Top-quark and jet production in post CT18 PDF analyses

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with

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2307.11153 [hep-ph]

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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. 2307.11153 [hep-ph]

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),…

Challenges:

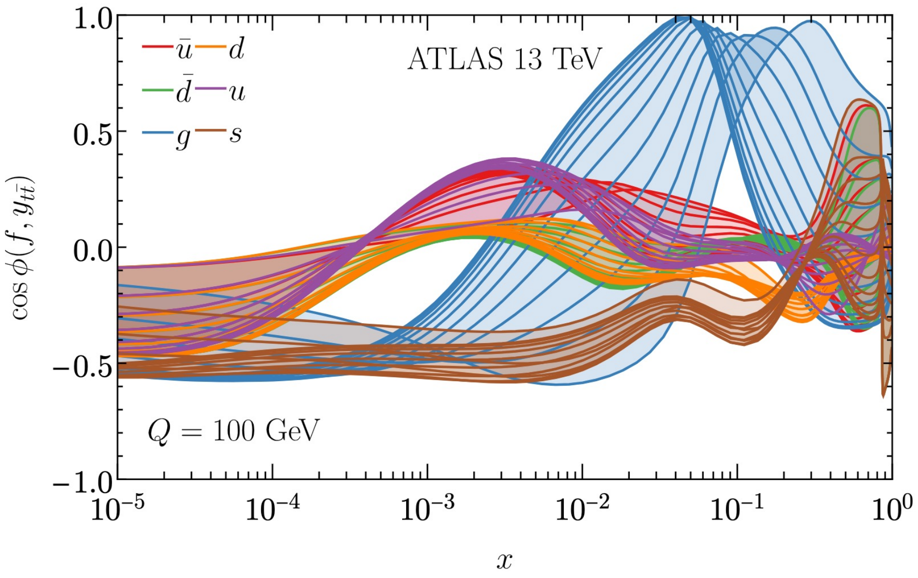
- Compatibility between various top-quark data in the post CT18 global fit
- Treatment of correlated systematic unc. and statistical correlations

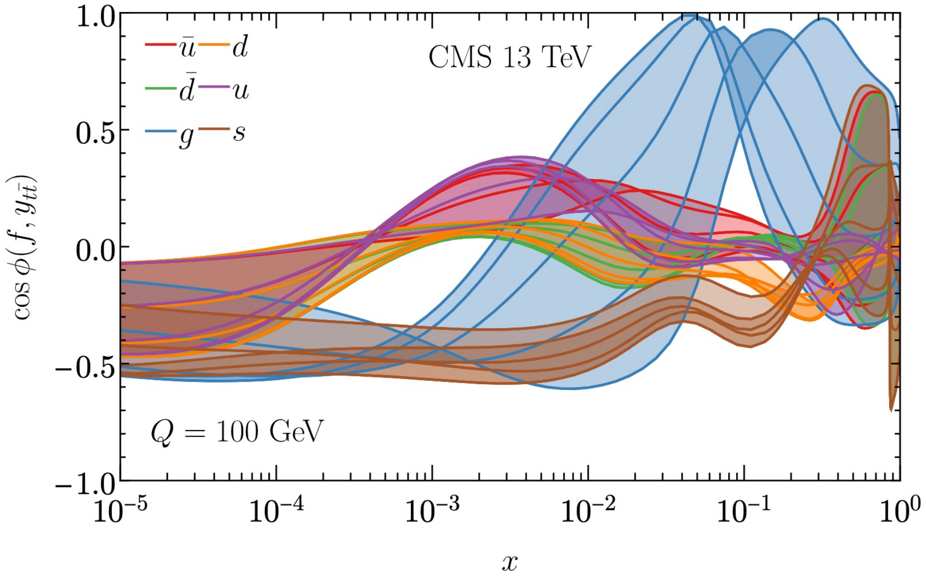
What are data telling us?

- 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)

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

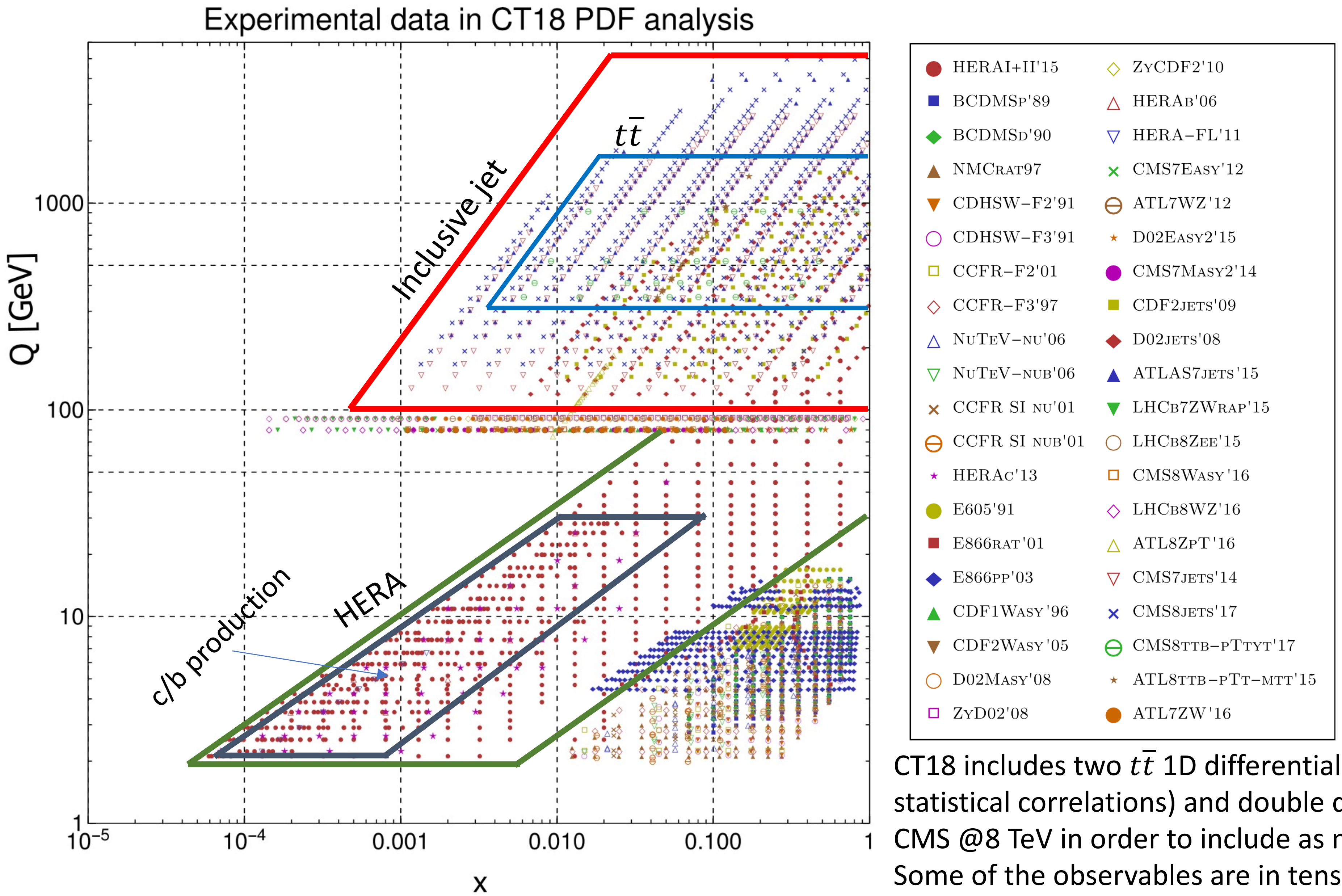
- In this kinematic region PDFs are poorly constrained by other experiments in global PDF fits.
- Top-quark pair production @LHC can already probe the gluon PDF at $x \gtrsim 0.01$





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

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



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 ttb ptT diff. distributions
1511.04716 ATLAS 8 TeV ttb mtt diff. distributions
1703.01630 CMS 8 TeV ttb (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

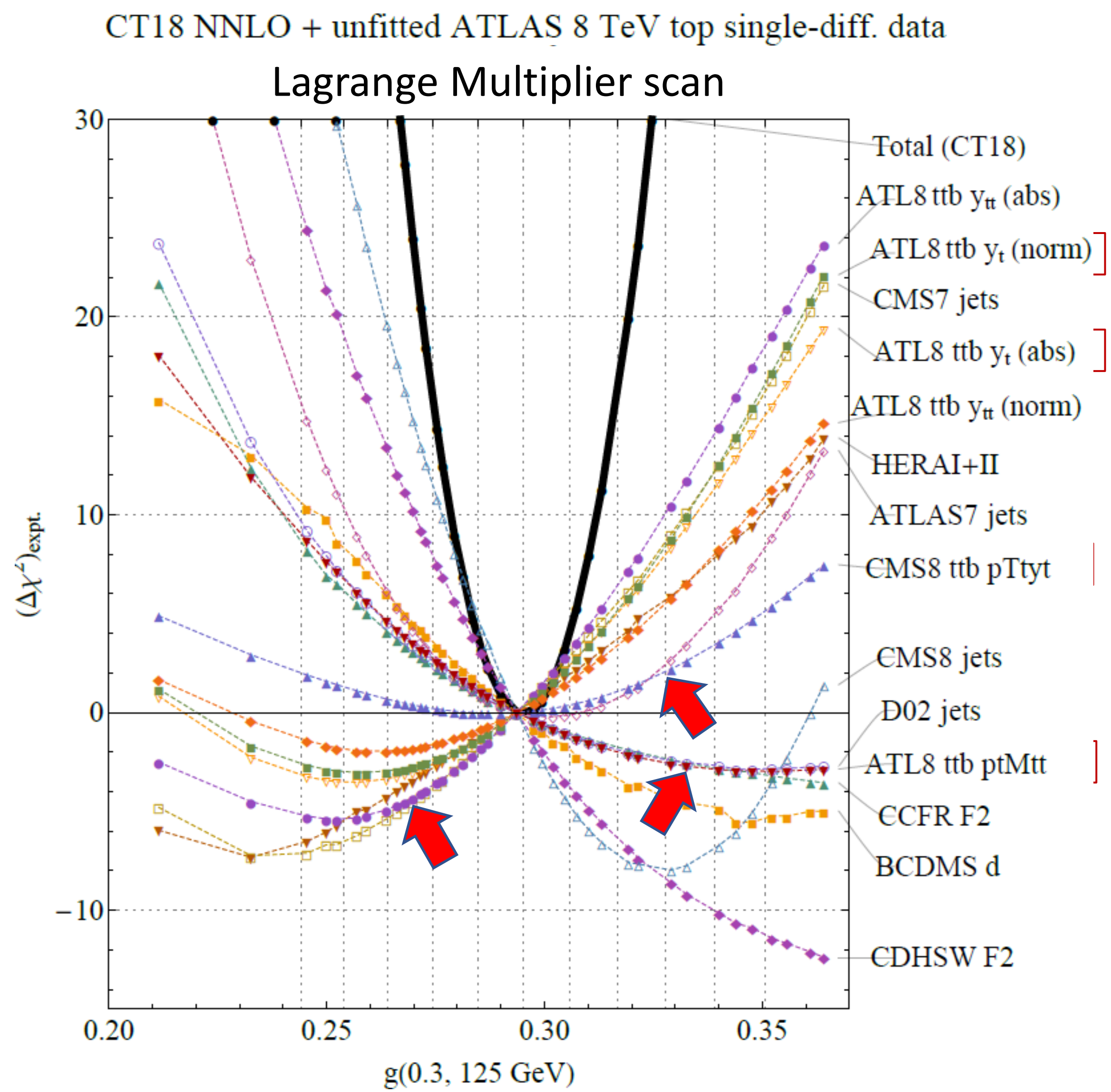


Figure by P. Nadolsky

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 $\mathrm{d}^2\sigma/(dp_{T,t}dm_{t\bar{t}})$ and CMS8 $\mathrm{d}^2\sigma/(dp_{T,t}dy_{t,ave})$

