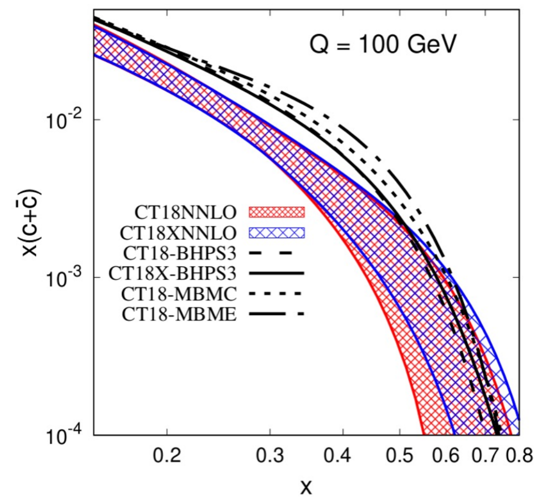
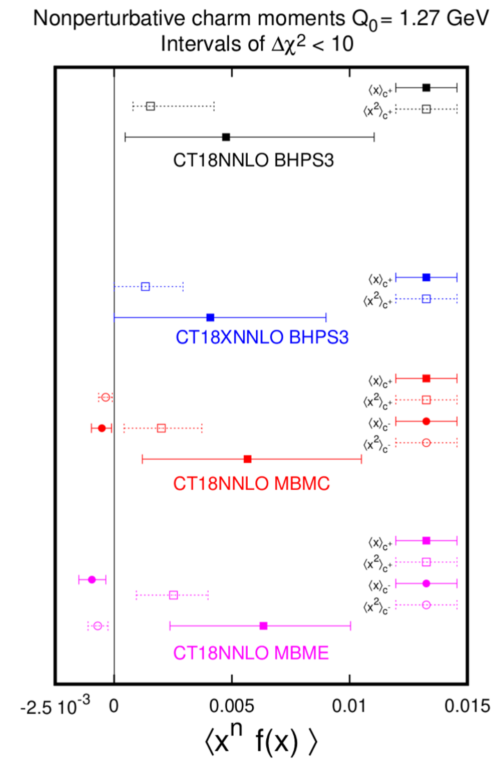
CT18 FC: heavy quarks in CTEQ-TEA QCD analyses

Tim Hobbs, ANL

recently published:
PLB 843 (2023) 137975





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

References

HQs, charm in the proton have extensive literature…

Heavy quarks in pQCD calculations

1. ACOT: Aivazis, Collins, Olness, Tung; PRD50 (1994) 3102-3138
2. NC DIS, NNLO: Guzzi, Nadolsky, Lai, Yuan; PRD86 (2012) 053005
3. CC DIS, NNLO: Gao, TJH, Nadolsky, Sun, Yuan; PRD105 (2022) 1, L011503

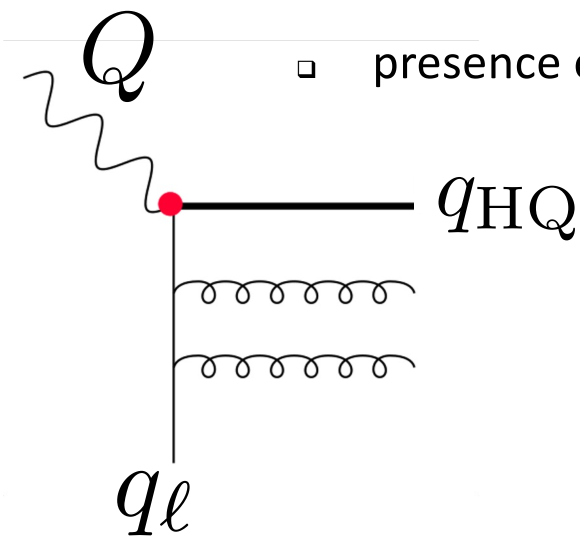
Intrinsic charm from nonperturbative methods and models:

1. BHPS: Brodsky, Hoyer, Peterson, Sakai, PLB 93 (1980) 451
2. Meson-Baryon models (MBM): TJH, Londergan, Melnitchouk, PRD 89 (2014) 074008
3. Light-front WF models: TJH, Alberg, Miller, PRD 96 (2017) 7, 074023

QCD analyses of nonperturbative charm

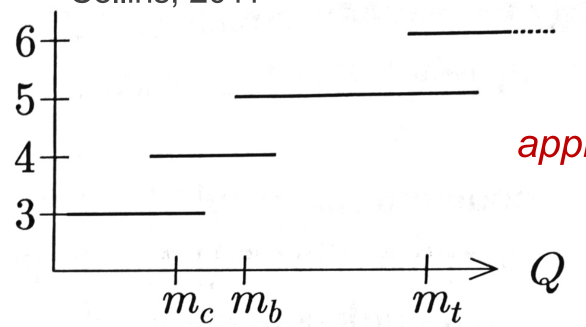
1. P. Jimenez-Delgado, TJH, Londergan, Melnitchouk, PRL114 (2015) 8, 082002; NLO fit; first analysis with EMC data
2. T.-J. Hou et al., JHEP 02 (2018) 059; QCD factorization with the NP charm and CT14 IC NNLO pheno analysis
3. → M. Guzzi, TJH, K. Xie, et al., arXiv:2211.01387; **new** CT18 FC analysis with LHC Run-1 and 2 data

QCD analyses traverse many scales, Q; variable flavor



- presence of HQ introduces an additional effective scale into hard process

Collins, 2011

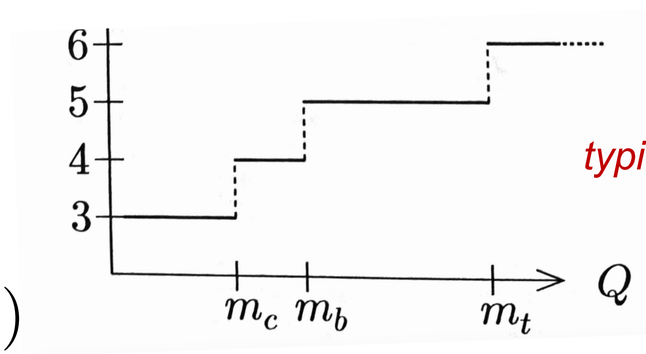


appropriate transition scales

$$Q \gg m_{\mathrm{HQ}}$$

- perturbatively-generated HQ PDFs resum large logs,

$$\sim \ln(Q^2/m_{\mathrm{HQ}}^2)$$



typical choices (ACOT)

→ number of active parton flavors is a scheme-dependent choice

- PDF fits typically assume a *variable flavor number* scheme with assumed number of active flavors; usually $n_F = 5$

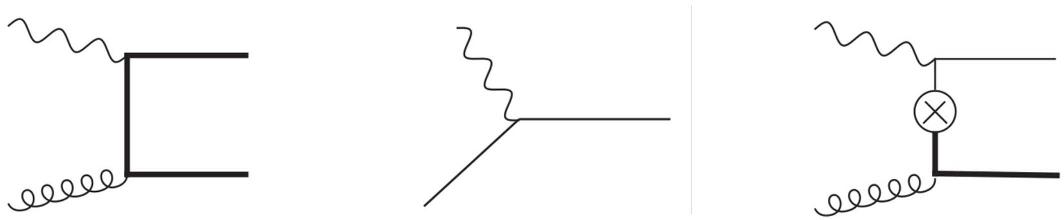
general-mass schemes: S-ACOT-χ

variable flavor-number scheme to interpolate between ZM and FFN regimes: **ACOT**

Aivazis, Collins, Olness, Tung; PRD**50** (1994) 3085-3118

→ systematic approach to incorporating HQ mass dependence

introduce subtraction term(s) to eliminate double counting between FC/FE contributions:



(FC) (FE) (SUB)

$$\begin{cases} Q \gtrsim M_Q \implies \text{(SUB)} \approx \text{(FE) such that } \mathrm{n}_f = 3 \text{ FC dominates} \\ Q \gg M_Q \implies \text{(SUB)} \approx \text{(FC) such that } \mathrm{n}_f = 4 \text{ FE dominates} \end{cases}$$

$$\chi(x, Q, M_Q) = x \left(1 + \frac{1}{Q^2} [\sum_{\text{F.S.}} M_Q]^2 \right)$$

"simplified" ACOT (S-ACOT): neglect full HQ mass dependence in FE graphs

[CT default] S-ACOT-χ: smooth HQ thresholds, approx. HQ mass dependence: $C_i(x) \to C_i(\chi)$

