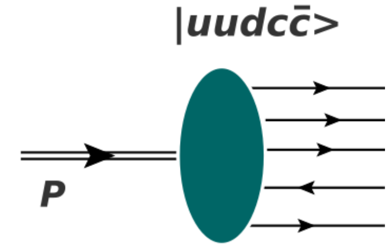
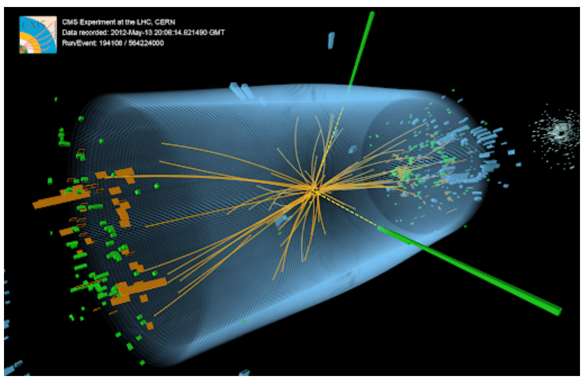
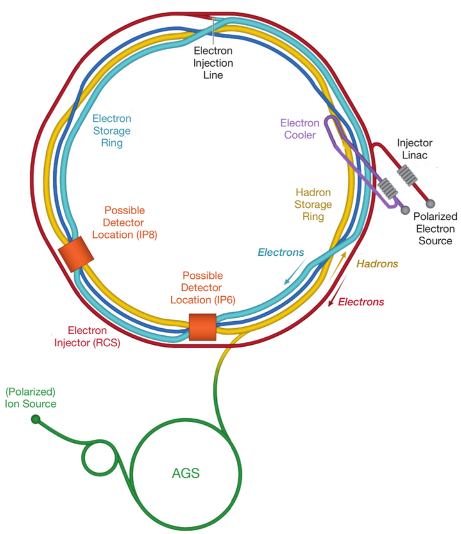
the proton's intrinsic charm remains concealed

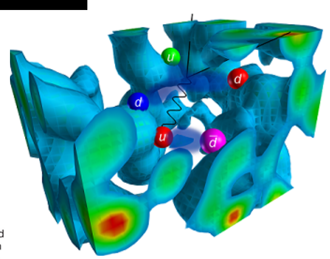
Tim Hobbs – Argonne National Lab

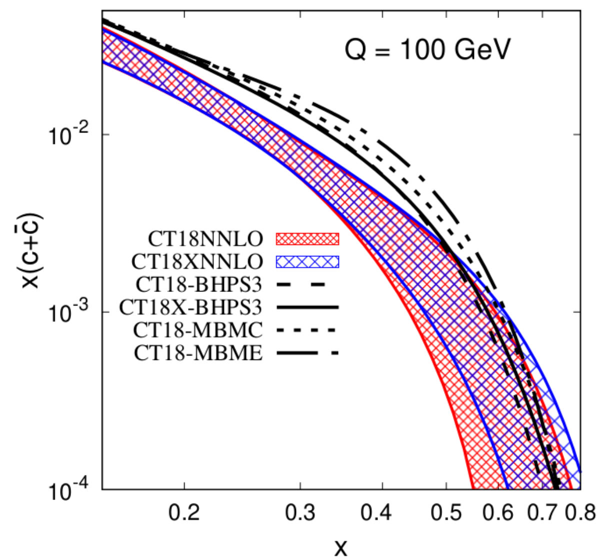
Argonne NATIONAL LABORATORY

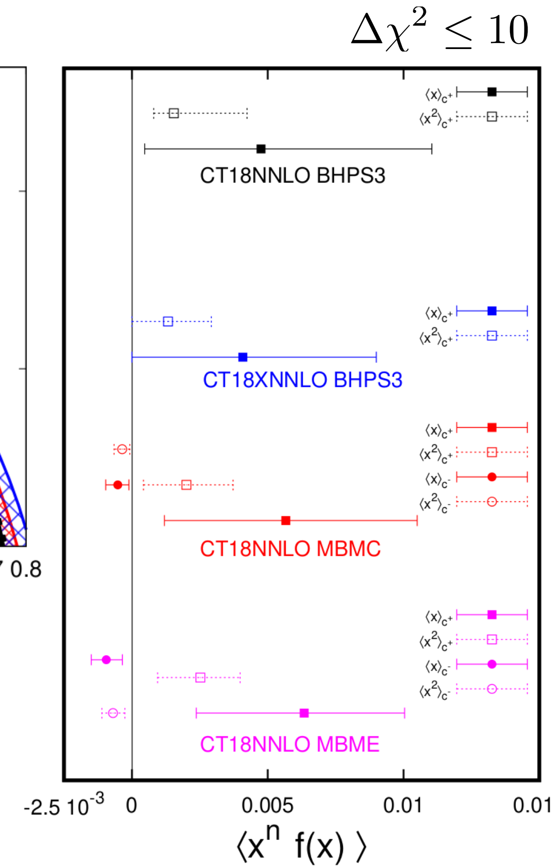












NEW

arXiv: 2211.01387

CT18 FC: revisiting nonperturbative or *fitted charm* (FC)

CTEQ

- reassess status of FC, especially following recent LHC data

extended talk tomorrow (7:30am CST), International Light Cone Advisory Committee [ILCAC]

recent paper, arXiv: 2211.01387

M. Guzzi, T. Hobbs, K. Xie, J. Huston, P. Nadolsky, and C.-P. Yuan

→ for the CTEQ-Tung et al. (CTEQ-TEA) Collaboration

this talk

i intrinsic charm (IC) vs. fitted charm (FC) in QCD

ii treatment of key **expts** with potential FC sensitivity

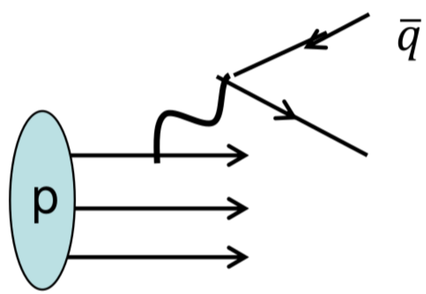
iii CT18 FC PDF analysis

iv comparison with other recent FC studies

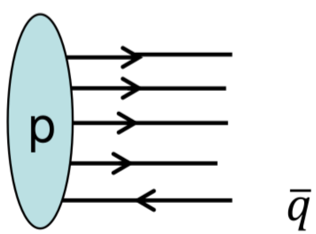
conclusion(s): necessary developments; high-impact data, calculations

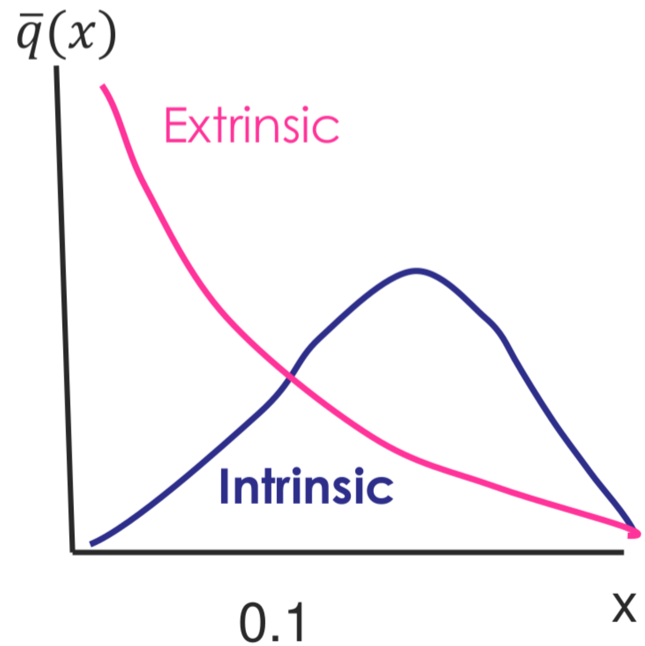
Extrinsic and intrinsic sea PDFs in nonperturbative models

"Extrinsic" sea
[maps on leading-power sea production from light flavors]



"Intrinsic" sea (excited Fock nonpert. states; beyond the leading-power production)



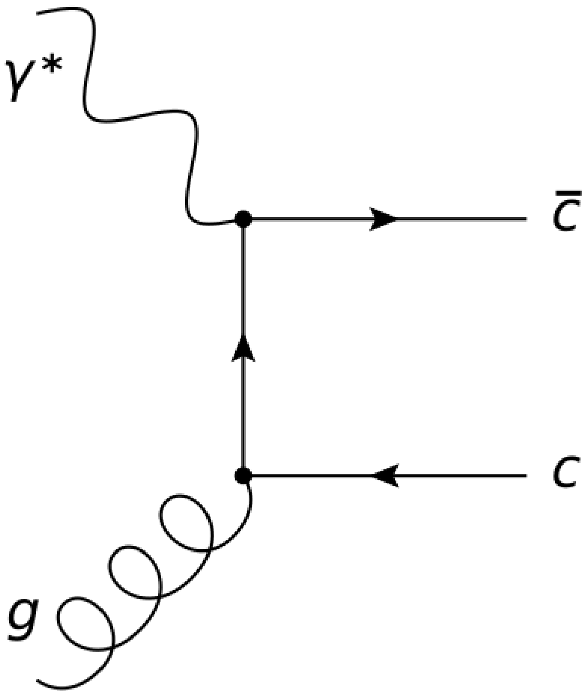


→ "intrinsic" charm (IC) from nucleon WF models based on this picture

…"extrinsic" generated radiatively; calculable in pQCD

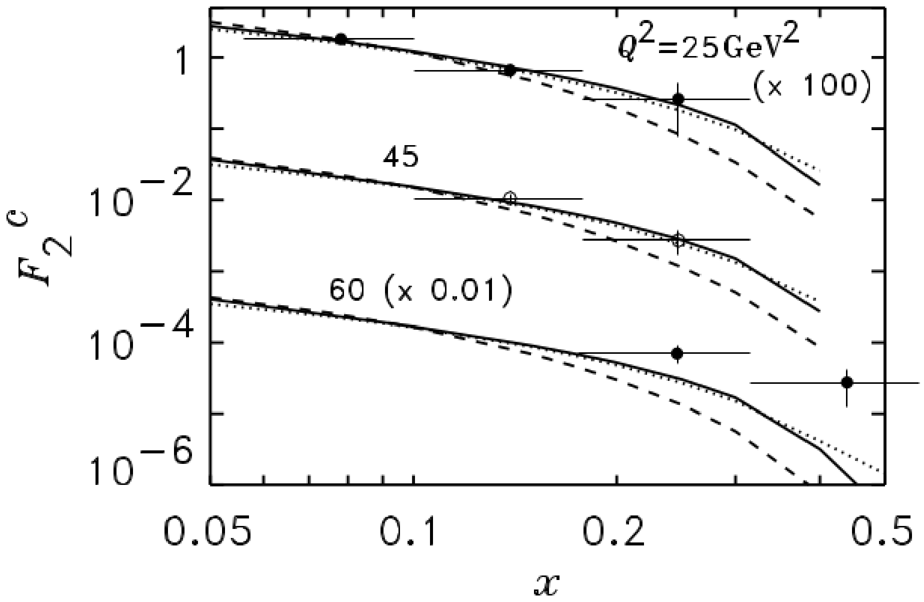
implementations of perturbative ('extrinsic') charm in QCD analyses

- $c(x, Q^2 \leq m_c^2) = \bar{c}(x, Q^2 \leq m_c^2) = 0$ (a vanishing boundary condition for perturbative evolution)



