Update from CTEQ-TEA and LHCb related

高俊 上海交通大学
CTEQ-TEA collaboration

第三届LHCb前沿物理研讨会

中国科学院大学，北京

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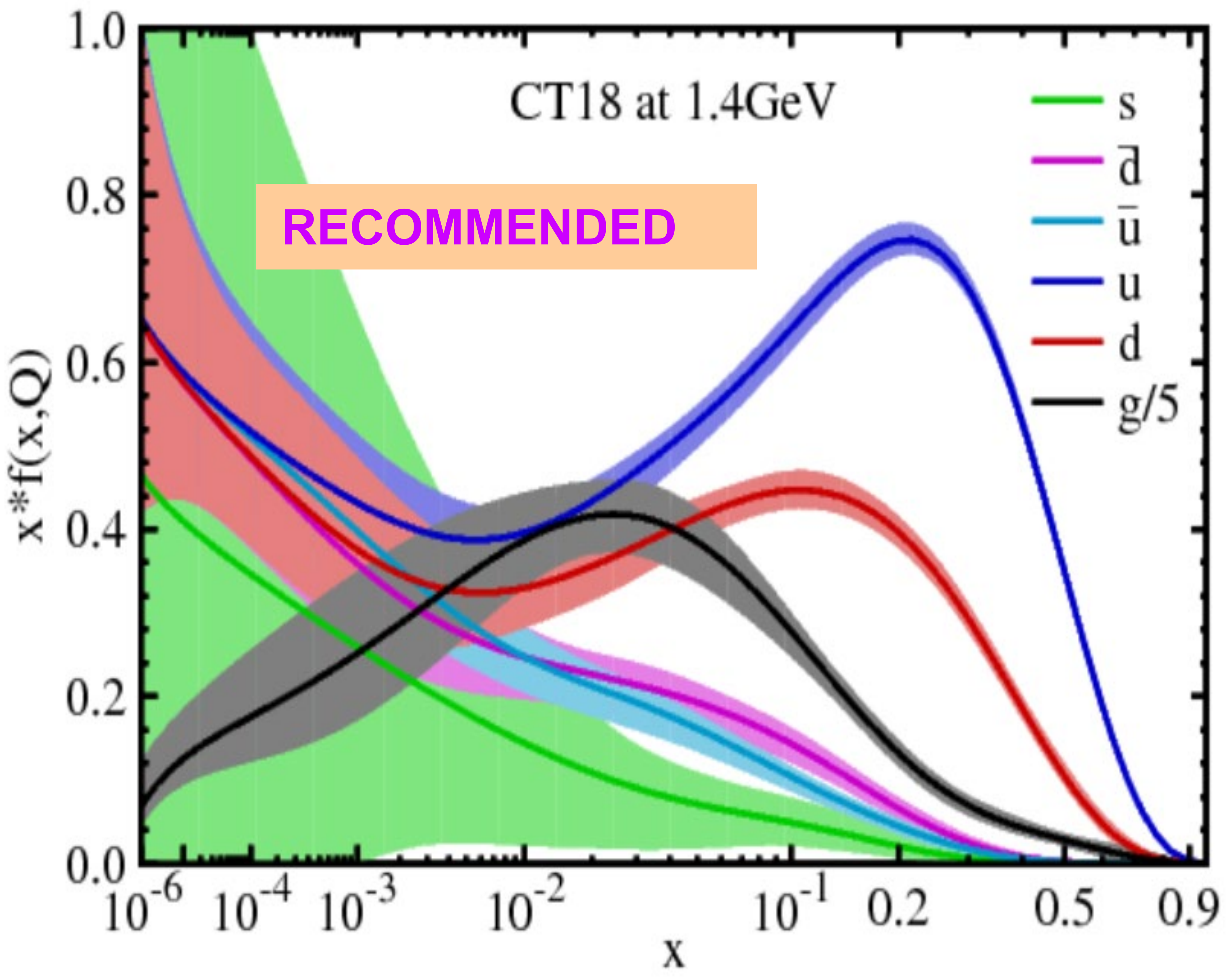
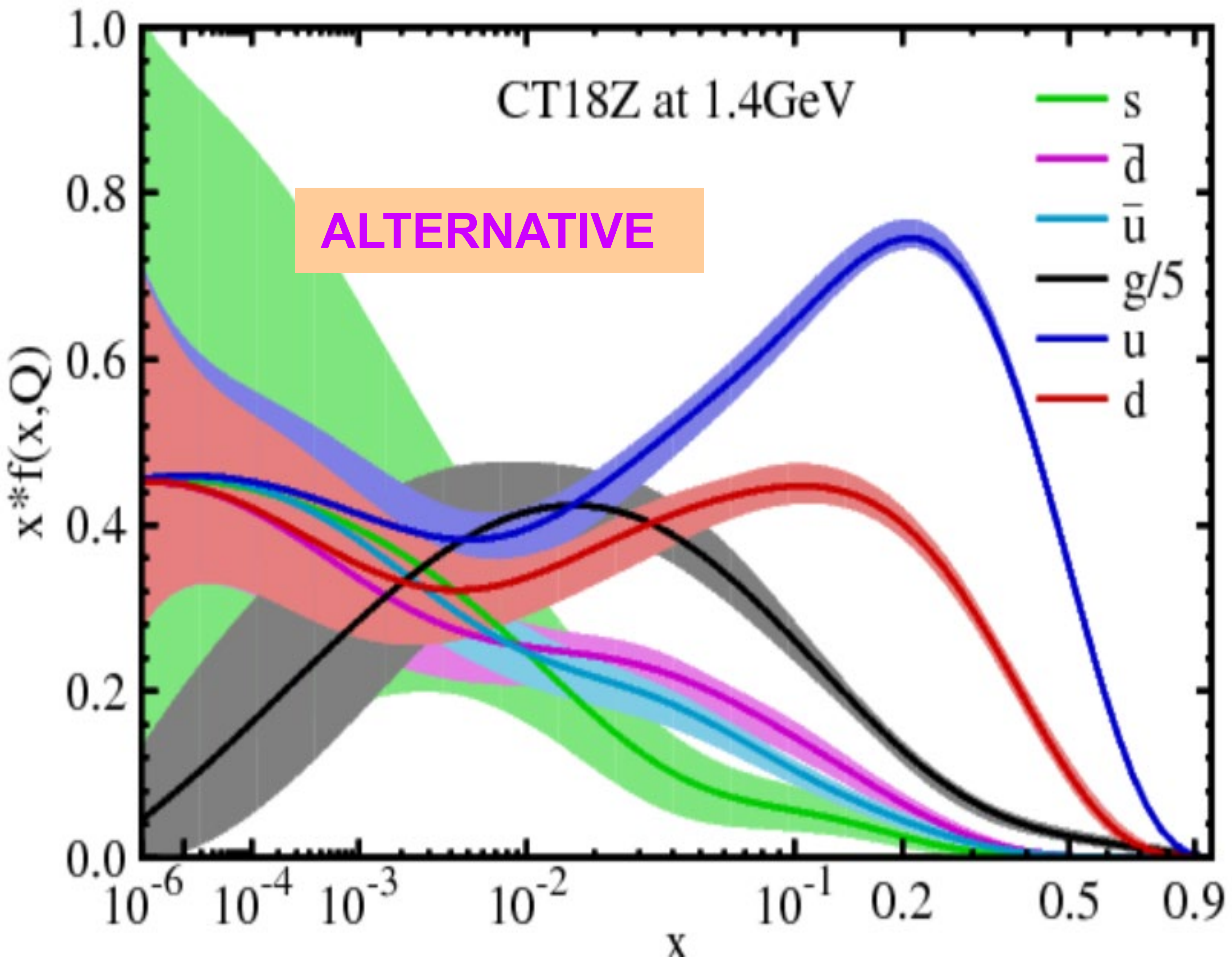
Overview

CT18 parton distributions

PRD 103 (2021) 014013

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



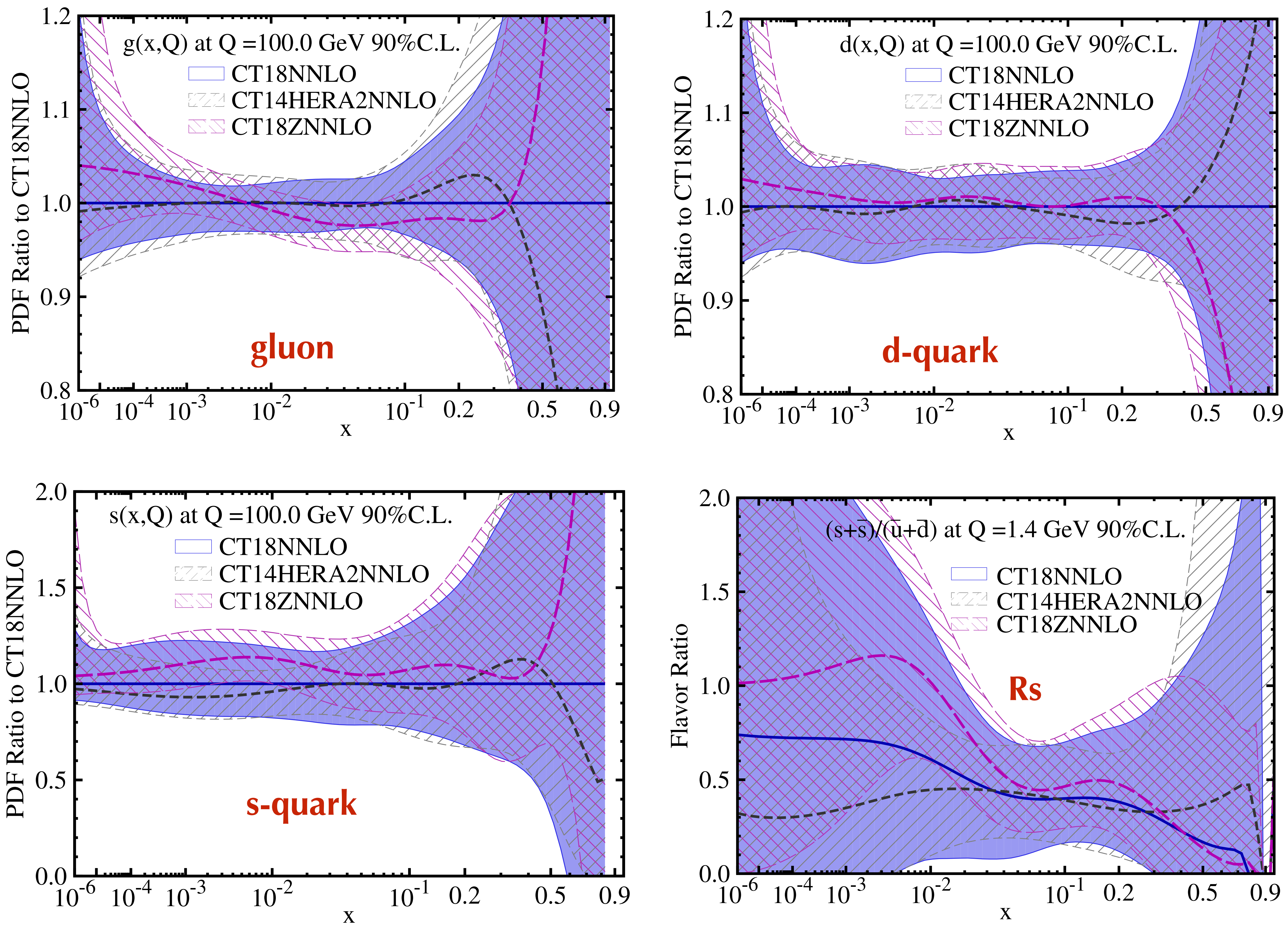


New CT18 NNLO grids **for precision calculations**

- **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

Overview

- CT18 PDFs show moderate reductions of PDF uncertainties due to new LHC data sets, and agree with previous CT14 within uncertainties; alternative fits CT18Z/A/X for evaluation of certain systematic effects

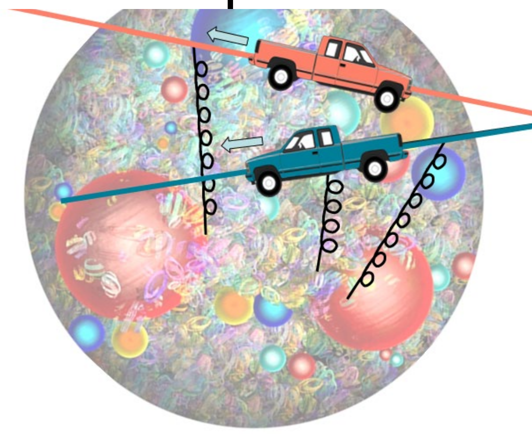


- CT18 vs CT14: gluon unc. reduced everywhere (jets, Z pT, top); d-quark unc. reduced at x~0.2 (LHCb W/Z); s-quark almost unchanged
- ATLAS 7 TeV W/Z data are not included in CT18 fit but in CT18A; CT18X uses a x-dependent scale in DIS to mimic small-x resummations
- CT18Z includes both variations, differences wrt. CT18 are most significant in s-quark and gluon/sea-quarks

[CT18, 1912.10053]

