

the persistent nonperturbative charm enigma

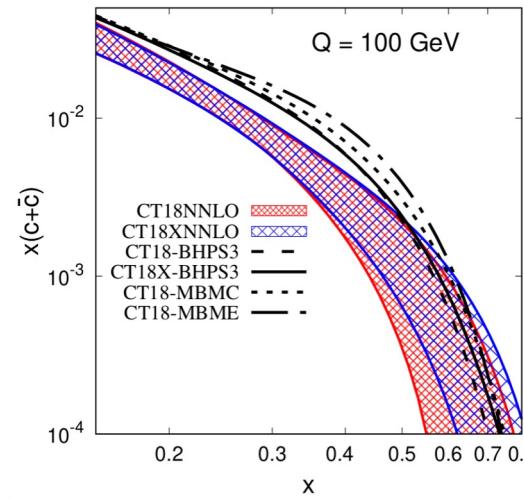
based on arXiv:2211.01387

Tim Hobbs, ANL

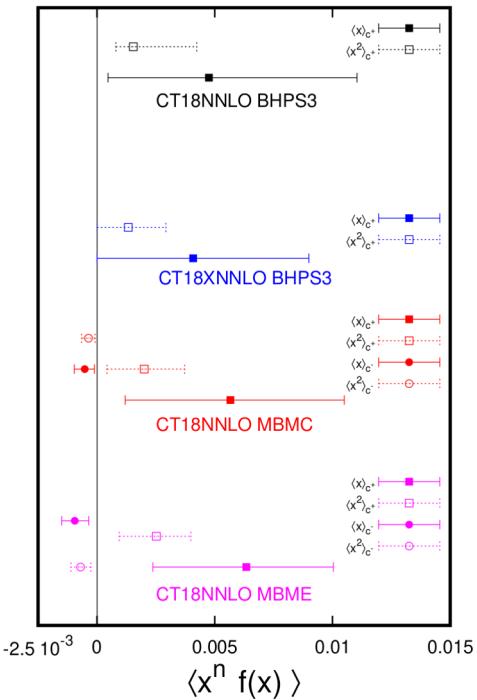


see also: 1707.00657
and 2205.10444

with M. Guzzi, K. Xie, J. Huston,
P. Nadolsky, C.-P. Yuan



Nonperturbative charm moments $Q_0 = 1.27 \text{ GeV}$
Intervals of $\Delta\chi^2 < 10$



and members of the
CTEQ-TEA (Tung Et. Al.) working group



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

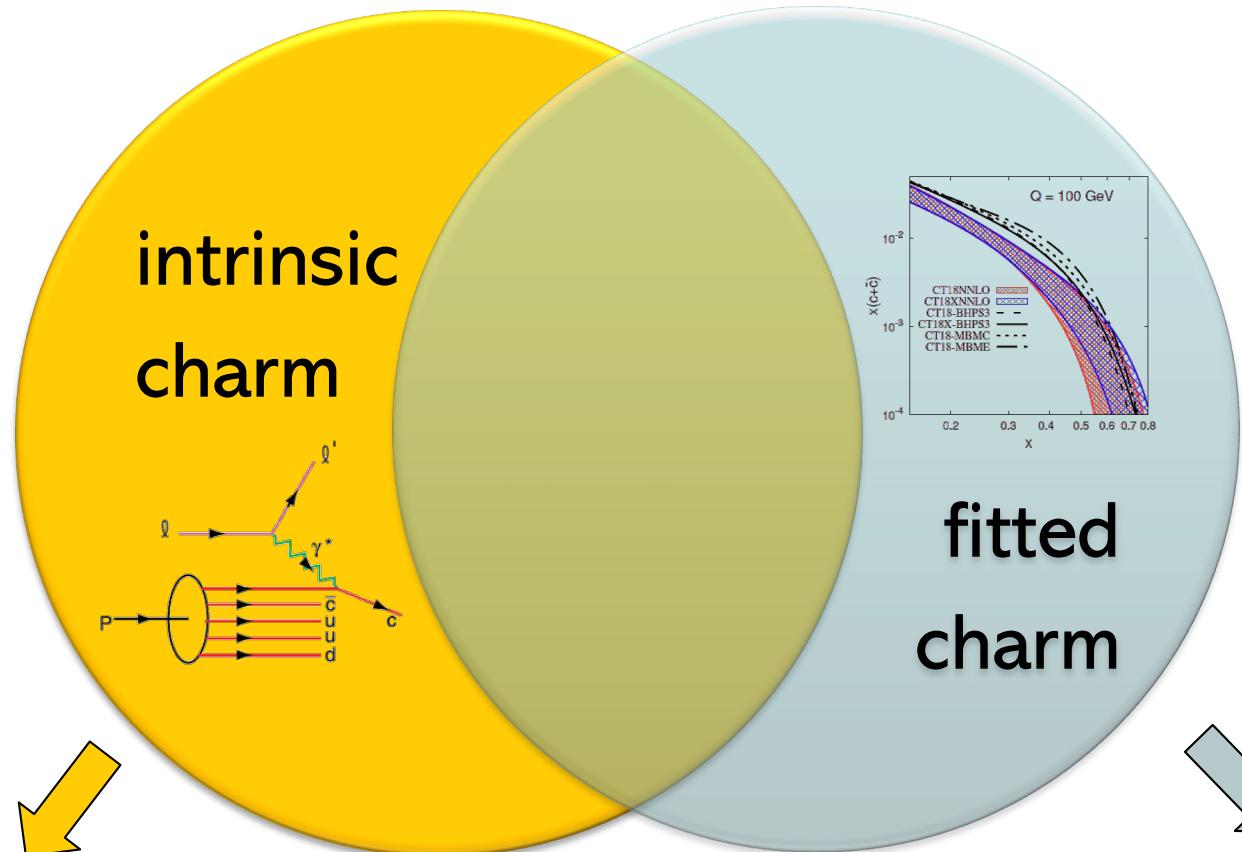
IC from nonperturbative methods and models:

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

challenging to formulate a rigorous definition of intrinsic 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 $x \gtrsim 0.2$

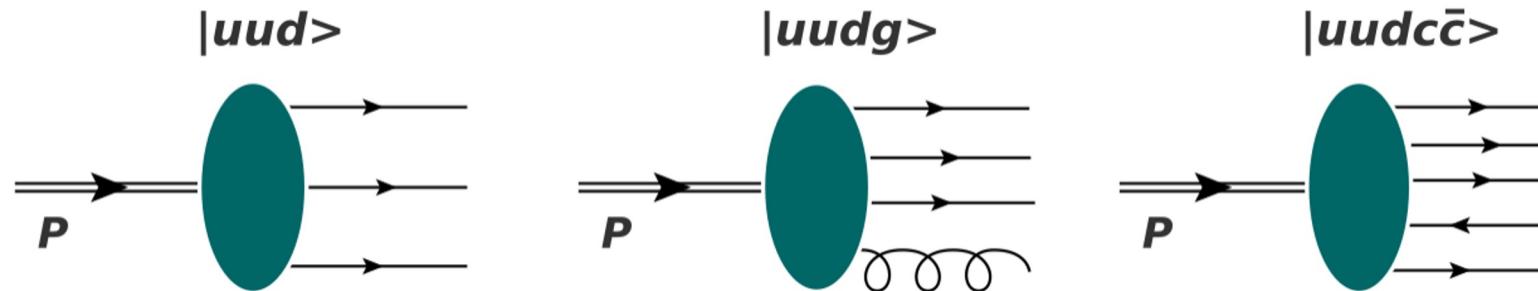
Connection?

