13 TeV Top-quark pair production impact on CT18 PDFs of the proton

Marco Guzzi

Kennesaw State University

with

A. Ablat, S. Dulat, T.-J. Hou,

I. Sitiwaldi, K. Xie, and C.-P. Yuan

Based on: A. Ablat, S. Dulat, M.G., T.-J. Hou, I. Sitiwaldi, K. Xie, and C.-P. Yuan, in preparation

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KENNESAW STATE UNIVERSITY

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-Jiun 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,∥]

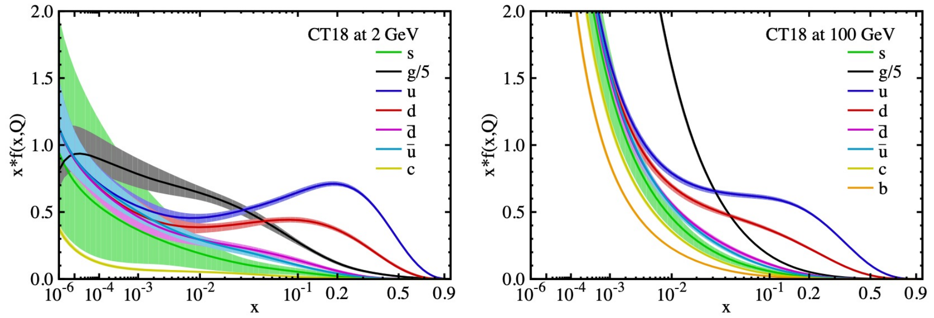


TABLE I. Datasets included in the CT18(Z) NNLO global analyses. Here we directly compare the quality of fit found for CT18 NNLO vs CT18Z NNLO on the basis of χ^2_E, $\chi^2_E/N_{pt,E}$, and S_E, in which $N_{pt,E}$, χ^2_E are the number of points and value of χ^2 for experiment E at the global minimum. 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 $Q^3 d^2\sigma_{pp}/(dQ dx_F)$	[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.

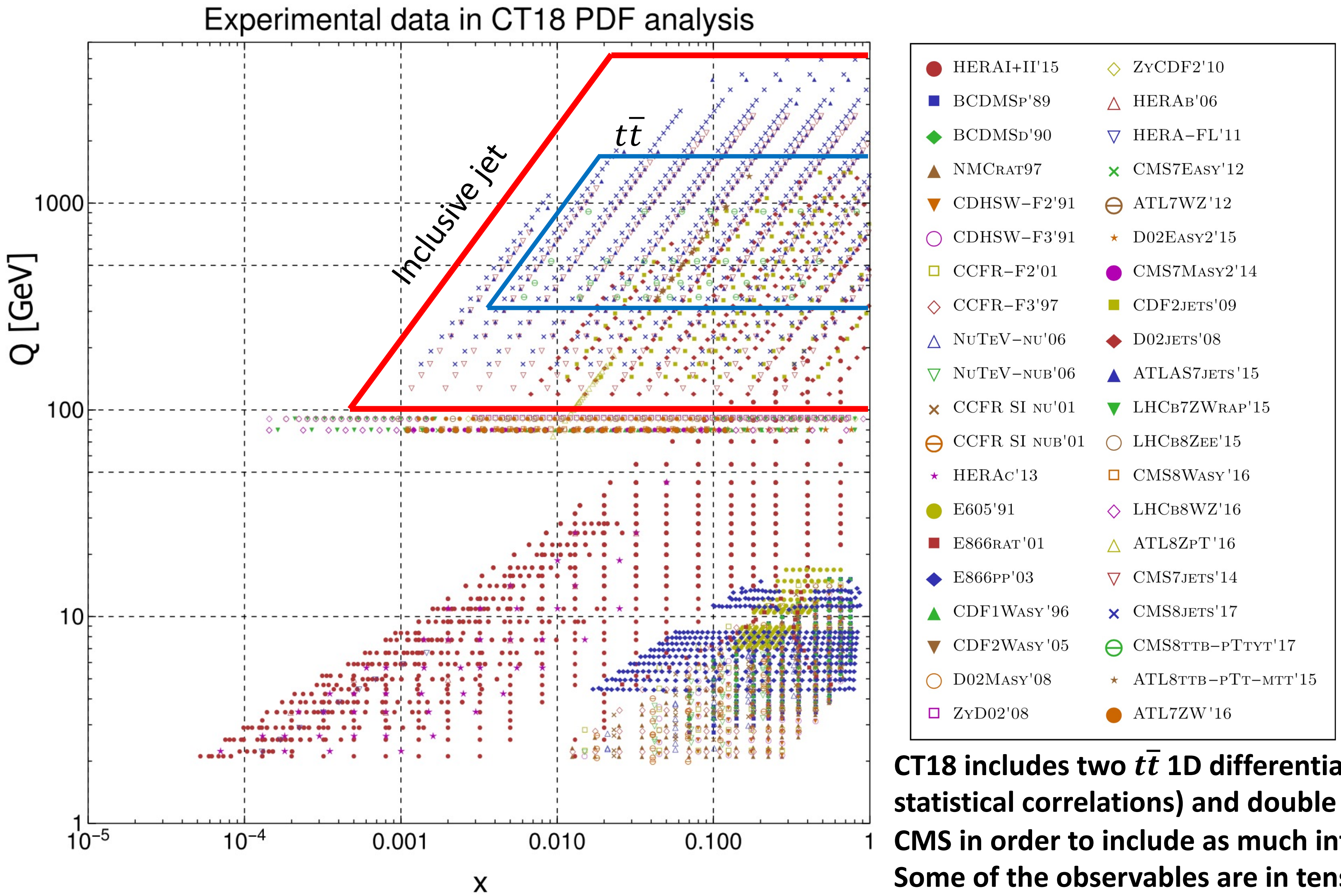
Exp. ID#	Experimental dataset		$N_{pt,E}$	χ^2_E	$\chi^2_E/N_{pt,E}$	S_E
245	LHCb 7 TeV 1.0 fb^{-1} W/Z forward rapidity cross sec.	[81]	33	53.8 (39.9)	1.6 (1.2)	2.2 (0.9)
246	LHCb 8 TeV 2.0 fb^{-1} $Z \to e^- e^+$ forward rapidity cross sec.	[82]	17	17.7 (18.0)	1.0 (1.1)	0.2 (0.3)
248‡	ATLAS 7 TeV 4.6 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)

Top-quark production measurements at the LHC 8TeV included in the CT18 global analysis.

Chosen such that:

- maximal amount of information included
- minimal conflict/tension with other data sets and among them

$t\bar{t}$ production kinematics in CT18



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

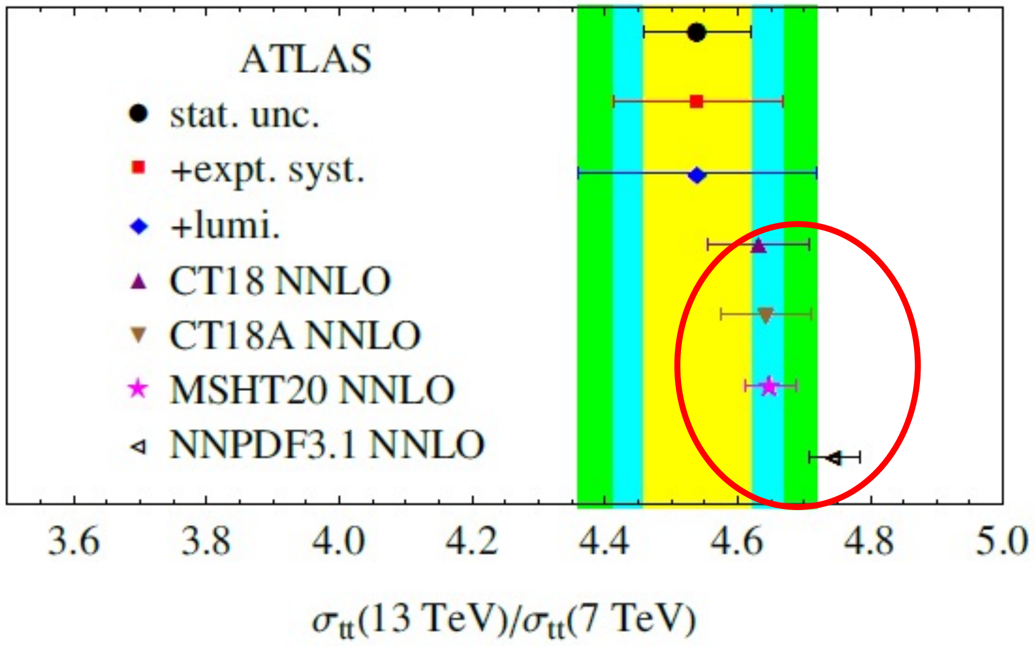
Top-quark
1511.04716 ATLAS 8 TeV ttb ptT diff. distributions
1511.04716 ATLAS 8 TeV ttb mtt diff. distributions
1703.01630 CMS 8 TeV ttb (pT , yt) 2d diff. distrib.