Overview

CTEQ-TEA presentations at DIS’2023



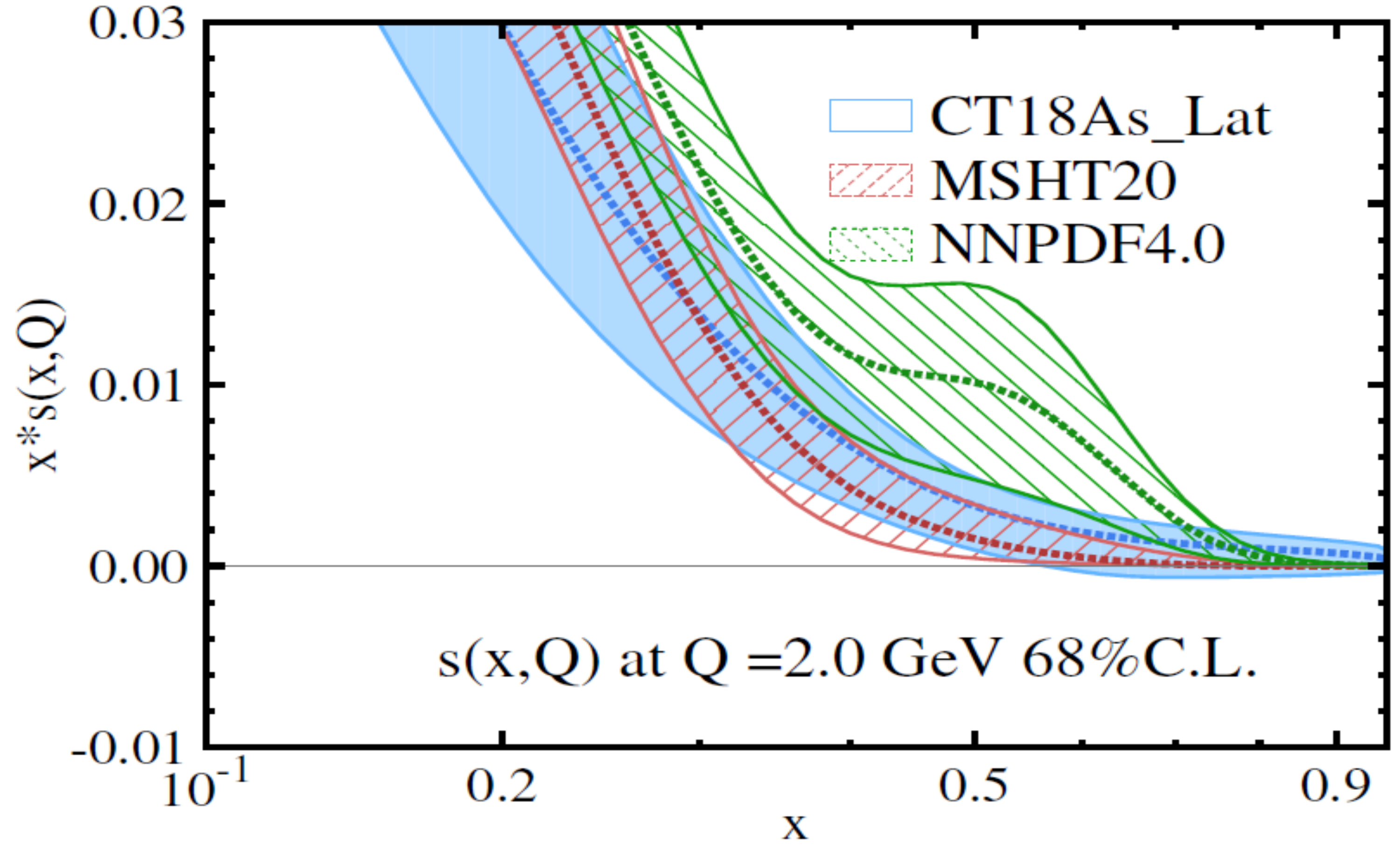
China: A. Ablat, S. Dulat, J. Gao, T.-J. Hou,
I. Sitiwaldi, M. Yan, and collaborators
Mexico: A. Courtoy
USA: T.J. Hobbs, M. Guzzi, X. Jing, P. Nadolsky
J. Huston, H.-W. Lin, D. Stump, C. Schmidt, K. Xie, C.-P. Yuan

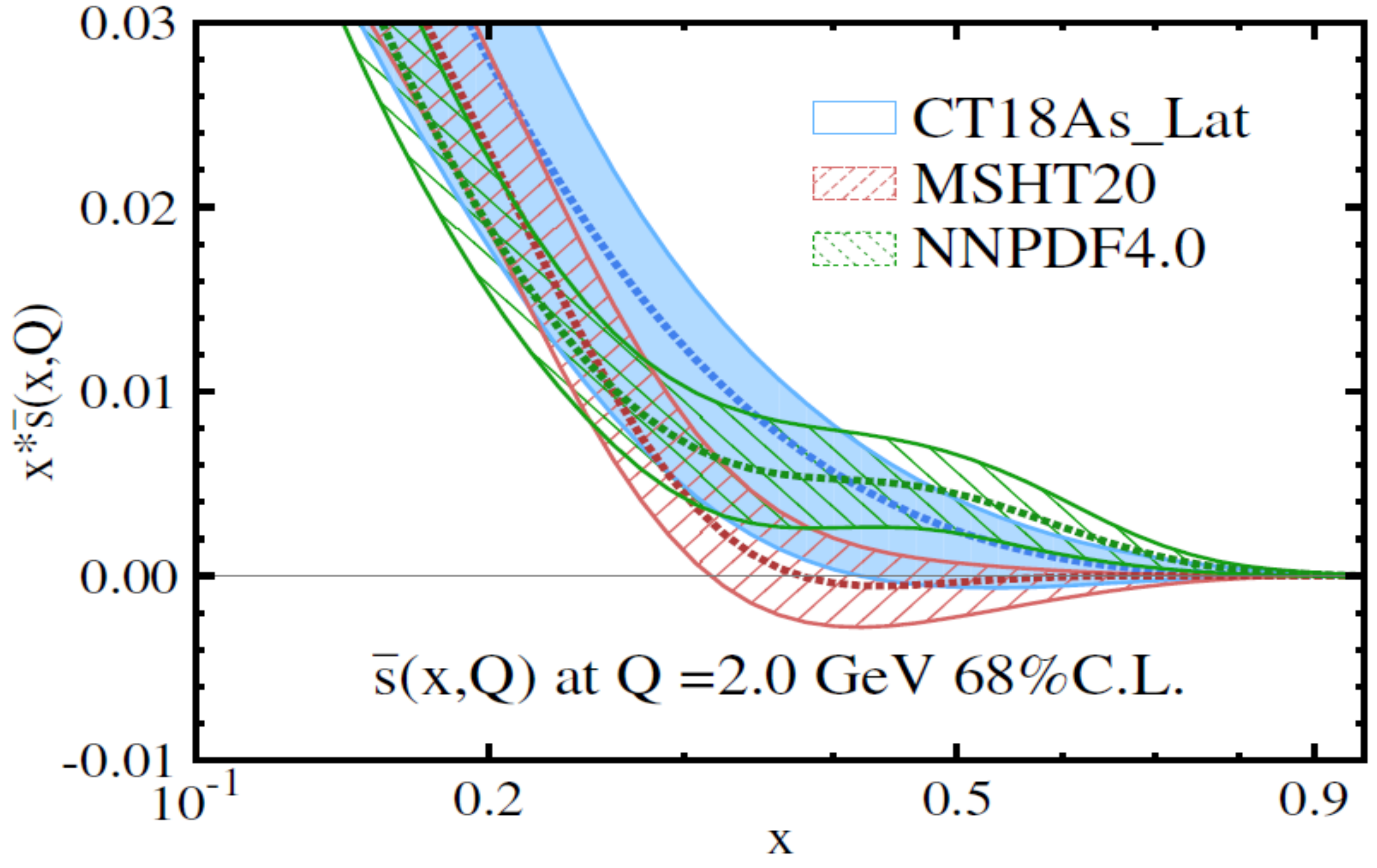
Toward a new generation of CT202X PDFs

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**

Overview

CT18As_Lat NNLO: Strangeness asymmetry with a lattice QCD constraint



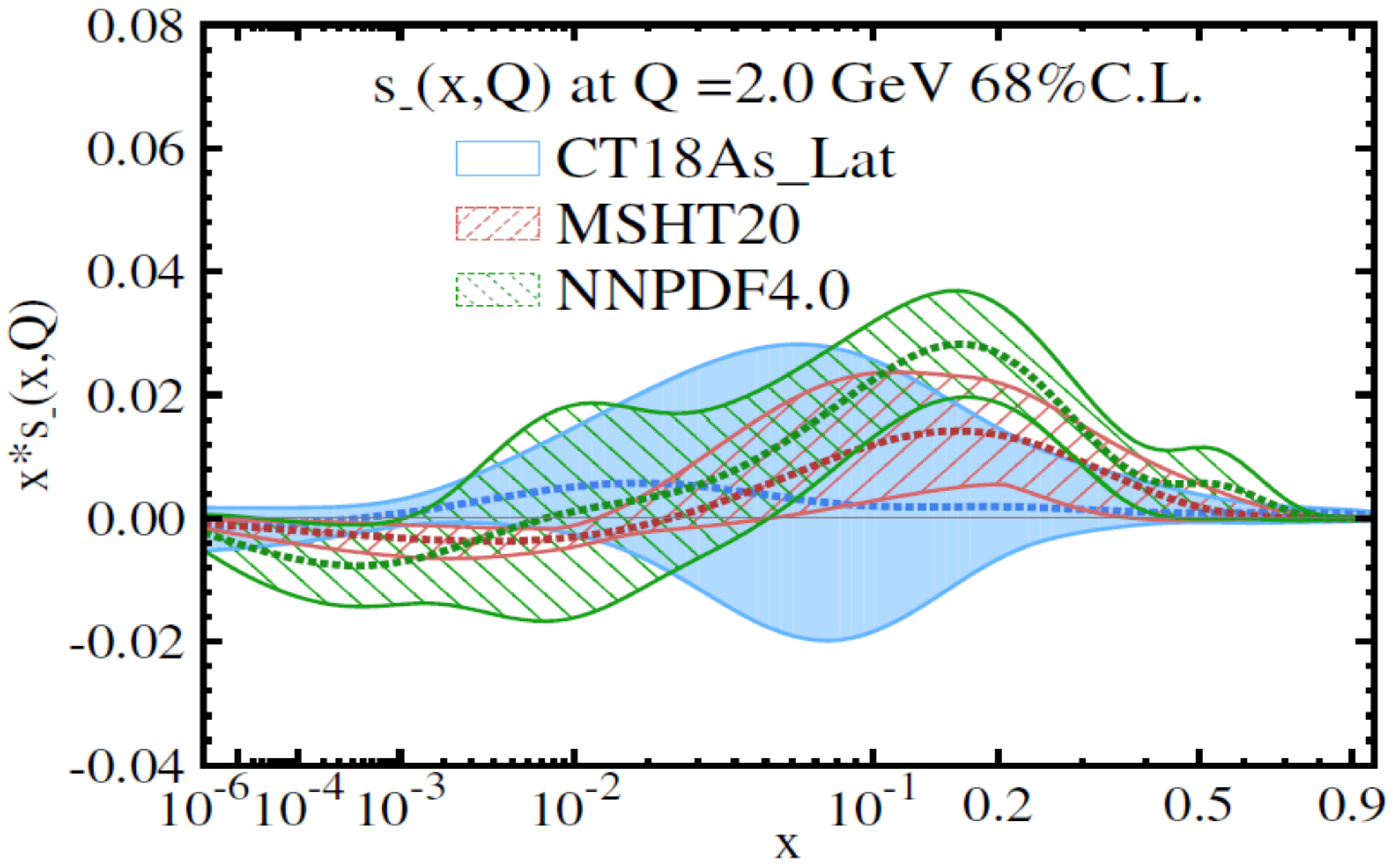


T.-J. Hou et al., arXiv: 2211.11064

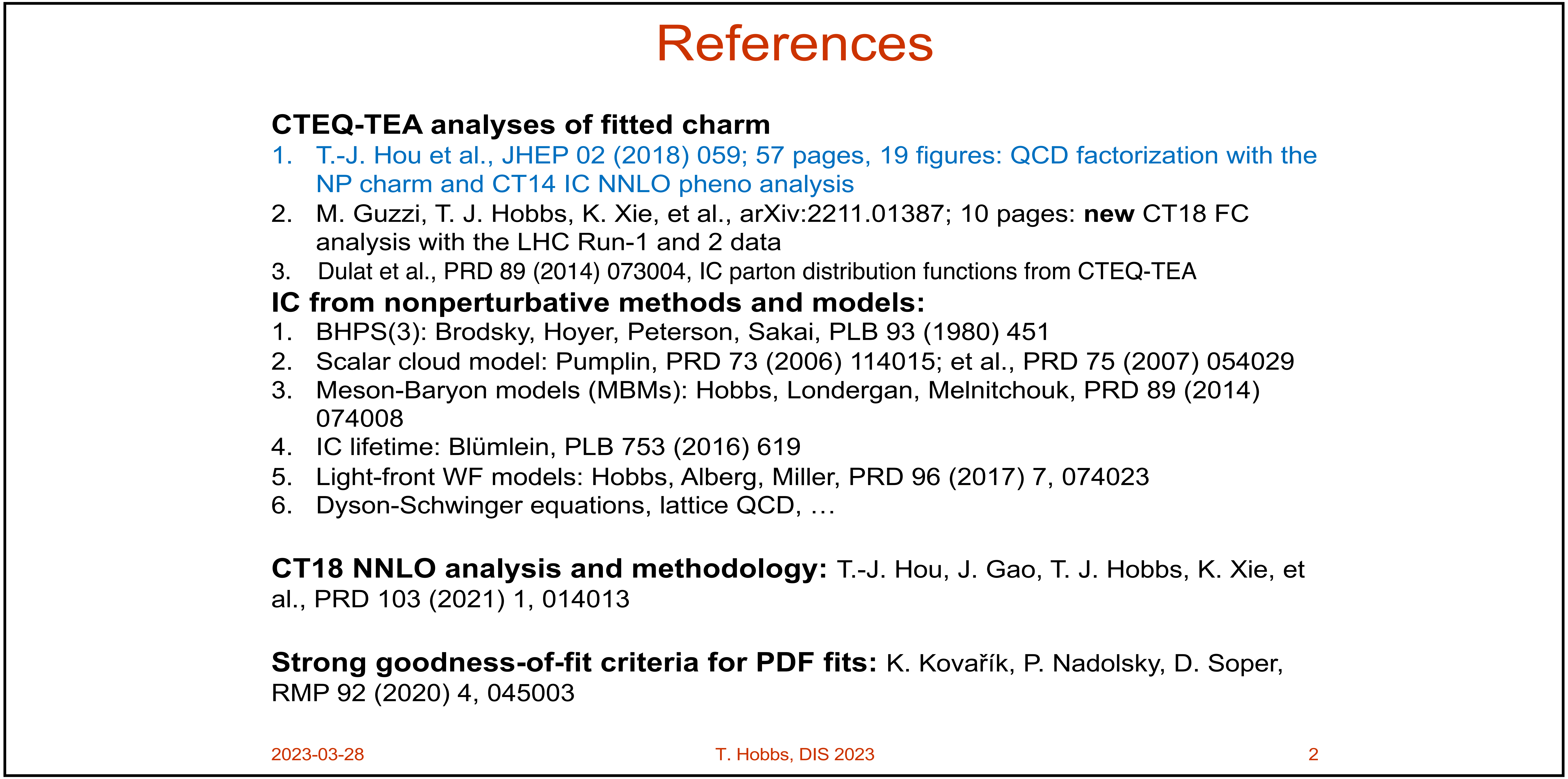
CT18As: CT18A with $s_{-} \equiv s - \bar{s} \neq 0$

