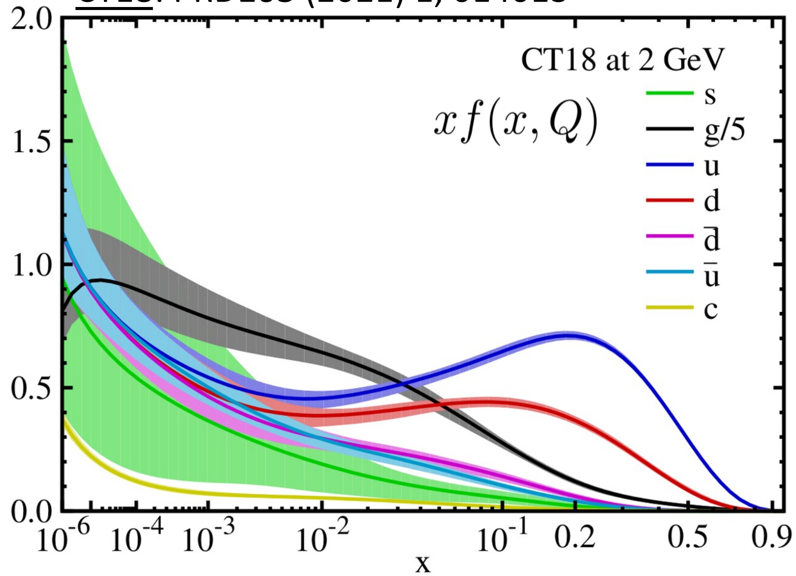
QCD analyses and next-generation PDF precision

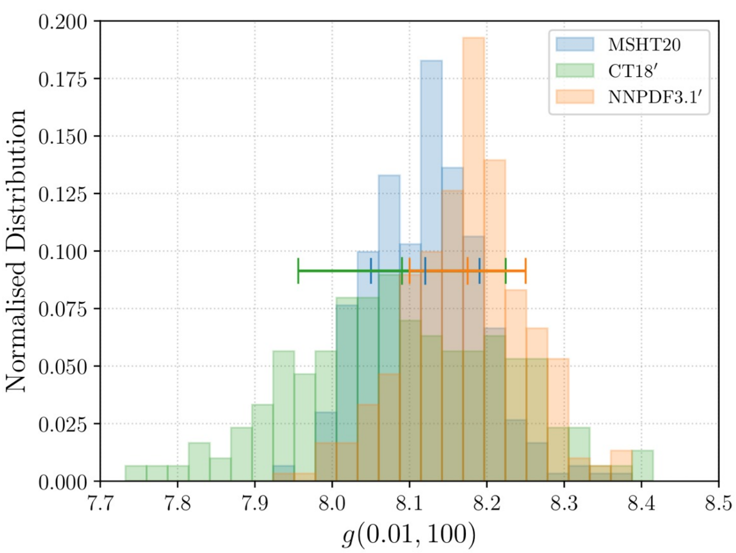
xFitter in the era of EIC and HL-LHC

Tim Hobbs, Argonne National Lab

2nd May 2023

CT18: PRD**103** (2021) 1, 014013





this talk: xFitter in the EIC era will confront twin realities

1: PDF accuracy: must develop an array of theory/analysis elements

→ HEP perspective: standard-candle measurements PDF-limited

→ complex interplay of non/perturbative QCD theory

→ need improved uncertainty quantification, benchmarking

see talks, Courtoy and Huston

2: improved EIC phenomenology will depend on many of these components

→ taming PDF dependence: unexplored phase-space; novel/rare processes

→ EIC is a 'PDF machine'; goal of mapping hadron structure

xFitter is a suitable testbed to demonstrate theory tools

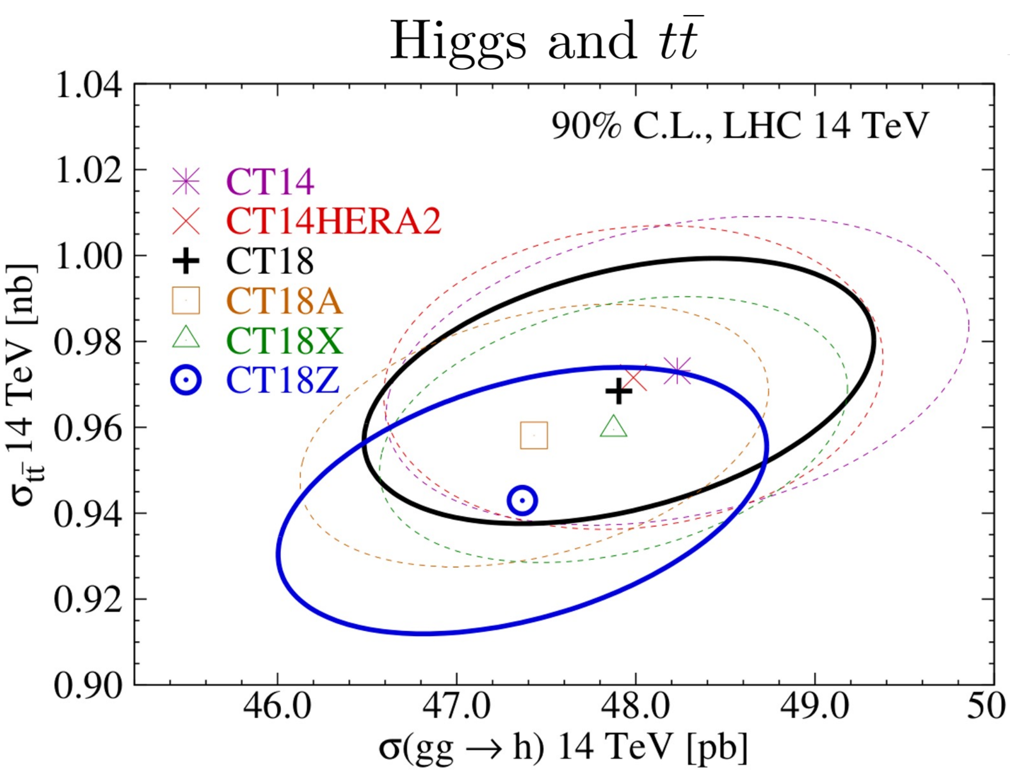
highlight via: i current status of PDFs; ii experimental opportunities (EIC)

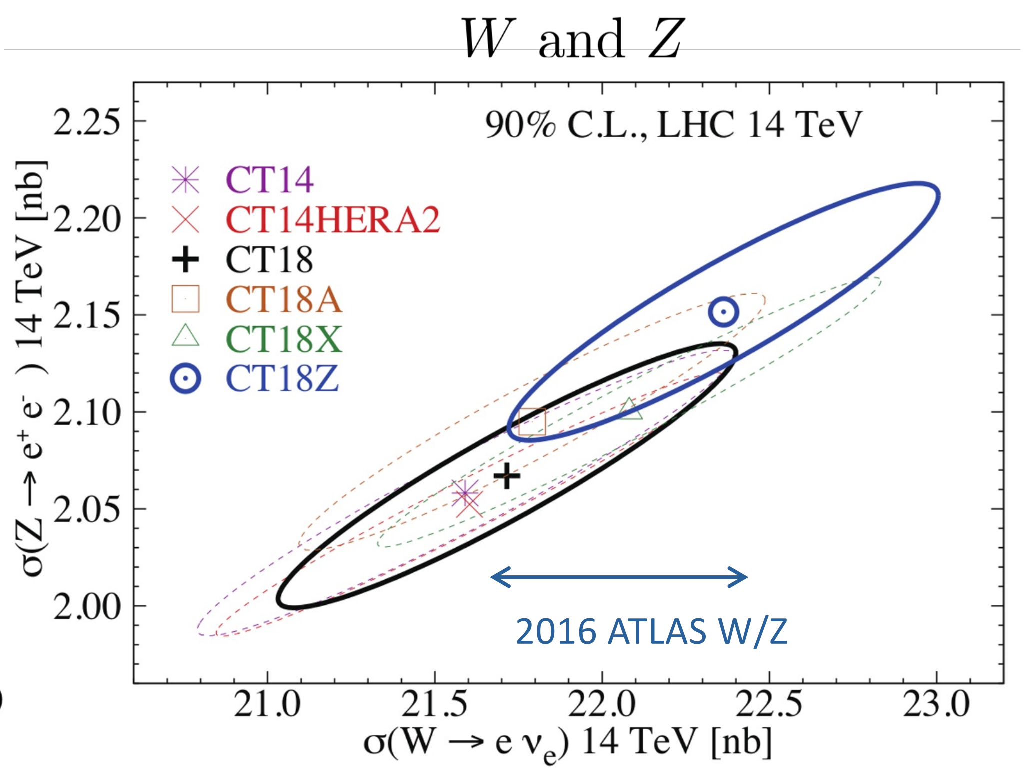
iii conclusion(s); xFitter possibilities

SM theory predictions from global analyses

from NNLO analyses, state-of-the-art predictions for fundamental LHC observables
→ *e.g.*, **total cross sections at 14 TeV**

CT18 NNLO, PRD **103** (2021) 1





Higgs, NNLO QCD: iHixs v1.3

$t\bar{t}$, NNLO+NNLL: Top++ v2.0

$$\mu_R = \mu_F = m_t; m_{W,Z}; m_H$$

NNLO QCD: Vrap v0.9

significant PDF-driven uncertainties; also, systematic effects: W cross sections sensitive to inclusion of 2016 7 TeV ATLAS inclusive W/Z data

i HEP standard-candle measurements are limited by PDF uncertainties

→ includes many observables: $\sigma_H\,,\ \sin^2\theta_W\,,\ m_W\,,\ \ldots$

→ this dependence NOT simply another 'theory uncertainty'

example: ATLAS, 1701.07240
PDF uncertainty in the W-mass charge splitting

→ recent CDF M_W measurement: significant PDF dependence
2205.03942 [hep-ph]

→ **cross-cutting effort spanning theory/expt to improve**

- heightened theory accuracy (HO, power corrections)
- novel measurements (EIC, LHC, νA)
- generator development   Snowmass21, Campbell et al.: 2203.11110

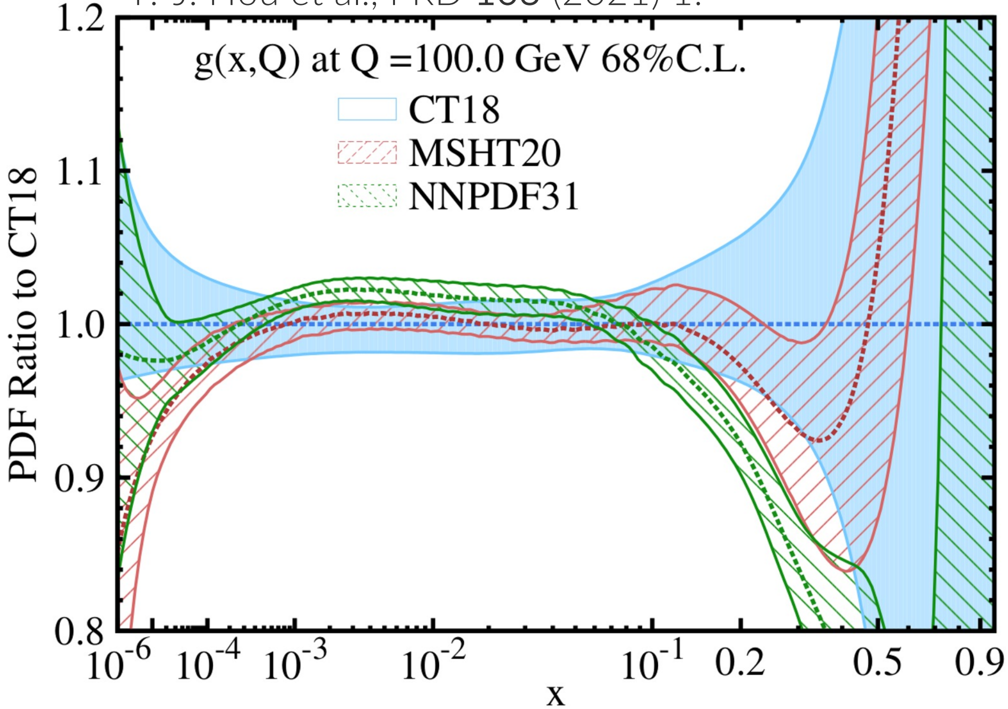
PDFs critical to next-generation precision

