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# New CTEQ-TEA Global Analysis with High Precision Data from the LHC

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Wu-Ki Tung Endowed Professor

Sept. 25, 2019

PDFLattice 2019 @ Kellogg Biological Station, Michigan

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.)



# Structure Functions and Parton Densities

Summary of WG1: DIS2019 (Torino, Italy, April 8-12, 2019)

- PDF global analysis (proton)
- PDF global analysis (nucleus)
- Impact of data to PDFs
- New progress in theoretical calculations
- Data Constraints on PDFs and nPDFs

Mark Sutton, University of Sussex  
C.-P. Yuan, Michigan State University  
Sasha Zenaiev, Hamburg University

<https://pos.sissa.it/352>

The DIS2019 Proceedings has just been published today!

Here, I will focus on PDF global analyses for the proton.



# DIS 2019: WG1 summary

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## PDF analyses for the proton ...

- MMHT
  - To be released soon, with QED corrections completed
- CT18 and CT18Z PDFs
  - CT18Z including ATLAS W, Z data - completed, ready to be released.
- NNPDF
  - Studying impact of missing higher order uncertainties
- ABMP16 – updated
- HERAPDF2.0 NNLOJets
  - Completed, with NNLO calculations
- ATLAS updates
  - ATLASepWZtop18 - fit with top, ATLASepWZ-Wjet19
- CMS updates
  - New fits including top data
- JAM19
  - Combined PDF and (pion and Kaon) FF fit

arXiv: 1907.02750

MMHT2015qed

This talk.

arXiv:1906.10698



# CT18 in a nutshell

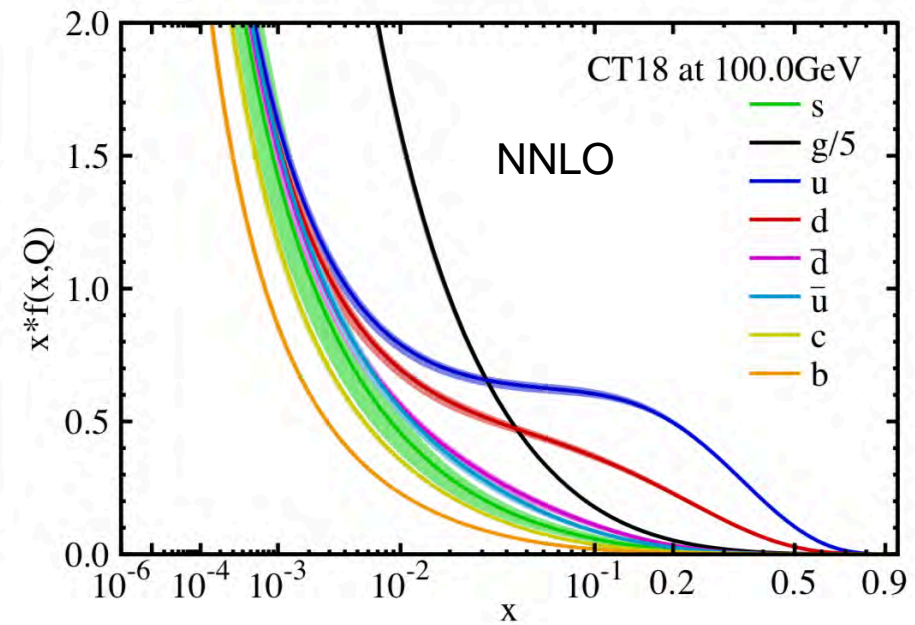
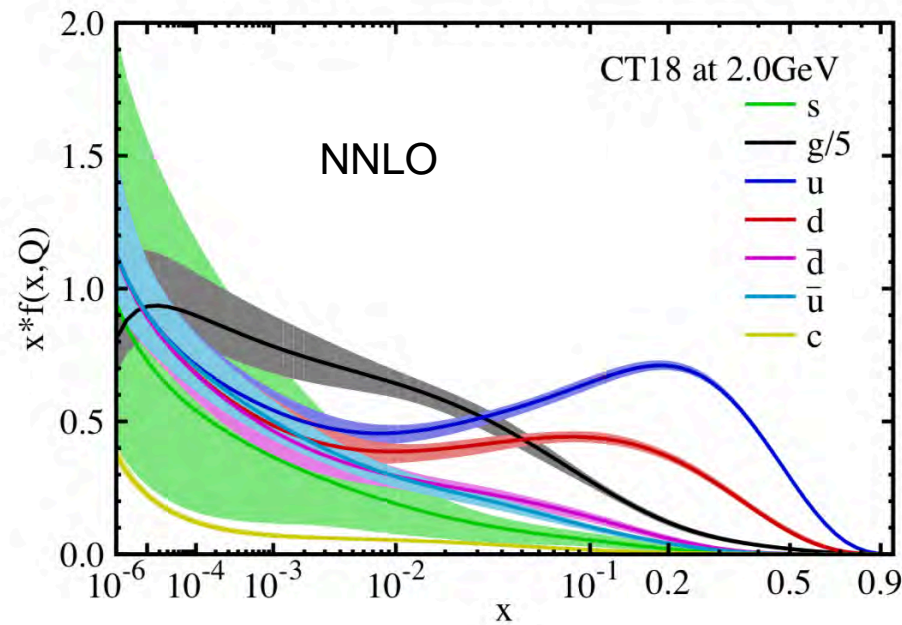
- Start with CT14-HERA2 (HERA I+II combined data released after publication of CT14)
- Examine a wide range of PDF parameterizations
- Use as much relevant LHC data as possible using applgrid/fastNLO interfaces to data sets, with NNLO/NLO K-factors, or fastNNLO tables in the case of top pair production.  
**Benchmark the predictions!**
- Examine **QCD scale dependence** in key processes
- Implement **parallelization** of the global PDF fitting to allow for faster turn-around time
- Validate the results using a **strong set of goodness-of-fit tests** (*Kovarik, PN, Soper, arXiv:1905.06957*)
- Use diverse statistical techniques (**PDFSense, ePump, Gaussian variables, Lagrange Multiplier scans**) to examine agreement between experiments



# CT18...

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- Main product is CT18 (NNLO, NLO,LO)



- Including full data set except for ATLAS 7 TeV W/Z, which has a sizeable impact on the global fit (strange quark)



# ...and family

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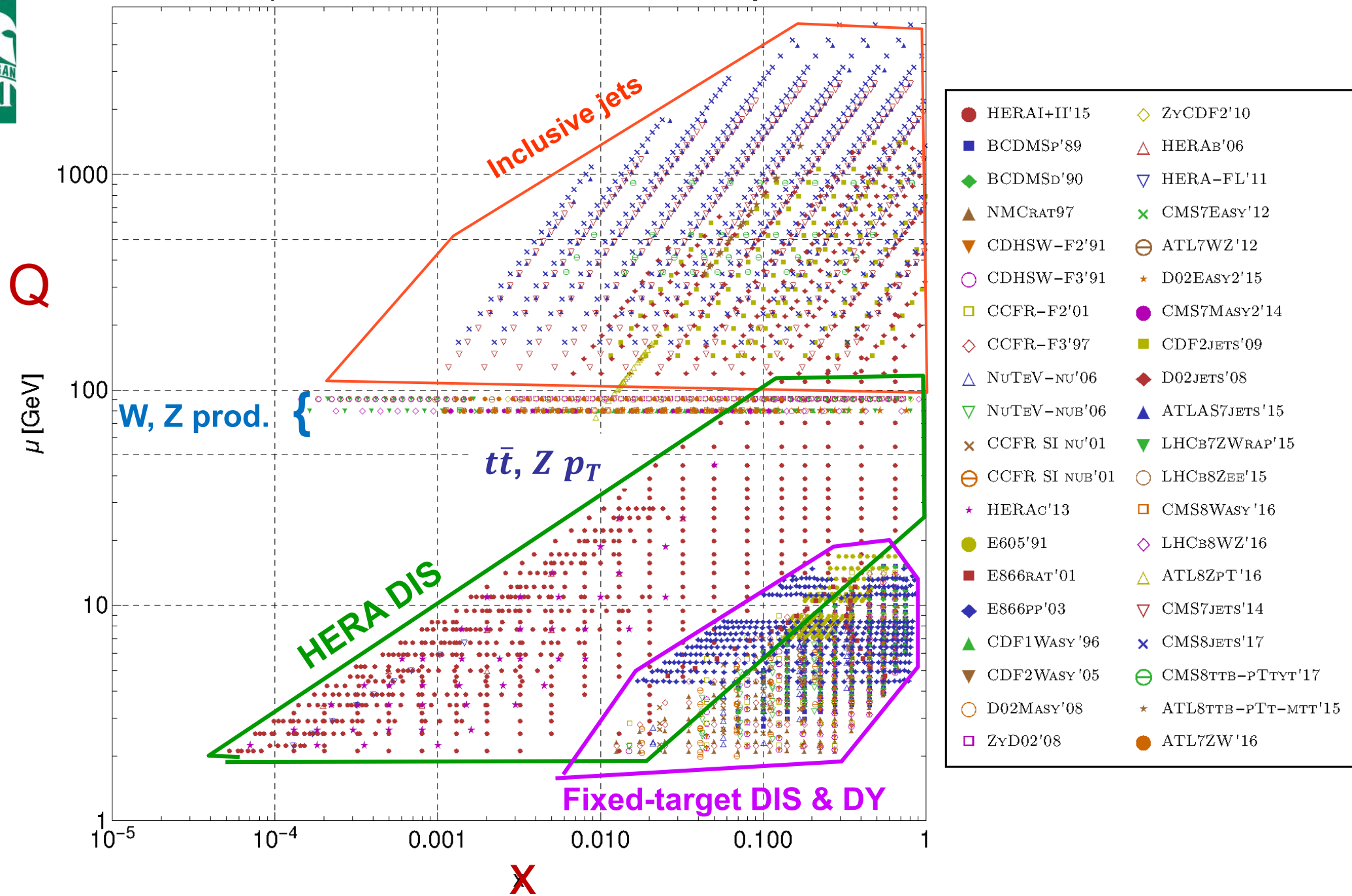
PDF ensemble	Factorization scale in DIS	ATLAS 7 Z/W data included?	CDHSW $F_2^{p,d}$ data included?	Pole charm mass, GeV
CT18	$\mu_{F,DIS}^2 = Q^2$	No	Yes	1.3
CT18X	$\mu_{F,DIS}^2 = 0.8^2 \left( Q^2 + \frac{0.3 \text{ GeV}^2}{x^{0.3}} \right)$	No	Yes	1.3
CT18A	$\mu_{F,DIS}^2 = Q^2$	Yes	Yes	1.3
CT18Z	$\mu_{F,DIS}^2 = 0.8^2 \left( Q^2 + \frac{0.3 \text{ GeV}^2}{x^{0.3}} \right)$	Yes	No	1.4

CT18 PDFs available from <https://tinyurl.com/ct18pdfs-1>



# Experimental data in CT18 PDF analysis

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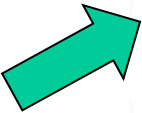




ID#	Experimental data set	$N_{pt,n}$	$\chi_n^2$	$\chi_n^2/N_{pt,n}$	$S_n$
160	HERAI+II 1 fb <sup>-1</sup> , H1 and ZEUS NC and CC $e^{\pm}p$ reduced cross sec. comb. [10]	1120	1408.7(1377.8)	1.3( 1.2)	5.7( 5.1)
101	BCDMS $F_2^p$ [22]	337	373.7( 383.8)	1.1( 1.1)	1.4( 1.8)
102	BCDMS $F_2^d$ [23]	250	280.4( 287.0)	1.1( 1.1)	1.3( 1.6)
104	NMC $F_2^d/F_2^p$ [24]	123	125.7( 116.2)	1.0( 0.9)	0.2( -0.4)
108	CDHSW <sup>†</sup> $F_2^p$ [25]	85	85.6( 86.8)	1.0( 1.0)	0.1( 0.2)
109	CDHSW <sup>†</sup> $F_3^p$ [25]	96	86.5( 85.6)	0.9( 0.9)	-0.7( -0.7)
110	CCFR $F_2^p$ [26]	69	78.8( 76.0)	1.1( 1.1)	0.9( 0.6)
111	CCFR $x F_3^p$ [27]	86	33.8( 31.4)	0.4( 0.4)	-5.2( -5.6)
124	NuTeV $\nu\mu\mu$ SIDIS [28]	38	18.5( 30.3)	0.5( 0.8)	-2.7( -0.9)
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS [28]	33	38.5( 56.7)	1.2( 1.7)	0.7( 2.5)
126	CCFR $\nu\mu\mu$ SIDIS [29]	40	29.9( 35.0)	0.7( 0.9)	-1.1( -0.5)
127	CCFR $\bar{\nu}\mu\mu$ SIDIS [29]	38	19.8( 18.7)	0.5( 0.5)	-2.5( -2.7)
145	H1 $\sigma_r^b$ [30]	10	6.8( 7.0)	0.7( 0.7)	-0.6( -0.6)
147	Combined HERA charm production [31]	47	58.3( 56.4)	1.2( 1.2)	1.1( 1.0)
169	H1 $F_L$ [16]	9	17.0( 15.4)	1.9( 1.7)	1.7( 1.4)
201	E605 Drell-Yan process [32]	119	103.4( 102.4)	0.9( 0.9)	-1.0( -1.1)
203	E866 Drell-Yan process $\sigma_{pd}/(2\sigma_{pp})$ [33]	15	16.1( 17.9)	1.1( 1.2)	0.3( 0.6)
204	E866 Drell-Yan process $Q^3 d^2\sigma_{pp}/(dQdx_F)$ [34]	184	244.4( 239.7)	1.3( 1.3)	2.9( 2.7)
225	CDF Run-1 electron $A_{ch}, p_{T\ell} > 25$ GeV [35]	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 [36]	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 [37]	9	9.1( 9.0)	1.0( 1.0)	0.2( 0.1)
260	DØ Run-2 $Z$ rapidity [38]	28	16.9( 18.7)	0.6( 0.7)	-1.7( -1.3)
261	CDF Run-2 $Z$ rapidity [39]	29	48.7( 61.1)	1.7( 2.1)	2.2( 3.3)
266	CMS 7 TeV 4.7 fb <sup>-1</sup> , muon $A_{ch}, p_{T\ell} > 35$ GeV [40]	11	7.9( 12.2)	0.7( 1.1)	-0.6( 0.4)
267	CMS 7 TeV 840 pb <sup>-1</sup> , electron $A_{ch}, p_{T\ell} > 35$ GeV [41]	11	11.8( 16.1)	1.1( 1.5)	0.3( 1.1)
268	ATLAS 7 TeV 35 pb <sup>-1</sup> $W/Z$ cross sec., $A_{ch}$ [42]	41	44.4 50.6)	1.1( 1.2)	0.4( 1.1)
281	DØ Run-2 9.7 fb <sup>-1</sup> electron $A_{ch}, p_{T\ell} > 25$ GeV [43]	13	22.8( 20.5)	1.8( 1.6)	1.7( 1.4)
504	CDF Run-2 inclusive jet production [44]	72	122.4( 117.0)	1.7( 1.6)	3.5( 3.2)
514	DØ Run-2 inclusive jet production [45]	110	113.8( 115.2)	1.0( 1.0)	0.3( 0.4)

Data sets employed in the CT18(Z) analysis. The numbers in round brackets are for the CT18Z fit.  $N_{pt,n}$ ,  $\chi^2$  are the number of points and value of  $\chi^2$  for the n-th experiment at the global minimum.  $S_n$  is the effective Gaussian parameter quantifying agreement with each experiment.

TABLE I. Data sets included in the CT18(Z) global analysis. The numbers in round brackets are for the CT18Z fit.

Only in  
CT18Z

ID#	Experimental data set	$N_{pt,n}$	$\chi_n^2$	$\chi_n^2/N_{pt,n}$	$S_n$
245	LHCb 7 TeV $1.0 \text{ fb}^{-1}$ $W/Z$ forward rapidity cross sec. [46]	33	53.8 ( 39.9)	1.6 ( 1.2)	2.2 ( 0.9)
246	LHCb 8 TeV $2.0 \text{ fb}^{-1}$ $Z \rightarrow e^-e^+$ forward rapidity cross. sec. [47]	17	25.8 ( 23.0)	1.5 ( 1.4)	1.4 ( 1.0)
248	ATLAS <sup>‡</sup> 7 TeV $4.6 \text{ fb}^{-1}$ , $W/Z$ combined cross sec. [19]	34	287.3 ( 88.7)	8.4 ( 2.6)	13.7 ( 4.8)
249	CMS 8 TeV $18.8 \text{ fb}^{-1}$ $W$ cross sec. and $A_{ch}$ [48]	11	11.4 ( 12.1)	1.0 ( 1.1)	0.2 ( 0.4)
250	LHCb 8 TeV $2.0 \text{ fb}^{-1}$ $W/Z$ cross sec. [49]	34	73.7 ( 59.4)	2.1 ( 1.7)	3.7 ( 2.6)
251	ATLAS 8 TeV $20.3 \text{ fb}^{-1}$ single diff. high-mass cross sec. [50]	12	20.4 ( 25.6)	1.7 ( 2.1)	1.6 ( 2.3)
253	ATLAS 8 TeV $20.3 \text{ fb}^{-1}$ , $Z p_T$ cross sec. [51]	27	30.2 ( 28.3)	1.1 ( 1.0)	0.5 ( 0.3)
542	CMS 7 TeV $5 \text{ fb}^{-1}$ , single incl. jet cross sec., $R = 0.7$ (extended in $y$ ) [52]	158	194.7 ( 188.6)	1.2 ( 1.2)	2.0 ( 1.7)
544	ATLAS 7 TeV $4.5 \text{ fb}^{-1}$ , single incl. jet cross sec., $R = 0.6$ [53]	140	202.7 ( 203.0)	1.4 ( 1.5)	3.3 ( 3.4)
545	CMS 8 TeV $19.7 \text{ fb}^{-1}$ , single incl. jet cross sec., $R = 0.7$ , (extended in $y$ ) [54]	185	210.3 ( 207.6)	1.1 ( 1.1)	1.3 ( 1.2)
573	CMS 8 TeV $19.7 \text{ fb}^{-1}$ , $t\bar{t}$ norm. double-diff. top $p_T$ & $y$ cross sec. [55]	16	18.9 ( 19.1)	1.2 ( 1.2)	0.6 ( 0.6)
580	ATLAS 8 TeV $20.3 \text{ fb}^{-1}$ , $t\bar{t} p_T^t$ and $m_{t\bar{t}}$ abs. spectrum [56]	15	9.4 ( 10.7)	0.6 ( 0.7)	-1.1 (-0.8)

TABLE II. High precision LHC measurements employed in the CT18(Z) analysis. The numbers in round brackets are for the CT18Z fit.  $N_{pt,n}$ ,  $\chi_n^2$  are the number of points and value of  $\chi^2$  for the  $n$ -th experiment at the global minimum.  $S_n$  is the effective Gaussian parameter [18, 57, 58] quantifying agreement with each experiment. The ATLAS data, labelled by  $\ddagger$ , are included in the CT18Z global fit, but not in CT18.

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# Treatment of new LHC data

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- Include processes that have a sensitivity for the PDFs of interest, and for which NNLO predictions are available.
- Include as large a rapidity interval for the jet data as possible
  - for ATLAS this involves using the ATLAS de-correlation model, rather than using a single rapidity interval. Using a single rapidity interval may result in selection bias. The result is a worse  $\chi^2$  due to the remaining tensions in the ATLAS jet data, and a reduced sensitivity compared to the CMS jet data.
  - the use of only a single jet rapidity interval provides incomplete information
- Use multiple t-tbar observables, possible using experimentally provided statistical correlations.
  - and for CMS, using the double differential calculation from Mitov et al
  - again, some of the observables are in tension with each other.
- NB: previous data (including CMS 7 TeV W,Z data) continue having an impact on global fits and tend to dilute the impact of new data



# Theory input

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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			$\frac{H_T}{4}, \frac{m_T}{2}$

When justified, a small Monte-Carlo error (typically 0.5%) added for NNLO/NLO K-factors, such as

- ❖ 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.