requires careful tracking of diagrams to organize calculation correctly

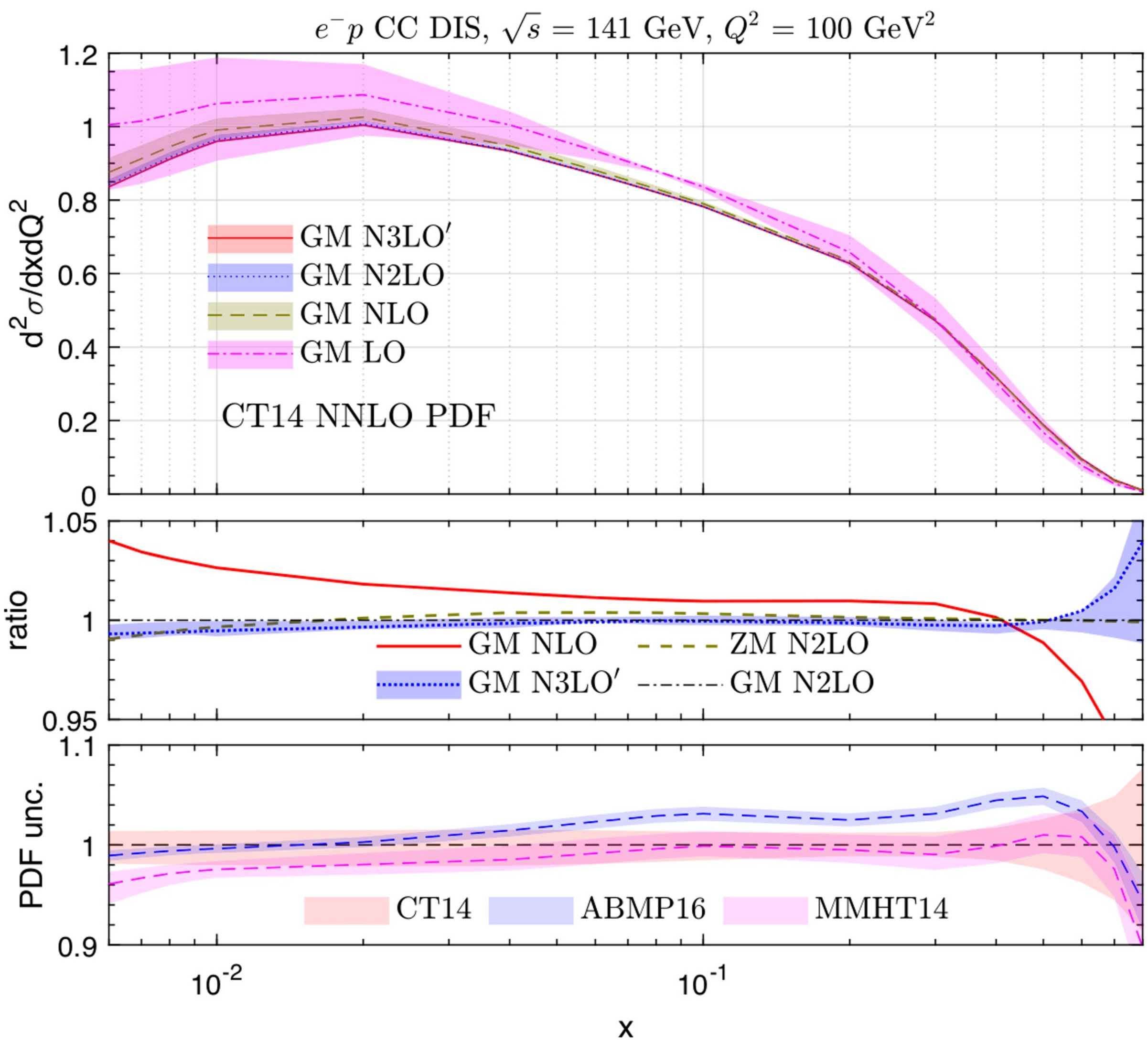
implications for PDF extractions at precise measurements

NNLO formalism generalizes to other DIS processes, e.g., CC DIS

PRD105 (2022) 1, L011503

→ Inclusive Reactions Study (YR7.1.1): CC DIS – including positron beam – may access *d*, *s* PDFs

arXiv: 2103.05419



(high-energy **EIC** collisions)

→ for N^{3}LO′, scale variations generally contained to $\lesssim 0.5 - 1\%$

→ strong perturbative convergence

significantly smaller than PDF-driven uncertainties, which can be as large as $\approx 2\%$

control over subtle QCD theory for heavy quarks may be important for PDF extractions at EIC, other expts

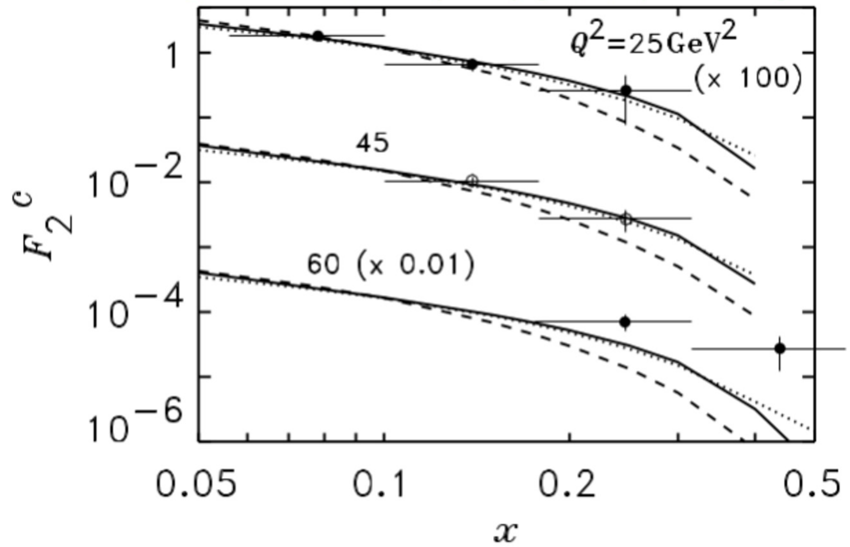
possible subtlety: nonperturbative heavy-quark PDFs --- 'intrinsic charm'

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

might also explore *nonperturbative* charm; *i.e.*, not radiatively generated,

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

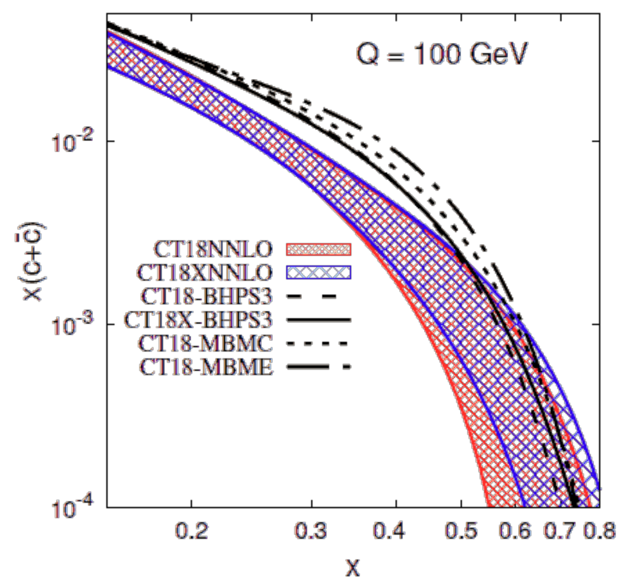
F. M. Steffens, W. Melnitchouk and A. W. Thomas, Eur. Phys. J. C **11**, 673 (1999) [hep-ph/9903441].



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):

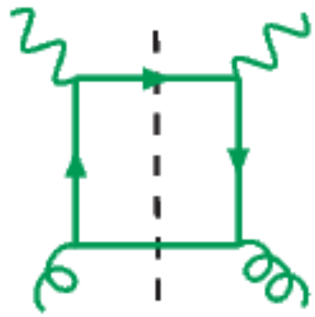
PDF fits: $$F(x,Q)^{[\mathrm{trunc}]} = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a^{(N_{ord})}\left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha(\mu)\right) f_{a/p}^{(N_{ord})}(\xi, \mu)$$

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

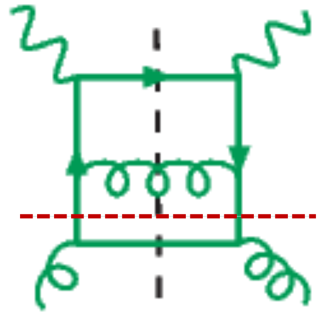
fitted charm component may potentially **absorb missing terms** of orders α_s^p with $p > N_{ord}$, or Λ^2/m_c^2, or Λ^2/Q^2

A twist-4 contribution in HERA DIS charm production ($\subset$ "intrinsic charm")

Twist-2
$\gamma^* g \to c\bar{c}$



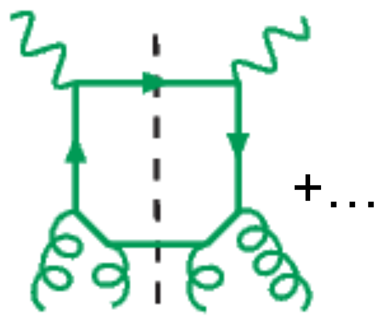
Order $\alpha_s(Q)$



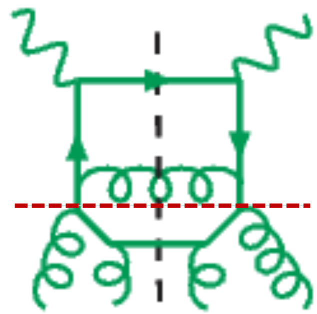
$\alpha_s^2(Q) \cdot \ln(Q^2/m_c^2)$

A ladder; must be resummed in $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme

Twist-4
$\gamma^*(gg) \to c\bar{c}$



$\alpha_s^2(Q) \cdot (\Lambda^2/Q^2)$
or $\alpha_s^2(Q) \cdot (\Lambda^2/m_c^2)$



$\alpha_s^3(Q) \cdot (\Lambda^2/m_c^2) \ln(Q^2/m_c^2)$

$\Lambda \lesssim 1$ GeV

The ladder subgraphs can be resummed as a part of $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2 > \Lambda^2$;

contributes to the boundary condition for $c(x,Q_0)$ at $Q_0 \approx m_c$;

obeys twist-2 DGLAP equations.

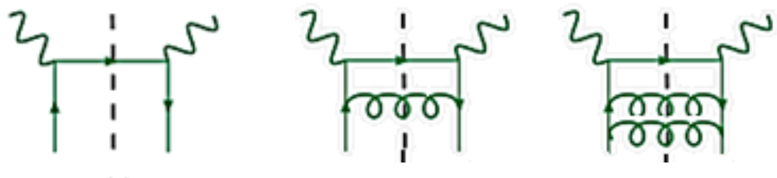
Collins, PRD58 (1998) 094002

Can be of order ~10% of the twist-2 α_s^2 term

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:

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

$c_{h,h}$ **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

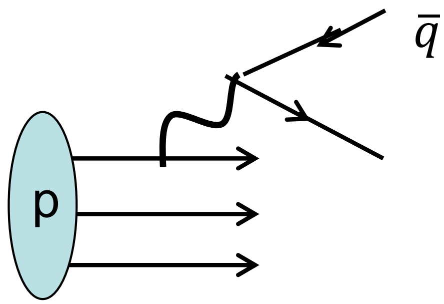
FC is compatible with any version of the ACOT scheme (cf. arXiv:1707.00657).

