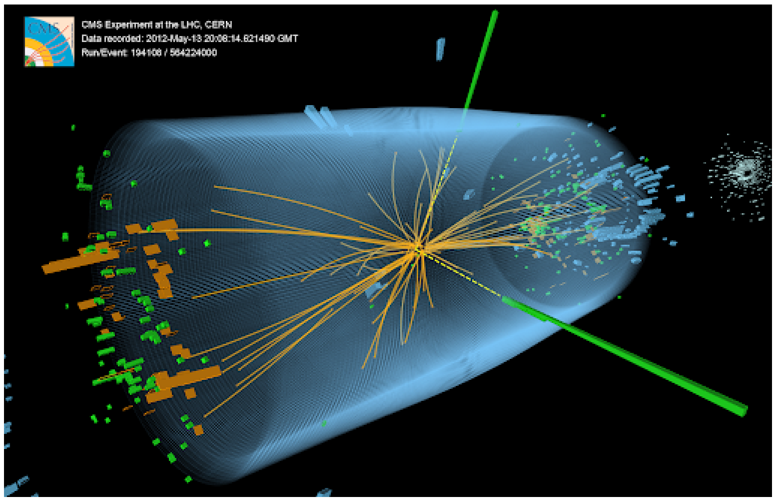
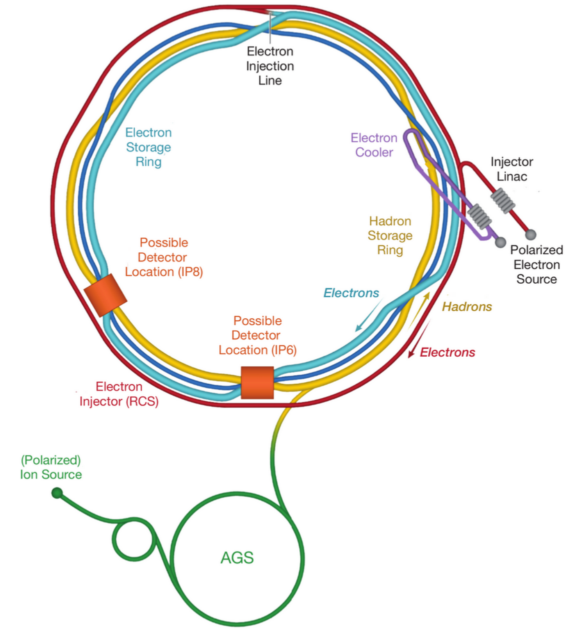
Frontiers in precision for global PDF analyses

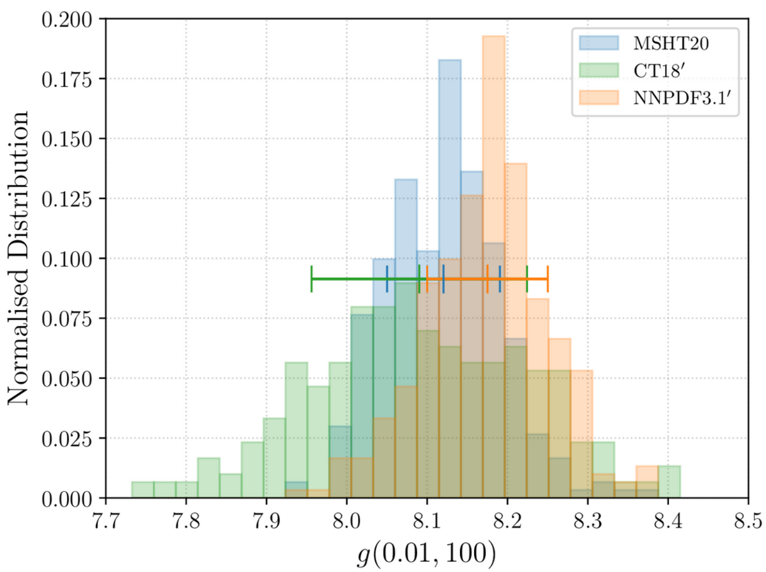
Tim Hobbs – Fermilab, IIT

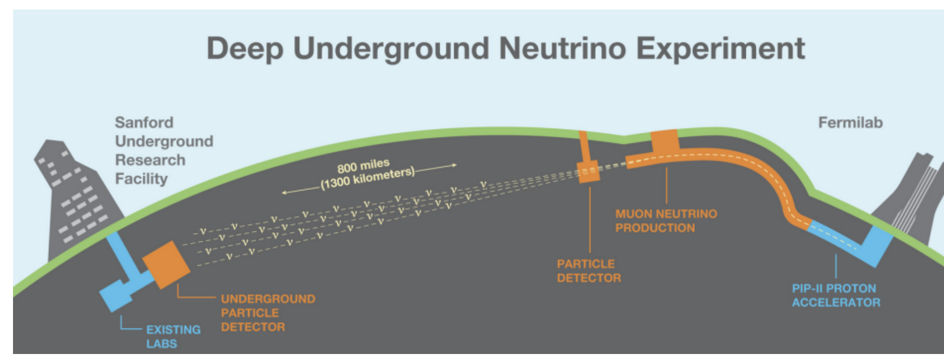
2nd August 2022

see ‘roundtable’:
High Precision
QCD Frontier









Fermilab

ILLINOIS INSTITUTE OF TECHNOLOGY

this talk: PDFs central to **2 core needs in fundamental QCD**

1: precision BSM searches limited by (incomplete) proton structure info

→ many standard-candle HEP measurements PDF-limited

→ taming PDF dependence: knowledge of hard-to-access phase-space regions

→ PDF studies vital to NP QCD (confinement!), mapping hadron structure

2: must interrogate (p)QCD to achieve higher theoretical accuracy

→ stability of PDF extractions partly depends on pQCD formalism

→ tests of, e.g., QCD factorization, (systematic) knowledge of limits needed

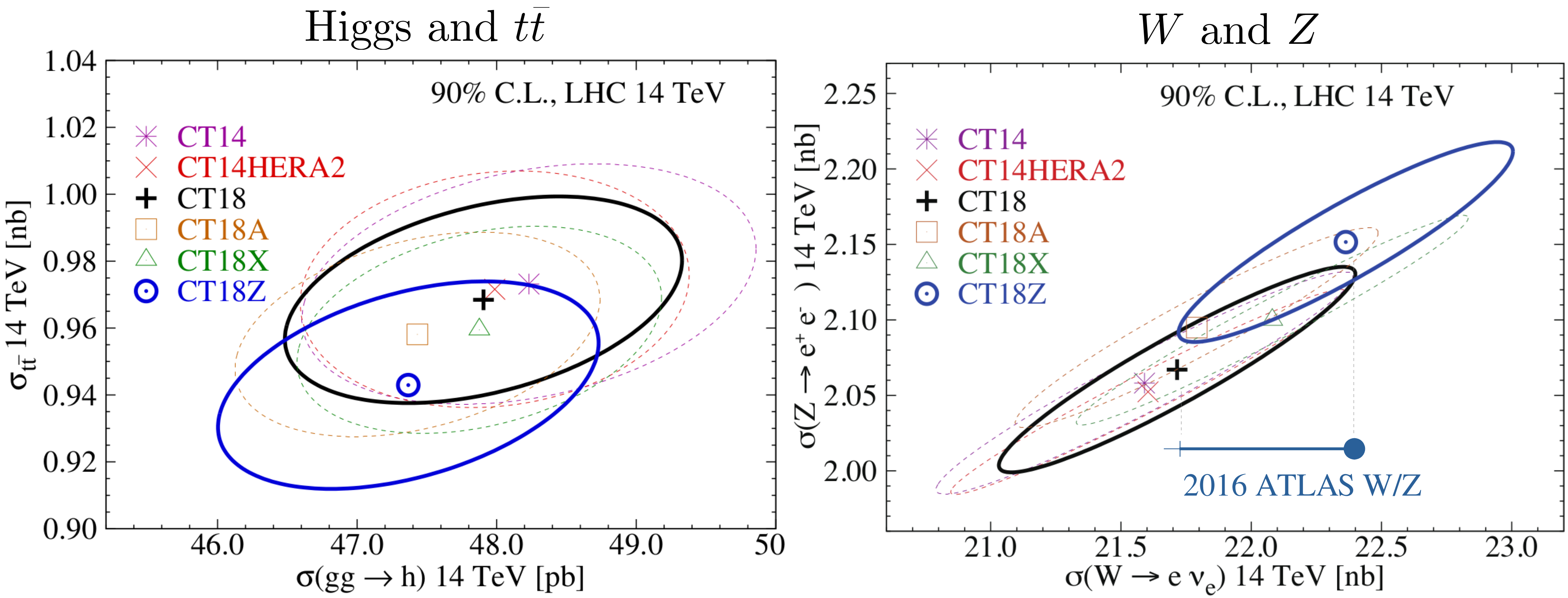
highlight through: i current status of PDFs; ii experimental opportunities (EIC)

iii conclusion(s)

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

high-interest SM quantities are precision-limited by PDFs

→ these include σ_H, $\sin^2\theta_W$, m_W, ...

ATLAS, 1701.07240

<u>for example</u>:

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

→ the PDF uncertainty can be a/the dominant uncertainty!