## Theoretical calculations for vector boson production

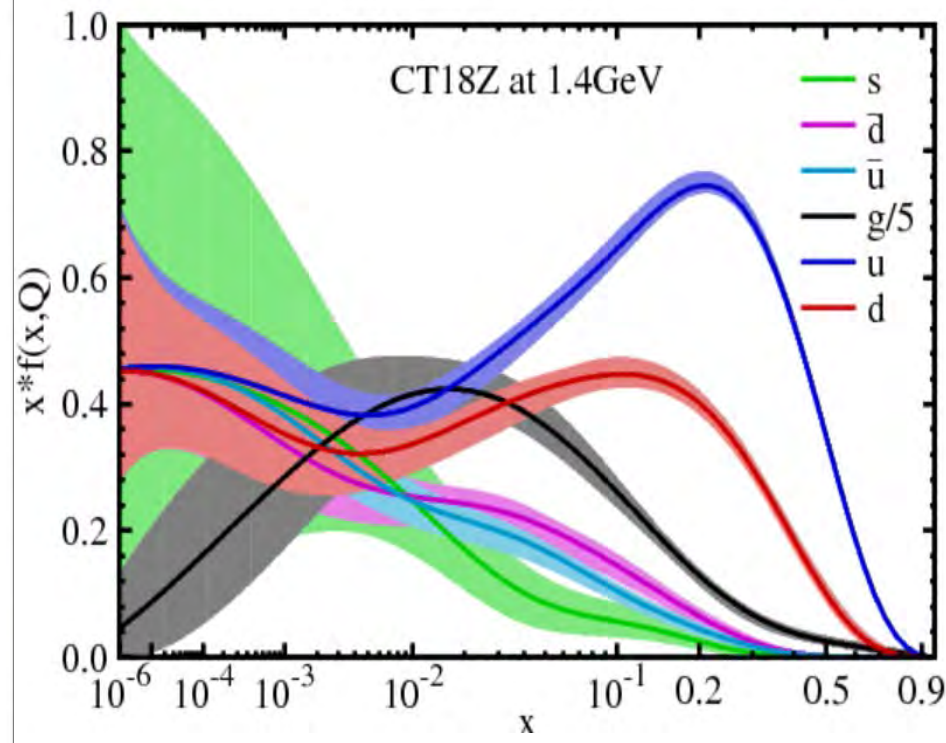
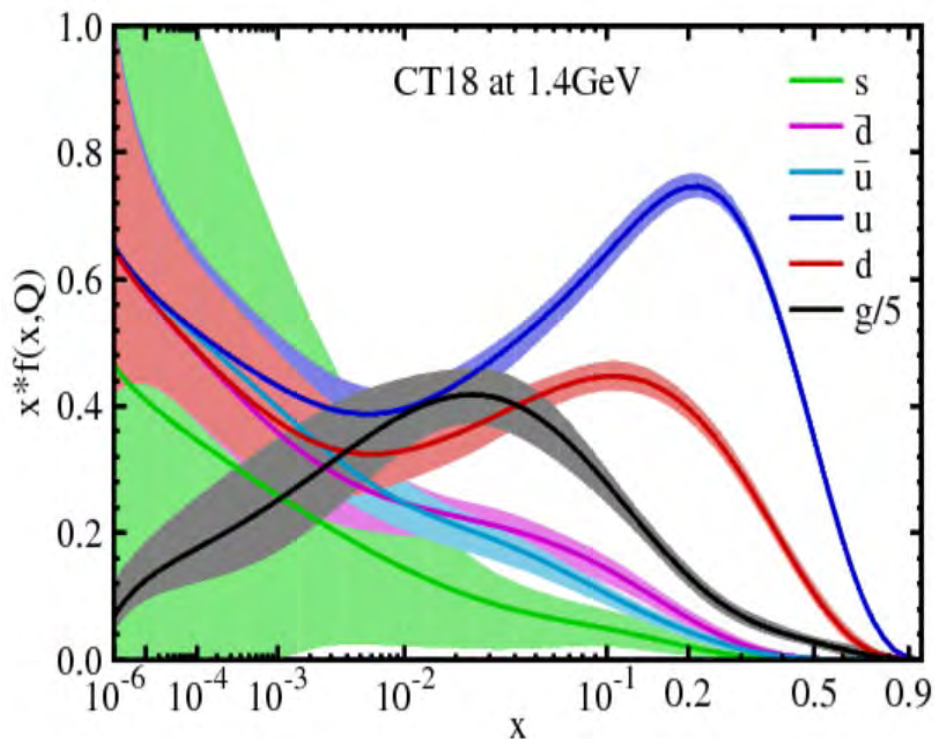
ID	Obs.	Expt.	fast table	NLO code	K-factors	$\mu_{R,F}$
245	$y_{\mu\mu}, \eta_\mu$	LHCb7ZW	APPLgrid	MCFM/aMCfast	MCFM/FEWZ	$M_{Z,W}$
246	$y_{ee}$	LHCb8Z				
250	$y_{\mu\mu}, \eta_\mu$	LHC8ZW				
249	$A(\mu)$	CMS8W				
253	$p_T^H$	ATL8Z	APPLgrid	MCFM	NNLOJet	$M_T^H$
201	$\sqrt{\tau}, y$	E605	CTEQ	FEWZ	$Q_{ll}$	
203	$\sigma_{pd}/\sigma_{pp}, x_F$	E866				
204	$Q, x_F$	E866				
225	$A(e)$	CDF1Z	CTEQ	ResBos	$M_W$	
227	$A(e)$	CDF2W				
234	$A(\mu)$	D02W				
281	$A(e)$	D02W				
260	$y_{ll}$	D02	CTEQ	VRAP	$Q_{ll}$	
261	$y_{ll}$	CDF2				
266	$A(\mu)$	CMS7W	CTEQ	ResBos	$M_W$	
267	$A(e)$	CMS7W				
268	$y_{ll}, \eta_l, A(l)$	ATL7ZW(2012)				
248	$y_{ll}, \eta_l$	ATL7ZW(2016)				APPLgrid



# CT18 parton distributions

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Four PDF ensembles: CT18 (default), A, X, and Z



CT18Z has enhanced gluon and strange PDFs at  $x \sim 10^{-4}$ , and reduced light-quark 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. CT18A and CT18X include some features of CT18Z.



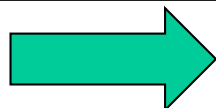
# We have also asked:

Which of 30+ eligible LHC experiments provide promising constraints on the CTEQ-TEA PDFs?

Do the LHC experiments agree among themselves and with other experiments?

A **consistent** answer emerges from a powerful combination of four methods:

See talk by  
Pavel Nadolsky



1. **Lagrange multiplier scans** } slow, most accurate
2. **PDFSense and  $L_2$  sensitivity**
3. **ePump** [Schmidt, Pumplin, Yuan, PRD 98, 094005]
4. **Effective Gaussian variables** } Fast approximations

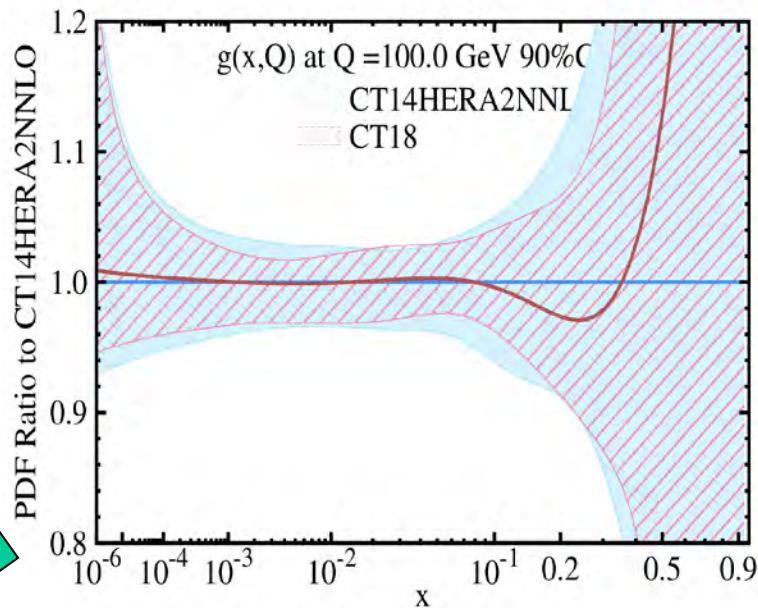
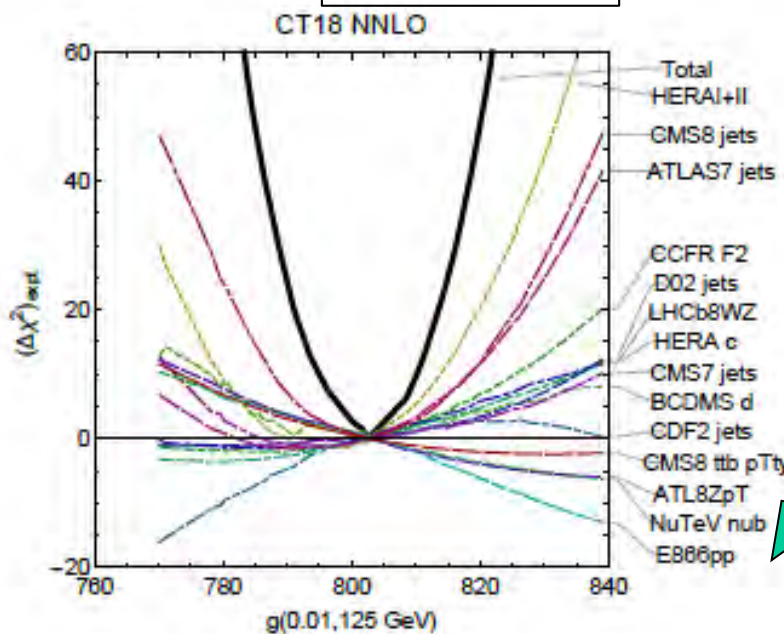
H.-L. Lai et al., arXiv:1007.2241

The LM scan technique was introduced in **Stump et al., Phys. Rev. D65 (2001) 014012**

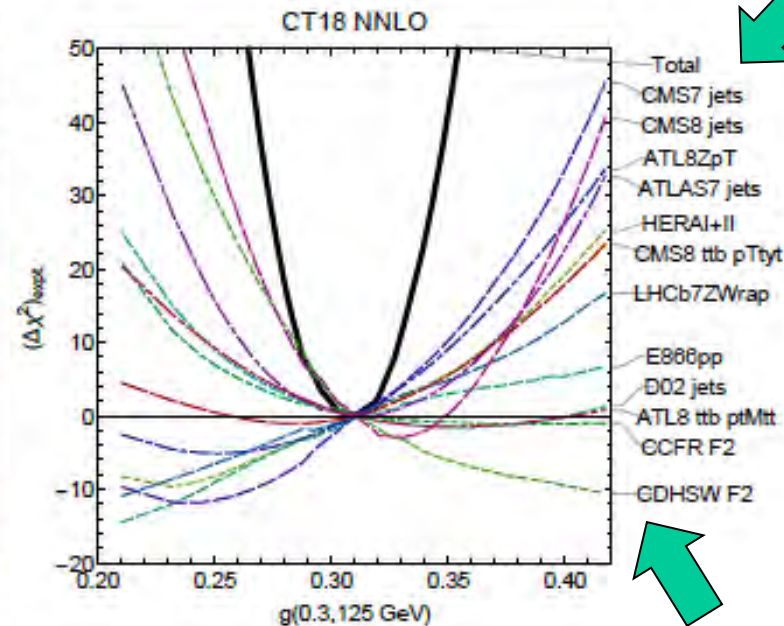


# Preview of CT18 PDFs (g-PDF)

G(0.01,125)



G(0.3,125)



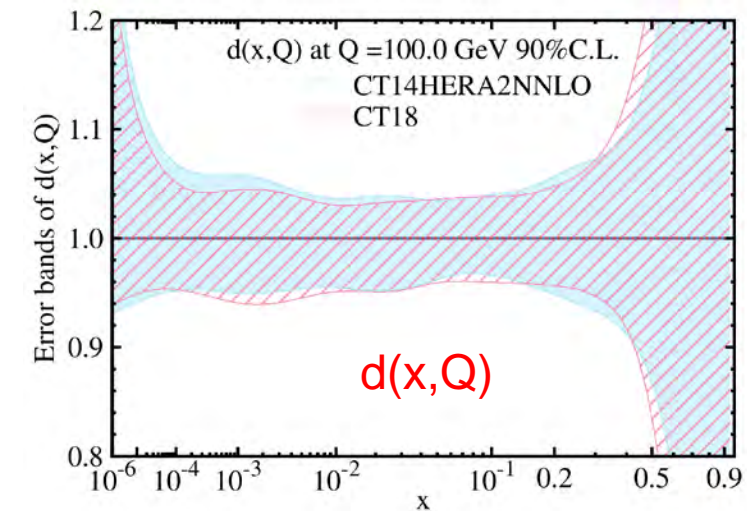
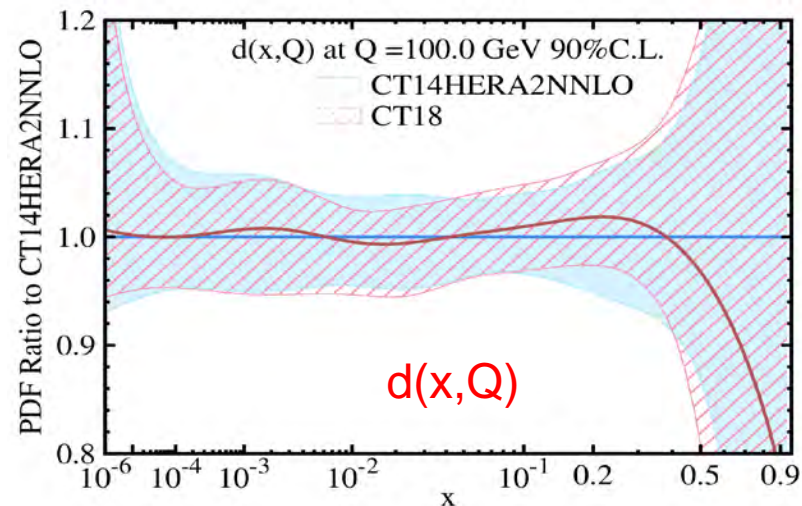
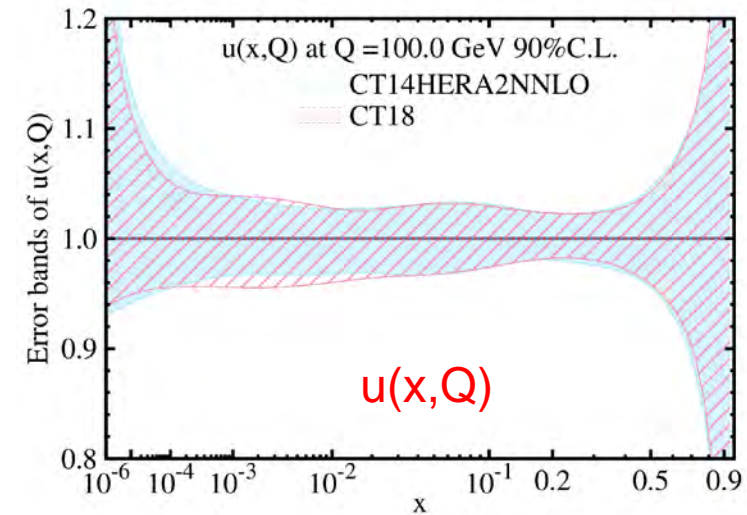
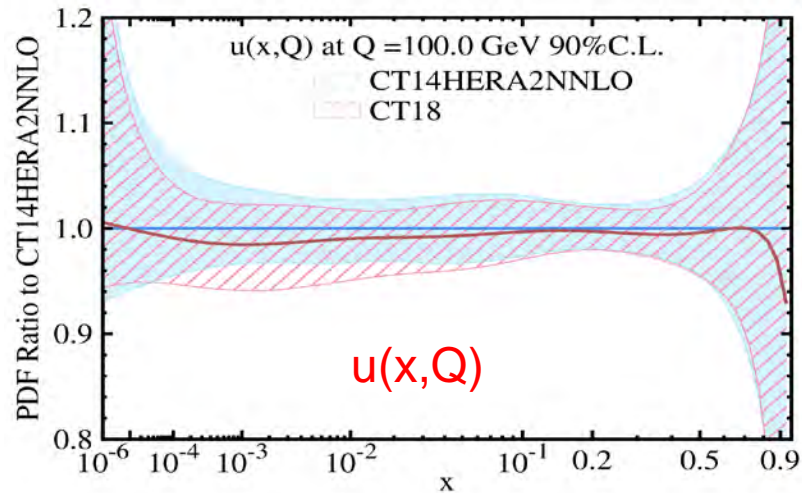
## Lagrange Multiplier Scans

- 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  $x \rightarrow 1$  is parametrization form dependent.



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

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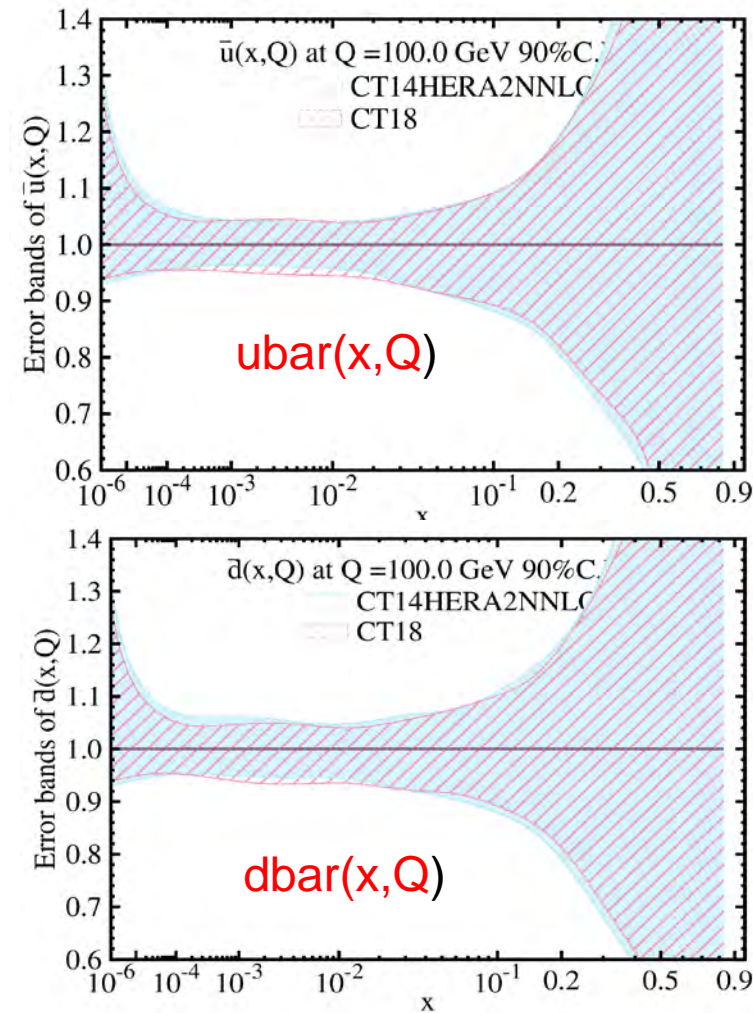
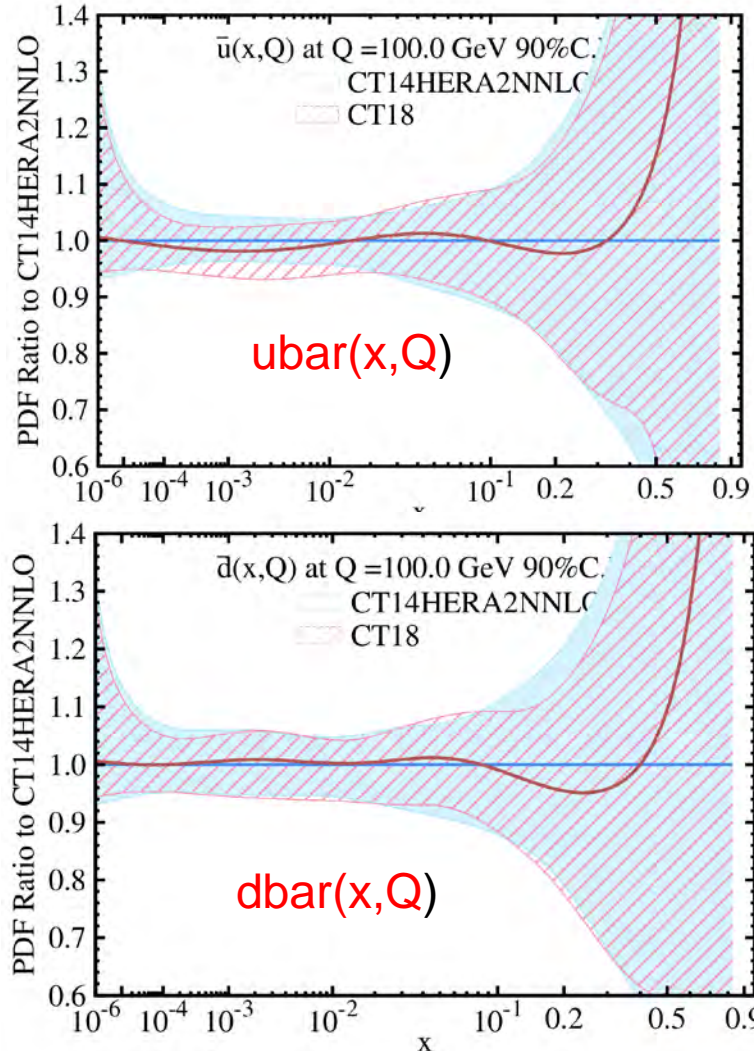


- Some changes on u and d at small x, and d around 0.2; mainly come from LHCb W and Z rapidity data, at 7 and 8 TeV.



