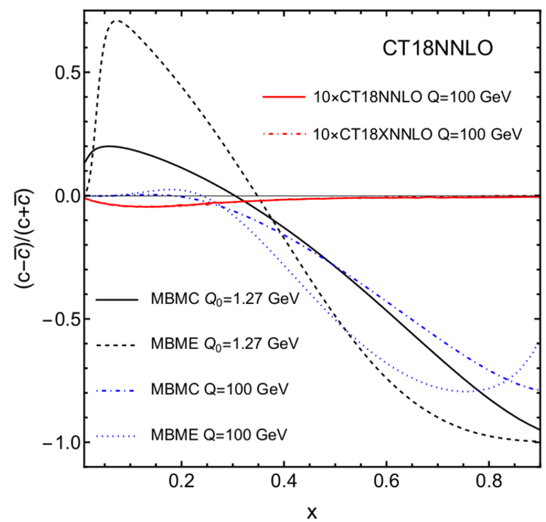
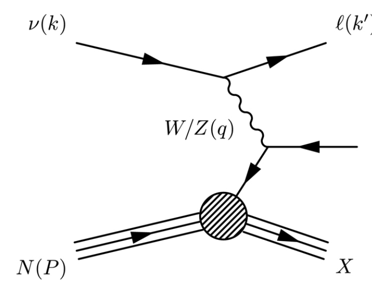
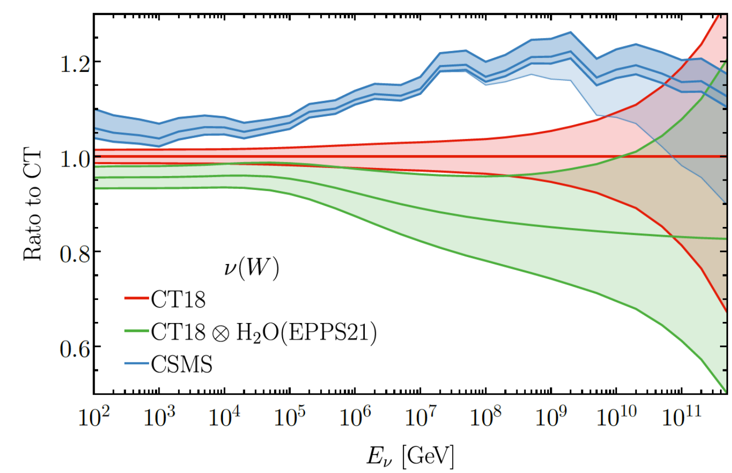
recent PDF developments at very high and low x

Tim Hobbs, ANL HEP Division Theory

recently released,
arXiv: 2303.13607
PLB843 (2023) 137975







Argonne NATIONAL LABORATORY

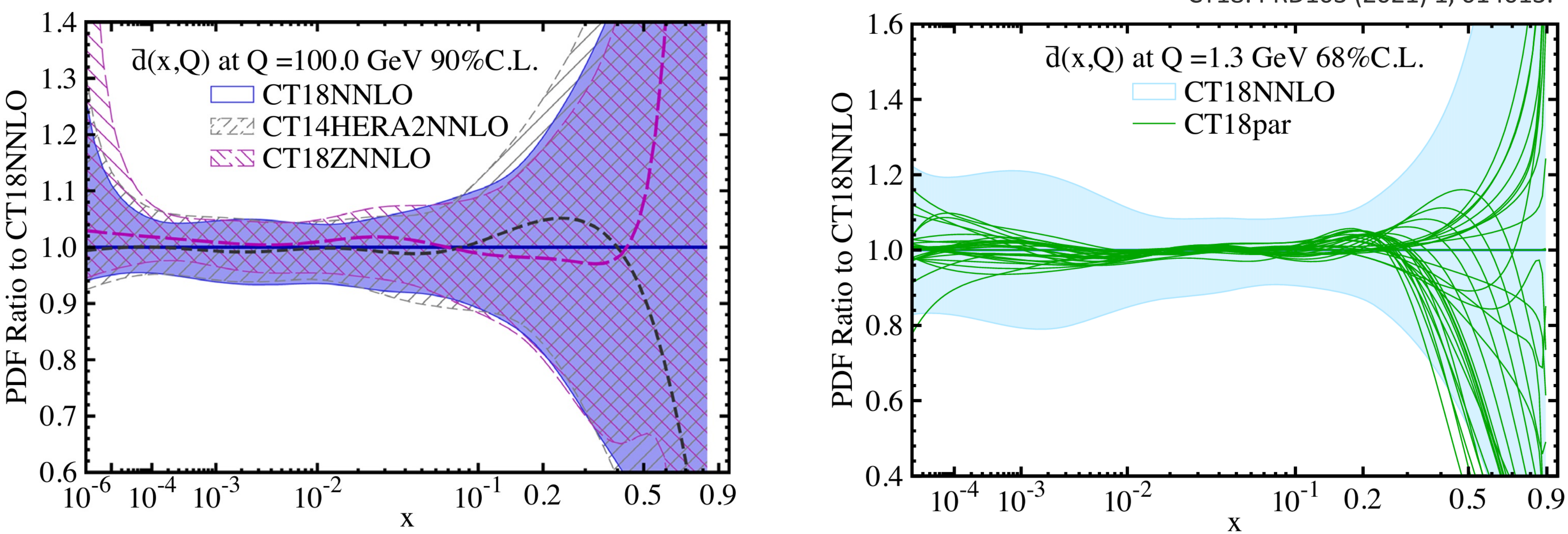
CTEQ

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

PDFs at high and low x remain challenging to constrain

- data sparsity from kinematical limitations in available experiments
  - → difficult to access x > 0.5 (systematics); x < 10^{-5} (energy restrictions)
  - → *e.g.*, high-, low-x sea PDFs: large errors; strong parametrization dependence

CT18: PRD103 (2021) 1, 014013.



- this talk: highlight two recent developments
  - → status of high-x sea --- nonperturbative charm
  - → phenomenology at low-x: ultra-high energy (UHE) neutrino scattering

recent CT high-x work: nonperturbative ('intrinsic') charm

June: PLB843 (2023) 137975

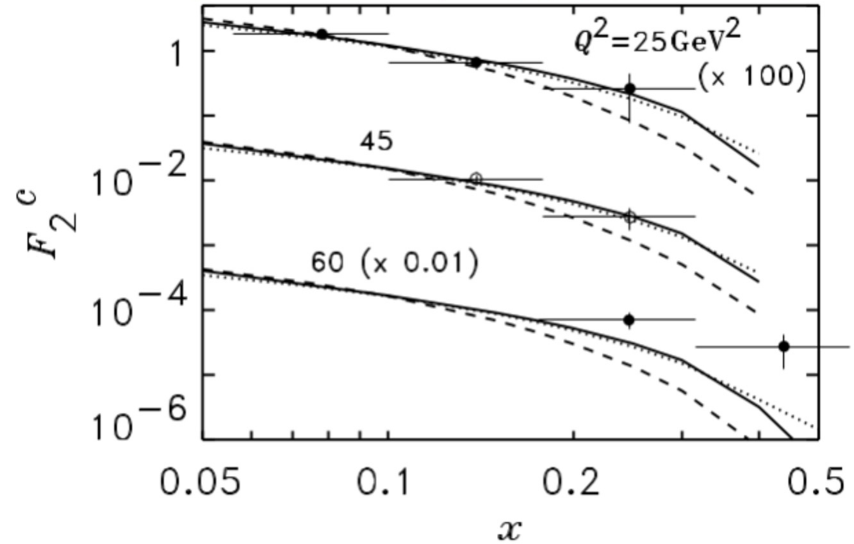
Guzzi, TJH, Xie, Huston, Nadolsky, Yuan

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

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

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

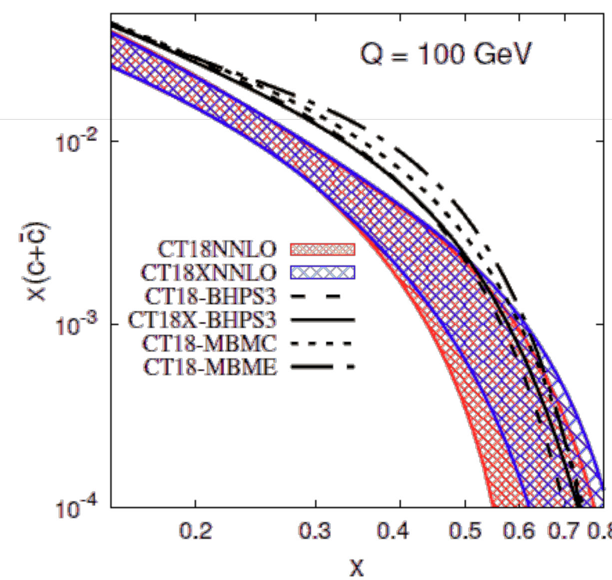
F. M. Steffens, W. Melnitchouk and A. W. Thomas, Eur. Phys. J. C **11**, 673 (1999) [hep-ph/9903441].



but can global PDF fits constrain intrinsic charm?

