

Designing Precision-Oriented PDF Sets for Electroweak Measurements at Hadron Colliders

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PDF Limitations on m_W

— Nominal
PDF set

Eur. Phys. J. C 84, 1309 (2024)



@ 7 TeV

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

CT18NNLO

Science 376, 170-176 (2022)

Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^ℓ model	1.8
p_T^W/p_T^ℓ model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

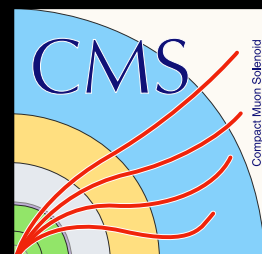
NNPDF 3.1 NNLO

Nature 652, 321–327 (2026)

CMS-SMP-23-002

Source of uncertainty	Impact (MeV)			
	Nominal		Global	
	in m_Z	in m_W	in m_Z	in m_W
Muon momentum calibration	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt-muon background	—	3.2	—	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

CT18ZNNLO



@ 13 TeV



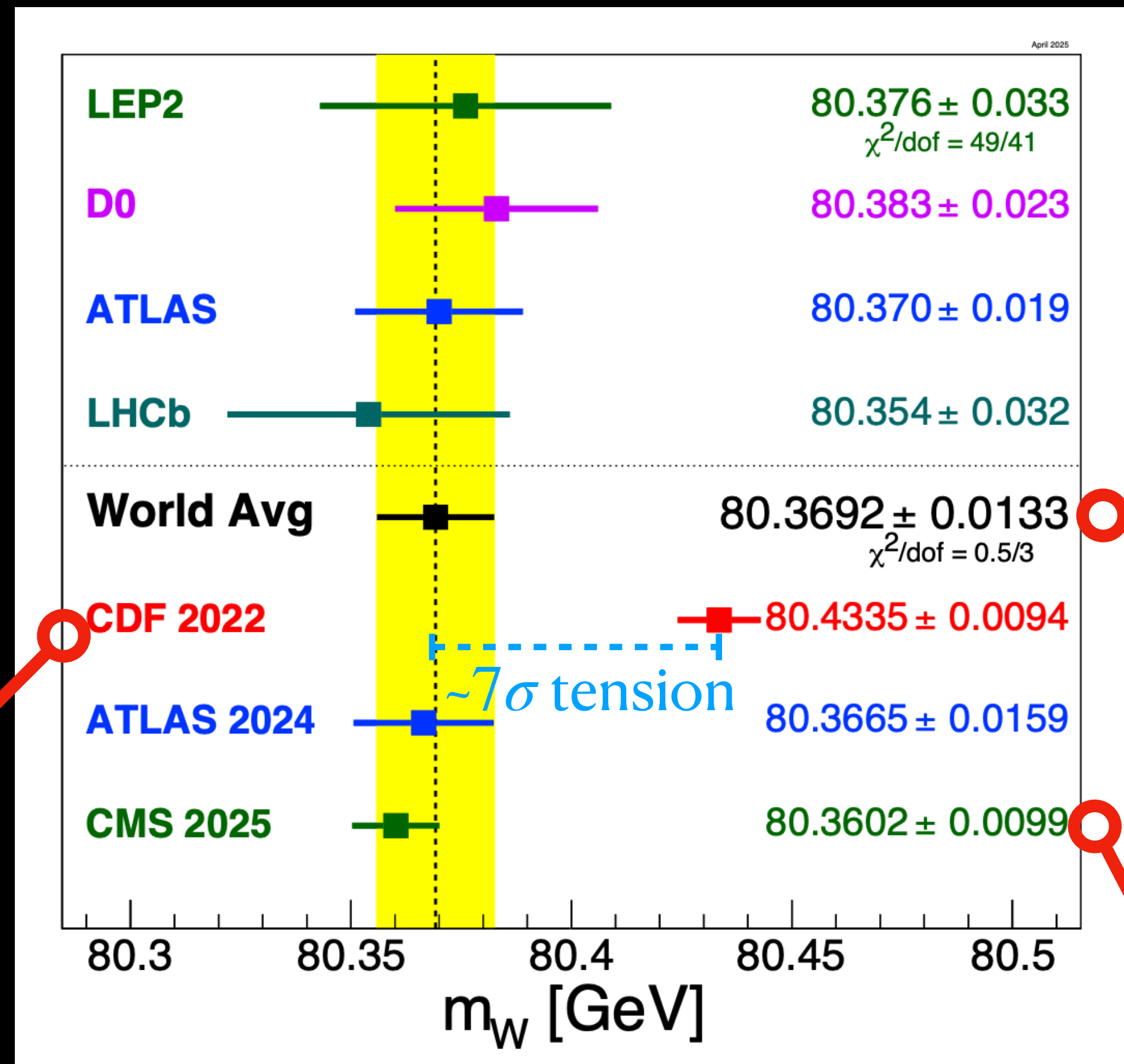
@ 1.96 TeV

PDF uncertainties are among the **dominant systematic uncertainties**: *Largest or second largest systematic*

Latest ATLAS and CMS measurements do **profiling on PDF eigenvectors**

Combination of m_W Measurements

- Performance of modern PDF sets for precision EW measurements through compatibility with a set of Drell-Yan measurements



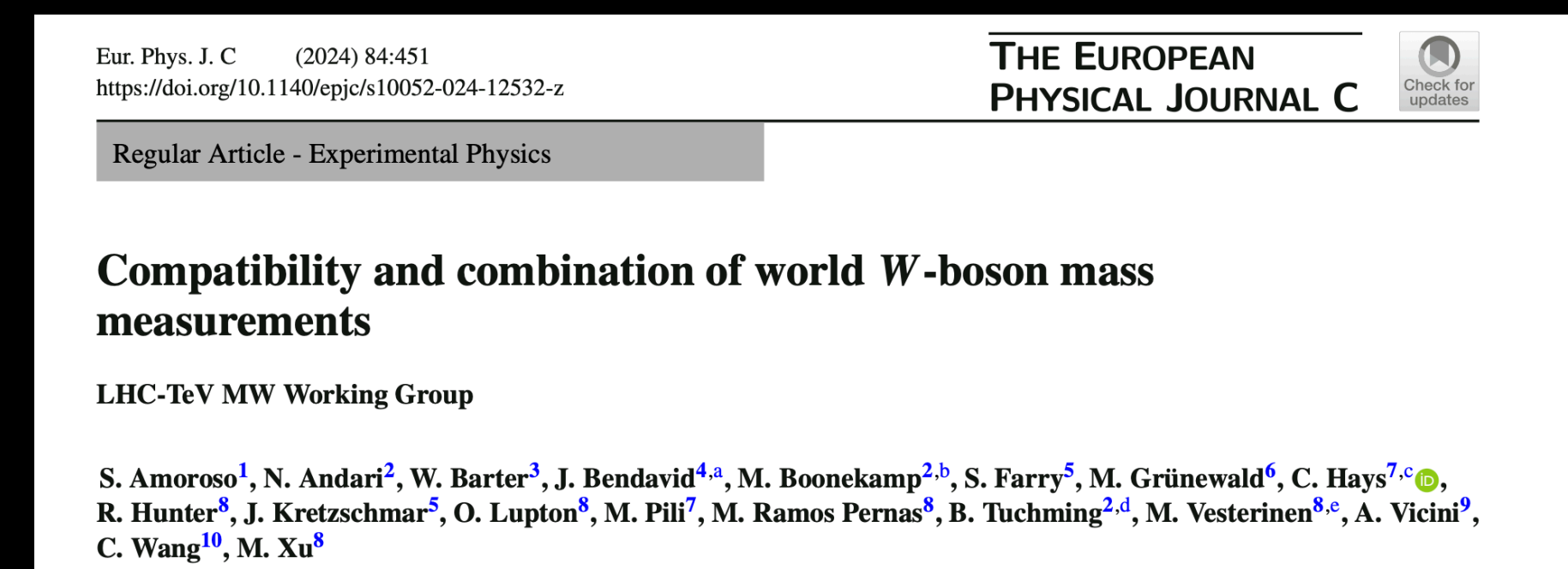
Most
precise

Most precise @ LHC

Measurement	NNPDF3.1	NNPDF4.0	MMHT14	MSHT20	CT14	CT18	ABMP16
CDF y_Z	24/28	28/28	30/28	32/28	29/28	27/28	31/28
CDF A_W	11/13	14/13	12/13	28/13	12/13	11/13	21/13
D0 y_Z	22/28	23/28	23/28	24/28	22/28	22/28	22/28
D0 $W \rightarrow e\nu A_\ell$	22/13	23/13	52/13	42/13	21/13	19/13	26/13
D0 $W \rightarrow \mu\nu A_\ell$	12/10	12/10	11/10	11/10	11/10	12/10	11/10
ATLAS peak CC y_Z	13/12	13/12	58/12	17/12	12/12	11/12	18/12
ATLAS $W^- y_\ell$	12/11	12/11	33/11	16/11	13/11	10/11	14/11
ATLAS $W^+ y_\ell$	9/11	9/11	15/11	12/11	9/11	9/11	10/11
Correlated χ^2	75	62	210	88	81	41	83
Total $\chi^2/\text{d.o.f.}$	200/126	196/126	444/126	270/126	210/126	162/126	236/126
$p(\chi^2, n)$	0.003%	0.007%	$< 10^{-10}$	$< 10^{-10}$	0.0004%	1.5%	10^{-8}

CT18

Combination of LEP, ATLAS, LHCb and D0 measurements



Eur.Phys.J.C 84 (2024) 5, 451

Next Combination of m_W Measurements

- With the release of the CMS measurement, it is important to extend this study to include more datasets
- Theory predictions with different PDF sets are compared with data using the **xFitter** framework:
 - χ^2 statistic that needs to incorporate *experimental correlations* and *PDF uncertainties*

NUISANCE
PARAMETER
REPRESENTATION

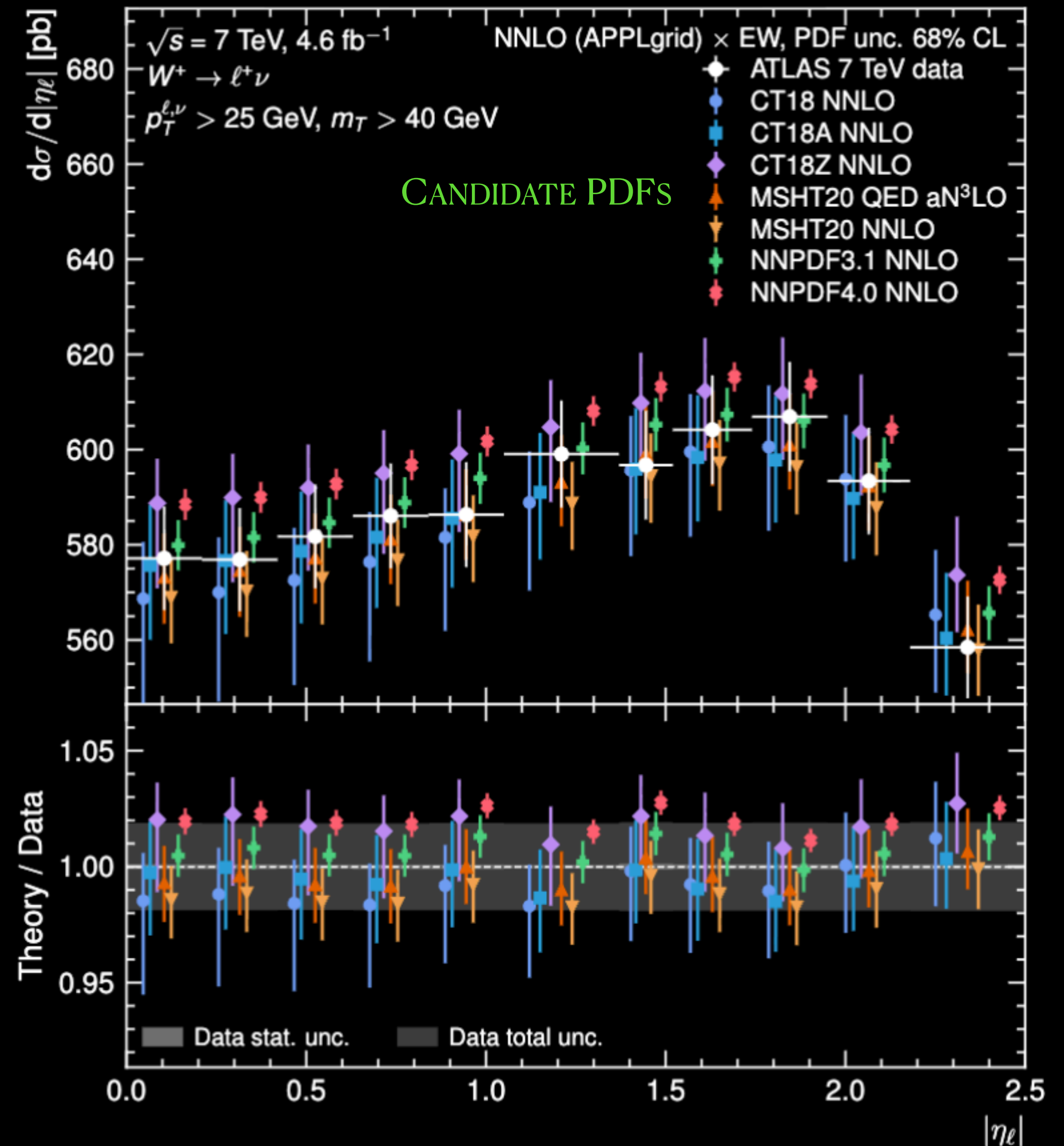
$$\chi^2(m, b) = \sum_i \frac{[\mu_i - m_i(1 - \sum_j \gamma_j^i b_j)]^2}{\delta_{i,\text{unc}}^2 m_i^2 + \delta_{i,\text{stat}}^2 \mu_i m_i (1 - \sum_j \gamma_j^i b_j)} + \sum_j b_j^2$$

- $\delta_{i,\text{stat}}$ and $\delta_{i,\text{unc}}$ are relative statistical and uncorrelated systematic uncertainties of the measurement i
- b_j are systematic nuisance parameters (including the PDF eigenvectors)
- The nuisance parameters are constrained during profiling, and shifts in the nuisance parameters give rise to a penalty term in the χ^2 : $\sum_j b_j^2$, “**Correlated Term**”
- Minimising over the b_j is equivalent to a χ^2 with the correlated systematics in the covariance matrix (exact for additive systematics), but in addition gives the shifts b_j i.e. how each systematic and PDF eigenvector is pulled
- PDF uncertainties enter via the Hessian eigenvectors of each set and all nuisance parameters are determined analytically

The shifts show how each **systematic and PDF nuisance parameters** is pulled by the data

