

fitted charm in CT18: the enduring nonperturbative charm problem

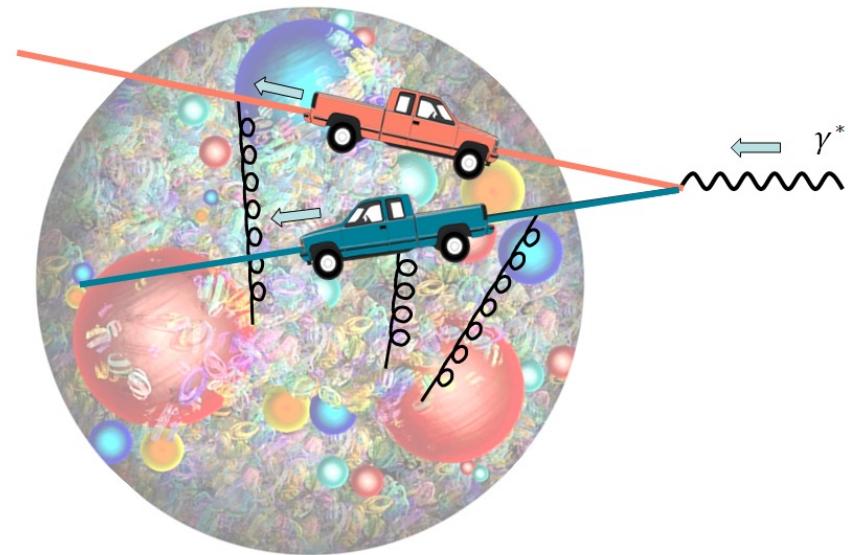
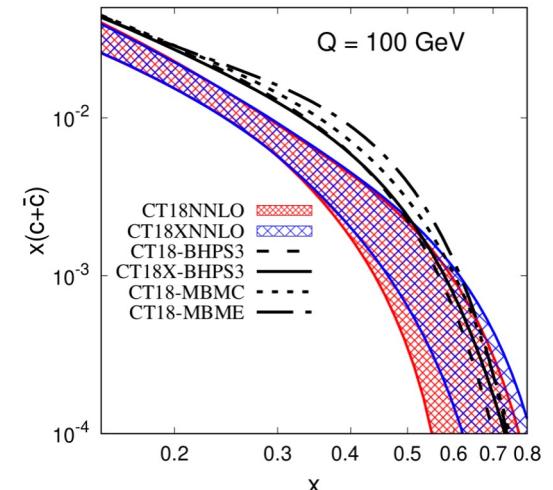
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P. Nadolsky, C.-P. Yuan

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



Just published:
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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

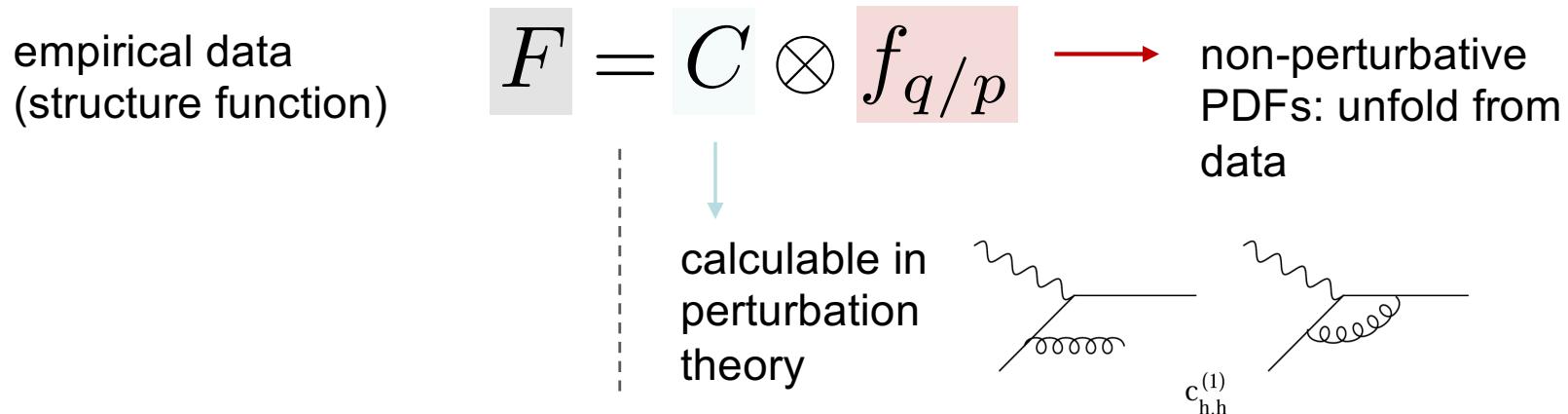
1. P. Jimenez-Delgado, **TJH**, Londergan, Melnitchouk, PRL114 (2015) 8, 082002; NLO fit; first analysis with EMC data
2. T.-J. Hou et al., JHEP 02 (2018) 059; QCD factorization with the NP charm and CT14 IC NNLO pheno analysis
3. M. Guzzi, **TJH**, K. Xie, et al., arXiv:2211.01387; new CT18 FC analysis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

QCD factorization provides access to nucleon structure

long-distance physics imprinted on PDFs --- inherently *nonperturbative* matrix elements

$$f_{q/p}(x, Q^2) = \int \frac{d\xi^-}{4\pi} e^{-i\xi^- k^+} \langle p | \bar{\psi}(\xi^-) \gamma^+ \mathcal{U}(\xi^-, 0) \psi(0) | p \rangle$$

- QCD factorization allows PDFs to be fitted from data; schematically:



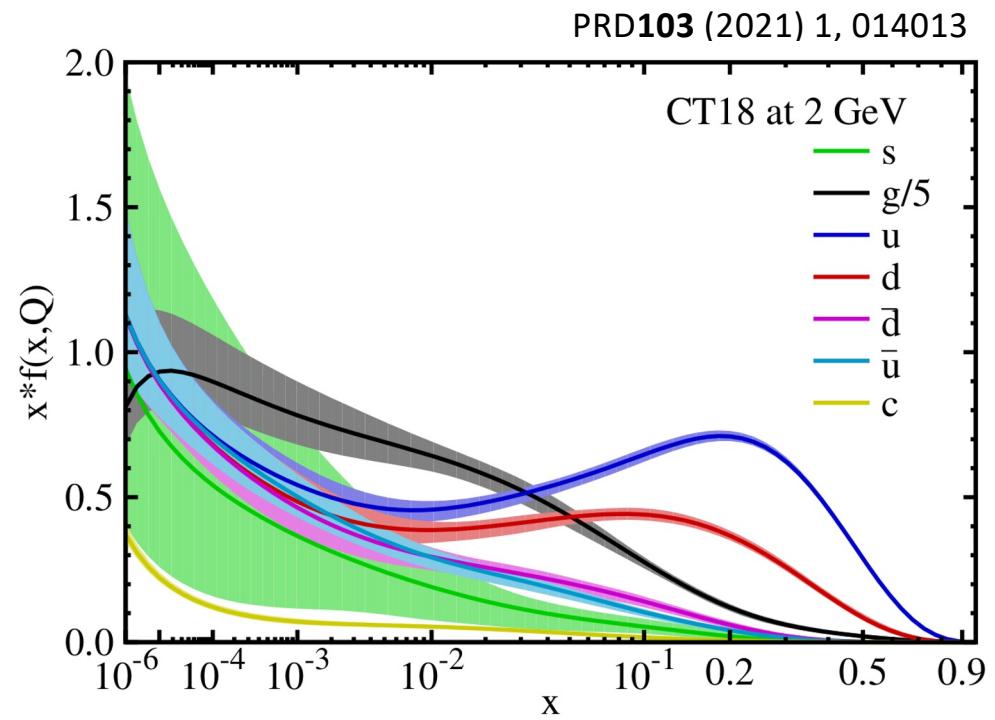
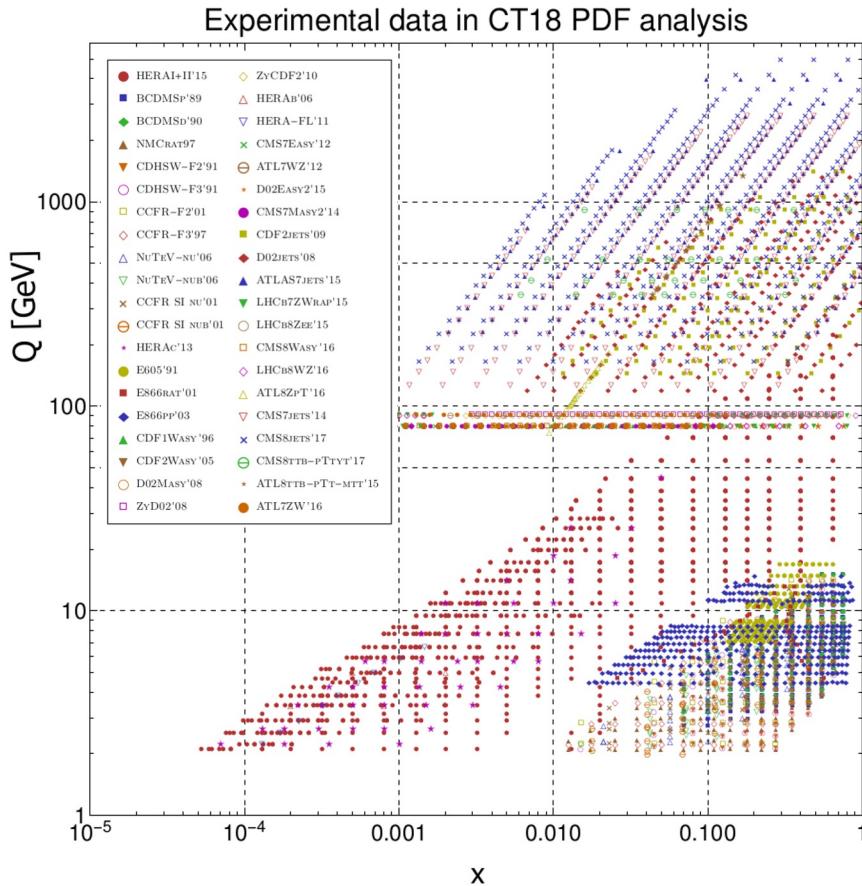
- PDFs are parametrized and fitted at some initial energy scale, $Q_0 \sim M = 1 \text{ GeV}$
→ perturbative *evolution* specifies dependence on $Q^2 > Q_0^2$
- must also unfold complicated flavor and x dependence, $x \in [10^{-5}, 0.7]$

fit the world's data from a diverse range of scales and processes

these ingredients combine in global QCD analyses

modern standard for HEP pheno: (N)NNLO; latest CTEQ-TEA NNLO analysis, CT18

→ published in 2021: combined fit of DIS, fixed-target, HERA, LHC Run-1; $N_{\text{pt}} = 3681$