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

analog: the fitted charm mass



PDF fits may include a fitted charm PDF

fitted charm = "higher-twist charm"

+ other (possibly not universal)

higher O(α_s), higher-power terms

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

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

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

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

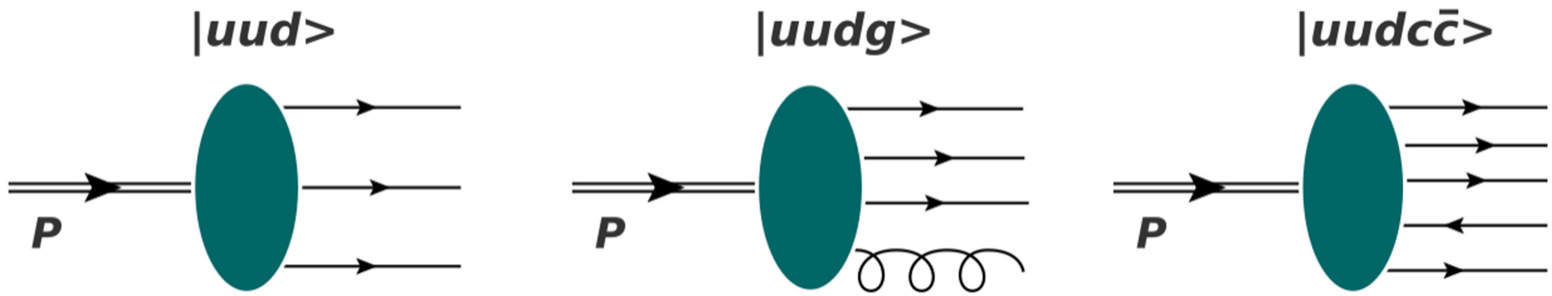
leading-power charm PDF component cancels at $Q \approx m_c$, up to a higher order

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

nonperturbative QCD can generate a low-scale charm PDF

Fock expansion

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

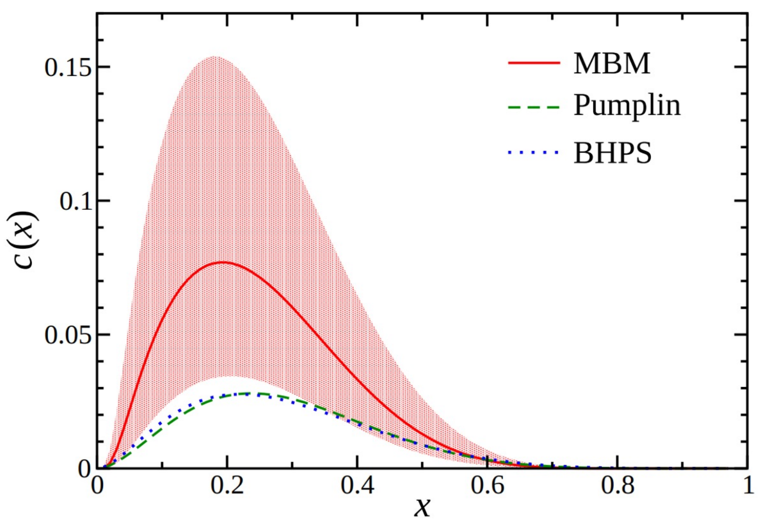


IC PDF: transition matrix element, $|\mathrm{proton}\rangle \to |uudc\bar{c}\rangle$ → old-fashioned PT; **scalar** field theory

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

('BHPS3': full mass dependence)

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



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

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

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

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

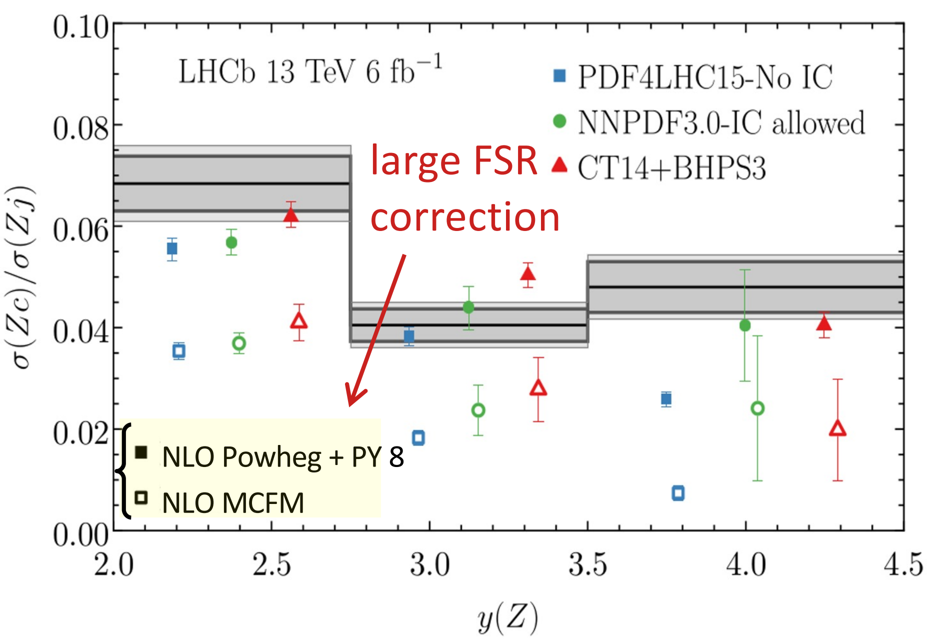
2022 LHCb 13 TeV data: (*Z+c*) / (*Z+jet*) ratios; 3 rapidity bins

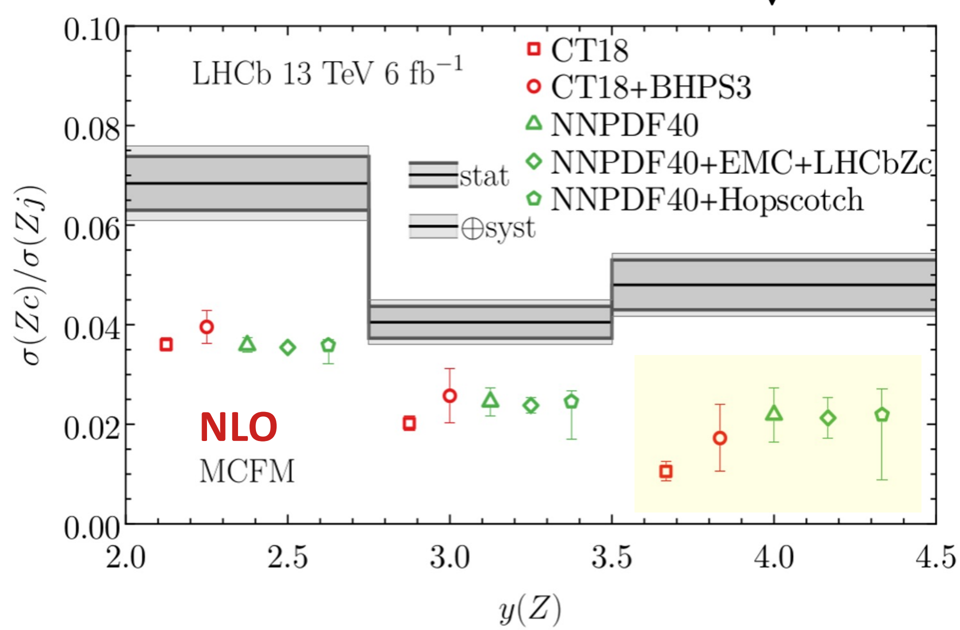
R. Aaij, *et al*. (LHCb); arXiv: 2109.08084.