$\rightarrow$

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



- *intermediate* Q^2:

$$F^c_{2,\ \mathrm{PGF}}(x, Q^2) \;=\; \frac{\alpha_s(\mu^2)}{9\pi} \int_x^{z'} \frac{dz}{z}\, C^{\mathrm{PGF}}(z, Q^2, m_c^2) \cdot xg\left(\frac{x}{z}, \mu^2\right)$$

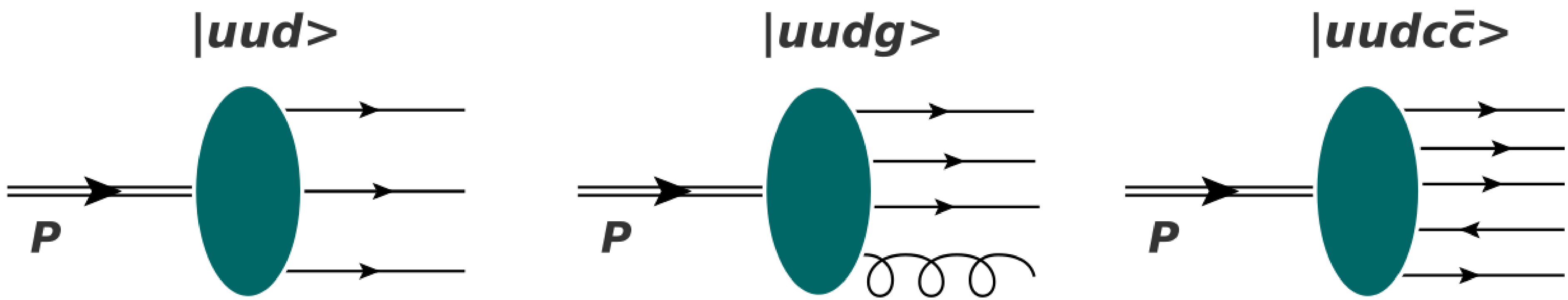
- *high* Q^2:

  massless **DGLAP** (i.e., *variable flavor-number* schemes)

nonperturbative QCD can generate a low-scale charm PDF

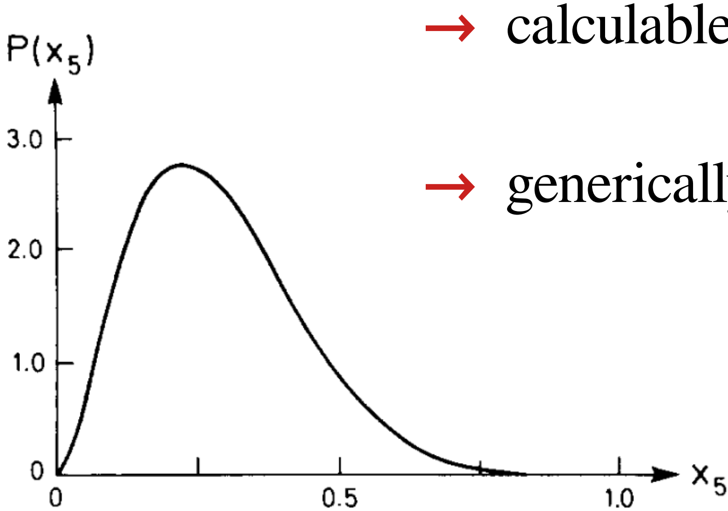
Fock expansion

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



- IC PDF: transition matrix element, $|\text{proton}\rangle \to |uudc\bar{c}\rangle$

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



→ calculable in old-fashioned perturbation theory; **scalar** field theory

→ generically yields valence-like shape; governed by charm masses

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

- alternative but similar representations exist

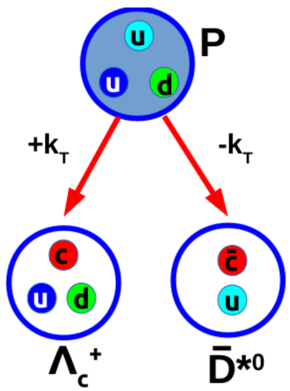
Blumlein; Phys. Lett. **B753** (2016) 619.

meson-baryon models (MBMs): 5-quark states from hadronic interactions

- we implement a framework which *conserves* **spin/parity**

- **nonperturbative** mechanisms are needed to break
  $c(x, Q^2 \leq m_c^2) = \bar{c}(x, Q^2 \leq m_c^2) = 0!$

We build an **EFT** which connects IC to properties of the hadronic spectrum: [TJH, J. T. Londergan and W. Melnitchouk, Phys. Rev. D89, 074008 (2014).]

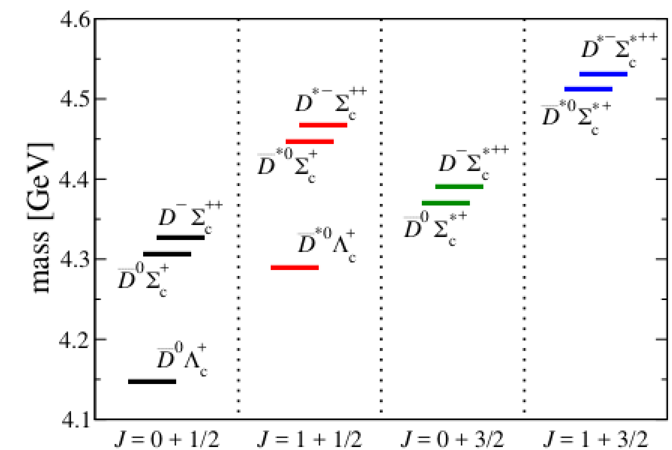


- $|N\rangle = \sqrt{Z_2}\,|N\rangle_0 + \sum_{M,B} \int dy\, f_{MB}(y)\, |M(y); B(1-y)\rangle$

$y = k^+/P^+$: k meson, P nucleon

$$c(x) = \sum_{B,M} \left[\int_x^1 \frac{d\bar{y}}{\bar{y}}\, f_{BM}(\bar{y})\, c_B\!\left(\frac{x}{\bar{y}}\right) \right]$$

- a similar *convolution* procedure may be used for $\bar{c}(x)$ . . .



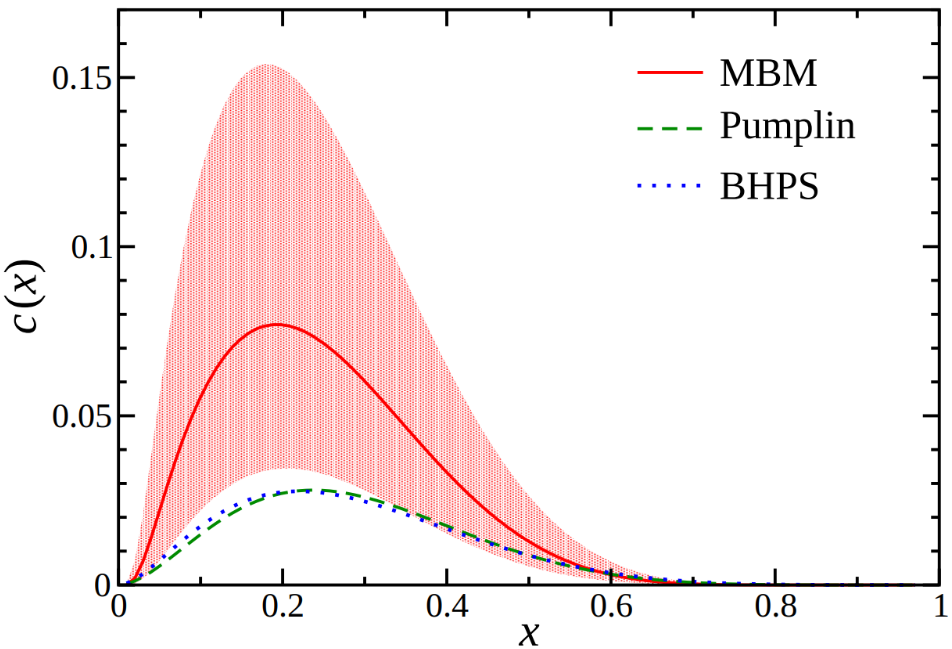
i

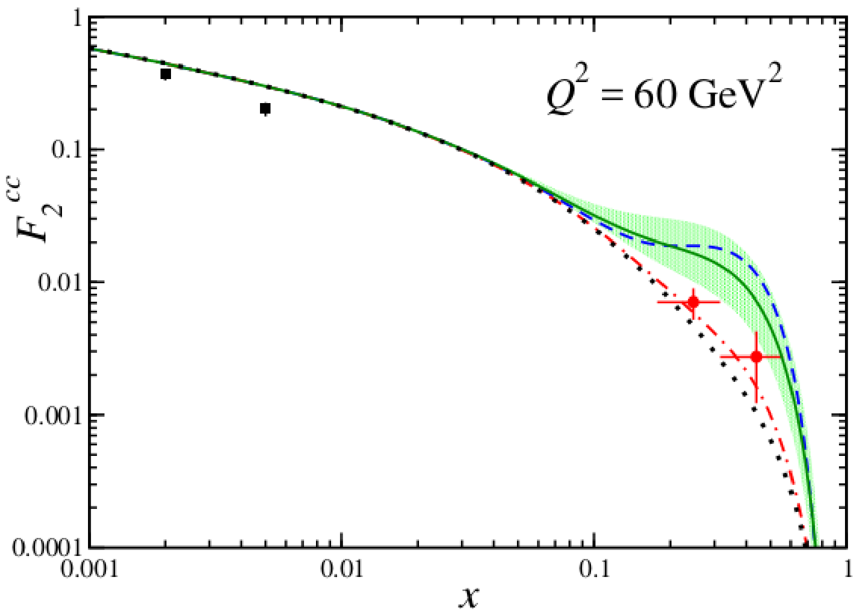
IC (MBM) depends on UV scale parameter, Λ; predicts high-x excess

- tune **universal** cutoff $\Lambda = \hat{\Lambda}$ to fit **ISR** $pp \to \Lambda_c X$ collider data

multiplicities, **momentum sum**:

$$\langle n \rangle^{(\mathrm{charm})}_{MB} \;=\; 2.40\% \; {}^{+2.47}_{-1.36}; \qquad P_c := \langle x \rangle_{\mathrm{IC}} \;=\; 1.34\% \; {}^{+1.35}_{-0.75}$$





$$F_2^{c\bar{c}}(x, Q^2) = \frac{4x}{9}\left[c(x, Q^2) + \bar{c}(x, Q^2)\right]$$

$\to$ evolve to EMC scale, $Q^2 = 60\ \mathrm{GeV}^2$

low-x H1/ZEUS data check *massless* **DGLAP** evolution i

IC models and **formal QCD**

- models simulate nucleon wave function; aim to *mimic* nonpert QCD
  - → bound-state structure driven by constituent-quark masses
  - → integrate away gluonic degrees-of-freedom
  - → connect to SU(4) flavor-symm breaking (in meson-baryon models [MBMs])