→ frontier efforts at the HL-LHC aim for (sub)percent precision

→ **large 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

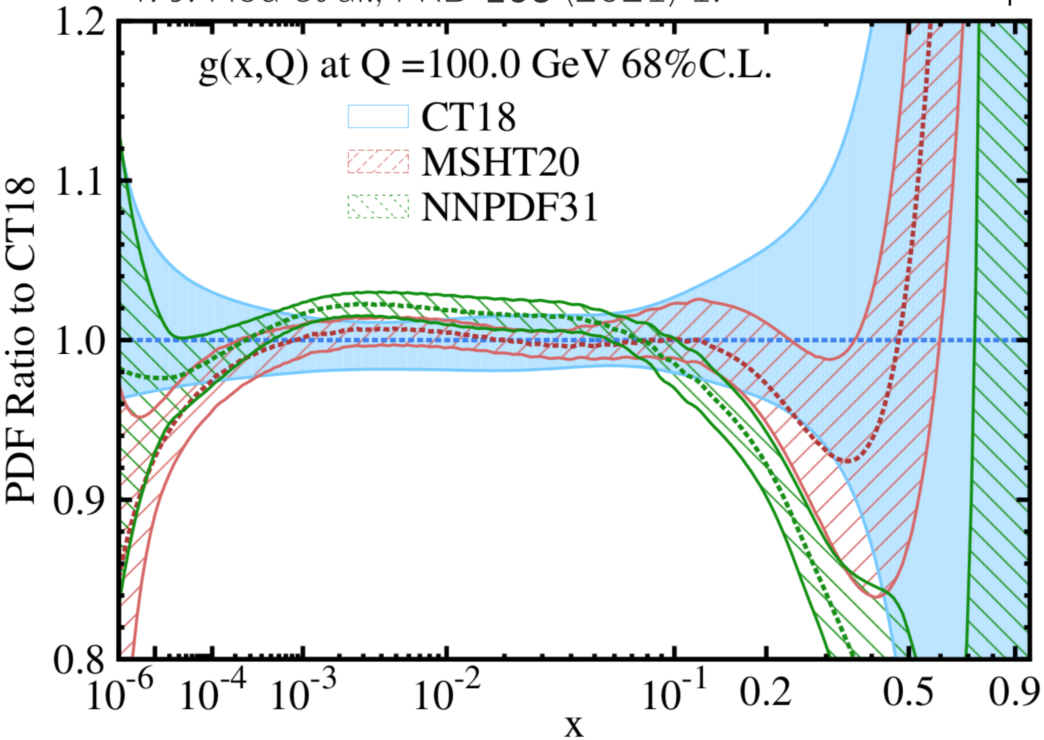
Snowmass21, Amoroso et al.: 2203.13923

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

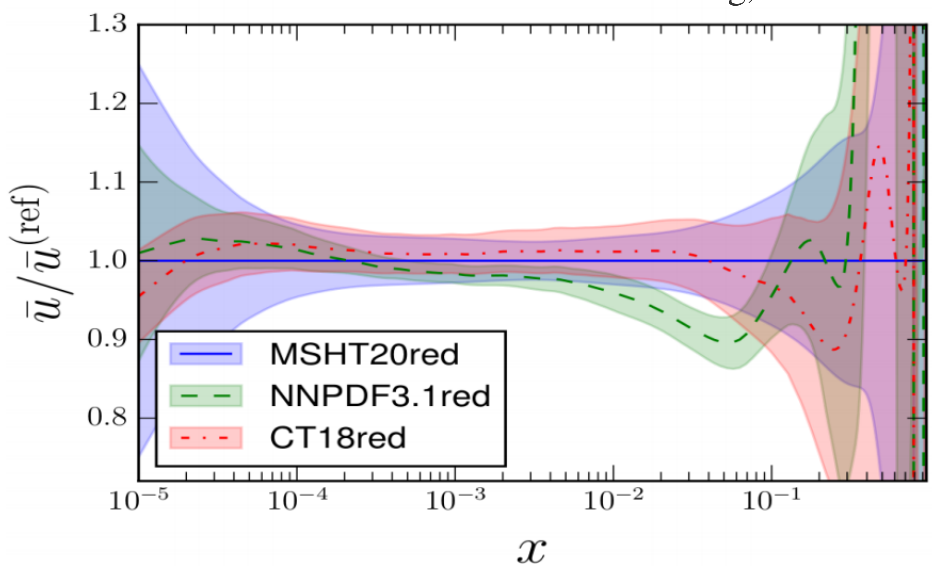
$$\sigma(AB \to W/Z+X) \;=\; \sum_n \alpha_s^n \sum_{a,b} \int dx_a dx_b\, f_{a/A}(x_a,\mu^2)\, \hat{\sigma}^{(n)}_{ab\to W/Z+X}(\hat{s},\, \mu^2)\, f_{b/B}(x_b,\mu^2)$$

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

contemporary NNLO 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

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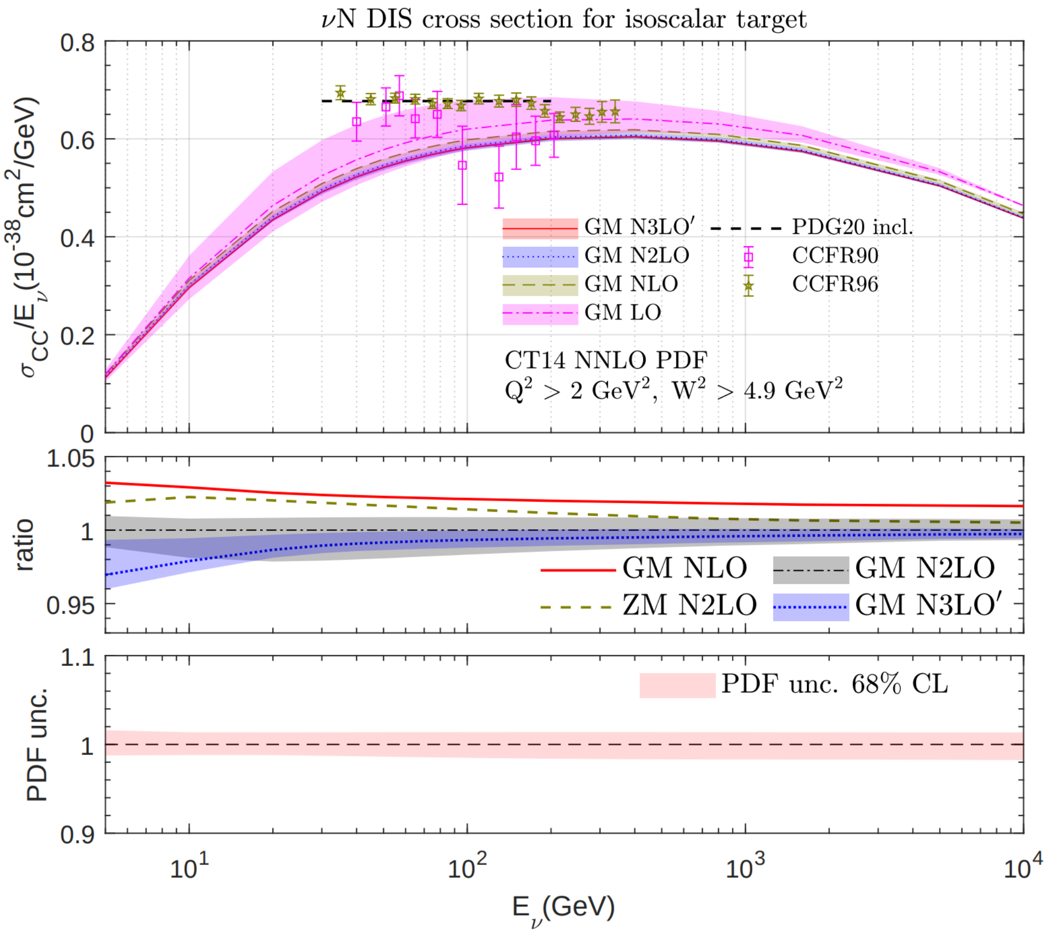
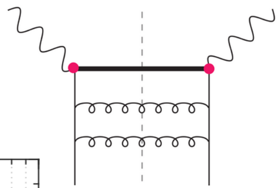
theory ingredients → higher pQCD accuracy

- current/future analyses involve interplay between pQCD & other dynamics
- NNLO+ necessary to stabilize scale uncertainties; especially over wide scales

