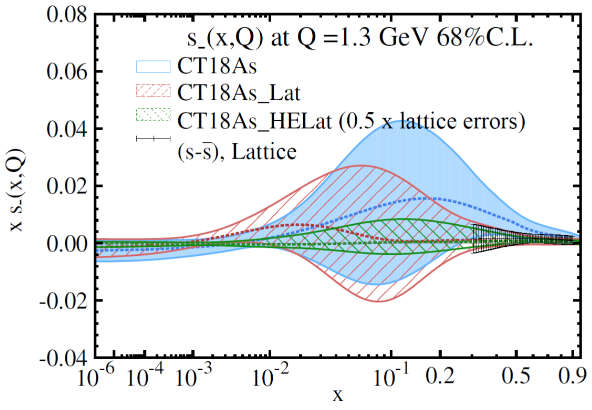
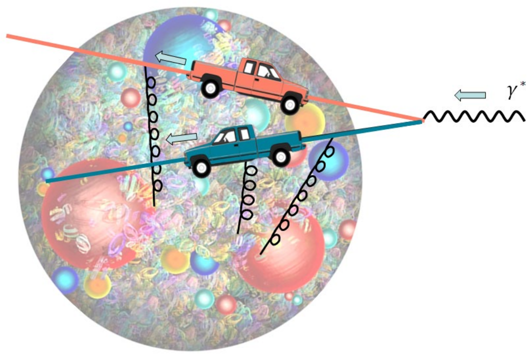
Update from CTEQ-TEA



Pavel Nadolsky

Southern Methodist University, USA

With CTEQ-TEA (Tung Et. Al.) working group

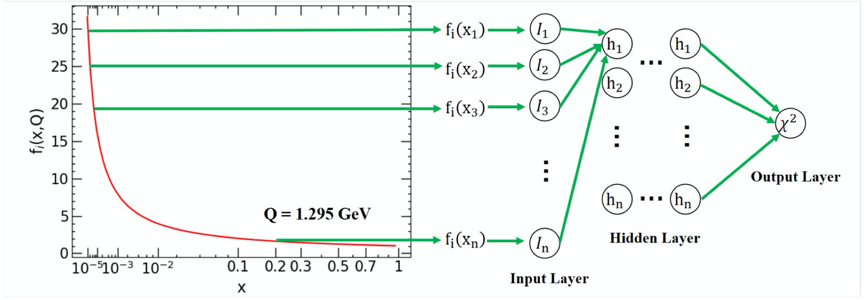


China: A. Ablat, S. Dulat, J. Gao, T.-J. Hou,
I. Sitiwaldi, M. Yan, and collaborators

Mexico: A. Courtoy

USA: T.J. Hobbs, M. Guzzi, X. Jing,
J. Huston, H.-W. Lin, D. Stump, C. Schmidt, K. Xie, C.-P. Yuan

SMU CTEQ Fermilab



CTEQ-TEA presentations at DIS'2023

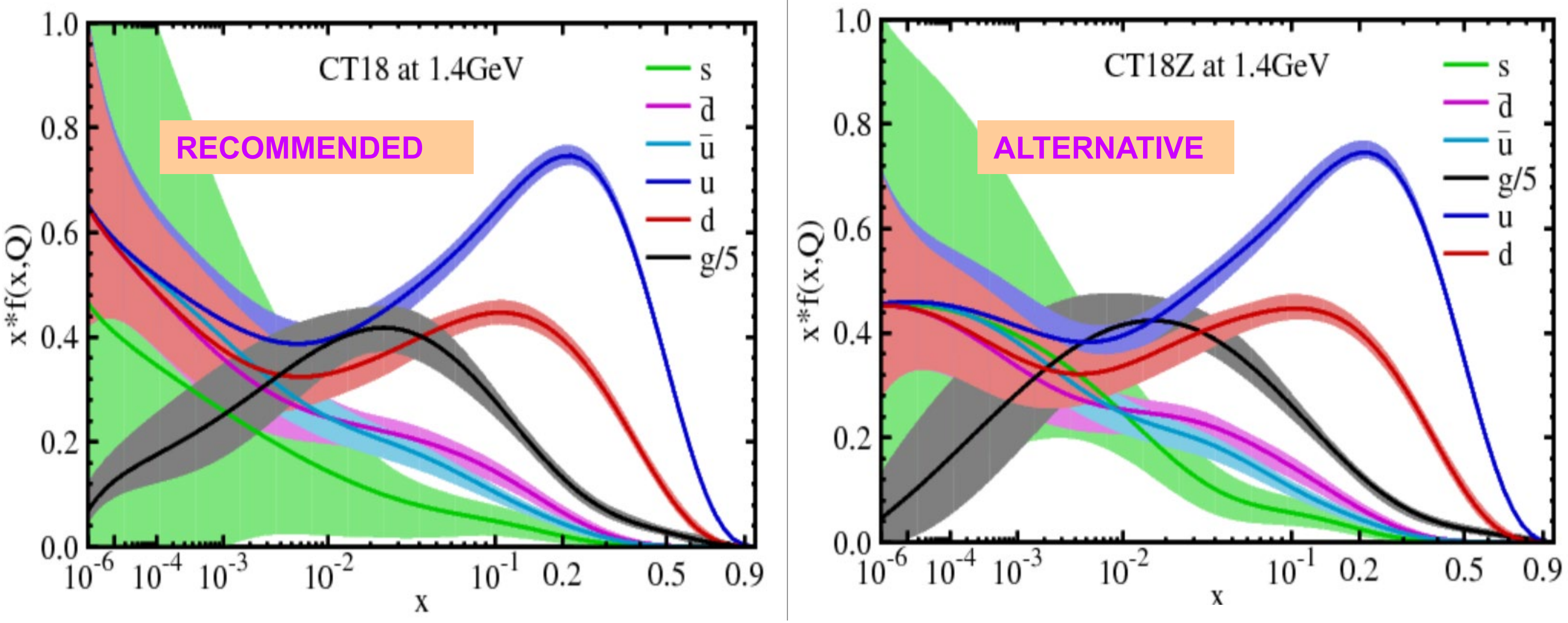
Toward a new generation of CT202X PDFs

1. Impact of Drell-Yan data on post-CT18 global fits	**Keping Xie**	**WG3**
2. Constraints from $t\bar{t}$ production at LHC 13 TeV	**Marco Guzzi**	**WG1**
3. Epistemic uncertainty quantification in PDF fits	**P. Nadolsky**	**WG1**
4. CT18 NNLO fitted charm PDFs *[arXiv:2211.01387]*	**Tim Hobbs**	**WG1**
5. Prospects for using lattice-QCD constraints in the global PDF analysis	**T.-J. Hou**	**Plenary**
6. CTEQ-TEA NNLO predictions for high-energy neutrino cross sections	**Dan Stump**	**WG3**
7. Simultaneous CTEQ-TEA extraction of PDFs and SMEFT contributions	**Tim Hobbs**	**WG3**
8. Small-x dynamics in CTEQ-TEA fits and Forward Physics Facility	**Keping Xie**	**WG2**

CT18 parton distributions

PRD 103 (2021) 014013

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



New CT18 NNLO grids **for precision calculations**

- **Soon to appear in the LHAPDF library**
- Contain more x and Q points – improved interpolation at the expense of slightly slower evaluation
- Crossing of quark mass thresholds implemented with multiple Q grids
- Complement the published (less dense) CT18 grids that remain sufficient for most applications

Toward a new generation of CT202X PDFs

1. **Identify sensitive, mutually consistent new experimental data sets** using preliminary fits and fast techniques (L_2 sensitivities and $ePump$)
2. Implement N3LO QCD and NLO EW contributions as they become available. N3LO accuracy is reached only when N3LO terms are **fully** implemented.
3. Meanwhile, "**NNLO+" PDFs**: e.g., include theoretical uncertainty due to QCD scale dependence for key processes as has been done in CT18/CT18X NNLO PDFs
4. Explore quark sea flavor dependence: $s - \bar{s}$ (CT18As), fitted charm (CT18FC),…
5. Include lattice QCD constraints (CT18As_Lat)
6. Next-generation PDF uncertainty quantification: META PDFs, Bézier curves, MC sampling, ML stress-testing, multi-Gaussian approaches, …

Impact of LHC 13 TeV $t\bar{t}$ production on CT2X PDFs

M. Guzzi, WG1

1D $t\bar{t}$ absolute distributions, NNLO QCD with different scale choices

			ePump updated Chi2/Npt				Global fit Chi2/Npt			
Exp	Obs	Npt	HT	HT/2	HT/4		HT/2	HT/4	HT/2	HT/4
ATLAS_hadron Channel	mtt	9	1.749	1.574	1.601		1.532026	1.4691		
	HTtt	11	1.982	1.769	1.585		1.499361	1.74098		
	ytt	12	1.279	1.15	0.938		1.051071	1.07351		
	pTt1	10	1.301	1.185	1.118		1.196207	1.33326		
	pTt2	8	1.132	0.843	1.047		0.84058	1.59056		
CMS_Dilep	mtt	7	3.457	3.068	3.142		3.121005	3.22675		
	ytt	10	1.66	0.969	0.679		0.938607	0.67252		
	pTt	6	3.598	3.701	3.679		3.558017	3.04841		
	yt	10	1.334	0.944	0.867		1.002635	0.68848		
ATLAS_LepJ CMS Bin	mtt	7	2.395	1.165	0.681		0.826805	0.65684		
	ytt	10	0.909	0.69	0.621		0.740418	0.74866		
	pTt	6	2.337	2.012	2.469		1.353523	1.43062		
	yt	10	1.298	1.073	1.095		1.161363	0.68198		
CMS_LepJ 137	mtt	15	1.485	1.383	1.808		1.203901	1.66676		
	ytt	10	6.469	6.238	6.424		6.005668	5.87508		
							NoStatCorrelation		WithStatCorrelation	
ATLAS_LepJ ATLAS Bin NoStatCorrelation	mtt	9	1.551	1.123	0.94		1.27	0.92206	1.287	0.963
	ytt	7	0.911	0.739	0.8		0.756	0.8975	0.751	0.921
	yB	9	1.396	1.267	1.532		0.8498	0.93335	0.858	0.992
	HTtt	9	1.352	0.909	0.933		0.805	0.80475	0.855	0.857
	mttyttybHttt	34	1.867	1.28	1.457		0.933	1.06487	1.585	1.322