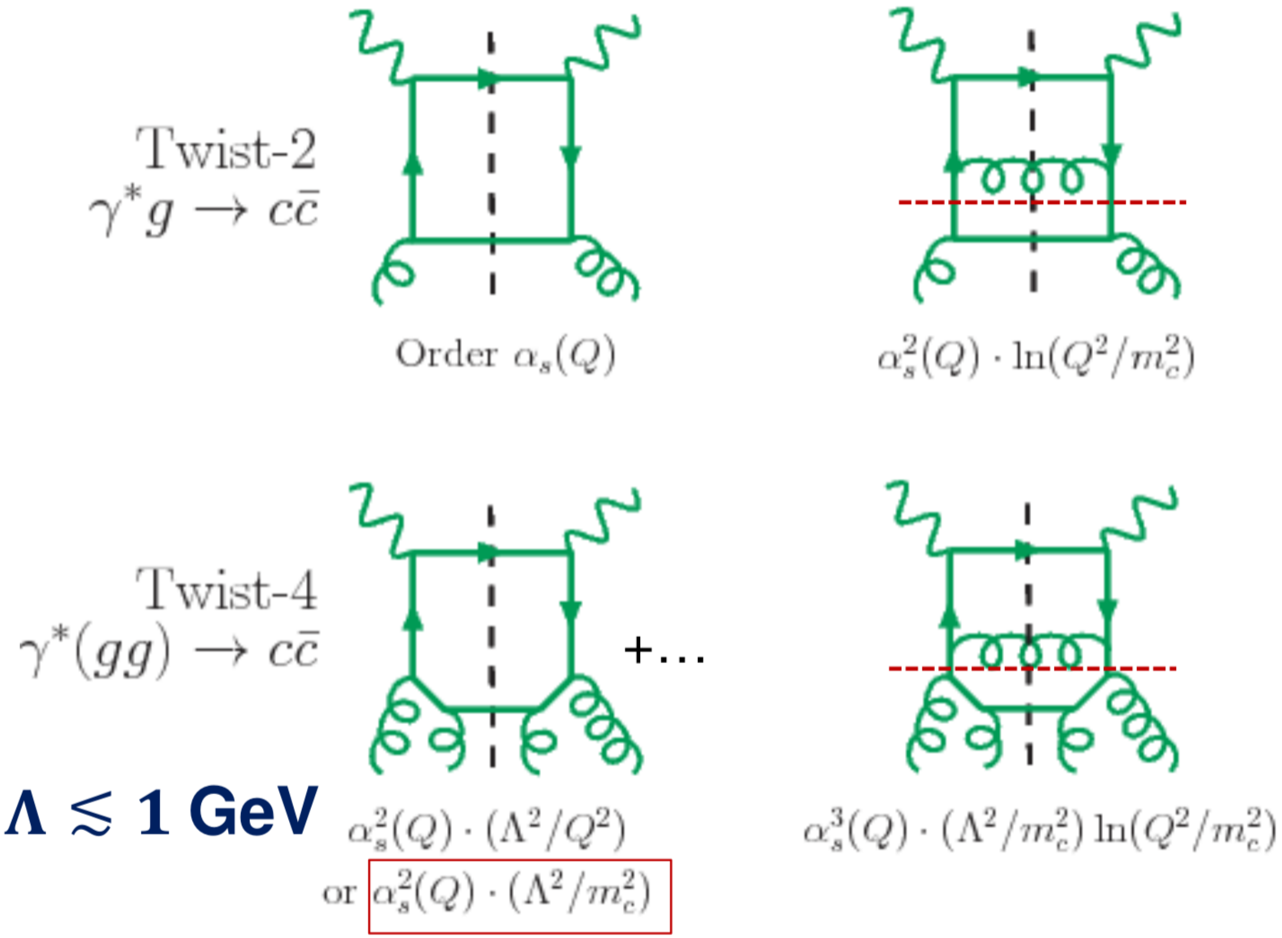
- <u>BUT</u>: IC models in systematically-improvable QCD calculations unclear
  - → based on *truncated* Fock-state or similar wave function expansions
  - → no obvious mapping onto factorization theorems
  - → ambiguity regarding fact. scale, μ, in IC models

$$F(x,Q) = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a \left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha_s(\mu) \right) f_{a/p}(\xi,\mu) + \mathcal{O}(\Lambda^2/m_c^2, \Lambda^2/Q^2)$$

- PDF analyses extract <u>fitted charm</u> (FC) ≠ intrinsic charm (IC)

IC may have complicated interplay with nonleading twist

- IC can be developed in twist expansion; systematic ordering of leading-, power-suppressed contributions



- control needed to avoid absorbing non-universal contributions into IC

formalism in CT14 IC, arXiv: 1707.00657

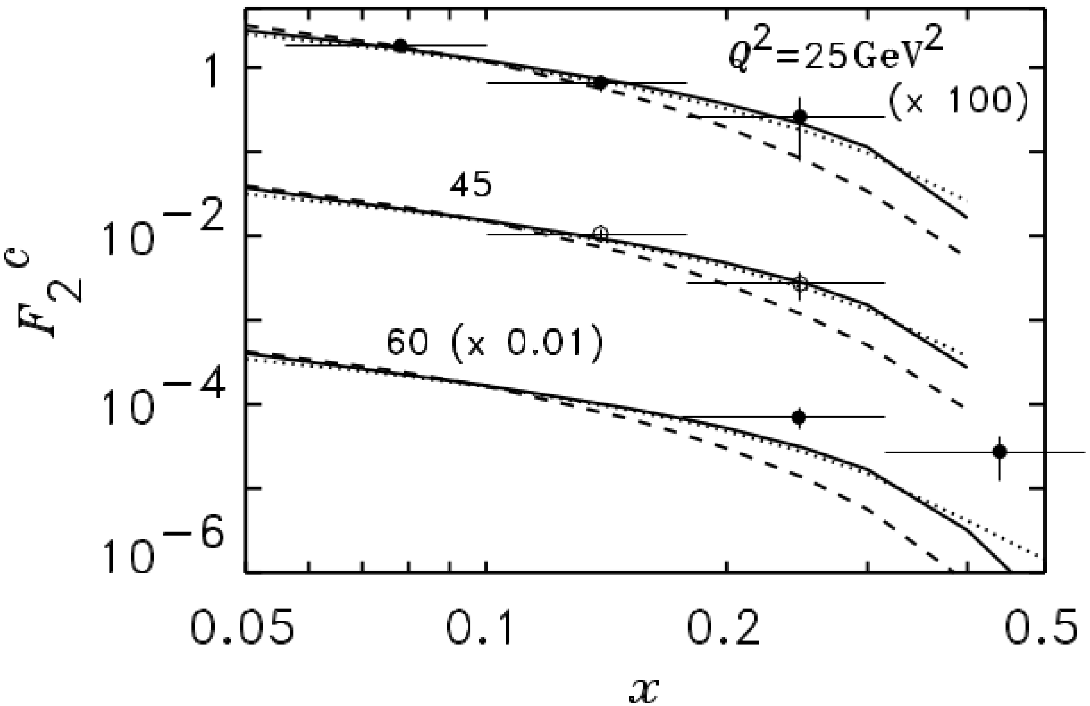
ii

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

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

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

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



→ 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

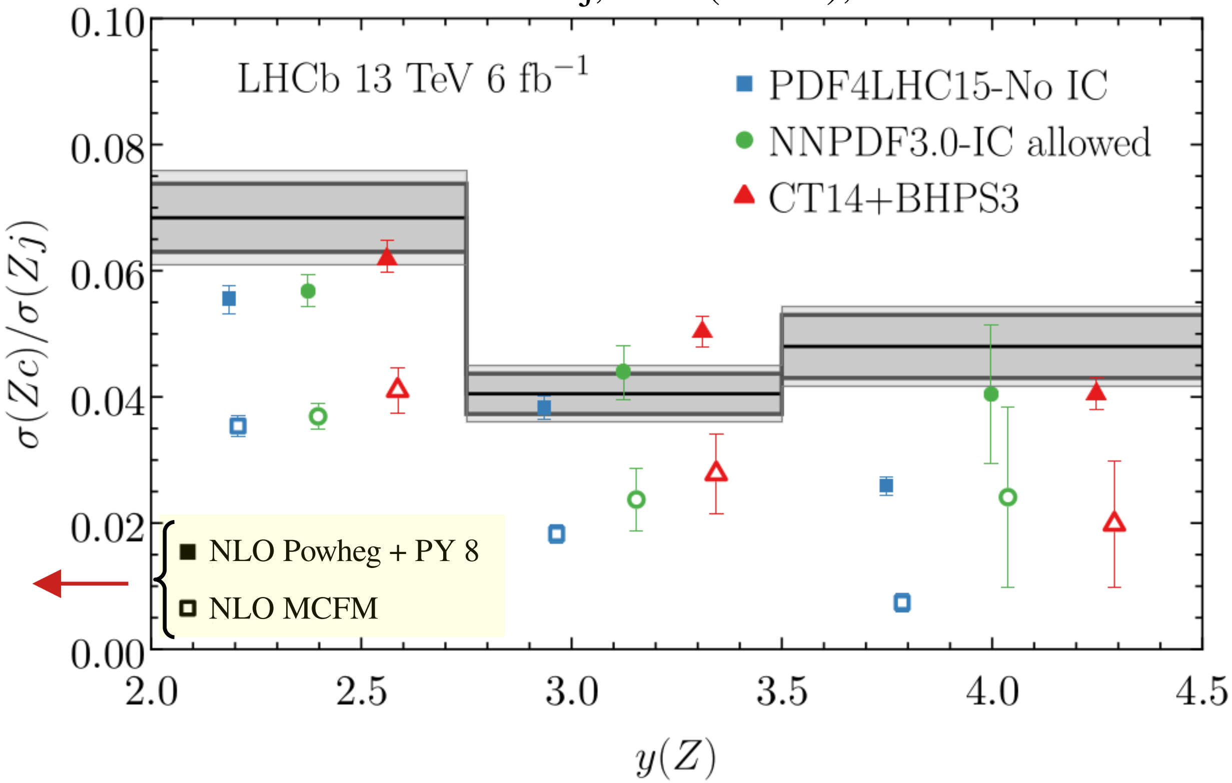
Z+c potentially sensitive to IC; sizable theory uncertainties

T. Boettcher, P. Ilten, M. Williams, 1512.06666

- 2022 LHCb 13 TeV data: (Z+c) / (Z+*jet*) ratios; 3 rapidity bins

  → calculated **NLO** cross-section ratio similarly depends on showering, hadronization

