New CTEQ Global Analysis with High Precision Data from the LHC

Tie-Jiun Hou

Northeastern University

June 27, 2019
EDS Blois 2019, ICISE, Quy Nhon

CTEQ-TEA group

- CTEQ – Tung et al. (TEA)
  in memory of Prof. Wu-Ki Tung, who established CTEQ Collaboration in early 90's.

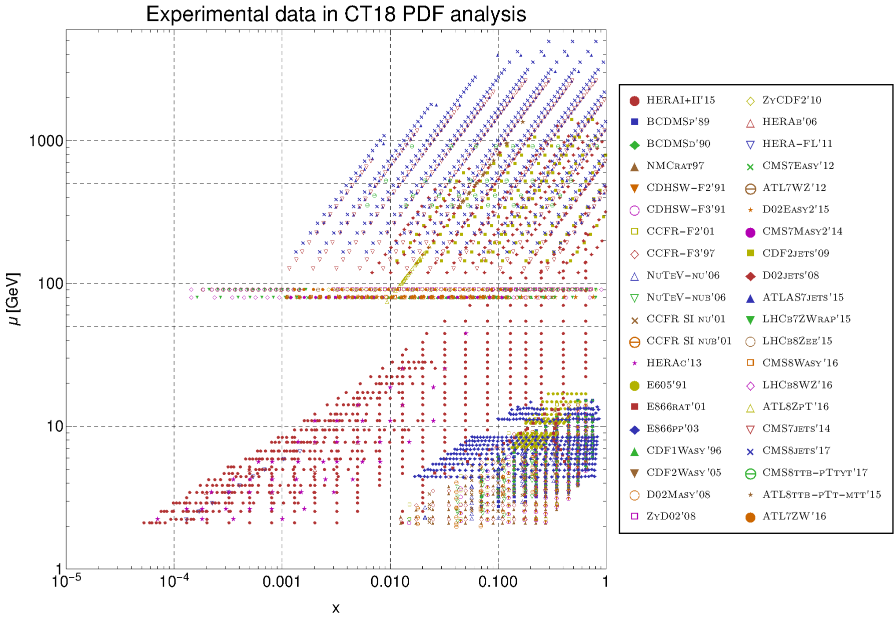
- Current members:
  Tie-Jiun Hou (Northeastern U., China)
  Sayipjamal Dulat, Ibrahim Sitiwaldi (Xinjiang U.)
  Jun Gao (Shanghai Jiaotong U.)
  Marco Guzzi (Kennesaw State U.)
  Timothy Hobbs, Pavel Nadolsky, Boting Wang, Keping Xie (Southern Methodist U.)
  Joey Huston, Jon Pumplin, Carl Schmidt, Dan Stump, Jan Winter, C.-P. Yuan (Michigan State U.)

CT18 in a nutshell

- Start with CT14-HERAII (HERAII combined data released after publication of CT14)
- Use as much relevant LHC 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
- Examine a wide range of non-perturbative PDF parameterizations
- Implement a parallelization of the global PDF fitting to allow for faster turn-around time
- Lagrange Multiplier studies to examine constraints of specific data sets on PDF distributions, or on $\alpha_s(m_z)$ and (in some case) the tensions (useful information)

LHC data sets included in CT18

245	1505.07024	LHCb Z (W) muon rapidity at 7 TeV(applgrid)
246	1503.00963	LHCb 8 TeV Z rapidity (applgrid);
249	1603.01803	CMS W lepton asymmetry at 8 TeV (applgrid)
250	1511.08039	LHCb Z (W) muon rapidity at 8 TeV(applgrid)
253	1512.02192	ATLAS 7 TeV Z p_T (applgrid)
542	1406.0324	CMS incl. jet at 7 TeV with R=0.7 (fastNLO)
544	1410.8857	ATLAS incl. jet at 7 TeV with R=0.6 (applgrid)
545	1609.05331	CMS incl. jet at 8 TeV with R=0.7 (fastNLO)
573	1703.01630	CMS 8 TeV $t\bar{t}$ (p_T, y_t) double diff. distributions (fastNNLO)
580	1511.04716	ATLAS 8 TeV $t\bar{t}$ p_T and $m_{t\bar{t}}$ diff. distributions (fastNNLO)
248	1612.03016	ATLAS 7 TeV Z and W rapidity (applgrid) $\rightarrow$ CT18Z PDFs