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

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



Intrinsic Charm



References

CTEQ-TEA analyses of fitted charm

1. T.-J. Hou et al., JHEP 02 (2018) 059; 57 pages, 19 figures: QCD factorization with the NP charm and CT14 IC NNLO pheno analysis
2. M. Guzzi, T. J. Hobbs, K. Xie, et al., arXiv:2211.01387; 10 pages: **new** CT18 FC analysis with the LHC Run-1 and 2 data
3. Dulat et al., PRD 89 (2014) 073004, IC parton distribution functions from CTEQ-TEA

IC from nonperturbative methods and models:

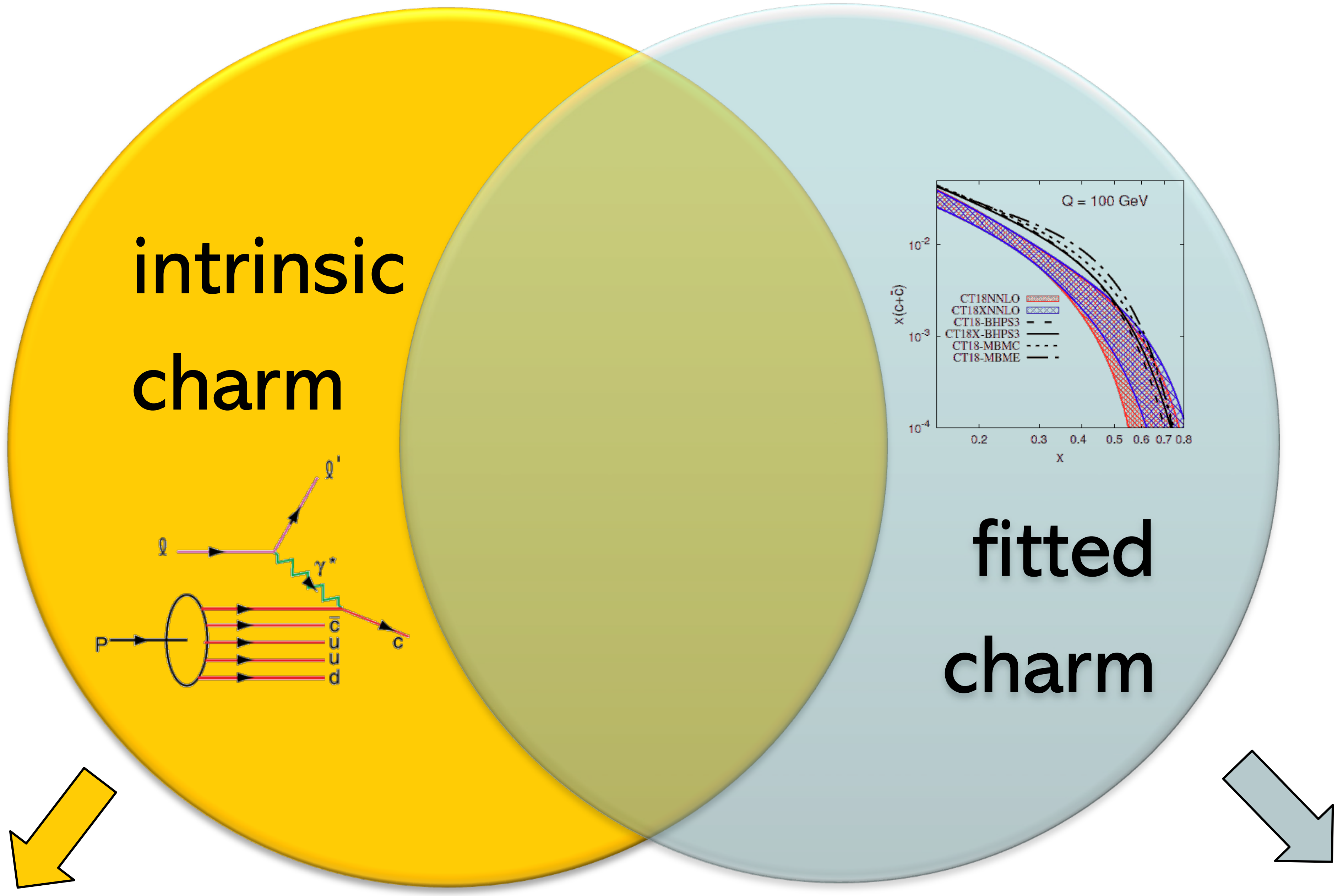
1. BHPS(3): Brodsky, Hoyer, Peterson, Sakai, PLB 93 (1980) 451
2. Scalar cloud model: Pumplin, PRD 73 (2006) 114015; et al., PRD 75 (2007) 054029
3. Meson-Baryon models (MBMs): Hobbs, Londergan, Melnitchouk, PRD 89 (2014) 074008
4. IC lifetime: Blümlein, PLB 753 (2016) 619
5. Light-front WF models: Hobbs, Alberg, Miller, PRD 96 (2017) 7, 074023
6. Dyson-Schwinger equations, lattice QCD, …

CT18 NNLO analysis and methodology: T.-J. Hou, J. Gao, T. J. Hobbs, K. Xie, et al., PRD 103 (2021) 1, 014013

Strong goodness-of-fit criteria for PDF fits: K. Kovařík, P. Nadolsky, D. Soper, RMP 92 (2020) 4, 045003

Intrinsic Charm

challenging to formulate a rigorous definition of intrinsic charm



intrinsic charm

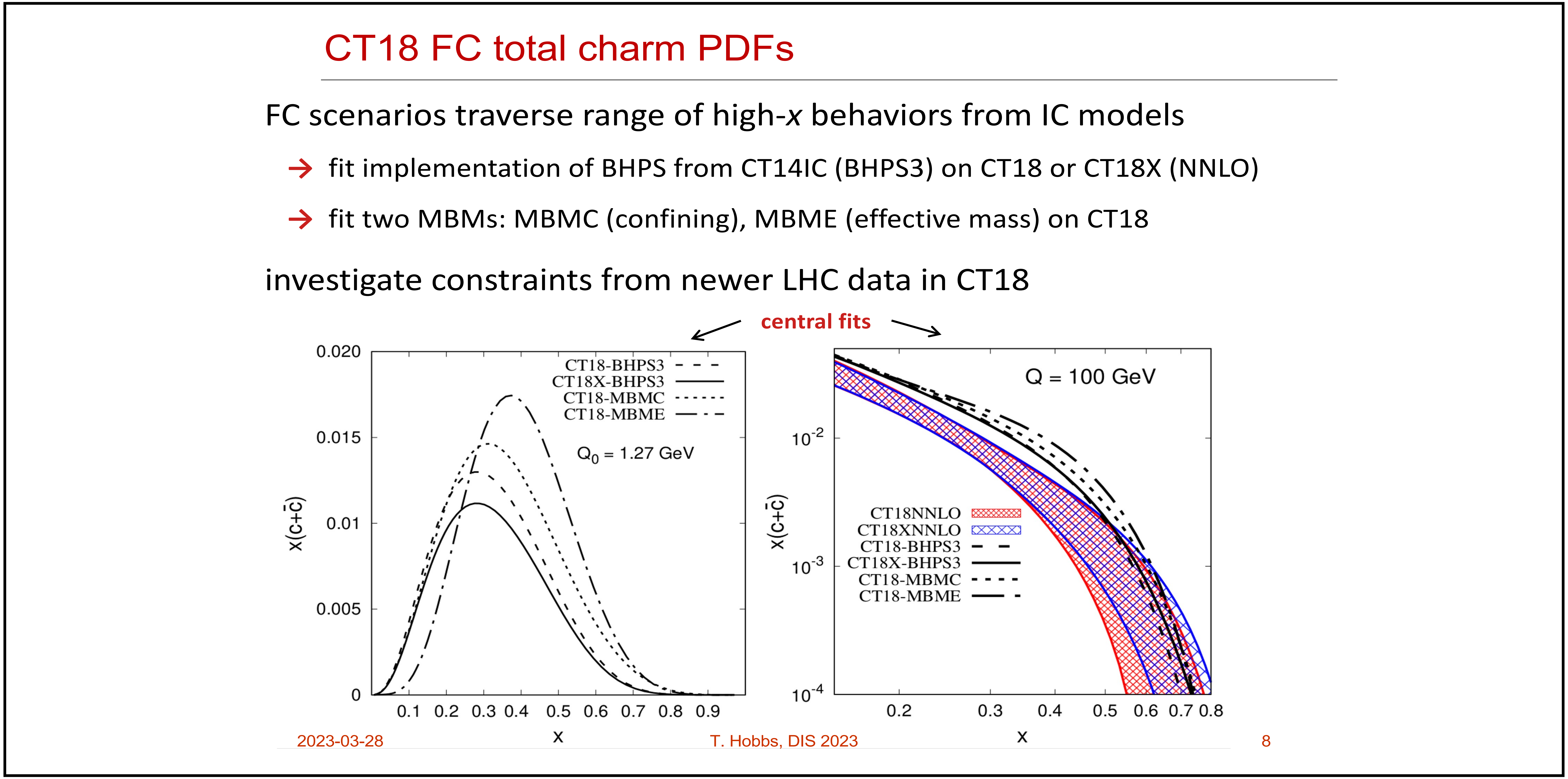
fitted charm

- The concept of nonperturbative methods
- Can refer to a component of the hadronic Fock state or the type of the hard process
- Predicts a typical enhancement of the charm PDF at $x \gtrsim 0.2$

Connection?

- A charm PDF parametrization at scale $Q_0 \approx 1$ GeV found by global fits [CT, NNPDF, …]
- Arises in perturbative QCD expansions over α_s and operator products
- May absorb process-dependent or unrelated radiative contributions

Fitted Charm



CT18 FC total charm PDFs

FC scenarios traverse range of high-*x* behaviors from IC models

- → fit implementation of BHPS from CT14IC (BHPS3) on CT18 or CT18X (NNLO)
- → fit two MBMs: MBMC (confining), MBME (effective mass) on CT18

investigate constraints from newer LHC data in CT18

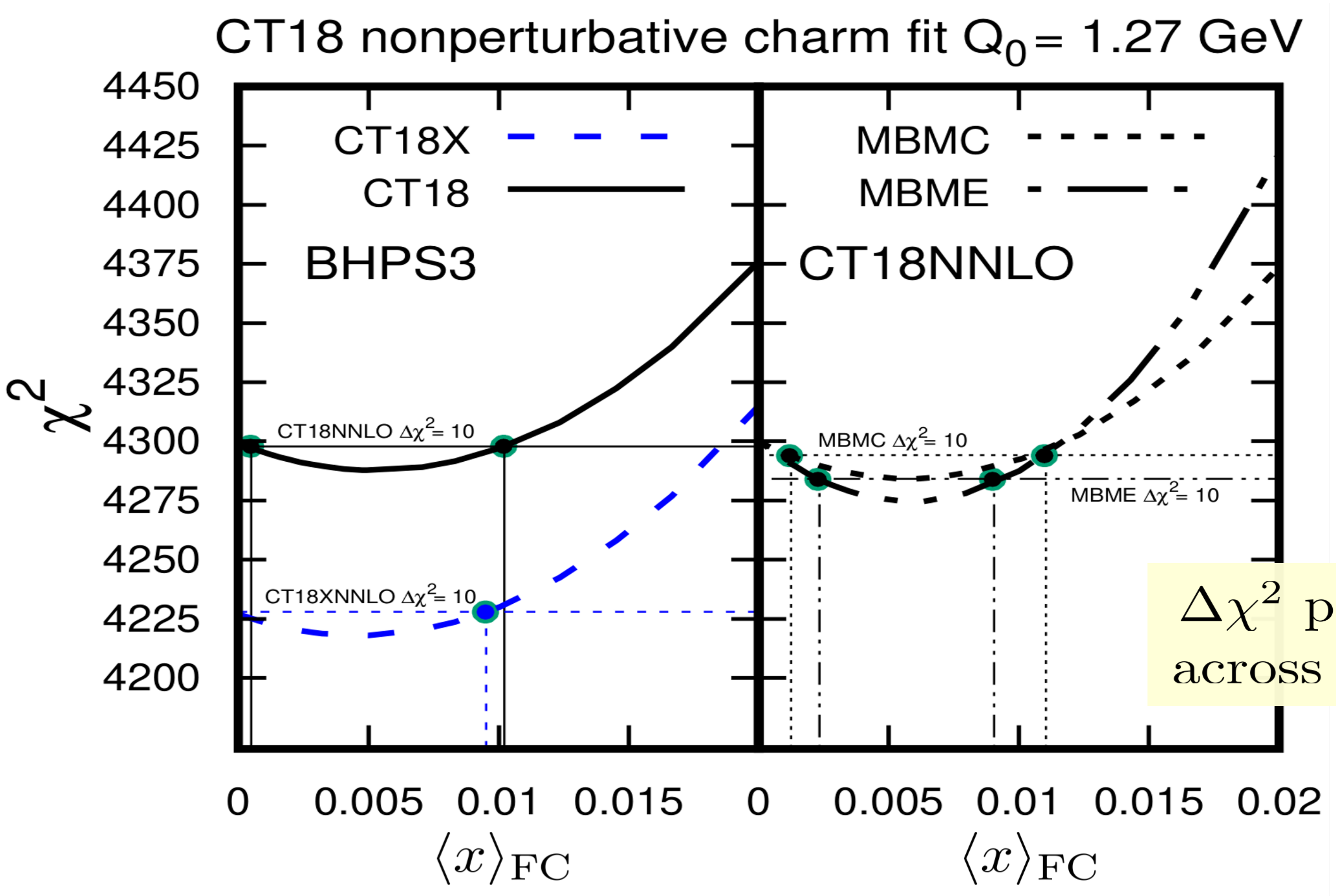
central fits

Fitted Charm

signal for FC in CT18 study, but with <u>shallower</u> $\Delta\chi^2$ than CT14 IC

FC uncertainty quantified by normalization via $\langle x \rangle_{\mathrm{FC}}$ for each input IC model

→ $\langle x \rangle_{\mathrm{FC}} \approx 0.5\%$ $(\Delta\chi^2 \gtrsim -25)$ vs. $\langle x \rangle_{\mathrm{FC}} \approx 0.8\!-\!1\%$ $(\Delta\chi^2 \gtrsim -40)$ CT14 IC



$\Delta\chi^2$ profiles similar across FC scenarios

Fitted Charm

FC PDF moments as F.o.M.

even restrictive uncertainties give moments consistent with zero

→ broaden further for default CT tol.

