A nonperturbative charm PDF and its LHC signatures

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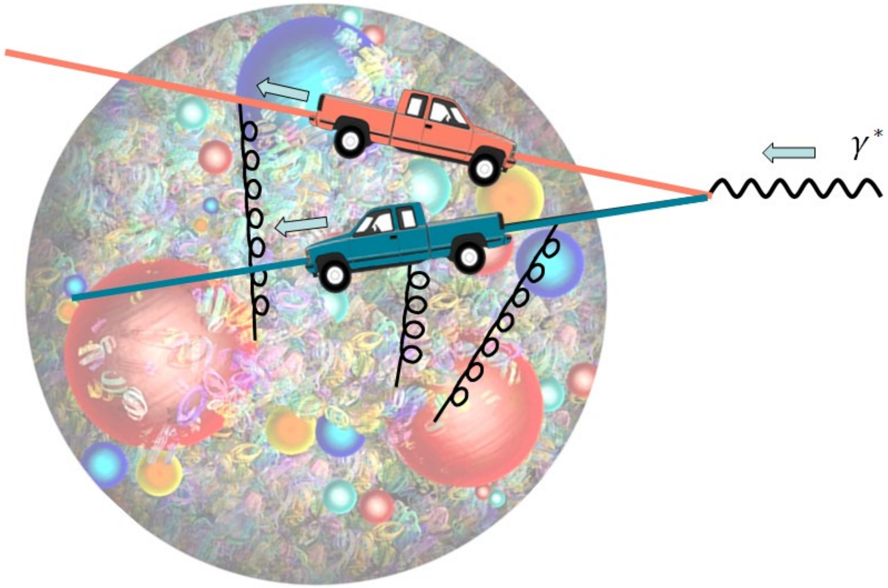
With M. Guzzi, T. Hobbs, J. Huston,
K. Xie, C.-P. Yuan, A. Courtoy, M. Yan

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



arXiv:2211.01387, 1707.00657
and 2205.10444

Charm and bottom scattering is pivotal for the LHC Run-3

Signal and background contributions in many EW/Higgs/BSM measurements

$(t\bar{t}H, V+H, V+Q, b\bar{b} \to H, \dots)$

EW precision measurements

(M_W, CKM matrix, CP violation, …)

Precision studies of QCD

- measurements of α_s, M_W,…
- constraints on gluon PDF and intrinsic heavy-flavor PDFs
- QCD radiation

(flavored jets, dead cones, fragmentation,…)

hadron spectroscopy

- (tetraquarks, etc.)

NNLO cross sections with massive c, b become available for the LHC. They elevate precision requirements for the relevant QCD theory

A NxLO cross section with massive quarks

Inclusive production of a final state F with inv. mass $M \gg 1$ GeV, including quarks with mass $m_q \sim 1$ GeV

$$\sigma_{pp\to FX}\left(M, m_q\right)$$

hadronic cross section

$$= \sum_{a,b=g,q,\bar{q}} \int_0^1 d\xi_1 \int_0^1 d\xi_2$$

summation over active flavors,
integration over momentum fractions

$$\times\ \hat{\sigma}_{ab\to A}\left(\alpha_s(\mu_R); M, m_q; N_f, \mu_R, \mu_F\right)$$

infrared & collinear safe hard cross section
[cf. D. Reichelt's talk on IRC-safe flavored jets]

$$\times f_{a/p}\left(\xi_1; N_f, \mu_F\right) f_{b/p}\left(\xi_2; N_f, \mu_F\right)$$

universal parton distribution functions

$$+O\left(\frac{\Lambda^2}{M^2}, \frac{\Lambda^2}{m_q^2}\right)$$

power-suppressed contributions of order

- Λ^2/M^2 (negligible)
- Λ^2/m_q^2 (can be non-negligible) ← give rise to **intrinsic PDFs**

A NxLO cross section with massive quarks

$$\sigma_{pp\to FX}(M,m_q) = \sum_{a,b=g,q,\bar{q}} \int_0^1 d\xi_1 \int_0^1 d\xi_2$$

$$\times\ \hat{\sigma}_{ab\to A}(\alpha_s(\mu_R); M, m_q; N_f, \mu_R, \mu_F)$$

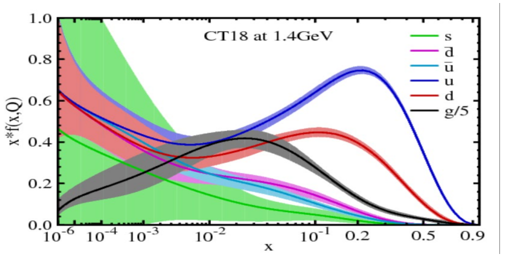
$$\times f_{a/p}(\xi_1; N_f, \mu_F) f_{b/p}(\xi_2; N_f, \mu_F)$$

$$+O\left(\frac{\Lambda^2}{M^2}, \frac{\Lambda^2}{m_q^2}\right)$$

Calculation of $\hat{\sigma}$ and a global fit of $f_{a/p}$ must be consistent in their factorization of mass-dependent cross sections and evolution of $\alpha_s, (\mu), m_q(\mu)$, and PDFs

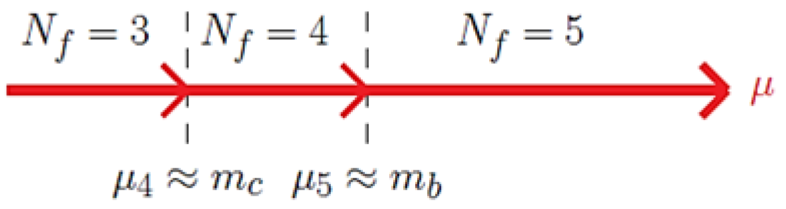
NNLO PDFs use such consistent **general-mass VFN schemes**:
SACOT-MPS, FONLL, TR', …

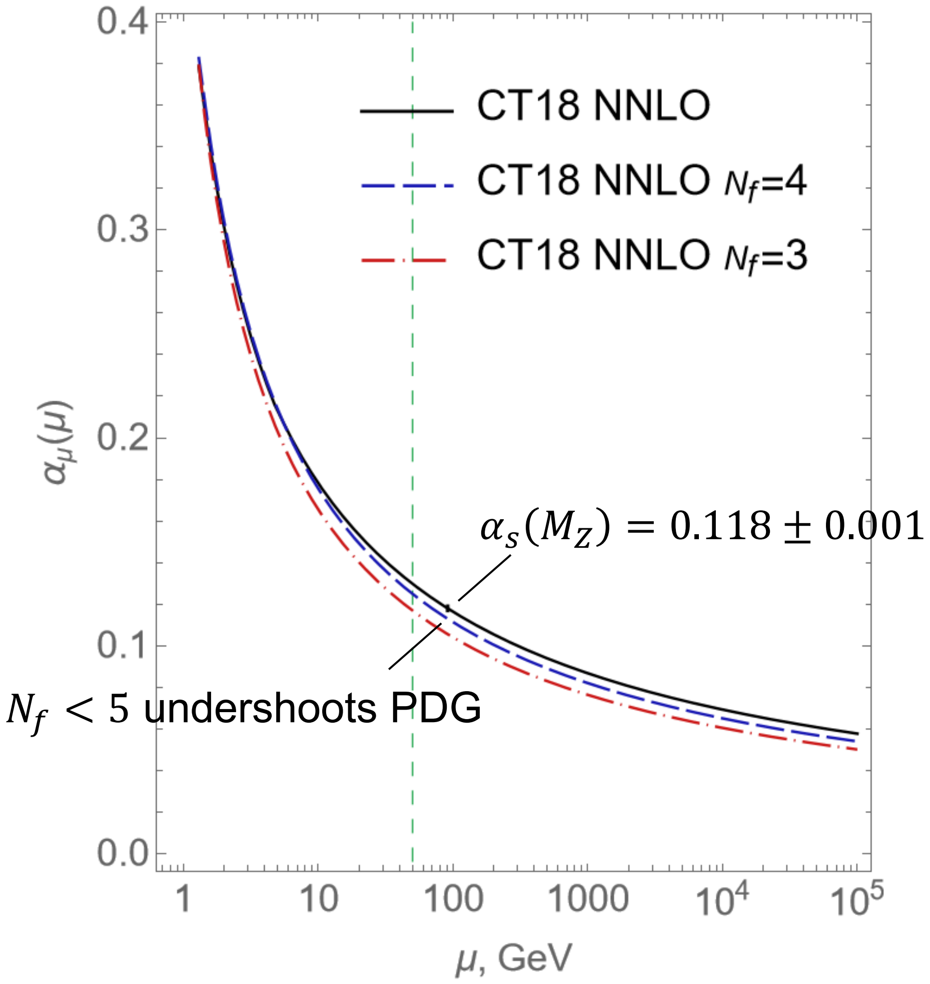
- used by CT18 NNLO PDFs
- combines exact mass dependence at $\mu_F^2 \sim m_q^2$ and resummation of mass logarithms at $\mu_F^2 \gg m_q^2$ both in ℓp and pp scattering



We recommend to use the SACOT-MPS scheme for NLO and NNLO calculations using CT PDFs

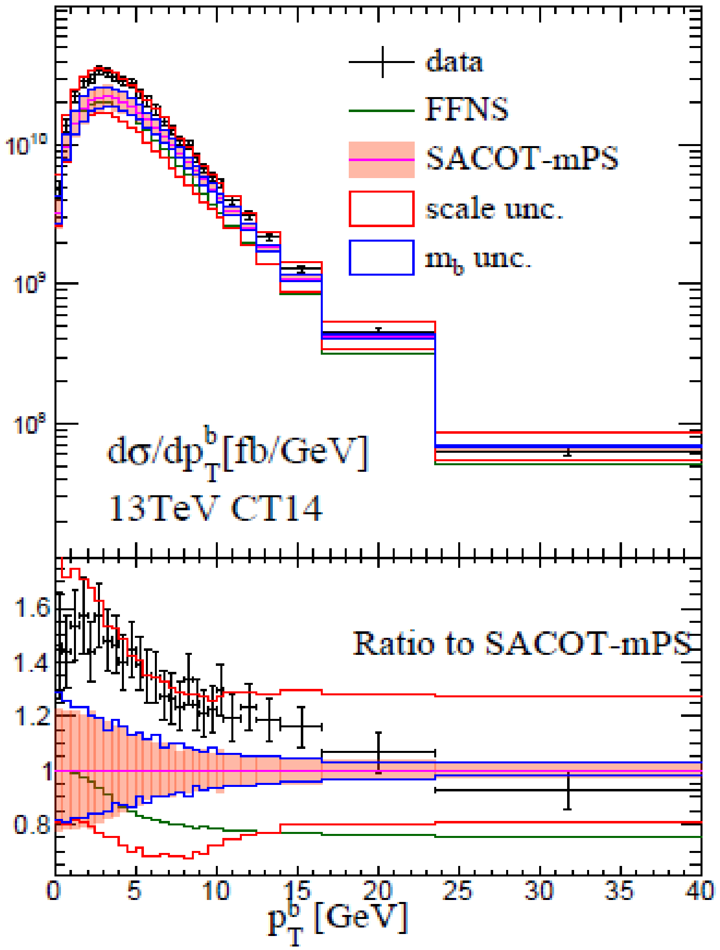
- Consistency of evolutions for $\alpha_s(\mu)$ and PDFs, and of $N_f \to N_f + 1$ matching at mass thresholds
- One N_f value and one PDF set in each μ range; $N_f^{max} = 5$ for CT18 NNLO PDFs
- $\alpha_s(\mu)$ is consistent with the PDG value of $\alpha_s(M_Z)$ at any μ. This is not the case in the $N_f = 3$ and 4 schemes





We recommend to use the SACOT-MPS scheme for NLO and NNLO calculations using CT PDFs

- Consistent factorization in hard cross sections and the global fit of PDFs
- Example applications at the LHC: $pp \to bX$, $pp \to ZbX$, ... ⇒ *Keping Xie's talk*

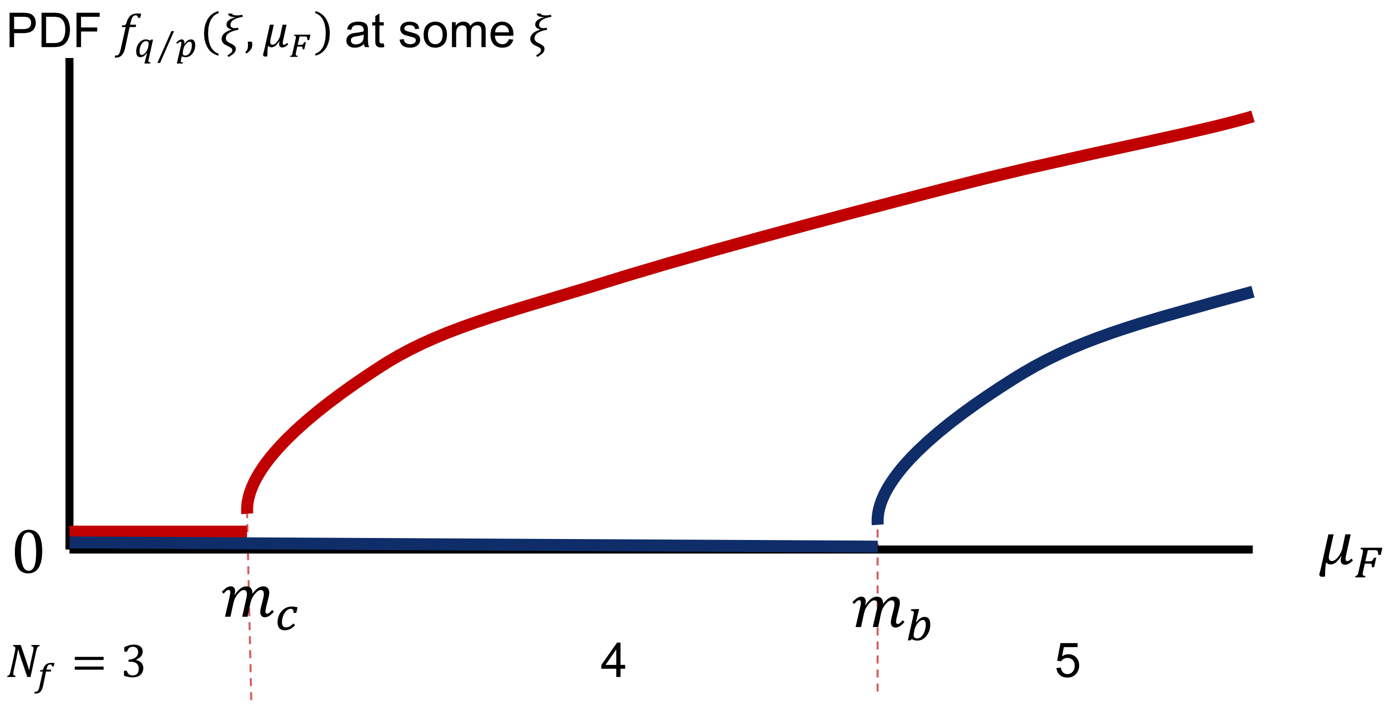


NLO inclusive b production @ LHCb 13 TeV (right): SACOT-MPS is in better agreement with data than either FFN or ZM schemes; readily extendable to other processes and NNLO

The initial condition for heavy-quark PDFs

At $\mu_F = m_q$, the heavy-quark PDF may receive a non-zero contribution from higher-twist terms Λ^2/m_q^2, in addition to the small contribution from perturbative $N_f \rightarrow N_f + 1$ matching

This contribution can be constrained as an independent function in a PDF fit



The SACOT-MPS scheme used by CT PDFs is a consistent framework to implement such “fitted” heavy-quark PDFs in DIS, other processes

[NOTE: The term “fitted charm PDF” is preferred to “intrinsic charm PDF” in this context.]

How large is the fitted charm?
How does it behave?

