CT18 Fitted Charm: possibilities at CERN FPF

Tim Hobbs, ANL

recently published:
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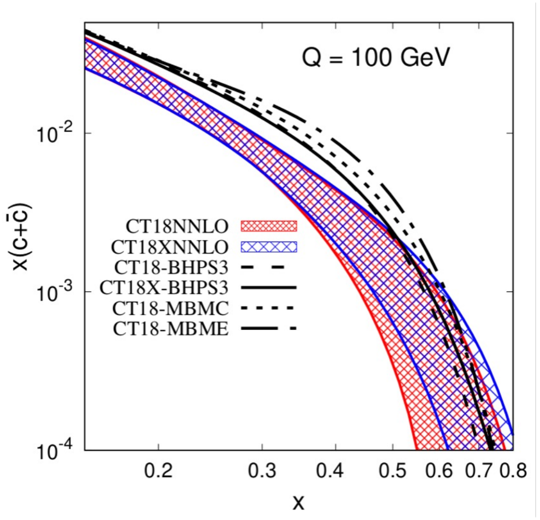
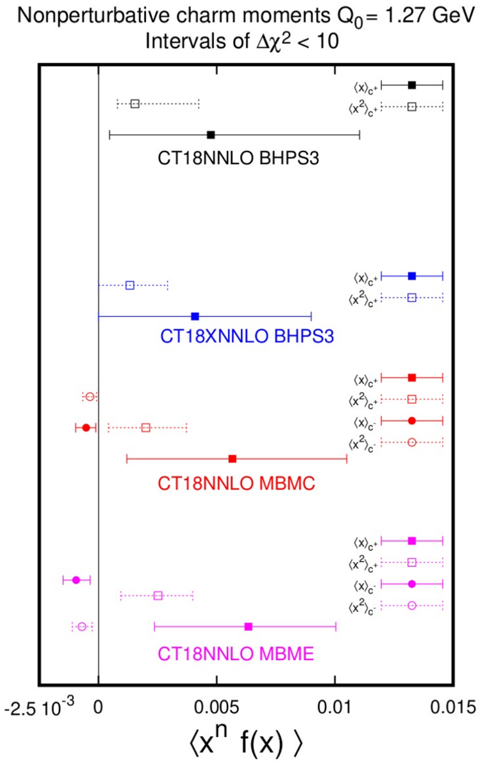




with M. Guzzi, K. Xie, J. Huston,
P. Nadolsky, C.-P. Yuan

see also: 1707.00657
and 2205.10444

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

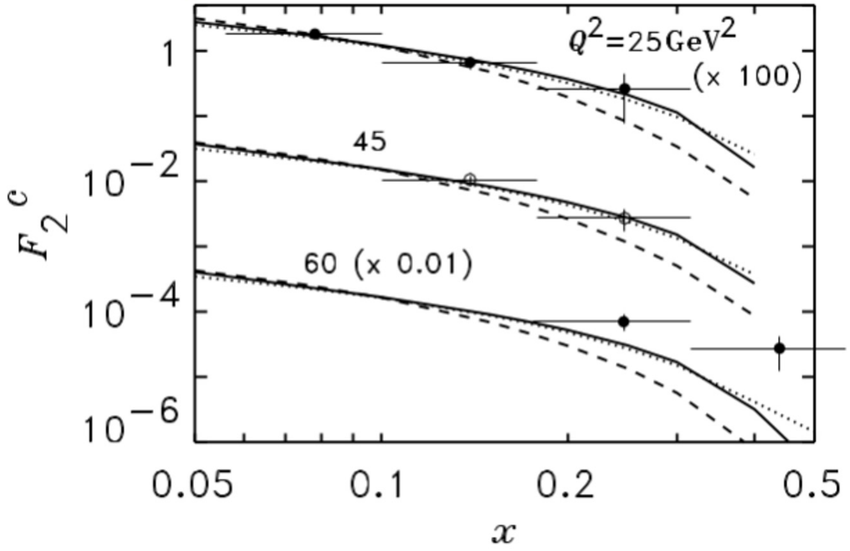
heavy quarks typically implemented *perturbatively* in QCD analyses

$$F_i = C_i \otimes f_{c/p}$$

might also explore *nonperturbative* charm; *i.e.*, <u>not</u> radiatively generated,

$$c(x, Q = m_c) = c^{\mathrm{IC}}(x) \neq 0$$

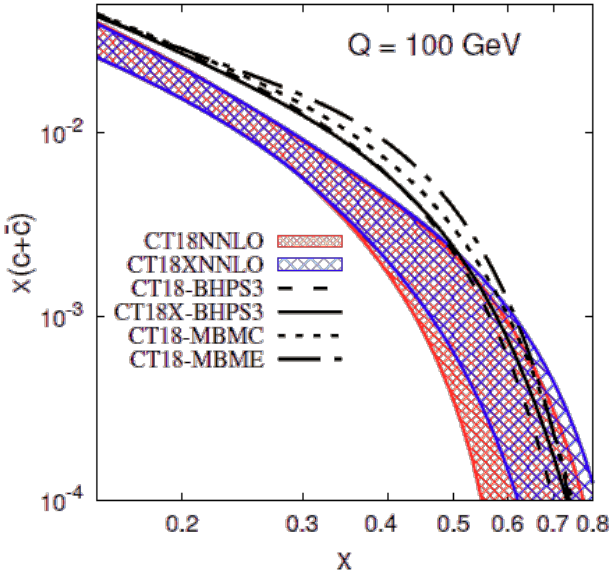
F. M. Steffens, W. Melnitchouk and A. W. Thomas, Eur. Phys. J. C **11**, 673 (1999) [hep-ph/9903441].



but can global PDF fits constrain "intrinsic" charm?

"fitted charm" is a more direct term to describe the charm PDF found in the global QCD fit

analog: the fitted charm mass



PDF fits may include a fitted charm PDF

fitted charm = “higher-twist charm”
+ other (possibly not universal)
higher O(α_s), higher-power terms

QCD factorization theorem for DIS structure function $F(x,Q)$ [Collins, 1998]:

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

PDF fits implement this formula only up to (N)NLO ($N_{ord} = 1$ or 2):

PDF fits: $$F(x,Q)^{[\mathrm{trunc}]} = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a^{(N_{ord})}\left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha(\mu)\right) f_{a/p}^{(N_{ord})}(\xi,\mu)$$

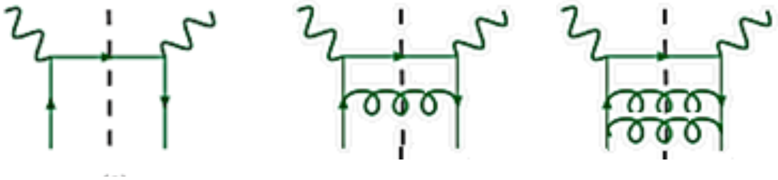
leading-power charm PDF component cancels at $Q \approx m_c$, up to a higher order

fitted charm component may potentially **absorb missing terms** of orders α_s^p with $p > N_{ord}$, or Λ^2/m_c^2, or Λ^2/Q^2

fitted charm contributions, practical implementation in CT18

Keep only $c_{h,h} \otimes f_h$:

Discard $C^{(k)}_{h,gg} \otimes f_{gg}$, etc.