# Preview of CT18 (ubar and dbar PDF)

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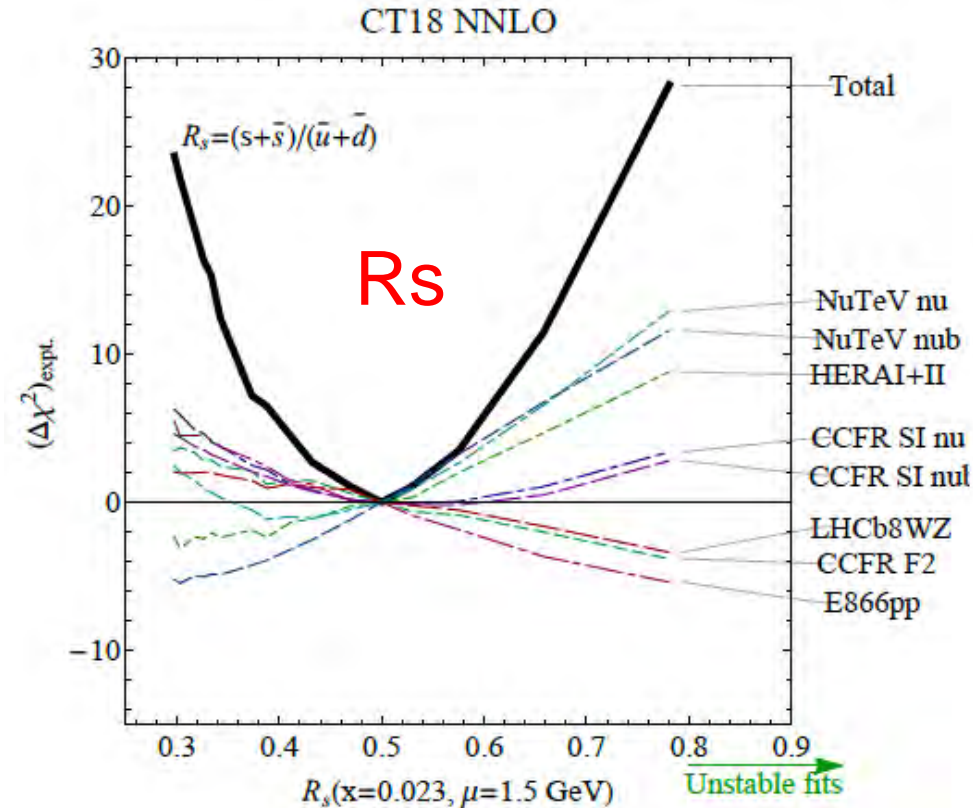
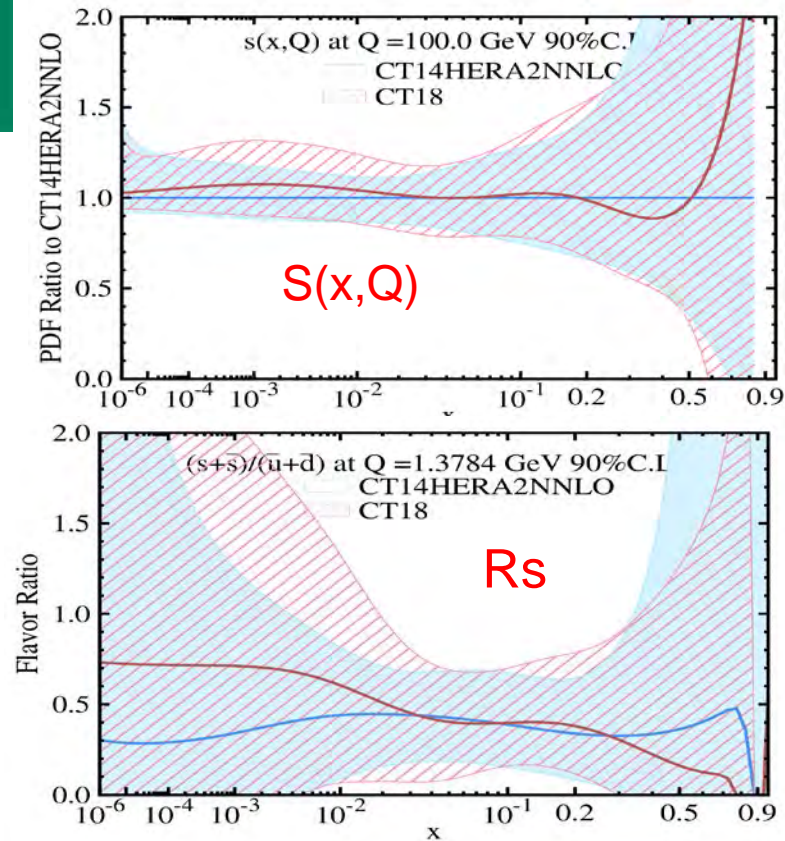


- Minor changes on  $\bar{u}$  and  $\bar{d}$  PDFs at small  $x$  region mainly come from LHCb W and Z rapidity data, at 7 and 8 TeV.
- The behavior of  $\bar{u}$  and  $\bar{d}$  PDFs, as  $x \rightarrow 1$ , is parametrization form dependent.



$$R_s = (s + \bar{s}) / (\bar{u} + \bar{d})$$

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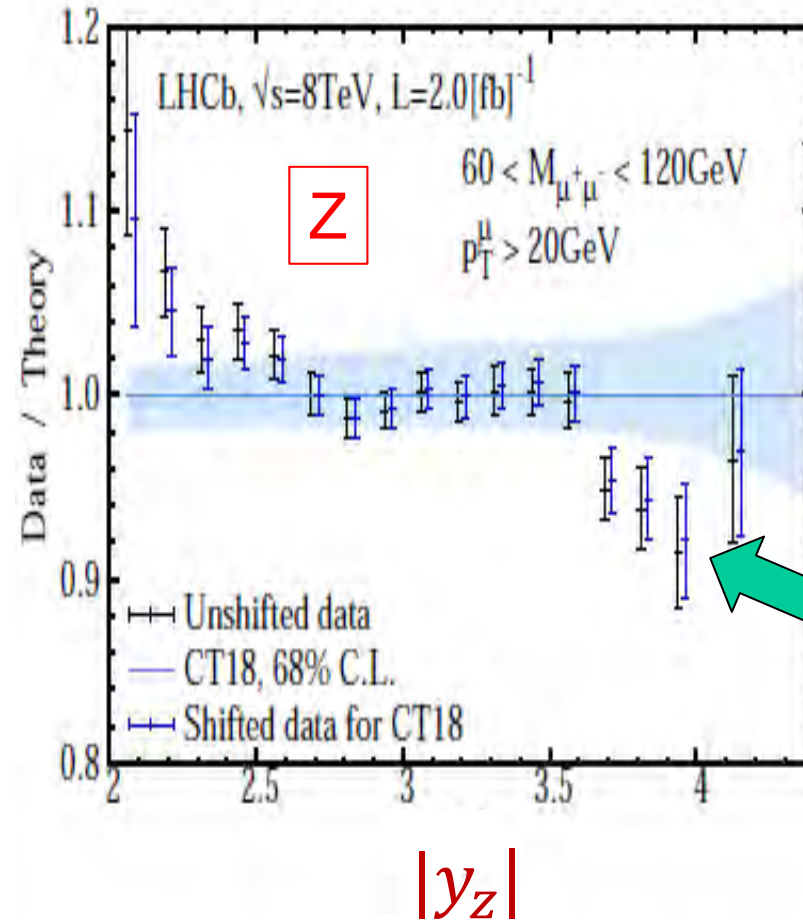
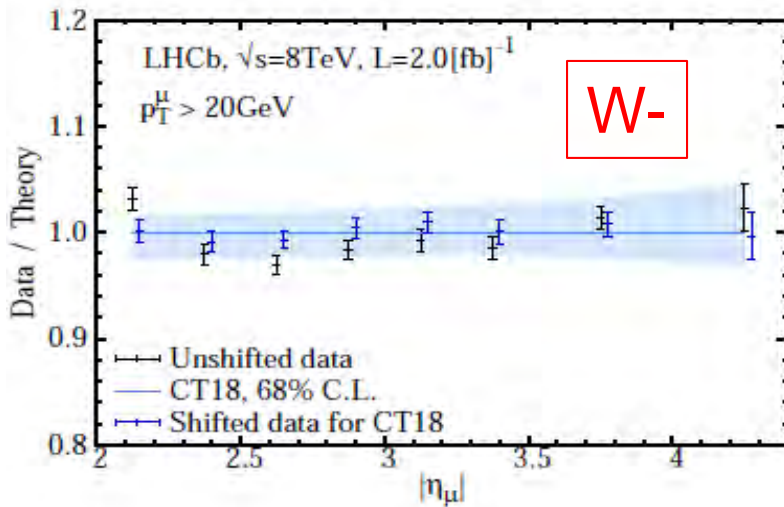
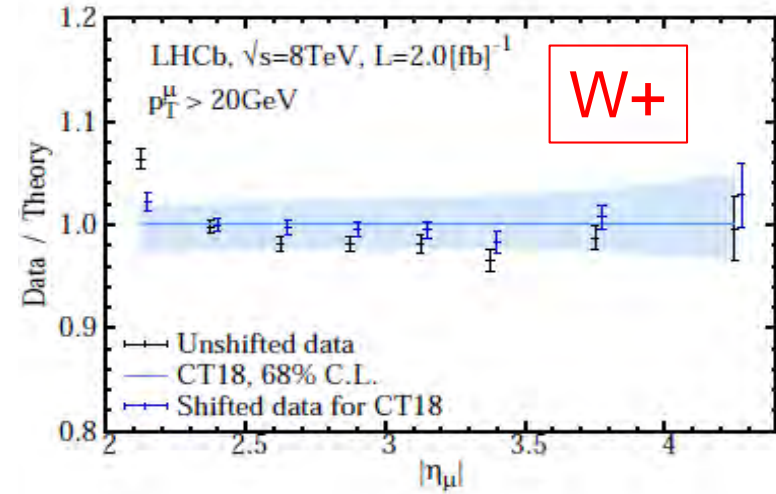


- LHCb W and Z (7,8 TeV) data prefer a larger s-PDF in the small-x region.
- NuTeV dimuon data strongly prefer a smaller  $R_s$  value, while the LHCb WZ data prefer a slightly larger  $R_s$  value.
- $R_s$  (CT18) =  $0.5 \pm 0.3$  for  $x = 0.023$  and  $Q^2 = 1.9 \text{ GeV}^2$ . (preliminary)  
(Compare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



# LHCb 8 TeV W and Z data in CT18 fit

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- 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: 1907.12177  
ePump study

arXiv:1511.08039

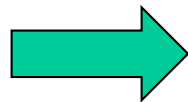


# CT18Z

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## 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  $\chi^2/\text{d.o.f} \sim 2.1$
- Remove CDHSW data
- Use a special  $x$ -dependent factorization scale  $\mu_{\text{DIS},x}$  at NNLO calculation.
- CT18Z uses a combination of  $\mu_{\text{DIS},x}$  (preferred by DIS) and an increased  $m_c^{\text{pole}} = 1.4 \text{ GeV}$  (preferred by LHC vector boson production, disfavored by DIS)



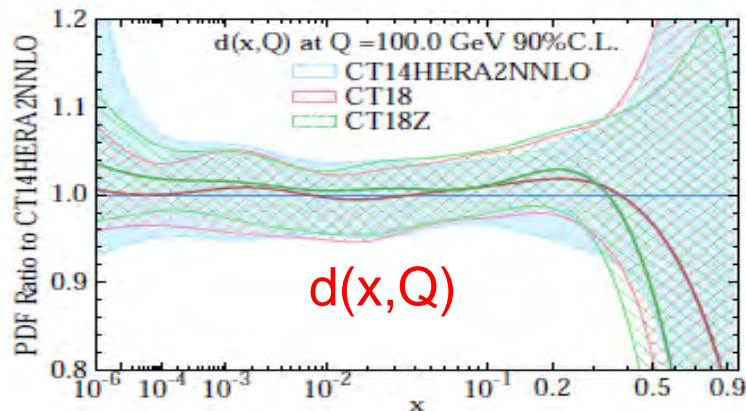
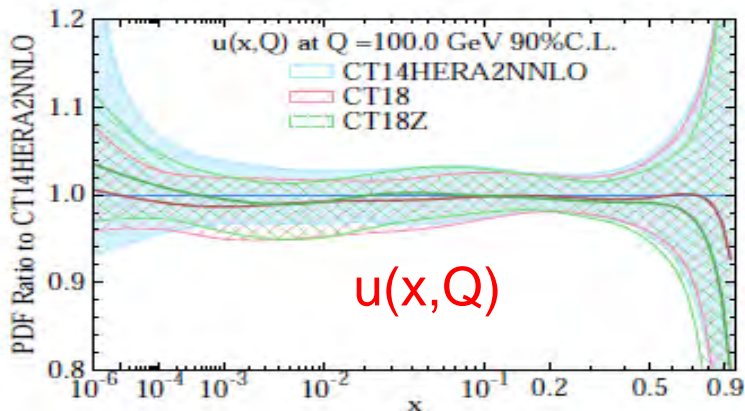
CT18Z PDFs



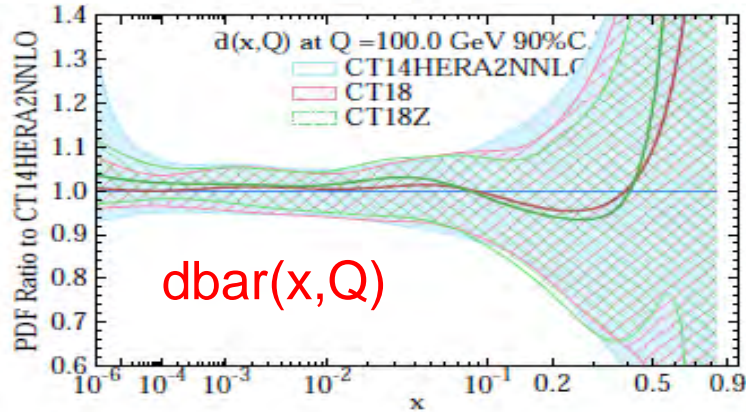
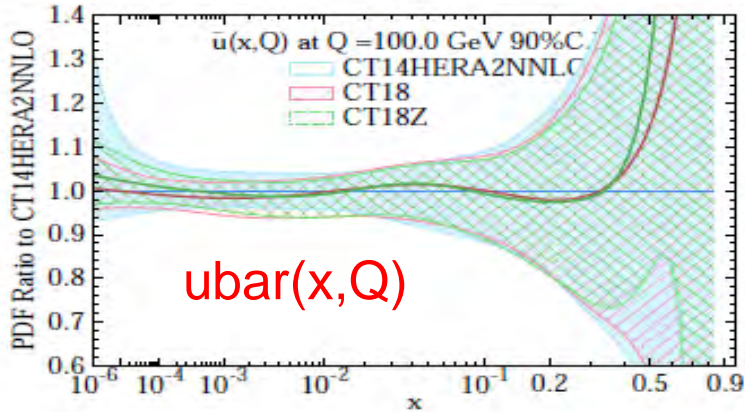
# CT18Z vs. CT18 PDFs

CTEQ

u and d increase at small-x

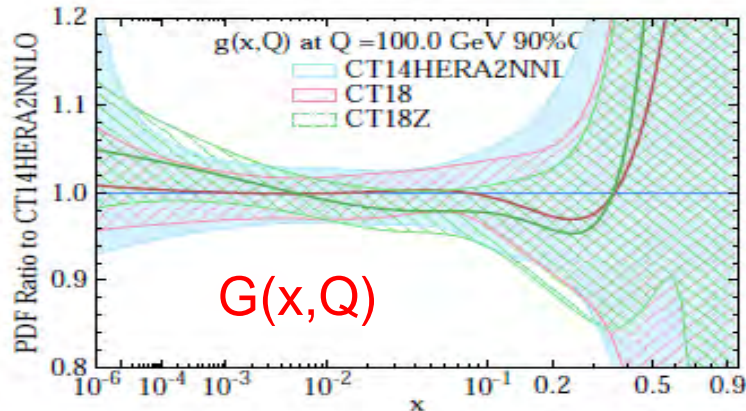
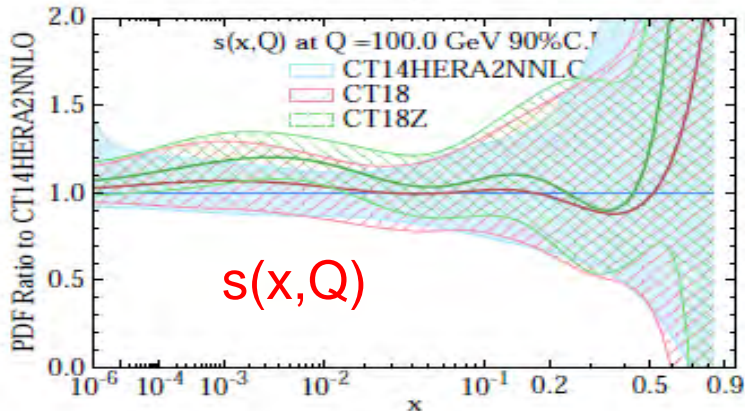


d increases at x ~ 0.2 - 0.3

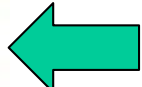
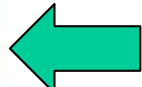
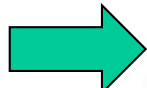
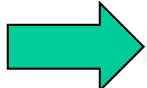


Q=100 GeV; at 90%CL

s increases at small-x



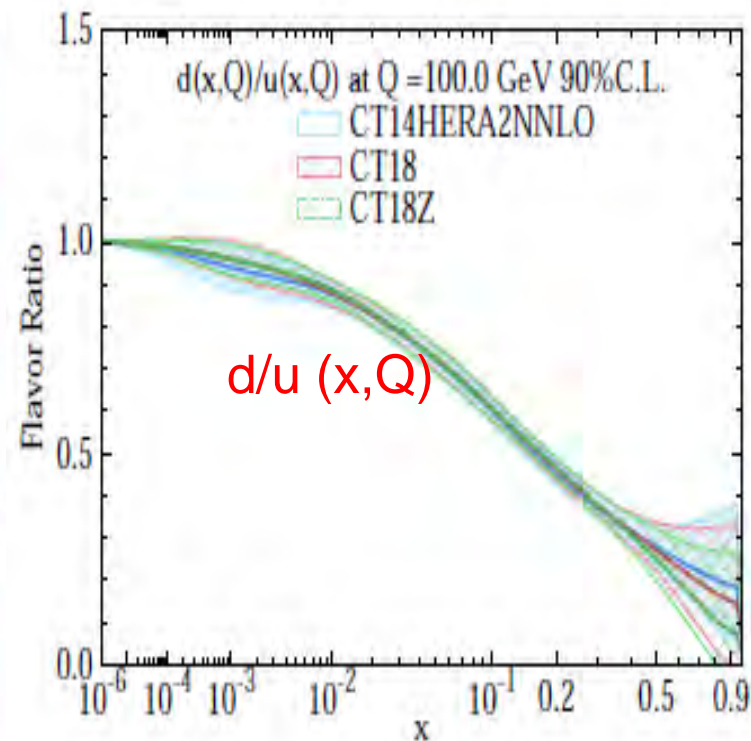
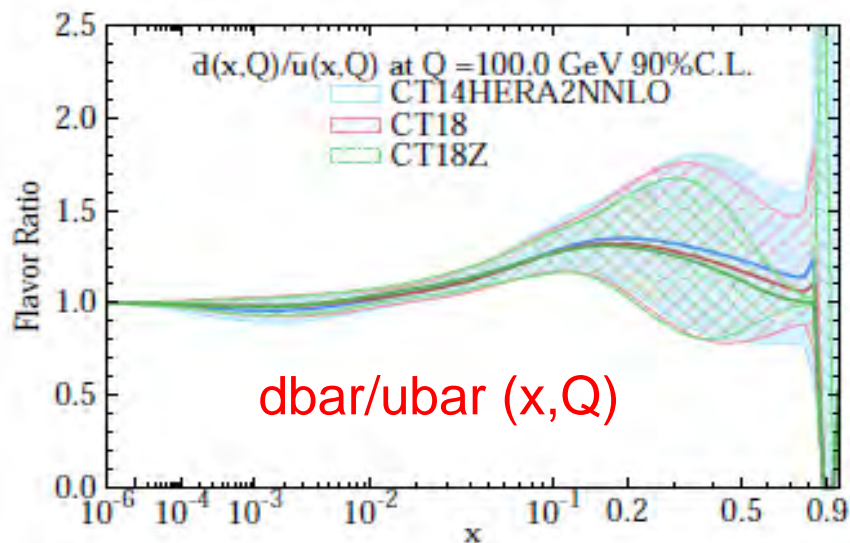
G increases at small-x, and decreases at x ~ 0.01 - 0.3



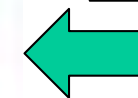


# CT18Z vs. CT18 PDFs

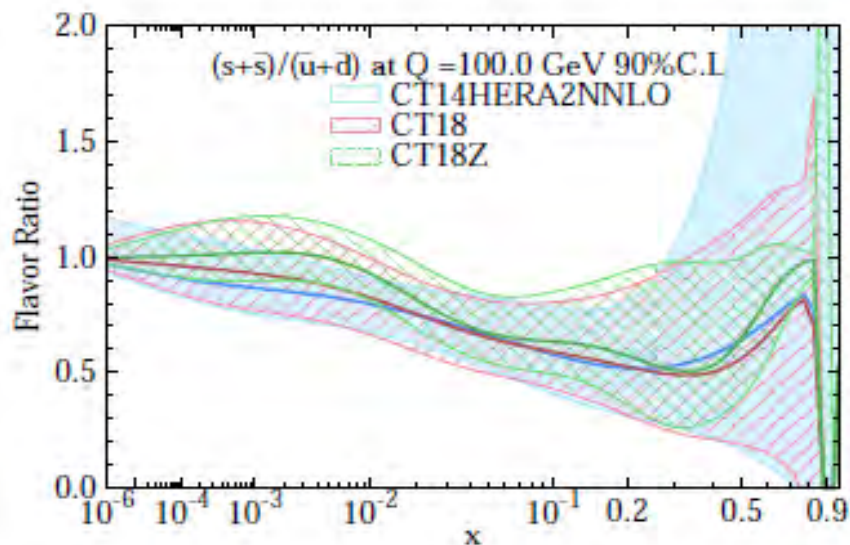
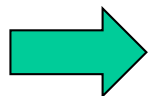
CTEQ



