CTEQ

New CTEQ Global Analysis with High Precision Data from the LHC

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WG1 @ DIS2019

CTEQ – Tung et al. (TEA)
in memory of Prof. Wu-Ki Tung

CTEQ-TEA group

- CTEQ – Tung et al. (TEA)

in memory of Prof. Wu-Ki Tung,

who co-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.), Tim Hobbs, Pavel Nadolsky, Bo-Ting Wang, Keping Xie (Southern Methodist U.), Joey Huston, Jon Pumplin, Dan Stump, Carl Schmidt, Jan Winter, CPY (Michigan State U.)

Outline

- CT18 in a nutshell
- LHC data set included after CT14
- Theory calculations @ NNLO
- Explore non-perturbative function forms
- Preview of CT18 PDFs
- α_s in CT18
- $gg \rightarrow H$ cross section
- Parton luminosities at the LHC
- CT18Z
- Impact of LHC top quark data (See talk by T.-J. Hou at WG1)
- PDFsense and ePump (See talk by P. Nadolsky at WG1)
- Summary

CT18 in a nutshell

- Start with CT14-HERAII (HERAII combined data released after publication of CT14)
- Examine a wide range of non-perturbative PDF parameterizations
- 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 ➡ compared to NNLO theory predictions.
- 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
- Implement a parallelization of the global PDF fitting to allow for faster turn-around time (X10)
- Lagrange Multiplier studies to examine constraints of specific data sets on PDF distributions, or on $\alpha_s(m_Z)$ and (in some cases) the tensions (useful information)

LHC data sets included in CT18

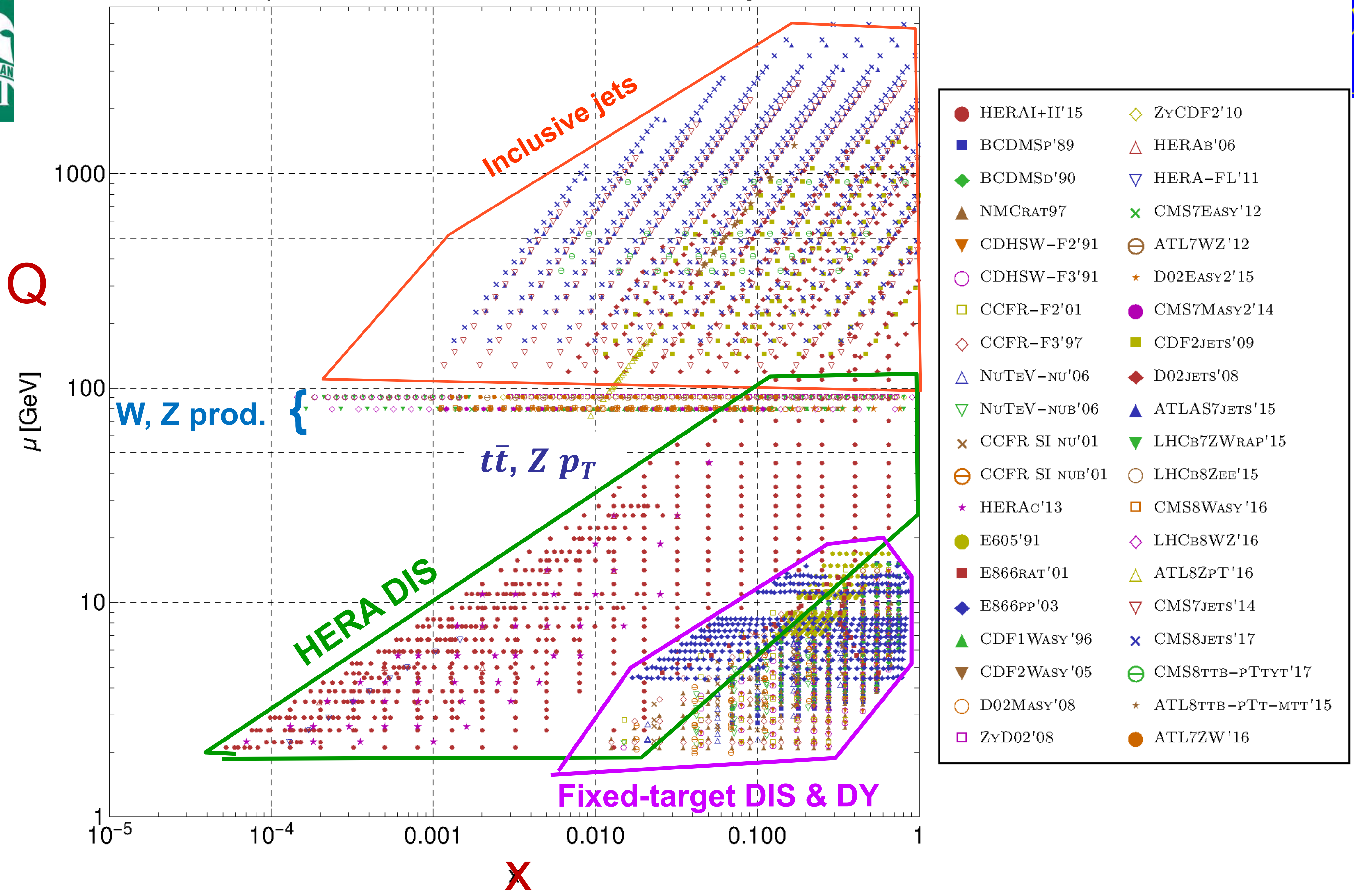
245 1505.07024 LHCb Z (W) muon rapidity at 7 TeV(applgrid)
246 1503.00963 LHCb 8 TeV Z rapidity (applgrid);
249 1603.01803 CMS W lepton asymmetry at 8 TeV (applgrid)
250 1511.08039 LHCb Z (W) muon rapidity at 8 TeV(applgrid)
253 1512.02192 ATLAS 7 TeV Z pT (applgrid)

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)

565 1511.04716 ATLAS 8 TeV tT pT diff. distributions (fastNNLO)
567 1511.04716 ATLAS 8 TeV tT mtT diff. distributions (fastNNLO)
573 1703.01630 CMS 8 TeV tT (pT , yt) double diff. distributions (fastNNLO)

248 1612.03016 ATLAS 7 TeV Z and W rapidity (applgrid) → CT18Z PDFs

Experimental data in CT18 PDF analysis



CT18 LHC data treatment

- CT18 analysis includes new LHC experiments on W/Z, high-p_T 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

- 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

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 and implement an additional, CMS-advocated de-correlation for $|y| > 2.5$ (private communication with Voutilainen)

- **CMS 8 TeV jet production** (ID 545) $N_{pt} = 185$ arXiv:1609.05331

→ systematics treated as in xFITTER per CMS literature, arXiv:1607.03663

- **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

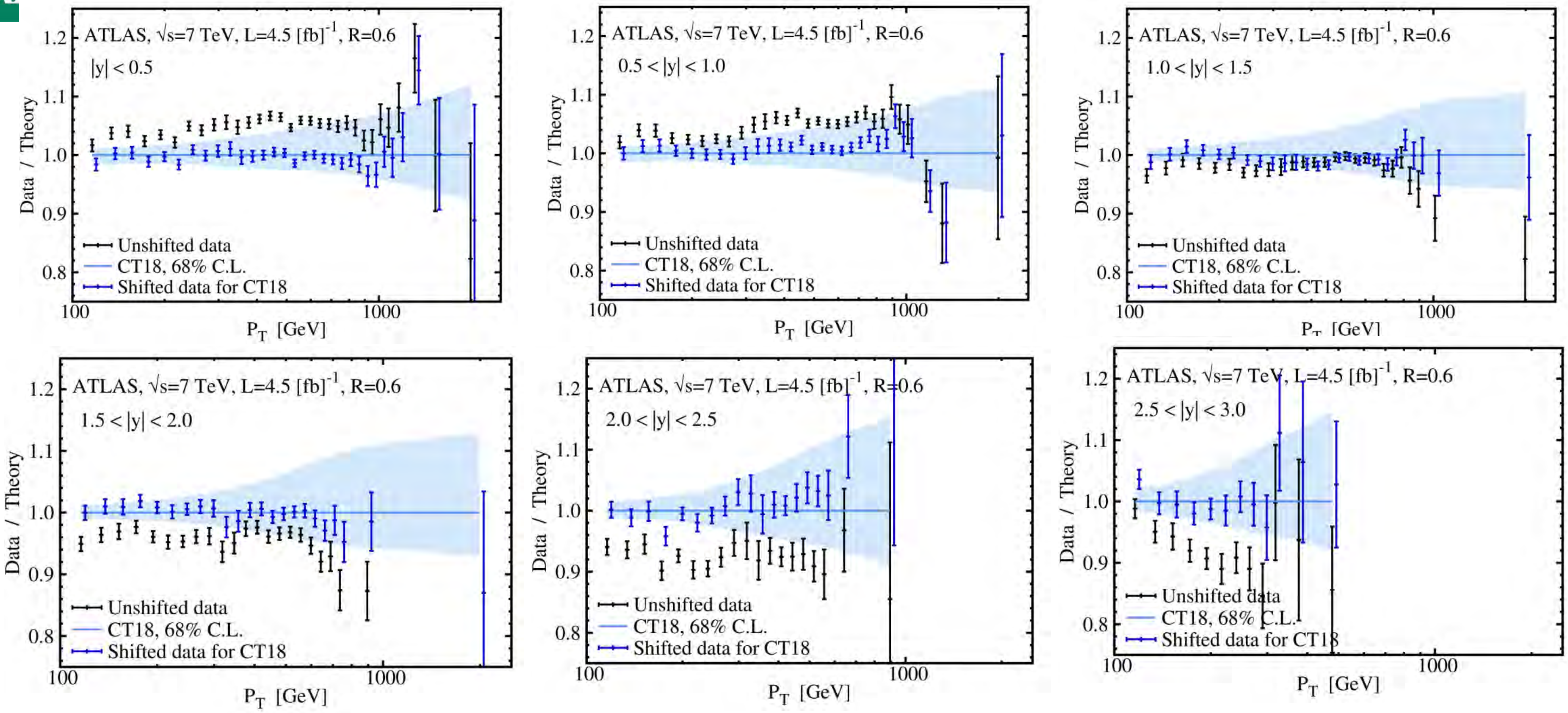
e.g., $\delta_{16} \to \delta_{16}^a,\ \delta_{16}^b,\ \delta_{16}^c$

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

→ 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

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 chi^2/Npt reduces from 2.34 to 1.68 for CT14HREA2NNLO.

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 pT and mtT distributions that directly probes large-x region; statistical correlations are included in order to fit pT and mtT simultaneously; fully correlated for experimental systematics except for decorrelation of PS sys. error.