In the absence of full computation, we (and other groups) make the simplest approximation:

$$F_{FC}(x, Q_0) = [c_{h,h} \otimes f^{FC}_{c/p}](x, Q_0)$$

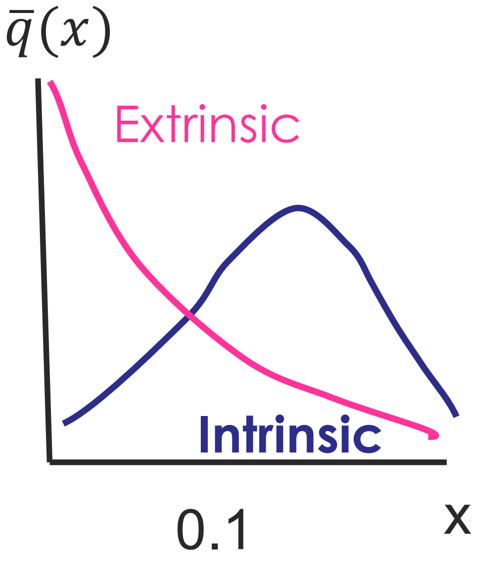
$\boldsymbol{c_{h,h}}$ **is the twist-2 charm DIS coefficient function** introduced to factorize the twist-4 ladder terms; defined according to the SACOT-MPS scheme

Start with $N_f = 3$ at $\mu_0 = m_c - \epsilon$, evolve to $\mu > \mu_0$ by incrementing N_f to 4 and 5

FC is compatible with any version of the ACOT scheme (cf. arXiv:1707.00657).

Flavor-excitation coefficient functions of these schemes differ by terms of $O(m_c^2/Q^2)$. Their overall differences are of $O(\Lambda^2/Q^2)$, i.e., within the accuracy of the factorization theorem.

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 $x \gtrsim 0.2$

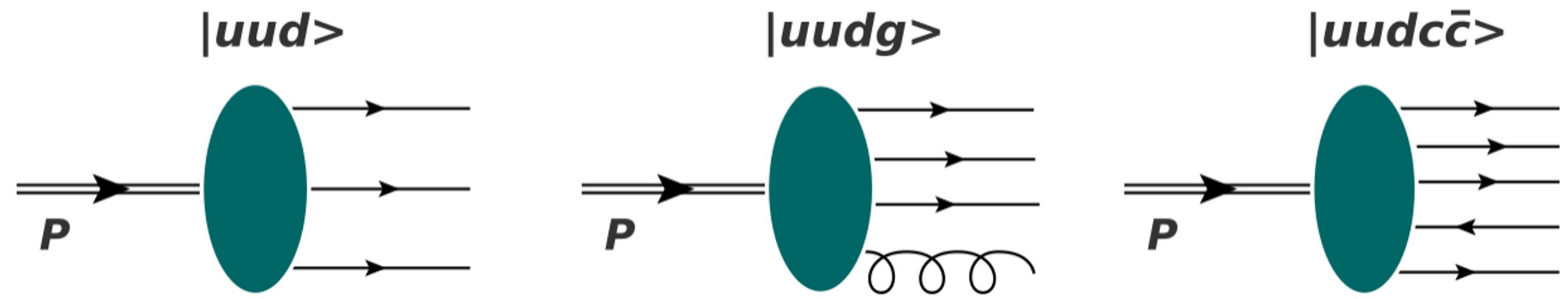
Connection?

- 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

nonperturbative QCD can generate a low-scale charm PDF

Fock expansion

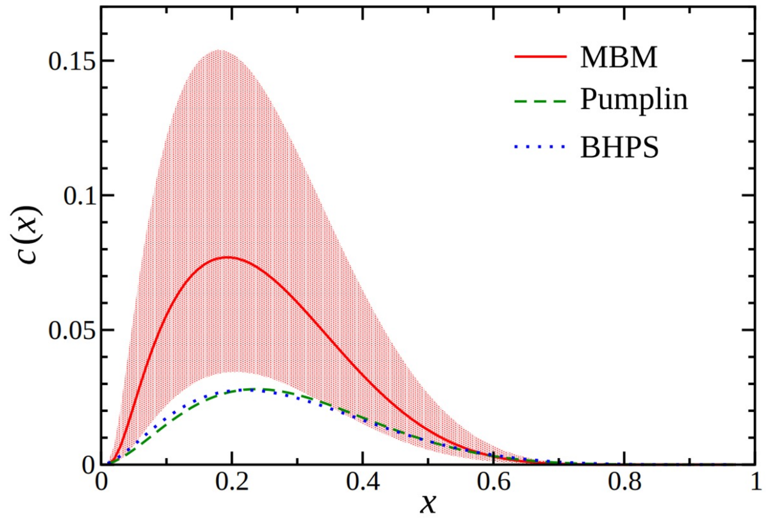
Brodsky, Hoyer, Peterson, Sakai (**BHPS**); Phys. Lett. **B93** (1980) 451.



IC PDF: transition matrix element, $|\mathrm{proton}\rangle \to |uudc\bar{c}\rangle$ → old-fashioned PT; **scalar** field theory

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

(‘BHPS3’: full mass dependence)



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

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

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

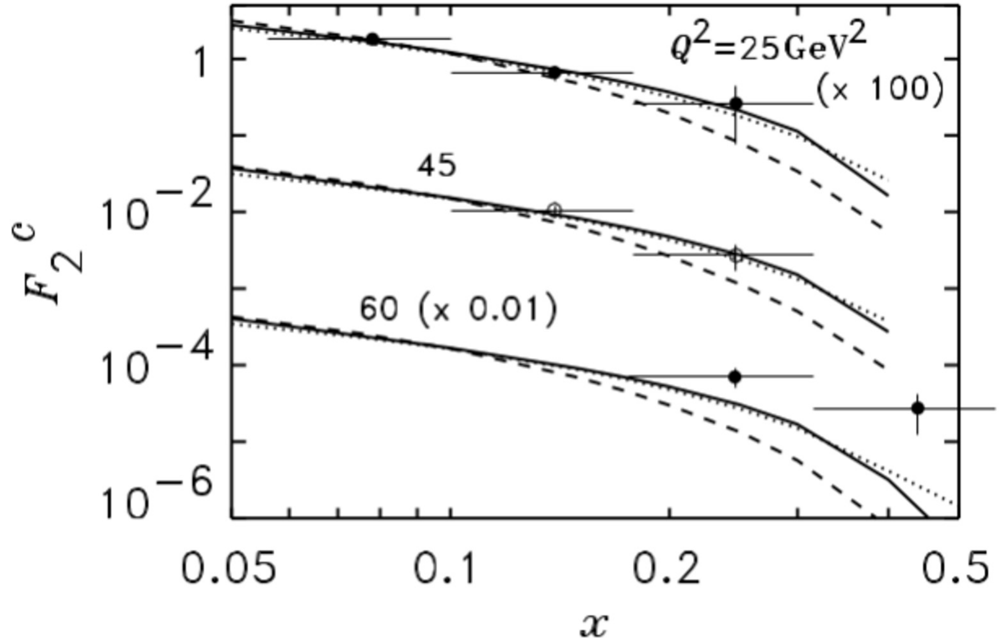
→ generically yields valence-like shape; governed by charm, hadronic mass scales

few expts with clear sensitivity; **EMC data challenging to fit**

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.