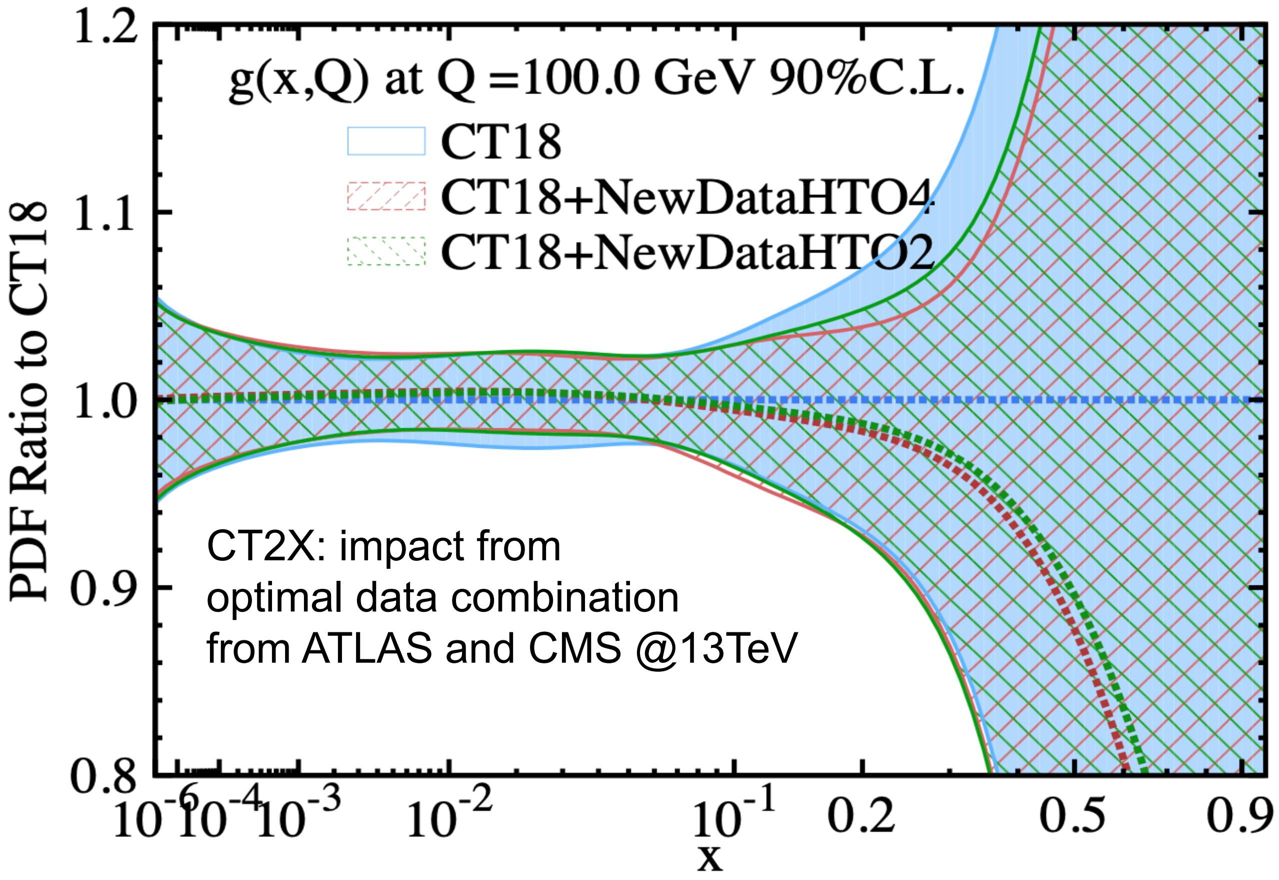
CT2X = CT18 + new optimal combination of top-quark pair production @LHC13 TeV from:

- ATLAS all hadronic, JHEP 01 (2021) 033, arXiv:2006.09274
- ATLAS lepton + jets, EPJC 79 (2019) 1028, arXiv:1908.07305
- CMS dilepton, JHEP 1902 (2019) 149, arXiv:1811.06625
- CMS lepton + jets, PRD 104 092013 (2021), arXiv:2108.02803

Correlated Systematic Uncertainties: **ATLAS -> nuisance parameters**
CMS -> Covariance matrix representation (converted to nuisance param.)

When statistical correlations not provided ➡ data added one at a time on top of the CT18 baseline

Scale choices in $t\bar{t}$ CT2X global analysis



Theory predictions:

- MATRIX (Catani, Grazzini et al. PRD 2019)
- FastNNLO (Czakon, et al. 1704.08551)

Blue band: CT18NNLO 90% C.L.

Hatched: CT18 + $t\bar{t}$ data

Green: $\mu_R = \mu_F = H_T/2$

Red: $\mu_R = \mu_F = H_T/4$

The scales giving the lowest χ^2 depend on the PDF set

Differences related to different scale choices are well within the CT18 PDF error band.

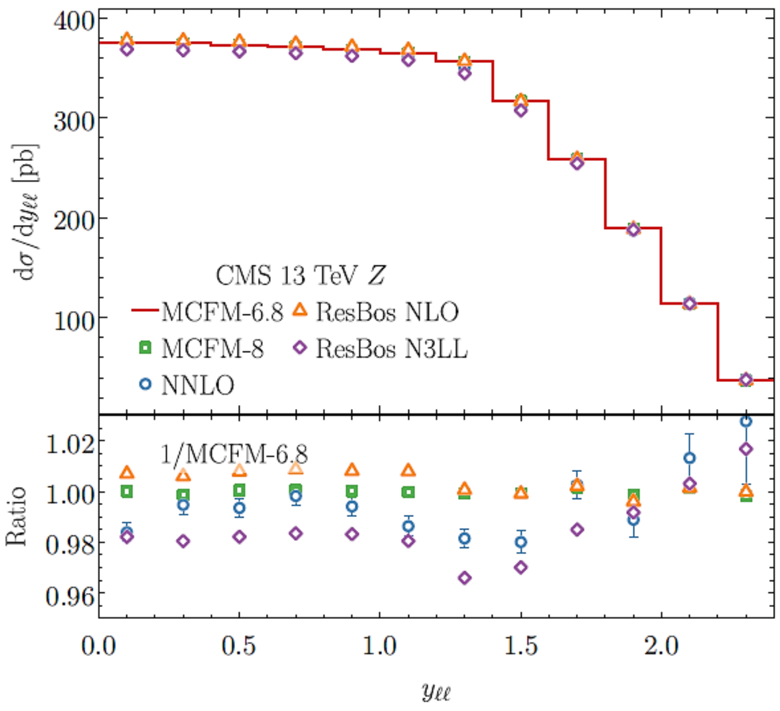
New post-CT18 LHC Drell-Yan data

K. Xie, WG3

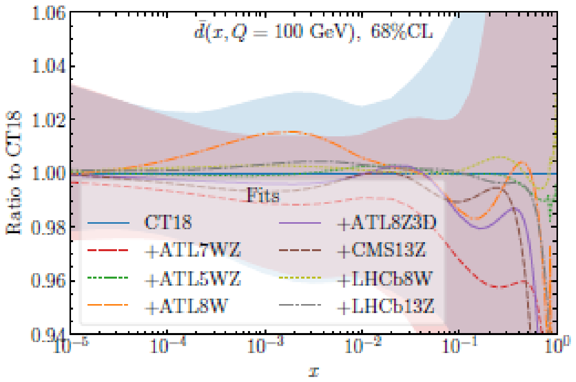
Boson	$\sqrt{s}$	Lumi	Observable	Ref.
ATLAS				
W, Z	2.76	4.0 pb^{-1}	$\sigma^{\text{fid,tot}}$	1907.03567
W, Z	13	81.0 pb^{-1}	σ^{fid}	1603.09222
W, Z	5.02	25.0 pb^{-1}	$(\eta_\ell, y_{\ell\ell})$	1810.08424
Z	8	20.2 fb^{-1}	$(m_{\ell\ell}, y_{\ell\ell})$	1710.05167
$W \to \mu\nu$	8	20.2 fb^{-1}	η_μ	1904.05631
Z	13	36.1 fb^{-1}	$p_T^{\ell\ell}$	1912.02844
CMS				
Z	13	2.8 fb^{-1}	$m_{\ell\ell}$	1812.10529
Z	13	35.9 fb^{-1}	(y, p_T, ϕ^*)	1909.04133
W	13	35.9 fb^{-1}	σ^{fid}, $y_W, (\eta_\ell, p_T^\ell)$	2008.04174
LHCb				
$W \to e\nu$	8	2.0 fb^{-1}	η_e	1608.01484
Z	13	294 pb^{-1}	σ^{fid}, (y, p_T, ϕ^*)	1607.06495
$Z \to \mu\mu$	13	5.1 fb^{-1}	σ^{fid}, (y, p_T, ϕ^*)	2112.07458

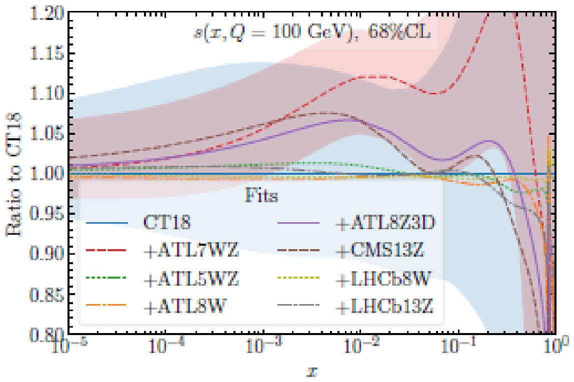
We mainly focus on (pseudo)rapidity distributions in this work.

