Impact on CT18 global analysis from high-precision Drell-Yan and top-quark pair production data

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C T E Q

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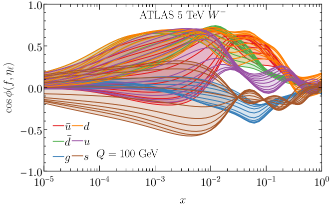
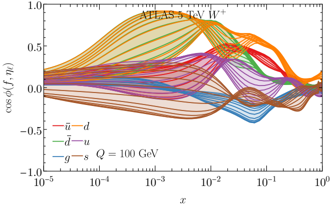
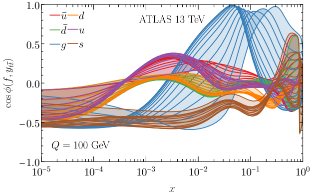
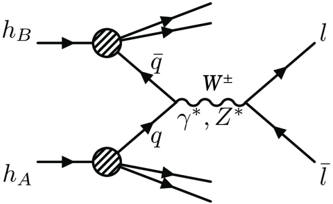
Drell-Yan

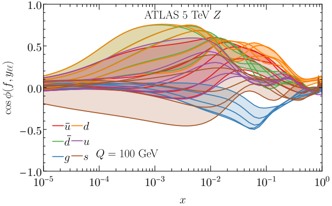


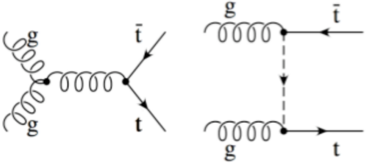


$t\bar{t}$







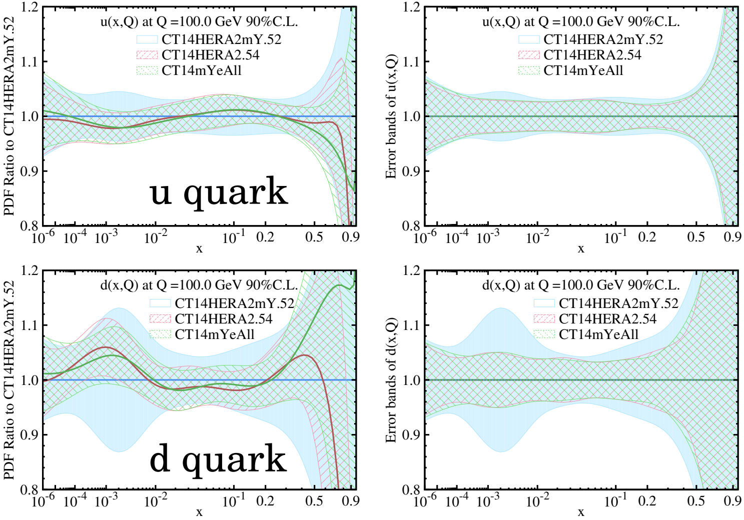


- Drell-Yan data helps constrain quark and anti-quark PDFs.
- $t\bar{t}$ pair production data helps constrain gluon PDF.