$d/u$  decreases at large- $x$



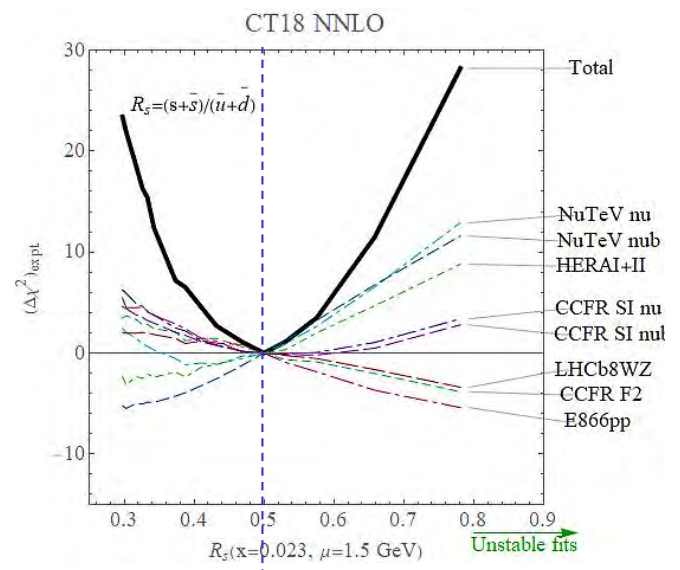
$R_s$  increases at small- $x$



$Q = 100$  GeV;  
at 90% CL

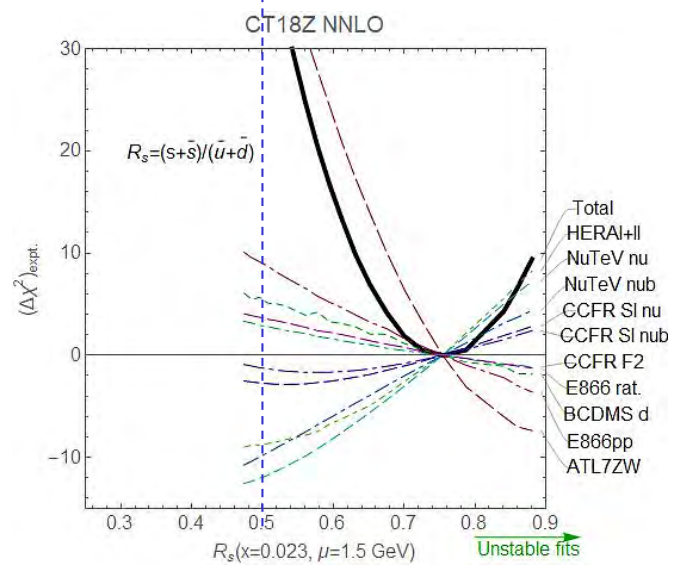


# Lagrange Multiplier scan: $R_s(x = 0.023, \mu = 1.5 \text{ GeV})$

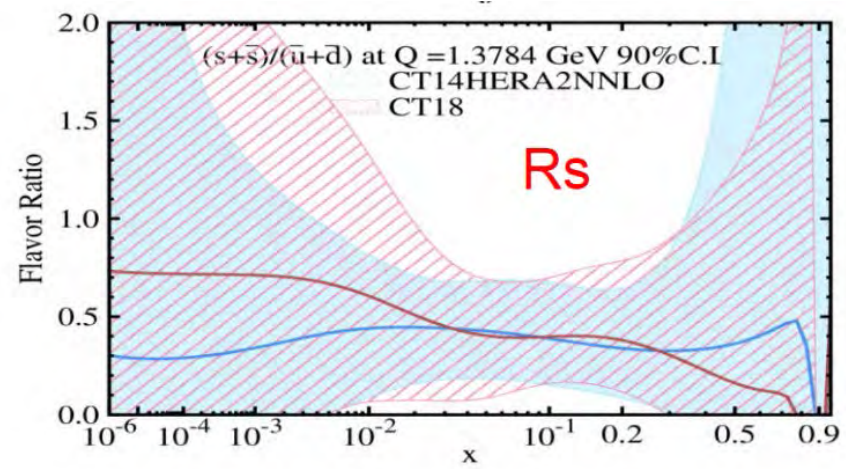


The CT18Z strangeness is increased primarily as a result of including the ATLAS 7 TeV W/Z production data (not in CT18), as well as because of using the DIS saturation scale and  $m_c^{\text{pole}} = 1.4 \text{ GeV}$

In either CT18 or CT18Z fit, observe instability in the fits for  $R_s > 1$  at  $x = 0.01 - 0.1$



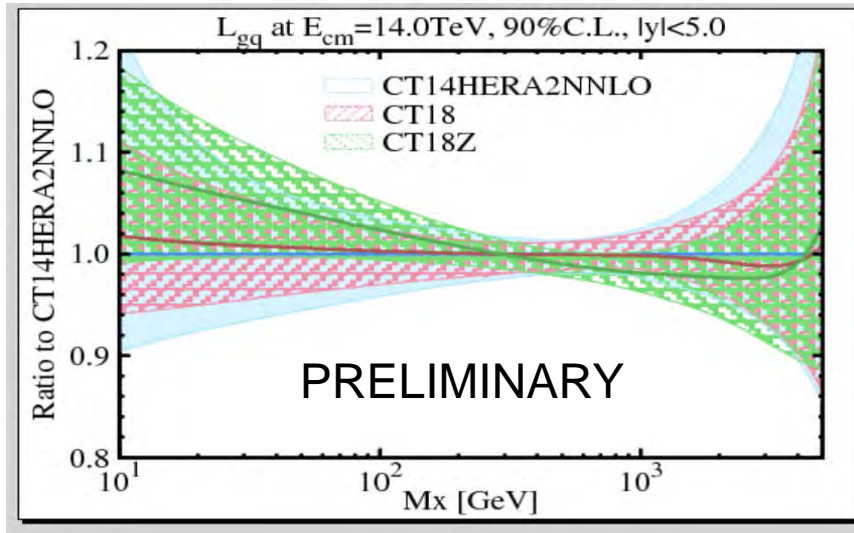
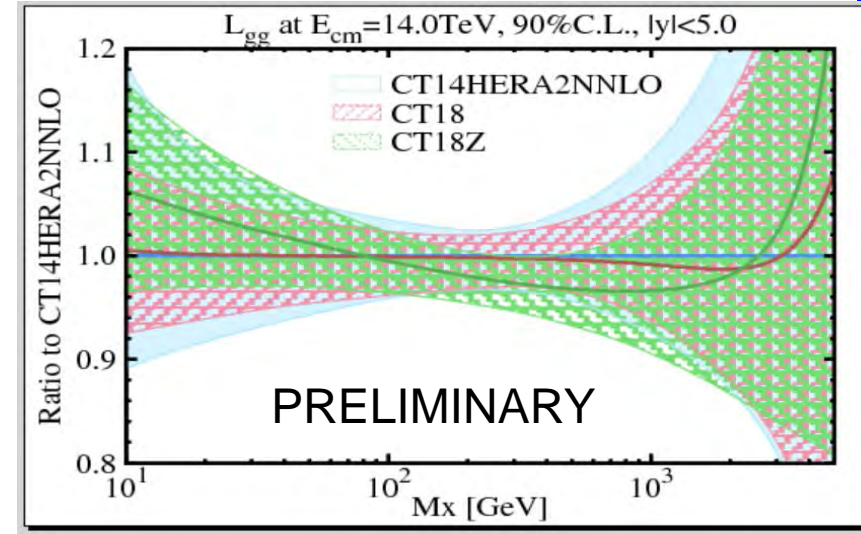
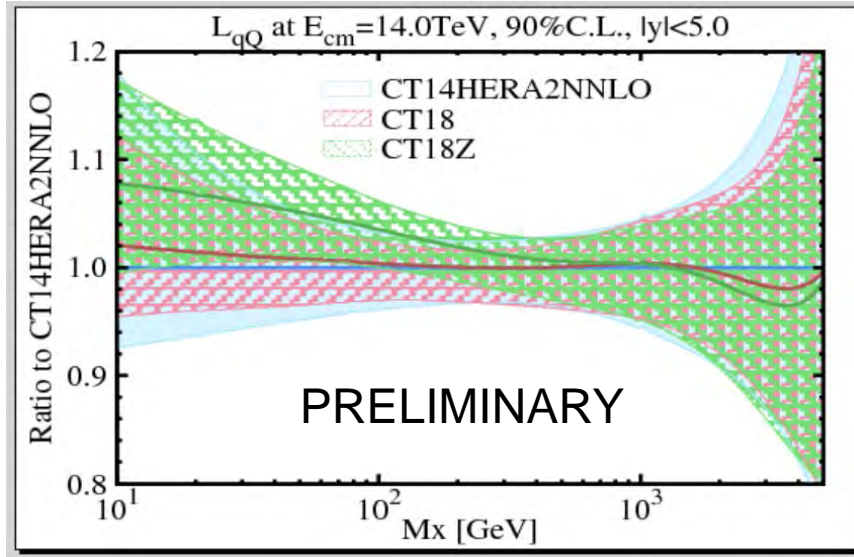
Compare to





# CT14, CT18 and CT18Z parton luminosities

CTEQ



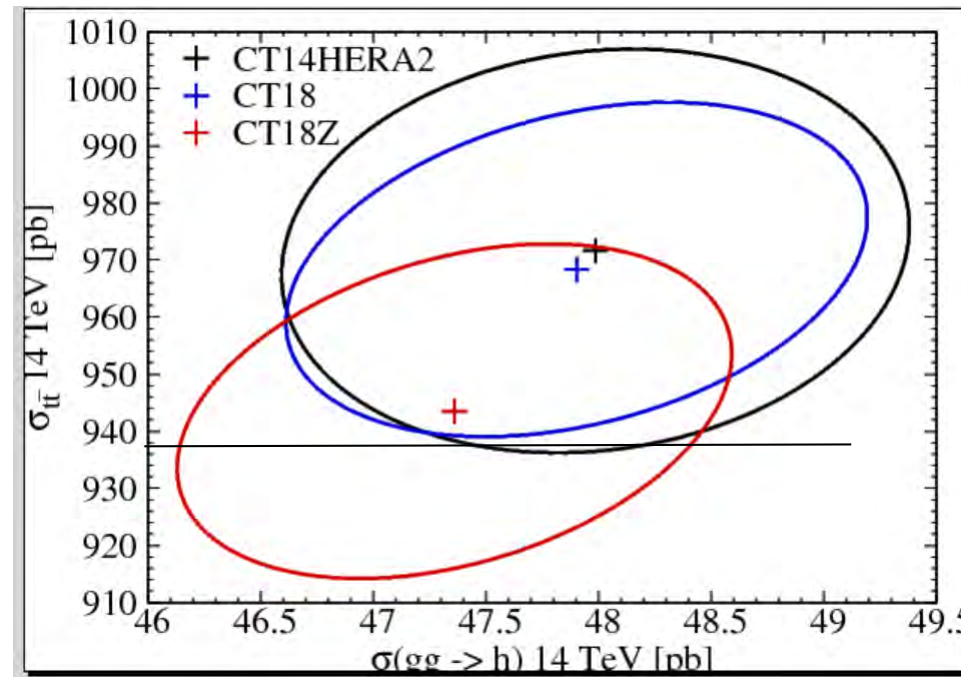
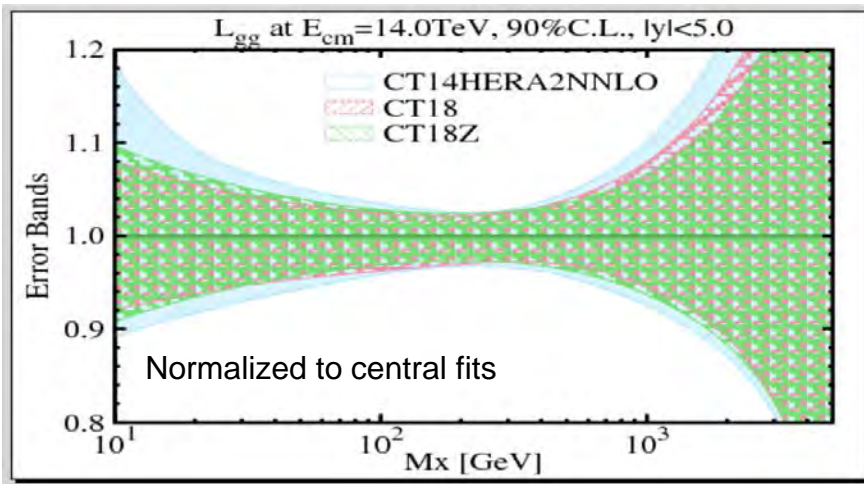
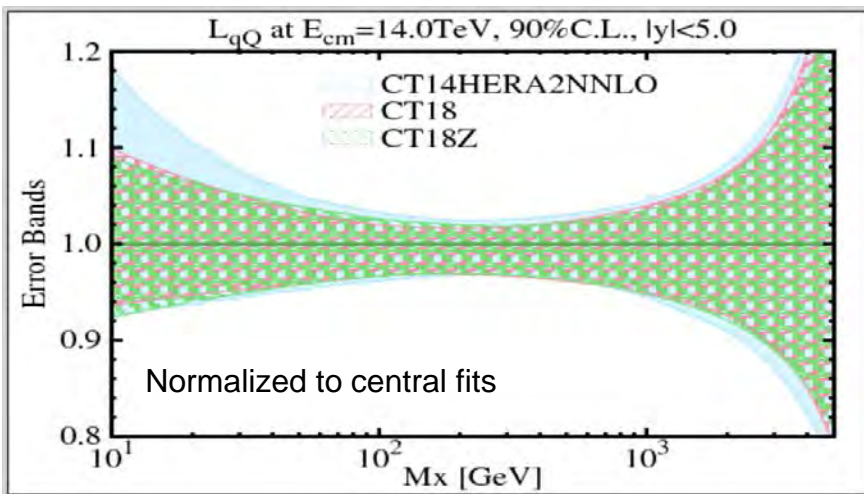
CT18 consistent with CT14

CT18Z has a somewhat different shape, especially at low invariant masses  $M_X$



# Mild reduction in nominal PDF error bands and cross section uncertainties

CTEQ

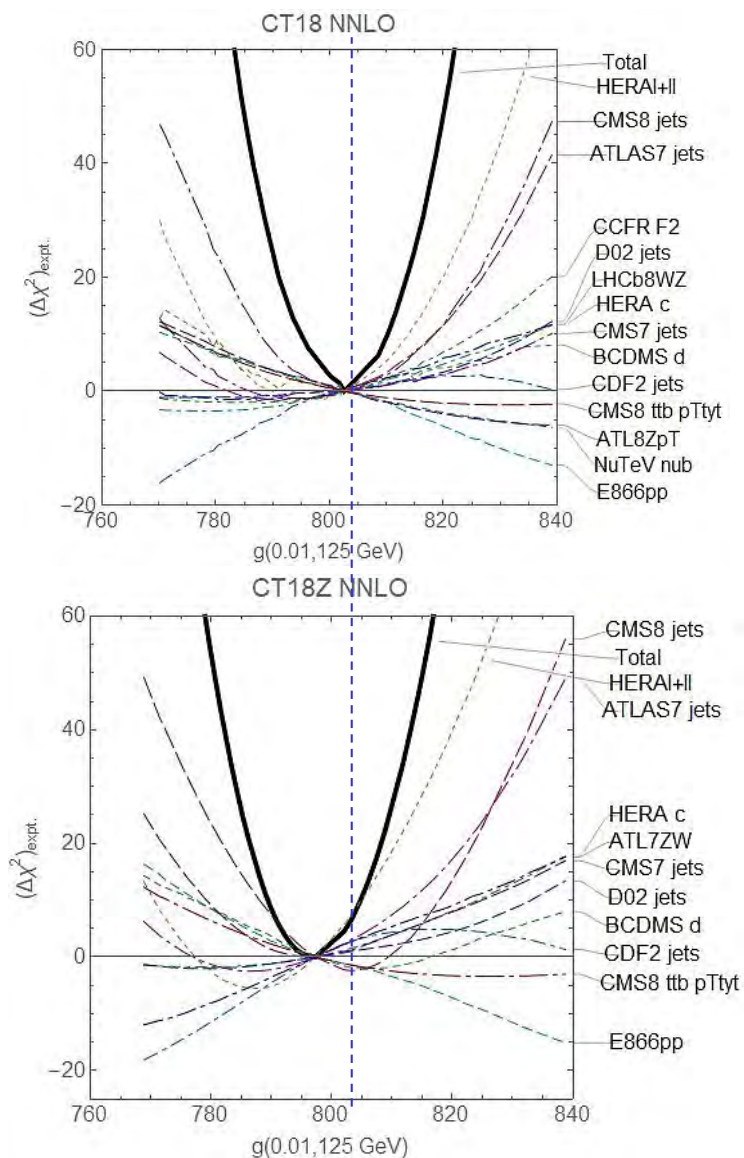


CT18Z  $gg \rightarrow H$  and  $t\bar{t}$  production cross sections lower by about 1 and 2.5% compared to CT14HERA2

PRELIMINARY



# Lagrange Multiplier scan: $g(0.01, 125 \text{ GeV})$



## Upper row: CT18

6500 core hours

- HERAI+II data set provides the dominant constraint, followed by ATLAS, CDF2, CMS, D02 jet production, HERA charm,...
- $t\bar{t}$  double-diff. cross sections provide weaker constraints

## Lower row: CT18Z

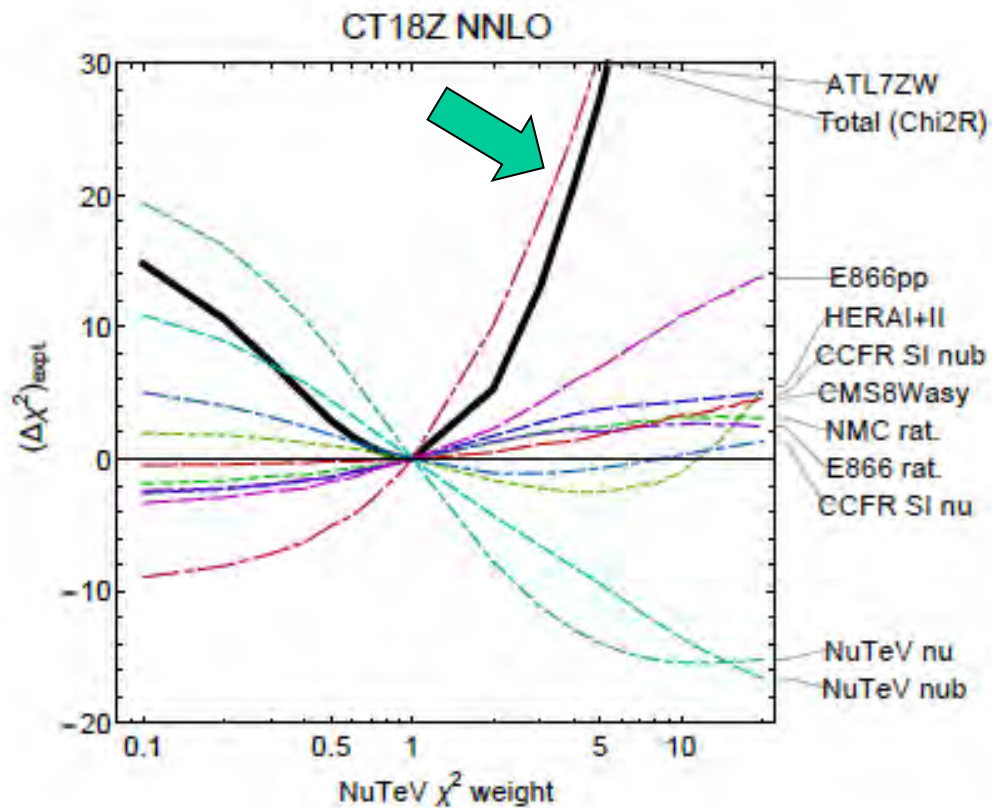
- CT18Z: a 1% lower NNLO gluon in the Higgs production region than for CT14/CT18