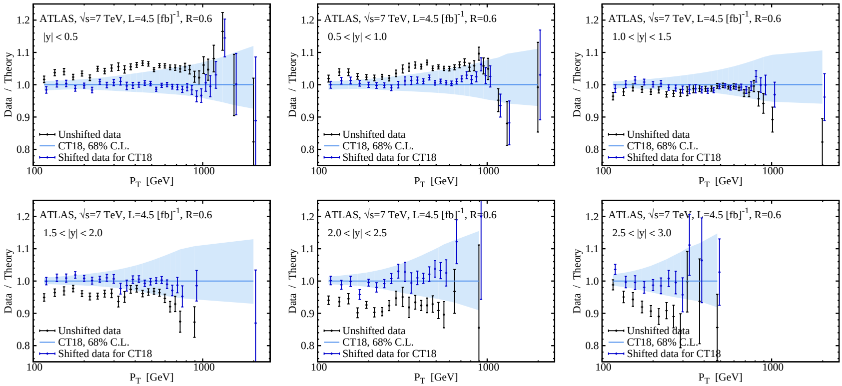


Experimental data in CT18 PDF analysis
μ [GeV]
x
1000
100
10
1
10⁻⁵
10⁻⁴
0.001
0.010
0.100
1
HERAI+II'15
BCDMSp'89
BCDMSd'90
NMCrat97
CDHSW-F2'91
CDHSW-F3'91
CCFR-F2'01
CCFR-F3'97
NuTeV-nu'06
NuTeV-nub'06
CCFR SI nu'01
CCFR SI nub'01
HERAc'13
E605'91
E866rat'01
E866pp'03
CDF1Wasy'96
CDF2Wasy'05
D02Masy'08
ZyD02'08
ZyCDF2'10
HERAb'06
HERA-FL'11
CMS7Easy'12
ATL7WZ'12
D02Easy2'15
CMS7Masy2'14
CDF2jets'09
D02jets'08
ATLAS7jets'15
LHCb7ZWrap'15
LHCb8Zee'15
CMS8Wasy'16
LHCb8WZ'16
ATL8ZpT'16
CMS7jets'14
CMS8jets'17
CMS8ttb-pTtyt'17
ATL8ttb-pTt-mtt'15
ATL7ZW'16

CT18 LHC data treatment

- CT18 analysis includes new LHC experiments on W/Z, high-pT Z, jet, $t\bar{t}$ production; up to 30 candidate LHC data sets available
- The challenge is to select and implement relevant and consistent experiments
- PDFSense (arXiv:1803.02777) to determine quantitatively which data will have impact on global PDF fit
- ePump (arXiv:1806.07950) on quickly exploring the impact of data prior to global fit within the Hessian approximation
- Good agreement between PDFSense, ePump results and global fit
- We include as large a rapidity interval for the ATLAS jet data as we can, using the ATLAS de-correlation model, rather than using a single rapidity interval. Using a single rapidity interval may result in selection bias.
- We use two $t\bar{t}$ single differential observables from ATLAS (using statistical correlations) and double differential measurement from CMS in order to include as much information as possible. Again, there is a risk of bias, as some of the observables are in tension with each other.
- Previous data continue having an impact on global fits and tend to dilute the impact of new data

De-correlation for incl. jet



- The corr. error "jes16" and "jes62" of ATLAS 7 TeV incl. jet data are decorrelated according to Table 6 of 1706.03192. Its χ^2/Npts reduces from 2.34 to 1.68 for CT14HERA2NNLO.