Ibrahim Sitiwaldi *et al.*, **PRD108(2023)3,034030, 2305.10733**

Alim Ablat *et al.*, **2307.11153**

CT14

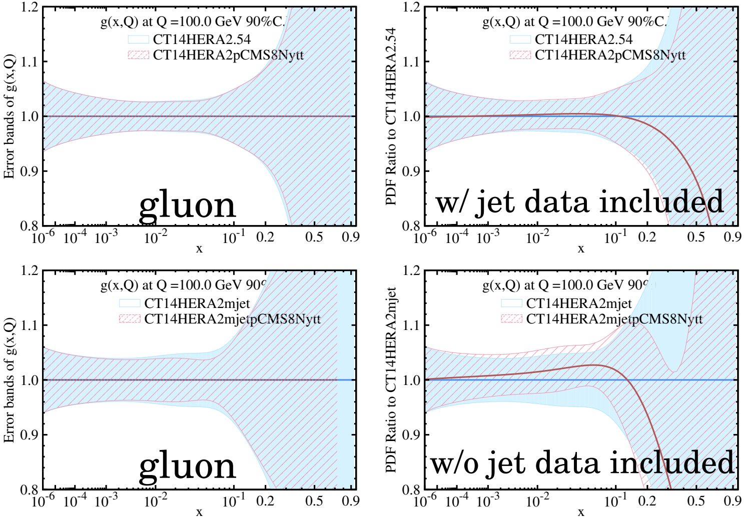


CT14HERA2mY: CT14HERA2 PDFs w/o Drell-Yan data

- Z production data helps constrain $d(\bar{d})$ quark more than $u(\bar{u})$ quark.
- $W^{\pm}$ production data helps constrain the difference/ratio of PDF flavors.

[Tie-Jiun Hou *et al.*, PRD100(2019)11, 114024, 1907.12177]

CT14



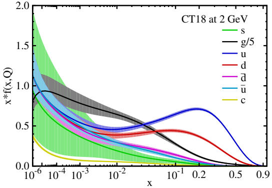
CT14HERA2pCMS8Nytt: CT14HERA2 PDFs with CMS 8 TeV $t\bar{t}$ data ($y_{t\bar{t}}$).

CT14HERA2mjet: CT14HERA2 PDFs w/o incl. jet data

- Due to limited events, the constraint ability of $t\bar{t}$ pair production data on gluon PDF is much smaller as compare to that of the jet data.

[**Musajan Kadir** *et al.*,**CPC45(2021)2,023111,2003.13740**]

CT18 in a nutshell



- Start from **CT14-HERAII**:
  [T.-J. Hou ***et al*****,PRD95,034003(2017)]**
  HERAII combined data released after publication of CT14 **[S. Dulat** ***et al*****,PRD93,033006(2016)]**
- Examine a **wide range of non-perturbative PDF parameterizations**.
- Use as much relevant **LHC Run II data** as possible; using applgrid/ fastNLO interfaces to data sets, with NNLO/NLO K-factors, or fastNNLO tables in the case of top pair (single and double differential) data.
- Implement a **parallelization** of the global PDF fitting to allow for faster turn-around time.
- Use diverse statistical techniques (**PDFSense**, **ePump**, **Gaussian variables**, **Lagrange Multiplier** scans) to examine agreement between experiments.

Data Sets Included in CT18 - Old Data

	160	HERA I+II comb.
	101	BCDMS F_2^p
	102	BCDMS F_2^d
	104	NMC F_2^d/F_2^p
	108†	CDHSW F_2^p
	109†	CDHSW $x_B F_3^p$
	110	CCFR F_2^p
DIS	111	CCFR $x_B F_3^p$
	124	NuTeV $\nu\mu\mu$ SIDIS
	125	NuTeV $\bar{\nu}\mu\mu$ SIDIS
dimuon	126	CCFR $\nu\mu\mu$ SIDIS
	127	CCFR $\bar{\nu}\mu\mu$ SIDIS
	145	H1 σ_r^b
	147	Comb. HERA charm
	169	H1 F_L

	201	E605 Drell-Yan process
	203	E866 Drell-Yan process $\sigma_{pd}/(2\sigma_{pp})$
	204	E866 Drell-Yan process $Q^3 d^2\sigma_{pp}/(dQdx_F)$
	225	CDF Run-1 lepton A_{ch}, $p_{T\ell} > 25$ GeV
	227	CDF Run-2 electron A_{ch}, $p_{T\ell} > 25$ GeV
	234	DØ Run-2 muon A_{ch}, $p_{T\ell} > 20$ GeV
DY	260	DØ Run-2 Z rapidity
	261	CDF Run-2 Z rapidity
	266	CMS 7 TeV 4.7 fb^{-1}, muon A_{ch}, $p_{T\ell} > 35$ GeV
	267	CMS 7 TeV 840 pb^{-1}, electron A_{ch}, $p_{T\ell} > 35$ GeV
	268‡‡	ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}
	281	DØ Run-2 9.7 fb^{-1} electron A_{ch}, $p_{T\ell} > 25$ GeV
Jet	504	CDF Run-2 inclusive jet production
	514	DØ Run-2 inclusive jet production