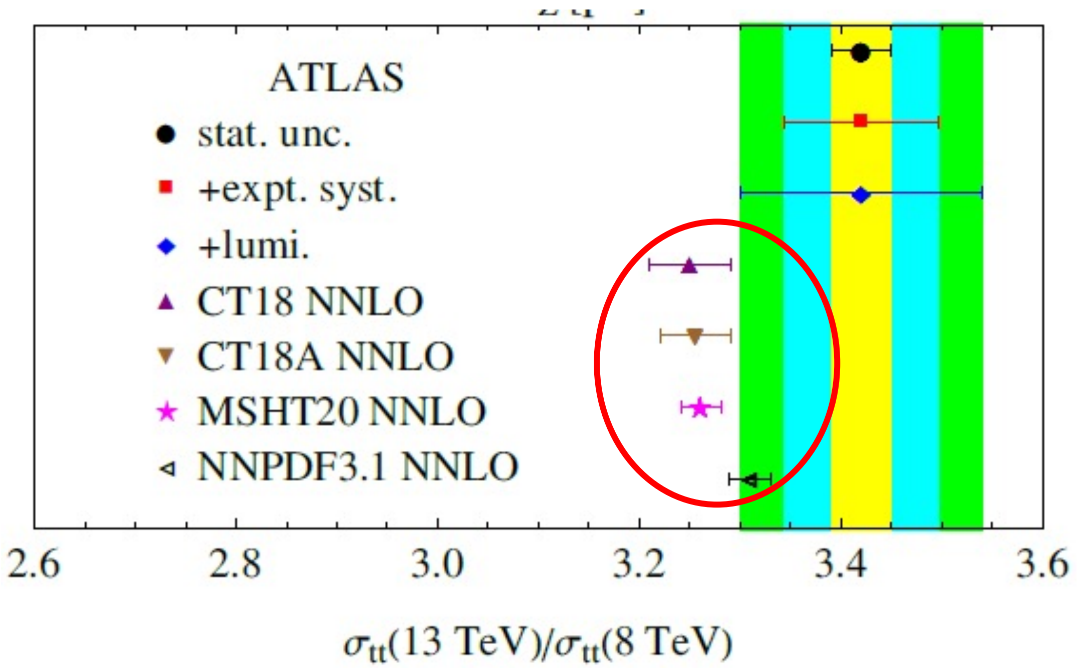
Jet production
1406.0324 CMS incl. jet at 7 TeV with R=0.7
1410.8857 ATLAS incl. jet at 7 TeV with R=0.6
1609.05331 CMS incl. jet at 8 TeV with R=0.7

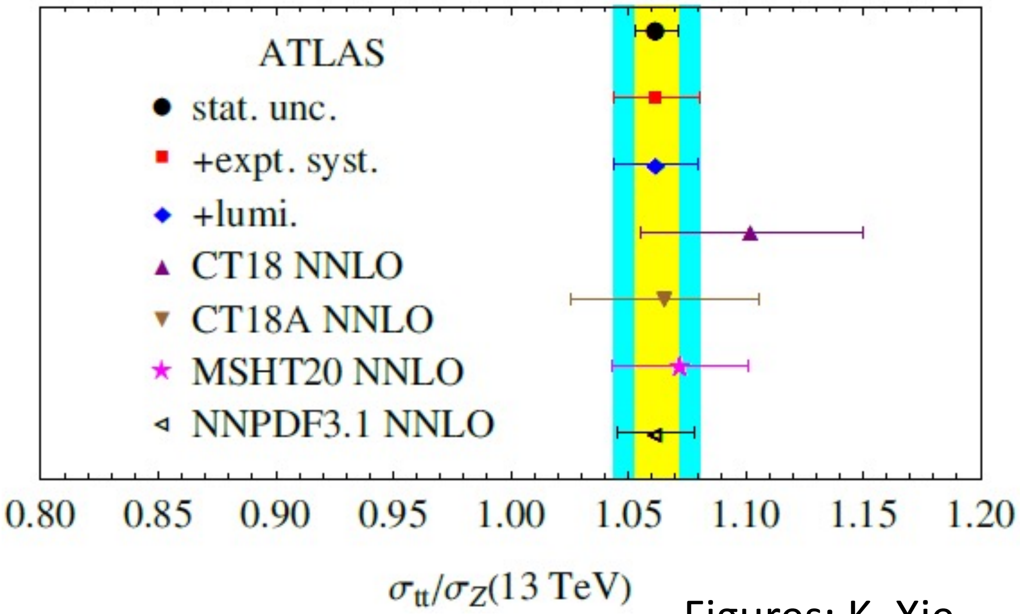
CT18 includes two $t\bar{t}$ 1D differential observables from ATLAS (using statistical correlations) and double differential measurements from CMS in order to include as much information as possible.
Some of the observables are in tension with each other.

What we learned from the CT18 global analysis

Ratios of NNLO $t\bar{t}$ and Z cross sections:
Check of the consistency between 13 TeV and 8 TeV ttbar differential distributions





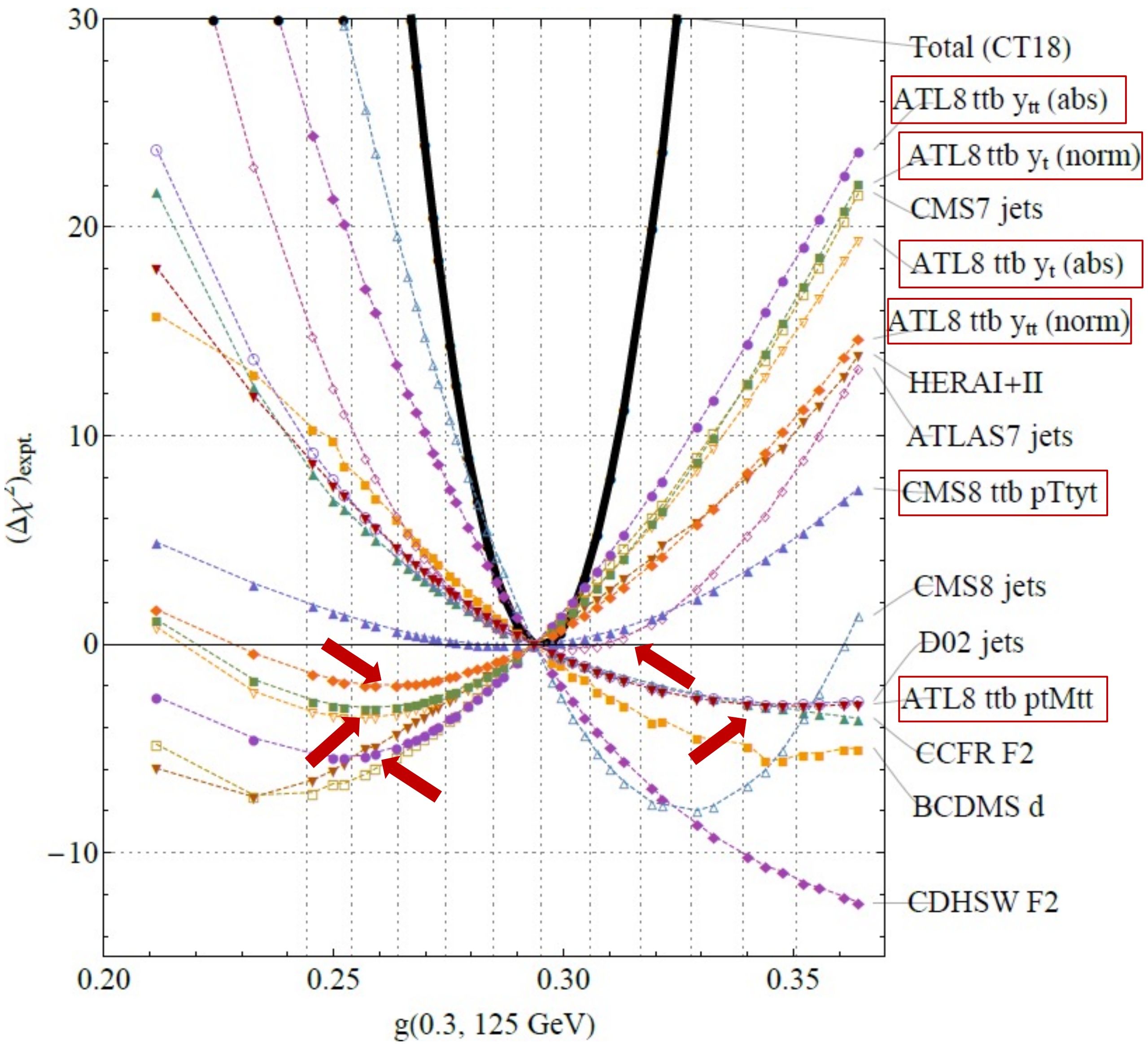


Some disagreement with $\sigma_{t\bar{t}}(8\text{ TeV})$?