- A charm PDF parametrization at scale $Q_0 \approx 1 \text{ GeV}$ 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

nonperturbative QCD can generate a low-scale charm PDF

Fock expansion

Brodsky, Hoyer, Peterson, Sakai (BHPs); Phys. Lett. **B93** (1980) 451.



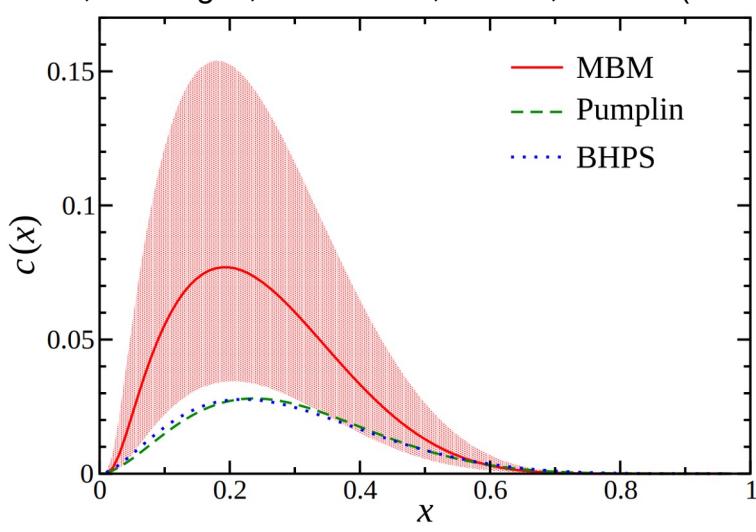
IC PDF: transition matrix element, $|\text{proton}\rangle \rightarrow |uudc\bar{c}\rangle$ → old-fashioned PT;

scalar field theory

$$P(p \rightarrow uudc\bar{c}) \sim \left[M^2 - \sum_{i=1}^5 \frac{k_{\perp i}^2 + m_i^2}{x_i} \right]^{-2}$$

('BHPs3': full mass dependence)

TJH, Londergan, Melnitchouk, PRD89, 074008 (2014).



$$m_c = m_{\bar{c}} \implies c^{\text{BHPs}}(x) = \bar{c}^{\text{BHPs}}(x)$$

→ more complex models: meson-baryon model (MBM); produce charm-anticharm asymmetry

→ generically yields valence-like shape; governed by charm, hadronic mass scales

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.

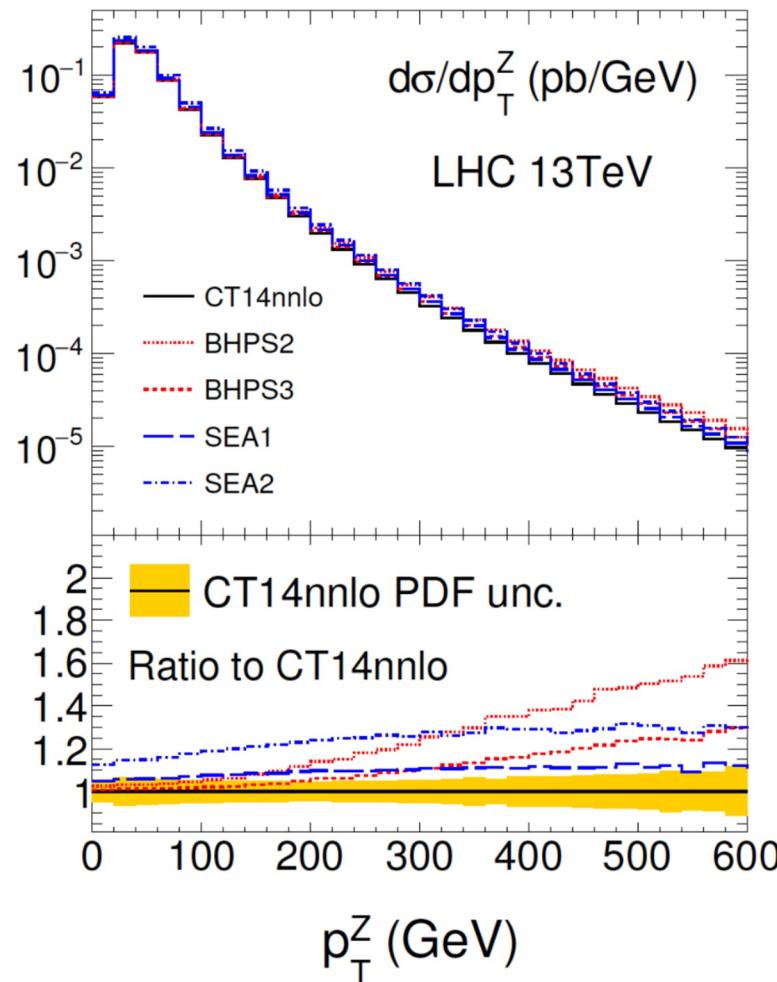
Candidate NNLO PDF fits	χ^2/N_{pts}			
	All Experiments	HERA inc. DIS	HERA $c\bar{c}$ SIDIS	EMC $c\bar{c}$ SIDIS
CT14 + EMC (weight=0), no IC	1.10	1.02	1.26	3.48
CT14 + EMC (weight=10), no IC	1.14	1.06	1.18	2.32
CT14 + EMC in BHPS model	1.11	1.02	1.25	2.94
CT14 + EMC in SEA model	1.12	1.02	1.28	3.46

FC at LHC: $Z+c$ suggested as sensitive probe

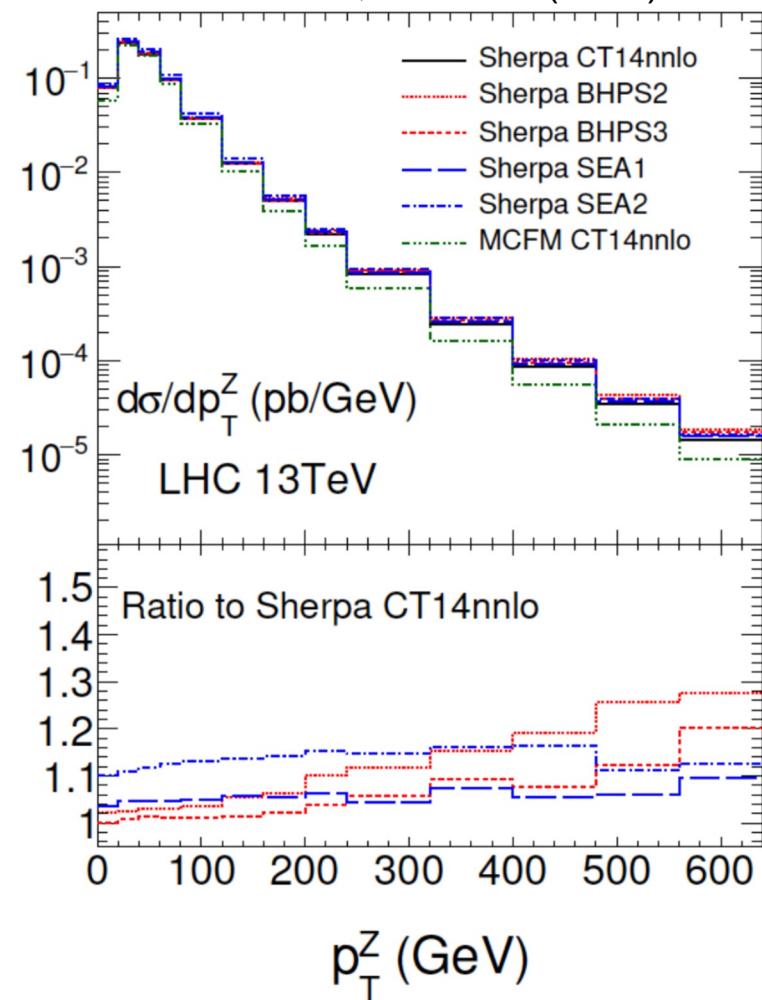
T. Boettcher, P. Ilten, M. Williams, 1512.06666; Bailas, Goncalves, 1512.06007