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

→ meanwhile, significant theory uncertainties

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





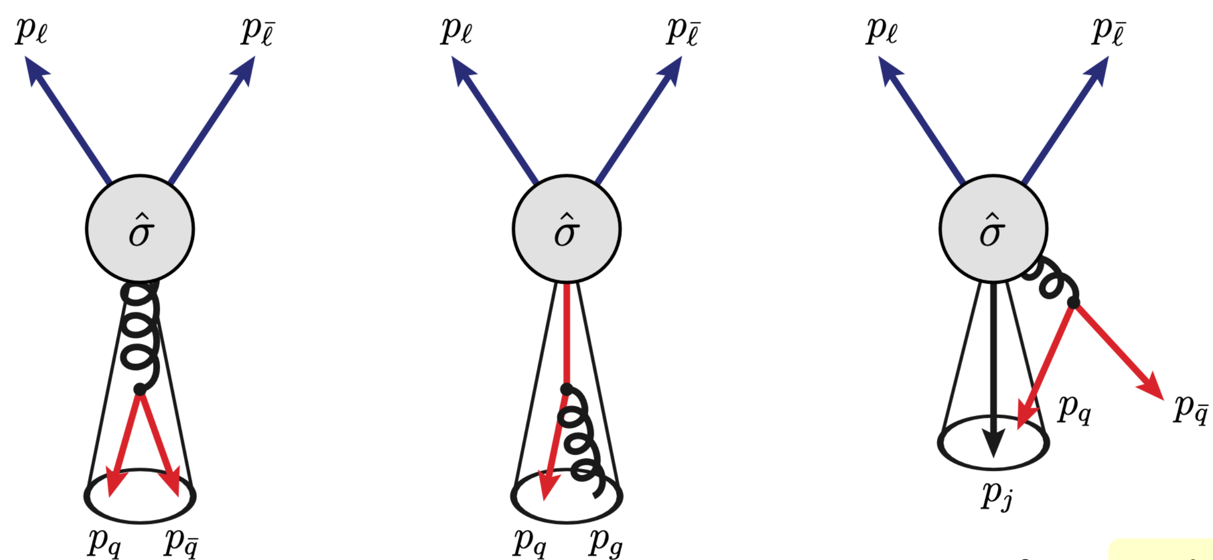
→ calculated **NLO** cross-section ratio similarly depends on showering, hadronization

NNLO calculations recently available, but not implemented in PDF fits

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

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

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



from Gauld et al., 2302.12844

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

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

- massless fixed-order calculation affected by divergences

theory improvements would help guarantee interpretation for PDF extractions

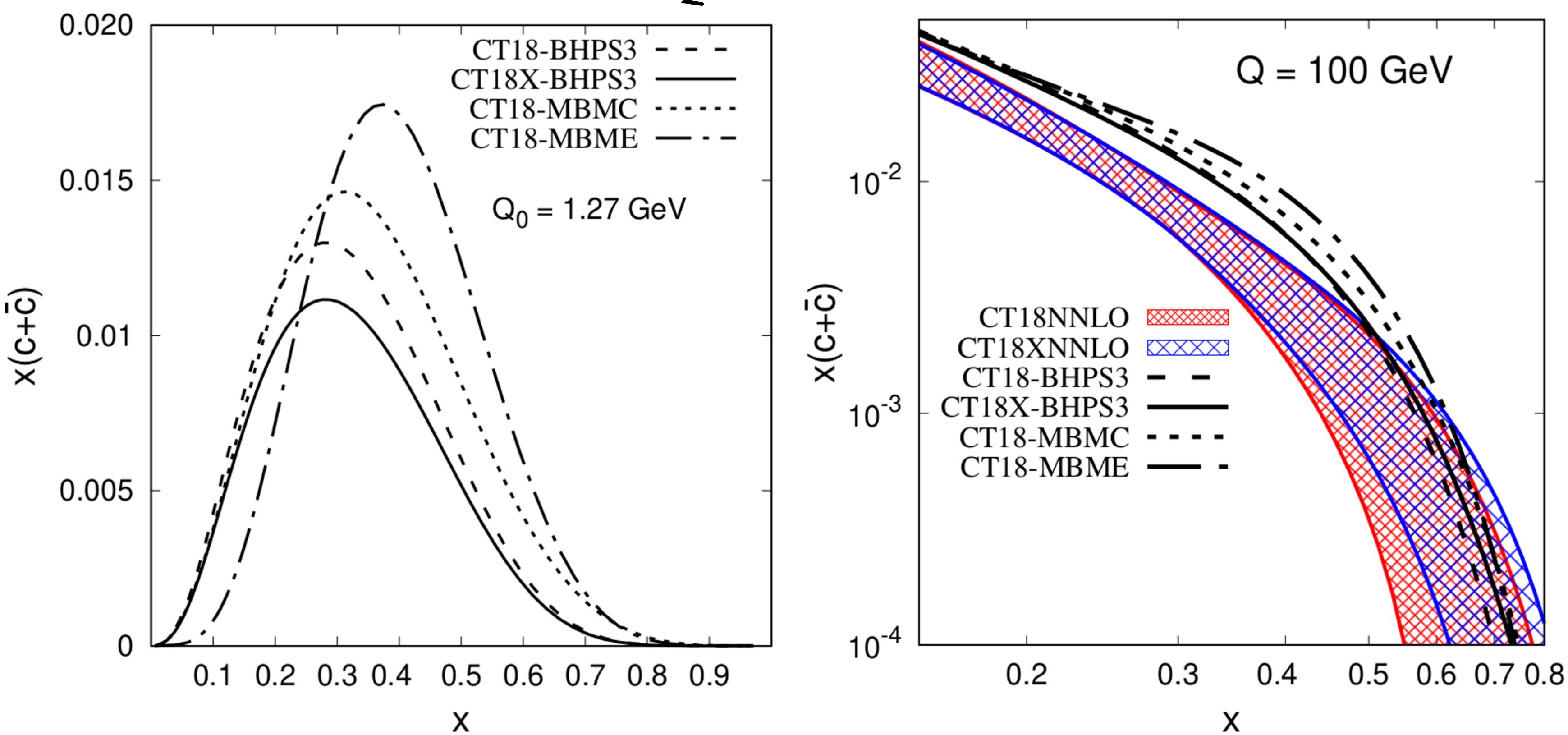
CT18 FC: fit charm against baseline CT data set