Treatment of LHC inclusive jet production data – **systematic error sources** and **de-correlations**

- **CMS, 7 TeV jet production** (ID 542) $N_{pt} = 158$

we de-correlate a Jet Energy Correction, JEC2 (`e05') according to arXiv:1410.6765 [hep-ex]

→ implement an additional, CMS-advocated de-correlation for $|y| > 2.5$

- **CMS, 8 TeV jet production** (ID 545) $N_{pt} = 185$

→ systematics treated in xFITTER as per CMS literature, arXiv:1607.03663 [hep-ex]

- **ATLAS, 7 TeV jet production** (ID 544) $N_{pt} = 140$

following ATLAS recommendations, de-correlate two Jet Energy Scale (JES) uncertainties, MJB fragm. (`jes16') and flavor response (`jes62'), according to arXiv:1706.03192 [hep-ex]

e.g., $\delta_{16} \to \delta_{16}^{a},\ \delta_{16}^{b},\ \delta_{16}^{c}$

$$\delta_{16}^{a} = f^{a}(|y|, p_T)\,\delta_{16}$$

→ de-correlation improves χ^2 by **~92 units** ; inclusion of a 0.5% theory error, another **~52**

χ^2/N_{pt}	evaluated, **CT14 HERA2 NNLO** original data	+ decorr.	+ 0.5% MC unc.	fitted, **CT18 prel. NNLO** with decorr./MC unc.
CMS, 7 TeV	1.58	1.45	1.35	1.29
CMS, 8 TeV	1.90	1.34	1.23	1.38
ATLAS, 7 TeV	2.34	1.68	1.31	1.46

Selected Top Quark Pair Observables from ATLAS and CMS

- Modest effect observed if t-tbar data are included together with the Tevatron and LHC jet production data.
- Its impact on gluon PDF is consistent with jet data, though jet data provide stronger constraint.
- For ATLAS 8 TeV, select the p_T and $m_{t\bar{t}}$ distributions that directly probes large-x region; statistical correlations are included in order to fit p_T and $m_{t\bar{t}}$ simultaneously; fully correlated for experimental systematics except for decorrelation of PS sys. error.

χ^2/Npts (with CT18 PDFs)	nominal	w/o PS decorrelation	w/o statistical correlation
ATLAS 8 TeV abs. $d\sigma/dp_T$ and $d\sigma/dm_{t\bar{t}}$ (Npts=15)	0.62	3.55	0.51
CMS 8 TeV nor. $d\sigma/dp_T dy_t$ (Npts=16)	1.18	-	-

Resources from xFitter

- Correlated systematic uncertainties are implemented using the covariance matrices from xFitter in the following experiments

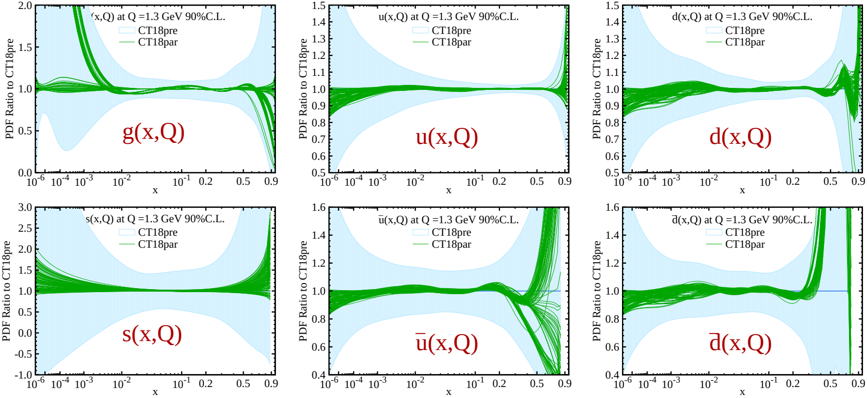
- ATLAS 7 TeV WZ xsec $4.6fb^{-1}$ (ID 248) 1612.03016
- CMS 8 TeV W($\rightarrow \mu\nu$) Asym. $18.8fb^{-1}$ (ID 249) 1603.01803
- LHCb (7,8) TeV WZ (μ-chan.) $(1,2)fb^{-1}$ (ID 245,250) 1505.07024, 1511.08039
- CMS 8 TeV Jet $19.7fb^{-1}$ (ID 545) 1609.05331, xFitter is the only resource to get its corr. sys. errors.