→ lattice may give $\langle x \rangle_{c^+}$, $\langle x^2 \rangle_{c^-}$

$$\langle x \rangle_{\mathrm{FC}} \equiv \langle x \rangle_{\mathrm{c+}} [Q_0 = 1.27\,\mathrm{GeV}]$$

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

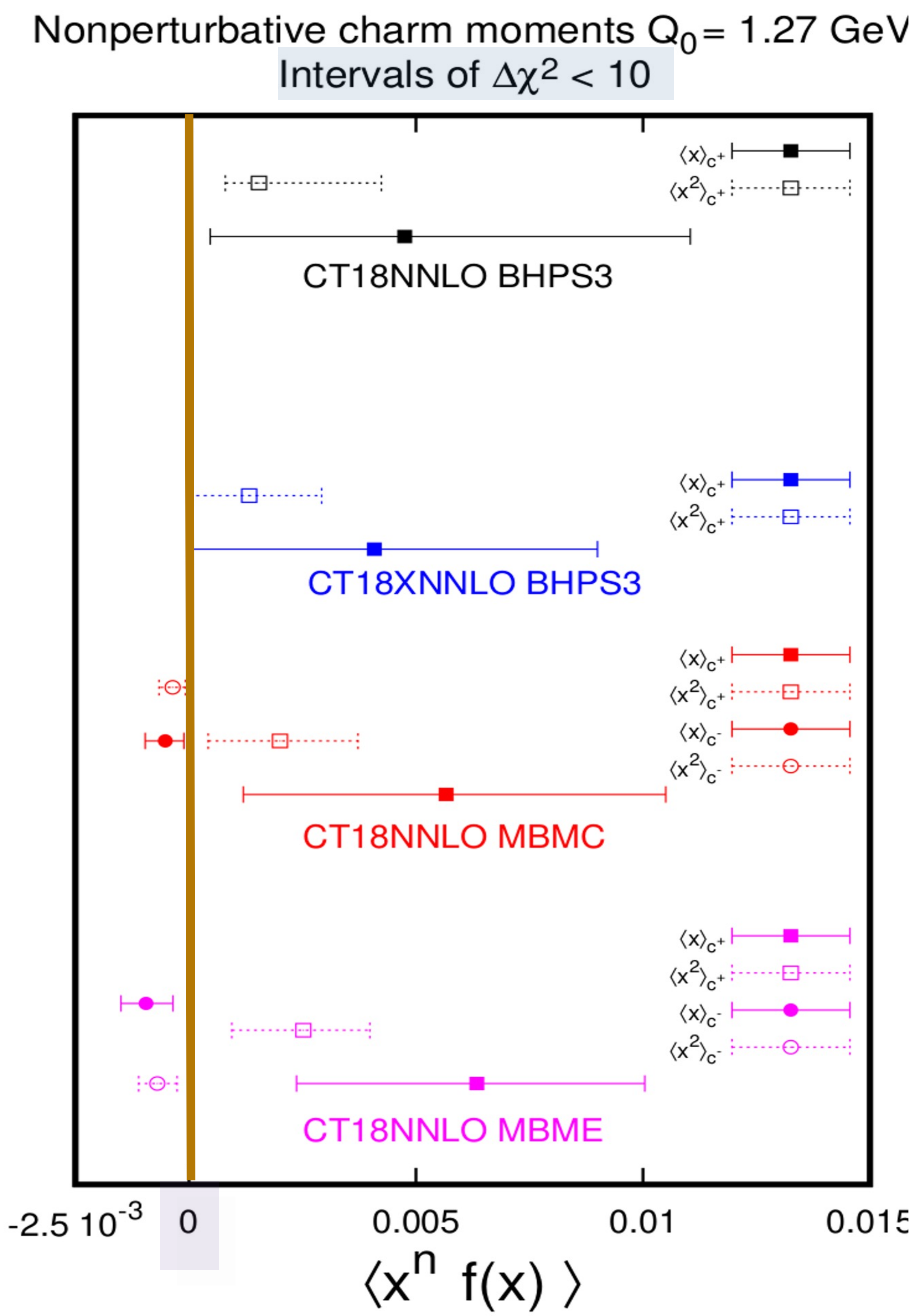
$$= 0.0041\,^{+0.0049}_{-0.0041}\,\left(^{+0.0091}_{-0.0041}\right),\ \mathrm{CT18X\ (BHPS3)}$$

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

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

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

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



Fitted Charm

few expts with ‘smoking gun’ sensitivity to FC; but **EMC data** (?)

historically, charm structure function data, $F_2^{c\bar{c}}$, from EMC were suggestive

J. J. Aubert *et al.* (EMC), NPB**213** (1983) 31–64.

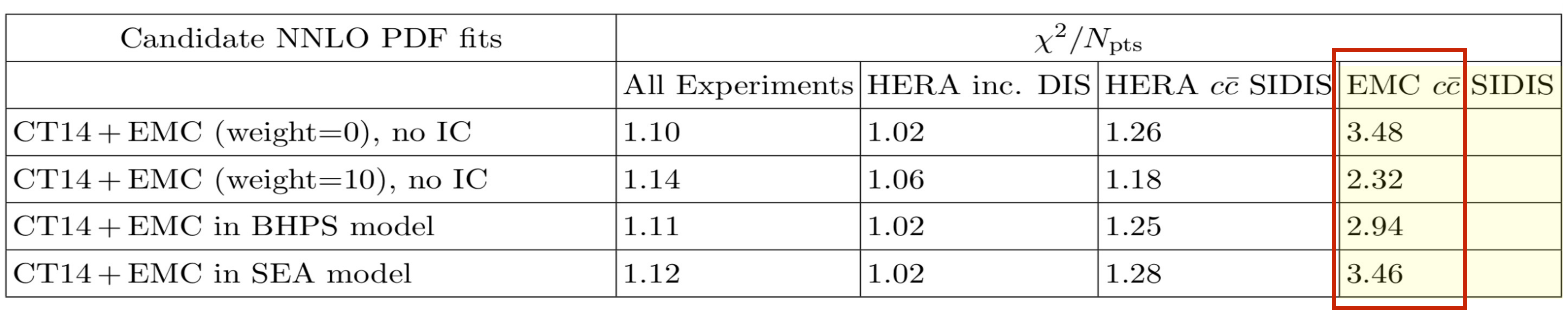
F. M. Steffens, W. Melnitchouk and A. W. Thomas, Eur. Phys. J. C **11**, 673 (1999) [hep-ph/9903441].

See Fig. 3 (lower panel)

- → hint of high-*x* excess in select Q^2 bins
- → data were analyzed only at LO
- → show anomalous Q^2 dependence
- → EMC data fit poorly in CT14 IC study

we do not include EMC in CT18 FC

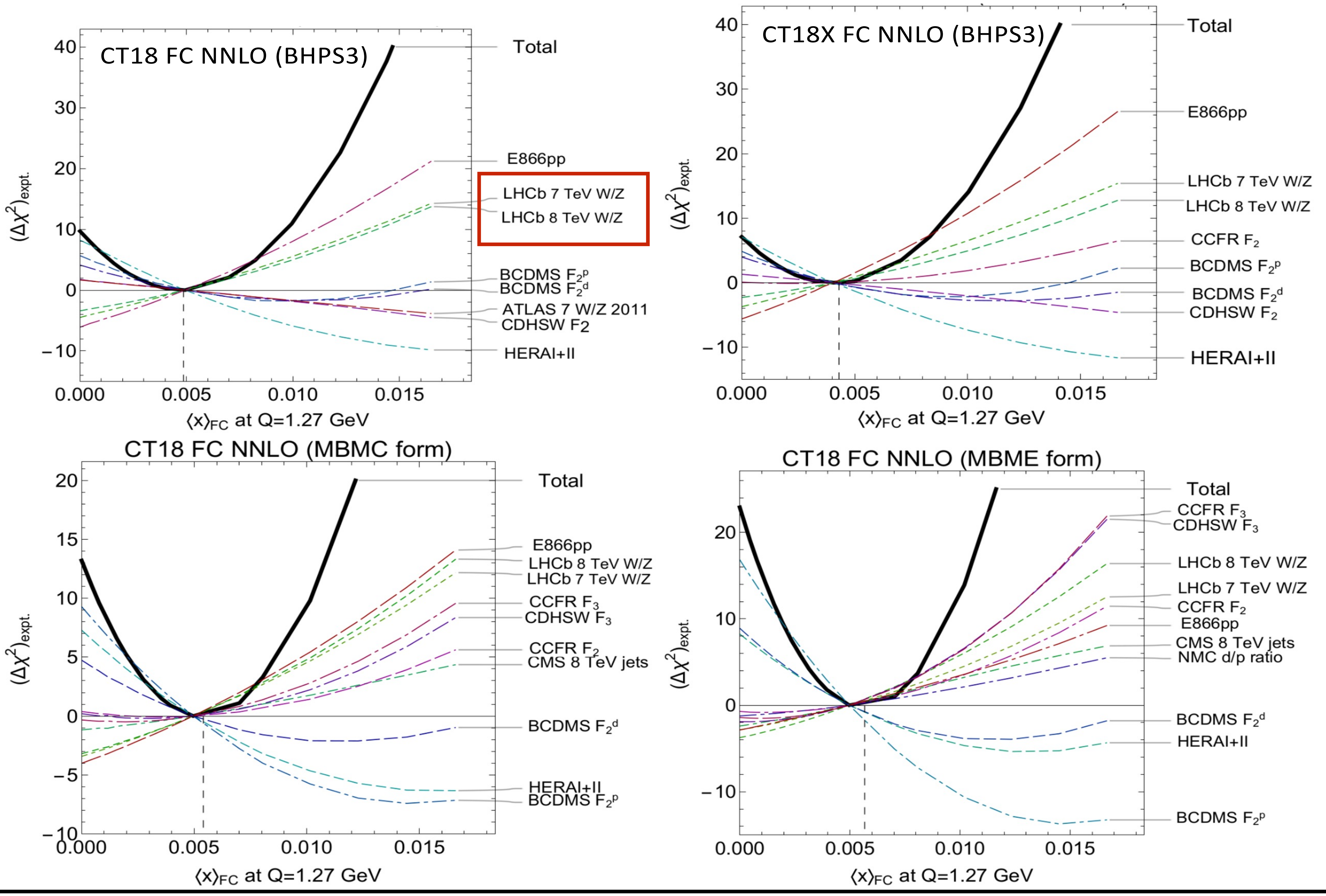
CT14 IC, arXiv: 1707.00657.



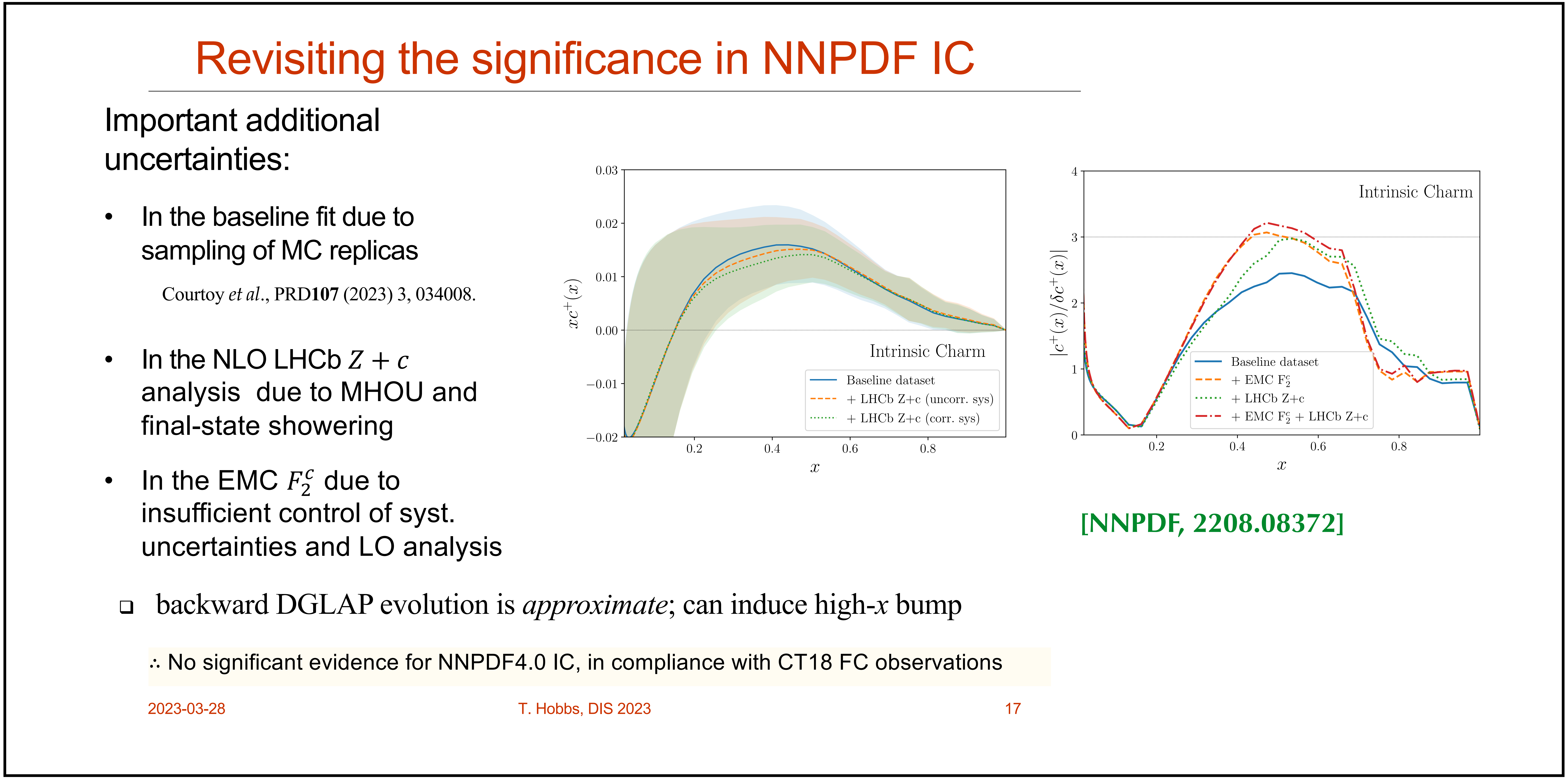
Candidate NNLO PDF fits	$\chi^2/N_{\rm pts}$			
	All Experiments	HERA inc. DIS	HERA $c\bar{c}$ SIDIS	EMC $c\bar{c}$ SIDIS
CT14 + EMC (weight=0), no IC	1.10	1.02	1.26	3.48
CT14 + EMC (weight=10), no IC	1.14	1.06	1.18	2.32
CT14 + EMC in BHPS model	1.11	1.02	1.25	2.94
CT14 + EMC in SEA model	1.12	1.02	1.28	3.46