Snowmass21, Amoroso et al.: 2203.13923

→ driven by marriage of latest theory, high-energy hadronic data

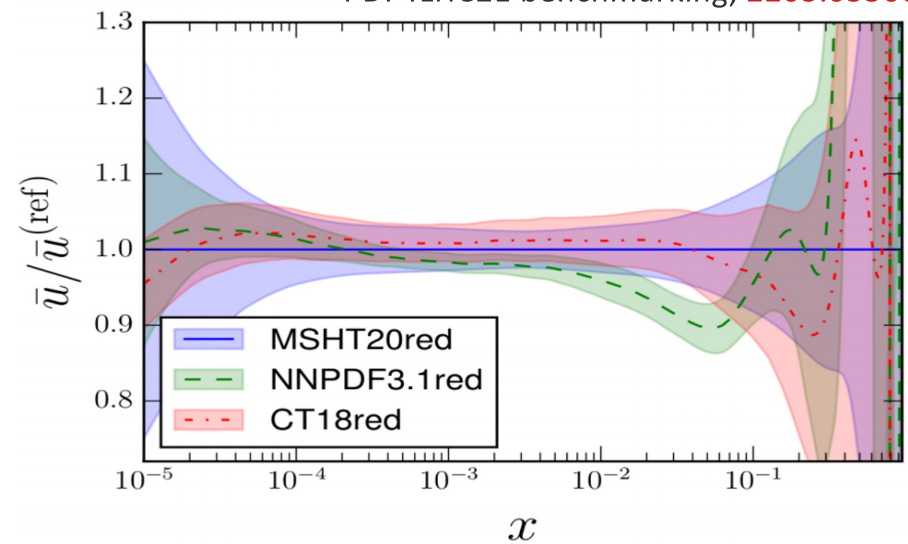
$$\sigma(AB \to W/Z+X) \;=\; \sum_n \alpha_s^n \sum_{a,b} \int dx_a dx_b\, f_{a/A}(x_a,\mu^2)\, \hat{\sigma}^{(n)}_{ab\to W/Z+X}\left(\hat{s},\, \mu^2\right) f_{b/B}(x_b,\mu^2)$$

T.-J. Hou et al., PRD **103** (2021) 1.



contemporary <u>NNLO</u> QCD fits

PDF4LHC21 benchmarking, 2203.05506



periodic benchmarking (PDF4LHC21) valuable to cross-check treatment of data

→ seek methodological independence in identifying data-driven PDF features i

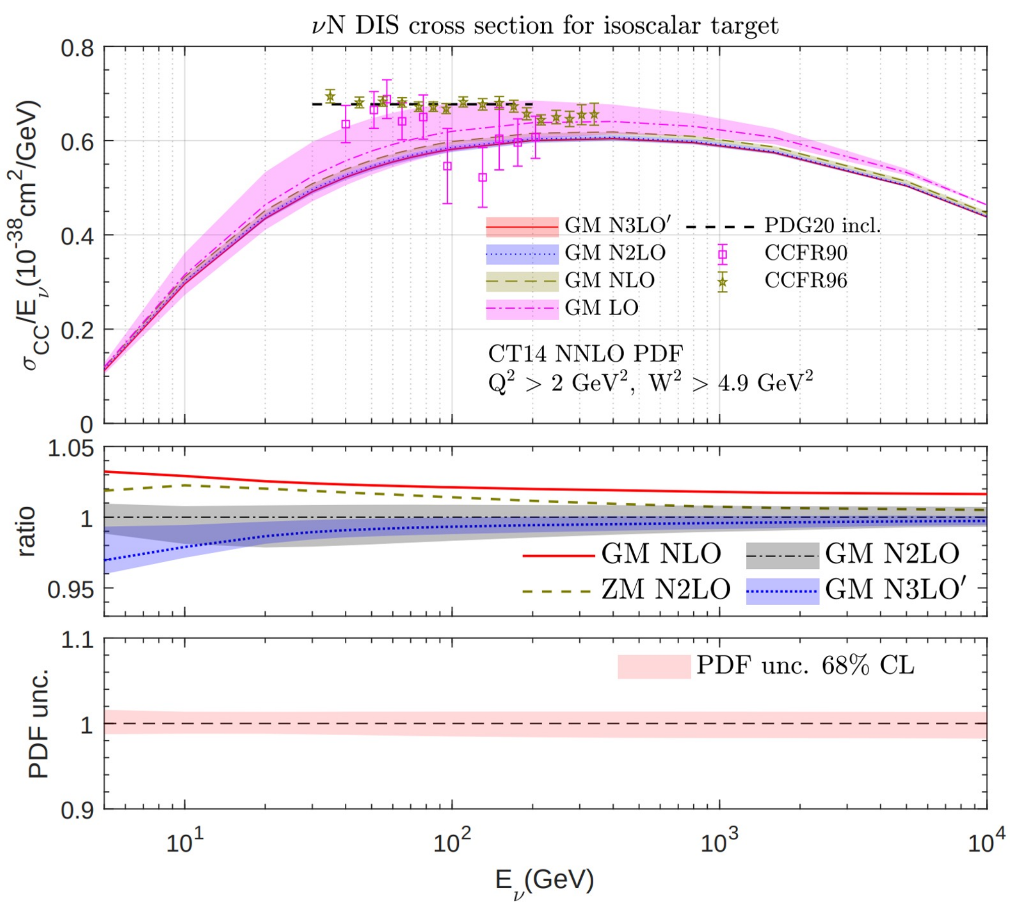
theory ingredients → higher pQCD accuracy

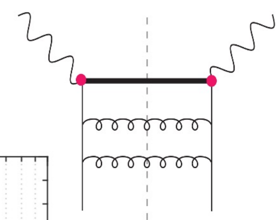
current/future analyses involve interplay between pQCD & other dynamics

NNLO+ necessary to stabilize scale uncertainties; especially over wide scales

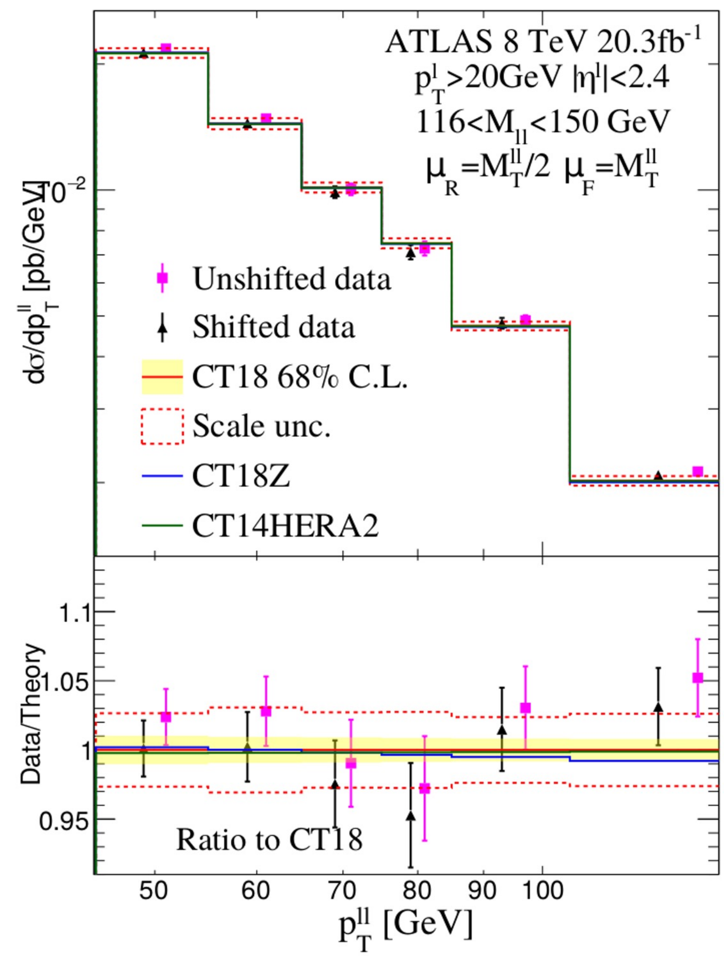
charge-current DIS

Gao, TJH, Nadolsky, Sun, Yuan: PRD**105** (2022) 1, L011503





NNLO scale variations at LHC



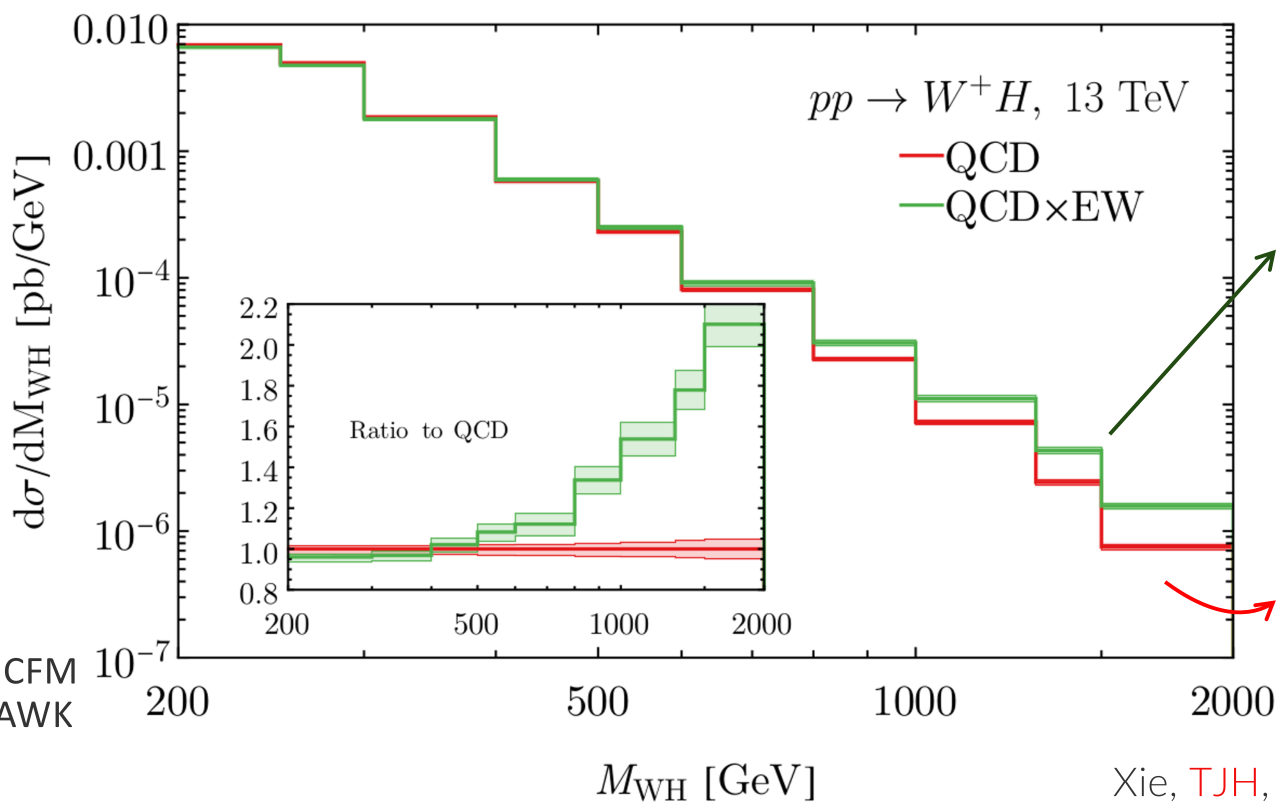
→ needed for DUNE, FASERν, EIC

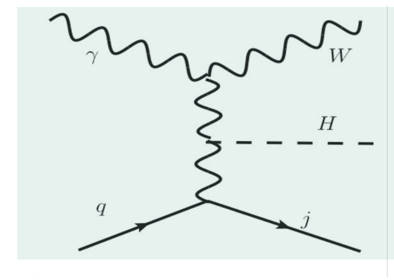
CT18 NNLO, PRD **103** (2021) 1

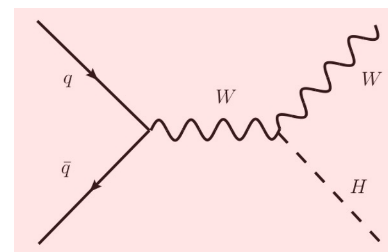
electroweak (EW) corrections also vital

at $\mathcal{O}(\alpha_s^2)$ accuracy, EW corrections and explicit $\gamma(x, \mu^2)$ needed

important for high-energy LHC processes: *e.g.*, 13 TeV W+H production







MCFM
HAWK

Xie, TJH, Hou, Schmidt, Yan, Yuan: 2106.10299

TeV-scale NLO EW corrections dominated (60%) by single-photon (PDF) contributions

→ requires **delicate** treatment along with QCD perturbative effects

necessary for electroweak precision: photon PDF

at $\mathcal{O}(\alpha_s^2)$ accuracy, EW corrections and explicit $\gamma(x, \mu^2)$ needed