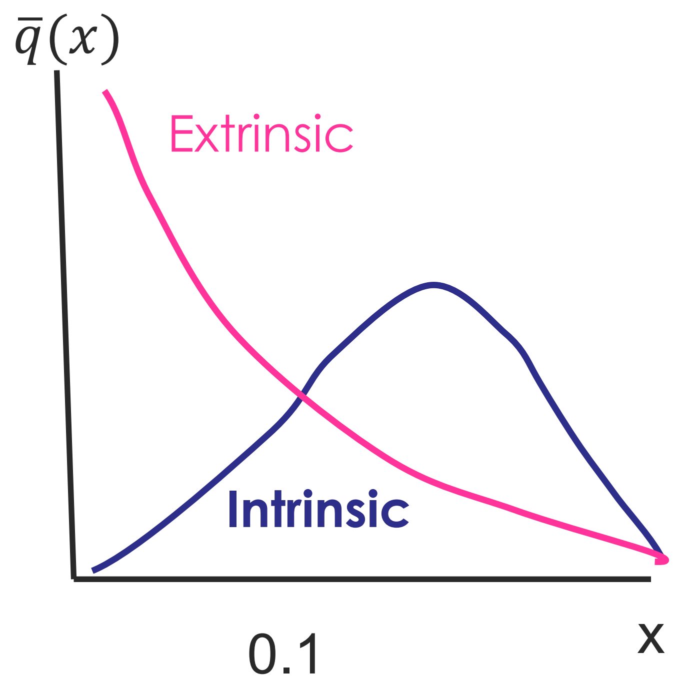
Flavor-excitation coefficient functions of these schemes differ by terms of $O(m_c^2/Q^2)$. Their overall differences are of $O(\Lambda^2/Q^2)$, i.e., within the accuracy of the factorization theorem.

In nonperturbative models:

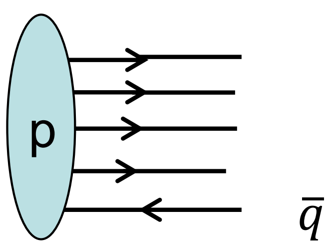
naturally formulated in language of proton *wave function*

→ **"Extrinsic" sea**
[maps onto leading-power sea production from light flavors]

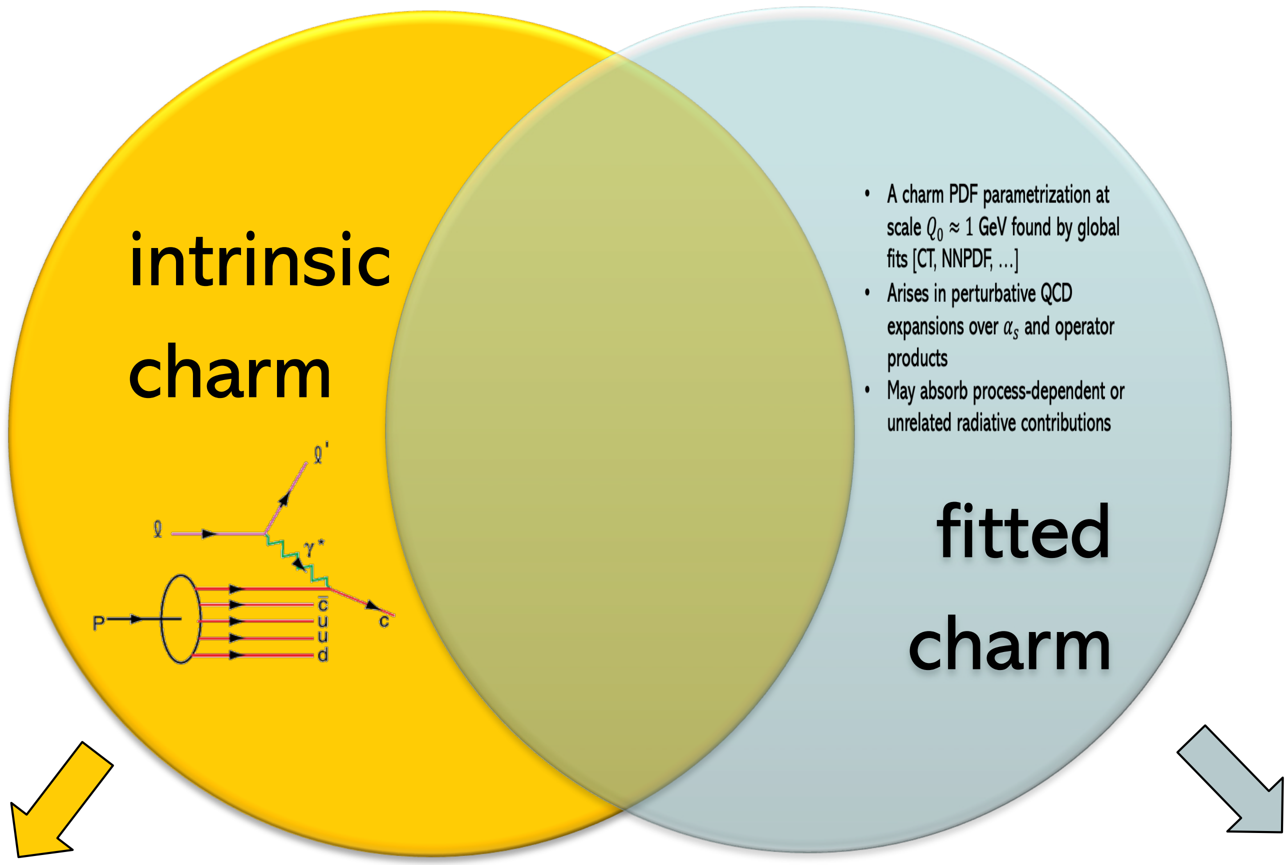




→ **"Intrinsic" sea**
[excited Fock nonpert. states;
…beyond leading-power production]



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 $x \gtrsim 0.2$

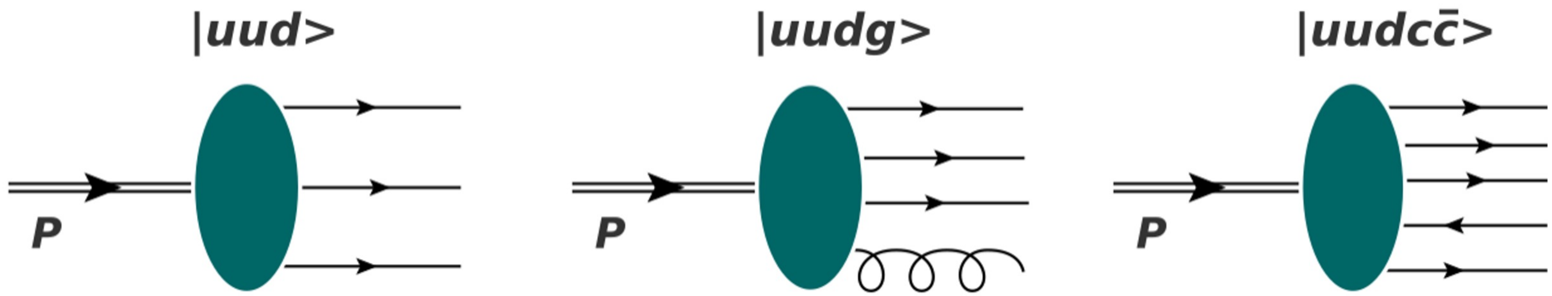
Connection?

- A charm PDF parametrization at scale $Q_0 \approx 1$ 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.

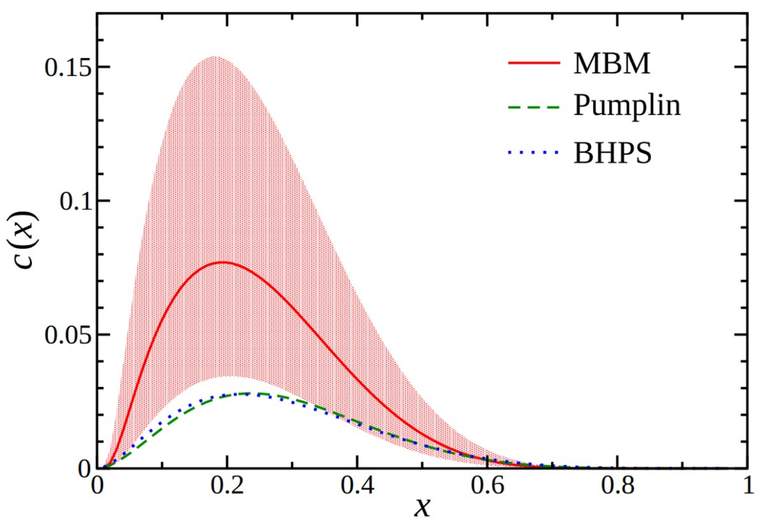


IC PDF: transition matrix element, $|\mathrm{proton}\rangle \to |uudc\bar{c}\rangle$ → old-fashioned PT; **scalar** field theory

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

('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).

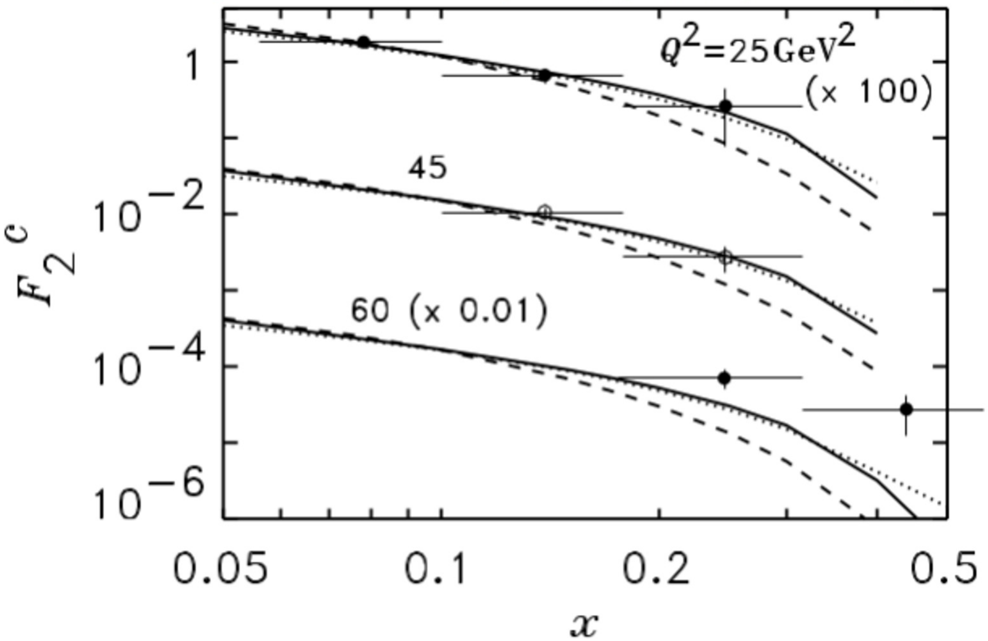
→ generically yields valence-like shape; governed by charm, hadronic mass scales

few expts with ‘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].