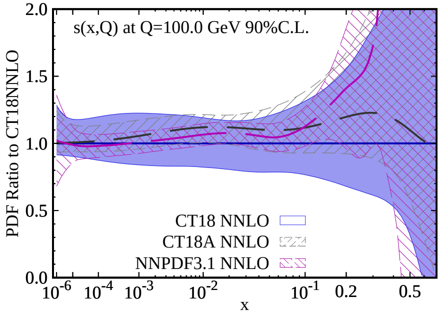
[Tie-Jiun Hou *et al.*,PRD103(2021)1,014013,1912.10053]

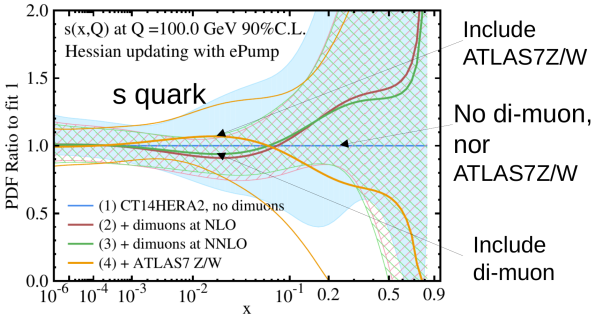
- Old fixed target data still have strong impact on PDFs.

LHC Data Sets Included in CT18 - New Data

DY	253	1512.02192	ATLAS 7 TeV Z p_T
	249	1603.01803	CMS W lepton asymmetry at 8 TeV
	215	1505.07024	LHCb Z (W) muon rapidity at 7 TeV
	246	1503.00963	LHCb 8 TeV Z rapidity
	250	1511.08039	LHCb Z (W) muon rapidity at 8 TeV
Jet	544	1410.8857	ATLAS incl. jet at 7 TeV with R=0.6
	542	1406.0324	CMS incl. jet at 7 TeV with R=0.7
	545	1609.05331	CMS incl. jet at 8 TeV with R=0.7
$t\bar{t}$	573	1703.01630	CMS 8 TeV $t\bar{t}$ (p_T, y_t) double diff. distributions
	580	1511.04716	ATLAS 8 TeV $t\bar{t}$ p_T and $m_{t\bar{t}}$ diff. distributions
	248	1612.03016	ATLAS 7 TeV Z and W rapidity $\rightarrow$ **CT18A PDFs**

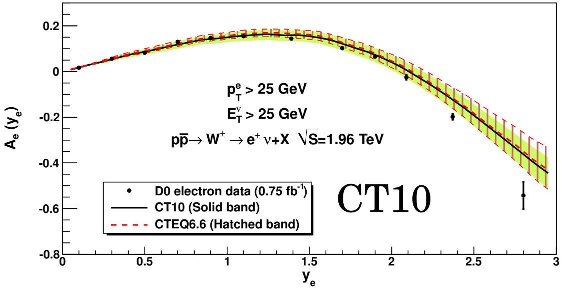
[Tie-Jiun Hou *et al.*,**PRD103(2021)1,014013,1912.10053]**

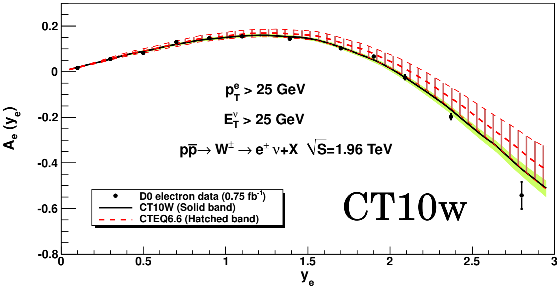




[Tie-Jiun Hou *et al.*,PRD103(2021)1, 014013, 1912.10053]