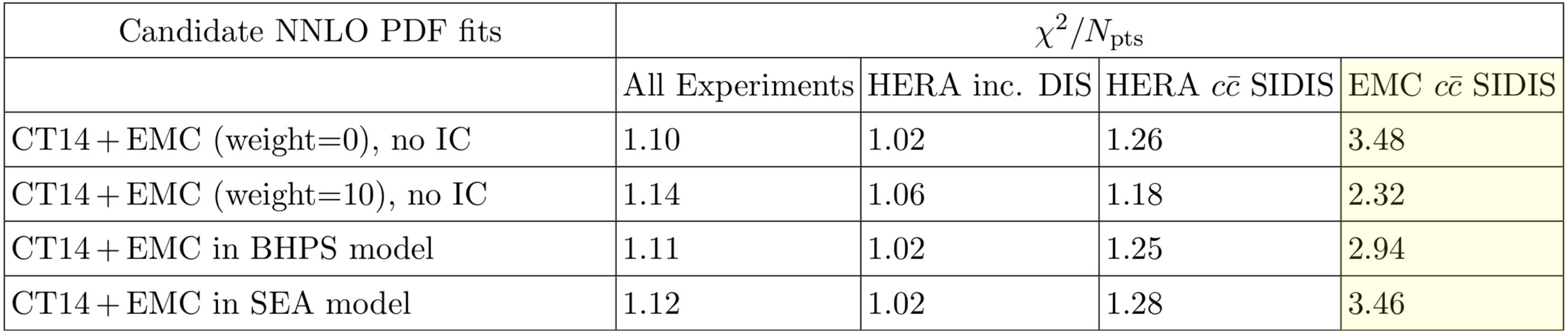
F. M. Steffens, W. Melnitchouk and A. W. Thomas, Eur. Phys. J. C **11**, 673 (1999) [hep-ph/9903441].



- → 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
- → closely related to high-x $g(x)$ PDF

not included 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

Z+*c* at LHCb: intriguing new data; need theory development

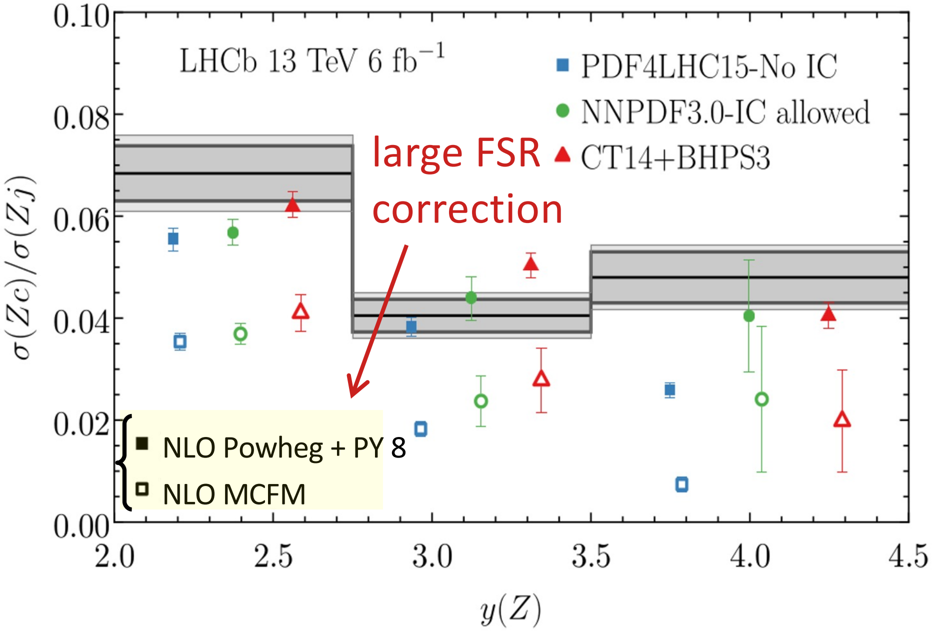
2022 LHCb 13 TeV data: (*Z*+*c*) / (*Z*+*jet*) ratios; 3 rapidity bins

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

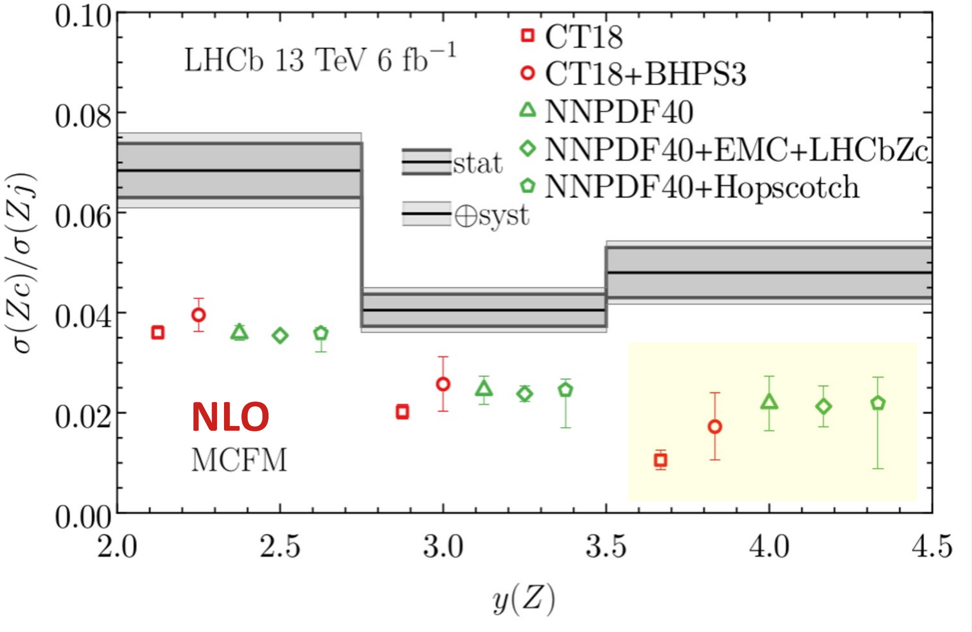
- FC slightly enhances ratio; not enough to improve agreement with data

→ meanwhile, significant theory uncertainties

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



large FSR correction



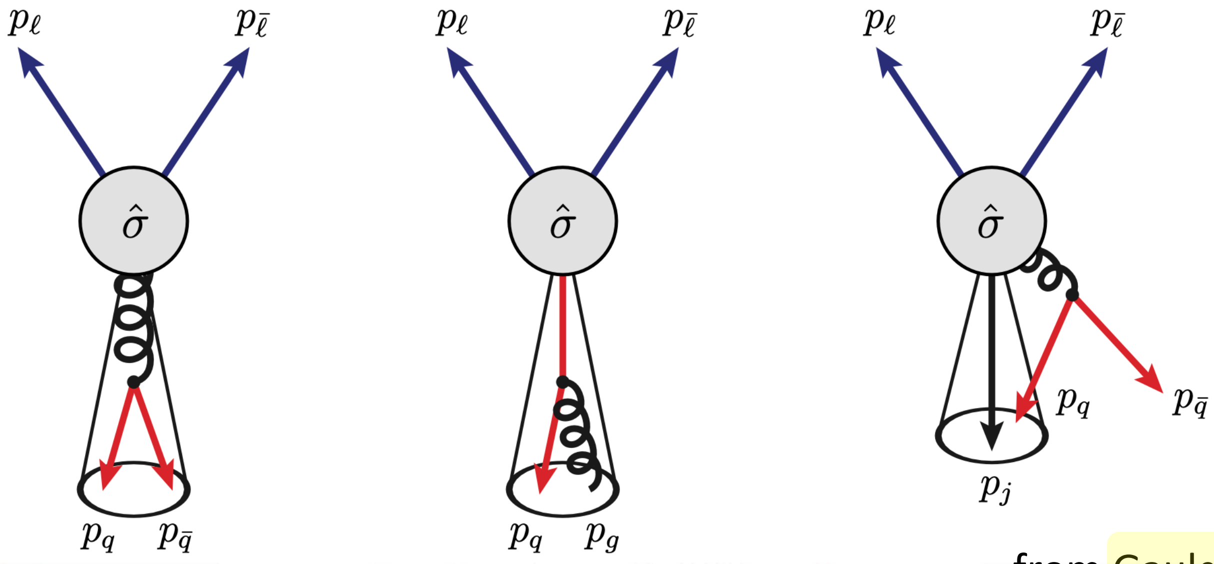
→ calculated **NLO** cross-section ratio similarly depends on showering, hadronization

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.