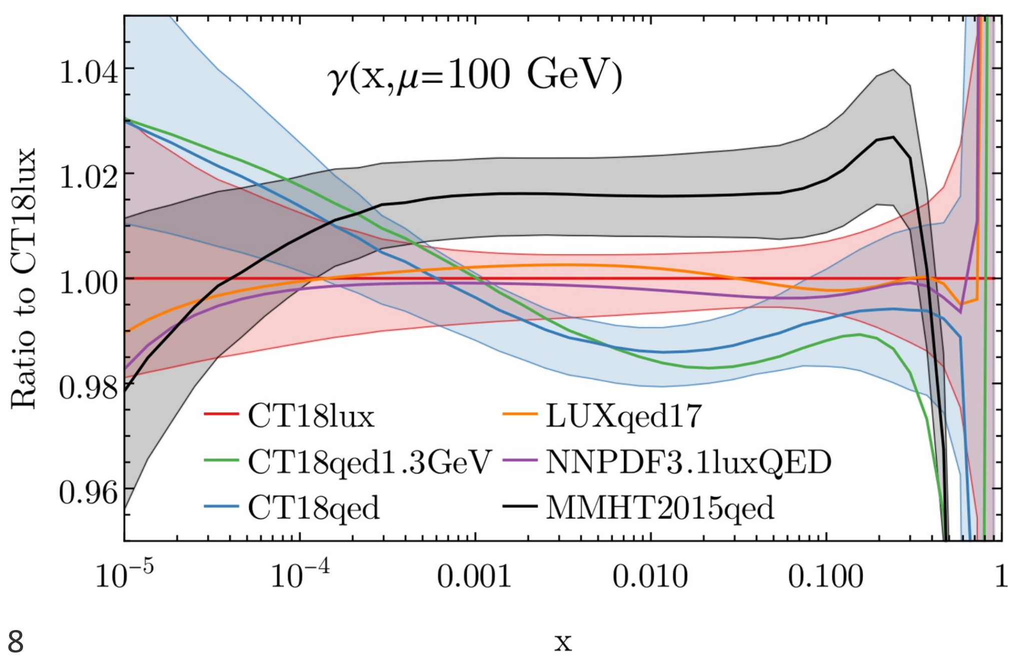
Xie, TJH, Hou, Schmidt, Yan, Yuan: PRD**105** (2022) 5, 054006

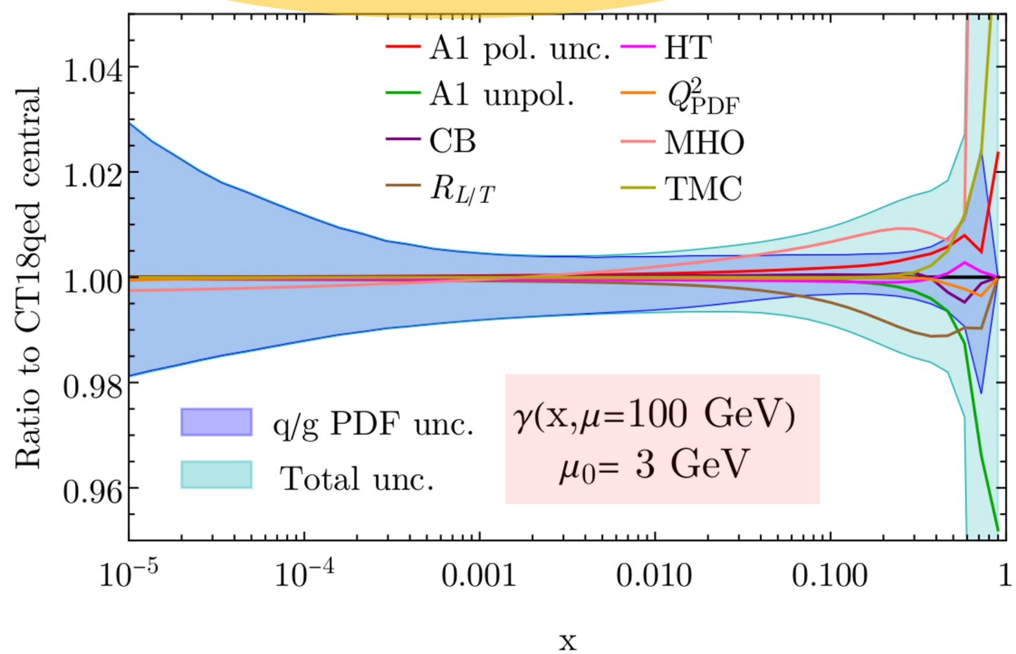
following CT14QED, CT18QED now interfaces LUX formalism

$$x\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{z}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{Q^2}{Q^2} \alpha_{\rm ph}^2(-Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L(x/z, Q^2) \right] - \alpha^2(\mu^2) z^2 F_2(x/z, \mu^2) \right\} + \mathcal{O}(\alpha^2, \alpha\alpha_s)$$

<u>depends on nonperturbative inputs</u> [kinematical cuts alone can't avoid this]

[*e.g.*, large-*x* physics...]





i **parametrization uncertainty**: nonperturbative fitting forms

initial PDFs still not generally calculable through rigorous QCD at $Q = Q_0 = m_c$ (to the needed precision…)

→ subject to complex nonperturbative dynamics

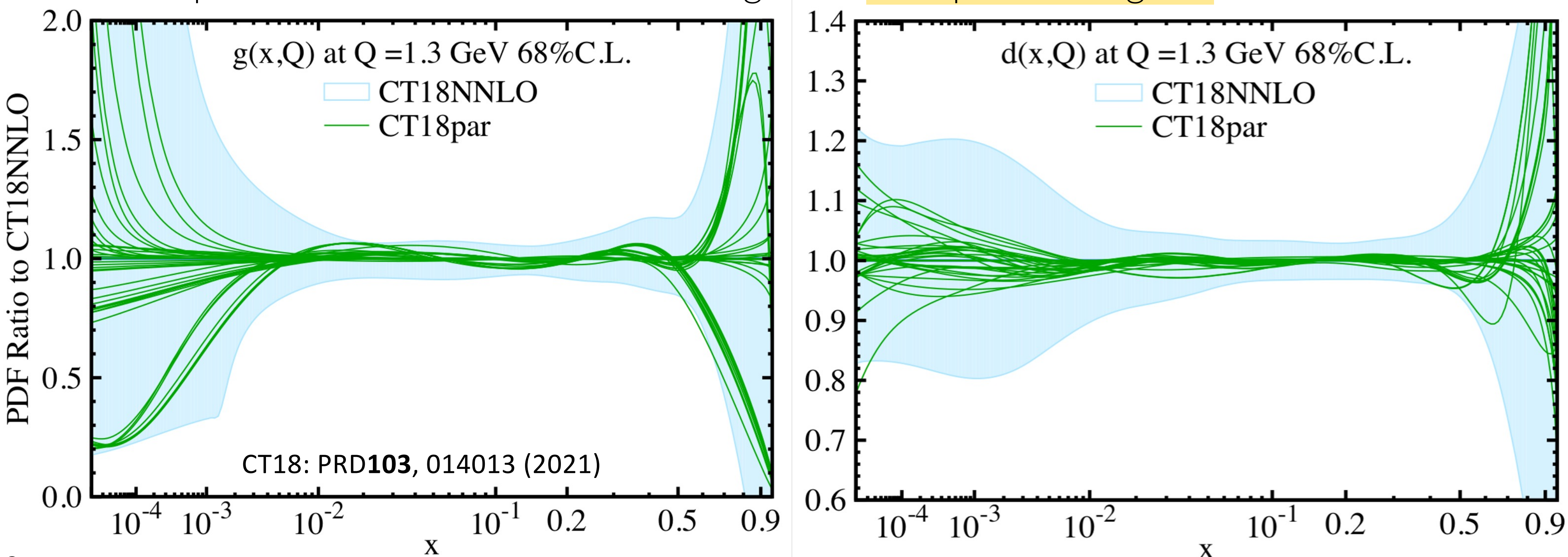
→ practice agnosticism w.r.t. initial parametrization

(some guidance from QCD, QCD-inspired models)

see talk, Lucas Kotz

→ explore model uncertainty with many forms

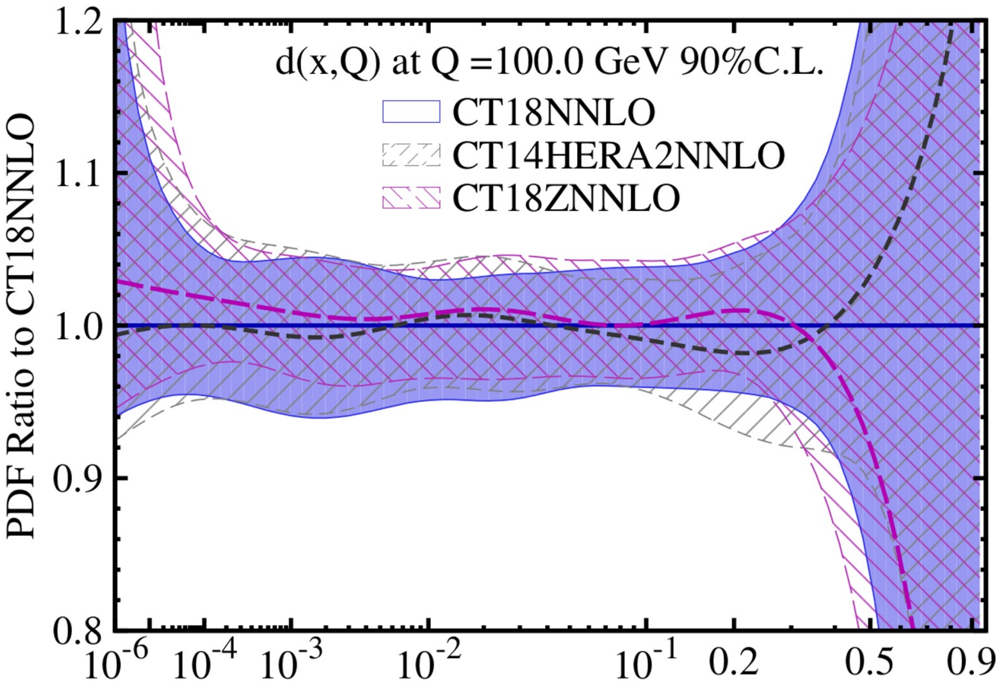
parametrization uncertainties largest in extrapolated regions