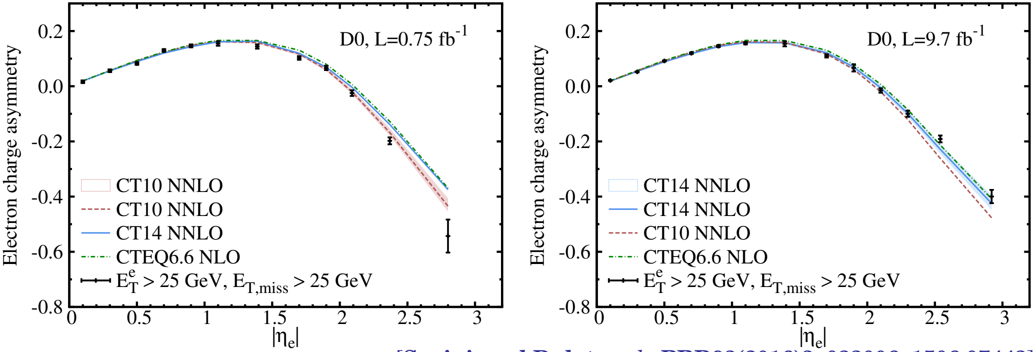
- The inclusion of the ATLAS 7 TeV Z/W data resulting an significant enhancement in strange PDF in middle x region.
- Noticeable tensions between the SIDIS di-muon data and the precision ATLAS 7 TeV Z/W data were found in global analysis.
- This lead us to split the CT18 PDFs into two branches: **CT18**, which constains no ATLAS 7 Z/W data, and 18A, which contains ATLAS 7 Z/W data.





- The CTEQ6.6 PDFs can not describe the DØ Run II W asymmetry data, $L = 0.75\ \text{fb}^{-1}$, **[DØ, PRL101, 211801(2008)]** well.
- This lead to two branches of CT10 PDFs:
  CT10: w/o the DØ data.
  CT10w, w/ the DØ data.

[Hung-Liang Lai *et al.*, PRD82(2010)074024, 1007.2241]



[Sayipjamal Dulat *et al.*, PRD93(2016)3, 033006, 1506.07443]

- The DØ updated data **[DØ,PRD91(2015)3,032007]**, $L = 9.7\ \text{fb}^{-1}$ superseed the old one.
- The new DØ data has better agreement with CTEQ6.6 and CT10 PDFs than CT10w PDFs.
- The new DØ data has been included in CT14 PDFs (and subsequent PDFs).