□ baseline for numerous follow-up studies, 2021-2023

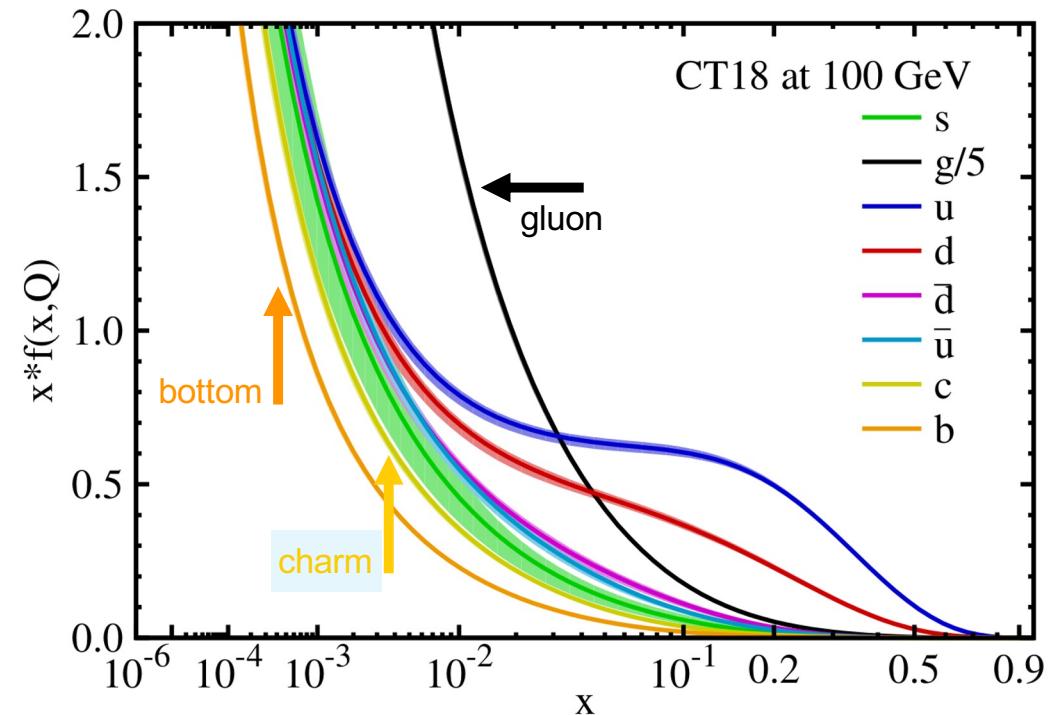
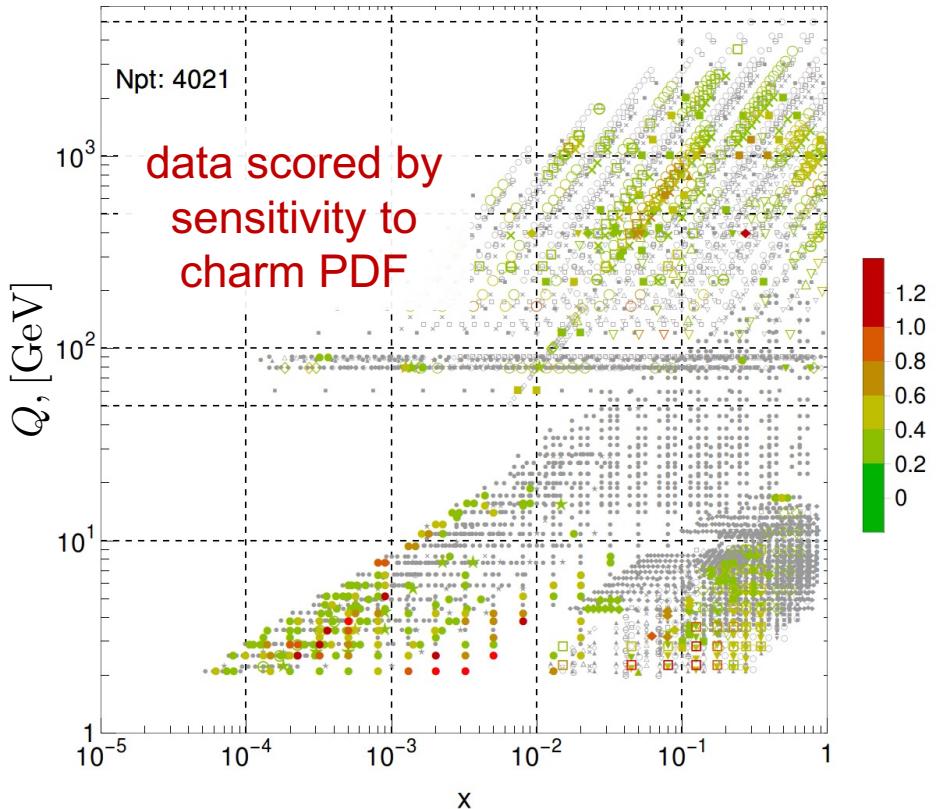
→ photon PDF; strangeness and lattice; SMEFT; UHE neutrino; LHC Drell-Yan, ...

charm PDF in global QCD fits

in CT18, charm generated perturbatively, predominantly through gluon splitting

→ charm PDF tracks gluon; constrained by large range of data

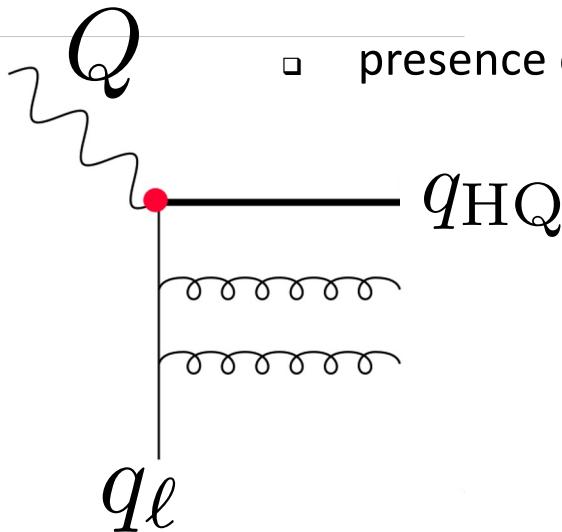
$|S_f|, c(x, Q)$ in CT14_{HERA2} NNLO



fitted data traverse wide variety of scales, including those with $Q \sim M_Q$

→ delicate treatment of HQs improves theory; stabilizes PDF extractions

QCD analyses traverse many scales, Q ; variable flavor



$$Q \gg m_{HQ}$$

- presence of HQ introduces an additional effective scale into hard process
- perturbatively-generated HQ
PDFs resum large logs,

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

→ 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 $n_F = 5$

evolution schemes and higher orders in QCD

higher order(s) in pQCD: improved accuracy in Wilson coeff., control over scale dependence
at given fixed order, nontrivial relationship with chosen heavy-quark (HQ) scheme

- fixed flavor-number (FFN): $Q \gtrsim M_Q$; flavor-creation (FC) processes with $n_f = 3$
- zero-mass (ZM) variable flavor-number: $Q \gg M_Q$; flavor-excitation (FE)
processes with $n_f = 4$

2 paradigms adapted to different regimes w.r.t. HQ mass scale; **Ξ interpolation scheme?**

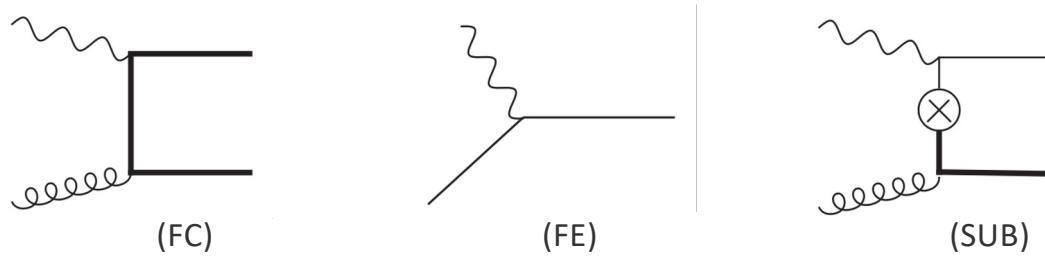
general-mass schemes: S-ACOT- χ

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:



$$\left\{ \begin{array}{l} Q \gtrsim M_Q \implies (\text{SUB}) \approx (\text{FE}) \text{ such that } n_f = 3 \text{ FC dominates} \\ Q \gg M_Q \implies (\text{SUB}) \approx (\text{FC}) \text{ such that } n_f = 4 \text{ FE dominates} \end{array} \right.$$

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

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

S-ACOT- χ : smooth HQ thresholds, include approx. HQ mass dependence: $C_i(x) \rightarrow C_i(\chi)$

formulation necessitates careful tracking of diagrams to organize calculation correctly 8

NNLO example: NC DIS

Guzzi, Nadolsky, Lai, Yuan Phys. Rev. D86, 053005 (2012)

[arXiv: 1108.5112]

at structure-function level, factorization allows separation of coeff. functions, PDFs:

$$F(x, Q) = \sum_{i=1}^{N_f^{fs}} e_i^2 \sum_{a=0}^{N_f} [C_{i,a} \otimes \Phi_{a/p}] (x, Q) \quad (F = F_{2,L})$$

compute S-ACOT- χ coeff. functions: expand in α_s each term in auxiliary partonic struct. func.:

$$F_{i,b}(\hat{x}, Q) = \sum_{a=0}^{N_f} [C_{i,a} \otimes \Phi_{a/b}] (\hat{x}, Q)$$

→ matching terms order-by-order,

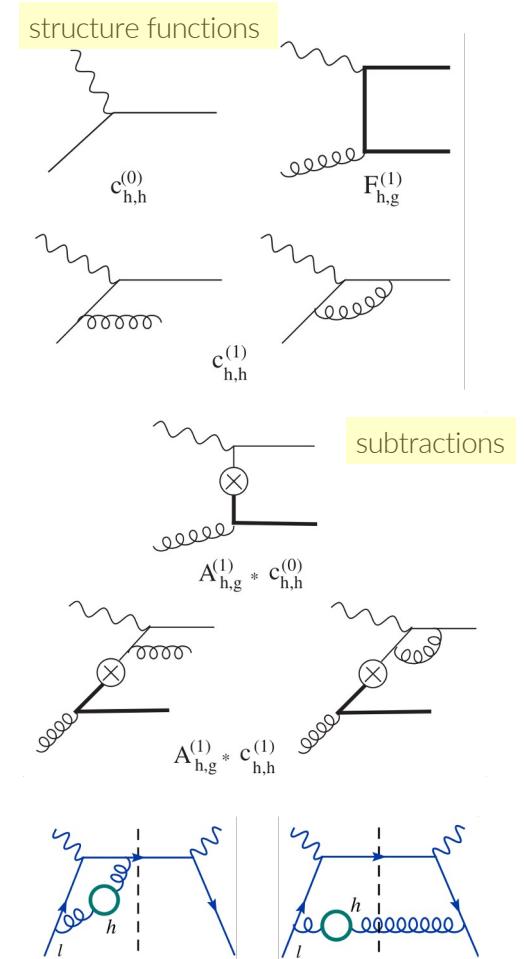
$$\left\{ \begin{array}{l} C_{i,b}^{(0)}(\hat{x}) = F_{i,b}^{(0)}(\hat{x}) \\ C_{i,b}^{(1)}(\hat{x}) = F_{i,b}^{(1)}(\hat{x}) - [C_{i,a}^{(0)} \otimes A_{ab}^{(1)}](\hat{x}) \\ C_{i,b}^{(2)}(\hat{x}) = F_{i,b}^{(2)}(\hat{x}) - [C_{i,a}^{(0)} \otimes A_{ab}^{(2)}](\hat{x}) - [C_{i,a}^{(1)} \otimes A_{ab}^{(1)}](\hat{x}) \end{array} \right.$$

organize into heavy-, light-quark pieces: $F = \sum_{l=1}^{N_l} F_l + F_h$

$$C_{h,g}^{(2)} = \hat{F}_{h,g}^{(2)} - A_{hg}^{(2)} - c_{h,h}^{(1)} \otimes A_{hg}^{(1)}$$

→ S-ACOT- χ : massless FE, χ -rescaled

→ light-quark SFs: additional flavor non-sing. (NS) disconnected graphs:



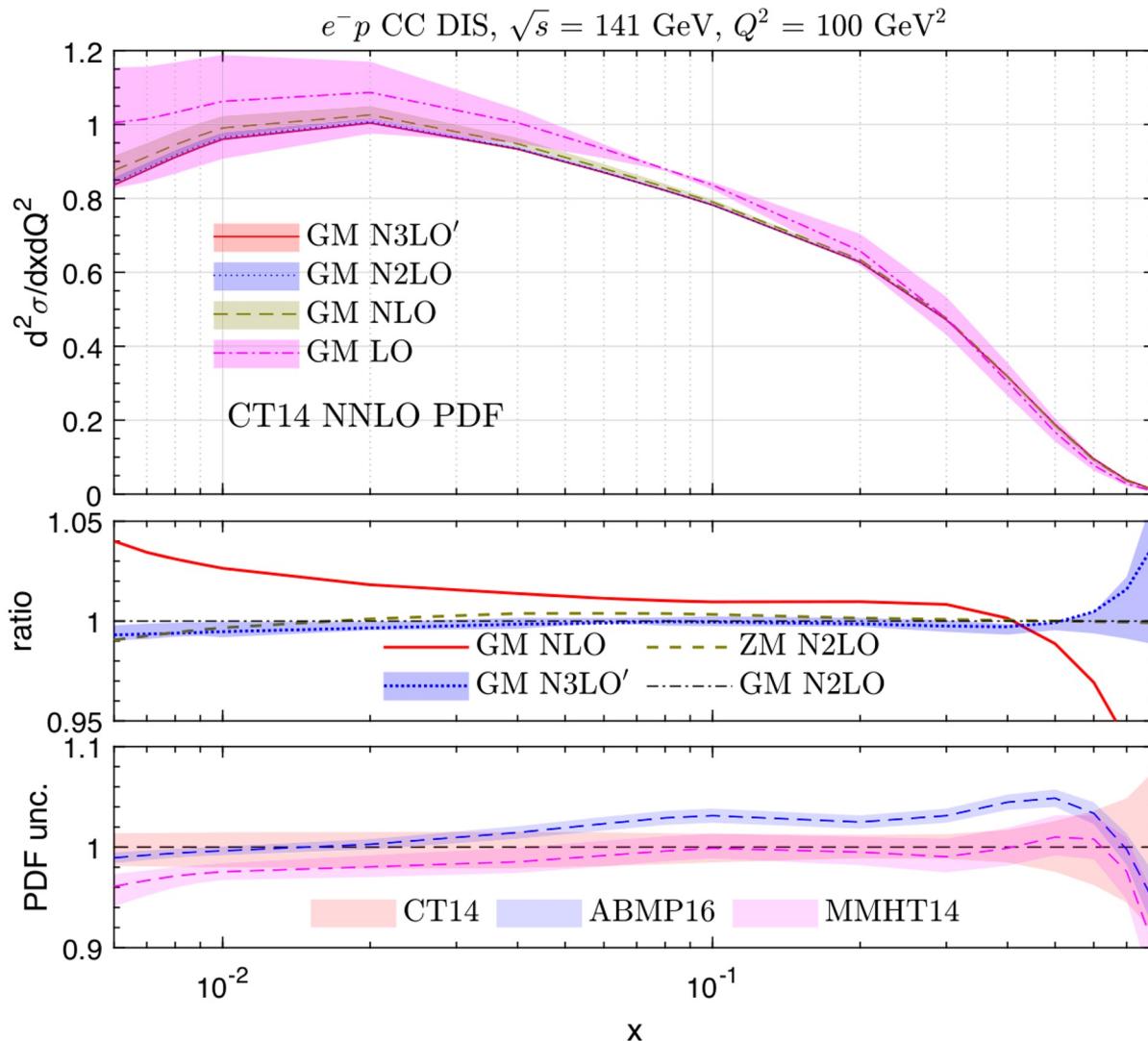
implications for PDF extractions at EIC

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^3LO' , 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

