS: S-ACOT- $\chi$  (default in CTEQ analyses) based on Collins' HF factorization in DIS
- Extend S-ACOT to PP collisions: S-ACOT-MPS. Now at NLO. NNLO needed.
- Implemented for inclusive charm [[FPF, 2109.10905](#), [2203.05090](#)] and bottom [[2203.06207](#)] production.
- S-ACOT-MPS can be extended to other processes (See Keping Xie's talk).

# What are data telling us?

- Heavy-quark production at the LHC at small  $p_T$  and large rapidity  $y$  of the heavy quark: sensitive to PDFs at both small and large  $x$  (especially true for c/b production)

$$x_{1,2} \approx \frac{\sqrt{p_T^2 + m_Q^2}}{\sqrt{S}} e^{\pm y}$$

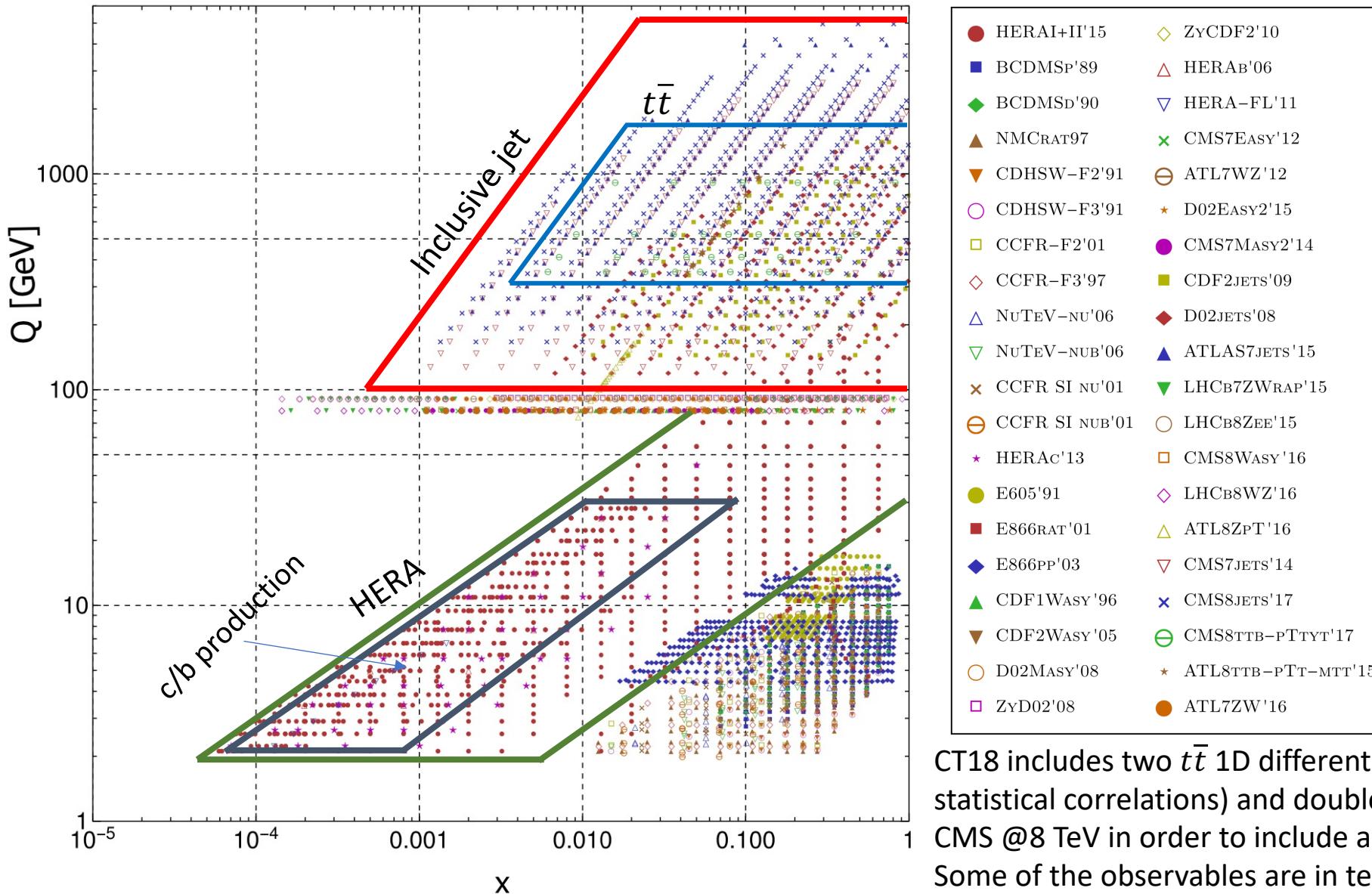
- In this kinematic region PDFs are poorly constrained by other experiments in global PDF fits.
- Top-quark pair production @LHC can already probe the gluon PDF at  $x \gtrsim 0.01$



Correlation plots with ePump for the ATLAS all-hadronic and CMS dilepton channel

# PDF Kinematics in the $Q$ - $x$ plane and the CT18 fit

Experimental data in CT18 PDF analysis



Jet and  $t\bar{t}$  complement each other in the kinematic plane. They impact the gluon PDF at large  $x$ . Important to disentangle the effect due to jet production and top-quark data.

## Top and jet Data in CT18

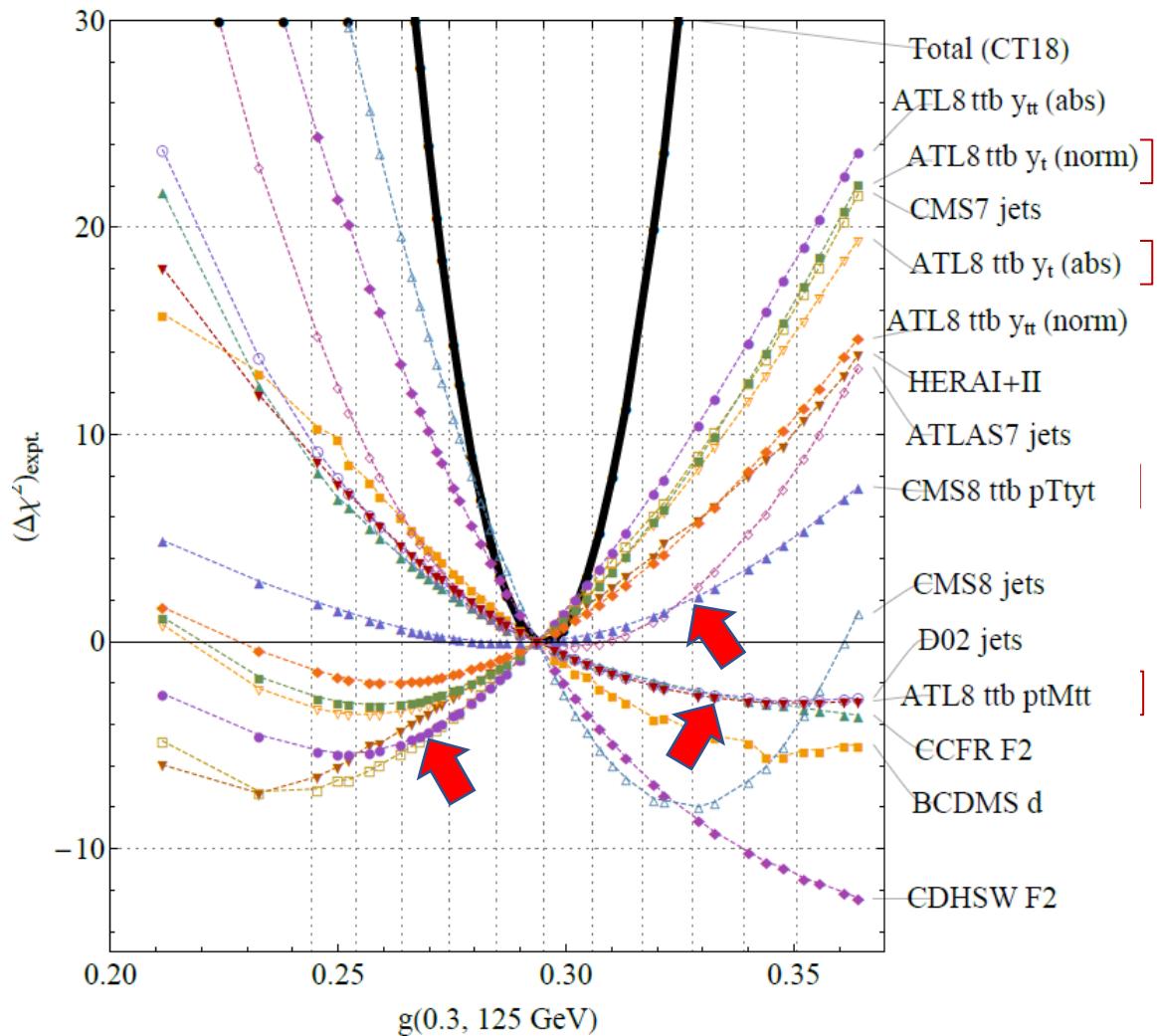
Top-quark  
1511.04716 ATLAS 8 TeV tt<sub>b</sub> ptT diff. distributions  
1511.04716 ATLAS 8 TeV tt<sub>b</sub> mtt diff. distributions  
1703.01630 CMS 8 TeV tt<sub>b</sub> (pT, yt) 2d diff. distrib.

Jet production  
1406.0324 CMS incl. jet at 7 TeV with R=0.7  
1410.8857 ATLAS incl. jet at 7 TeV with R=0.6  
1609.05331 CMS incl. jet at 8 TeV with R=0.7

CT18 includes two  $t\bar{t}$  1D differential observables from ATLAS (using statistical correlations) and double differential measurements from CMS @8 TeV in order to include as much information as possible. Some of the observables are in tension with each other.

# Constraints from 8 TeV $t\bar{t}$ production data in CT18

CT18 NNLO + unfitted ATLAS 8 TeV top single-diff. data



Realistic PDF error estimates account for multiple PDF functional forms and some disagreements between the measurements.