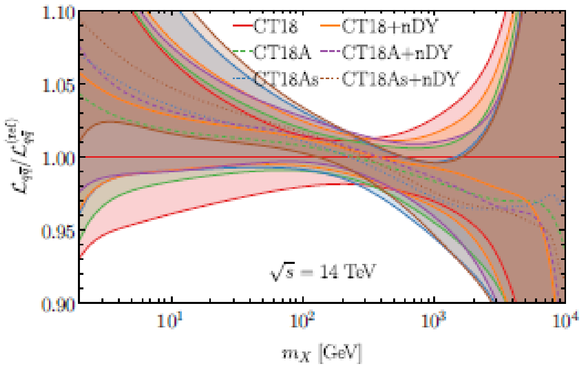
Multiple candidate fits to explore the impact of 8 and 13 TeV Drell-Yan data using NNLO and resummed N3LL-NNLO cross sections

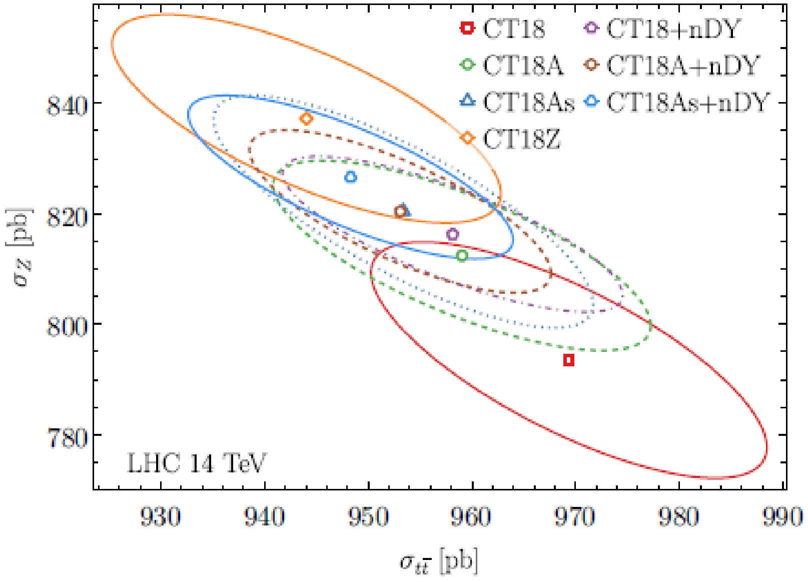


Post-CT18 LHC Drell-Yan data [See K. Xie's talk for the details.]



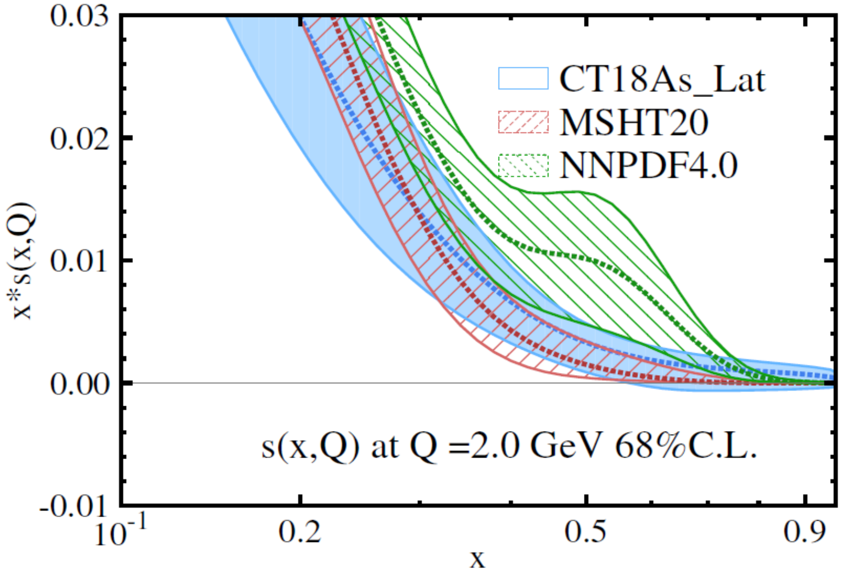






- Most of the post-CT18 LHC Drell-Yan data are consistent with the ATLAS 7 TeV W, Z precision measurement, which enhance the strangeness (CT18A).
- Exceptions for ATLAS and LHCb 8 TeV W data, which push the $d(\bar{d})$ PDFs to the opposite direction.
- The post-CT18 LHC Drell-Yan data shrink the error bands.
- The joint impact of these new data sets pull the PDFs and predictions from CT18 to CT18Z direction.

