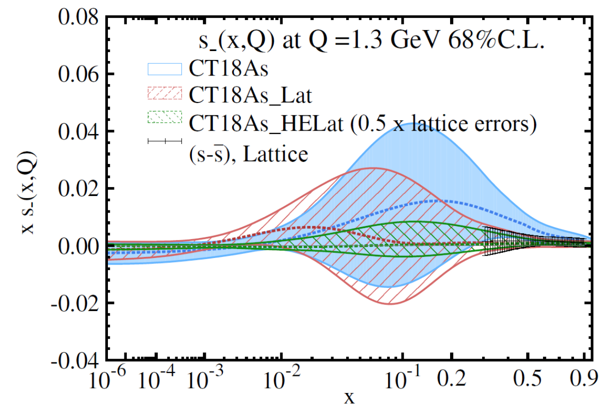
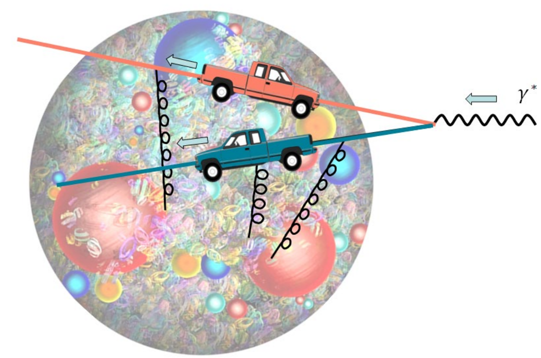
Update from CTEQ-TEA



Pavel Nadolsky

Southern Methodist University, USA

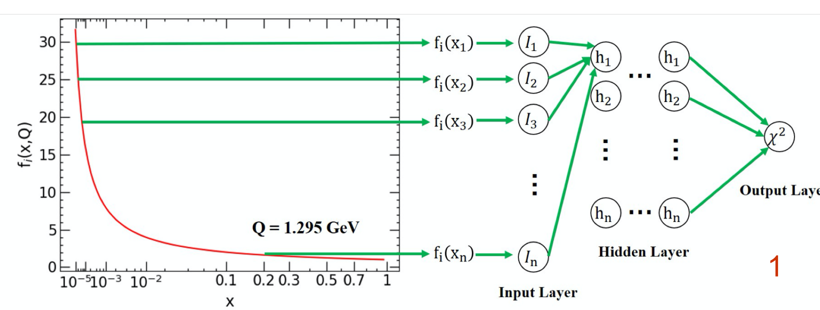
With CTEQ-TEA (Tung Et. Al.) working group



China: A. Ablat, S. Dulat, J. Gao, T.-J. Hou, I. Sitiwaldi, and M. Yan

Mexico: A. Courtoy

USA: T.J. Hobbs, M. Guzzi, X. Jing, J. Huston, H.-W. Lin, C. Schmidt, K. Xie, C.-P. Yuan



2022-11-23

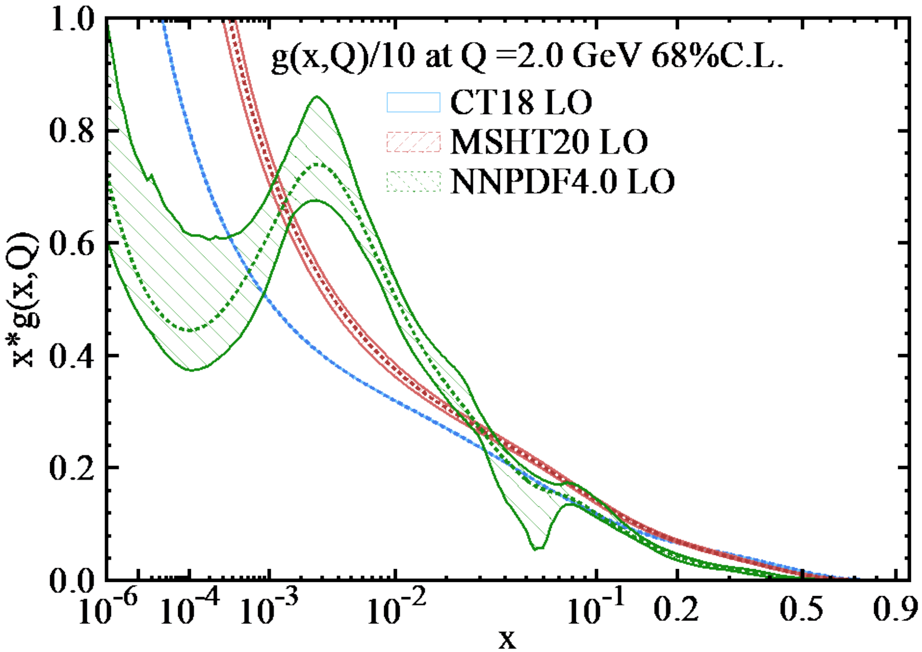
CTEQ-TEA recent results

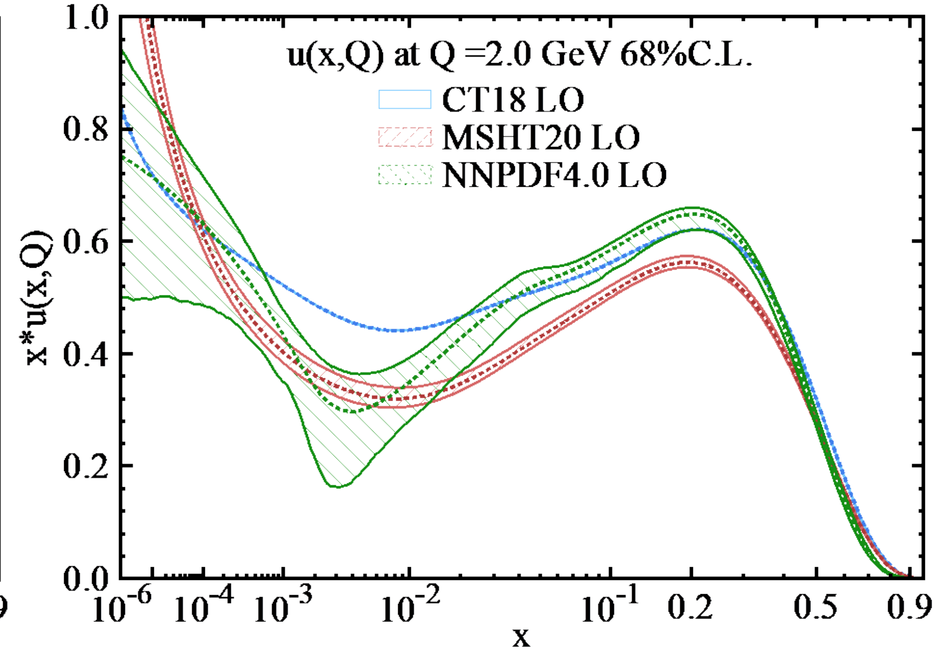
1. **Finished**
   - ☑ CT18 LO: LO analysis for Monte Carlo event generators
   - ☑ CT18 CS: Two-component sea (anti)quark PDFs with lattice inputs
   - ☑ CT18 As: Strangeness asymmetry and PDFs with lattice inputs
   - ☑ CT18 FC: NNLO constraints on fitted/intrinisic charm
   - ☑ CT18 & SMEFT: Machine learning and SMEFT in CT18 framework
   - The sampling paradigm to understand PDF tolerance ⇒ A. Courtoy's talk
   - CT18qed: Including photon as a parton of the proton
   - The NNLO CC DIS calculation in SACOT-MPS scheme
   - Large-x PDFs
   - Deuteron and nuclear corrections
   - SeaQuest (E906) and STAR constraints on sea quarks

   } reported at other meetings
2. **Ongoing:**
   - ☑ Impact of the LHC $t\bar{t}$ production
   - ☑ Impact of the LHC Drell-Yan production
   - PDFs at small x: Forward charm and bottom production; FPF

CT18 LO parton distributions
M. Yan et al., arXiv:2205.00137

Complement CT18 NNLO and NLO PDFs





❊ From the CT18 data set, exclude

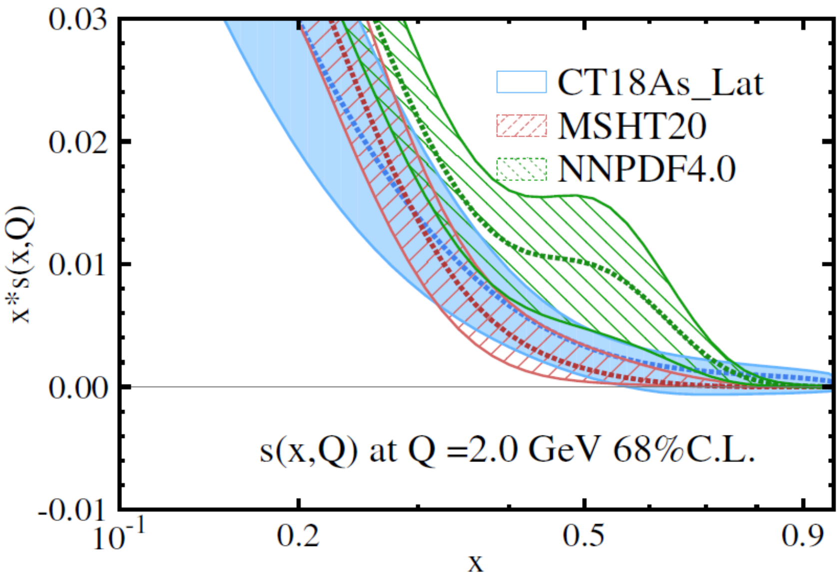
- H1 F_L structure function
- H1 bottom reduced cross section
- Combined HERA charm production
- ATLAS 8TeV Z boson p_T^{ll} distribution
- ATLAS 7TeV W/Z rap. distributions, and $A_{\rm ch.}$ with $\int dt\, \mathcal{L} = 35\ \mathrm{pb}^{-1}$

❊ Apply a K-factor to Drell-Yan data

$$K(Q) = 1 + \frac{\alpha_s(Q)}{\pi}\frac{C_F \pi^2}{2}$$

❊ We do not provide error sets for CT18 LO because of its very large theoretical uncertainties.