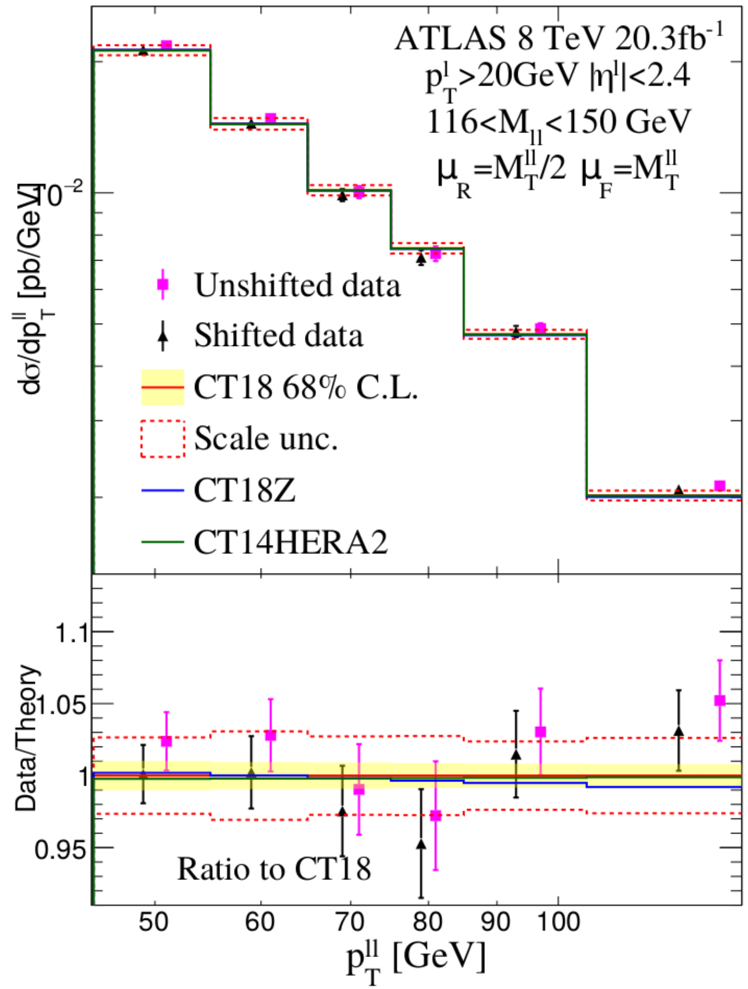
charge-current DIS

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





NNLO scale variations at LHC



→ needed for DUNE, FASERν, EIC

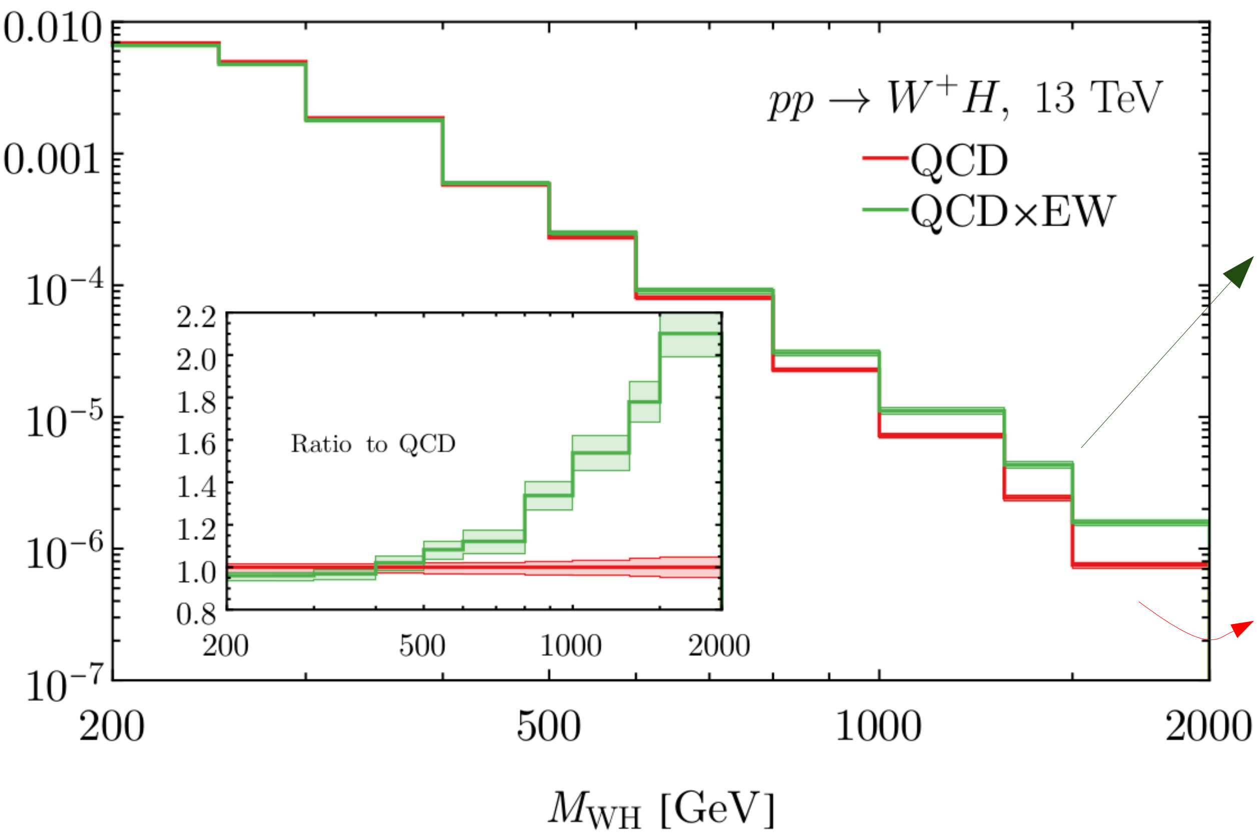
CT18 NNLO, PRD **103** (2021) 1

electroweak (EW) corrections also vital

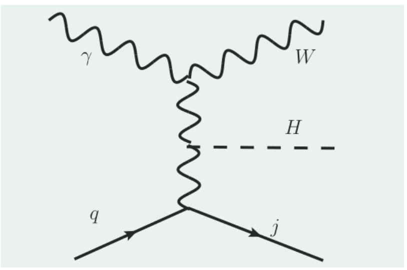
- at $\mathcal{O}(\alpha_s^2)$ accuracy, EW corrections and explicit $\gamma(x, \mu^2)$ needed

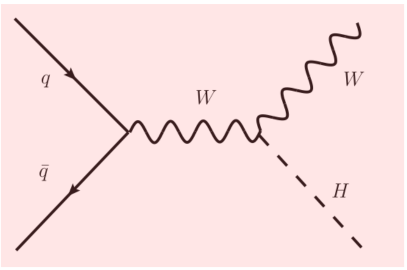
Xie, TJH, Hou, Schmidt, Yan, Yuan: PRD**105** (2022) 5, 054006

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



MCFM
HAWK





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

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

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necessary for electroweak precision: photon PDF

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

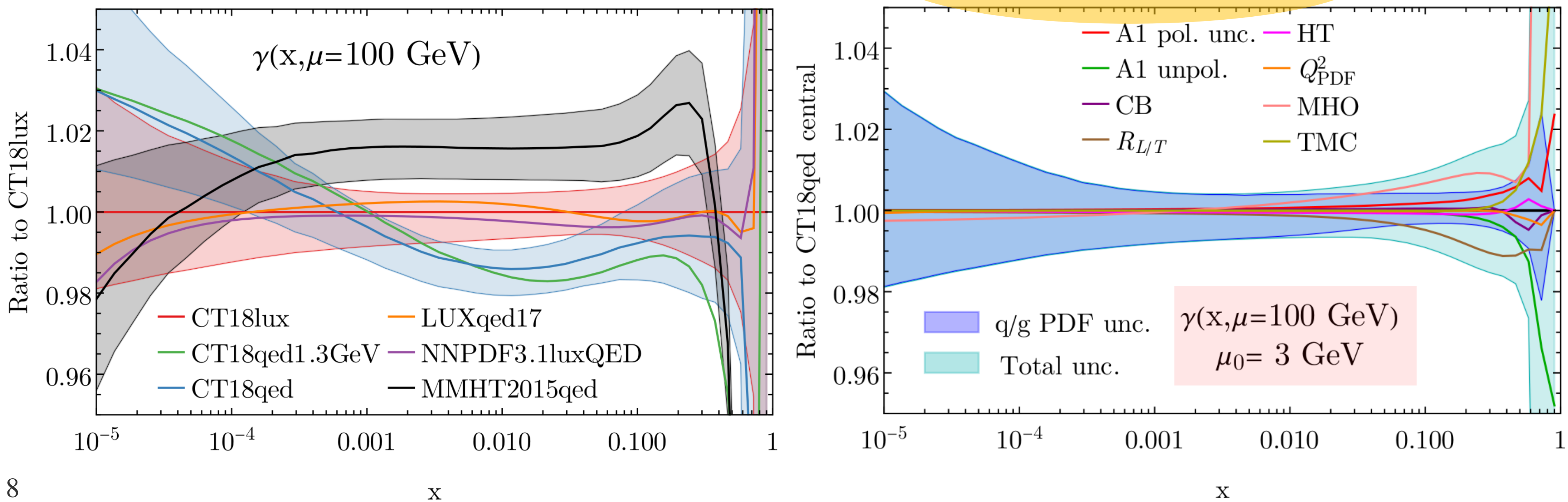
Xie, TJH, Hou, Schmidt, Yan, Yuan: PRD**105** (2022) 5, 054006

- following CT14QED, CT18QED now interfaces LUX formalism

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

- depends on nonperturbative inputs [kinematical cuts alone can't avoid this]

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



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parametrization uncertainty: nonperturbative fitting forms

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

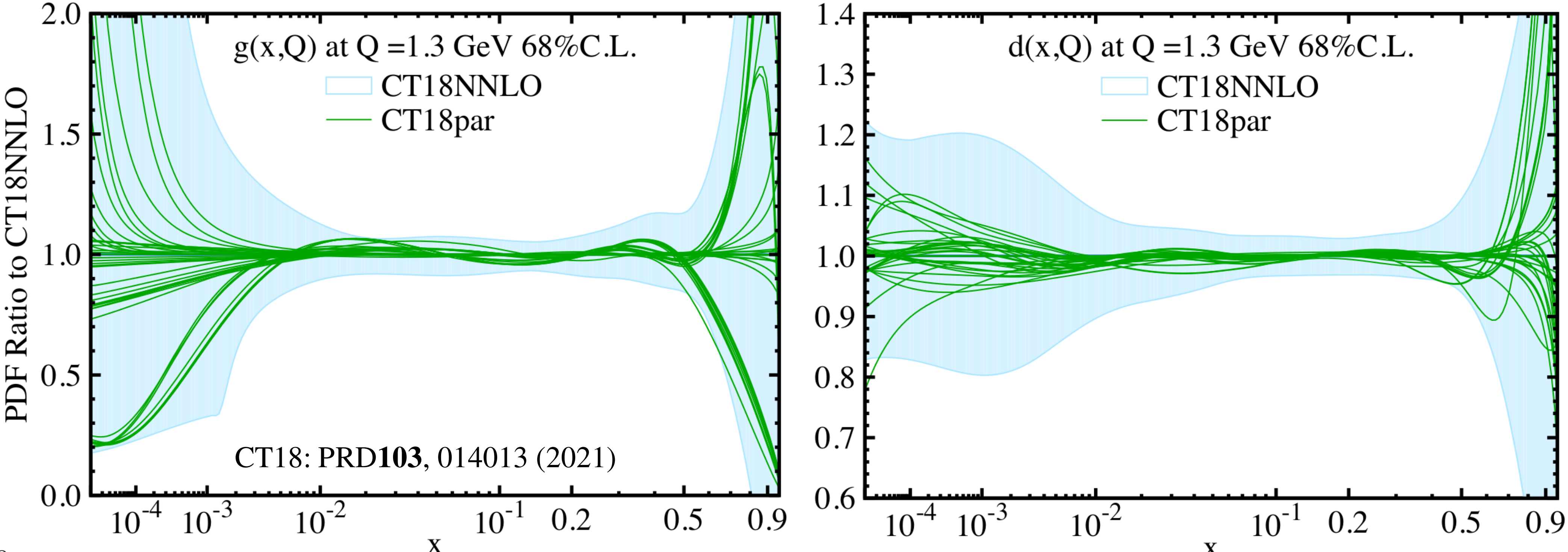
→ subject to complex nonperturbative dynamics

→ practice agnosticism w.r.t. initial parametrization

(some guidance from QCD, QCD-inspired models)

→ explore model uncertainty with many forms

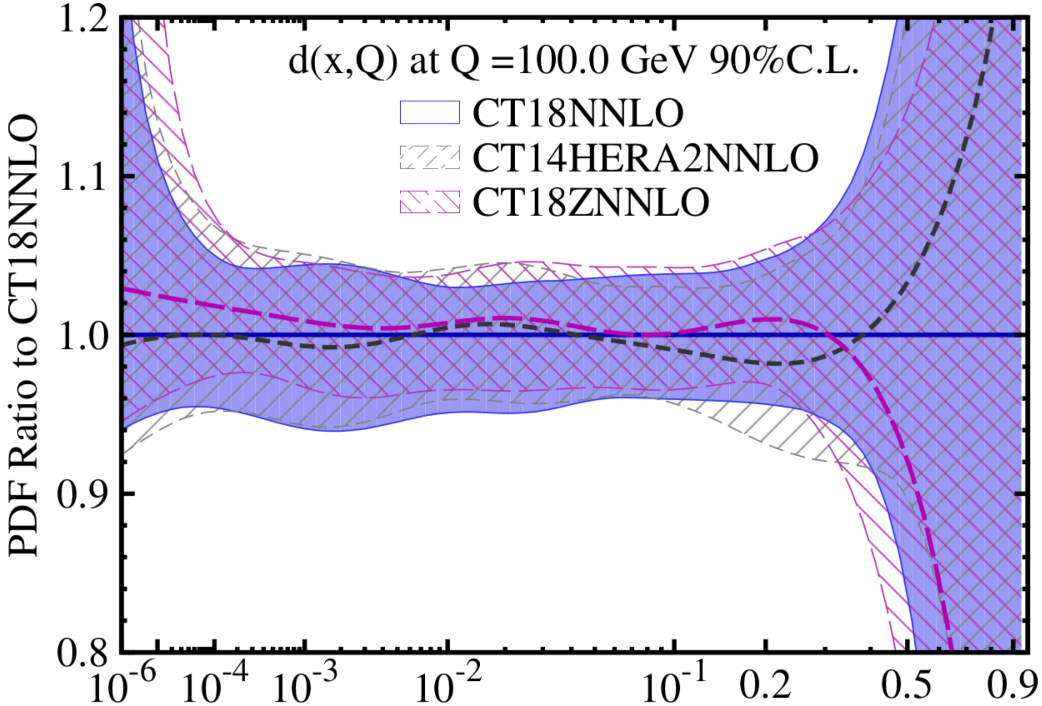
parametrization uncertainties largest in extrapolated regions