CT18As_Lat NNLO: Strangeness asymmetry with a lattice QCD constraint

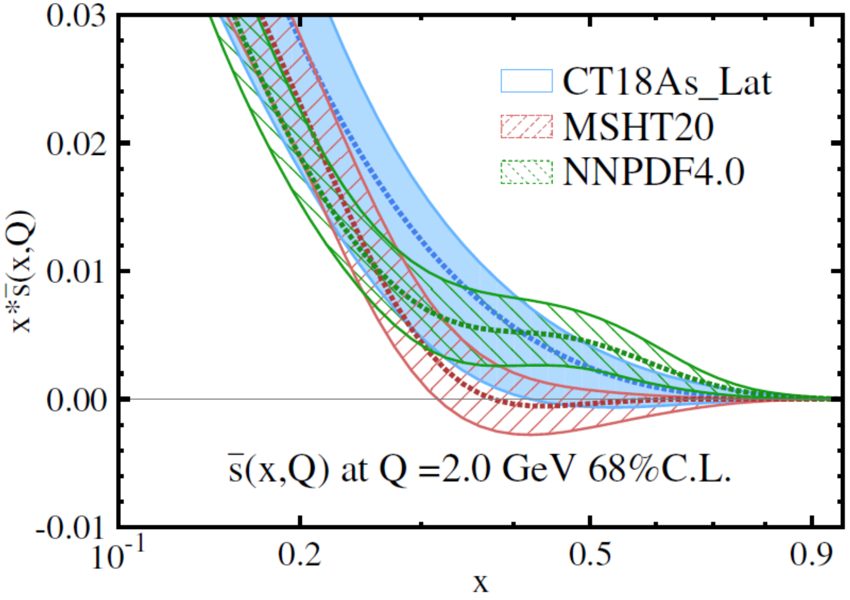


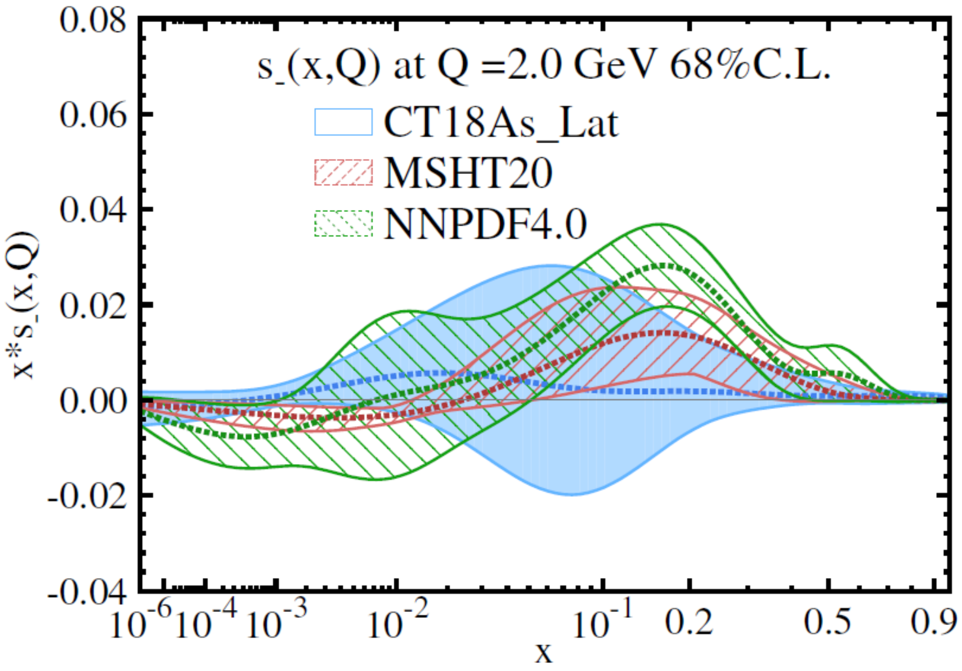
T.-J. Hou et al., arXiv: 2211.11064

CT18As: CT18A with $s\_ \equiv s - \bar{s} \neq 0$

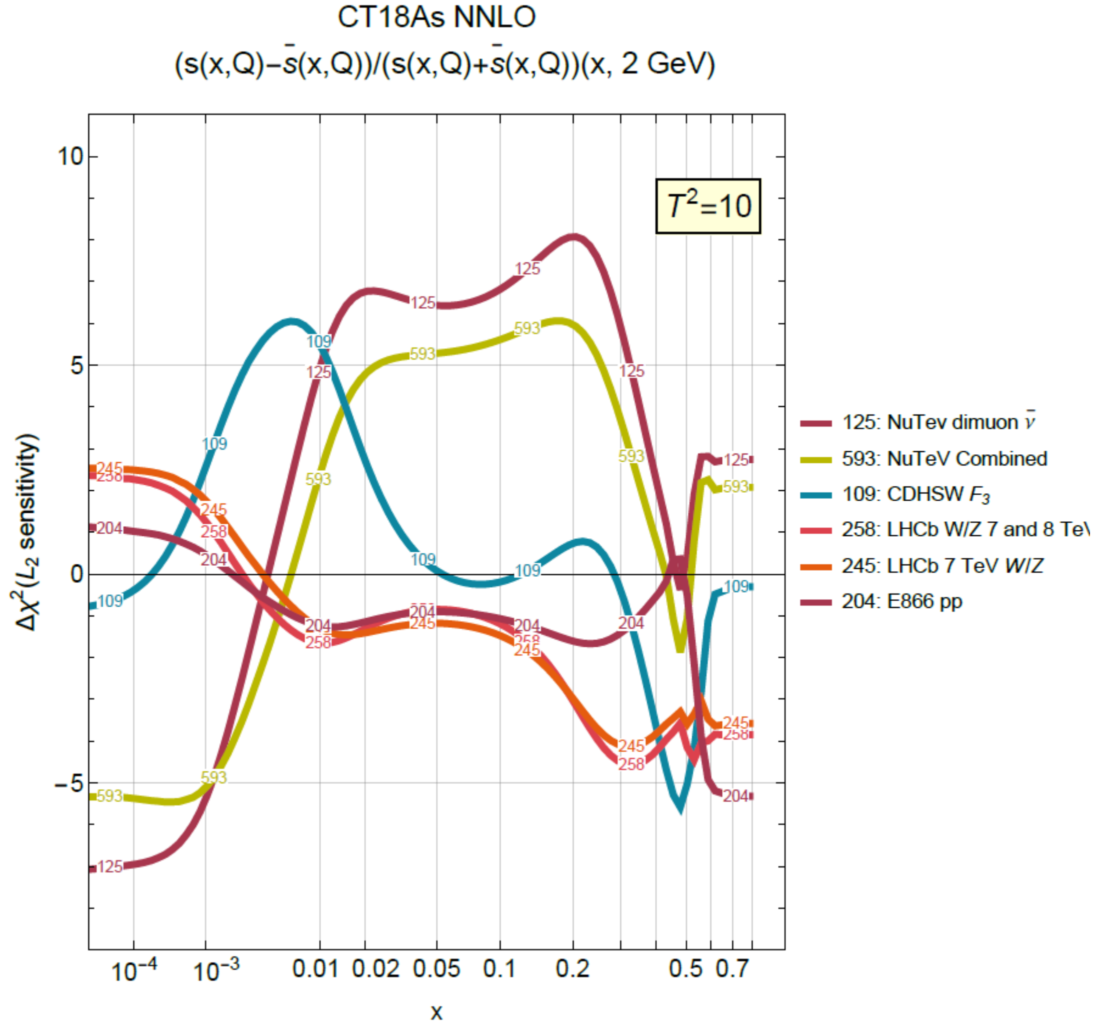
CT18As_Lat: CT18As with a lattice constraint on $s\_(x)$ at $0.3 \leq x \leq 0.8$.

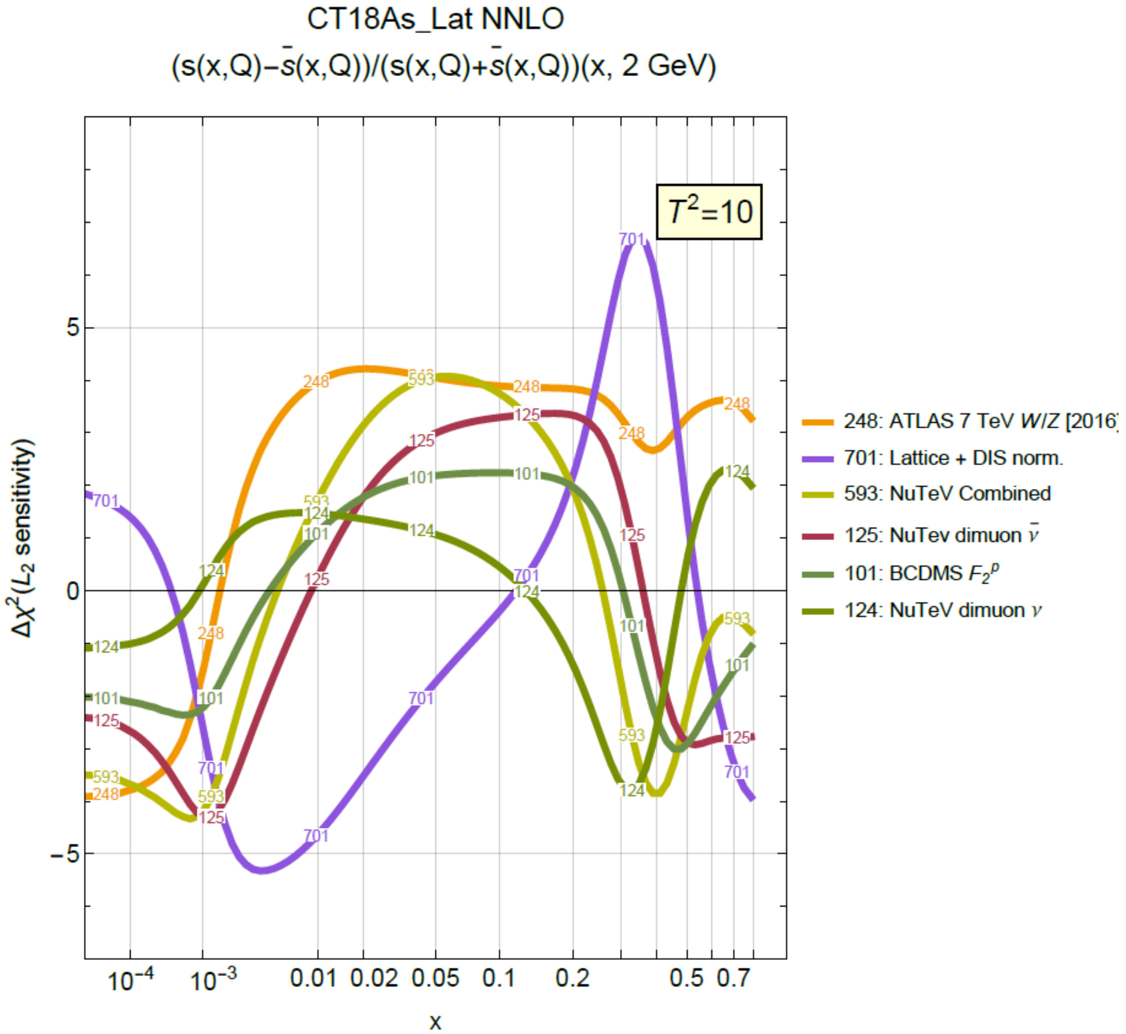
$$\int_0^1 s\_(x)dx = 0$$





Sensitivity of experiments to the strangeness asymmetry





Preference for $s - \bar{s} \neq 0$ at $x > 0.1$ emerges from competing χ^2 pulls of NuTeV dimuon, LHCb W/Z, BCDMS and E866 fixed-target cross sections. We estimated it using the L_2 sensitivity fast technique *[T. Hobbs et al., arXiv:1904.00022]*. The lattice prediction by *R. Zhang et al., 2005.01124* is consistent with $s - \bar{s} = 0$ at $x > 0.3$.

New CT18 Fitted Charm analysis

T. Hobbs, WG1

moments of the FC PDFs often used to characterize magnitude, asymmetry

$$\langle x^n \rangle_{c^\pm} = \int_0^1 dx\, x^n (c \pm \bar{c})[x, Q]$$

$$\langle x \rangle_{\rm FC} \equiv \langle x \rangle_{c^+}[Q_0 = 1.27\,{\rm GeV}]$$ ...at NNLO.

$$= 0.0048\,^{+0.0063}_{-0.0043}\,\left(^{+0.0090}_{-0.0048}\right),\ \text{CT18 (BHPS3)}$$

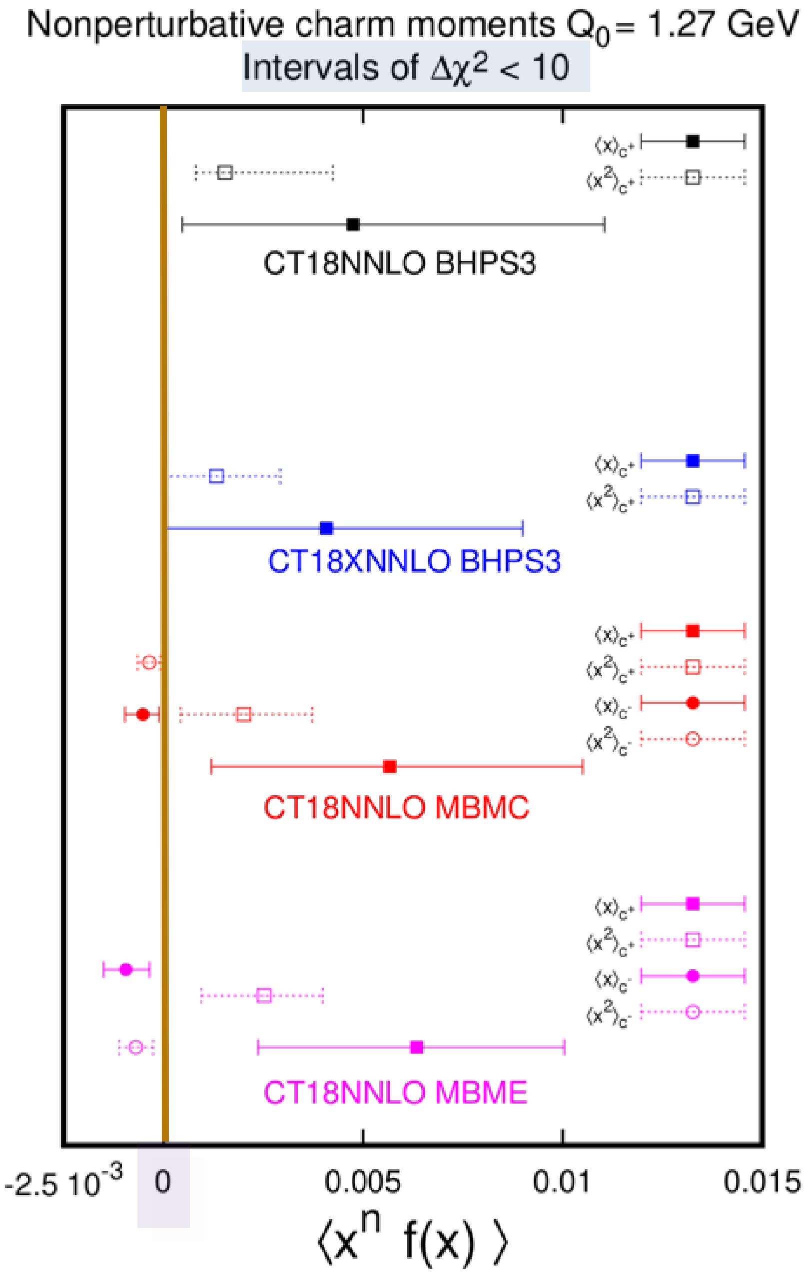
$$= 0.0041\,^{+0.0049}_{-0.0041}\,\left(^{+0.0091}_{-0.0041}\right),\ \text{CT18X (BHPS3)}$$