...have seen how HQs are implemented *perturbatively* in QCD analyses

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

what about *nonperturbative charm*; not radiatively generated,

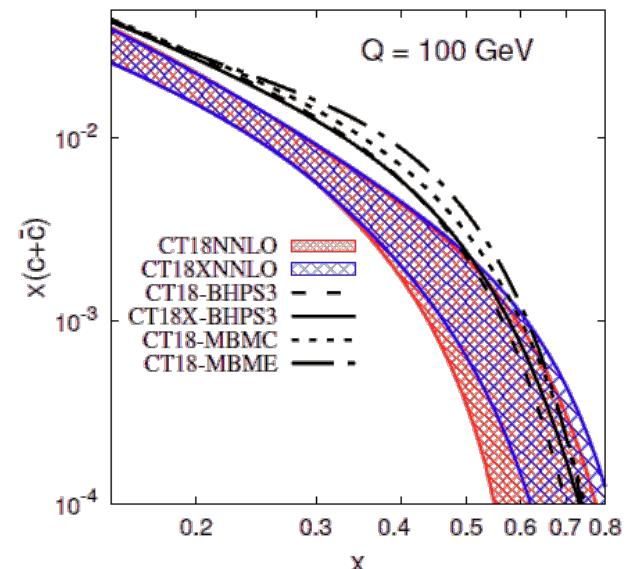
$$c(x, Q = m_c) = c^{\text{IC}}(x) \neq 0$$

Do global PDF fits constrain “intrinsic” charm?

“fitted charm” (FC) is a more direct term to describe the charm PDF found in the global QCD fit

in fact, all global analyses test fitted charm; they vary in terms of flexibility

→ all fits depend on assumptions/methodology

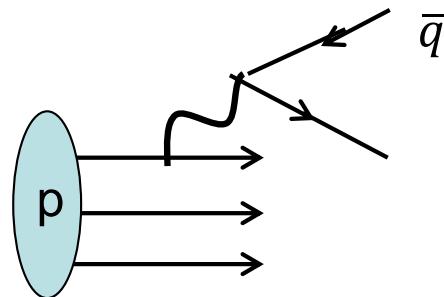


historically, intrinsic charm formulated in nonperturbative models

naturally framed in language of proton wave *function*

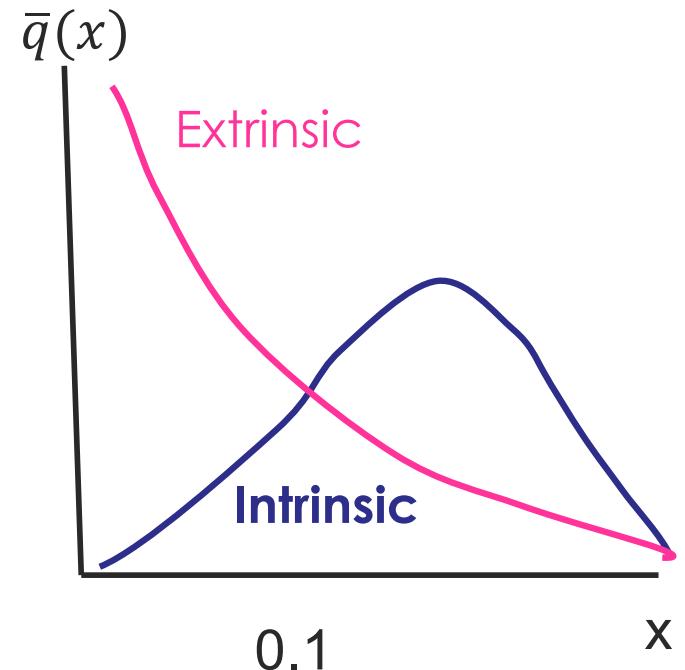
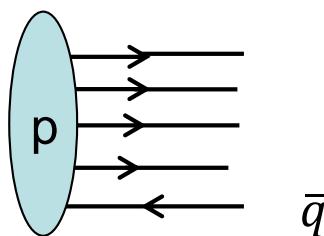
→ “Extrinsic” sea

[maps onto leading-power sea production from light flavors]

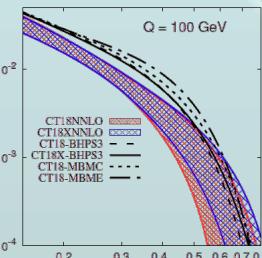
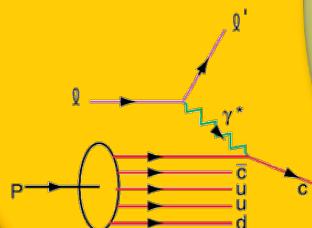


→ “Intrinsic” sea

[excited Fock nonpert. states;
beyond leading-power production]



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 $x \gtrsim 0.2$



- 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

PDF fits may include a fitted charm PDF

fitted charm = “higher-twist charm”
+ other (possibly not universal)
higher $\mathcal{O}(\alpha_s)$, higher-power terms

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

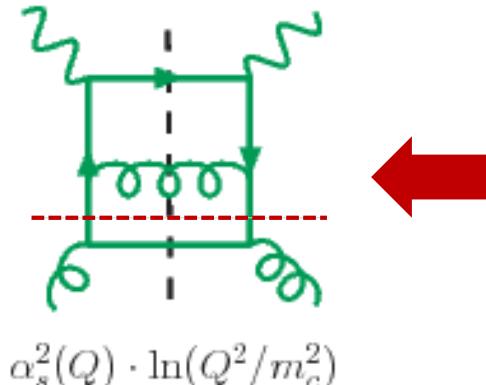
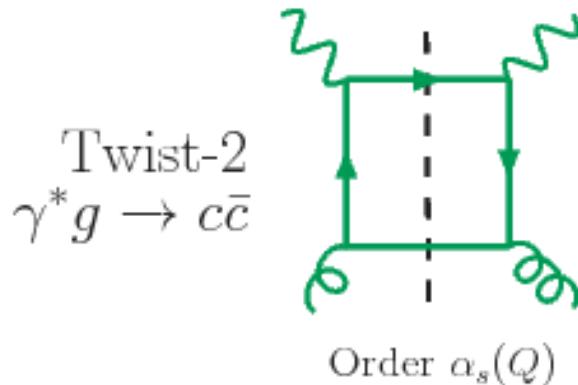
All α_s orders:
$$F(x, Q) = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a \left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha(\mu) \right) f_{a/p}(\xi, \mu) + \mathcal{O}(\Lambda^2/m_c^2, \Lambda^2/Q^2)$$

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

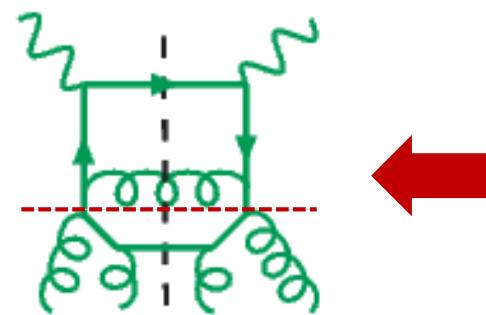
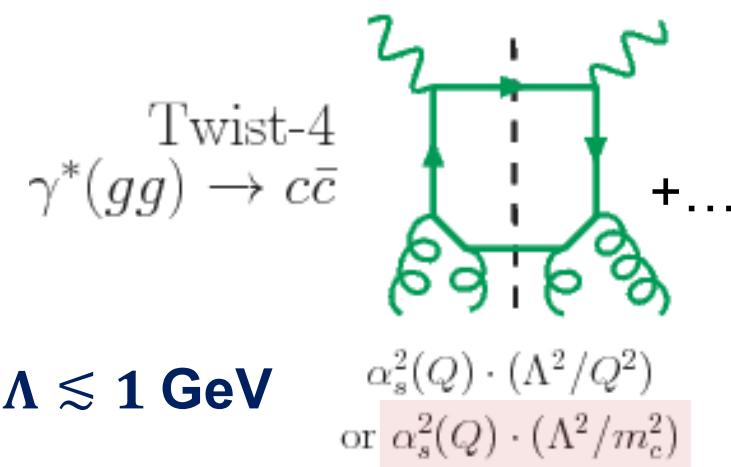
PDF fits:
$$F(x, Q)^{[\text{trunc}]} = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a^{(N_{ord})} \left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha(\mu) \right) f_{a/p}^{(N_{ord})}(\xi, \mu)$$

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”)



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



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

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

Collins, PRD58 (1998) 094002

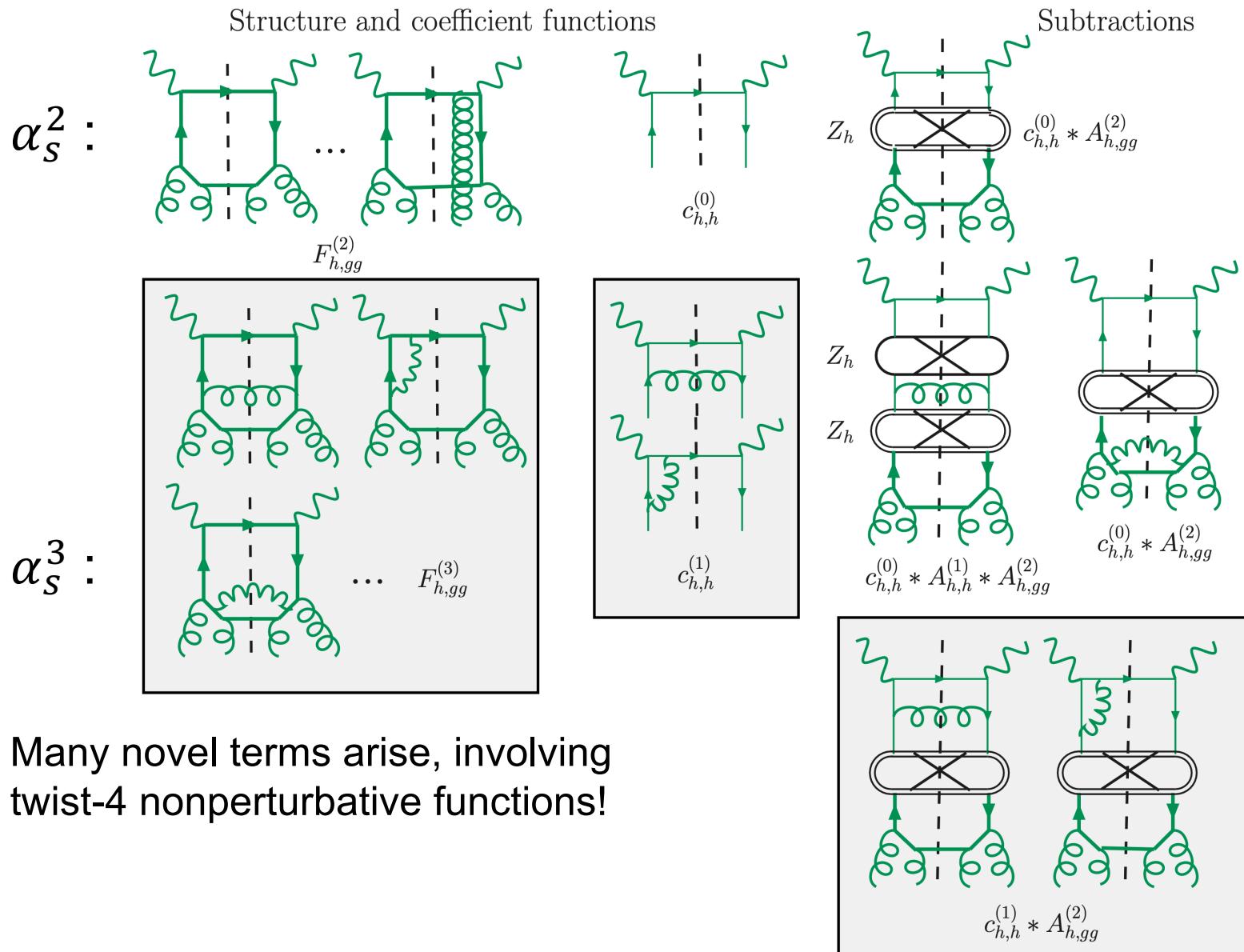
Can be of order $\sim 10\%$ of the twist-2 α_s^2 term

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.