CTEQ-TEA NNLO analyses of fitted charm

1. T.-J. Hou et al., *JHEP* 02 (2018) 059; 57 pages, 19 figures: QCD factorization with the NP charm and CT14 IC NNLO pheno analysis
2. M. Guzzi, T. J. Hobbs, K. Xie, et al., *Phys.Lett.B* 843 (2023) 137975; **new** CT18 FC analysis with the LHC Run-1 and 2 data

A recorded ILCAC seminar at
https://indico.knu.ac.kr/event/626/

NNPDF NNLO analyses of "intrinsic" charm

1. R. Ball et al., *Eur.Phys.J.C* 76 (2016) 11, 647
2. R. Ball et al., *Nature* 608, (2022) 483

IC from nonperturbative methods and models:

1. BHPS: Brodsky, Hoyer, Peterson, Sakai, PLB 93 (1980) 451
2. BHPS3: Bluemlein, PLB 753 (2016) 619
3. Meson-Baryon models (MBM): Hobbs, Londergan, Melnitchouk, PRD 89 (2014) 074008
4. Light-front WF models: Hobbs, Alberg, Miller, PRD 96 (2017) 7, 074023
5. Dyson-Schwinger equations, lattice QCD, …

CT14IC NNLO: allowed momentum fractions carried by fitted charm

T.-J. Hou et al., JHEP 02 (2018) 059

BHPS model:

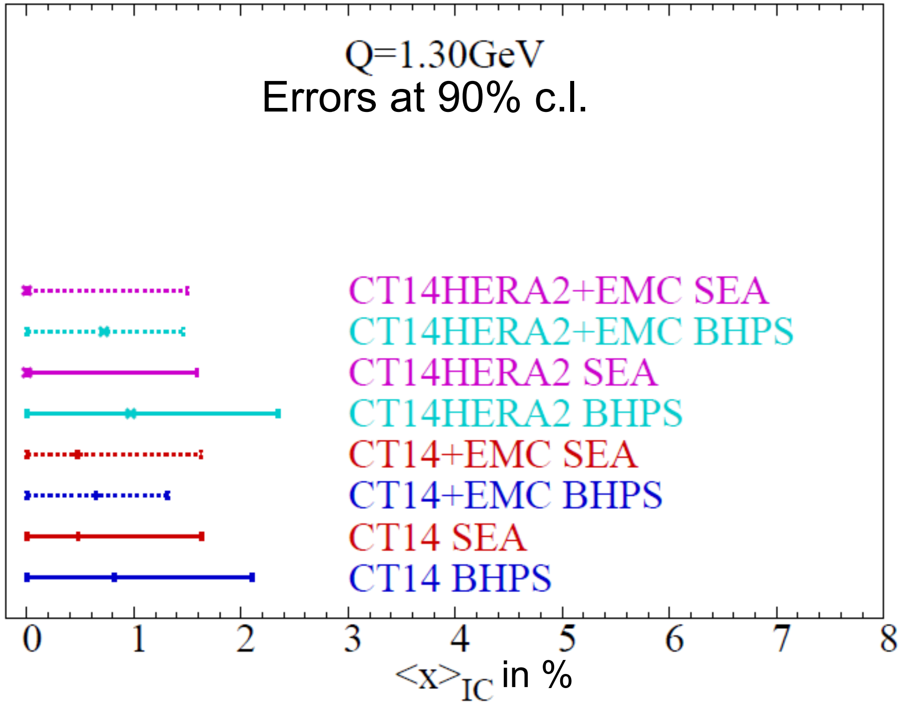
- $\langle x \rangle_{IC} < 2\%$ at 90% c.l.
- Mild preference ($\Delta\chi^2 \approx -40$) for $\langle x \rangle_{IC} \approx 0.8\%$

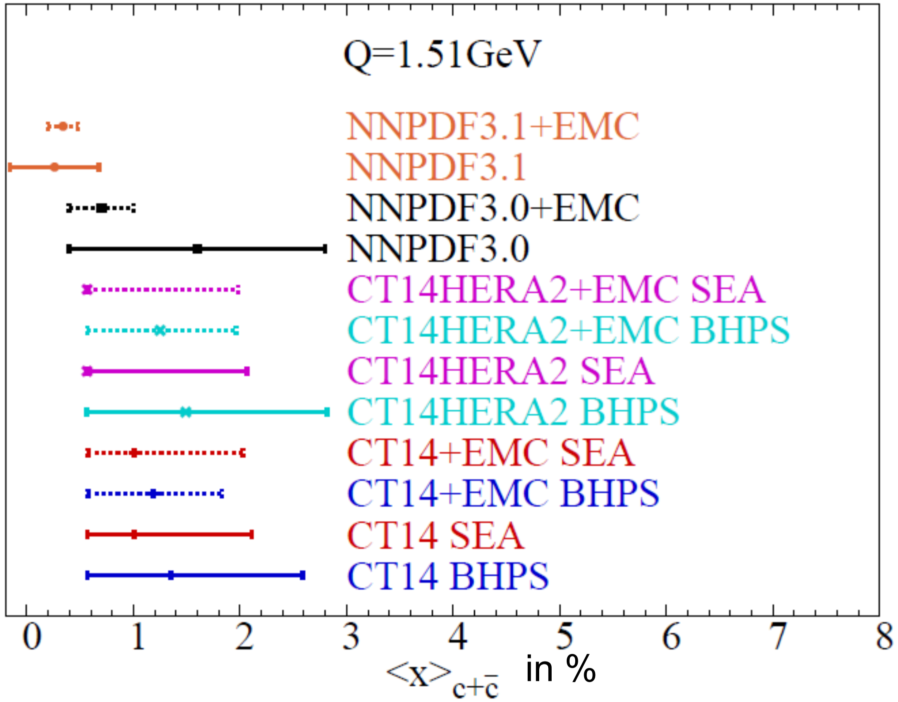
SEA model:

$\langle x \rangle_{IC} < 1.6\%$

No preference for $\langle x \rangle_{IC} \neq 0$

Many detailed studies to validate robustness of these constraints





Sources of differences	CT14 IC	NNPDF3.x
α_s order	NNLO only	NLO, NNLO
Settings	90% c.l., $Q_0 = m_c^{pole} = 1.3$ GeV	68% c.l., $Q_0 = m_c^{pole} = 1.51$ GeV
LHC 8 TeV W, Z	Under validation; mild tension with HERA DIS data	Included; strong effect despite a smallish data sample
1983 EMC F_{2c} data included?	Only as a cross check (unknown syst. effects in EMC data)	Optional, strong effect on the PDF error

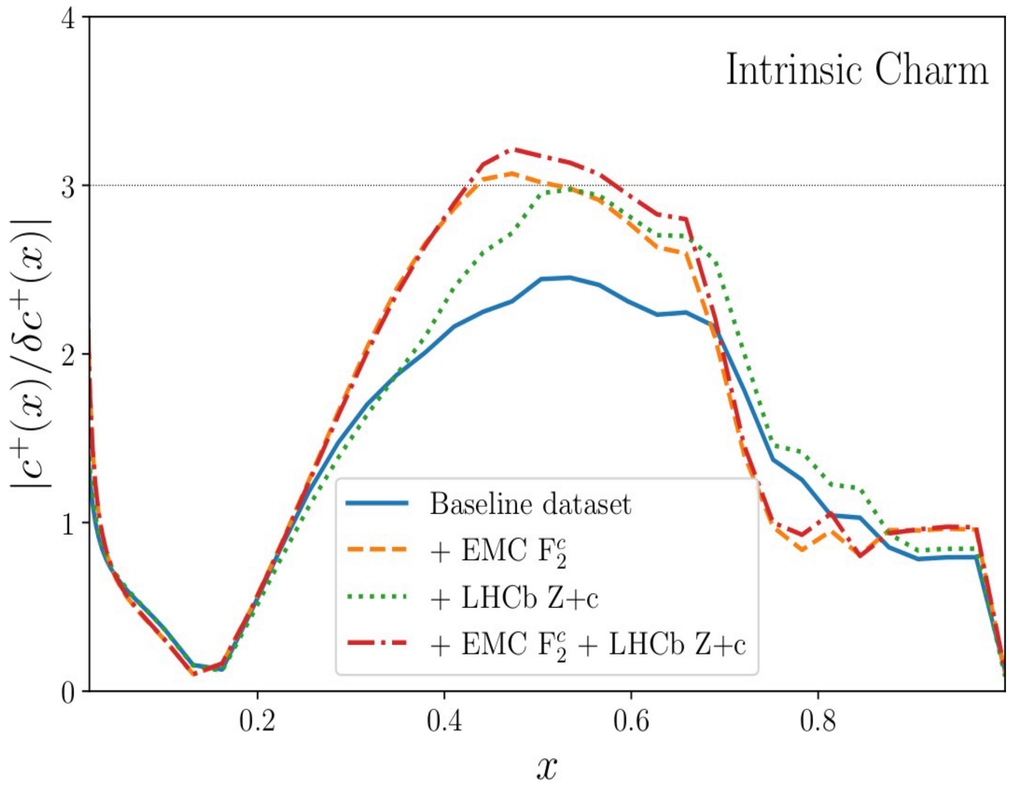
NNPDF4.0 IC analysis

R. Ball et al., Nature 608 (2022) 483

A fitted charm is given by a NN parameterization in the baseline fit

Local significance ($\approx 2.5\sigma$) for $c_{IC}(x, Q_0) \neq 0$ at $x \approx 0.5$ in the baseline fit;

significance increases to $\approx 3\sigma$ after adding constraints from EMC F_2^c data and LHCb $Z + c$ data at NLO



CT18 FC total charm PDFs

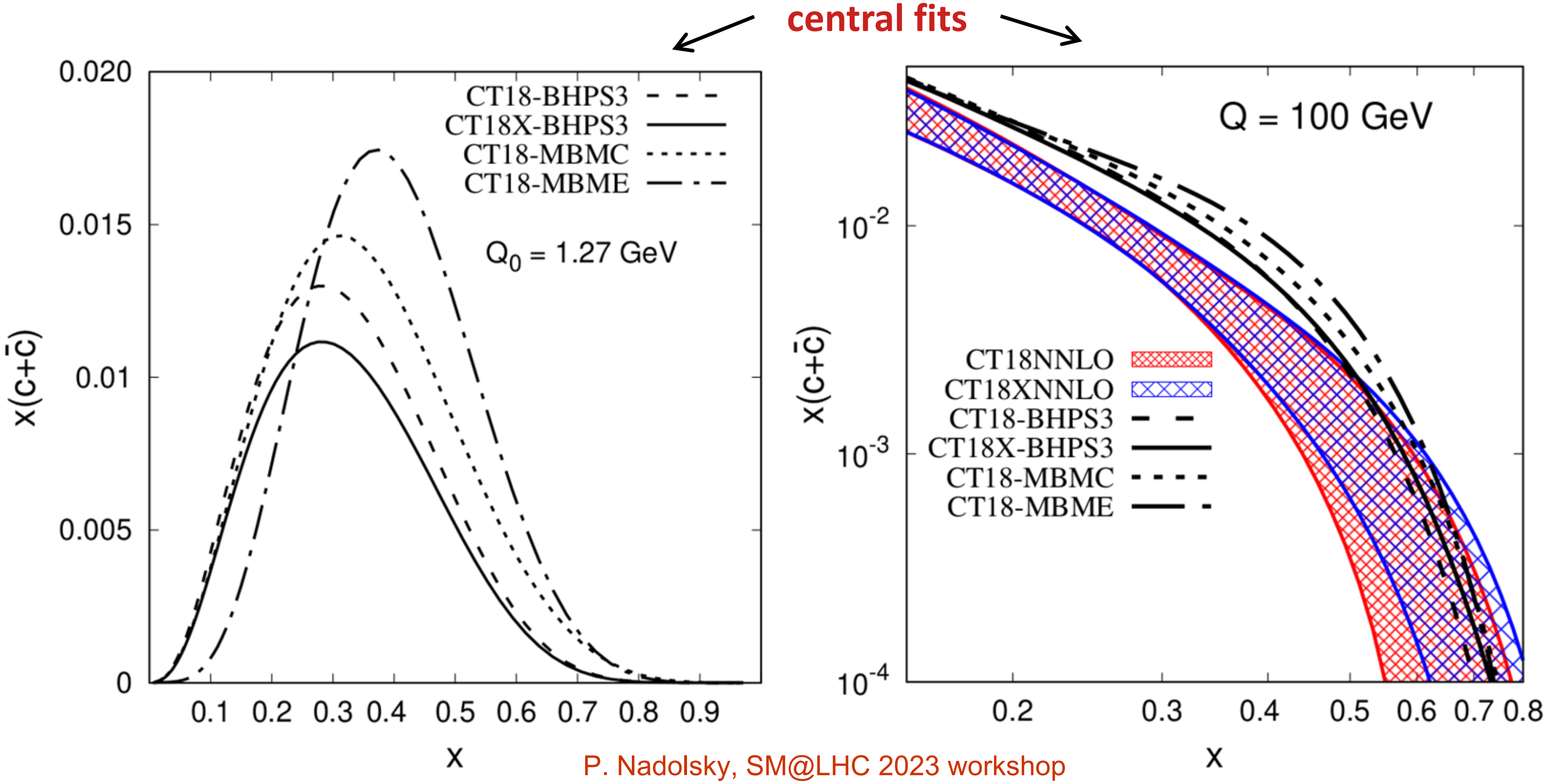
M. Guzzi, T. J. Hobbs, K. Xie, et al., Phys.Lett.B 843 (2023) 137975

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

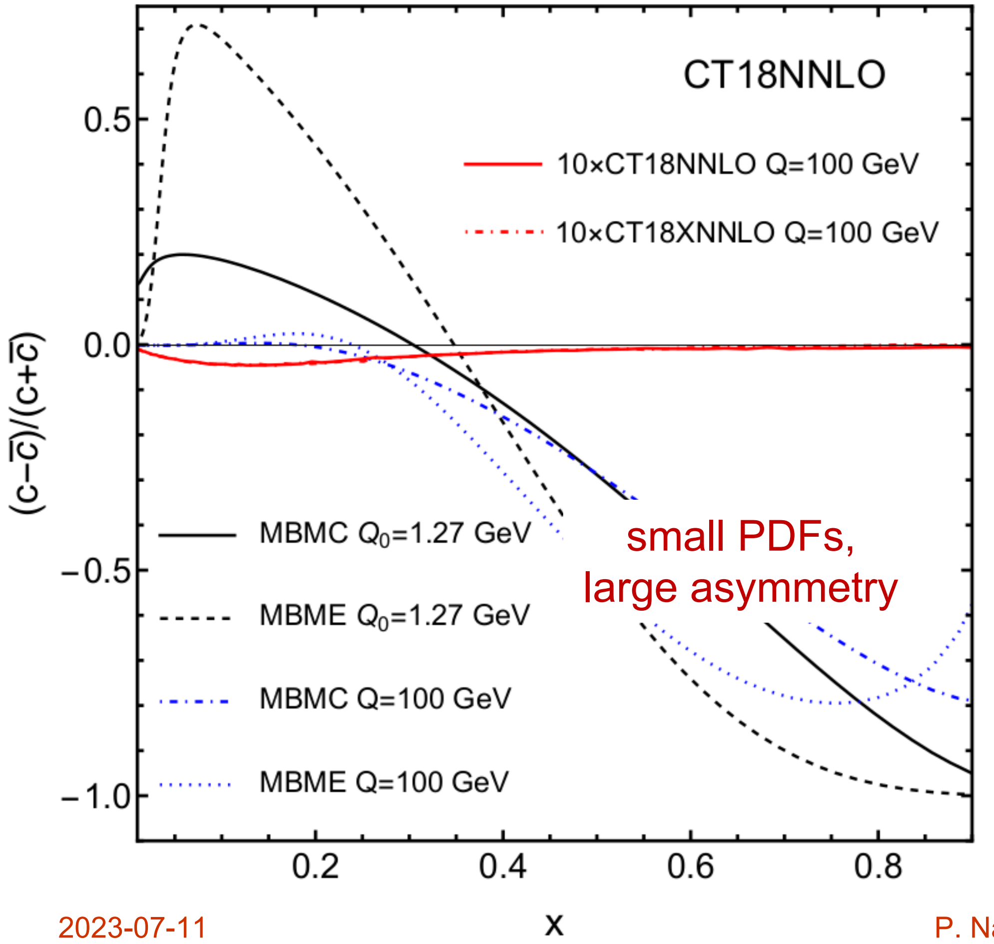
central fits



possible charm-anticharm asymmetries

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

→ the examined MBM models allow large $c \neq \bar{c}$ due to soft interactions



[the magnitudes of the asymmetry are examples, not unique predictions]