They predict milder impact from  $t\bar{t}$  data

In the figure, pulls on the gluon from ATLAS8  $y_{t\bar{t}}$  and  $y_t$  distributions (absolute or normalized) agree with HERA DIS, oppose ATLAS8  $d^2\sigma/(dp_{T,t}dm_{t\bar{t}})$  and CMS8  $d^2\sigma/(dp_{T,t}dy_{t,\text{ave}})$

# Impact of LHC 13 TeV $t\bar{t}$ production on CT2X PDFs

Extensive analysis in which the impact of 1D absolute distributions is explored with different scale choices

Exp	Obs	Npt	ePump updated Chi2/Npt			HT/2	Global fit Chi2/Npt		HT/2	HT/4	
			HT	HT/2	HT/4		HT/2	HT/4			
ATLAS_hadron Channel	mtt	9.00	1.75	1.57	1.60		1.53	1.47			
	HTtt	11.00	1.98	1.77	1.59		1.50	1.74			
	ytt	12.00	1.28	1.15	0.94		1.05	1.07			
	pTt1	10.00	1.30	1.19	1.12		1.20	1.33			
	pTt2	8.00	1.13	0.84	1.05		0.84	1.59			
CMS_Dilep	mtt	7.00	3.46	3.07	3.14		3.12	3.23			
	ytt	10.00	1.66	0.97	0.68		0.94	0.67			
	pTt	6.00	3.60	3.70	3.68		3.56	3.05			
	yt	10.00	1.33	0.94	0.87		1.00	0.69			
ATLAS_LepJ CMS Bin	mtt	7.00	2.40	1.17	0.68		0.83	0.66			
	ytt	10.00	0.91	0.69	0.62		0.74	0.75			
	pTt	6.00	2.34	2.01	2.47		1.35	1.43			
	yt	10.00	1.30	1.07	1.10		1.16	0.68			
CMS_LepJ 137 fb <sup>-1</sup>	mtt	15.00	1.49	1.38	1.81		1.20	1.67			
	ytt	10.00	6.47	6.24	6.42		6.01	5.88			
ATLAS_LepJ ATLAS Bin NoStatCorrelation						NoStatCorrelation			WithStatCorrelation		
	mtt	9.00	1.55	1.12	0.94		1.27	0.92		1.29	0.96
	ytt	7.00	0.91	0.74	0.80		0.76	0.90		0.75	0.92
	yB	9.00	1.40	1.27	1.53		0.85	0.93		0.86	0.99
	HTtt	9.00	1.35	0.91	0.93		0.81	0.80		0.86	0.86
	mtt ytybHtt	34.00	1.87	1.28	1.46		0.93	1.06		1.59	1.32

CT2X  $\supset$  CT18 + new optimal combination of top-quark pair production @LHC13 TeV from:

- ATLAS all hadronic, JHEP 01 (2021) 033, arXiv:2006.09274
- ATLAS lepton + jets, EPJC 79 (2019) 1028, arXiv:1908.07305
- CMS dilepton, JHEP 1902 (2019) 149, arXiv:1811.06625
- CMS lepton + jets, PRD 104 092013 (2021), arXiv:2108.02803

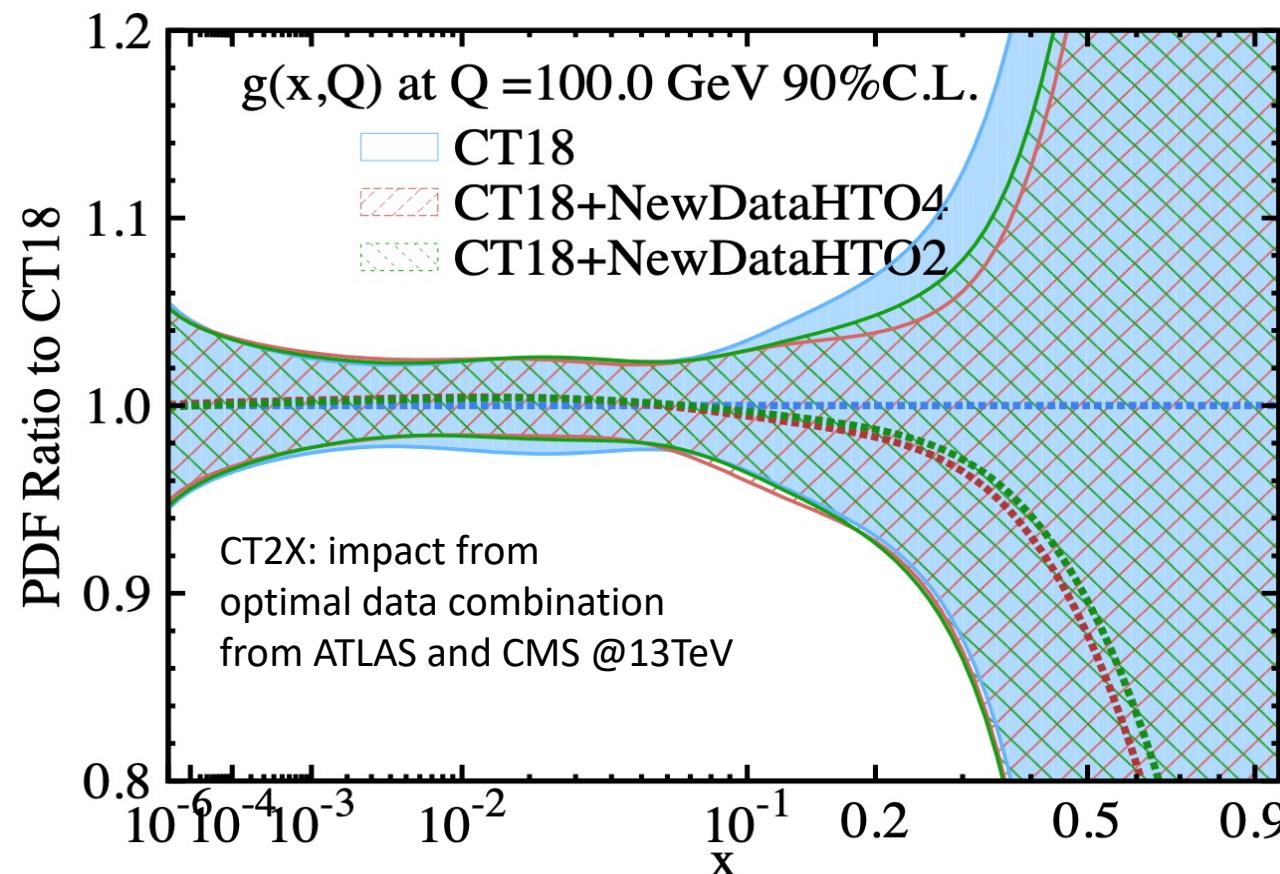
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Correlated Systematic Uncertainties: ATLAS -> nuisance parameters

CMS -> Covariance matrix representation (converted to nuisance param.)

When statistical correlations not provided  data added one at a time on top of the CT18 baseline

# Global fit: impact from new baseline and scale choice



Optimal baseline consists of 1D absolute Xsec from

- ATLAS all hadronic, ytt
- ATLAS lepton + jets, ytt and stat. comb. {ytt, Mtt, yBtt, HTtt} have very similar impact
- CMS dilepton, ytt
- CMS lepton + jets, Mtt

Theory predictions:

- MATRIX (Catani, Grazzini et al. PRD 2019)
- FastNNLO (Czakon, et al. 1704.08551)

Blue band: CT18NNLO 90% C.L.

Hatched bands: CT18 + new data

Green:  $\mu_R = \mu_F = H_T/2$

Red:  $\mu_R = \mu_F = H_T/4$

Differences related to different scale choices are well within the CT18 PDF error band.

# Theory predictions: setup

- CMS (dilepton ch): FastNLO grids for the NNLO theory– ([Czakon et al. 1704.08551](#))
- ATLAS: bin-by-bin NNLO/NLO K-factors generated by MATRIX ([Catani, Grazzini, et al. PRD2019](#))

The NLO QCD calculation is obtained using our in-house APPLGrid fast tables ([Carli et al. EPJC 2010](#)) for the public MCFM calculation ([Campbell, Ellis JPG 2015](#))

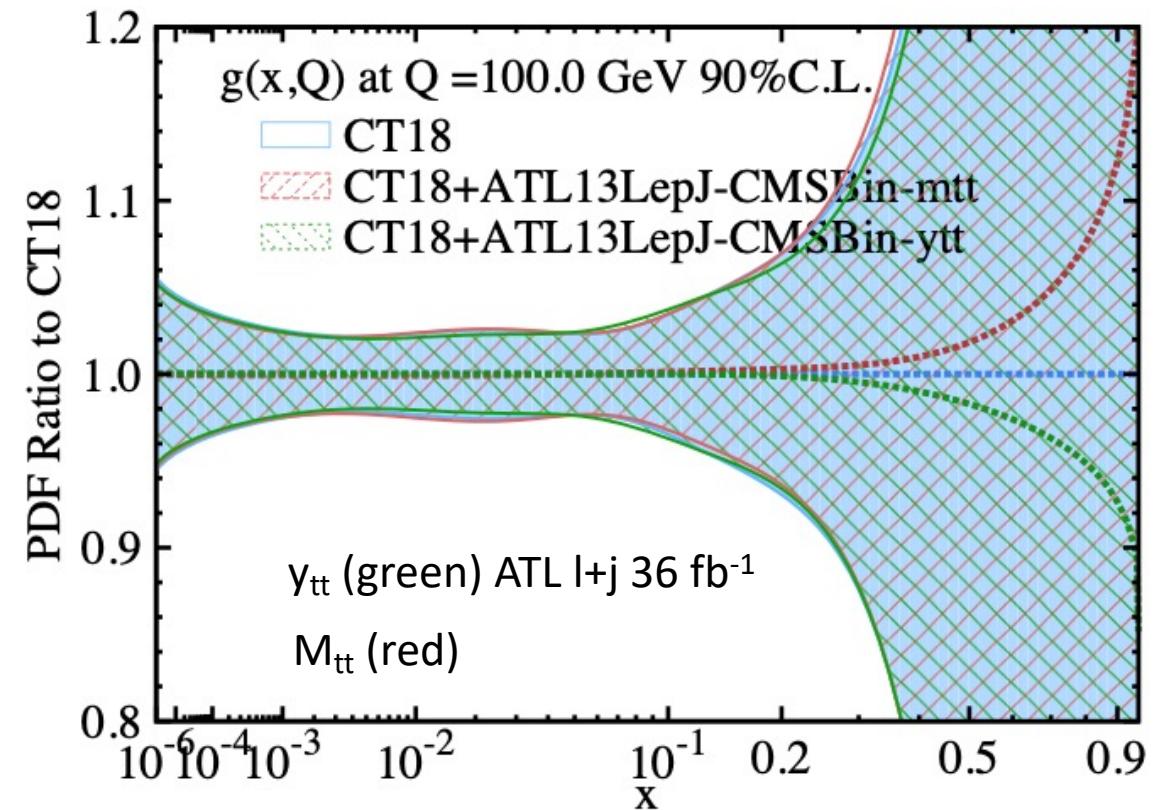
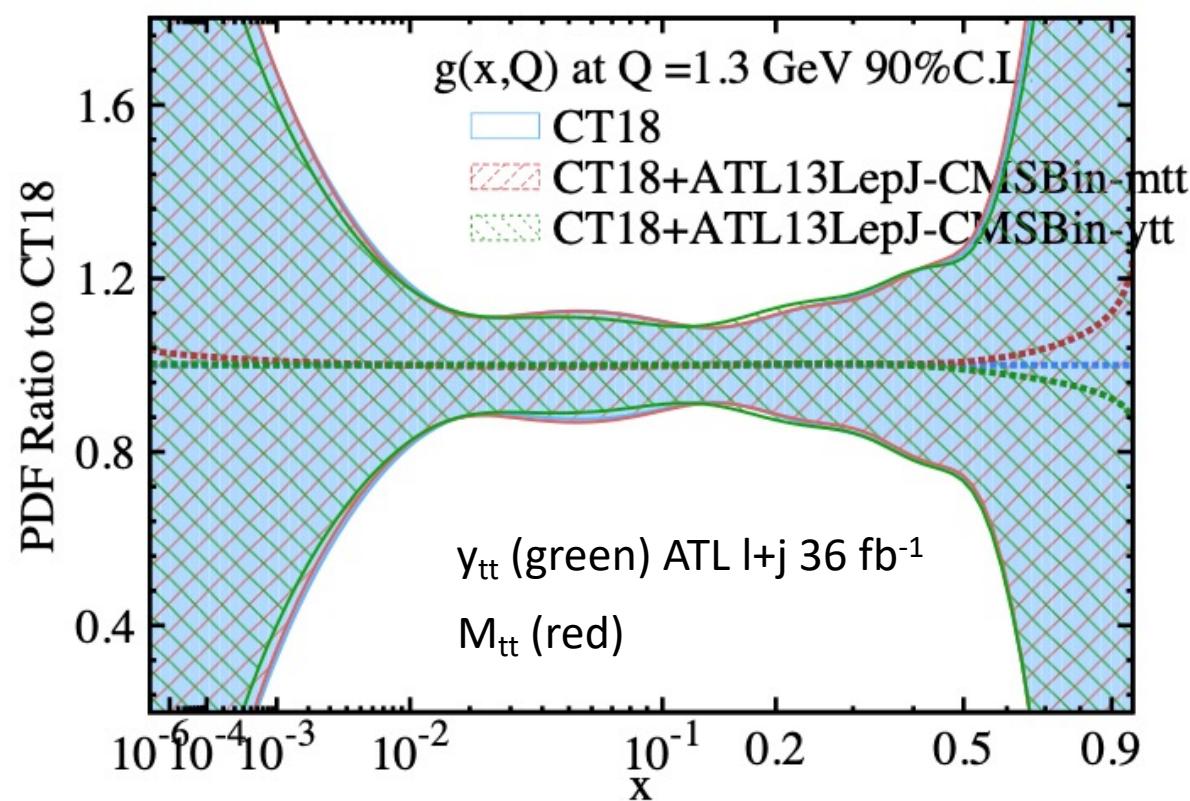
- $m_t(\text{pole}) = 172.5 \text{ GeV}$
- Fact/Ren scale choice:

$m_{tt}, p_{T,tt}, y_{tt}, y_t$  use:  $H_T/4$  and  $H_T/2$ ;  $p_{T,t}$ , use  $M_T$ ;  $p_{T,t} \text{ avg}$  use  $M_T/2$  ([Czakon et al. JHEP 2017](#))

$$\mu_F = \mu_R = H_T/4 = \left( \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} \right) / 4 \quad \mu_{F,R} = M_T^t/2 = \sqrt{m_t^2 + p_T^2}/2$$

- **EW corrections considered:** negligible impact on our fits.

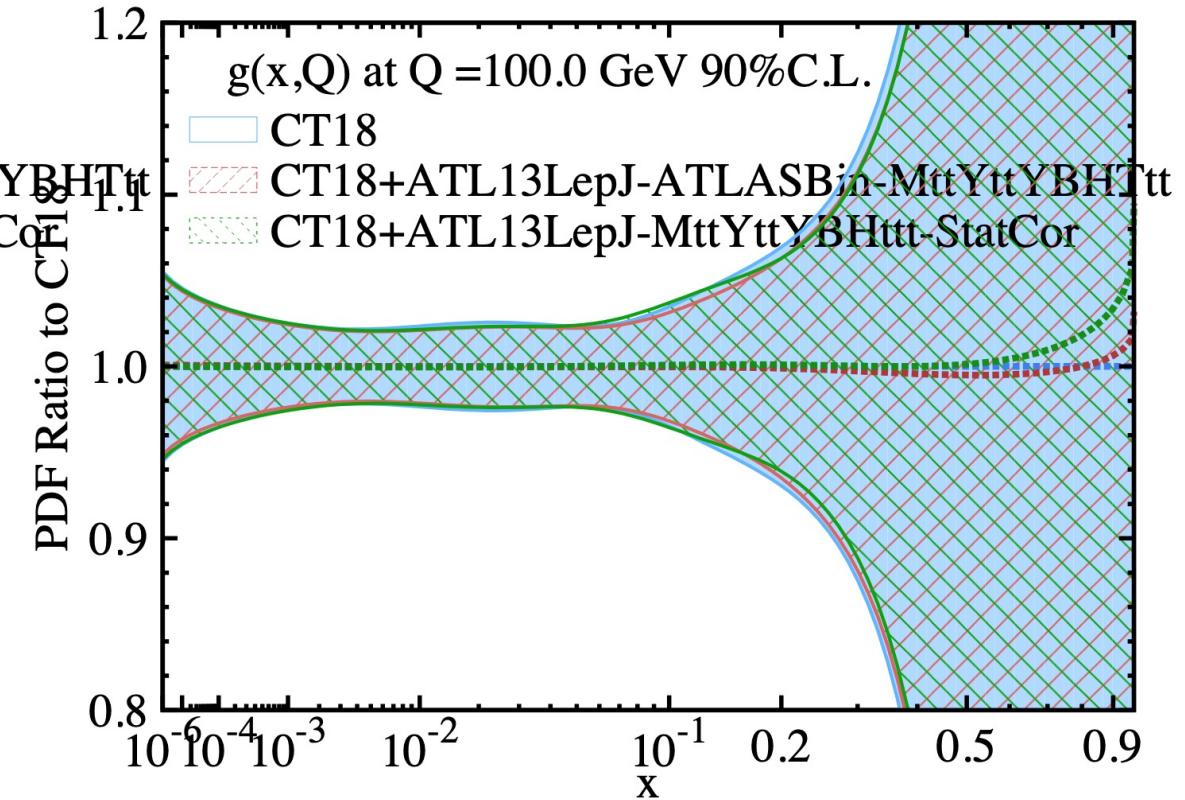
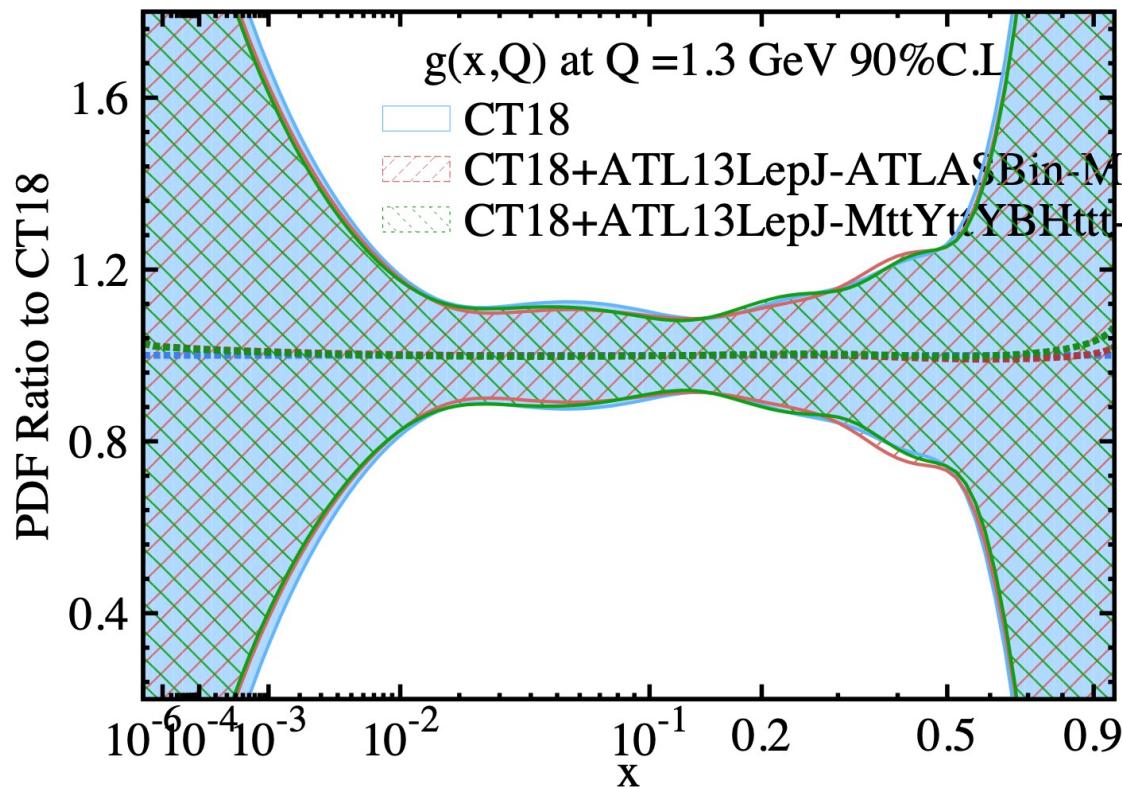
# Global fit: Impact on $g(x,Q)$ from ATLAS lep+jets



$M_{tt}$  and  $y_{tt}$  1D absolute distributions added one by one in the global fit

Pulls are not in the same direction.  $M_{tt}$  badly described in terms of  $\chi^2/N_{pt}$ . We select  $y_{tt}$  1D absolute

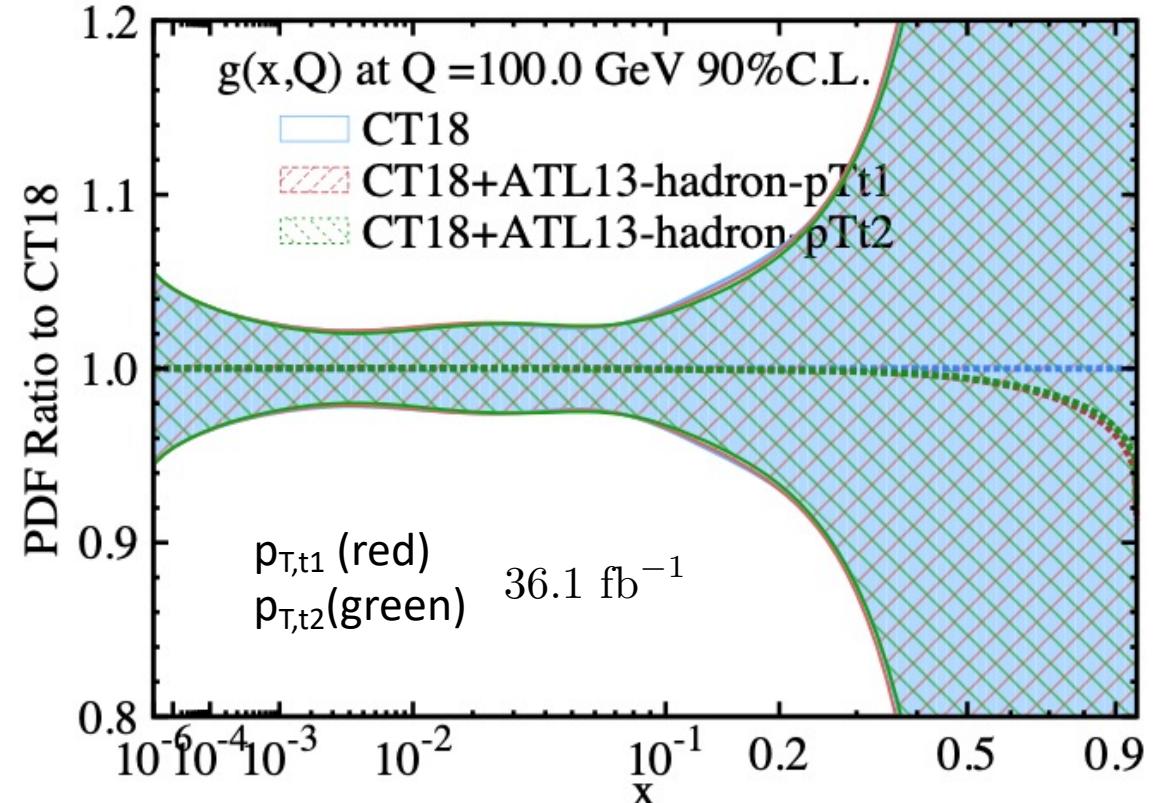
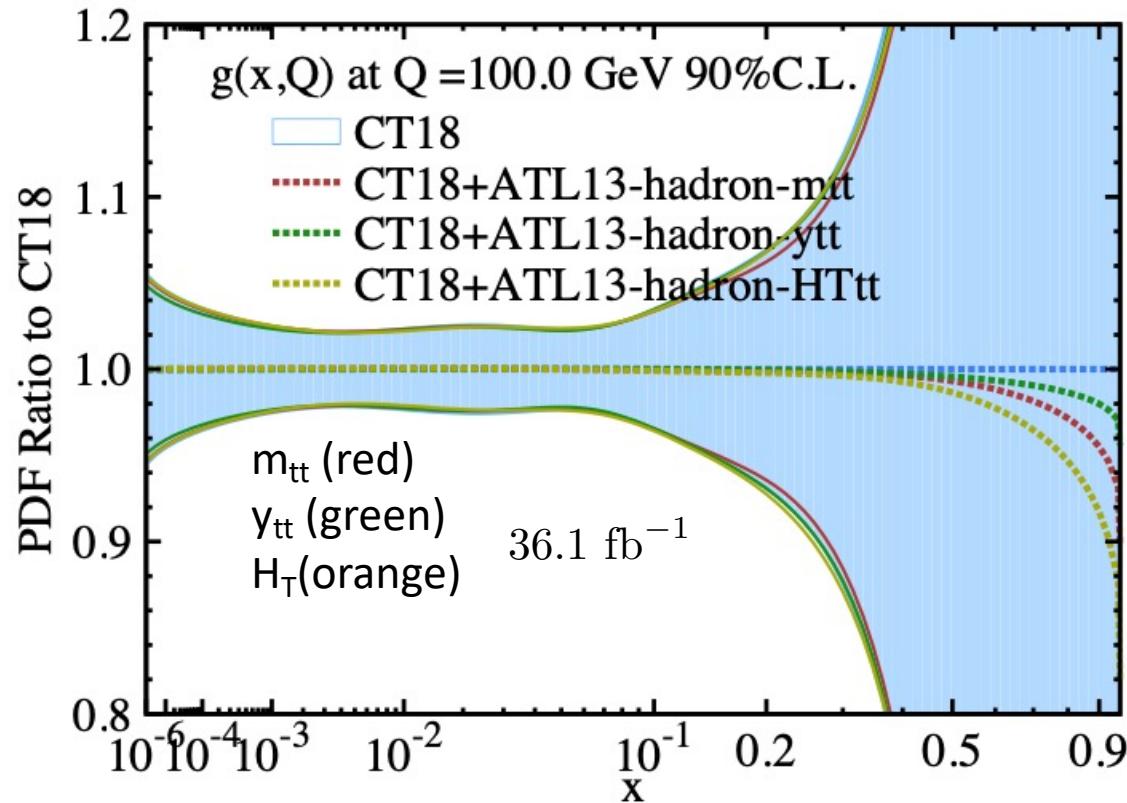
# Impact of statistical correlations in ATLAS lep+jets