ACOT-like factorization for twist-4 charm contributions (an example)

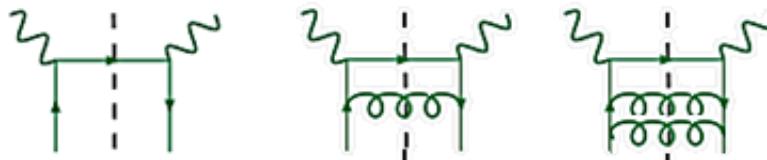


Many novel terms arise, involving twist-4 nonperturbative functions!

Fitted charm contributions, practical implementation in CT18

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

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



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

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

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

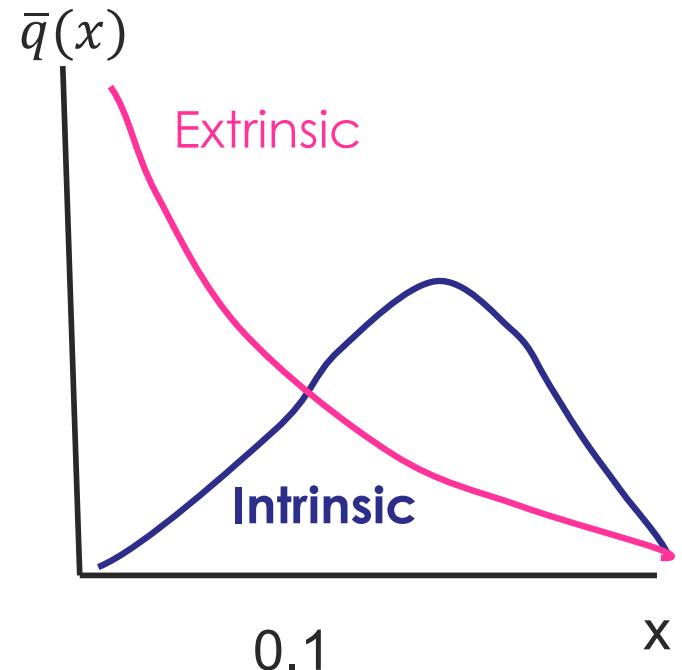
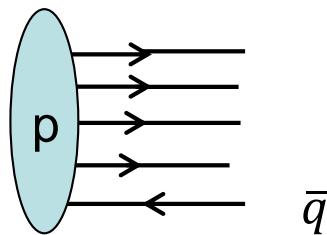
Start with $N_f = 3$ at $\mu_0 = m_c - \epsilon$, evolve to $\mu > \mu_0$ by incrementing N_f to 4 and 5

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.

Part 2. IC models and CT18 FC global analysis

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



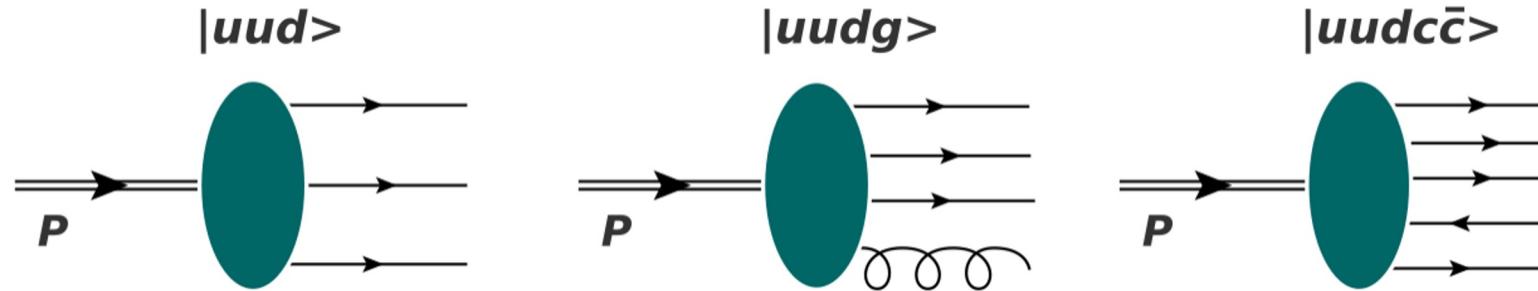
what nonperturbative physics produces ‘intrinsic charm’ component?

- resulting properties
- phenomenological connections?
- potential extraction in fits

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, $|\text{proton}\rangle \rightarrow |uudcc\bar{c}\rangle$

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

- 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

Blümlein; 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

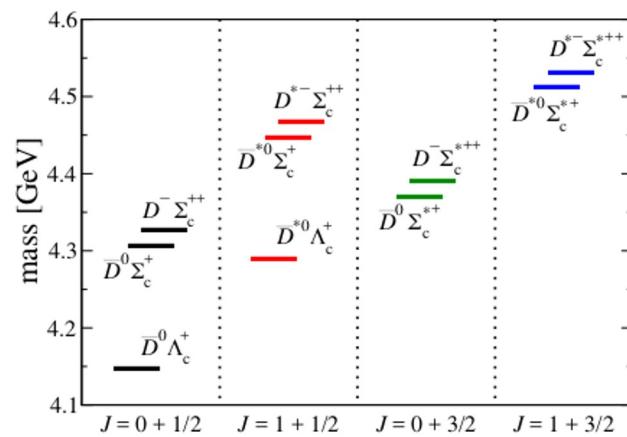
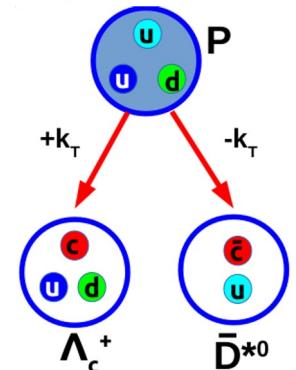
$$c(x, Q^2 \leq m_c^2) = \bar{c}(x, Q^2 \leq m_c^2) = 0!$$

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).]

- $|N\rangle = \sqrt{Z_2} |N\rangle_0 + \sum_{M,B} \int dy \mathbf{f}_{MB}(y) |M(y); B(1-y)\rangle$
 $y = k^+/P^+$: 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 $\bar{c}(x)$...



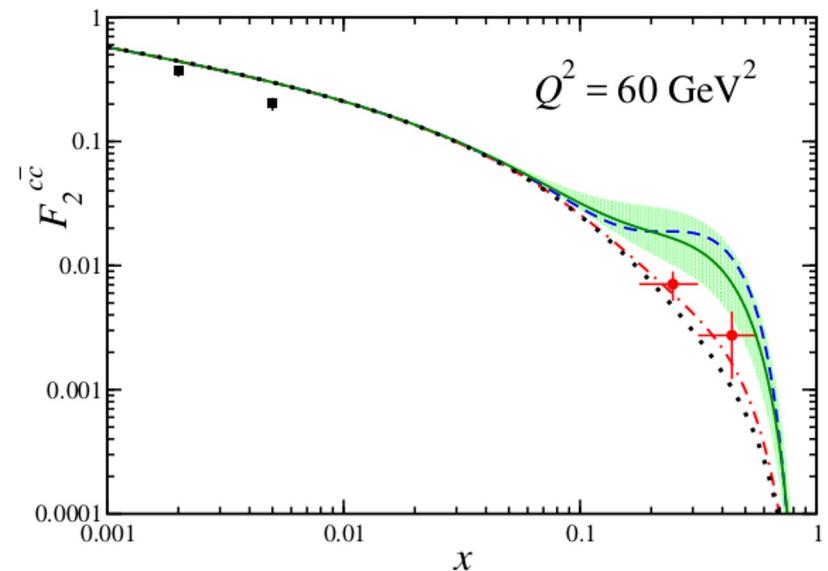
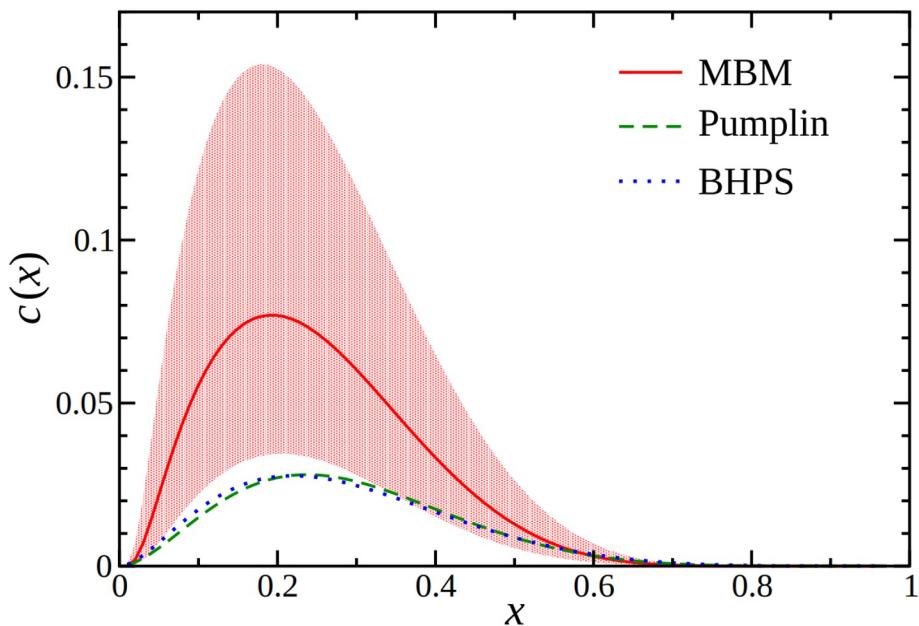
IC (MBM) depends on UV scale parameter, Λ ; predicts high- x excess

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

multiplicities, momentum sum:

$$\langle n \rangle_{MB}^{(\text{charm})} = 2.40\% {}^{+2.47}_{-1.36};$$

$$P_c := \langle x \rangle_{\text{IC}} = 1.34\% {}^{+1.35}_{-0.75}$$



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

→ evolve to **EMC** scale, $Q^2 = 60$ GeV 2

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

IC models and formal QCD

models simulate nucleon wave function; aim to *mimic* nonpert QCD

- bound-state structure driven by constituent-quark masses
- connect to SU(4) flavor-symm breaking (in meson-baryon models [MBMs])

also, light-front models may relate PDFs, form factors, ...

ex.: TJH, Alberg, Miller, PRD96 (2017) 7, 074023; Sufian et al, PLB808 (2020) 135633.

$$|\Psi_P^\lambda(P^+, \mathbf{P}_\perp)\rangle = \frac{1}{16\pi^3} \sum_{q=c,\bar{c}} \int \frac{dx d^2\mathbf{k}_\perp}{\sqrt{x(1-x)}} \psi_{q\lambda_q}^\lambda(x, \mathbf{k}_\perp) |q; xP^+, x\mathbf{P}_\perp + \mathbf{k}_\perp\rangle$$

BUT: unclear mapping, IC models → systematically-improvable QCD calc.

- based on *truncated* Fock-state or similar wave function expansions
- no obvious mapping onto factorization theorems (also truncated in fits)
- ambiguity regarding fact. scale, μ , in IC models

again, intrinsic charm (IC) ≠ fitted charm (FC) extracted in PDF analyses

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.

→ 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

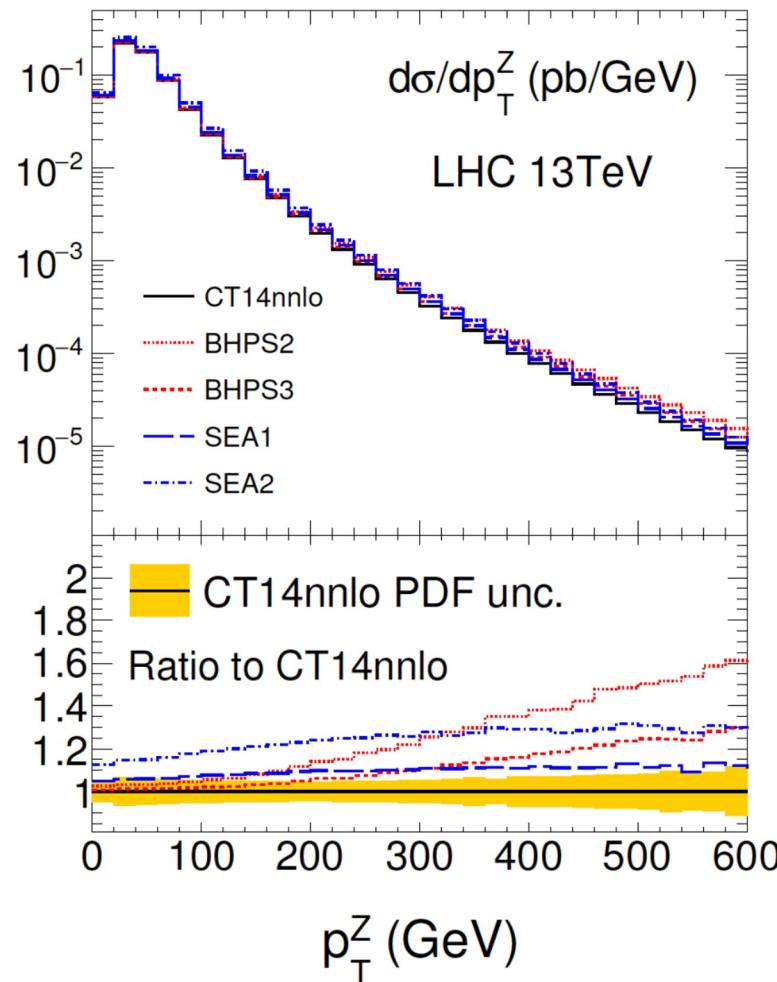
FC at LHC: $Z+c$ suggested as sensitive probe