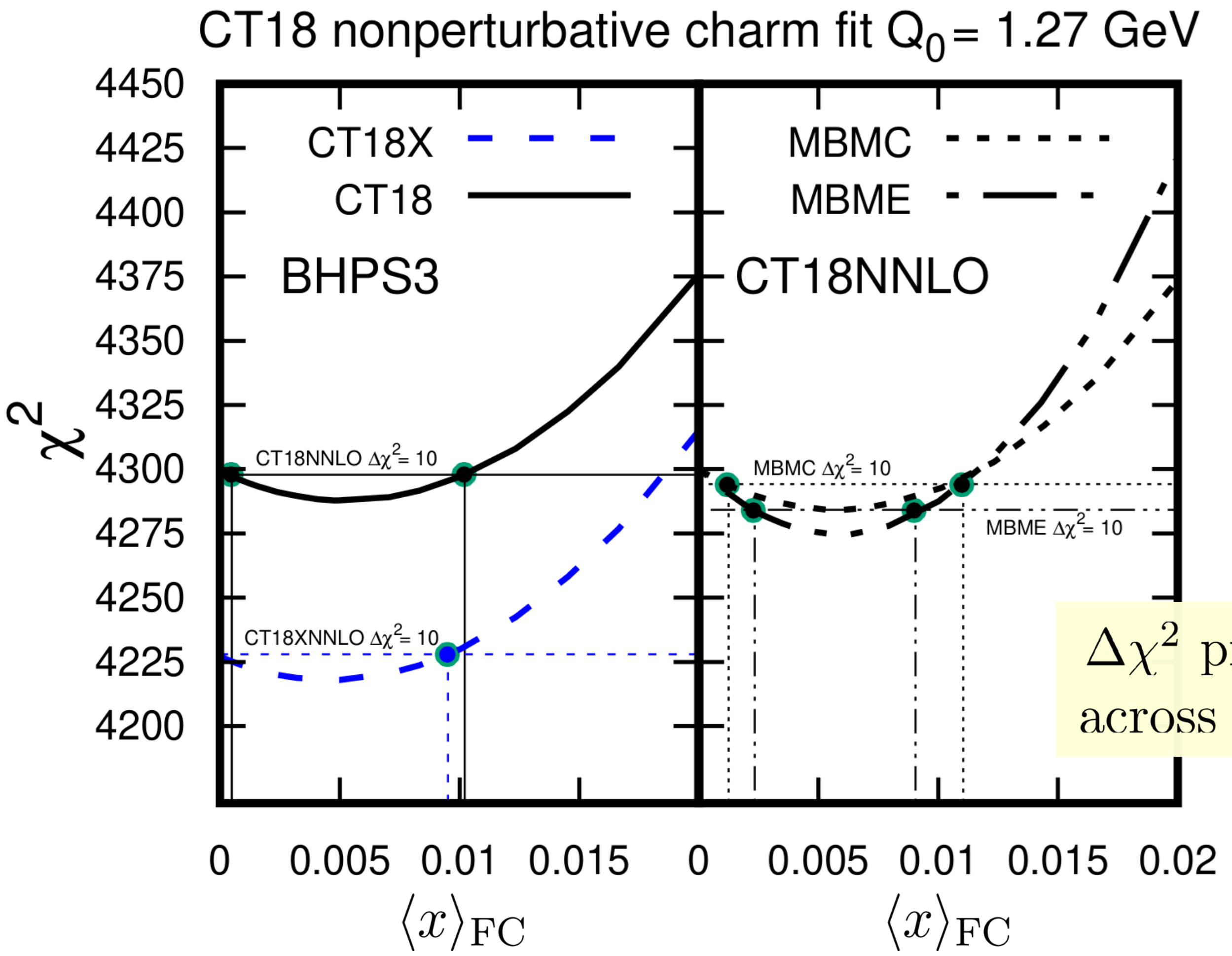
→ observation of a large $c \neq \bar{c}$ asymmetry would be a strong evidence of the nonperturbative dynamics

Hobbs, Londergan, Melnitchouk, Phys. Rev. D 89 (2014) 074008

weak signal for FC in CT18 study, 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

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

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

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

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

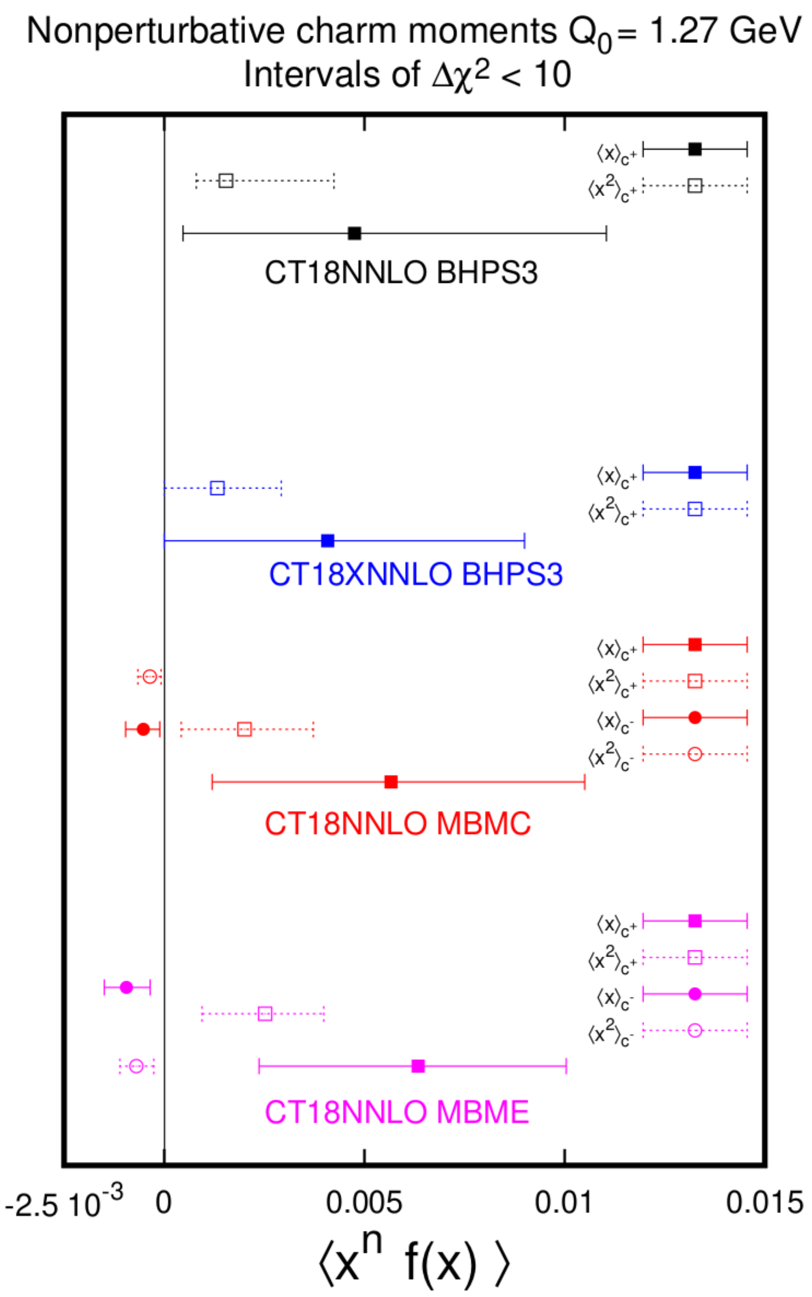
$$= 0.0041\, {}^{+0.0049}_{-0.0041} \left({}^{+0.0091}_{-0.0041}\right),\ \mathrm{CT18X\ (BHPS3)}$$

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

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

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

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



FC PDF moments

even restrictive uncertainties give moments consistent with zero

→ broaden further for default CT tol.

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

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

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

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

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

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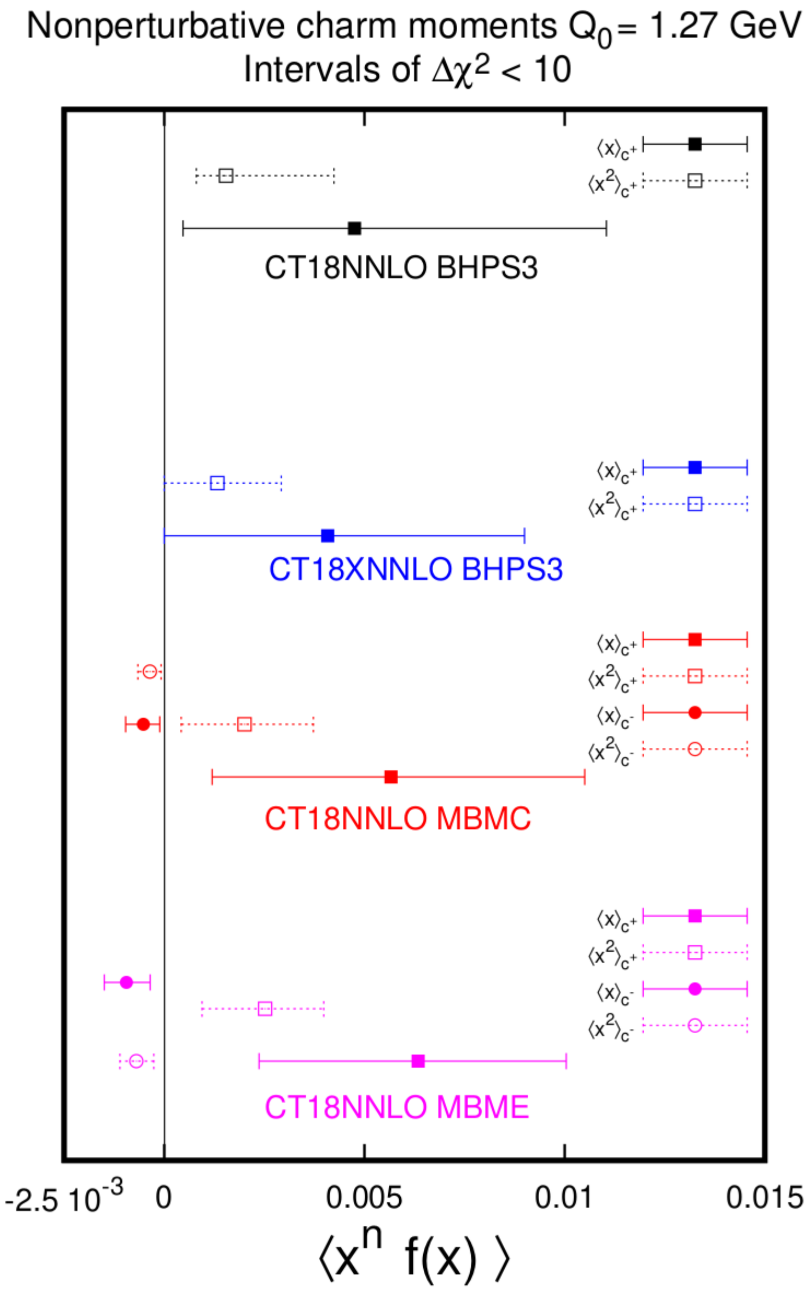
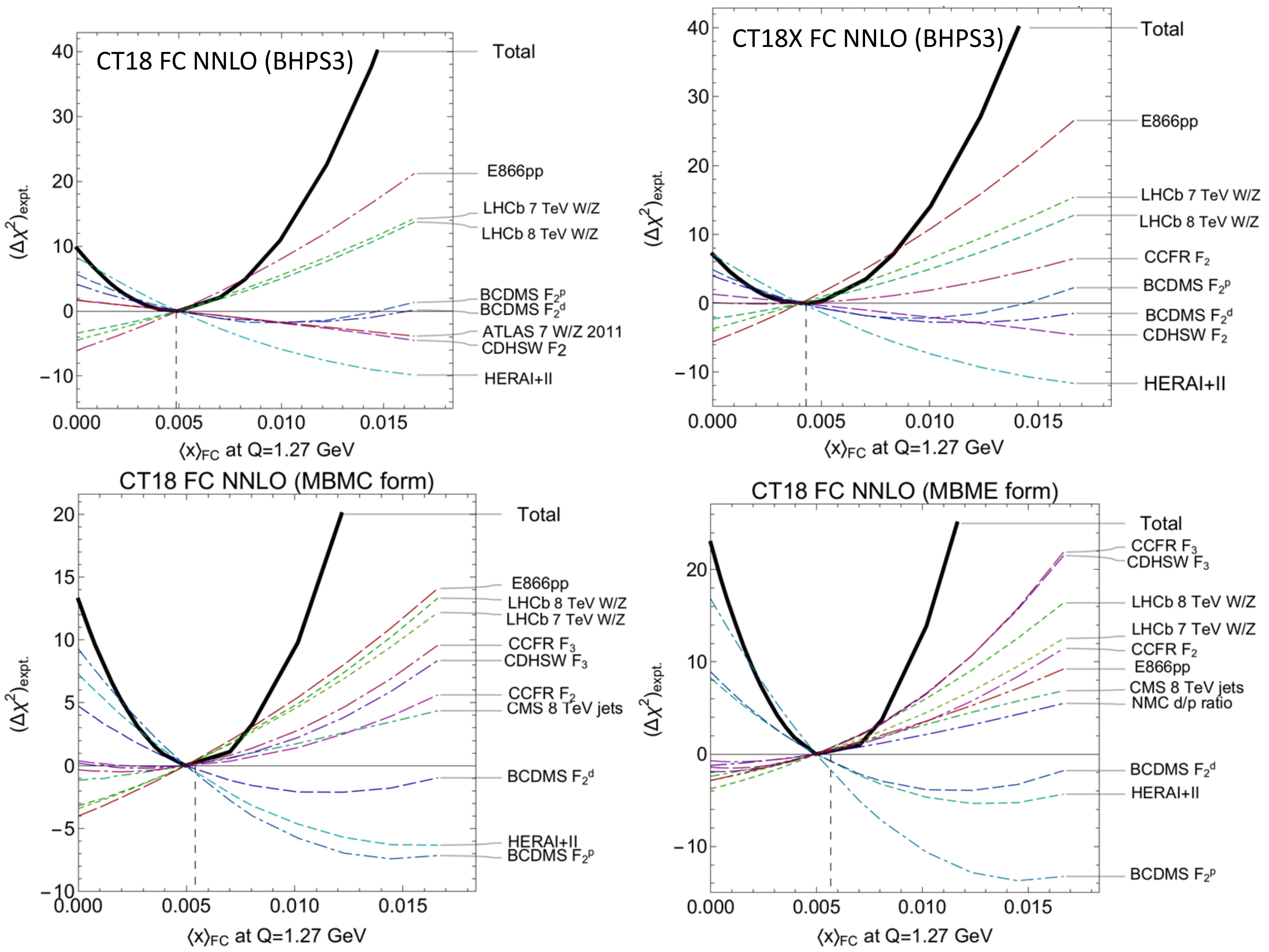


data pull opposingly on $\langle x \rangle_{\rm FC}$; depend on FC scenario, enhancing error

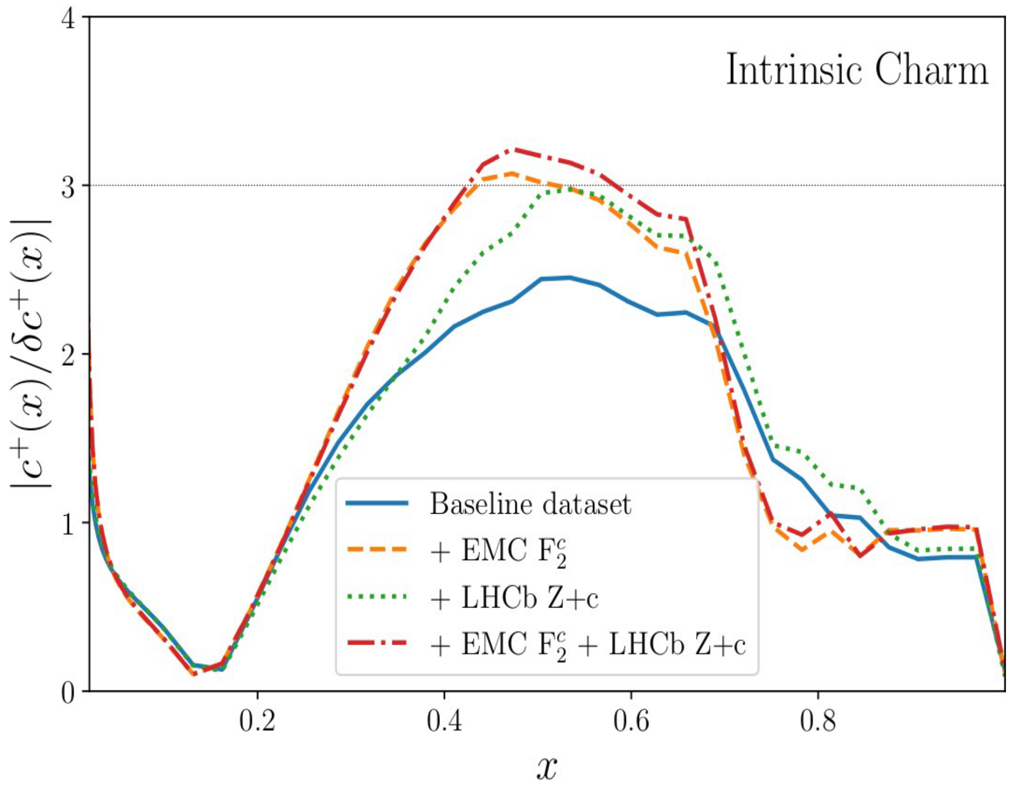


Revisiting the significance in NNPDF4.0 IC

R. Ball et al., Nature 608 (2022) 483

By considering important additional uncertainties:

- In the baseline fit due to sampling of MC replicas (Courtoy et al., *Phys.Rev.D* 107 (2023) 034008)
- In the NLO LHCb $Z + c$ analysis due to MHOU and final-state showering
- In the EMC F_2^c due to insufficient control of syst. uncertainties and LO analysis



∴ … we expect no significant evidence for NNPDF4.0 IC, in compliance with CT18 FC observations