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

Exp	Obs	$N_{\rm pt}$	ePump			Global fit	
			H_T	$H_T/2$	$H_T/4$	$H_T/2$	$H_T/4$
ATL13had	$m_{t\bar{t}}$	9	1.75	1.57	1.60	1.53	1.47
	$H_T^{t\bar{t}}$	11	1.98	1.77	1.59	1.50	1.74
	$y_{t\bar{t}}$	12	1.28	1.15	0.94	1.05	1.07
	p_{T,t_1}	10	1.30	1.19	1.12	1.20	1.33
	p_{T,t_2}	8	1.13	0.84	1.05	0.84	1.59
CMS13ll	$m_{t\bar{t}}$	7	3.46	3.07	3.14	3.12	3.23
	$y_{t\bar{t}}$	10	1.66	0.97	0.68	0.94	0.67
	$p_{T,t}$	6	3.60	3.70	3.68	3.56	3.05
	y_t	10	1.33	0.94	0.87	1.00	0.69
CMS13lj	$m_{t\bar{t}}$	15	1.49	1.38	1.81	1.20	1.67
	$y_{t\bar{t}}$	10	6.47	6.24	6.42	6.01	5.88
ATL13lj	CMS bins						
	$m_{t\bar{t}}$	7	2.40	1.17	0.68	0.83	0.66
	$y_{t\bar{t}}$	10	0.91	0.69	0.62	0.74	0.75
	$p_{T,t}$	6	2.34	2.01	2.47	1.35	1.43
	y_t	10	1.30	1.07	1.10	1.16	0.68
	ATLAS bins without statistical correlation (NSC)						
	$m_{t\bar{t}}$	9	1.55	1.12	0.94	1.27	0.92
	$y_{t\bar{t}}$	7	0.91	0.74	0.80	0.76	0.90
	$y_{t\bar{t}}^B$	9	1.40	1.27	1.53	0.85	0.93
	$H_T^{t\bar{t}}$	9	1.35	0.91	0.93	0.81	0.80
	$m_{t\bar{t}}+y_{t\bar{t}}+y_{t\bar{t}}^B+H_T^{t\bar{t}}$	34	1.87	1.28	1.46	0.93	1.06
	ATLAS bins with statistical correlations (WSC)						
	$m_{t\bar{t}}$	9	1.68	1.35	0.98	1.29	0.96
	$y_{t\bar{t}}$	7	0.88	0.75	0.92	0.75	0.92
	$y_{t\bar{t}}^B$	9	1.06	0.87	1.01	0.86	0.99
	$H_T^{t\bar{t}}$	9	1.40	0.85	0.85	0.86	0.86
	$m_{t\bar{t}}+y_{t\bar{t}}+y_{t\bar{t}}^B+H_T^{t\bar{t}}$	34	3.10	1.61	1.32	1.59	1.32

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

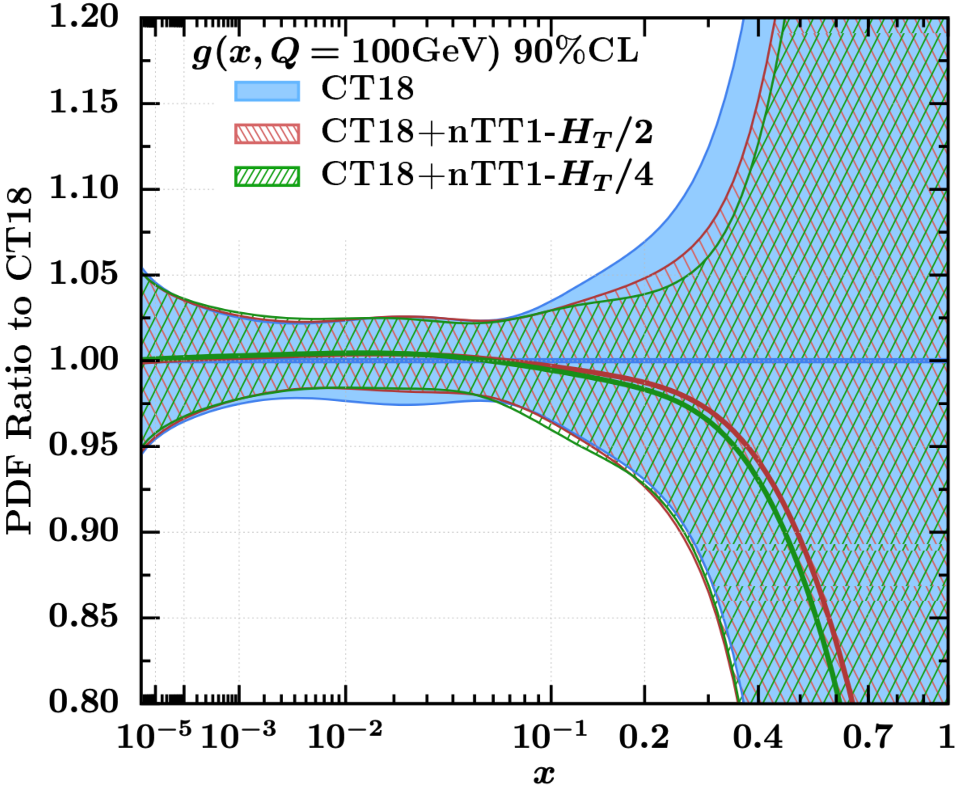
CT2X ⊃ CT18 + new optimal combination of top-quark pair production @LHC13 TeV from:

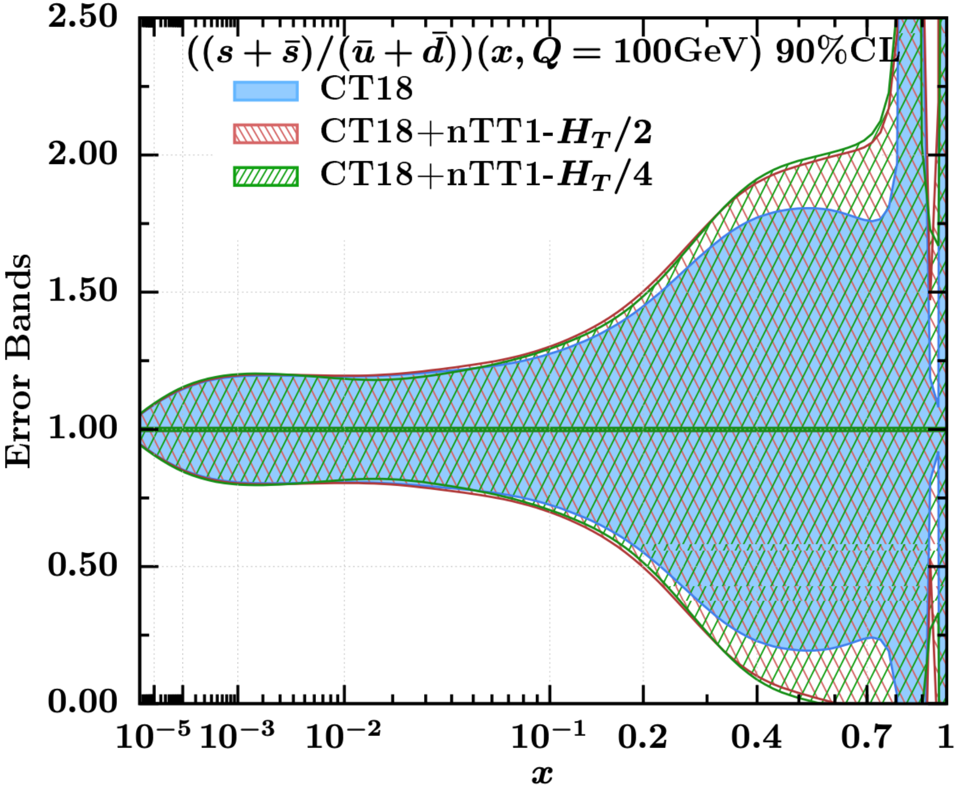
- ATLAS all hadronic, JHEP 01 (2021) 033, arXiv:2006.09274
- ATLAS lepton + jets, EPJC 79 (2019) 1028, arXiv:1908.07305
- CMS dilepton, JHEP 1902 (2019) 149, arXiv:1811.06625
- CMS lepton + jets, PRD 104 092013 (2021), arXiv:2108.02803

Correlated Systematic Uncertainties: **ATLAS -> nuisance parameters**
CMS -> Covariance matrix representation

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

Global fit: impact from new baseline and μ-scale





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.

Optimal baselines consist of combinations 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 calculation 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) generated with MCFM (Campbell, Ellis JPG 2015)