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

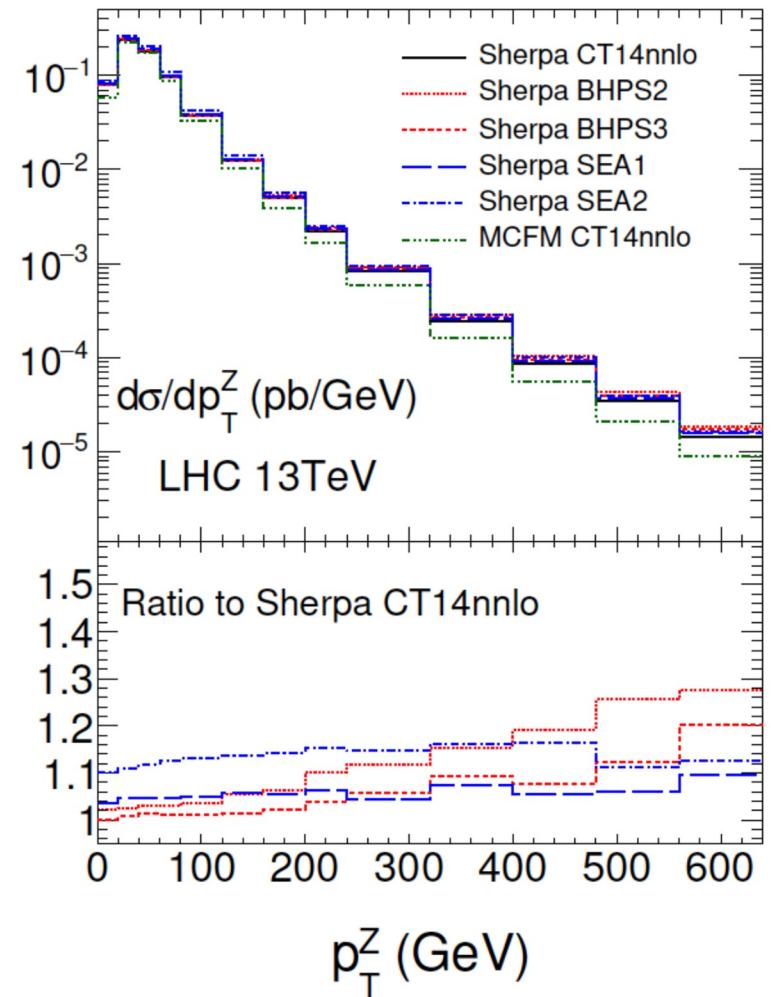
p_T spectra, rapidity dists nominally sensitive to high- x charm PDF

→ 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

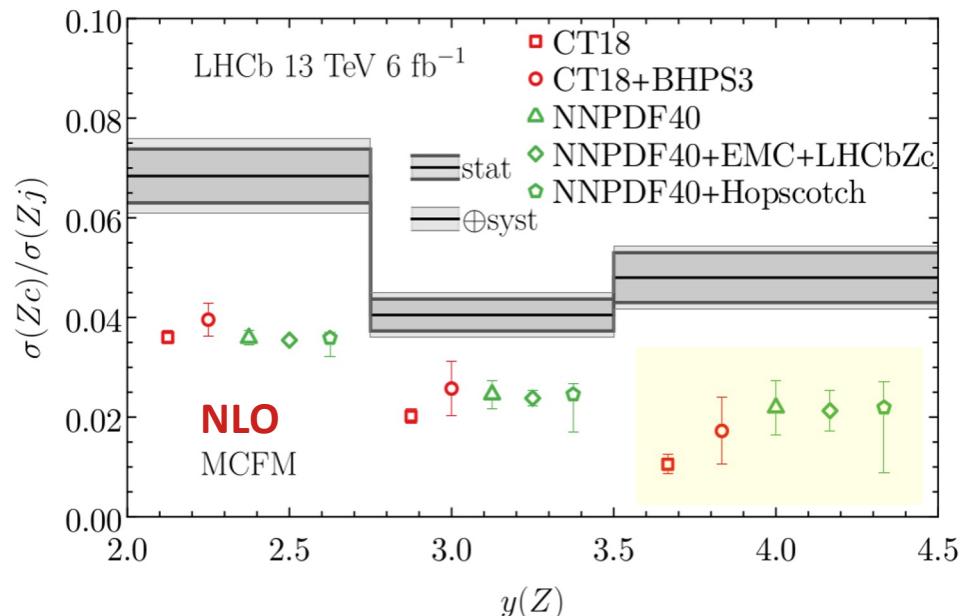
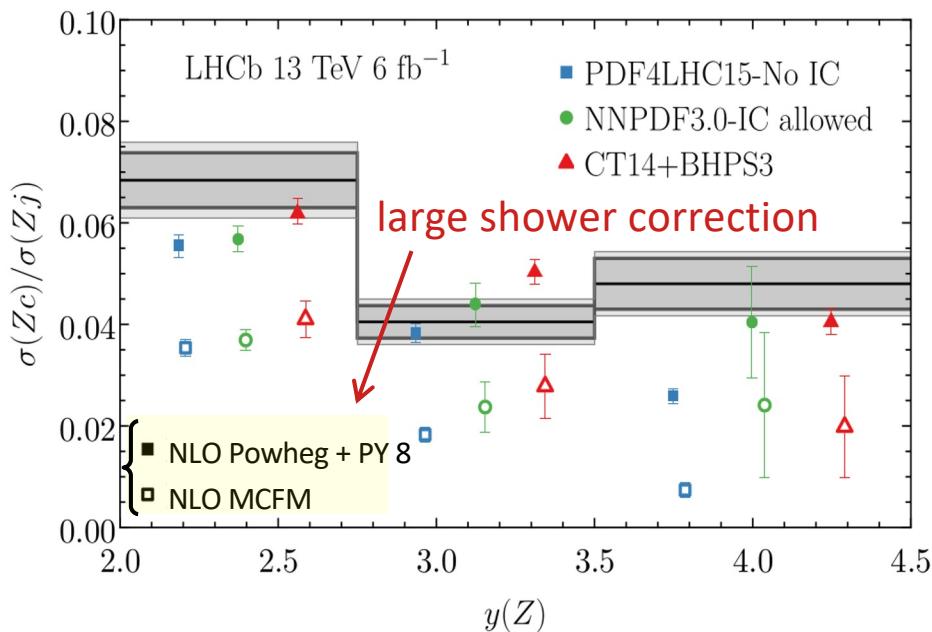
R. Aaij, *et al.* (LHCb); arXiv: 2109.08084.

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

→ meanwhile, significant theory uncertainties and considerations

(HO; showering, hadronization; IRC safety; MPI; ...)

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



→ 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](https://arxiv.org/abs/2302.12844) M. Czakon, *et al.*; arXiv: 2011.01011.

might other HEP experiments be sensitive to FC?

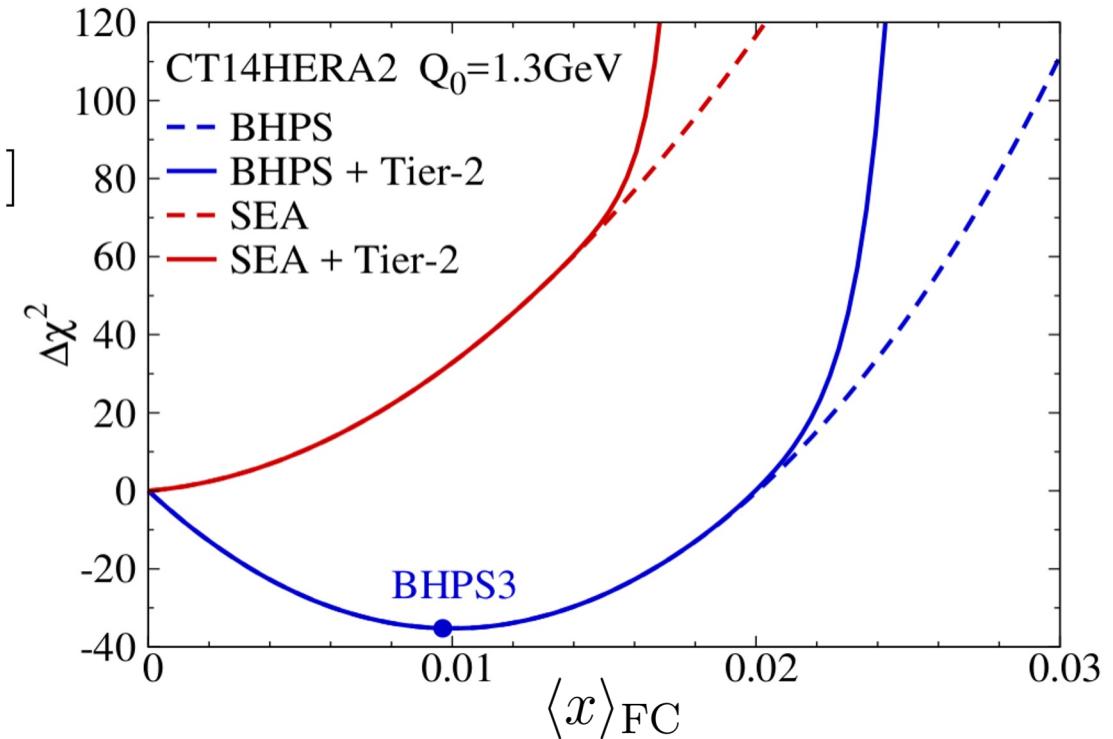
must be assessed using comprehensive global QCD analysis of PDFs

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

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

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

cf. PRL114, no. 8 082002 (2015):
5 σ -limit to FC from low- W DIS data



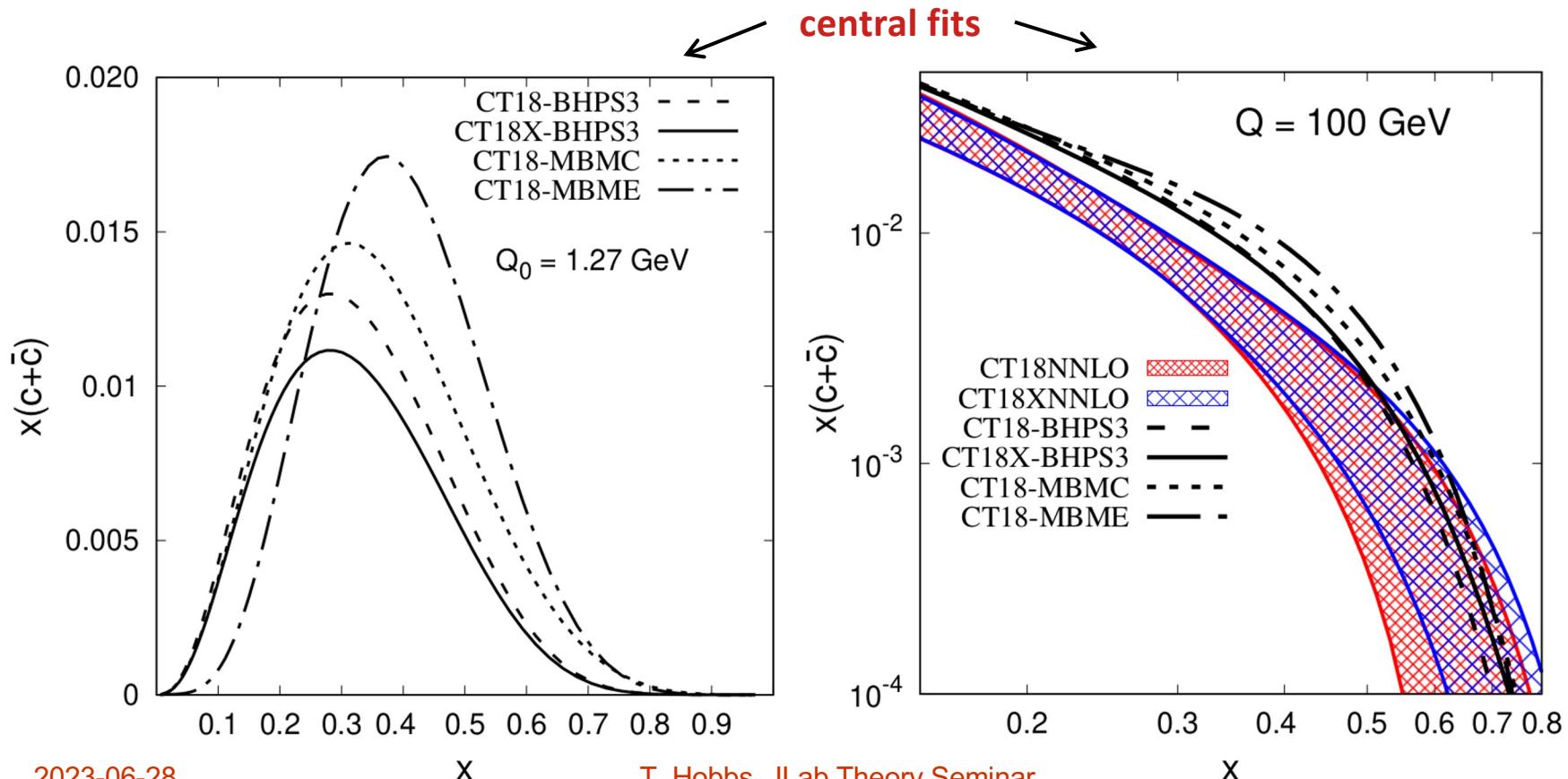
since CT14 IC, many LHC measurements have been released; natural to ask if these possess *collective* sensitivity to FC