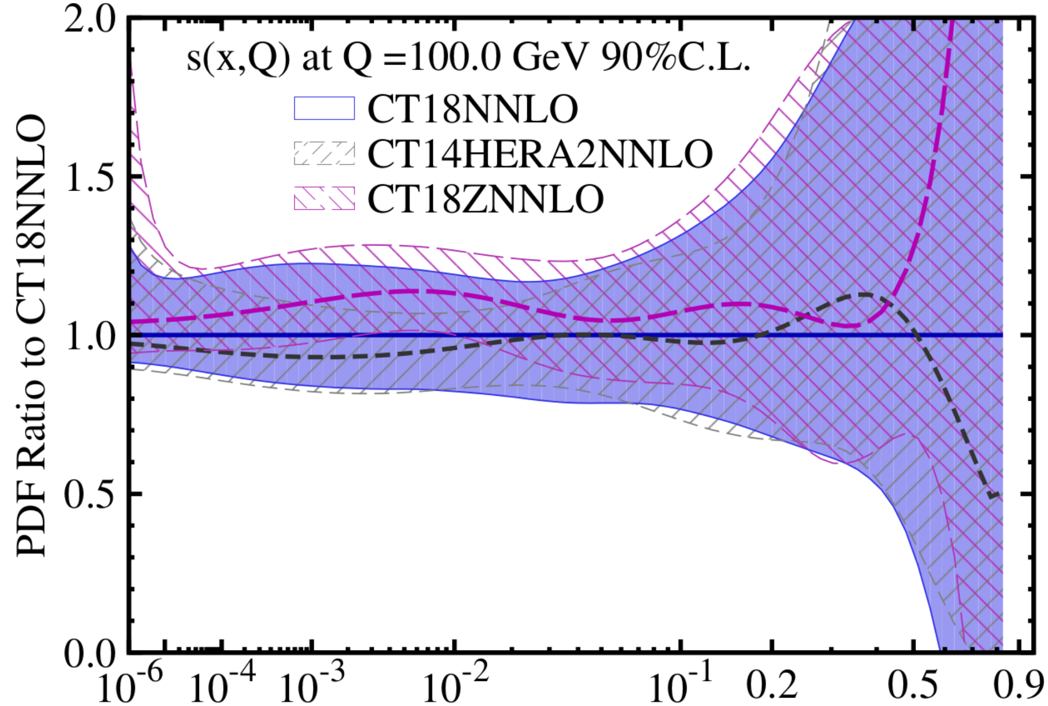


high-x PDFs remain dominated by large uncertainties

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

→ limited data → extrapolation → data tensions

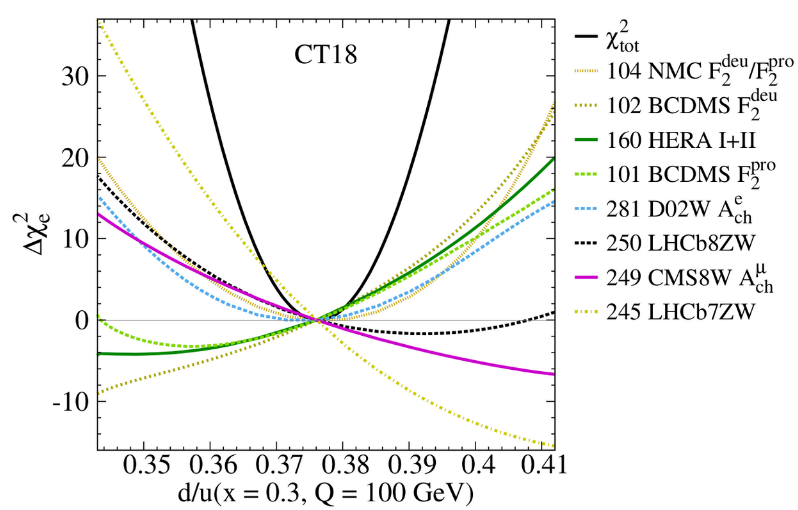




- competing pulls of fitted data at high-x also restrict precision; *e.g.*,

→ BCDMS, F_2^d

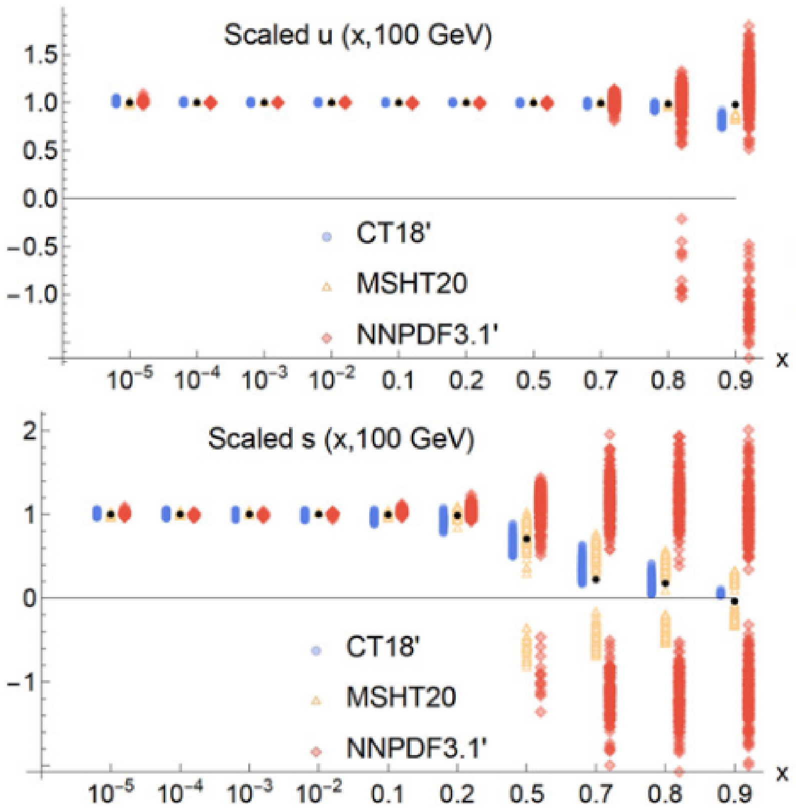
→ LHCb, W/Z 7 TeV



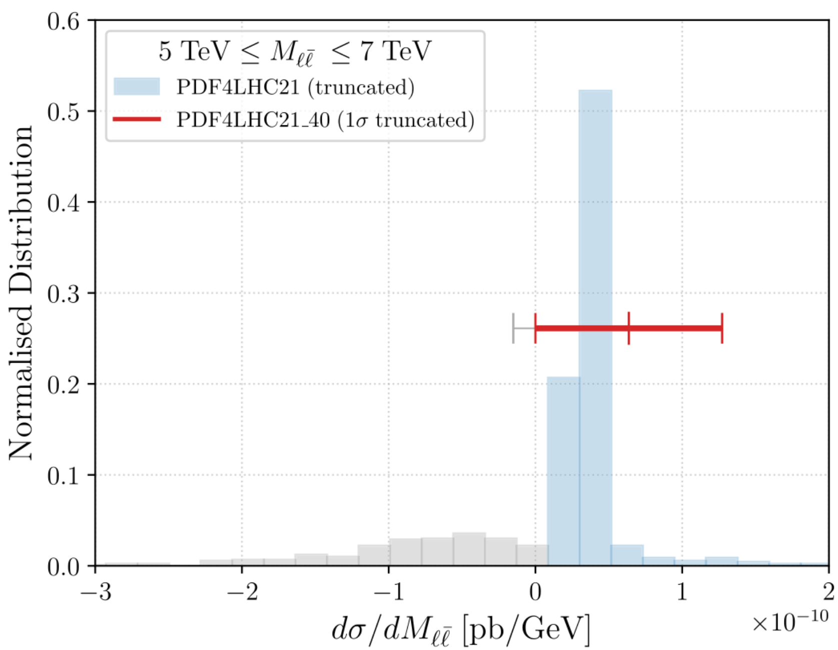
understanding PDFs and their uncertainties: high x

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:

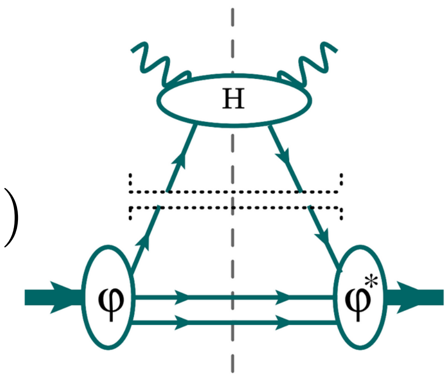


- strong need for high-x sensitive data: JLab12 [24]; (HL-)EIC; FASERν

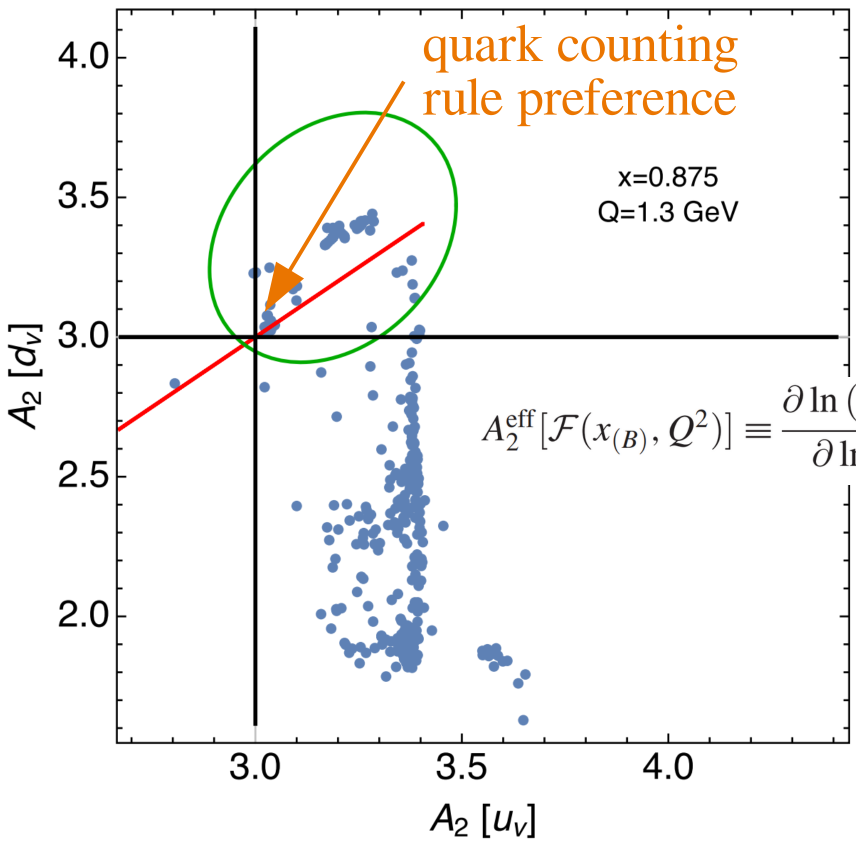
Courtoy, Huston Nadolsky, Xie, Yan, Yuan: 2205.10444