p_T spectra, rapidity distributions nominally sensitive to high- x charm PDF
→ parton-shower effects can dampen high- p_T tails

$Z+c$ NLO LHC 13 TeV



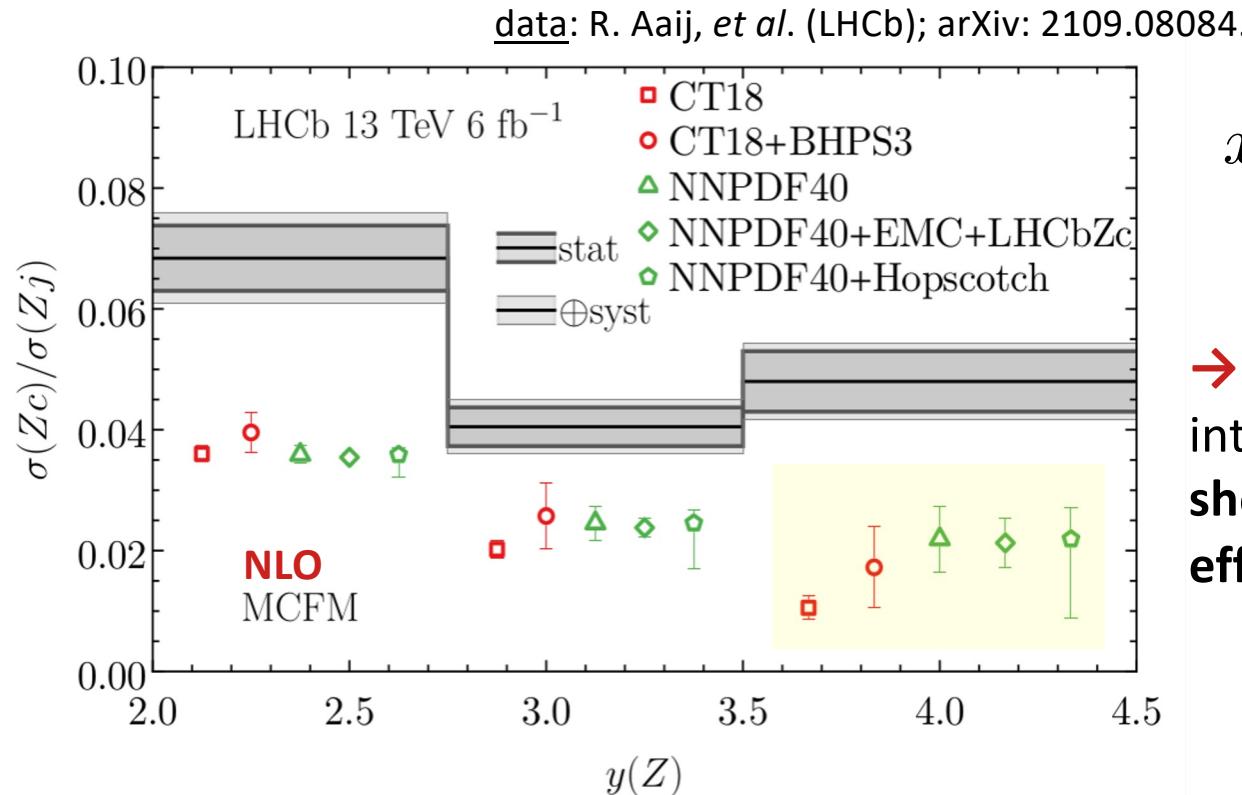
Hou *et al.*, JHEP 02 (2018) 059.



Z+c theory predictions carry sizable uncertainties

assuming MCFM at NLO, can vary underlying PDFs, test inclusion of FC

→ FC slightly enhances ratio; not enough to improve agreement with data



$$x \sim \frac{Q}{\sqrt{s}} e^y$$

→ need **NNLO** theory interface; control over **showering, final-state effects**

- ❑ theory accuracy not yet sufficient to leverage expt. precision for PDFs
- ❑ NNLO calculations recently available, but not implemented in PDF fits

R. Gauld, et al.; arXiv: 2005.03016; [2302.12844](#)

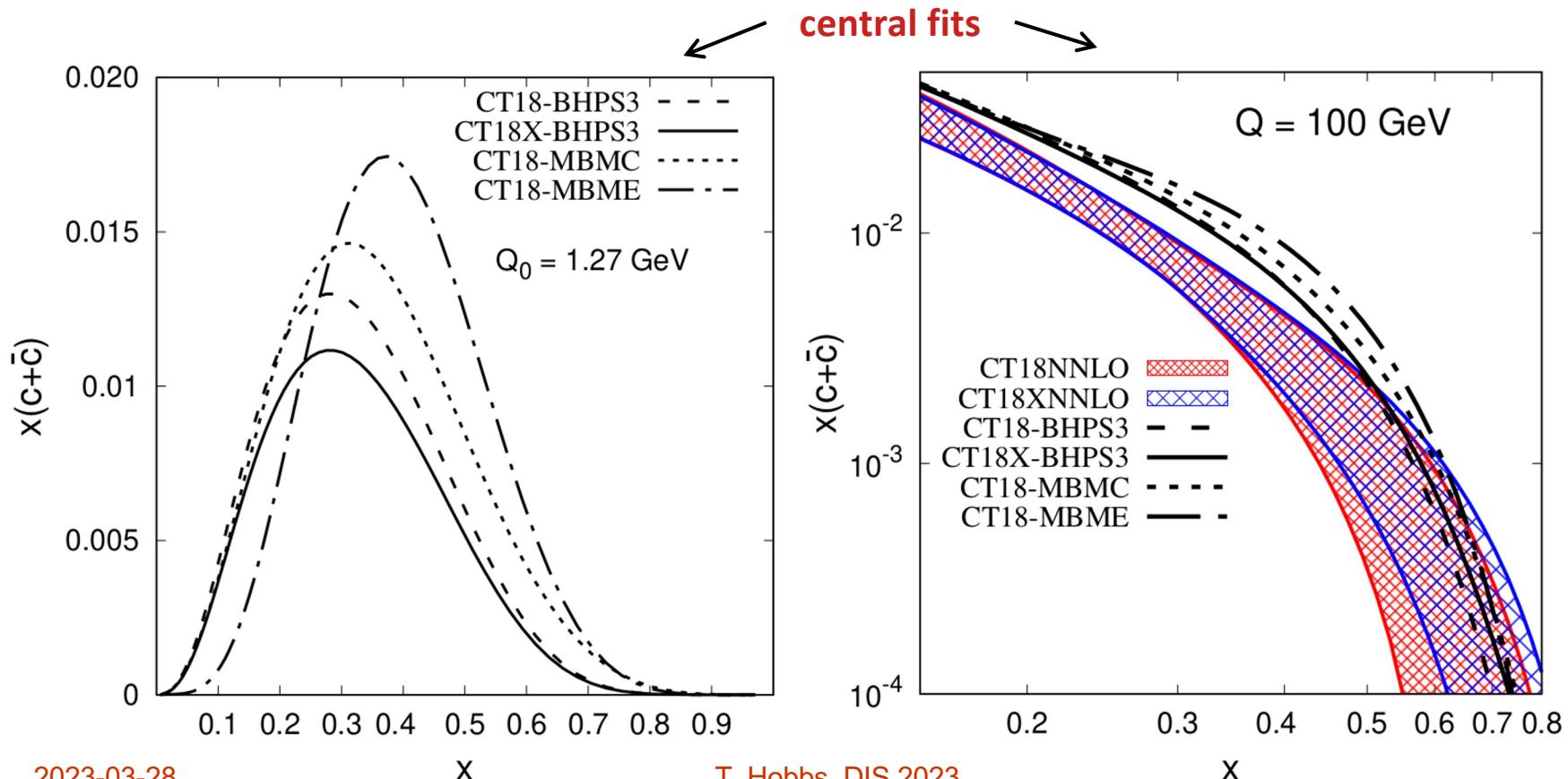
M. Czakon, et al.; arXiv: 2011.01011.