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

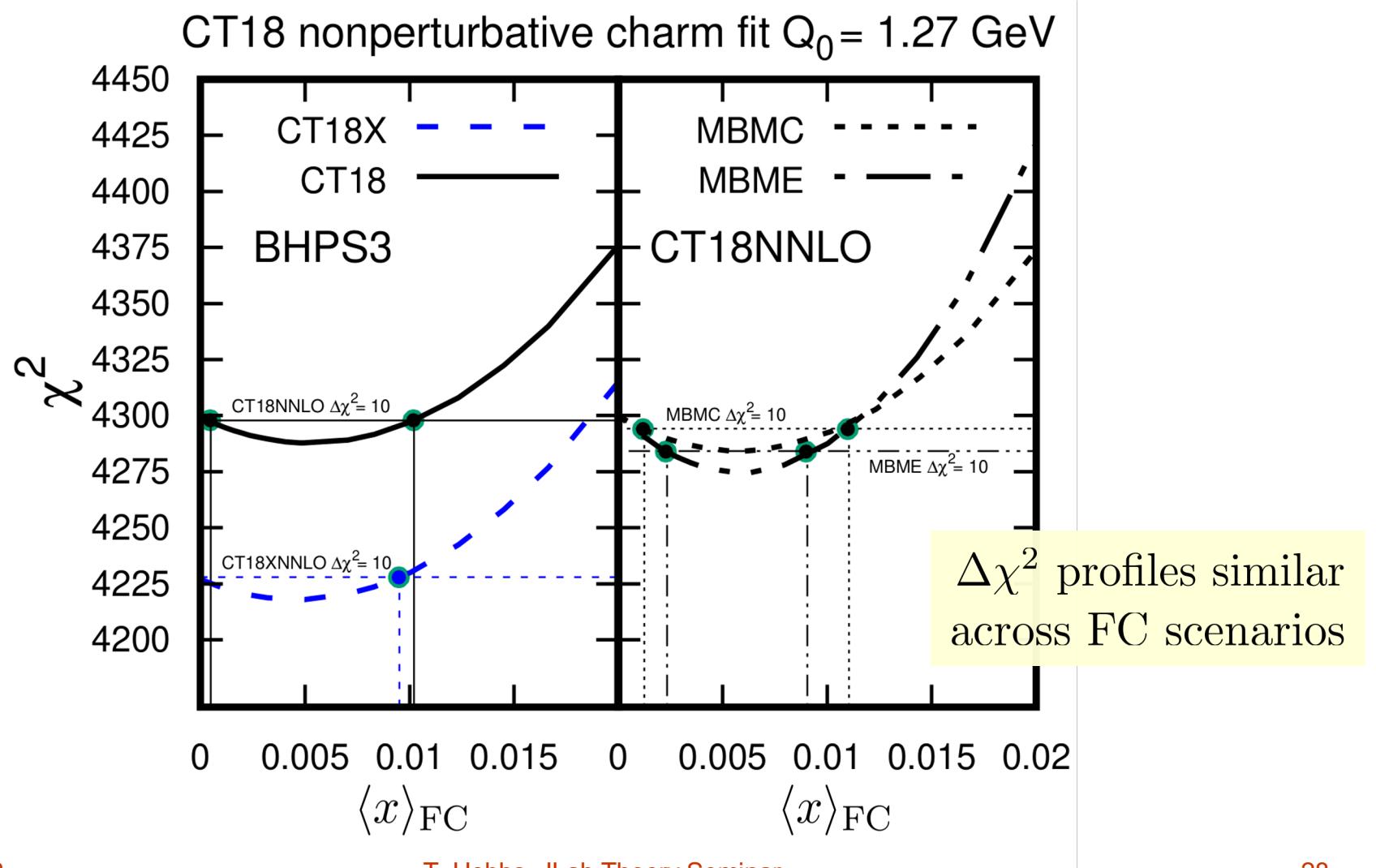
investigate constraints from newer LHC data in CT18



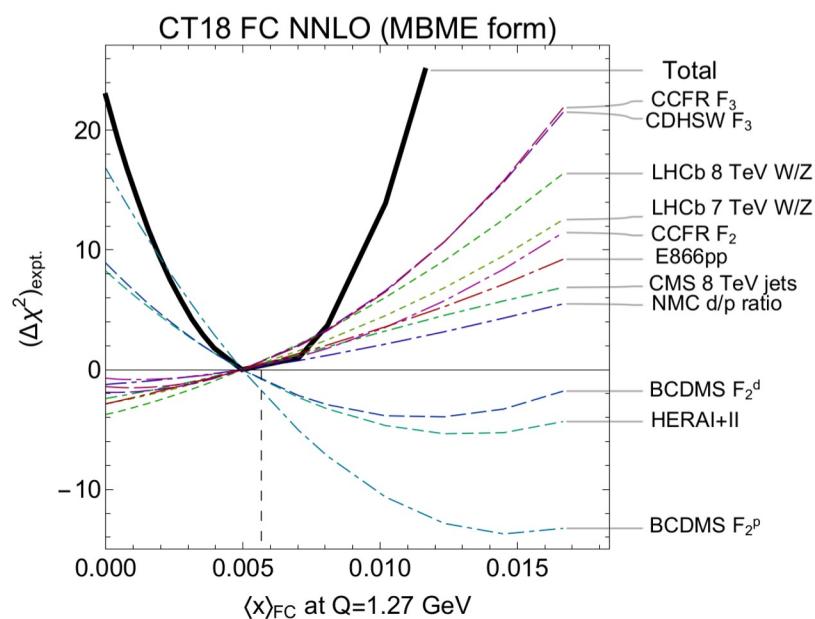
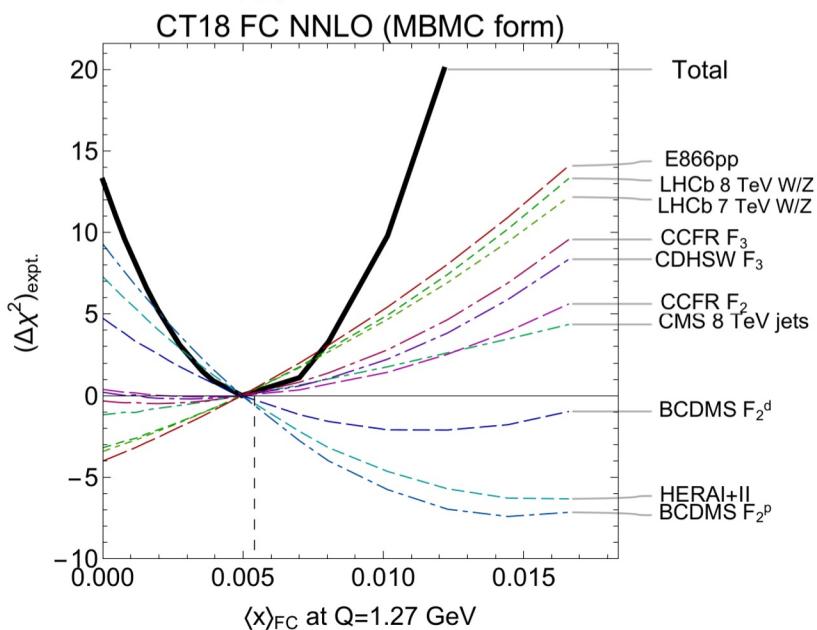
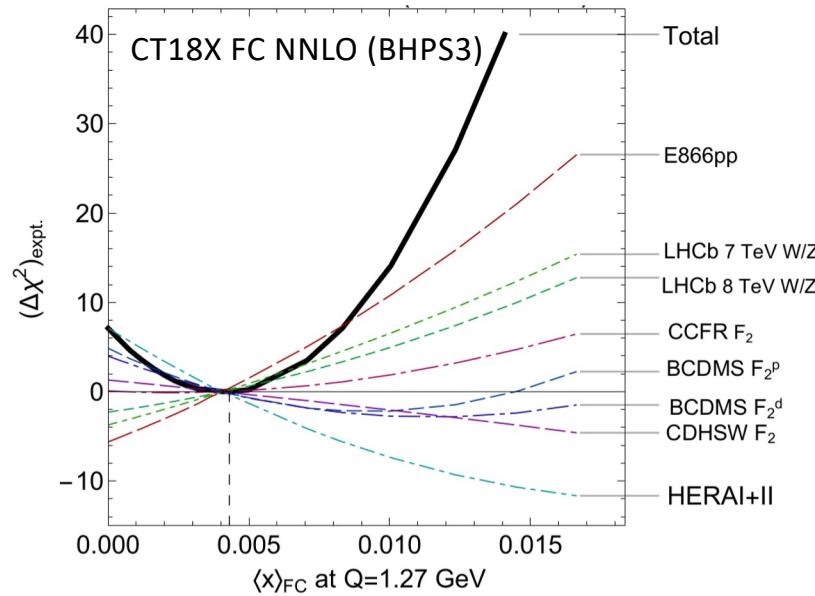
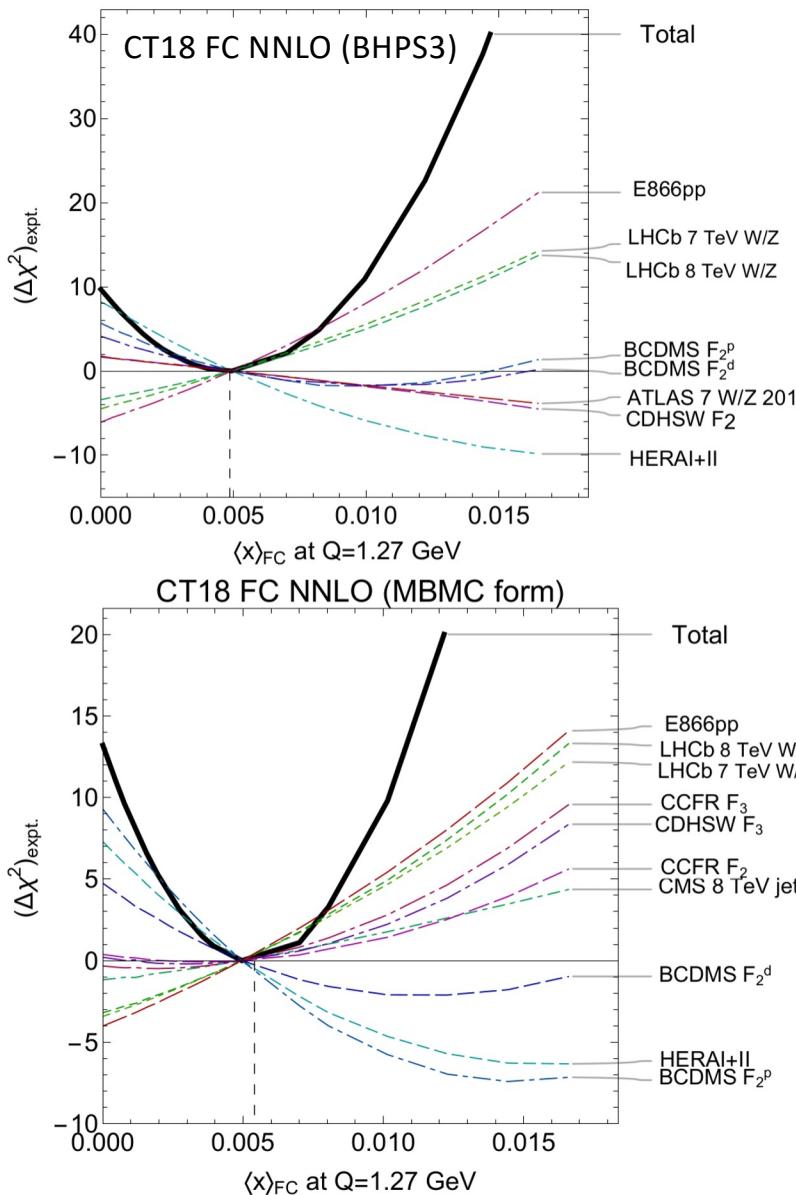
signal for FC in CT18 study, but with shallower $\Delta\chi^2$ than CT14 IC