Fitted Charm

data pull opposingly on $\langle x \rangle_{\mathrm{FC}}$; depend on FC scenario, enhancing error



Fitted Charm



Revisiting the significance in NNPDF IC

Important additional uncertainties:

- In the baseline fit due to sampling of MC replicas

  Courtoy *et al*., PRD**107** (2023) 3, 034008.

- In the NLO LHCb $Z + c$ analysis due to MHOU and final-state showering
- In the EMC F_2^c due to insufficient control of syst. uncertainties and LO analysis

[NNPDF, 2208.08372]

❑ backward DGLAP evolution is *approximate*; can induce high-x bump

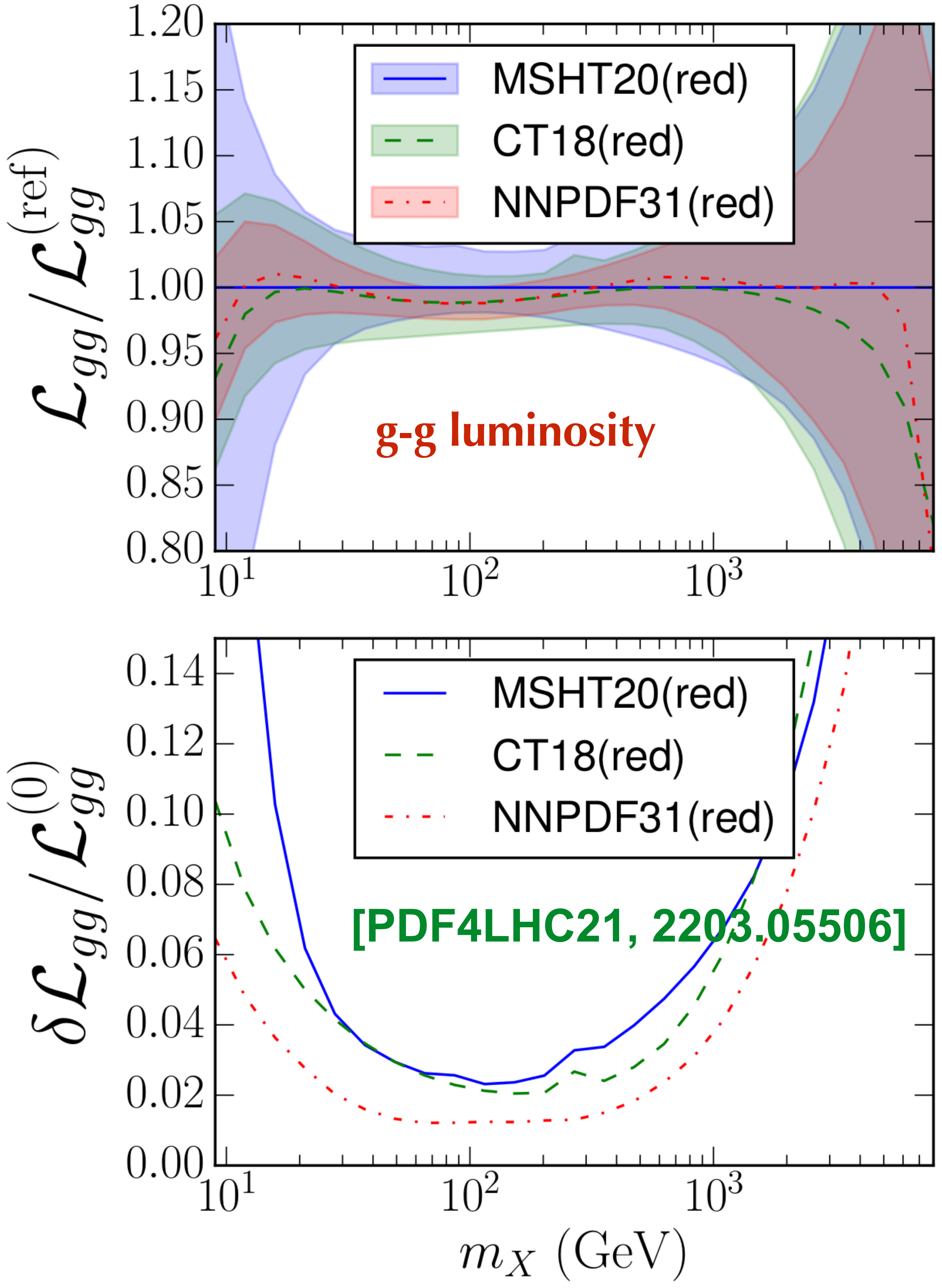
∴ No significant evidence for NNPDF4.0 IC, in compliance with CT18 FC observations

2023-03-28 T. Hobbs, DIS 2023 17

Fitted Charm

- Textbook criterion “$\Delta\chi^2=1$” on estimation of uncertainties is not reliable in global fit, involving large data samples and degrees of freedoms; PDF unc. depends very much on methodologies including “tolerance”

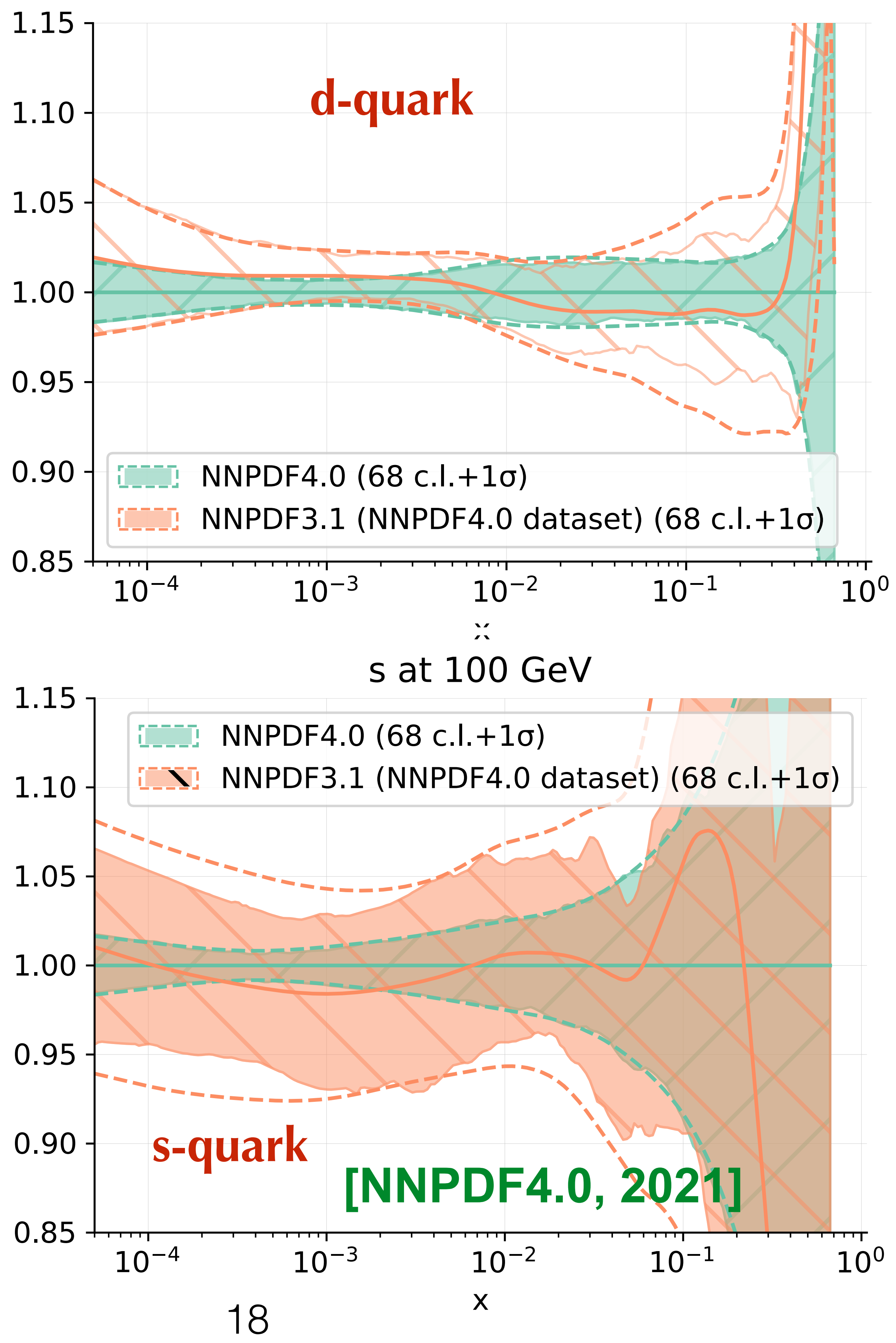
PDFs from reduced fits



g-g luminosity

[PDF4LHC21, 2203.05506]

NNPDF methodology update



d-quark

s-quark

[NNPDF4.0, 2021]

- CT uses tier1+tier2 tolerance, MSHT uses a pure dynamic tolerance, both close to a hypothesis test criterion
- NNPDF3.1 uses ML algorithm with effective tolerance that is smaller than CT and MSHT as checked explicitly from reduced fits
- substantial changes on methodologies for NN4.0 vs. NN3.1 further affect the uncertainty

Fitted Charm

- Measurement of Z bosons produced in association with charm-quark jet in the forward region at LHCb provide great sensitivity to intrinsic Charm **[LHCb, 2109.08084]**