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

- → fit implementation of BHPS from CT14IC (BHPS3) on CT18 or CT18X (NNLO)
- → fit two MBMs: MBMC (confining), MBME (effective mass) on CT18

investigate constraints from newer LHC data in CT18

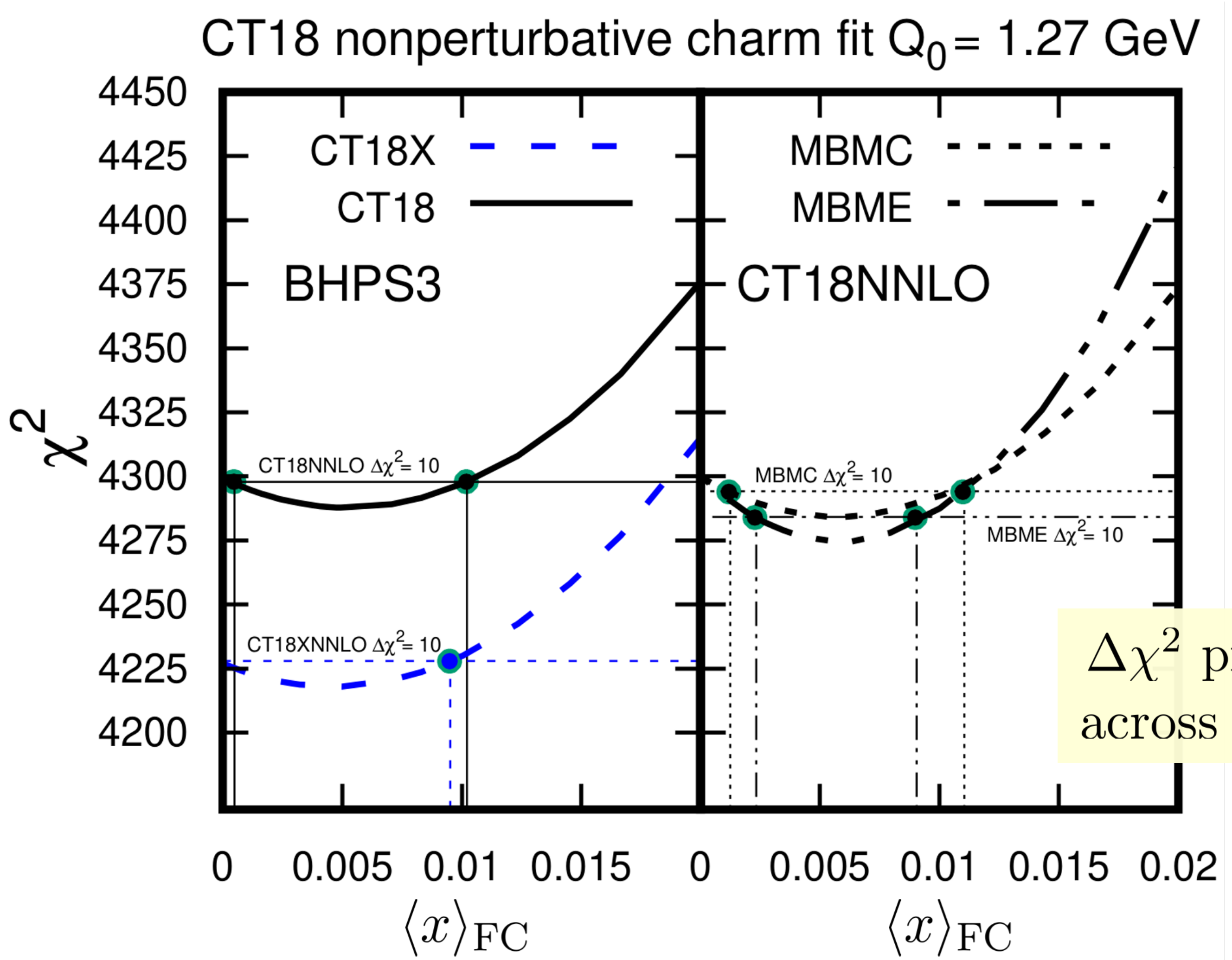
central fits



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

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

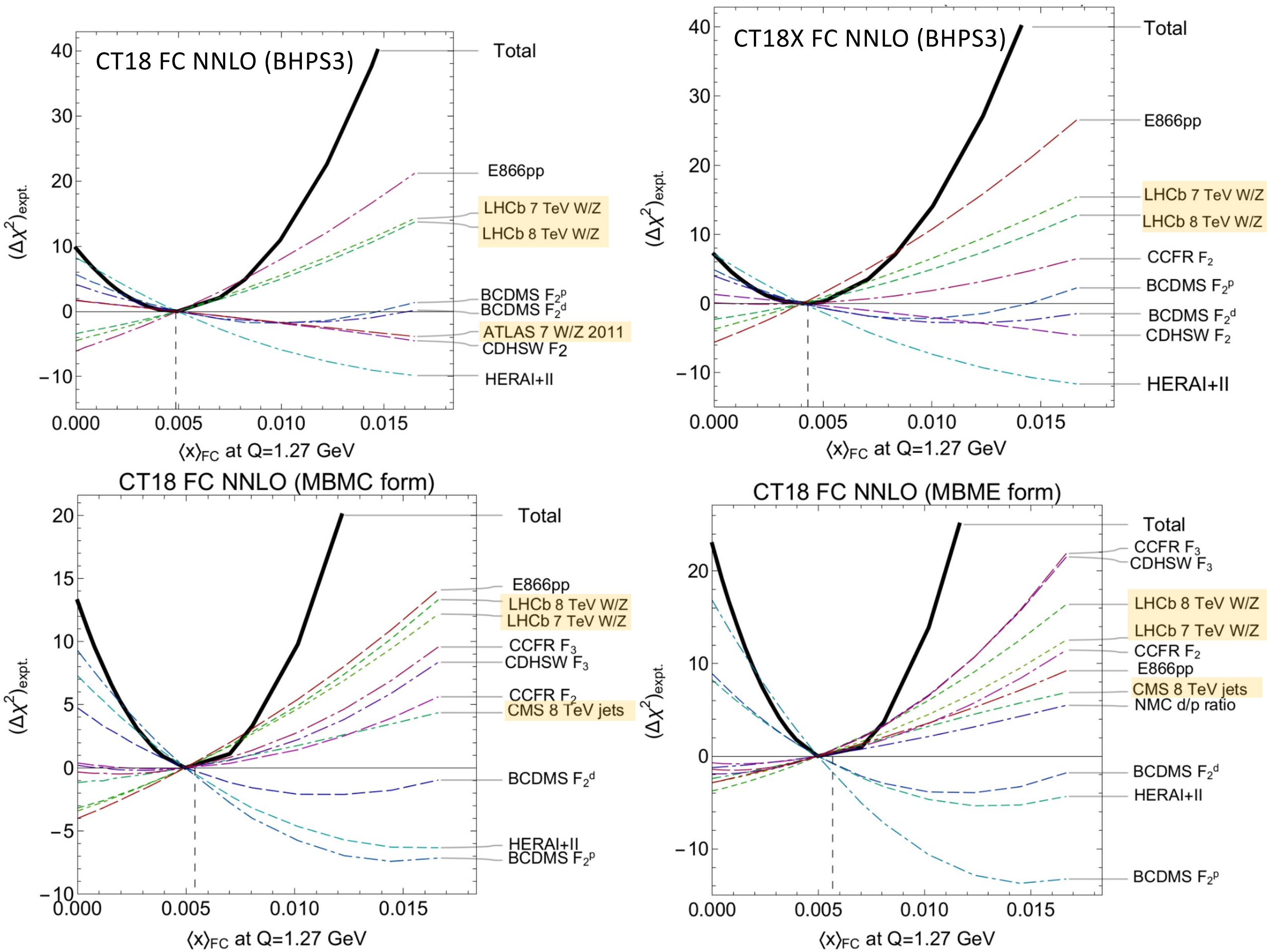
→ $\langle x \rangle_{\rm FC} \approx 0.5\%$ $(\Delta\chi^2 \gtrsim -25)$ vs. $\langle x \rangle_{\rm FC} \approx 0.8\!-\!1\%$ $(\Delta\chi^2 \gtrsim -40)$ CT14 IC