extracting high-x dependence in PDF fits

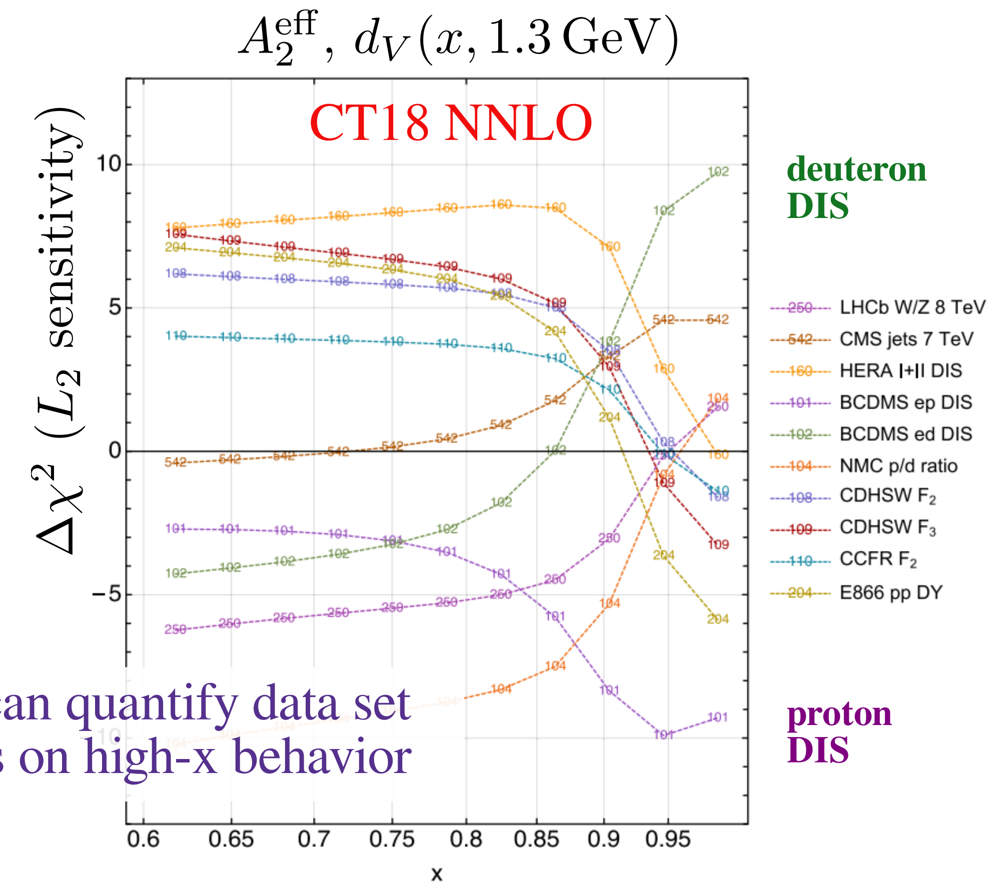
- high-x PDFs, ratios [e.g., d/u] connected to details of proton WF
- behavior at $x \to 1$ an important nonpert. discriminator
- CT18, parametrize $f_{a/A}(x, Q_0^2) = x^{A_{1,a}}(1-x)^{A_{2a}} \times \Phi_a(x)$



Courtoy and Nadolsky, PRD**103**, 054029 (2021)



$$A_2^{\rm eff}[\mathcal{F}(x_{(B)}, Q^2)] \equiv \frac{\partial \ln(\mathcal{F}(x_{(B)}, Q^2))}{\partial \ln(1 - x_{(B)})}$$



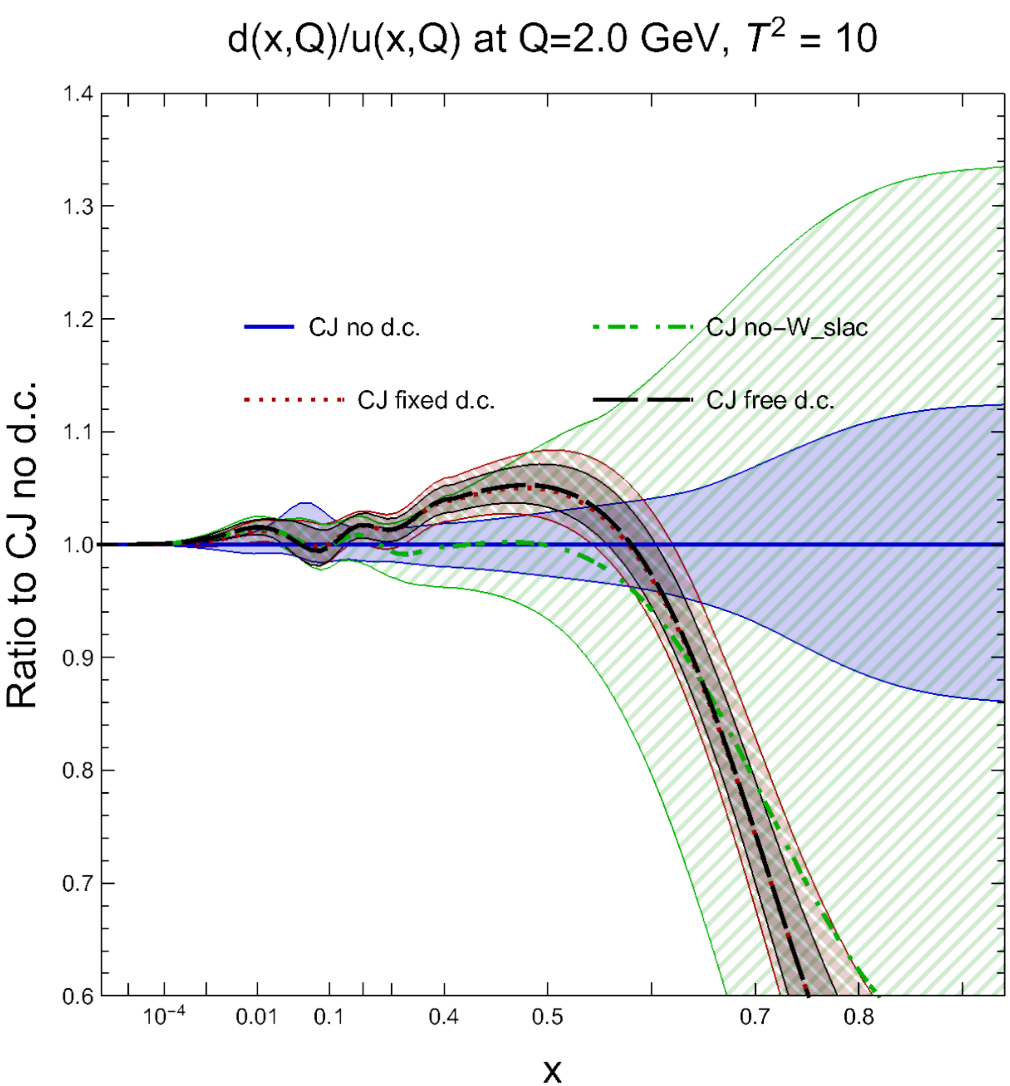
we can quantify data set pulls on high-x behavior

light-nuclear corrections: deuteron and high-x PDFs

- d-PDF information from deuteron scattering; nuclear corrections relevant

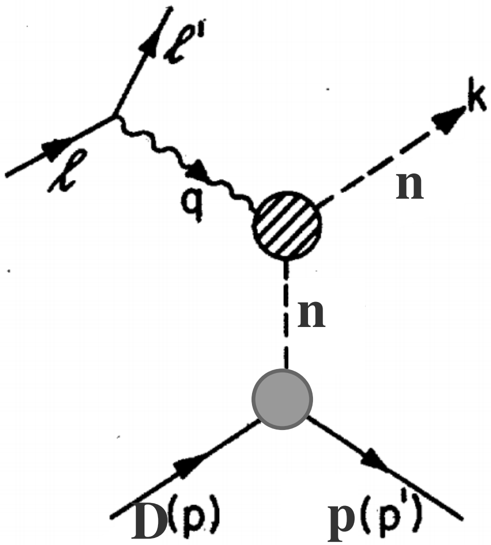
$$f^d(x,Q^2) = \int \frac{dz}{z} \int dp_N^2 \, \mathcal{S}^{N/d}(z,p_N^2) \, \widetilde{f}^N(x/z,p_N^2,Q^2)$$

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



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heavy-nuclear effects relevant for proton structure studies

- beyond few-body systems, CT, other analyses use heavy-nuclei for flavor separation

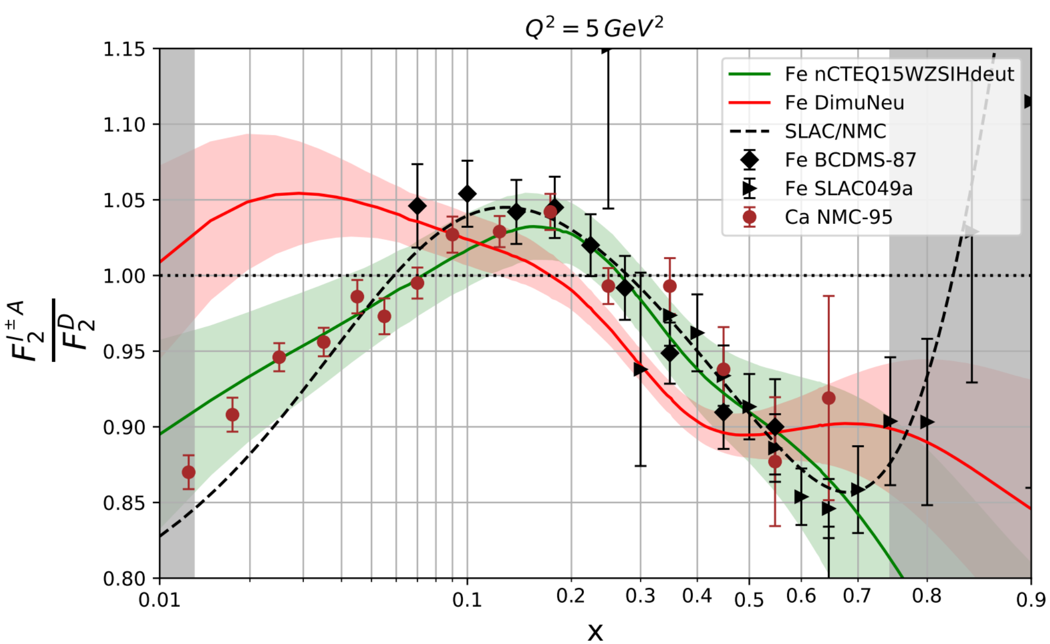
[e.g., νA for strangeness]