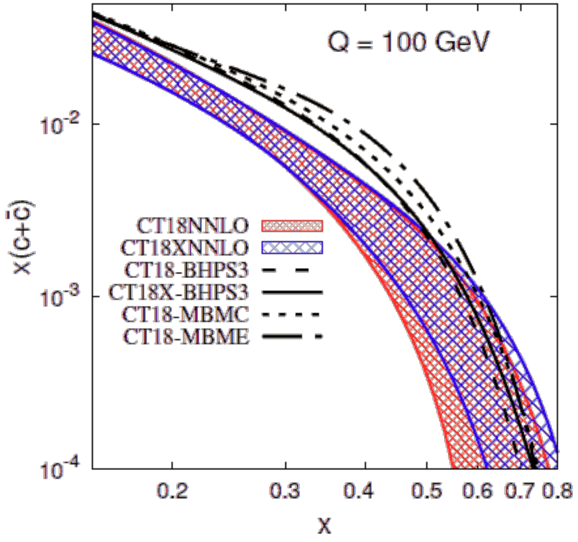
See PLB 843 (2023) 137975

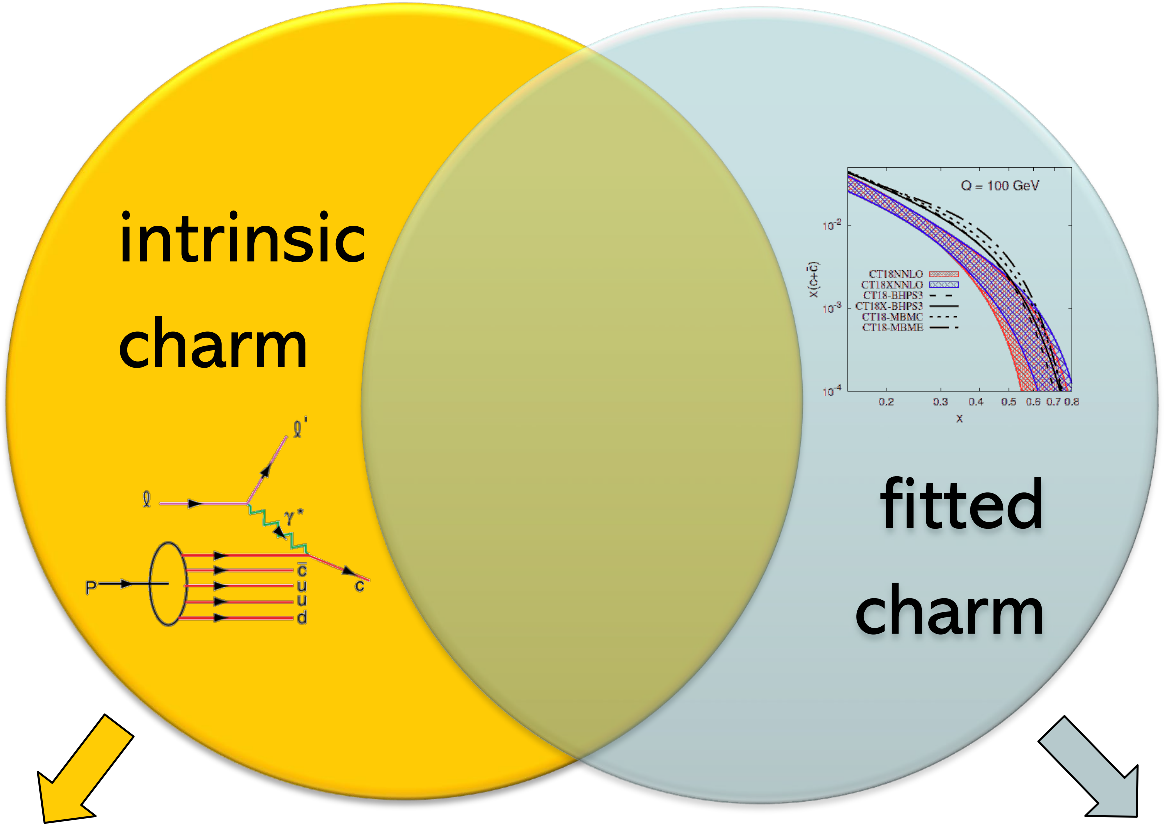
Additional comments

Do 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





- 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

In perturbative QFT:

Intrinsic Chevrolets at the SSC

Stanley J. Brodsky (SLAC), John C. Collins (IIT, Chicago and Argonne), Stephen D. Ellis (Washington U., Seattle), John F. Gunion (UC, Davis), Alfred H. Mueller (Columbia U.)

Aug, 1984

10 pages

Part of DESIGN AND UTILIZATION OF THE SUPERCONDUCTING SUPER COLLIDER. PROCEEDINGS, 1984 SUMMER STUDY, SNOWMASS, USA, JUNE 23 - JULY 13, 1984

Proceedings of: 1984 DPF Summer Study on the Design and Utilization of the Superconducting Super Collider (SSC) (Snowmass 84), 227

Report number: DOE/ER/40048-21 P4, SLAC-PUB-15471

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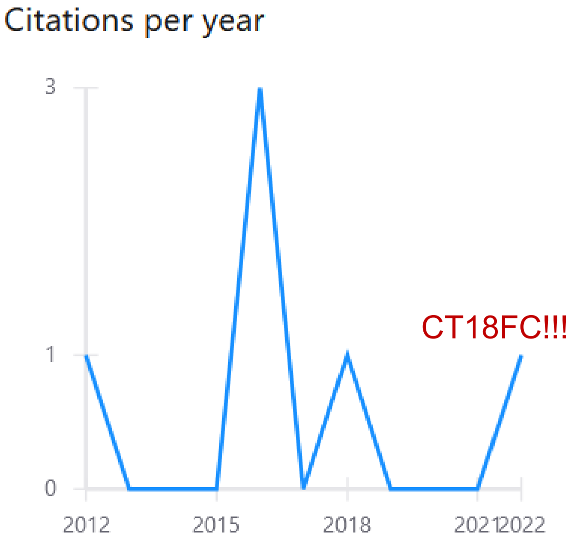


An intrinsic Chevrolet is attached to the target hadron by ≥ 2 gluon propagators

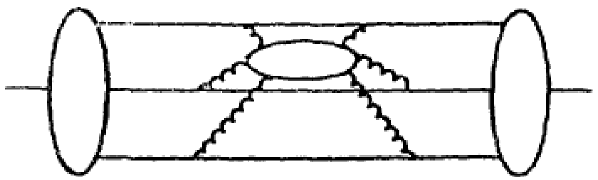


Fig. 1. Example of intrinsic heavy quark contribution to the proton wave function in QCD.

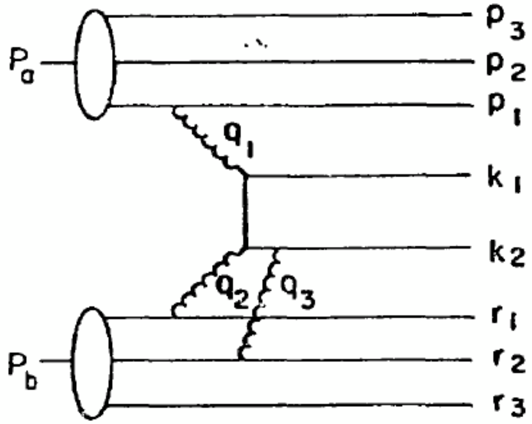
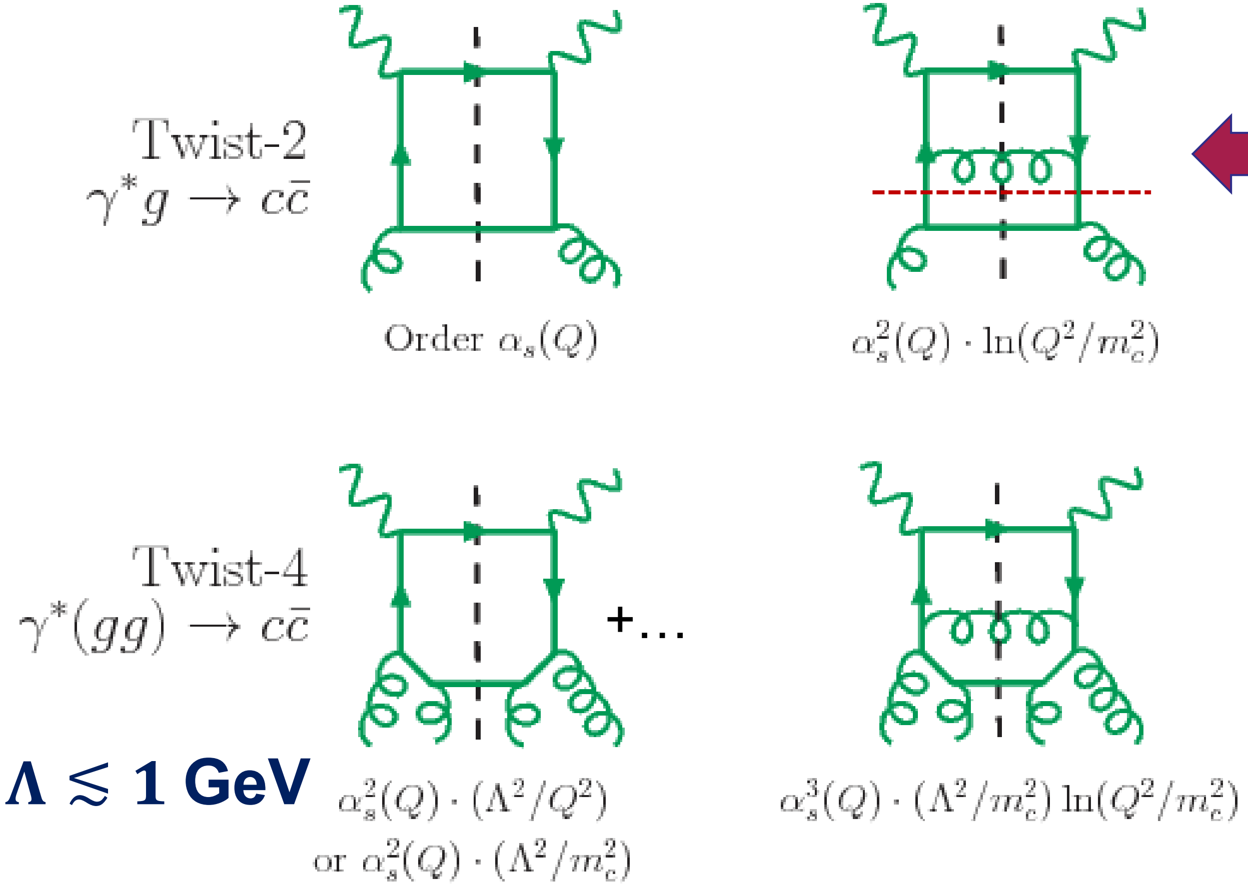


Fig. 3. Typical diagram for heavy quark production with extra gluon corresponding to intrinsic production.

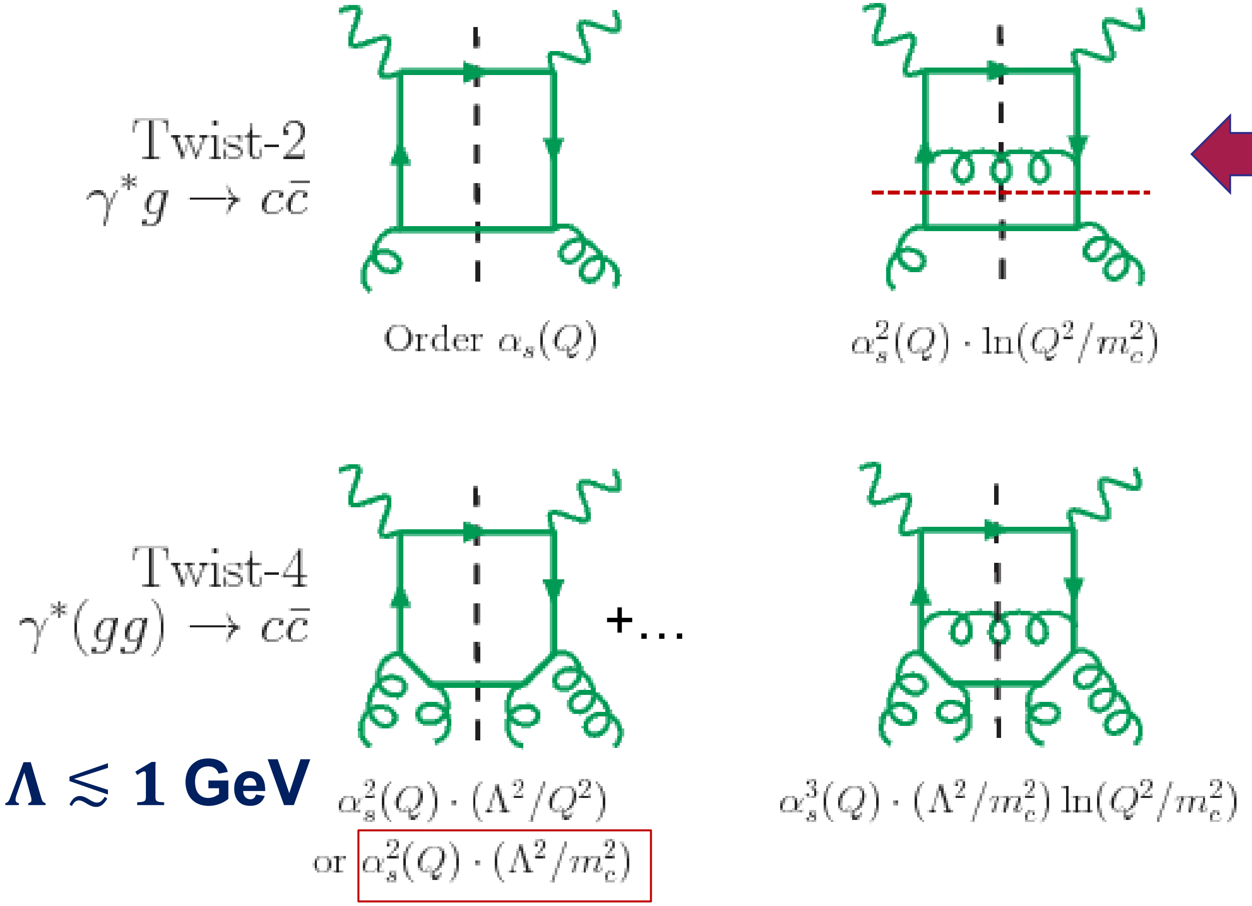
A twist-4 contribution in HERA DIS charm production ($\subset$ "intrinsic charm")



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

$\Lambda \lesssim 1$ GeV

A twist-4 contribution in HERA DIS charm production (⊂ “intrinsic charm”)

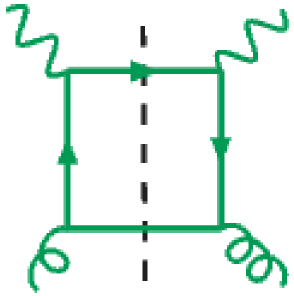


A ladder; must be resummed in $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme

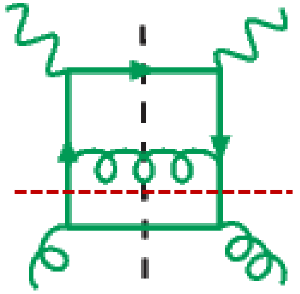
Can be of order 10% of the twist-2 α_s^2 term

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

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



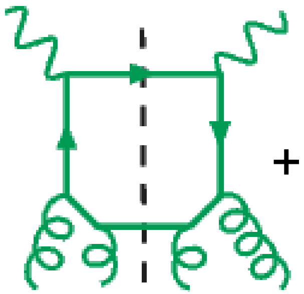
Order $\alpha_s(Q)$



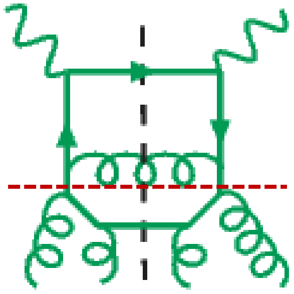
$\alpha_s^2(Q) \cdot \ln(Q^2/m_c^2)$

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



+…



$\Lambda \lesssim 1$ GeV

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

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

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.