Theory calculations @NNLO

Obs.	Expt.	fast table	NLO code	K-factors	R,F scales
Inclusive jet	ATL 7 CMS 7/8	APPLgrid fastNLO	NLOJet++	NNLOJet	p_T, p_T^1
p_T^Z	ATL 8	APPLgrid	MCFM	NNLOJet	$\sqrt{Q^2 + p_{T,Z}^2}$
W/Z rapidity W asymmetry	LHCb 7/8 ATL 7 CMS 8	APPLgrid	MCFM/aMCfast	FEWZ/MCFM	$M_{W,Z}$
DY (low,high mass)	ATL 7/8 CMS 8	APPLgrid	MCFM/aMCfast	FEWZ/MCFM	Q_{ll}
$t\bar{t}$	ATL 8 CMS 8	fastNNLO			$\frac{H_T}{4}, \frac{m_T}{2}$

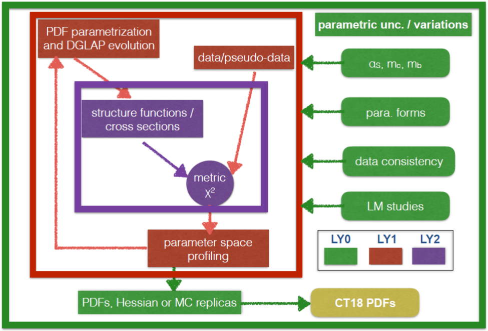
- Studies of QCD scale dependence and other theory uncertainties for DIS, high-p_T Z, jet production
- An uncorrelated error of 0.5% is included for:
  ATLAS 7 TeV and CMS 7/8 TeV jet production, and
  ATLAS 8 TeV high-p_T Z production to account for numerical uncertainties in the MC integration of NNLO cross sections.
- Alternative renormalization/factorization scale choices were examined in high-p_T Z production, do not significantly alter the conclusions.

Explore various non-perturbative parametrization forms of PDFs



- CT18 – sample result of exploring various non-perturbative parametrization forms.
- There is no data to constrain very large or very small x region.

Fitting code parallelization with multi-threads

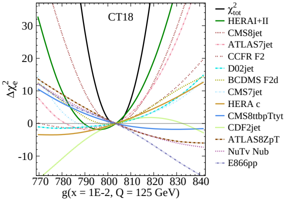


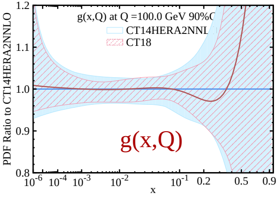
Typical 3-layer structure of the CT18 global analysis, from various scans to global minimization, then to the chi2 calculations upgrade to a parallelized version of the fitting code, two-layer parallelization:

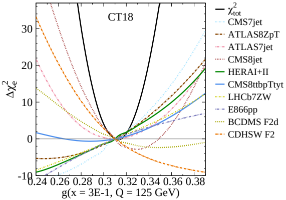
- LY1, through rearrangement of the minimization algorithm, a factor of 4 5 improvement on speed;
- LY2, via redistribution of the data sets, further improved by a factor of 2

$\rightarrow$ About a factor of 10 improvement in speed

Preview of CT18 PDFs (g-PDF)