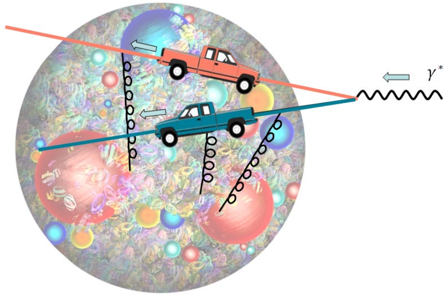
$$= 0.0057\,^{+0.0048}_{-0.0045}\,\left(^{+0.0084}_{-0.0057}\right),\ \text{CT18 (MBMC)}$$

$$= 0.0061\,^{+0.0030}_{-0.0038}\,\left(^{+0.0064}_{-0.0061}\right),\ \text{CT18 (MBME)}$$

$\Delta\chi^2 \leq 10$ (restrictive tolerance)

$\Delta\chi^2 \leq 30$ (~CT standard tolerance)



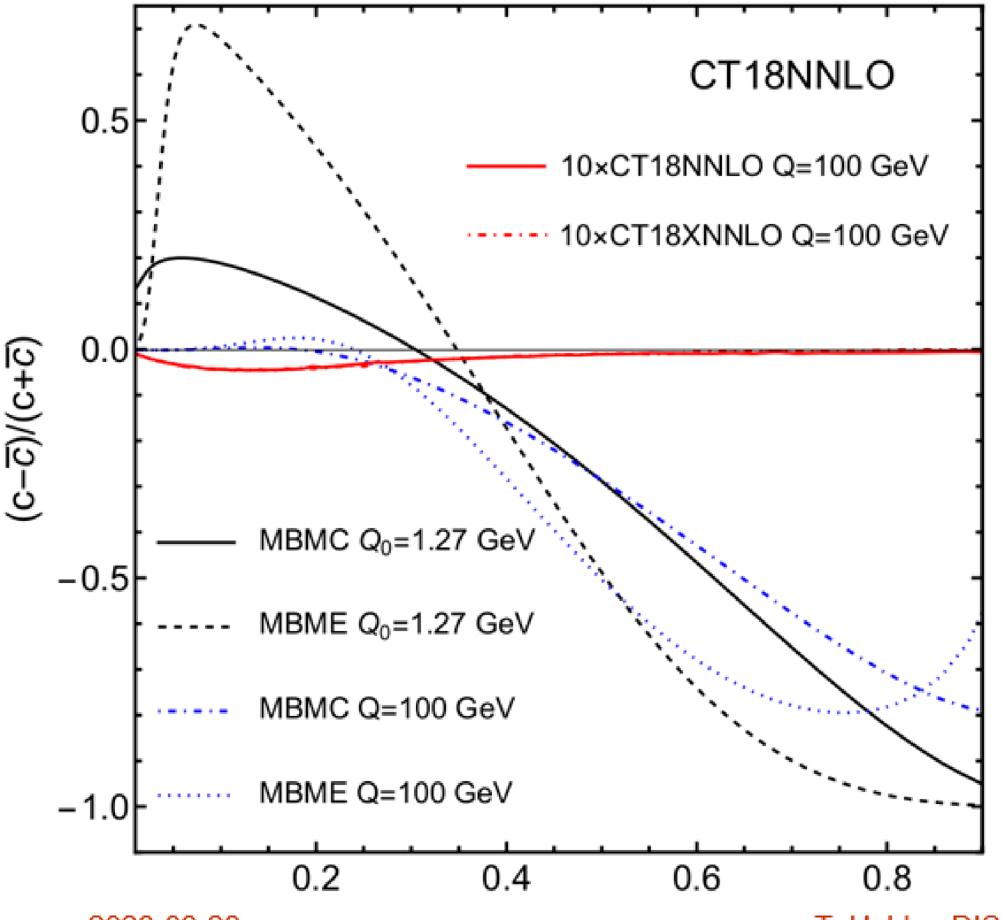


possible charm-anticharm asymmetries

pQCD only very weakly breaks $c = \bar{c}$ through HO corrections

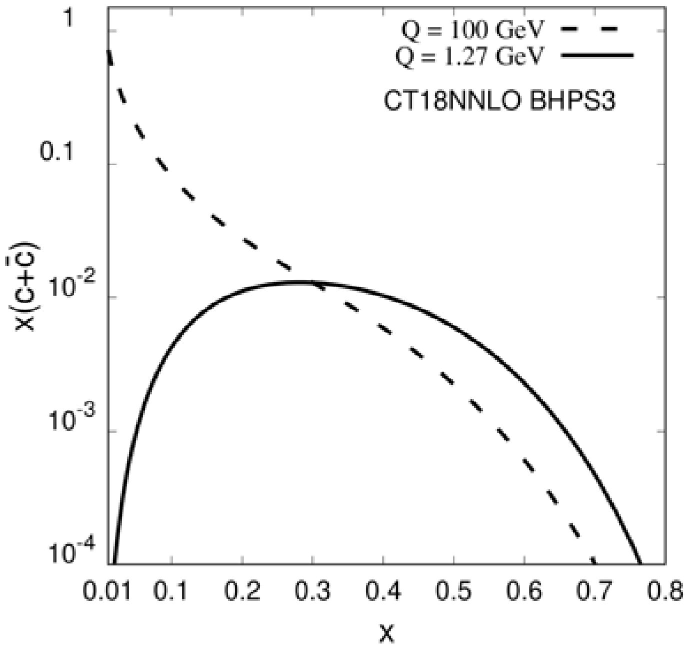
→ large(r) charm asymmetry would signal nonpert dynamics, IC

→ MBM breaks $c = \bar{c}$ through hadronic interactions



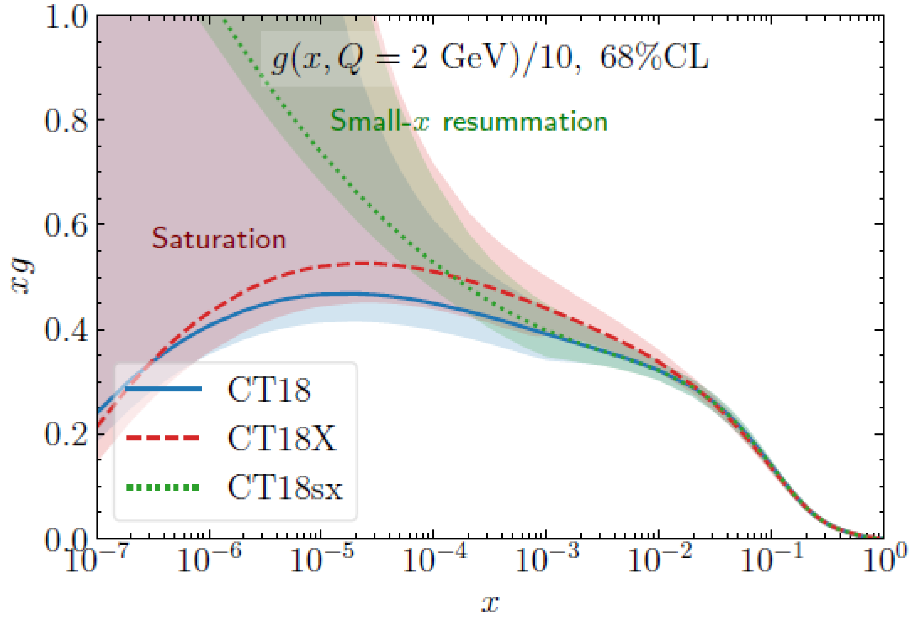
consider two MBM models as ***examples*** (not predictions)