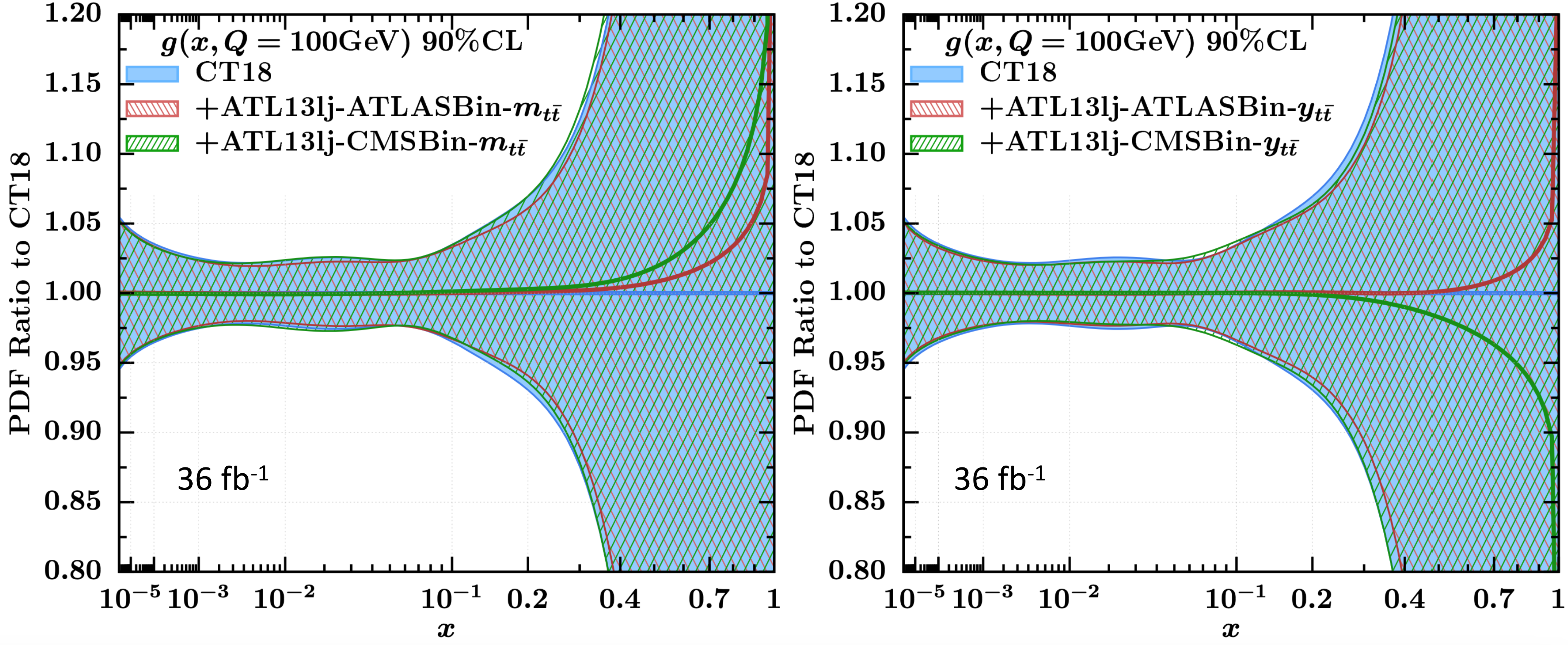
- m_t(pole) = 172.5 GeV
- Fact/Ren scale choice:

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

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

- EW corrections considered: negligible impact on our fits.

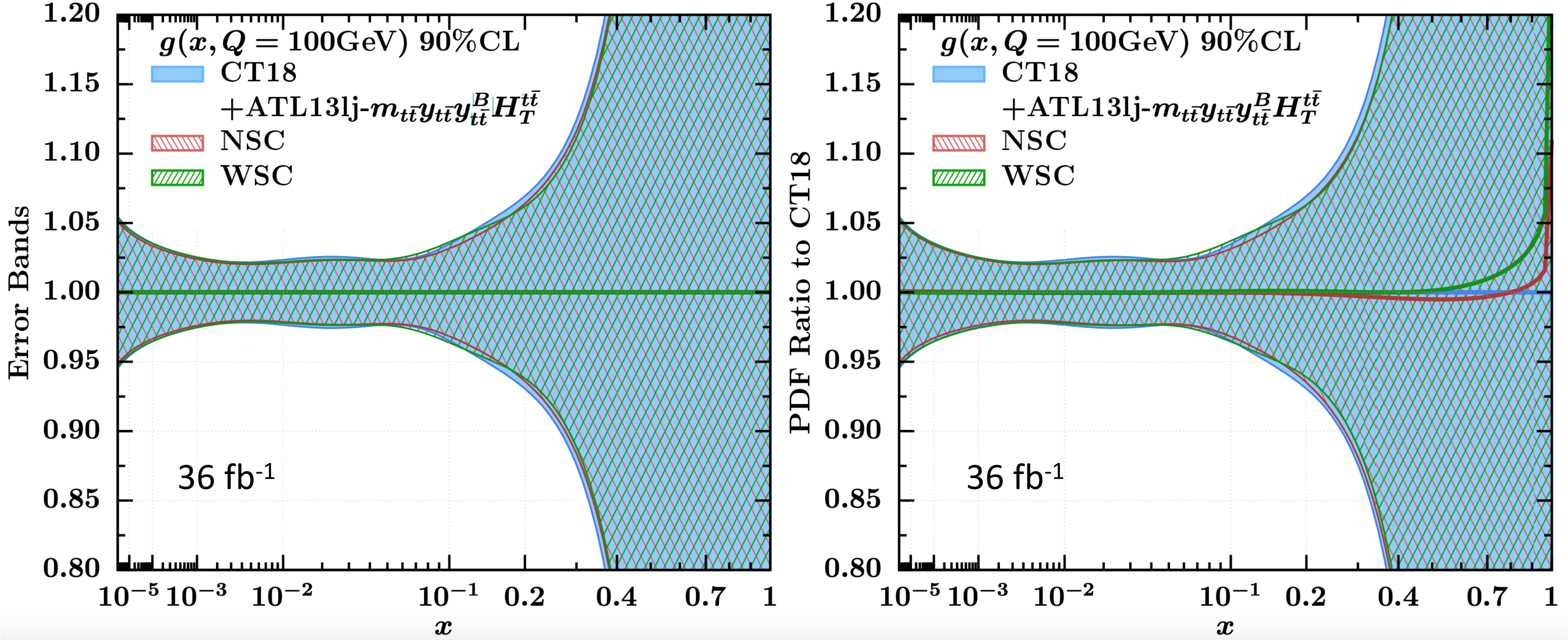
Global fit: Impact on g(x,Q) from ATLAS lep+jets



M_{tt} and y_{tt} 1D absolute distributions added one by one in the global fit.
Different results when different binning for the same distr. are used

Pulls are not in the same direction. M_{tt} badly described in terms of χ^2/Npt. We select y_{tt} 1D absolute

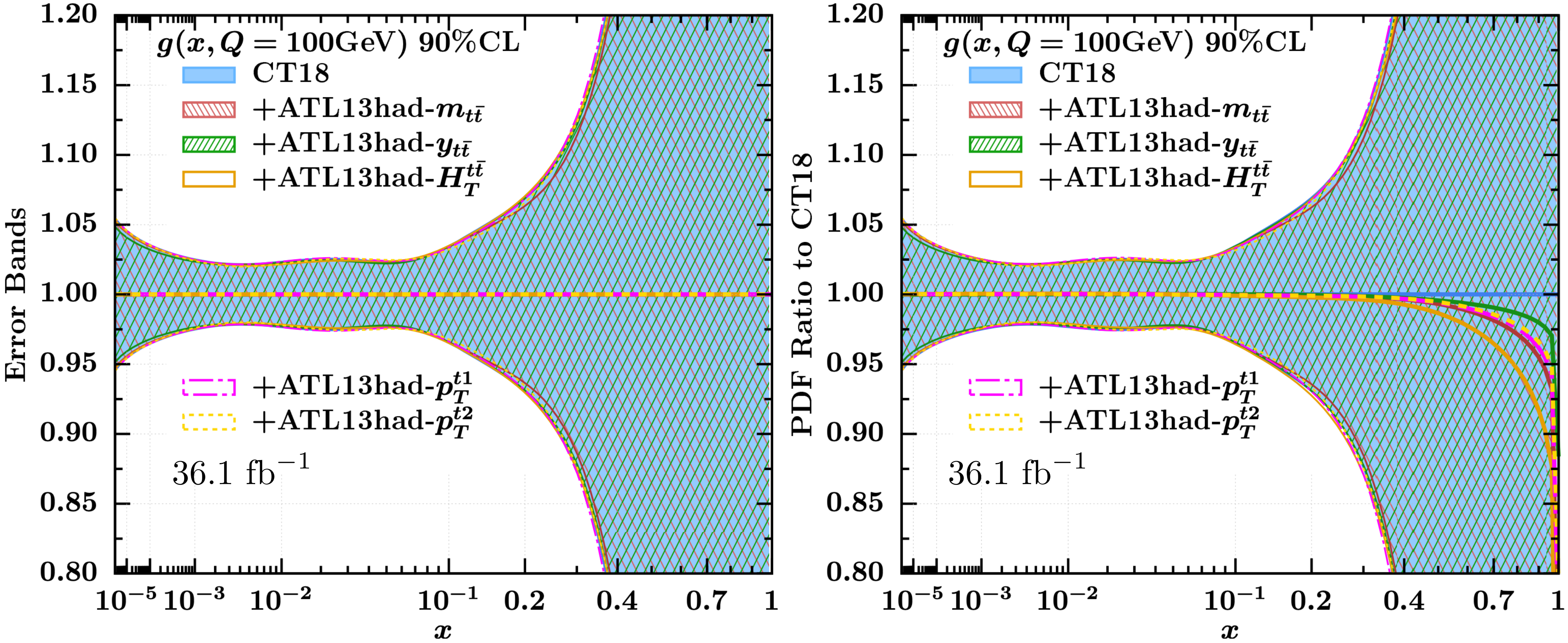
Impact of statistical correlations in ATLAS lep+jets



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
	mttyttybHttt	34	1.867	1.28	1.457		0.933	1.06487	1.585	1.322

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

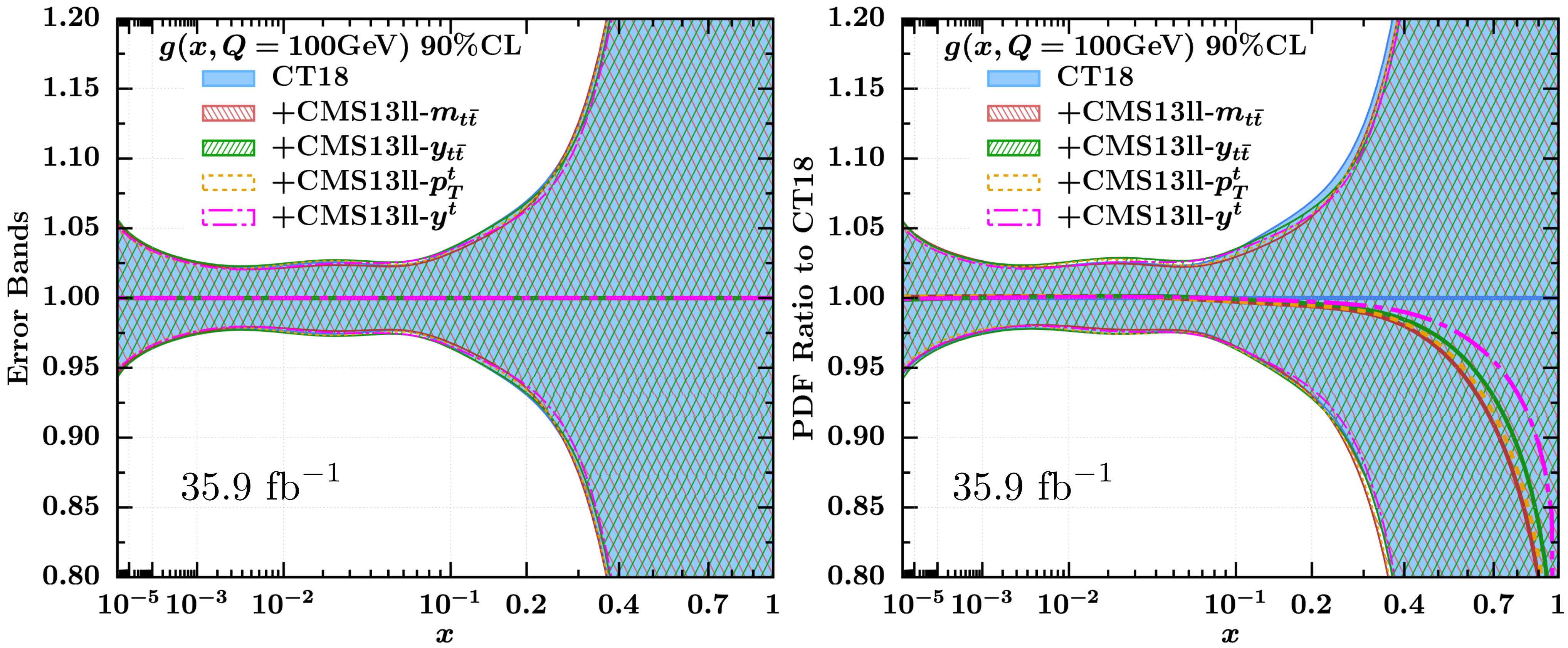
Global fit: Impact on g(x,Q) from ATLAS all hadronic



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.