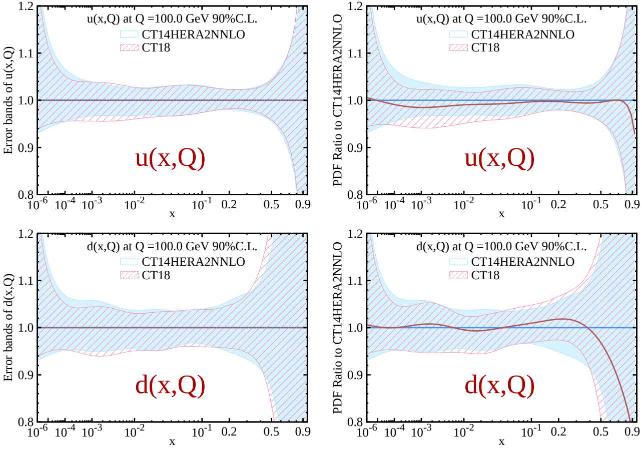




Lagrange Multiplier Scans

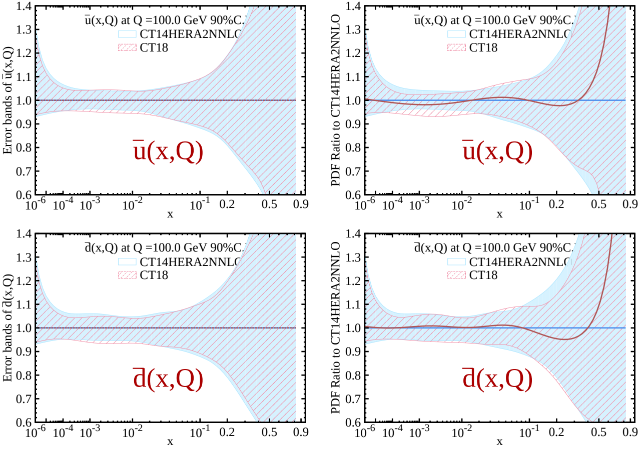
- At x around 0.01, ATLAS8 Z p_T data prefer a slightly larger gluon PDF.
- At x around 0.3, competing with the CDHSW F_2 and Tevatron jet data, which prefer larger gluon, the ATLAS7 jet, CMS7 jet and ATLAS8 Z p_T data prefer a smaller gluon; some tension found in CMS7 and CMS8 jet data.
- The gluon PDF as $x \to 1$ is parametrization form dependent.

Preview of CT18 (u-PDF and d-PDF)



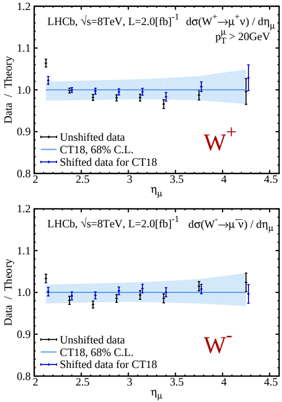
- Some changes on u and d at small x, and d around 0.2; mainly come from LHCb W and Z rapidity data, at 7 and 8 TeV.

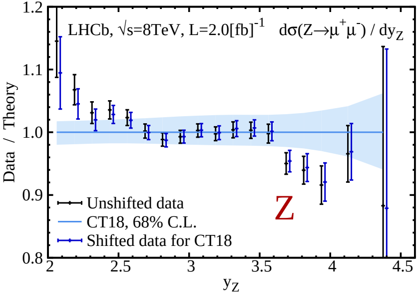
Preview of CT18 ($\bar{u}$-PDF and $\bar{d}$-PDF)



- Minor changes on ubar and dbar PDFs at small x region mainly come from LHCb W and Z rapidity data, at 7 and 8 TeV.
- The behavior of ubar and dbar PDFs, as $x \to 1$, is parametrization form dependent.

LHCb 8 TeV W and Z data in CT18 fit

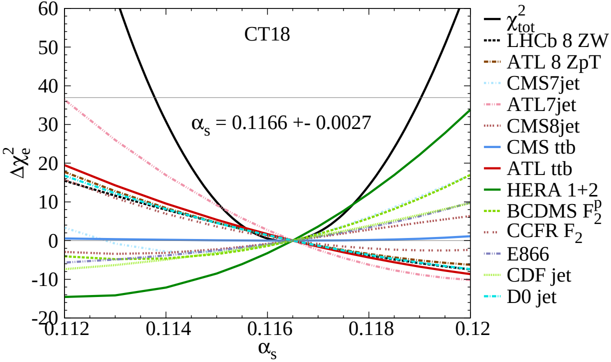




arXiv:1511.08039

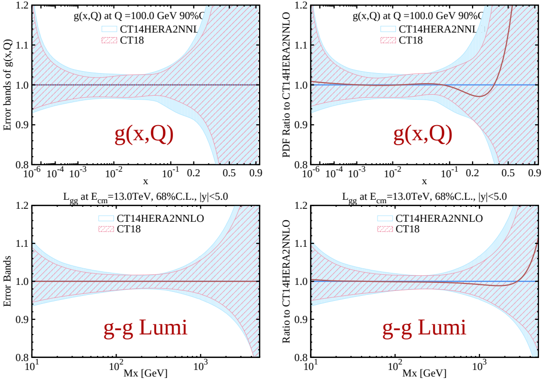
- Z data dominate the fit.
- Not able to fit some large Z rapidity
- Show slight tension with CCFR F2 and CMS 7 TeV W-lepton asymmetry data