CT18As_Lat NNLO: Strangeness asymmetry with a lattice QCD constraint

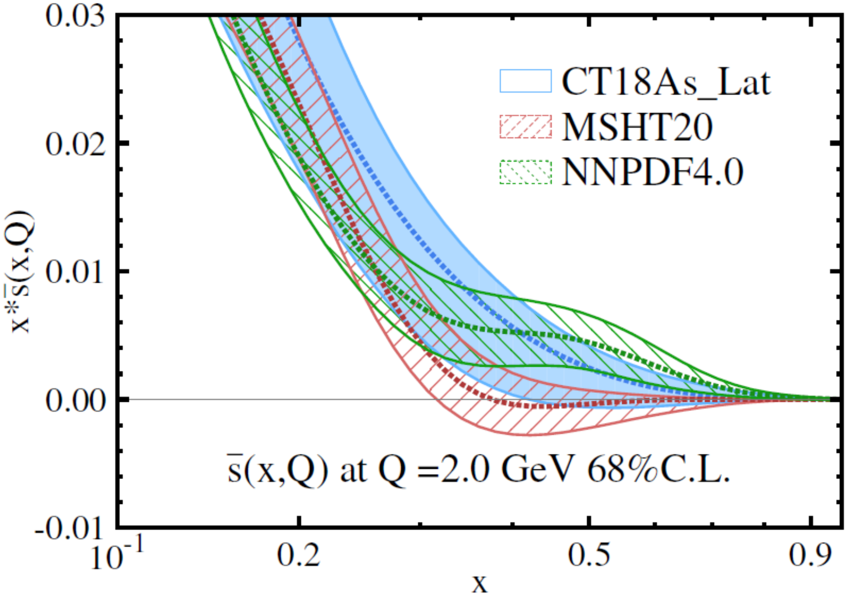


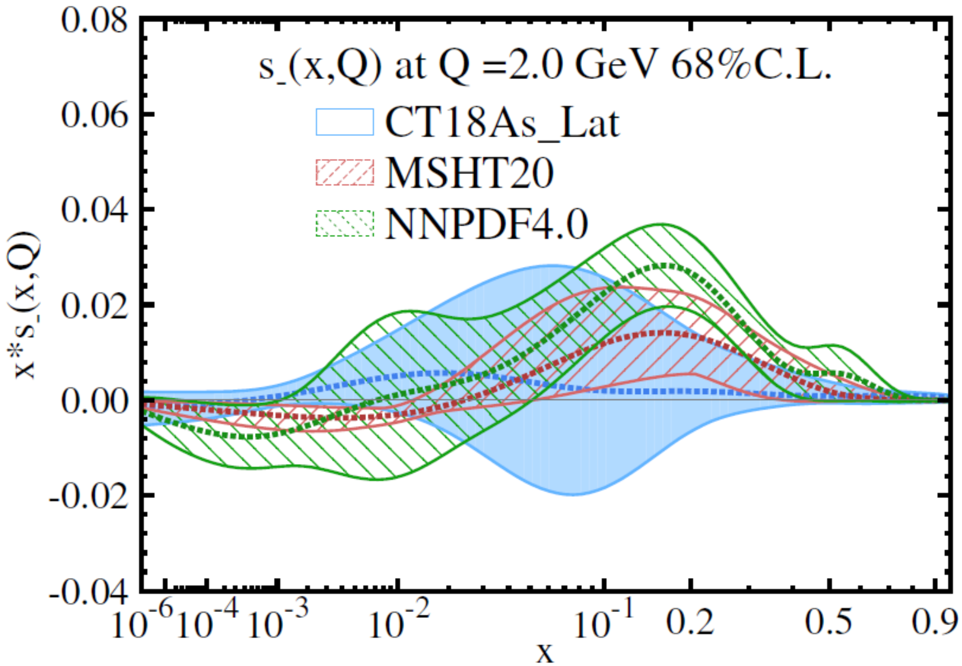
T.-J. Hou et al., arXiv: 2211.11064

CT18As: CT18A with $s_- \equiv s - \bar{s} \neq 0$

CT18As_Lat: CT18As with a lattice constraint on $s_-(x)$ at $0.3 \leq x \leq 0.8$.

$$\int_0^1 s_-(x)dx = 0$$

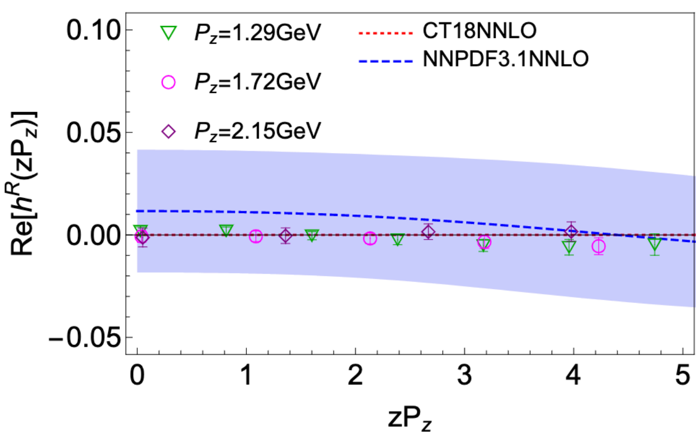


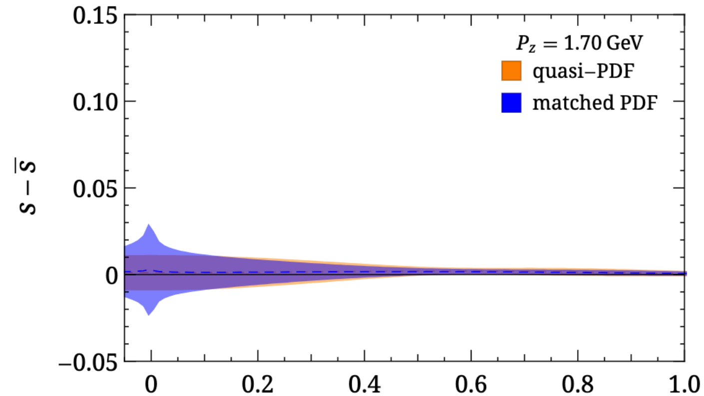


CT18As_Lat NNLO

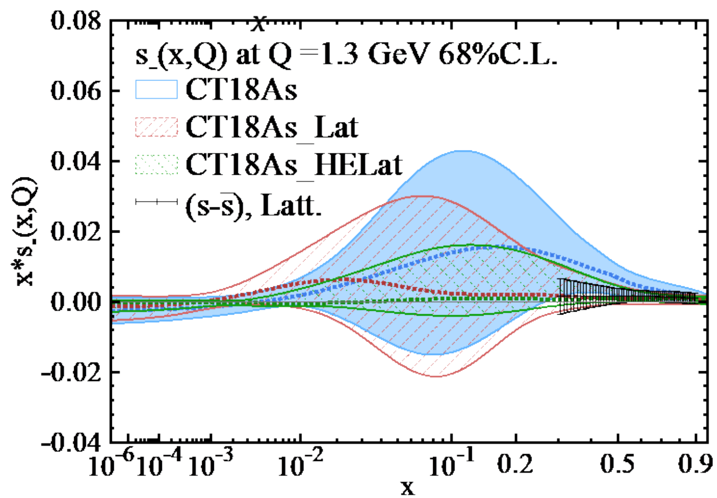
T.-J. Hou et al., arXiv: 2211. 11064

Include lattice data on s_{-} obtained by the MSULat/quasi-PDF method (Lin et al, 2005.12015)





- The lattice prediction disfavors a large $s_{-}(x,Q)$ at $x > 0.3$
- **CT18As_HELat:** PDFs if the lattice errors are reduced by 1/2



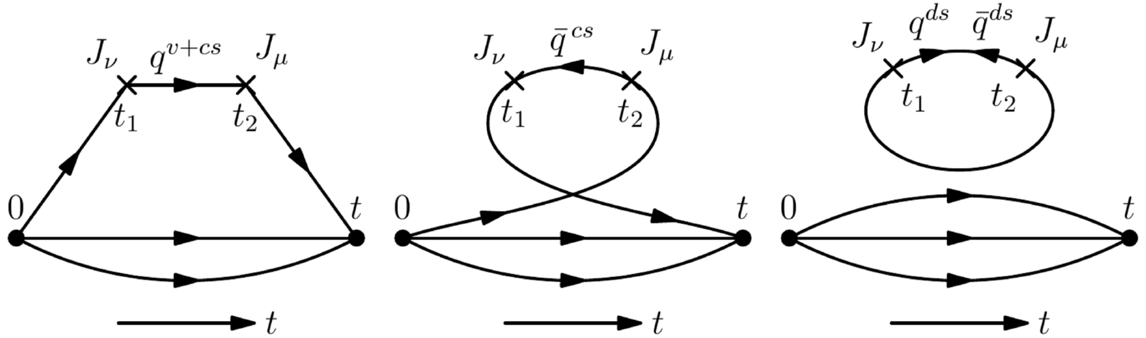
$Q = 2.0$ GeV	CT18A	CT18As	CT18As_Lat	LQCD
				0.052(12) [50]
$\langle x \rangle_{s_+}$	0.043(10)	0.052(17)	0.048(16)	0.051(26)(5) [51]

CT18CS: two-component sea (anti)quark PDFs

T.-J. Hou et al., PRD 106 (2022)

In lattice QCD:

$\bar{u}$ and $\bar{d}$ PDFs consist of connected (cs) and disconnected (ds) components.
$\int dx\ \left(\bar{d}(x) - \bar{u}(x)\right) \neq 0$ can be generated from connected 4-point configurations in Euclidean path-integral formalism (K. F. Liu et al., PRD 62 (2000)).



In CT18CS, sea quark is parametrized with both CS and DS components at $Q = 1.3$GeV:

- $u = u_v + \bar{u},\ \bar{u} = u^{cs} + q^{ds}$
- $d = d_v + \bar{d},\ \bar{d} = d^{cs} + q^{ds}$
- $s = \bar{s} = s^{ds} = q^{ds}/R$
- a constraint from lattice

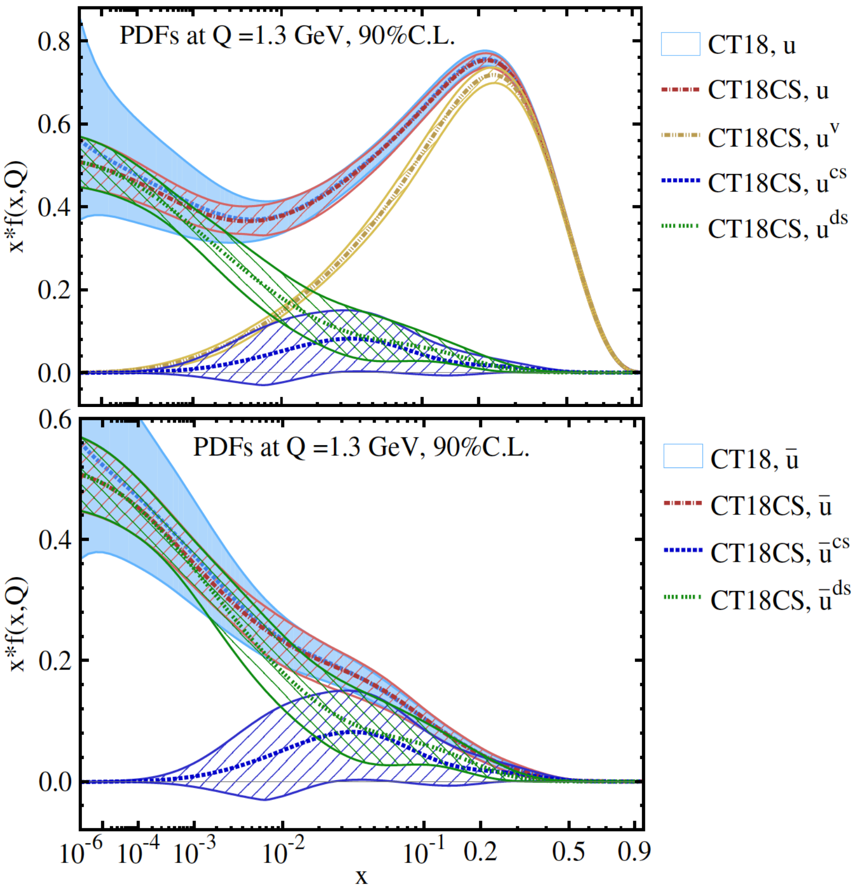
$$\frac{1}{R} = \frac{\langle x \rangle_{s+\bar{s}}}{\langle x \rangle_{\bar{u}+\bar{d}}(DI)} = 0.822(69)(78)$$

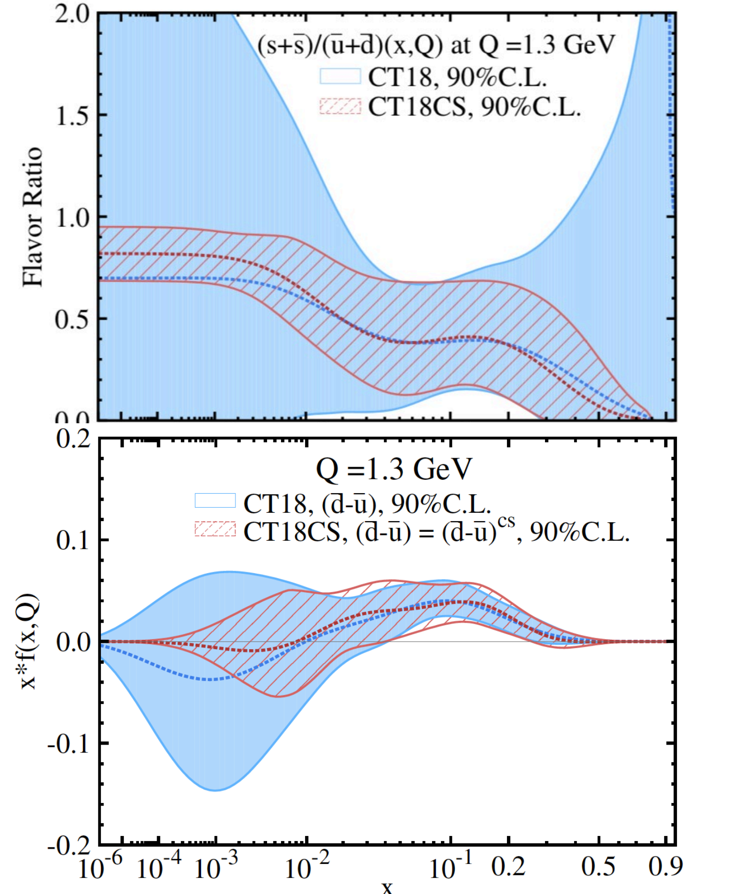
(K. F. Liu et al., PRD 102 (2020)).