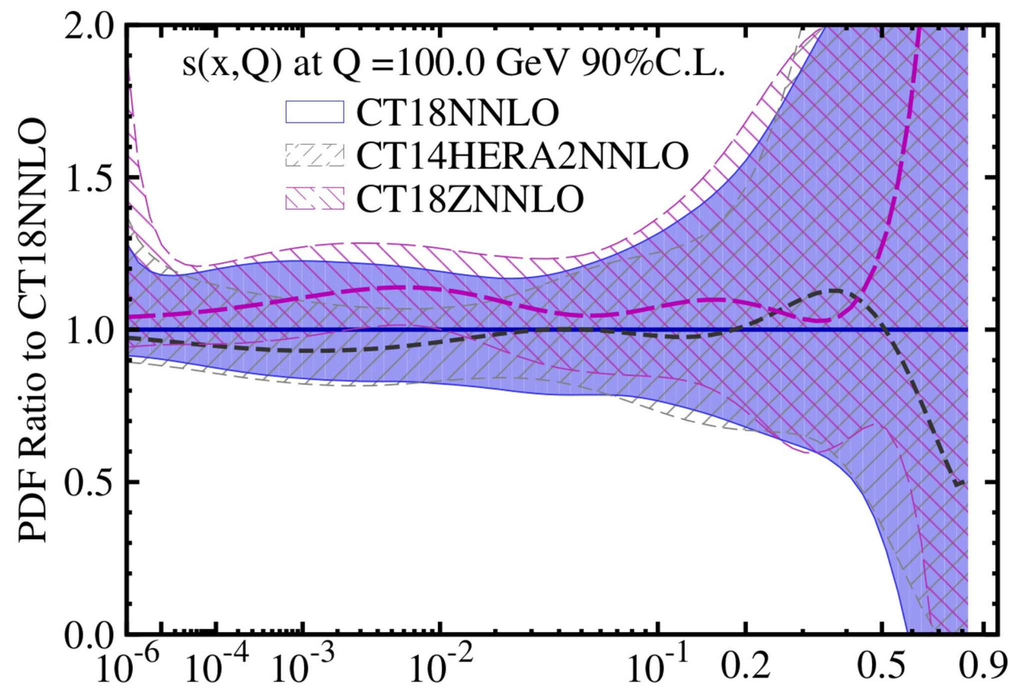


high-*x* PDFs remain dominated by large uncertainties

PDF (Hessian) uncertainties enlarge dramatically in high-*x* limit

→ limited data → extrapolation → data tensions

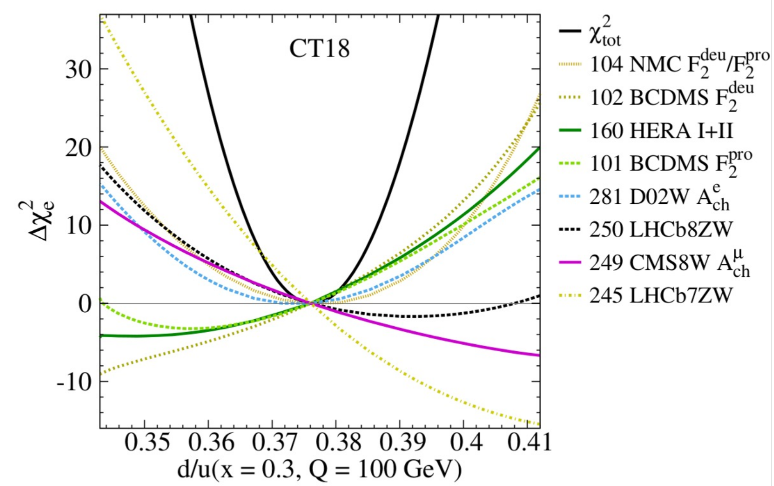




competing pulls of fitted data at high-*x* also restrict precision; *e.g.,*

→ BCDMS, F_2^d

→ LHCb, W/Z 7 TeV



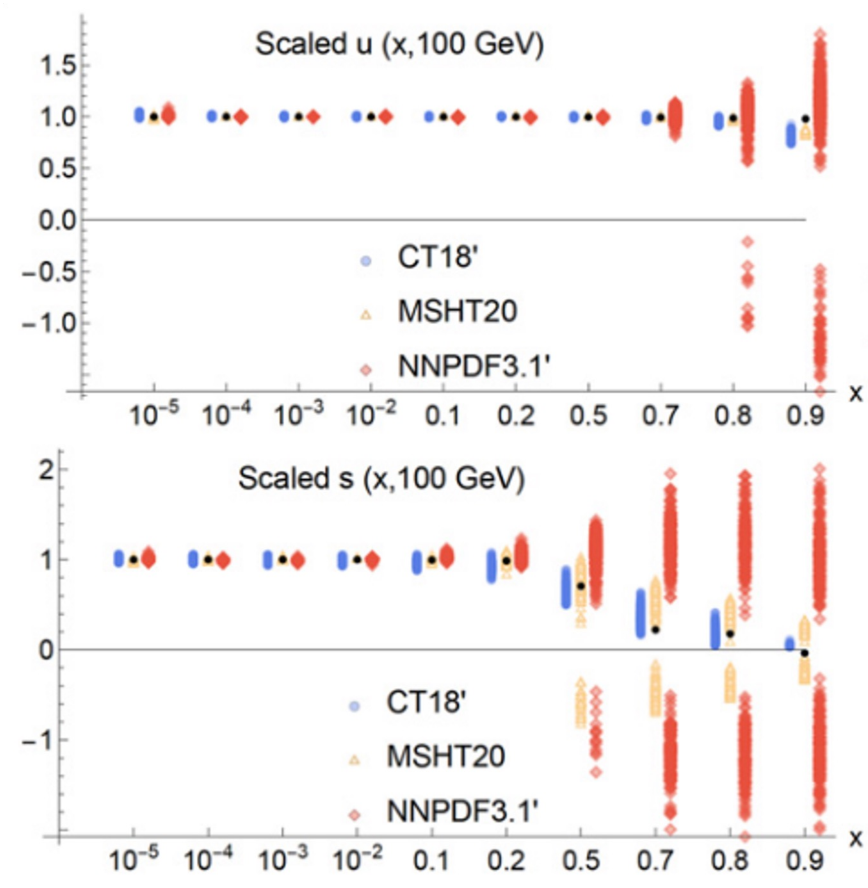
i

understanding PDFs and their uncertainties: high *x*

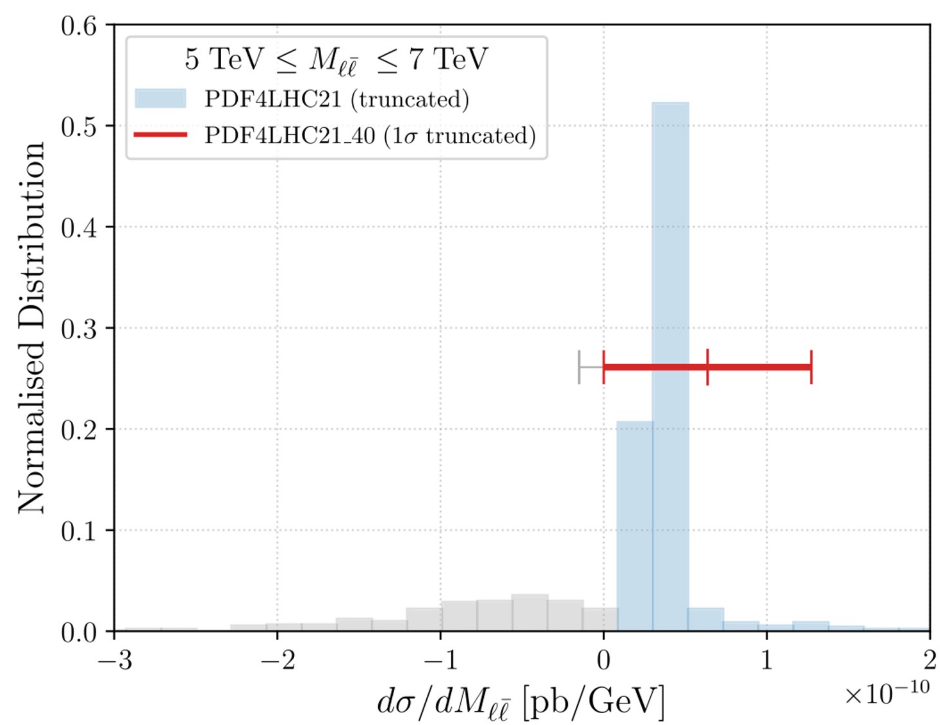
PDF4LHC21 benchmarking: 2203.05506

MC sampling of high-*x* PDFs can sometimes produce irregularities

→ *e.g.*, positive-definiteness not always guaranteed for $x \to 1$



→ can produce subtle but non-negligible phenomenological consequences:



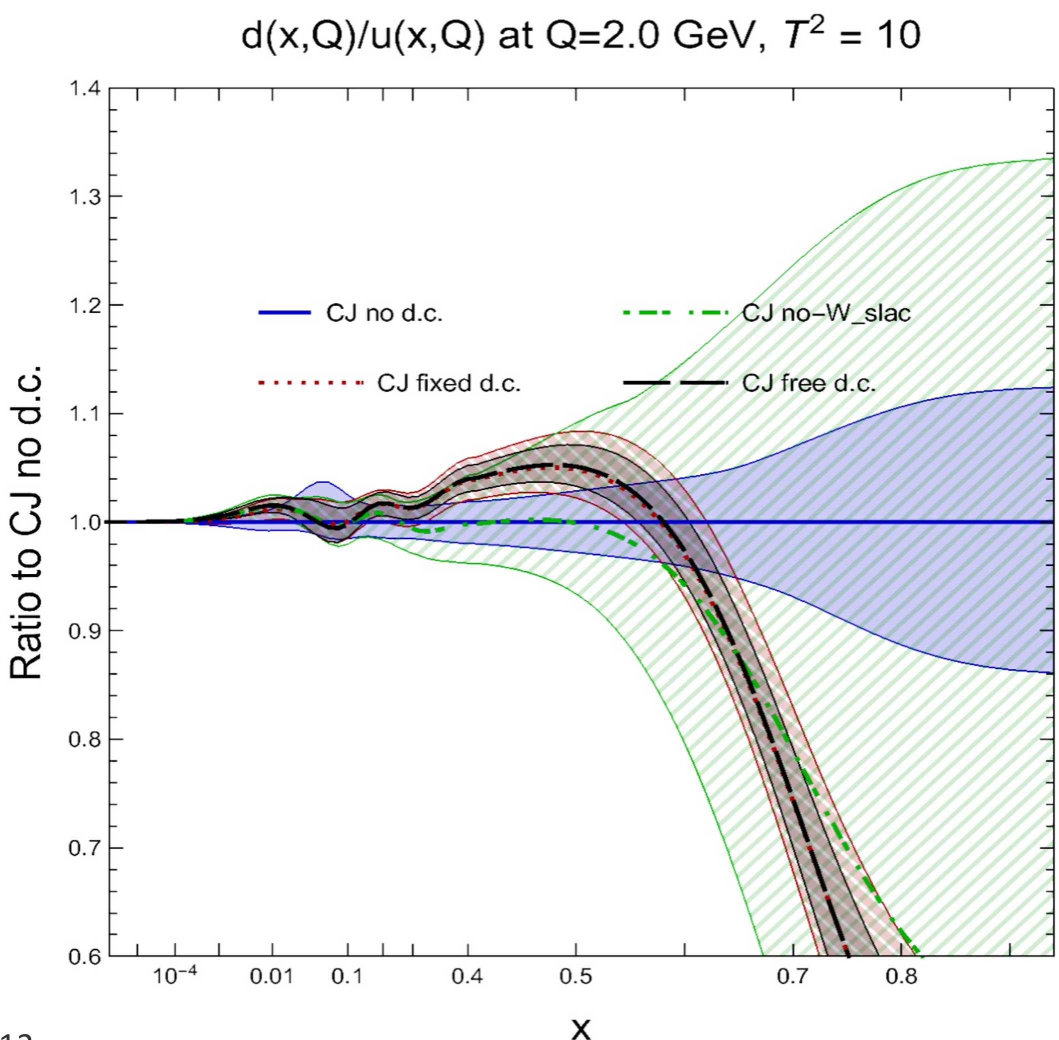
strong need for high-*x* sensitive data: (HL-)EIC; JLab12 [24]

Courtoy, Huston Nadolsky, Xie, Yan, Yuan: 2205.10444

example: high-*x* physics and light-nuclear (deuteron) corrections

d-PDF information from deuteron scattering; nuclear corrections relevant

$$f^d(x,Q^2) = \int \frac{dz}{z} \int dp_N^2\, \mathcal{S}^{N/d}(z,p_N^2)\, \widetilde{f}^N(x/z,p_N^2,Q^2)$$



Accardi, TJH, Jing, Nadolsky: EPJC**81** (2021) 7, 603

corrections are generally ~percent-level, but can become larger, especially at <u>high *x*</u>

impacts LHC observables; necessary for high precision

heavy-nuclear effects relevant for proton structure studies

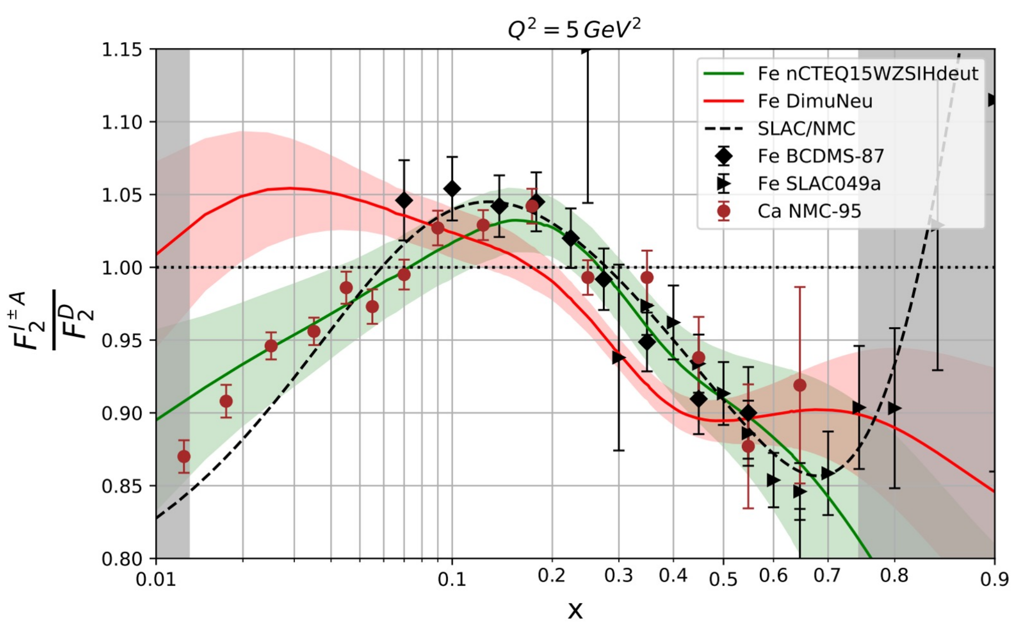
beyond few-body systems, PDF analyses often use <u>heavy nuclei</u> for flavor separation