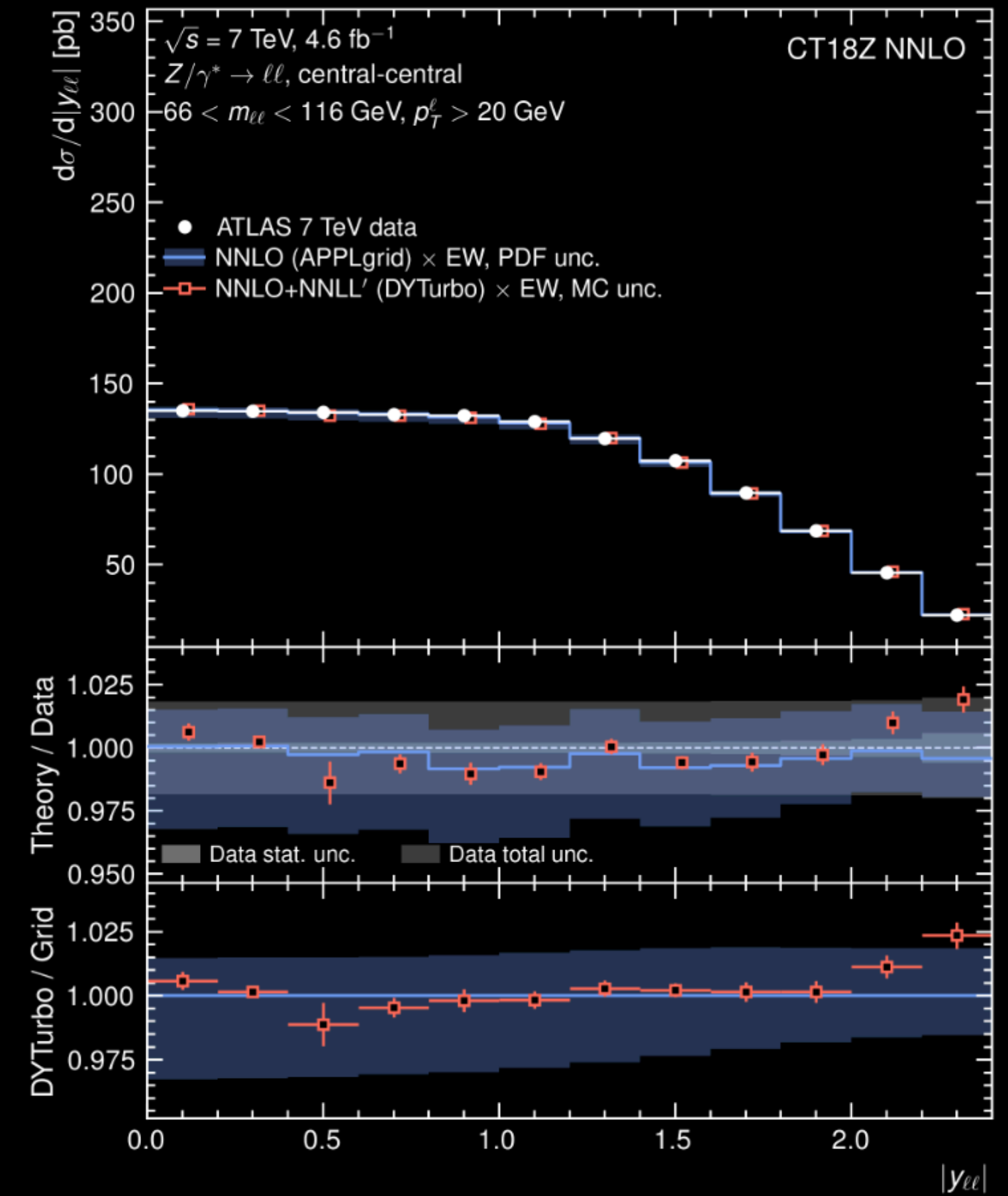
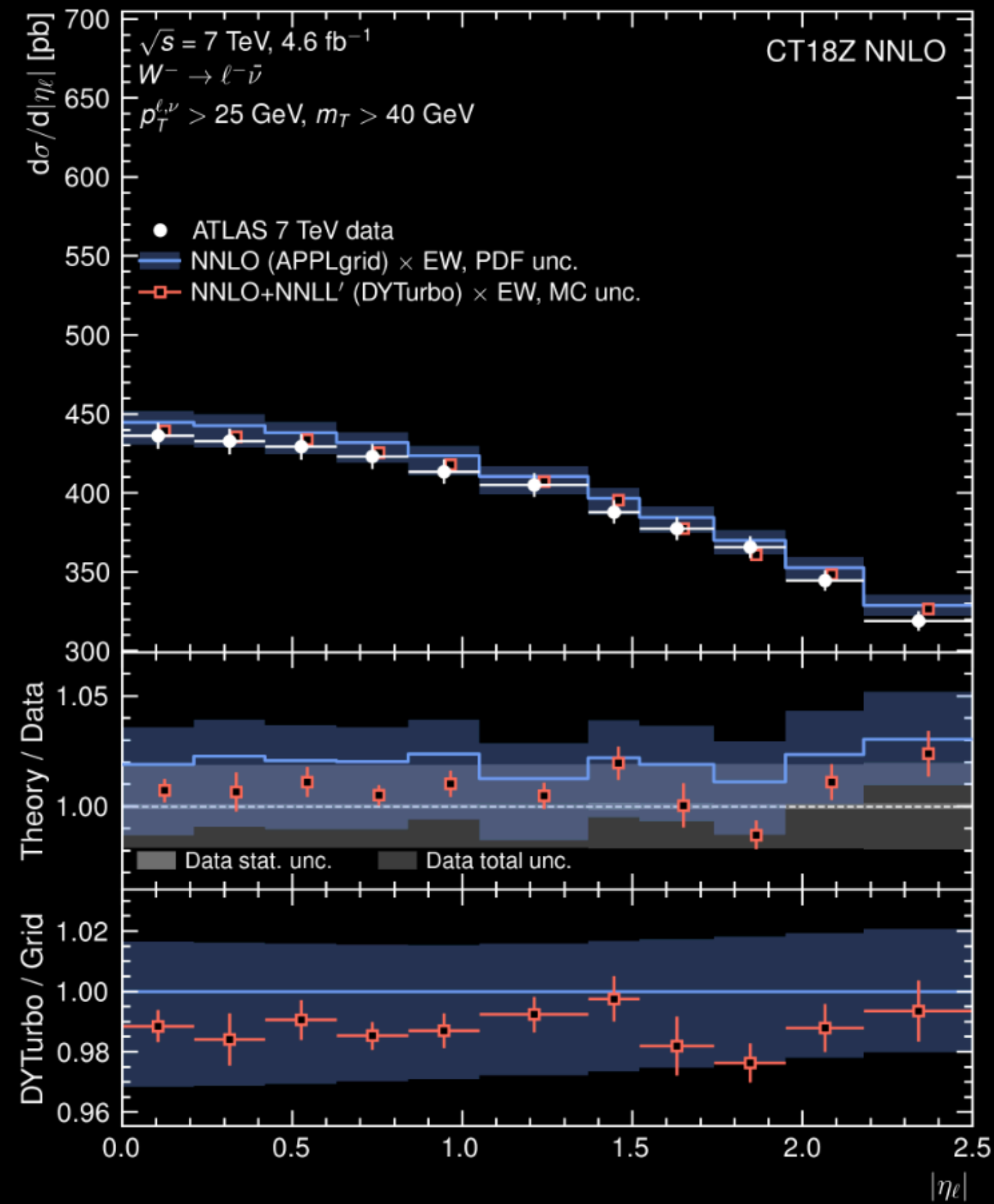
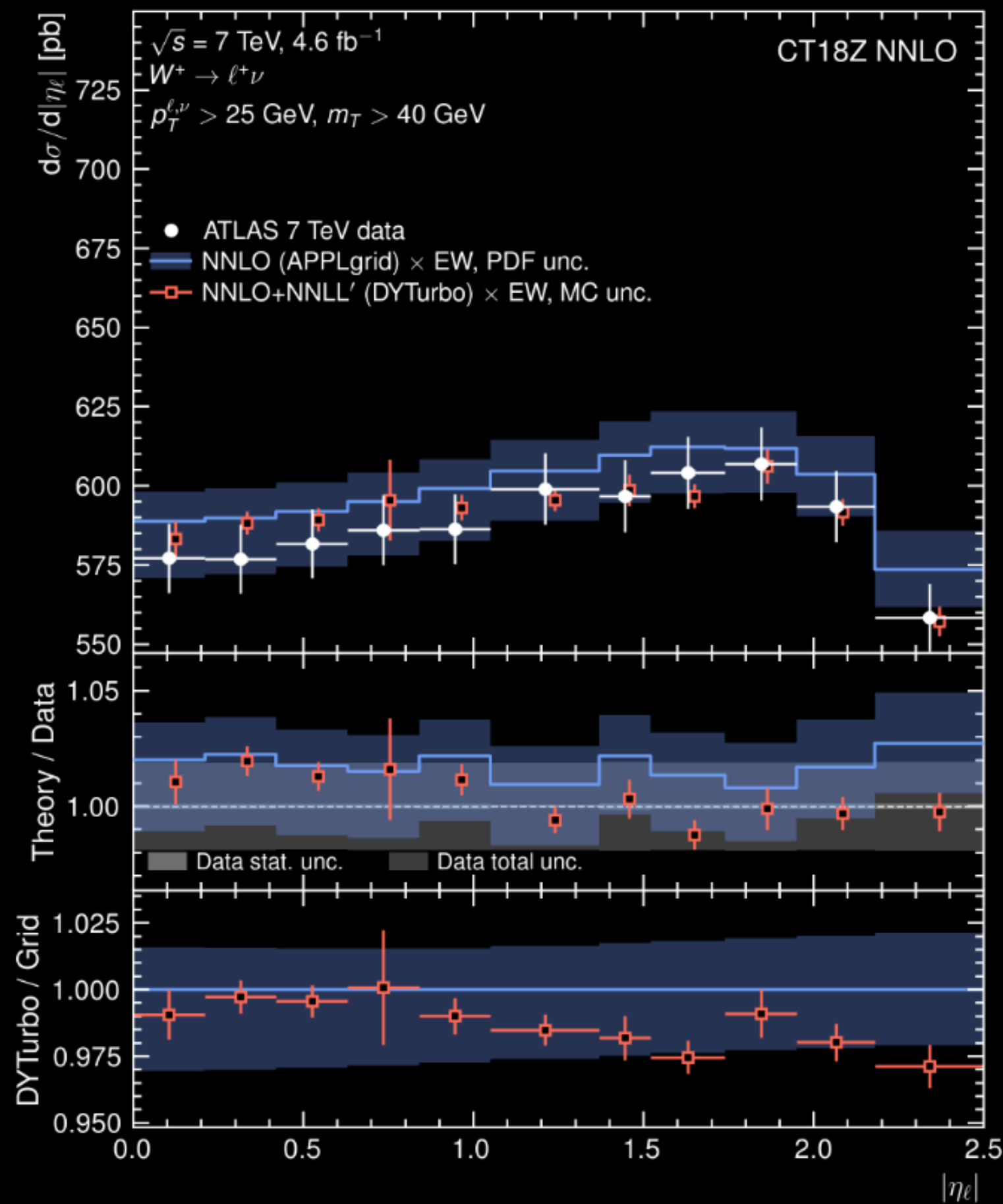
Theory Predictions

- Previous combination effort used fixed order theory calculations at NNLO in QCD with NLO electroweak corrections
- This iteration
 - Fixed order: NNLO or NLO depending on the availability of APPLgrids
 - NLO EW corrections only for ATLAS 7 TeV so far
 - Resummation effects studied
- Example of variations seen when different PDF sets are used for ATLAS 7 TeV data:



Theory Predictions: Resummation Effects

- To study resummation effects, theory predictions for the ATLAS 7 TeV $W^+/W^-/Z^0$ measurements were done using DYTurbo at NNLO + NNLL accuracy
- Example with CT18ZNNLO:



- Deviations from the FO prediction up to $\sim 3\%$: can add the ratio as a KFactor on the FO predictions $\rightarrow$ Work in progress to understand the need for smoothing function, increased accuracy for DYTurbo runs etc.

Plethora of Drell-Yan Measurements and Compatibility Results

● Grouped according to correlations:

Measurement	FO	CT18 NNLO (Scaled)	CT18A NNLO (Scaled)	CT18Z NNLO (Scaled)	MSHT20 QED N ³ LO	MSHT20 NNLO	NNPDF 3.1	NNPDF 4.0
ATLAS 7 TeV measurements								
ATLAS 7 TeV $W^- \eta_\ell$	NNLO + NLO	9.26/11	8.85/11	9.04/11	8.96/11	8.76/11	9.00/11	9.00/11
ATLAS 7 TeV $W^+ \eta_\ell$	NNLO + NLO	7.77/11	7.60/11	7.76/11	7.49/11	7.47/11	7.60/11	7.73/11
ATLAS 7 TeV peak CC y_Z	NNLO + NLO	8.23/12	8.03/12	8.08/12	8.07/12	7.86/12	8.30/12	9.26/12
Correlated χ^2 Contribution		21.84	18.80	17.74	20.43	19.98	19.97	19.86
ATLAS 13 TeV measurements								
ATLAS 13 TeV σ_{W^-}	NNLO + LO	0.14/1	0.21/1	0.16/1	0.10/1	0.16/1	0.03/1	0.005/1
ATLAS 13 TeV σ_{W^+}	NNLO + LO	0.10/1	0.05/1	0.02/1	0.08/1	0.07/1	0.06/1	0.13/1
ATLAS 13 TeV σ_{Z^0}	NNLO + LO	0.03/1	0.0003/1	0.08/1	0.03/1	0.04/1	0.004/1	0.003/1
Correlated χ^2 Contribution		0.20	0.063	0.19	0.15	0.33	0.003	0.20
CMS 7 TeV measurements								
CMS 7 TeV $W \rightarrow \mu\nu A_\ell$	NNLO + LO	2.91/11	2.86/11	2.87/11	2.99/11	2.90/11	2.64/11	2.87/11
CMS 7 TeV $W \rightarrow e\nu A_\ell$	NNLO + LO	1.15/11	1.12/11	1.13/11	1.25/11	1.36/11	1.12/11	1.18/11
Correlated χ^2 Contribution		22.37	21.84	21.83	23.21	24.07	20.32	22.98
LHCb 7 TeV measurements								
LHCb 7 TeV $W^- \eta_\ell$	NNLO + LO	7.42/8	6.91/8	7.15/8	6.18/8	6.40/8	6.65/8	7.86/8
LHCb 7 TeV $W^+ \eta_\ell$	NNLO + LO	5.84/8	5.60/8	5.23/8	5.37/8	5.62/8	5.19/8	4.28/8
LHCb 7 TeV y_Z	NNLO + LO	2.50/17	2.37/17	2.30/17	2.41/17	2.32/17	2.46/17	2.75/17
Correlated χ^2 Contribution		28.64	26.02	25.77	26.20	26.09	26.05	32.37
LHCb 13 TeV measurement								
LHCb 13 TeV y_Z	NNLO + LO	6.20/18	6.36/18	6.12/18	6.74/18	6.45/18	5.66/18	6.19/18
Correlated χ^2 Contribution		12.79	12.90	11.77	13.42	12.79	11.41	12.02
CDF 1.96 TeV W measurement								
CDF 1.96 TeV $W \rightarrow e\nu A_{\gamma W}$	NLO + LO	14.27/13	15.33/13	14.34/13	15.15/13	15.06/13	13.73/13	13.16/13
Correlated χ^2 Contribution		0.50	0.66	0.44	1.56	1.74	0.72	0.56
CDF 1.96 TeV Z measurement								
CDF 1.96 TeV y_Z	NNLO + LO	26.00/28	26.14/28	25.91/28	27.25/28	26.83/28	26.22/28	25.86/28
Correlated χ^2 Contribution		0.66	0.50	0.40	0.38	0.39	0.39	0.17
D0 1.96 TeV Z measurement								
D0 1.96 TeV y_Z	NNLO + LO	22.67/28	22.81/28	22.63/28	24.34/28	23.69/28	22.36/28	23.04/28
Correlated χ^2 Contribution		0.002	0.003	0.002	0.007	0.004	0.0009	0.001
D0 1.96 TeV $W \rightarrow \mu\nu$ measurement								
D0 1.96 TeV $W \rightarrow \mu\nu A_\ell$	NNLO + LO	11.28/10	11.30/10	11.25/10	11.05/10	10.89/10	13.46/10	14.25/10
Correlated χ^2 Contribution		1.29	1.09	1.28	1.05	0.78	0.46	0.32
D0 1.96 TeV $W \rightarrow e\nu$ measurement								
D0 1.96 TeV $W \rightarrow e\nu A_\ell$	NLO + LO	34.77/13	34.28/13	35.39/13	45.44/13	42.79/13	26.50/13	34.79/13
Correlated χ^2 Contribution		0.49	0.56	0.47	0.40	0.74	1.40	1.44
PDF nuisance parameters (shared by all measurements)								
Correlated χ^2 Contribution		20.15	17.57	15.53	19.19	13.75	26.90	21.86
Combined run								
Correlated χ^2 (total)		108.93	100.00	95.42	105.99	100.65	107.63	111.77
Total χ^2/dof		269.44/202	259.83/202	254.89/202	278.90/202	269.30/202	258.61/202	274.13/202
$p(\chi^2, n)$		0.11%	0.38%	0.69%	0.03%	0.11%	0.44%	0.05%

FOCUS ON FO PREDICTIONS FOR NOW!