Exp	Obs	Npt	ePump updated Chi2/Npt				Global fit Chi2/Npt		With statistical corr	
			HT	HT/2	HT/4		HT/2	HT/4	HT/2	HT/4
ATLAS_LepJ ATLAS Bin NoStatCorrelation	mtt	9	1.551	1.123	0.94		1.27	0.92206	1.287	0.963
	ytt	7	0.911	0.739	0.8		0.756	0.8975	0.751	0.921
	yB	9	1.396	1.267	1.532		0.8498	0.93335	0.858	0.992
	HTtt	9	1.352	0.909	0.933		0.805	0.80475	0.855	0.857
	mtttybyHttt	34	1.867	1.28	1.457		0.933	1.06487	1.585	1.322

Some impact on the  $\chi^2/Npt$  but almost no impact on PDFs and their errors.

# Global fit: Impact on $g(x,Q)$ from ATLAS all hadronic

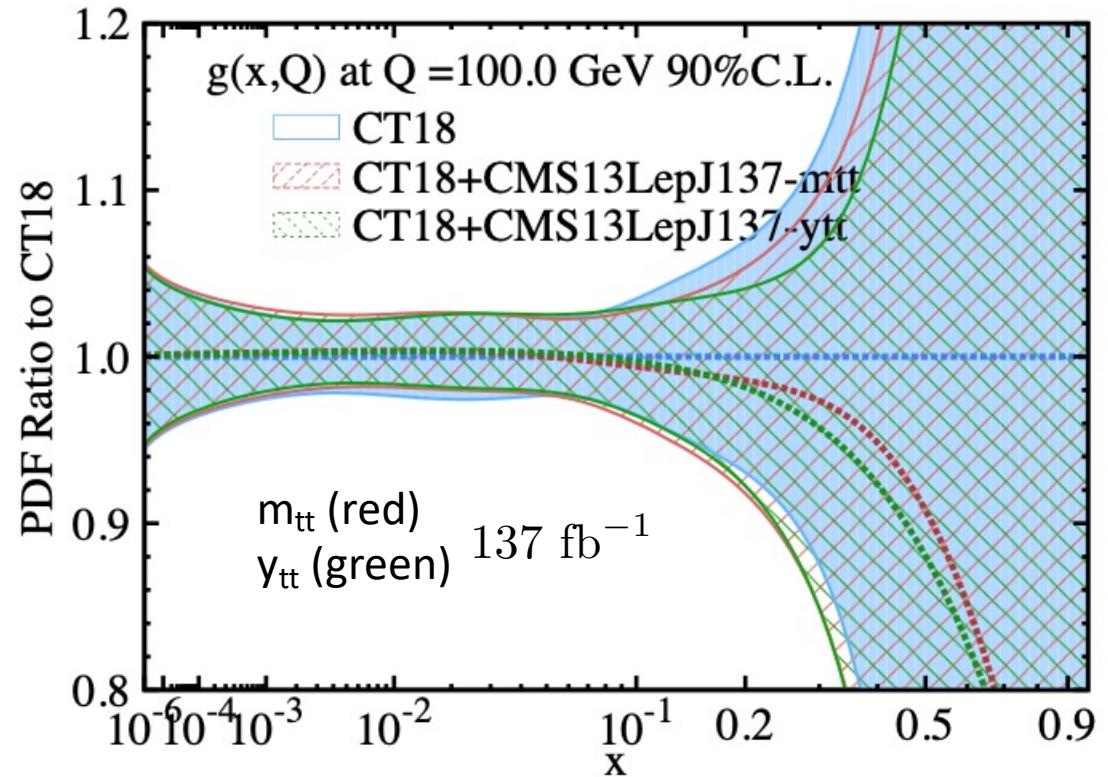
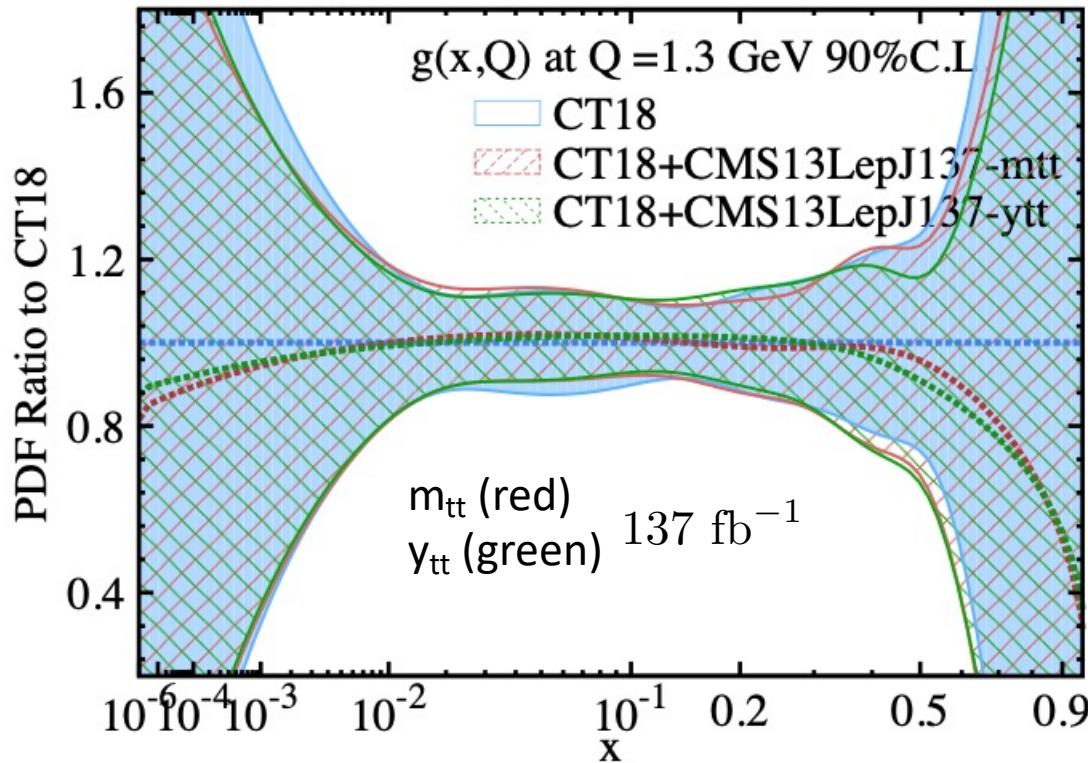


$m_{tt}$ ,  $p_{T,t1}$ ,  $p_{T,t2}$ ,  $H_T$ , and  $y_{tt}$  1D absolute distributions added one by one in the global fit.

Pulls are in the same direction here.

Impact is very small and confined in the extrapolation PDF parametrization region.