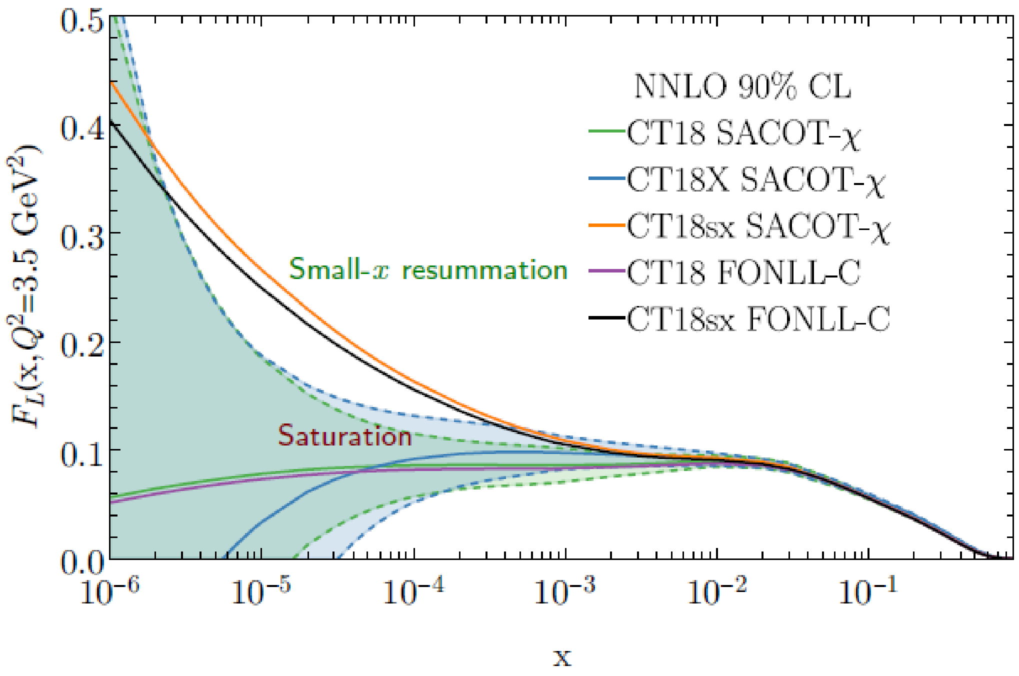
→ asym. small but ratio (left) can be bigger; will be hard to extract from data

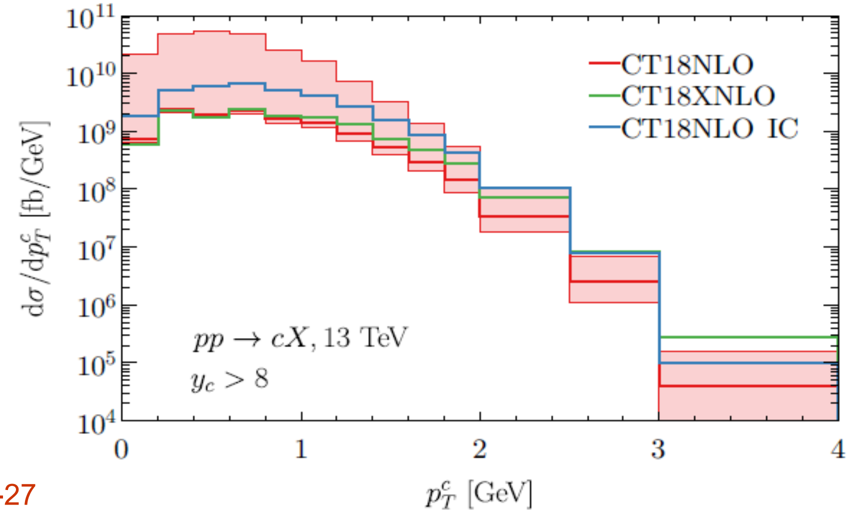


Small−x dynamics in CTEQ-TEA PDFs

K. Xie, WG2







- Both the BFKL resummation (CT18sx) and saturation (CT18X) models improve the description of HERA DIS data, which enhances gluon PDF at small x and low Q^2.
- F_L at $x \to 0$ is enhanced (stays ≈ constant) with resummation (saturation) models.
- Forward charm production at CERN FPF gets large uncertainty from small-x dynamics.

CT18 NNLO high-energy neutrino DIS cross sections from 10^2 to 10^7 GeV

K. Xie et al., arXiv:2303.13607

D. Stump, WG3

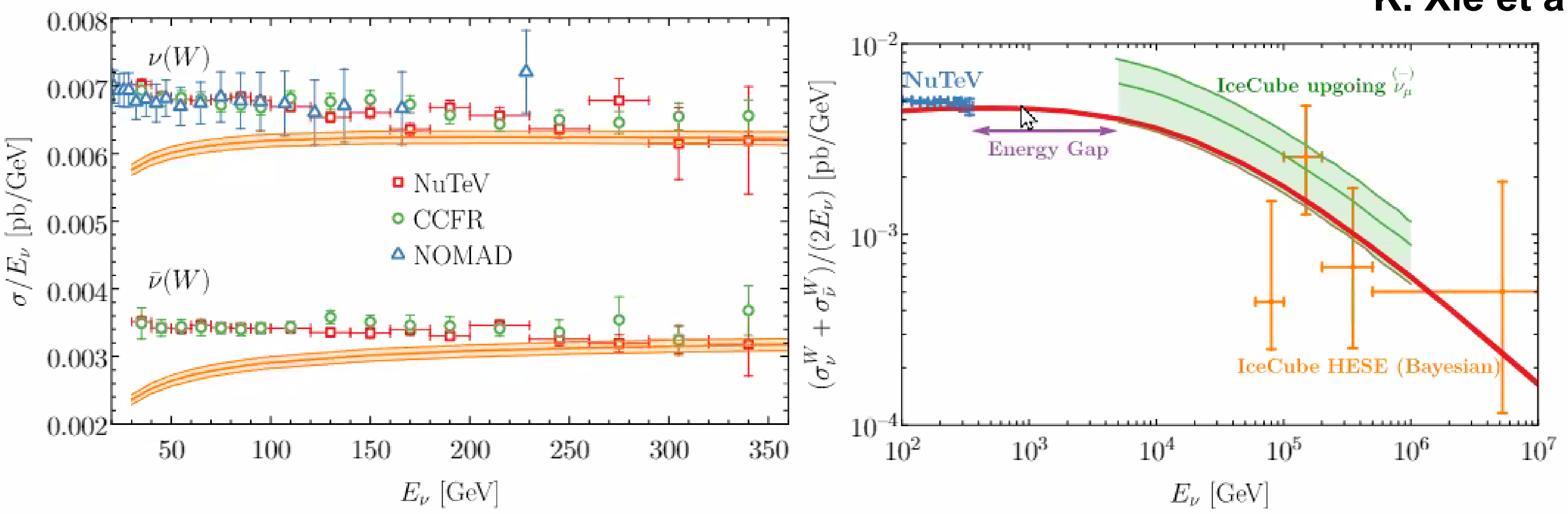


FIG. 20. Left: The CT18 predictions for the neutrino-isoscalar charged-current cross sections divided by the (anti)neutrino energy, σ/E_ν, in comparison with data measured at accelerator-based experiments [88–90]. Right: The CT18 prediction of the averaged neutrino-isoscalar charged-current cross sections divided by neutrino energy in the energy gap (360 GeV $\lesssim E_\nu \lesssim$ 6 TeV), which can be measured by the FASER and other FPFs at the LHC [15, 16]. We included cross sections below 360 GeV measured by NuTeV [88] and above 6.3 (60) TeV by IceCube upgoing $\overset{(-)}{\nu}_\mu$ [9] (HESE Bayesian [10]) analyzes.

CTEQ-TEA global analysis of SMEFT

T. Hobbs, WG3

[J. Gao, MS Gao, T. Hobbs, DY Liu, XM Shen, 2211.01094]

◆ In search for **new physics** at hadron colliders, one key problem is of the **degeneracy** of PDF variations and the new physics contributions.

↓ Described in the framework of **SMEFT**

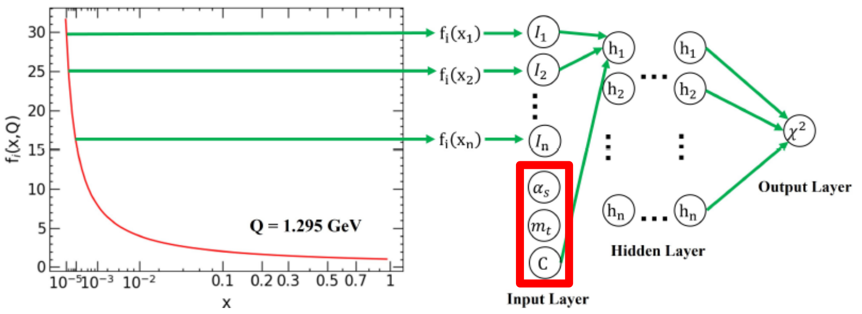
↓ **Joint fits** of PDFs and BSM parameters

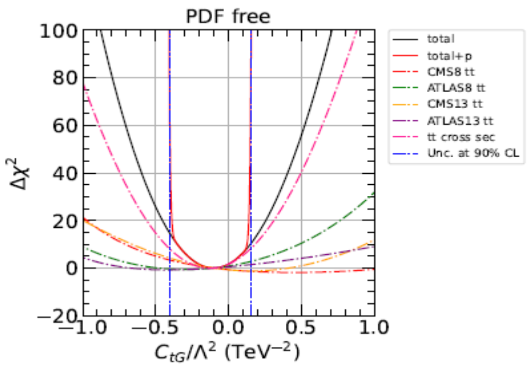
◆ We focus on several operators relevant for **top-quark pair (O^1_{tu}, O^1_{td}, O_{tG}, O^8_{tq})** and **jet production (O_1)** at hadron colliders.