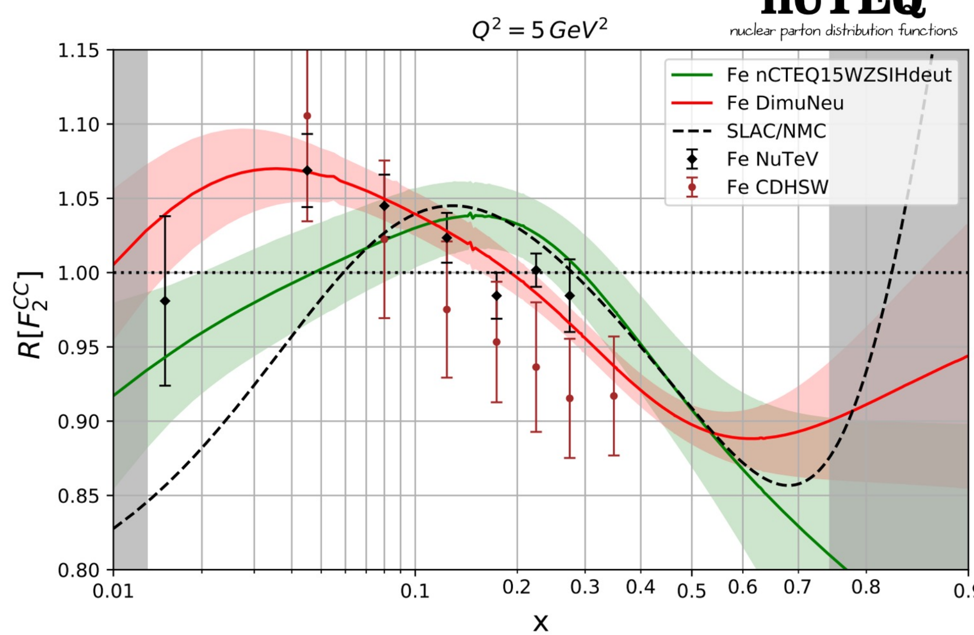
[e.g., νA for strangeness]

requires knowledge of nuclear corrections; these directly fitted by nPDF analyses

→ better control over *x*, *A* dependence can benefit nucleon PDF extractions

ongoing questions of statistical compatibility of neutrino-, charged-lepton scattering:





nCTEQ nuclear parton distribution functions

Muzakka, Duwentäster, TJH et al., 2204.13157

(HL-)EIC can help unravel these issues

→ higher luminosity helpful for nuclear collisions, which have lower $\sqrt{s}$

i nonperturbative theory developments: lattice QCD inputs

recent years: progress in *ab initio* hadron-structure calculations from LQCD

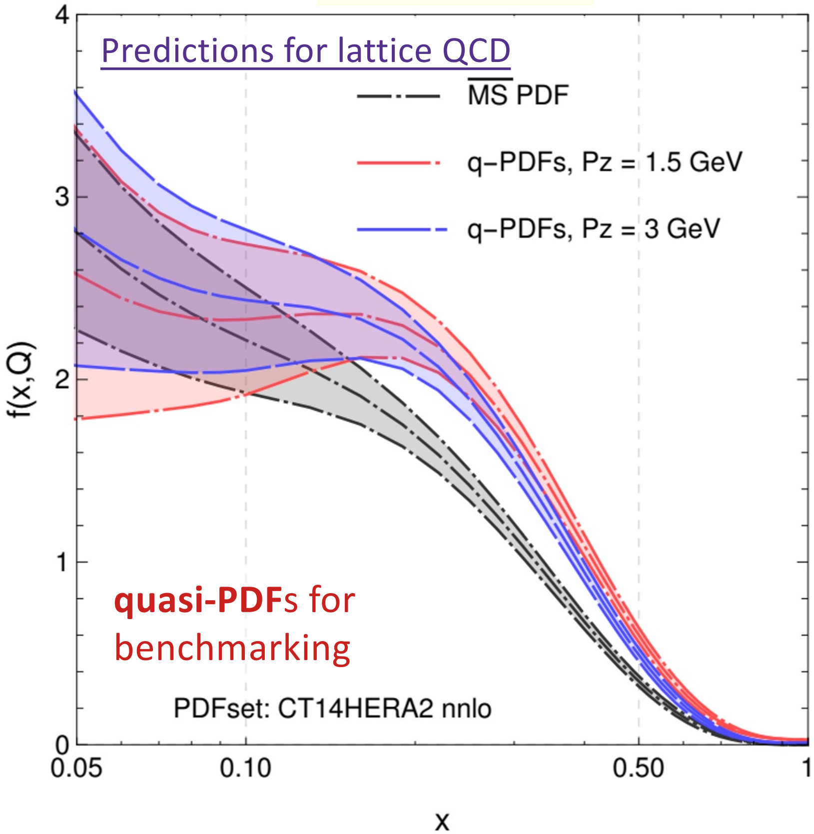
→ quasi-PDFs, pseudo-PDFs, quasi-TMDs, …

there are be important synergies between PDF fitting and lattice QCD

[overlaps with EIC; νDIS; LHC]

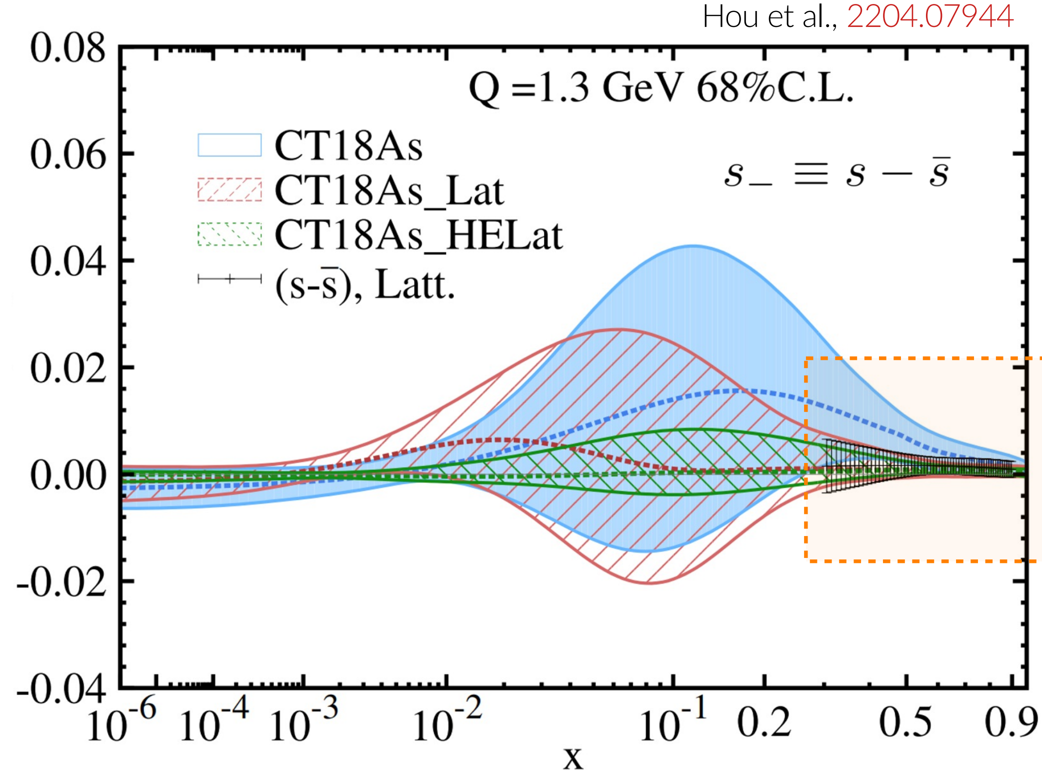
TJH, Wang, Nadolsky, Olness, PRD**100** (2019) 9, 094040

u–d at $\mu_F = 3$GeV



lattice data can potentially inform high-*x* behavior of quark sea

Hou et al., 2204.07944



ii

PDF precision both aided and challenged by experiments

array of (DIS) measurements needed as kinematical lever-arm; distinct EW probes

→ as proxy, consider role of EIC program: impacts on high *x*, HEP pheno.

see talk, Olness

EIC explores unique, complementary region in $[x, Q^2]$

→ strong coverage of quark-to-hadron transition region between HERA, JLab12

arXiv: 2007.14419

analogous nuclear DIS coverage

Eur. Phys. J. **A52** (2016) 9, 268.