R. Aaij, *et al.* (LHCb); arXiv: 2109.08084.



$$x \sim \frac{Q}{\sqrt{s}} \exp y$$

differ due to large FSR correction ←

- NNLO calculations recently available, but not implemented in PDF fits

R. Gauld, *et al.*; arXiv: 2005.03016.

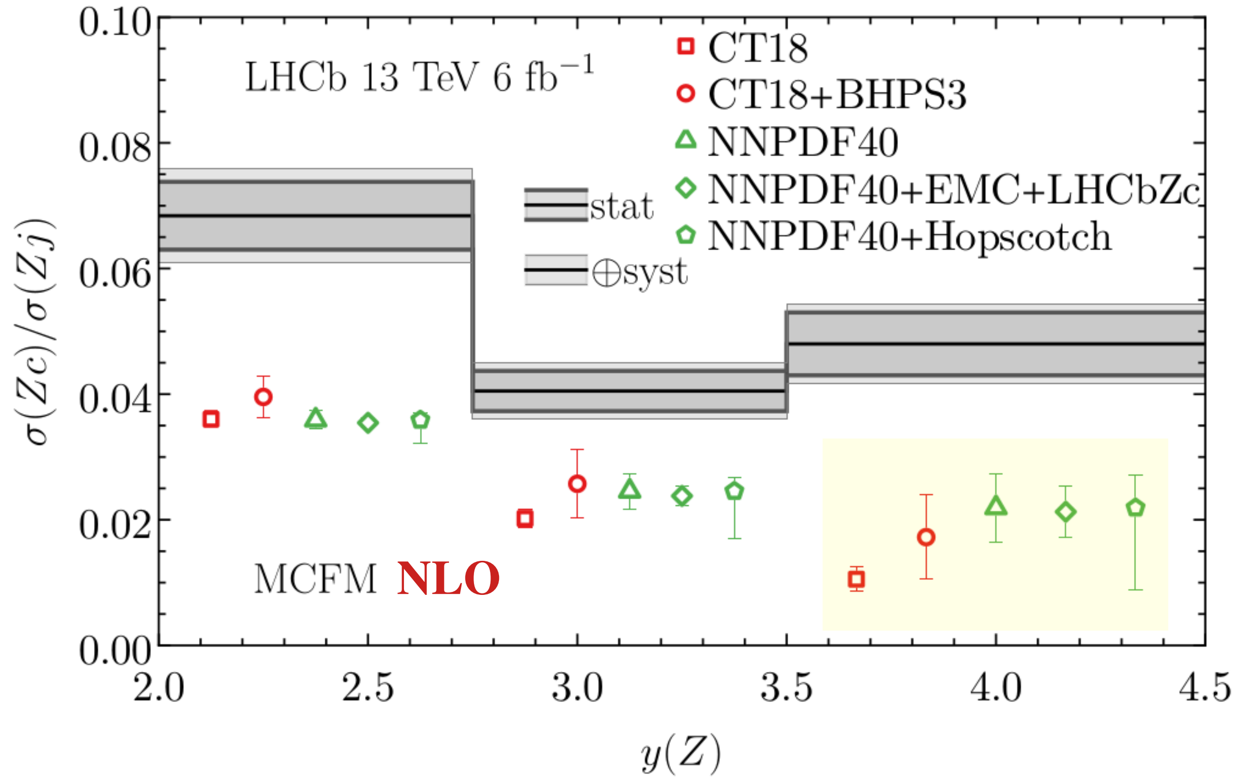
M. Czakon, *et al.*; arXiv: 2011.01011.

theory uncertainties currently larger than PDF variations

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

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

R. Aaij, *et al.* (LHCb); arXiv: 2109.08084.



$$x \sim \frac{Q}{\sqrt{s}} \exp y$$

- theory accuracy not yet sufficient to leverage expt. precision for PDFs

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

might other HEP experiments be sensitive to FC?

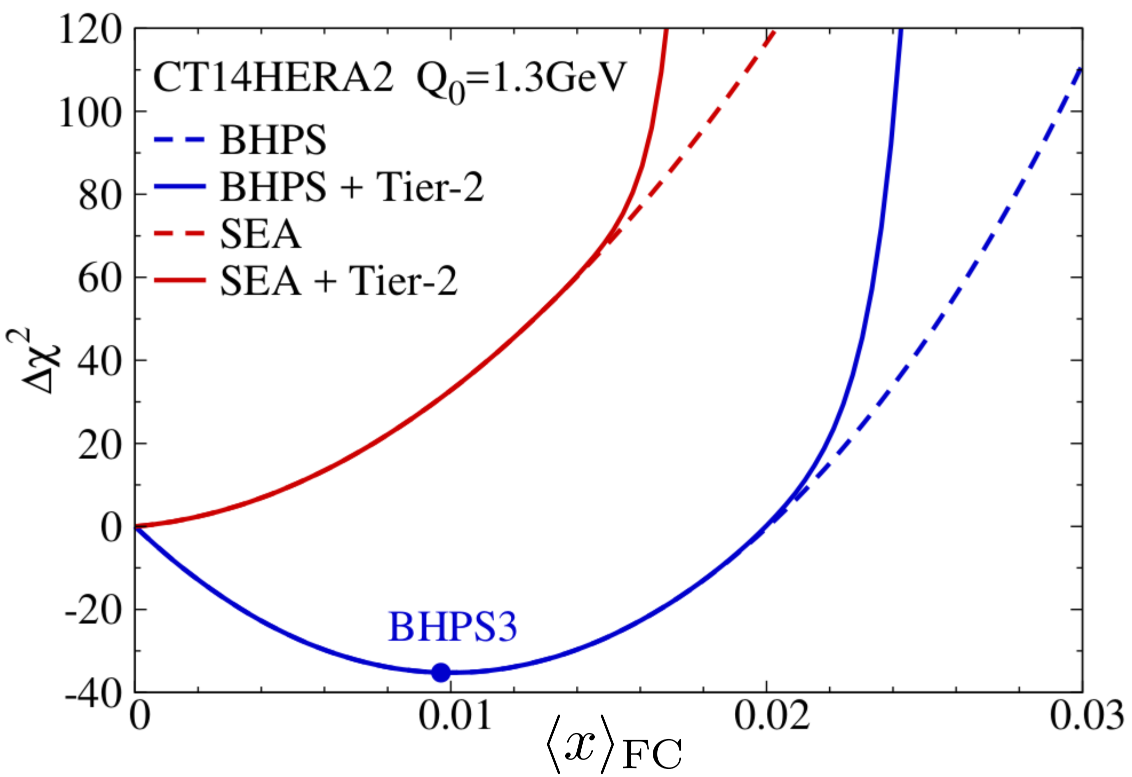
- **must be assessed using comprehensive global QCD analysis of PDFs**

- CT performed such an analysis, CT14 IC in arXiv: 1707.00657

→ found $\langle x \rangle_{\rm FC} < 2\%$, but with large uncertainty consistent with zero FC

$$\langle x \rangle_{\rm FC} = \int_0^1 dx\, x [c(x, Q_0) + \bar{c}(x, Q_0)]$$

- **included many details on theory and analysis of IC**



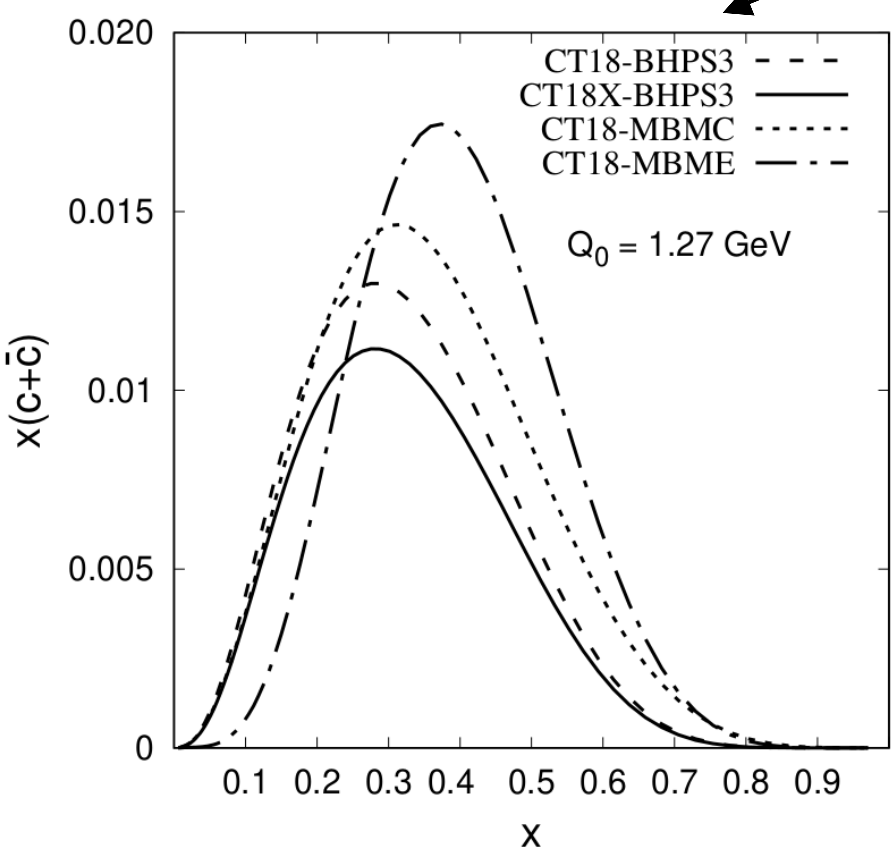
- since CT14 IC, many LHC measurements have been released; natural to ask if these possess *collective* sensitivity to FC