- $x \to 0$:
  $q^{ds} \propto x^{-1}; u^{cs}, d^{cs} \to u_v, d_v;$
  $\bar{d}/\bar{u} \to 1$;
- $x \to 1$:
  $d/u \to d/u$ of CT18
  $\bar{d}/\bar{u} \to \bar{d}/\bar{u}$ of CT18

CT18CS: two-component sea (anti)quark PDFs

T.-J. Hou et al., PRD 106 (2022)





The CT18CS PDF provide direct comparison between lattice calculations and global analysis for each partonic degree of freedom.

PDF	$<x>_{u^v}$	$<x>_{d^v}$	$<x>_g$	$<x>_{\bar{u}}$	$<x>_{\bar{d}}$	$<x>_s$
CT18	0.325(5)	0.134(4)	0.385(10)	0.0284(22)	0.0361(27)	0.0134(52)
CT18CS	0.323(4)	0.136(3)	0.384(12)	0.0287(25)	0.0364(34)	0.0137(39)

PDF	$<x>_{u^{v+cs}}$	$<x>_{d^{v+cs}}$	$<x>^*_{\bar{u}^{cs}}$	$<x>^*_{\bar{d}^{cs}}$	$<x>^\dagger_{u^{ds}}$
CT18CS	0.335(7)	0.155(8)	0.0120(64)	0.0197(70)	0.0167(49)

CTEQ-TEQ global analysis of SMEFT

[J. Gao, MS Gao, T. Hobbs, DY Liu, XM Shen, 2211.01094]

- In search for **new physics** at hadron colliders, one key problem is on the **degeneracy** of PDF variations and the new physics contributions.

  ↓ Described in the framework of **SMEFT**

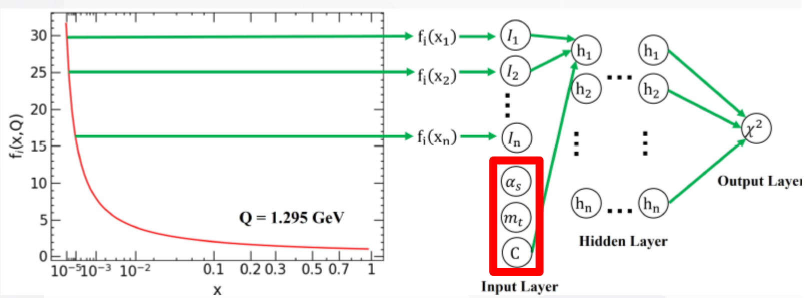
  ↓ **Joint fits** of both PDFs and BSM parameters

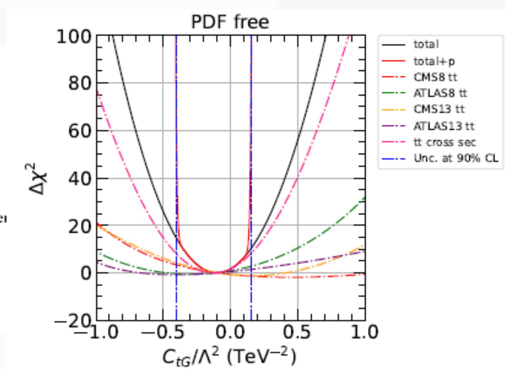
- We focus on several operators relevant for **top-quark pair (O^1_{tu}, O^1_{td}, O_{tG}, O^8_{tq})** and **jet production (O_1)** at hadron colliders.

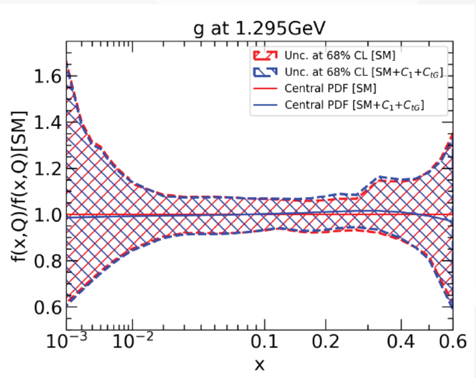
$$O^1_{tu} = \sum_{i=1}^{2} (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i), \quad O^1_{td} = \sum_{i=1}^{3} (\bar{t}^\mu t)(\bar{d}_i\gamma_\mu d_i), \quad O_1 = 2\pi(\Sigma_{i=1}^{3}\bar{q}_{Li}\gamma_\mu q_{Li})(\Sigma_{j=1}^{3}\bar{q}_{Lj}\gamma^\mu q_{Lj})$$

$$O_{tG} = ig_s(\bar{Q}_{L,3}\tau^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} + \text{h.c.}, \quad O^8_{tq} = \sum_{i=1}^{2} (\bar{Q}_i\gamma_\mu T^A Q_i)(\bar{t}\gamma^\mu T^A t)$$

- We obtain self-consistent constraints on SMEFT with **Lagrange Multiplier** scans based on the **Neural Network** approach.







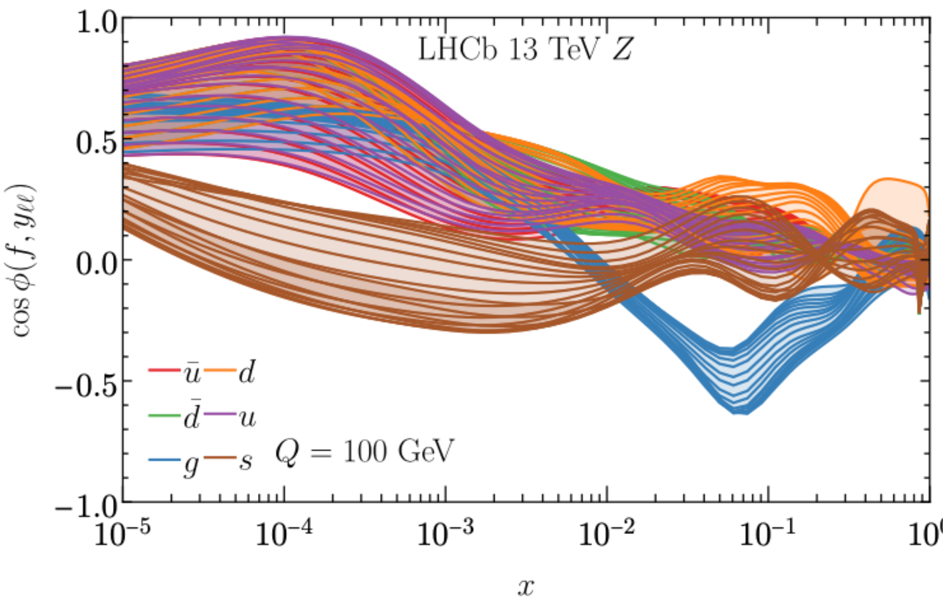
- We find mild correlations between the extracted Wilson coefficients, PDFs, and other QCD parameters.

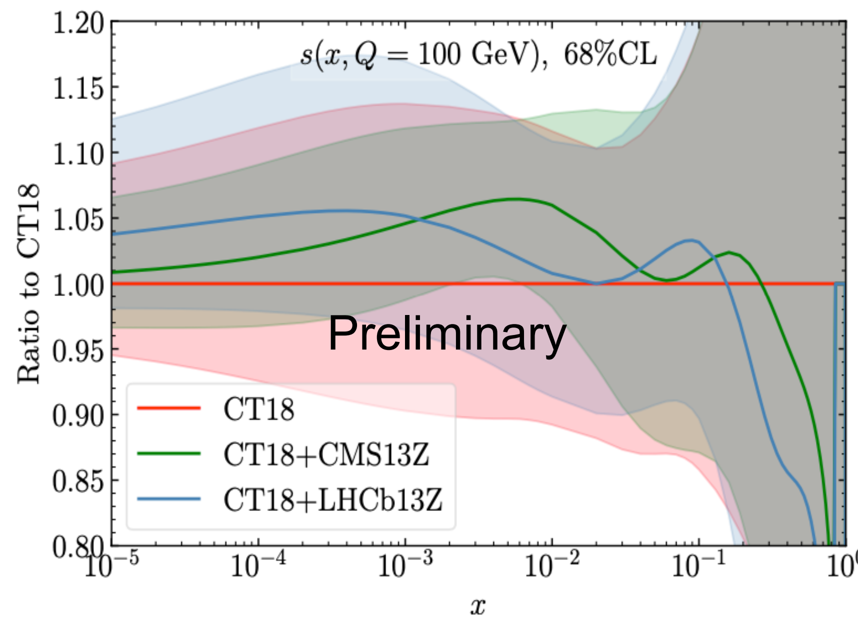
Impact of New LHC Drell-Yan data on CT18 PDFs

ID	Expt.	N_{pt}	χ^2	χ^2/N_{pt}	S_E
	CT14HERA2 data				
201	E605DY	119	103.4(102.4)	0.9(0.9)	-1.0(-1.1)
203	E866 $\sigma_{pd}/(2\sigma_{pp})$	15	16.1(17.9)	1.1(1.2)	0.3(0.6)
204	E866 $Q^3 d^2\sigma_{pp}/(dQdx_F)$	184	244(240)	1.3(1.3)	2.9(2.7)
225	CDF1Z $A(e)$	11	9.0(9.3)	0.8(0.8)	-0.3(-0.2)
227	CDF2W $A(e)$	11	13.5(13.4)	1.2(1.2)	0.6(0.6)
234	DØ2W $A(\mu)$	9	9.1(9.0)	1.0(1.0)	0.2(0.1)
260	DØ2Z $y_{\ell\ell}$	28	16.9(18.7)	0.6(0.7)	-1.7(-1.3)
261	CDF2Z $y_{\ell\ell}$	29	48.7(61.1)	1.7(2.1)	2.2(3.3)
266	CMS7W $A(\mu)$	11	7.9(12.2)	0.7(1.1)	-0.6(0.4)
267	CSM7W $A(e)$	11	4.6(5.5)	0.4(0.5)	-1.6(-1.3)
268	ATL7WZ$_{(2012)}$	41	44.4(50.6)	1.1(1.2)	0.4(1.1)
281	DØ2W $A(e)$	13	22.8(20.5)	1.8(1.6)	1.7(1.4)
	New LHC data				
245	LHCb7WZ(μ)	33	53.8(39.9)	1.6(1.2)	2.2(0.9)
246	LHCb8Z(e)	17	17.7(18.0)	1.0(1.1)	0.2(0.3)
248	ATL7WZ$_{(2016)}$	34	287.3(88.7)	8.4(2.6)	13.7(4.8)
249	CMS8W $A(\mu)$	11	11.4(12.1)	1.0(1.1)	0.2(0.4)
250	LHCb8WZ(μ)	34	73.7(59.4)	2.1(1.7)	3.7(2.6)
253	ATL8ZpT	27	30.2(28.3)	1.1(1.0)	0.5(0.3)