	χ^2/N_{pt} (with CT18 PDFs)	nominal	w/o PS decorrelation	w/o statistical correlation
ATLAS 8 TeV 1511.04716	ATLAS 8 TeV abs. dσ/d pT & dσ/d mtt (Npts=15)	0.62	3.55	0.51
CMS 8 TeV 1703.01630	CMS 8 TeV nor. $d^2\sigma/(d\ pT\ d\ yt)$ (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 cross sections 4.6** fb^{-1} (ID 248) arXiv:1612.03016
- **CMS 8 TeV W(→$\mu\nu$) Asymmetry 18.8** fb^{-1} (ID 249) arXiv:1603.01803
- **LHCb (7,8) TeV WZ (μ-chan.) (1,2)** fb^{-1} (ID 245,250) arXiv:1505.07024, 1511.08039

- **CMS 8 TeV Jet 19.7** fb^{-1} (ID 545) arXiv: 1609.05331
  xFitter is the only resource to get its corr. sys. errors.

CT18: advancements in theoretical and statistical methodology

- In-house development of fast ApplGrid/FastNLO calculations
- Parallelization of CTEQ fitting code
- Studies of QCD scale dependence and other theory uncertainties for DIS, high-p_T Z, jet production
- Studies of non-perturbative PDF functional forms

➢ 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.

Theory calculations @NNLO

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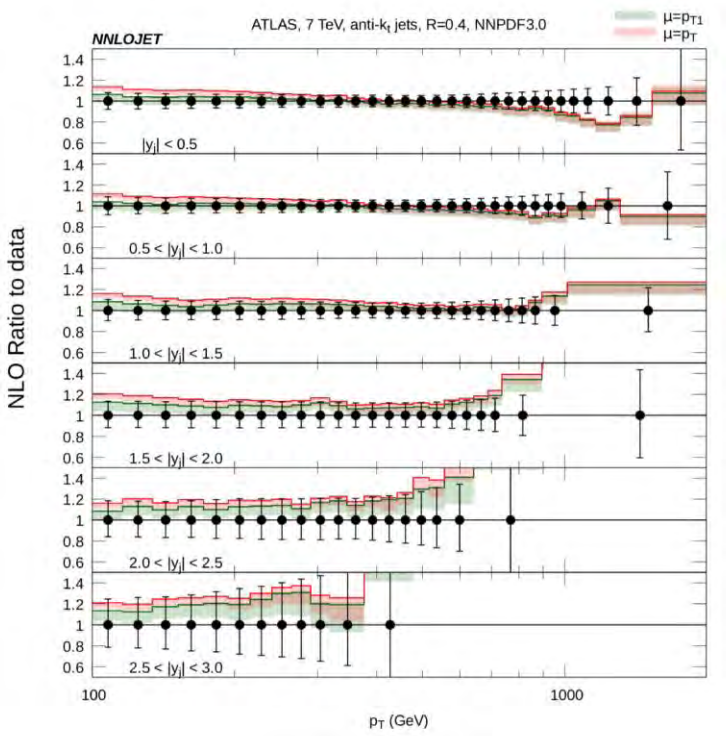
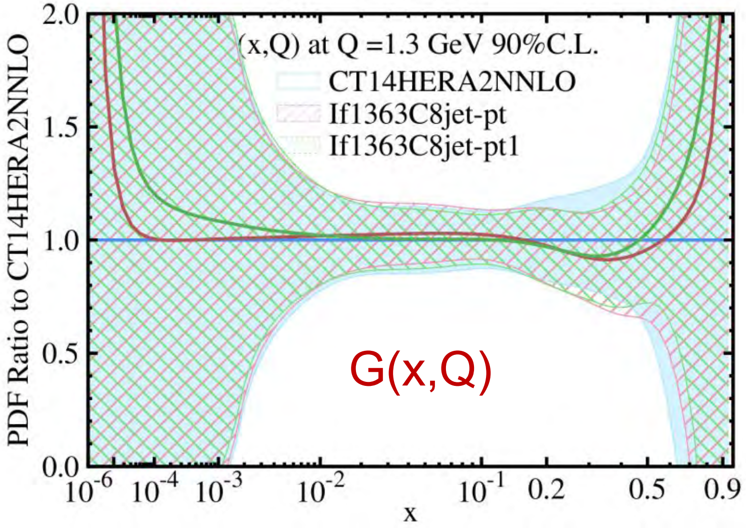
- Jet pT, (W,Z) rapidity, Z pT, t-tbar

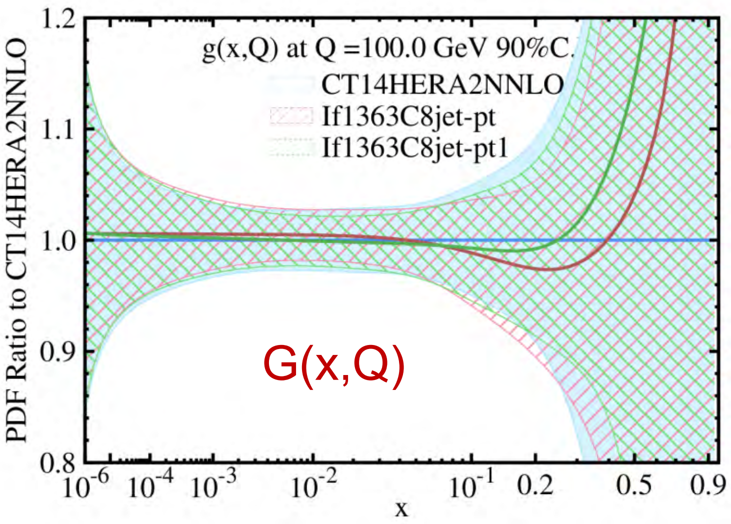
Obs.	Expt.	fast table	NLO code	K-factors	R,F scales
Inclusive jet	ATL 7 CMS 7/8	APPLgrid fastNLO	NLOJet++	NNLOJet	p_T, p_T^1
p_T^Z	ATL 8	APPLgrid	MCFM	NNLOJet	$\sqrt{Q^2 + p_{T,Z}^2}$
W/Z rapidity W asymmetry	LHCb 7/8 ATL 7 CMS 8	APPLgrid	MCFM/aMCfast	FEWZ/MCFM	$M_{W,Z}$
DY (low,high mass)	ATL 7/8 CMS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

pT v.s. pT1

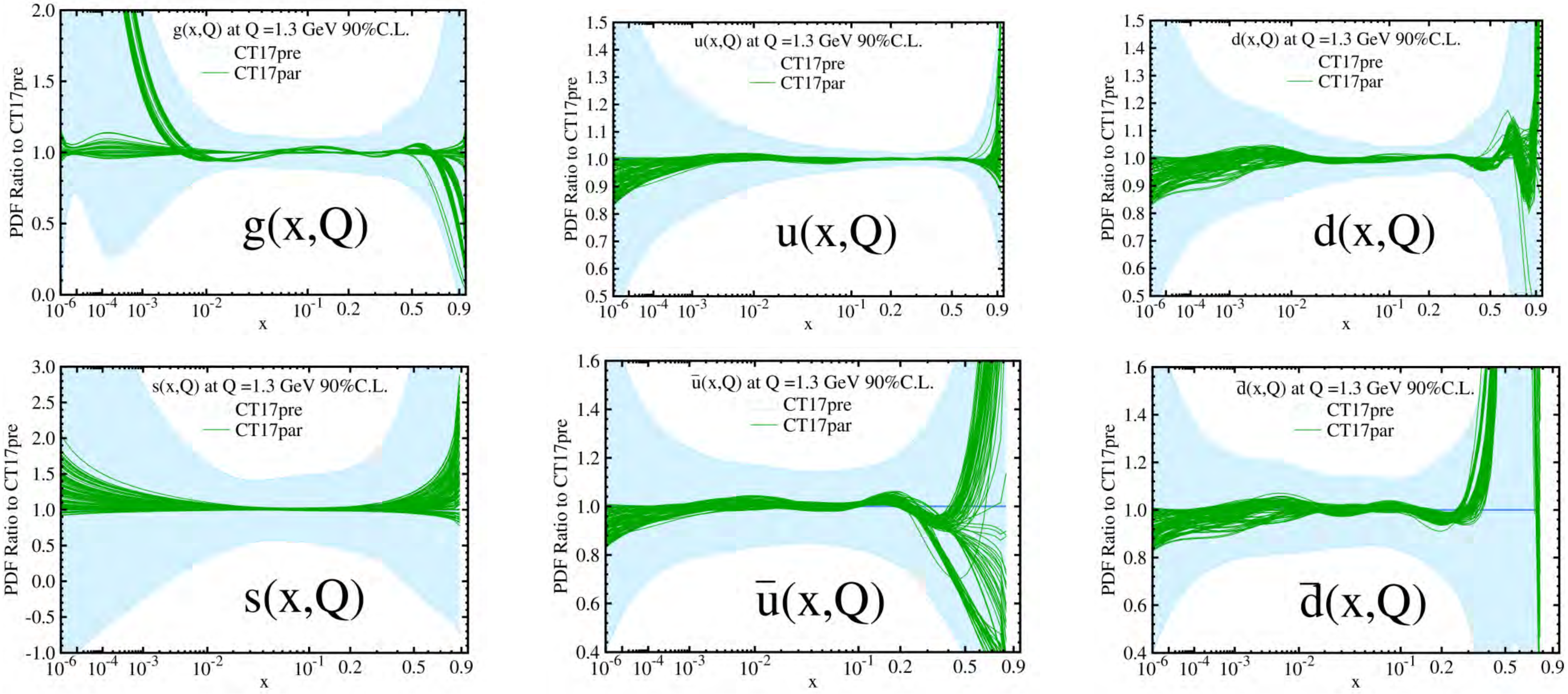
- Non-negligible difference between scale choice of pT (inclusive jet pT) and lead jet pT (pT1) for NNLO predictions
- Nominal choice by CTEQ-TEA is pT
- In fact, fitted gluon is almost exactly the same in kinematic region where difference is important.
- There is a resilience in the global fit due to other data present in this kinematic region (and evolution)