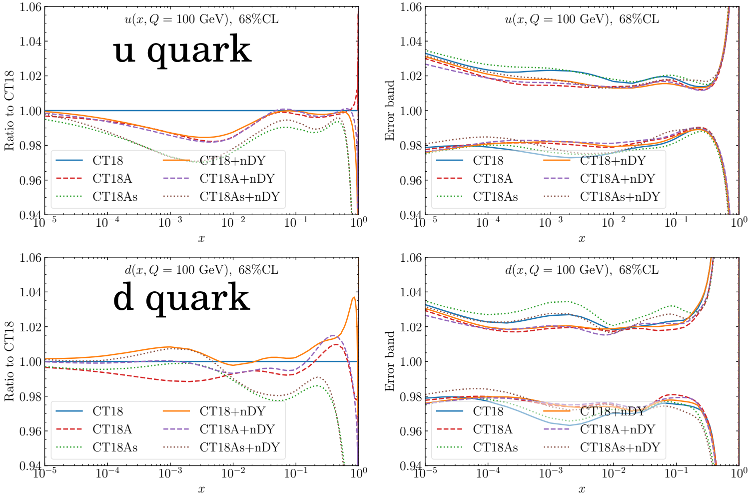
New Drell-Yan Data Post-CT18

215	ATL5WZ	1810.08424	ATLAS W and Z lepton rapidity at 5.02 TeV
211	ATL8W	1904.05631	ATLAS W muon pseudo-rapidity at 8 TeV
214	ATL8Z3D	1710.05167	ATLAS Z m_{ll}-y_{ll}-$\cos\theta^*$ at 8 TeV
212	CMS13Z	1909.04133	CMS Z rapidity at 13 TeV
216	LHCb8W	1608.01484	LHCb forward electron pseudo-rapidity at 8 TeV
213	LHCb13Z	1607.06495	LHCb forward Z lepton rapidity at 13 TeV

Ibrahim Sitiwaldi *et al.*, PRD108(2023)3, 034030, 2305.10733

- Using the framework of CT18, leave the parametrization for the future study.
- We mainly focus on the (pseudo-)rapidity distribution in this work.
- NNLO = NLO(Applgrid, MCFM 6.8) $\times K\left(\frac{\text{NNLO(Resbos2, N3LL)}}{\text{NLO(MCFM 6.8)}}\right)$ (Theory prediction of ATL8Z3D was obtained from ATLAS directly. NNLO QCD and NLO EW corrections are folded into the K-factors with NNLOjet)

Impact of the DY Data: CT18 or CT18A?



CT18: w/o ATL7ZW

CT18A: w/ ATL7ZW

CT18As: CT18A w/ s asym.

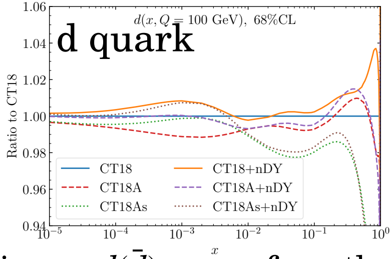
nDY: All new DY data sets

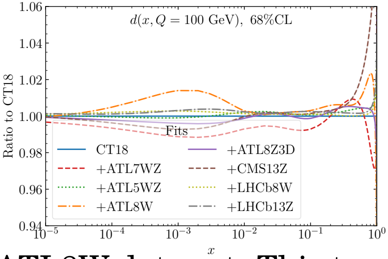
- New DY data drive new fitted PDFs closer to CT18A PDFs rather than CT18 PDFs.

Impact of the DY Data: CT18 or CT18A?

ID	Experiment	$N_{\rm pt}$	$\chi^2/N_{\rm pt}$				
			Pre-fit†	ePump†	CT18	CT18A	CT18As
215	ATLAS 5.02 TeV W, Z	27	1.15	0.96	1.07	0.74	0.71
211	ATLAS 8 TeV W	22	4.96	2.98	2.46	2.72	2.49
214	ATLAS 8 TeV Z 3D	188	1.95	1.18	1.16	1.13	1.14
212	CMS 13 TeV Z	12	9.24	2.93	2.75	1.89	2.02
216	LHCb 8 TeV W	(16)14	(3.48)1.52	(3.24)1.45	(2.81)1.33	(1.89)1.45	(3.00)1.52
	LHCb 13 TeV Z	18	0.89	0.88	0.99	0.92	0.90
213	LHCb 13 TeV $Z \to \mu^+\mu^-$	(18)16	(2.39)1.27	(2.33)1.17	(2.55)1.12	(2.49)1.12	(2.28)0.87