$\alpha_s(M_z)$



- The fixed target F_2 data and HERA DIS data prefer smaller α_s value.
- The ATLAS 8TeV Z p_T, ATLAS 7 TeV incl. jet data, bring the central value of $\alpha_s(M_z)$ from $0.115^{+0.006}_{-0.004}$ (CT14) to 0.1166 ± 0.0027 (CT18).

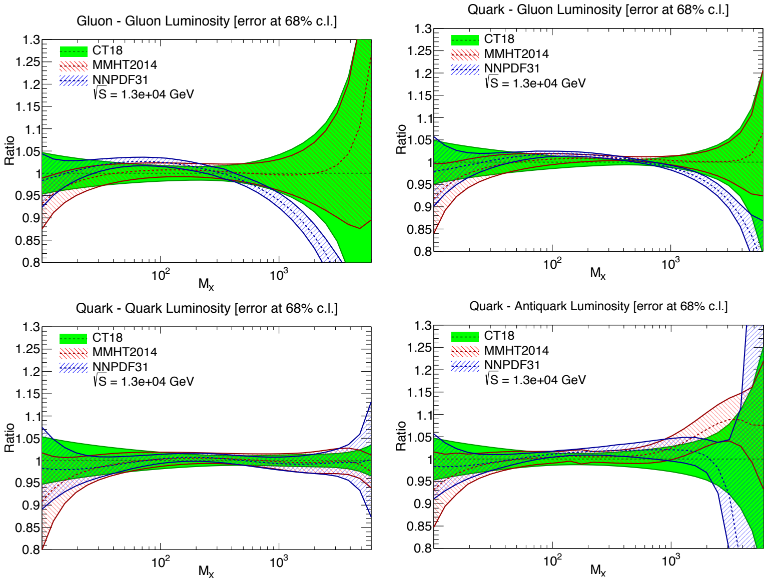
$\sigma(gg \to H)$ CT18 v.s. CT14



	$\sigma(gg \to h)$ 7 TeV
CT14	14.67 $\pm$0.46
CT18	14.57 $\pm$0.44
	$\sigma(gg \to h)$ 8 TeV
CT14	18.70 $\pm$0.57
CT18	18.45 $\pm$0.55
	$\sigma(gg \to h)$ 13 TeV
CT14	42.78 $\pm$1.32
CT18	42.43 $\pm$1.26
	$\sigma(gg \to h)$ 14 TeV
CT14	48.23 $\pm$1.50
CT18	47.91 $\pm$1.42

- PDF induced errors (at 90% $C.L.$) are reduced by about 5% as compared to CT14 predictions.

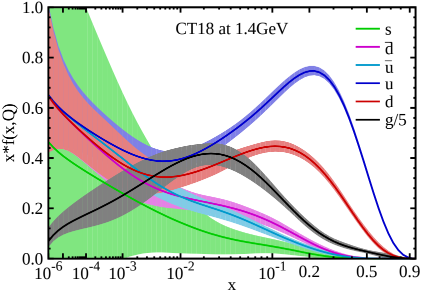
PDF Luminosities at 13 TeV LHC CT18, MMHT14 and NNPDF3.1

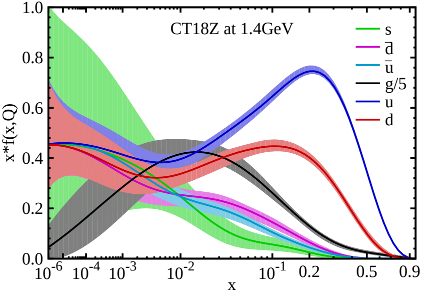


CT18Z
LHC data treatment

- Start with CT18 data set
- Add in ATLAS 7 TeV W and Z rapidity data (arXiv:1612.03016; $4.6fb^{-1}$); large $\chi^2/d.o.f \sim 2.1$
- Remove CDHSW data
- Use a special x-dependent factorization scale mDIS,x at NNLO calculation
- CT18Z uses a combination of mDIS,x (preferred by DIS) and an increased $m_c^{pole} = 1.4$ GeV (preferred by LHC vector boson production, disfavored by DIS)