Figures: K. Xie

Lagrange Multiplier scan: $g(x = \mathbf{0.3}, \mathbf{125\ GeV})$

In under-constrained directions, the Lagrange Multiplier method complements the Hessian approach.



Fair overall agreement. But observe strong opposite pulls from CMS7 and CMS8+ATLAS7 jet production data sets

$t\bar{t}$ production: 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 $d^2\sigma/(dp_{T,t}dy_{t,ave})$

Tensions between the ttbar observables lead to different pulls on the gluon distribution.

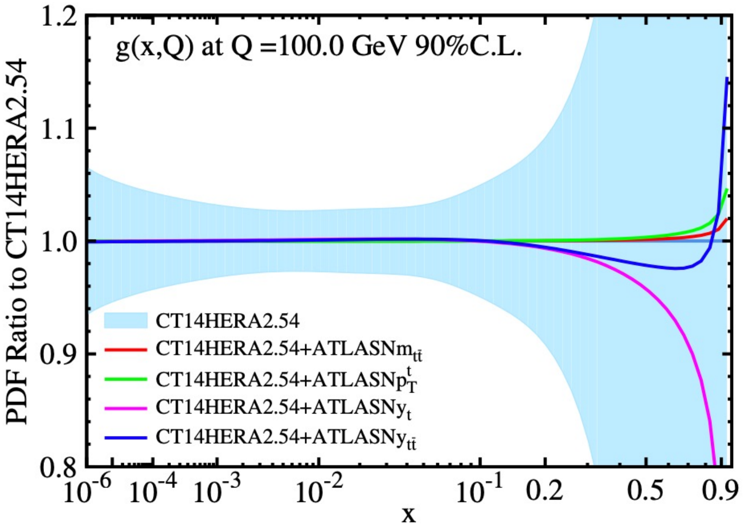
Figure: P. Nadolsky

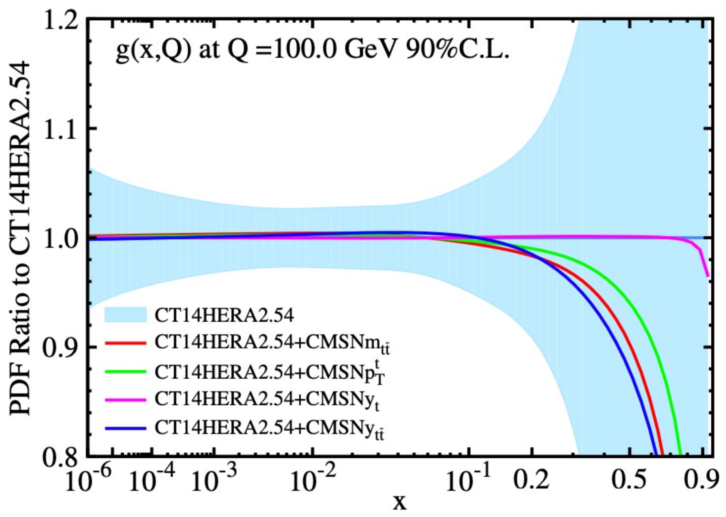
Recent CTEQ related exploratory studies with ePump

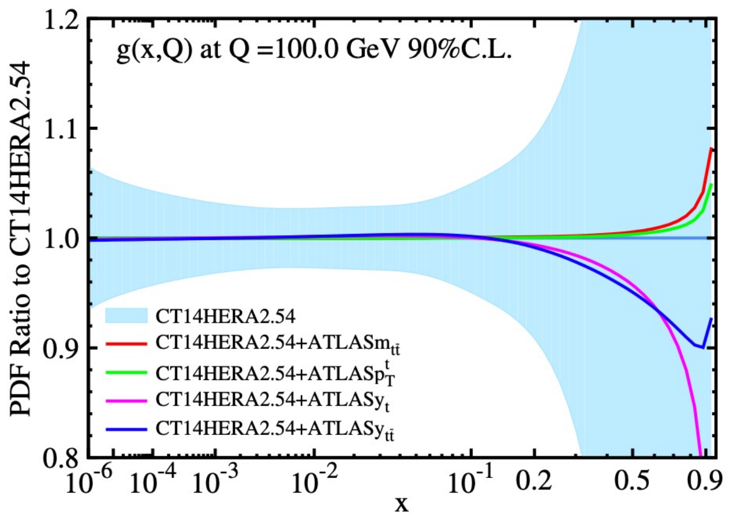
- 1912.08801 (Czakon, Dulat, Hou, et. al.) Exploratory study of 8 TeV $t\bar{t}$ 2D diff. Distrib. @CMS with ePump (Error PDF Updating Method) code.
- 2003.13740 (Kadir, Ablat, Dulat, Hou, Sitiwaldi) Impact of 8 TeV $t\bar{t}$ 1D diff distrib. @ATLAS and @CMS with ePump

- Differential distributions provide minor constraints on the gluon PDF when inclusive jet production data are included in the analysis. The impact depends on what data baseline is used.

- Pulls in different directions at large x are observed for different distributions







LHC 13 TeV $t\bar{t}$ measurements beyond CT18

JHEP 01 (2021) 033, 2021 - arXiv: 2006.09274

- ATLAS: Measurements of $t\bar{t}$ differential cross-sections at 13 TeV in the all-hadronic channel (1D); 36.1 fb^{-1}IL

JHEP 1902 (2019) 149, 2019 - arXiv:1811.06625

- CMS: Measurements of $t\bar{t}$ differential cross sections at 13 TeV using events containing two leptons (1D); 35.9 fb^{-1}IL

Label in data list	Npt	N. Corr sys unc	Exp	Corr Sys
5 20 ATL13mtt	9	67	ATLAS	Nuisance par: given
5 21 ATL13ytt	12	67	ATLAS	Nuisance par: given
5 22 ATL13HTtt	11	67	ATLAS	Nuisance par: given
5 23 ATL13pTt1	10	67	ATLAS	Nuisance par: given
5 24 ATL13pTt2	8	67	ATLAS	Nuisance par: given
5 25 CMS13mtt	7	6	CMS	Nuisan par: Sigma-K dec
5 26 CMS13pTt	6	5	CMS	Nuisan par: Sigma-K dec
5 27 CMS13yt	10	9	CMS	Nuisan par: Sigma-K dec
5 28 CMS13ytt	10	9	CMS	Nuisan par: Sigma-K dec

Planning to include 13 TeV lepton + Jet from CMS and ATLAS

These are all full phase space absolute measurements

Theory predictions: setup

- CMS: FastNNLO grids – (Czakon et al. 1704.08551)
- ATLAS: bin-by-bin NNLO/NLO K-factors generated by MATRIX (Catani, 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(pole) = 172.5 GeV
- Fact/Ren scale choice:

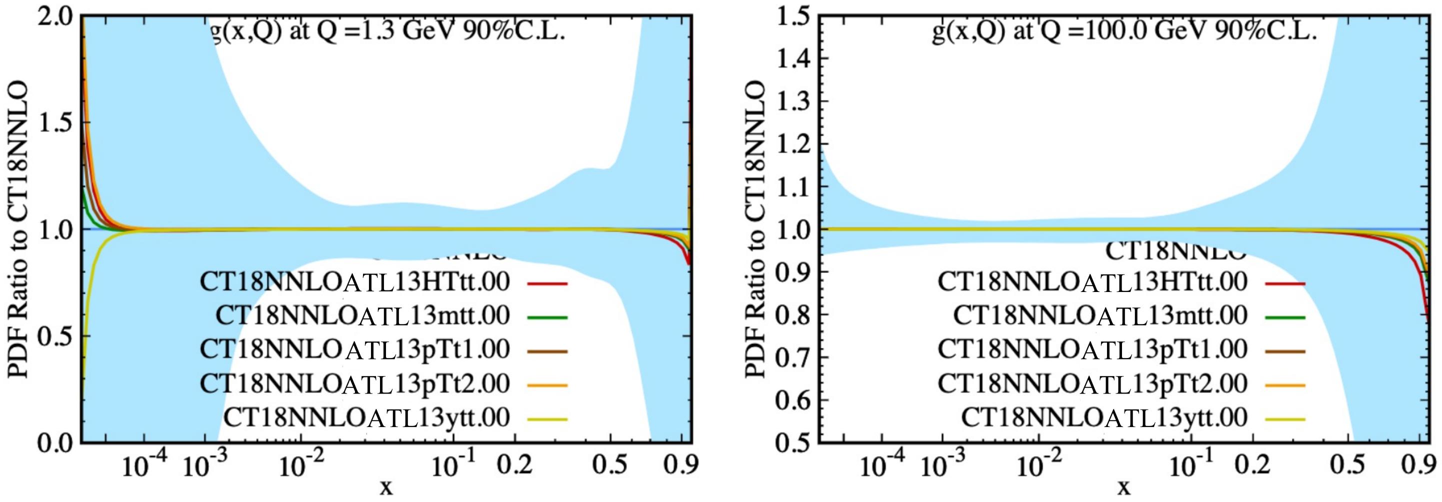
m_{tt}, $p_{T,tt}$, y_{tt}, y_t use $H_T/4$; $p_{T,t}$, use M_T; $p_{T,t\ avg}$ use $M_T/2$ (Czakon et al. JHEP 2017)