PDF impacts compared to high-value fixed-target DIS

ePump: Schmidt, Pumplin, and Yuan; PRD98 (2018) no.9, 094005

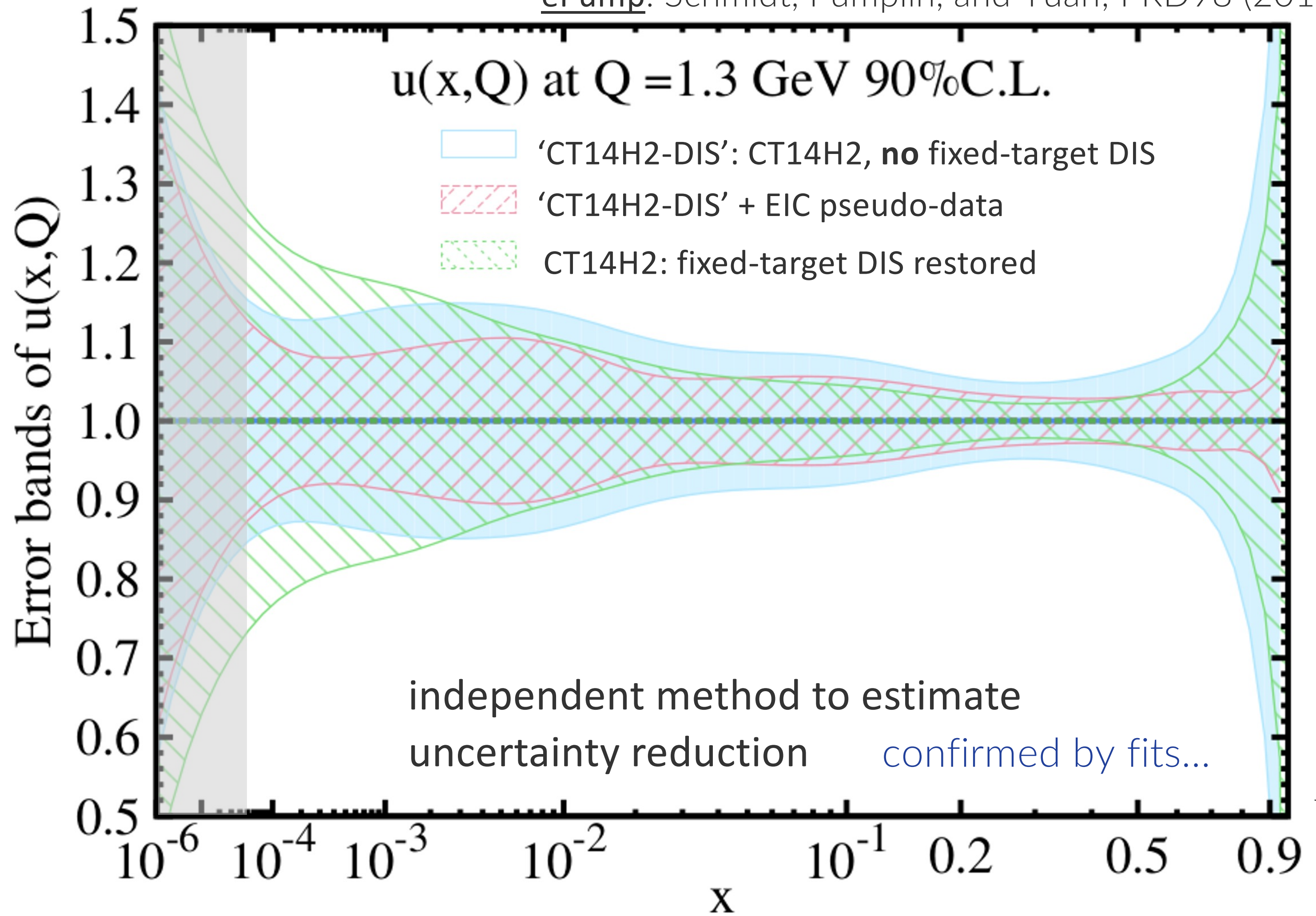


figure: S. Dulat

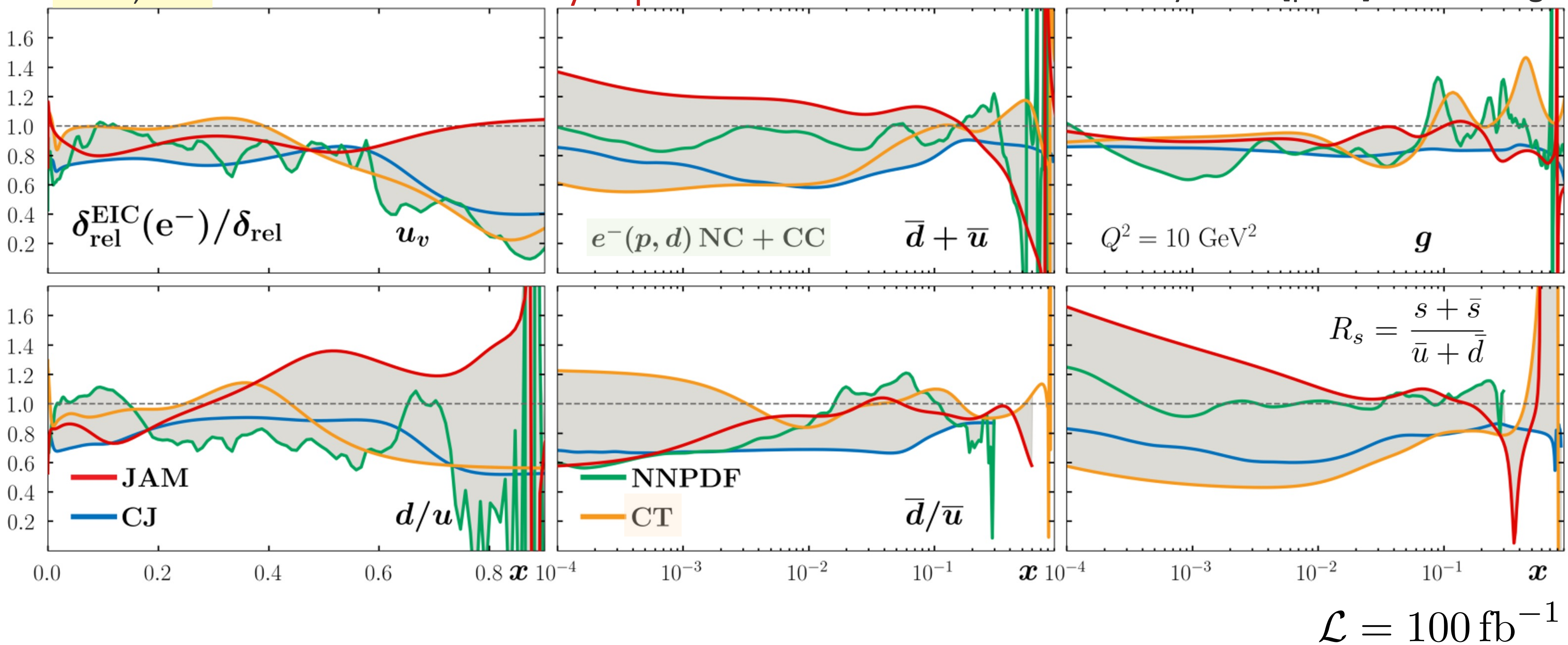
inclusive EIC may surpass total impact of fixed-target DIS in modern fits

→ useful for negotiating among existing high-impact data; high lumi could extend further

reductions to PDF uncertainties: <u>inclusive</u> DIS data

impact from simulated (optimistic) pseudodata; estimated by various methods, groups

EIC YR, 7.1.1 PDF uncertainty improvement ~1 year of [peak] data-taking



broad impact, including on high-x u-, d-PDFs; probes of gluon, quark sea to low x

→ <u>inclusive studies</u> – indications of systematics limitations; **must also investigate**

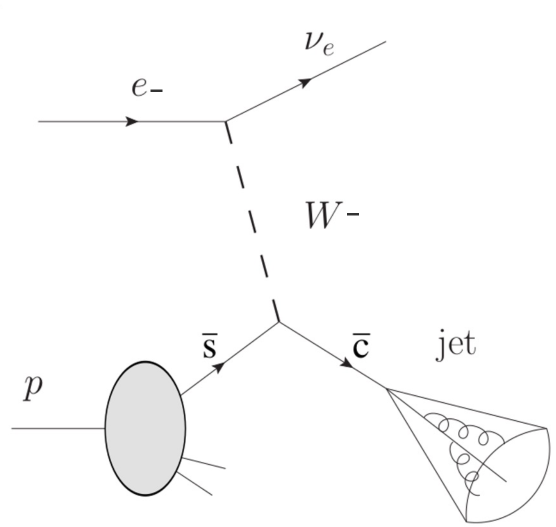
ii

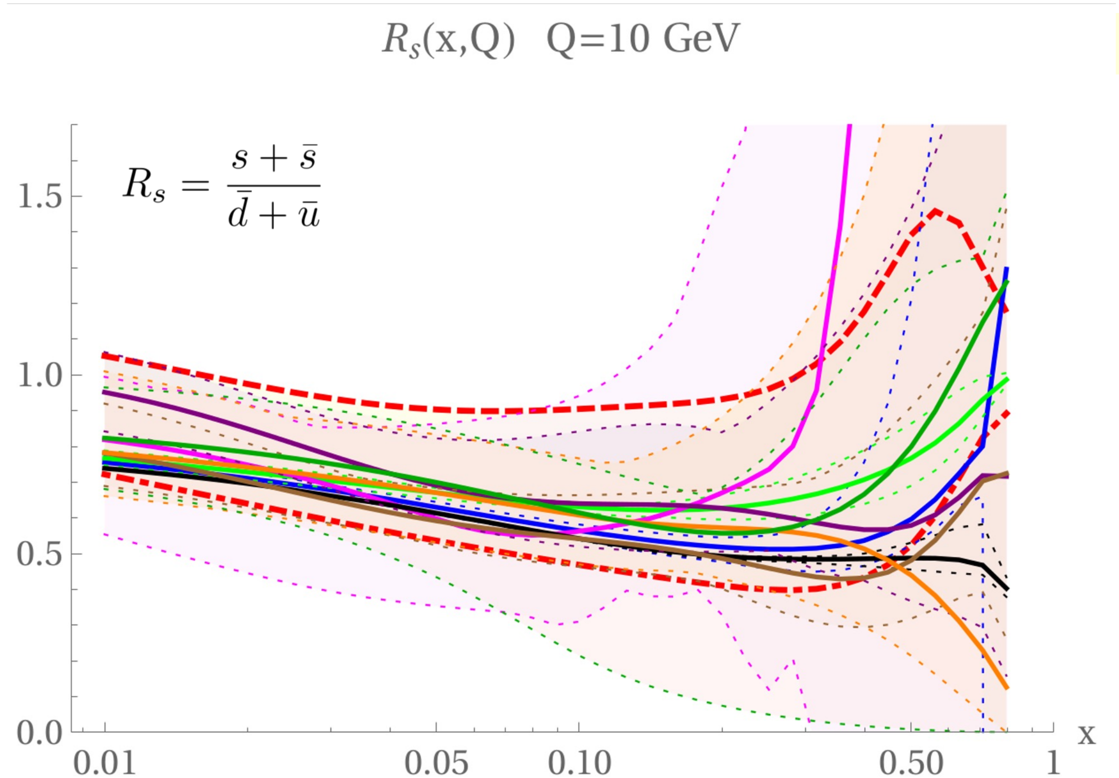
precision QCD through jet and heavy-flavor production

DIS jet production, including through charge-current interactions, provides further access to quark-level information

Arratia, Furletova, TJH, Olness, Sekula; PRD **103** (2021) 7, 074023

100 fb^{-1} CC DIS (10M simulated events), at 10x275 GeV (e^- on **p**); Q^2 > 100 GeV^2





final-state tagging provides lever arm for flavor separation (here, strangeness)

n.b.: event generation, detector sim from PYTHIA8 + DELPHES; FASTJET reconstruction

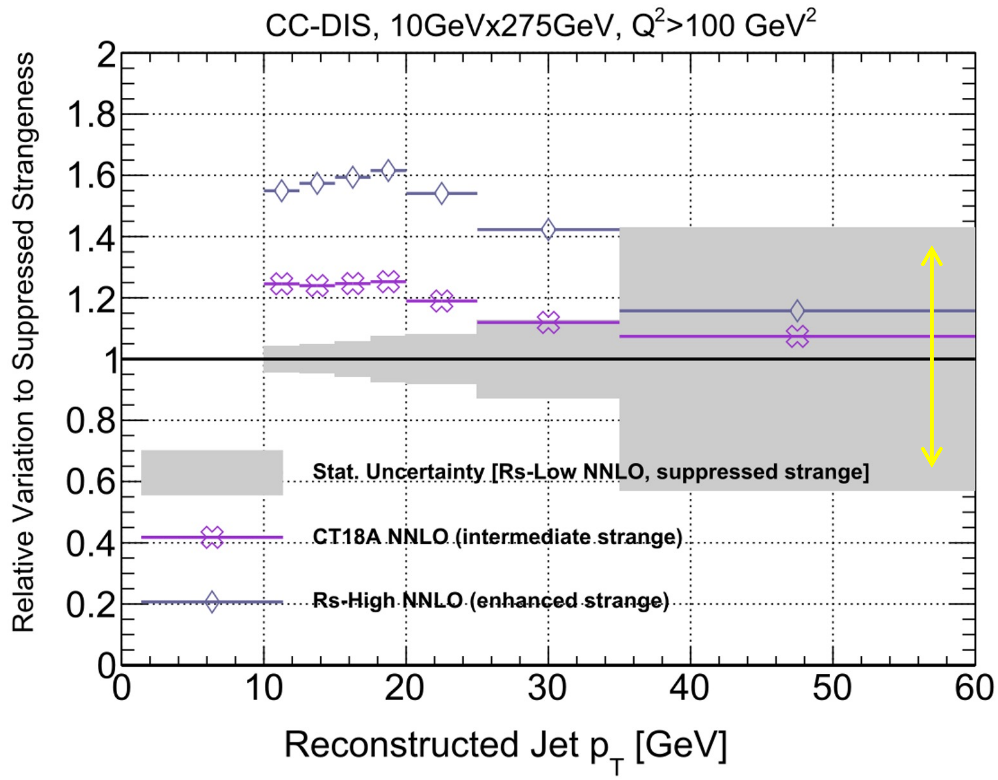
→ analogous jet measurements might be extended to nonperturbative heavy flavor

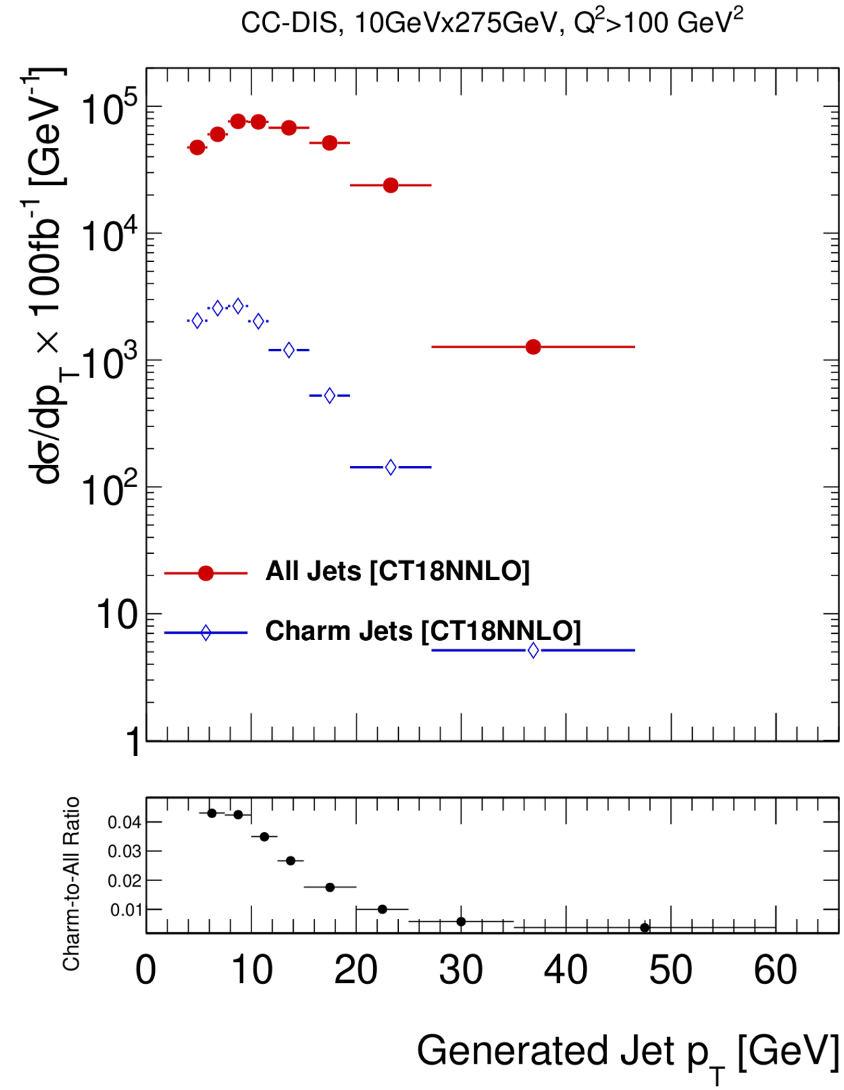
ii

precision QCD through jet and heavy-flavor production

challenging measurement: final-state flavor tagging; Jacquet-Blondel reconstruction