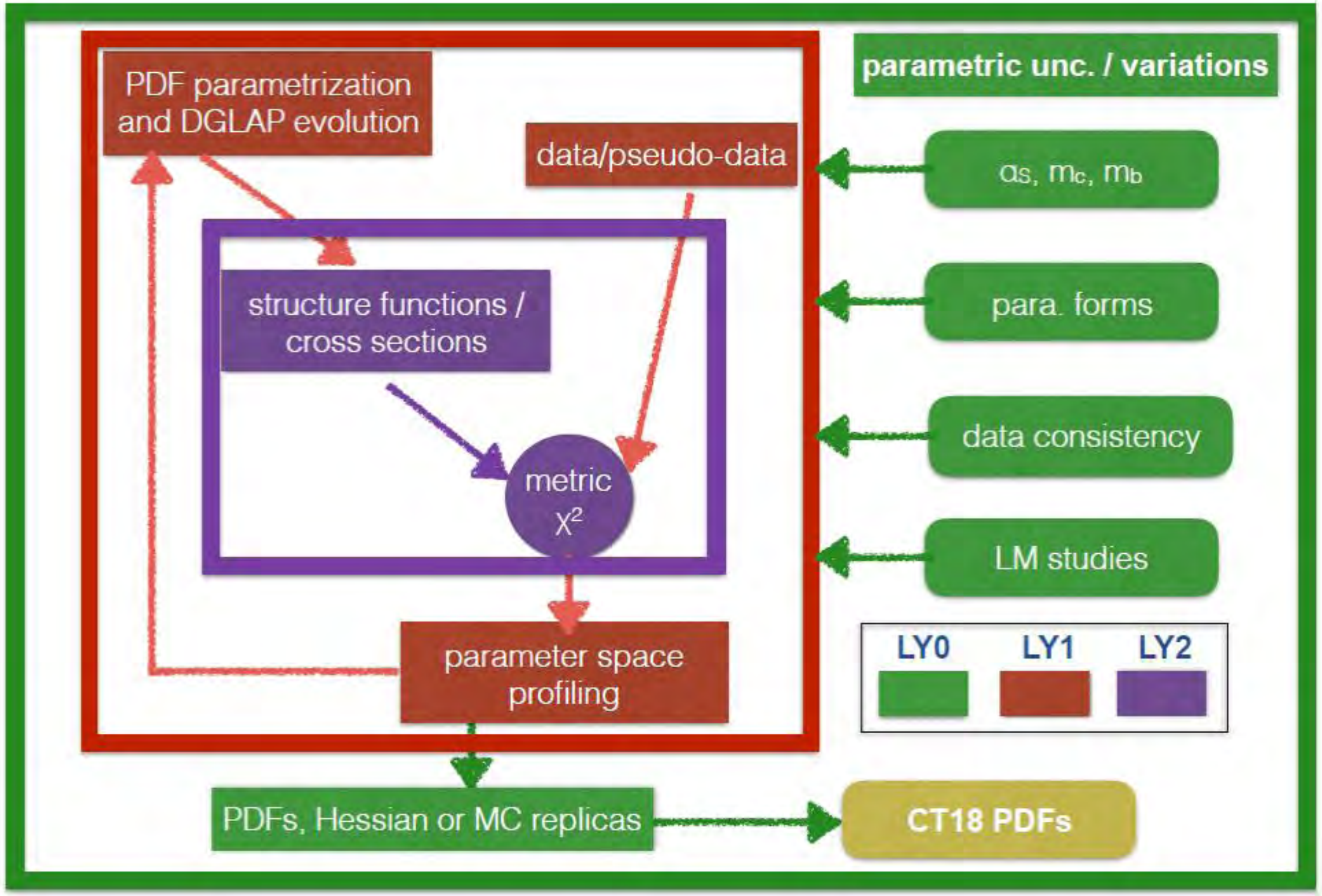


Explore various non-perturbative parametrization forms of PDFs



- 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

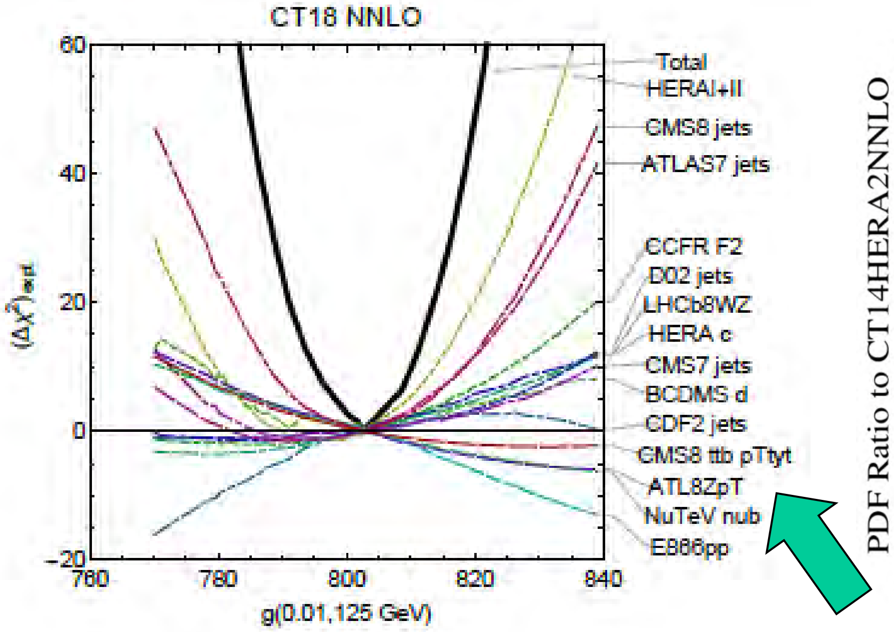
upgrade to a parallelized version of the fitting code, two-layer parallelization:

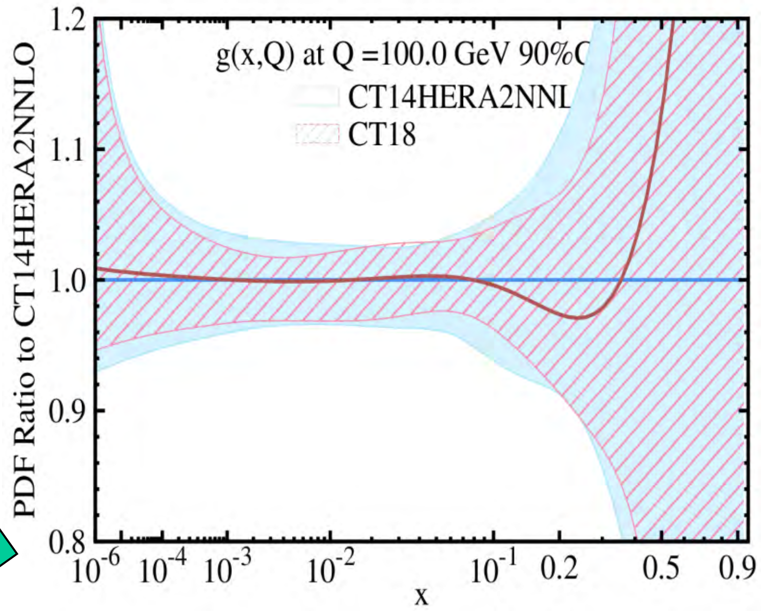
1. LY1, through rearrangement of the minimization algorithm, a factor of 4~5 improvement on speed;
2. LY2, via redistribution of the data sets, further improved by a factor of 2

About a factor of 10 improvement in speed

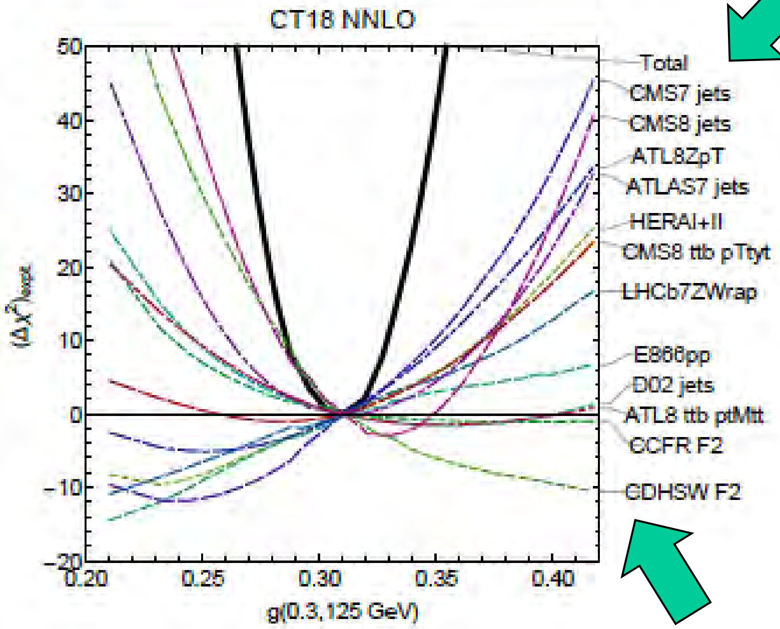
Preview of CT18 PDFs (g-PDF)

G(0.01,125)





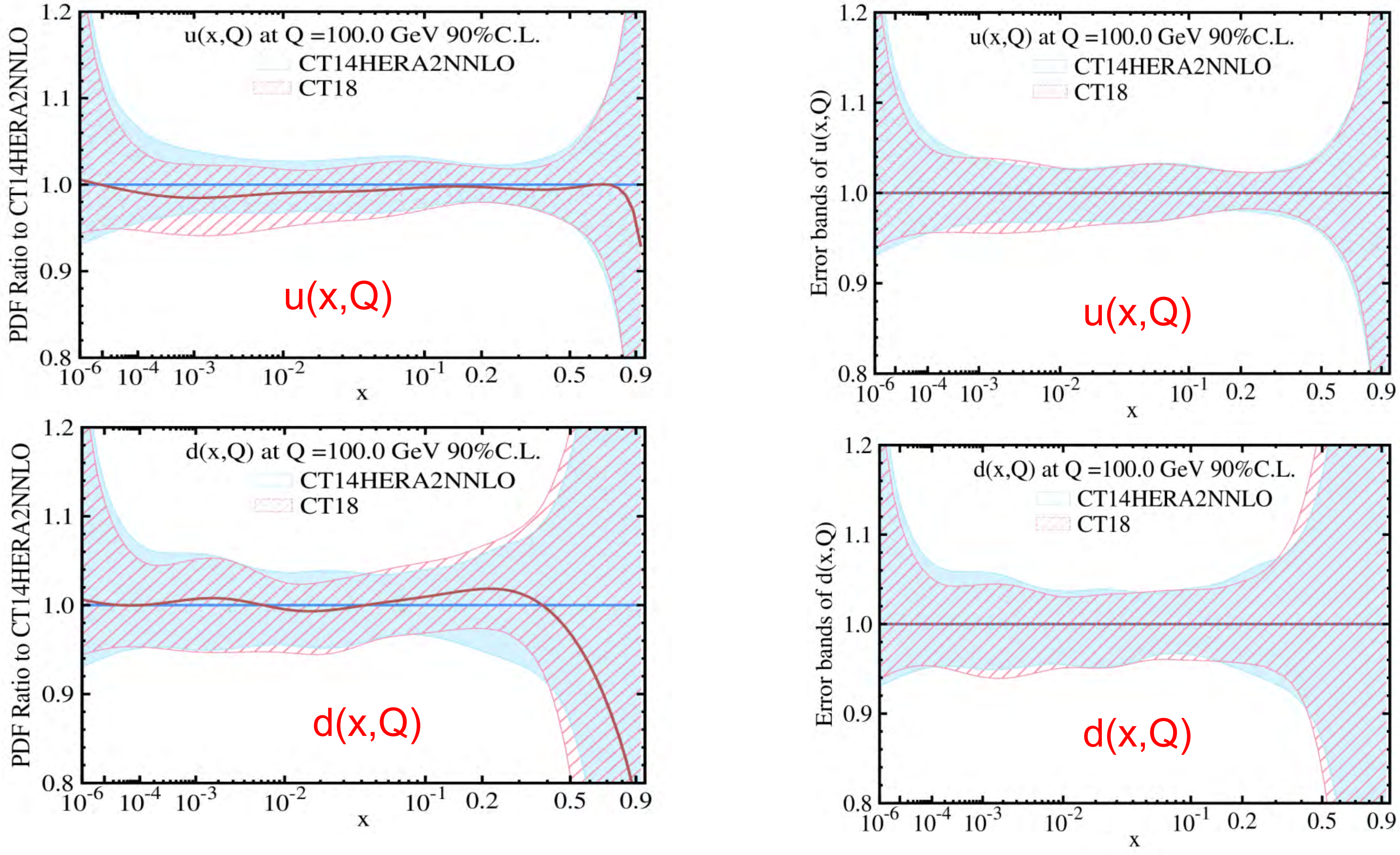
G(0.3,125)