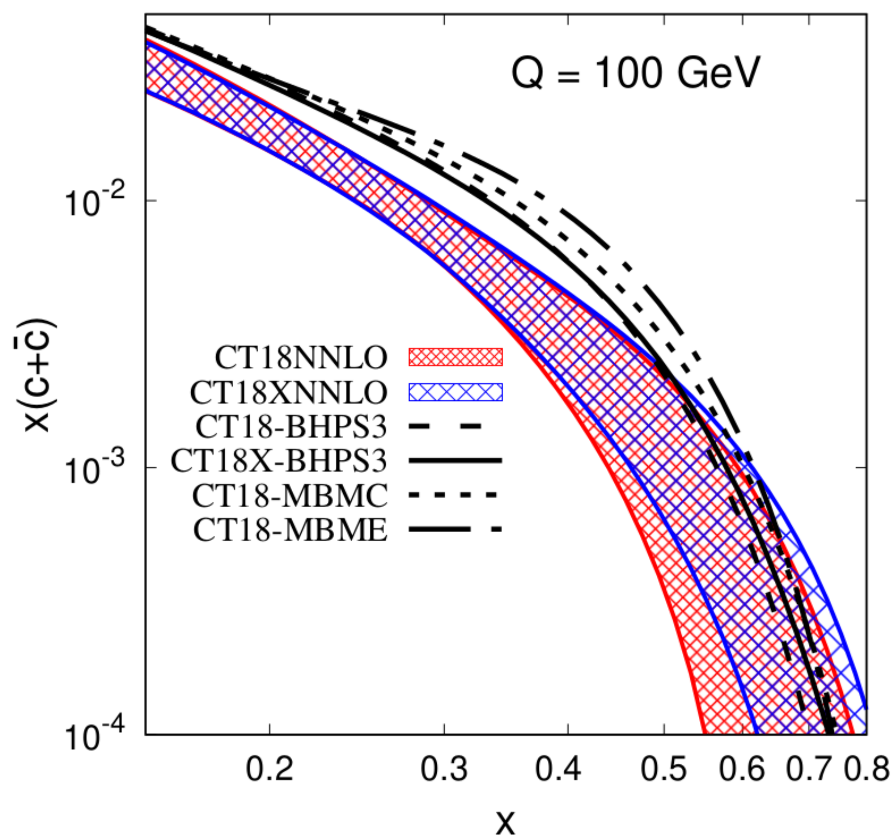
CT18 FC total charm PDFs

- 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

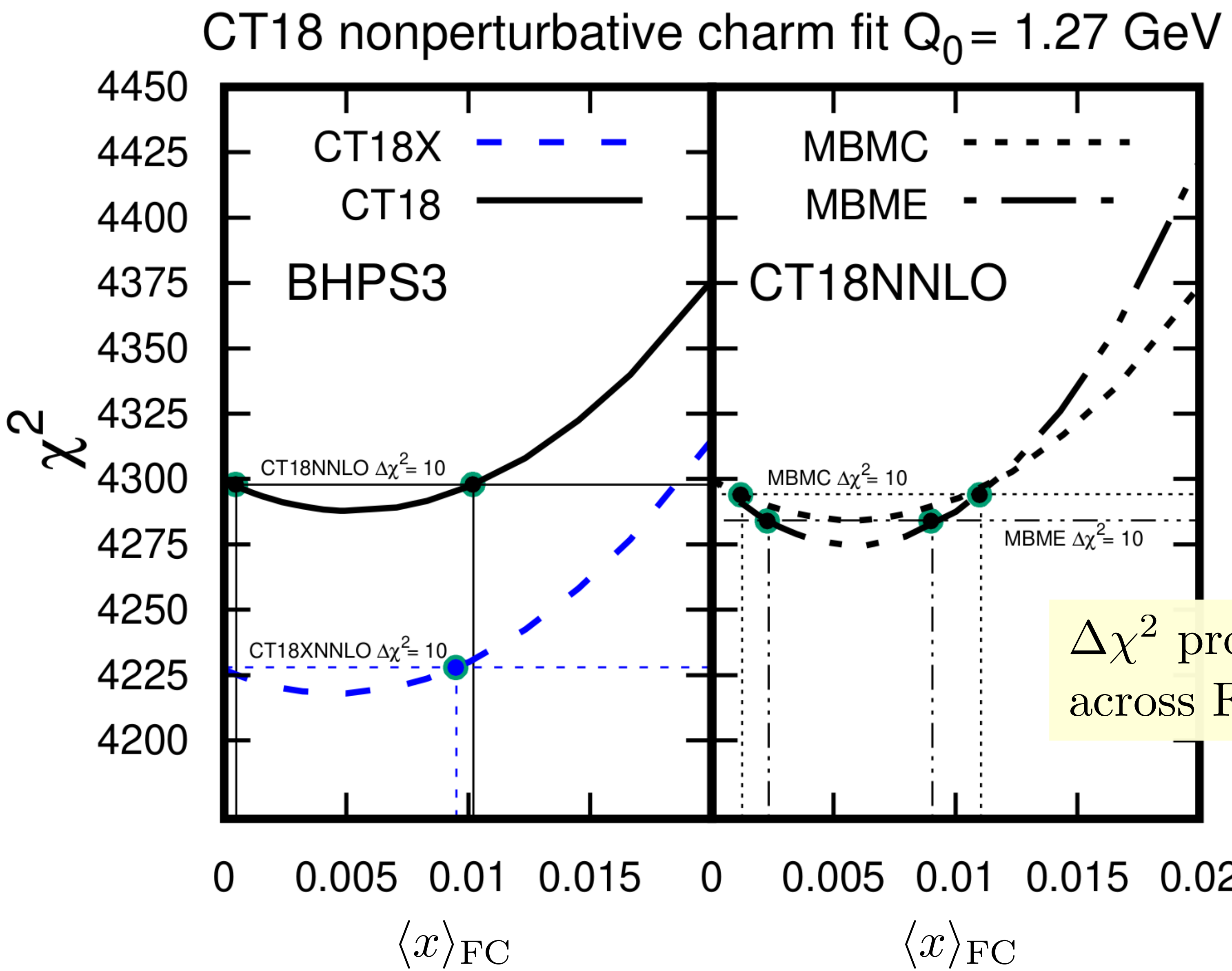




signal for FC in CT18 study, but with shallower $\Delta\chi^2$ than CT14 IC

- 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

iii

FC PDF moments as F.o.M.

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

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

...at NNLO.

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

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

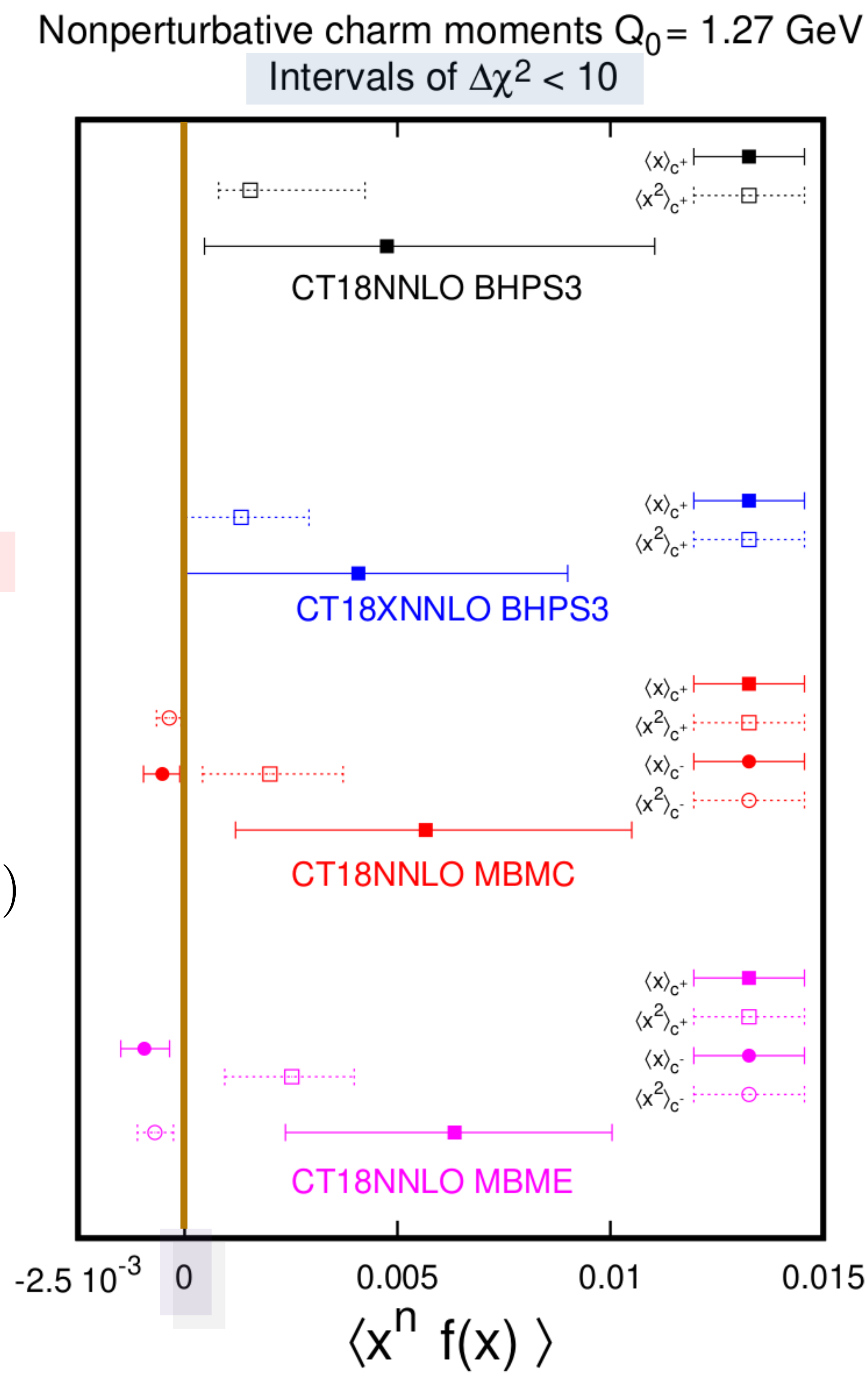
$$= 0.0041\,^{+0.0049}_{-0.0041}\,\left(^{+0.0091}_{-0.0041}\right),\ {\rm CT18X\ (BHPS3)}$$

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

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

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

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



iii FC PDF moments as F.o.M.

- **even restrictive uncertainties give moments consistent with zero**

→ broaden further for default CT tol.

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

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

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

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

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

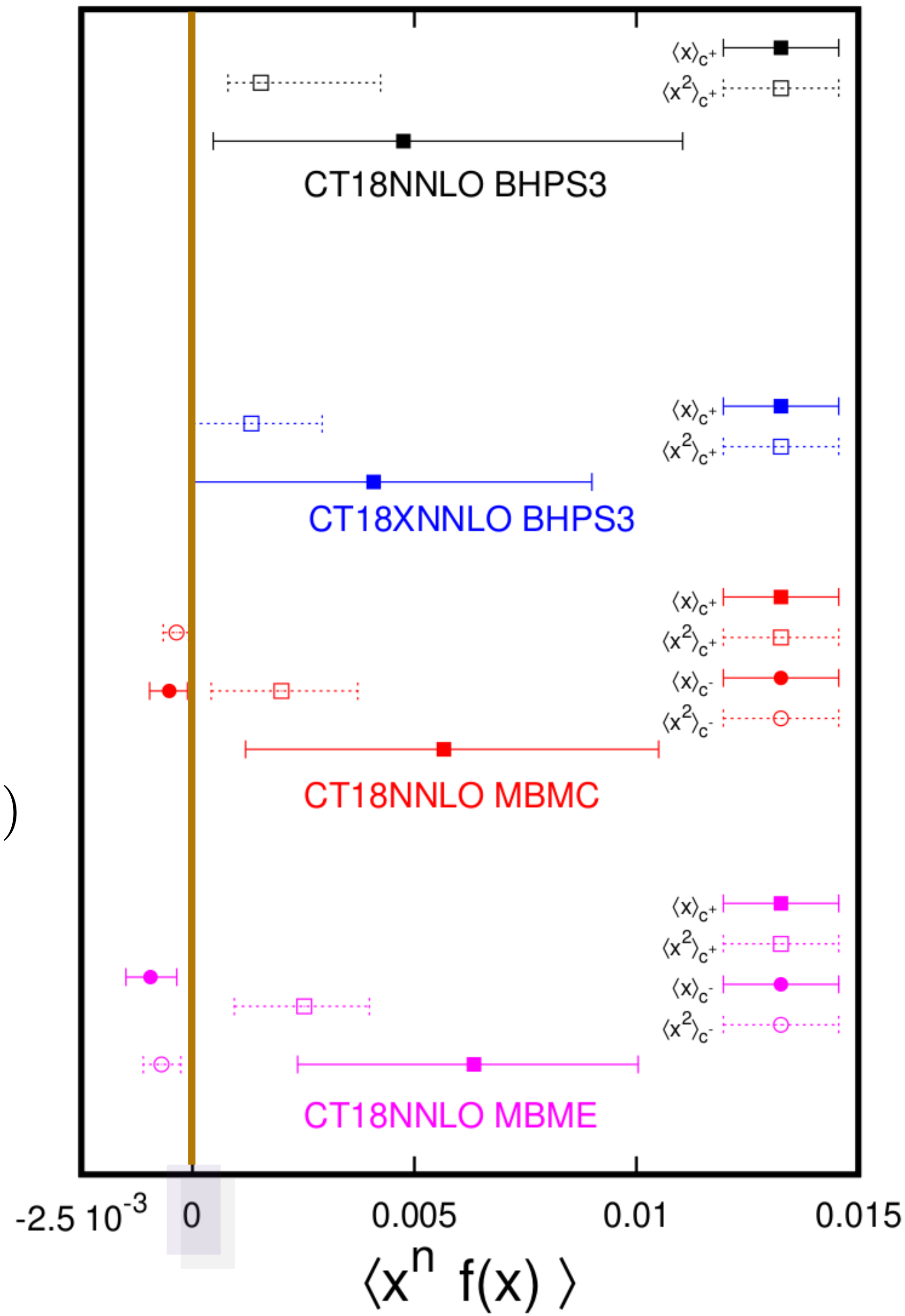
$$= 0.0061\,^{+0.0030}_{-0.0038}\ \left(^{+0.0064}_{-0.0061}\right),\ \mathrm{CT18\ (MBME)}$$