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

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:

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

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

PDF fits:

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

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

The 'fitted charm component' may approximate for missing terms of orders α_s^p with $p > N_{ord}$, or Λ^2/m_c^2, or Λ^2/Q^2

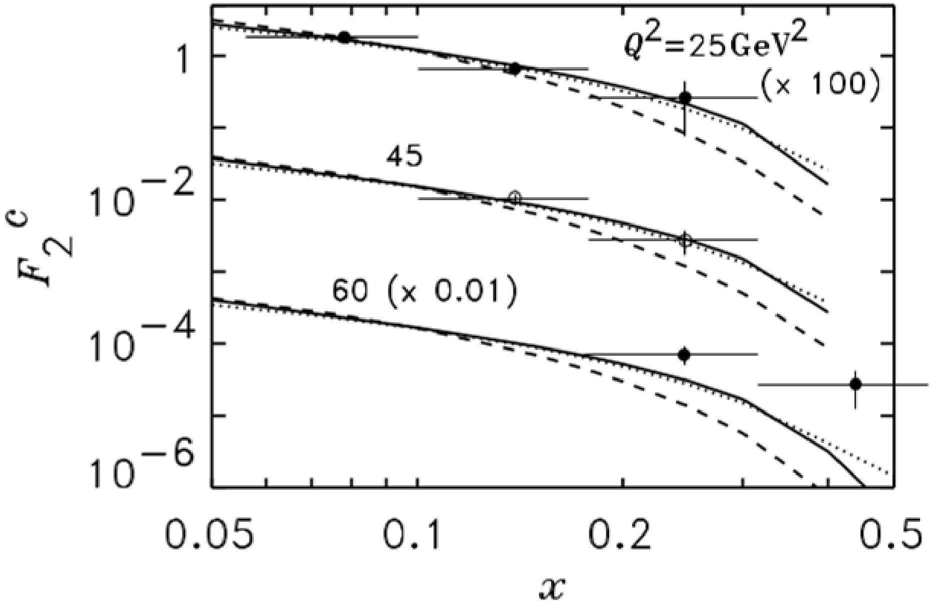
EMC F_2^c, LHCb $Z + c$ production, and future experiments

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 two Q^2 bins

→ data were analyzed only at LO

→ EMC data fit poorly in CT14 IC study

→ CT14 PDFs overpredict most EMC bins (consequence of a large gluon PDF)

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

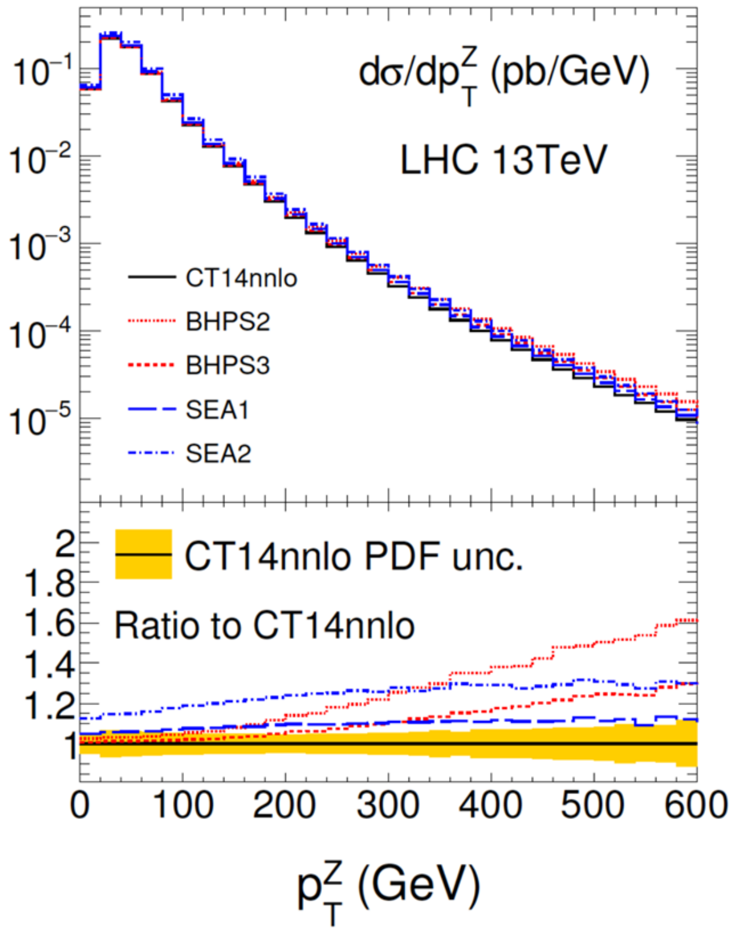
T. Boettcher, P. Ilten, M. Williams, 1512.06666; Bailas, Goncalves, 1512.06007

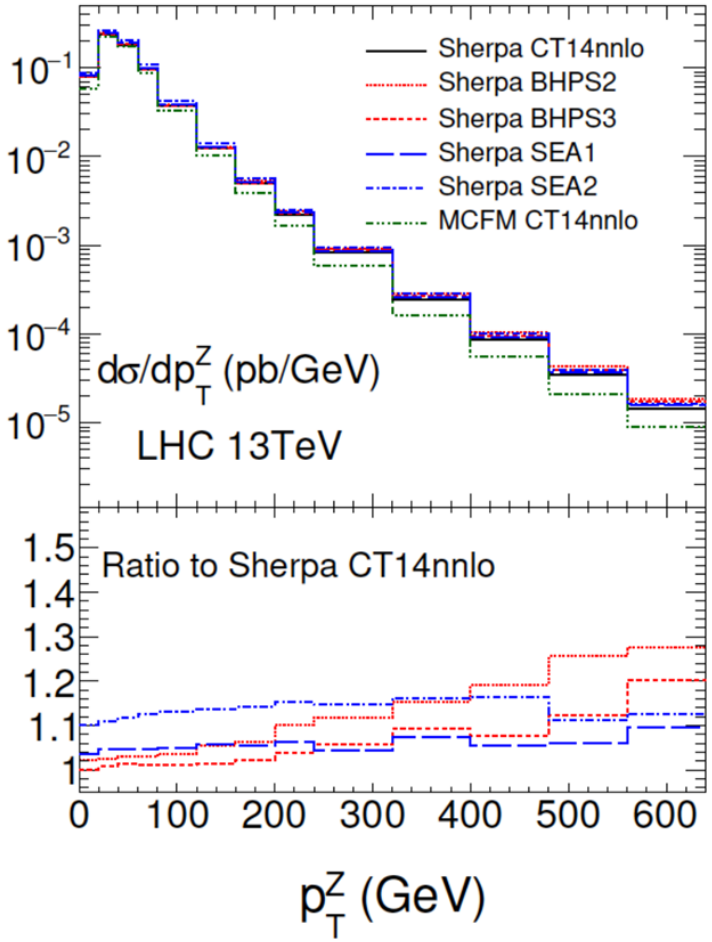
p_T spectra, rapidity dists nominally sensitive to high-x charm PDF

→ parton-shower effects can dampen high-p_T tails

Z+c NLO LHC 13 TeV

[Hou et al., arXiv:1707.00657]



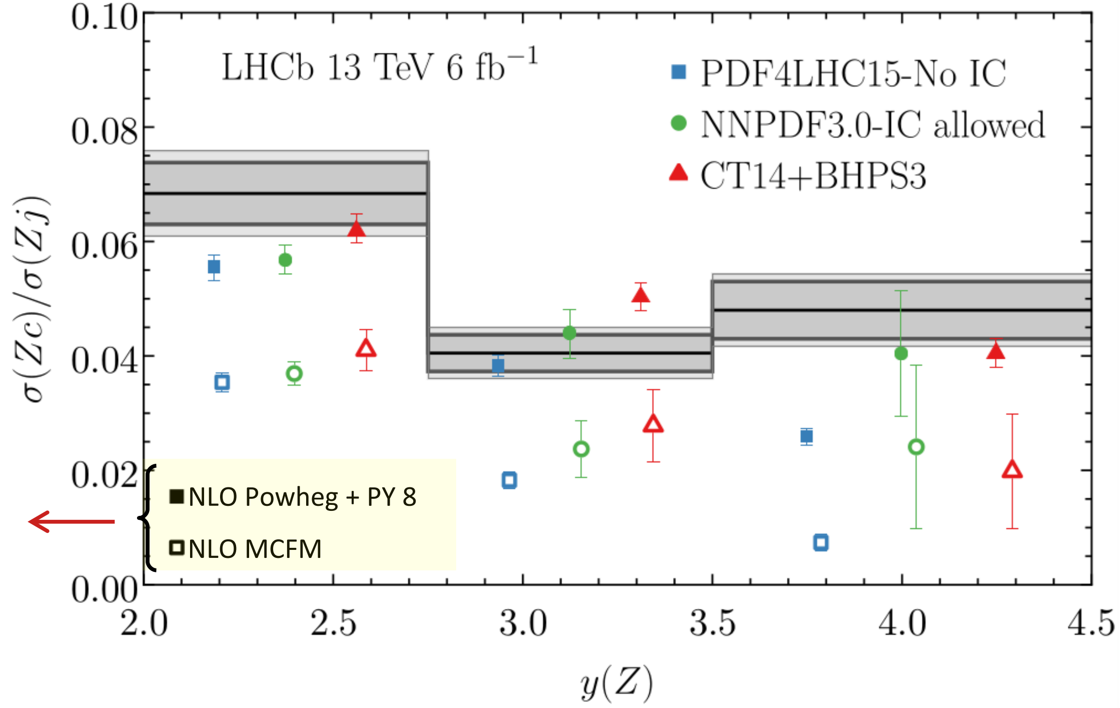


$Z+c$ theory predictions for flavored anti-k_T jets are IR sensitive

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.



differ due to large FSR correction

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

NNLO calculations recently available, but not implemented in PDF fits

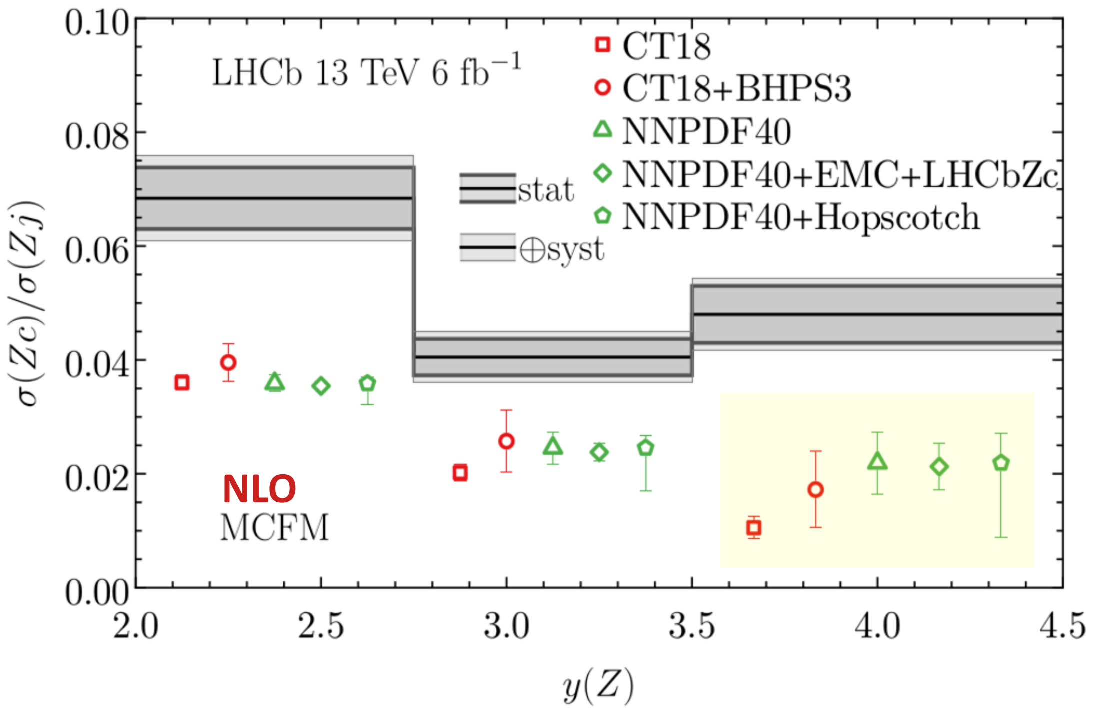
R. Gauld, *et al.*; arXiv: 2005.03016; 2302.12844
M. Czakon, *et al.*; arXiv: 2011.01011.

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

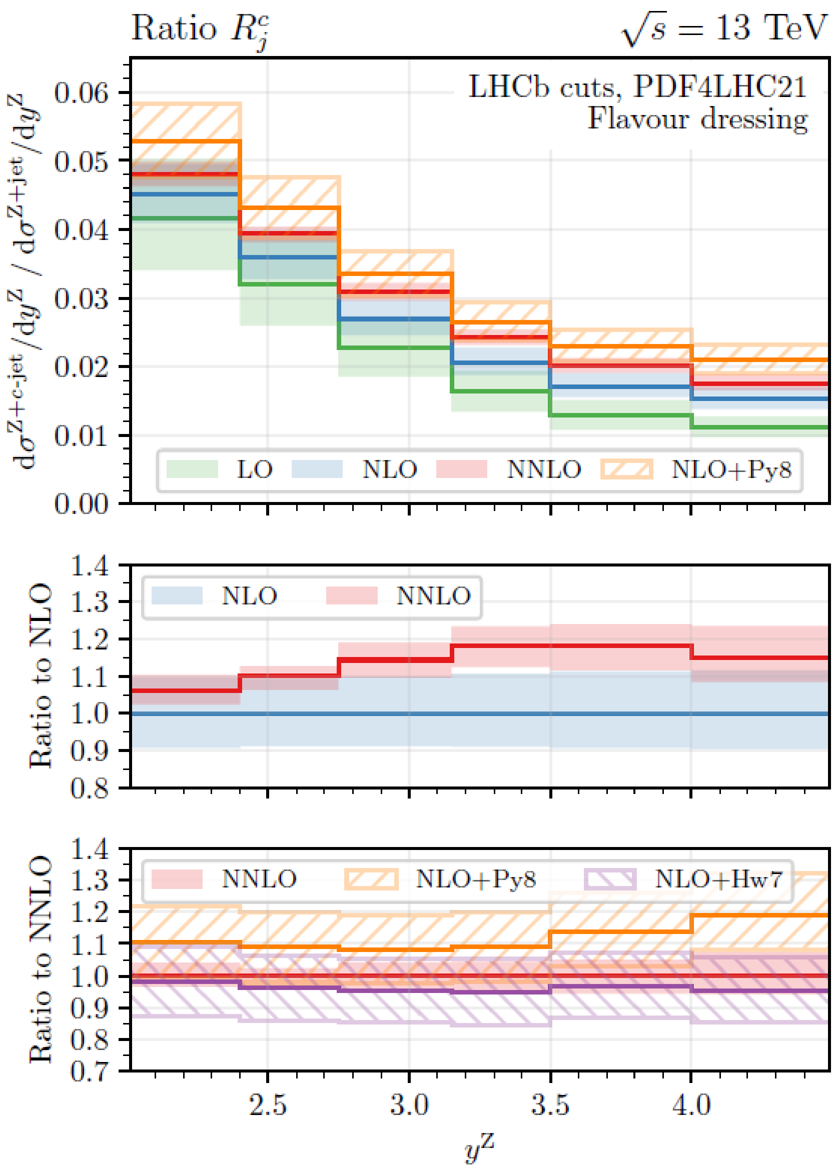
R. Aaij, *et al*. (LHCb); arXiv: 2109.08084.



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

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

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

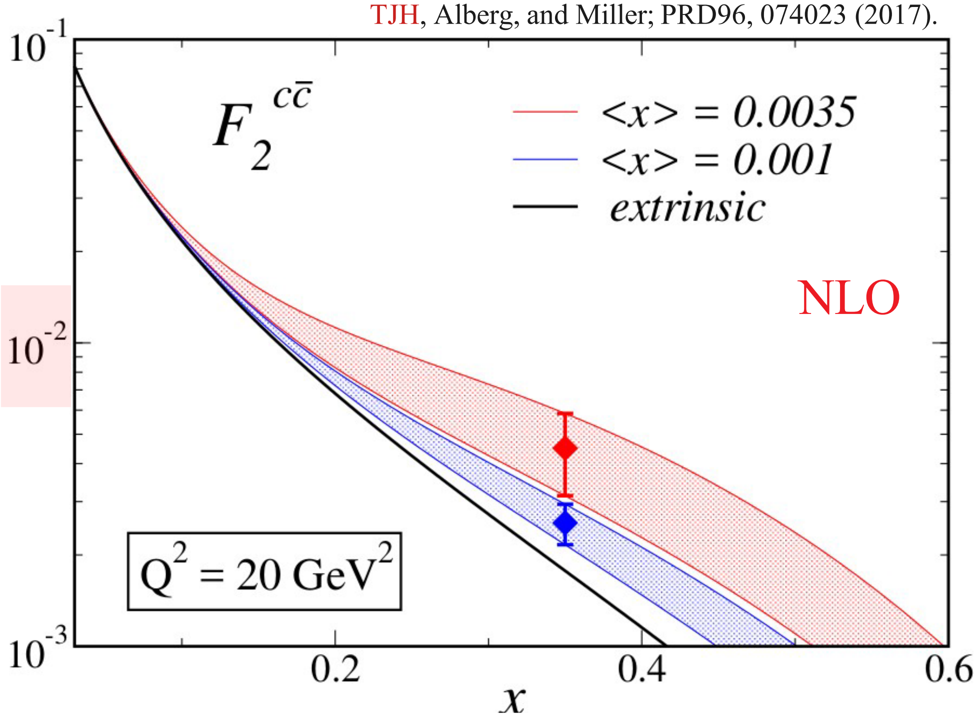


R. Gauld, et al., 2302.12844

Differences between NLO+Pythia 8 and NLO+Herwig 7 dilute dependence on the fitted charm