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

- EW corrections considered: negligible effect on our fits.

ePump gluon PDF from ATLAS and CMS 13 TeV $t\bar{t}$ data

ATLAS 13 TeV



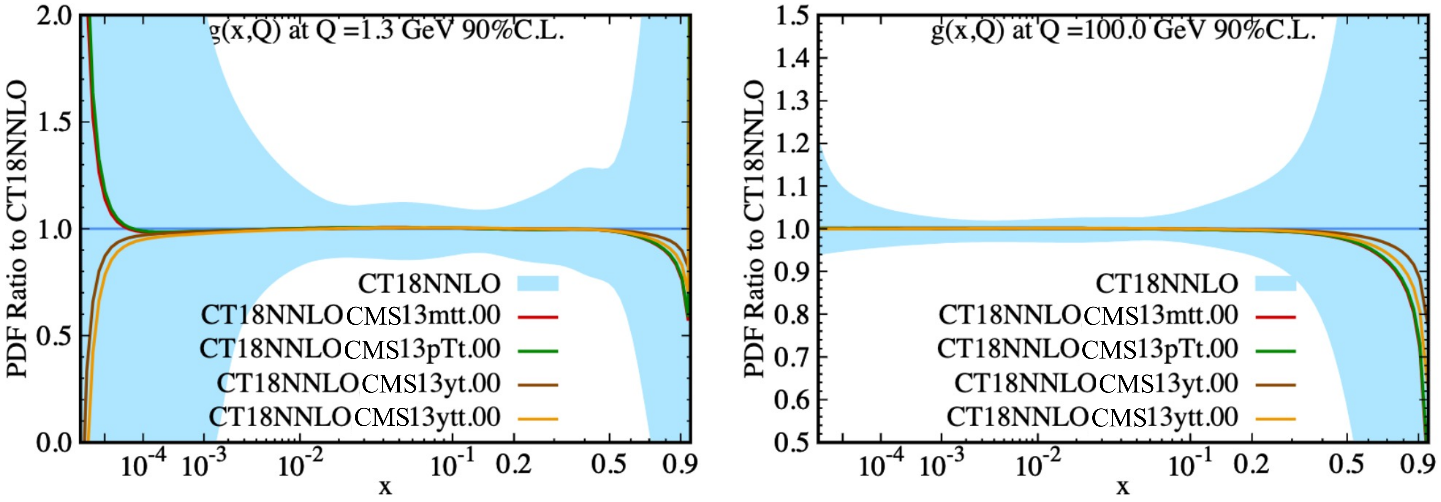
Here, data are included individually one at a time.

Error PDF Updating Method (ePump):
impact from each individual data set from
ATL and CMS at large x, (x > 0.5) at Q=100 GeV.

Pulls from different distributions at large x
seem to be consistent.

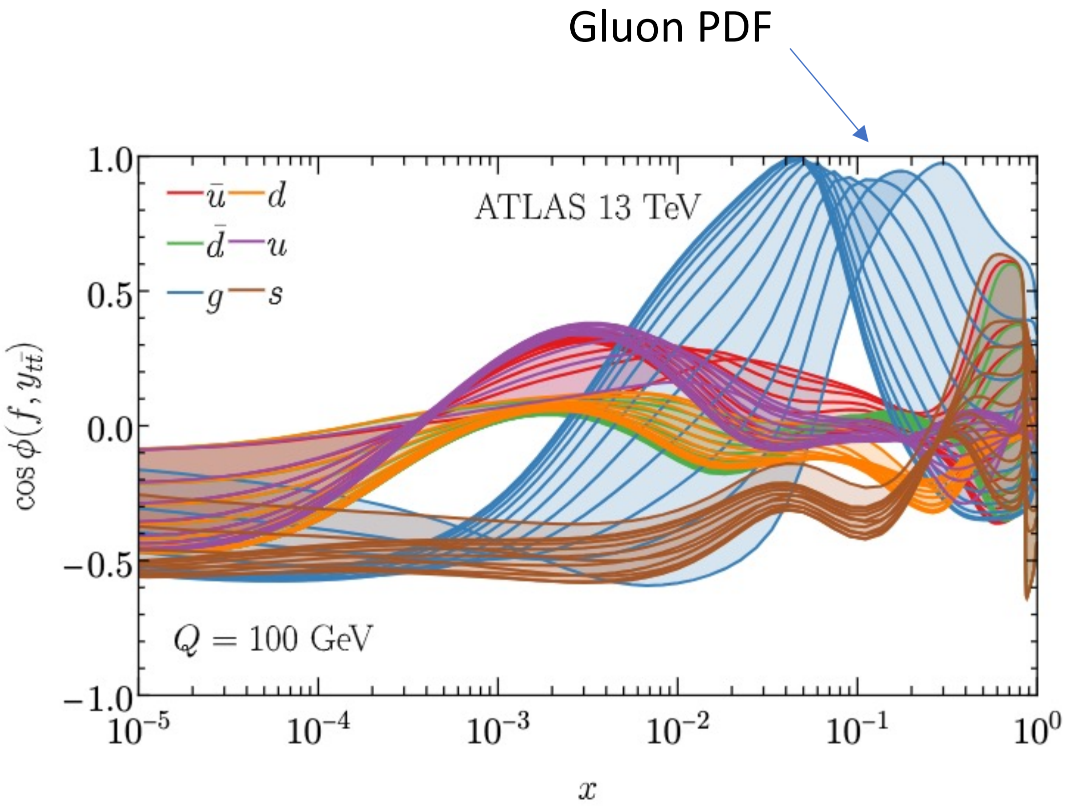
ePump: Schmidt, Pumplin, and Yuan, PRD 2018

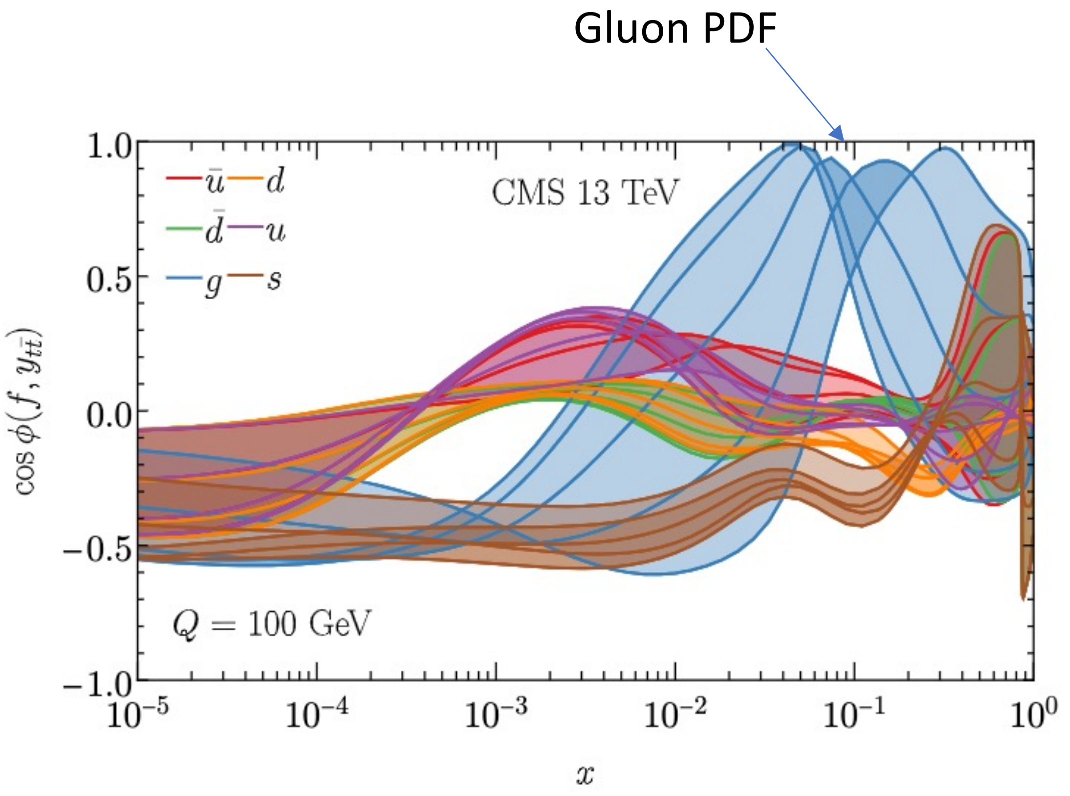
CMS 13 TeV



CT18NNLO 90% C.L.