- → 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

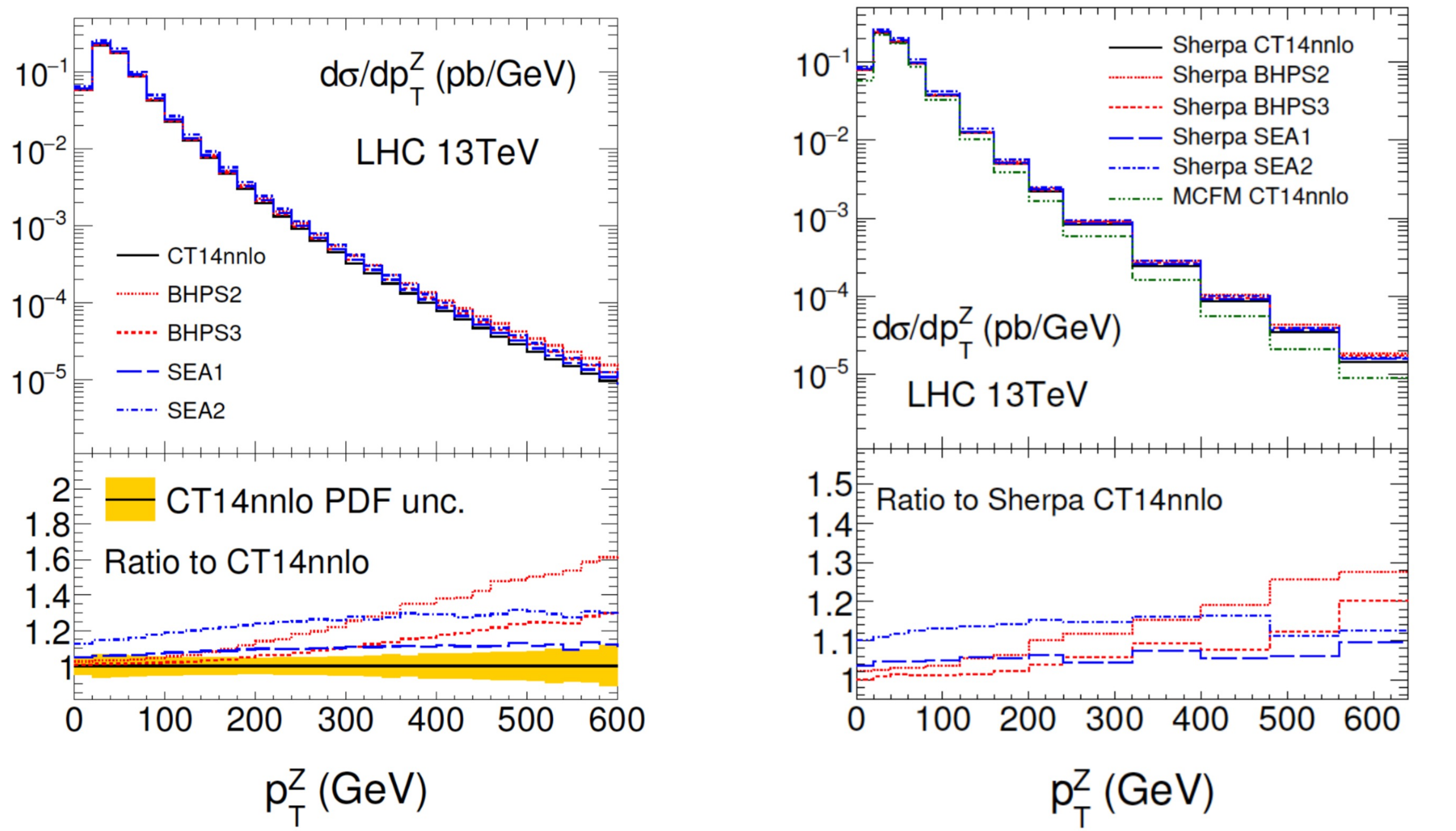
T. Boettcher, P. Ilten, M. Williams, 1512.06666; Bailas, Goncalves, 1512.06007

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., arXiv:1707.00657]



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

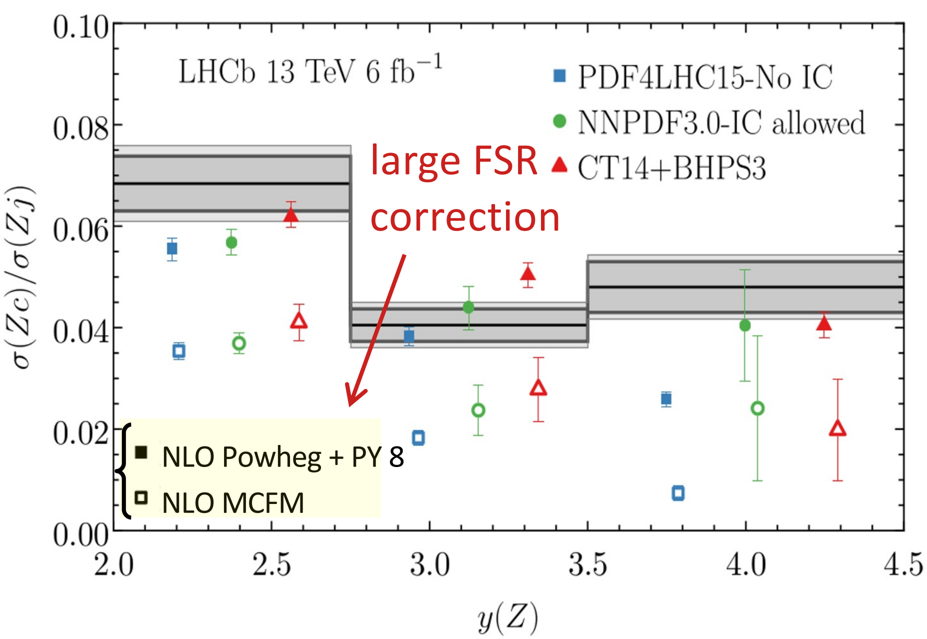
2022 LHCb 13 TeV data: (*Z+c*) / (*Z+jet*) ratios; 3 rapidity bins

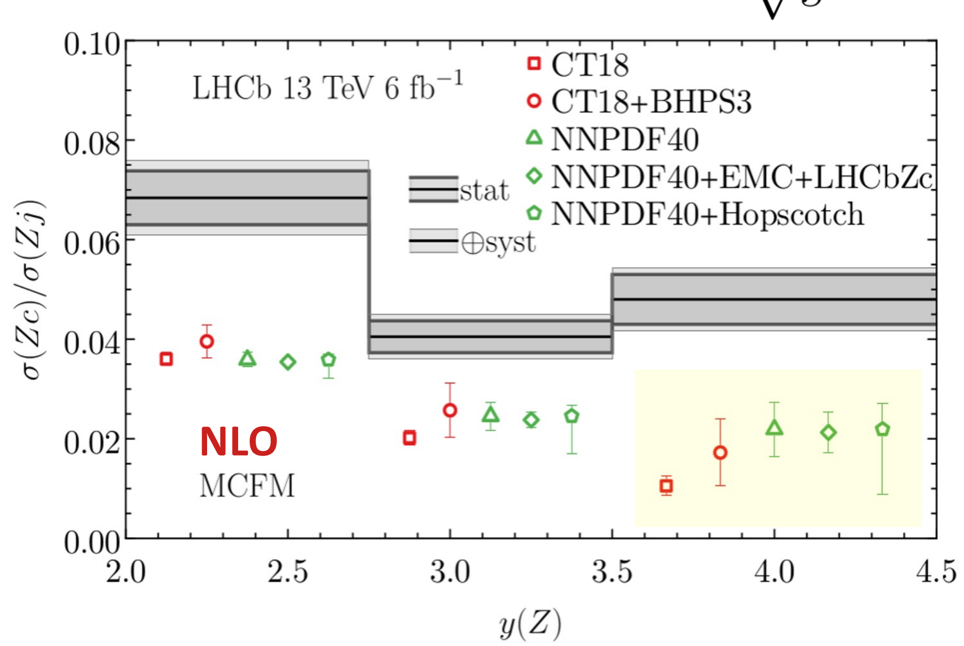
R. Aaij, *et al*. (LHCb); arXiv: 2109.08084.

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

→ meanwhile, significant theory uncertainties

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





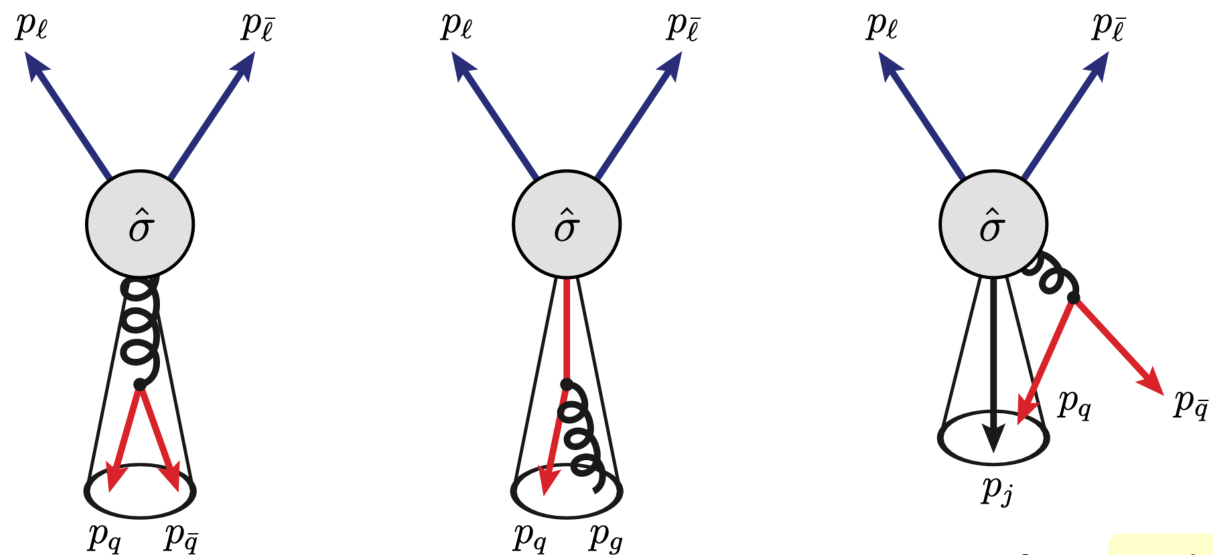
→ calculated **NLO** cross-section ratio similarly depends on showering, hadronization