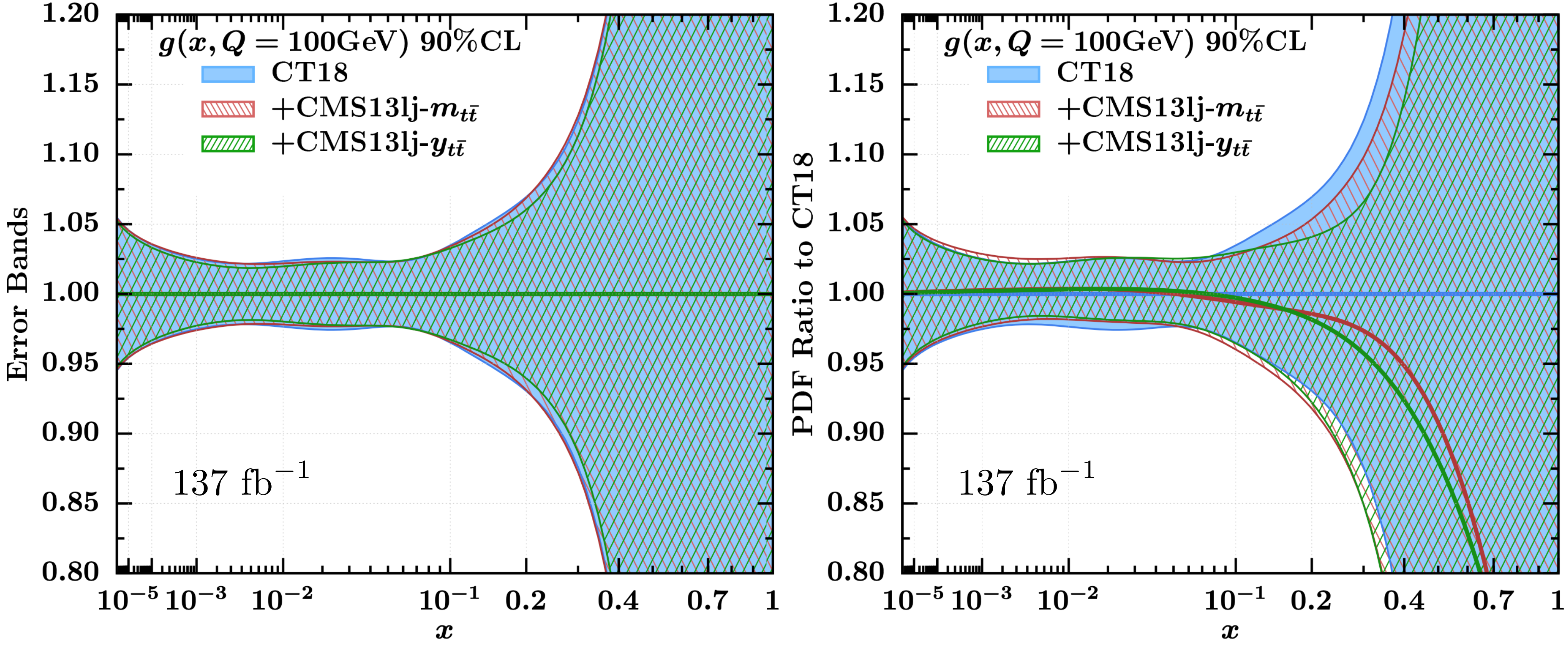
Global fit: Impact on g(x,Q) from CMS dilep



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

Pulls are in the same direction here. Moderate impact

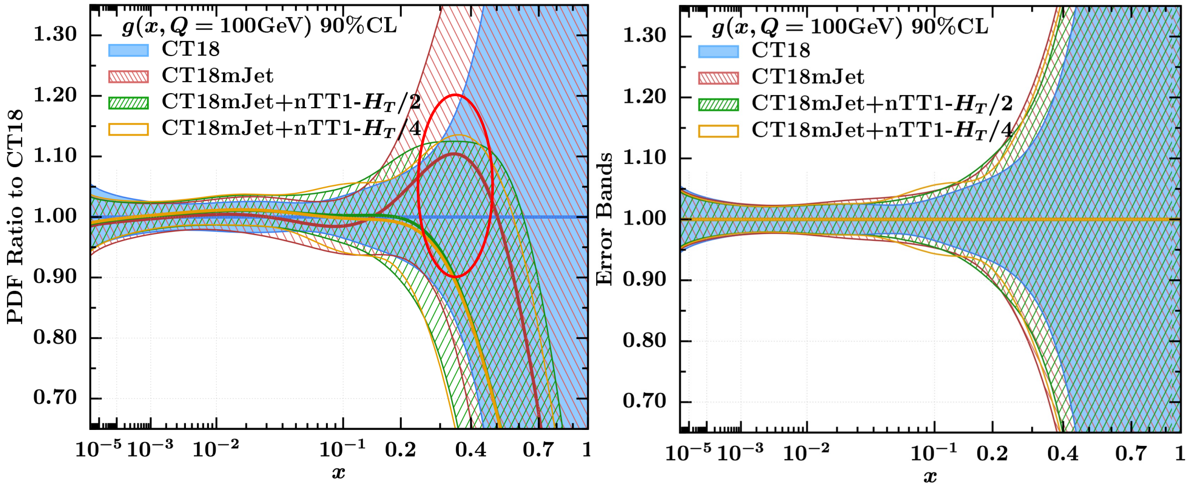
Global fit: Impact on g(x,Q) from CMS lep+jets



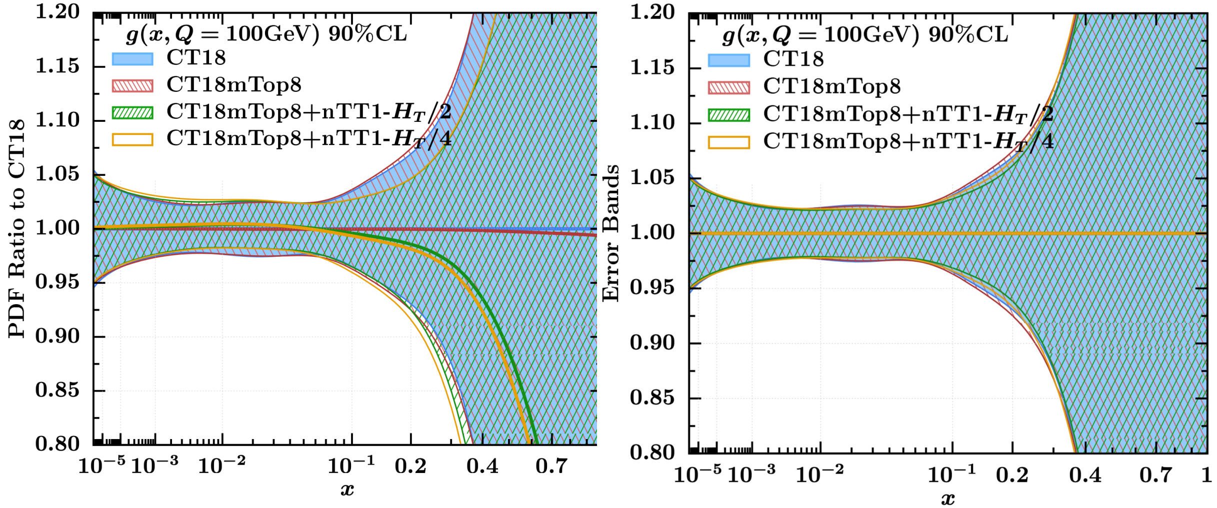
m_{tt} , and y_{tt} 1D absolute distributions added one by one in the global fit

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

Interplay between top-quark and jet data in CT2X



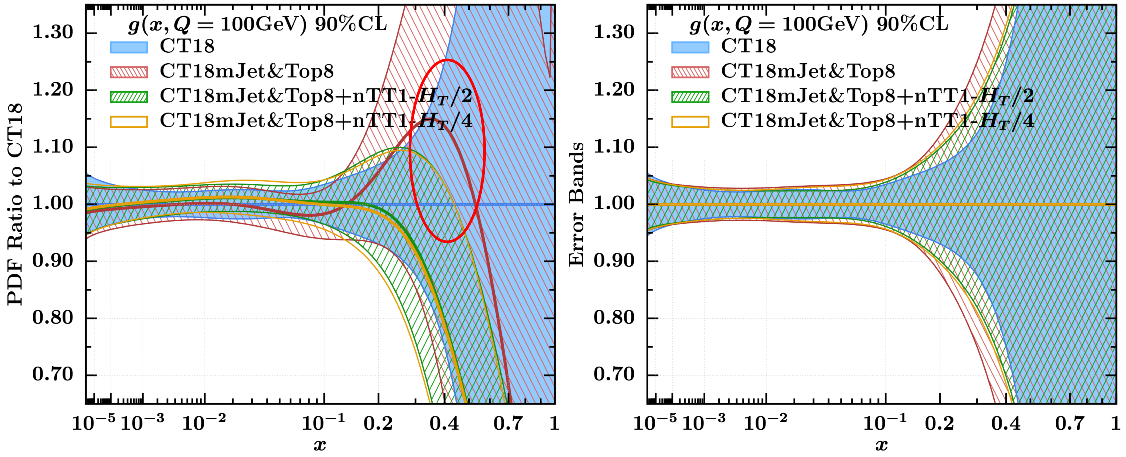
Global fit without jet data vs CT18NNLO



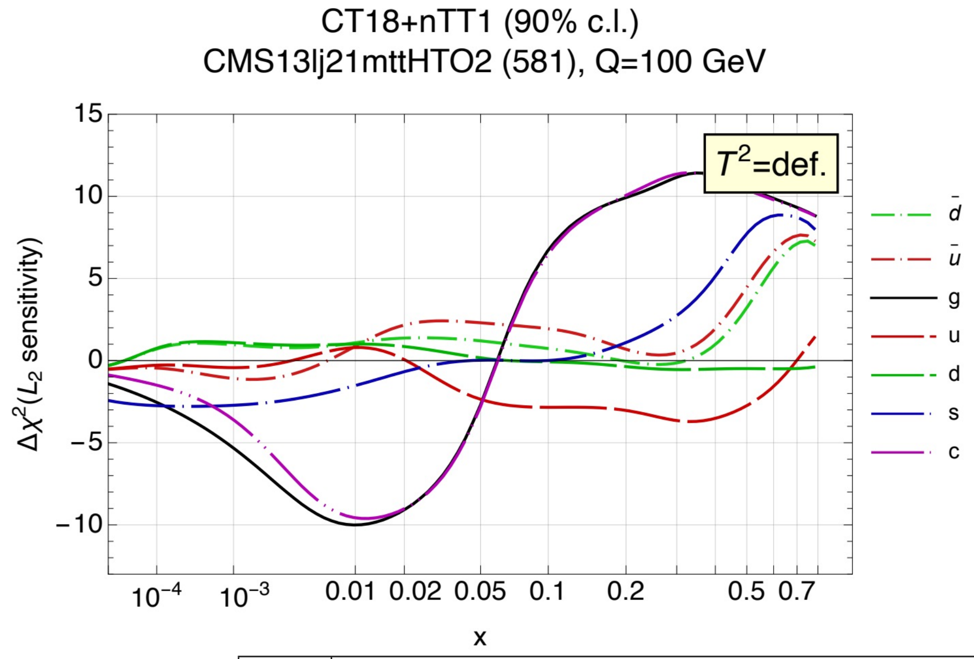
Global fit without $t\bar{t}$ data vs CT18NNLO