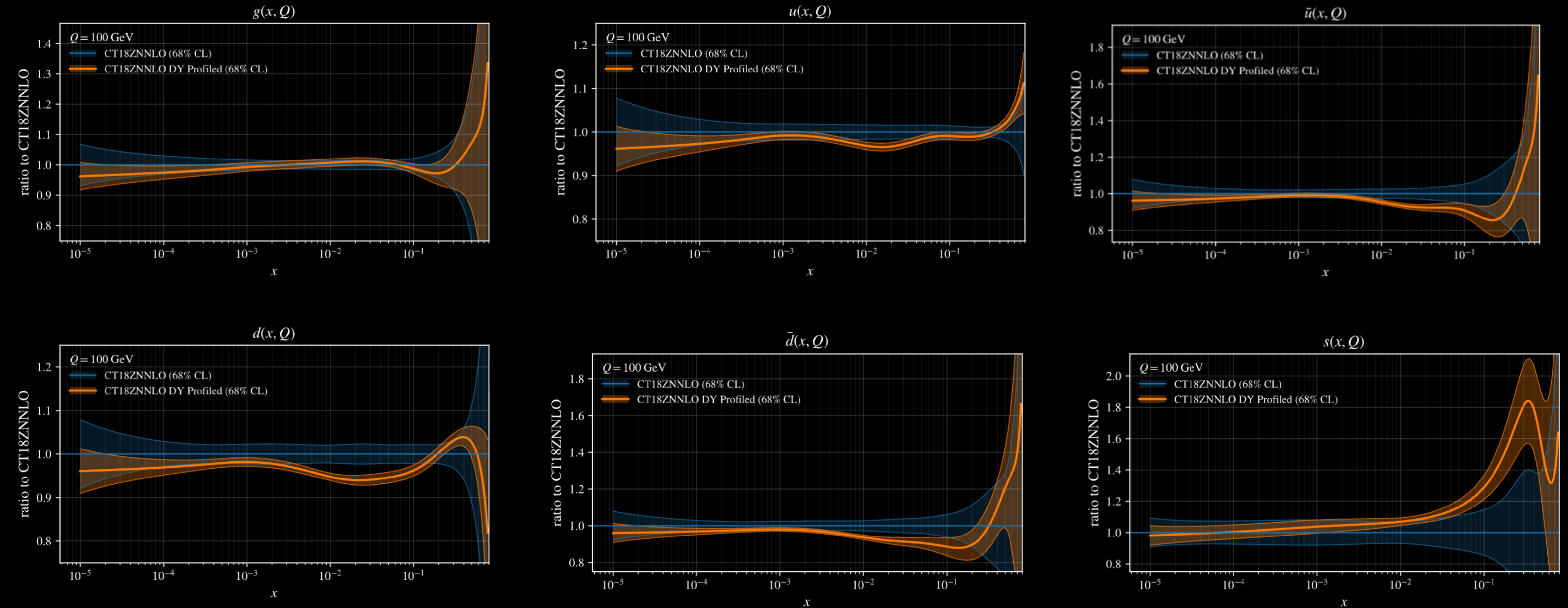
- The CT PDF uncertainties correspond to 68% coverage, obtained by rescaling the PDF eigenvectors by 1/1.645
- ATLAS 7 TeV, CMS 7 TeV, and LHCb measurements contribute significantly to the total correlated χ^2 values
- CT18ZNNLO has the lowest χ^2 among the PDF sets considered

Profiled CT18ZNNLO: A Study

• $Q = 100 \text{ GeV}$ shown here

• $\bar{u}$ and $\bar{d}$ drop 5-11% between $x = 0.01 - 0.1$

• g stays inside the CT18Z band

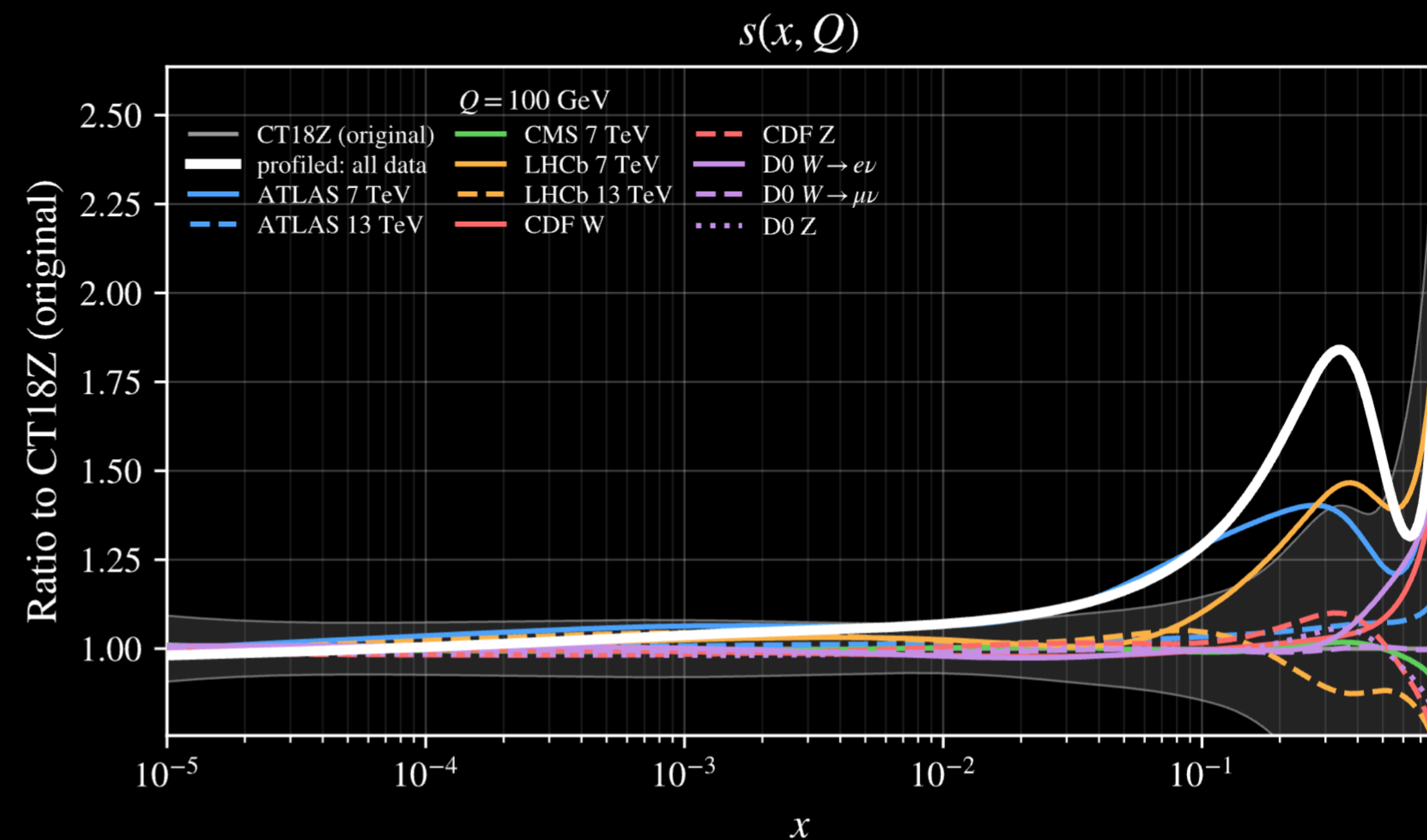


Something “strange” is happening

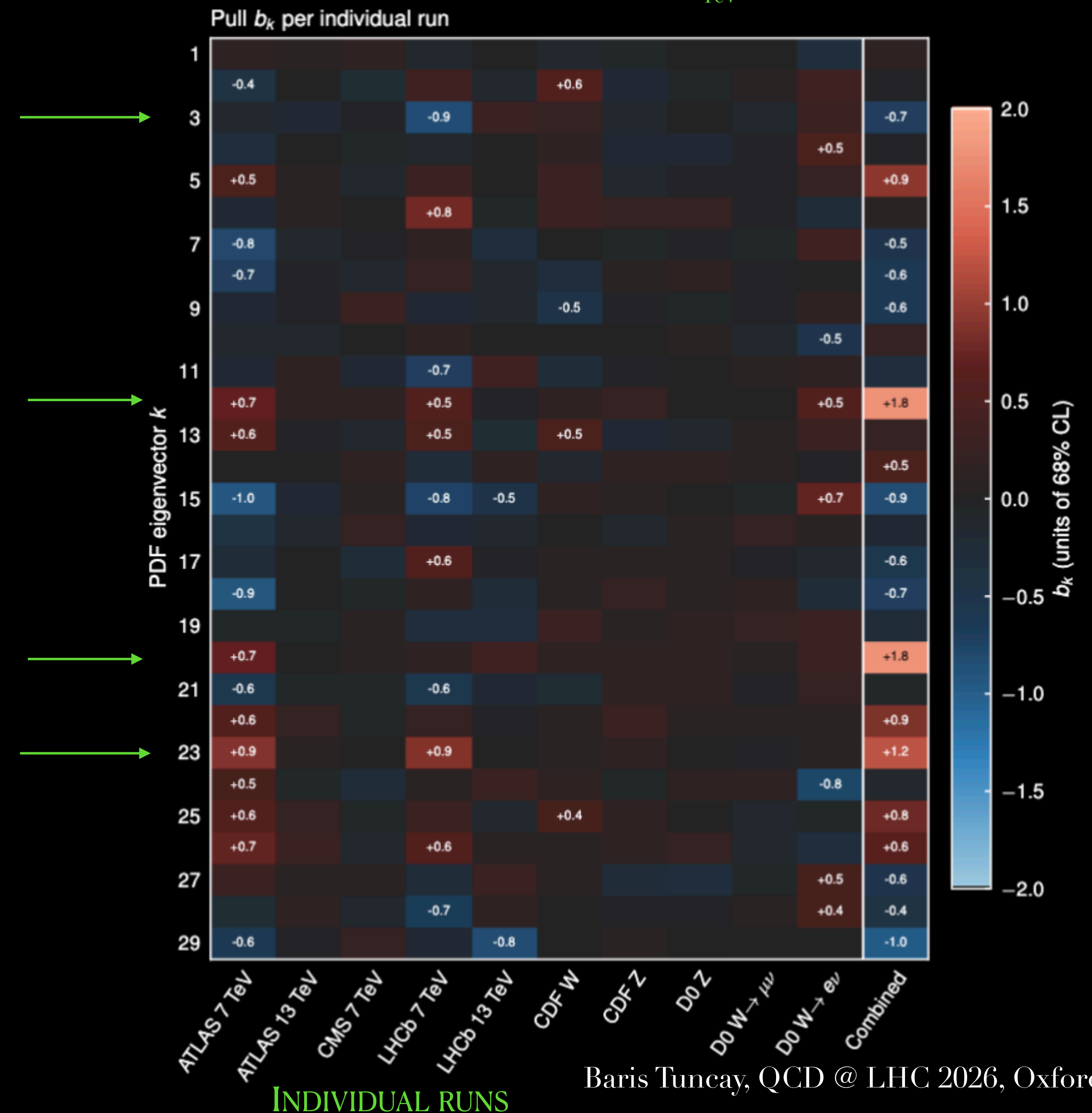
Profiled CT18ZNNLO

- Profiling with individual correlated groups was also done to understand the shifts/tensions