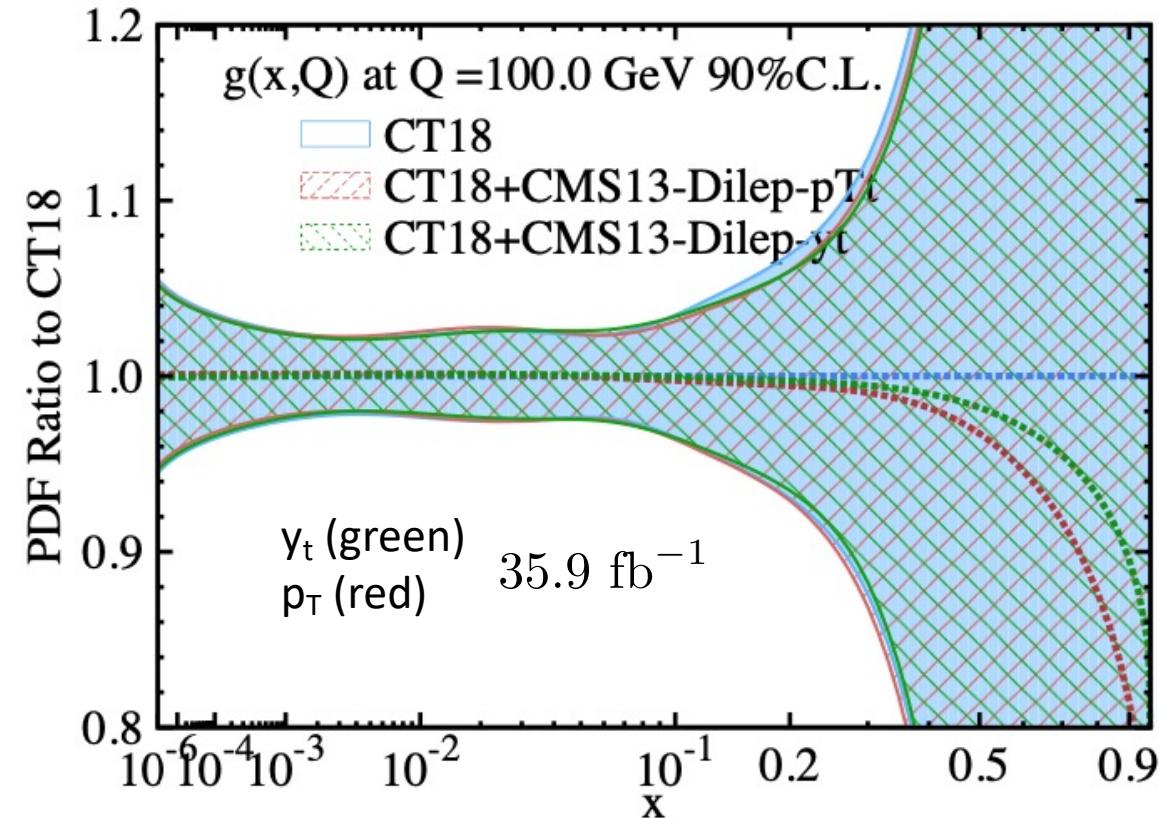
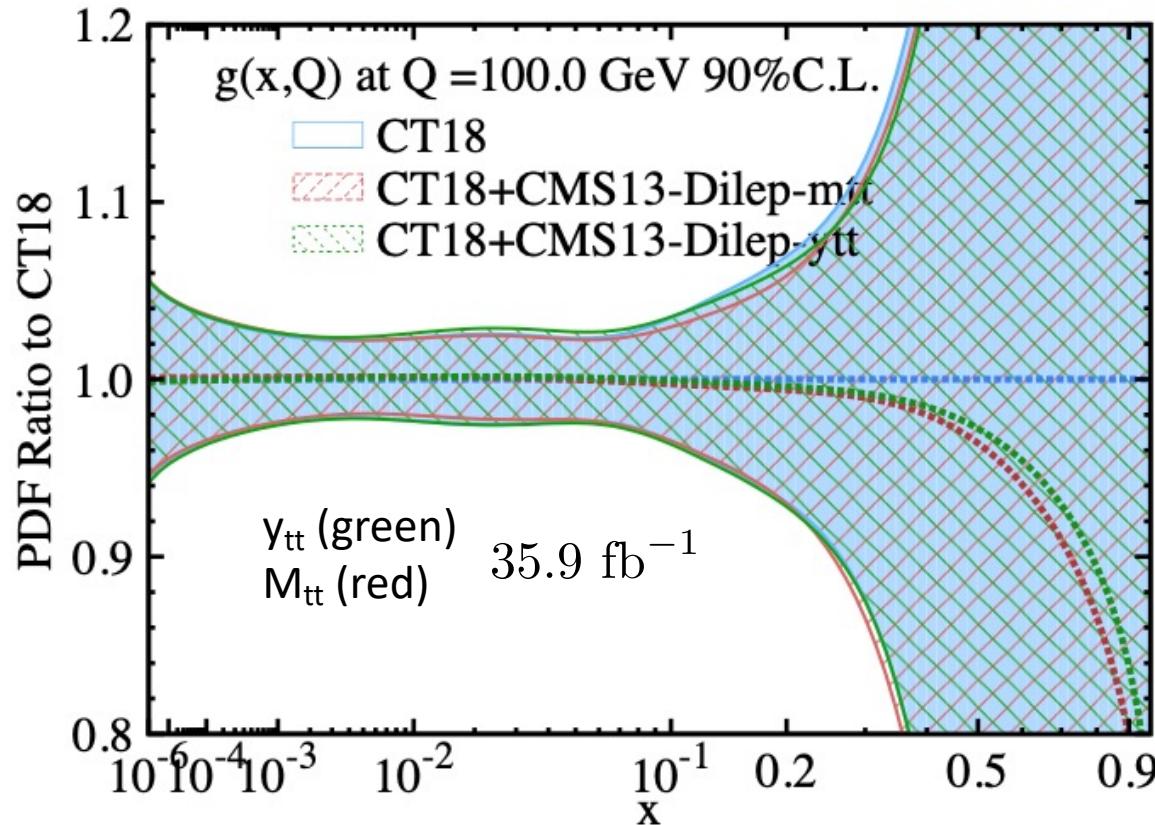
# Global fit: Impact on $g(x,Q)$ from CMS lep+jets



$m_{tt}$ , and  $y_{tt}$  1D absolute distributions added one by one in the global fit

Pulls are in the same direction here: stronger impact due to the higher precision of these data

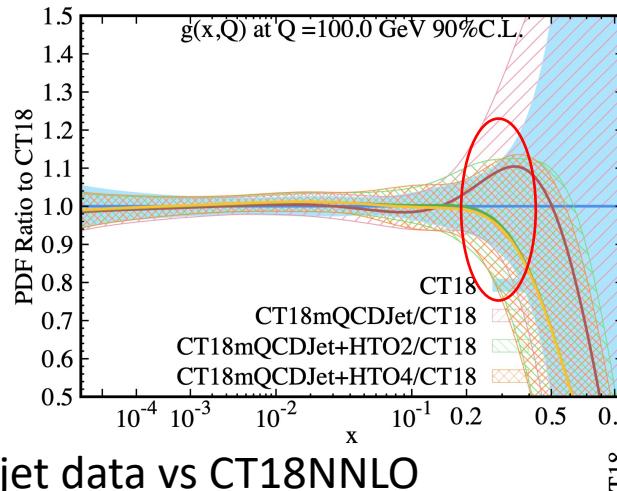
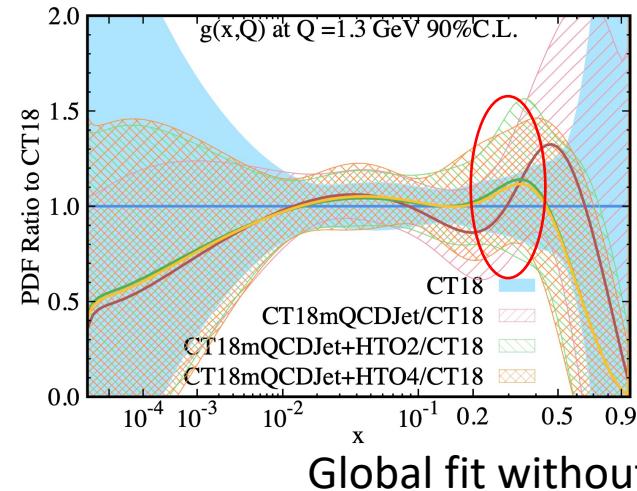
# Global fit: Impact on $g(x,Q)$ from CMS dilep



$m_{t\bar{t}}$ ,  $p_T$ ,  $y_{t\bar{t}}$ , and  $y_t$  1D absolute distributions added one by one in the global fit

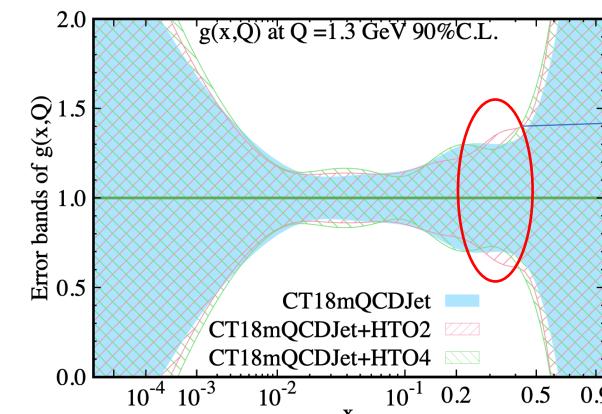
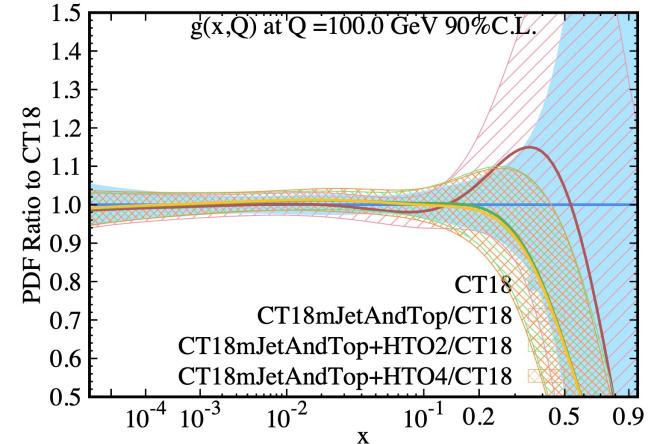
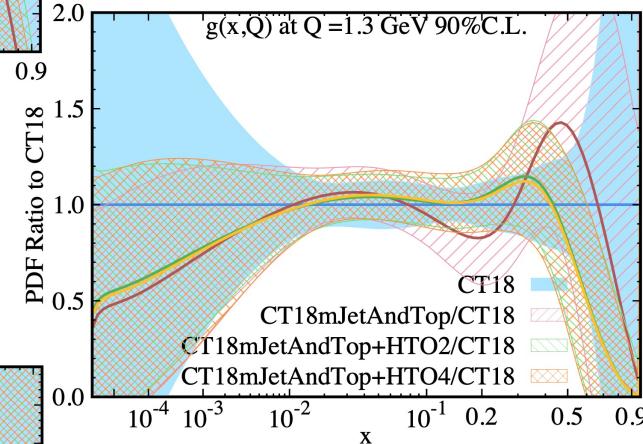
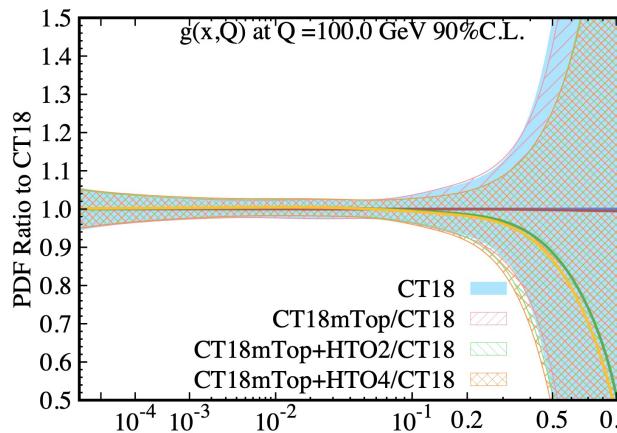
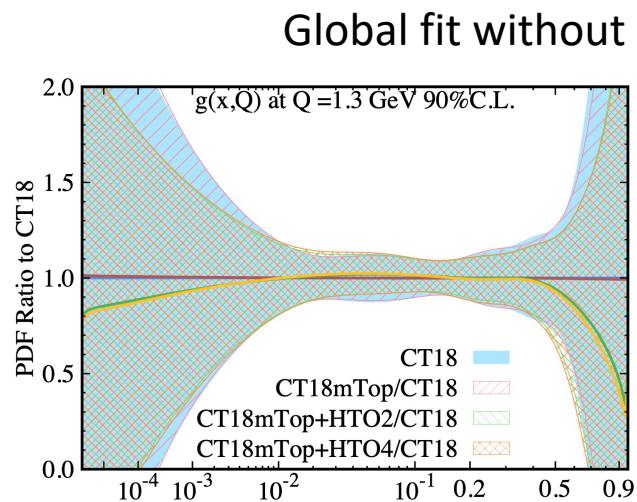
Pulls are in the same direction here. Moderate impact