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

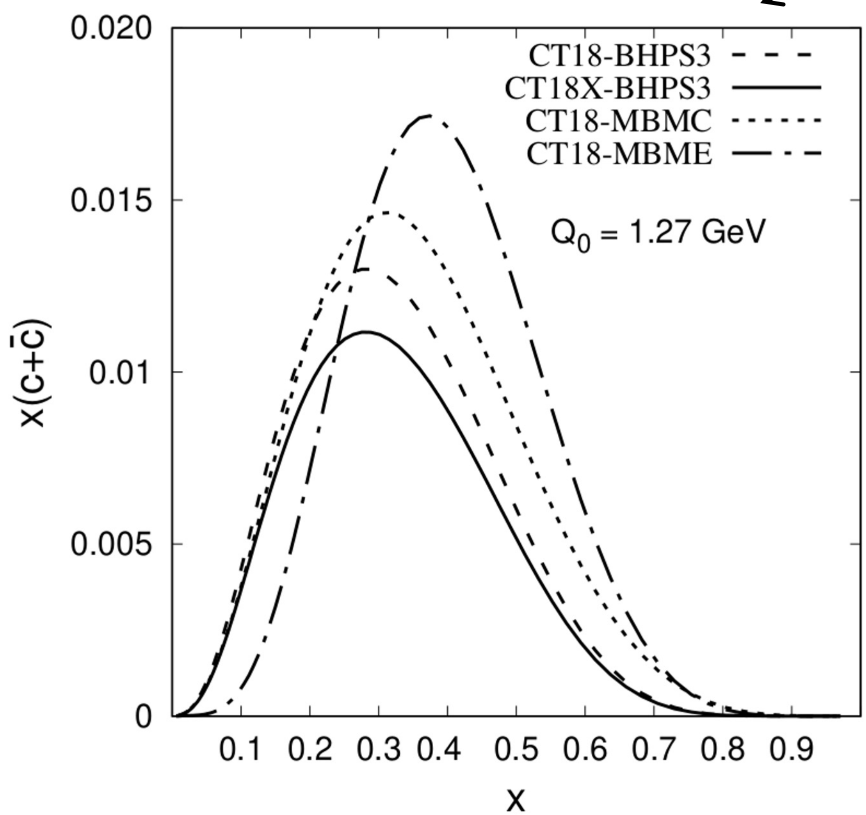
CT18 FC: fit charm against baseline CT data set

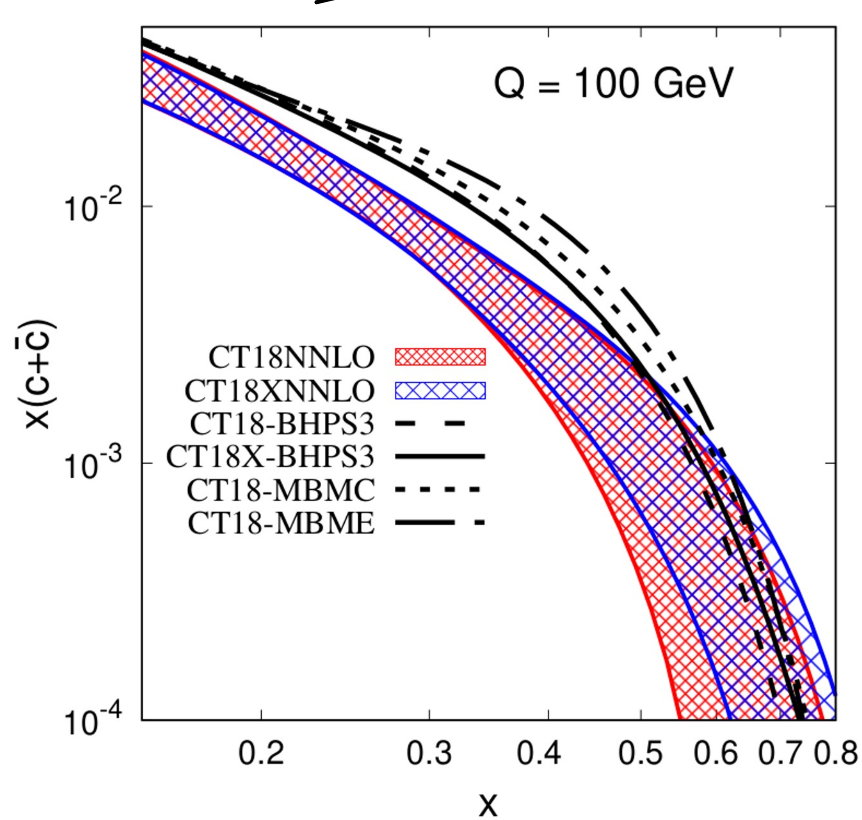
FC scenarios traverse range of high-*x* behaviors from IC models

- → 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

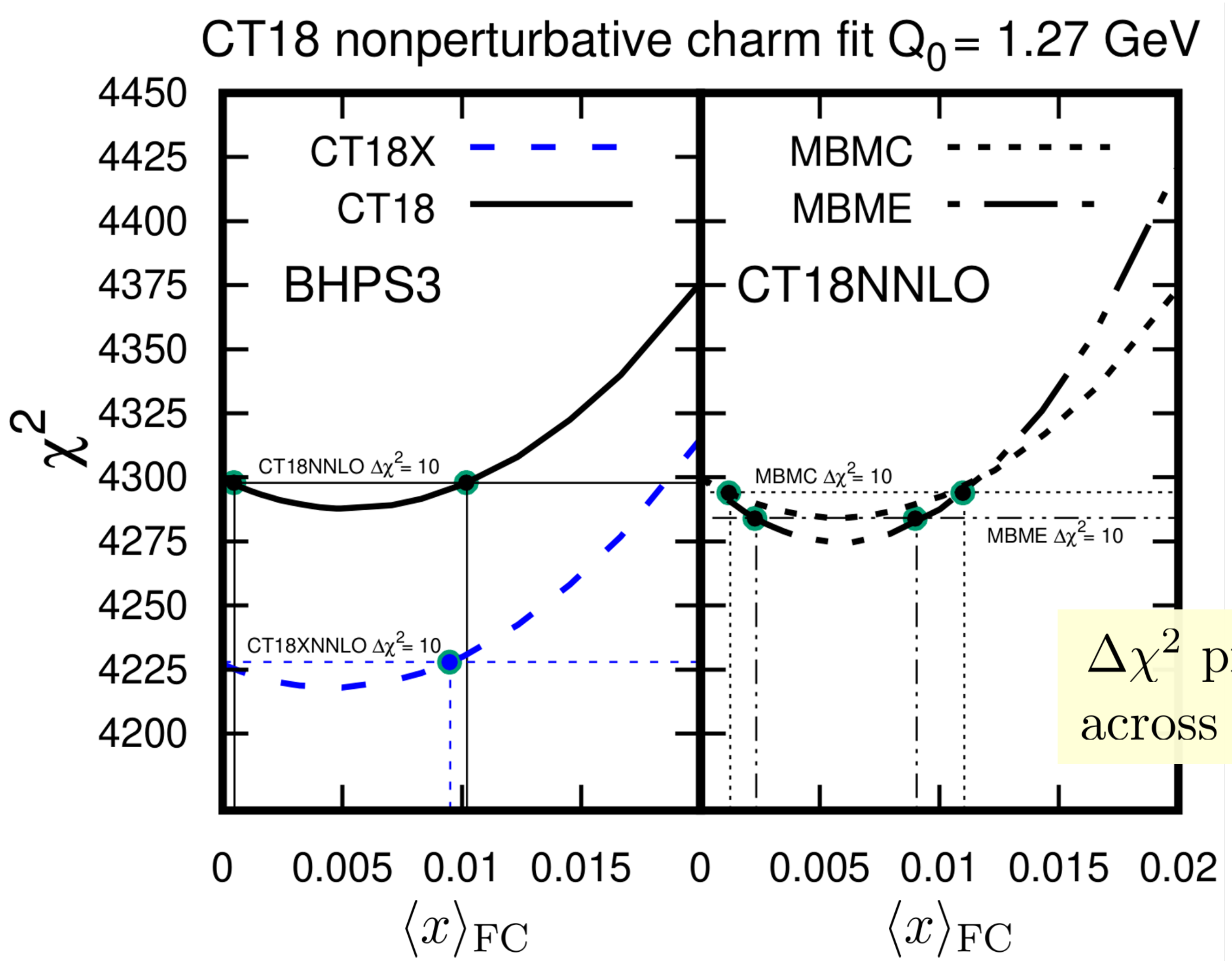




signal for FC in CT18 study, but with shallower $\Delta\chi^2$ than CT14 IC

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

FC PDF moments as F.o.M.

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

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

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

...at NNLO.