Z+*c* at LHCb: intriguing new data; need theory development

- in addition to NNLO corrections, IRC safety poses challenges to jet algorithms:



from Gauld et al., 2302.12844

- multi-parton interactions (MPI) can represent a significant correction

  → ~10% effect on $(Z{+}c)/(Z{+}jet)$, especially for $y(Z) > 3.5$; large uncertainty

- massless fixed-order calculation affected by divergences

theory improvements would help guarantee interpretation for PDF extractions

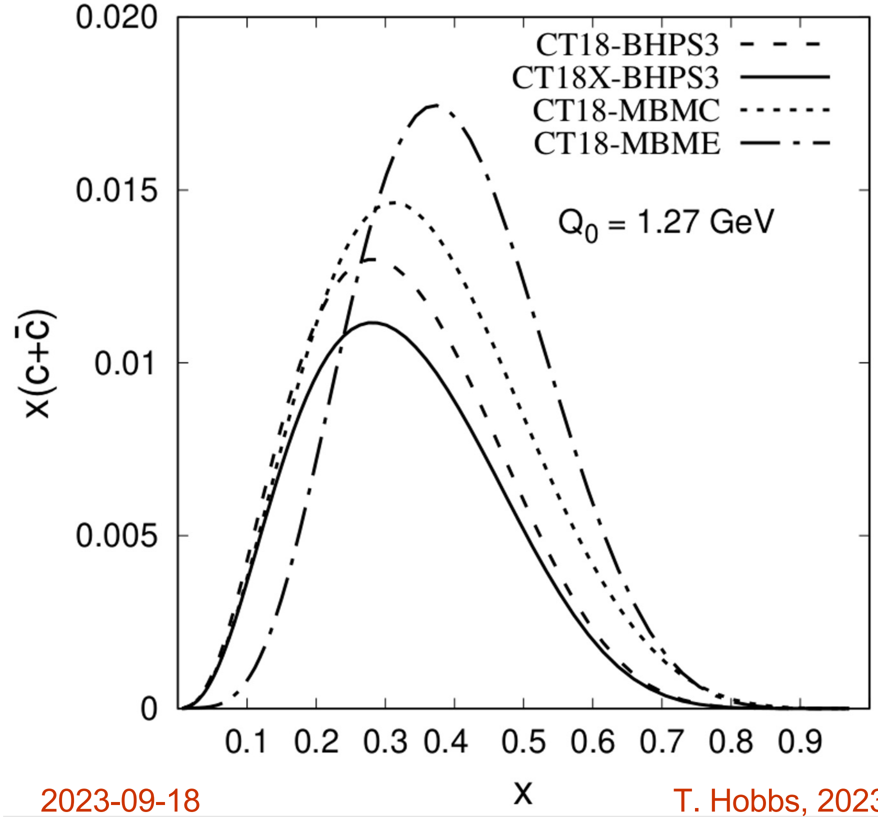
CT18 FC total charm PDFs

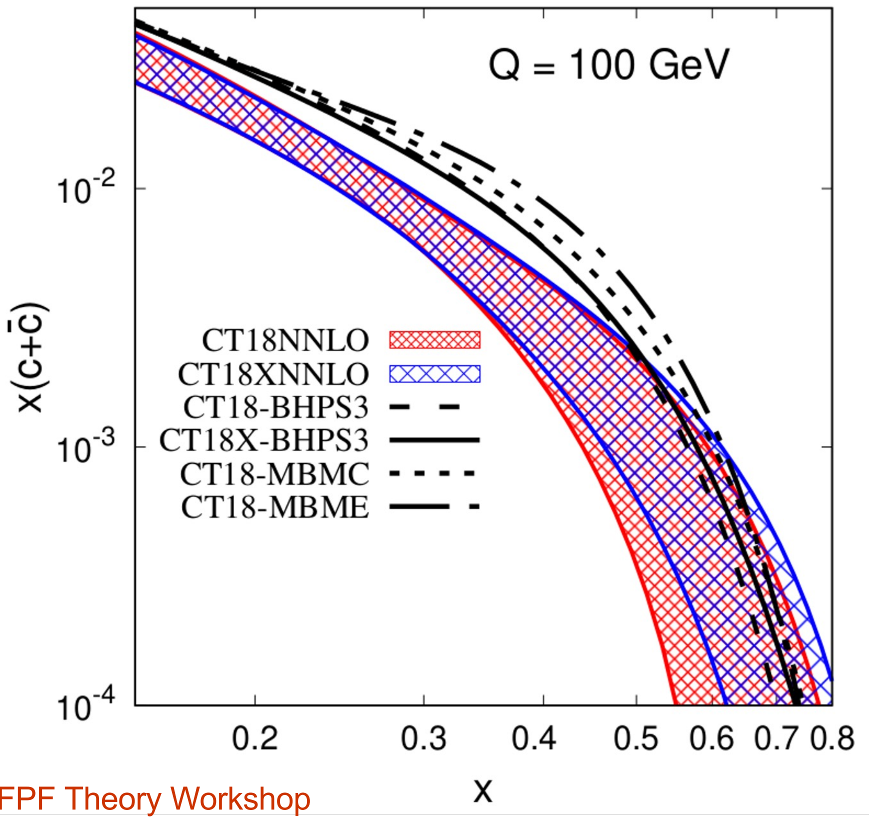
FC scenarios traverse range of high-*x* behaviors from IC models