# Interplay between top-quark and jet data in CT2X



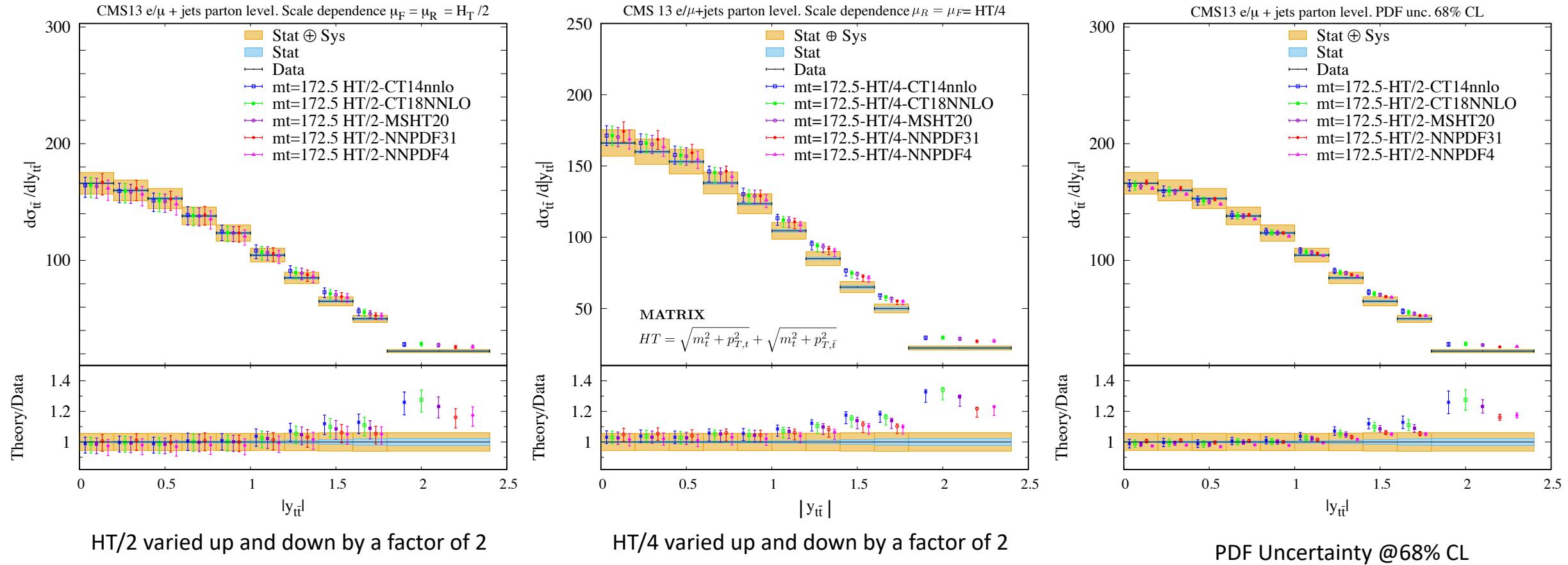
- CT18mTop = CT18 without all ttbar 8 TeV and 13 TeV
- CT18mQCDJet = CT18 without all jet data
- CT18mQCDJet+HTO2(4) = CT18 without all jet data but with ttbar 13 TeV (HT/2(4) central scale)
- CT18mTop+HTO2(4) = CT18 without all ttbar 8 TeV but with ttbar 13 TeV TeV (HT/2(4) central scale)

Global fit without jet and  $t\bar{t}$  data vs CT18NNLO



# Theory errors: scale choice

Scale uncertainty: the recommended scale choice is not always the best. We select the scale choice that yields the smaller  $\chi^2/N_{pt}$



# Messages from the ttbar 13 TeV analysis

- First comprehensive study on the impact of LHC 13TeV ttbar data on CT PDFs
- Most of the impact: high-precision data from CMS
- Pulls on the gluon not in the same direction for some distr. in ATLAS
- Scale uncertainty: the recommended scale choice is not always the best
- Interplay between jets and ttbar: jets still place stronger constraints on  $g(x)$
- Optimal baseline for CT2X: ATLAS hadronic:  $y_{tt}$  absolute, CMS dilepton:  $y_{tt}$  absolute, ATLAS lep+jet:  $y_{tt}$ , CMS lep+jet:  $m_{tt}$  absolute.
- ttbar 13 TeV data prefer a softer gluon at large  $x$ , similar to the LHC jet data.

# BACK UP

# The CT18 analysis

## New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC

Tie-Jiun Hou,<sup>1,†</sup> Jun Gao,<sup>2</sup> T. J. Hobbs,<sup>3,4</sup> Keping Xie,<sup>3,5</sup> Sayipjamal Dulat,<sup>6,‡</sup> Marco Guzzi,<sup>7</sup> Joey Huston,<sup>8</sup> Pavel Nadolsky,<sup>9,§</sup> Jon Pumplin,<sup>8,\*</sup> Carl Schmidt,<sup>8</sup> Ibrahim Sitiwaldi,<sup>6</sup> Daniel Stump,<sup>8</sup> and C.-P. Yuan<sup>8,||</sup>

TABLE I. Datasets included in the CT18(Z) NNLO global analyses. Here we directly compare the quality of fit found for CT18 NNLO vs CT18Z NNLO on the basis of  $\chi_E^2$ ,  $\chi_E^2/N_{pt,E}$ , and  $S_E$ , in which  $N_{pt,E}$ ,  $\chi_E^2$  are the number of points and value of  $\chi^2$  for experiment  $E$  at the global minimum.  $S_E$  is the effective Gaussian parameter [38,42,56] quantifying agreement with each experiment. The ATLAS 7 TeV 35 pb<sup>-1</sup>  $W/Z$  dataset, marked by ‡, is replaced by the updated one (4.6 fb<sup>-1</sup>) in the CT18A and CT18Z fits. The CDHSW data, labeled by †, are not included in the CT18Z fit. The numbers in parentheses are for the CT18Z NNLO fit.

Exp. ID#	Experimental dataset	$N_{pt,E}$	$\chi_E^2$	$\chi_E^2/N_{pt,E}$	$S_E$
160	HERA I + II 1 fb <sup>-1</sup> , H1 and ZEUS NC and CC $e^\pm p$ reduced cross sec. comb.	[30]	1120	1408 (1378)	1.3 (1.2) 5.7 (5.1)
101	BCDMS $F_2^p$	[57]	337	374 (384)	1.1 (1.1) 1.4 (1.8)
102	BCDMS $F_2^d$	[58]	250	280 (287)	1.1 (1.1) 1.3 (1.6)
104	NMC $F_2^d/F_2^p$	[59]	123	126 (116)	1.0 (0.9) 0.2 (-0.4)
108†	CDHSW $F_2^p$	[60]	85	85.6 (86.8)	1.0 (1.0) 0.1 (0.2)
109†	CDHSW $x_B F_3^p$	[60]	96	86.5 (85.6)	0.9 (0.9) -0.7 (-0.7)
110	CCFR $F_2^p$	[61]	69	78.8 (76.0)	1.1 (1.1) 0.9 (0.6)
111	CCFR $x_B F_3^p$	[62]	86	33.8 (31.4)	0.4 (0.4) -5.2 (-5.6)
124	NuTeV $\nu\mu\mu$ SIDIS	[63]	38	18.5 (30.3)	0.5 (0.8) -2.7 (-0.9)
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	[63]	33	38.5 (56.7)	1.2 (1.7) 0.7 (2.5)
126	CCFR $\nu\mu\mu$ SIDIS	[64]	40	29.9 (35.0)	0.7 (0.9) -1.1 (-0.5)
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	[64]	38	19.8 (18.7)	0.5 (0.5) -2.5 (-2.7)
145	H1 $\sigma_r^p$	[65]	10	6.8 (7.0)	0.7 (0.7) -0.6 (-0.6)
147	Combined HERA charm production	[66]	47	58.3 (56.4)	1.2 (1.2) 1.1 (1.0)
169	H1 $F_L$	[33]	9	17.0 (15.4)	1.9 (1.7) 1.7 (1.4)
201	E605 Drell-Yan process	[67]	119	103.4 (102.4)	0.9 (0.9) -1.0 (-1.1)
203	E866 Drell-Yan process $\sigma_{pd}/(2\sigma_{pp})$	[68]	15	16.1 (17.9)	1.1 (1.2) 0.3 (0.6)
204	E866 Drell-Yan process $Q^3 d^2\sigma_{pp}/(dQdx_F)$	[69]	184	244 (240)	1.3 (1.3) 2.9 (2.7)
225	CDF run-1 lepton $A_{ch}$ , $p_{T\ell} > 25$ GeV	[70]	11	9.0 (9.3)	0.8 (0.8) -0.3 (-0.2)
227	CDF run-2 electron $A_{ch}$ , $p_{T\ell} > 25$ GeV	[71]	11	13.5 (13.4)	1.2 (1.2) 0.6 (0.6)
234	DØ run-2 muon $A_{ch}$ , $p_{T\ell} > 20$ GeV	[72]	9	9.1 (9.0)	1.0 (1.0) 0.2 (0.1)
260	DØ run-2 $Z$ rapidity	[73]	28	16.9 (18.7)	0.6 (0.7) -1.7 (-1.3)
261	CDF run-2 $Z$ rapidity	[74]	29	48.7 (61.1)	1.7 (2.1) 2.2 (3.3)
266	CMS 7 TeV 4.7 fb <sup>-1</sup> , muon $A_{ch}$ , $p_{T\ell} > 35$ GeV	[75]	11	7.9 (12.2)	0.7 (1.1) -0.6 (0.4)
267	CMS 7 TeV 840 pb <sup>-1</sup> , electron $A_{ch}$ , $p_{T\ell} > 35$ GeV	[76]	11	4.6 (5.5)	0.4 (0.5) -1.6 (-1.3)
268‡	ATLAS 7 TeV 35 pb <sup>-1</sup> $W/Z$ cross sec., $A_{ch}$	[77]	41	44.4 (50.6)	1.1 (1.2) 0.4 (1.1)
281	DØ run-2 9.7 fb <sup>-1</sup> electron $A_{ch}$ , $p_{T\ell} > 25$ GeV	[78]	13	22.8 (20.5)	1.8 (1.6) 1.7 (1.4)
504	CDF run-2 inclusive jet production	[79]	72	122 (117)	1.7 (1.6) 3.5 (3.2)
514	DØ run-2 inclusive jet production	[80]	110	113.8 (115.2)	1.0 (1.0) 0.3 (0.4)