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**



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



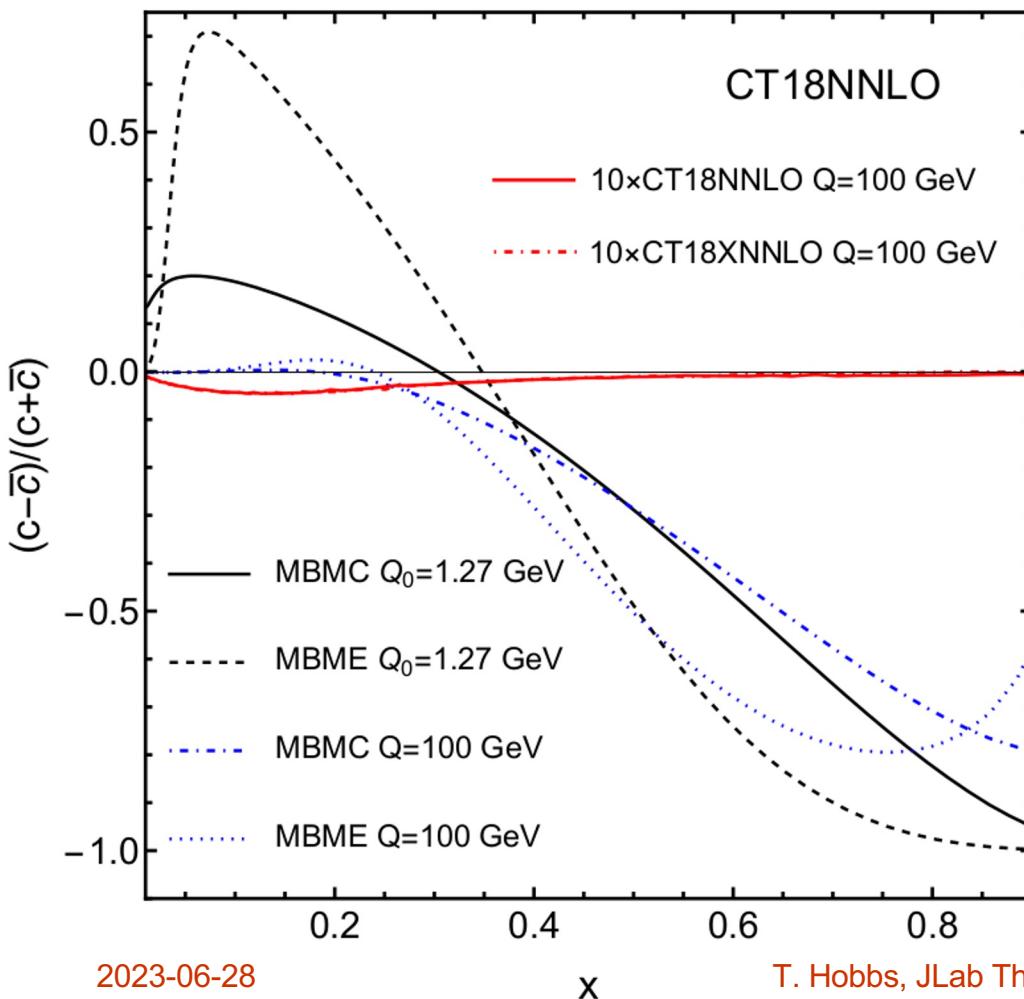
NB: FC uncertainty related to other PDF uncertainties; e.g., high- x gluon PDF

larger high- x gluon in CT leaves less “room” for FC

possible charm-anticharm asymmetries; 1st inclusion in PDF fit

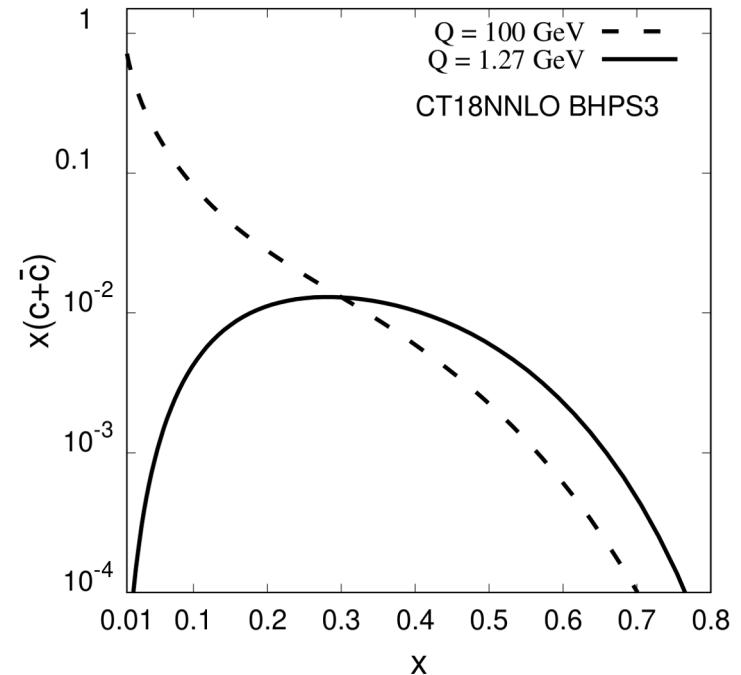
pQCD only very weakly breaks $c = \bar{c}$ through HO corrections

- 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



FC PDF moments as F.o.M.

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

moments typify FC size, asymmetry

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

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

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

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

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

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

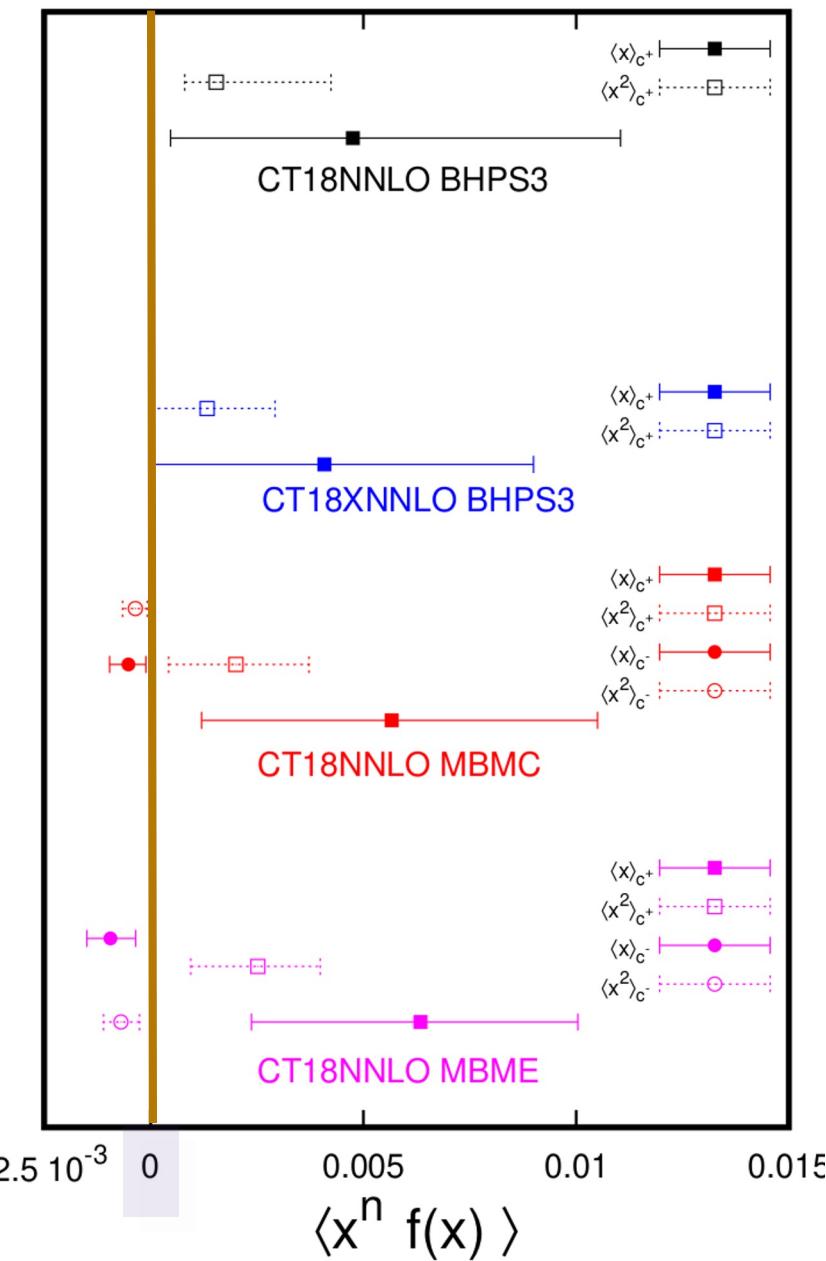
$$\Delta\chi^2 \leq 10$$

(restrictive tolerance)

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

(~CT standard tolerance)

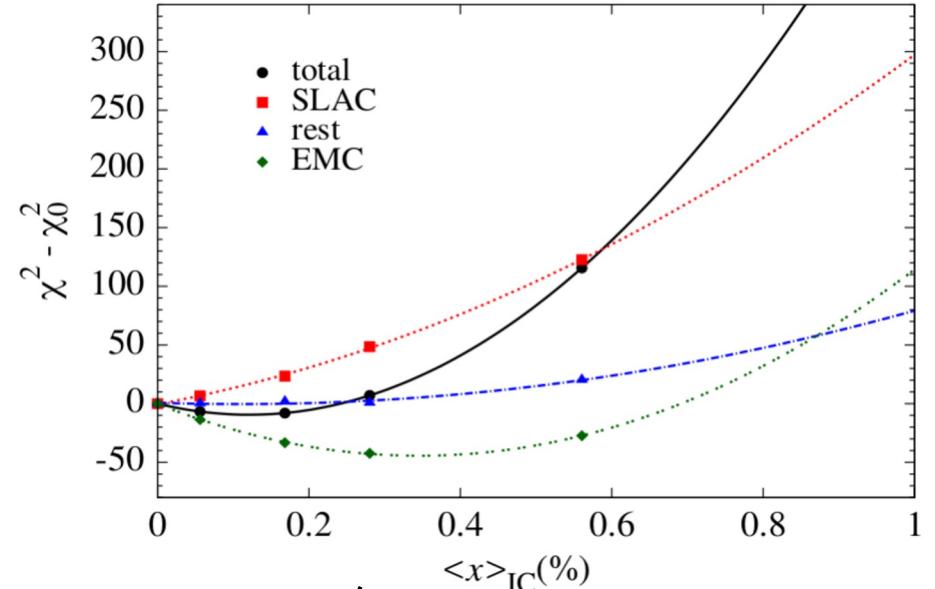
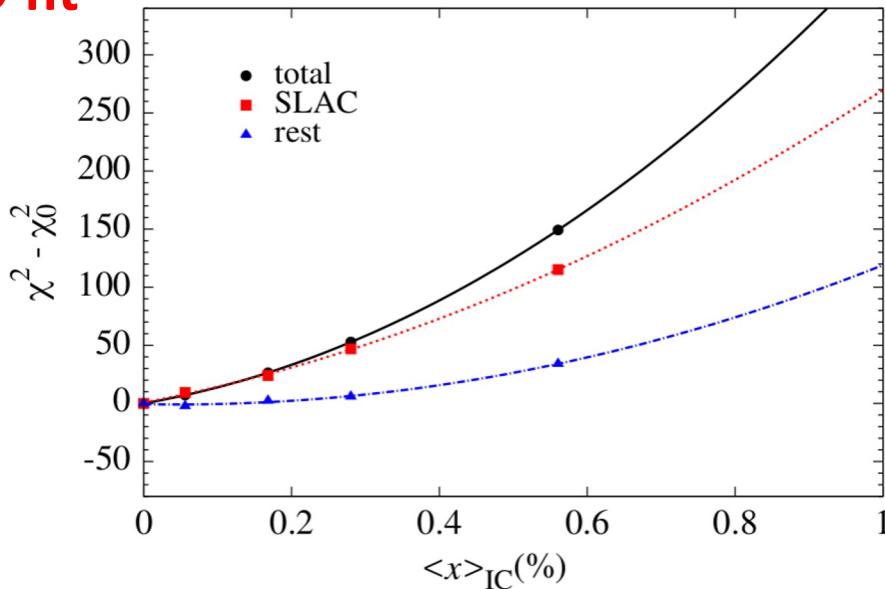
Nonperturbative charm moments $Q_0 = 1.27 \text{ GeV}$
Intervals of $\Delta\chi^2 < 10$



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, 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

see Figure 1, 2208.08372v2

- **Two classes of uncertainties need further scrutiny:**
 1. Missing higher-order uncertainties (MHOU): N3LO in DIS, etc.; N2LO in $Z+c$ production
 2. Parametrization sampling uncertainty (PSU): underestimation of PDFU

NNPDF IC PDFs and moments

NNPDF, Nature 608 (2022) 7923, 483.