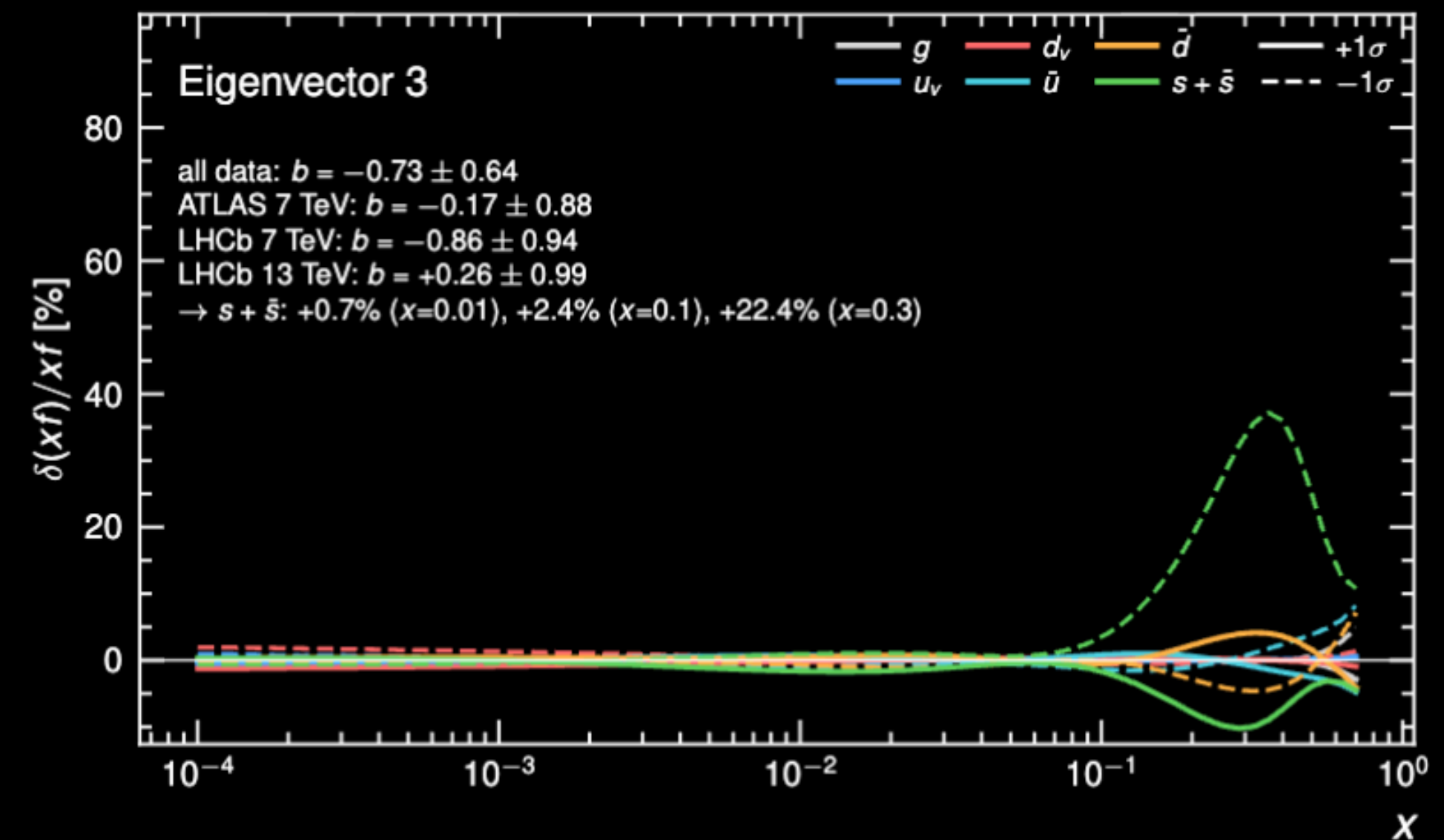
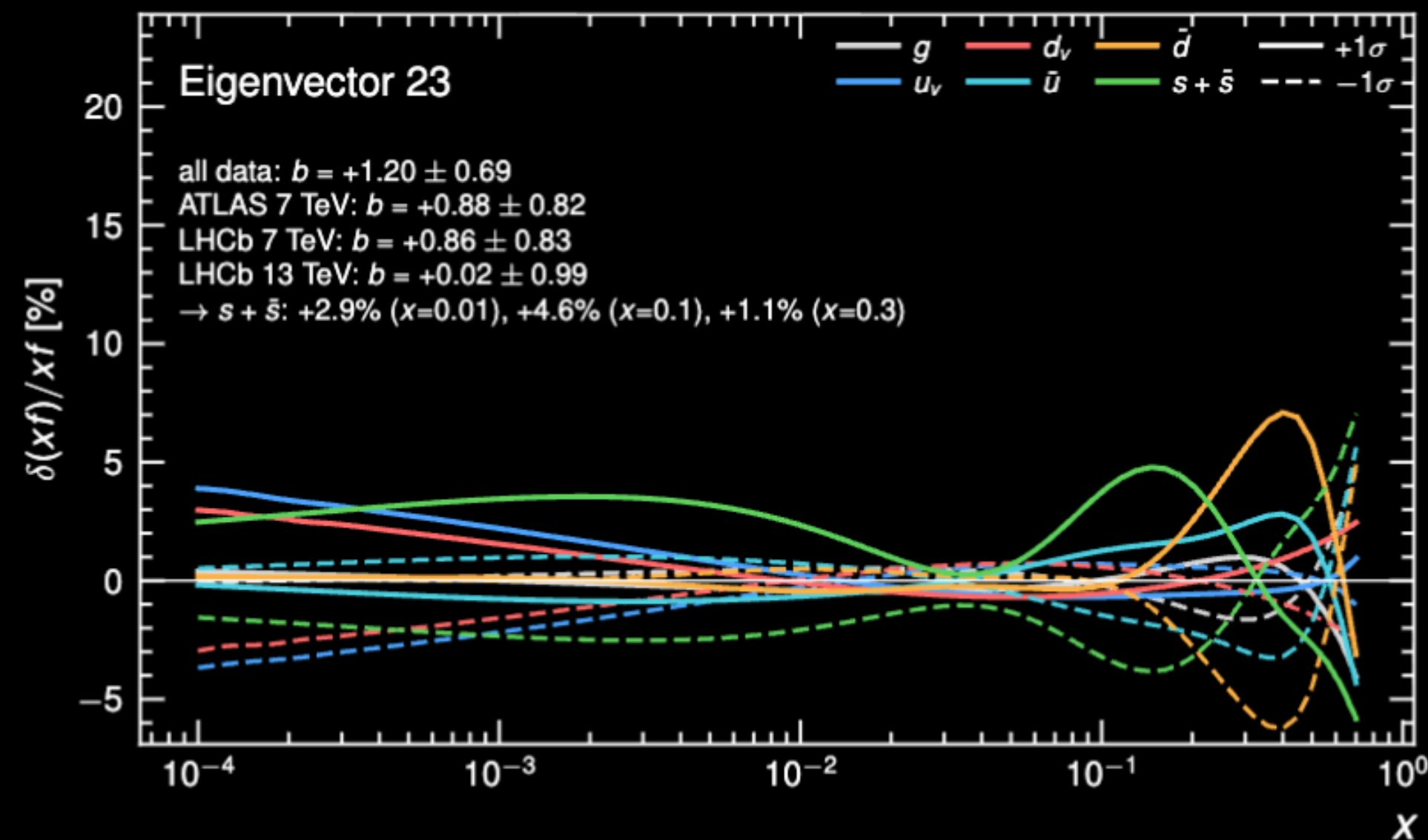
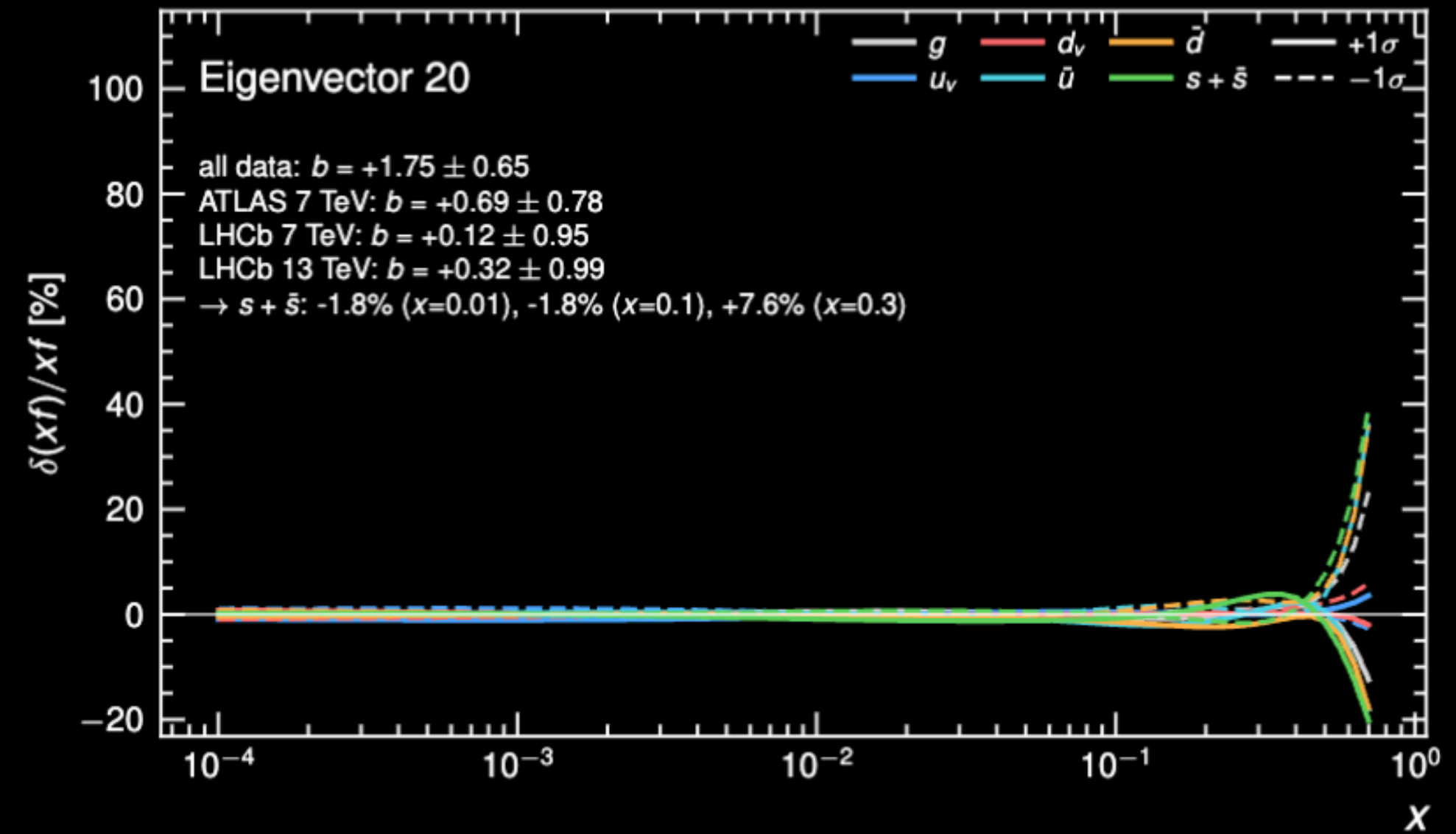
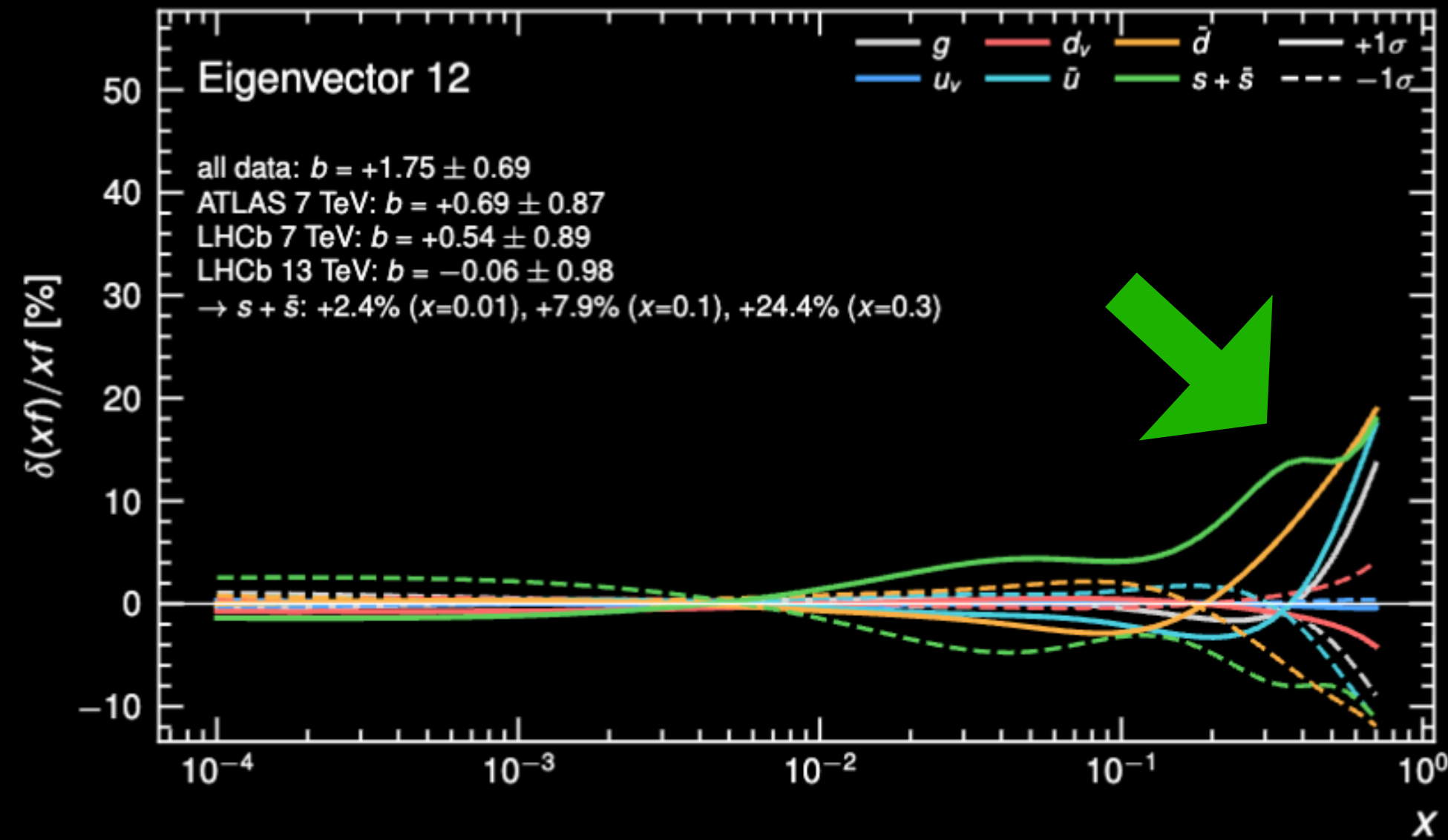
Opposite pulls between measurement groups:
D0 $W \rightarrow e\nu$ pulls against ATLAS and LHCb 7 TeV



- Both ATLAS 7 TeV and LHCb 7 TeV datasets want to push strangeness up at high- x
- Pulls in 4 PDF eigenvectors seem to be the driving force