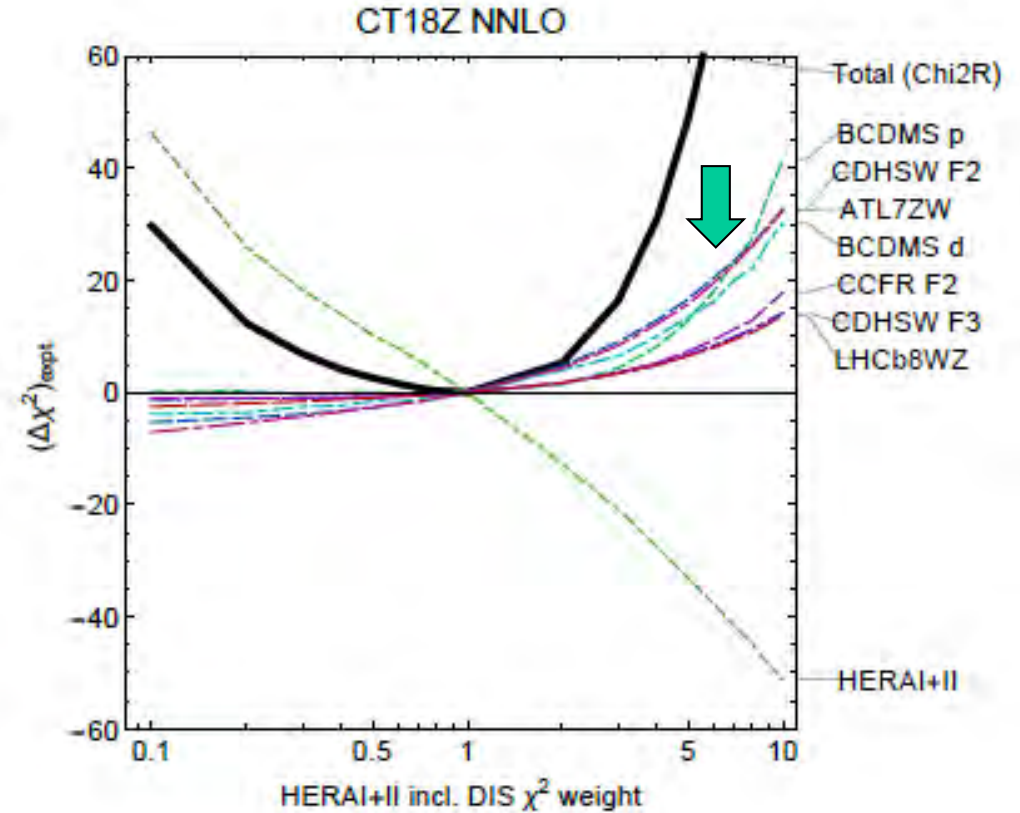
# CT18Z fit

CTEQ

➤ 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



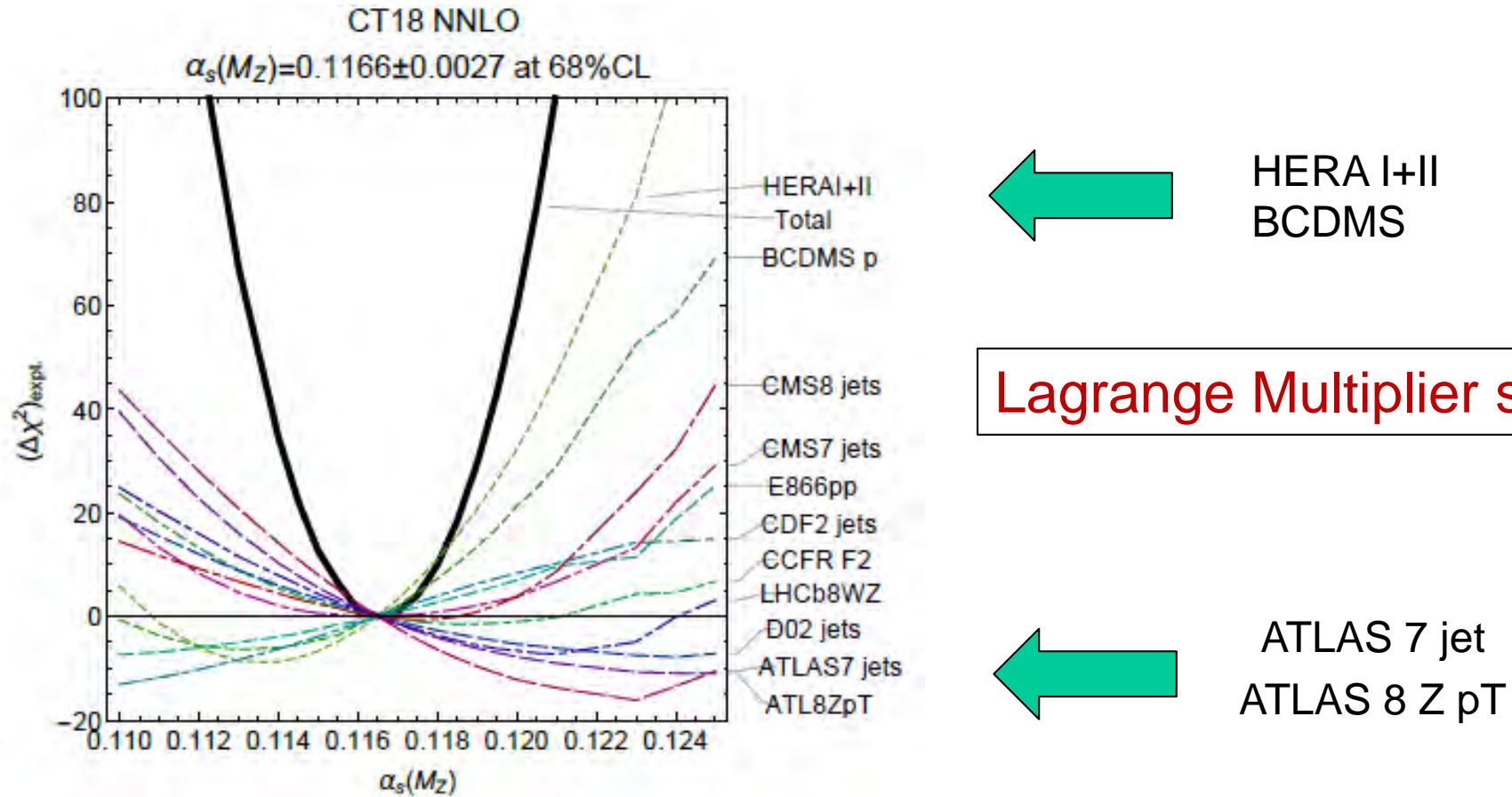
# Fitting $\alpha_s(Mz)$ for CT18

## Using Lagrange Multiplier Scan



# $\alpha_s (M_Z)$ for CT18

CTEQ



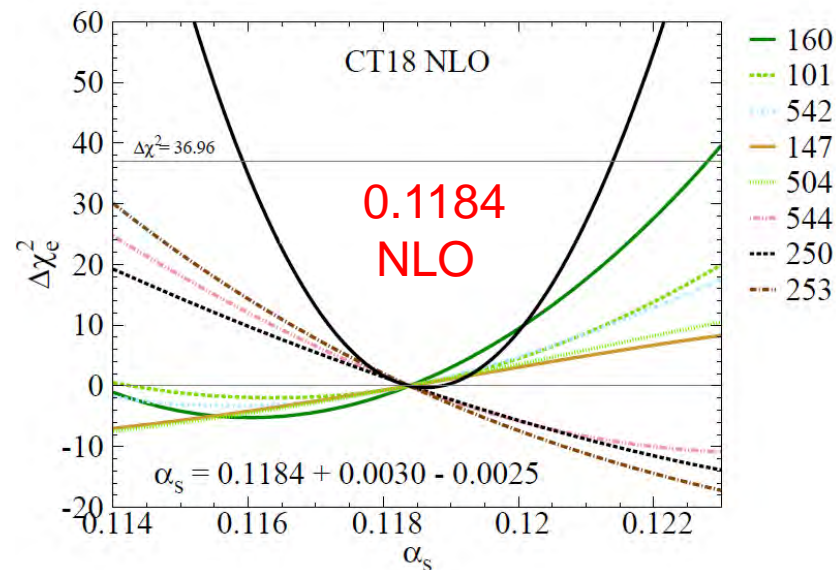
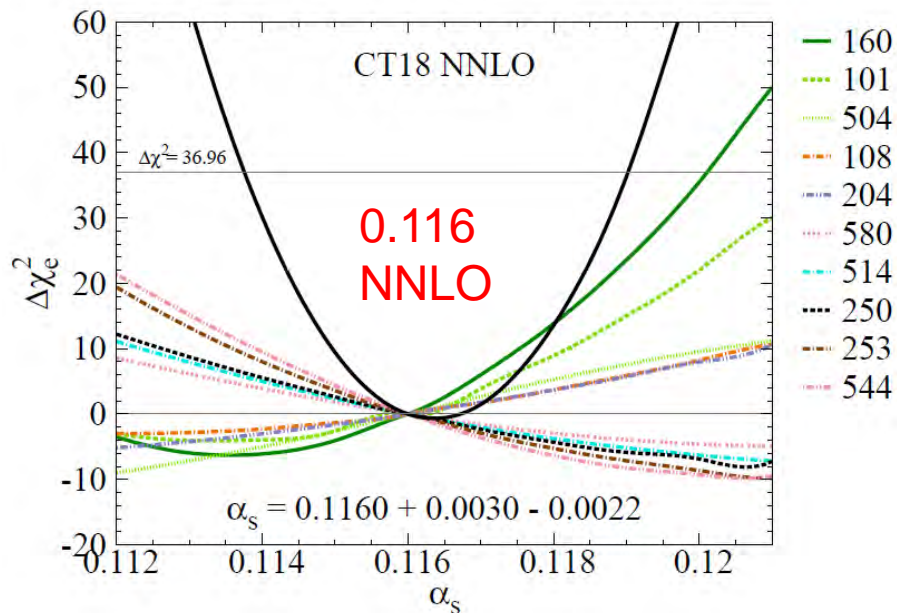
- The fixed target F2 data and HERA DIS data prefer smaller  $\alpha_s$  value.
- The ATLAS 8TeV Z pT and ATLAS 7 TeV incl. jet data, bring the central value of  $\alpha_s (M_Z)$  from  $0.115_{-0.004}^{+0.006}$  (CT14) to  $0.1166 \pm 0.0027$  (CT18).



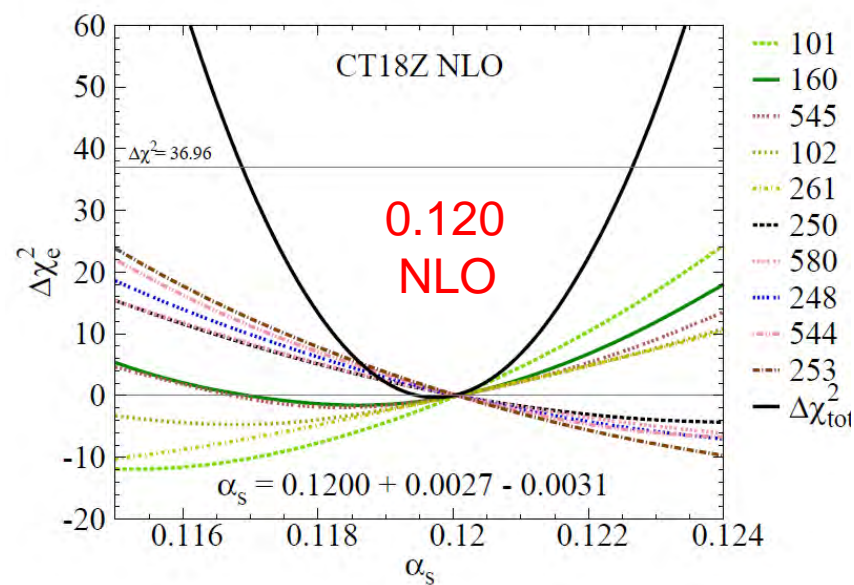
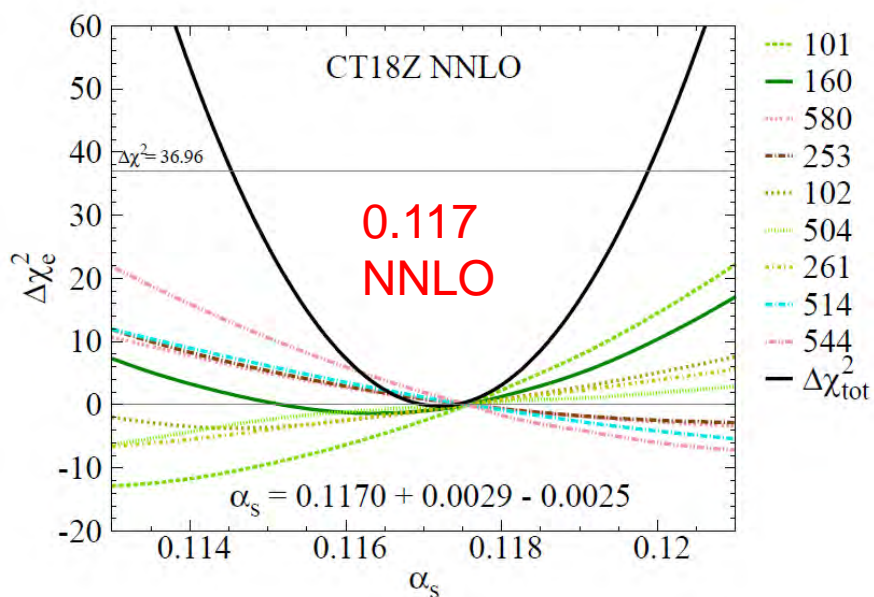
# $\alpha_s$ (Mz) for CT18(Z) at (N)NLO

CTEQ

CT18



CT18Z





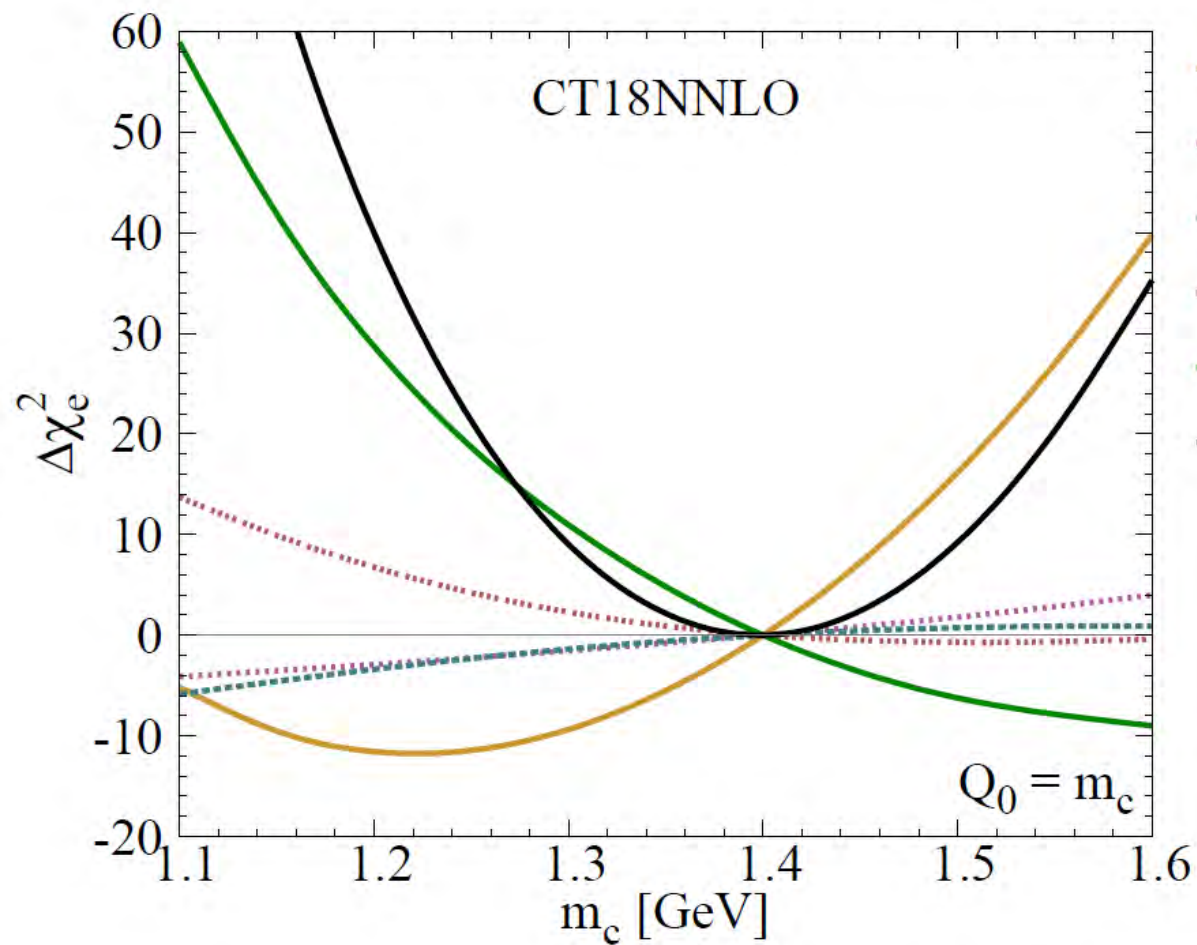
Fitting  $m_c$  (charm quark pole mass) for CT18

Using Lagrange Multiplier Scan



# $m_c$ for CT18

CTEQ



- 147 Comb. HERA charm prod.
- ⋯ 125 NuTeV  $\bar{\nu}\mu\mu$  SIDIS
- - - 169 H1  $F_L$
- ⋯ 545 CMS 8 TeV incl. jet,  $R = 0.7$
- 160 HERAI+II
- $\chi_{\text{tot}}^2$

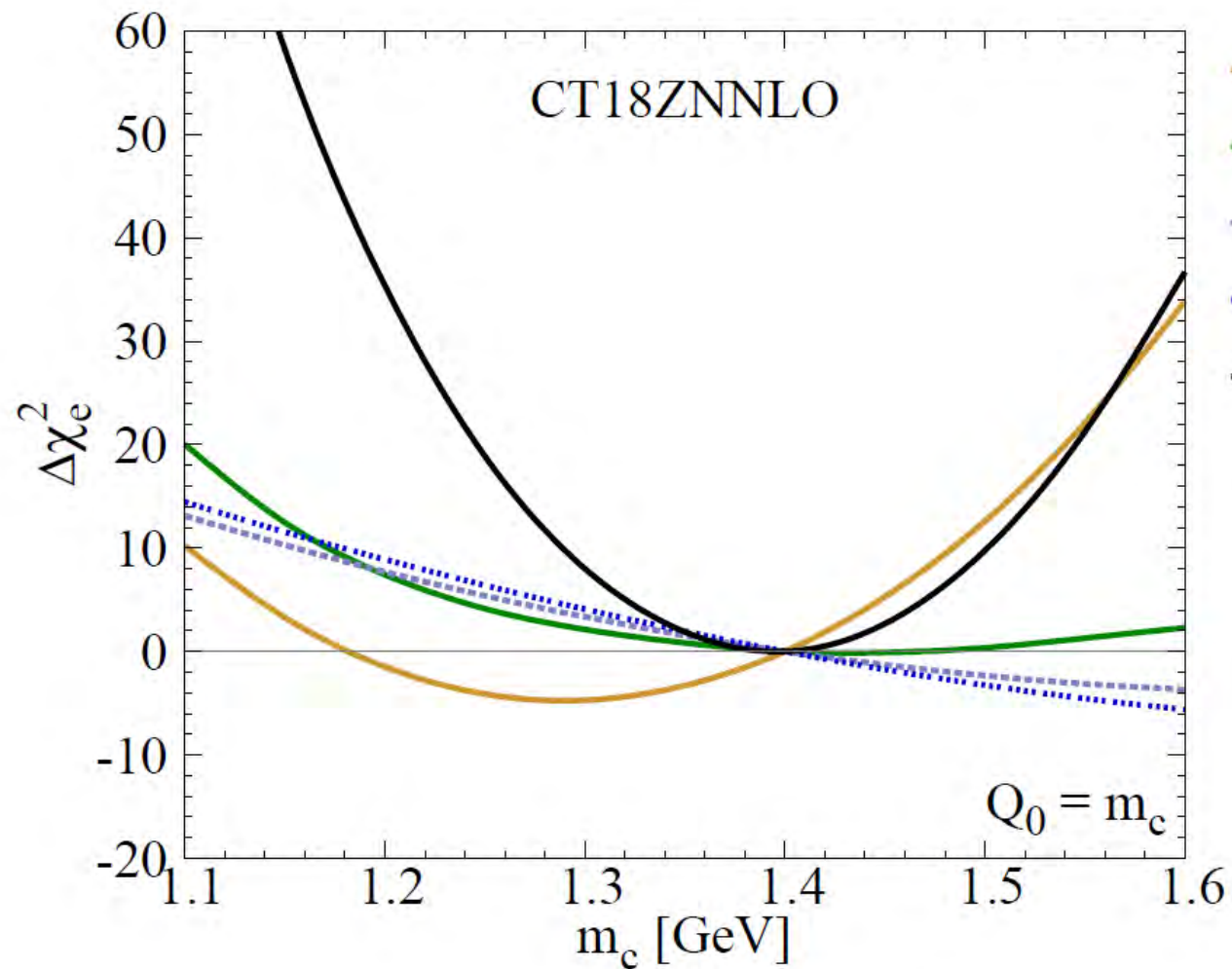
Only show the most sensitive data sets

Total data points: about 3700  
Chi<sup>2</sup>/Npt: 1.17

$m_c \sim 1.4 \text{ GeV}$



# $m_c$ for CT18Z



- 147 Comb. HERA charm prod.
- 160 HERAI+II
- ⋯ 124 NuTeV  $\nu\mu\mu$  SIDIS
- ⋯ 248 ATLAS 7 TeV  $4.6 \text{ fb}^{-1}$  W/Z
- $\chi_{\text{tot}}^2$

Only show the most sensitive data sets

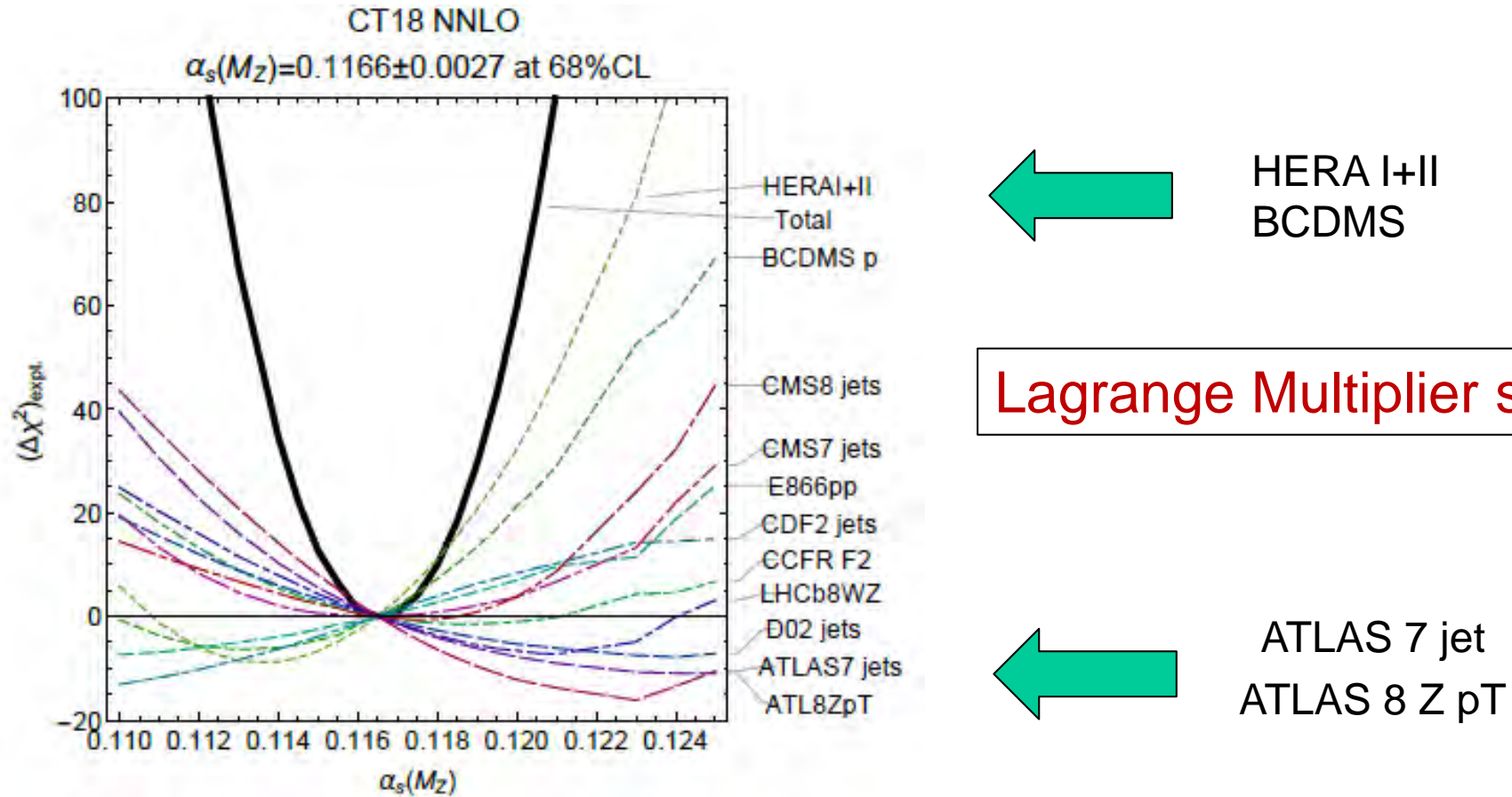
Total data points: about 3500  
Chi<sup>2</sup>/Npt: 1.19