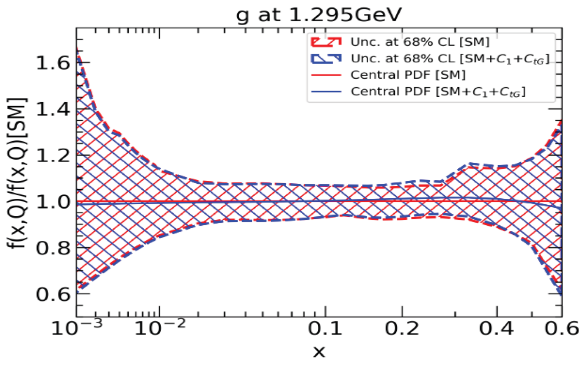
$$O^1_{tu} = \sum_{i=1}^{2} (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i), \quad O^1_{td} = \sum_{i=1}^{3} (\bar{t}^\mu t)(\bar{d}_i\gamma_\mu d_i), \quad O_1 = 2\pi(\textstyle\sum_{i=1}^{3}\bar{q}_{Li}\gamma_\mu q_{Li})(\sum_{j=1}^{3}\bar{q}_{Lj}\gamma^\mu q_{Lj})$$

$$O_{tG} = ig_s(\bar{Q}_{L,3}\tau^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} + \text{h.c.}, \quad O^8_{tq} = \sum_{i=1}^{2} (\bar{Q}_i\gamma_\mu T^A Q_i)(\bar{t}\gamma^\mu T^A t)$$

◆ We obtain self-consistent constraints on SMEFT with **Lagrange Multiplier** scans based on a **Neural Network** approach.

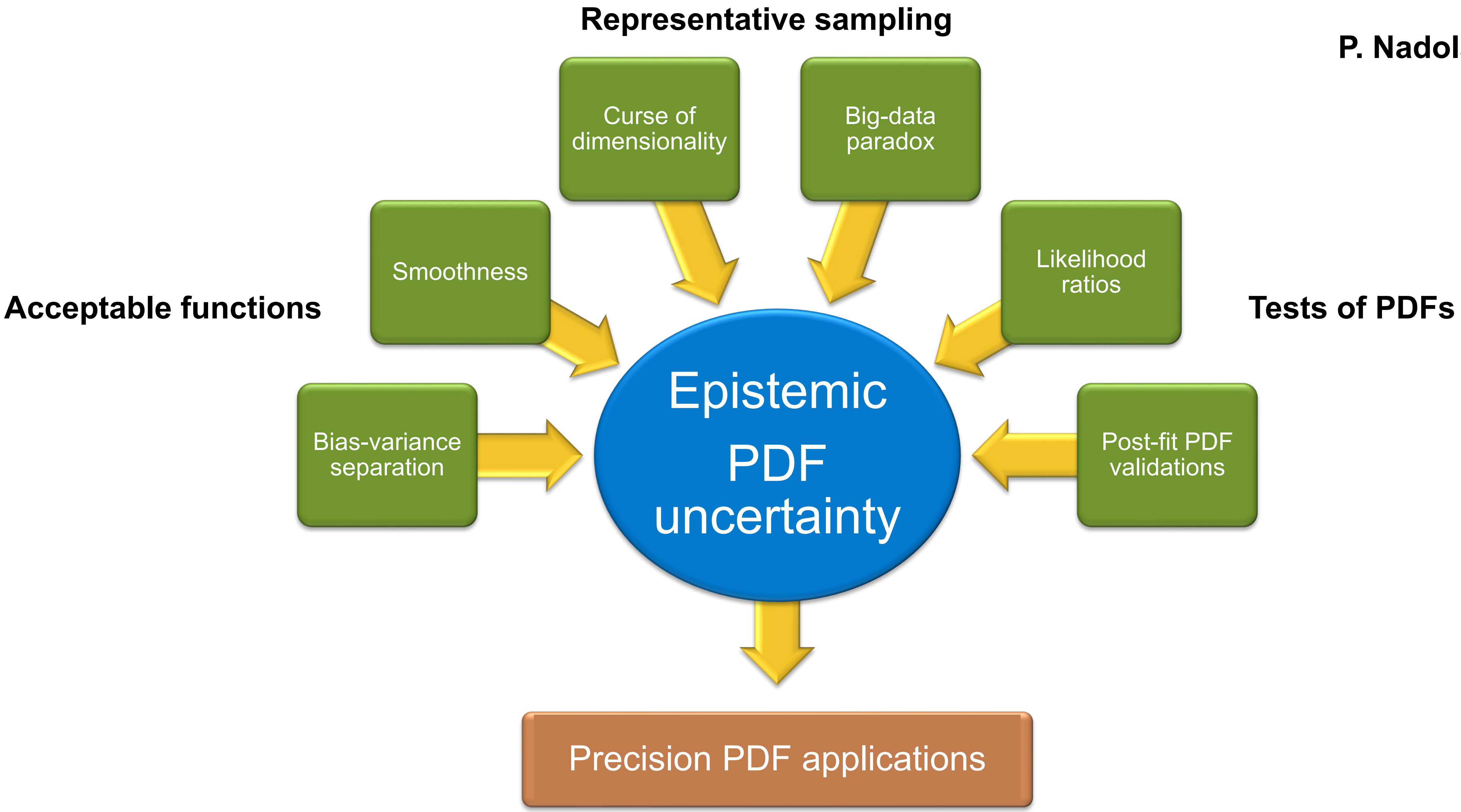






◆ We find mild correlations between the SMEFT Wilson coefficients, PDFs (e.g. the high-x gluon), and other QCD parameters.

P. Nadolsky, WG1



Epistemic PDF uncertainty is important in W boson mass and α_s measurements

ATLAS-CONF-2023-004

PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

Table 2: Overview of fitted values of the W boson mass for different PDF sets. The reported uncertainties are the total uncertainties.

ATLAS-CONF-2023-015

The statistical analysis for the determination of $\alpha_s(m_Z)$ is performed with the xFitter framework [60]. The value of $\alpha_s(m_Z)$ is determined by minimising a χ^2 function which includes both the experimental uncertainties and the theoretical uncertainties arising from PDF variations:

$$\chi^2(\beta_{\rm exp},\beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,\rm exp} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,\rm th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\rm exp}^2 + \sum_k \beta_{k,\rm th}^2 . \qquad (1)$$

profiling of CT and MSHT PDFs requires to include a tolerance factor $T^2 > 10$ as in the ePump code

[T.J. Hou et al., 1912.10053, Appendix F]

Collaborations with other groups

Snowmass'21 whitepaper:
Proton structrure at the precision frontier

S. Amoroso et al., Acta Physica Polonica B 53 (2022) 12, A1

A summary of recent trends in the global analysis of proton PDFs

1. Status of modern NNLO PDFs and their applications
2. Future experiments to constrain PDFs
3. Theory of PDF analysis at N2LO and N3LO
4. New methodological advancements
   - Experimental systematic uncertainties in PDF fits
   - Theoretical uncertainties in PDF fits
   - Machine learning/AI connections
5. Delivery of PDFs; PDF ensemble correlations in critical applications
6. PDFs and QCD coupling strength on the lattice
7. Nuclear, meson, transverse-momentum dependent PDFs
8. Public PDF fitting codes
9. Fast (N)NLO interfaces
10. PDF4LHC21 recommendation and PDF4LHC21 PDFs for the LHC analyses

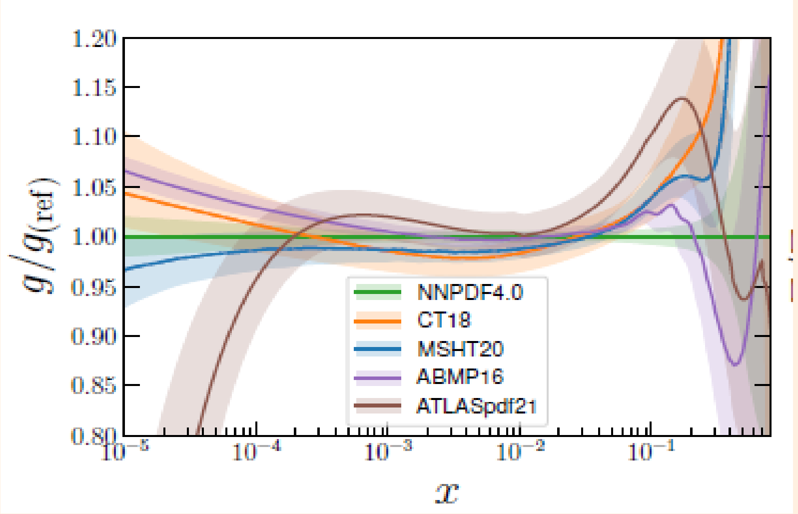
Progress in PDF analysis

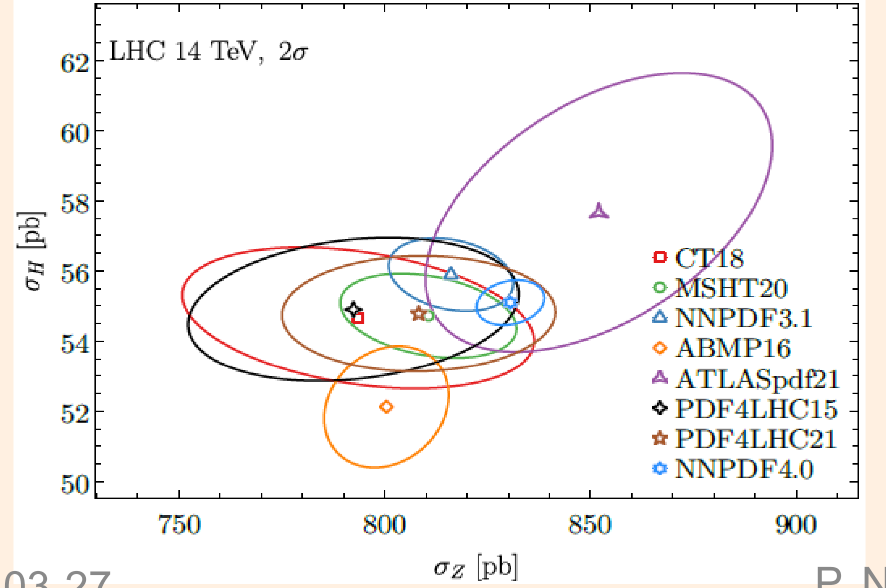
Snowmass 2021 whitepaper: Proton structure at the precision frontier