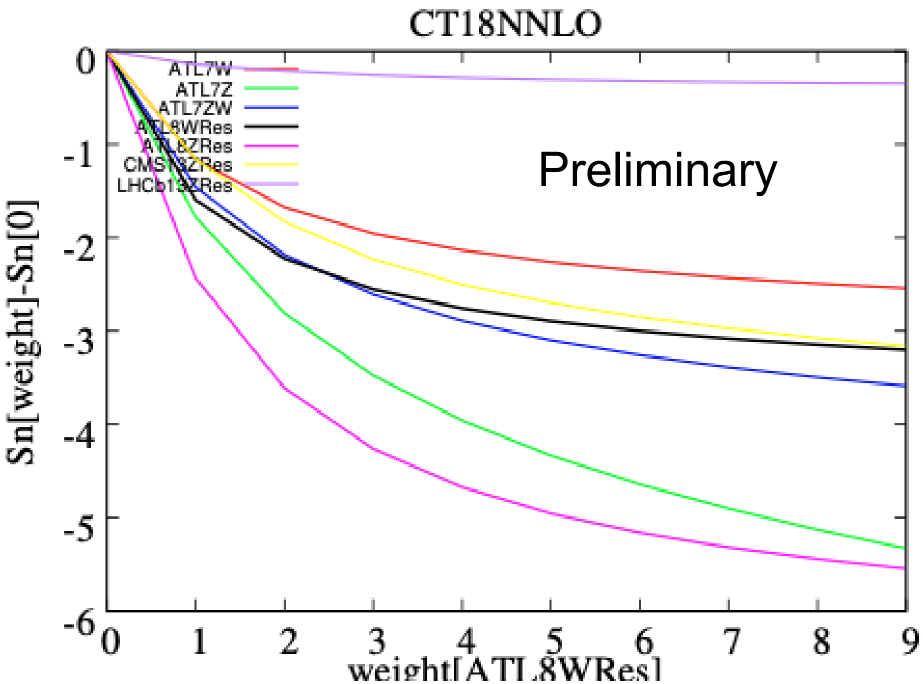
- Drell-Yan data play the essential role at constraining (anti)quark sea
- Most of the Drell-Yan data are fitted fairly
- LHCb can constrain the small-x region.
- The LHCb and CMS 13 TeV Z data are not fitted well

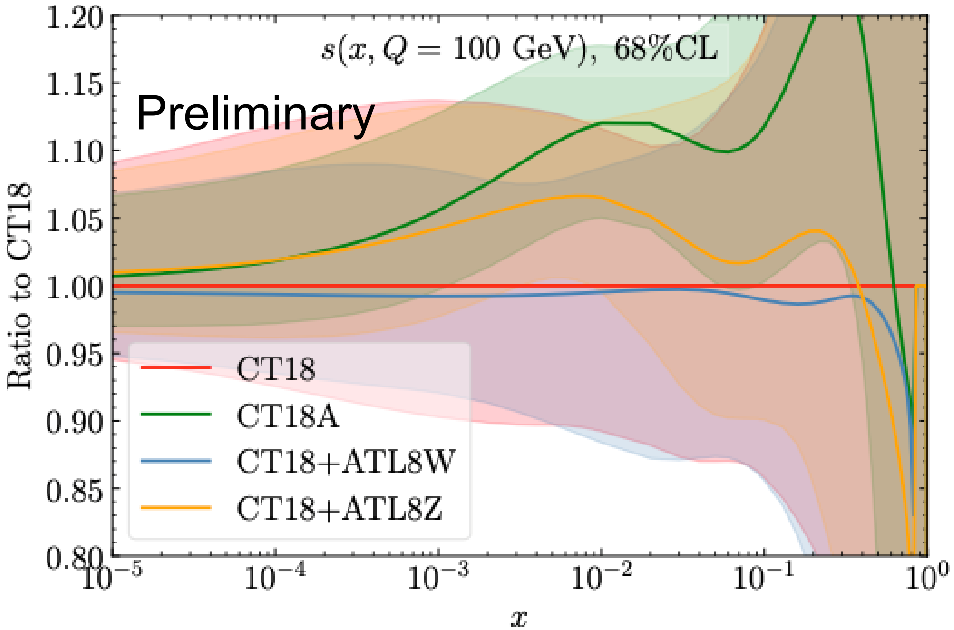
#ID	Experimental data set	N_{pt}	N_{corr}	χ^2/N_{pt}	R^2
211	ATL8W	22	45	2.78	16.7
212	CMS13Z	12	6	3.39	12.4
213	LHCb13Z	18	6	4.07	7.97
214	AL8Z3D	188	278	1.16	20.8





Consistency between the ATLAS 7/8 TeV W & Z data





Message from CT18/A fits

- ATLAS 7 TeV W/Z precision data are in tension with other data, especially HERA and NuTeV
- We provide alternative fits CT18A/Z to include ATLAS 7 TeV W/Z data

Post-CT18 data

- With the help from ATLAS group, we can fit ATLAS 8 Z data well
- ATLAS 8 TeV W (Z) data are consistent with 7 TeV W (Z) data
- Z data have strong impact on the strangeness, are consistent with ATLAS 7 TeV Z data

Impact of LHC 13 TeV $t\bar{t}$ production on CT18 PDFs

Extensive analysis in which the impact of 1D absolute distributions is explored

			ePump updated Chi2/Npt				Global fit Chi2/Npt	
Exp	Obs	Npt	HT	HT/2	HT/4		HT/2	HT/4
ATLAS hadronic channel 36.1 fb^-1	mtt	9	1.749	1.574	1.601		1.532026	1.4691
	HTtt	11	1.982	1.769	1.585		1.499361	1.74098
	ytt	12	1.279	1.15	0.938		1.051071	1.07351
	pTt1	10	1.301	1.185	1.118		1.196207	1.33326
	pTt2	8	1.132	0.843	1.047		0.84058	1.59056
CMS dilepton channel 35.9 fb^-1	mtt	7	3.457	3.068	3.142		3.121005	3.22675
	ytt	10	1.66	0.969	0.679		0.938607	0.67252
	pTt	6	3.598	3.701	3.679		3.558017	3.04841
	yt	10	1.334	0.944	0.867		1.002635	0.68848
ATLAS lepton + jet 36 fb^-1	mtt	7	2.395	1.165	0.681		0.826805	0.65684
	ytt	10	0.909	0.69	0.621		0.740418	0.74866
	pTt	6	2.337	2.012	2.469		1.353523	1.43062
	yt	10	1.298	1.073	1.095		1.161363	0.68198
CMS lepton + jet 137 fb^-1	mtt	15	1.485	1.383	1.808		1.203901	1.66676
	ytt	10	6.469	6.238	6.424		6.005668	5.87508

ATLAS all hadronic, JHEP 01 (2021) 033, arXiv:2006.09274
ATLAS lepton + jets, EPJC 79 (2019) 1028, arXiv:1908.07305
CMS dilepton, JHEP 1902 (2019) 149, arXiv:1811.06625
CMS lepton + jets, PRD 104 092013 (2021), arXiv:2108.02803

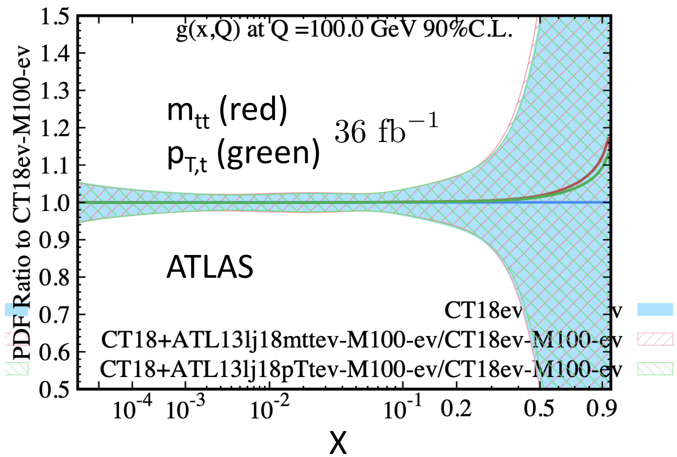
A. Ablat, S. Dulat, M. Guzzi, T.-J. Hou, I. Sitiwaldi, K. Xie, and C.-P. Yuan

Correlated Systematic Uncertainties: **ATLAS -> nuisance parameters**
CMS -> Covariance matrix representation (converted to nuisance param.)

Statistical correlations not provided → data added one at a time on top of the CT18 baseline

Impact of LHC 13 TeV $t\bar{t}$ production on CT18 PDFs

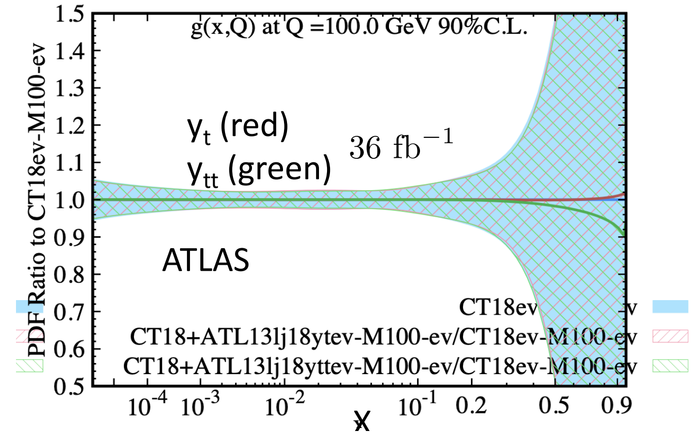
Global analysis: Impact on g(x,Q) from ATLAS and CMS lep+jets

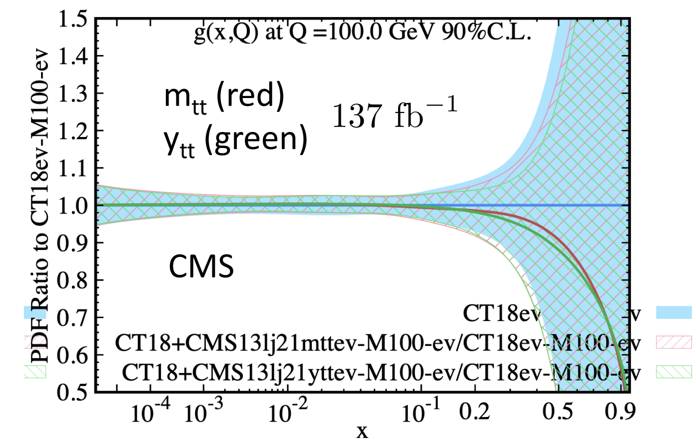


Theory predictions:

- MATRIX (Catani, Grazzini et al. PRD 2019)
- FastNNLO (Czakon, et al. 1704.08551)

Blue band: CT18NNLO 90%CL
Hatched band: CT18+new data





- m_{tt} , $p_{T,t}$,y_t , and y_{tt} 1D absolute distributions added one at a time in the global fit. Pulls not in the same direction for ATLAS.
- Stronger impact of CMS due to higher precision, but theory description not optimal for all distributions.
- Impact of different scale choices (HT/2 and HT/4) explored.
- Overall, 13 TeV data seem to prefer a softer gluon at large x.