Profiled CT₈ZNNLO: Pulls in Eigenvectors

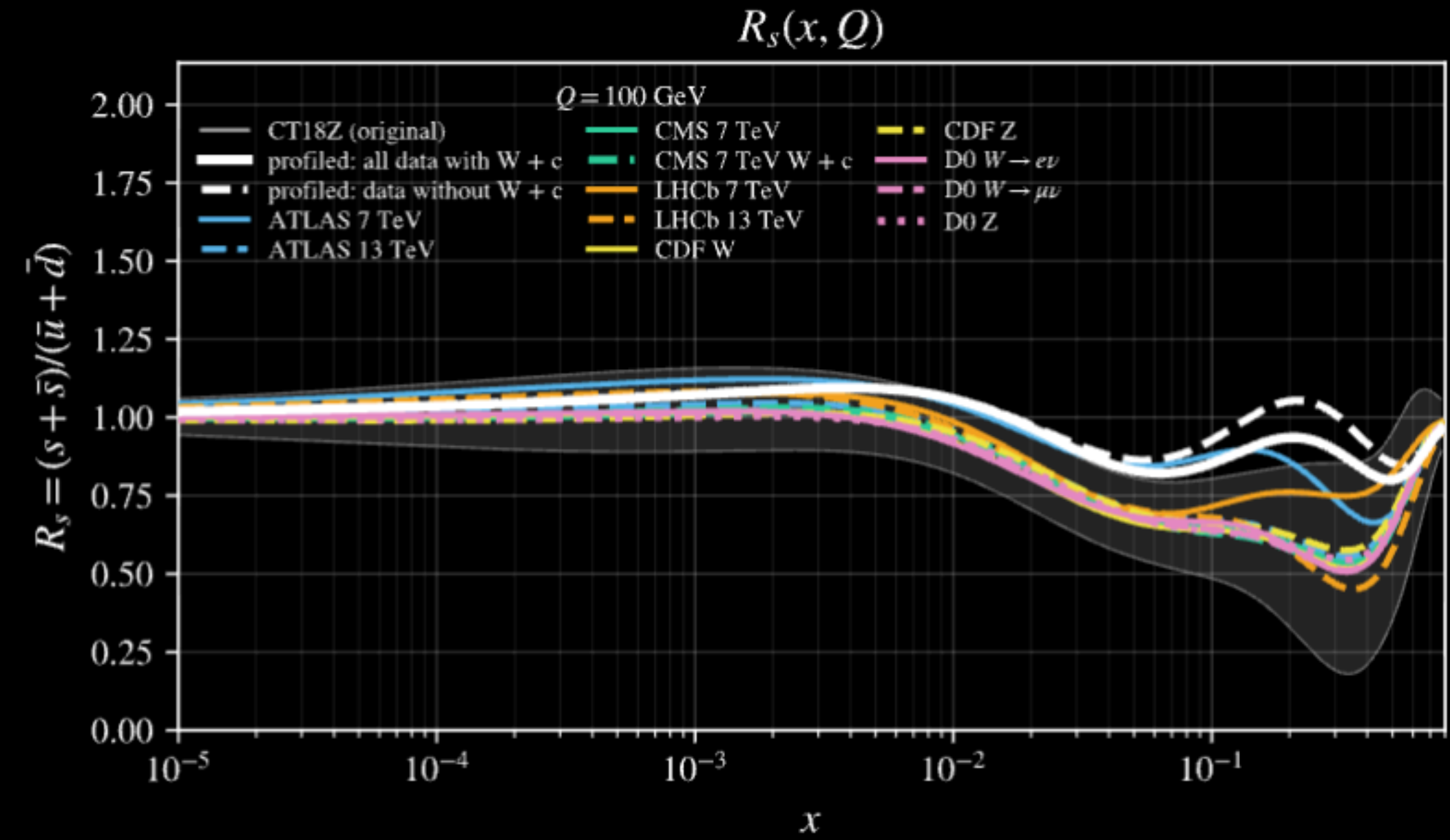
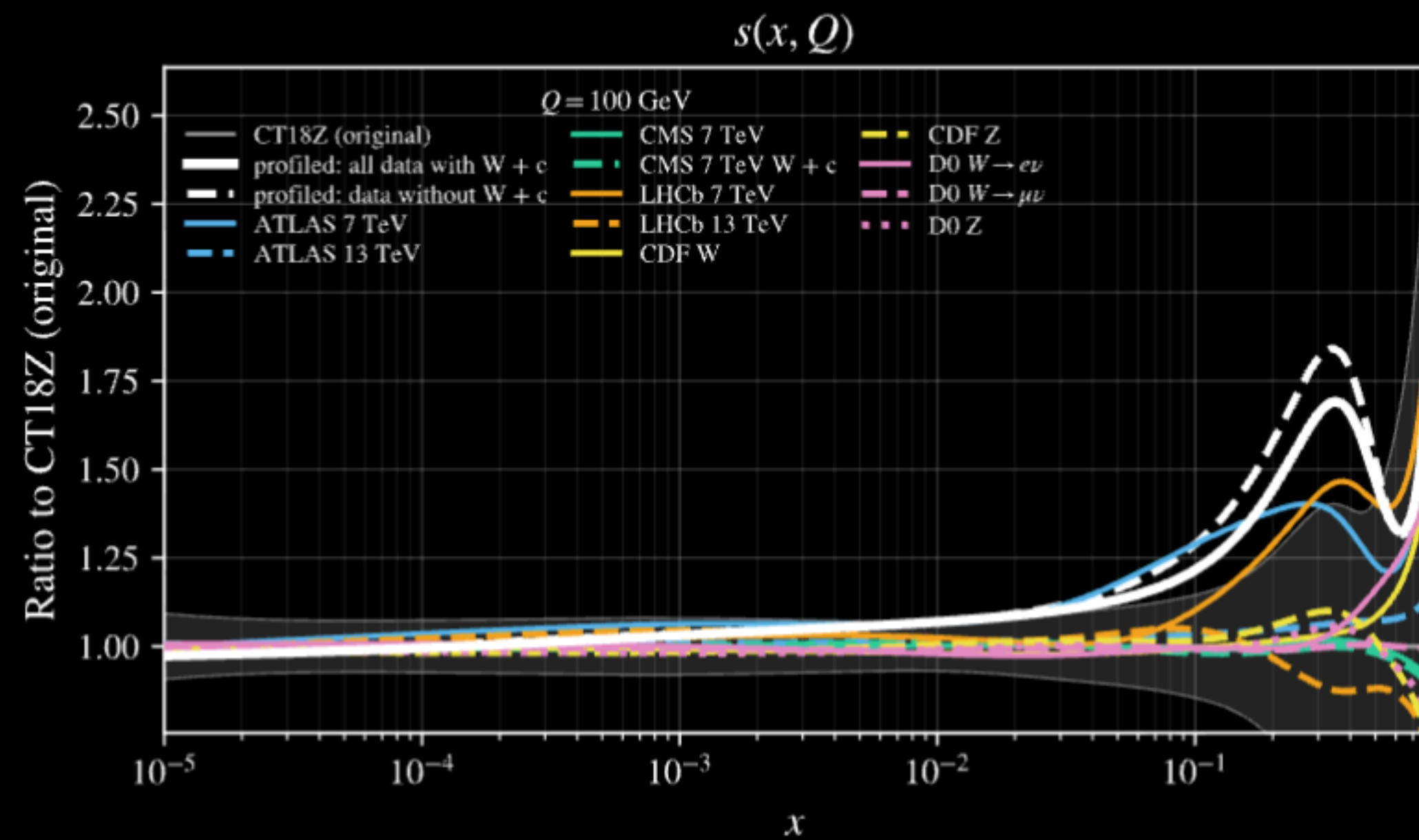


–1 σ shift of
 Eigenvector 3 shifts
 strange PDF up to
 37% at high- x



Profiled CT18ZNNLO: Tackling the Strangeness

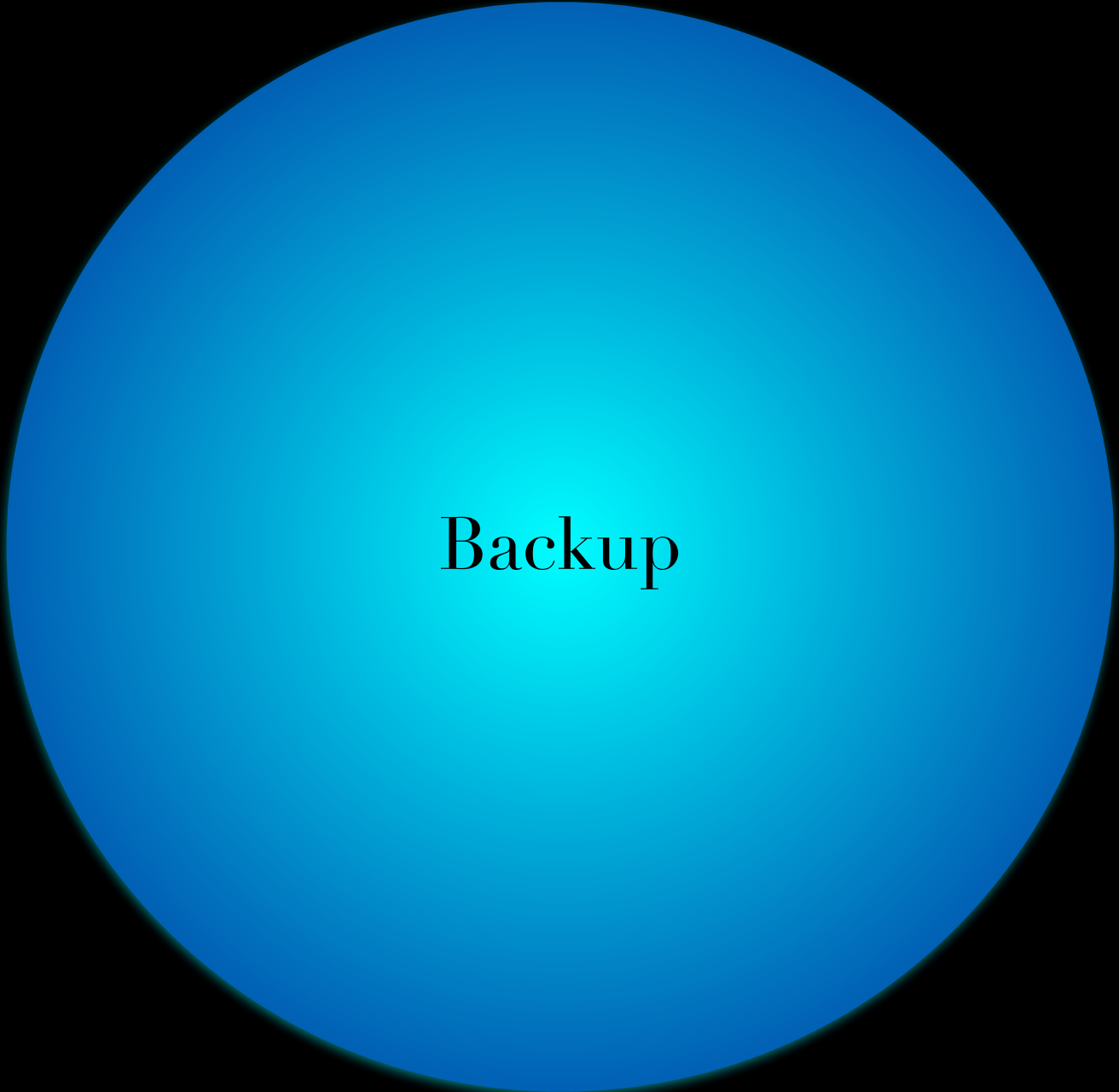
- Studied the effect of adding a dataset that probes the strange PDF directly: CMS 7 TeV $W + c$
 - NLO (QCD) + LO (EW) grids



- Pulls back the eigenvectors slightly!

Conclusions and Next Steps

- PDF uncertainties remain dominant in m_W measurements: *Different measurements adopt different nominal PDF sets and PDF uncertainty strategy*
- For the next iteration of the combination, we want to understand the constraints imposed by the individual DY measurements: *Compatibility + PDF Profiling with DY measurements from ATLAS, CMS, LHCb, D0, CDF*
 - CT18ZNNLO gives the best description for the DY measurements considered
- Profiling CT18ZNNLO with these DY measurements lead to a high- x strangeness enhancement, *driven by the ATLAS and LHCb 7 TeV datasets*
- Direct probe on strange PDF, CMS $W + c$ measurement, pulls it back slightly, but enhancement still prominent
 - Study what other datasets could be added to pull it back further
 - Examine the effect of resummed predictions via KFactors
 - Effects of changing tolerance in profiling need to be understood
 - Feed the tensions seen in the pulls to the combination effort
 - Possible addition of GRIDs: ATLAS 7 TeV $W + c$, CMS 13 TeV W