- → 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

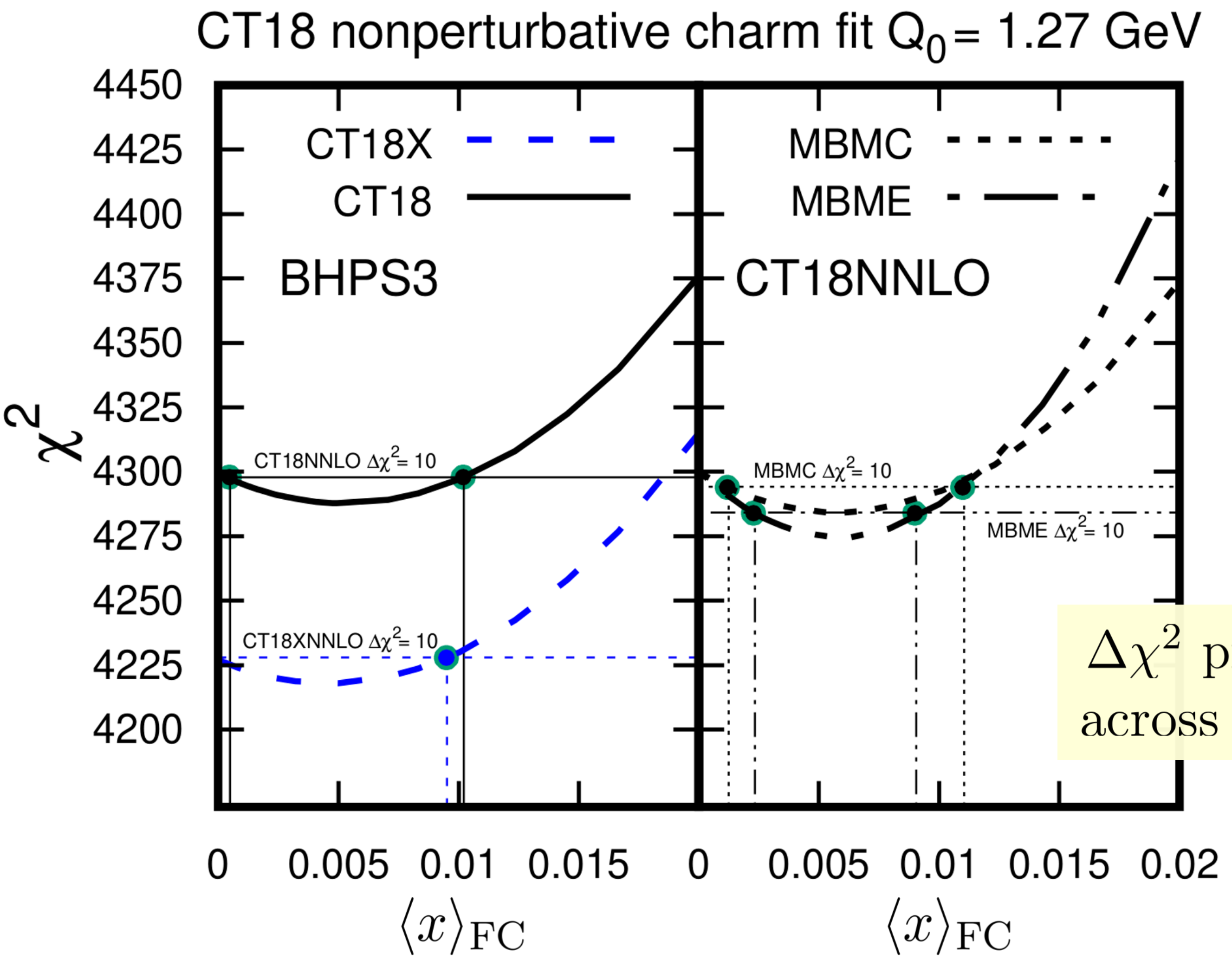




signal for FC in CT18 study, but with <u>shallower</u> $\Delta\chi^2$ than CT14 IC

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

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



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

FC PDF moments as F.o.M.

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

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

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

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

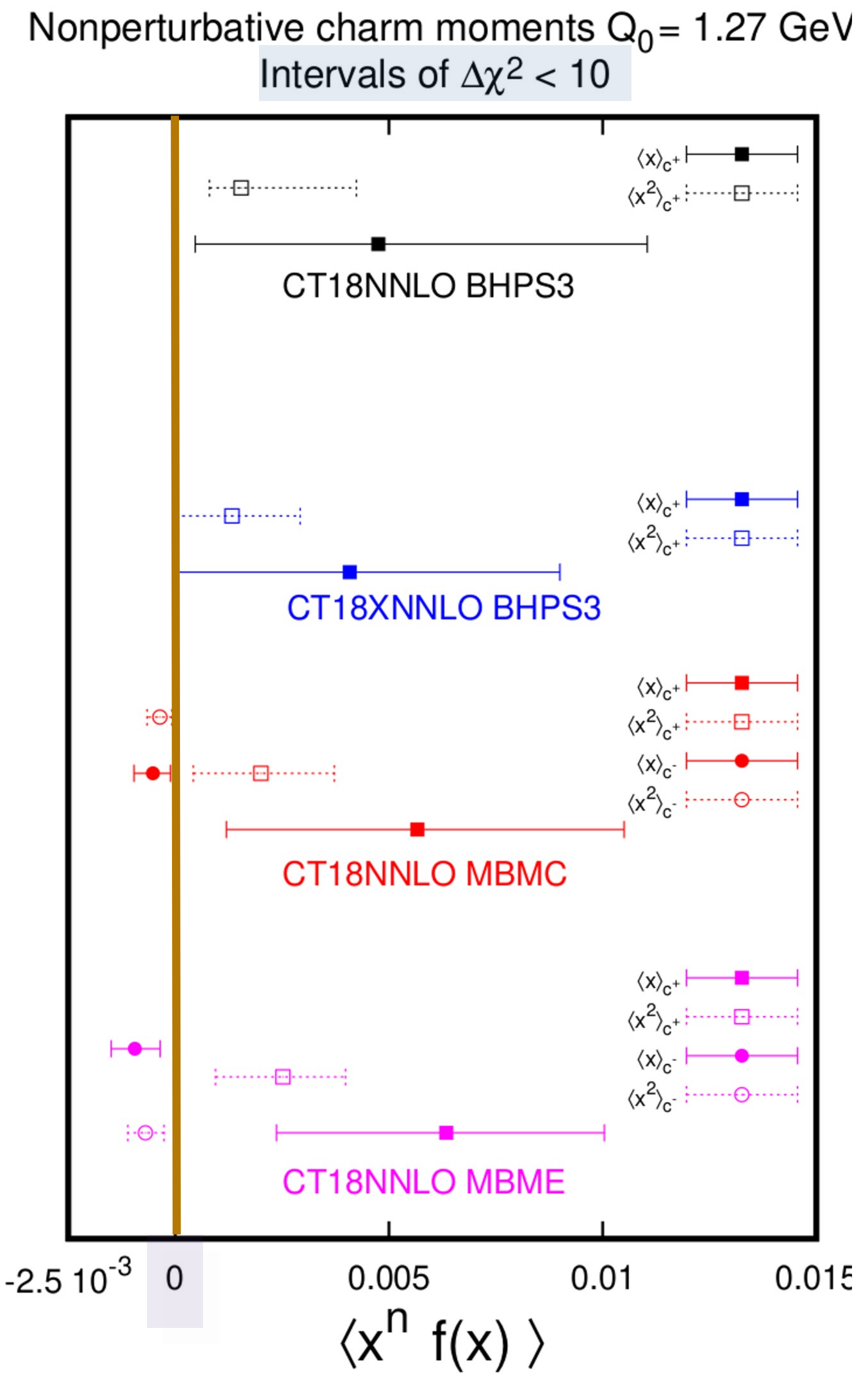
$$= 0.0041\,^{+0.0049}_{-0.0041}\,\left(^{+0.0091}_{-0.0041}\right),\ \mathrm{CT18X\ (BHPS3)}$$

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

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

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

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



FC PDF moments as F.o.M.

even restrictive uncertainties give moments consistent with zero

→ broaden further for default CT tol.