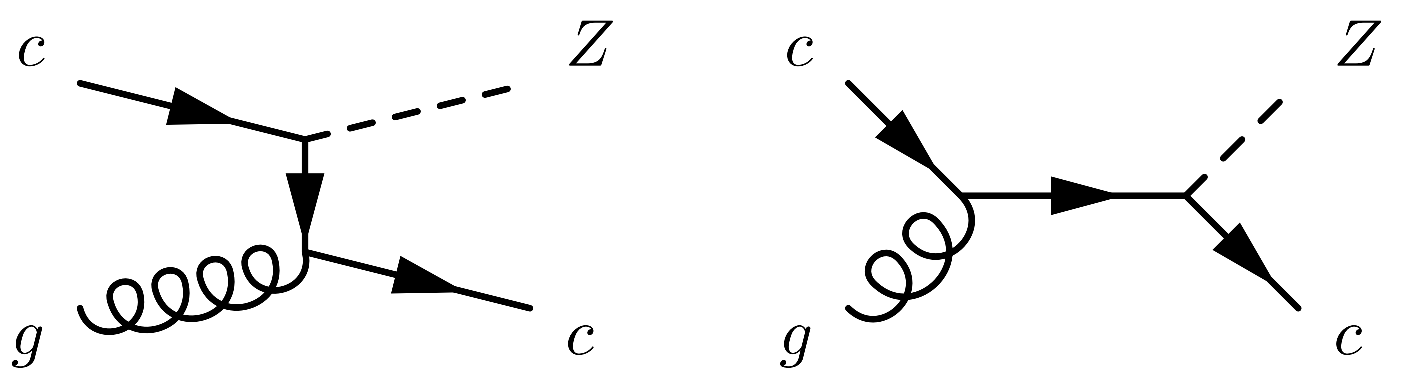
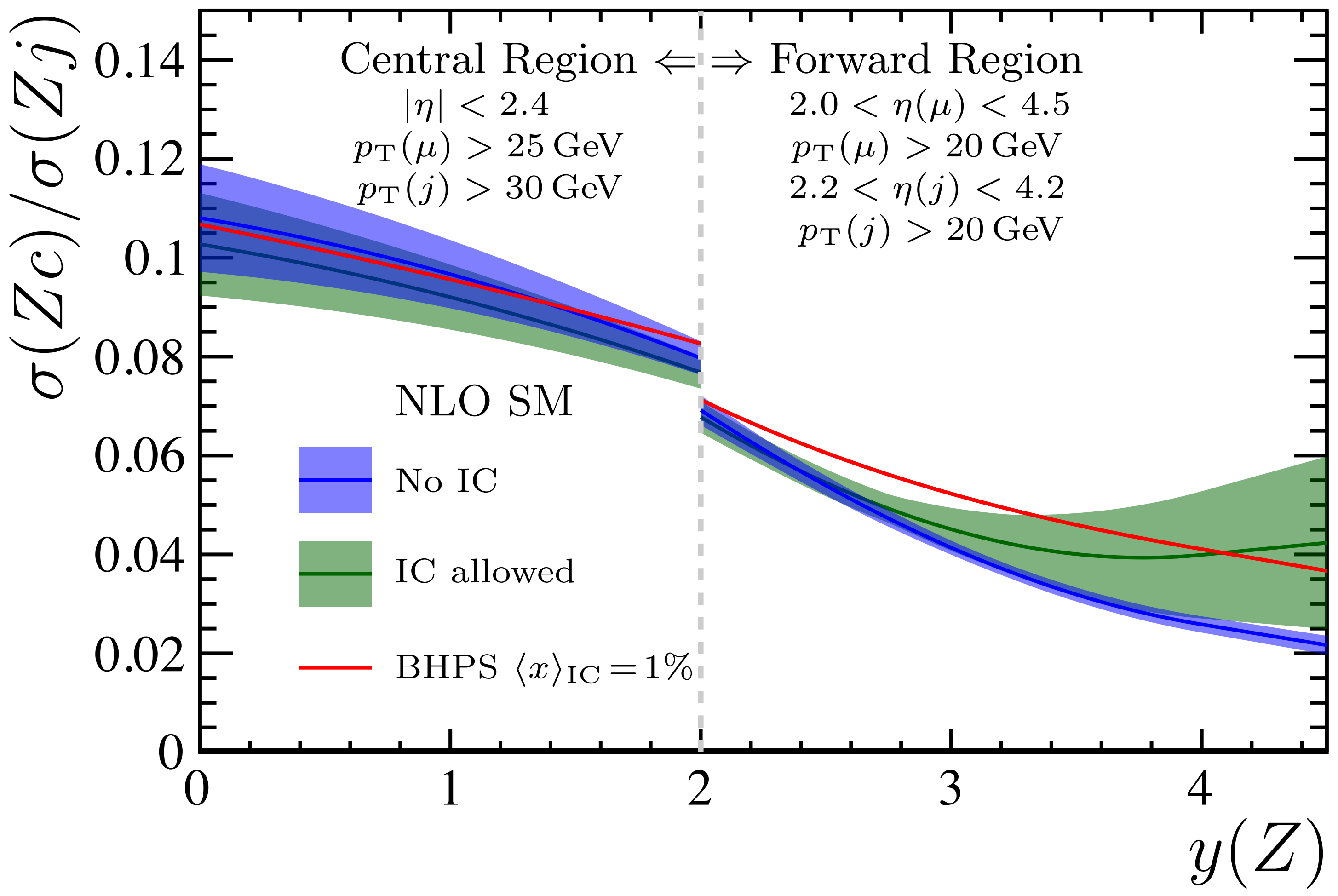
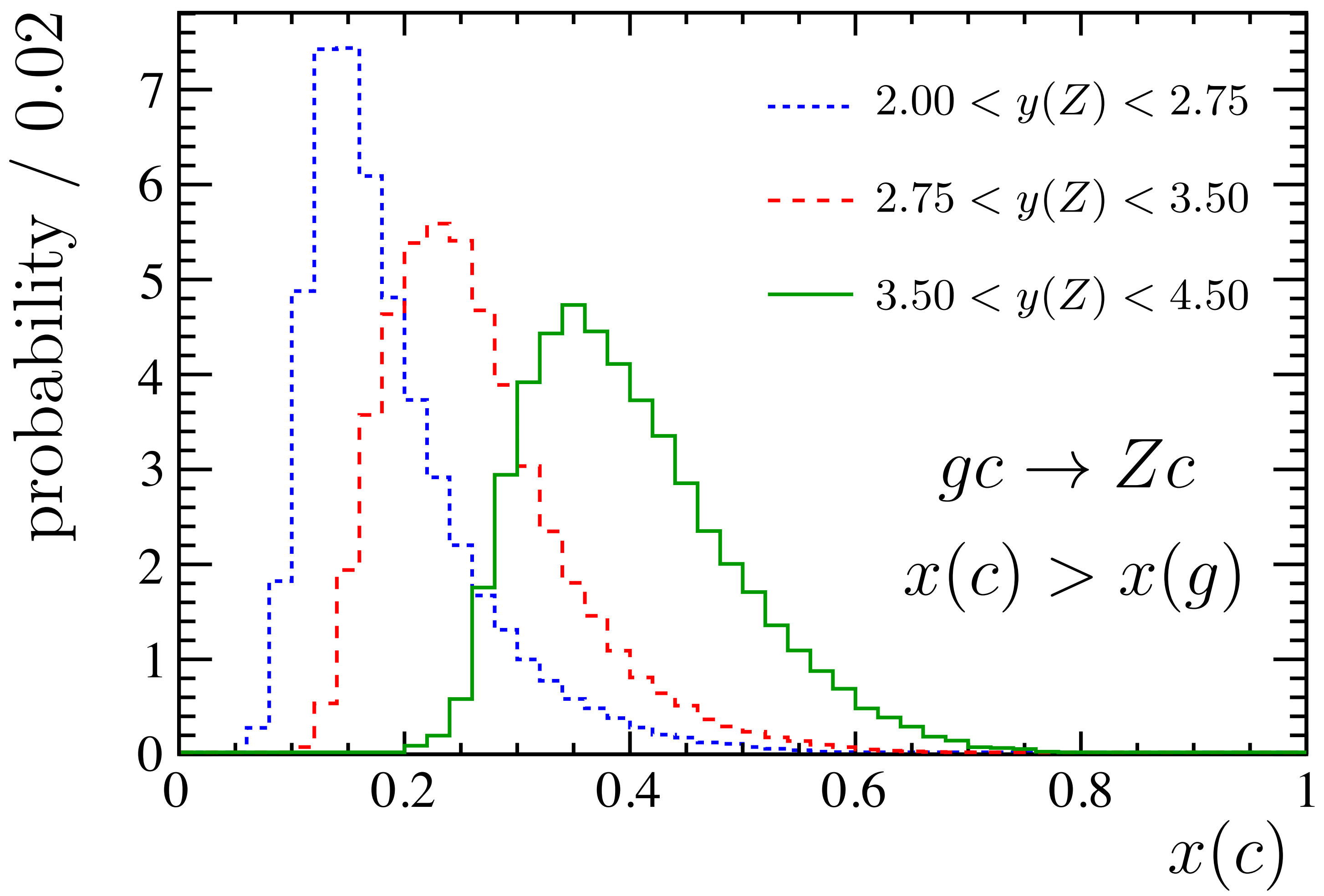
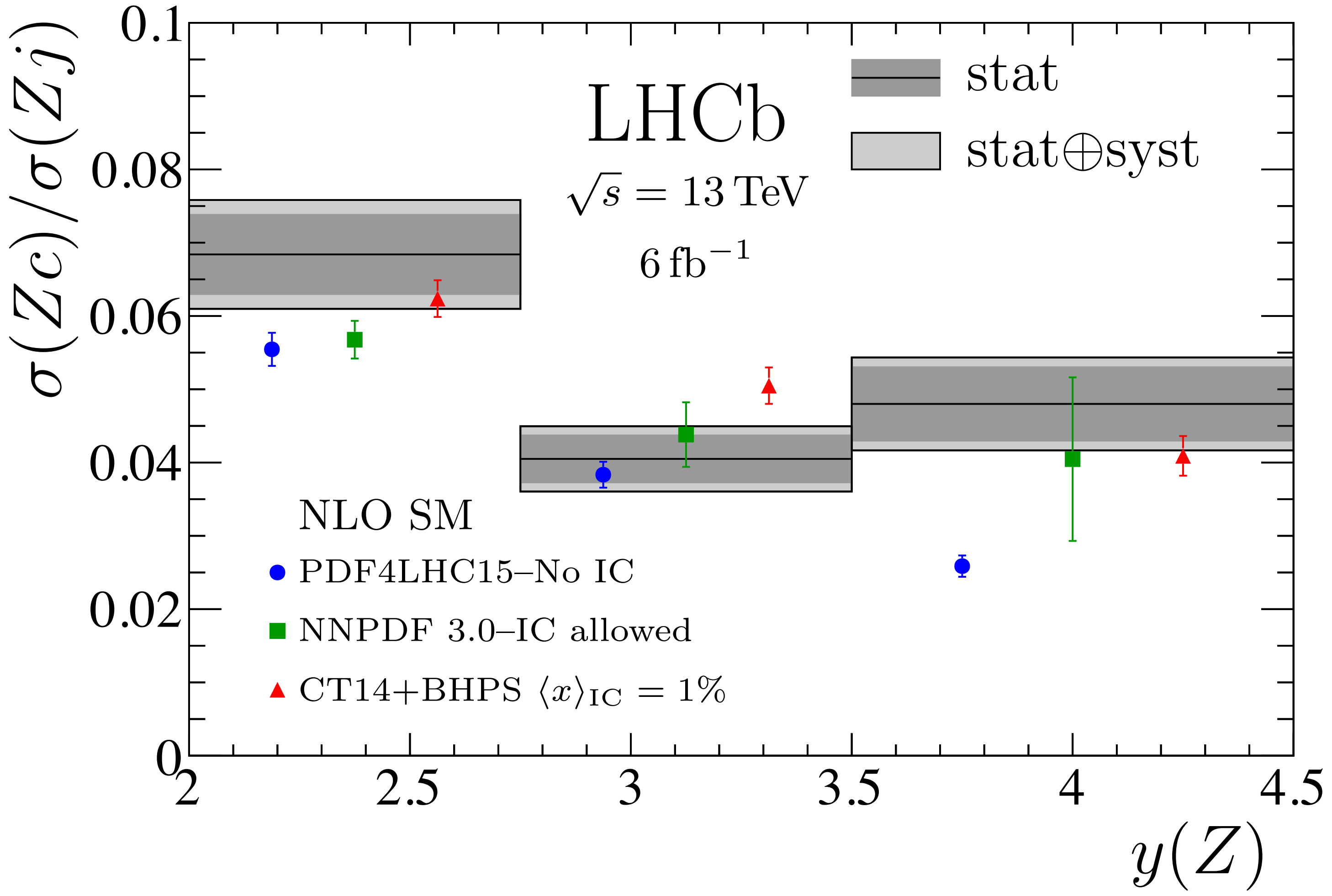


Figure 1: Leading-order Feynman diagrams for $gc \to Zc$ production.