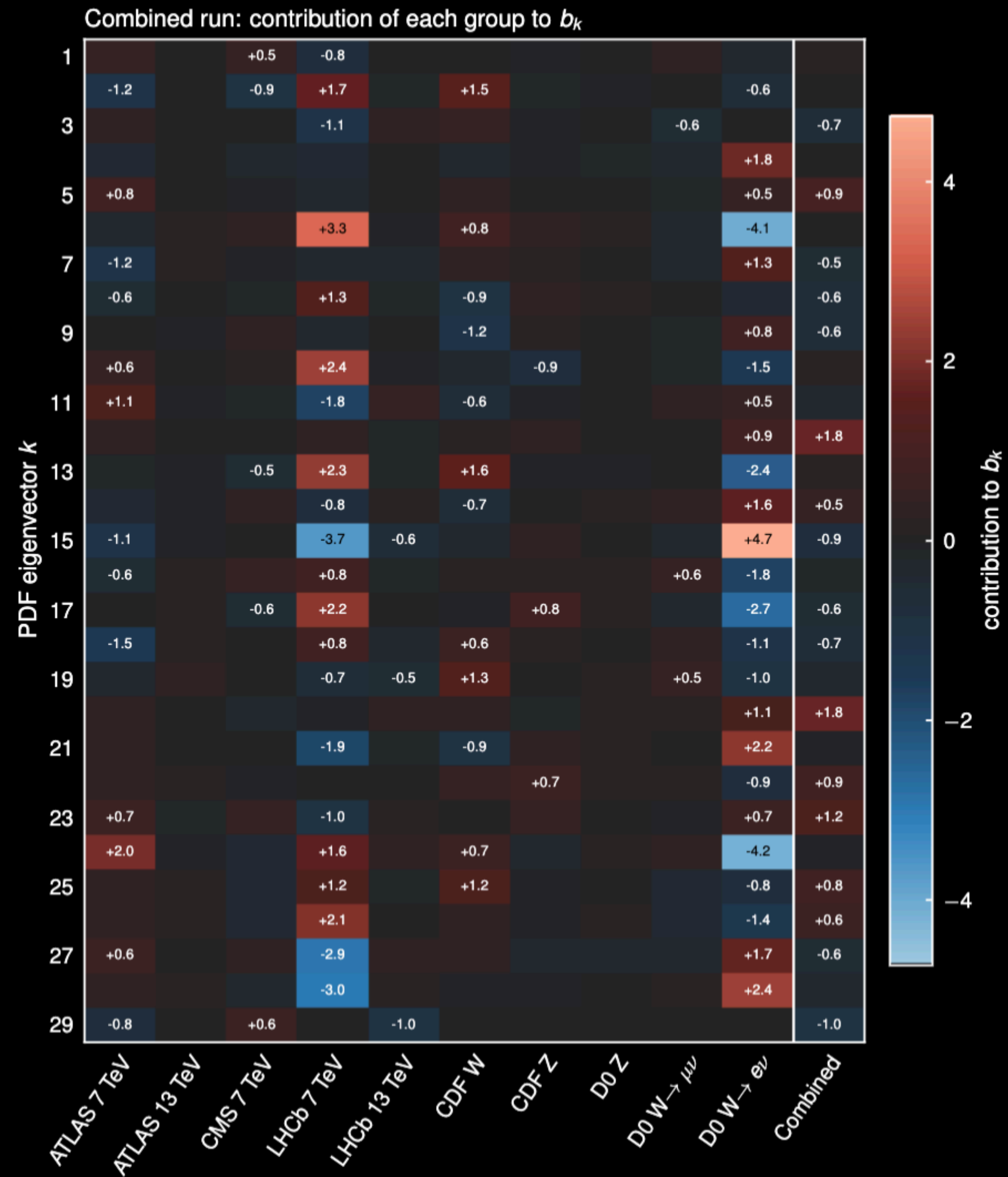


Backup

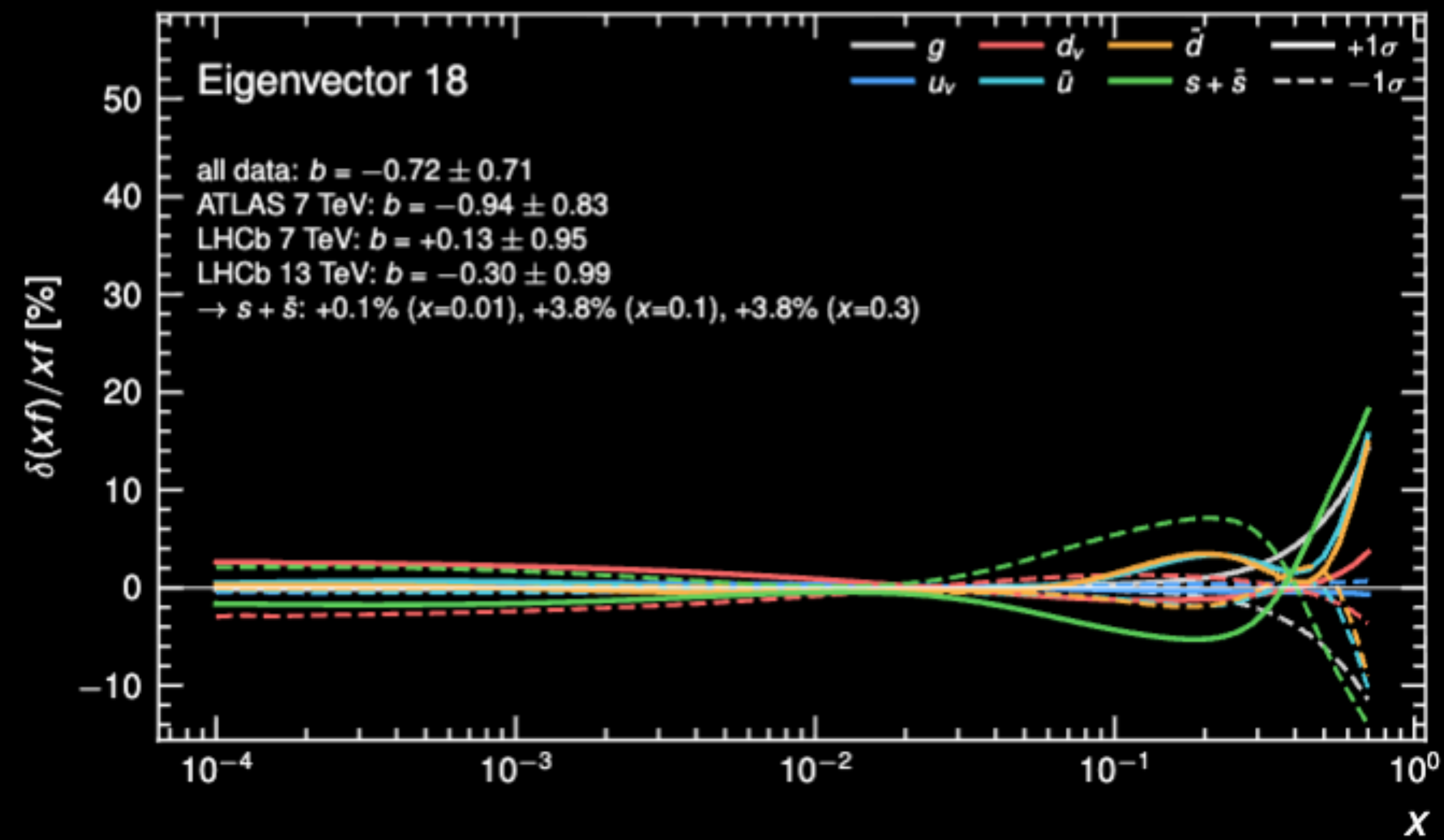
Individual Profiling Runs

Measurement	FO	CT18	CT18A	CT18Z	MSHT20 QED	MSHT20	NNPDF	NNPDF	Best Candidate
		NNLO (Scaled)	NNLO (Scaled)	NNLO (Scaled)	N ³ LO	NNLO	3.1	4.0	
ATLAS 7 TeV measurements									
ATLAS 7 TeV $W^- \eta_\ell$	NNLO + NLO	8.16/11	7.85/11	8.24/11	7.86/11	8.00/11	8.87/11	8.89/11	MSHT20 NNLO
ATLAS 7 TeV $W^+ \eta_\ell$	NNLO + NLO	7.43/11	7.33/11	7.54/11	7.43/11	7.32/11	7.91/11	7.99/11	
ATLAS 7 TeV peak CC y_Z	NNLO + NLO	9.39/12	9.06/12	9.20/12	9.61/12	8.68/12	8.77/12	10.48/12	
	Correlated χ^2	32.76	25.35	24.93	23.89	23.22	32.42	29.11	
	Total χ^2 /dof	57.74/34	49.59/34	49.91/34	48.79/34	47.23/34	57.98/34	56.47/34	
ATLAS 13 TeV measurements									
ATLAS 13 TeV σ_{W^-}	NNLO + LO	0.15/1	0.01/1	0.07/1	0.004/1	0.02/1	0.04/1	0.05/1	MSHT20 NNLO
ATLAS 13 TeV σ_{W^+}	NNLO + LO	0.92/1	0.59/1	0.60/1	0.63/1	0.49/1	0.75/1	0.56/1	
ATLAS 13 TeV σ_{Z^0}	NNLO + LO	0.53/1	0.20/1	0.04/1	0.26/1	0.18/1	0.27/1	0.04/1	
	Correlated χ^2	1.43	0.27	0.78	0.23	0.24	0.13	0.34	
	Total χ^2 /dof	3.03/3	1.06/3	1.49/3	1.13/3	0.93/3	1.19/3	1.00/3	
CMS 7 TeV measurements									
CMS 7 TeV $W \rightarrow \mu\nu A_\ell$	NNLO + LO	2.58/11	2.58/11	2.59/11	2.64/11	2.67/11	2.72/11	2.76/11	CT18NNLO
CMS 7 TeV $W \rightarrow e\nu A_\ell$	NNLO + LO	1.08/11	1.09/11	1.11/11	1.14/11	1.27/11	1.08/11	1.21/11	
	Correlated χ^2	19.28	19.61	19.96	21.12	21.70	20.72	22.51	
	Total χ^2 /dof	22.95/22	23.29/22	23.66/22	24.90/22	25.64/22	24.51/22	26.48/22	
LHCb 7 TeV measurements									
LHCb 7 TeV $W^- \eta_\ell$	NNLO + LO	3.28/8	3.27/8	3.29/8	2.89/8	2.89/8	5.32/8	4.19/8	CT18ZNNLO
LHCb 7 TeV $W^+ \eta_\ell$	NNLO + LO	3.56/8	3.55/8	3.42/8	4.33/8	4.29/8	5.15/8	4.03/8	
LHCb 7 TeV y_Z	NNLO + LO	2.66/17	2.58/17	2.51/17	2.86/17	2.63/17	2.82/17	2.97/17	
	Correlated χ^2	28.81	27.02	26.40	31.26	27.53	36.03	37.65	
	Total χ^2 /dof	38.31/33	36.43/33	35.62/33	41.34/33	37.34/33	49.32/33	48.84/33	
LHCb 13 TeV measurement									
LHCb 13 TeV y_Z	NNLO + LO	11.20/18	11.20/18	11.43/18	11.86/18	11.65/18	11.21/18	11.62/18	NNPDF4.0
	Correlated χ^2	9.04	8.72	7.85	8.31	7.72	7.70	7.13	
	Total χ^2 /dof	20.24/18	19.92/18	19.28/18	20.17/18	19.37/18	18.90/18	18.76/18	
CDF 1.96 TeV W measurement									
CDF 1.96 TeV $W \rightarrow e\nu A_{y^W}$	NLO + LO	13.16/13	13.71/13	13.13/13	13.77/13	13.63/13	11.99/13	12.92/13	NNPDF 4.0
	Correlated χ^2	2.93	4.10	1.80	2.30	2.75	1.98	0.72	
	Total χ^2 /dof	16.09/13	17.81/13	14.93/13	16.07/13	16.39/13	13.96/13	13.63/13	
CDF 1.96 TeV Z measurement									
CDF 1.96 TeV y_Z	NNLO + LO	25.32/28	25.18/28	25.96/28	29.03/28	26.69/28	24.50/28	27.47/28	CT18ANNLO
	Correlated χ^2	0.62	0.61	0.73	1.43	0.93	1.41	0.76	
	Total χ^2 /dof	25.94/28	25.79/28	26.69/28	30.47/28	27.62/28	25.91/28	28.23/28	
D0 1.96 TeV Z measurement									
D0 1.96 TeV y_Z	NNLO + LO	22.11/28	22.34/28	22.90/28	24.90/28	23.68/28	22.53/28	23.69/28	CT18NNLO
	Correlated χ^2	0.04	0.18	0.39	0.27	0.19	0.08	0.09	
	Total χ^2 /dof	22.15/28	22.53/28	23.29/28	25.18/28	23.86/28	22.60/28	23.78/28	
D0 1.96 TeV $W \rightarrow \mu\nu$ measurement									
D0 1.96 TeV $W \rightarrow \mu\nu A_\ell$	NNLO + LO	11.09/10	11.17/10	11.16/10	11.53/10	11.17/10	13.66/10	14.43/10	CT18ANNLO
	Correlated χ^2	0.90	0.74	0.79	0.91	1.15	1.92	4.11	
	Total χ^2 /dof	11.99/10	11.91/10	11.95/10	12.44/10	12.32/10	15.58/10	18.54/10	
D0 1.96 TeV $W \rightarrow e\nu$ measurement									
D0 1.96 TeV $W \rightarrow e\nu A_\ell$	NLO + LO	17.46/13	17.69/13	17.04/13	27.48/13	25.56/13	20.94/13	22.80/13	CT18ZNNLO
	Correlated χ^2	4.63	4.88	3.67	11.66	8.78	7.31	10.32	
	Total χ^2 /dof	22.09/13	22.57/13	20.72/13	39.14/13	34.34/13	28.25/13	33.12/13	
		CT18 NNLO (Scaled)	CT18A NNLO (Scaled)	CT18Z NNLO (Scaled)	MSHT20 QED N ³ LO	MSHT20 NNLO	NNPDF 3.1	NNPDF 4.0	Best Candidate
Individual run sum									
	Total χ^2 /dof	240.53/202	230.90/202	227.54/202	259.63/202	245.04/202	258.20/202	268.85/202	CT18ZNNLO
	$p(\chi^2, n)$	3.29%	7.97%	10.50%	0.39%	2.08%	0.46%	0.12%	
Combined run									
	Total χ^2 /dof	269.44/202	259.83/202	254.89/202	278.90/202	269.30/202	258.61/202	274.13/202	CT18ZNNLO
	$p(\chi^2, n)$	0.11%	0.38%	0.69%	0.03%	0.11%	0.44%	0.06%	