Arratia, Furletova, TJH, Olness, Sekula; PRD **103** (2021) 7, 074023





charm production suppressed by >2 orders of magnitude; p_T cross section steeply falling

reduced $\delta_{\rm stat}$ could significantly enhance knowledge of p_T dependence

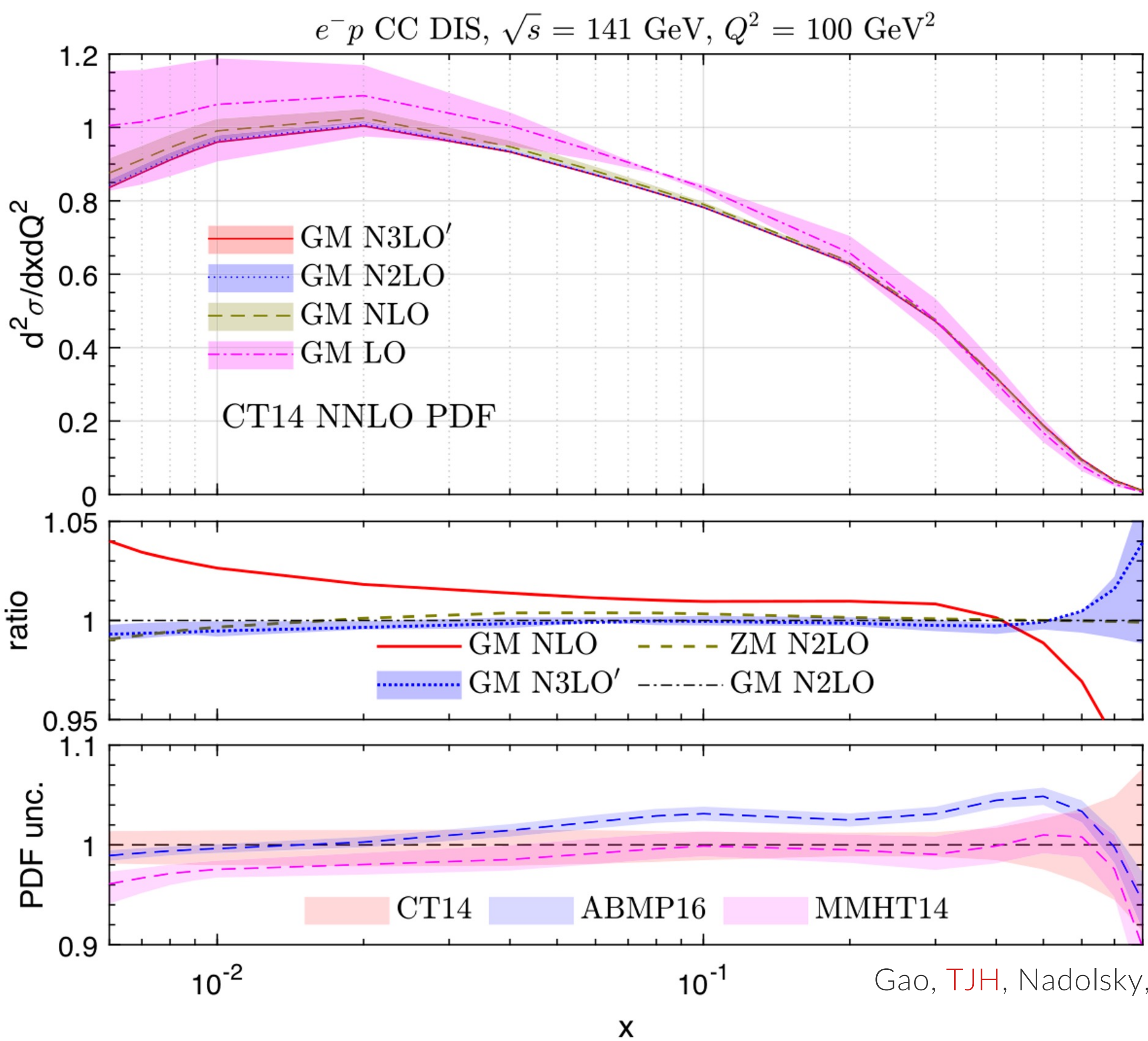
→ PDF impacts of rarer processes may require dedicate theory studies (xFitter utility)

ii

(CC) DIS at NNLO and beyond

extracting PDF information from CC DIS requires robust theory accuracy

→ can compute NNLO, approximate ~N^3LO corrections for highest energies at EIC



strong perturbative convergence

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

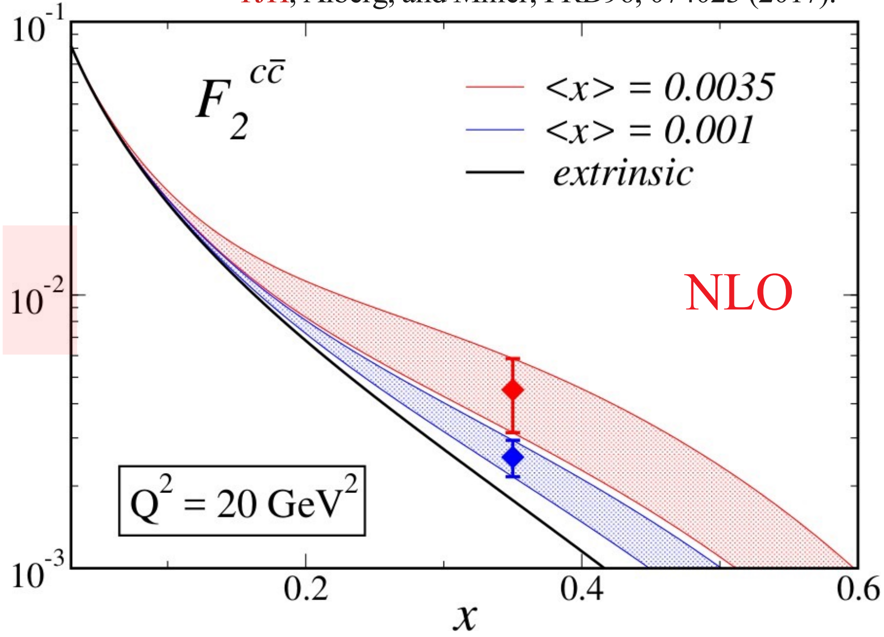
significantly smaller than PDF-driven uncertainties, which can be as large as $\approx 2\%$

vital ingredient in EIC PDF program

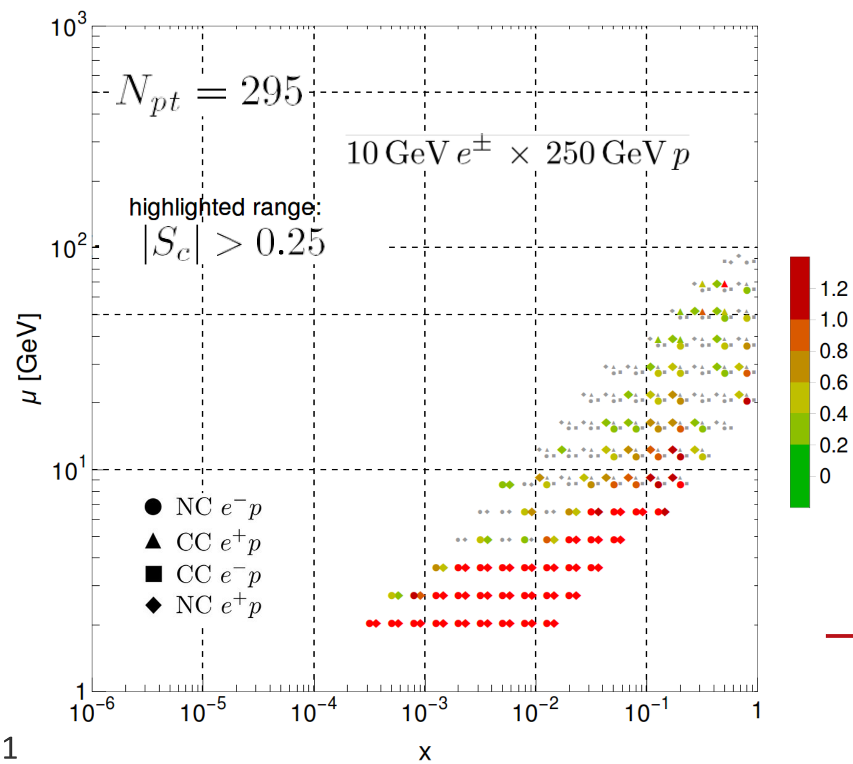
note improvements at high *x*: suggests possible synergy with high-luminosity measurements

Gao, TJH, Nadolsky, Sun, Yuan: PRD**105** (2022) 1, L011503

TJH, Alberg, and Miller; PRD96, 074023 (2017).



| S_f | for c(x,μ), CT14 HERA2 NNLO



require more data to resolve nonperturbative charm

arXiv:2211.01387

EIC + lattice QCD will constrain nonperturbative charm scenarios

- enhanced nonperturbative charm 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 nonperturbative signals would be expected