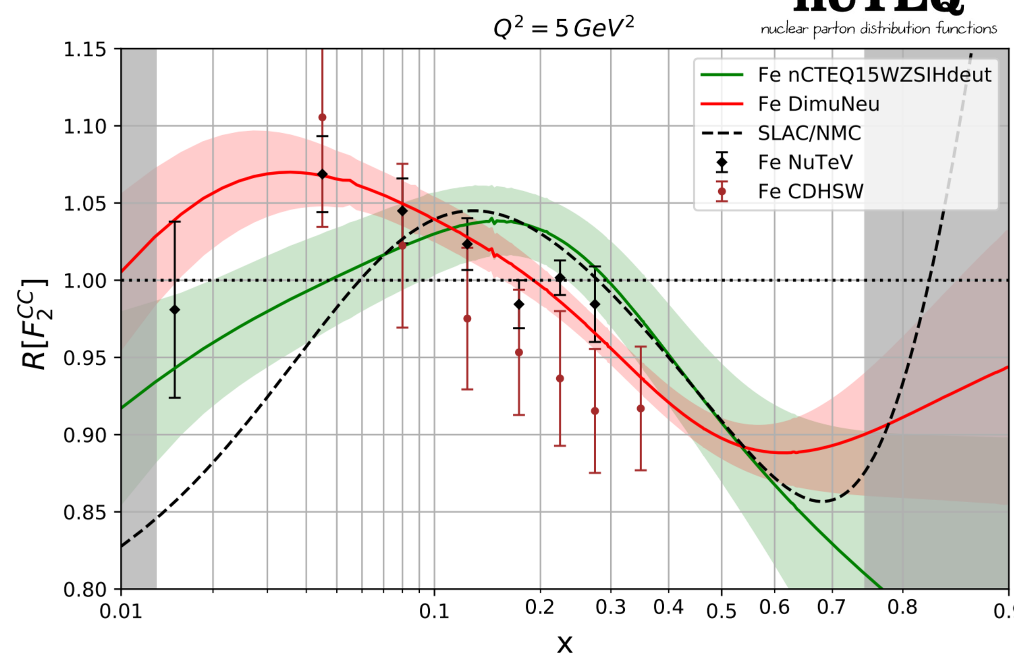
- requires knowledge of nuclear corrections; these directly fitted by nPDF analyses

→ 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 $\sqrt{s}$

nonperturbative theory developments: lattice QCD inputs

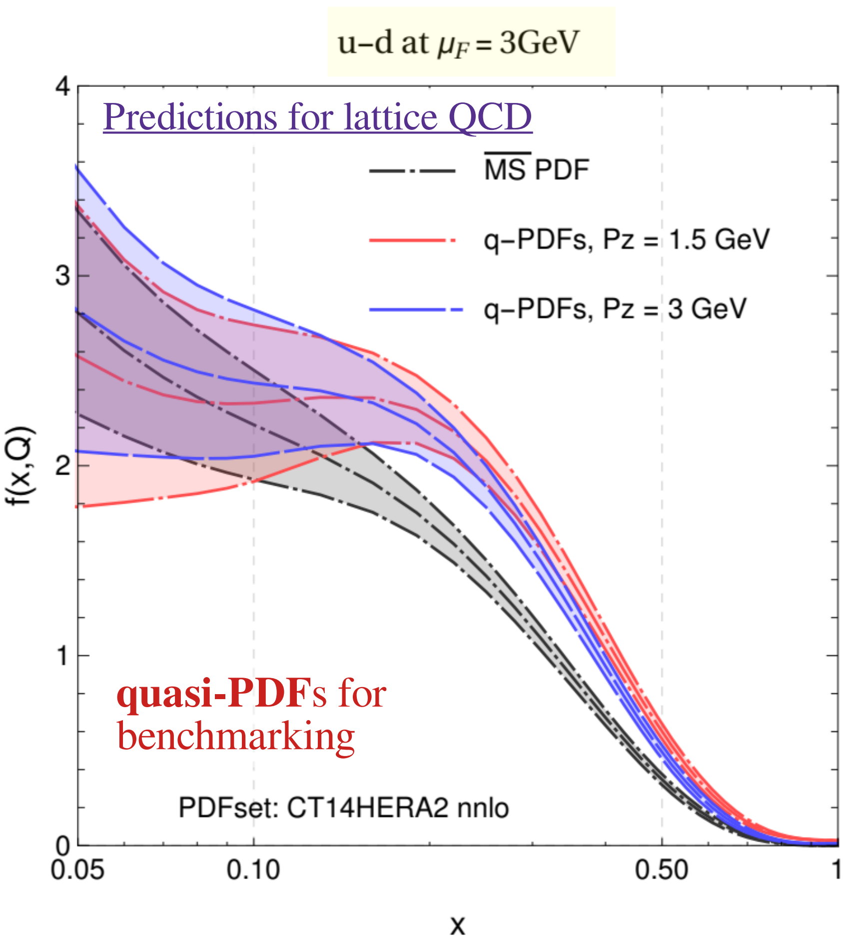
- recent years: progress in *ab initio* hadron-structure calculations from LQCD

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

there are be important synergies between PDF fitting and lattice QCD

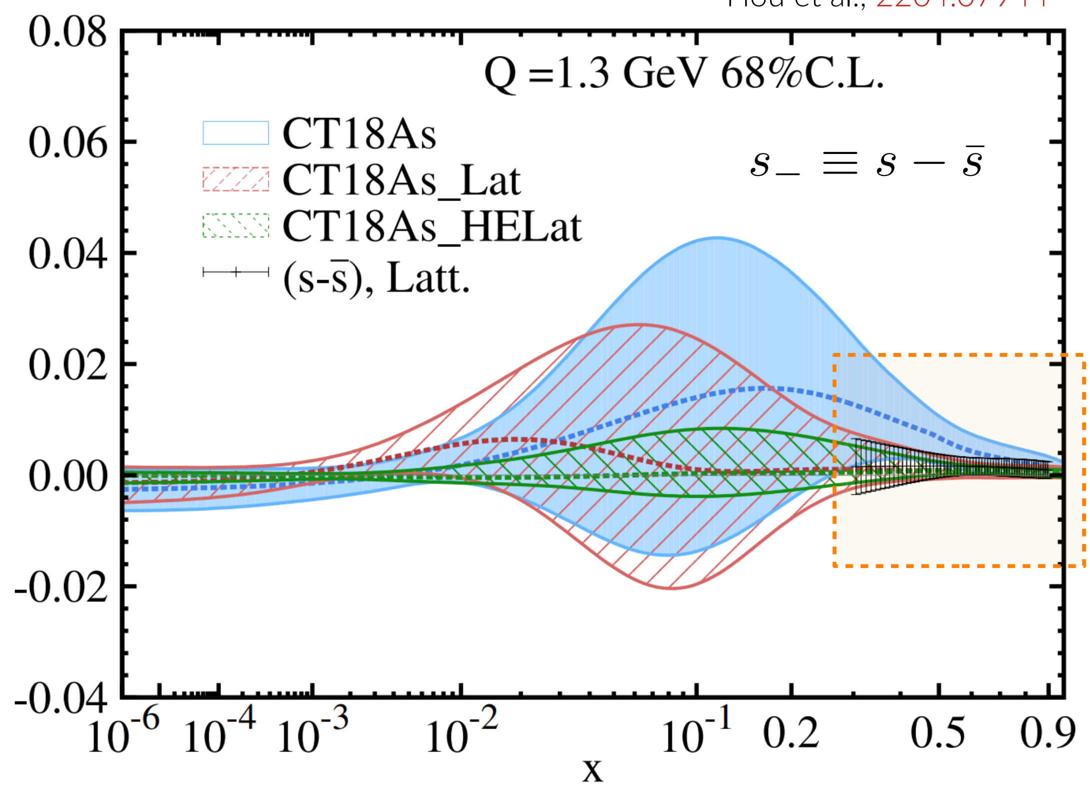
[overlaps with EIC; νDIS; LHC]

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



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

Hou et al., 2204.07944



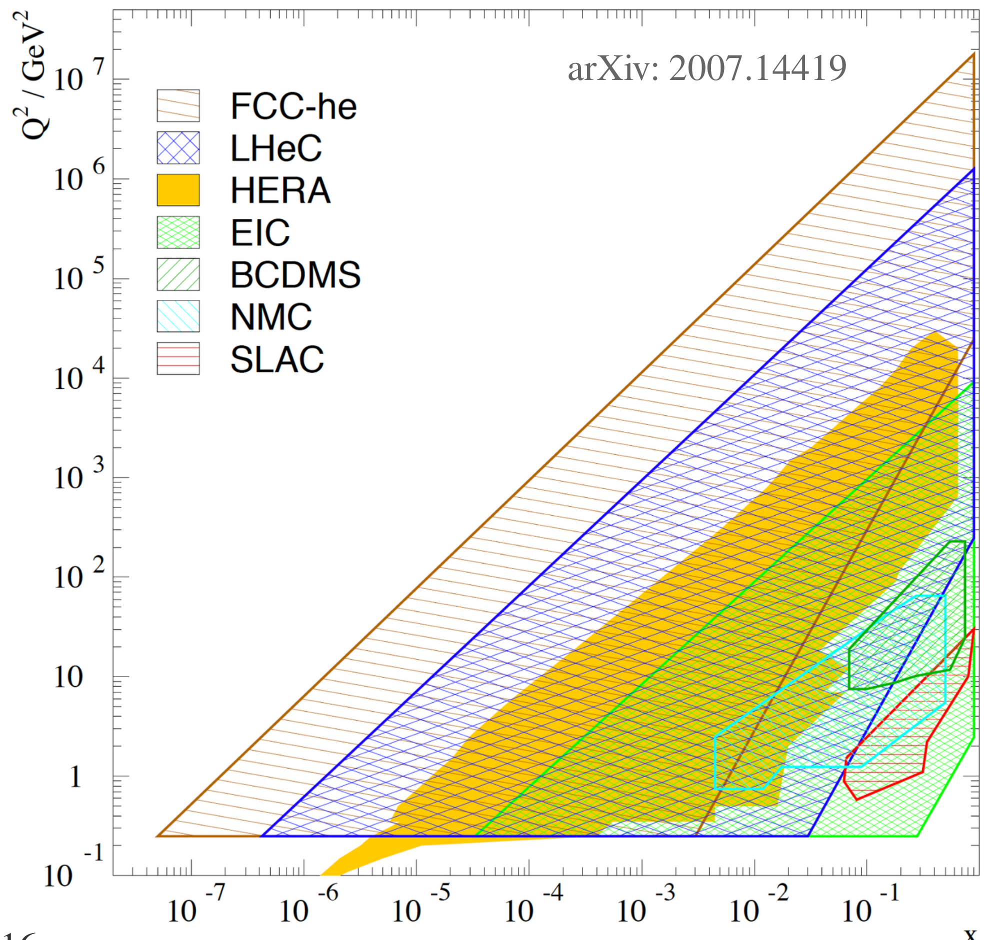
PDF precision both aided and challenged by experiments

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

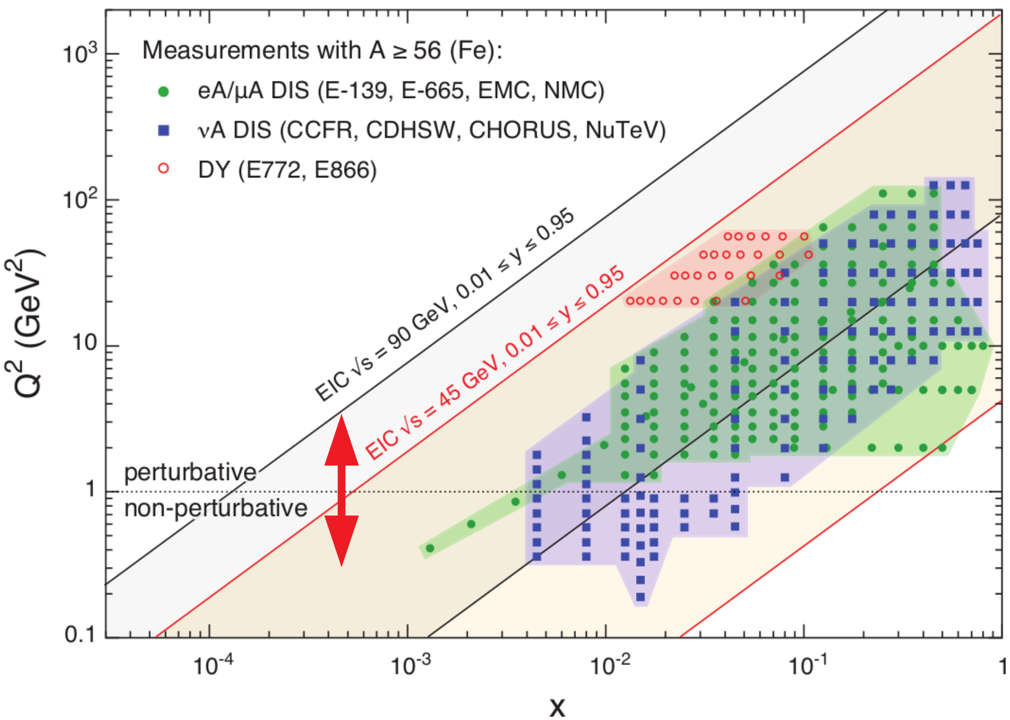
  → as proxy, consider role of EIC program: impacts on high x, HEP pheno.