Individual Profiling Runs

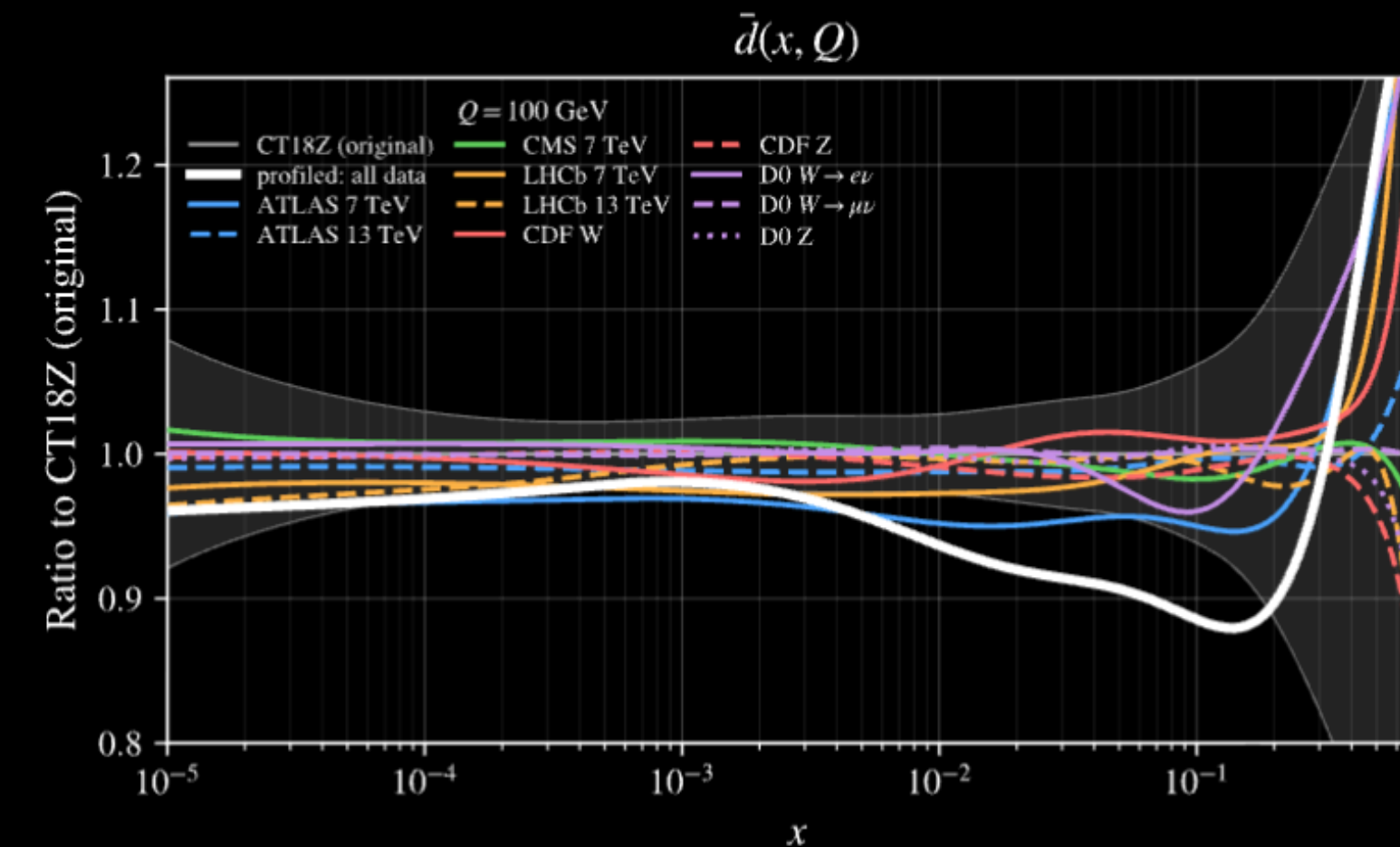
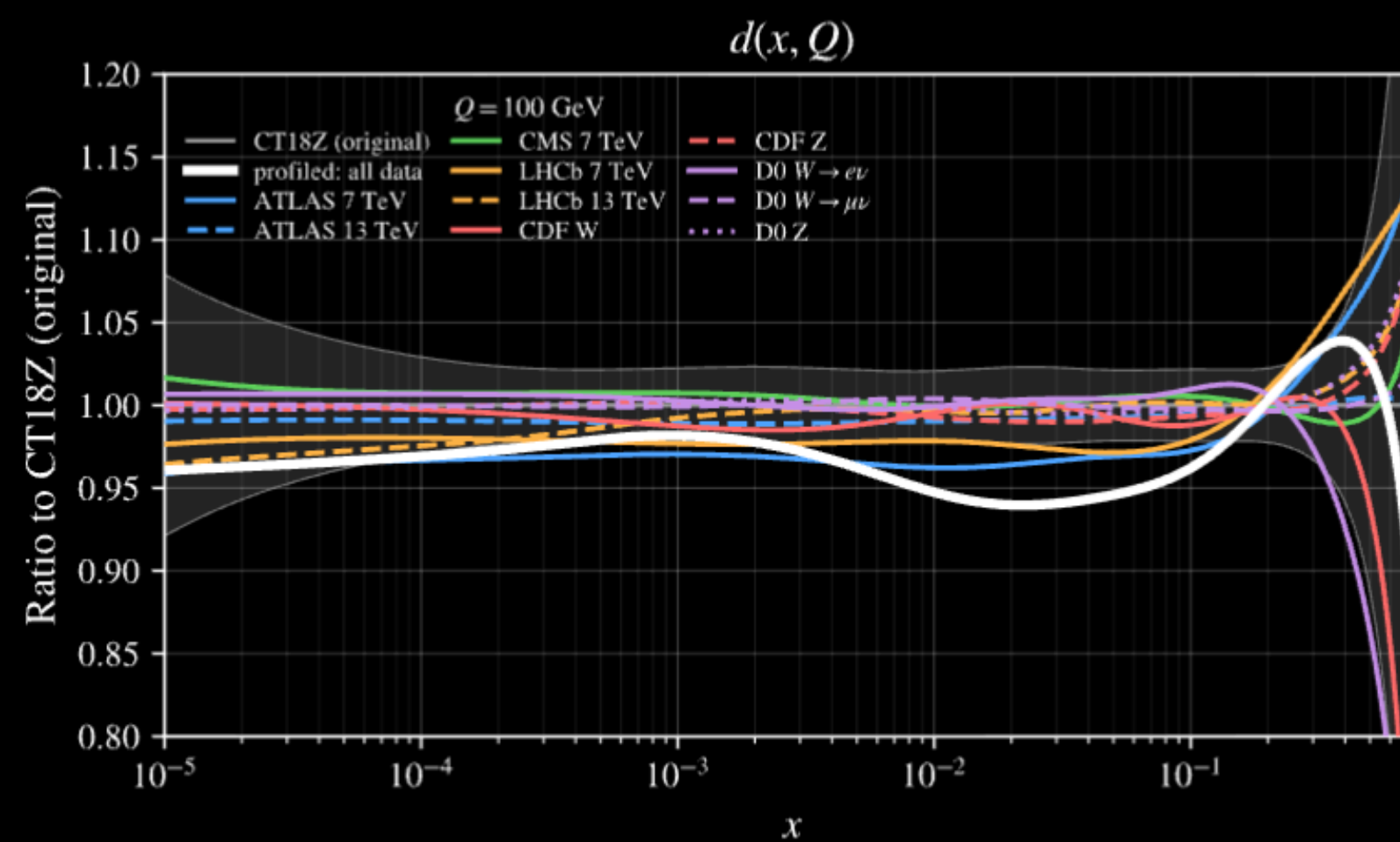
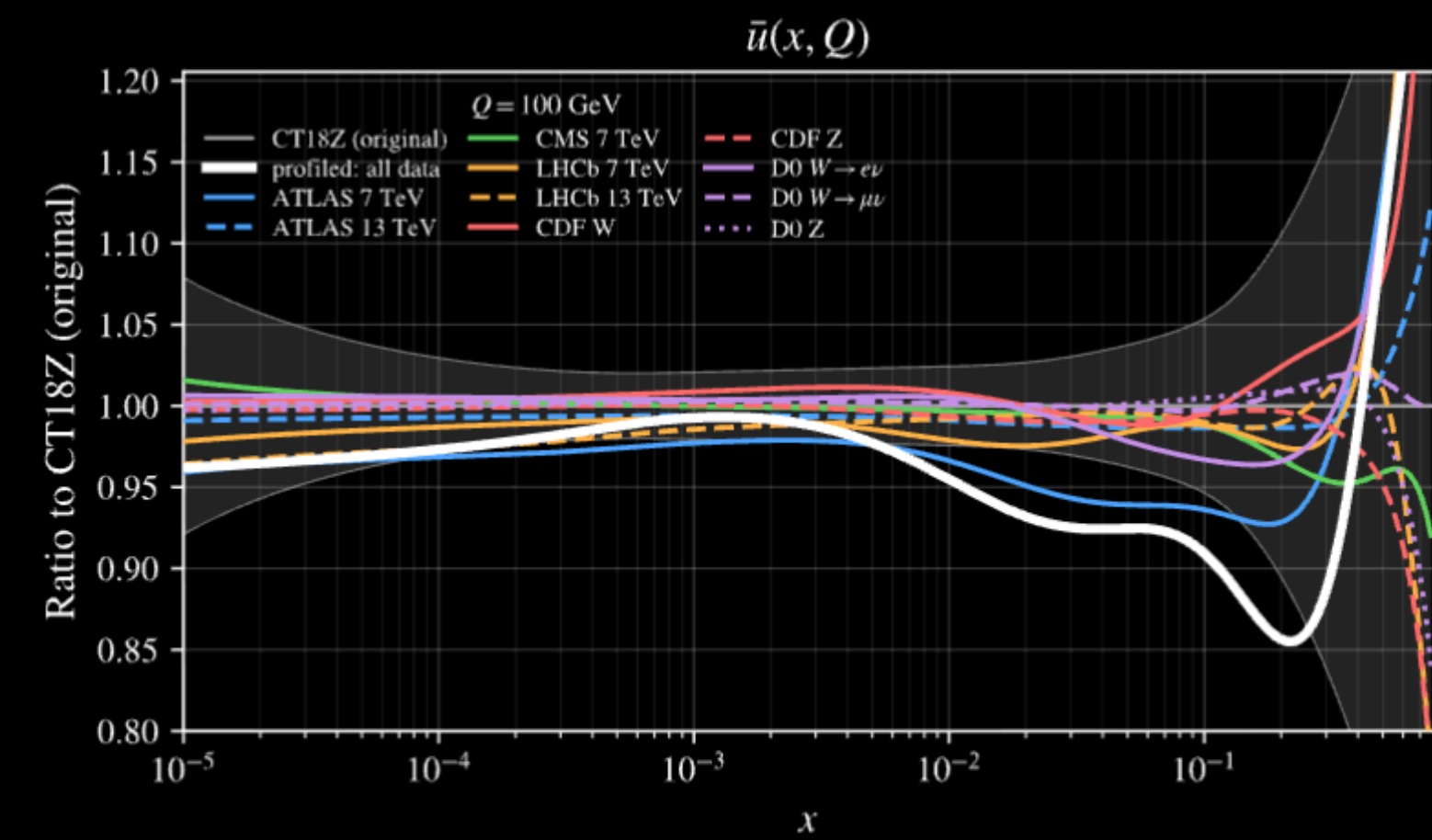
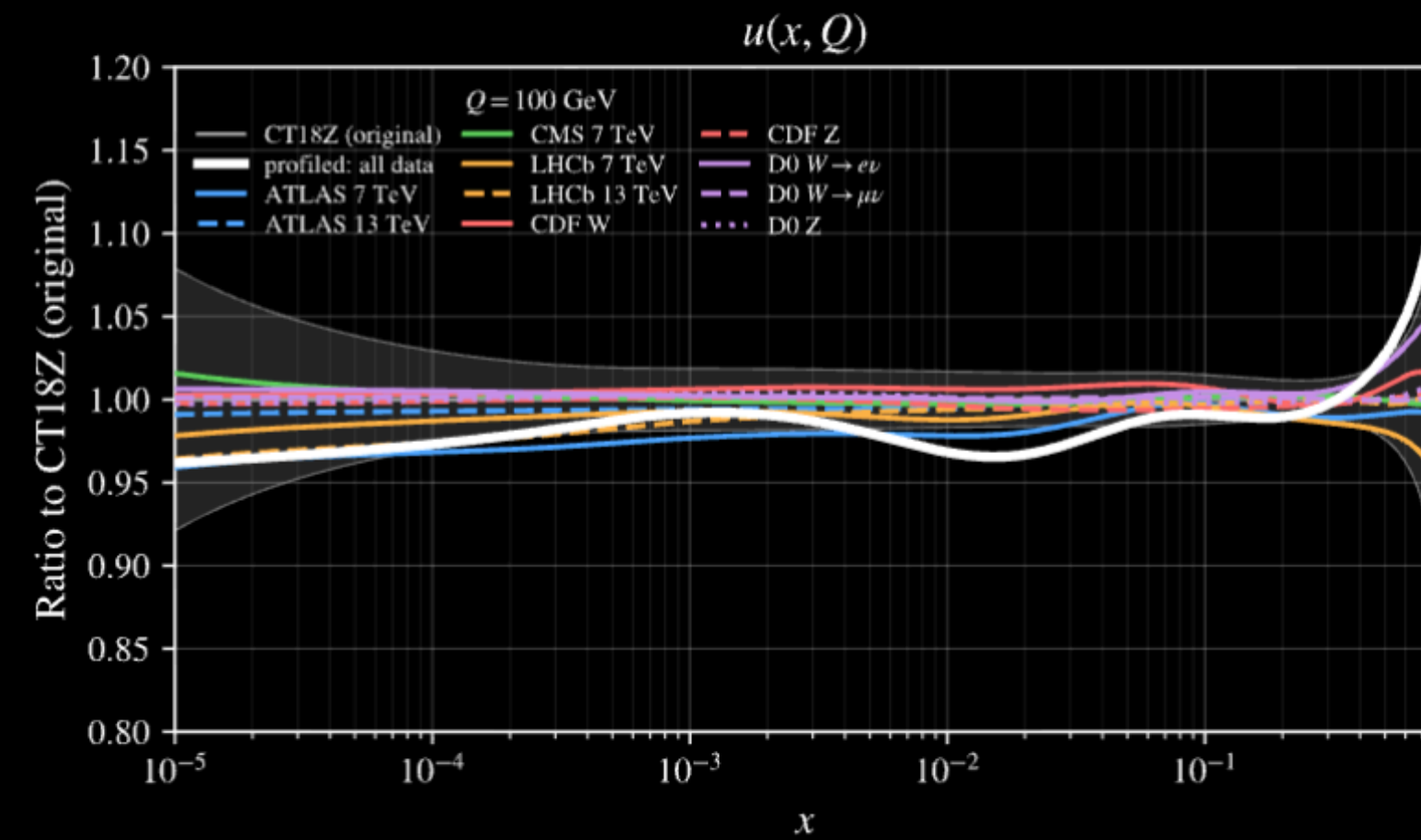
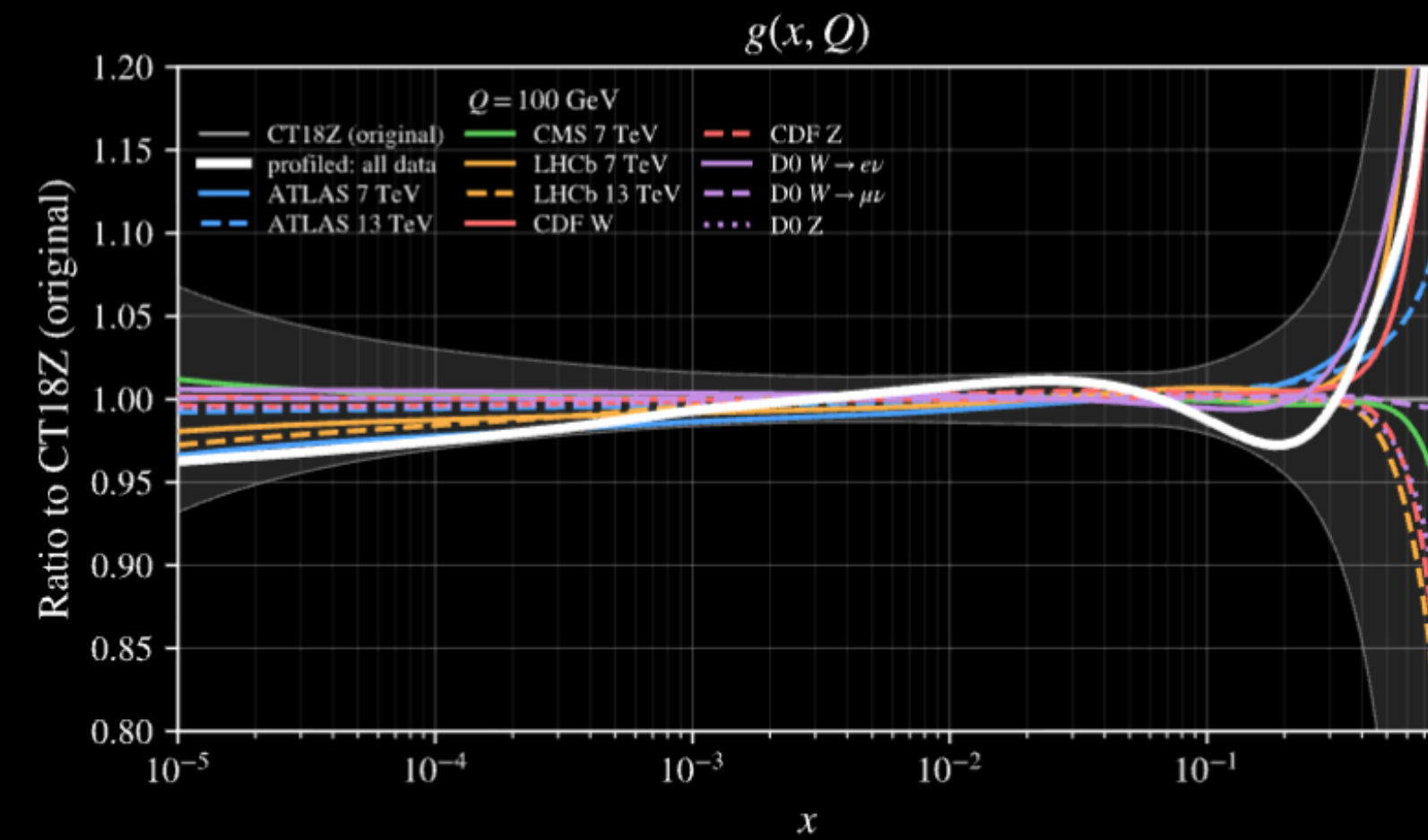


Individual Profiling Runs



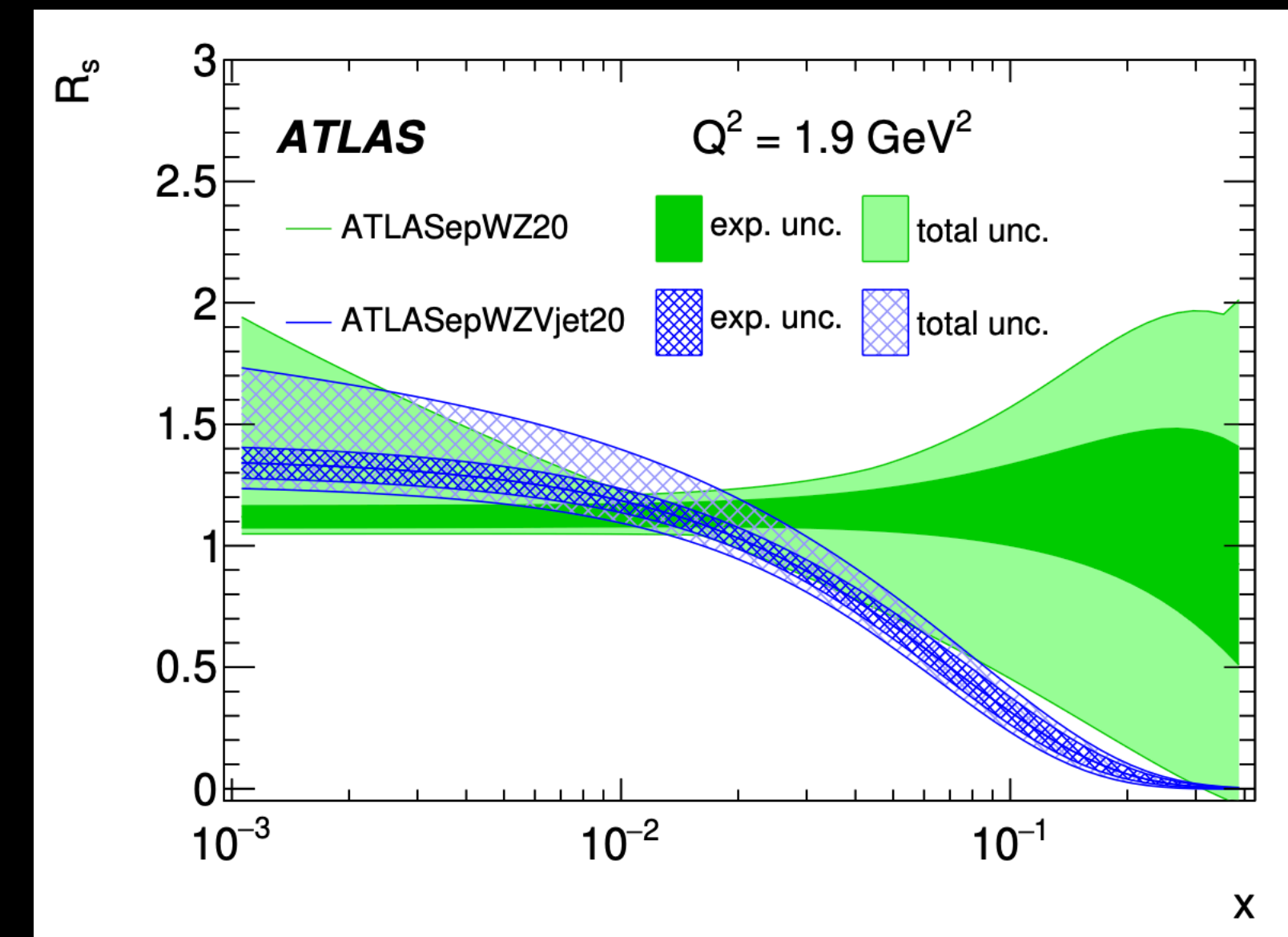
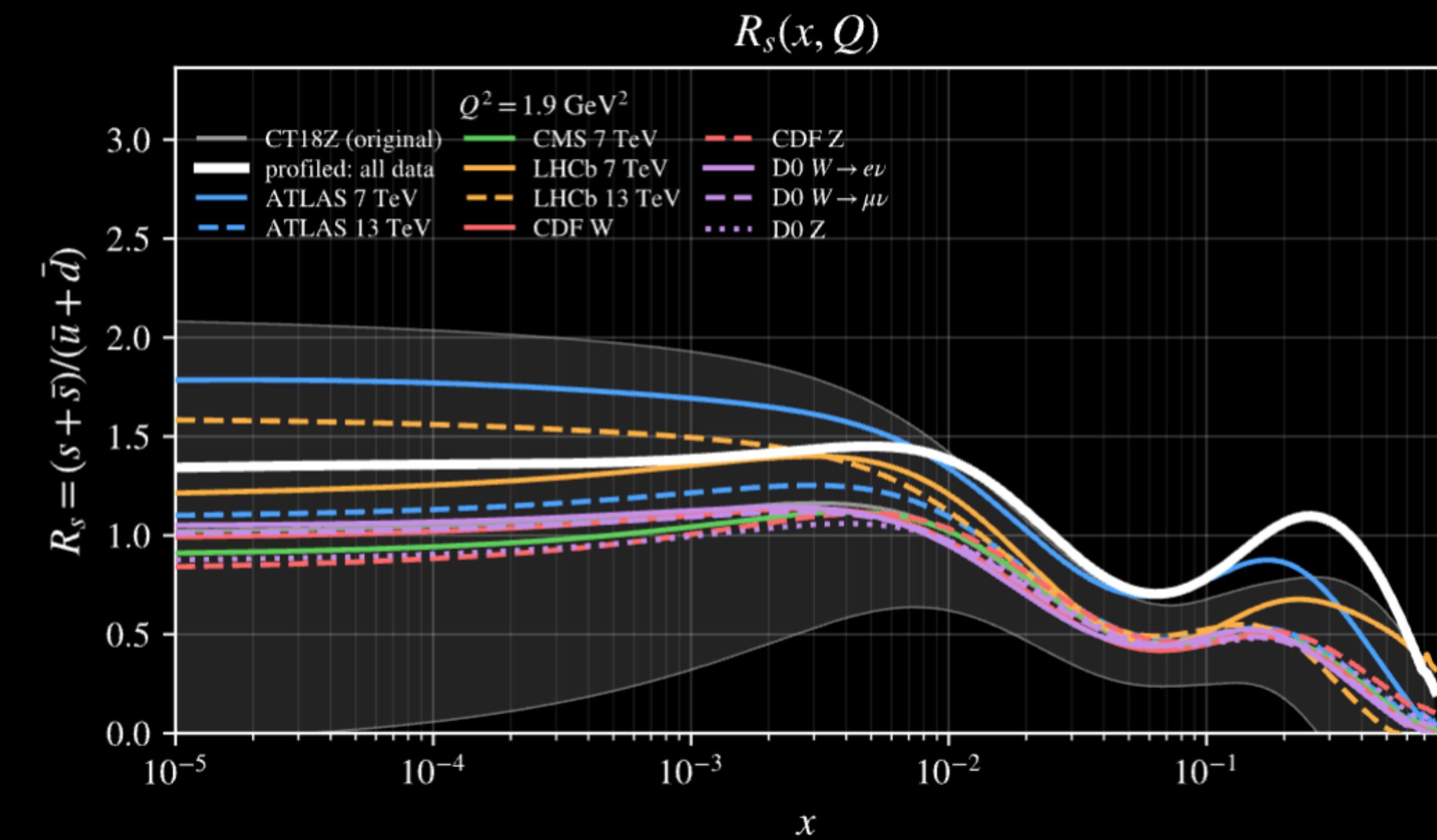
Profiled CT18ZNNLO