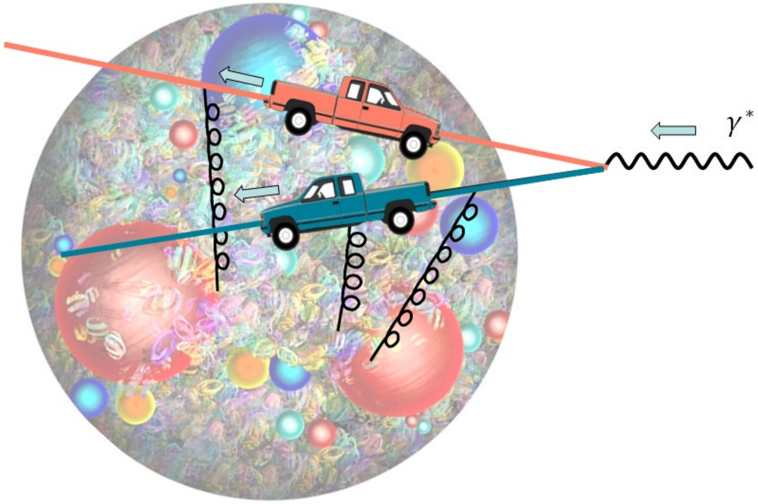
CT18FC

Proton's intrinsic charm remains concealed

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., arXiv:2211.01387; 10 pages: **new** CT18 FC analysis with the LHC Run-1 and 2 data

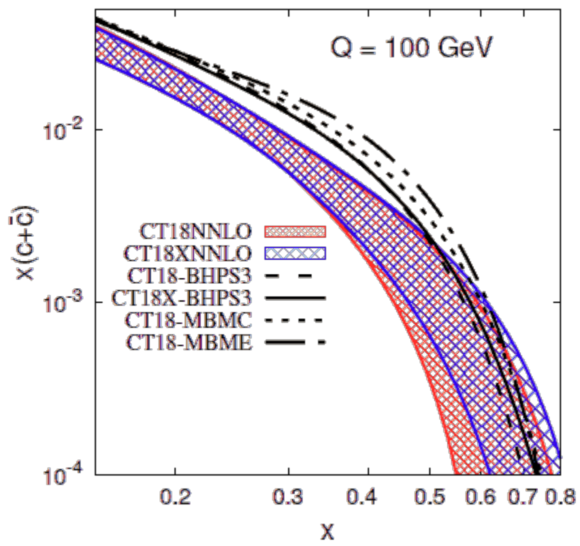
A recorded ILCAC seminar at
https://indico.knu.ac.kr/event/626/



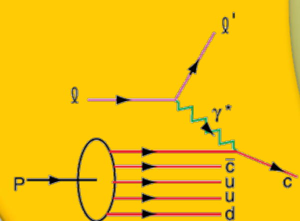
Do global PDF fits constrain intrinsic charm?

“Fitted charm” is a more direct term to describe the charm PDF found in the global QCD fit

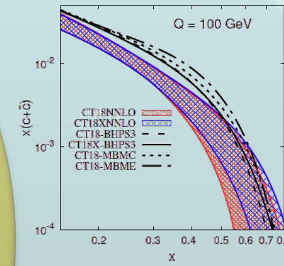
Analog: the fitted charm mass



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

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

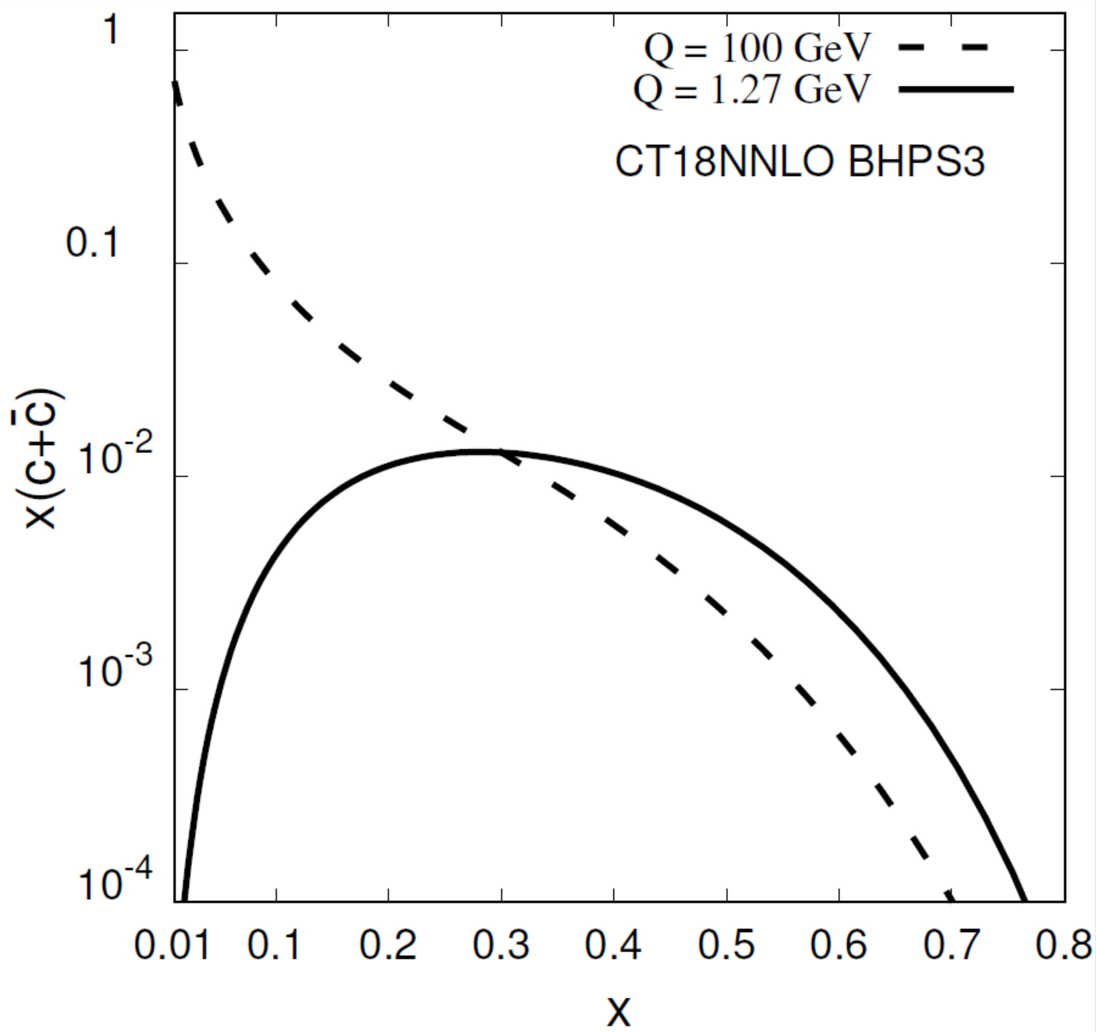
The PDF fits implement this formula up to (N)NLO ($N_{ord} = 1$ or 2):

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

Can DGLAP evolution mimic an FC?



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 $x \lesssim 0.3$.

Either a genuine IC or missing higher orders in DGLAP evolution can produce a bump-like shape of FC at $Q \sim m_c$.