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

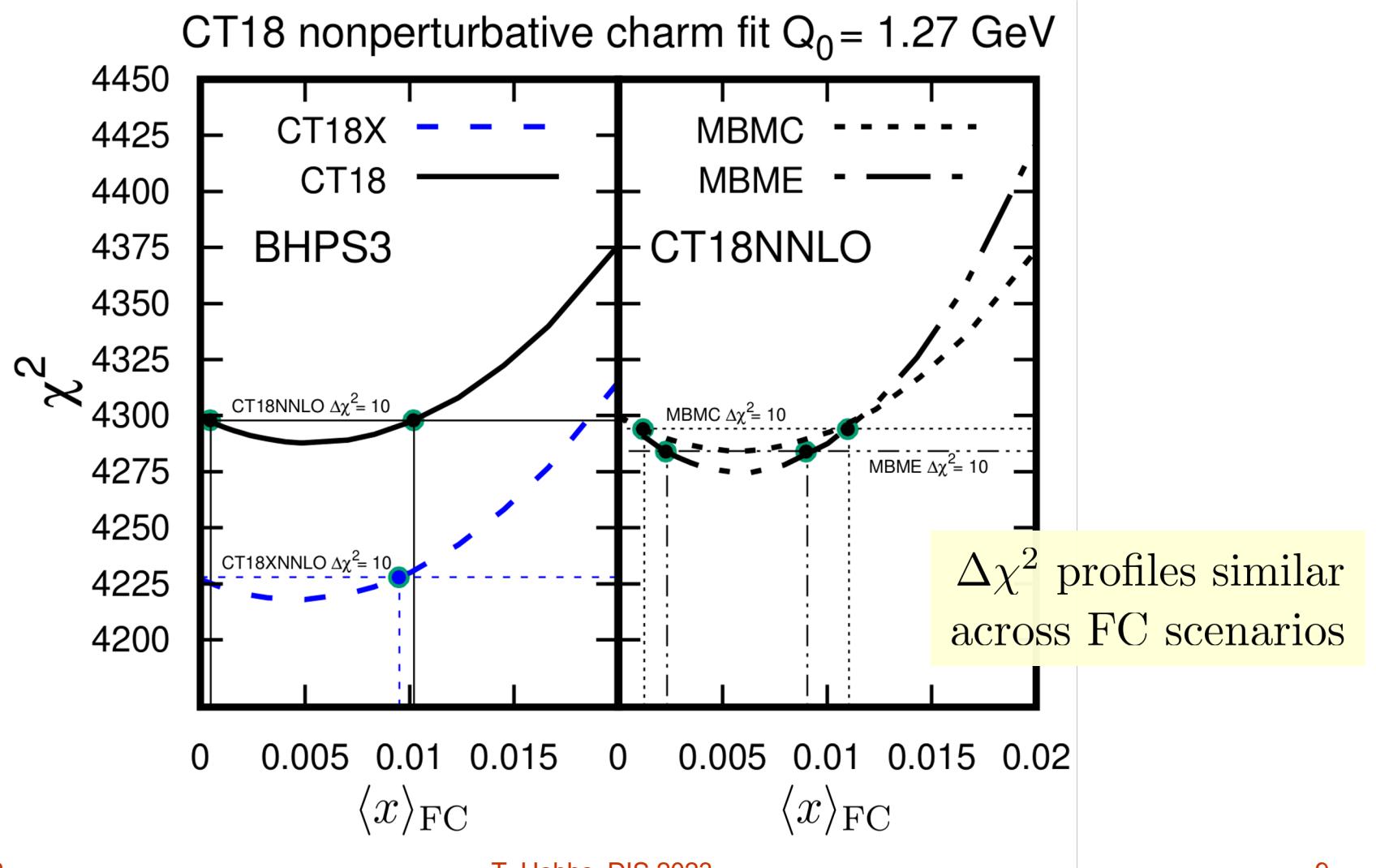
investigate constraints from newer LHC data in CT18



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

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

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



FC PDF moments as F.o.M.