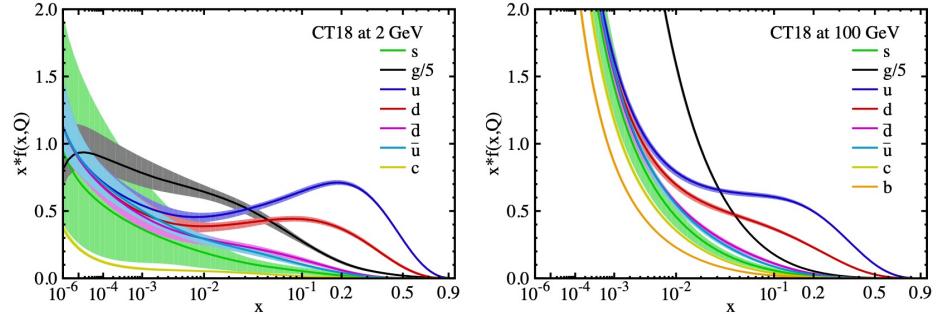


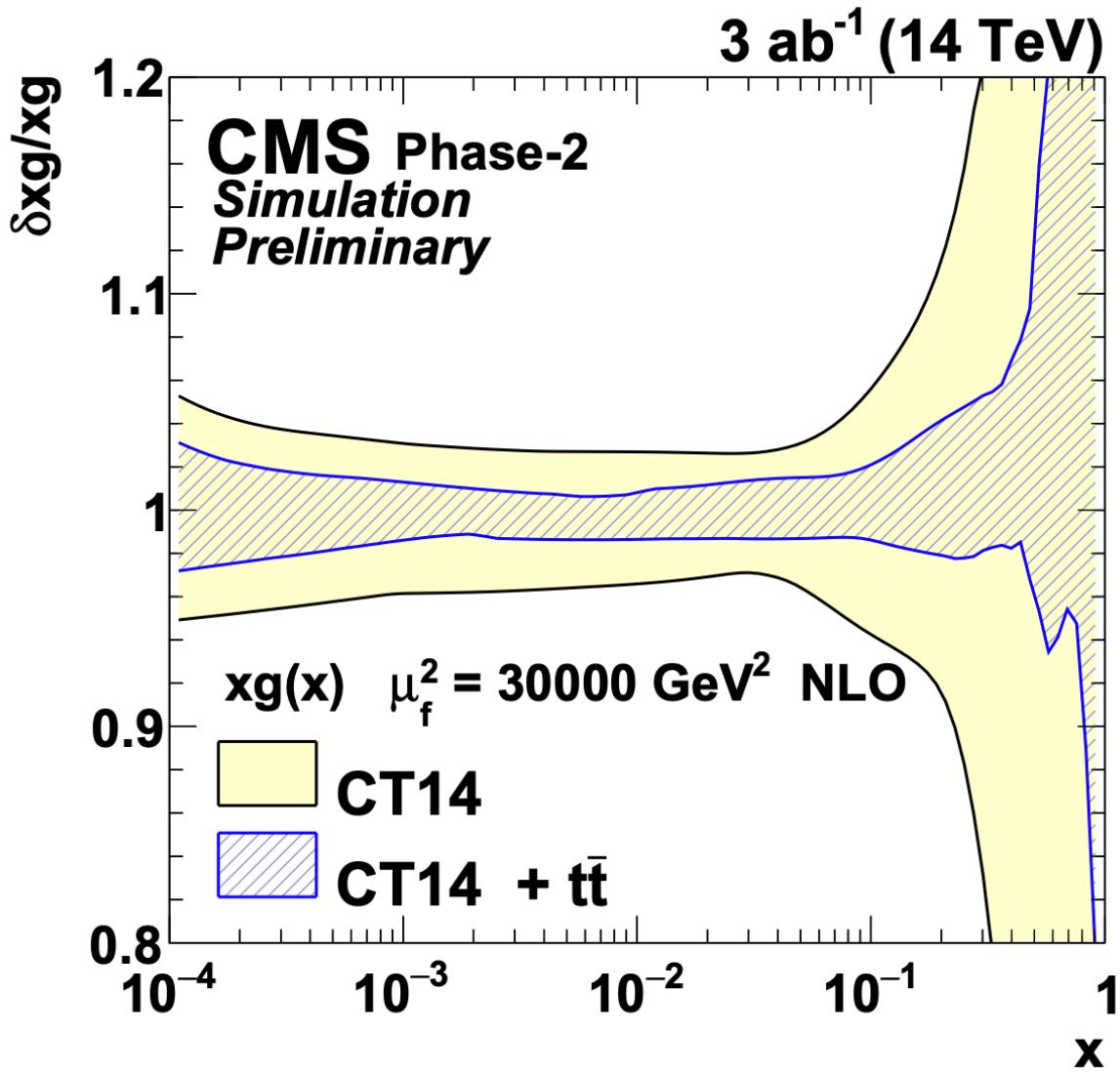
TABLE II. Like Table I, for newly included LHC measurements. The ATLAS 7 TeV  $W/Z$  data (4.6 fb<sup>-1</sup>), labeled by ‡, are included in the CT18A and CT18Z global fits, but not in CT18 and CT18Z.

Exp. ID#	Experimental dataset	$N_{pt,E}$	$\chi_E^2$	$\chi_E^2/N_{pt,E}$	$S_E$
245	LHCb 7 TeV 1.0 fb <sup>-1</sup> $W/Z$ forward rapidity cross sec.	[81]	33	53.8 (39.9)	1.6 (1.2) 2.2 (0.9)
246	LHCb 8 TeV 2.0 fb <sup>-1</sup> $Z \rightarrow e^-e^+$ forward rapidity cross sec.	[82]	17	17.7 (18.0)	1.0 (1.1) 0.2 (0.3)
248‡	ATLAS 7 TeV 4.6 fb <sup>-1</sup> , $W/Z$ combined cross sec.	[39]	34	287.3 (88.7)	8.4 (2.6) 13.7 (4.8)
249	CMS 8 TeV 18.8 fb <sup>-1</sup> muon charge asymmetry $A_{ch}$	[83]	11	11.4 (12.1)	1.0 (1.1) 0.2 (0.4)
250	LHCb 8 TeV 2.0 fb <sup>-1</sup> $W/Z$ cross sec.	[84]	34	73.7 (59.4)	2.1 (1.7) 3.7 (2.6)
253	ATLAS 8 TeV 20.3 fb <sup>-1</sup> , $Z$ $p_T$ cross sec.	[85]	27	30.2 (28.3)	1.1 (1.0) 0.5 (0.3)
542	CMS 7 TeV 5 fb <sup>-1</sup> , single incl. jet cross sec., $R = 0.7$ (extended in $y$ )	[86]	158	194.7 (188.6)	1.2 (1.2) 2.0 (1.7)
544	ATLAS 7 TeV 4.5 fb <sup>-1</sup> , single incl. jet cross sec., $R = 0.6$	[9]	140	202.7 (203.0)	1.4 (1.5) 3.3 (3.4)
545	CMS 8 TeV 19.7 fb <sup>-1</sup> , single incl. jet cross sec., $R = 0.7$ , (extended in $y$ )	[87]	185	210.3 (207.6)	1.1 (1.1) 1.3 (1.2)
573	CMS 8 TeV 19.7 fb <sup>-1</sup> , $t\bar{t}$ norm. double-diff. top $p_T$ and $y$ cross sec.	[88]	16	18.9 (19.1)	1.2 (1.2) 0.6 (0.6)
580	ATLAS 8 TeV 20.3 fb <sup>-1</sup> , $t\bar{t}$ $p_T^t$ and $m_{t\bar{t}}$ abs. spectrum	[89]	15	9.4 (10.7)	0.6 (0.7) -1.1 (-0.8)

Heavy-flavor production measurements at HERA and LHC included in the CT18 NNLO QCD global analysis.

Top-quark pair production diff. Xsec. measurements at 8TeV

# How constraining are $t\bar{t}$ data @LHC run III (and beyond)?

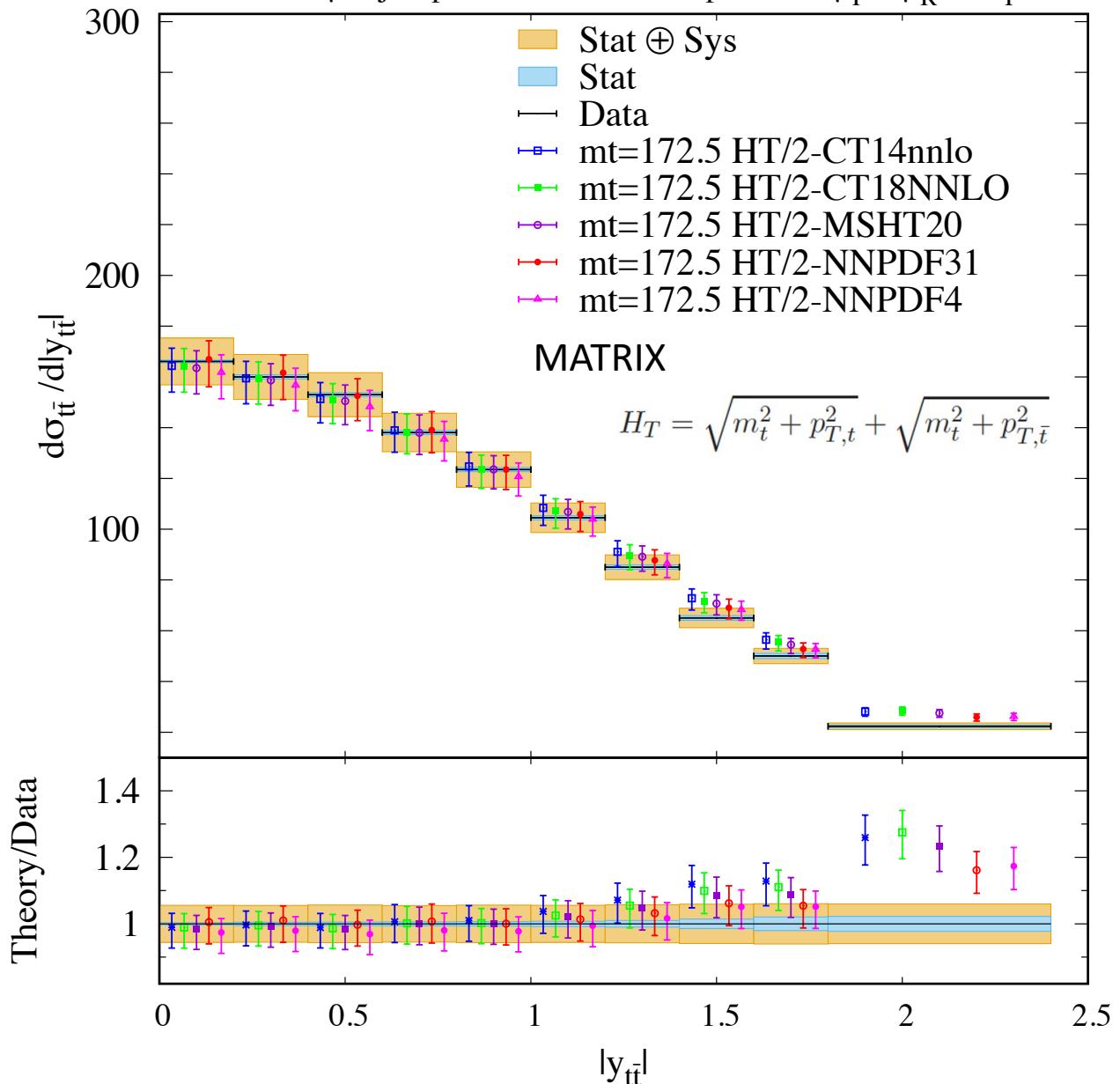


Projections with  $\Delta\chi^2 = 1$  tolerance predict strong constraints on the gluon and other flavors.

Such projections effectively emphasize a given measurement over the other experiments.

Figure: An estimated reduction of the relative uncertainty on the gluon PDF by profiling CT14 PDFs using simulated  $t\bar{t}$  measurements at the HL-LHC [CMS-PAS-FTR-18-015].