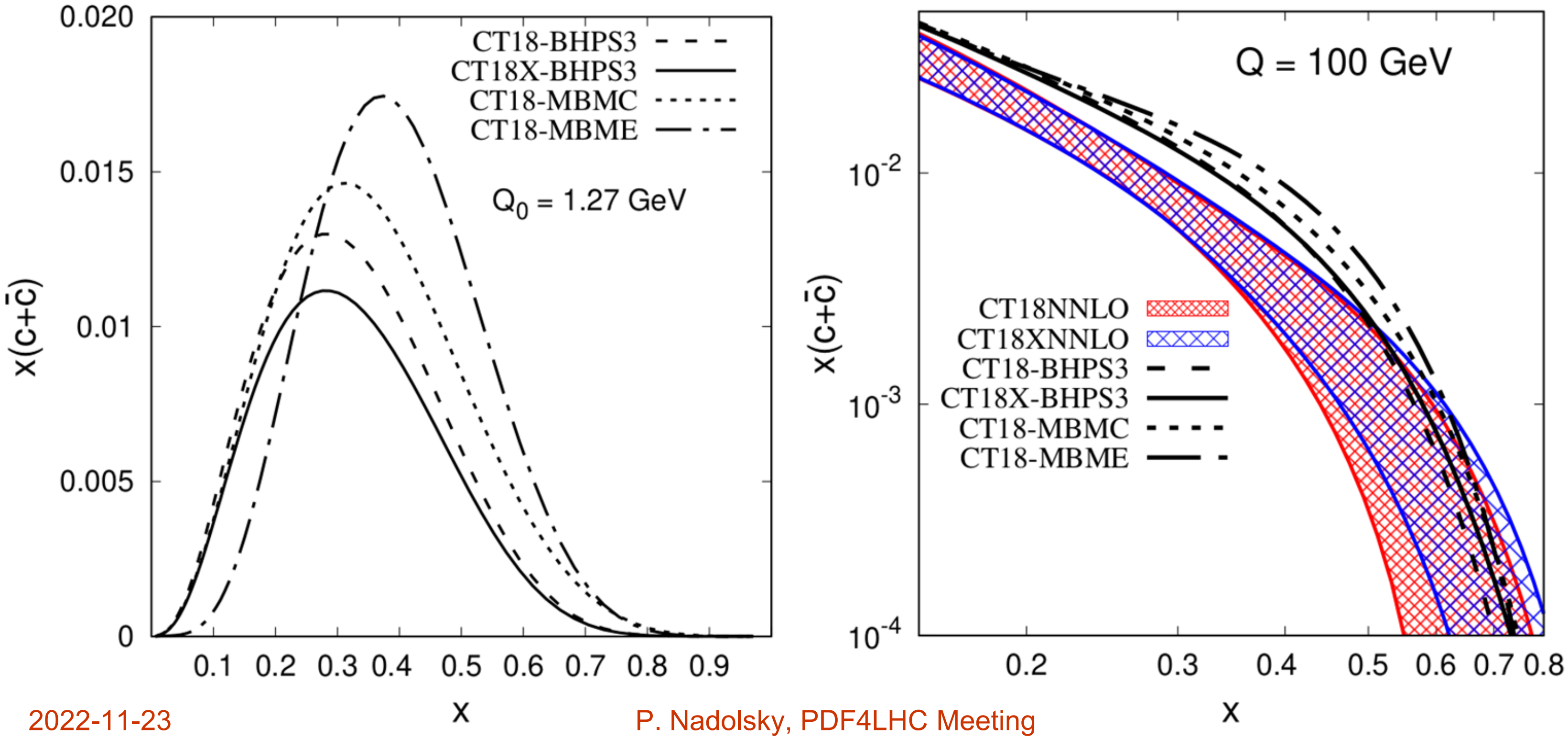
CT18 FC total charm PDFs

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

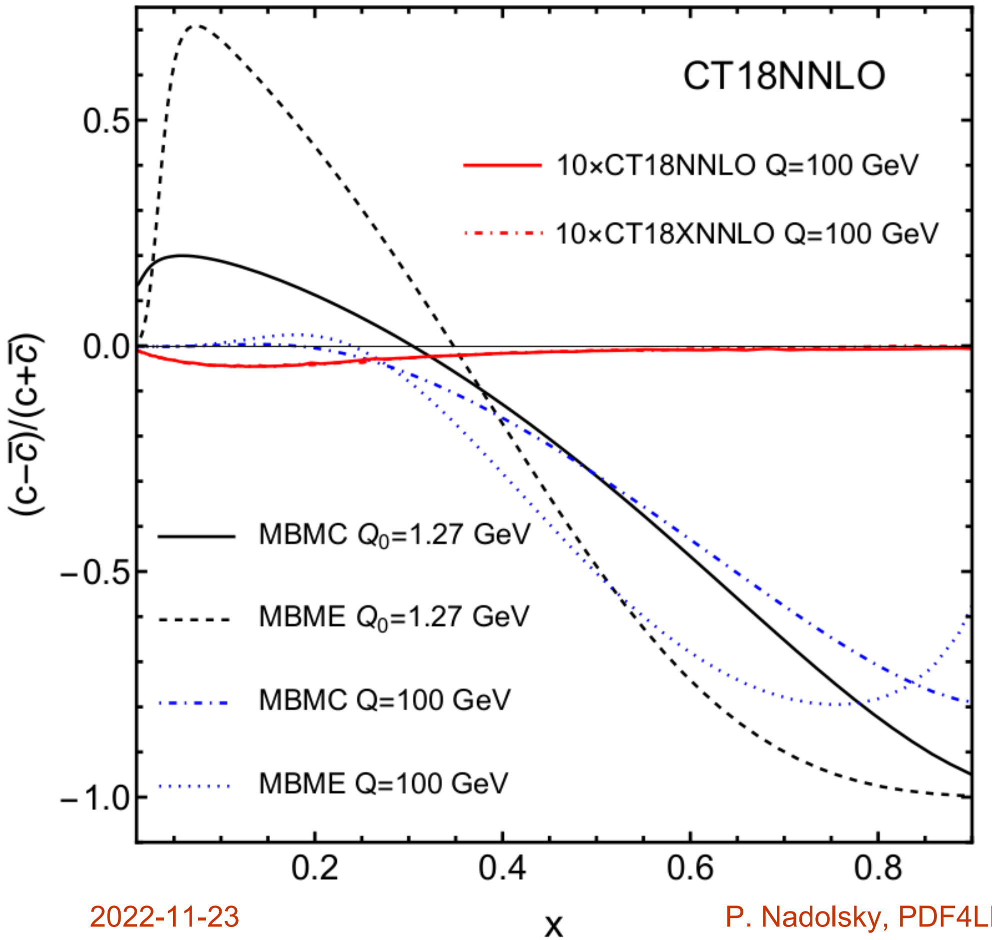


possible charm-anticharm asymmetries

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



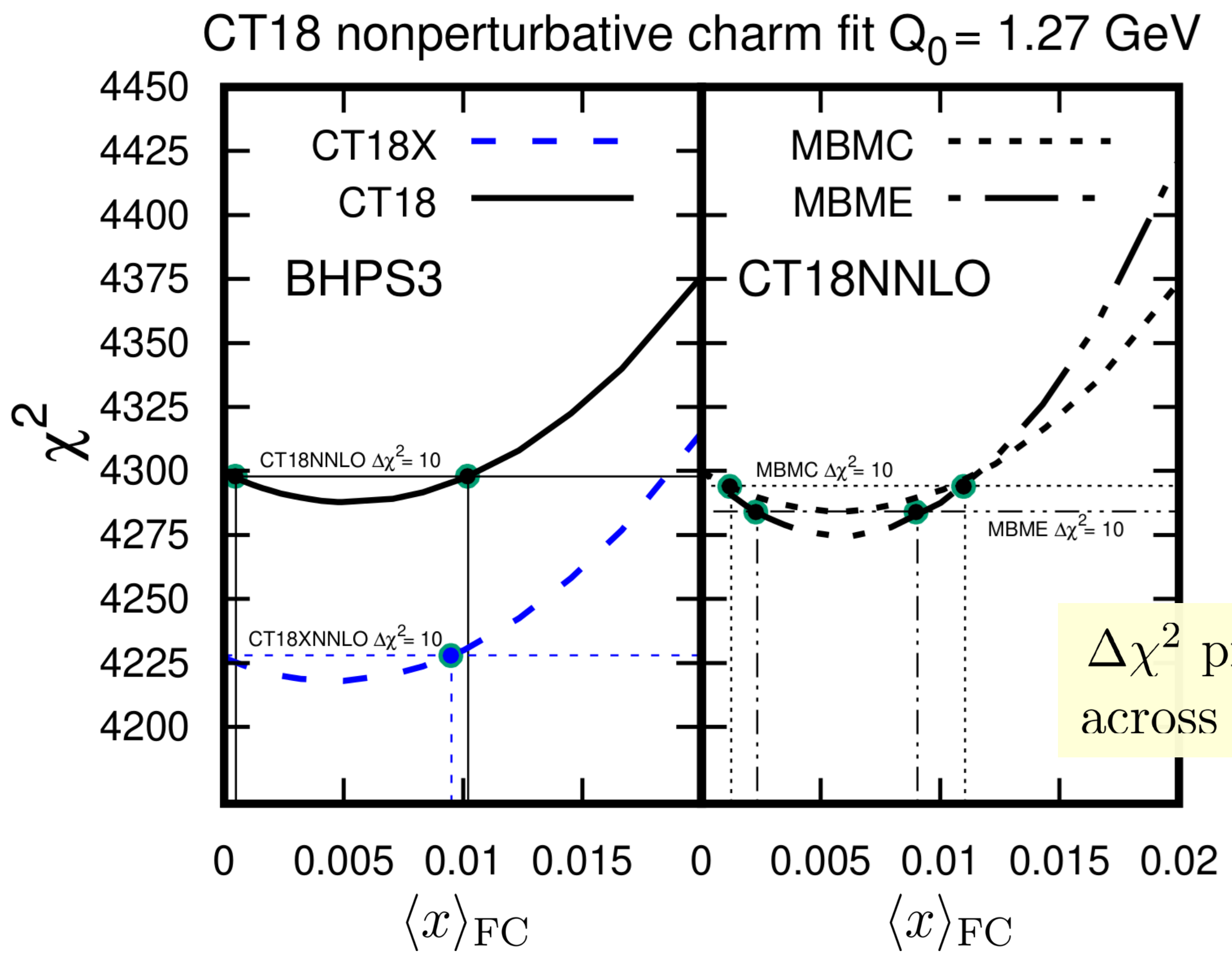
consider two MBM models as ***examples*** (<u>not predictions</u>)

→ asymptotically small, but ratio can be bigger; will be hard to extract from data

signal for FC in CT18 study, but with shallower $\Delta\chi^2$ 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. $\langle x \rangle_{\rm FC} \approx 0.8\text{–}1\%$ $(\Delta\chi^2 \gtrsim -40)$ CT14 IC



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

FC PDF moments

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

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

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

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

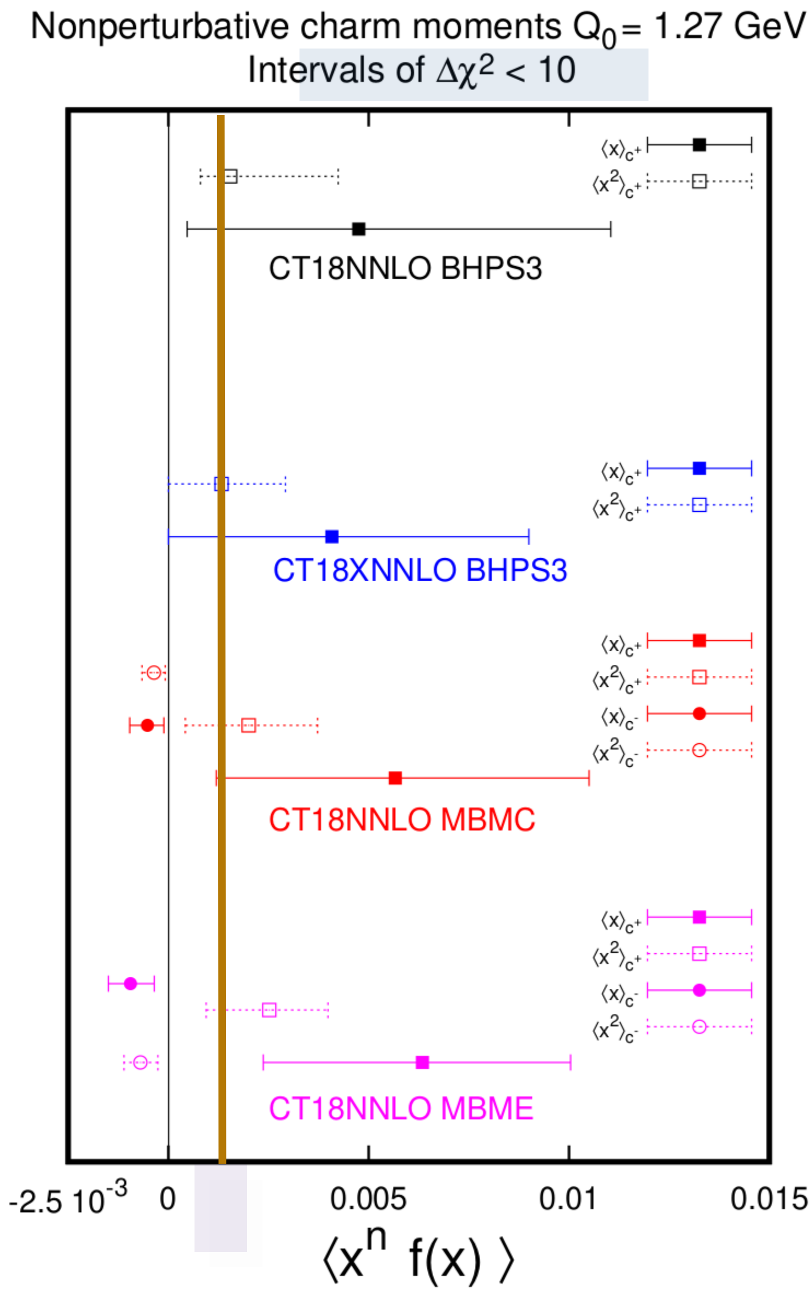
$$= 0.0041\,^{+0.0049}_{-0.0041}\,(^{+0.0091}_{-0.0041}),\ {\rm CT18X\ (BHPS3)}$$

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

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

$\Delta\chi^2 \leq 10$ (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 $\langle x \rangle_{c^+}$, $\langle x^2 \rangle_{c^-}$