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

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

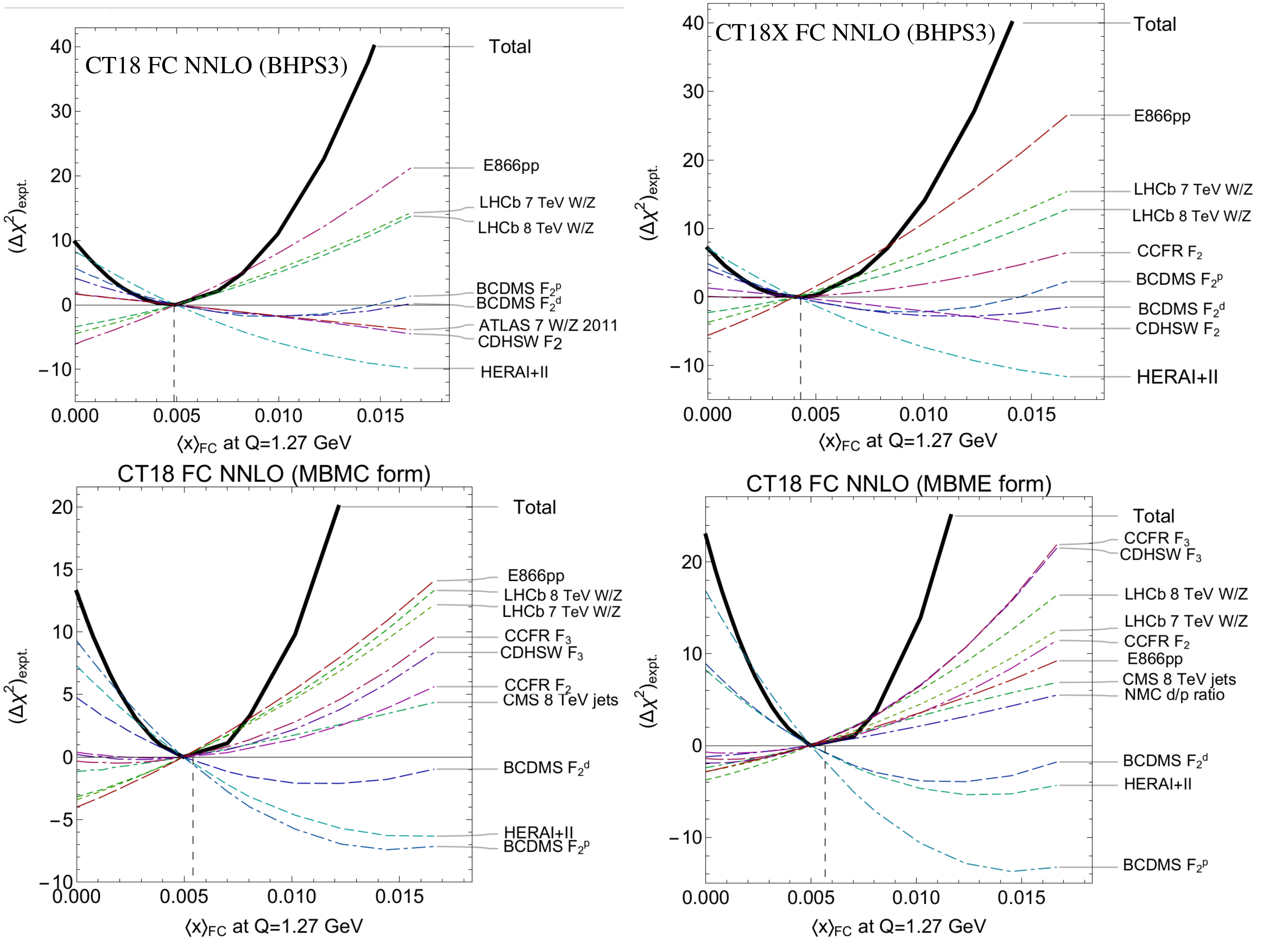
Nonperturbative charm moments Q_0= 1.27 GeV

Intervals of $\Delta\chi^2 < 10$



iii

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



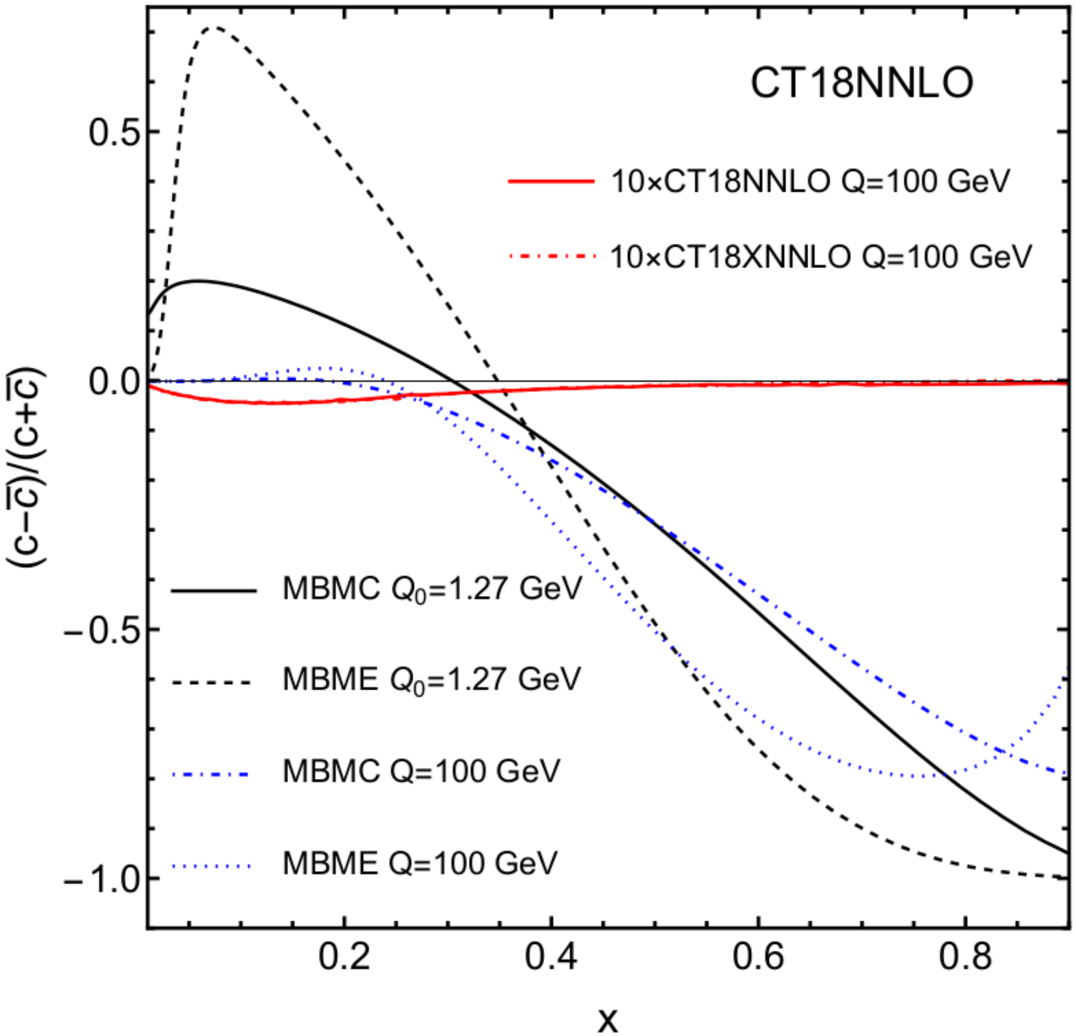
iii

possible charm-anticharm asymmetries

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

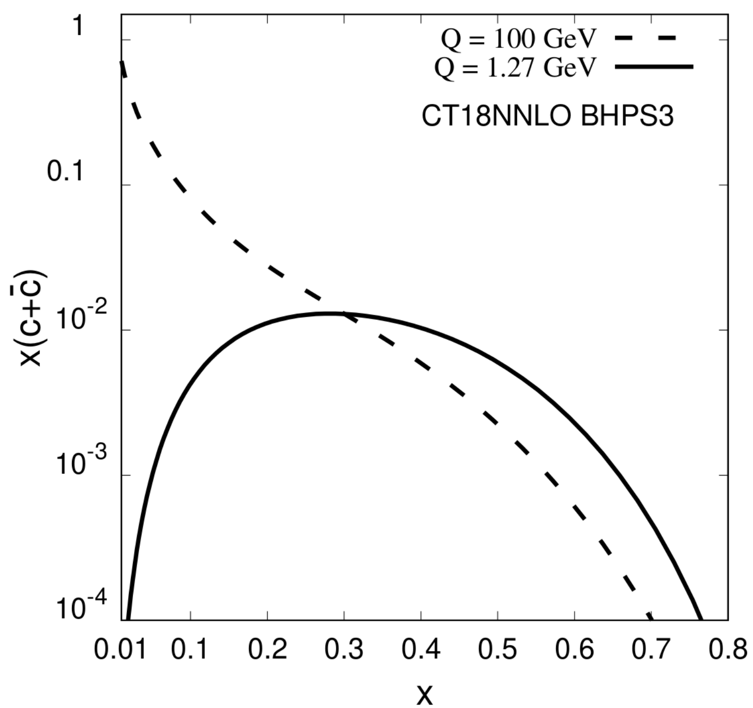
  → large(r) charm asymmetry would signal nonpert dynamics, IC

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



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

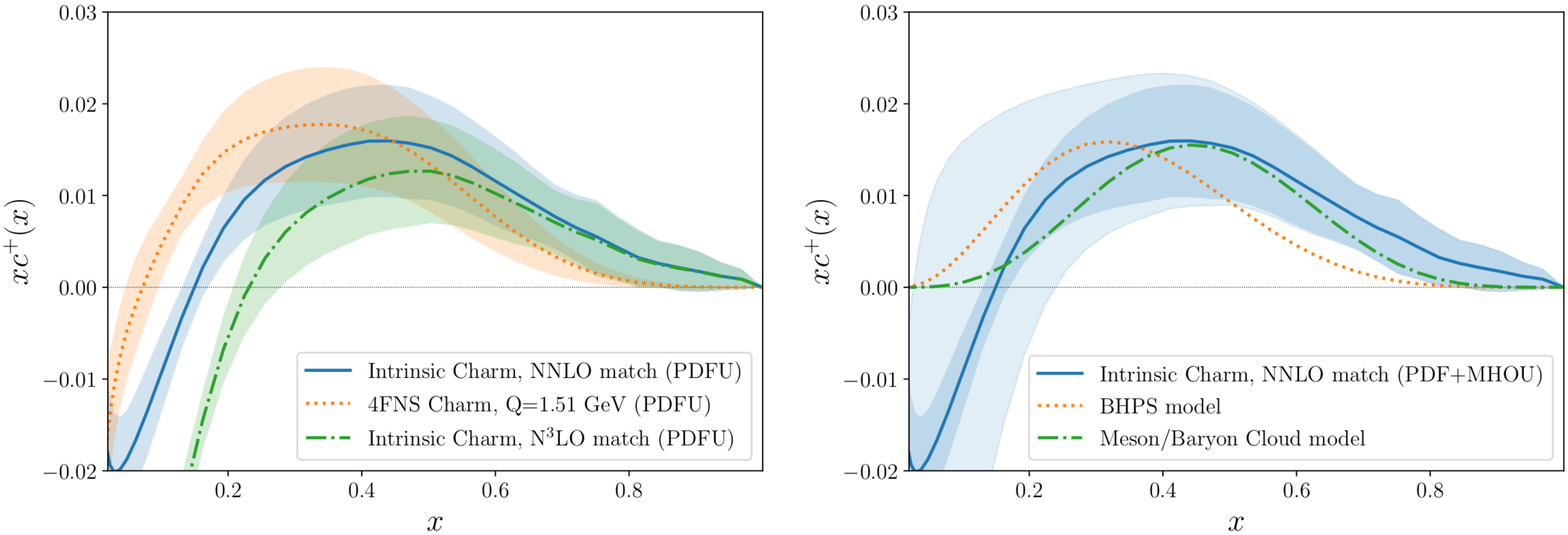
→ asym. small but ratio (left) can be bigger; will be hard to extract from data



recent NNPDF IC analysis

NNPDF, Nature 608 (2022) 7923, 483.