+nDY



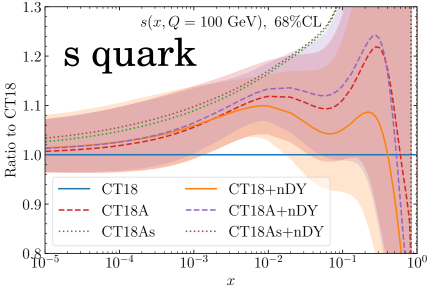


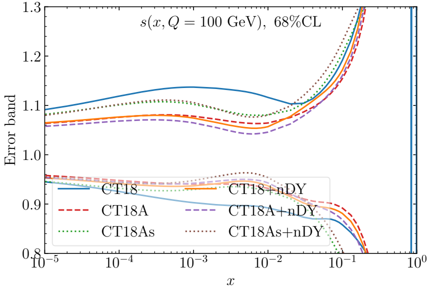
+ individual data sets

- Tension on $d(\bar{d})$ comes from the ATL8W data set. This tension can be relased by more flexibility in $s(\bar{s})$ quark degree of freedom.

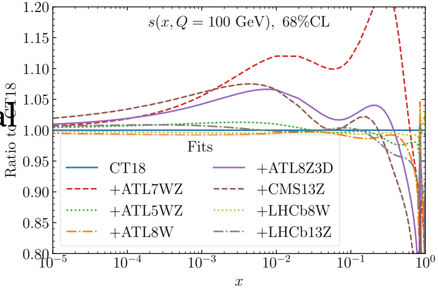
Impact of the DY Data: CT18 or CT18A?

+nDY



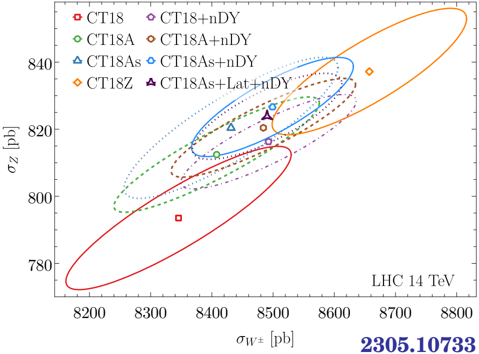


+ individual data sets



- The new Drell-Yan data sets drive the strange PDF closer to CT18A than CT18.
- Mild tension in the strange PDF comes from the ATL8W and LHCb8W data sets.

Standard Candles: σ_Z v.s. σ_W



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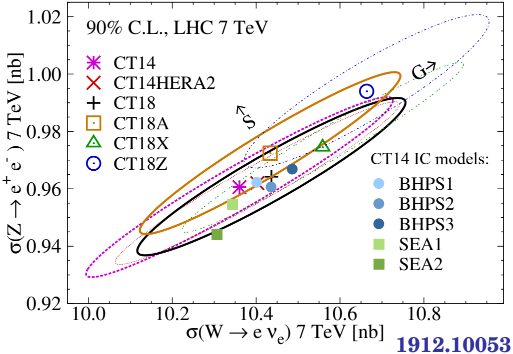


1912.10053

Semi-major axis: $\sigma_Z + \sigma_{W^\pm}$, is most related to the gluon PDF.
Semi-minor axis: $\sigma_Z / \sigma_{W^\pm}$, is most related to the strange PDF

- The new Drell-Yan data sets drive the CT18 to the direction of more gluon and stange PDFs.

New $t\bar{t}$ Pair Production Data Post-CT18

532	ATL13lj	1908.07305	ATLAS lepton+jets channel at 13 TeV CMS-bin
587	ATL13lj	1908.07305	ATLAS lepton+jets channel at 13 TeV ATL-bin
521	ATL13had	2006.09274	ATLAS all-hadronic channel at 13 TeV
528	CMS13ll	1811.06625	CMS dilepton channel at 13 TeV
581	CMS13lj	2108.02803	CMS lepton + jets channel at 13 TeV

Alim Ablat *et al.*, 2307.11153.