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

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

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

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

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

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

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

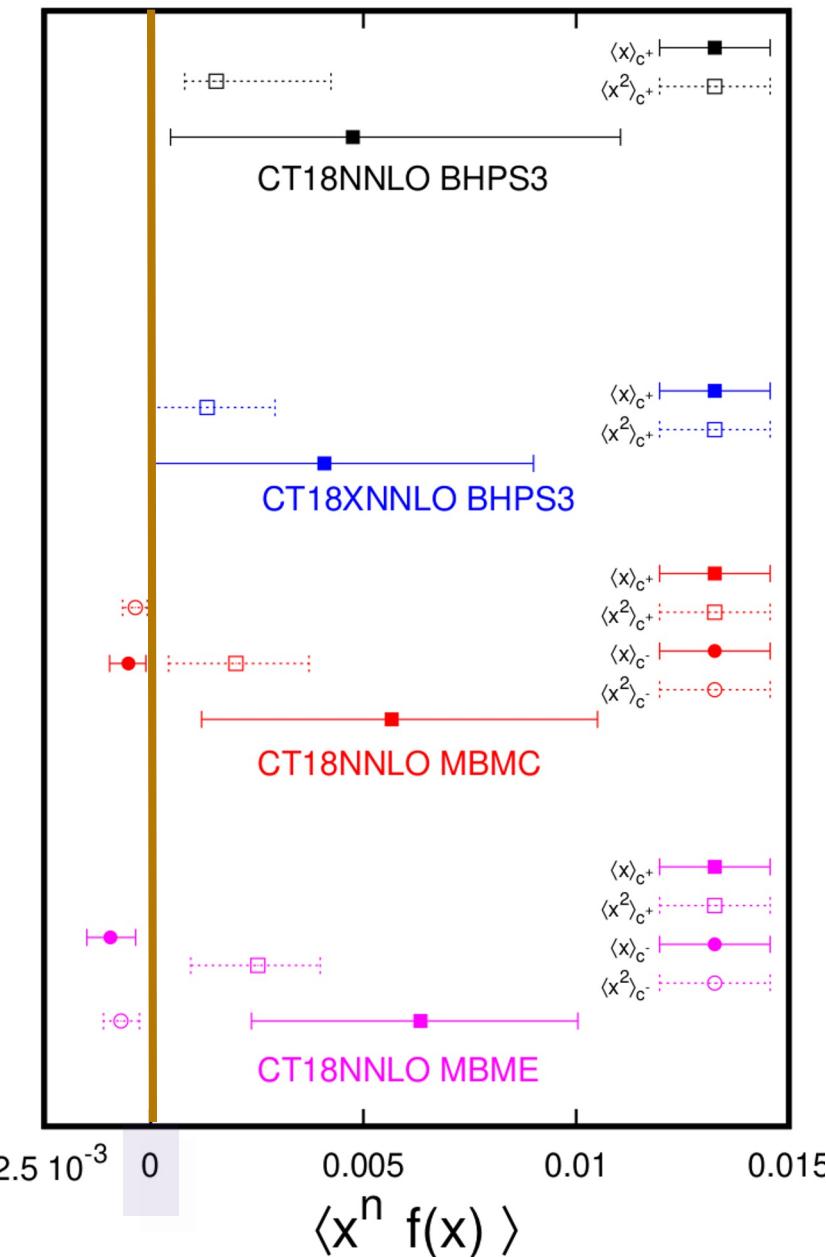
$$\Delta\chi^2 \leq 10$$

(restrictive tolerance)

$$\Delta\chi^2 \leq 30$$

(~CT standard tolerance)

Nonperturbative charm moments $Q_0 = 1.27 \text{ GeV}$
Intervals of $\Delta\chi^2 < 10$



FC PDF moments as F.o.M.

even restrictive uncertainties give moments consistent with zero

- broaden further for default CT tol.
- lattice may give $\langle x \rangle_{c^+}$, $\langle x^2 \rangle_{c^-}$

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

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

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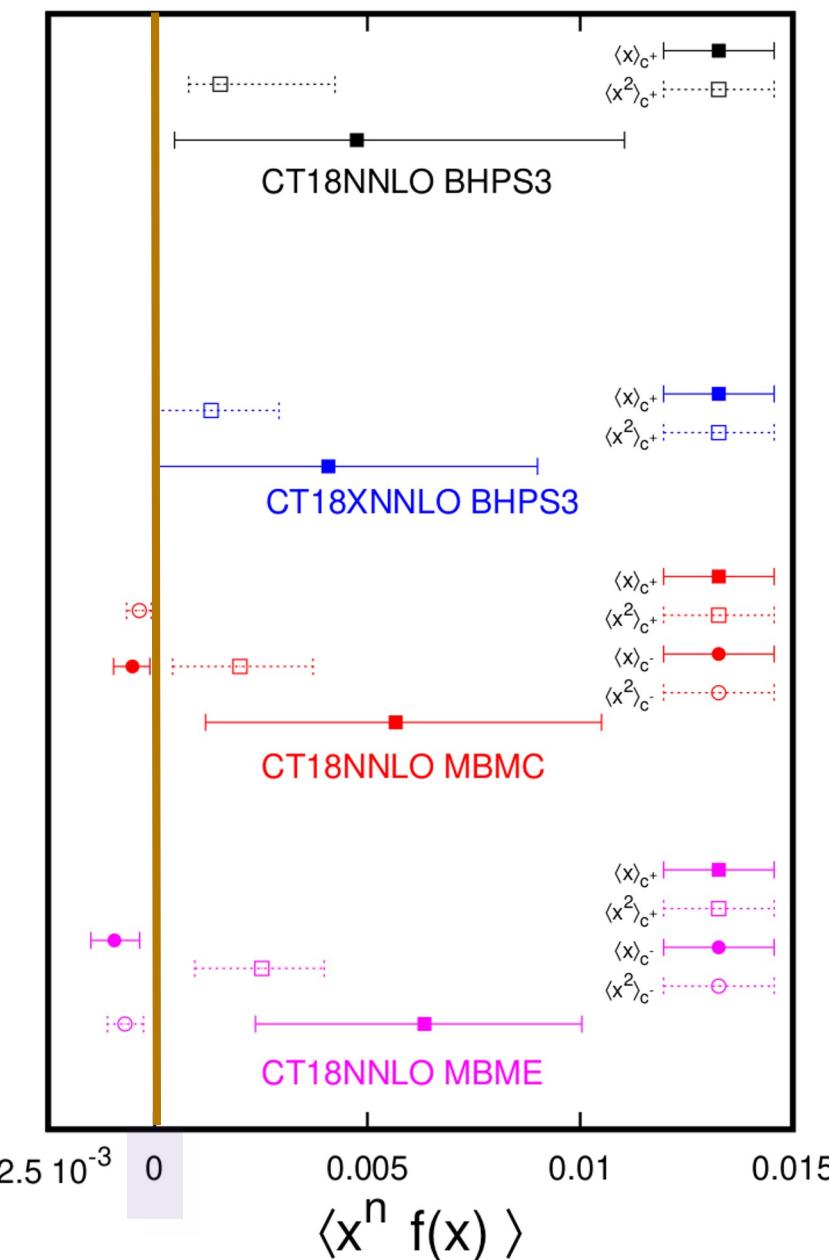
$$\Delta\chi^2 \leq 10$$

(restrictive tolerance)