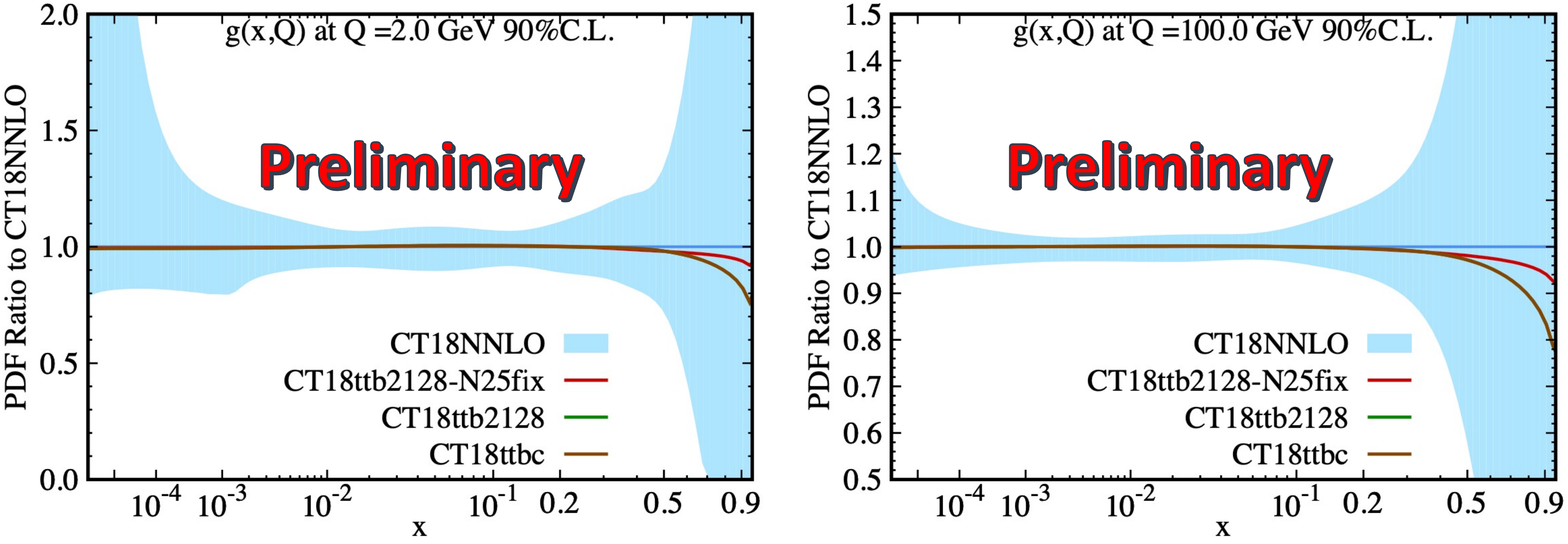
Sensitivity of $t\bar{t}$ production @13 TeV to PDFs





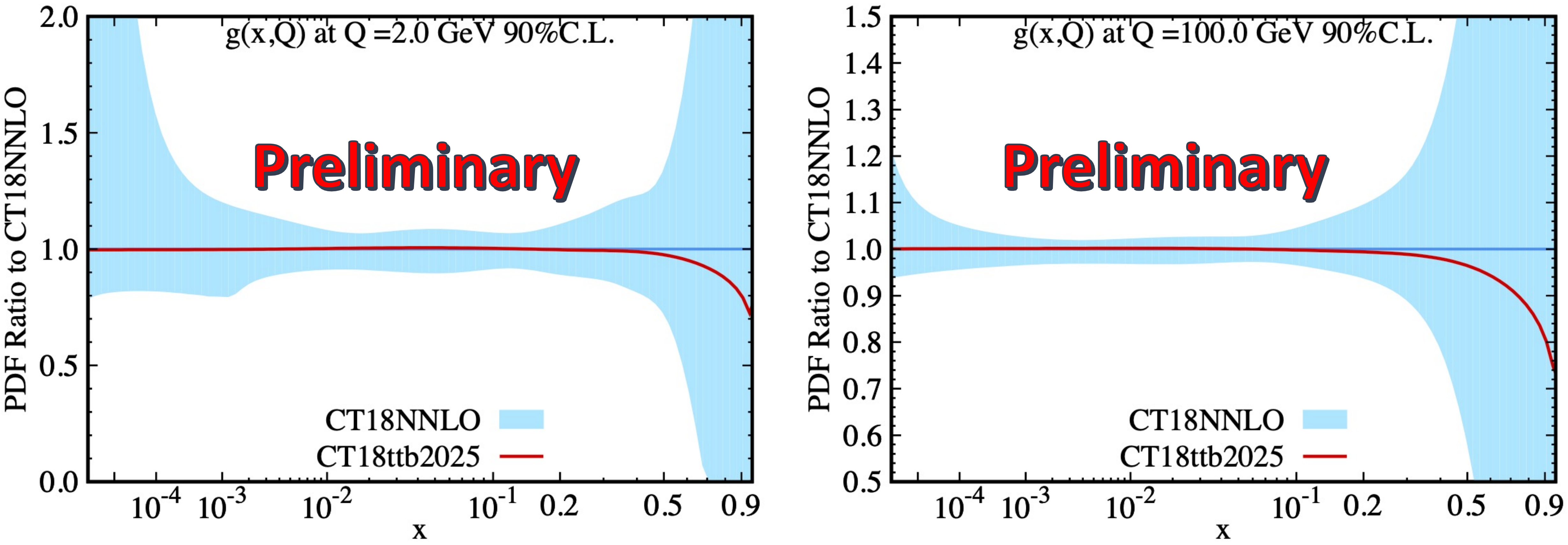
Correlation cosine between ATLAS and CMS measurements and the CT18NNLO PDFs at 100 GeV.

Global fit: Impact from y_{tt} 1D from CMS + ATLAS



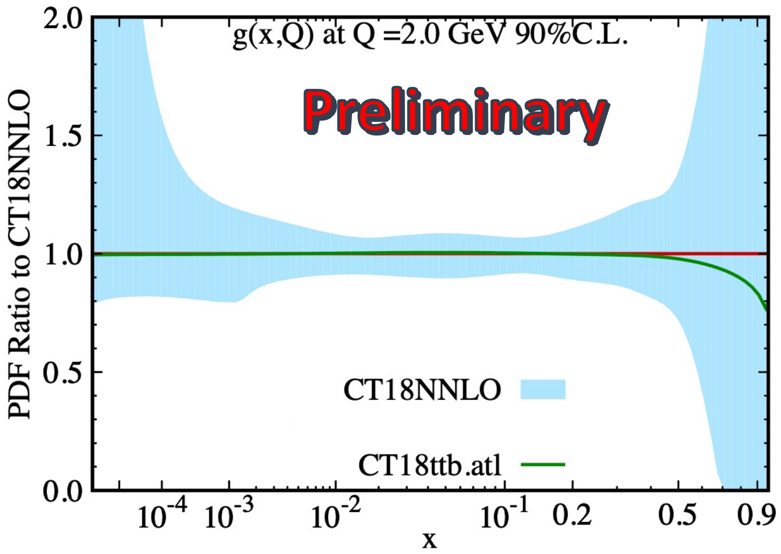

```
ATLAS: DATA SET 521 ; NORM Fac =   1.00000 ; # of pts =   12 ; chi^2 =    12.796140 S=    0.29377 chi^2/N =    1.06634
CMS  : DATA SET 528 ; NORM Fac =   1.00000 ; # of pts =   10 ; chi^2 =     6.415790 S=   -0.77071 chi^2/N =    0.64158
```