$m_c \sim 1.4 \text{ GeV}$



# $\alpha_s (M_Z)$ for CT18

CTEQ



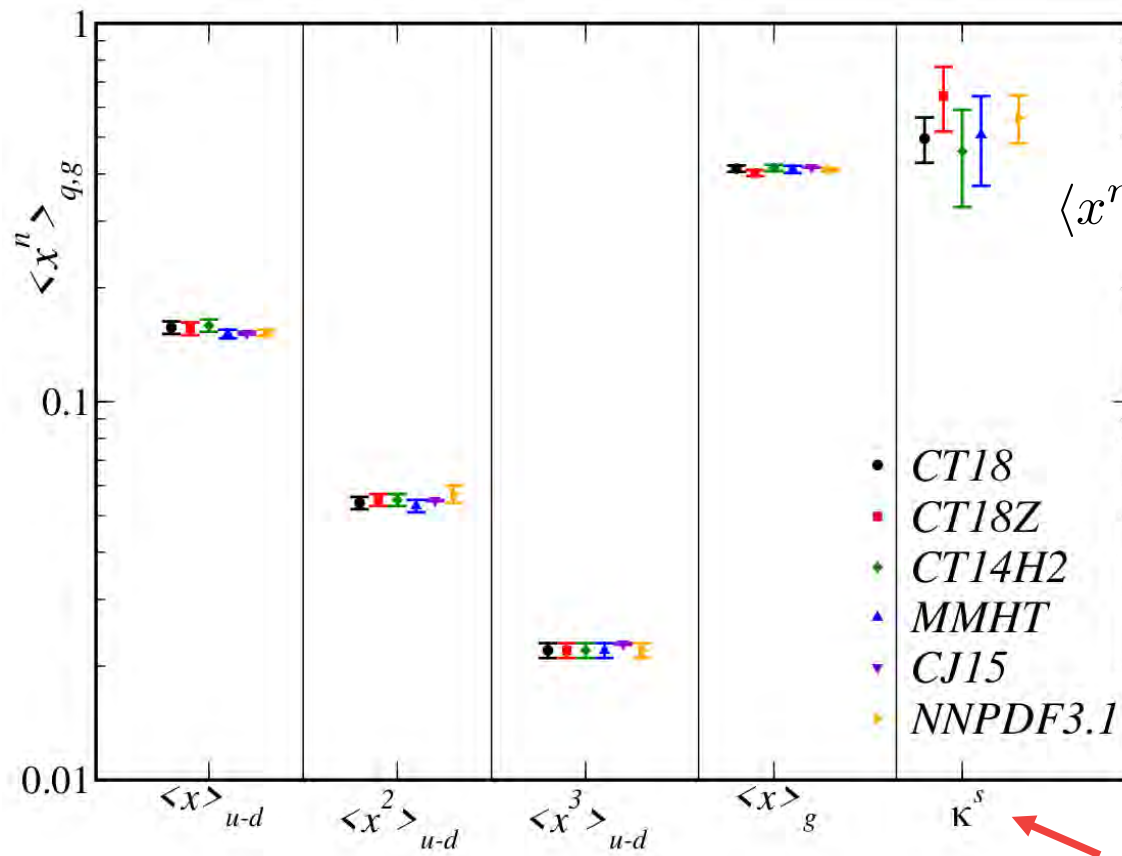
- The fixed target F2 data and HERA DIS data prefer smaller  $\alpha_s$  value.
- The ATLAS 8TeV Z pT and ATLAS 7 TeV incl. jet data, bring the central value of  $\alpha_s (M_Z)$  from  $0.115_{-0.004}^{+0.006}$  (CT14) to  $0.1166 \pm 0.0027$  (CT18).



# PDF moments from CT18

See talk by Tim Hobbs

# PDF moments from CT18



$$\langle x^n \rangle_{q,g} = \int dx x^n f_{q,g}(x, \mu = 2 \text{ GeV})$$

- progress in lattice QCD, which can evaluate PDF Mellin moments, suggests a possible future synergy with QCD global analyses

PDF-Lattice whitepaper – Lin et al., arXiv:1711.07916.

PDFSense analysis – Hobbs et al., arXiv:1904.00022.

→ good agreement among phenomen. predictions of isovector, gluon moments!

→ constraints are significantly weaker for moments of the light quark sea distributions, e.g., the strangeness suppression ratio,  $\kappa^s \equiv \langle x \rangle_{s+\bar{s}} / \langle x \rangle_{\bar{u}+\bar{d}}$

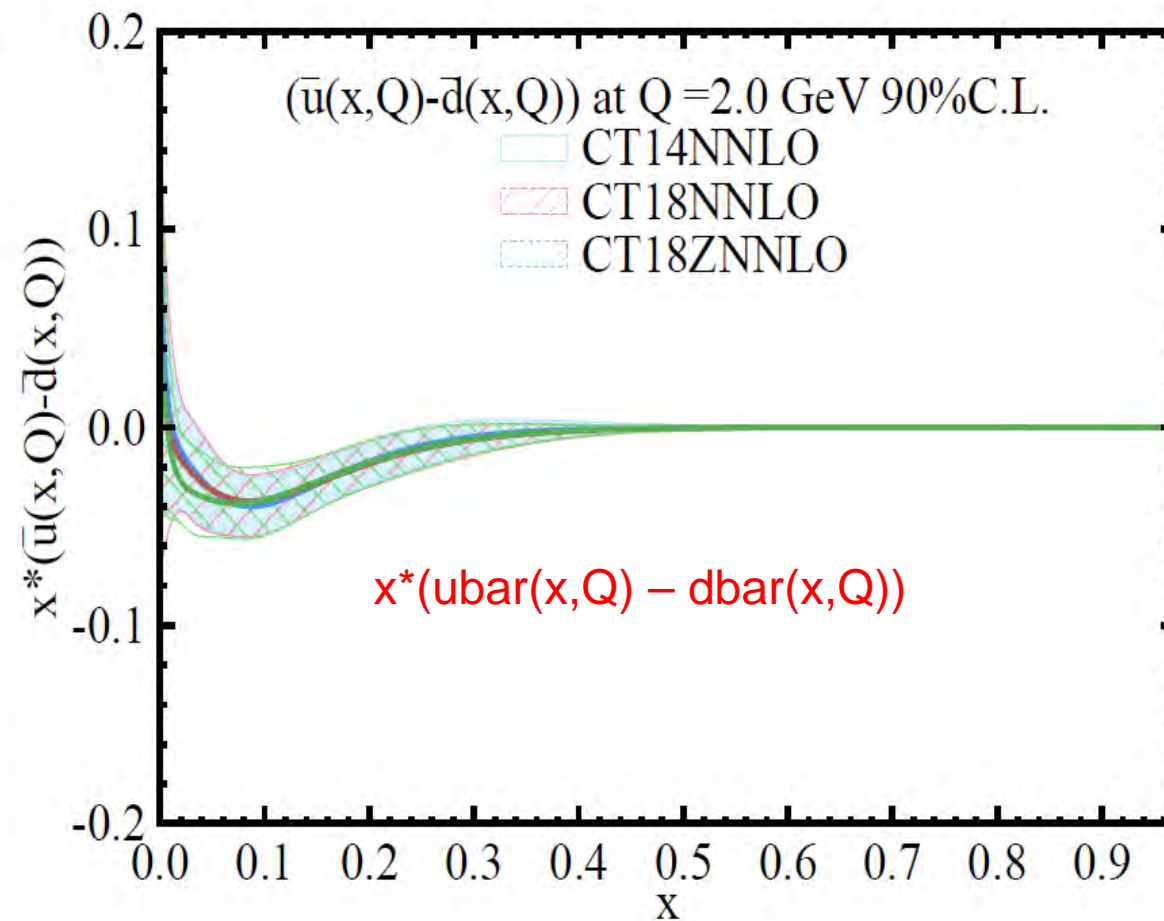
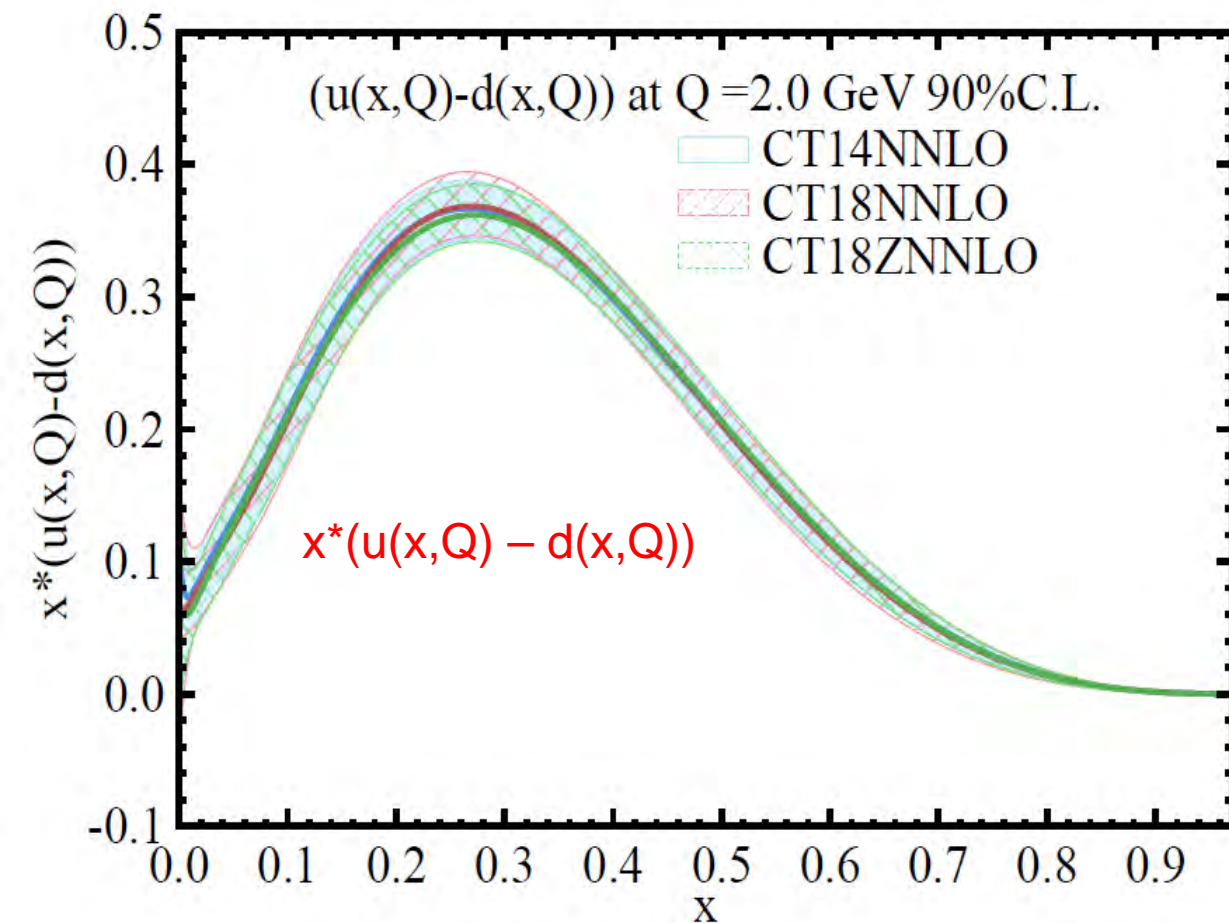
## CT18 moment results

PDF moment	CT18	CT18Z	CT14H2
$\langle x \rangle_{u^+ - d^+}$	$0.157 \pm 0.006$	$0.156 \pm 0.006$	$0.159 \pm 0.006$
$\langle x^2 \rangle_{u^- - d^-}$	$0.054 \pm 0.002$	$0.055 \pm 0.002$	$0.055 \pm 0.002$
$\langle x^3 \rangle_{u^+ - d^+}$	$0.022 \pm 0.001$	$0.022 \pm 0.001$	$0.022 \pm 0.001$
$\langle x \rangle_g$	$0.413 \pm 0.008$	$0.402 \pm 0.007$	$0.415 \pm 0.008$
$\kappa^s$	$0.496 \pm 0.068$	$0.643 \pm 0.125$	$0.459 \pm 0.132$



# Various PDF comparisons

CTEQ





# Summary

CTEQ

- 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 weakened 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, in which NNLO DIS cross sections with an  $x$ -dependent factorization scale, behaving like NNLO+NNLx resummed ones, are incorporated in CT18Z PDFs.

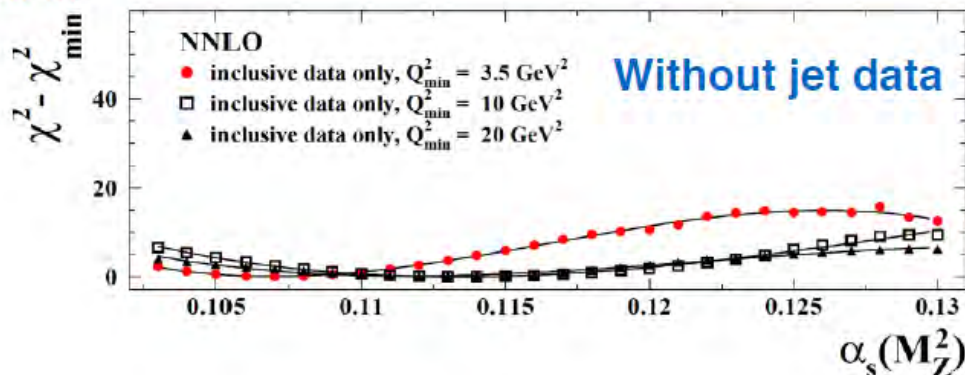
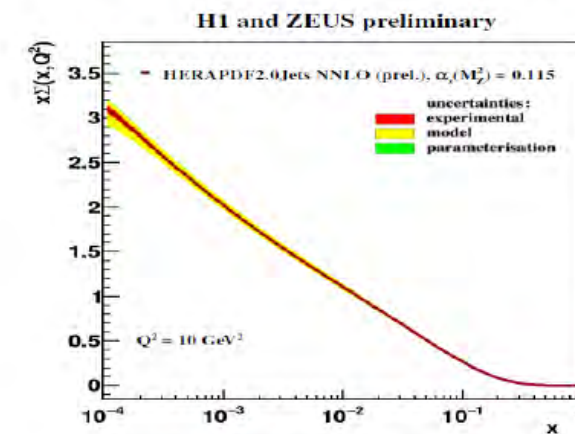
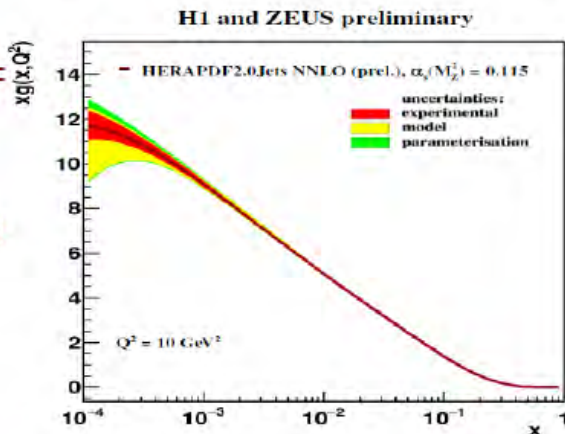
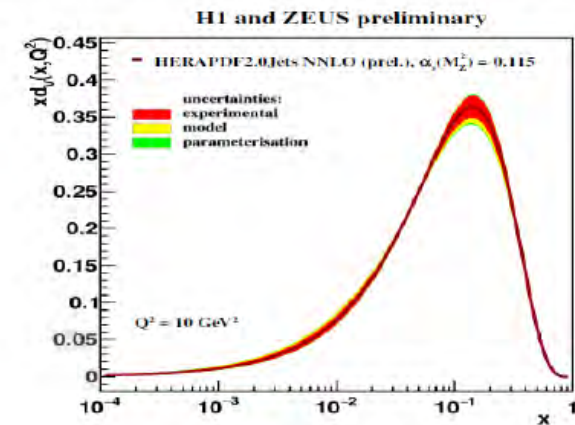
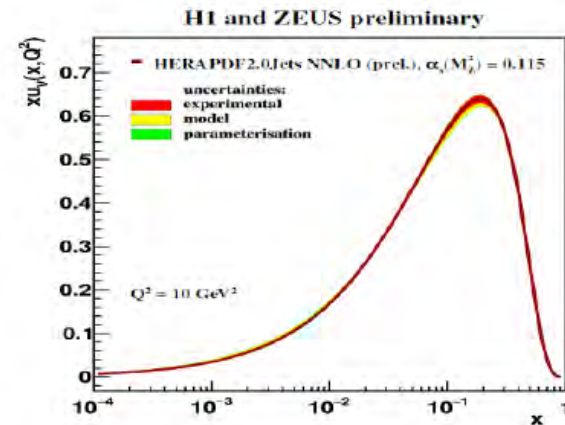


Backup slides

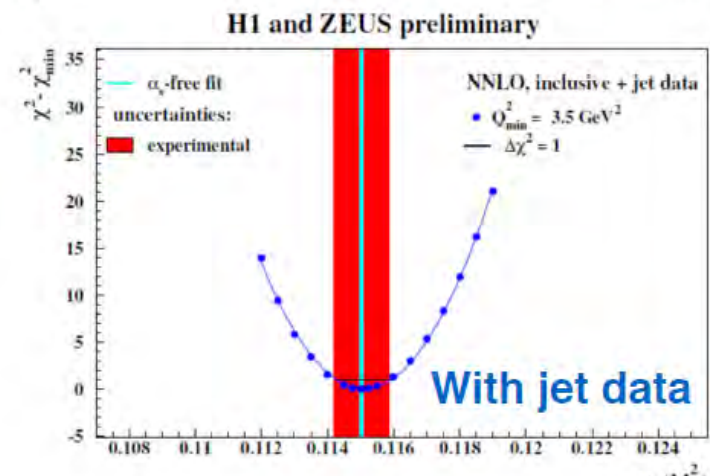
# New HERAPDF 2.0 fit

Mandy Cooper-Sarkar  
on behalf of H1 and ZEUS

- First inclusion of Inclusive DIS data with DIS Jet data from ZEUS and H1
  - Jet processes calculated **at full NNLO using NNLOJET** interfaced to APPLfast
- New NNLO fit favours lower  $\alpha_s$  ...
  - $\alpha_s(M_Z) = 0.1150 \pm 0.0008(\text{exp}) + 0.0002 - 0.0005(\text{model/param}) \pm 0.0006(\text{had}) \pm 0.0027(\text{scale})$
  - Compared the NLO result  $\alpha_s(M_Z) = 0.1183 \pm 0.0009(\text{exp}) \pm 0.0005(\text{model/param}) \pm 0.0012(\text{had}) + 0.0037 - 0.0030(\text{scale})$
- Two new PDF sets:
  - HERAPDF2.0JetsNNLO  $\alpha_s(M_Z) = 0.118$  – the PDF value
  - HERAPDF2.0JetsNNLO  $\alpha_s(M_Z) = 0.115$  – The value favoured by the new fit



add DIS jet data



# Update to the MMHT PDF

Robert Thorne

- Inclusion of new LHC data sets - largely electroweak processes, particularly precise ATLAS W, Z 7 TeV results. Implications for strange with NNLO corrections to dimuon production.
- Extended parameterisation and eigenvectors sets, using Chebyshev polynomials  
Problems with correlated uncertainties - jets and differential top data.
- Completion and imminent release of MMHT PDFs with QED corrections.

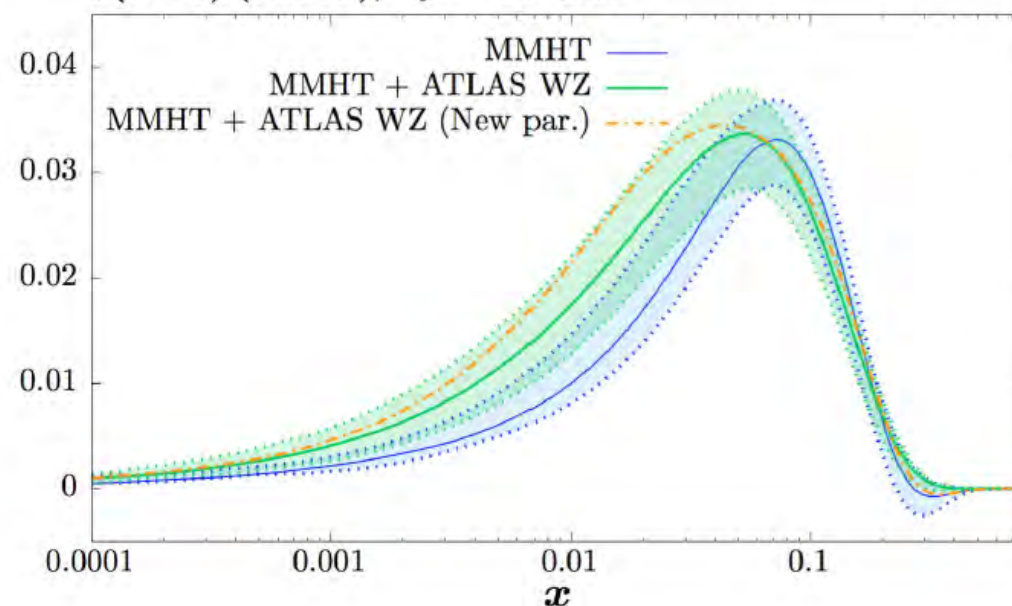
Including ATLAS W, Z data in fit goes from  $\chi^2/N_{pts} \sim 387/61 \rightarrow \chi^2/N_{pts} \sim 108/61$  (with scales set to  $\mu_{R,F} = M_{W,Z}/2$ ).