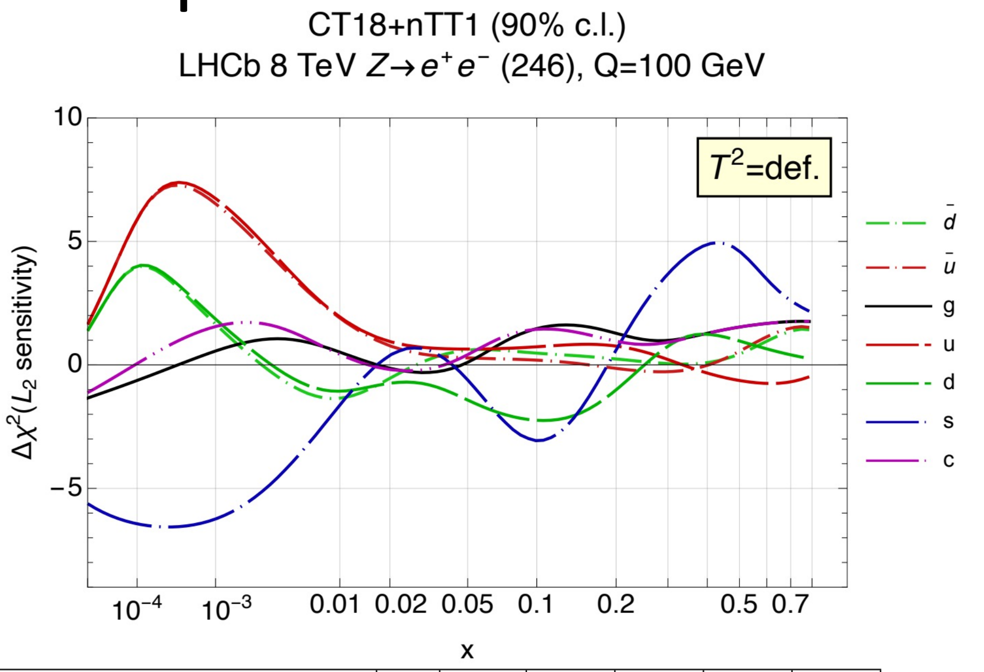
- CT18mTop = CT18 without all ttbar 8 TeV and 13 TeV
- CT18mJet = CT18 without all jet data
- CT18mJet+nTT1-HT/2(4) = CT18 without all jet data but with ttbar 13 TeV (HT/2(4) central scale)
- CT18mTop+nTT1-HT/2(4) = CT18 without all ttbar 8 TeV but with ttbar 13 TeV (HT/2(4) central scale)

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



L2-Sensitivity study of optimal baselines





ID#	Experimental data set	N_{pt}	CT18	$H_T/2$ nTT1	$H_T/2$ nTT2	$H_T/4$ nTT1	$H_T/4$ nTT2
110	CCFR F_2^p [197]	69	1.1	1.1	1.1	1.2	1.2
246	LHCb 8 TeV 2.0 fb^{-1} $Z\to e^-e^+$ forward rapidity cross sec. [193]	17	1.0	1.5	1.5	1.5	1.5
250	LHCb 8 TeV 2.0fb^{-1} W/Z cross sec. [194]	34	2.1	2.2	2.2	2.2	2.2
545	CMS 8 TeV 19.7 fb^{-1}, single incl. jet cross sec., $R=0.7$, (extended in y) [195]	185	1.1	1.2	1.2	1.2	1.2
573	CMS 8 TeV 19.7 fb^{-1}, $t\bar{t}$ norm. double-diff. top p_T and y cross sec. [20]	16	1.2	1.2	1.2	1.1	1.1
580	ATLAS 8 TeV 20.3 fb^{-1}, $t\bar{t}$ $p_{T,t}$ and $m_{t\bar{t}}$ abs. spectrum [17]	15	0.6	0.7	0.7	0.7	0.7
521	ATLAS 13 TeV 36.1 fb^{-1}, $t\bar{t}$ abs. $y_{t\bar{t}}$ cross sec. all-hadronic [22]	12	-	1.0	1.0	1.1	1.1
528	CMS 13 TeV 35.9 fb^{-1}, $t\bar{t}$ abs. $y_{t\bar{t}}$ cross sec. dilepton ch. [24]	10	-	0.8	0.8	0.5	0.7
532	ATLAS 13 TeV 36 fb^{-1}, $t\bar{t}$ abs. $y_{t\bar{t}}$ cross sec. l+j ch. cms-bin [21]	10	-	0.7	-	0.8	-
587	ATLAS 13 TeV 36 fb^{-1}, $t\bar{t}$ abs. $y_{t\bar{t}}, m_{t\bar{t}}, y^B_{t\bar{t}}, H_T^{tt}$ cross secs. l+j ch. [21]	34	-	-	0.7	-	1.1
581	CMS 13 TeV 137 fb^{-1}, $t\bar{t}$ abs. $m_{t\bar{t}}$ cross sec. l+j ch. [26]	15	-	1.1	1.1	1.6	1.7

Data sets of the extended NNLO global QCD analysis including the optimal combinations CT18+nTT1 and CT18+nTT2.
Here we directly compare the quality-of-fit found for CT18+nTT1 and CT18+nTT2 vs. CT18 NNLO

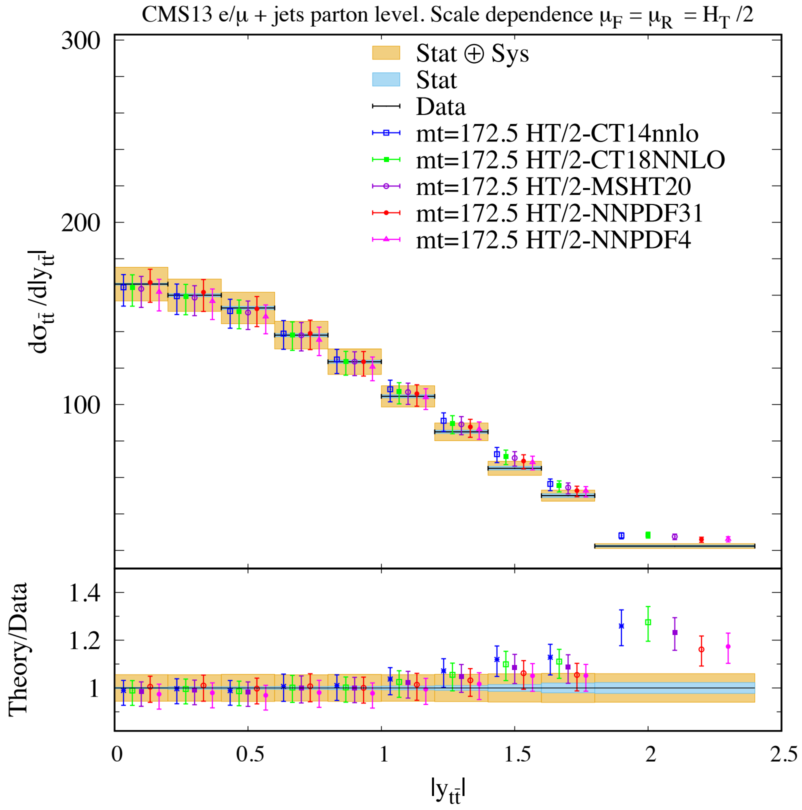
Messages from the ttbar 13 TeV analysis

- First comprehensive study on the impact of LHC 13TeV ttbar data on CT PDFs
- Most of the impact: high-precision data from CMSl+j 13 TeV 137 fb^{-1}
- 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: ytt absolute, CMS dilepton: ytt absolute, ATLAS lep+jet: ytt, CMS lep+jet: mtt absolute.
- ttbar 13 TeV data prefer a softer gluon at large x, similar to the LHC jet data.