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

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

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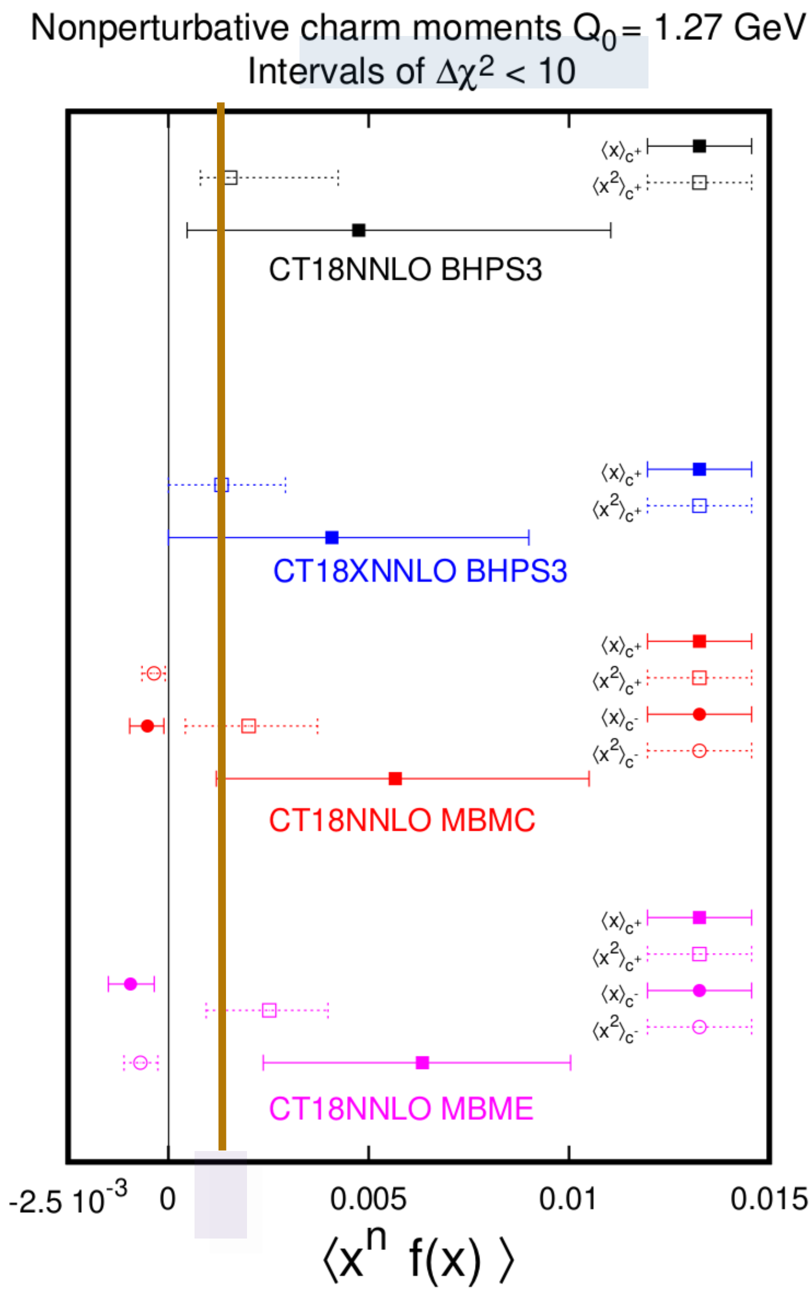
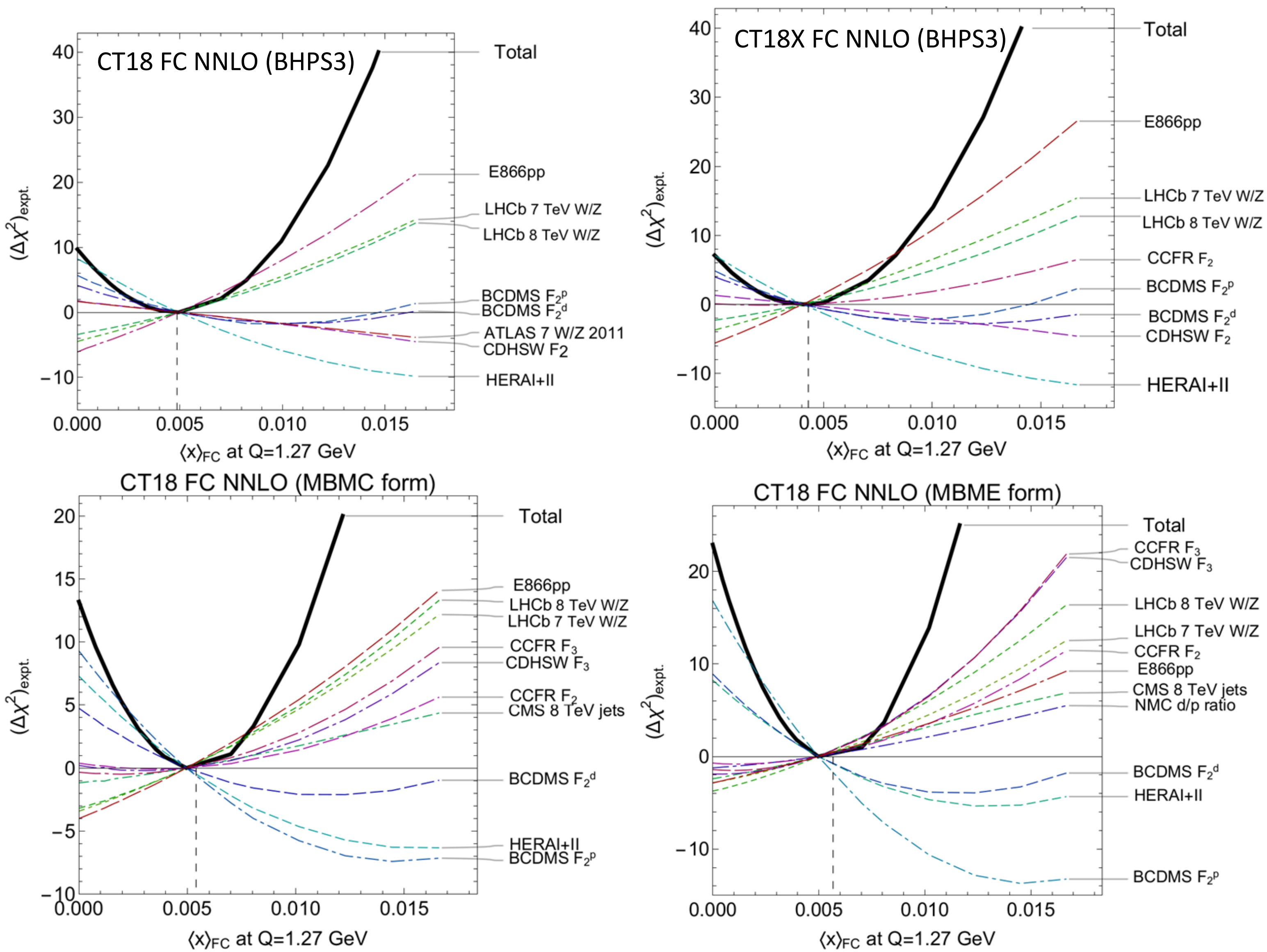


data pull opposingly on $\langle x \rangle_{\mathrm{FC}}$; depend on FC scenario, enhancing error

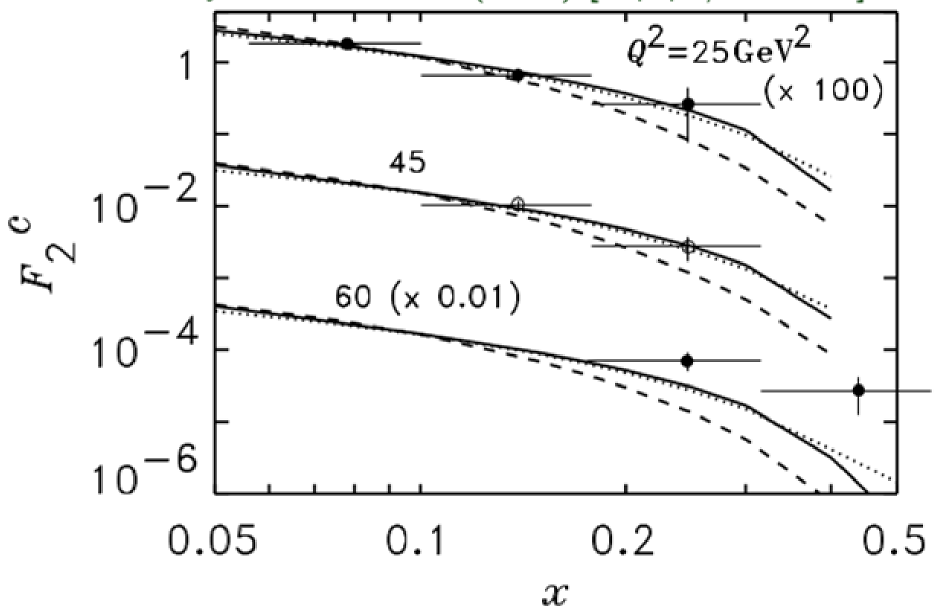


few expts with ‘smoking gun’ sensitivity to FC; but **EMC data** (?)

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

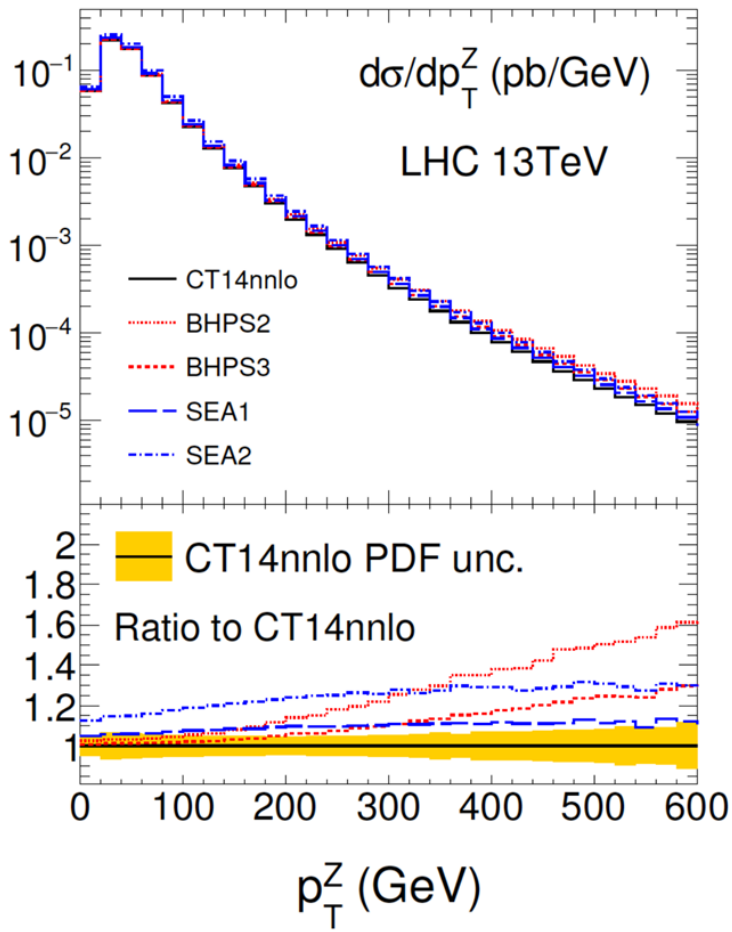
T. Boettcher, P. Ilten, M. Williams, 1512.06666; Bailas, Goncalves, 1512.06007

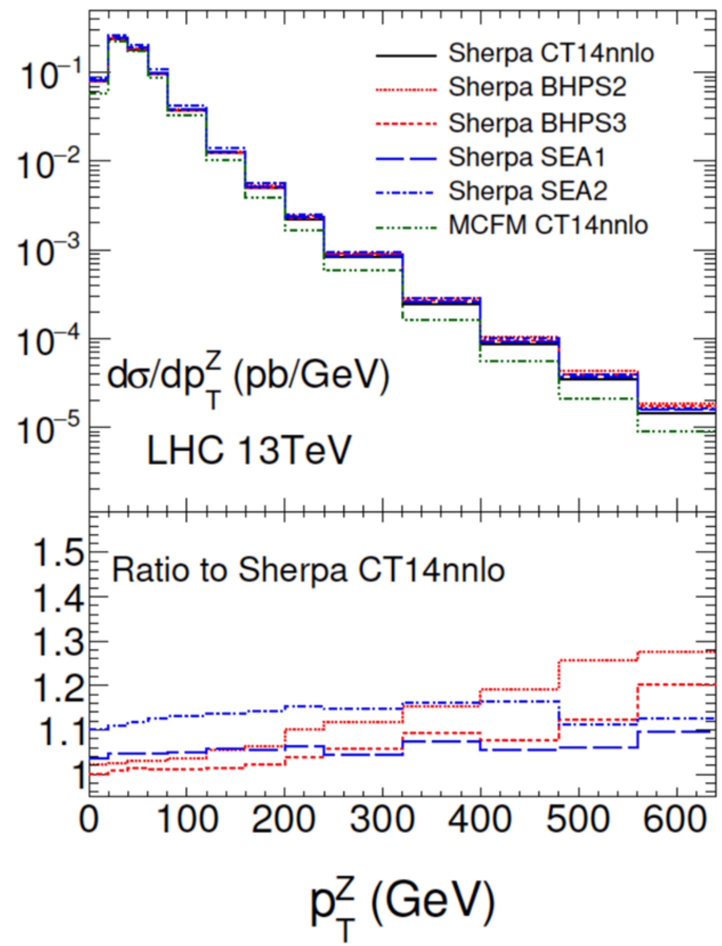
p_T spectra, rapidity dists nominally sensitive to high-*x* charm PDF