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

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



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

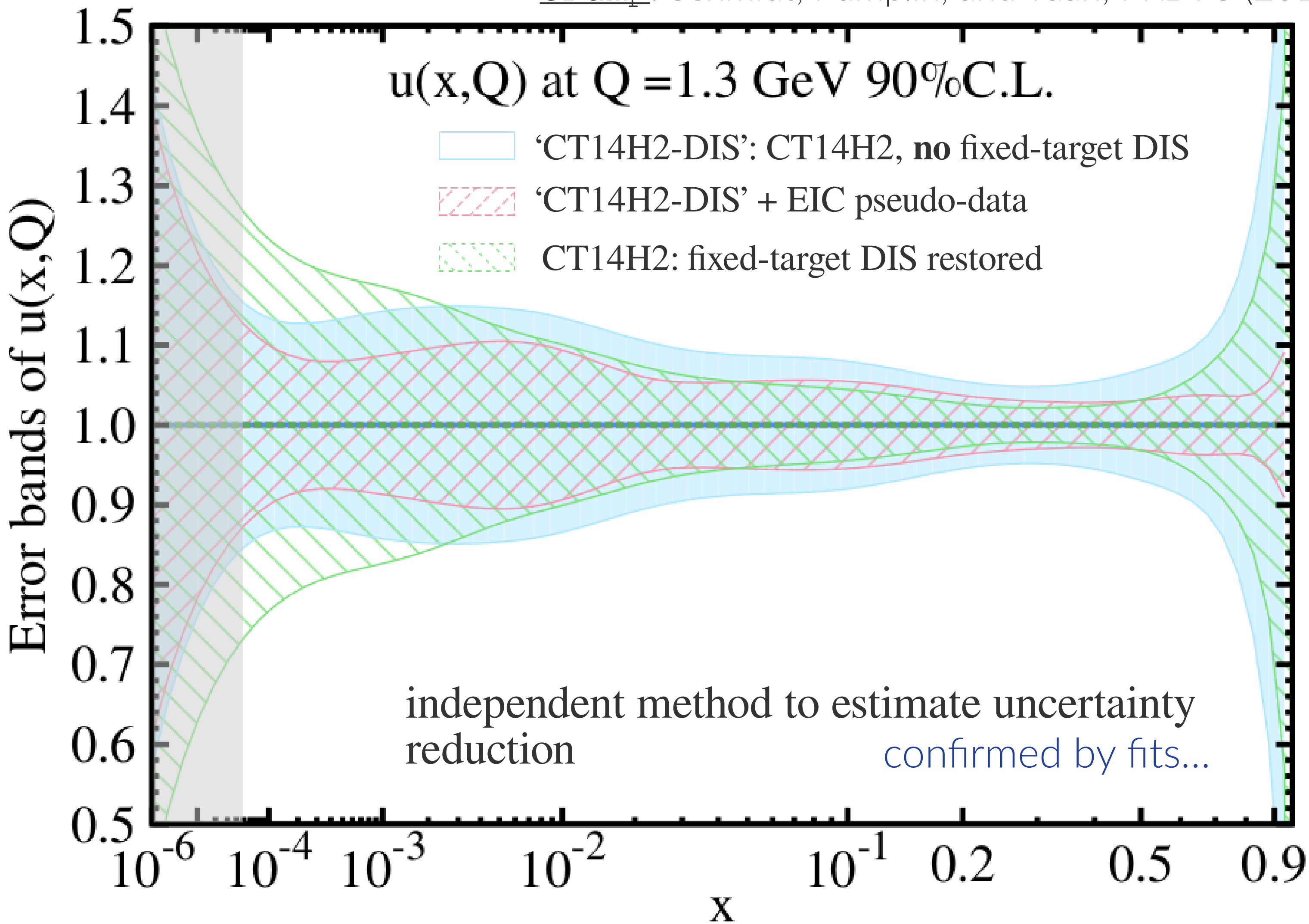


figure: S. Dulat

- **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

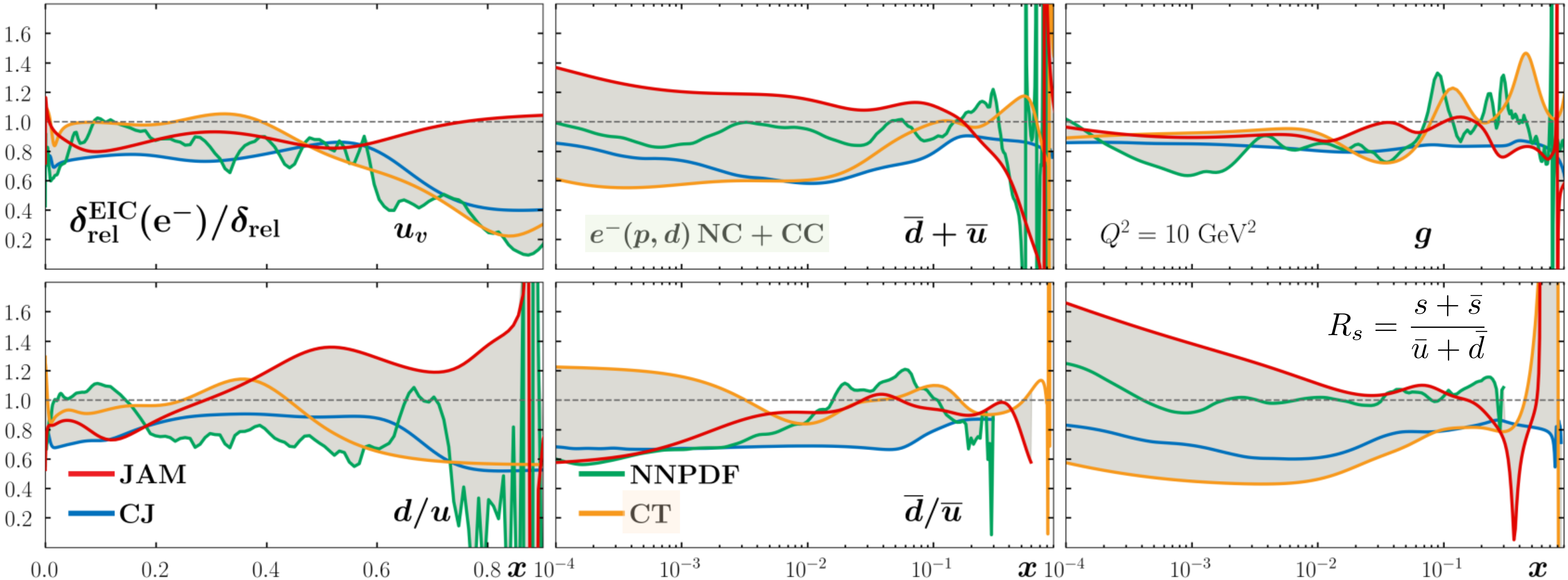
reductions to PDF uncertainties: inclusive DIS data

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

EIC YR, 7.1.1

PDF uncertainty improvement

~1 year of [peak] data-taking



$\mathcal{L} = 100\,\mathrm{fb}^{-1}$

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

→ inclusive studies – indications of systematics limitations; **must also investigate**

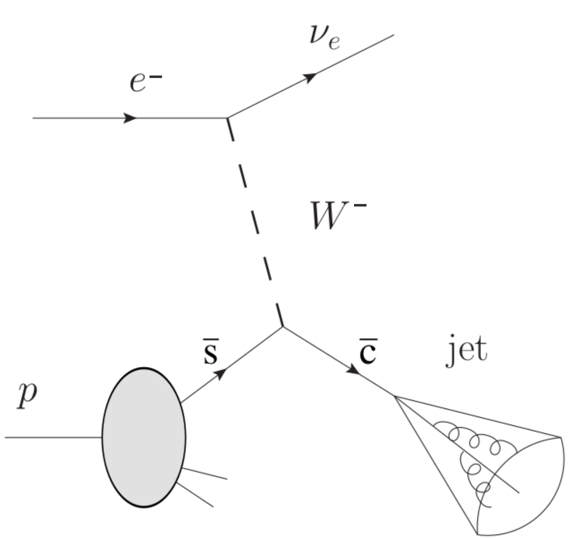
precision QCD through jet and heavy-flavor production

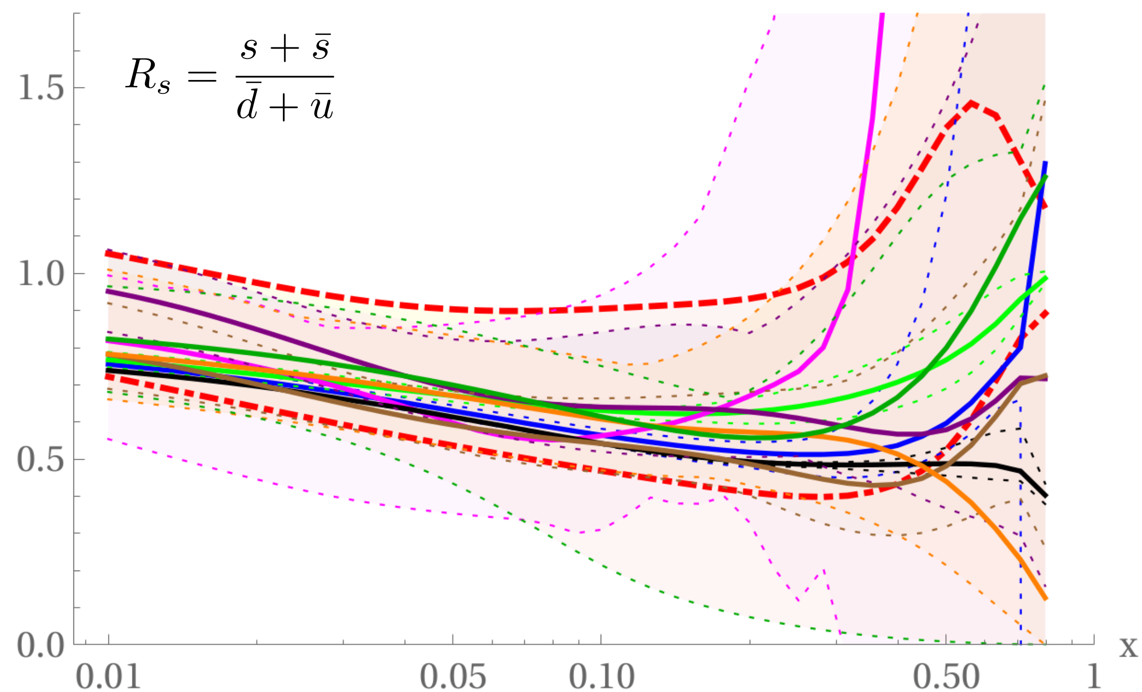
- DIS jet production, including through charge-current interactions, provides further access to quark-level information