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

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

Run-1 LHC expts generally prefer smaller magnitudes of FC



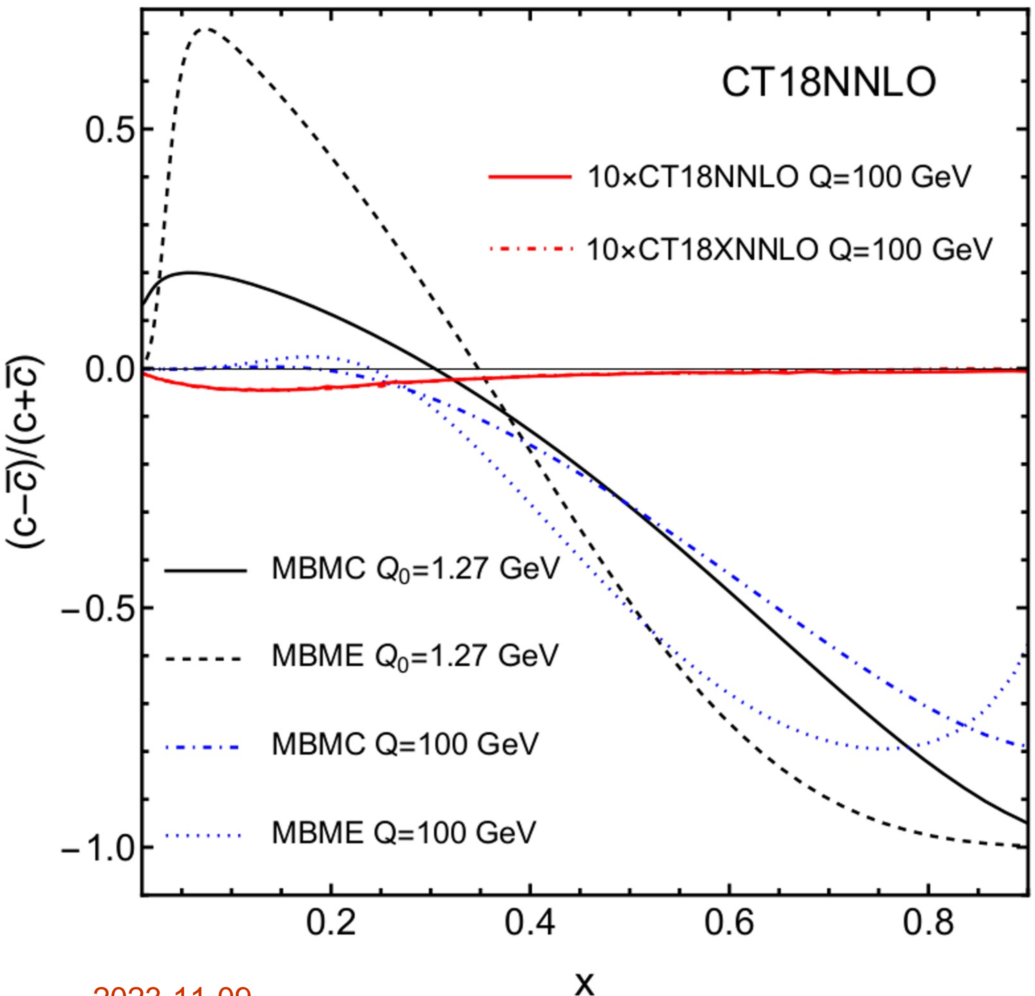
possible charm-anticharm asymmetries

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

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

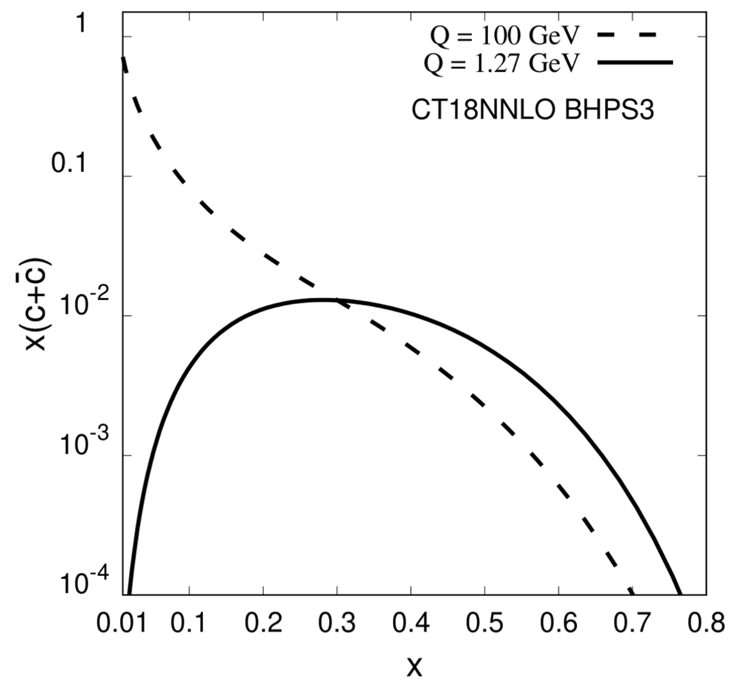
→ MBM breaks $c = \bar{c}$ through hadronic interactions

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



first global fit with charm asymmetry

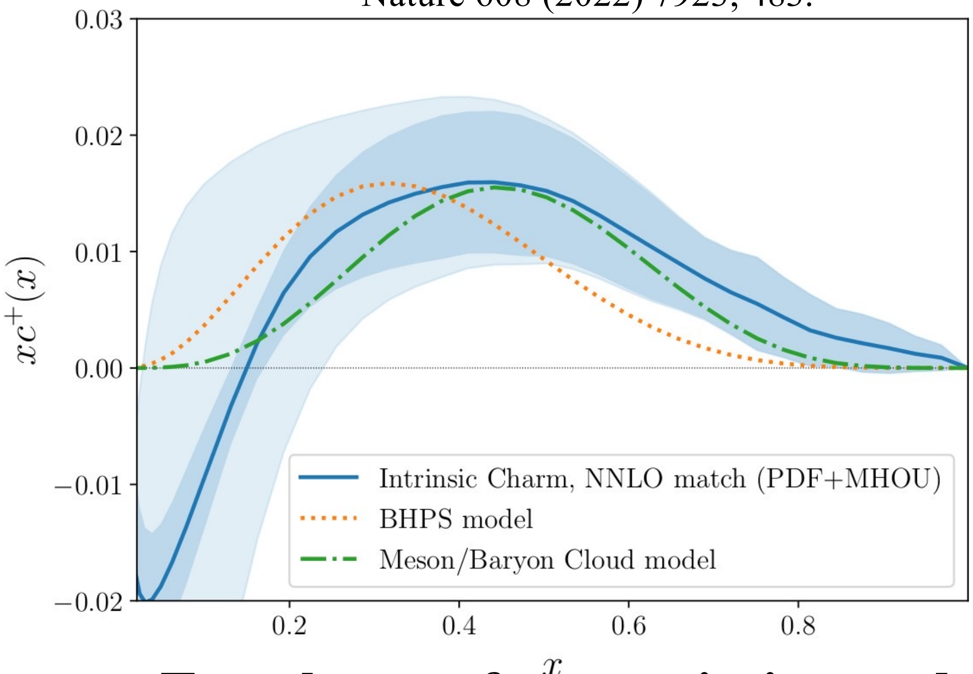
→ asym. small but ratio (left) can be bigger; will be hard to extract from data



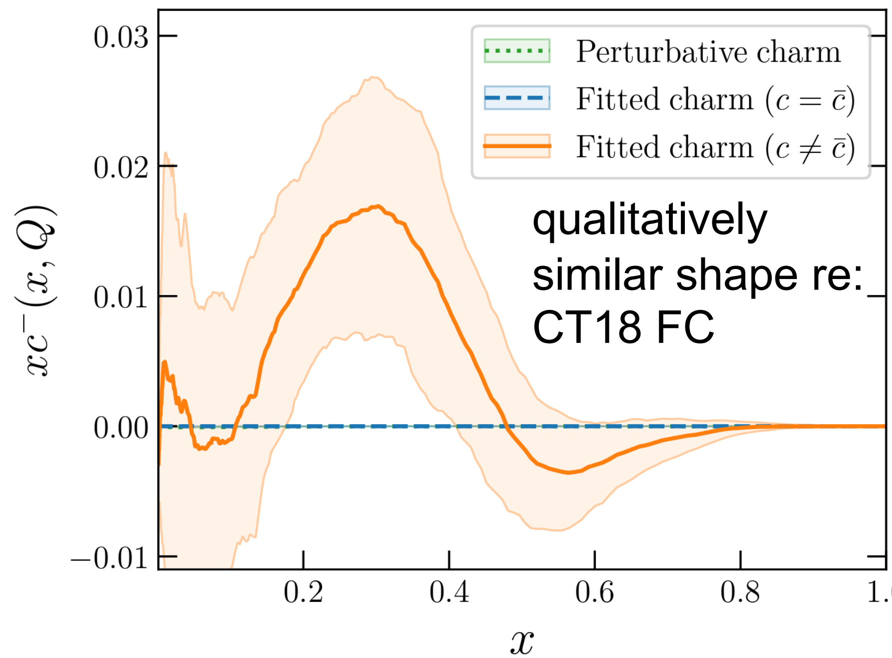
other recent analyses

- 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

Nature 608 (2022) 7923, 483.