Deterioration in fit to other data  $\Delta\chi^2 \sim 54$ . CMS double differential Z/ $\gamma$  data CCFR/NuTeV dimuon data Drell-Yan asymmetry.

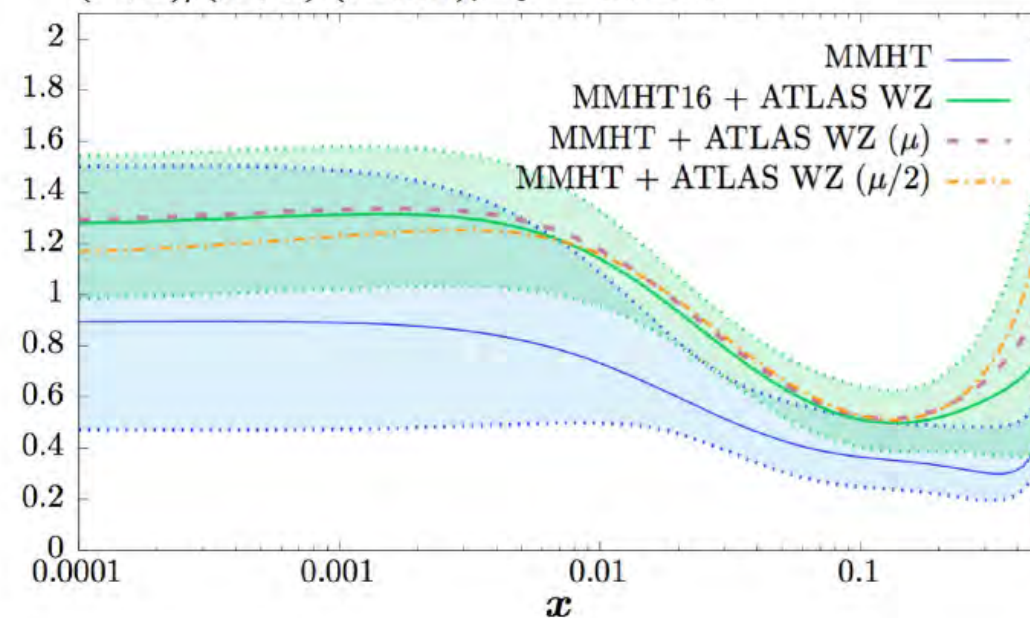
Ratio of  $(s + \bar{s})$  to  $\bar{u} + \bar{d}$ , i.e.  $R_s$  at  $Q^2 = 1.9 \text{ GeV}^2$ .

At  $x = 0.023$   $R_s \sim 0.83 \pm 0.15$ . Compare to ATLAS with  $R_s = 1.13^{+0.08}_{-0.13}$

$x(\bar{d} - \bar{u})$  (NNLO),  $Q^2 = 10^4 \text{ GeV}^2$



$(s + \bar{s})/(\bar{u} + \bar{d})$  (NNLO),  $Q^2 = 1.9 \text{ GeV}^2$



# NNPDF - including theory uncertainties

Cameron Voisey

- Attempting to better quantify theoretical uncertainties due to missing higher orders
- Theory uncertainties induced correlations between experiments

**Construct**  $\text{cov}_{\text{th}}$  from **scale variations** to estimate:

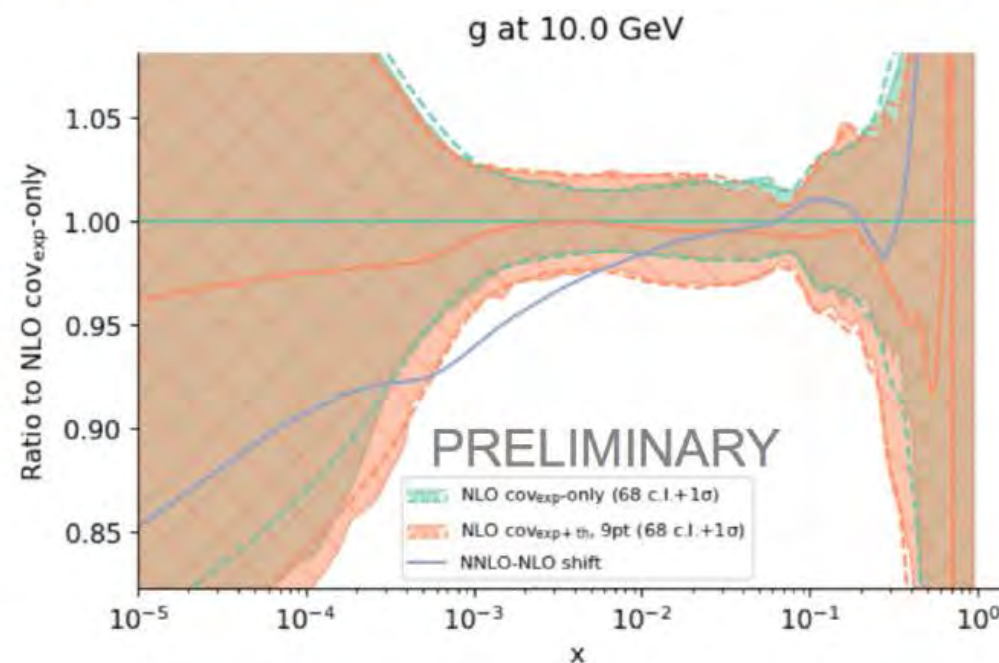
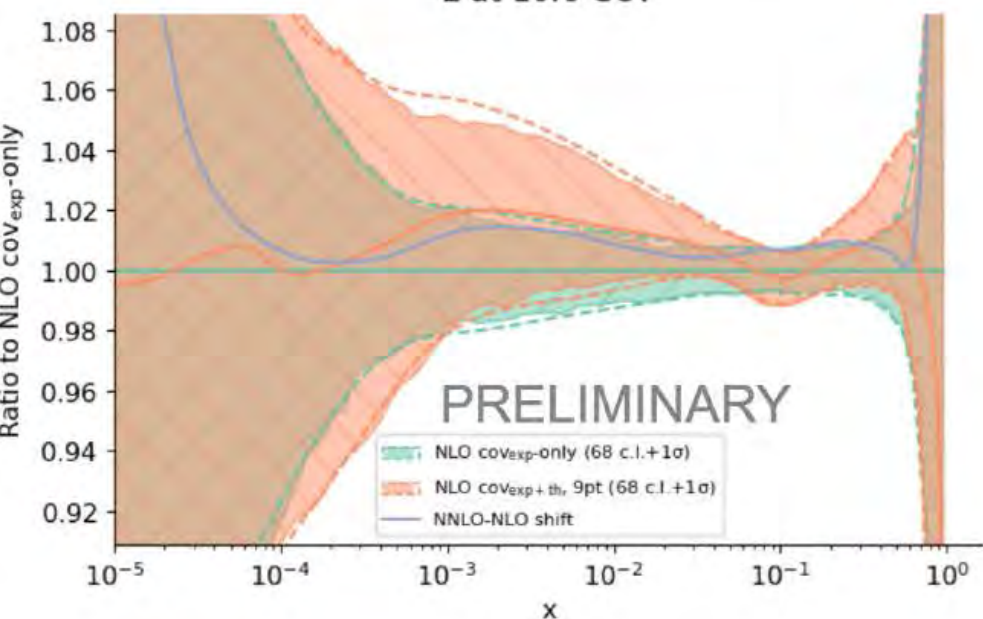
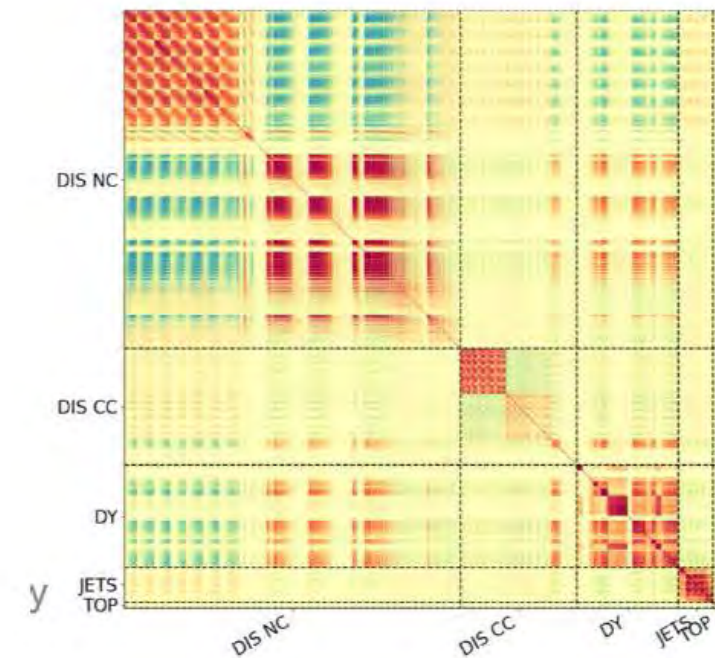
1. MHOUs on each point
2. Correlations between points

$i, j$ : data points

$k$ : scale combinations

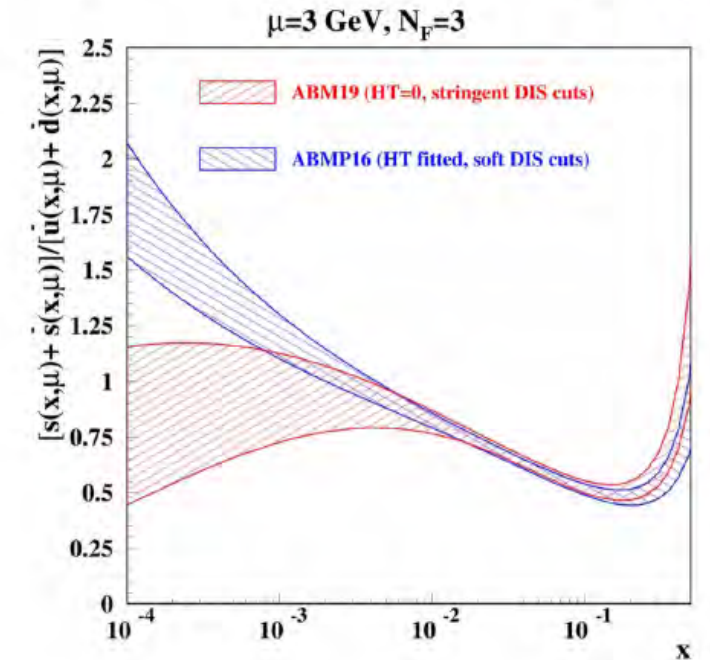
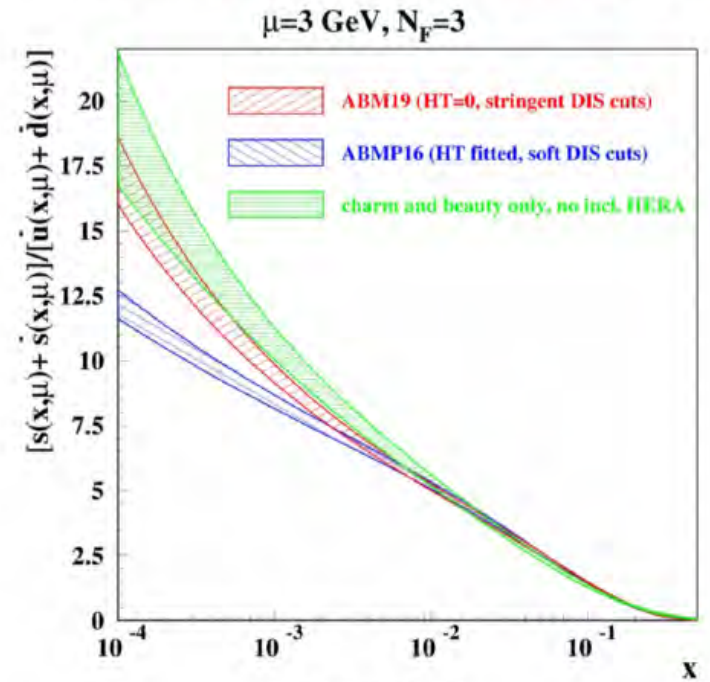
$$\text{cov}_{\text{th},ij} = \frac{1}{N} \sum_k \Delta_i^{(k)} \Delta_j^{(k)} \quad \Delta_i^{(k)} = t_i(\mu_R, \mu_F) - t_i(\mu_{R,0}, \mu_{F,0})$$

$\Sigma$  at 10.0 GeV



# ABM Sergey Alekhin

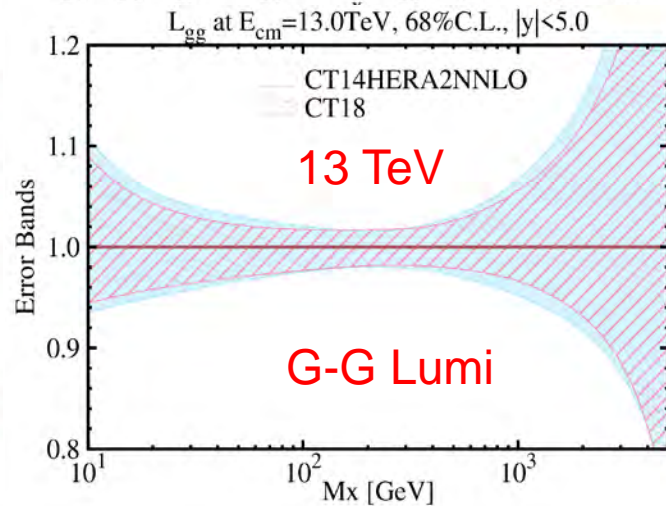
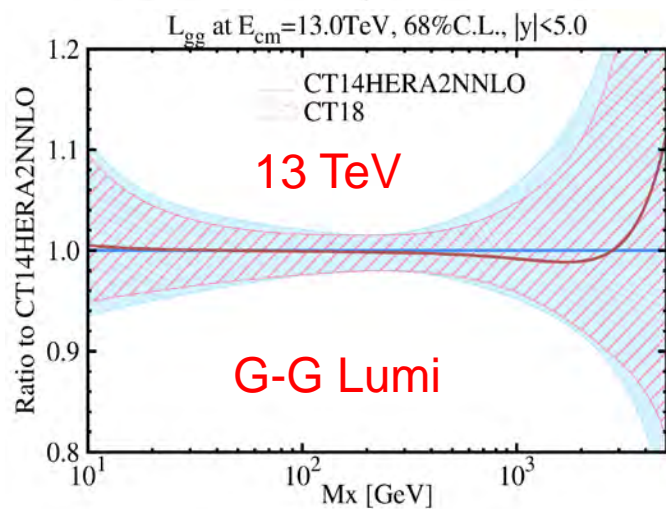
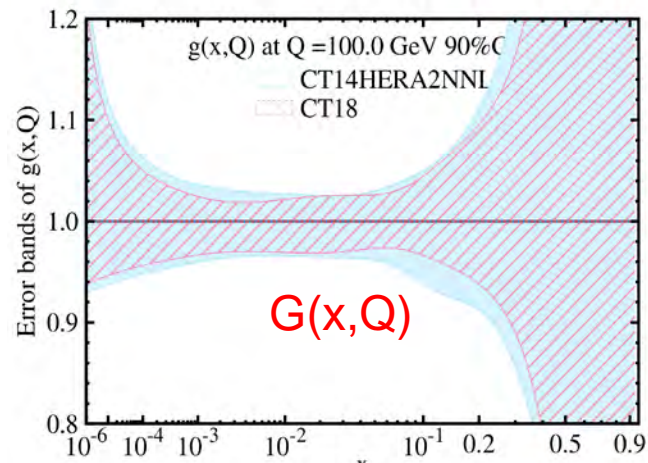
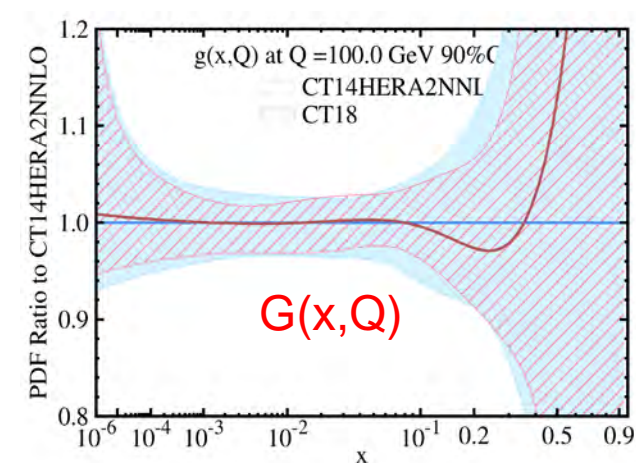
- Update to the ABM PDF including higher twist effects, top pair production
- Stringent cuts, lower strange at low  $x$ , higher gluon
- Impact of the higher-twist terms is minimized
  - Small- $x$  gluon goes higher, consistent with the constraint from charm/beauty; small- $x$  strange sea goes lower at small  $x$ , consistent with 1 within errors; valence quarks stable
  - Reasonable description of the recent charm/beauty HERA data with  $m_c(m_c)=1.245\pm 0.019(\text{exp.})$  GeV
    - $m_b(m_b)=3.96\pm 0.10(\text{exp.})$  GeV
- Update of the pair- and single-top production with
  - $m_t(m_t)=160.8\pm 1.1$  GeV
  - $m_t(m_t)=161.1\pm 3.8$  GeV (single-top only)
  - potential impact on the  $d/u$  ratio from  $t/\bar{t}$ , however validation of MC tools is still needed
- Steady progress with accommodating more DY data into the fit
  - Recent ATLAS data at 5 and 7 TeV
  - Double differential data on Z-boson production from CMS and ATLAS





# $\sigma(gg \rightarrow H)$ CT18 vs. CT14

CTEQ



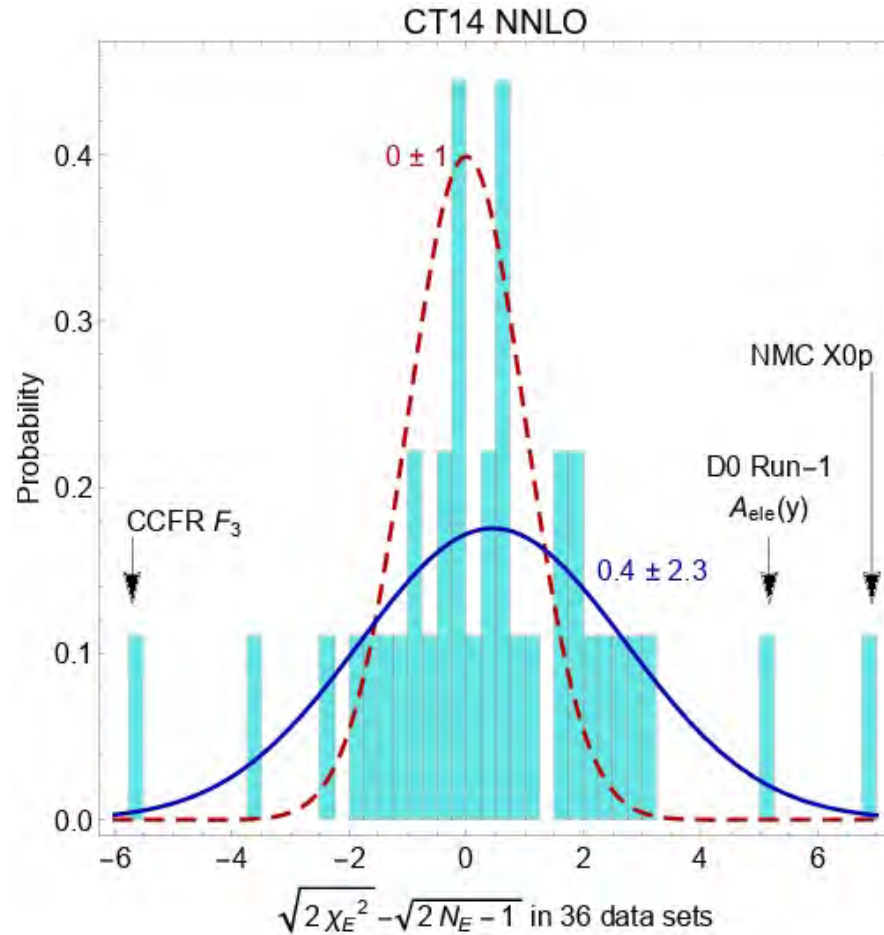
	7 TeV	
	$\sigma(\text{gg-h})$	$\delta\sigma \text{ sym}(90\% \text{C.L.})$
CT14NNLO	14.67	0.46
CT18	14.57	0.44
	8 TeV	
	$\sigma(\text{gg-h})$	$\delta\sigma \text{ sym}(90\% \text{C.L.})$
CT14NNLO	18.70	0.57
CT18	18.45	0.55
	13 TeV	
	$\sigma(\text{gg-h})$	$\delta\sigma \text{ sym}(90\% \text{C.L.})$
CT14NNLO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



# Effective Gaussian variables

CTEQ



Define  $S_n(\chi^2, N_{pt})$  for experiment  $n$  so that, in a perfect fit, it would approximately obey the standard normal distribution  $N(0,1)$  (mean=0, half-width=1) independently of  $N_{pt,n}$

$$S_n(\chi^2, N_{pt}) \equiv \sqrt{2\chi^2} - \sqrt{2N_{pt} - 1}$$

[H.-L. Lai et al., arXiv:1007.2241;