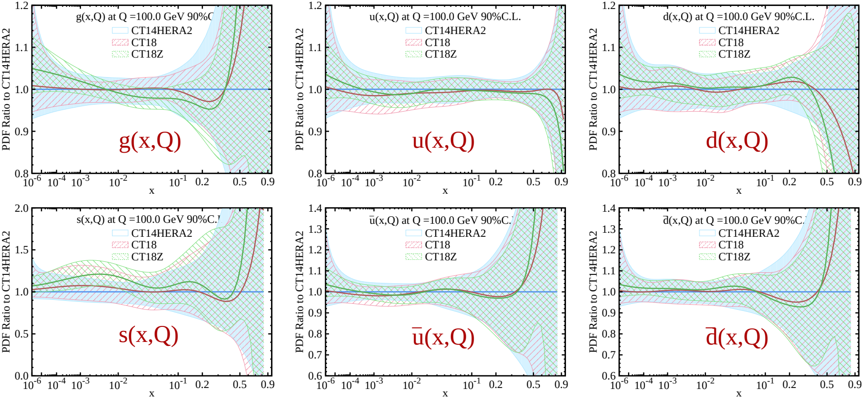
PDF uncertainty bands
CT18 vs. CT18Z





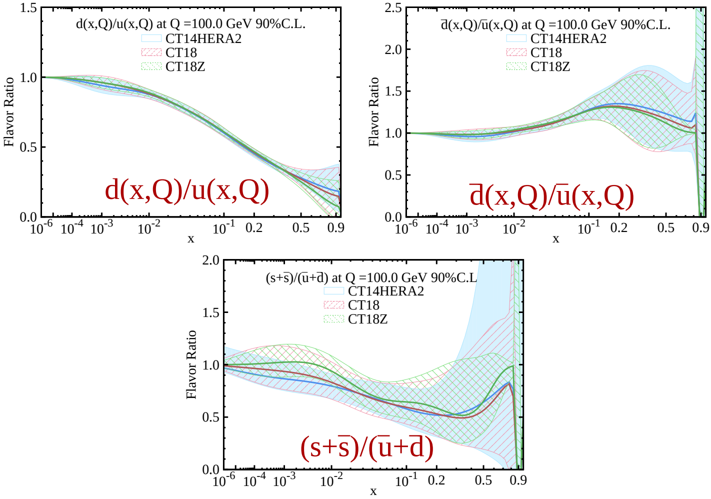
CT18Z has enhanced gluon, u-, d- and s-PDFs at $x \sim 10^{-4}$, and reduced g-PDFs at $x > 10^{-2}$. The CT18Z fit is performed so as to maximize the differences from CT18 PDFs, while preserving about the same goodness-of-fit as for CT18 analysis.

CT18Z vs.CT18 PDFs



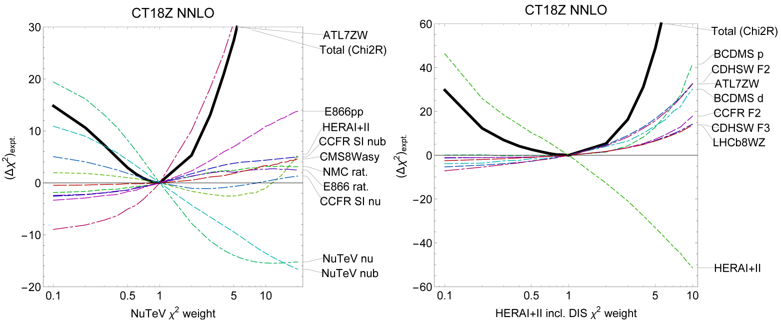
- G increases at small-x, and decreases at $x \sim 0.010.3$
- u and d increase at small-x
- d increases at $x \sim 0.2 - 0.3$
- s increases at small-x