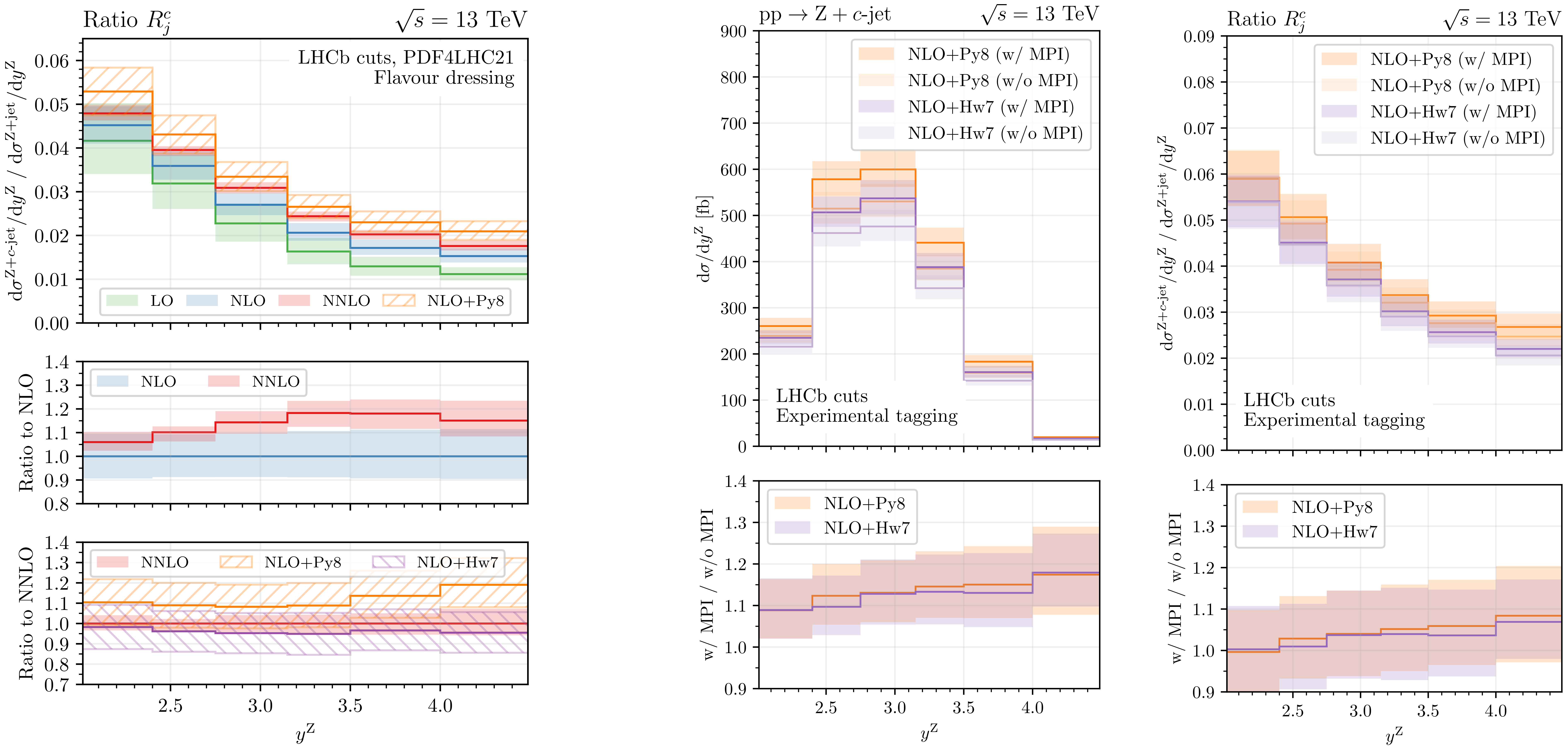






Fitted Charm

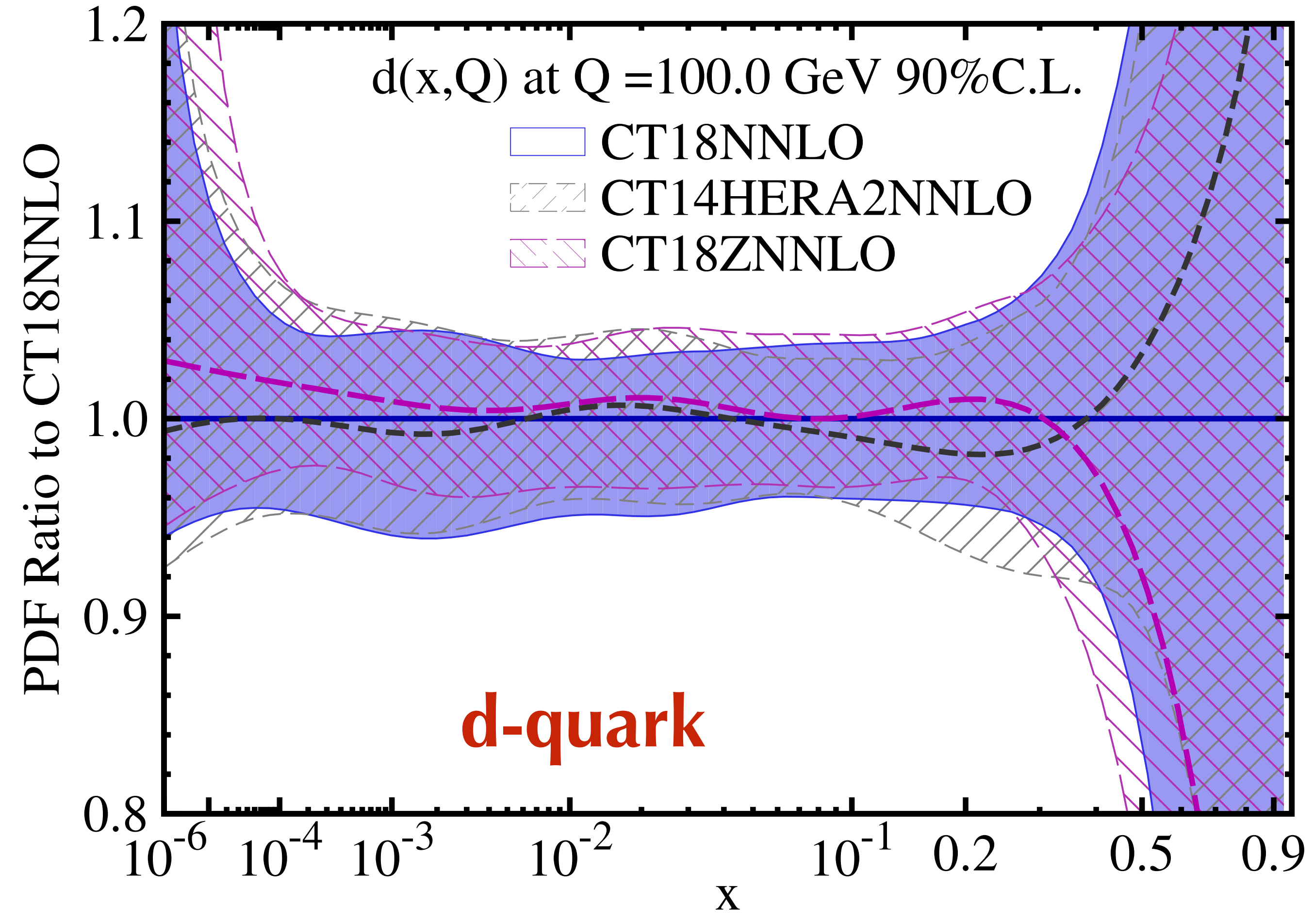
- Theoretical predictions with inclusions of realistic NNLO QCD corrections and a faithful evaluation of theoretical uncertainties due to parton shower, fragmentations, multi-parton scatterings are required before we can include the LHCb data into a NNLO PDF analysis **[2302.12844]**

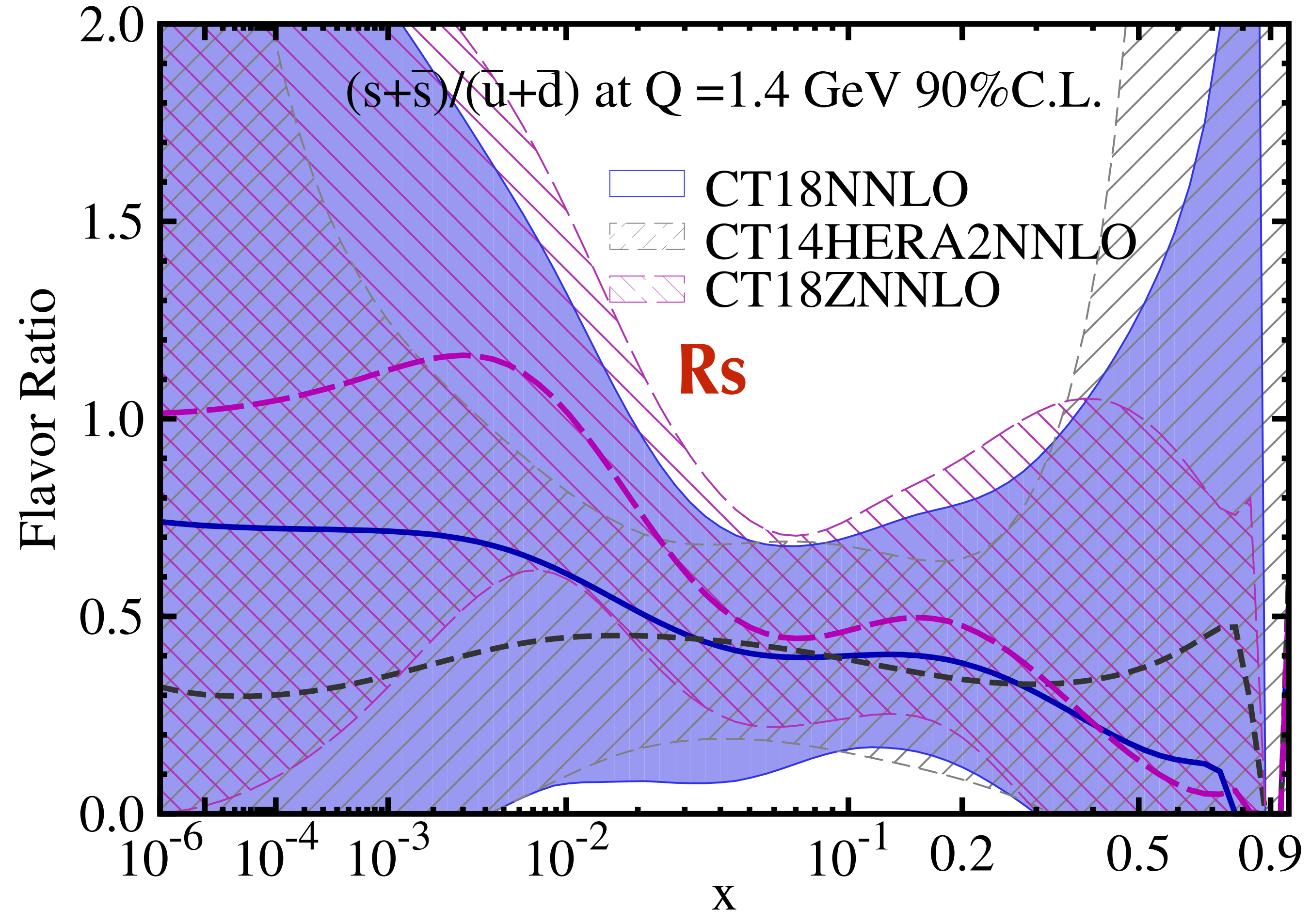


Drell-Yan processes

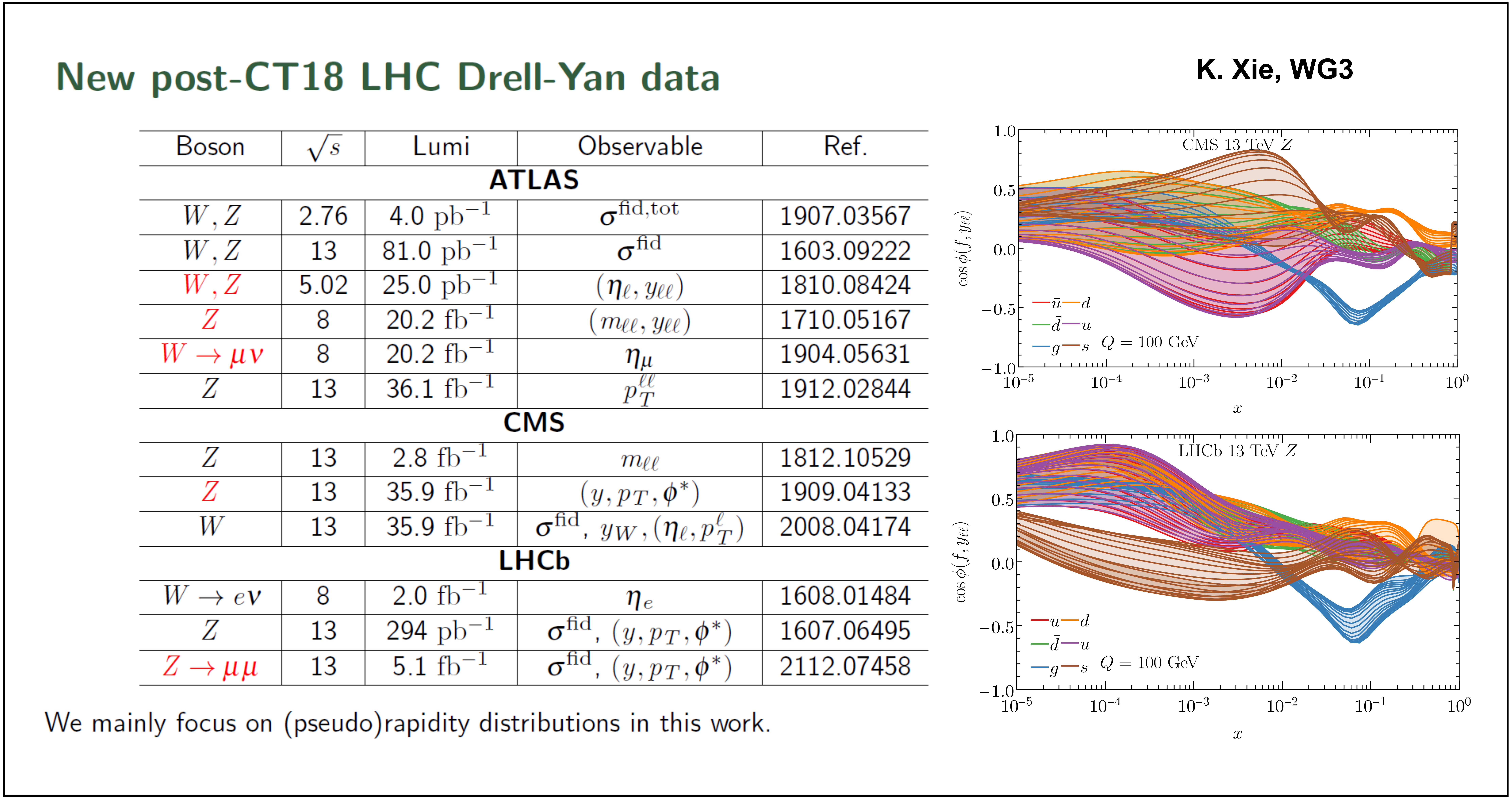
Drell-Yan data in CT18(Z) global analyses

ID	Expt.	N_{pt}	χ^2	χ^2/N_{pt}	S_E
		CT14HERA2 data			
201	E605DY	119	103.4(102.4)	0.9(0.9)	-1.0(-1.1)
203	E866 $\sigma_{pd}/(2\sigma_{pp})$	15	16.1(17.9)	1.1(1.2)	0.3(0.6)
204	E866 $Q^3 d^2\sigma_{pp}/(dQ dx_F)$	184	244(240)	1.3(1.3)	2.9(2.7)
225	CDF1Z $A(e)$	11	9.0(9.3)	0.8(0.8)	-0.3(-0.2)
227	CDF2W $A(e)$	11	13.5(13.4)	1.2(1.2)	0.6(0.6)
234	D∅2W $A(\mu)$	9	9.1(9.0)	1.0(1.0)	0.2(0.1)
260	D∅2Z $y_{\ell\ell}$	28	16.9(18.7)	0.6(0.7)	-1.7(-1.3)
261	CDF2Z $y_{\ell\ell}$	29	48.7(61.1)	1.7(2.1)	2.2(3.3)
266	CMS7W $A(\mu)$	11	7.9(12.2)	0.7(1.1)	-0.6(0.4)
267	CSM7W $A(e)$	11	4.6(5.5)	0.4(0.5)	-1.6(-1.3)
268	ATL7WZ$_{(2012)}$	41	44.4(50.6)	1.1(1.2)	0.4(1.1)
281	D∅2W $A(e)$	13	22.8(20.5)	1.8(1.6)	1.7(1.4)
		New LHC data			
245	LHCb7WZ(μ)	33	53.8(39.9)	1.6(1.2)	2.2(0.9)
246	LHCb8Z(e)	17	17.7(18.0)	1.0(1.1)	0.2(0.3)
248	ATL7WZ$_{(2016)}$	34	287.3(88.7)	8.4(2.6)	13.7(4.8)
249	CMS8W $A(\mu)$	11	11.4(12.1)	1.0(1.1)	0.2(0.4)
250	LHCb8WZ(μ)	34	73.7(59.4)	2.1(1.7)	3.7(2.6)
253	ATL8ZpT	27	30.2(28.3)	1.1(1.0)	0.5(0.3)