→ parton-shower effects can dampen high-p_T tails

Z+c NLO LHC 13 TeV

[Hou et al., arXiv:1707.00657]



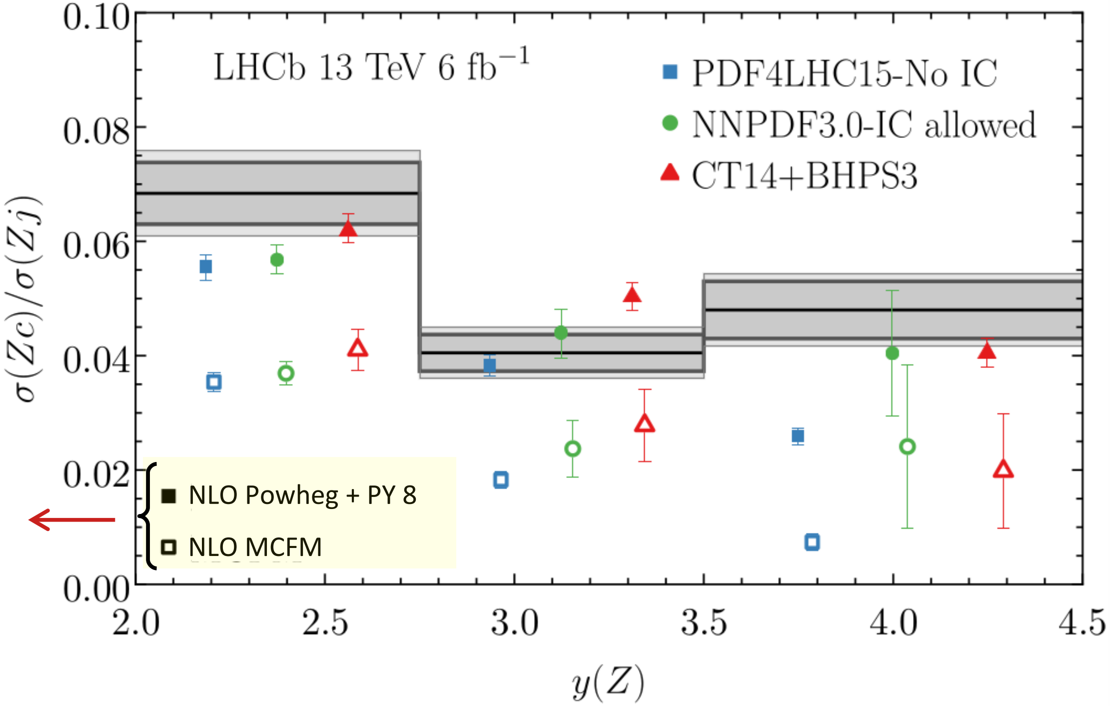


Z+c theory predictions carry sizable uncertainties

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

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

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



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

differ due to large FSR correction

NNLO calculations recently available, but not implemented in PDF fits

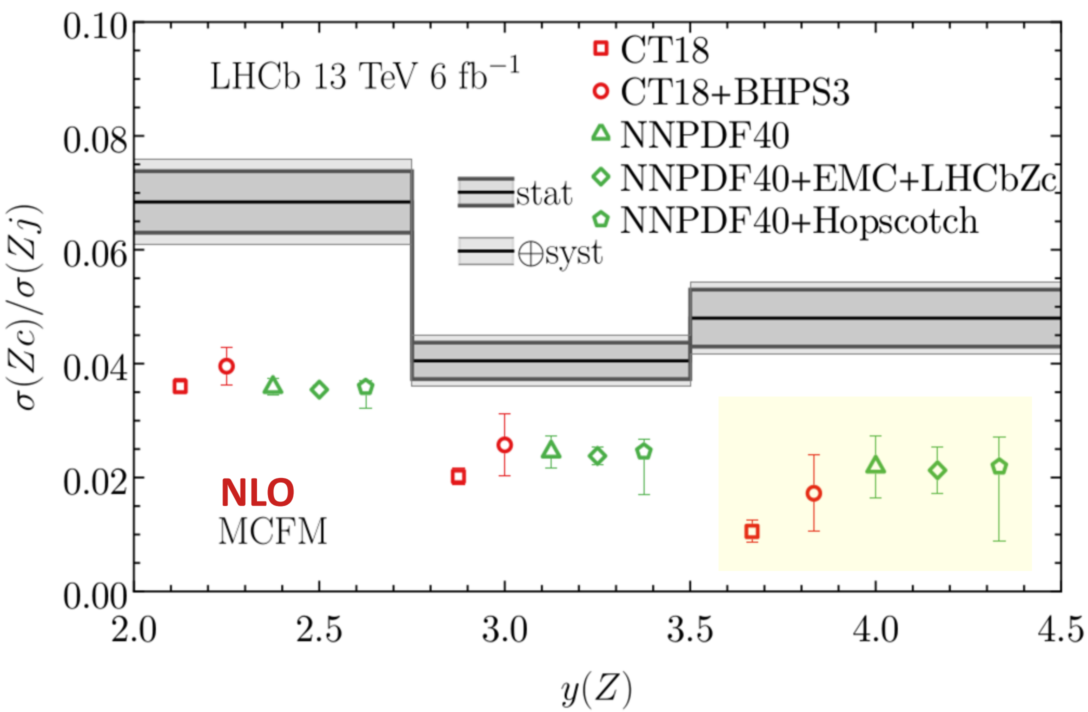
R. Gauld, *et al*.; arXiv: 2005.03016.
M. Czakon, *et al*.; arXiv: 2011.01011.

theory uncertainties currently larger than PDF variations

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

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

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

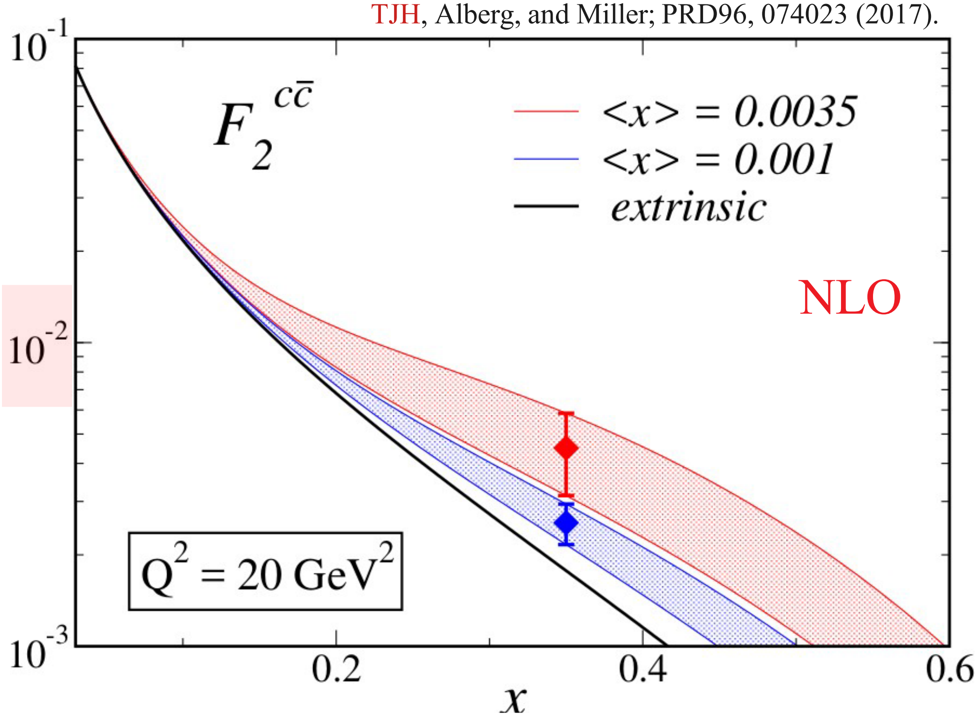


$$x \sim \frac{Q}{\sqrt{s}} \exp y$$

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

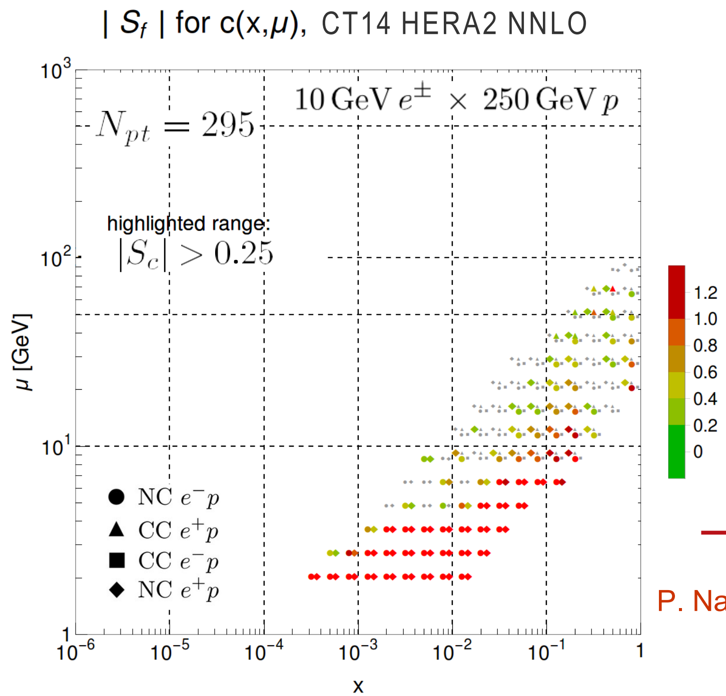
→ need NNLO theory interface; control over showering, final-state effects

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

CTEQ-TEA recent results

1. **Finished**
   - ☑ CT18 LO: LO analysis for Monte Carlo event generators
   - ☑ CT18 CS: Two-component sea (anti)quark PDFs with lattice inputs
   - ☑ CT18 As: Strangeness asymmetry and PDFs with lattice inputs
   - ☑ CT18 FC: NNLO constraints on fitted/intrinisic charm
   - ☑ CT18 & SMEFT: Machine learning and SMEFT in CT18 framework
   - The sampling paradigm to understand PDF tolerance ⇒ A. Courtoy's talk
   - CT18qed: Including photon as a parton of the proton
   - The NNLO CC DIS calculation in SACOT-MPS scheme
   - Large-x PDFs
   - Deuteron and nuclear corrections
   - SeaQuest (E906) and STAR constraints on sea quarks

   } reported at other meetings
2. **Ongoing:**
   - ☑ Impact of the LHC $t\bar{t}$ production
   - ☑ Impact of the LHC Drell-Yan production
   - PDFs at small x: Forward charm and bottom production; FPF

Happy Thanksgiving!