Lagrange Multiplier Scans

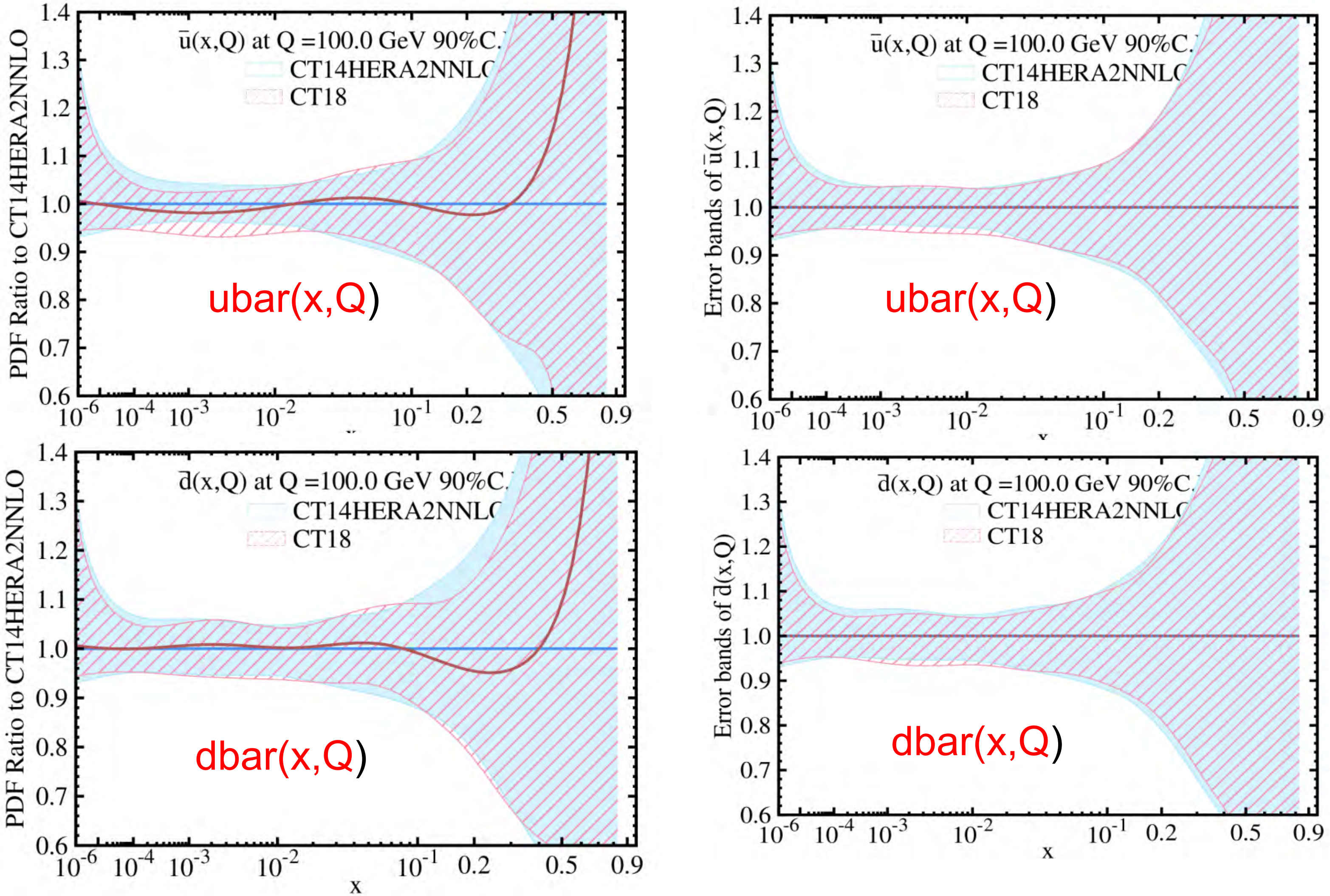
- At x around 0.01, ATLAS8 Z pT data prefer a slightly larger gluon PDF.
- At x around 0.3, competing with the CDHSW F2 and Tevatron jet data, which prefer larger gluon, the ATLAS7 jet, CMS7 jet and ATLAS8 Z pT data prefer a smaller gluon; some tension found in CMS7 and CMS8 jet data.
- The gluon PDF as $x \to 1$ is parametrization form dependent.

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



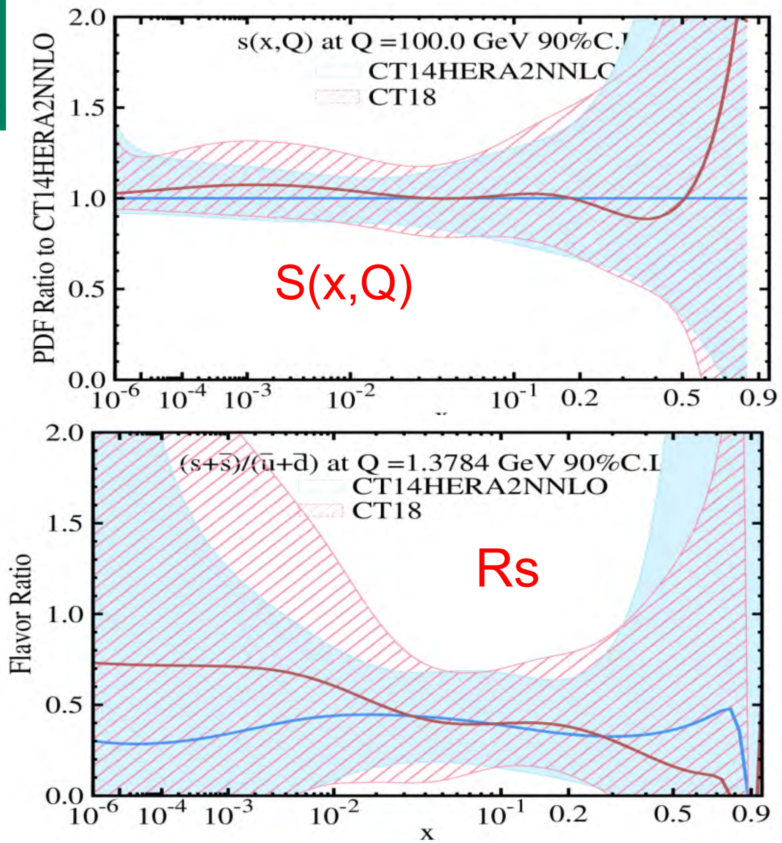
- Some changes on u and d at small x, and d around 0.2; mainly come from LHCb W and Z rapidity data, at 7 and 8 TeV.

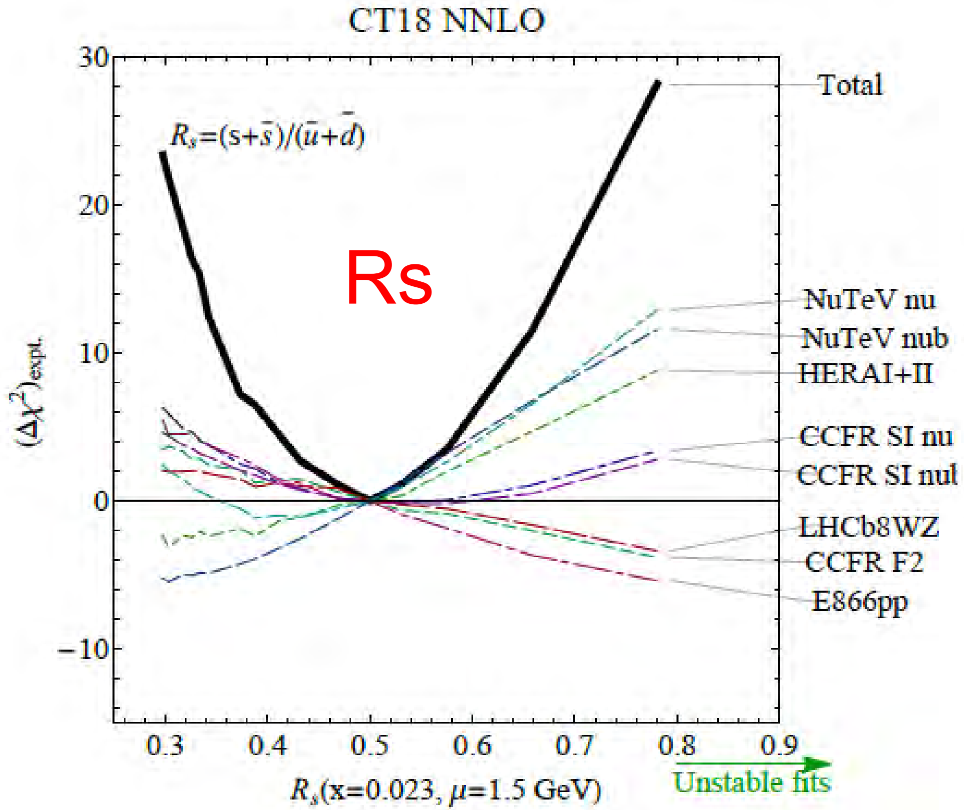
Preview of CT18 (ubar and dbar PDF)



- 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.