- In addition to the combined run, profiling with individual correlated groups was also done to understand the shifts/tensions

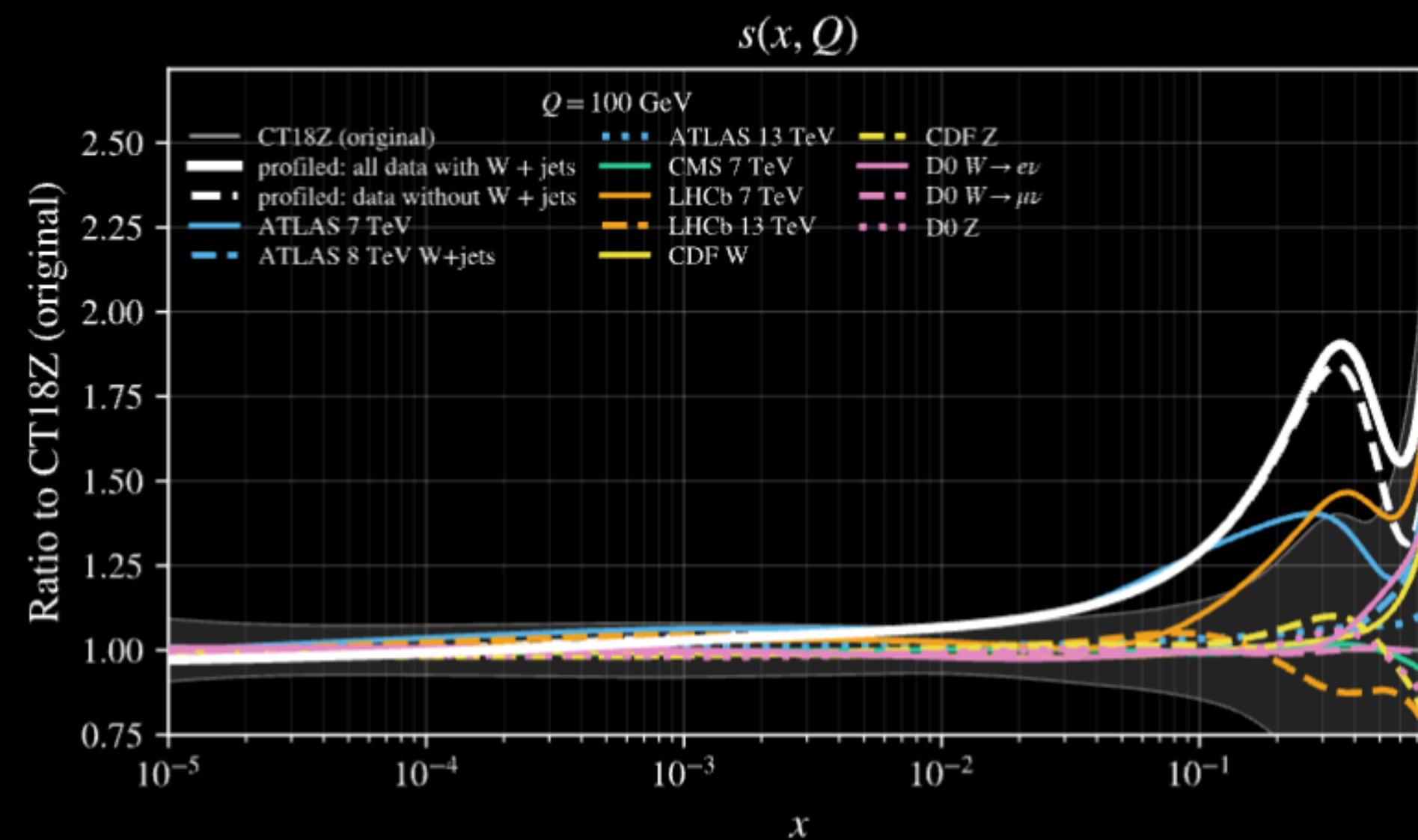


- $\bar{u}$ and $\bar{d}$ drop 5-11% between $x = 0.01 - 0.1$
- g stays inside the CT18Z band

W+jets?



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Datasets in CT18ZNNLO

TABLE I. Datasets included in the CT18(Z) NNLO global analyses. Here we directly compare the quality of fit found for CT18 NNLO vs CT18Z NNLO on the basis of χ_E^2 , $\chi_E^2/N_{pt,E}$, and S_E , in which $N_{pt,E}$, χ_E^2 are the number of points and value of χ^2 for experiment E at the global minimum. S_E is the effective Gaussian parameter [38,42,56] quantifying agreement with each experiment. The ATLAS 7 TeV 35 pb⁻¹ W/Z dataset, marked by ‡‡, is replaced by the updated one (4.6 fb⁻¹) in the CT18A and CT18Z fits. The CDHSW data, labeled by †, are not included in the CT18Z fit. The numbers in parentheses are for the CT18Z NNLO fit.

Exp. ID#	Experimental dataset		$N_{pt,E}$	χ_E^2	$\chi_E^2/N_{pt,E}$	S_E
160	HERAI + II 1 fb ⁻¹ , H1 and ZEUS NC and CC $e^\pm p$ reduced cross sec. comb.	[30]	1120	1408 (1378)	1.3 (1.2)	5.7 (5.1)
101	BCDMS F_2^p	[57]	337	374 (384)	1.1 (1.1)	1.4 (1.8)
102	BCDMS F_2^d	[58]	250	280 (287)	1.1 (1.1)	1.3 (1.6)
104	NMC $F_2^d/\bar{F}_2^p$	[59]	123	126 (116)	1.0 (0.9)	0.2 (−0.4)
108†	CDHSW F_2^p	[60]	85	85.6 (86.8)	1.0 (1.0)	0.1 (0.2)
109†	CDHSW $x_B F_3^p$	[60]	96	86.5 (85.6)	0.9 (0.9)	−0.7 (−0.7)
110	CCFR F_2^p	[61]	69	78.8 (76.0)	1.1 (1.1)	0.9 (0.6)
111	CCFR $x_B \bar{F}_3^p$	[62]	86	33.8 (31.4)	0.4 (0.4)	−5.2 (−5.6)
124	NuTeV $\nu\mu\mu$ SIDIS	[63]	38	18.5 (30.3)	0.5 (0.8)	−2.7 (−0.9)
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	[63]	33	38.5 (56.7)	1.2 (1.7)	0.7 (2.5)
126	CCFR $\nu\mu\mu$ SIDIS	[64]	40	29.9 (35.0)	0.7 (0.9)	−1.1 (−0.5)
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	[64]	38	19.8 (18.7)	0.5 (0.5)	−2.5 (−2.7)
145	H1 σ_r^b	[65]	10	6.8 (7.0)	0.7 (0.7)	−0.6 (−0.6)
147	Combined HERA charm production	[66]	47	58.3 (56.4)	1.2 (1.2)	1.1 (1.0)
169	H1 F_L	[33]	9	17.0 (15.4)	1.9 (1.7)	1.7 (1.4)
201	E605 Drell-Yan process	[67]	119	103.4 (102.4)	0.9 (0.9)	−1.0 (−1.1)
203	E866 Drell-Yan process $\sigma_{pd}/(2\sigma_{pp})$	[68]	15	16.1 (17.9)	1.1 (1.2)	0.3 (0.6)
204	E866 Drell-Yan process $Q^3 d^2\sigma_{pp}/(dQdx_F)$	[69]	184	244 (240)	1.3 (1.3)	2.9 (2.7)
225	CDF run-1 lepton A_{ch} , $p_{T\ell} > 25$ GeV	[70]	11	9.0 (9.3)	0.8 (0.8)	−0.3 (−0.2)
227	CDF run-2 electron A_{ch} , $p_{T\ell} > 25$ GeV	[71]	11	13.5 (13.4)	1.2 (1.2)	0.6 (0.6)
234	DØ run-2 muon A_{ch} , $p_{T\ell} > 20$ GeV	[72]	9	9.1 (9.0)	1.0 (1.0)	0.2 (0.1)
260	DØ run-2 Z rapidity	[73]	28	16.9 (18.7)	0.6 (0.7)	−1.7 (−1.3)
261	CDF run-2 Z rapidity	[74]	29	48.7 (61.1)	1.7 (2.1)	2.2 (3.3)
266	CMS 7 TeV 4.7 fb ⁻¹ , muon A_{ch} , $p_{T\ell} > 35$ GeV	[75]	11	7.9 (12.2)	0.7 (1.1)	−0.6 (0.4)
267	CMS 7 TeV 840 pb ⁻¹ , electron A_{ch} , $p_{T\ell} > 35$ GeV	[76]	11	4.6 (5.5)	0.4 (0.5)	−1.6 (−1.3)
268‡‡	ATLAS 7 TeV 35 pb ⁻¹ W/Z cross sec., A_{ch}	[77]	41	44.4 (50.6)	1.1 (1.2)	0.4 (1.1)
281	DØ run-2 9.7 fb ⁻¹ electron A_{ch} , $p_{T\ell} > 25$ GeV	[78]	13	22.8 (20.5)	1.8 (1.6)	1.7 (1.4)
504	CDF run-2 inclusive jet production	[79]	72	122 (117)	1.7 (1.6)	3.5 (3.2)
514	DØ run-2 inclusive jet production	[80]	110	113.8 (115.2)	1.0 (1.0)	0.3 (0.4)

TABLE II. Like Table I, for newly included LHC measurements. The ATLAS 7 TeV W/Z data (4.6 fb⁻¹), labeled by ‡, are included in the CT18A and CT18Z global fits, but not in CT18 and CT18X.

Exp. ID#	Experimental dataset		$N_{pt,E}$	χ_E^2	$\chi_E^2/N_{pt,E}$	S_E
245	LHCb 7 TeV 1.0 fb ⁻¹ W/Z forward rapidity cross sec.	[81]	33	53.8 (39.9)	1.6 (1.2)	2.2 (0.9)
246	LHCb 8 TeV 2.0 fb ⁻¹ $Z \rightarrow e^- e^+$ forward rapidity cross sec.	[82]	17	17.7 (18.0)	1.0 (1.1)	0.2 (0.3)
248‡	ATLAS 7 TeV 4.6 fb ⁻¹ , W/Z combined cross sec.	[39]	34	287.3 (88.7)	8.4 (2.6)	13.7 (4.8)
249	CMS 8 TeV 18.8 fb ⁻¹ muon charge asymmetry A_{ch}	[83]	11	11.4 (12.1)	1.0 (1.1)	0.2 (0.4)
250	LHCb 8 TeV 2.0 fb ⁻¹ W/Z cross sec.	[84]	34	73.7 (59.4)	2.1 (1.7)	3.7 (2.6)
253	ATLAS 8 TeV 20.3 fb ⁻¹ , Z p_T cross sec.	[85]	27	30.2 (28.3)	1.1 (1.0)	0.5 (0.3)
542	CMS 7 TeV 5 fb ⁻¹ , single incl. jet cross sec., $R = 0.7$ (extended in y)	[86]	158	194.7 (188.6)	1.2 (1.2)	2.0 (1.7)
544	ATLAS 7 TeV 4.5 fb ⁻¹ , single incl. jet cross sec., $R = 0.6$	[9]	140	202.7 (203.0)	1.4 (1.5)	3.3 (3.4)
545	CMS 8 TeV 19.7 fb ⁻¹ , single incl. jet cross sec., $R = 0.7$, (extended in y)	[87]	185	210.3 (207.6)	1.1 (1.1)	1.3 (1.2)
573	CMS 8 TeV 19.7 fb ⁻¹ , $t\bar{t}$ norm. double-diff. top p_T and y cross sec.	[88]	16	18.9 (19.1)	1.2 (1.2)	0.6 (0.6)
580	ATLAS 8 TeV 20.3 fb ⁻¹ , $t\bar{t}$ p_T^t and $m_{t\bar{t}}$ abs. spectrum	[89]	15	9.4 (10.7)	0.6 (0.7)	−1.1 (−0.8)