arXiv: 2311.00743



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

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

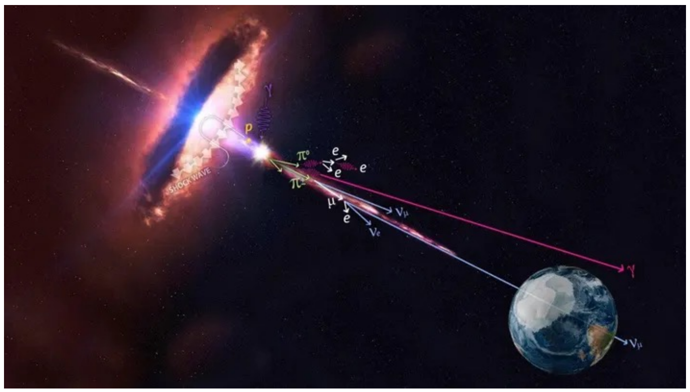
   $\langle x \rangle_{\mathrm{FC}} = 0.62 \pm 0.28\%$ *without* MHOU $\langle x \rangle_{\mathrm{FC}} = 0.62 \pm 0.61\%$ *with* MHOU

2. Parametrization sampling uncertainty (underestimation of PDFU); more acute for asym.

similar pheno limitations from incomplete PDF knowledge at (very) low x

UHE neutrinos: probe matter at extreme scales, BSM sensitivity

- relevant energies are those attained at *neutrino telescopes*, *e.g.*, IceCube



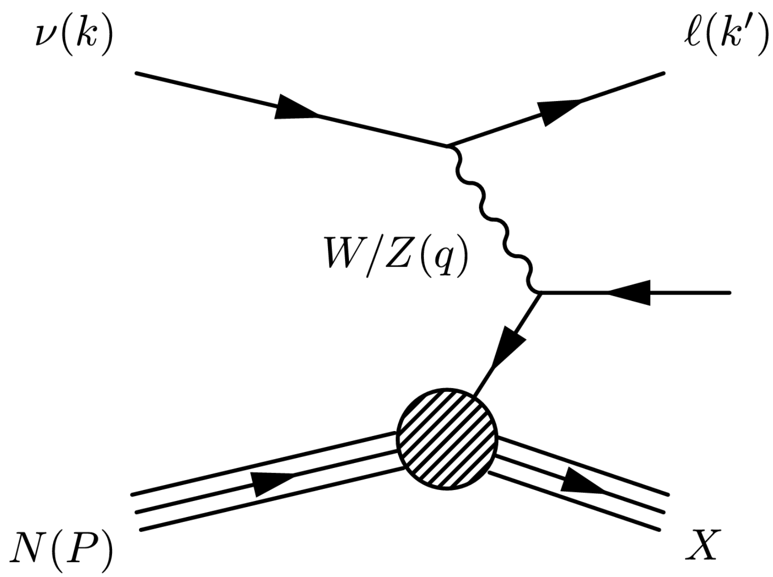
Xie, Gao, TJH, Stump, Yuan arXiv: 2303.13607

'high energy': $10^3 < E_\nu < 10^8$ GeV

'ultra-high energy' (UHE): $E_\nu > 10^8$ GeV

- far exceed energy scales achievable at terrestrial facilities (e.g., the LHC)
  - → potentially probe saturation physics at extremely low x
  - → test BSM scenarios: leptoquarks, hidden extra dimensions, …
  - → provide information on 6 of 9 flavor oscillation channels
  - → yield insights into astrophysics ('multi-messenger' astronomy)

high-energy neutrino scattering dominated by DIS



- high-energy neutrino interactions resolve quark-level structure of hadrons and nuclei

- precision tied to knowledge of proton and nuclear structure functions:

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} = \frac{G_F^2 m_N E_\nu}{\pi(1+Q^2/M_{W,Z}^2)^2}\left[\frac{y^2}{2}2xF_1 + \left(1 - y - \frac{m_N x y}{2E_\nu}\right)F_2 \pm y\left(1-\frac{y}{2}\right)xF_3\right]$$

- requires control over corresponding parton distribution functions (PDFs):

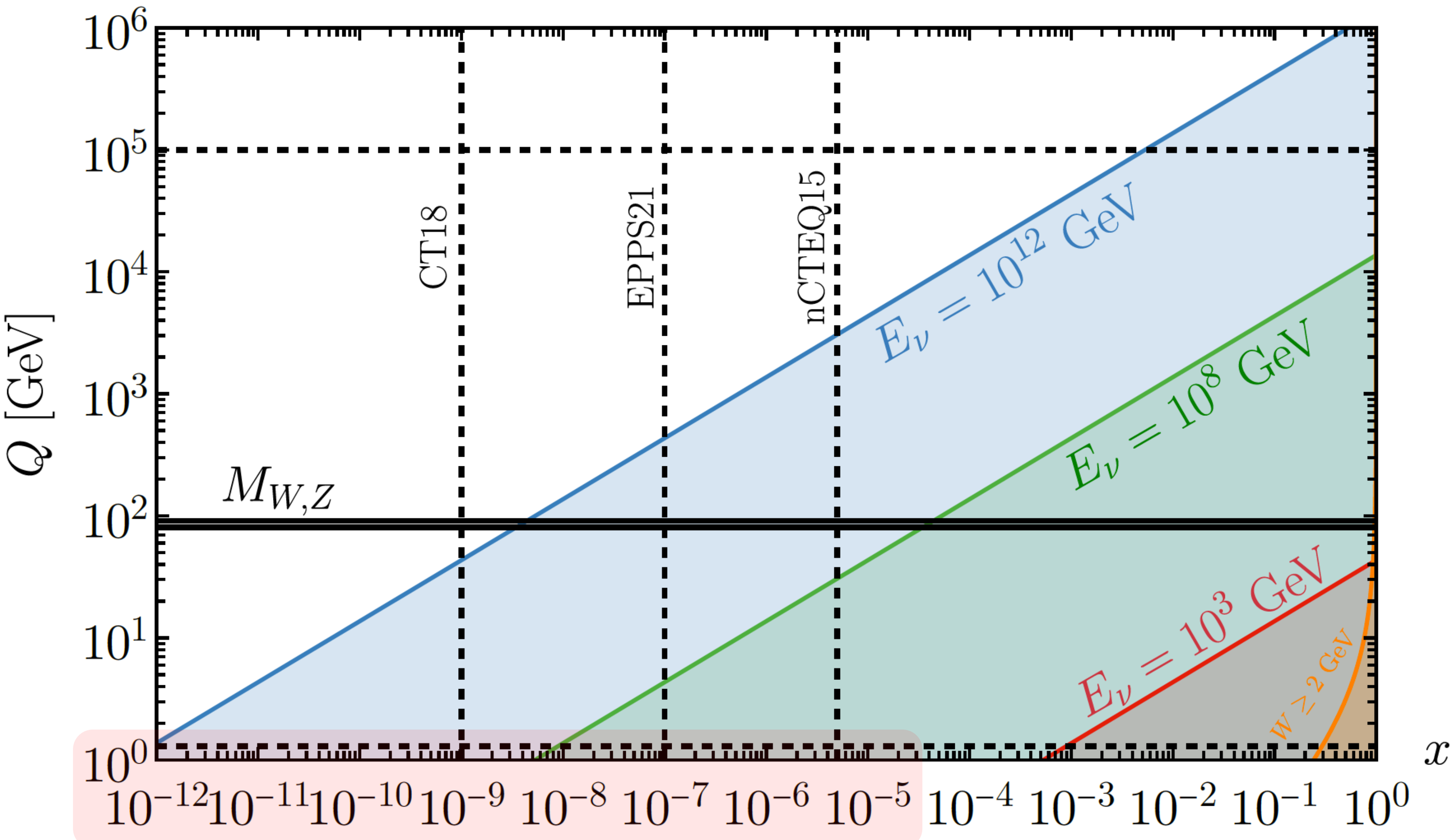
$$F_2^{\nu(W^+)} = 2x\left(\sum_i d_i + \sum_j \bar{u}_j\right)$$