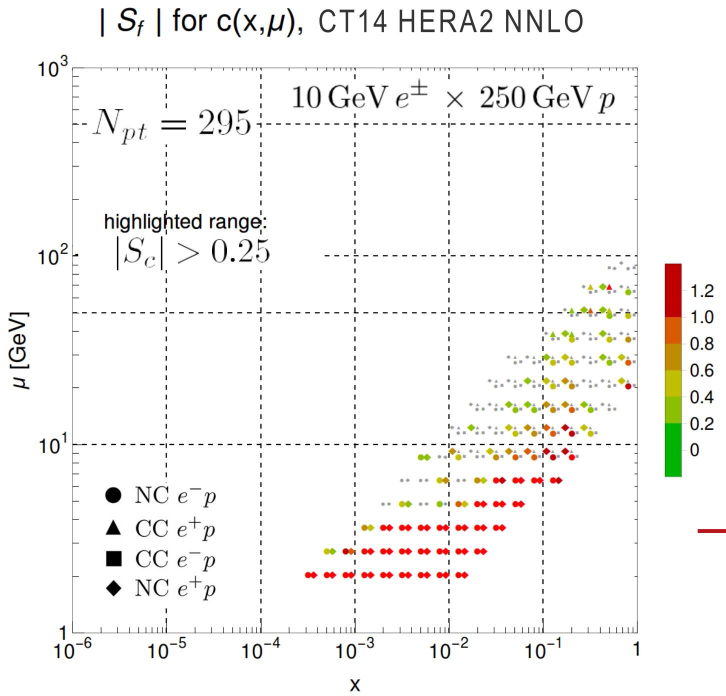
Improvements expected with development of IRC-insensitive flavored jet algorithms (next talk), massive PS at NLL (e.g. *Assi, Hoeche, arXiv:2307.00728*)

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

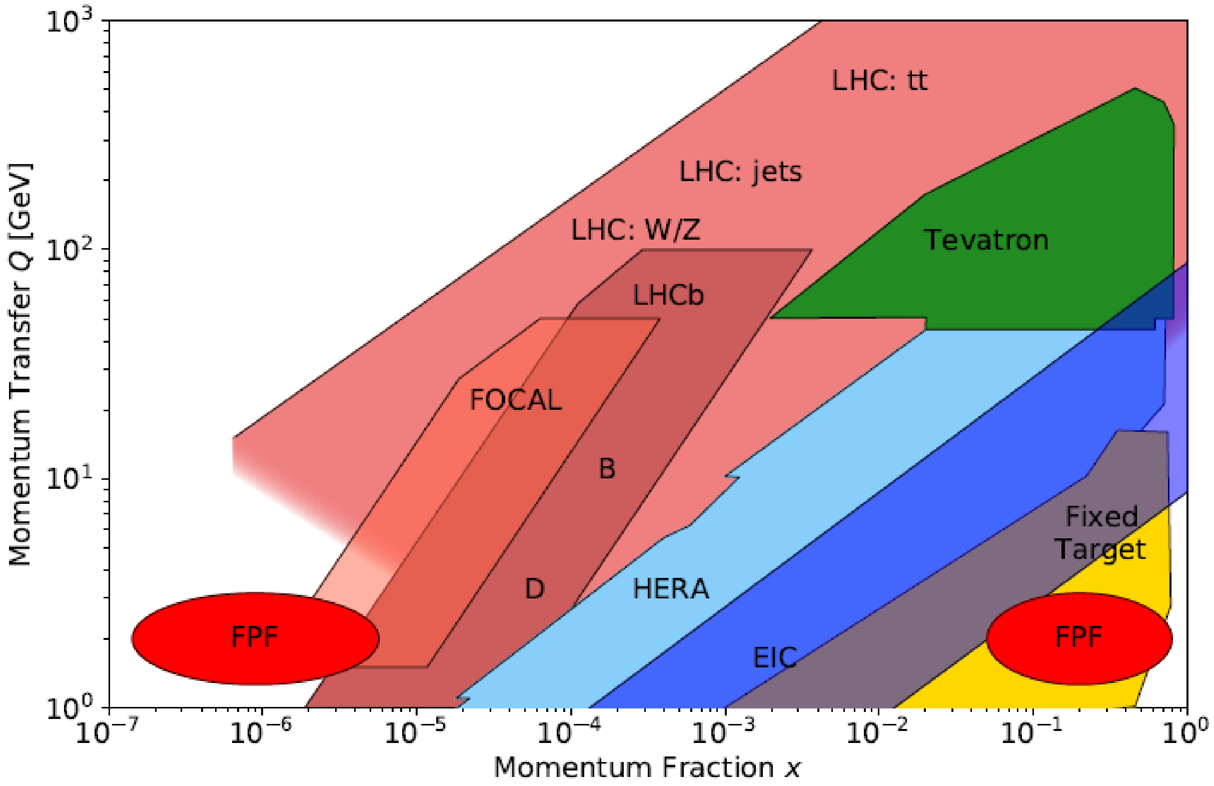


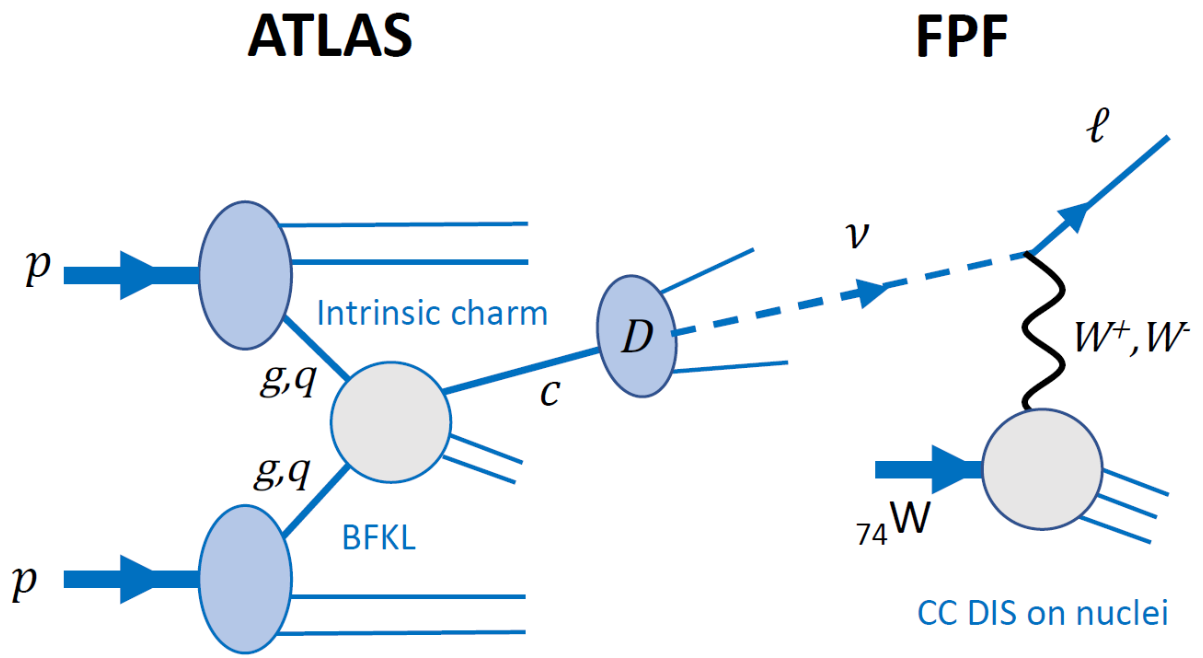
essential complementary input from LHC; CERN FPF

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

The Forward Physics Facility at CERN

L. A. Anchordoqui *et al.*, "The Forward Physics Facility: Sites, Experiments, and Physics Potential," arXiv:2109.10905 [hep-ph].
J. L. Feng *et al.*, "The Forward Physics Facility at the High-Luminosity LHC," arXiv:2203.05090





The FPF can clarify multiple aspects of QCD in the new forward region **in coordination** with the HL-LHC and EIC, including intrinsic charm

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

Backup

SACOT

= Simplified Aivazis-Collins-Olness-Tung scheme

ACOT, PRD 50 3102 (1994); Collins, PRD 58 (1998) 094002;
Kramer, Olness, Soper, PRD (2000) 096007; Tung, Kretzer, Schmidt, J.Phys. G28 (2002) 983

The default heavy-quark scheme of CTEQ-TEA PDFs
Implementation is based upon, and closely follows, the proof of QCD factorization for DIS with massive quarks *(Collins, 1998)*

MPS/χ prescription $\equiv$ Kinematic matching based on **m**assive **p**hase **s**pace to improve perturbative convergence near HF production threshold

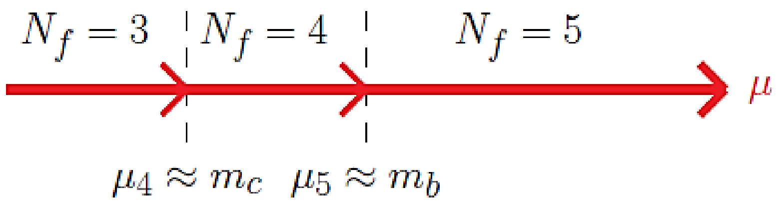
Applied

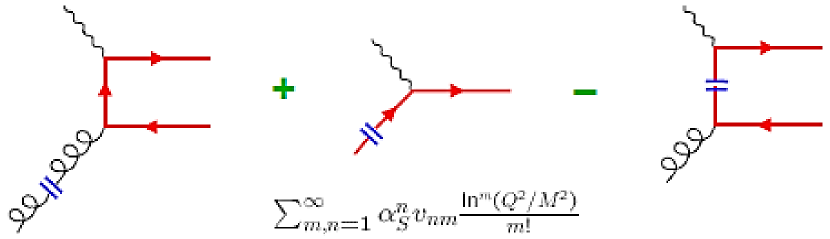
- to NNLO in NC DIS (Guzzi et al.; arXiv:1108.5112)

- to NLO in heavy-flavor hadroproduction using MCFM

(Xie, Campbell, Nadolsky, 2019-2020)

SACOT-MPS scheme: advantages

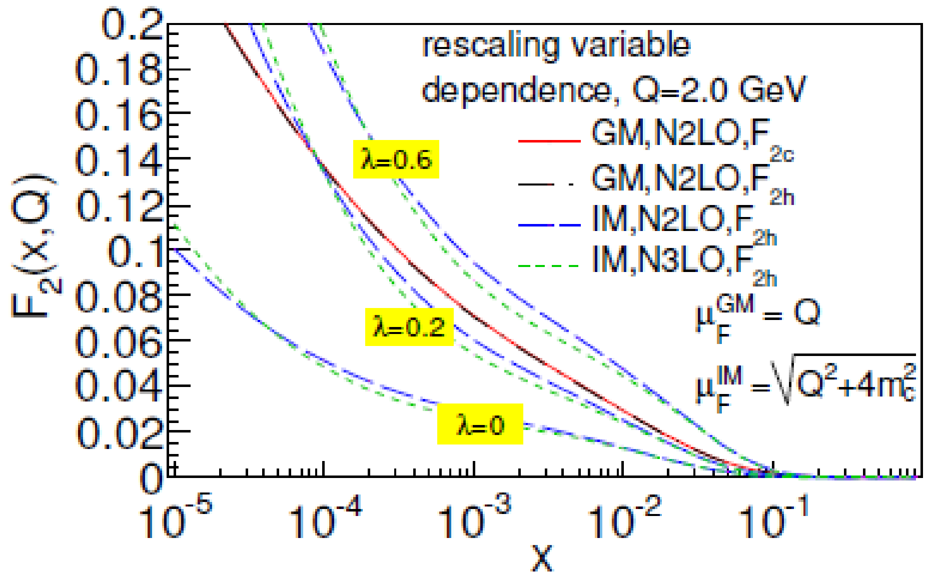


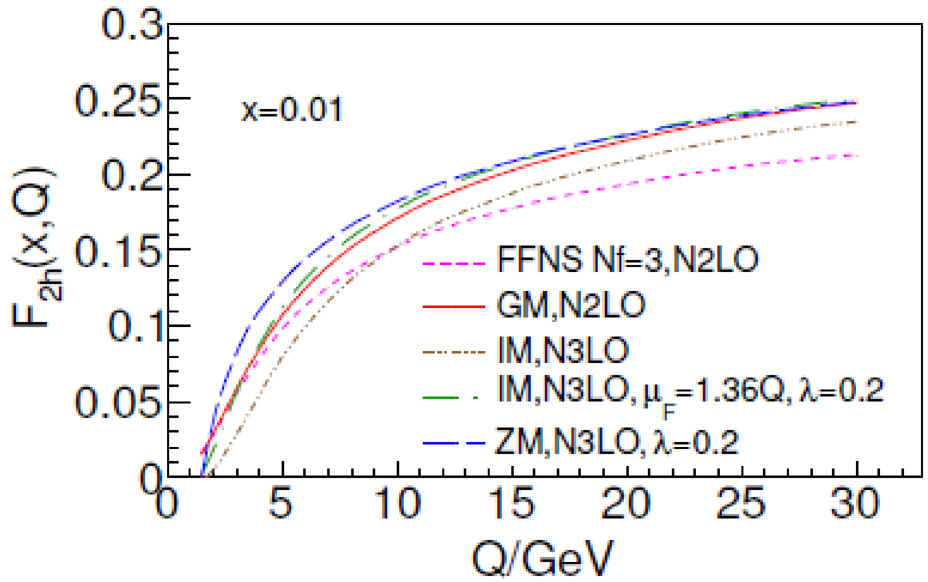


- A general-mass variable-flavor number (GM-VFN) scheme
  - Perturbatively convergent at all factorization scales $Q \gtrsim m_Q$
  - reduces to the zero-mass $\overline{MS}$ scheme at $Q^2 \gg m_Q^2$, without additional renormalization
  - reduces to the fixed-flavor number scheme at $Q^2 \sim m_Q^2$
- Relatively simple
  - One value of N_f (and one PDF set) in each Q range
  - Sets $m_Q = 0$ in $|M|^2$ with incoming c or b
  - Straightforward matching based on kinematical rescaling

Other common heavy-quark schemes: FONLL, TR', SACOT-m_T,…

The SACOT-MPS scheme can be straightforwardly extended to N3LO DIS





The intermediate-mass (IM) approximation to the SACOT-MPS scheme, using approximate N3LO matrix elements

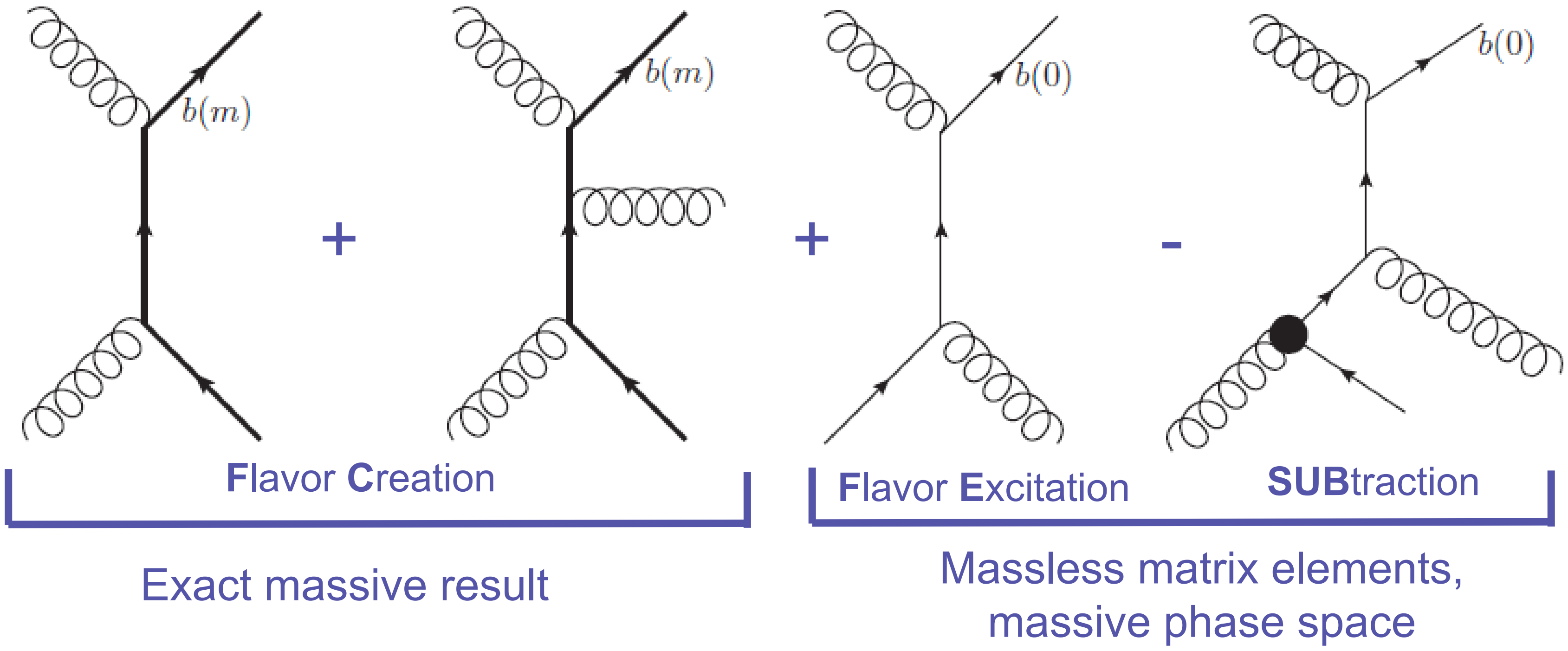
The exact flavor structure of the GM-VFN scheme at N3LO is readily reproduced