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

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

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

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

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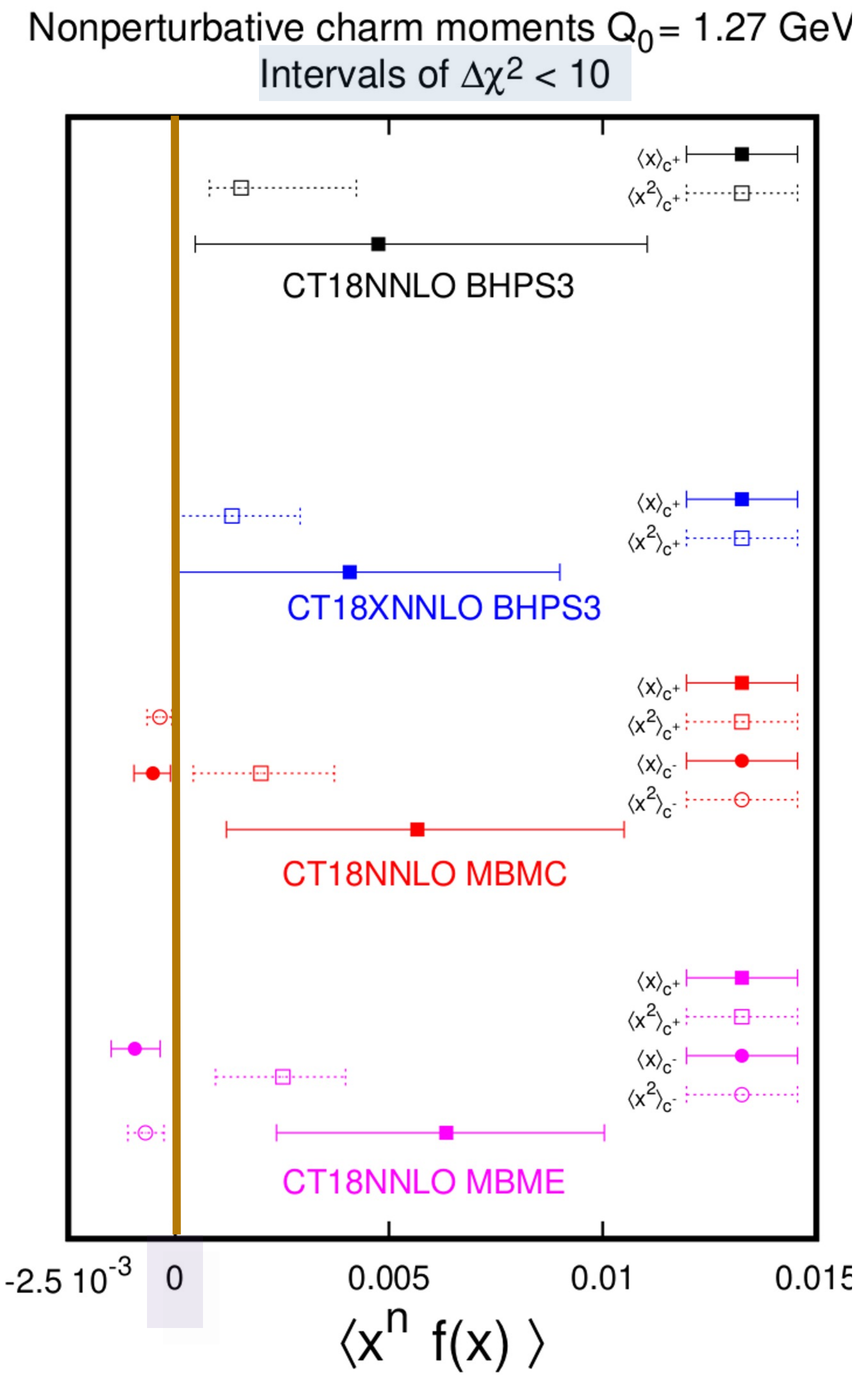
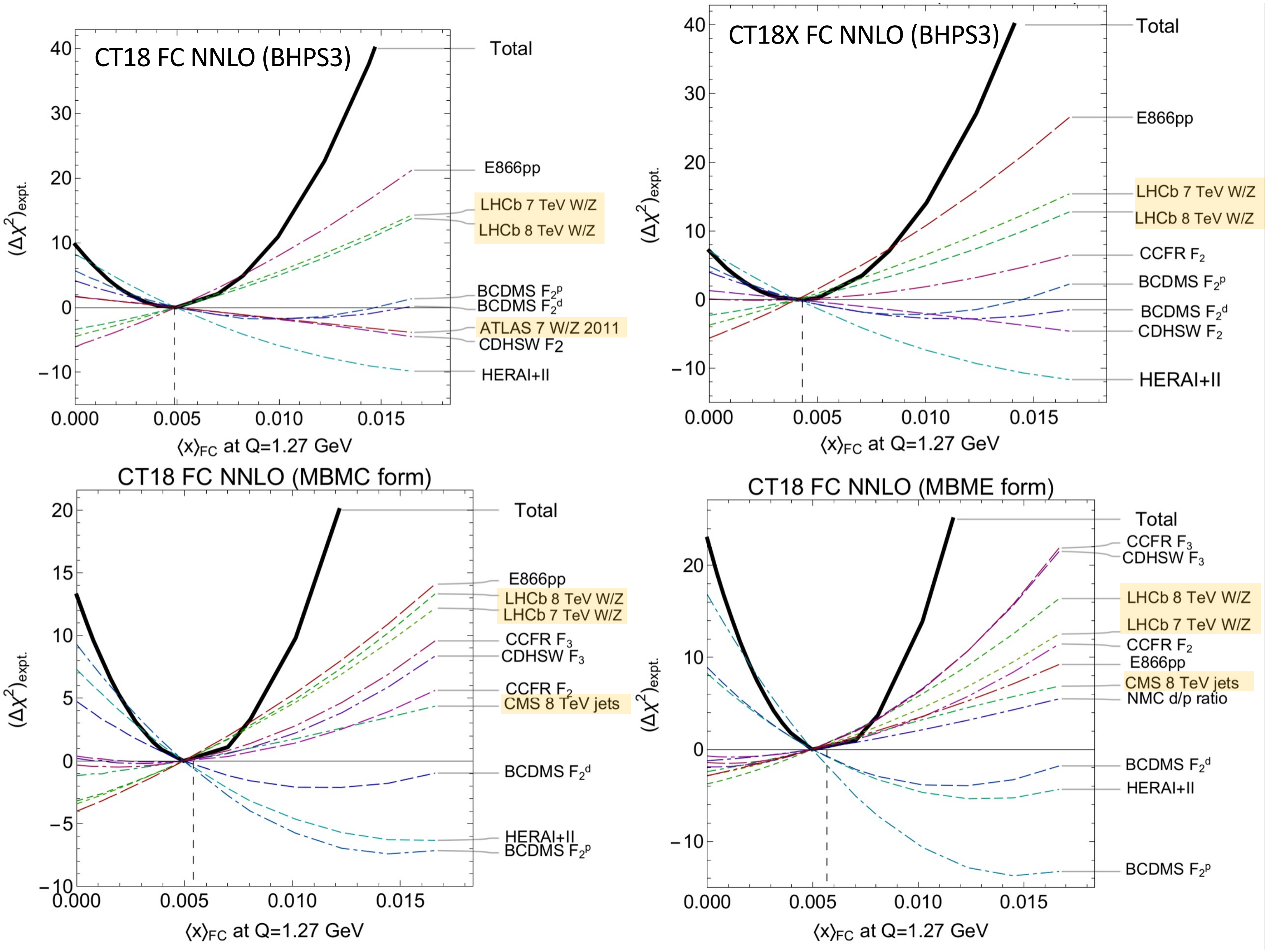


data pull opposingly on $\langle x \rangle_{\mathrm{FC}}$; depend on FC scenario, enhancing error