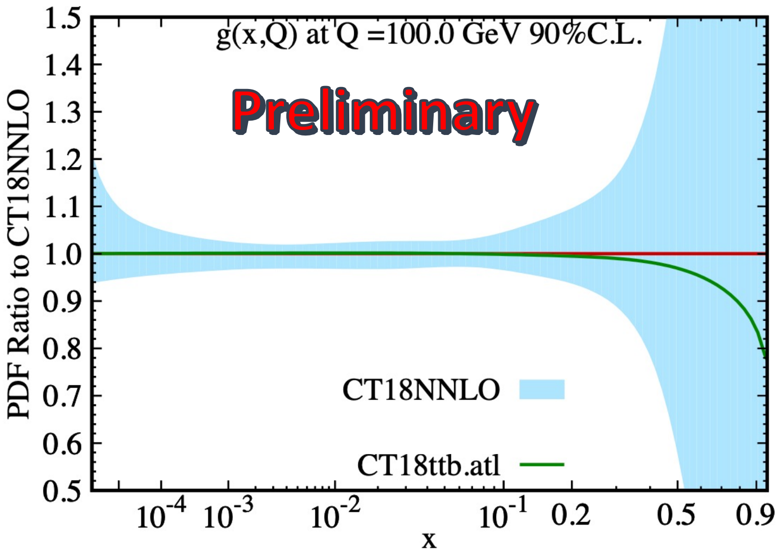
Global fit: Impact from m_{tt} 1D from CMS + ATLAS




```
ATLAS: DATA SET 520 ; NORM Fac =   1.00000 ; # of pts =    9 ; chi^2 =    13.109893 S=    1.00223 chi^2/N =    1.45665
CMS  : DATA SET 525 ; NORM Fac =   1.00000 ; # of pts =    7 ; chi^2 =    22.179648 S=    2.82669 chi^2/N =    3.16852
```

Global fit: Impact from all ATL 1D: ytt, mtt pT1, pT2, Htt



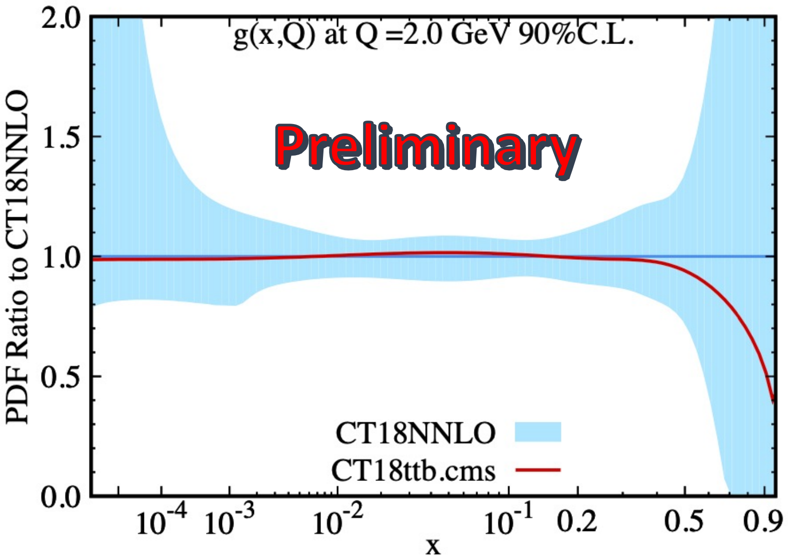


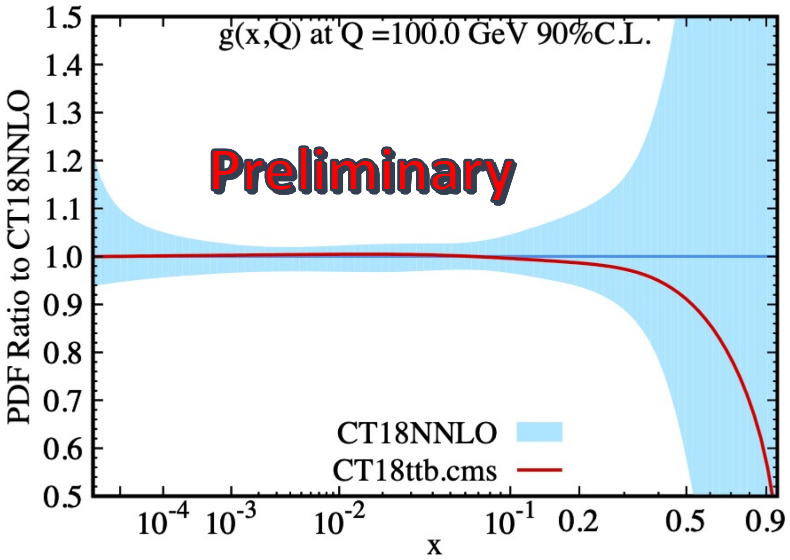

```
ATLAS
mtt  DATA SET 520 ; chi^2/N = 1.45793
ytt  DATA SET 521 ; chi^2/N = 1.06780
HTtt DATA SET 522 ; chi^2/N = 1.72802
pTt1 DATA SET 523 ; chi^2/N = 1.32391
pTt2 DATA SET 524 ; chi^2/N = 1.58153
```

For illustrative purpose only

Data sets from each experiment are included with no statistical correlations.