[Bowen Wang, Ph. D. thesis, 2015;
see also Stavreva et al., arXiv:1203.0282]

SACOT-MPS scheme for heavy-quark production at hadron colliders

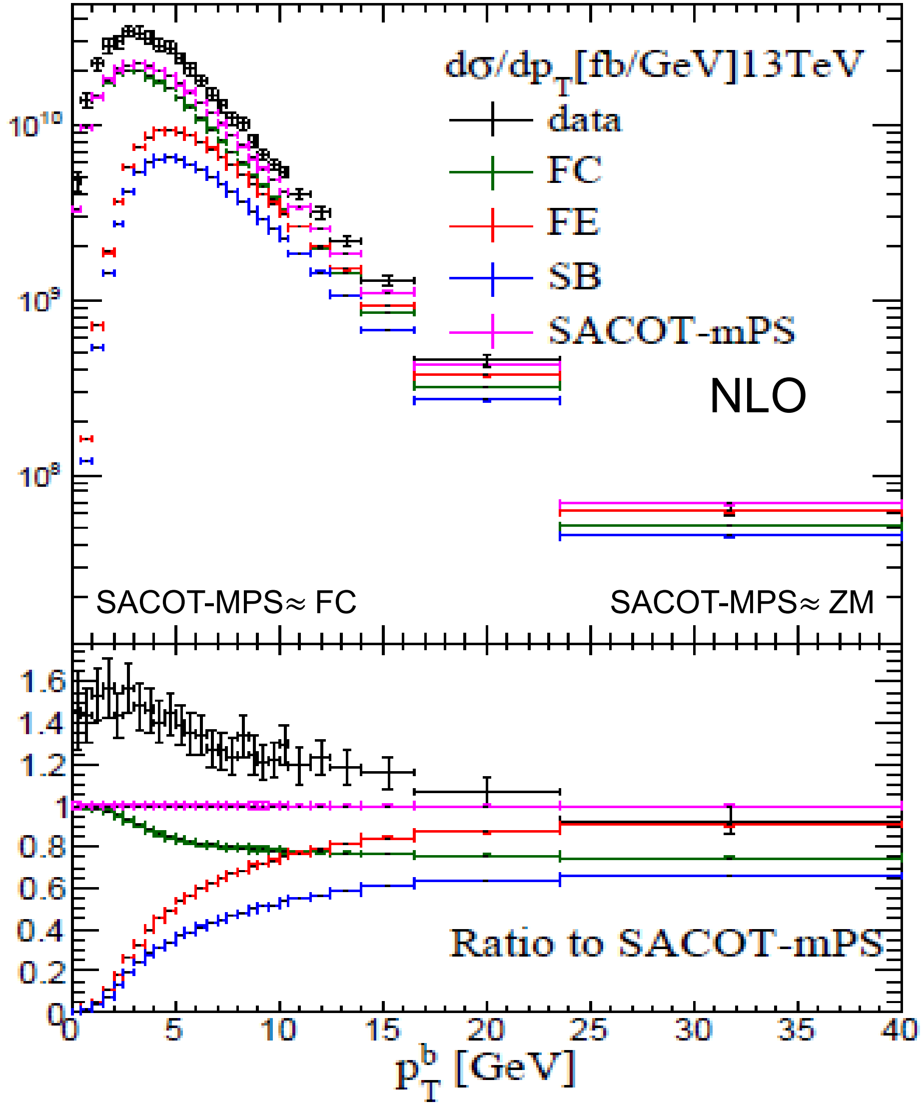
[Keping Xie, Ph. D. thesis, 2019; cf. talk by Keping]

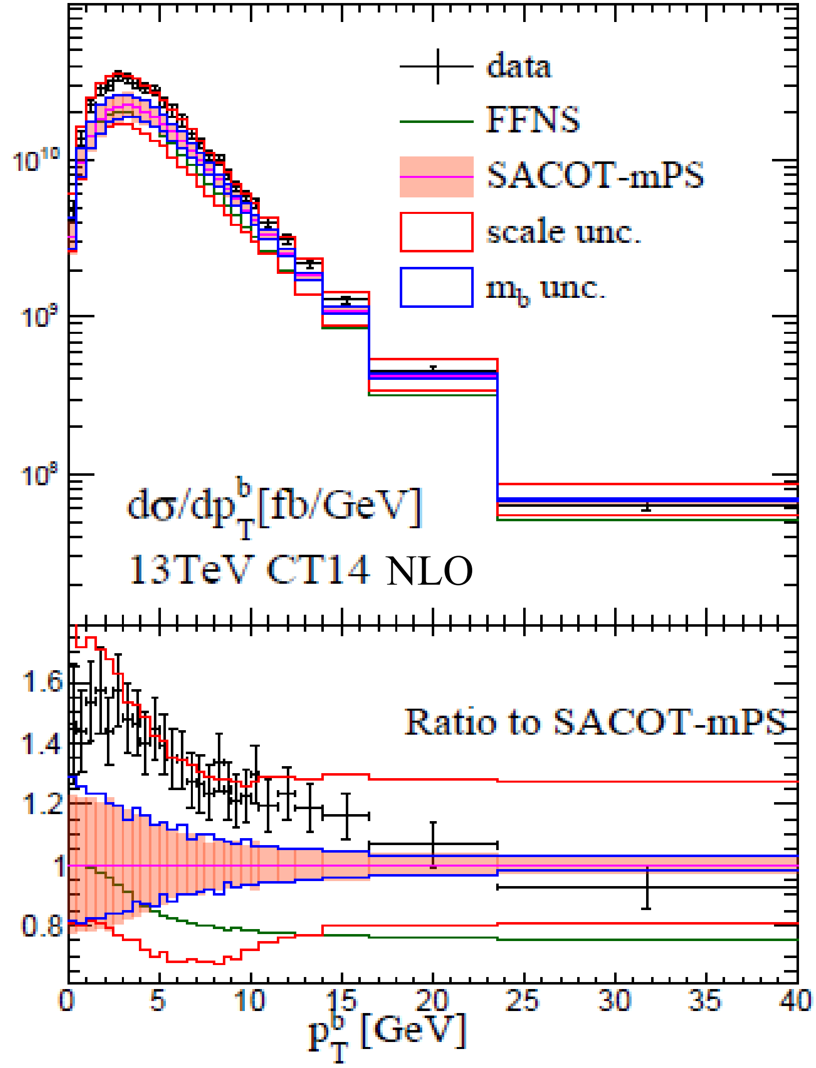
- A straightforward implementation for $pp \to bX$, other processes
- Realized in the MCFM code



α_s and PDFs with $N_f = 5$ in all terms

SACOT-MPS NLO predictions for b-quark production at LHCb 13 TeV

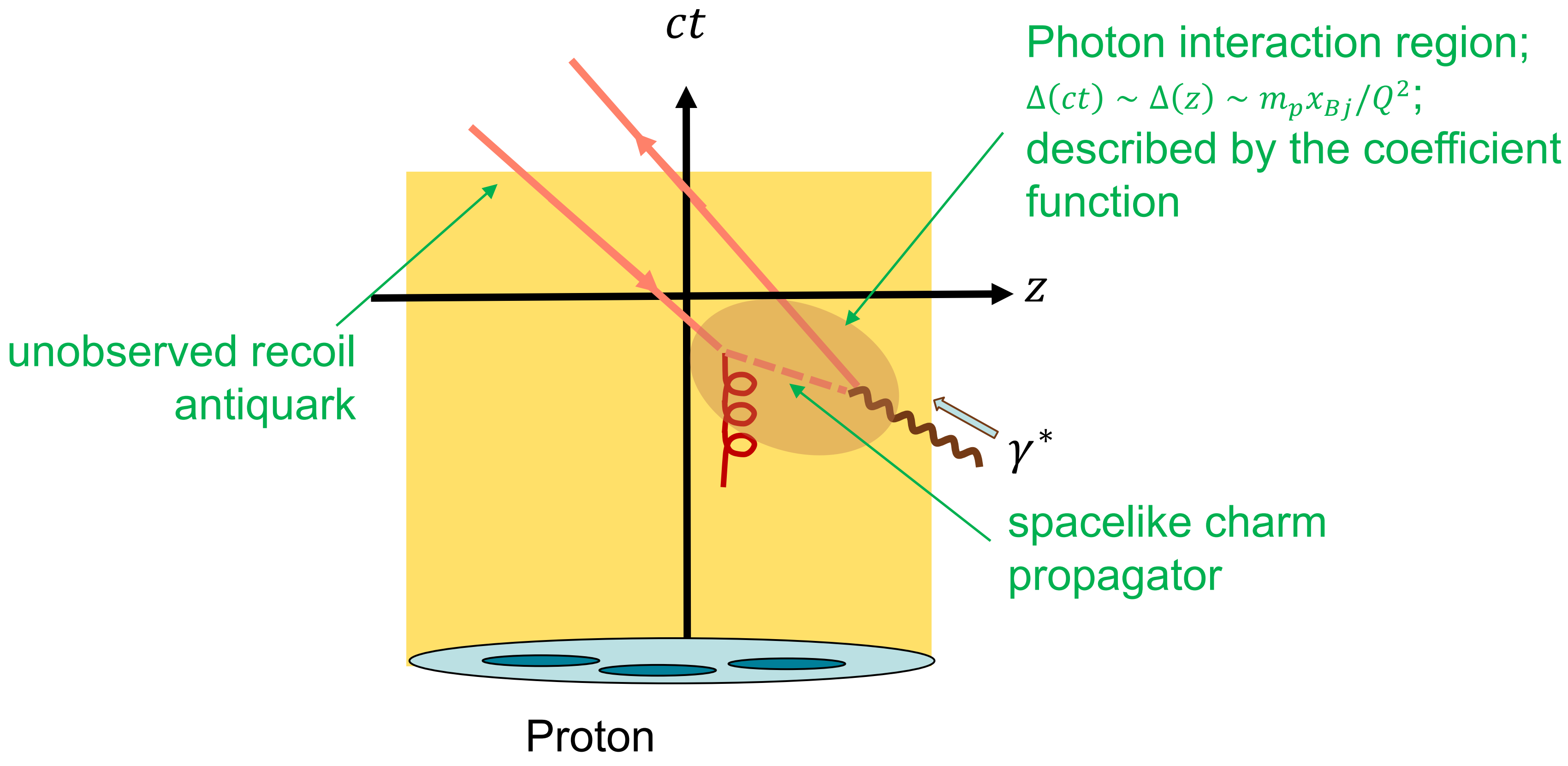




SACOT-MPS is in better agreement with data than either FFN or ZM schemes; readily extendable to other processes and NNLO

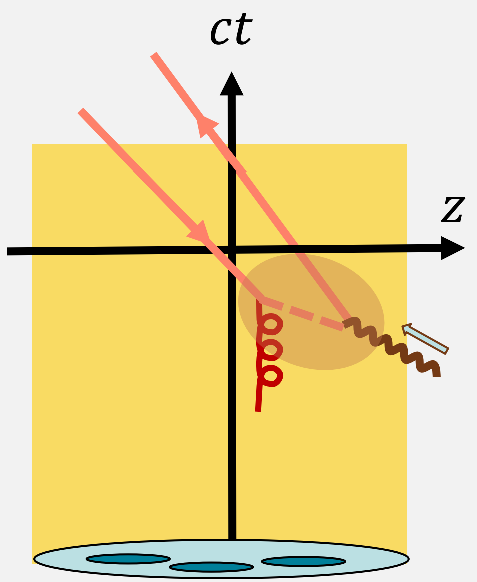
DIS in the rest frame of the proton, space-time diagram

Extrinsic production



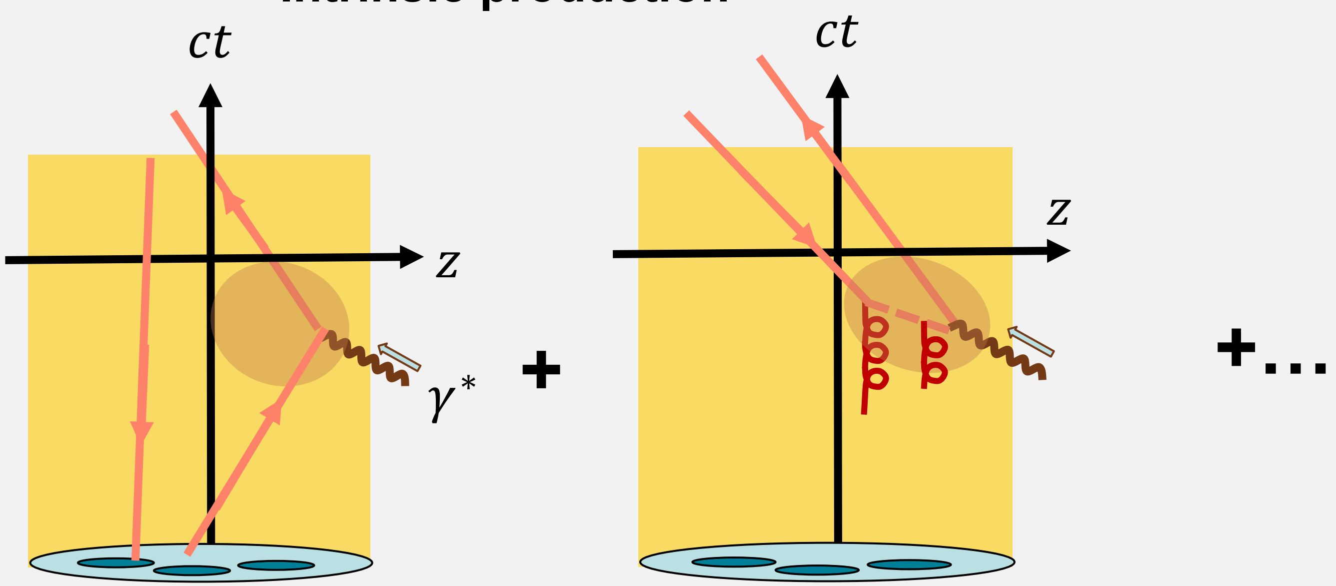
DIS in the rest frame of the proton, leading kinematic configurations

Extrinsic production



Leading power (twist-2): charm connected by 1 collinear gluon to the proton

Intrinsic production

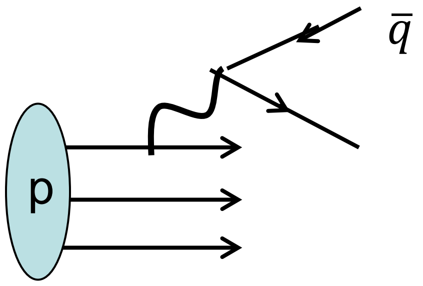


<u>Negligible</u> mixing with excited asymptotic states ($|uudc\bar{c}\rangle$,…);

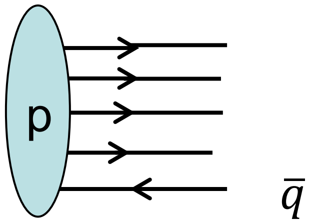
Higher powers in Λ^2/m_c^2 (not necessarily small): charm and proton connected by 2 or more gluons

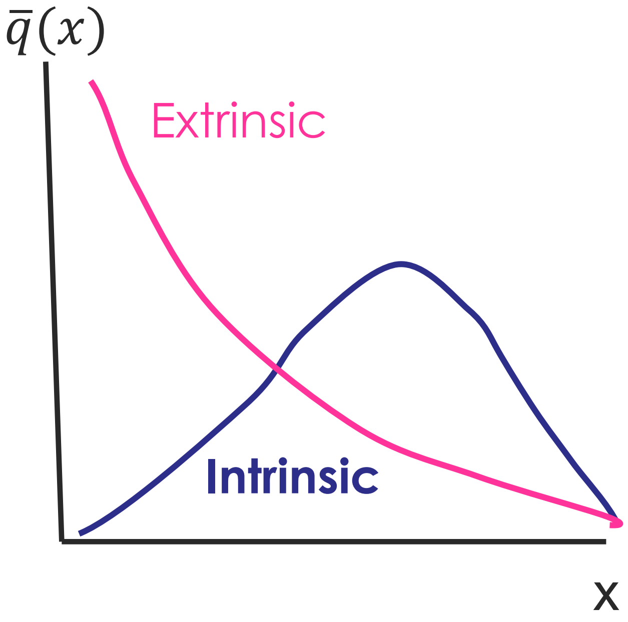
In nonperturbative models:

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



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





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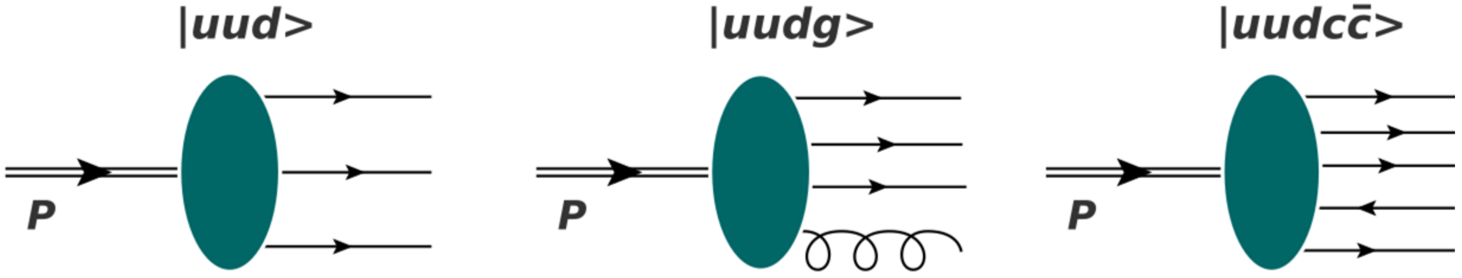
nonperturbative QCD can generate a low-scale charm PDF

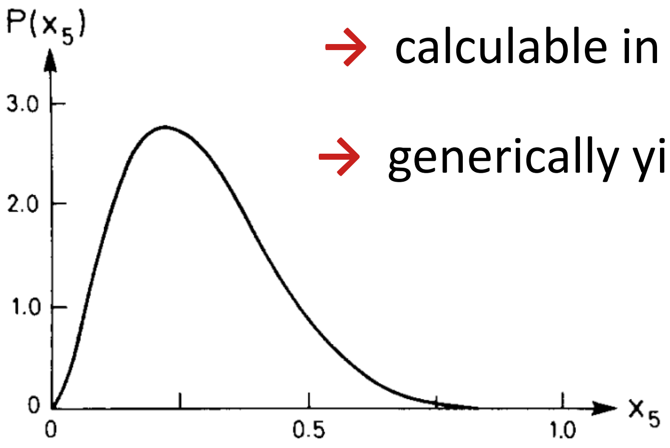
Fock expansion

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



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

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



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

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

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

alternative but similar representations exist

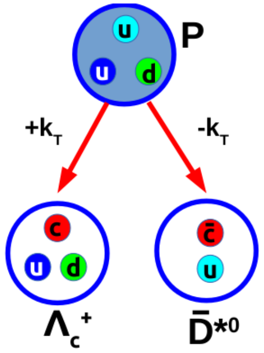
Blumlein; Phys. Lett. **B753** (2016) 619.