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

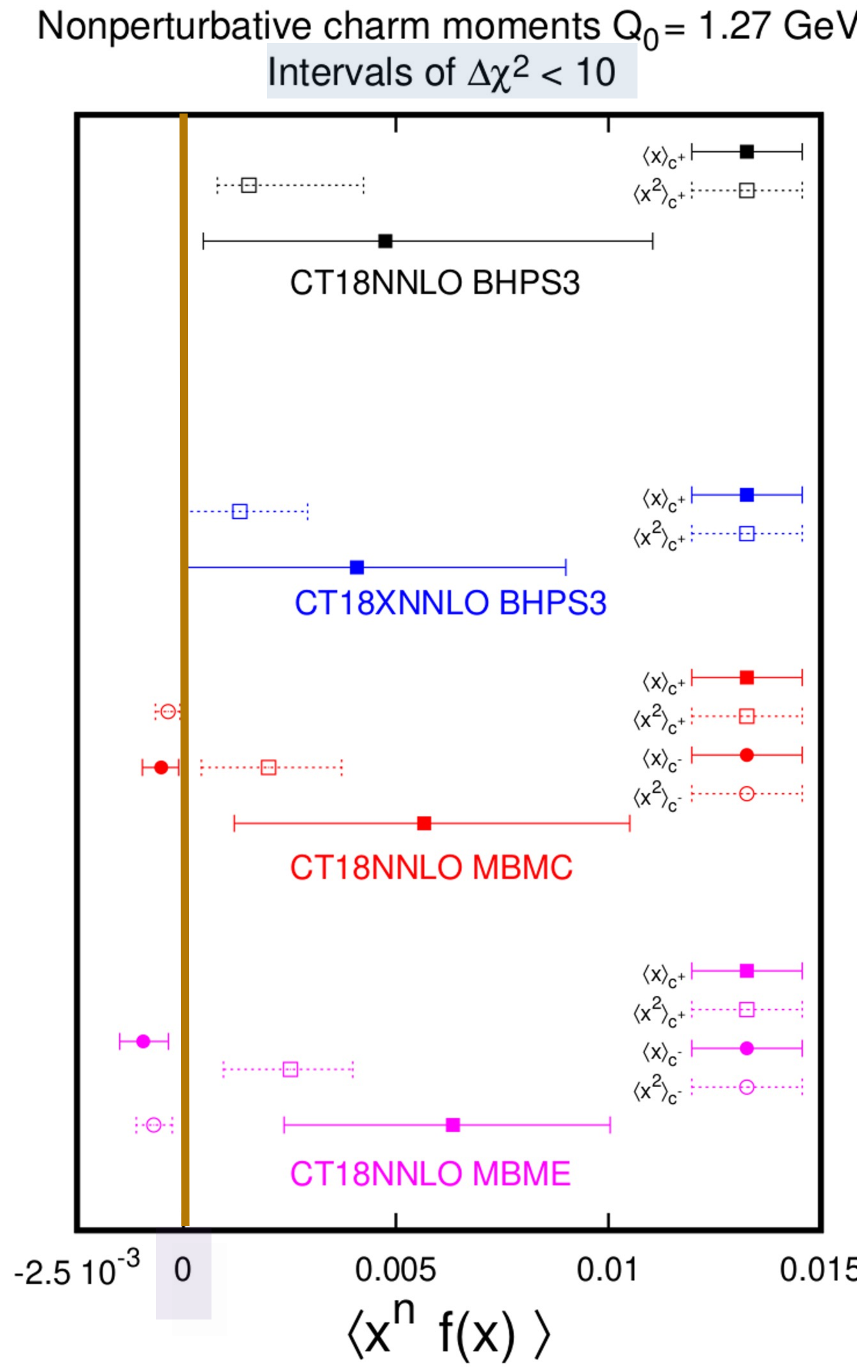
$$= 0.0041\,{}^{+0.0049}_{-0.0041}\,\left({}^{+0.0091}_{-0.0041}\right),\ \text{CT18X (BHPS3)}$$

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

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

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

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



FC PDF moments as F.o.M.

even restrictive uncertainties give moments consistent with zero

→ broaden further for default CT tol.

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

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

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

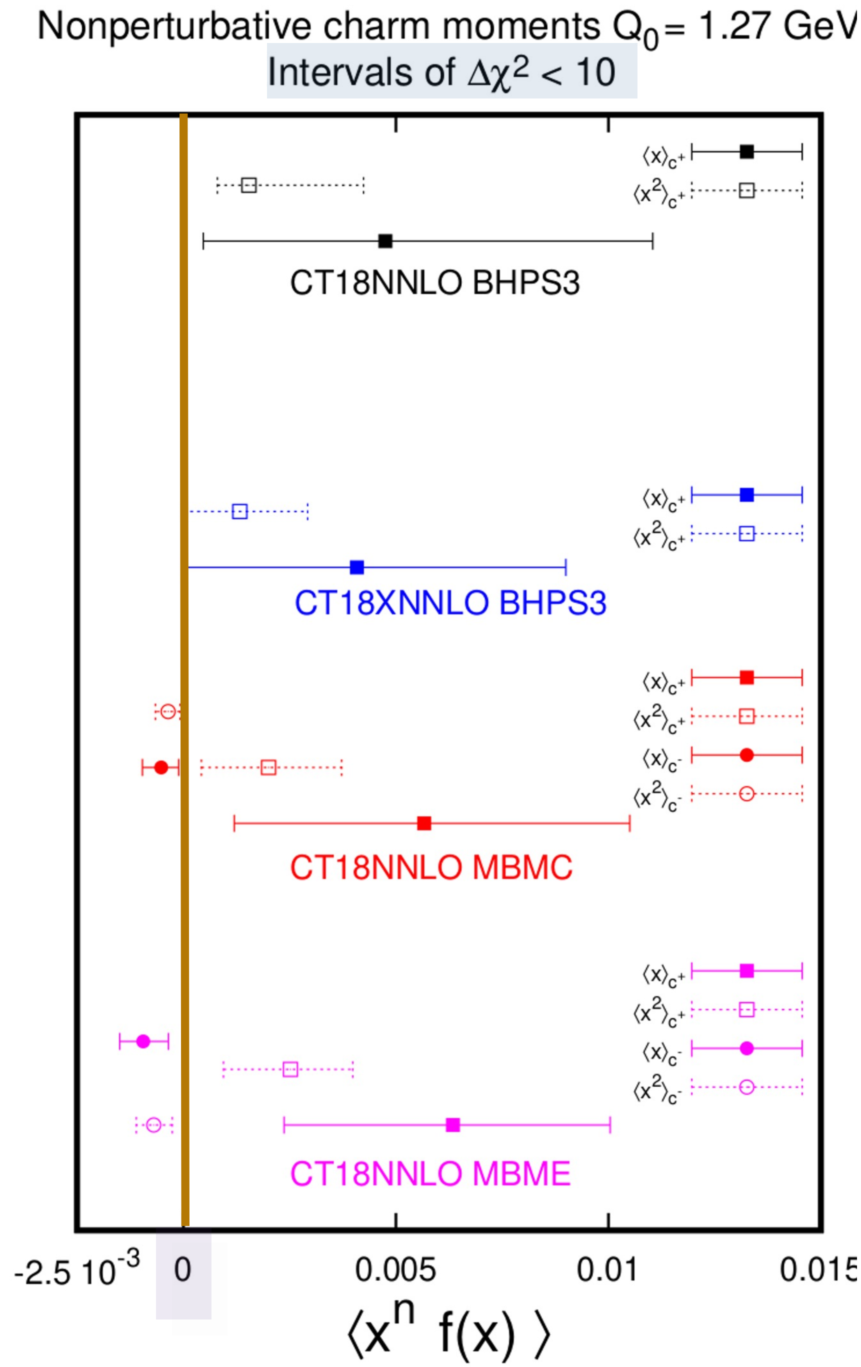
$$= 0.0041\,^{+0.0049}_{-0.0041}\,\left(^{+0.0091}_{-0.0041}\right),\ \text{CT18X (BHPS3)}$$

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

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

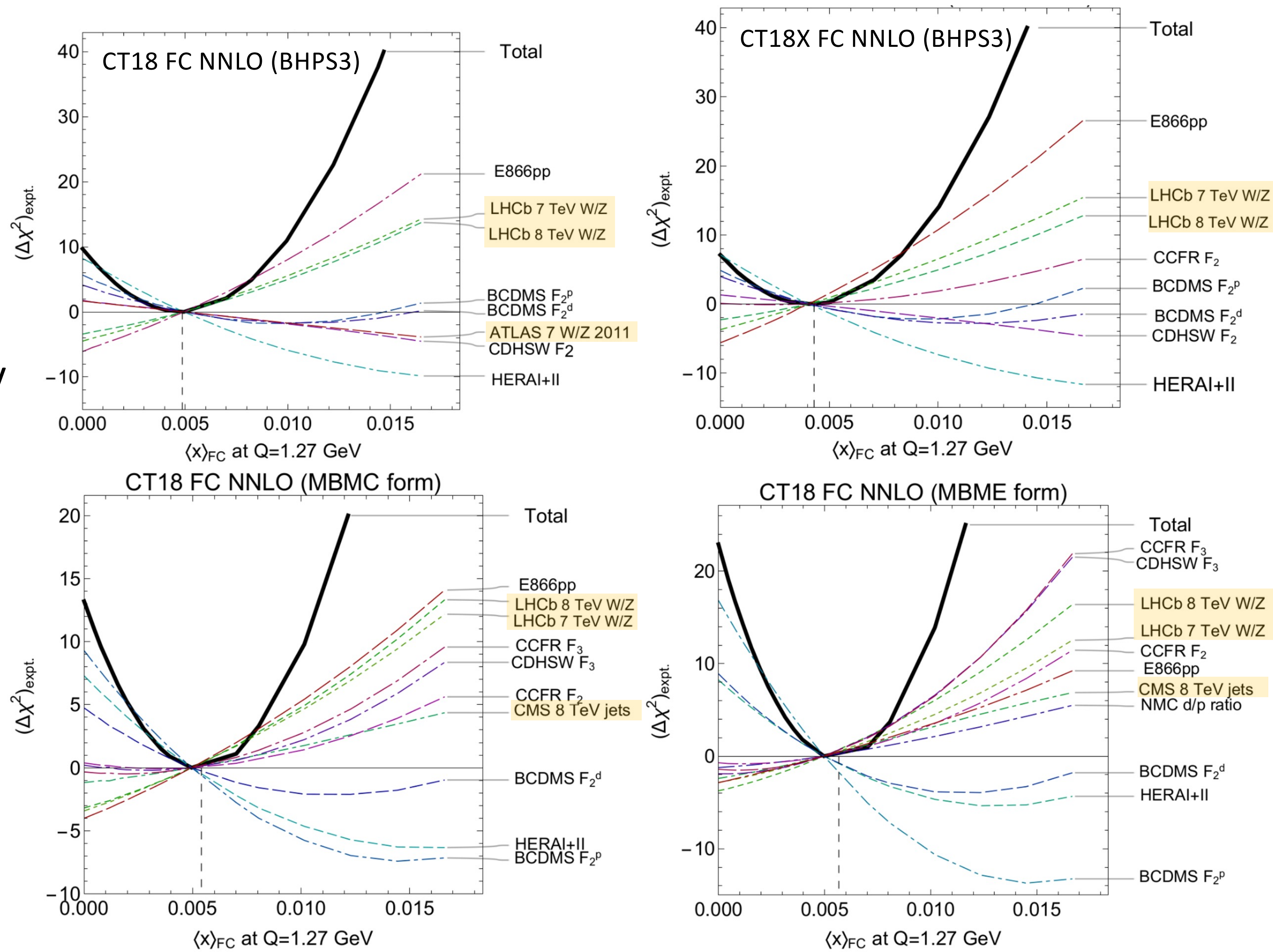
$\Delta\chi^2 \leq 10$ (restrictive tolerance)