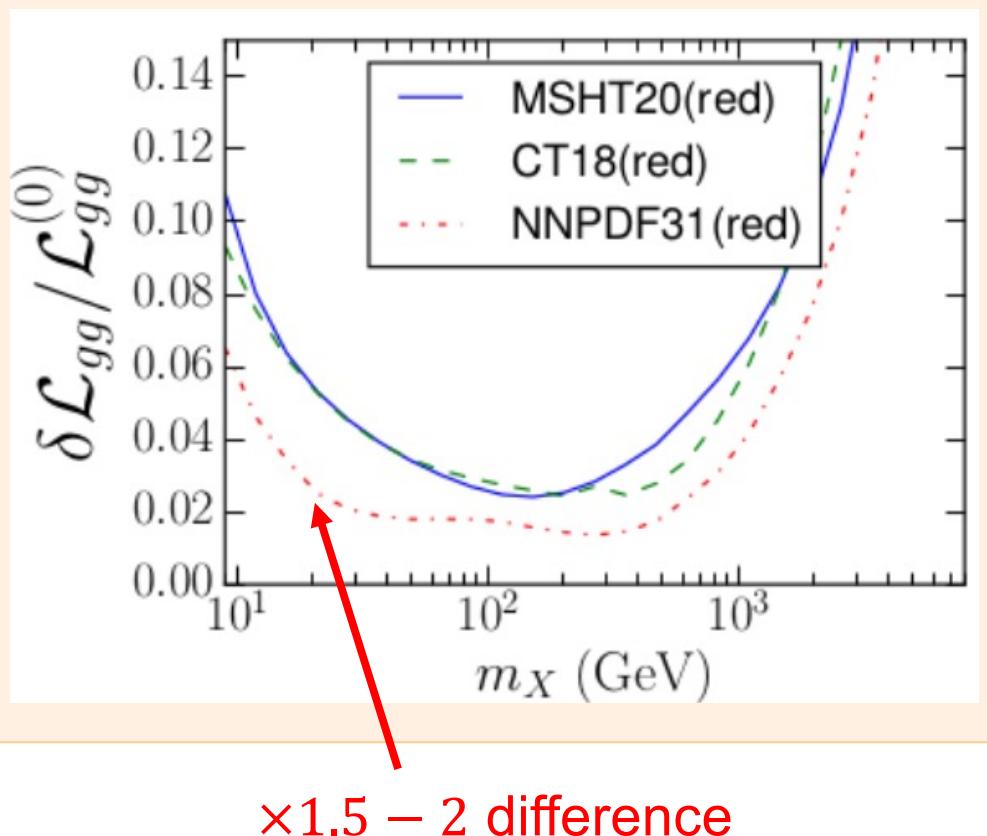
- perturbative instability from MHOU in DGLAP affects low- x behavior
 - matching at fixed NNLO gives negative FC, unlike IC models
 - MHOU persists to quite high $x < 0.1$ or more

see Figure 1, 2208.08372v2

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

differing PDF errors explained by epistemic uncertainties

Relative PDF uncertainties on the gg luminosity at 14 TeV in three PDF4LHC21 fits to the **identical** reduced global data set



While the fitted data sets are identical or similar in several such analyses, the differences in uncertainties can be explained by methodological choices adopted by the PDF fitting groups.

NNPDF3.1' and especially 4.0 (based on the NN's+ MC technique) tend to give smaller nominal uncertainties in data-constrained regions than CT18 or MSHT20

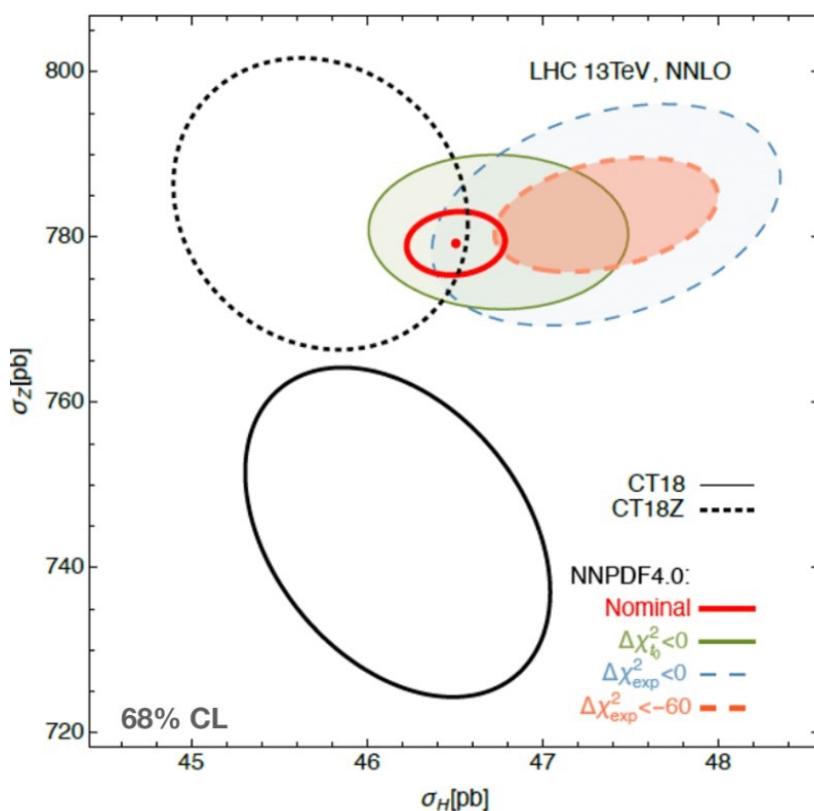
**Epistemic uncertainties
explain many such differences**

Details in [arXiv:2203.05506](https://arxiv.org/abs/2203.05506), [arXiv:2205.10444](https://arxiv.org/abs/2205.10444)

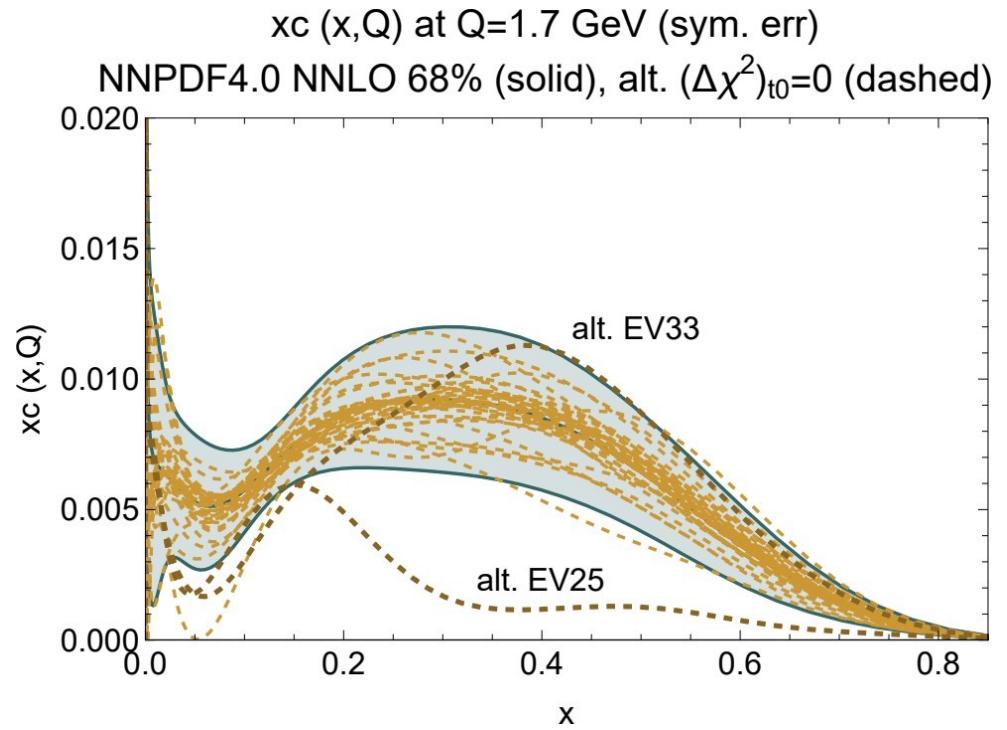
more representative sampling can also enlarge MC uncertainties

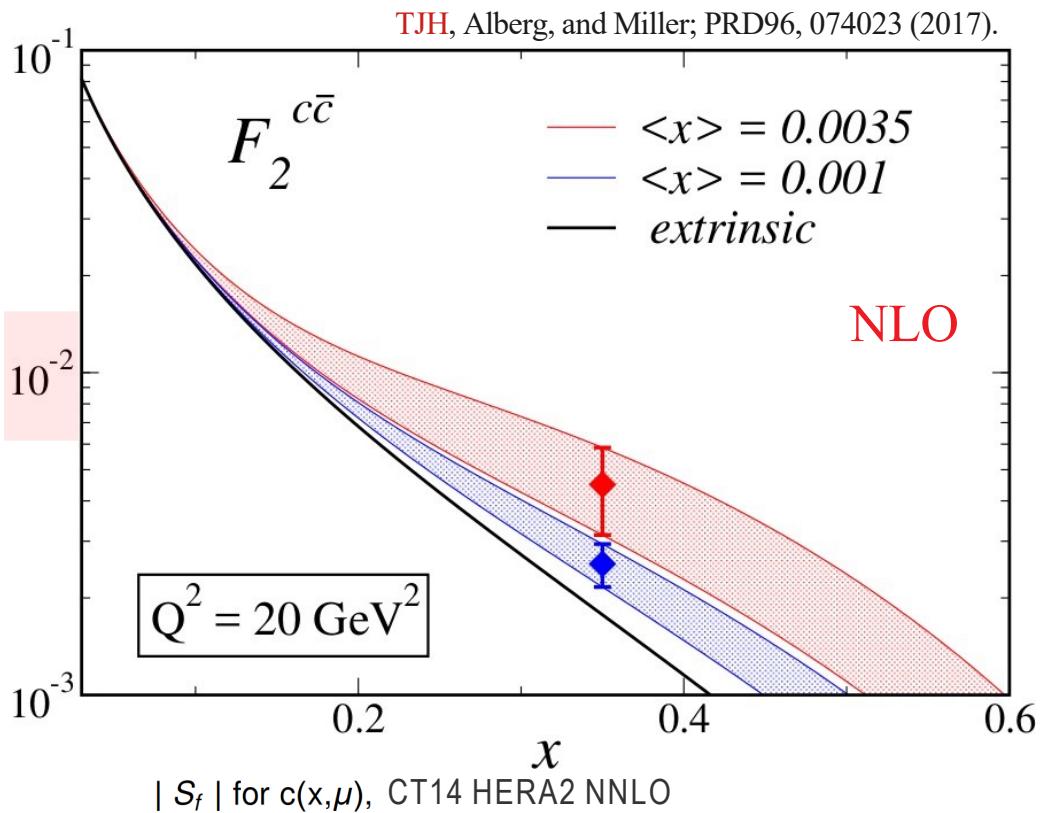
Courtoy *et al.*, arXiv: 2205.10444

- 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



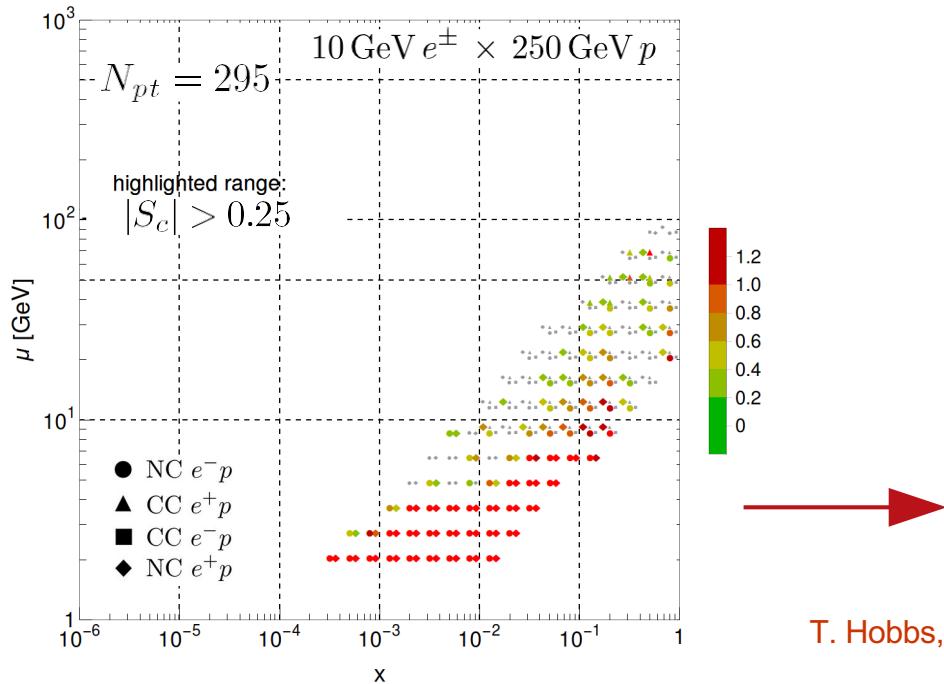


future data will inform FC

EIC + lattice QCD
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

HQ theory is a frontier area for QCD accuracy

→ e.g., improved HQ mass-dependent pQCD necessary for PDF stability

- 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 (expts; lattice; PDF benchmarking)