leading-order! …modern HEP calculations NNLO+

low-x PDFs and uncertainties are key to cross sections

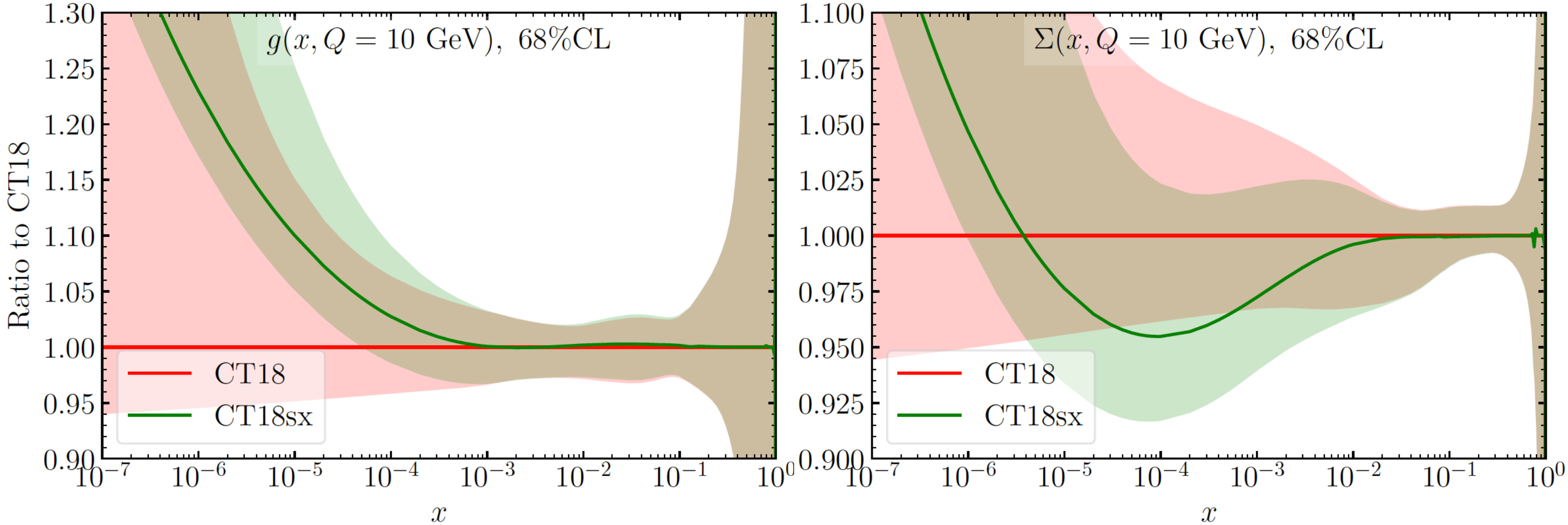
$$\sigma = \int_{Q^2_{\rm min}}^{2m_N E_\nu} dQ^2 N(Q^2) \int_{x_{\rm min}}^{1} \frac{dx}{x} \mathcal{F}(x, Q^2)$$

- total cross sections influenced by low x at increasing energies



cross sections sensitive to proton PDF extrapolation region

- gluon and singlet PDF uncertainties become poorly controlled below $x \lesssim 10^{-5} - 10^{-4}$

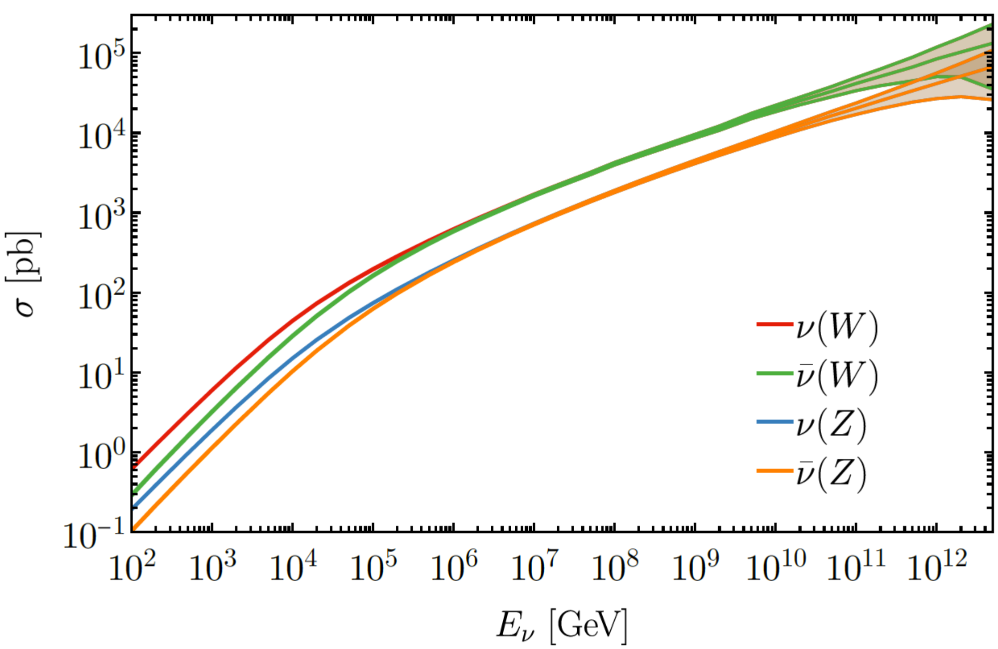


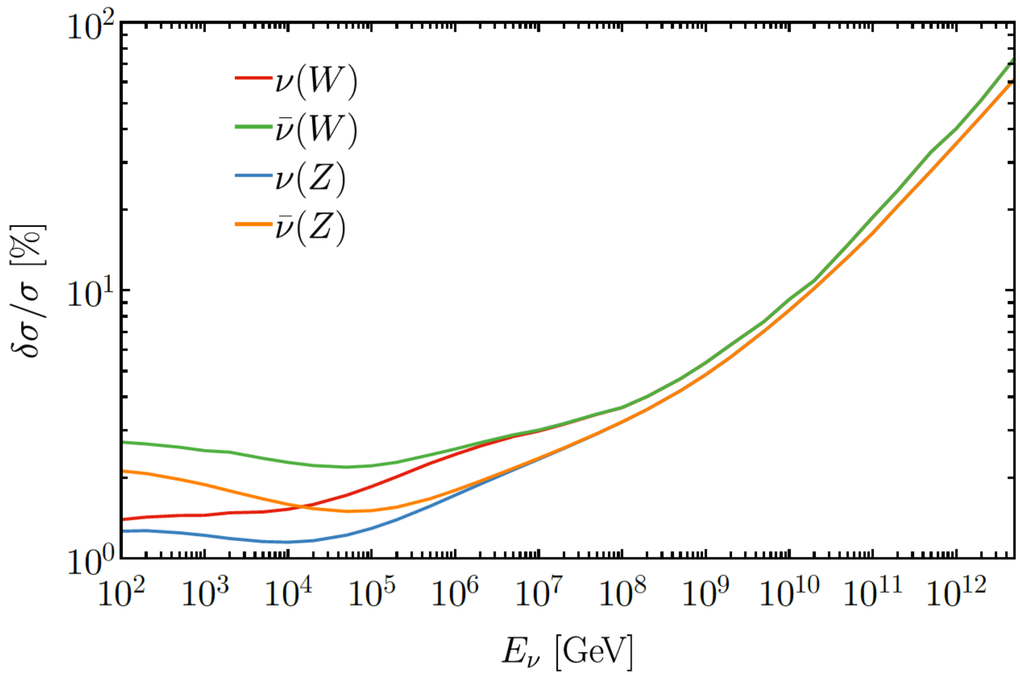
- parametrization, low-x resummation and related effects become significant