Drell-Yan processes



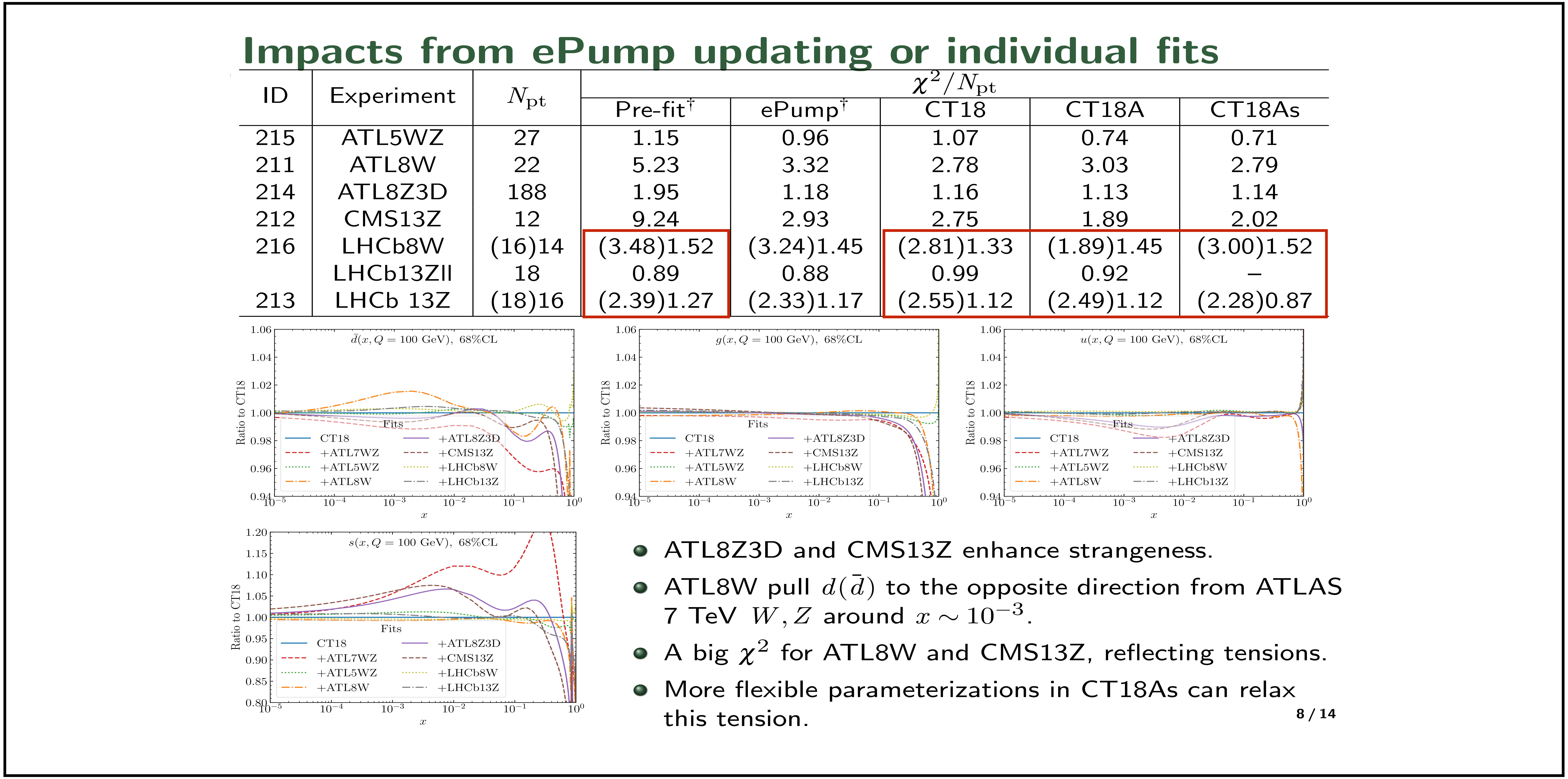
New post-CT18 LHC Drell-Yan data

K. Xie, WG3

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

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

Drell-Yan processes



Impacts from ePump updating or individual fits

ID	Experiment	N_{pt}	χ^2/N_{pt}				
			Pre-fit†	ePump†	CT18	CT18A	CT18As
215	ATL5WZ	27	1.15	0.96	1.07	0.74	0.71
211	ATL8W	22	5.23	3.32	2.78	3.03	2.79
214	ATL8Z3D	188	1.95	1.18	1.16	1.13	1.14
212	CMS13Z	12	9.24	2.93	2.75	1.89	2.02
216	LHCb8W	(16)14	(3.48)1.52	(3.24)1.45	(2.81)1.33	(1.89)1.45	(3.00)1.52
	LHCb13Zll	18	0.89	0.88	0.99	0.92	–
213	LHCb 13Z	(18)16	(2.39)1.27	(2.33)1.17	(2.55)1.12	(2.49)1.12	(2.28)0.87

- ATL8Z3D and CMS13Z enhance strangeness.
- ATL8W pull $d(\bar{d})$ to the opposite direction from ATLAS 7 TeV W, Z around $x \sim 10^{-3}$.
- A big χ^2 for ATL8W and CMS13Z, reflecting tensions.
- More flexible parameterizations in CT18As can relax this tension.

Conclusion

CTEQ-TEA presentations at DIS'2023

Toward a new generation of CT202X PDFs

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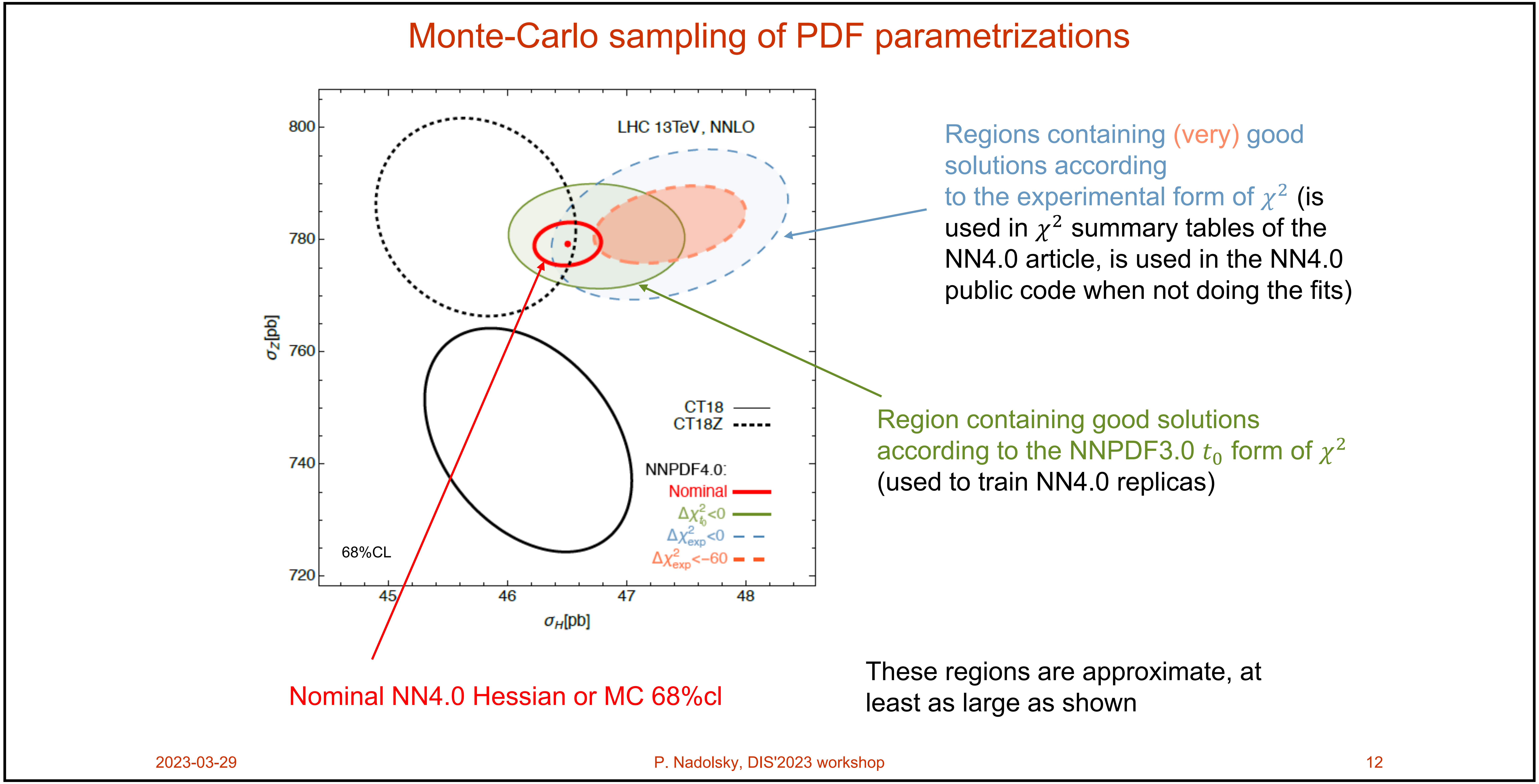
8. Small-x dynamics in CTEQ-TEA fits and Forward Physics Facility	**Keping Xie**	**WG2**

Thank you for your attention!

Fitted Charm



Monte-Carlo sampling of PDF parametrizations

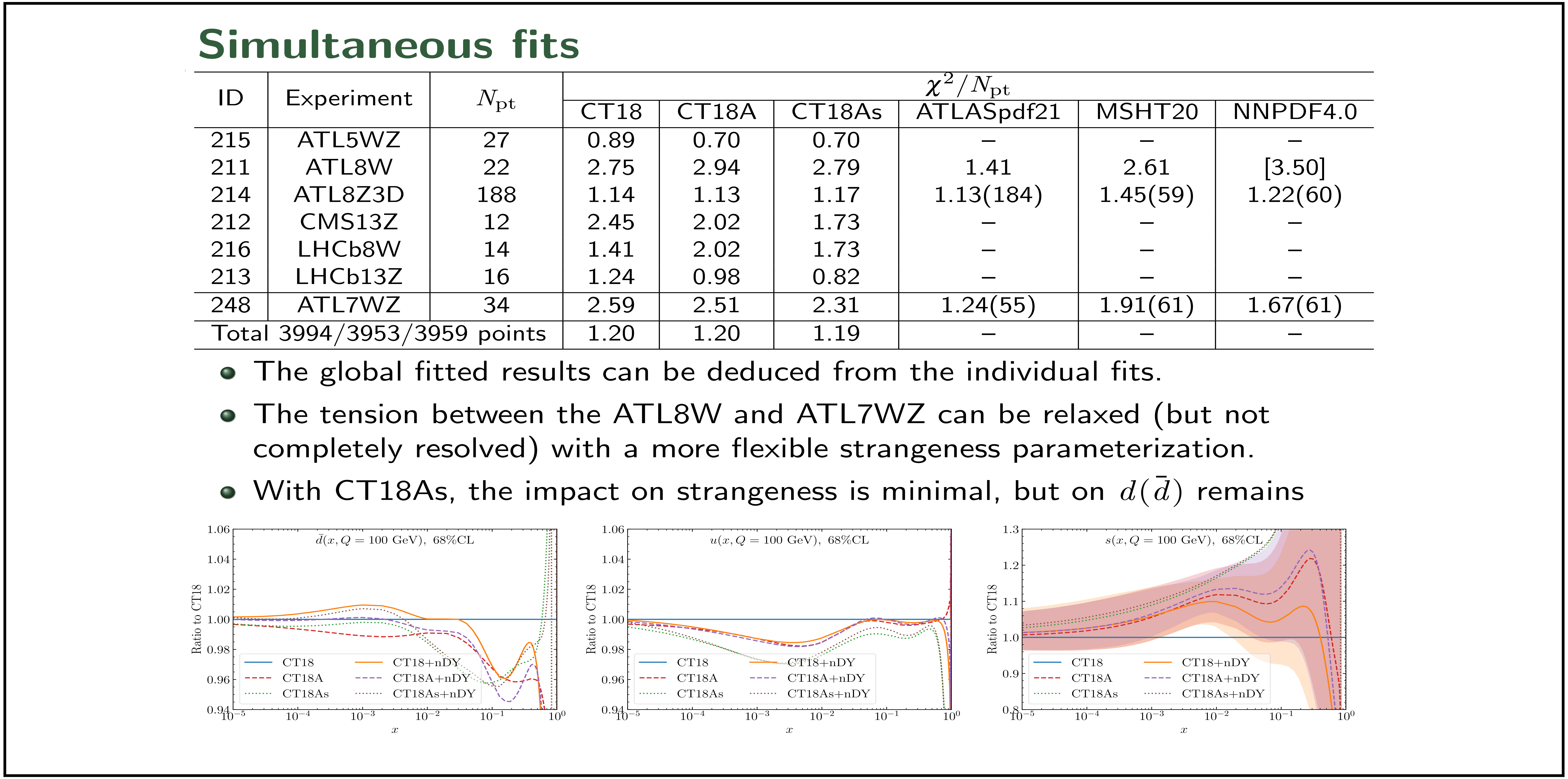
Regions containing (very) good solutions according to the experimental form of χ^2 (is used in χ^2 summary tables of the NN4.0 article, is used in the NN4.0 public code when not doing the fits)

Region containing good solutions according to the NNPDF3.0 t_0 form of χ^2 (used to train NN4.0 replicas)

Nominal NN4.0 Hessian or MC 68%cl

These regions are approximate, at least as large as shown

Drell-Yan processes



Simultaneous fits

ID	Experiment	$N_{\rm pt}$	$\chi^2/N_{\rm pt}$					
			CT18	CT18A	CT18As	ATLASpdf21	MSHT20	NNPDF4.0
215	ATL5WZ	27	0.89	0.70	0.70	–	–	–
211	ATL8W	22	2.75	2.94	2.79	1.41	2.61	[3.50]
214	ATL8Z3D	188	1.14	1.13	1.17	1.13(184)	1.45(59)	1.22(60)
212	CMS13Z	12	2.45	2.02	1.73	–	–	–
216	LHCb8W	14	1.41	2.02	1.73	–	–	–
213	LHCb13Z	16	1.24	0.98	0.82	–	–	–
248	ATL7WZ	34	2.59	2.51	2.31	1.24(55)	1.91(61)	1.67(61)
Total 3994/3953/3959 points			1.20	1.20	1.19	–	–	–

- The global fitted results can be deduced from the individual fits.
- The tension between the ATL8W and ATL7WZ can be relaxed (but not completely resolved) with a more flexible strangeness parameterization.
- With CT18As, the impact on strangeness is minimal, but on $d(\bar{d})$ remains