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).**]

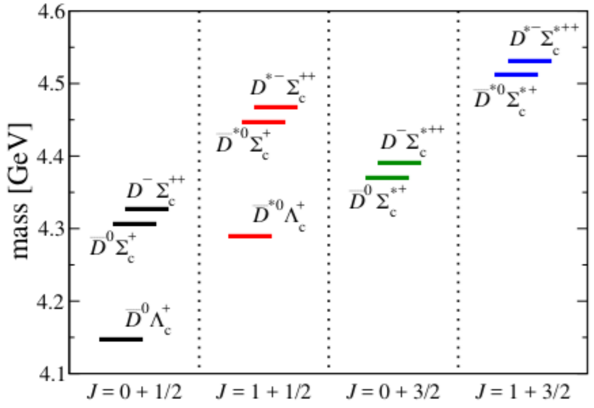


- $$|N\rangle = \sqrt{Z_2}\,|N\rangle_0 + \sum_{M,B} \int dy\, f_{MB}(y)\, |M(y); B(1-y)\rangle$$

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

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

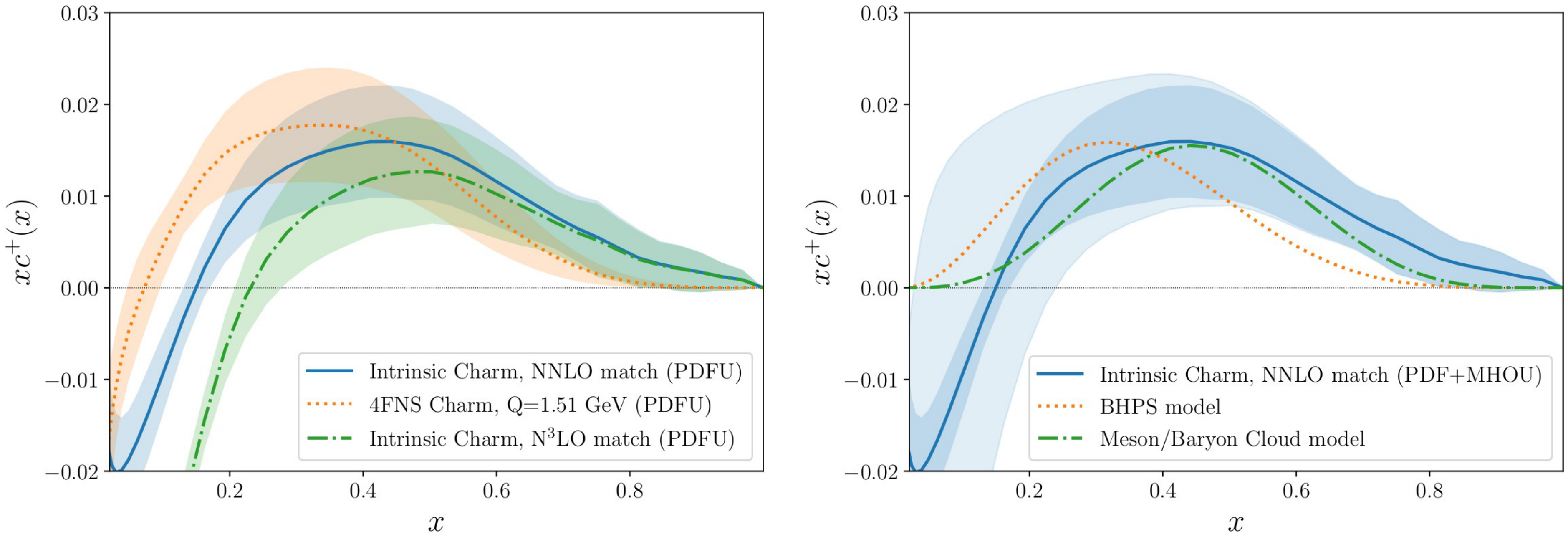
- a similar *convolution* procedure may be used for $\bar{c}(x)$ . . .



NNPDF IC PDFs and moments

NNPDF, Nature 608 (2022) 7923, 483.

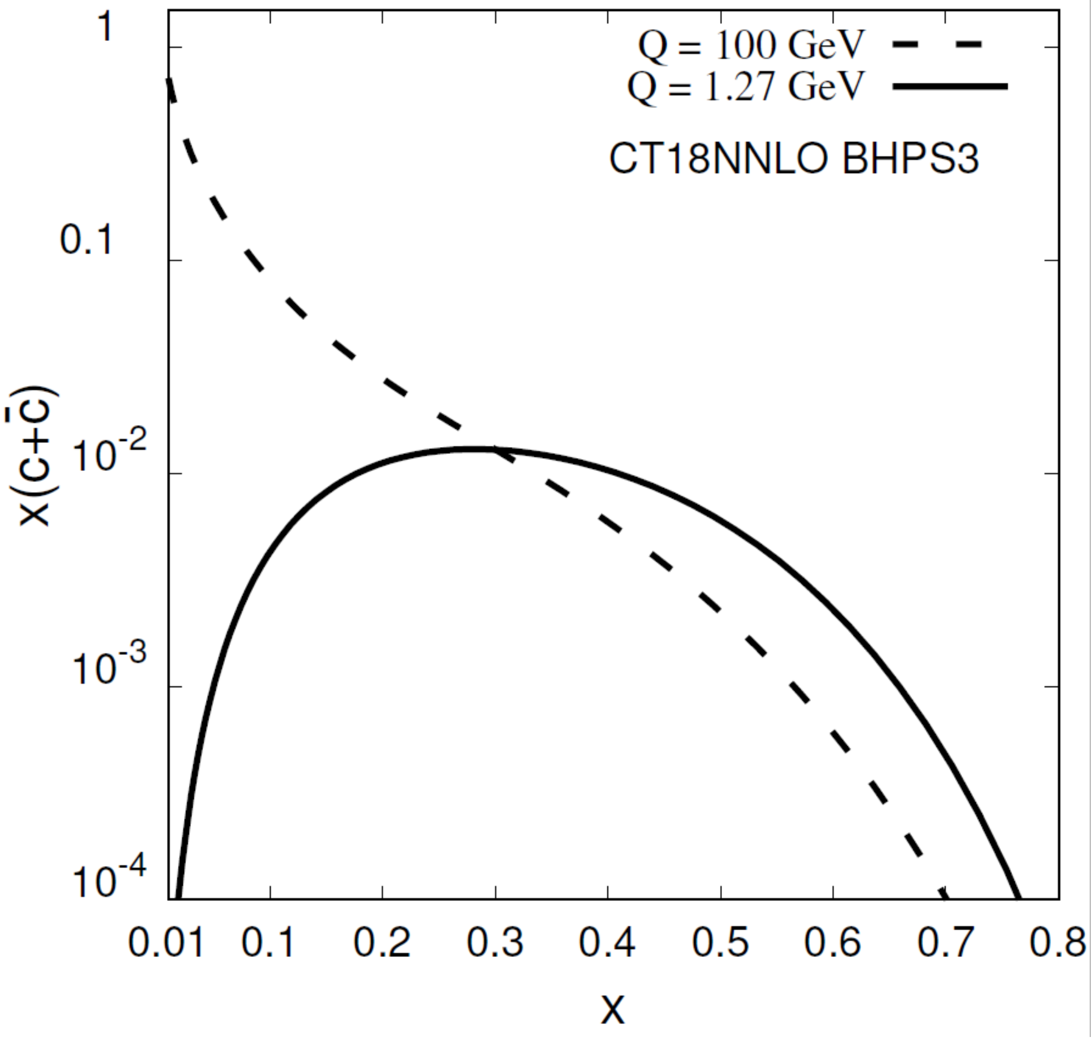
- large perturbative instability from MHOU in DGLAP affects low-x behavior
  - → matching at fixed NNLO gives negative FC, unlike IC models



→ 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: $\langle x \rangle_{\mathrm{FC}} = 0.62 \pm 0.61\%$

Backward DGLAP evolution is approximate



Data constrain the PDFs at $Q > 2$ GeV.

When PDFs are evolved at N2LO down to $Q \approx 1.3$ GeV, the charm PDF is increased at $x \gtrsim 0.3$ and decreased at $x \lesssim 0.3$.

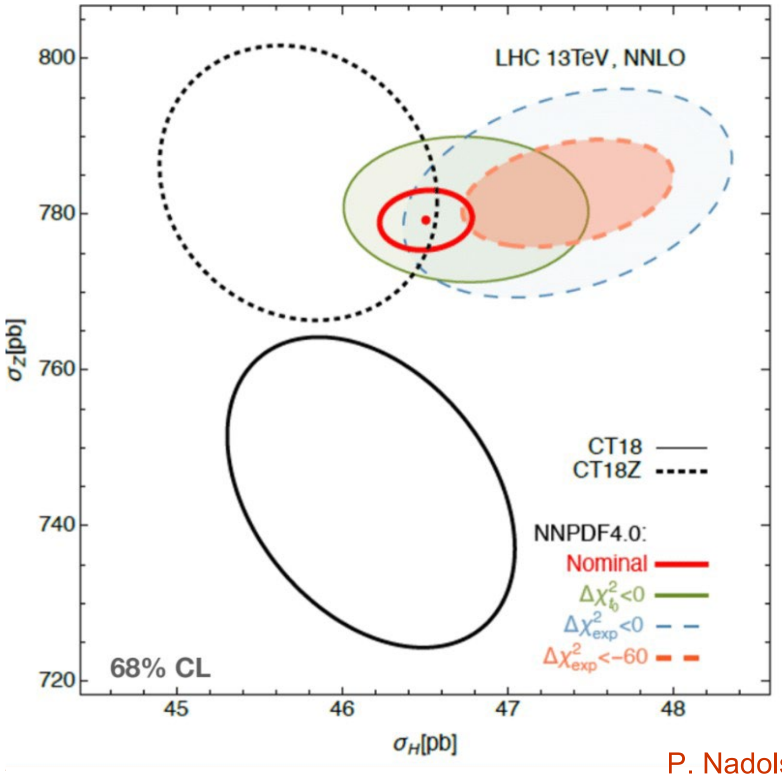
MHOU in DGLAP evolution can produce the bump-like shape.

more representative sampling can enlarge MC uncertainties

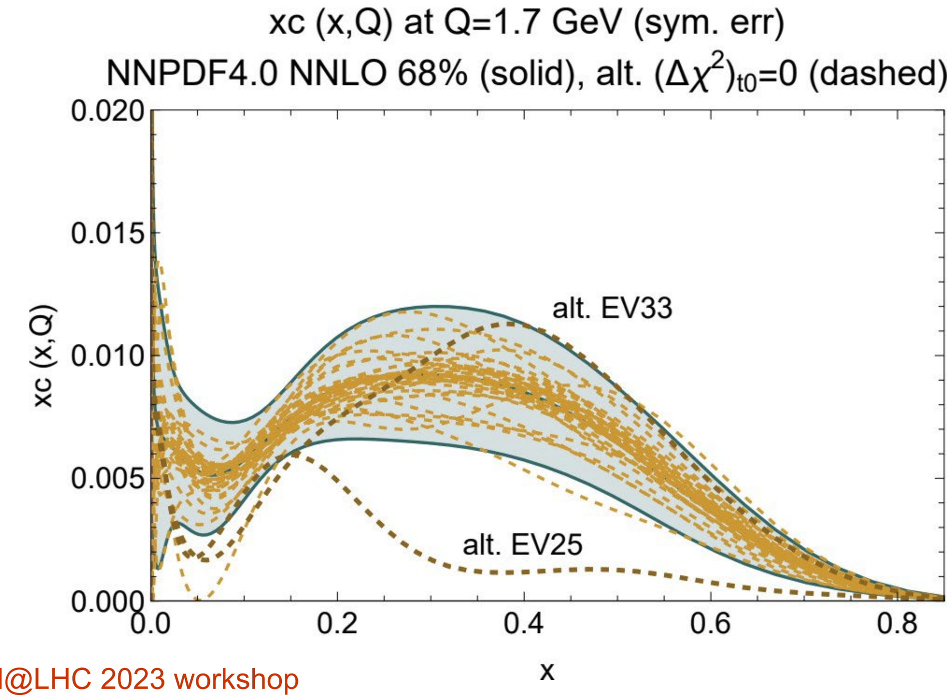
Courtoy *et al.*, arXiv: 2205.10444.

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

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



- substantially broadens high-x FC error

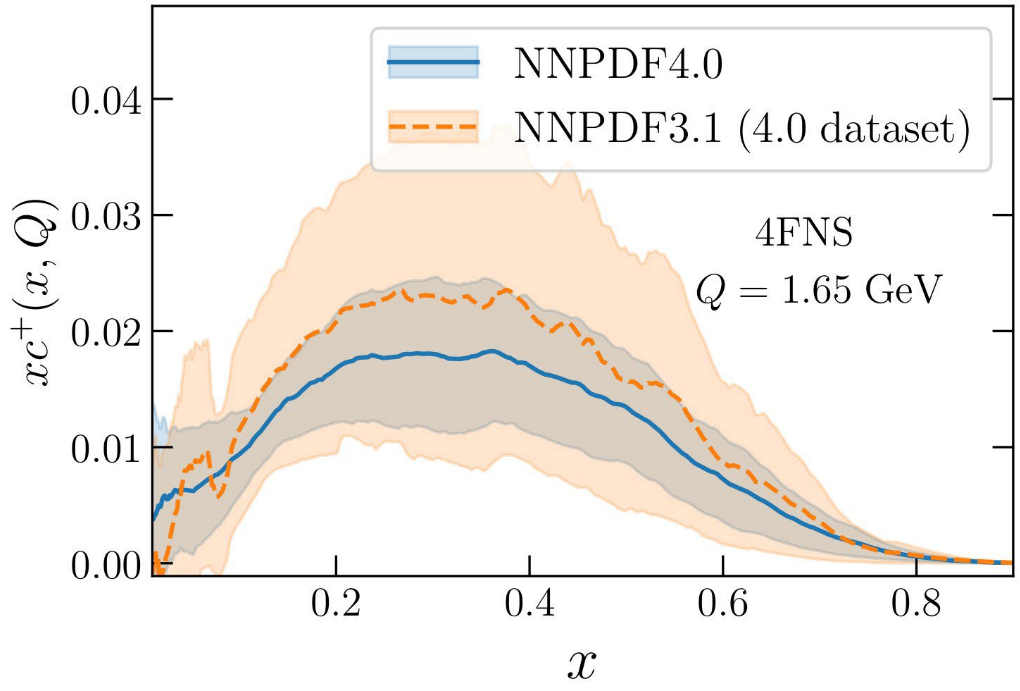


more representative sampling can enlarge MC uncertainties

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



both curves based on same underlying data