→ CT18sx: alternative small-x study; enhancements to extracted PDFs at low x

proton PDF uncertainties influence the HE cross section

- low-x PDF uncertainties ultimately produce ~100% variations in total cross sections
  - → NNLO (isoscalar) single-nucleon interaction; (also aN^{3}LO)

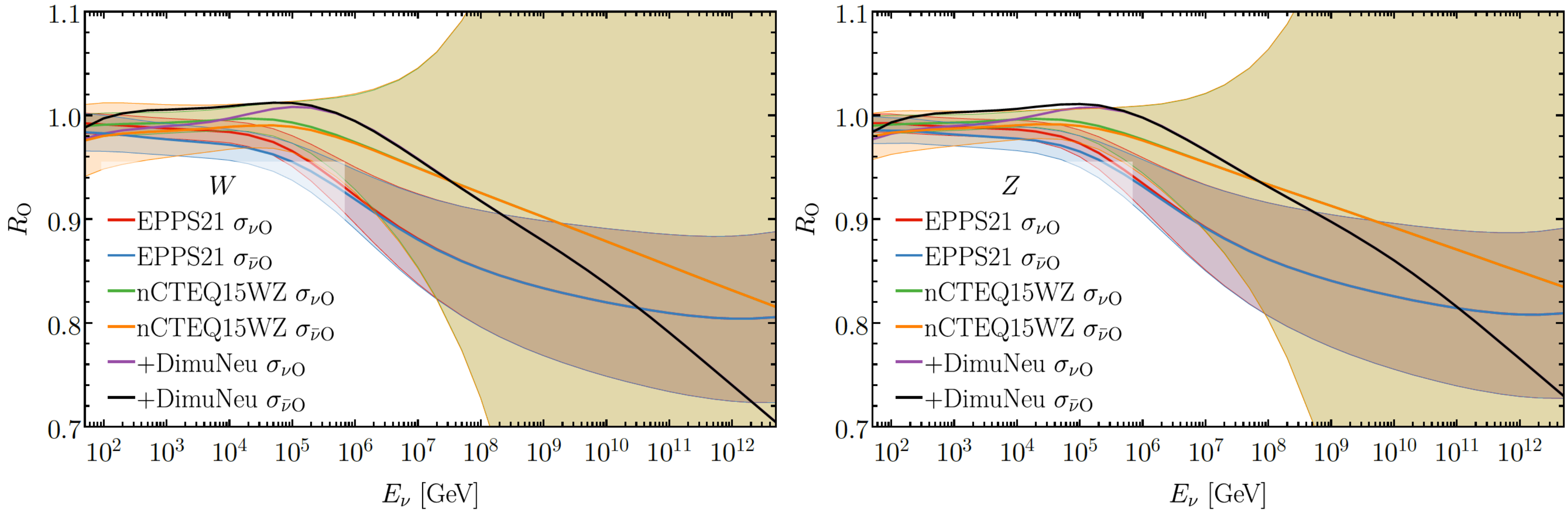




- little charge dependence, as uncertainties driven by large low-x uncertainties

nuclear scattering introduces further corrections, uncertainties

- uncertainties still larger for A-dependent nPDFs, especially at low x (data sparsity)
  - → example: high-energy suppression of cross section tied to nuclear shadowing

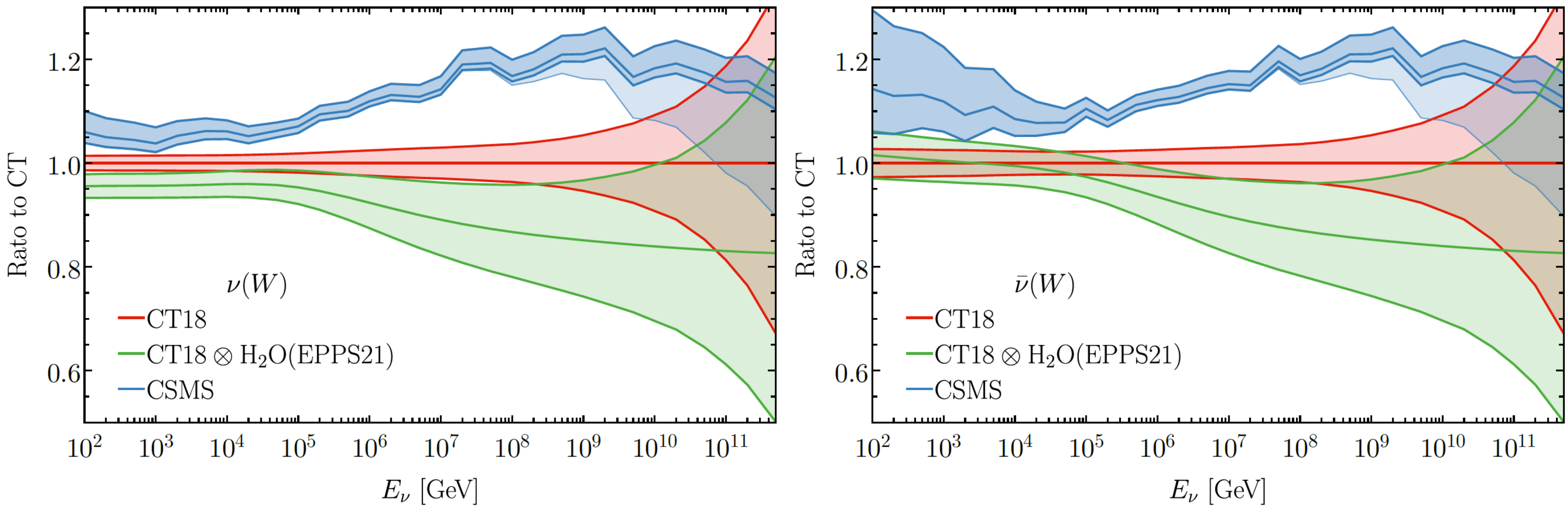


- open questions related to process independence, tensions in nPDF extractions
  - → weak vs. EM scattering from nuclei [**DimuNeu** above --- neutrino only fit]

Muzakka et al., PRD106 (2022) 7, 074004

see talk: M. Klasen

QCD uncertainties remain challenging at high energies



- combined CT18 and EPPS21 uncertainties represent a more aggressive scenario

  → nCTEQ15-based predictions enlarge high-energy uncertainties further

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- many additional model considerations: heavy-quark mass effects; extrapolations, …

  → compelling arena to test QCD across HEP-NP!

  arXiv: 2303.13607

  e.g., nuclear models in saturation regime could strengthen BSM sensitivity…

  see talk: Keping, related issues in nu-A scattering

outlook

- high- and low-x remain vital frontiers in PDF determinations
  - → **experimental frontier**, due to lack of sensitive data
  - → **theory frontier**: input in terms of formalism, statistical treatment needed
    - → perturbative effects, resummation; HQ dynamics; …

      connections to BSM sensitivity
    - → also, subtleties in PDF parametrization dependence; extrapolations
- these considerations apply to **fitted charm** and **UHE neutrino** examples in this talk
- need for novel approaches to PDF parametrization, associated uncert. quantification
  - → see talk(s): Aurore and Pavel
- complementary approaches involving ML (e.g., NNPDF-style NN parametrizations)
  - → such methods can be challenging to interpret

    Brandon Kriesten and TJH
  - → forthcoming paper (this month):
    interpretability, hyperparameter sensitivity of ML models at high-x