- NNPDF have recently claimed 3σ evidence for 'IC'
  - → based on local (x-dependent) deviation of FC PDF from perturbative scenario
  - → implies crucial dependence on size and shape of PDF uncertainty



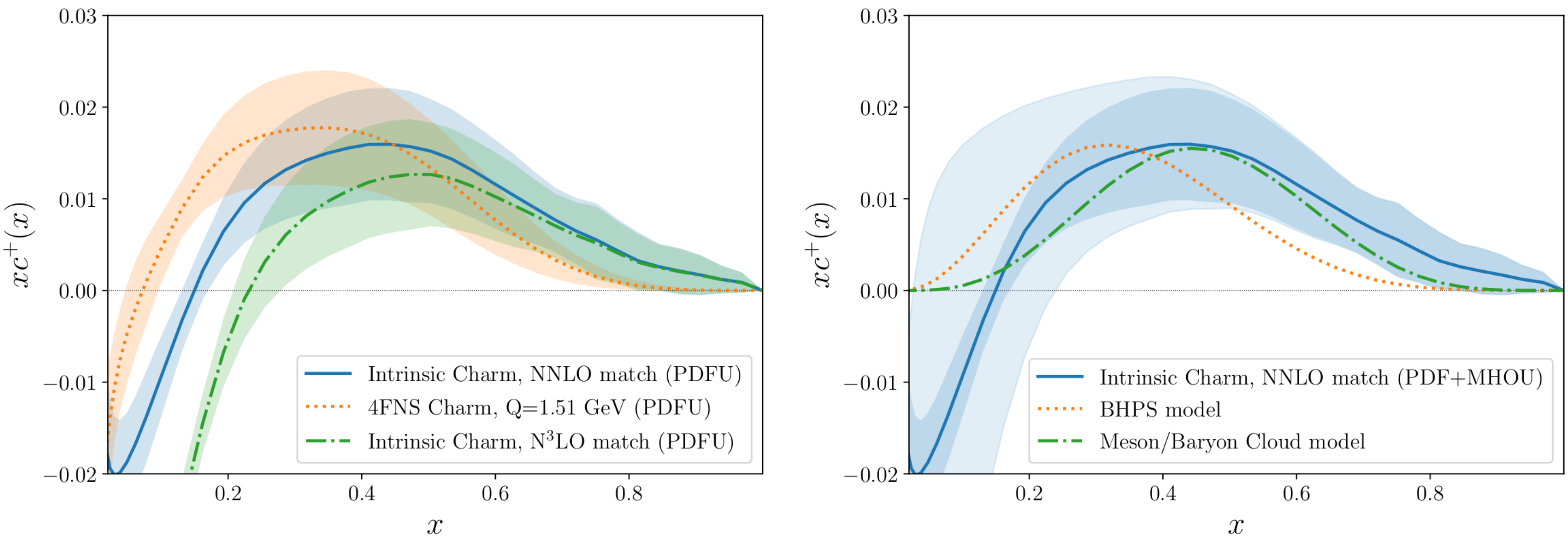
  - → NNPDF FC distribution is particularly hard, peaking at $x \gtrsim 0.4$
  - → intriguing behavior at low x

iv

NNPDF IC, PDFs and moments

NNPDF, Nature 608 (2022) 7923, 483.

- large perturbative instability from MHOU affects low-*x* behavior
  - → matching at fixed NNLO gives negative FC, unlike IC models
  - → MHOU persists to quite high $x < 0.1$ or more



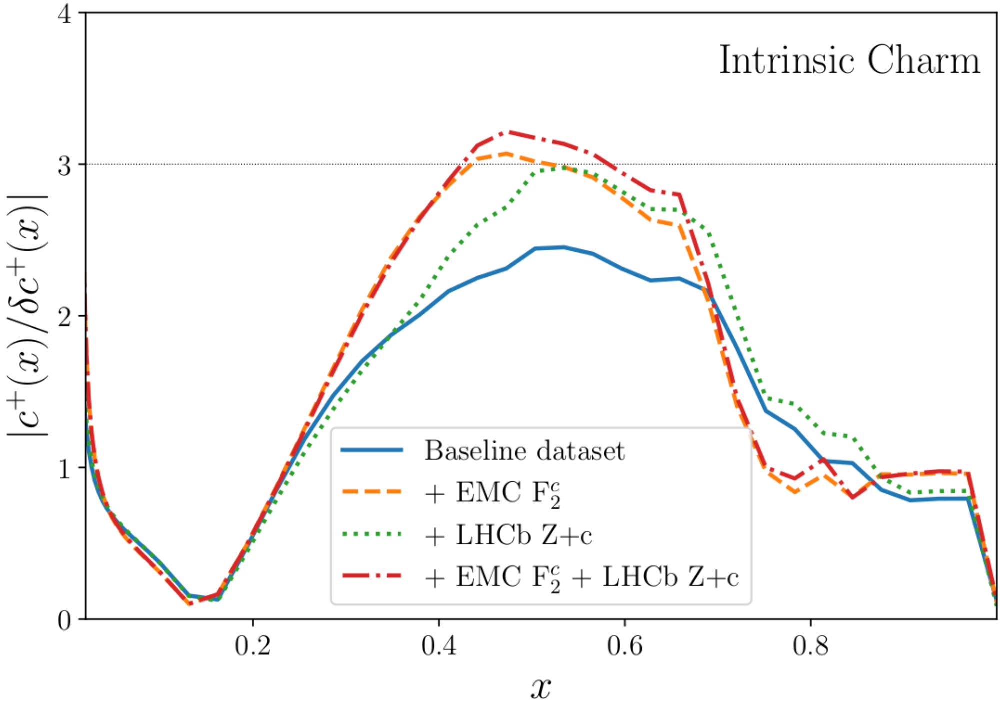
- → MHOU excluded to obtain a nominal charm fraction, $\langle x \rangle_{\mathrm{FC}} = 0.62 \pm 0.28\%$
- → if MHOU is included, consistency with zero: $\langle x \rangle_{\mathrm{FC}} = 0.62 \pm 0.61\%$

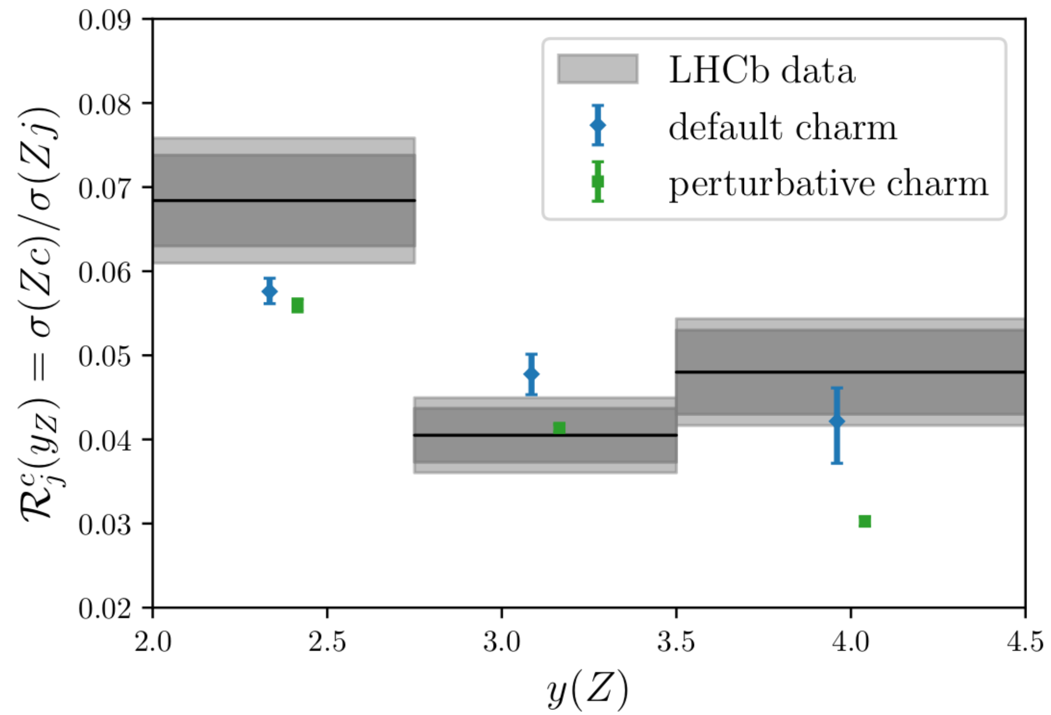
iv

specific experiments in NNPDF IC

- 3σ significance reached with inclusion of LHCb *Z+c* data

  → theory uncertainties for these data (*e.g.*, showering algorithms) remain large





- NNPDF approach 3σ significance with baseline dataset

  → similar group of expts in CT18 FC do not yield strong signal

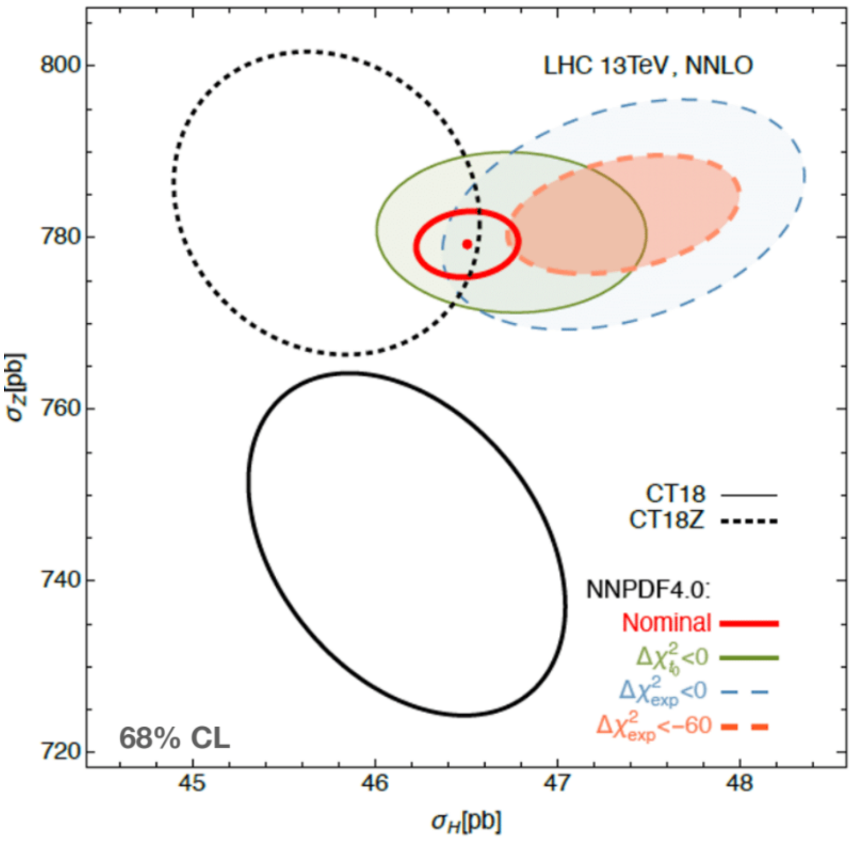
  connected to differing PDF uncertainty quantifications