Global fit: Impact from all CMS 1D: yt, mtt pTt, ytt



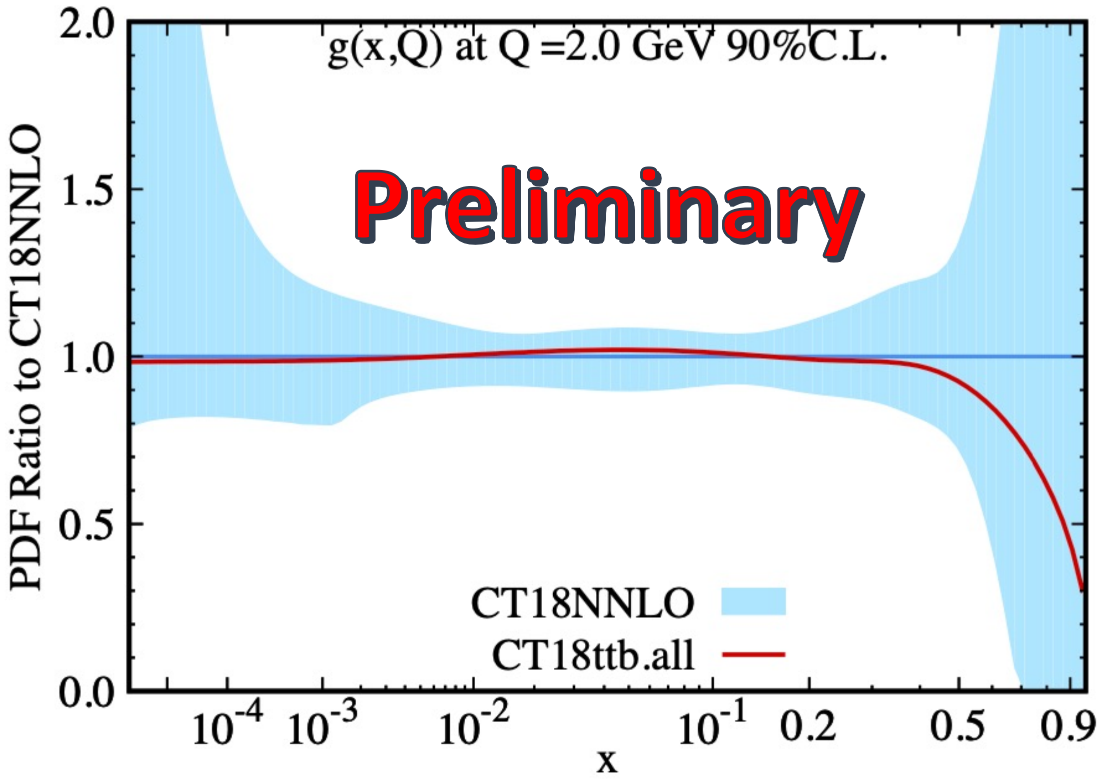


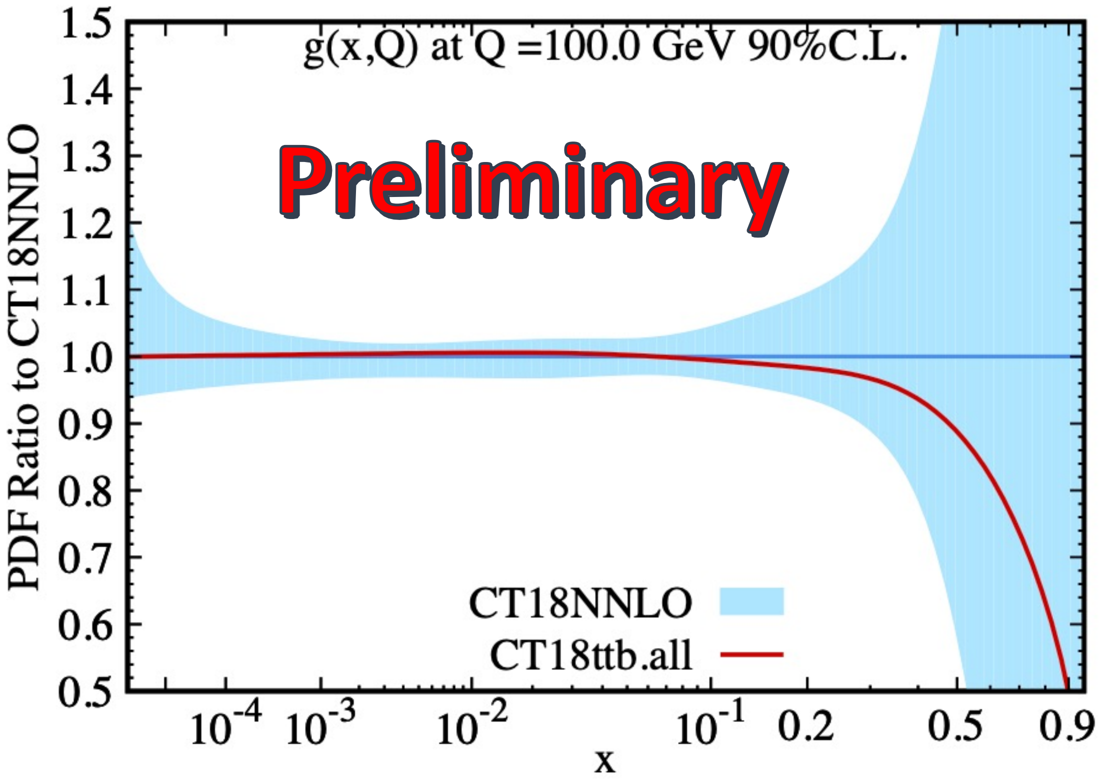

```
CMS
mtt DATA SET 525 ; chi^2/N = 3.02887
pTt DATA SET 526 ; chi^2/N = 2.90375
yt  DATA SET 527 ; chi^2/N = 0.63991
ytt DATA SET 528 ; chi^2/N = 0.55449
```

For illustrative purpose only

Counting the same events multiple times

Global fit: Impact from all $t\bar{t}$ data at 13 TeV ATL+CMS






```
ATL mtt  DATA SET 520 ;  chi^2/N = 1.42643
ATL ytt  DATA SET 521 ;  chi^2/N = 1.05387
ATL HTtt DATA SET 522 ;  chi^2/N = 1.67374
ATL pTt1 DATA SET 523 ;  chi^2/N = 1.29656
ATL pTt2 DATA SET 524 ;  chi^2/N = 1.55261
CMS mtt  DATA SET 525 ;  chi^2/N = 2.96862
CMS pTt  DATA SET 526 ;  chi^2/N = 2.83397
CMS yt   DATA SET 527 ;  chi^2/N = 0.62119
CMS ytt  DATA SET 528 ;  chi^2/N = 0.52401
```

Cumulative impact: gluon affected at $x > 0.1$
Small impact at intermediate x

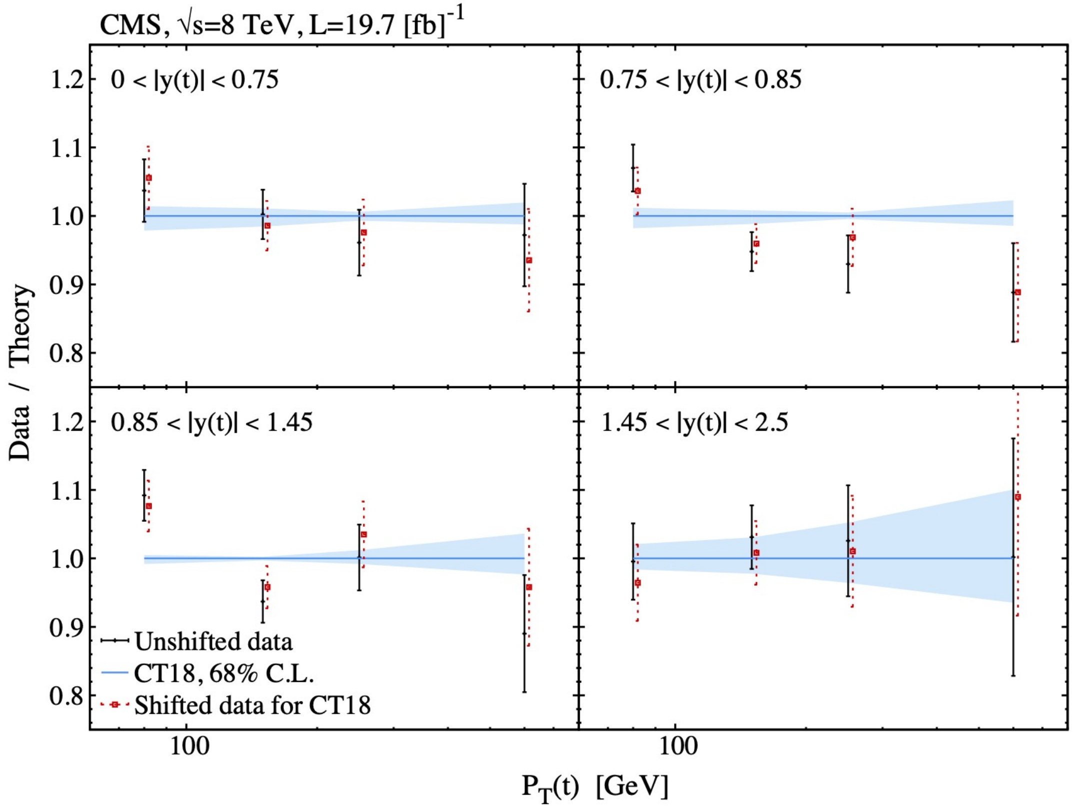
Stat. correlation between data ignored: **For illustrative purpose only**

Conclusions

- We explored the impact of 13 TeV $t\bar{t}$ LHC measurements on the CT18 PDFs
- $t\bar{t}$ measurements are critical to understand the gluon at large x
- Overall, the impact is found to be mild. This may change when $t\bar{t}$ prod. in lepton+jet ch @13 TeV is included.
- Impact of $t\bar{t}$ production at the LHC 13 TeV will further complement that of jet data on the gluon PDF, particularly in the large x region.
- $t\bar{t}$ and jets overlap in the Q-x plane, but matrix elements and phase space suppression are different and constraints on the gluon PDF may be placed at different values of x.
- Detailed information on both covariance and nuisance parameter representations for experimental errors is critical for full exploitation of data in PDF determinations
- Critical to set constraints on m_t, α_s, g-PDF correlations

BACKUP

$t\bar{t}$ data at the LHC 8 TeV in CT18



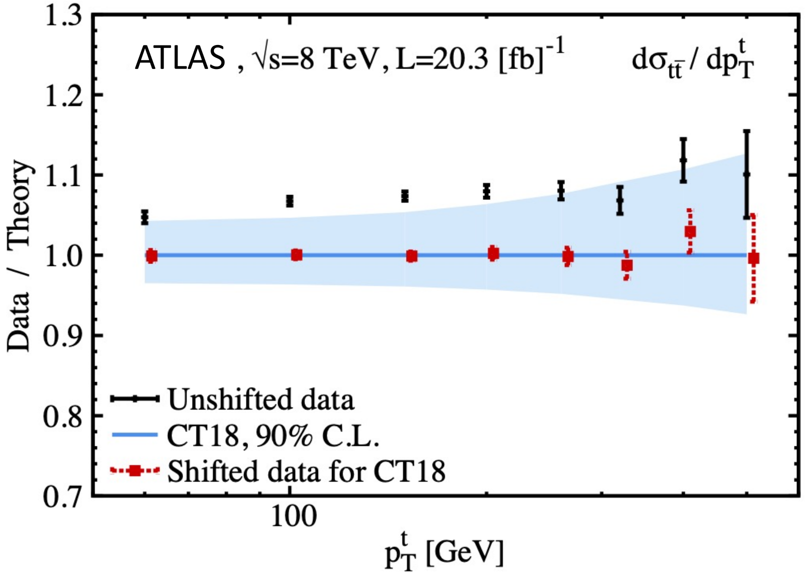
Effect of correlated errors in fitting the CMS data is relatively minimal.