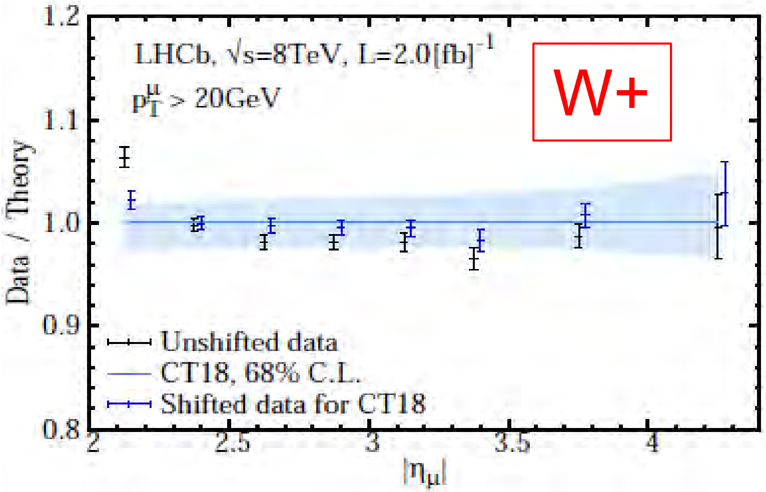
Rs=(s+sbar)/(ubar+dbar)

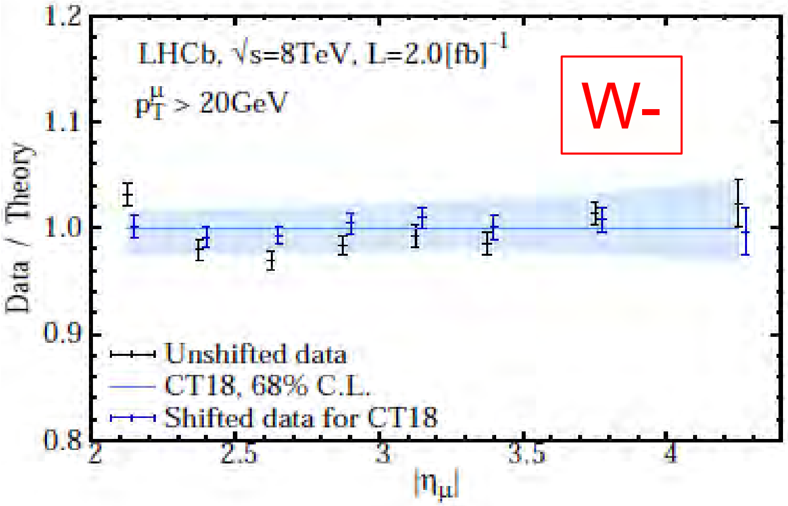


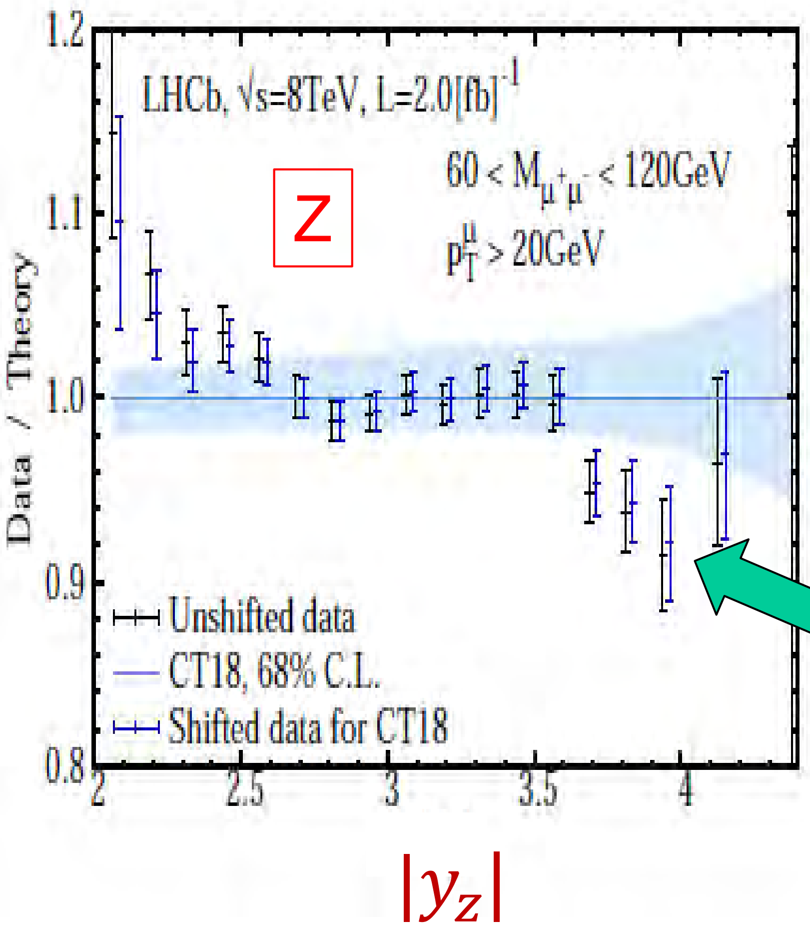


- LHCb W and Z (7,8 TeV) data prefer a larger s-PDF in the small-x region.
- NuTeV dimuon data strongly prefer a smaller Rs value, while the LHCb WZ data prefer a slightly larger Rs value.
- Rs (CT18)= 0.5 ± 0.3 for x = 0.023 and Q^2 = 1.9 GeV^2 . (preliminary)
  (Compare to ATLAS with $R_s = 1.13^{+0.08}_{-0.13}$)

LHCb 8 TeV W and Z data in CT18 fit



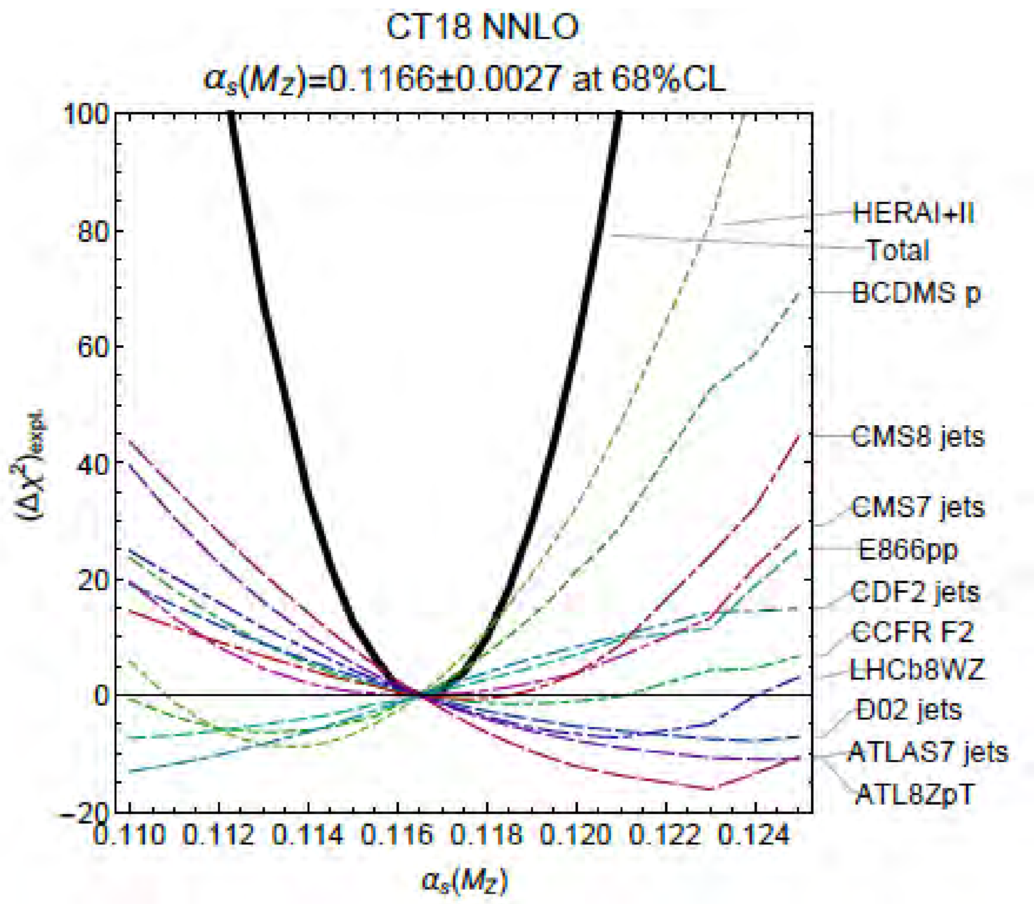




- Z data dominate the fit
- not able to fit some large Z rapidity
- show slight tension with CCFR F2 and CMS 7 TeV W-lepton asymmetry data

arXiv:1511.08039

α_s (Mz) for CT18



HERA I+II

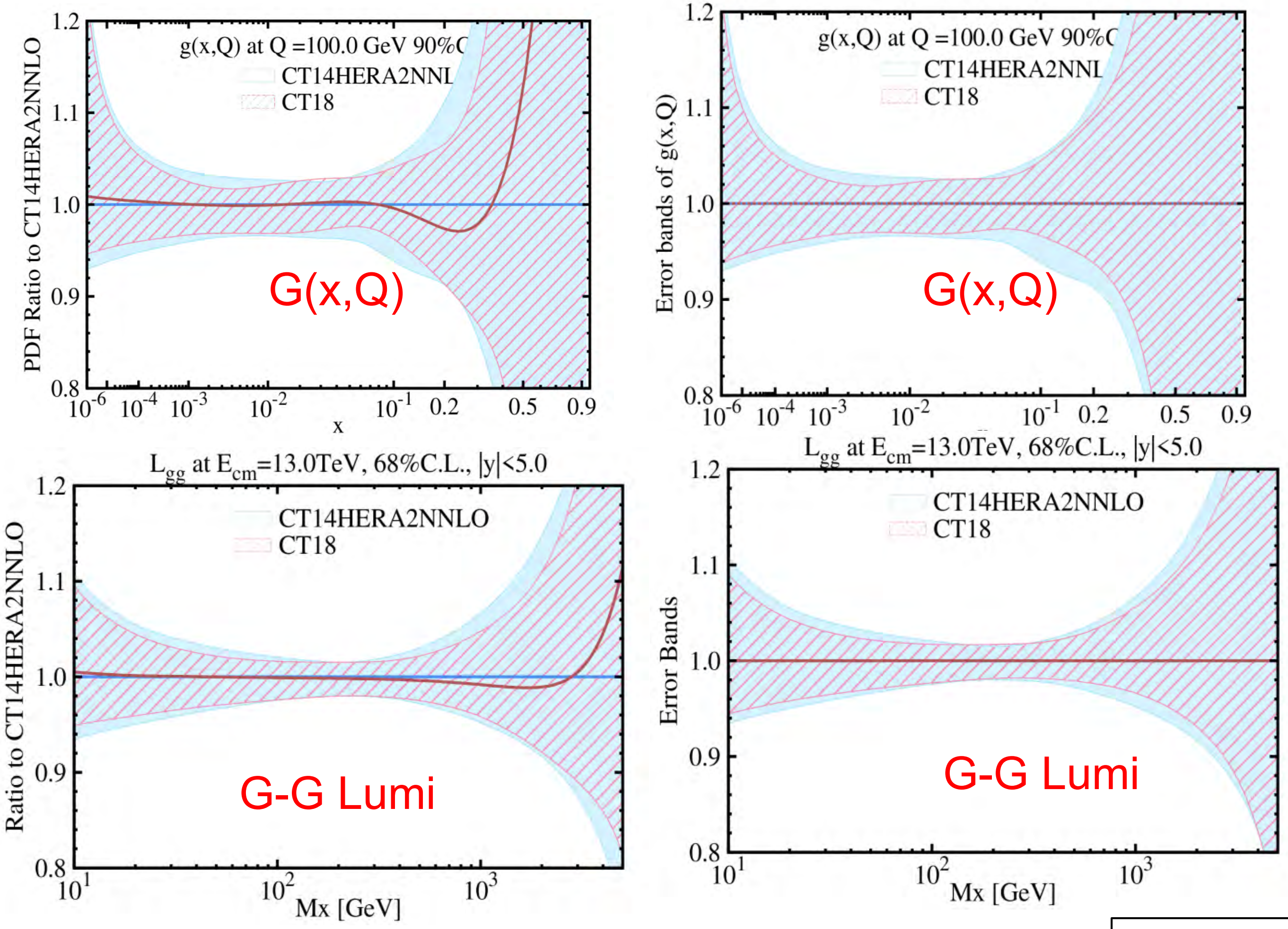
Lagrange Multiplier scan

ATLAS 7 jet

ATLAS 8 Z pT

- The fixed target F2 data and HERA DIS data prefer smaller αs value.
- The ATLAS 8TeV Z pT and ATLAS 7 TeV incl. jet data, bring the central value of αs (Mz) from $0.115^{+0.006}_{-0.004}$ (CT14) to 0.1166 ± 0.0027 (CT18).