S.Dulat et al., arXiv:1309.0025;

K. Kovarik, P.N., D. Soper, arXiv:1905.06957]

An empirical  $S_n$  distribution can be compared to  $N(0,1)$  visually or using a statistical (Anderson-Darling, Kolmogorov-Smirnov, ...) test

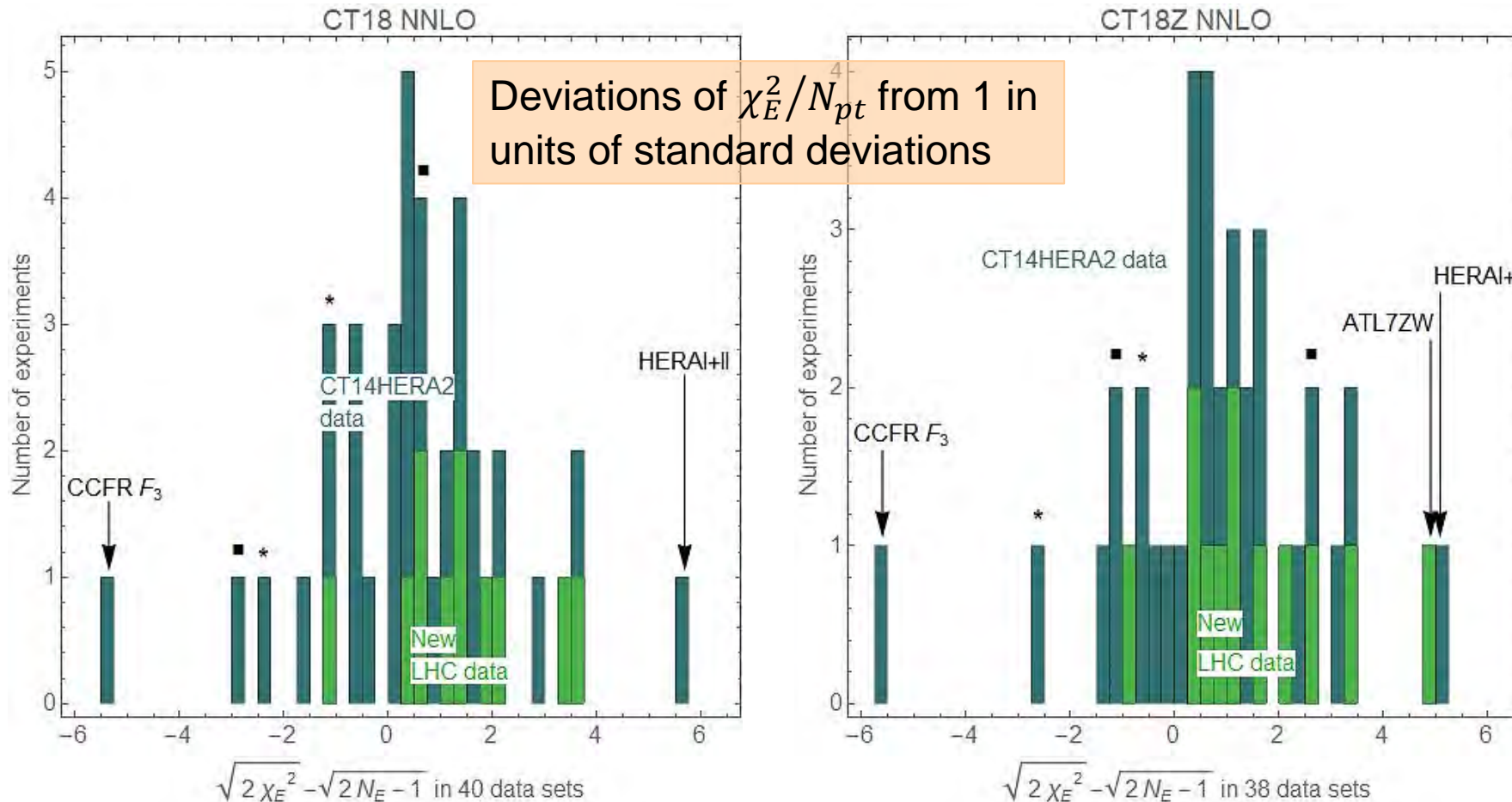


# CT18 (CT18Z) NNLO

13 (14) new LHC experiments with  
665 (711) data points

LHC experiments, especially ATLAS 7  
TeV  $Z, W$  production (only in the CT18A  
and Z fits) tend to have elevated  $\chi_n^2/N_{pt}$   
in global fits

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# CT14 PDFs with HERA1+2 (=HERA2) combination

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Separate the four HERA2 DIS processes;  
( $Q_{\text{cut}} = 2 \text{ GeV}$ )

	$N_{\text{pts}}$	$\chi^2_{\text{red.}} / N_{\text{pts}}$
NC $e^+p$	880	1.11
CC $e^+p$	39	1.10
NC $e^-p$	159	1.45
CC $e^-p$	42	1.52
totals		
[reduced $\chi^2$ ] / N	1120	1.17
$\chi^2 / N$	1120	1.25
$R^2 / N$	1120	0.08

$e^+p$  data are fitted fine

$e^-p$  data are fitted poorly

← reduced  $\chi^2$  values

←  $\chi^2 = [\text{reduced } \chi^2] + R^2$

← The quadratic penalty for 162 systematic errors = 87.5

Fair (not perfect) agreement; can be mildly improved by the QCD scale choice

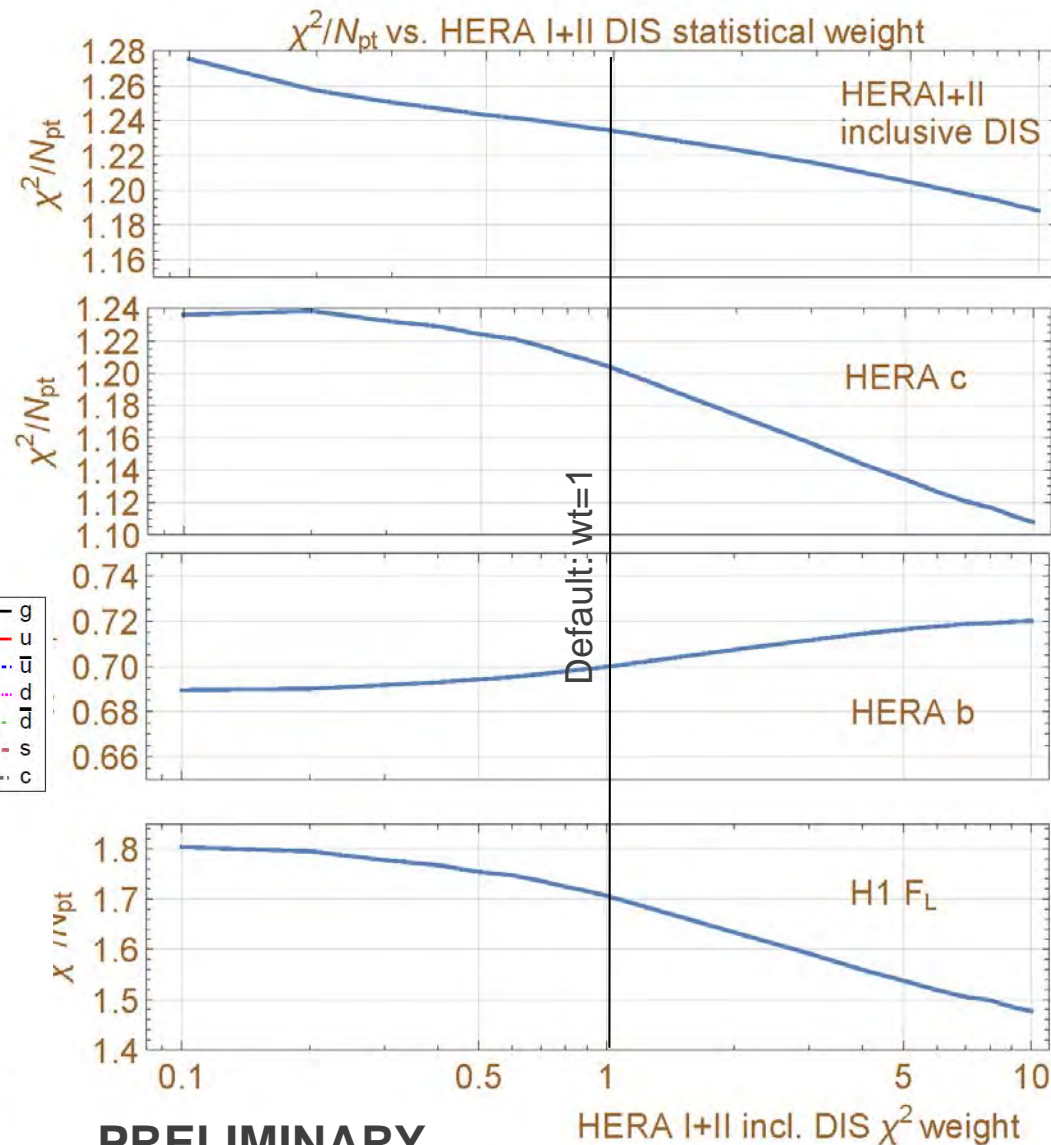
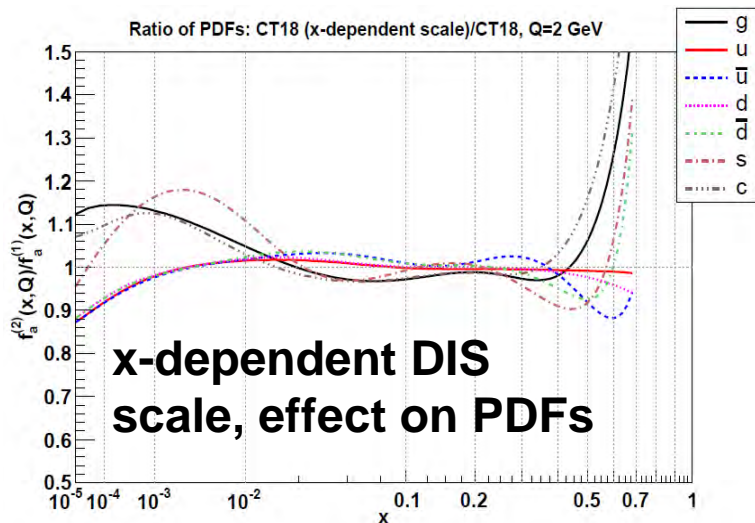


# CT18X and Z: a special factorization scale in DIS

CTEQ

The CT18Z fits uses a  $\mu_{DIS,X}$  scale that reproduces many features of NNLO-NLLx fits with  $\ln(1/x)$  resummation by the NNPDF [arXiv:1710.05935] and xFitter [1802.0064] groups.

$$\mu_{DIS,X}^2 = 0.8^2 \left( Q^2 + \frac{0.3 \text{ GeV}^2}{x^{0.3}} \right)$$



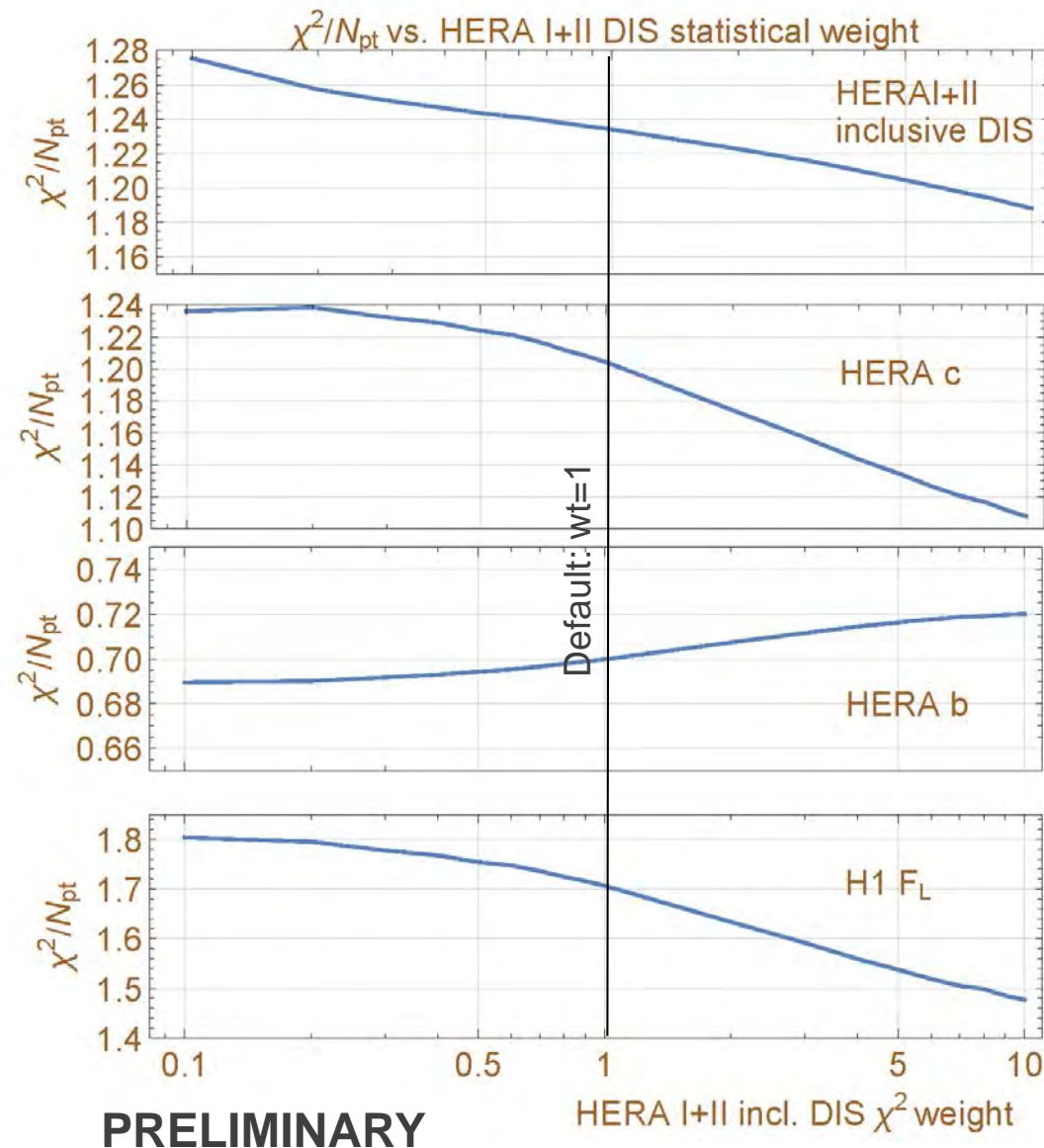
PRELIMINARY



# CT18X and Z: a special factorization scale in DIS

Right: when the  $\chi^2$  weight for the inclusive HERA I+II DIS is increased to  $wt = 10$  to suppress pulls from the other experiments,  $\chi^2_{CT18Z}/N_{pt}$  for HERA I+II DIS and HERA charm production decreases to about the same levels as in HERA-only NNLO+NLLx fits by other groups.

- NNLO with an  $x$ -dependent scale is statistically indistinguishable from BFKL resummation in the CT18  $x$ - $Q$  region ( $Q > 2$  GeV)





# CT14: parametrization forms

CTEQ

- CT14 relaxes restrictions on several PDF combinations that were enforced in CT10. [These combinations were not constrained by the pre-LHC data.]

The assumptions  $\frac{\bar{d}(x, Q_0)}{\bar{u}(x, Q_0)} \rightarrow 1$ ,  $u_v(x, Q_0) \sim d_v(x, Q_0) \propto x^{A_{1v}}$  with  $A_{1v} \approx -\frac{1}{2}$  at  $x < 10^{-3}$  are relaxed once LHC  $W/Z$  data are included

CT14 parametrization for  $s(x, Q)$  includes extra parameters

- Candidate CT14 fits have 30-35 free parameters
- In general,  $f_a(x, Q_0) = Ax^{a_1}(1-x)^{a_2}P_a(x)$
- CT10 assumed  $P_a(x) = \exp(a_0 + a_3\sqrt{x} + a_4x + a_5x^2)$   
exponential form conveniently enforces positive definite behavior  
but power law behaviors from  $a_1$  and  $a_2$  may not dominate
- In CT14,  $P_a(x) = G_a(x)F_a(z)$ , where  $G_a(x)$  is a smooth factor  
 $z = 1 - 1(1 - \sqrt{x})^{a_3}$  preserves desired Regge-like behavior at low  $x$  and high  $x$  (with  $a_3 > 0$ )
- Express  $F_a(z)$  as a linear combination of Bernstein polynomials:

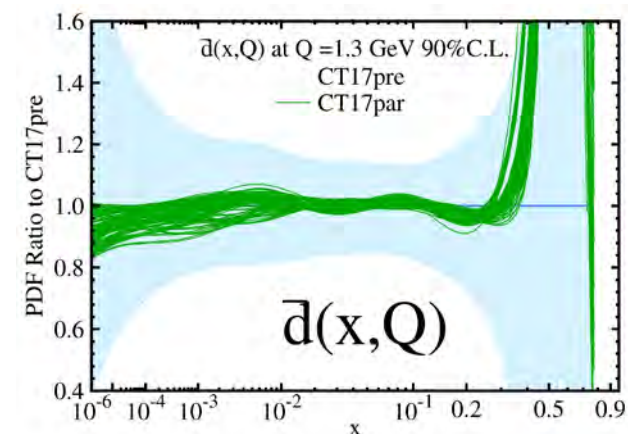
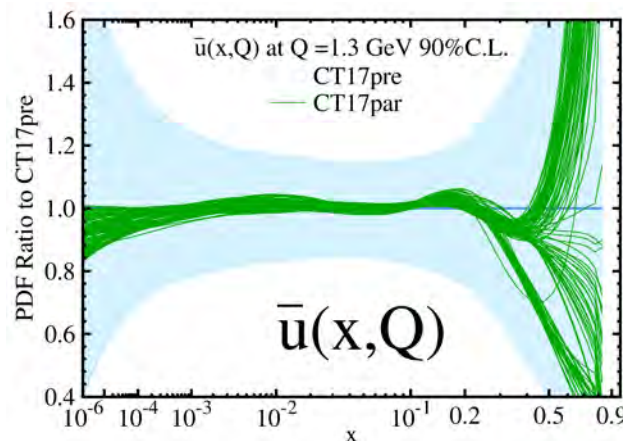
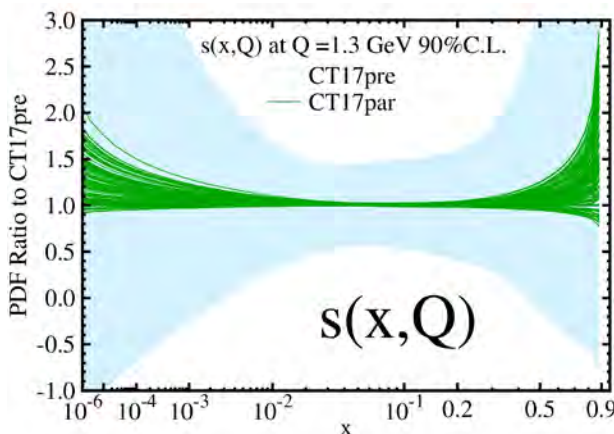
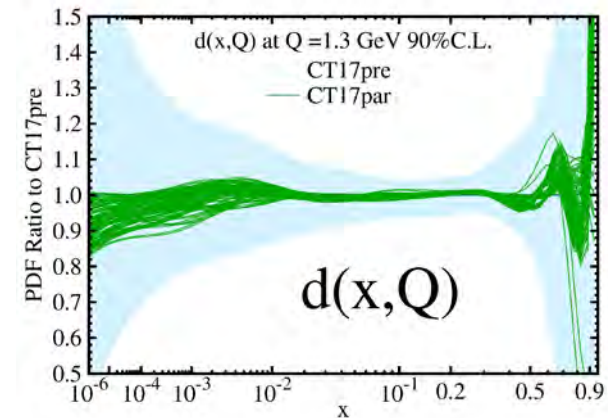
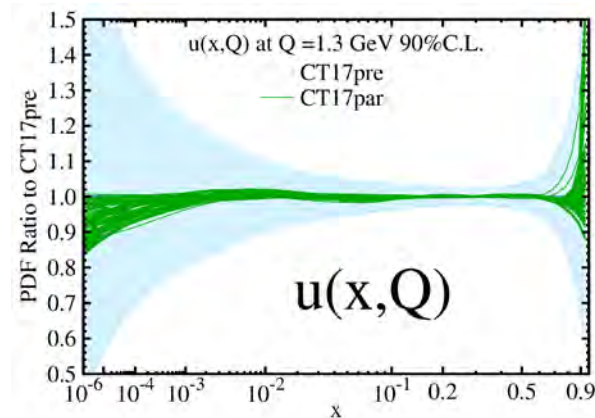
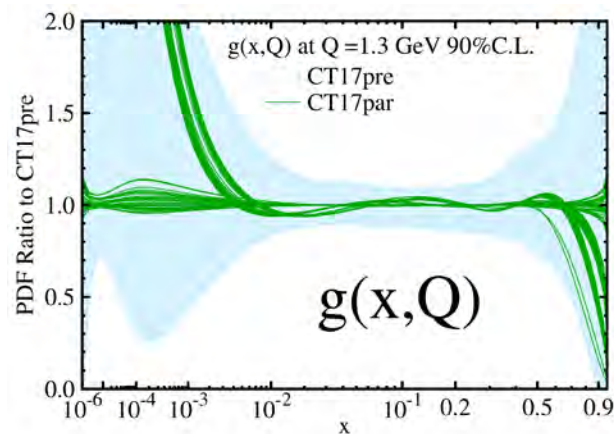
$$z^4, 4z^3(1-z), 6z^2(1-z)^2, 4z(1-z)^3, (1-z)^4$$

each basis polynomial has a single peak, with peaks at different values of  $z$ ;  
reduces correlations among parameters



# Explore various non-perturbative parametrization forms of PDFs

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