Run-1 LHC expts generally prefer smaller magnitudes of FC

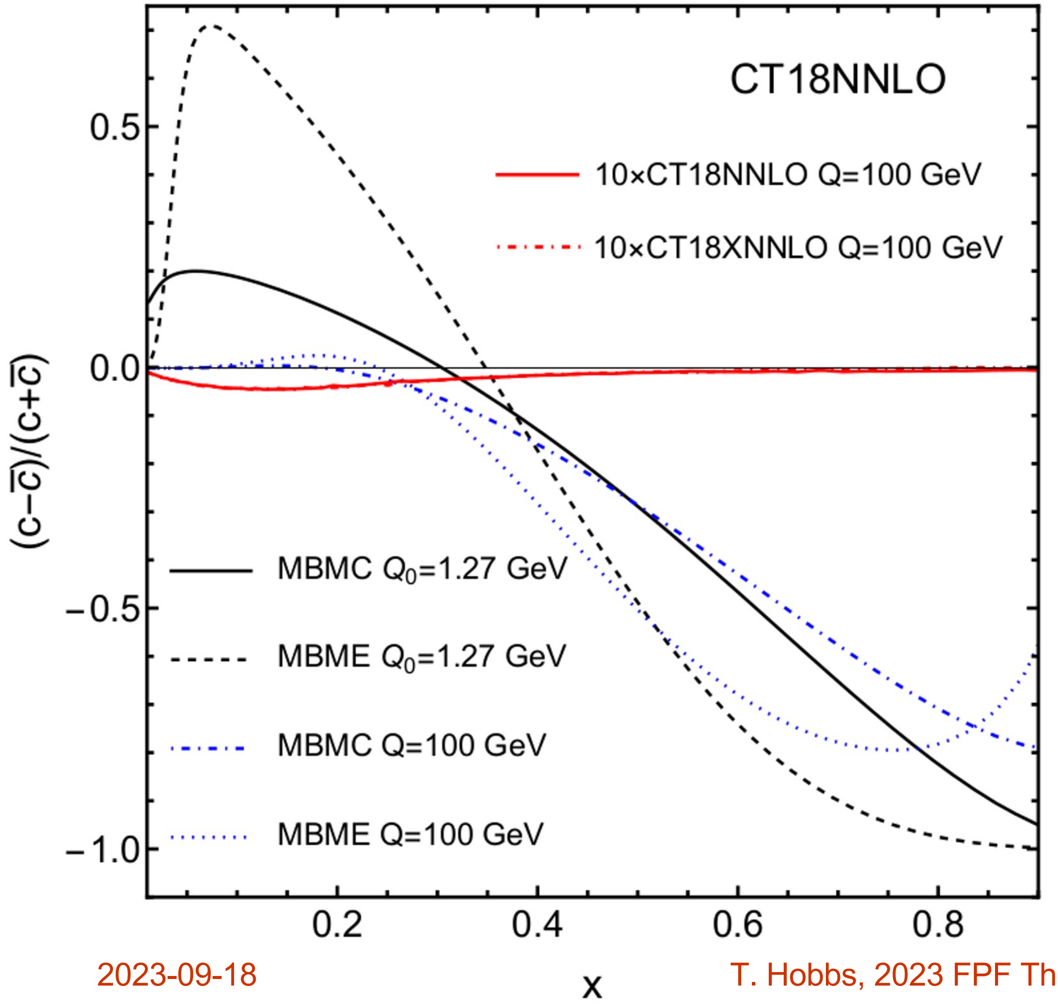


possible charm-anticharm asymmetries

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

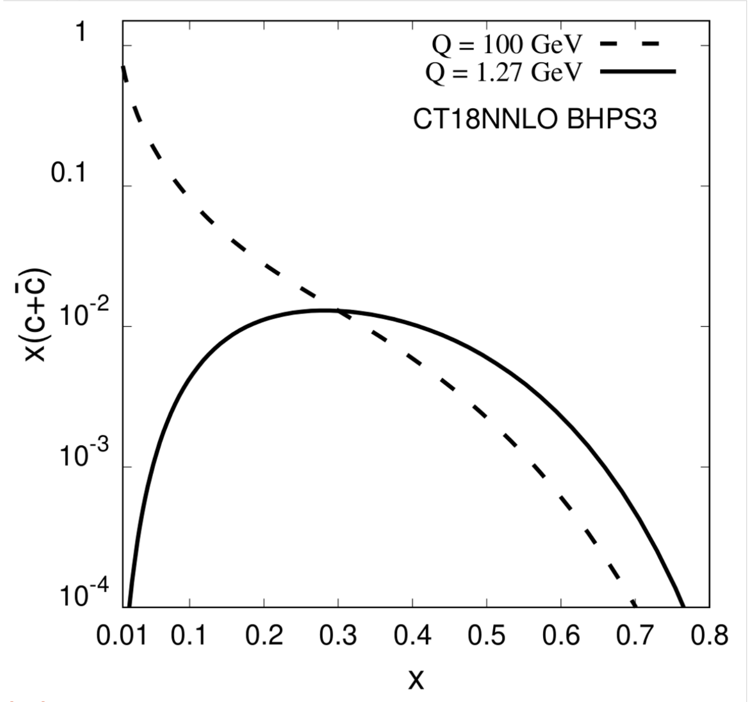
→ large(r) charm asymmetry would signal nonpert dynamics, IC

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



consider two MBM models as ***examples*** (<u>not predictions</u>)

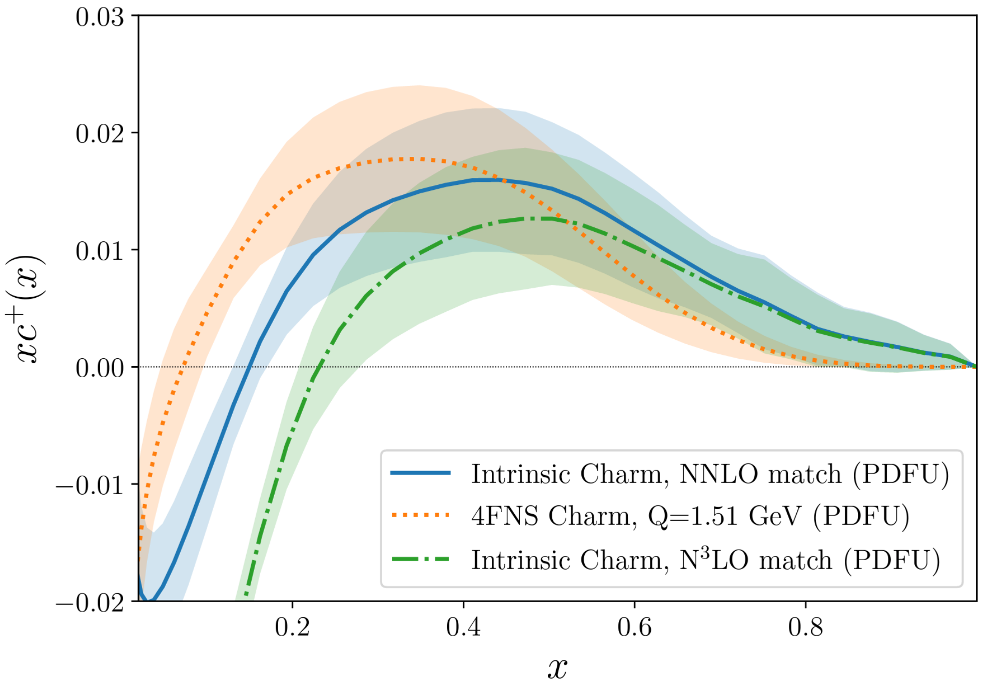
→ asym. small but ratio (left) can be bigger; will be hard to extract from data