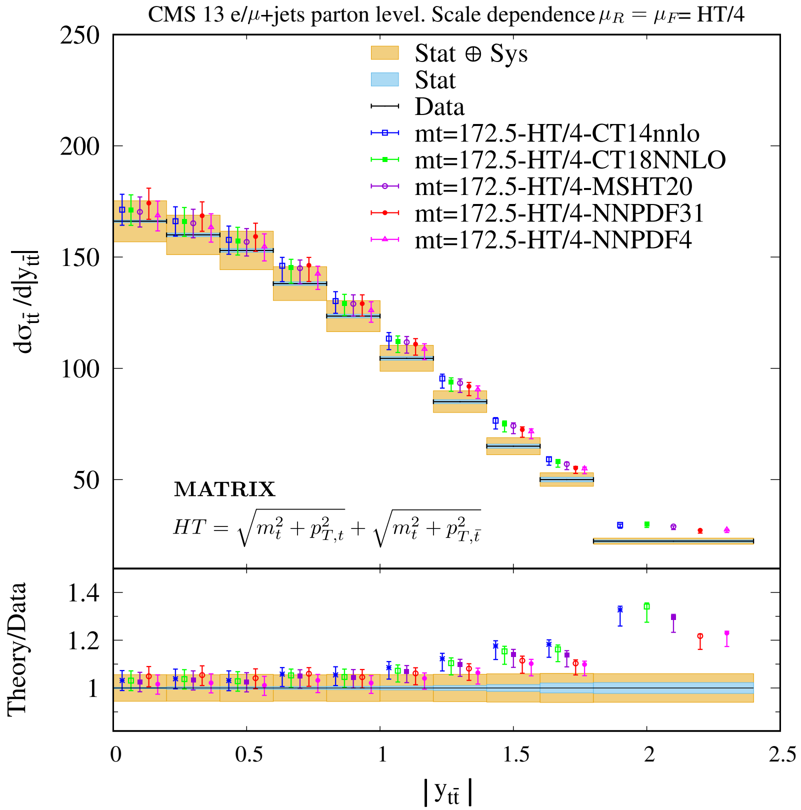
BACK UP

Theory errors: scale choice

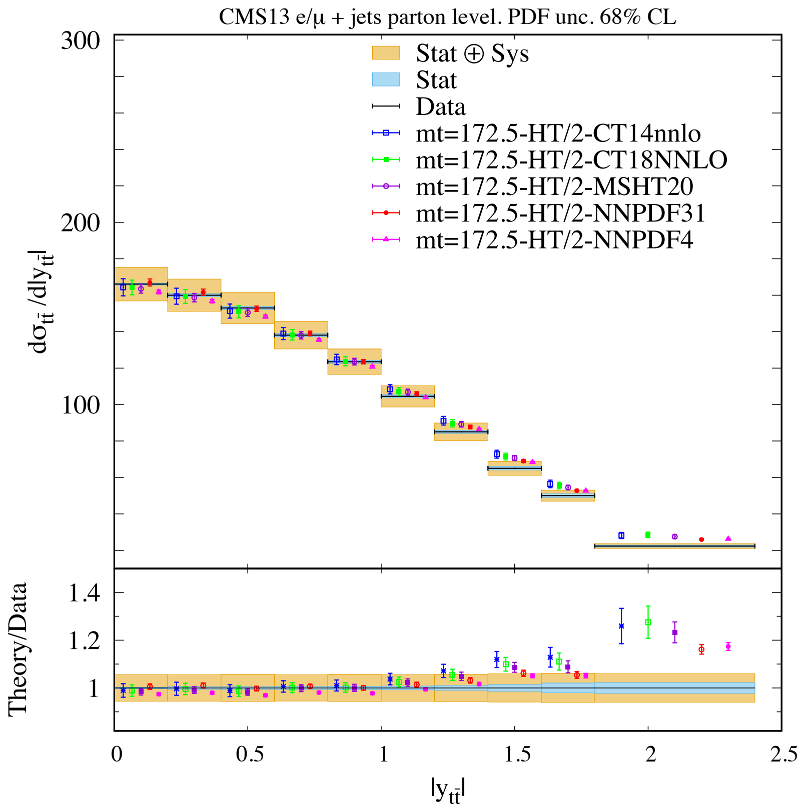
Scale uncertainty: the recommended scale choice is not always the best. We select the scale choice that yields the smaller χ^2/Npt



HT/2 varied up and down by a factor of 2

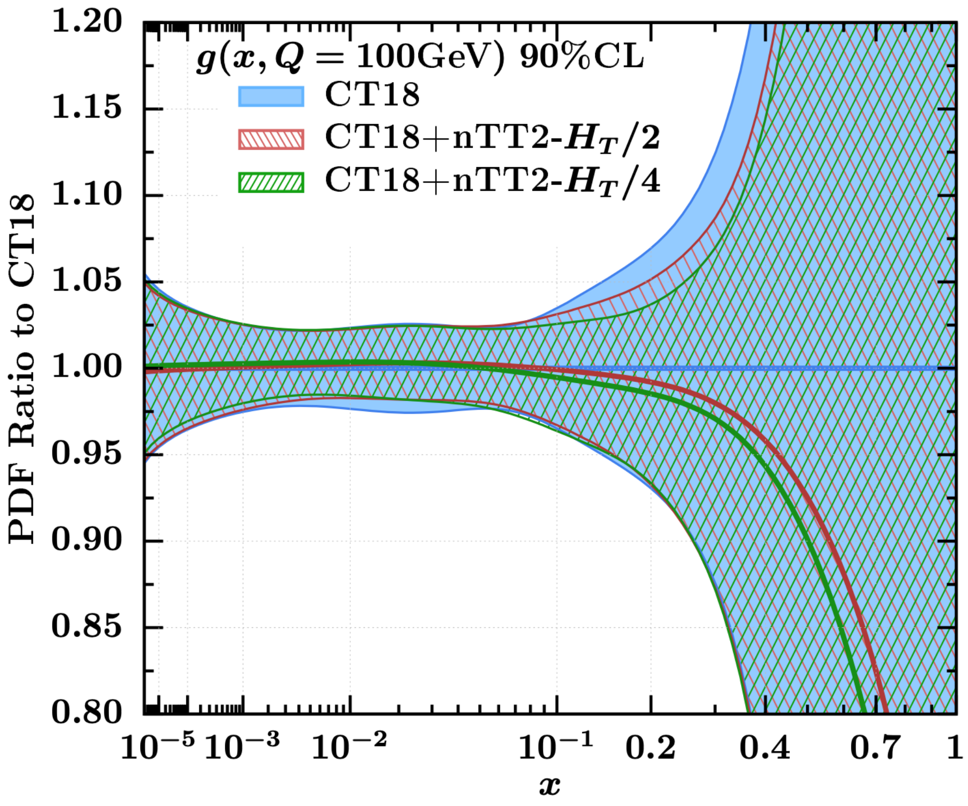


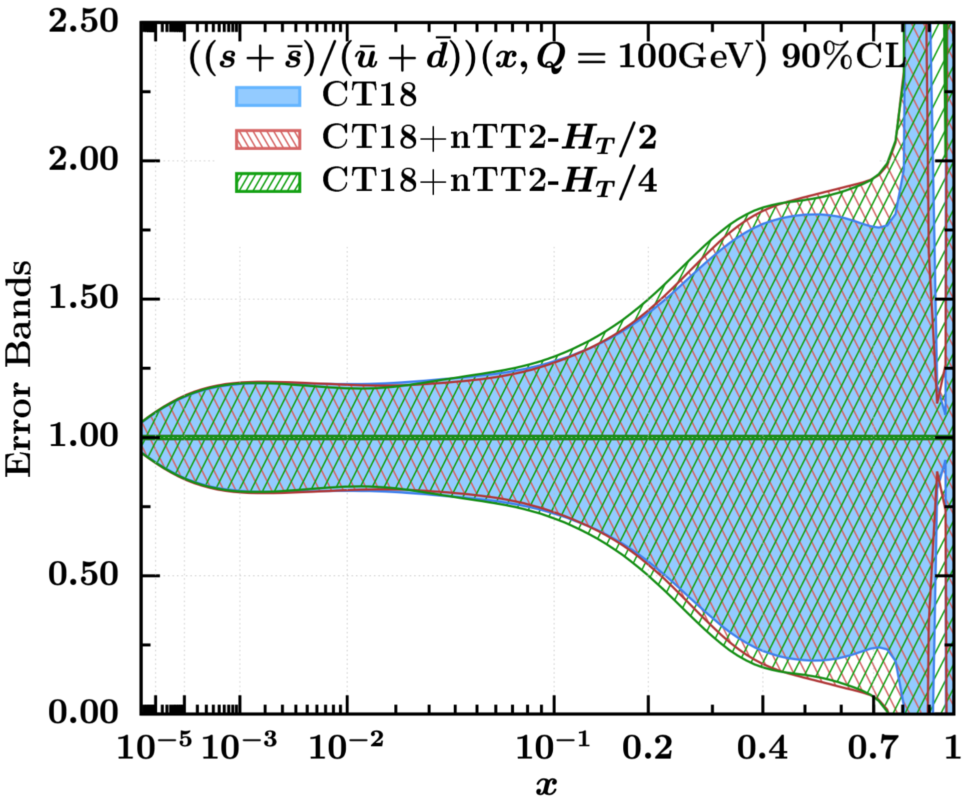
HT/4 varied up and down by a factor of 2



PDF Uncertainty @68% CL

Global fit: impact from new nTT2 baseline





The CT18 analysis

PHYSICAL REVIEW D **103,** 014013 (2021)

Editors' Suggestion

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

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

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 χ^2_E, $\chi^2_E/N_{pt,E}$, and S_E, in which $N_{pt,E}$, χ^2_E are the number of points and value of χ^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^{-1} W/Z dataset, marked by ‡‡, is replaced by the updated one (4.6 fb^{-1}) 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		$N_{pt,E}$	χ^2_E	$\chi^2_E/N_{pt,E}$	S_E
160	HERAI + II 1 fb^{-1}, 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 σ_r^b	[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^{-1}, 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^{-1}, 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^{-1} 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^{-1} 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)

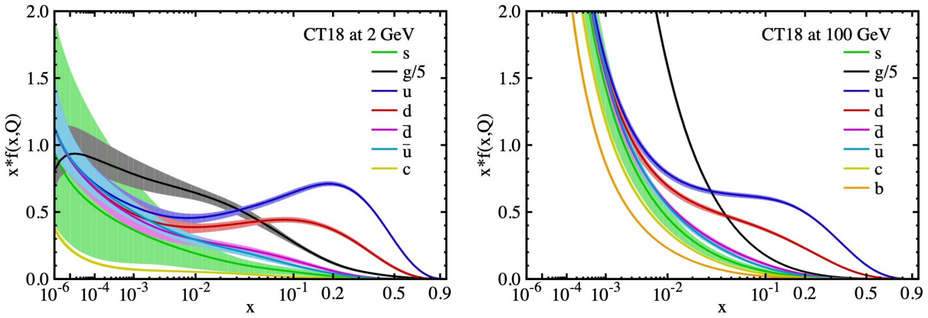
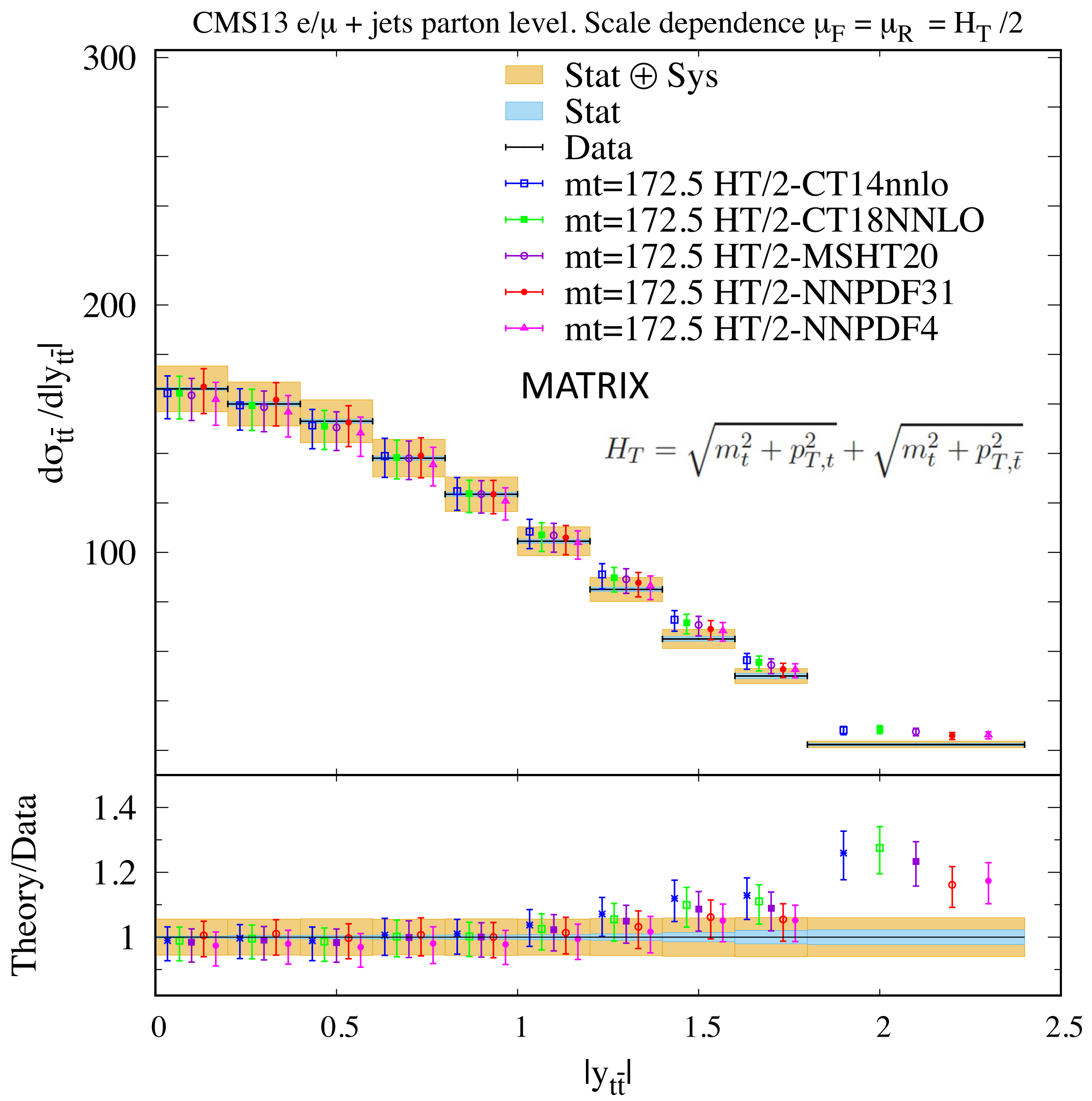