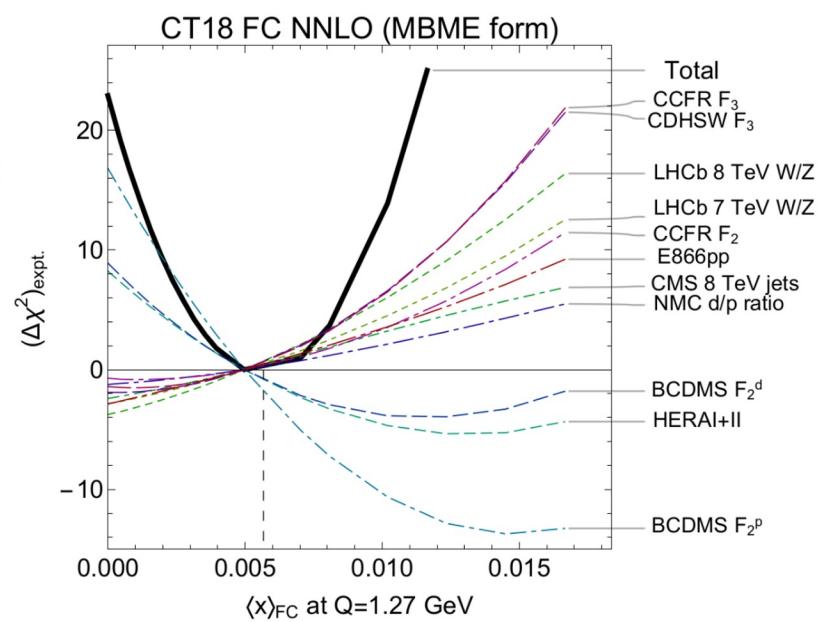
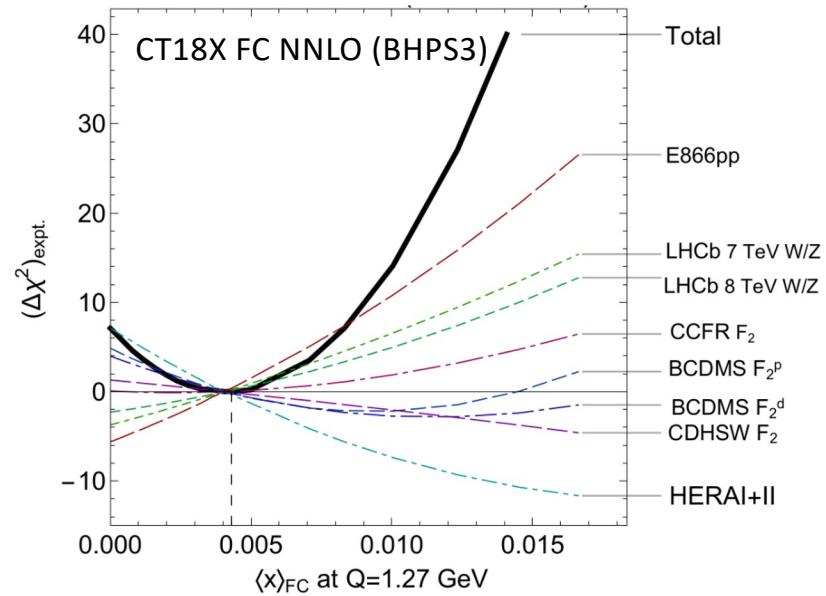
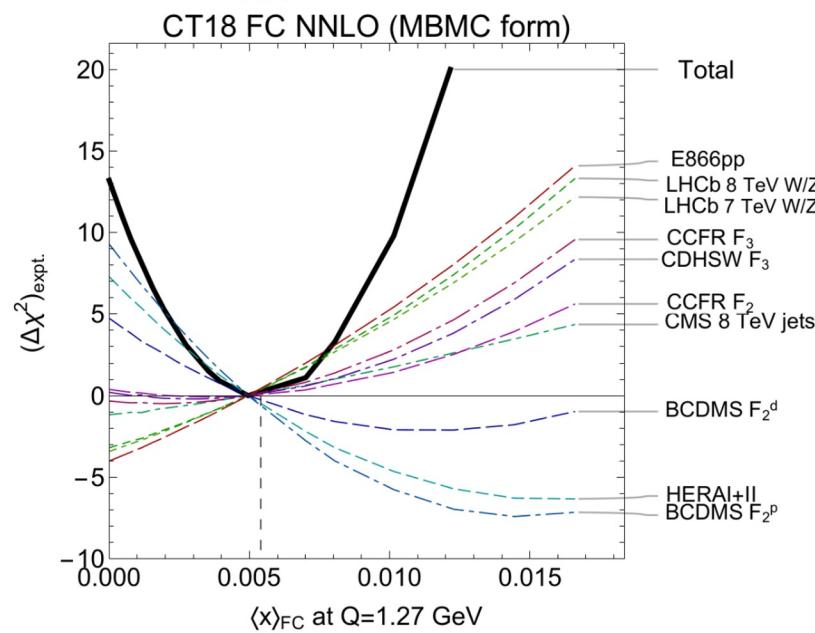
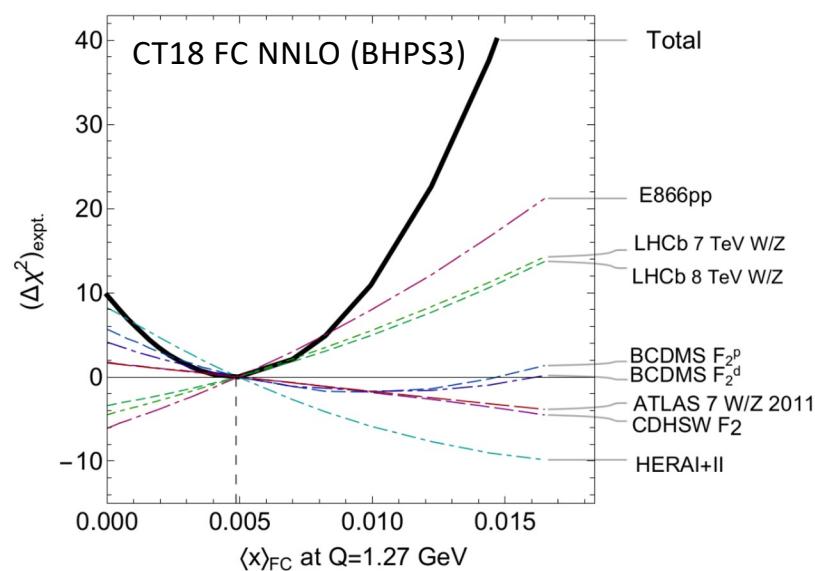
$$\Delta\chi^2 \leq 30$$

(~CT standard tolerance)

Nonperturbative charm moments $Q_0 = 1.27 \text{ GeV}$
Intervals of $\Delta\chi^2 < 10$



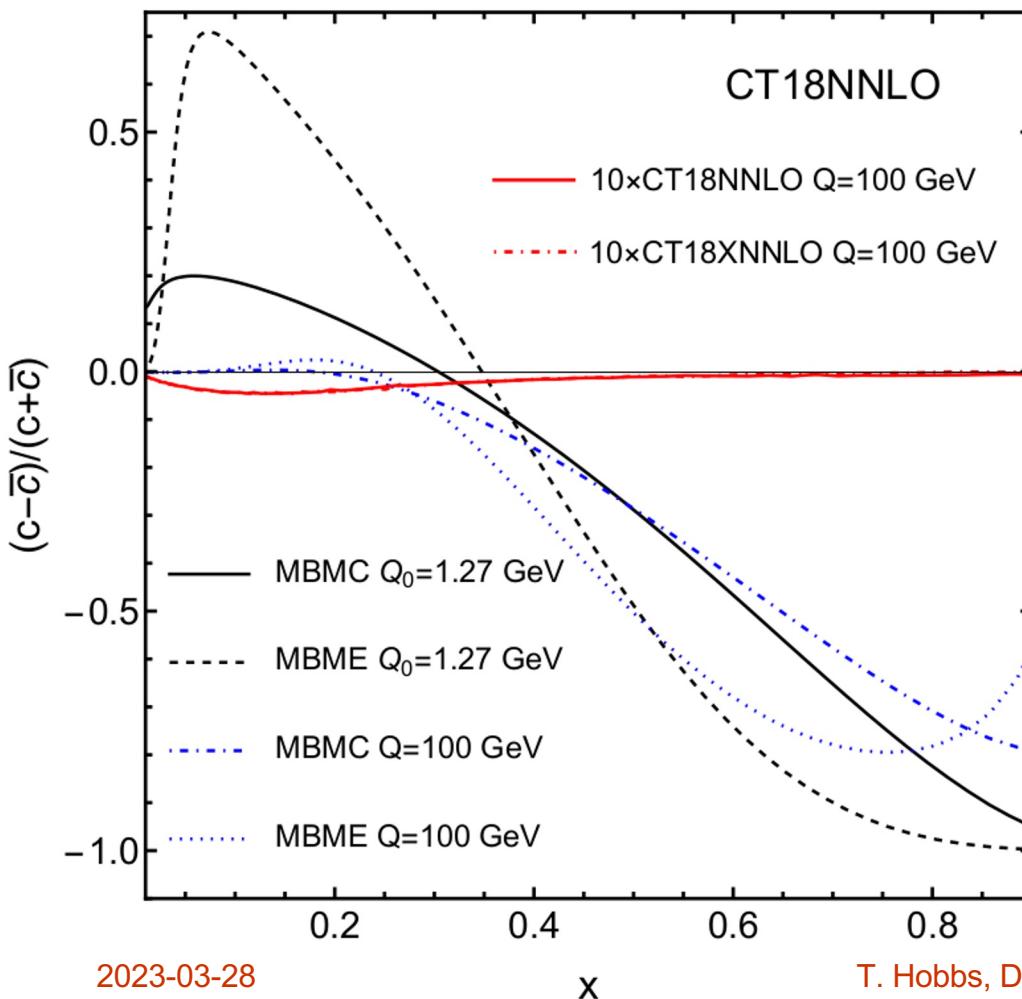
data pull opposingly on $\langle x \rangle_{\text{FC}}$; depend on FC scenario, enhancing error