ii

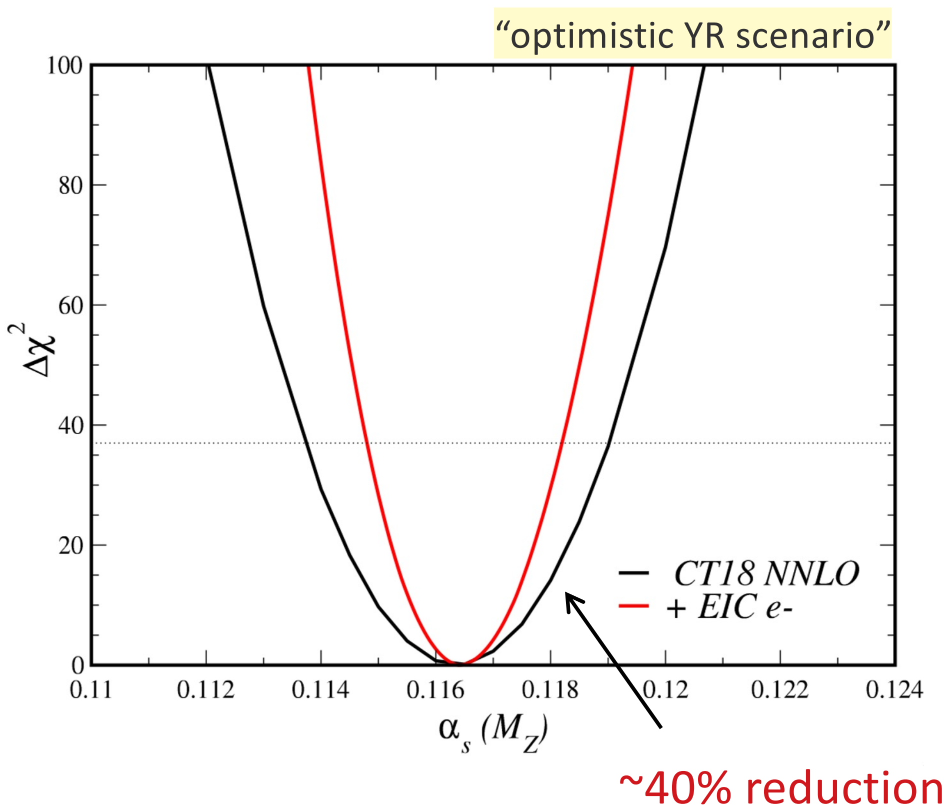
EIC and SM inputs: α_s

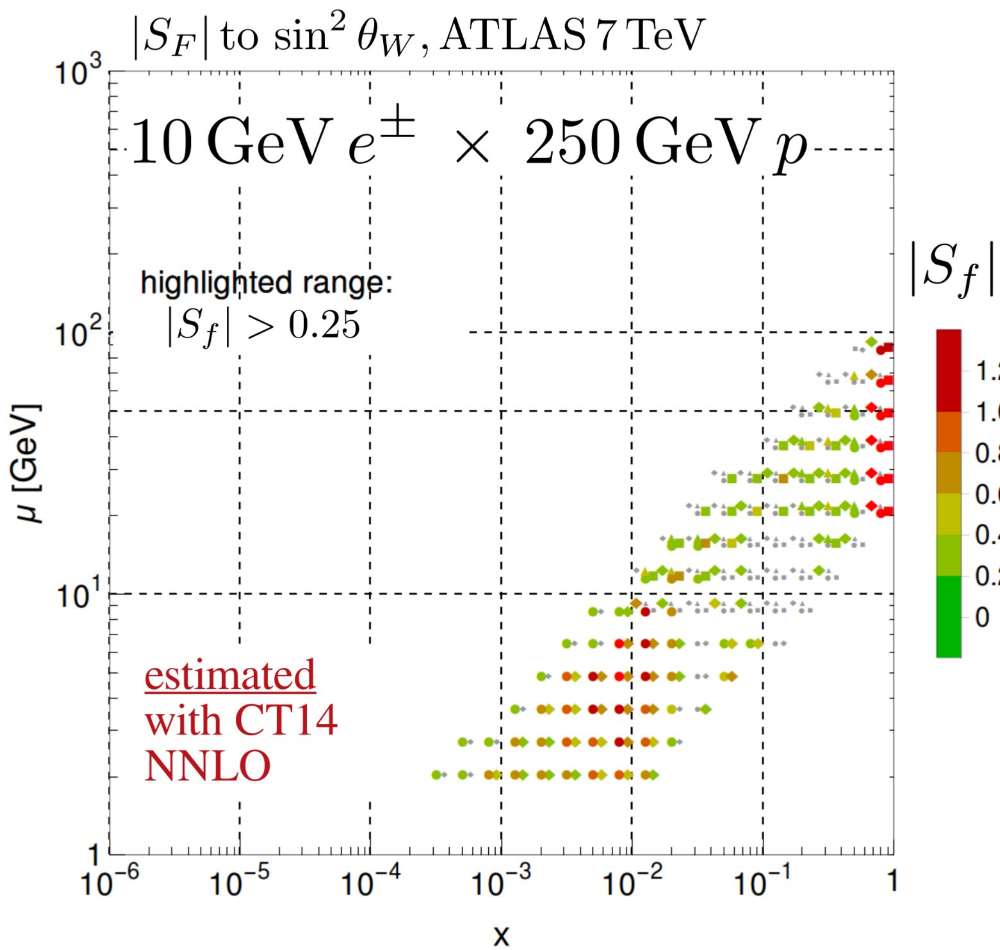
part of moving toward N^{3}LO PDFs, precise determinations needed for α_s

similar argument for m_Q

from inclusive data alone

B.-T. Wang et al., PRD 98 (2018) 9.



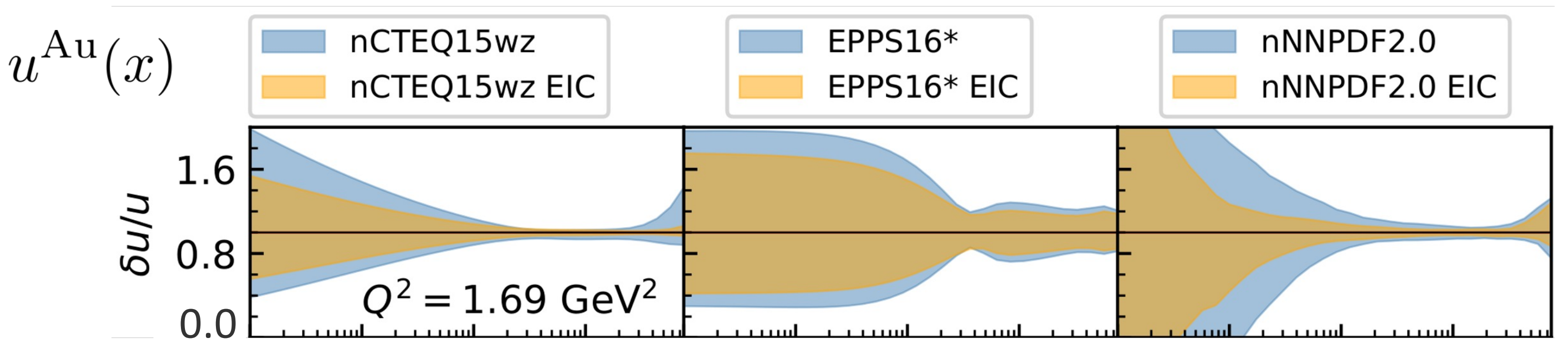


also: precise α_s extractions based on global event shapes; N-jettiness, τ_N

robust PDF sensitivity to $\sin^2\theta_W$ from A_{FB}

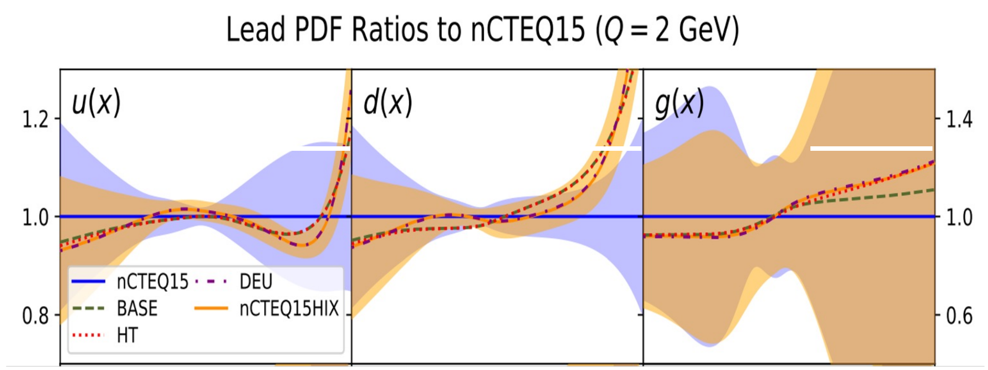
understanding nuclear effects

→ EIC: measure only “clean” DIS from hadrons; but also explore nuclear medium!



EIC YR, 7.3.3

nPDFs can inform nuclear effects in free-nucleon studies and *vice versa*:



Segarra et al., PRD **103** (2021) 11, 114015

→ nuclear effects: jet production, hadronization; implications for AA, UPC programs

nuclear *A* dependence requires copious data: **high luminosity at EIC essential**

ii

sensitivity to possible 'new' QCD measurements

strong interest in measurements connecting event-level observables to fundamental QCD

e.g., QCD jets (various observables, constructions)

→ closely related to tests of QCD factorization

event-shape measurements: energy correlation functions well-explored at LHC

Energy-Energy Correlation

→ explore scaling to EIC kinematics

Transverse EEC

→ further understanding of TMD physics

accurate control over relevant cross sections will require more theory

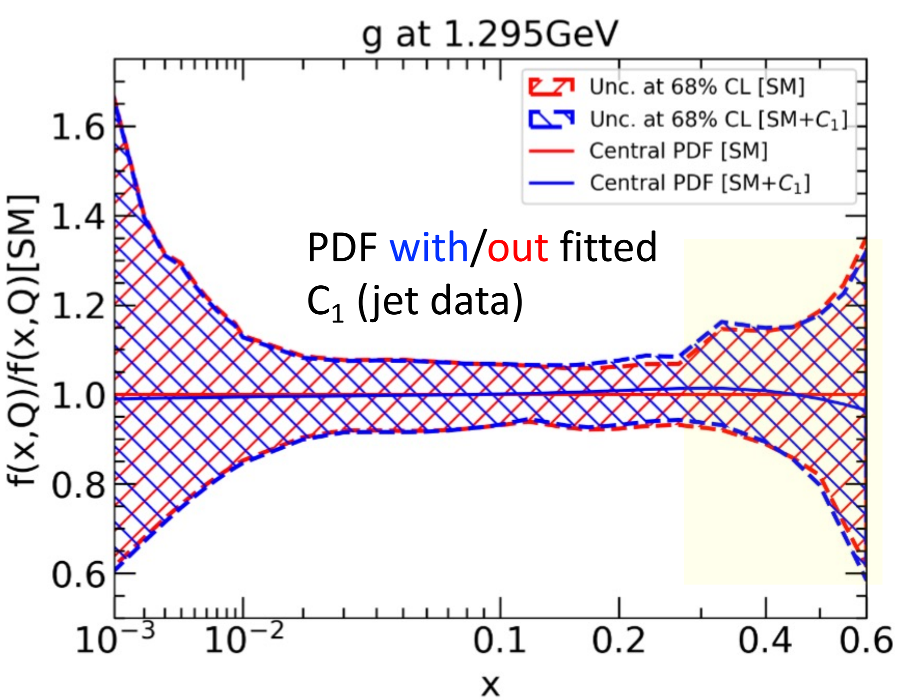
BSM aspects in joint fits with PDFs

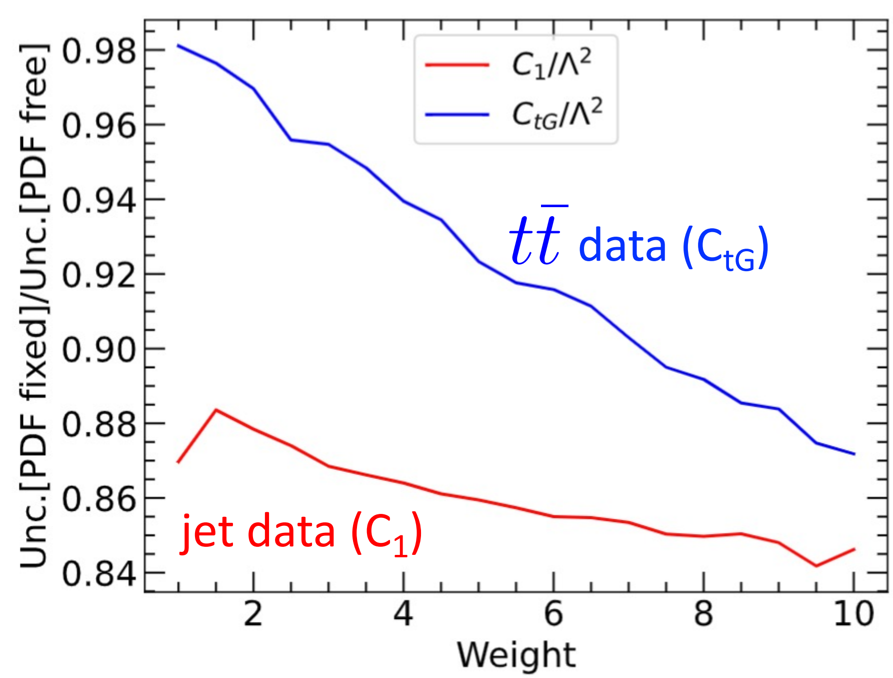
arXiv:2211.01094

- ongoing effort to constrain BSM model independently via EFT (SMEFT) global fits

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i O_i^{(6)}}{\Lambda^2} + \ldots$$

→ to minimize bias: jointly fit PDFs, SMEFT; examine PDF-SMEFT correlations





- PDF-SMEFT correlations (*e.g.*, with high-*x* gluon) are <u>mild</u> for jet, $t\bar{t}$ data

→ likely more severe with higher precision (HL-LHC); requires further development iii

conclusions: xFitter for PDFs in EIC era

PDF and HEP accuracy require interlocking theory and analysis inputs

- → pQCD and EW theory development
- → nonperturbative QCD formalism and modeling
- → for many precision applications, these are *not* separable
- → parallel frontier: uncertainty quantification (benchmarking, algorithm dev)

EIC will reciprocally inform and depend on these aspects

- → strong PDF and QCD sensitivity across many processes
- → conversely, need theory development to ensure interpretation of data

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xFitter as **modular**, open-source framework can play a valuable role

as a testbed, xFitter theory modules can be refined, released to community

- → many calculations highlighted here amenable to such development
- → analysis modules may also be benchmarked inside xFitter