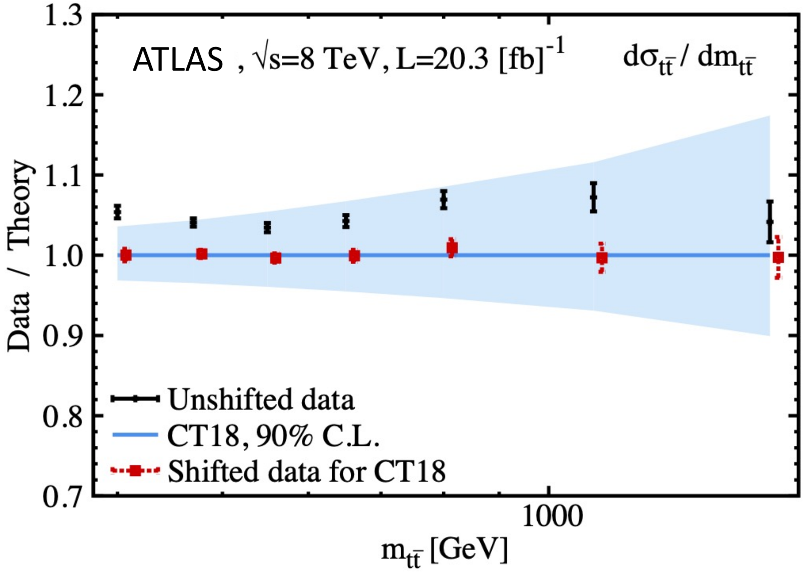
Good description of the analogous ATLAS pTt and mtt critically depends on the use of nuisance parameters to compensate for correlated systematics.

Observed effect on the CT18 PDFs is modest, when ttbar data are included together with the Tevatron and LHC jet production.

Inclusion of 1d or 2d differential Xsec would not lead to a significant reduction of the CT18 PDF uncertainty.

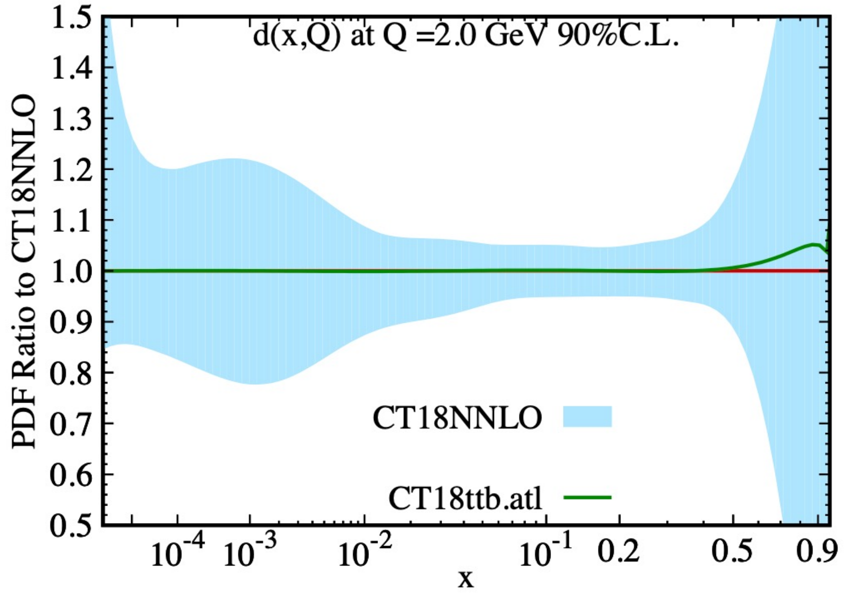
Impact on the gluon PDF compatible with the jet data. Jet data provide stronger constraints due to their larger numbers of data points, wider kinematic range, and relatively small statistical and systematic errors.

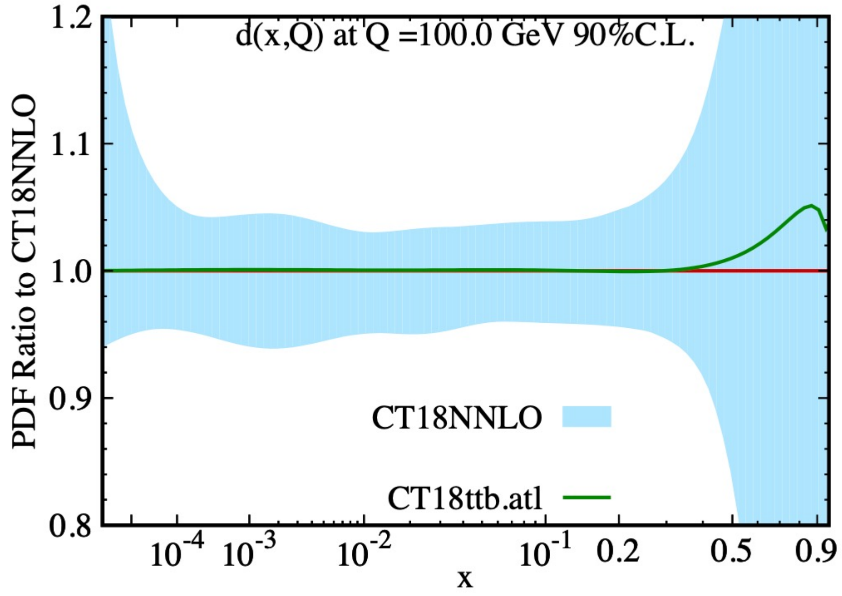




CT18, PRD 2021

Impact from all ATL 1D: ytt, mtt pT1, pT2, Htt

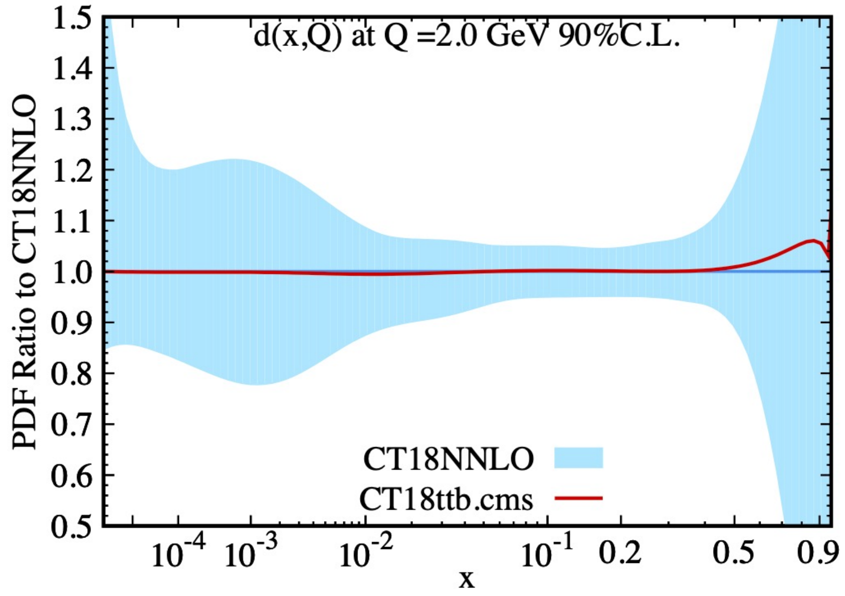


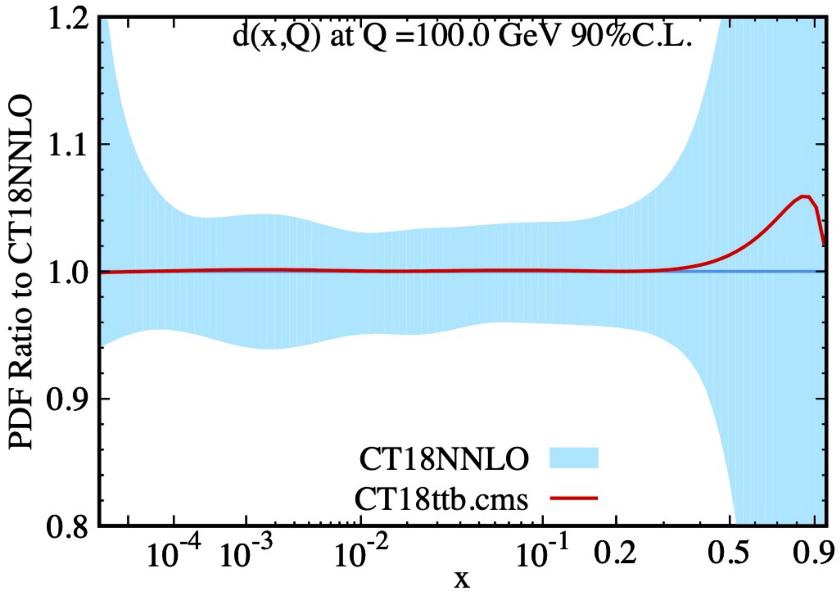


For illustrative purpose only

There is a compensating effect on other PDFs, e.g., *d* and *dv*

Impact from all CMS 1D: yt, mtt pTt, ytt





For illustrative purpose only