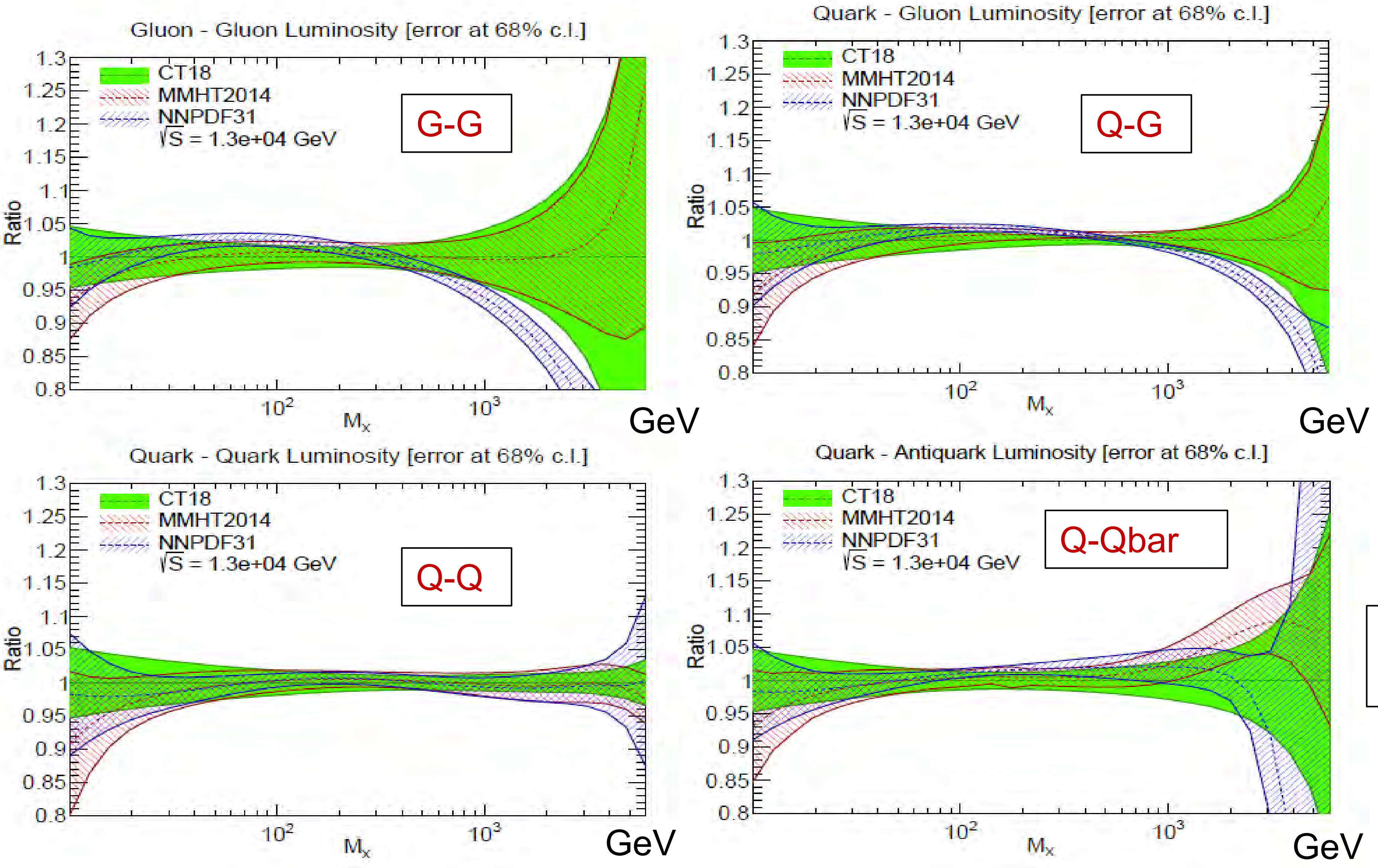
$\sigma(gg \to H)$ CT18 vs. CT14



	σ(gg-h)	$\delta\sigma$ sym(90%C.L.)
7 TeV		
CT14NNLO	14.67	0.46
CT18	14.57	0.44
8 TeV		
CT14NNLO	18.70	0.57
CT18	18.45	0.55
13 TeV		
CT14NNLO	42.78	1.32
CT18	42.43	1.26
14 TeV		
CT14NNLO	48.23	1.50
CT18	47.91	1.42

PDF induced errors (at 90% CL) are reduced by about 5% as compared to CT14 predictions.

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



PDF errors at 68% CL

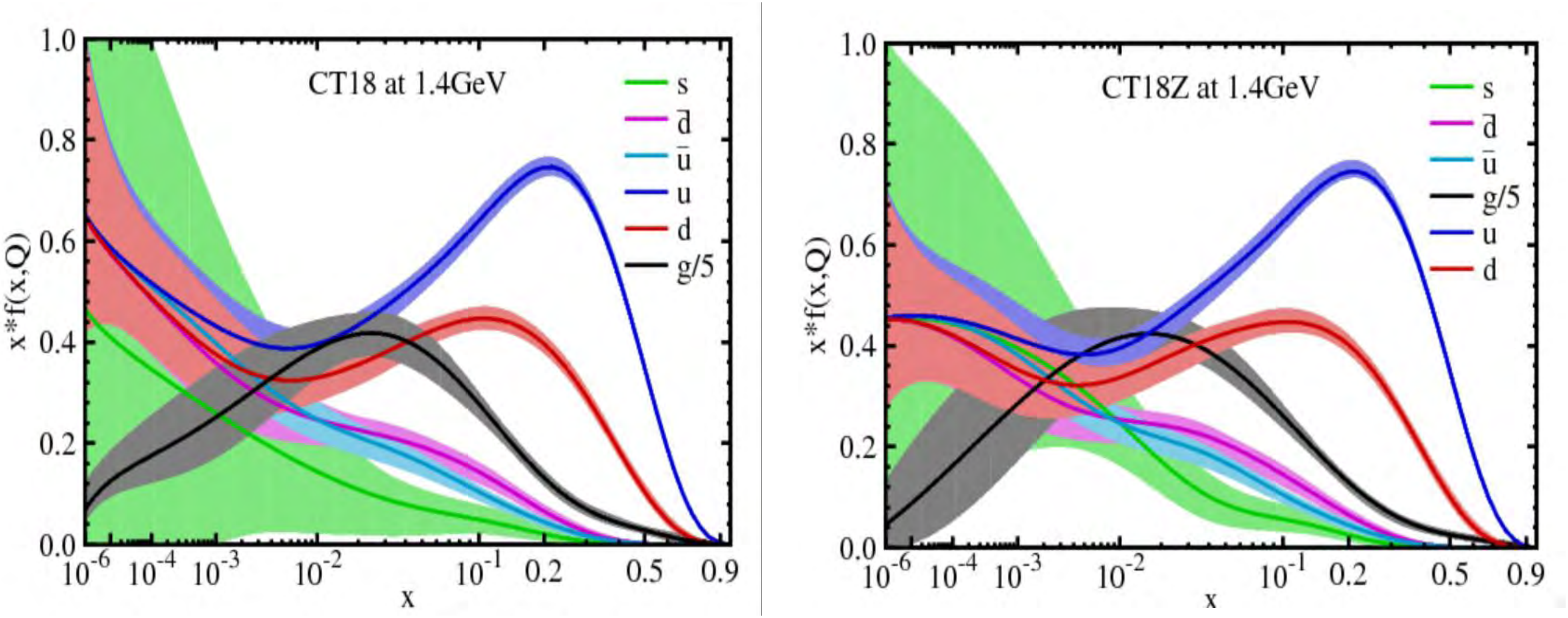
CT18Z
LHC data treatment

- Start with CT18 data set
- Add in ATLAS 7 TeV *W* and *Z* rapidity data (arXiv:1612.03016; 4.6 1/fb); large chi^2/d.o.f ~ 2.1
- Remove CDHSW data
- Use a special x-dependent factorization scale $\mu_{DIS,x}$ at NNLO calculation (See talk by P. Nadolsky at WG1)
- CT18Z uses a combination of $\mu_{DIS,x}$ (preferred by DIS) and an increased m_c^{pole} = 1.4 GeV (preferred by LHC vector boson production, disfavored by DIS)

→ CT18Z PDFs

PDF uncertainty bands
CT18 vs. CT18Z

Two PDF ensembles: CT18 and 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