possible charm-anticharm asymmetries

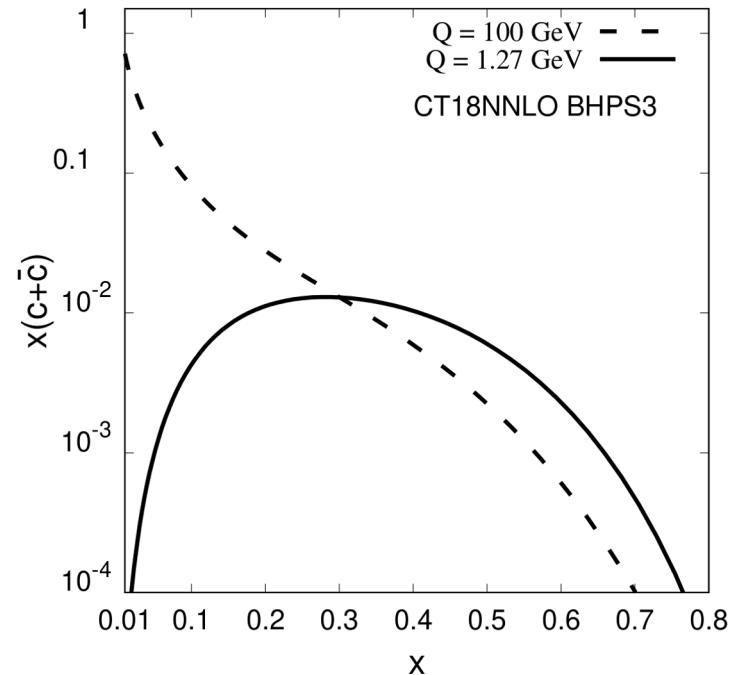
pQCD only very weakly breaks $c = \bar{c}$ through HO corrections

- 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)

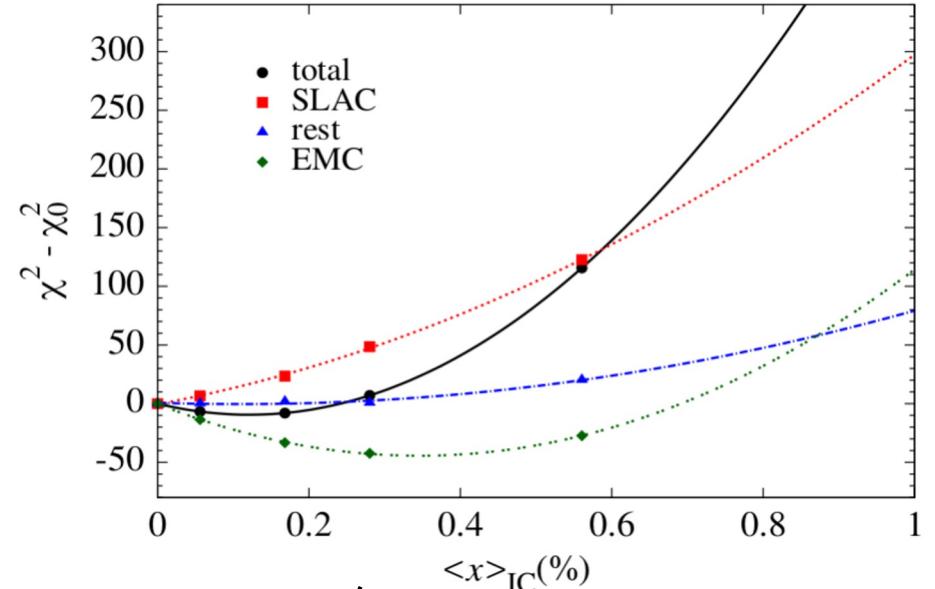
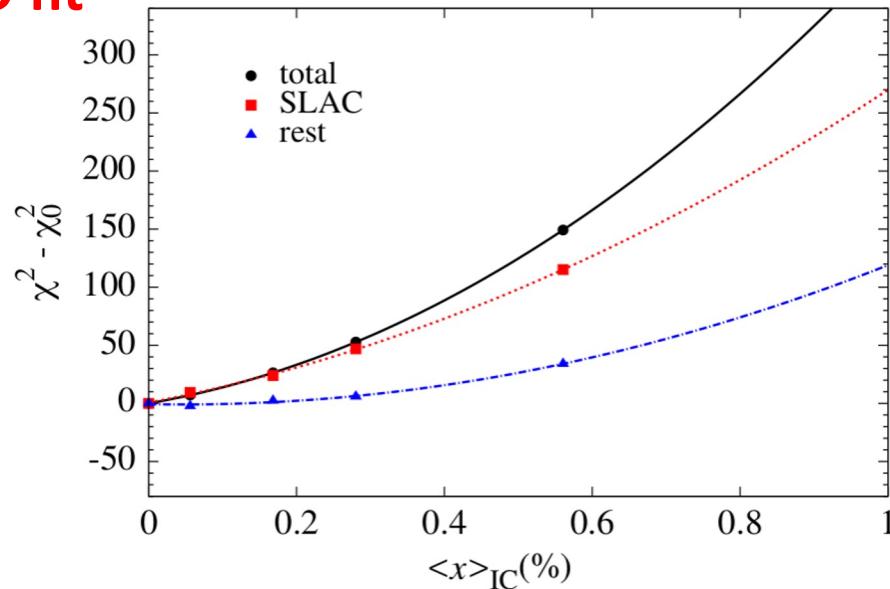
- asym. small but ratio (left) can be bigger; will be hard to extract from data



re: other studies → first full fit with EMC data; no signal for ‘IC’

P. Jimenez-Delgado, TJH, J. T. Londergan and W. Melnitchouk; PRL 114, no. 8, 082002 (2015).

NLO fit



‘SLAC + REST’ $\implies \langle x \rangle_{\text{IC}} < 0.1\%$; at 5σ !