ATL13lj:

- We concern the $m_{t\bar{t}}, y_{t\bar{t}}, y_{t\bar{t}}^{Boost} = \frac{1}{2}(y^{t,had} + y^{t,lep})$ and $H_T^{t\bar{t}} = p_T^{t,had} + P_T^{t,lep}$ distributions, where *had* and *lep* refered to the hadronically and leptonically decaying top quarks.
- Two bin resolutions:

Npts	$m_{t\bar{t}}$	$y_{t\bar{t}}$	$y_{t\bar{t}}^{Boost}$	$H_T^{t\bar{t}}$
ATL bin	9	7	9	9
CMS bin	7	10	6	10

- Bin-by-bin statistical correlations are made available for ATL bin.

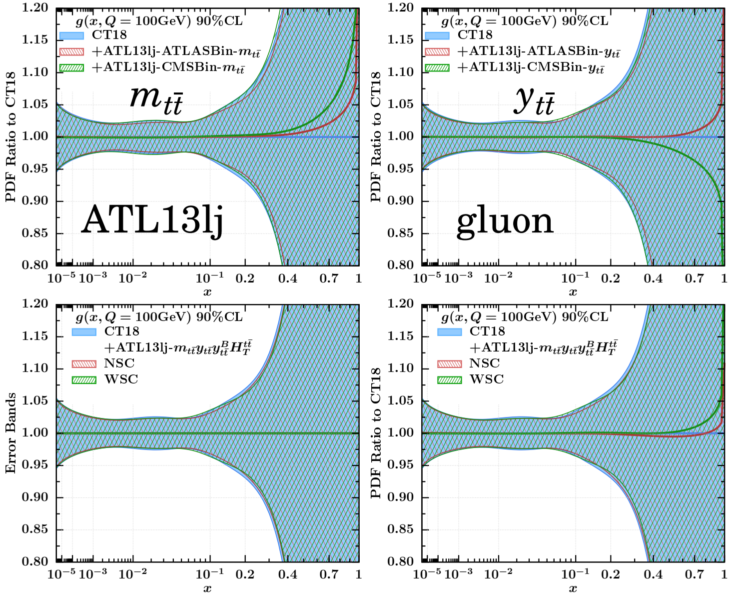
New $t\bar{t}$ Pair Production Data Post-CT18

- Distributions concerned in this work:
  CMS13ll: $m_{t\bar{t}}, y_{t\bar{t}}, p_{T,t}(p_{T,\bar{t}}), y_t(y_{\bar{t}})$
  CMS13lj: $m_{t\bar{t}}, y_{t\bar{t}}$
  ATL13had: $m_{t\bar{t}}, y_{t\bar{t}}, H_T^{t\bar{t}} = p_{T,t} + p_{T,\bar{t}}, p_{T,t_1}, p_{T,t_2}$
  The $p_{T,t_1(t_2)}$ is the p_T of the leading (trailing) top quark.

- Using the framework of CT18, leave the parametrization for the future study.

- NNLO=NLO(Applgrid, MCFM 6.8) $\times K\left(\frac{\text{NNLO(MATRIX)}}{\text{NLO(MCFM 6.8)}}\right)$
  (q_T-subtraction method. 1711.06631)

- Central-scale choices $\mu_R = \mu_F = H_T/4$ or $H_T/2$ are examined.