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



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



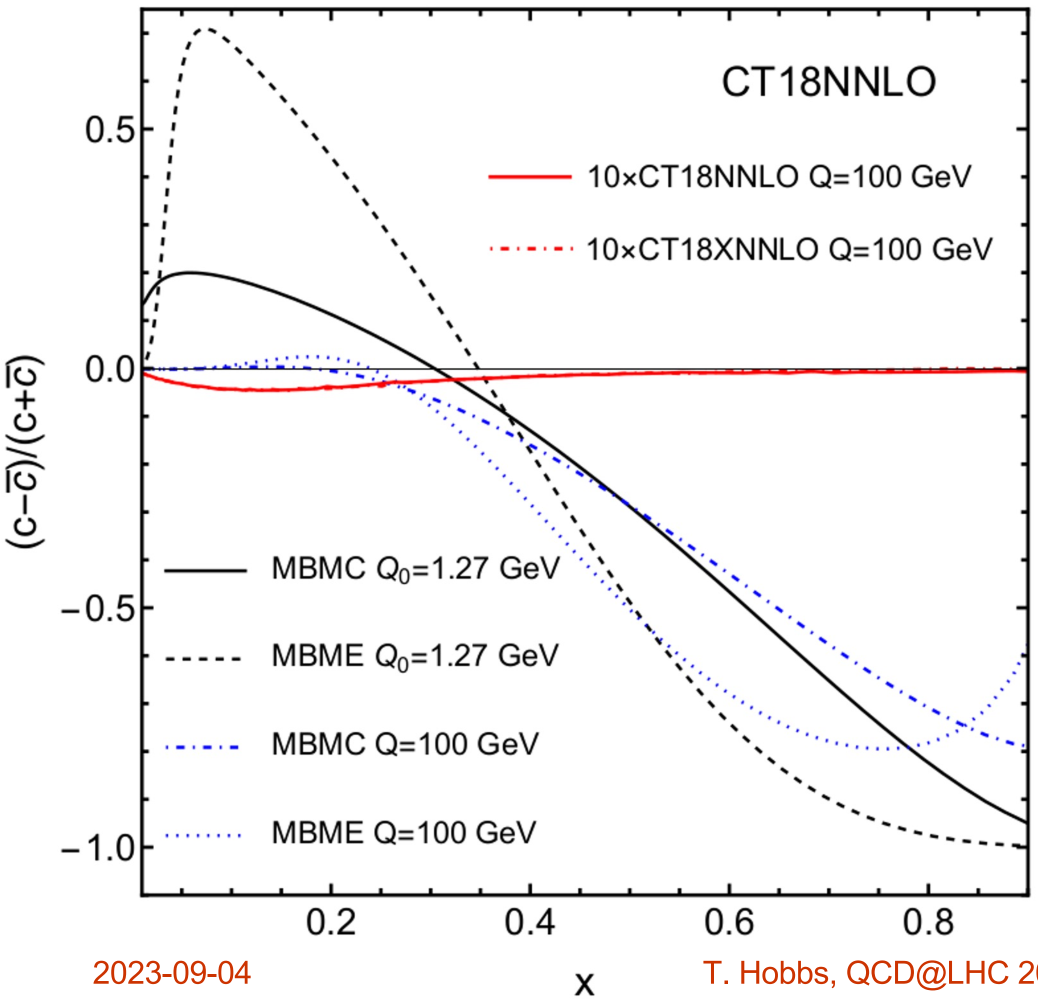
possible charm-anticharm asymmetries

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

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

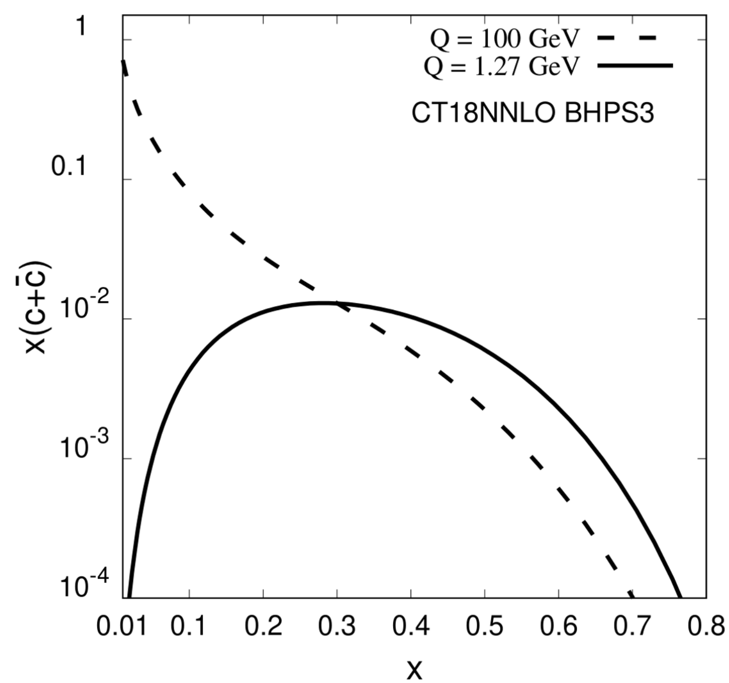
→ MBM breaks $c = \bar{c}$ through hadronic interactions

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



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

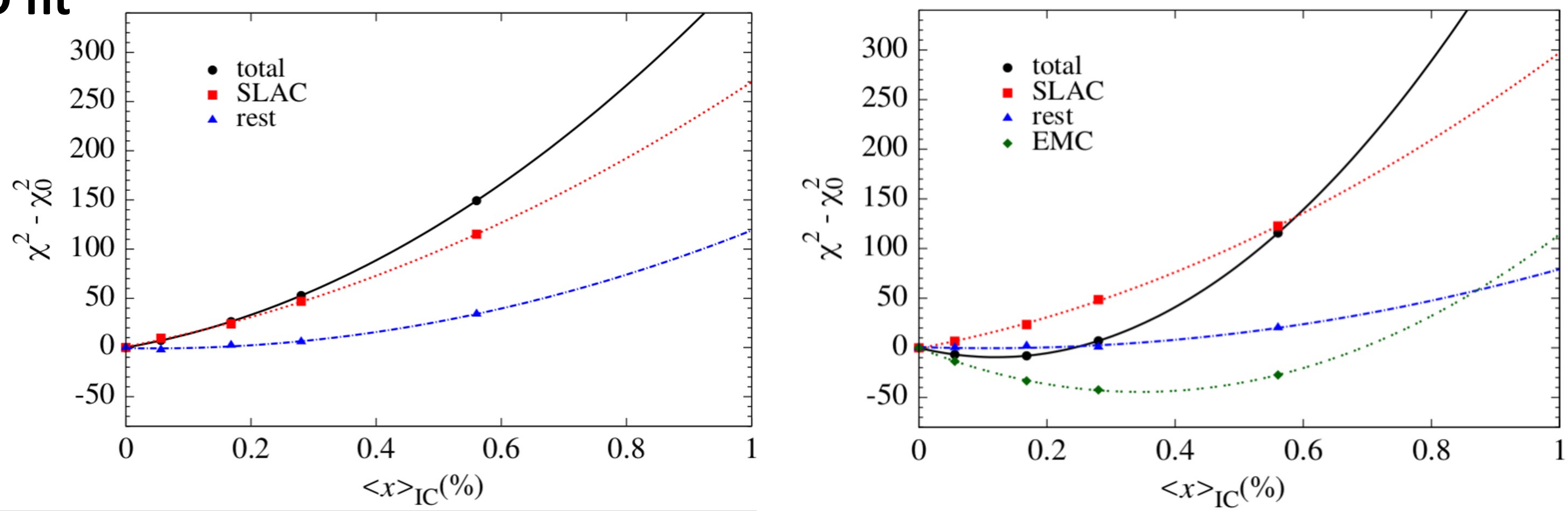
→ asym. small but ratio (left) can be bigger; will be hard to extract from data



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' $\Longrightarrow$ $\langle x\rangle_{\rm IC} < 0.1\%$; at 5σ !

'REST' only $\Longrightarrow$ $\langle x\rangle_{\rm IC} < 0.1\%$; at 1σ

as in CT, can be related to hardness of gluon PDF, x ~ 0.1

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

+ SLAC/'REST': $\langle x\rangle_{\rm IC} = \mathbf{0.13 \pm 0.04\%}$

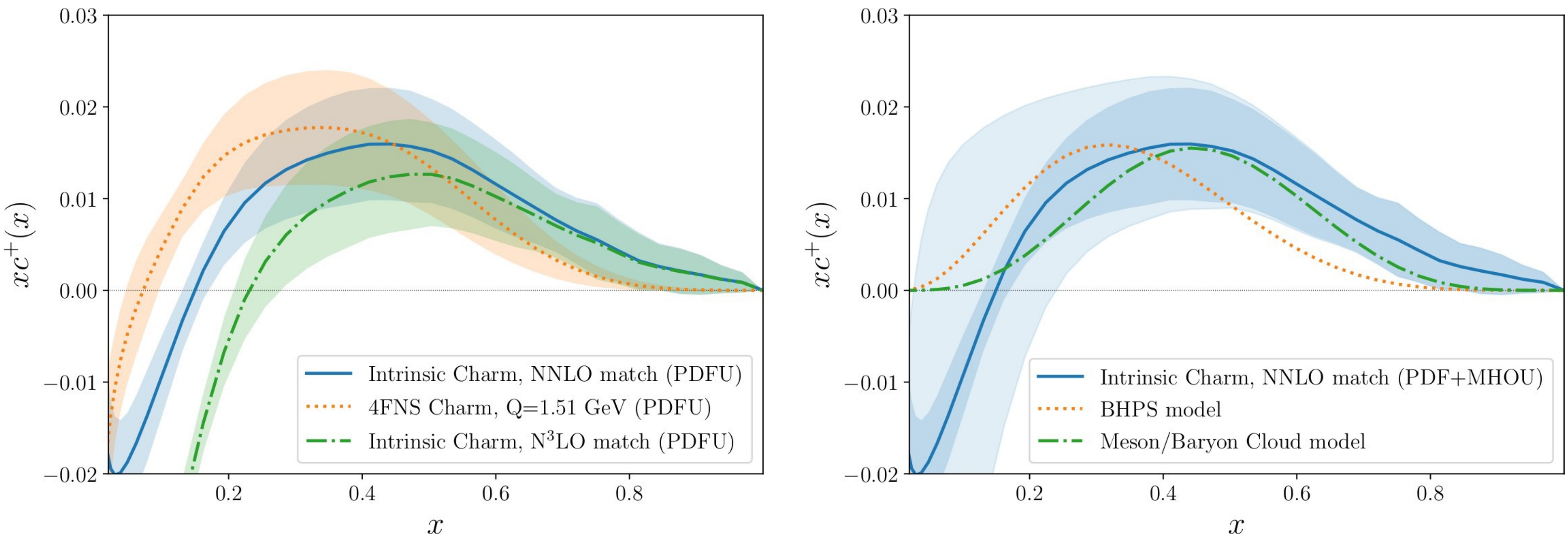
included SLAC DIS; used more restrictive tolerance criterion, $\Delta\chi^2 = 1$