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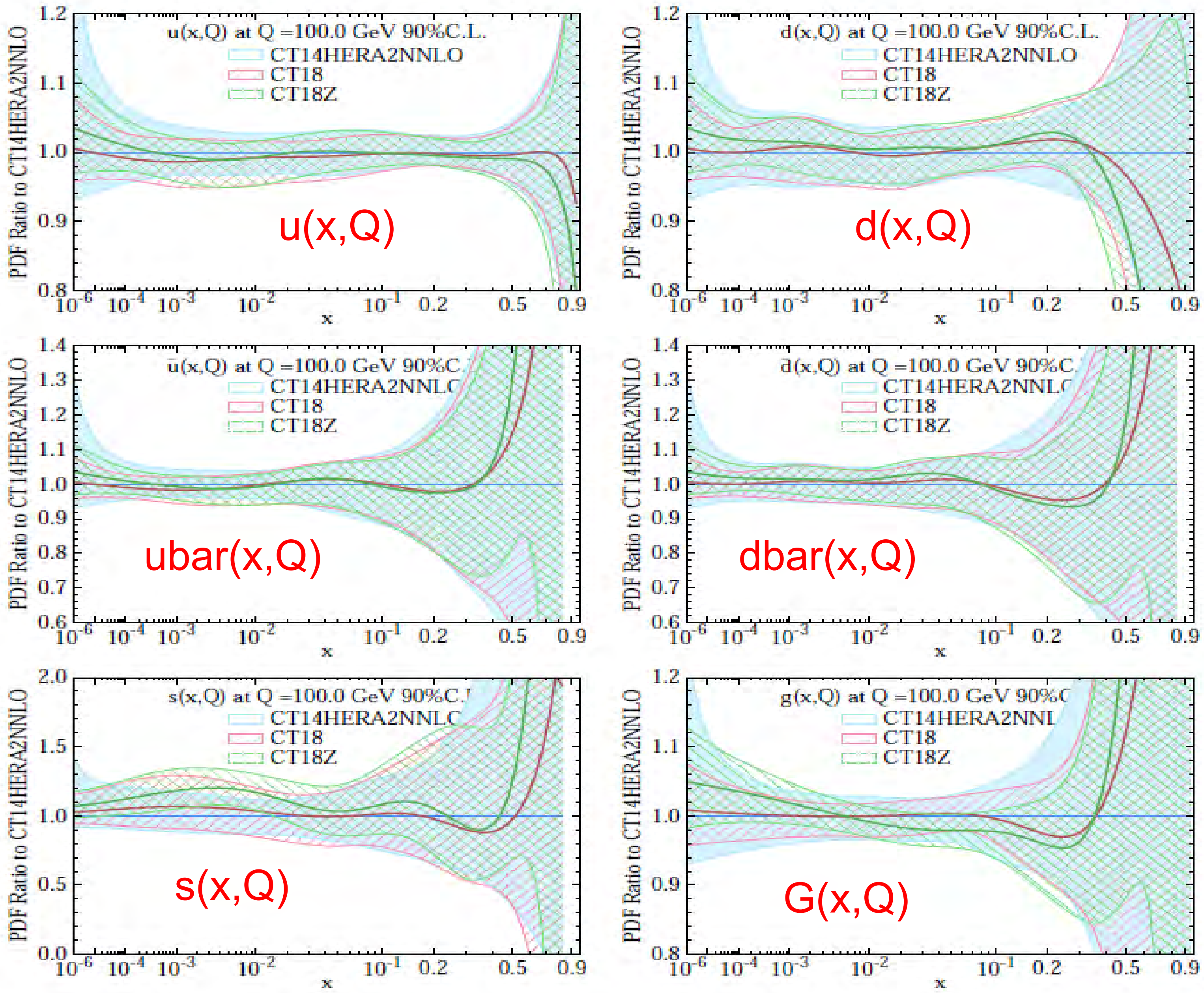
u and d increase at small-x

s increases at small-x

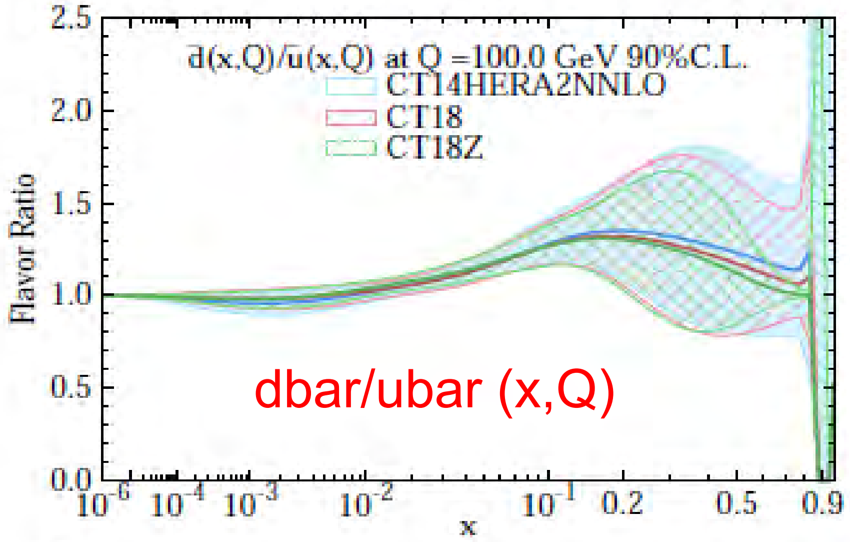


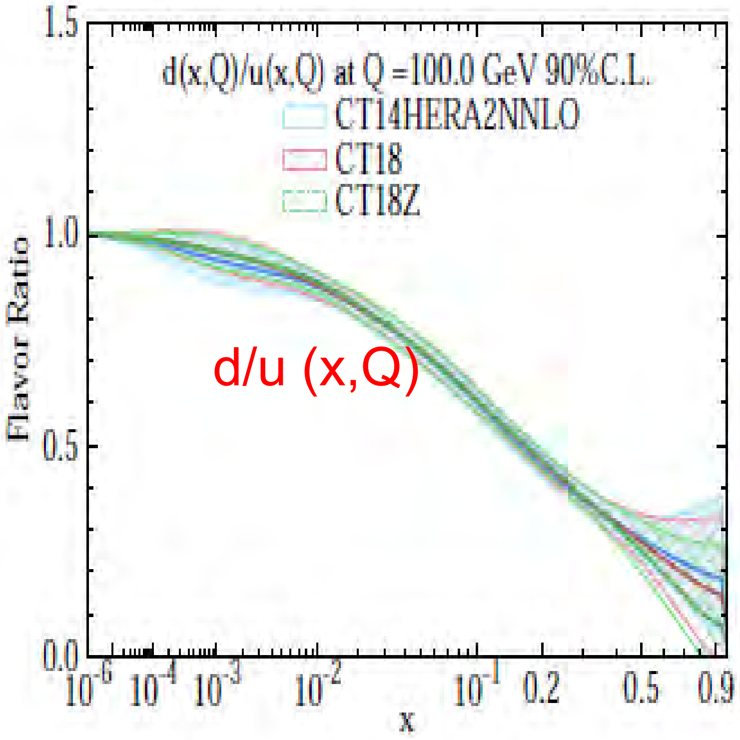
d increases at $x \sim 0.2 - 0.3$

Q=100 GeV; at 90%CL

G increases at small-x, and decreases at $x \sim 0.01 - 0.3$

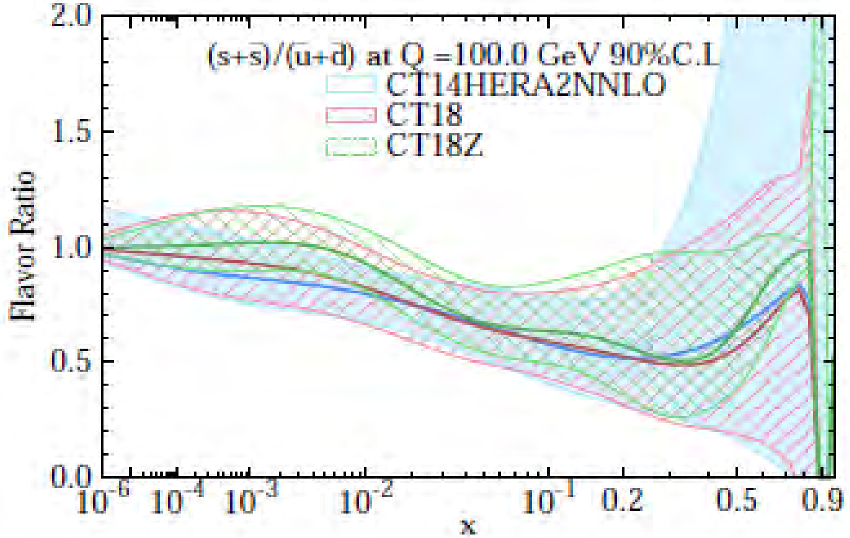
CT18Z vs.CT18 PDFs





d/u decreases at large-x

Rs increases at small-x

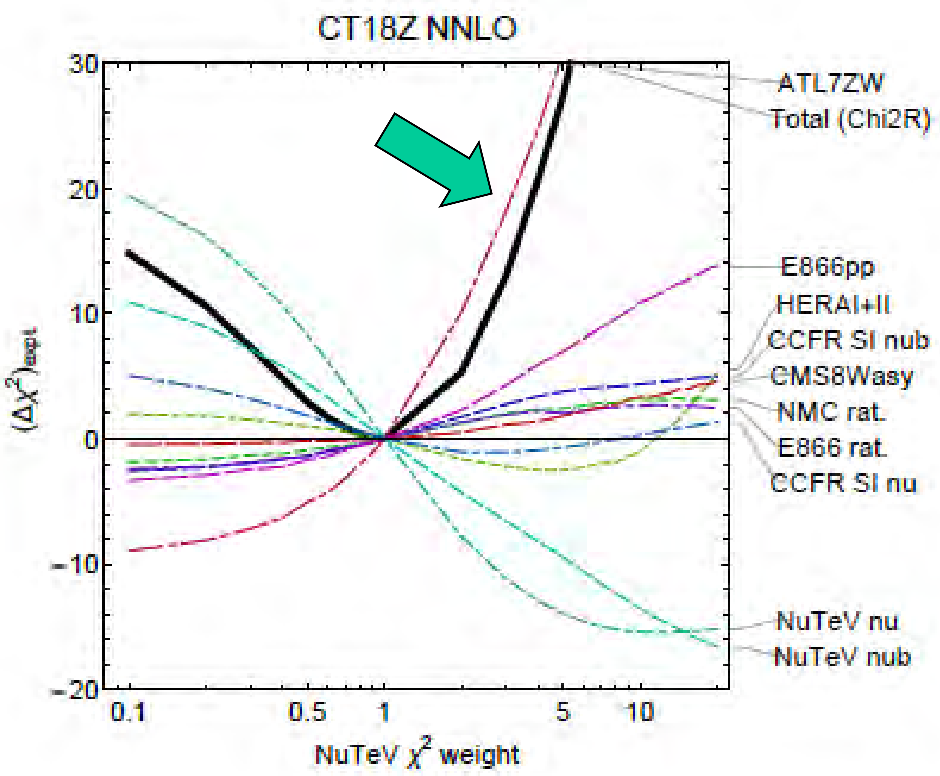


(s+sbar)/(ubar+dbar) (x,Q)