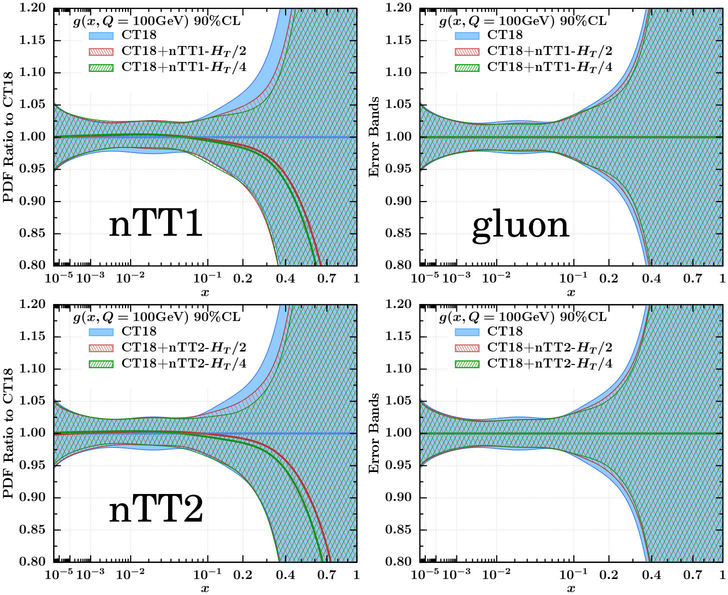


NSC: w/o statistical correlations

WSC: w/ statistical correlations

2307.11153

- The ATL13lj data provide minor impact to gluon PDF in large x region.
- The difference between CMS bin and ATL bin is mild.
- Statistical correlations have a negligible impact on the gluon PDF errors.



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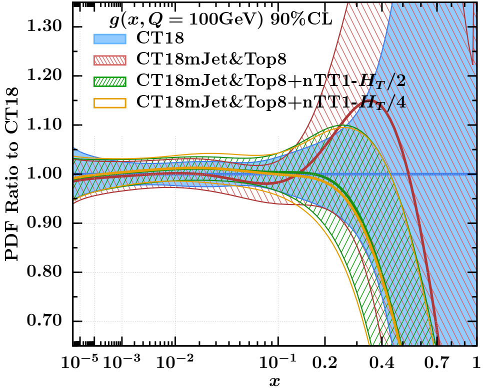
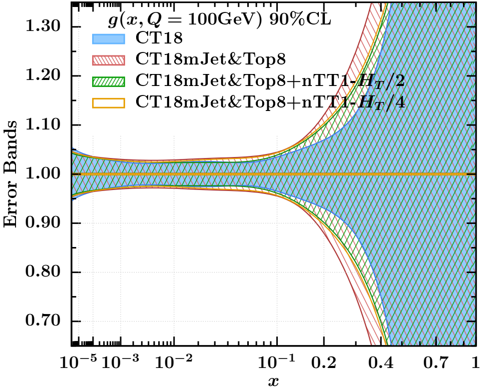
nTT1 = ATL13had-$y_{t\bar{t}}$ + CMS13ll-$y_{t\bar{t}}$ + CMS13lj-$m_{t\bar{t}}$ + ATL13lj-$y_{t\bar{t}}$(CMS bin)

nTT2 = ATL13had-$y_{t\bar{t}}$ + CMS13ll-$y_{t\bar{t}}$ + CMS13lj-$m_{t\bar{t}}$ + ATL13lj-$y_{t\bar{t}} + y^B_{t\bar{t}} + m_{t\bar{t}} + H_T^{t\bar{t}}$ w/o stat. corr. (ATL bin)

- New $t\bar{t}$ data prefer softer gluon for $x > 0.2$.
- Stronger ability to reduce the uncertainty of gluon PDF as compare to that in CT18.





CT18mJetTop8: CT18 w/o jet and $t\bar{t}$ data.

- New $t\bar{t}$ data prefer softer gluon for $x > 0.2$ as compare to jet data.
- New $t\bar{t}$ data provide similar constraints in the middle x region on central PDF and uncertainty as jet data.

Summary

- Using the framework of CT18, we examined the high-precision Drell-Yan and top-quark pair production data and left the parametrization for the future study.
- The impact of the new Drell-Yan data on the CT18 strangeness PDF is consistent with ATL7WZ in the CT18A fit. Tension with the ATL7WZ data on the $\bar{d}(d)$ PDF is observed, driven by the ATL8W data.
- New $t\bar{t}$ pair production data prefer softer gluon PDF in the large x region, and they complement that of inclusive jet production data. In the end, the new $t\bar{t}$ pair production data provide a mild impact in reducing the uncertainty of gluon PDF as compared to inclusive jet production data.