‘REST’ only $\implies \langle x \rangle_{\text{IC}} < 0.1\%$; at 1σ



EMC alone: $\langle x \rangle_{\text{IC}} = 0.3 - 0.4\%$

+ SLAC/‘REST’: $\langle x \rangle_{\text{IC}} = 0.13 \pm 0.04\%$

...but $F_2^{c\bar{c}}$ poorly fit — $\chi^2 \sim 4.3$ per datum!

included SLAC DIS; used more restrictive tolerance criterion,
 $\Delta\chi^2 = 1$

recent NNPDF IC analysis

- NNPDF have recently claimed 3σ evidence for ‘IC’
 - based on local (x -dependent) deviation of FC PDF from the ‘no-FC’ scenario
 - implies crucial dependence on size and shape of PDF uncertainty

NNPDF, Nature 608 (2022) 7923, 483.

See Fig. 1 (left and right panels)

→ **Two classes of uncertainties need further scrutiny:**

1. Missing HO unc (MHOU): N3LO in DIS, etc.; N2LO in Z+c production

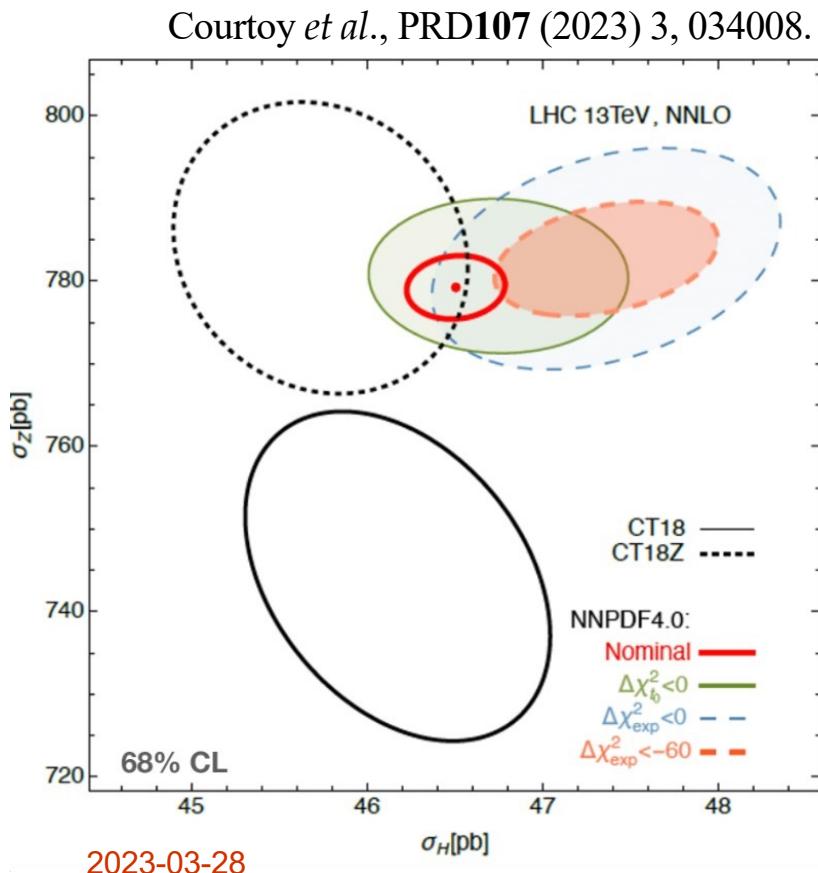
$$\langle x \rangle_{\text{FC}} = 0.62 \pm 0.28\% \quad \text{without MHOU}$$

$$\langle x \rangle_{\text{FC}} = 0.62 \pm 0.61\% \quad \text{with MHOU}$$

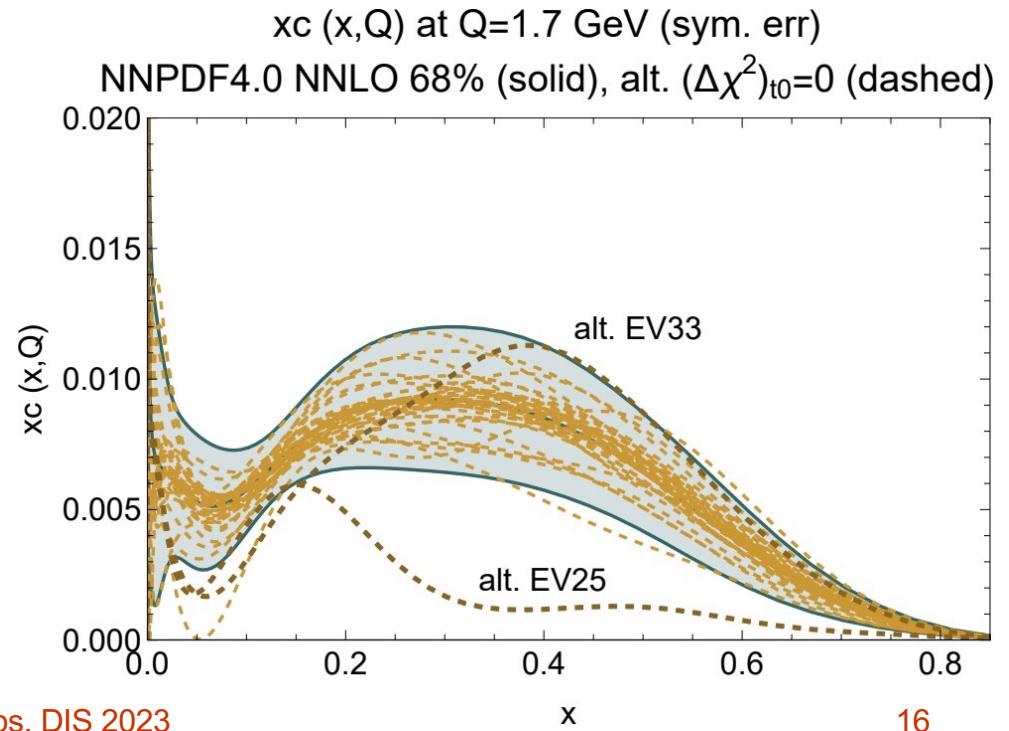
2. Parametrization sampling uncertainty (underestimation of PDFU)

more representative sampling can enlarge MC uncertainties

- default replica-training in MC studies may omit otherwise acceptable solutions
- more comprehensive sampling with the public NNPDF4.0 code impacts PDF errors of cross sections



- substantially broadens high- x FC error



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.

NNPDF, Nature 608 (2022) 7923, 483.

See Fig. 2 (lower-right panel)

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

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

conclusions

- size, shape of nonpert charm remains **indeterminate**
 - theoretical ambiguities in relation between FC/IC unresolved
 - need more sensitive data; FC currently consistent with zero

concordance with enlarged error estimates: $\langle x \rangle_{\text{FC}} \sim 0.5\%$, well below evidence-level

- need more NNLO and better showering calculations (*e.g.*, for $Z+c$)
- further progress in quantifying and estimating PDF uncertainties

opportunities to improve knowledge of FC:

- promising experiments at LHC; EIC; CERN FPF
- lattice data on key charm PDF moments; quasi-PDFs
- direct benchmarking of FC among PDF fitting groups