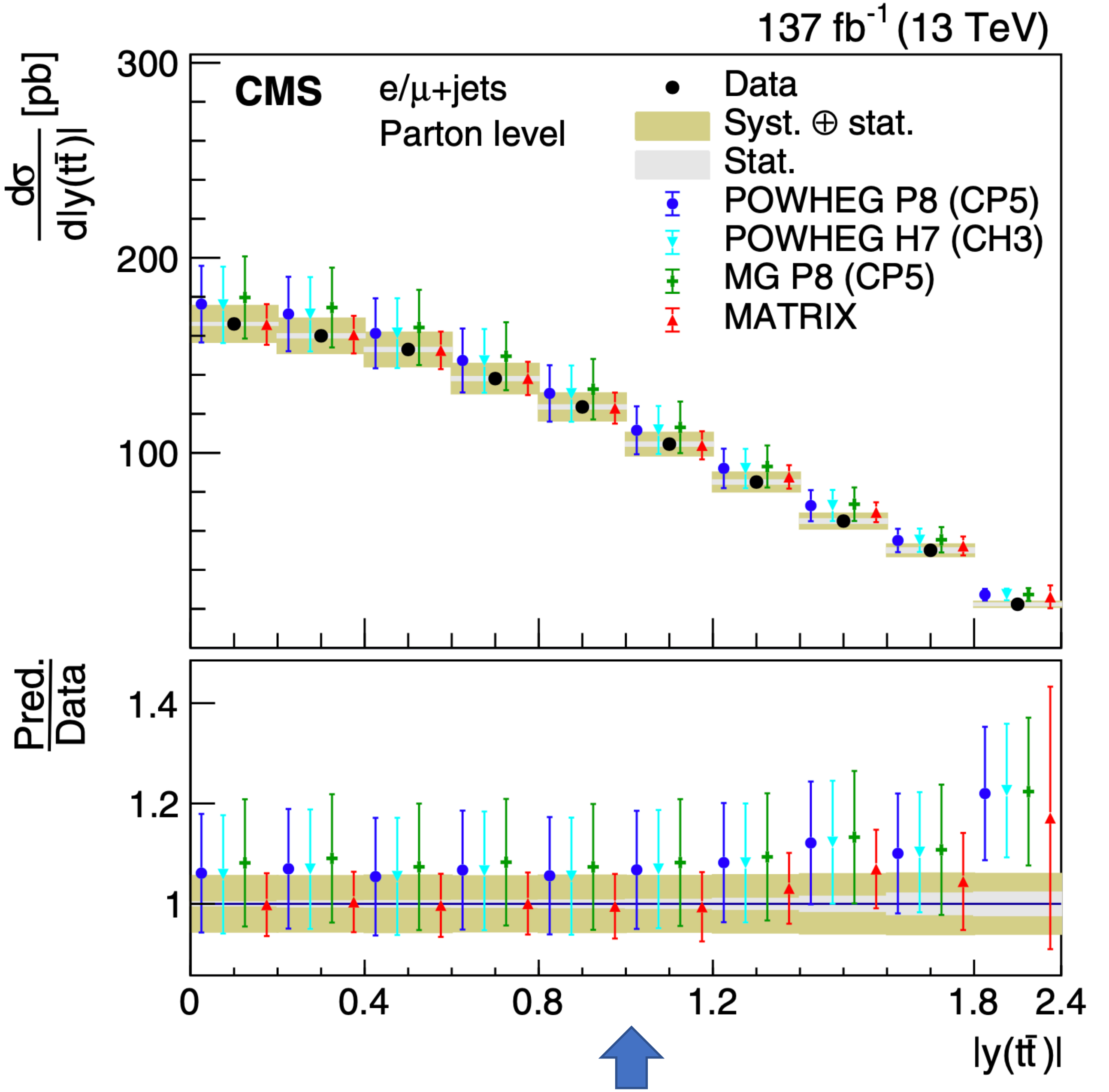
TABLE II. Like Table I, for newly included LHC measurements. The ATLAS 7 TeV W/Z data (4.6 fb^{-1}), labeled by ‡, are included in the CT18A and CT18Z global fits, but not in CT18 and CT18X.

Exp. ID#	Experimental dataset		$N_{pt,E}$	χ^2_E	$\chi^2_E/N_{pt,E}$	S_E
245	LHCb 7 TeV 1.0 fb^{-1} 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^{-1} $Z \to e^-e^+$ 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^{-1}, 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^{-1} 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^{-1} 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^{-1}, 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^{-1}, 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^{-1}, 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^{-1}, 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^{-1}, $t\bar{t}$ 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^{-1}, $t\bar{t}$ 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





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

Figure from CMS publication, arXiv:2108.02803

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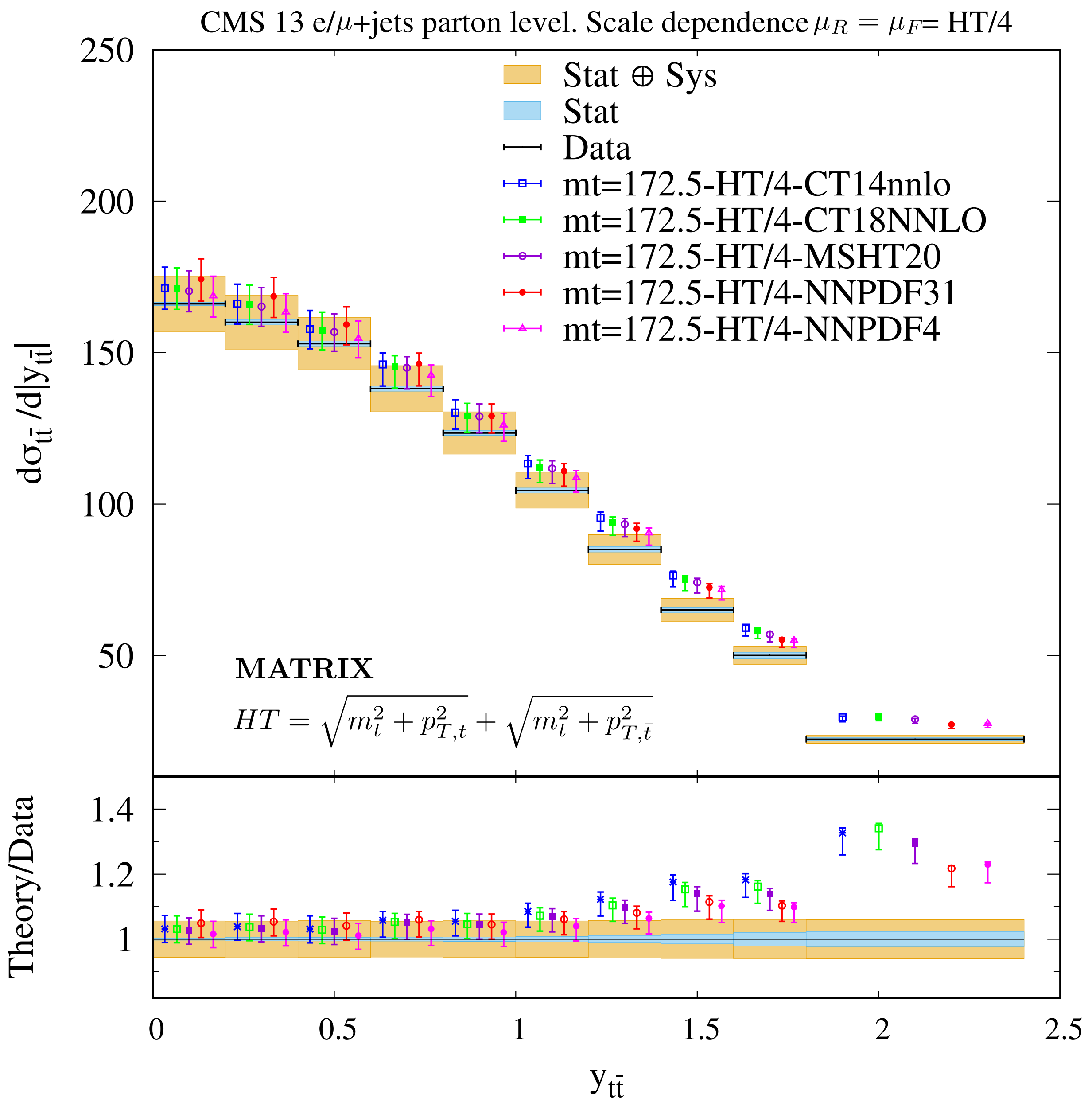