CMS13 e/ $\mu$  + jets parton level. Scale dependence  $\mu_F = \mu_R = H_T / 2$



SCALE DEPENDENCE: HT/2 varied up and down by a factor of 2

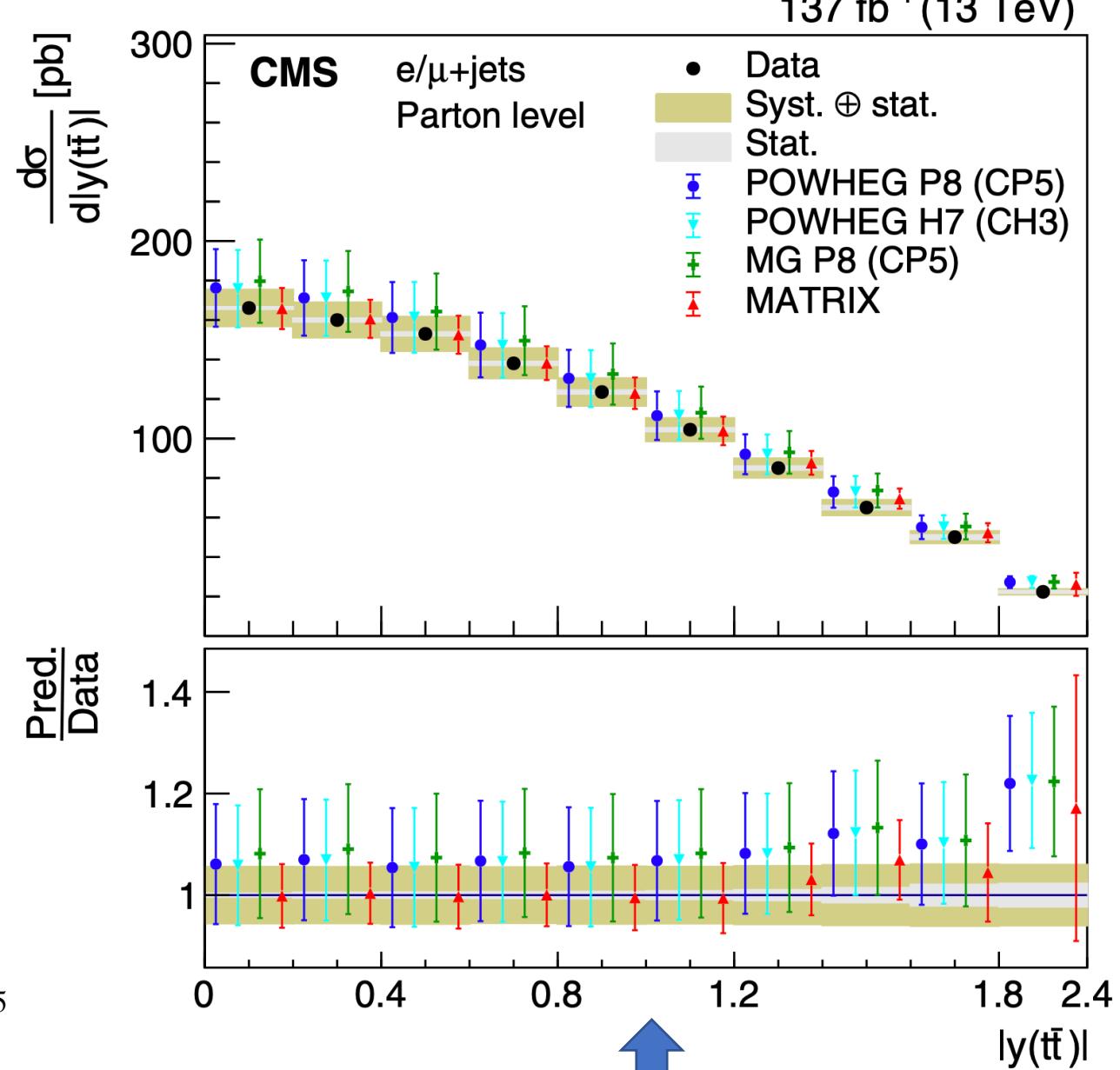
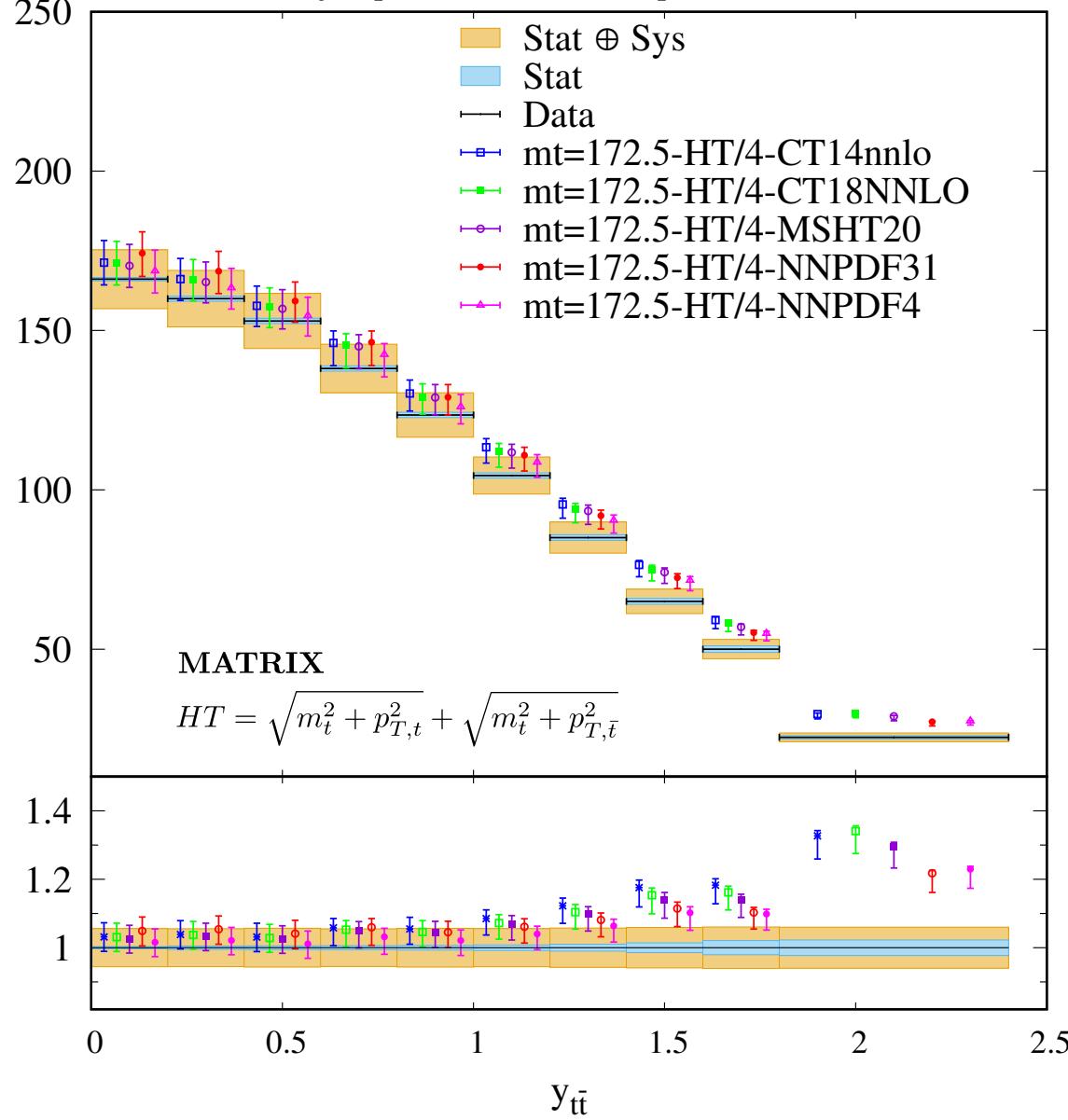


Figure from CMS publication, arXiv:2108.02803  
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CMS 13 e/ $\mu$ +jets parton level. Scale dependence  $\mu_R = \mu_F = HT/4$



SCALE DEPENDENCE: HT/4 varied up and down by a factor of 2

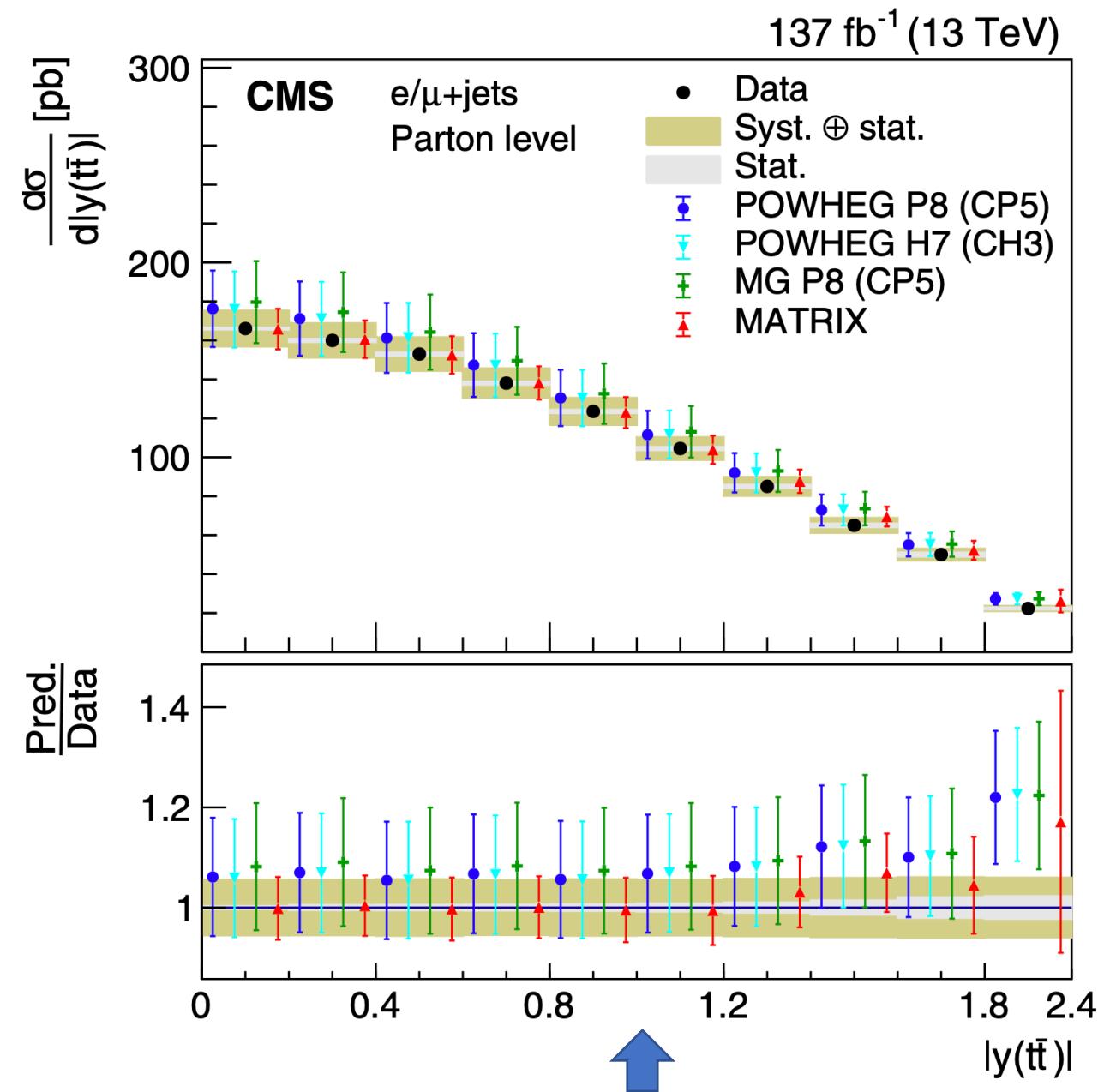


Figure from CMS publication, arXiv:2108.02803  
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