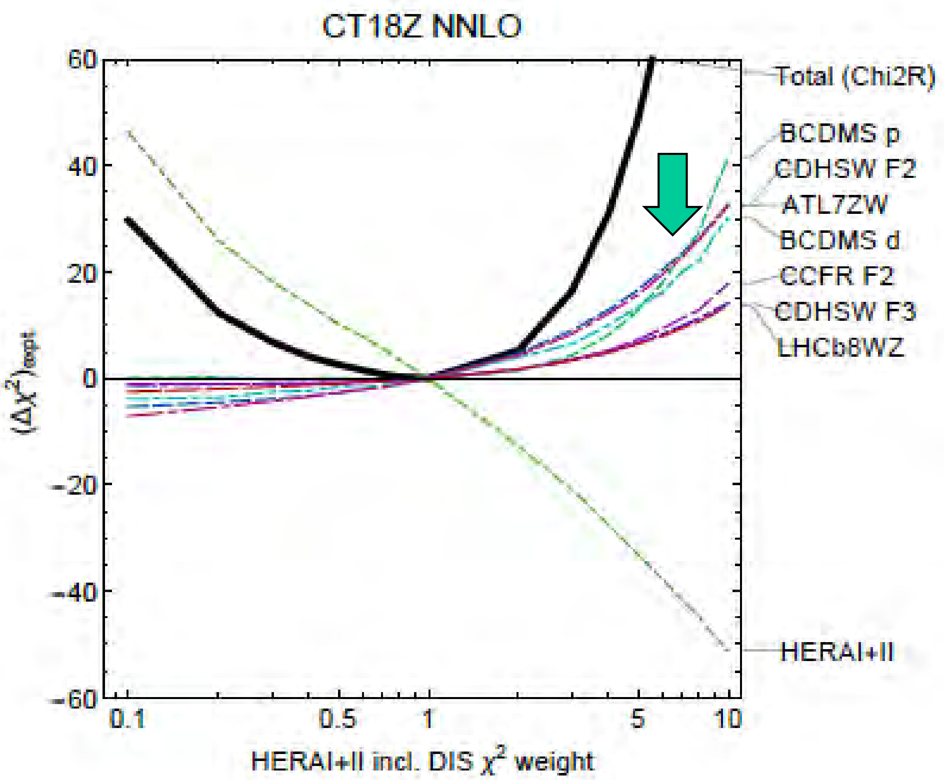
Q=100 GeV; at 90%CL

CT18Z fit

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



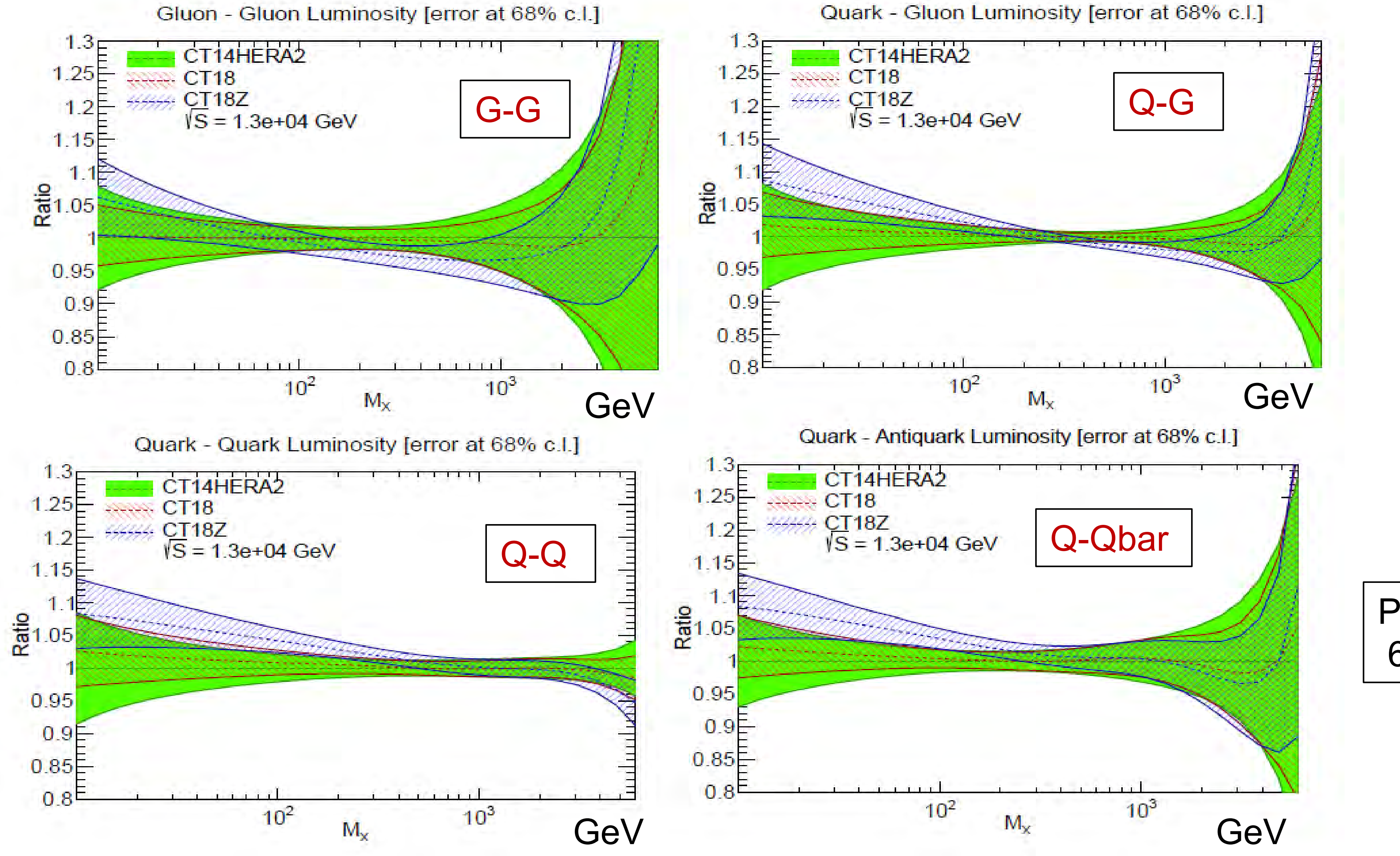
NuTeV di-muon data



HERA I+II data

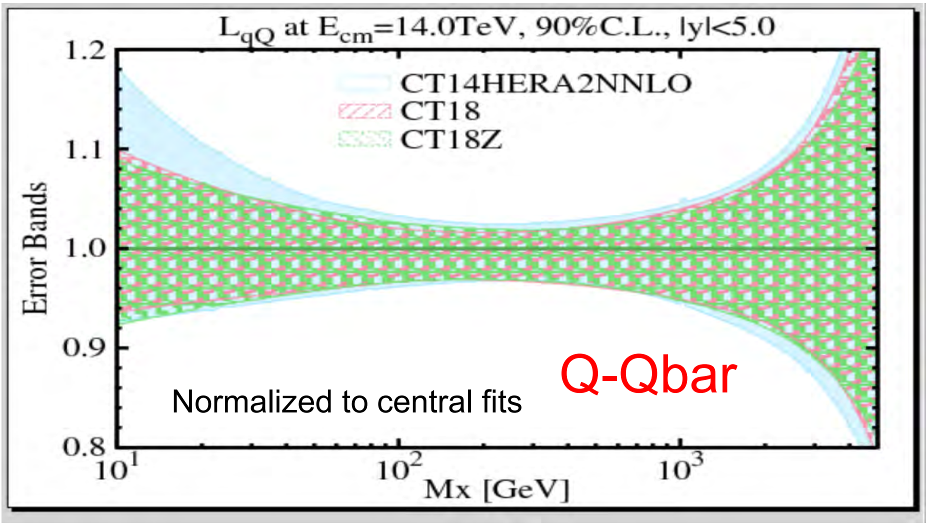
PDF Luminosities at 13 TeV LHC
CT14HERA2, CT18 and CT18Z

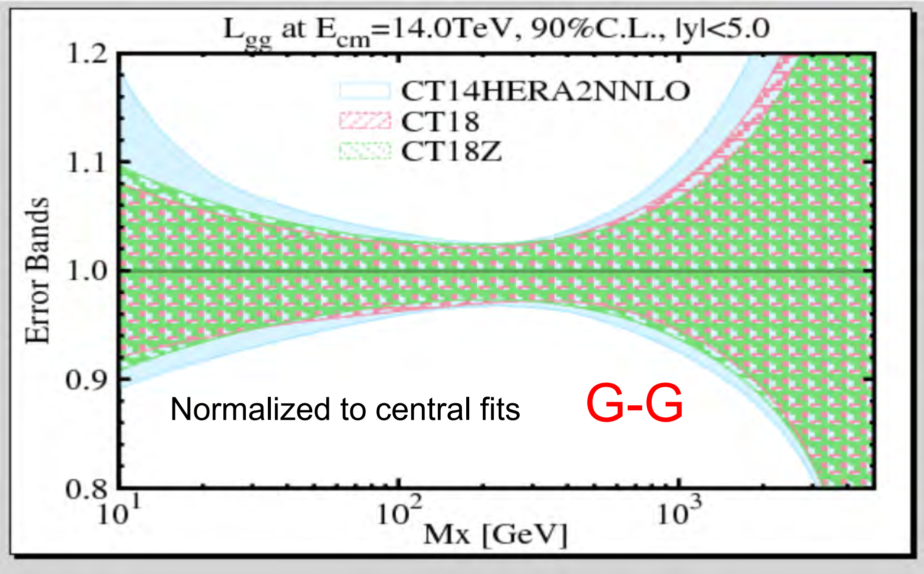
C T E Q



PDF errors at 68% CL

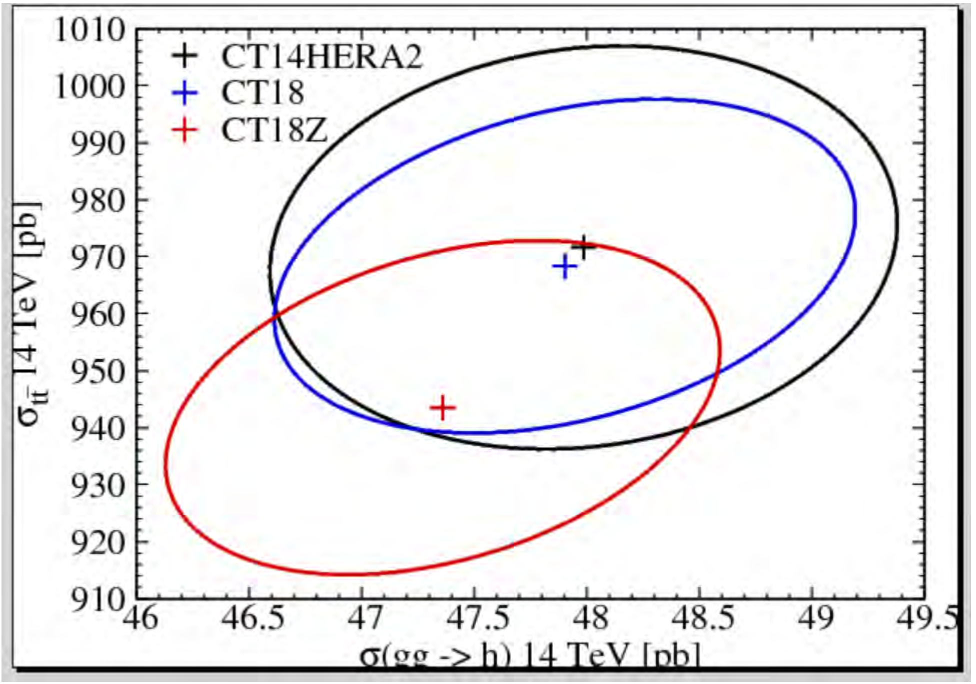
Mild reduction in nominal PDF error bands and cross section uncertainties





$\sigma(\bar{t}t)$

@ 14 TeV LHC



$\sigma(gg \to H)$

PDF errors at 90% CL

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 pT 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.