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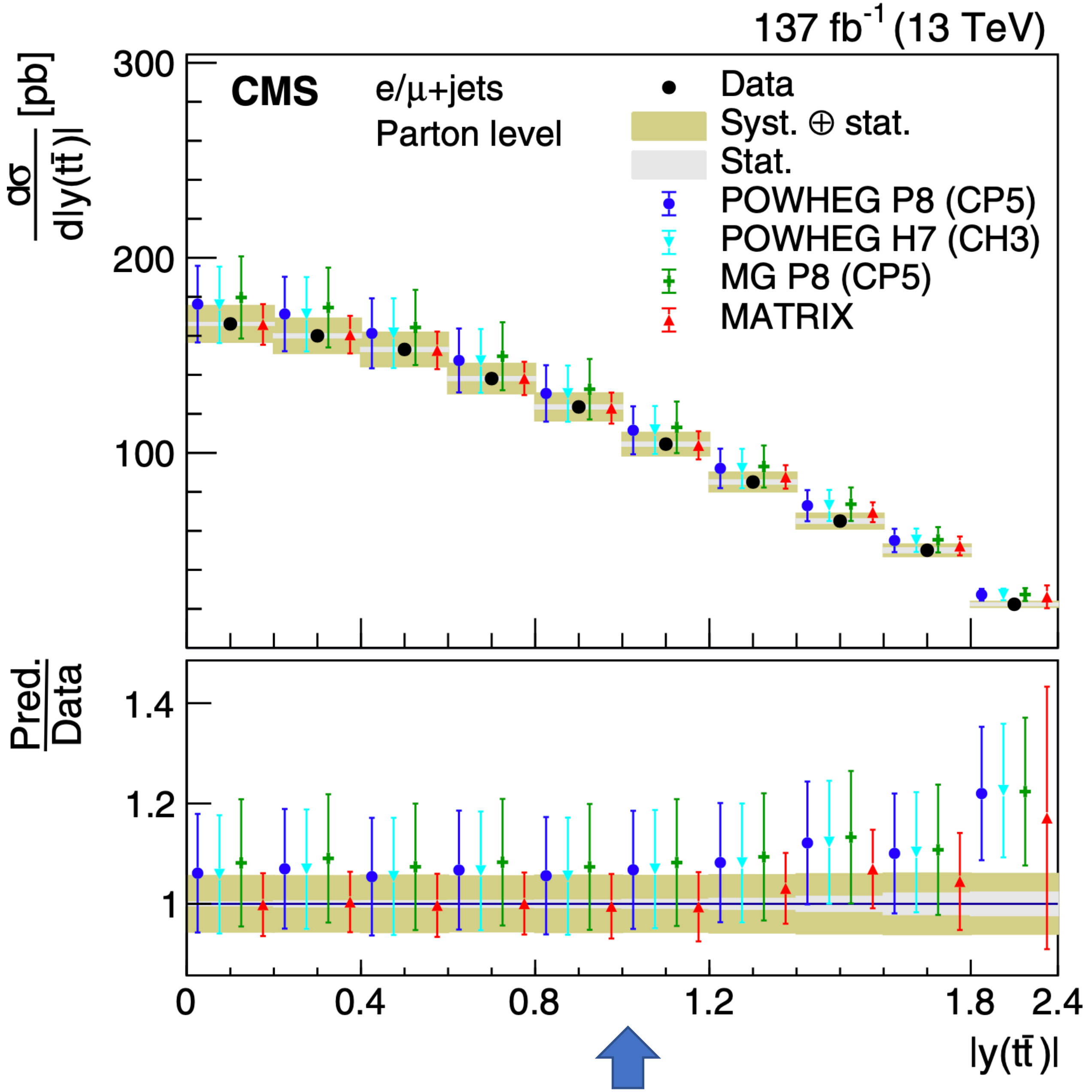

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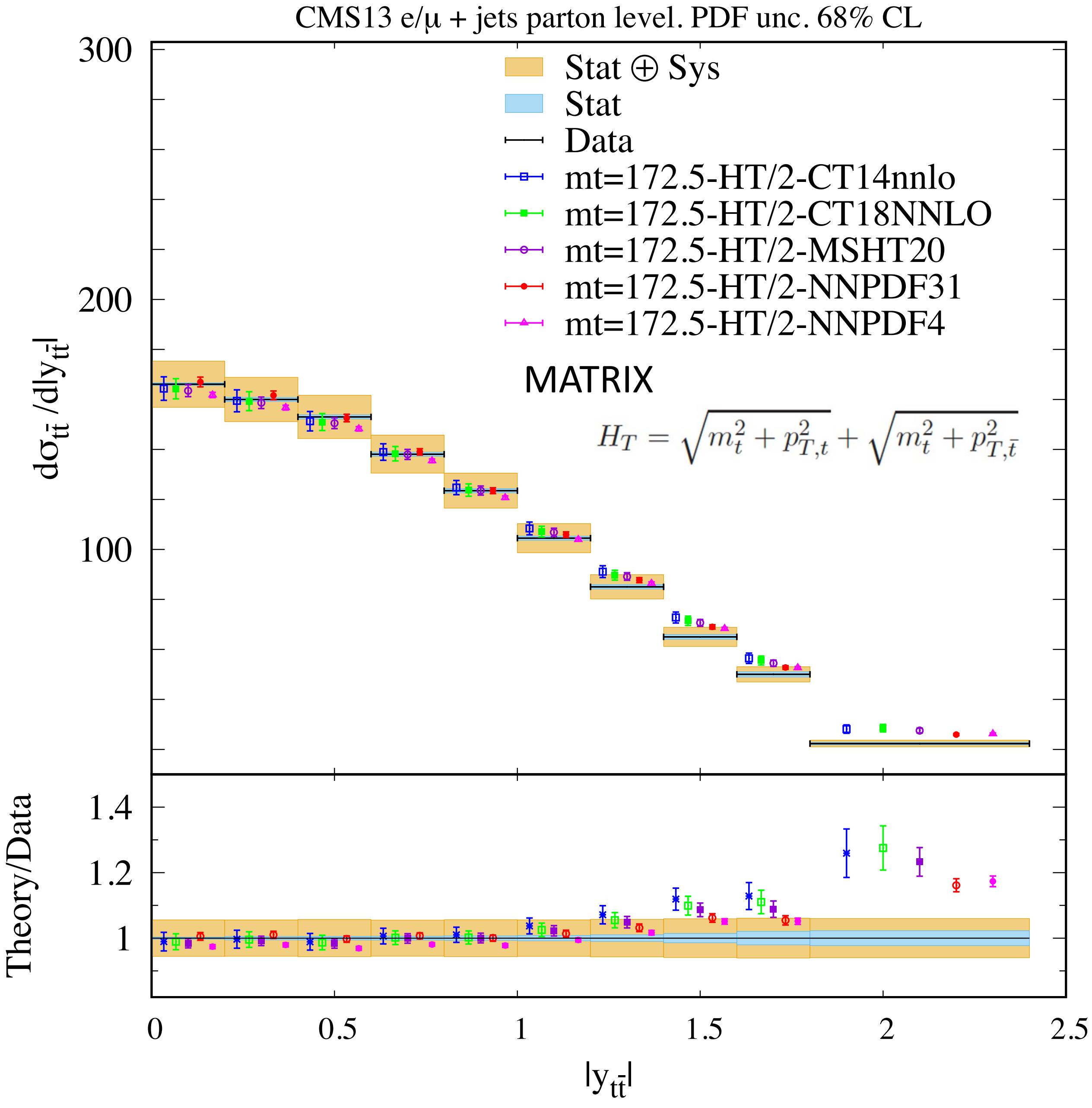
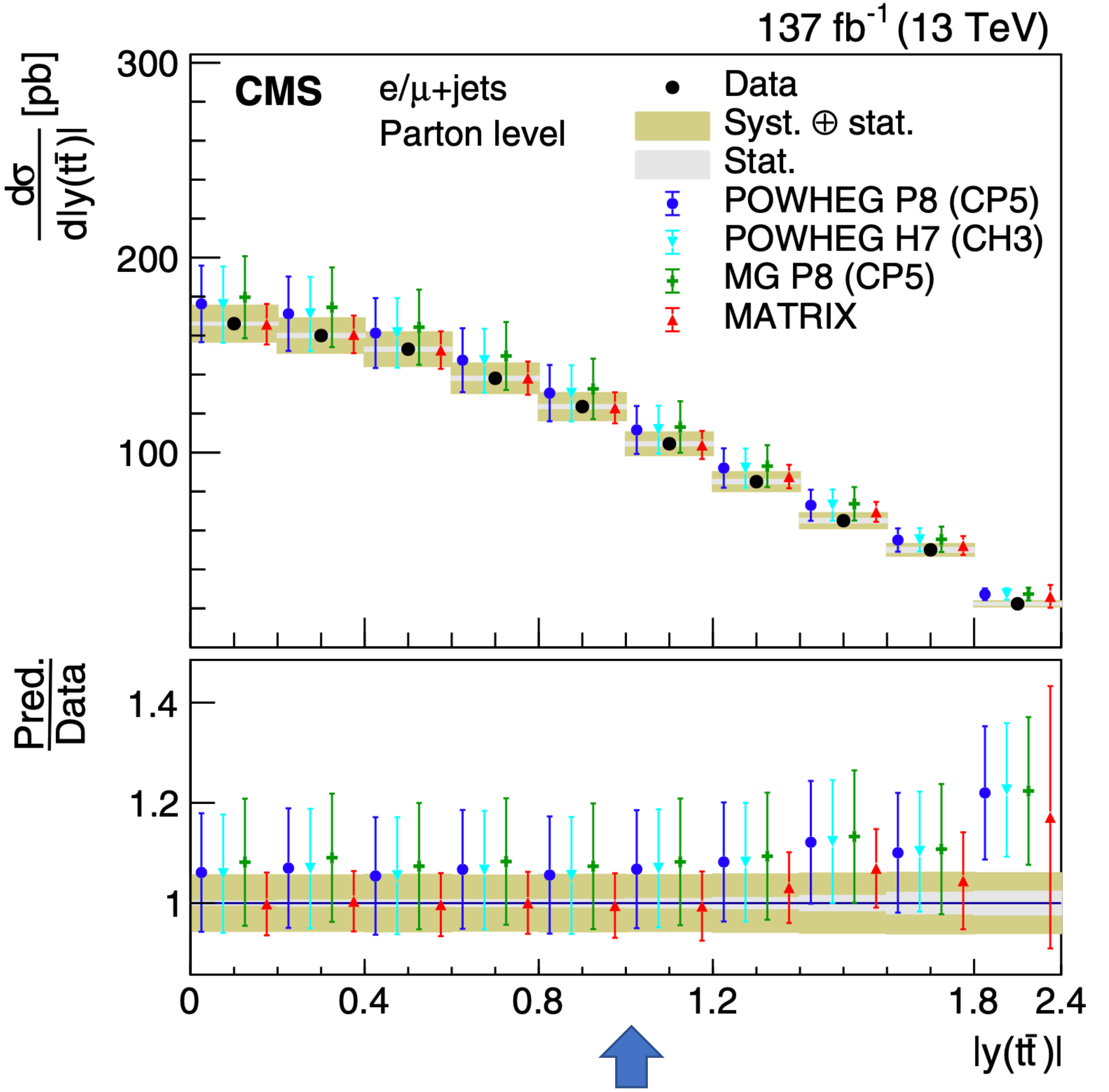


PDF Uncertainty @68% CL



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