CT18Z vs.CT18 PDFs



- d/u decreases at large-x
- r_s increases at small-x

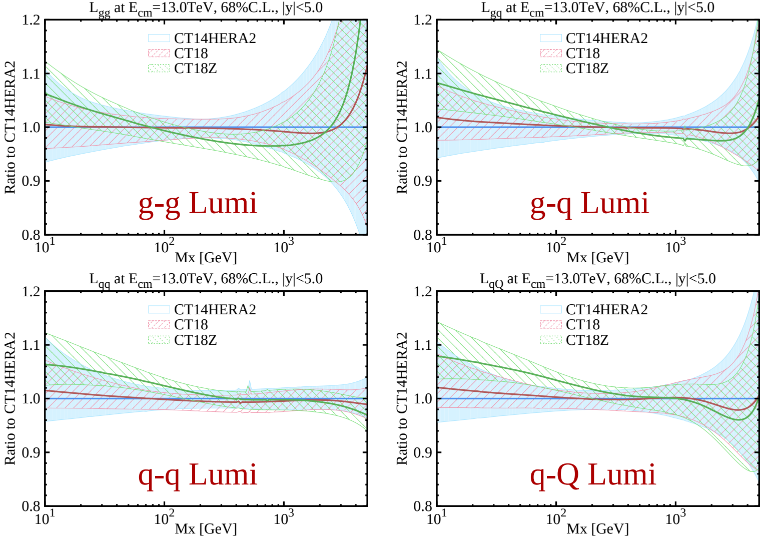
CT18Z fit



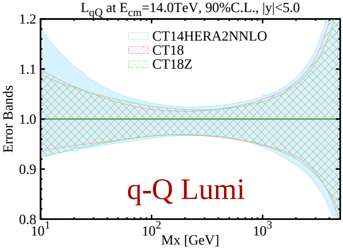
NuTeV χ^2 weight HERA I+II incl. DIS χ^2 weight

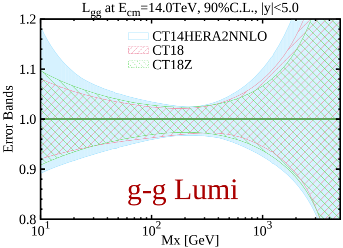
- ATLAS 7 TeV W and Z rapidity data have obvious tensions with NuTeV di-muon data; and some tension with HERA I+II data.

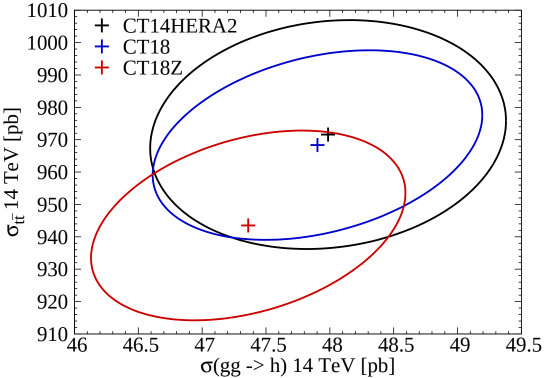
PDF Luminosities at 13 TeV LHC
CT14HERA2, CT18 and CT18Z



Mild reduction in nominal PDF error bands and cross section uncertainties







Summary

- A new CT18 PDF analysis is ready for its public release.
- The CT18 PDF uncertainty is mildly reduced at NNLO compared to the CT14 PDF uncertainty.
- 700+ data points from 12 new LHC data sets. The LHC constraints on the CT18 PDFs are weaken by some inconsistencies between the LHC data sets and the pre-LHC data sets.
- HERA DIS and fixed-target experiments deliver key constraints on CT18 PDFs.
- We observe some impact on PDFs from ATLAS and CMS incl. jet data, ATLAS, CMS, LHCb W/Z data and ATLAS 8 TeV Z p_T data. LHC top quark pair data provides a similar impact to g-PDF as incl. jet data, but cannot reduce g-PDF errors as strong as incl. jet data due to its much smaller number of data points.
- ATLAS 7 TeV W and Z rapidity data is included in the CT18Z PDF analysis.