S. Amoroso et al., Acta Physica Polonica B 53 (2022) 12, A1

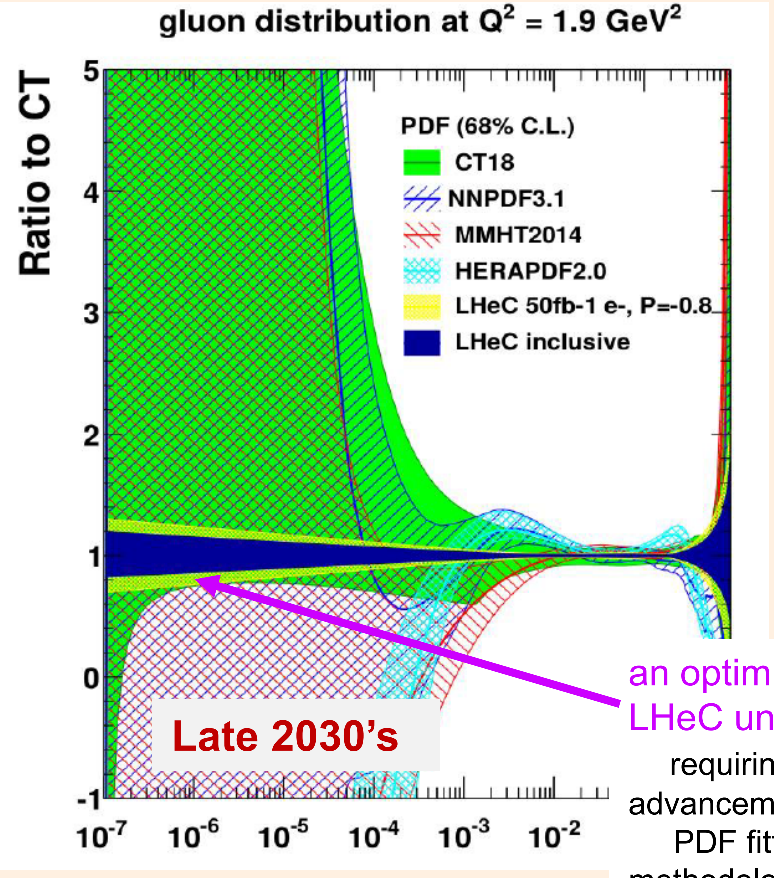
The current status

2022





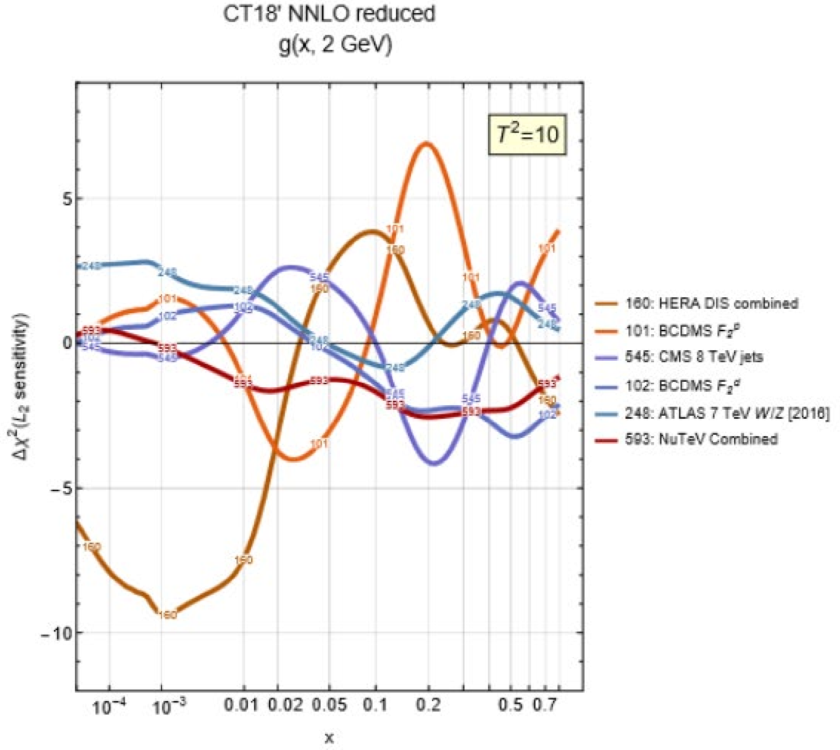
…and future prospects

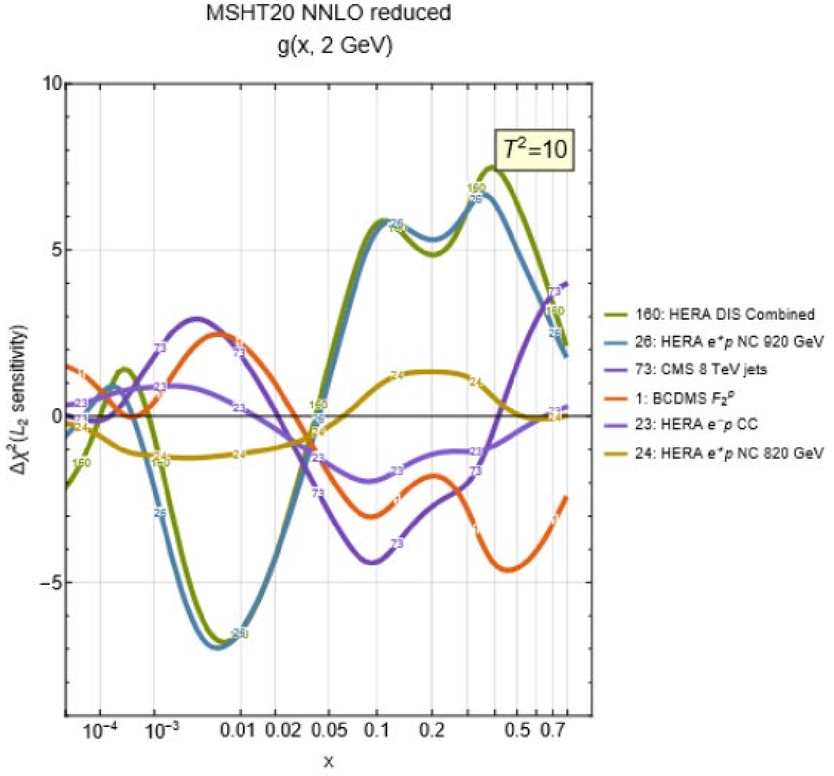


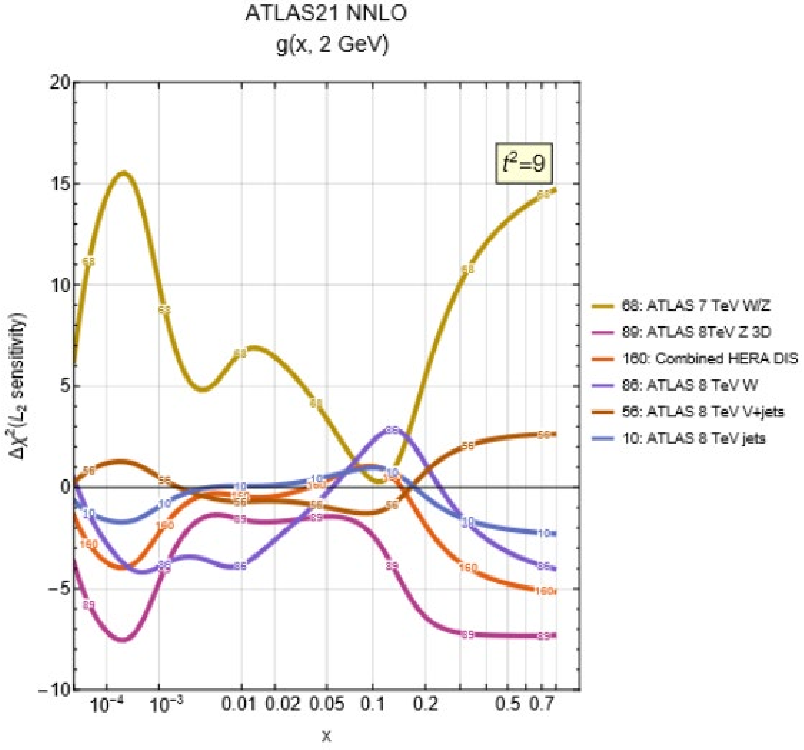
an optimistic post-LHeC uncertainty, requiring all advancements in the PDF fitting methodology

An ATLAS, CTEQ-TEA, and MSHT comparative study of NNLO PDF sensitivities

Preview







- Comparisons of strengths of constraints from individual data sets in 8 PDF analyses using the common L_2 sensitivity metric
- An interactive website to plot such comparisons [2070 figures in total]

CTEQ-TEA presentations at DIS’2023

Toward a new generation of CT202X PDFs

1. Impact of Drell-Yan data on post-CT18 global fits	**Keping Xie**	**WG3**
2. Constraints from $t\bar{t}$ production at LHC 13 TeV	**Marco Guzzi**	**WG1**
3. Epistemic uncertainty quantification in PDF fits	**P. Nadolsky**	**WG1**
4. CT18 NNLO fitted charm PDFs *[arXiv:2211.01387]*	**Tim Hobbs**	**WG1**
5. Prospects for using lattice-QCD constraints in the global PDF analysis	**T.-J. Hou**	**Plenary**
6. CTEQ-TEA NNLO predictions for high-energy neutrino cross sections	**Dan Stump**	**WG3**
7. Simultaneous CTEQ-TEA extraction of PDFs and SMEFT contributions	**Tim Hobbs**	**WG3**
8. Small-x dynamics in CTEQ-TEA fits and Forward Physics Facility	**Keping Xie**	**WG2**

Thank you for your attention!