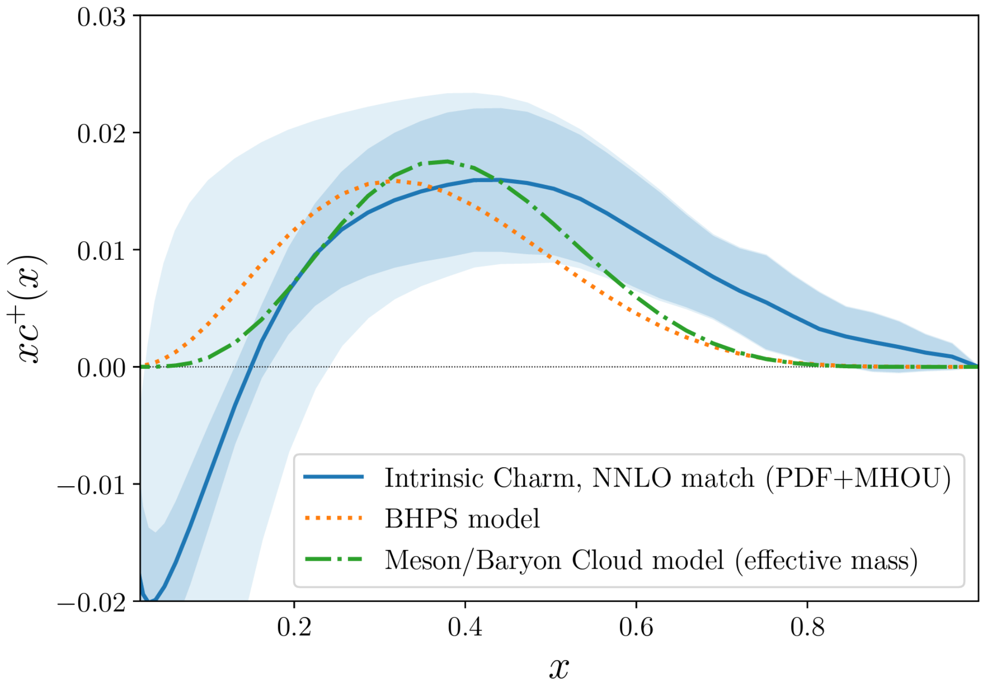


recent NNPDF IC analysis

NNPDF, Nature 608 (2022) 7923, 483.

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





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

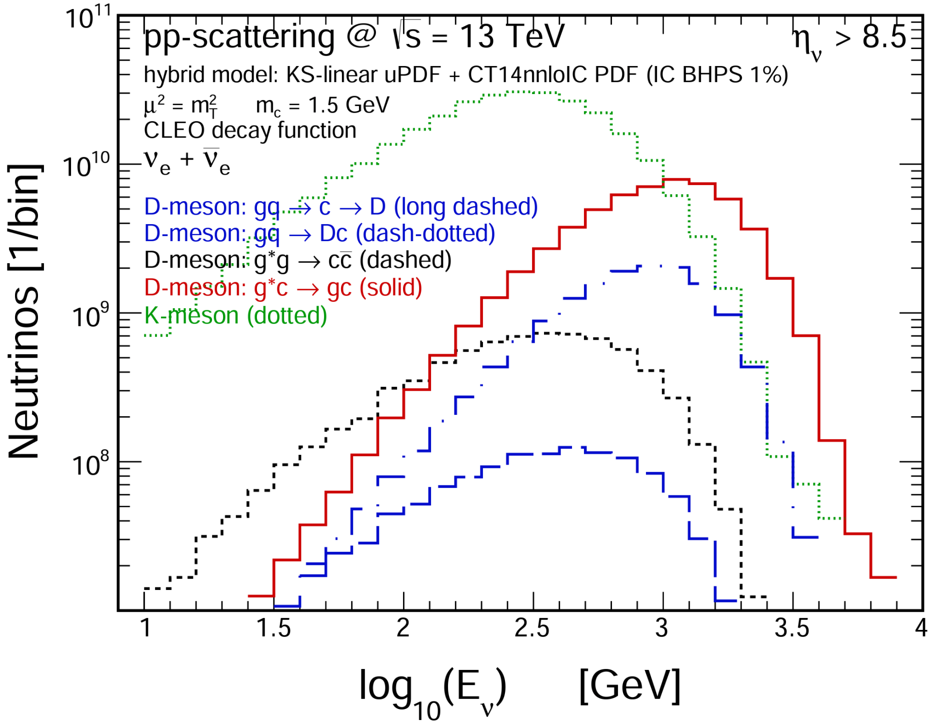
1. Missing HO unc (MHOU): N3LO in DIS, etc.; N2LO in Z+c production

$\langle x\rangle_{\mathrm{FC}} = 0.62 \pm 0.28\%$ *without* MHOU $\langle x\rangle_{\mathrm{FC}} = 0.62 \pm 0.61\%$ *with* MHOU

2. Parametrization sampling uncertainty (underestimation of PDFU)

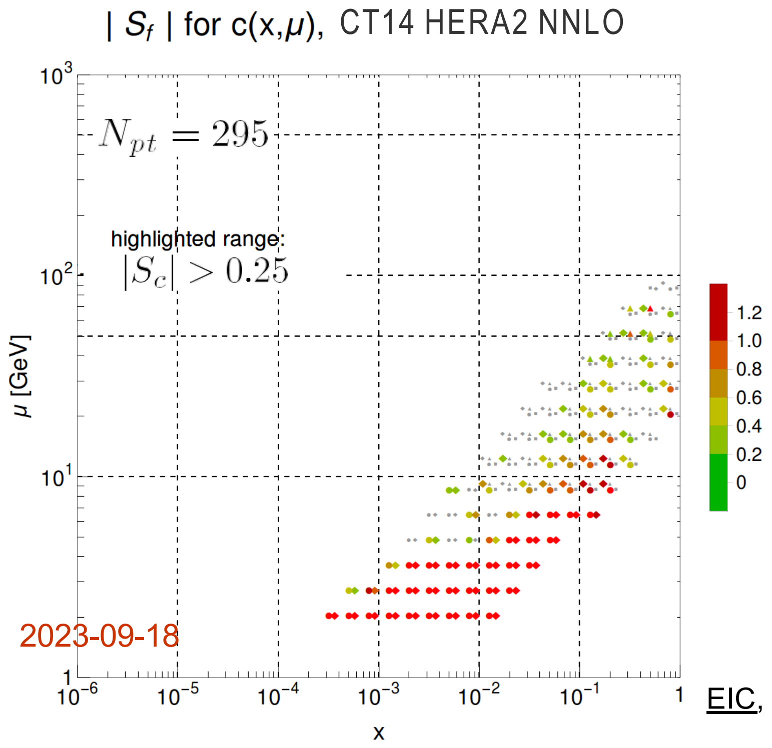
future data will inform FC

- ❑ experiments like **FPF**, EIC + lattice QCD may potentially constrain FC scenarios



→ possible FC sensitivity at CERN FPF: k_T factorization-based study

(FPF Whitepaper, 2203.05090)



2023-09-18

- enhanced FC momentum implied by EMC data → small high-*x* effects in structure function; <u>need high precision</u>

future experiments are expected to have precise sensitivity to the few- GeV, high-*x* region where FC signals are to be expected

<u>EIC</u>, see also: TJH, Alberg, and Miller; PRD96, 074023 (2017).

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; CERN FPF; EIC

→ lattice data on key charm PDF moments; quasi-PDFs

→ direct benchmarking of FC among PDF fitting groups