iv more representative sampling can enlarge MC uncertainties

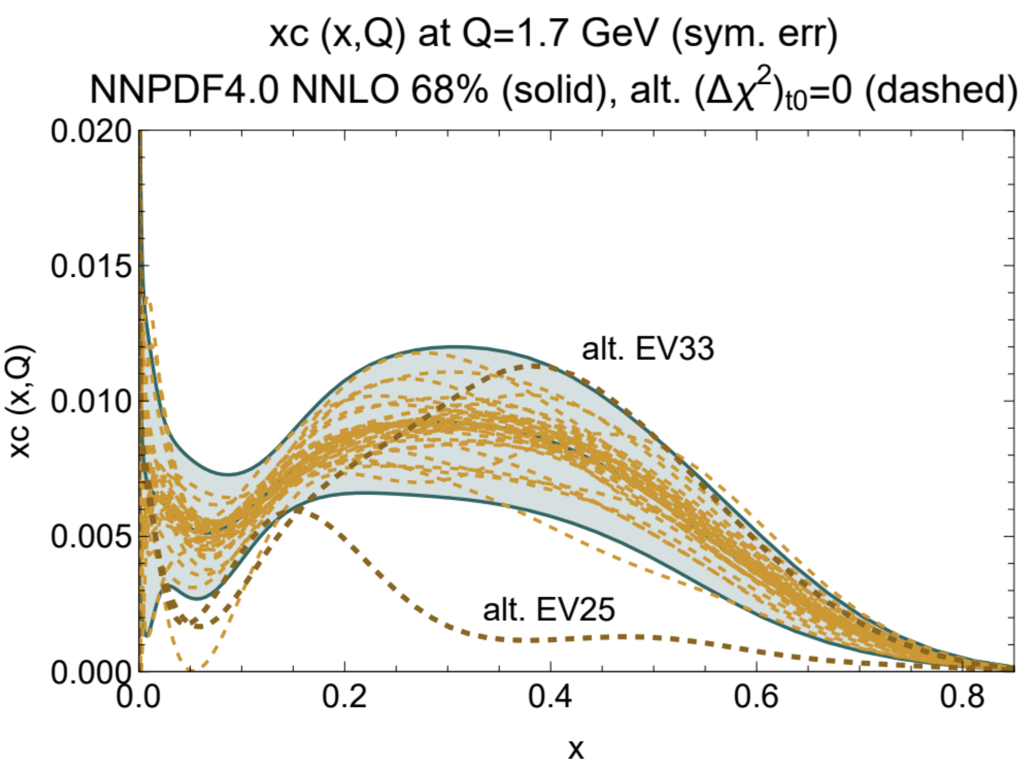
Courtoy *et al.*, arXiv: 2205.10444.

- default replica-training in MC studies may omit otherwise acceptable solutions

- more comprehensive sampling impacts PDF errors of cross sections



- substantially broaden high-x FC error

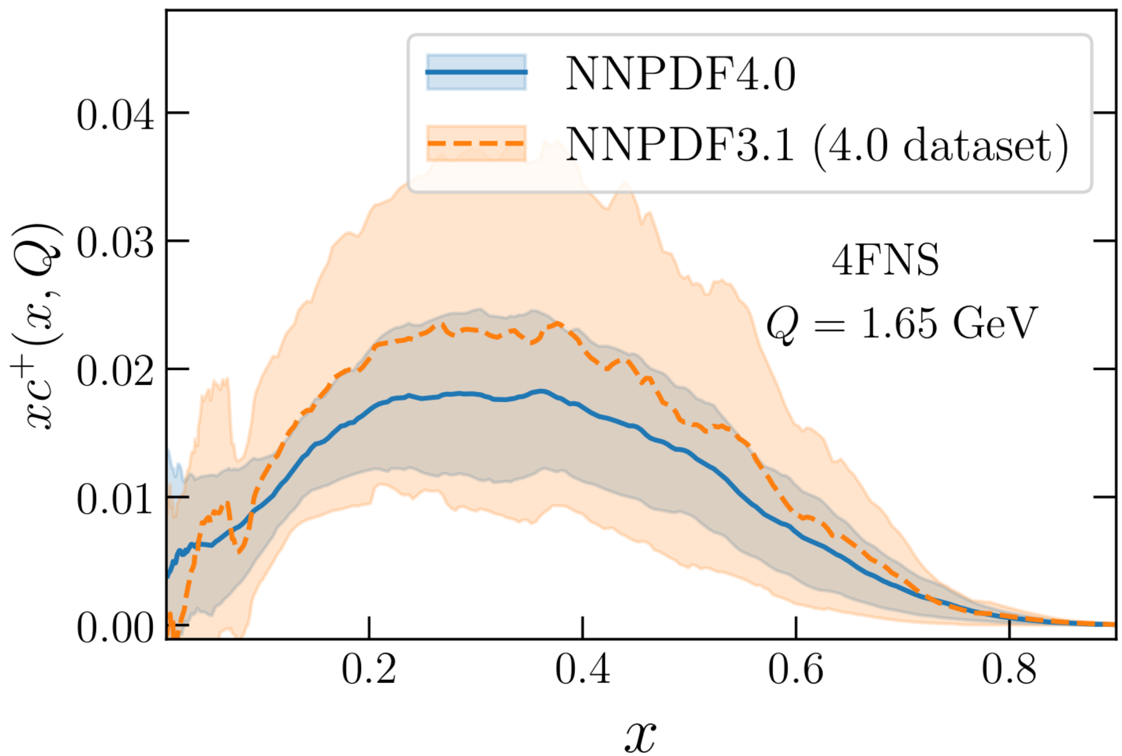


iv more representative sampling can enlarge MC uncertainties

Courtoy *et al.*, arXiv: 2205.10444.

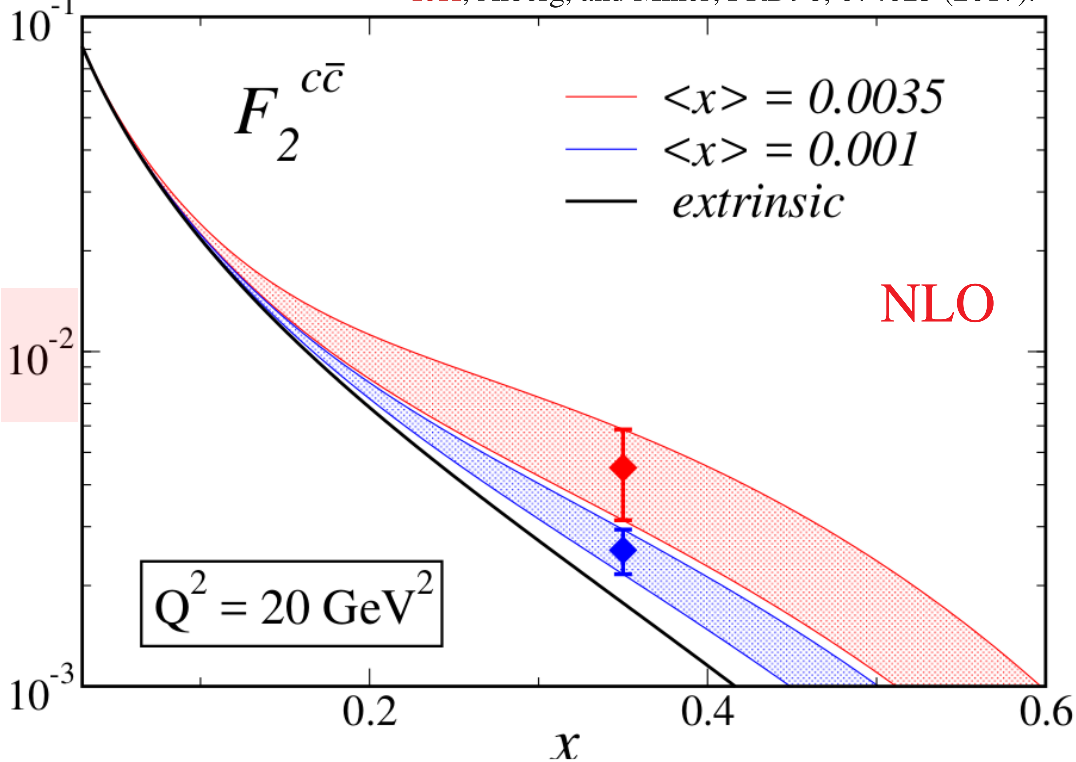
- default replica-training in MC studies may omit otherwise acceptable solutions

→ alternate fitting methodologies (NNPDF3.1 vs. 4.0) produce significant differences in PDF uncertainty



both curves based on same underlying data

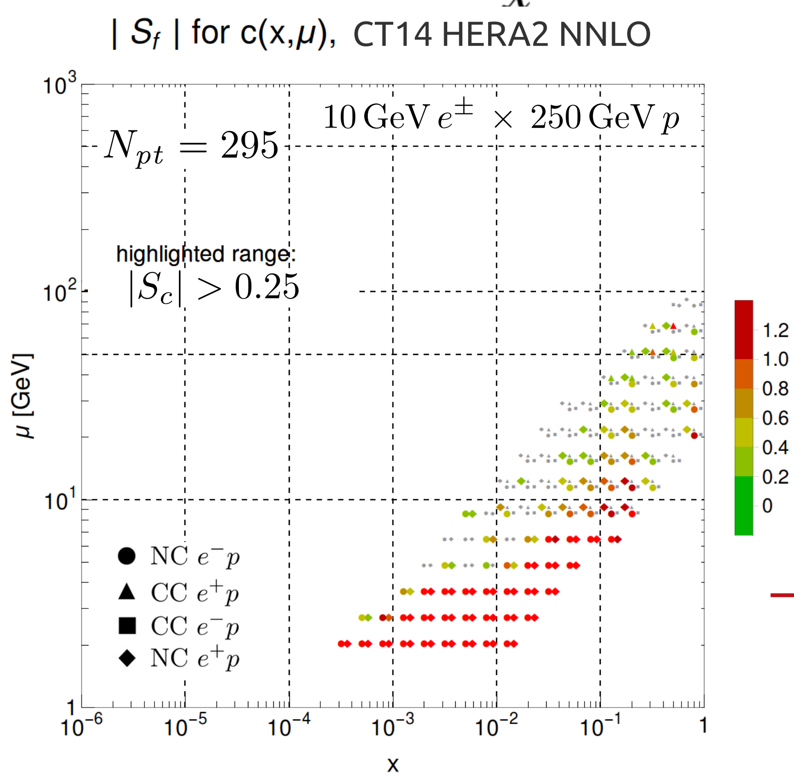
TJH, Alberg, and Miller; PRD**96**, 074023 (2017).



future data will inform FC

EIC will constrain FC scenarios

enhanced FC momentum implied by EMC data → small high-x effects in structure function; need high precision



- **essential complementary input from LHC; CERN FPF**

EIC will measure precisely in the few-GeV, high-x region where FC signals are to be expected

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: $\langle x \rangle_{\rm FC} \sim 0.5\%$, 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