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

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

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

2. Parametrization sampling uncertainty (underestimation of PDFU)

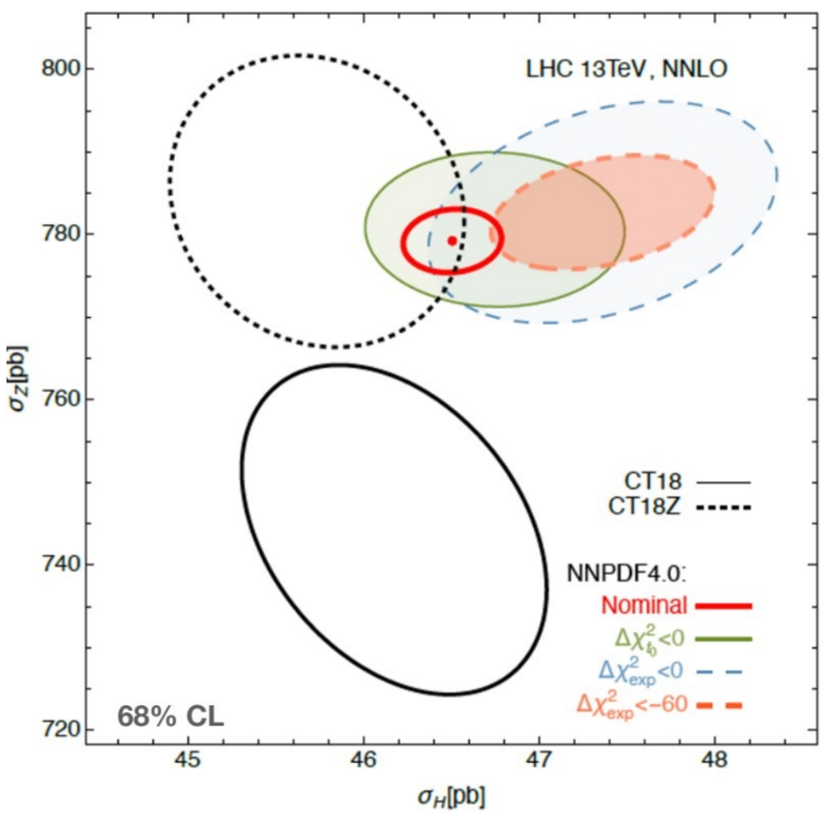
MC uncertainties closely connected to sampling strategy

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

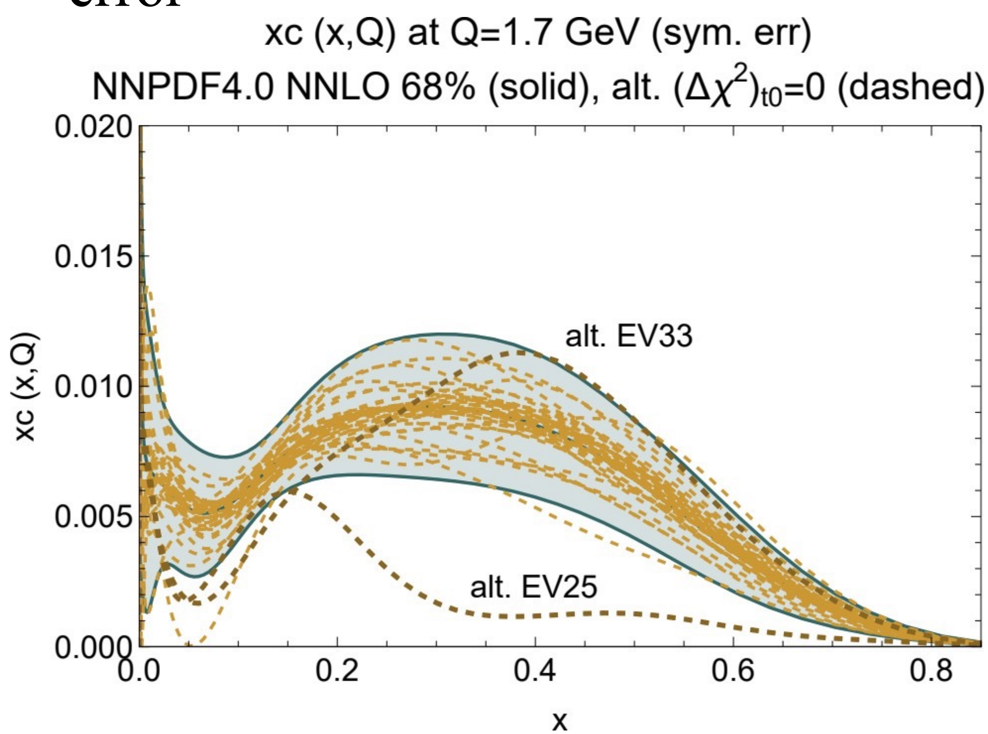
Courtoy *et al.*, PRD**107** (2023) 3, 034008.

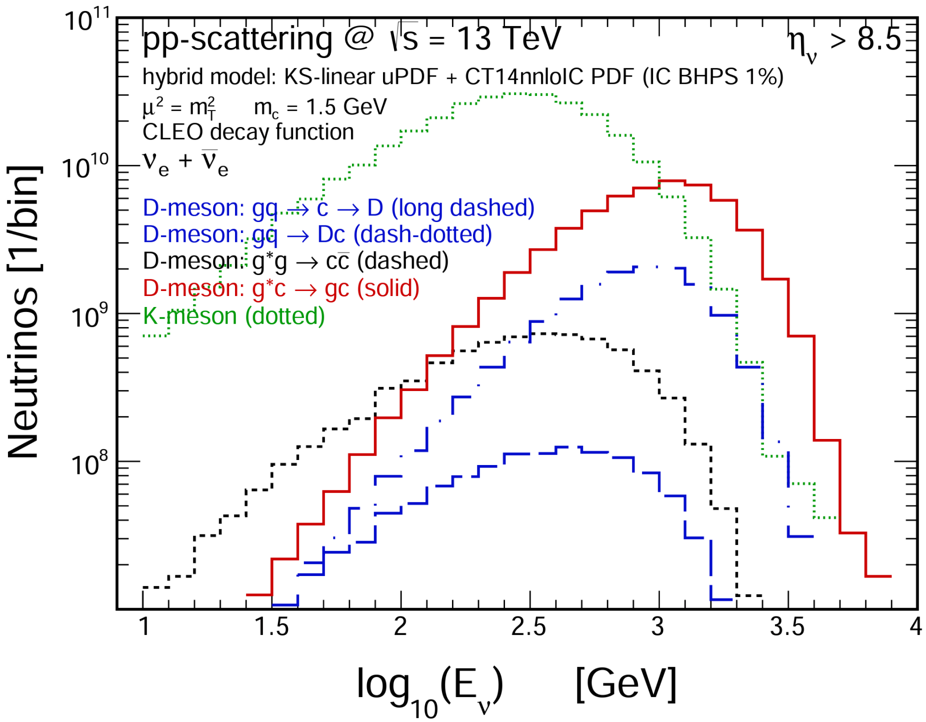
see also, NNPDF response: 2211.12961.

- broader sampling with the public NNPDF4.0 code impacts PDF errors of cross sections



- substantially broadens high-x FC error



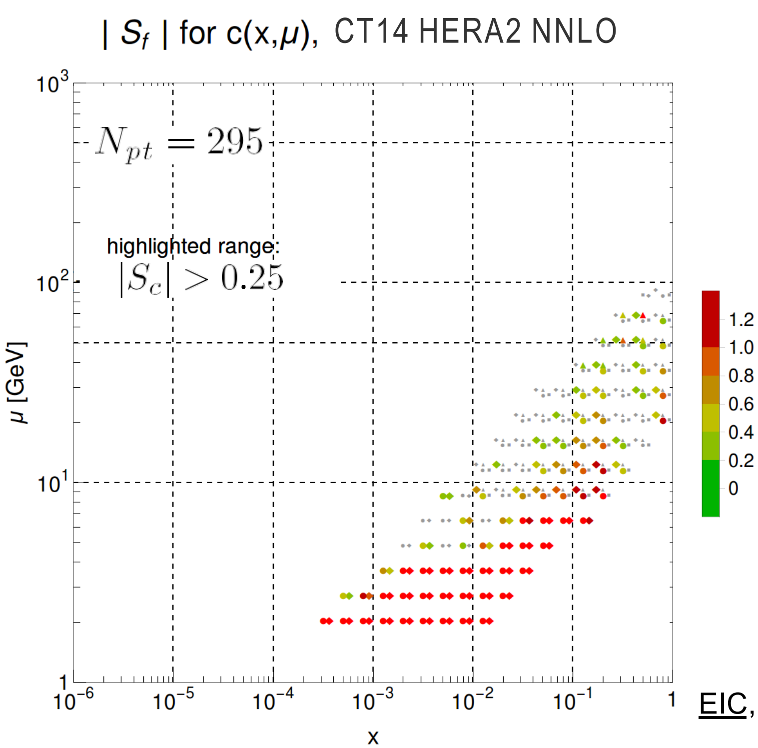


future data will inform FC

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

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

(FPF Whitepaper, 2203.05090)



- 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).

outlook

- size, shape of nonpert charm remains indeterminate

$\rightarrow$ theoretical ambiguities in relation between FC/IC unresolved

$\rightarrow$ need more sensitive data; FC currently consistent with zero

concordance with enlarged error estimates: $\langle x \rangle_{\mathrm{FC}} \sim 0.5\%$, 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:

$\rightarrow$ promising experiments at LHC, FPF; EIC

$\rightarrow$ lattice data on key charm PDF moments; quasi-PDFs

$\rightarrow$ direct benchmarking of FC among PDF fitting groups