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

R_s(x,Q)   Q=10 GeV

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





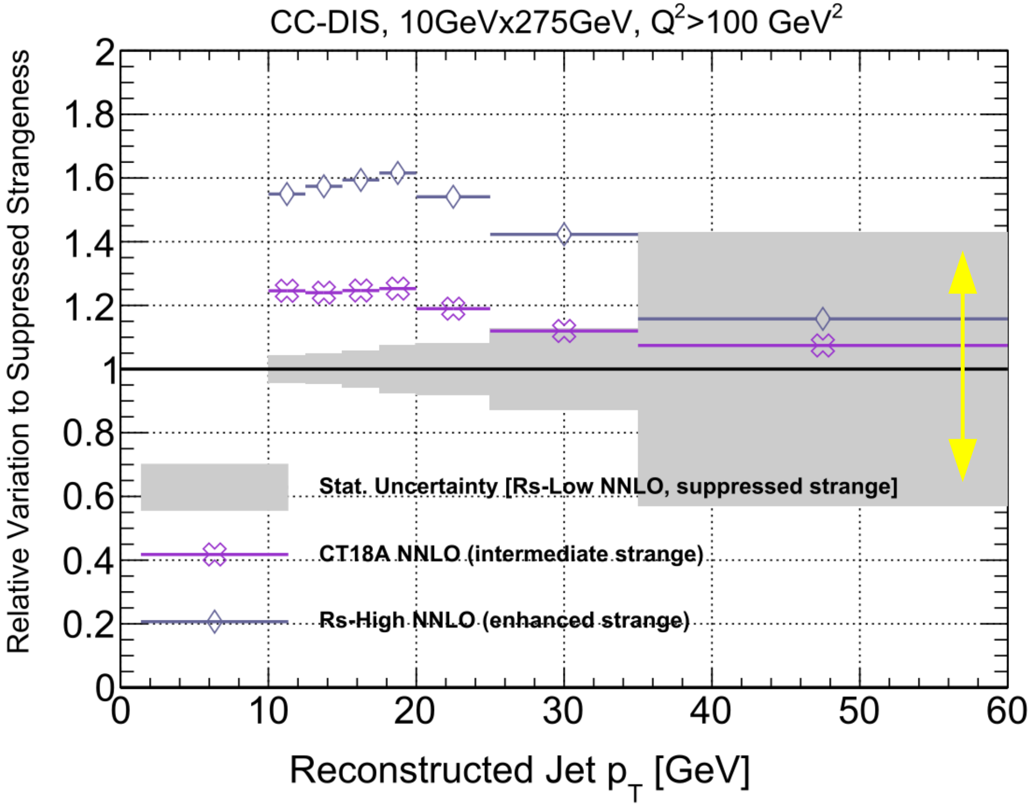
final-state tagging provides lever arm for flavor separation (here, strangeness)

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

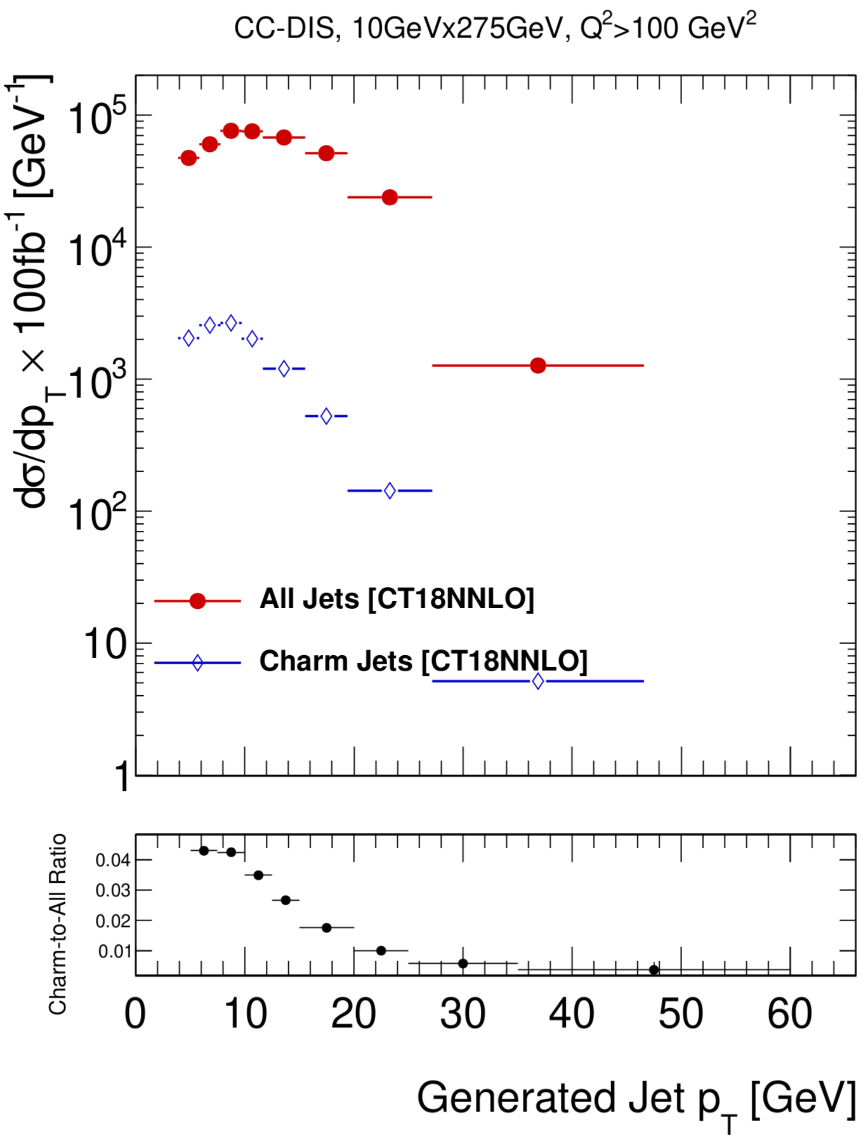
→ analogous jet measurements might be extended to nonperturbative heavy flavor

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

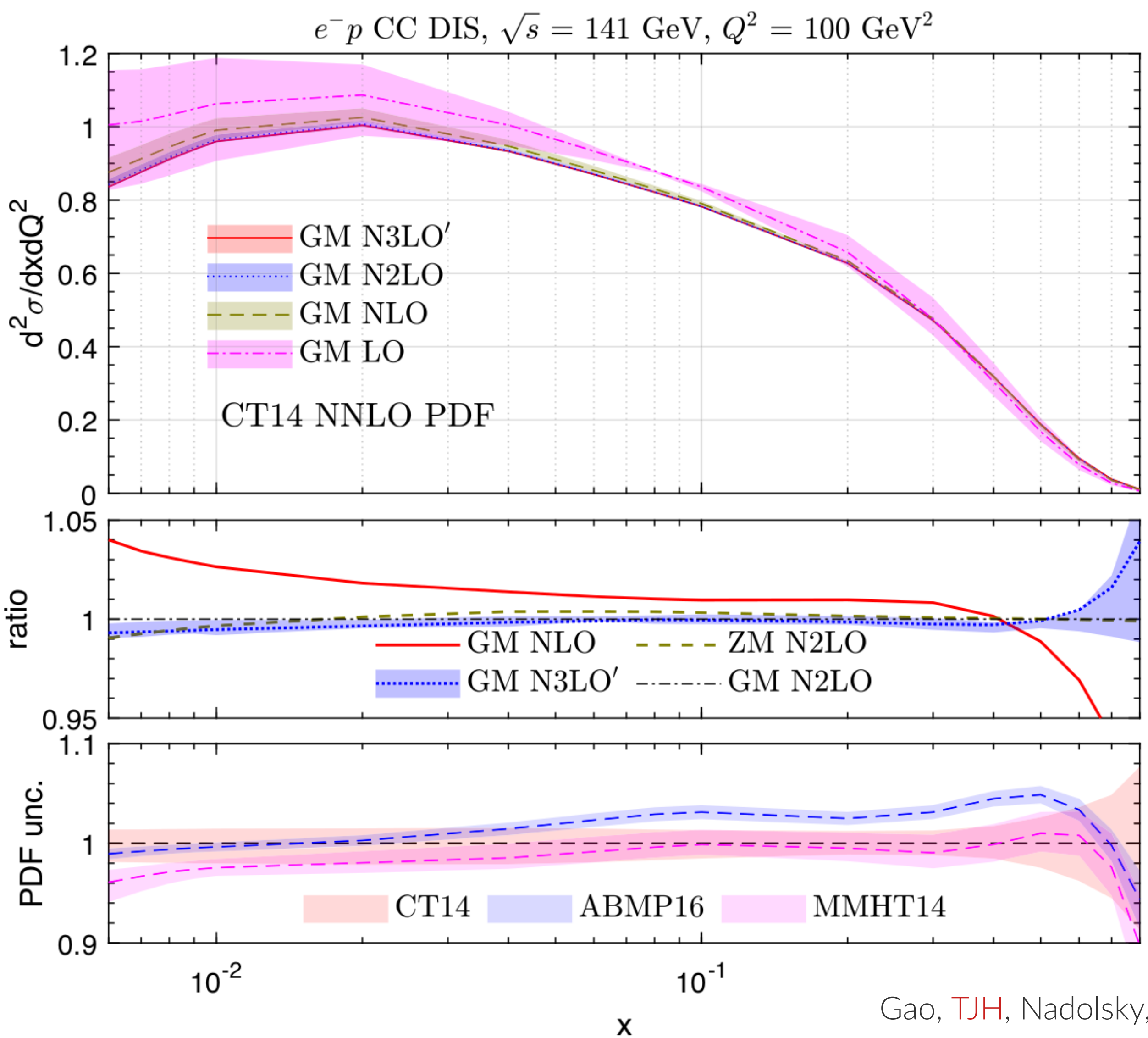
- reduced δ_{stat} could significantly enhance knowledge of p_T dependence

→ greater event rates may furnish enhanced discriminating power

(CC) DIS at NNLO and beyond

- extracting PDF information from CC DIS requires robust theory accuracy

  → can compute NNLO, approximate N³LO corrections for highest energies at EIC



- strong perturbative convergence

  → for N³LO′, 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 ii

precise EIC data impact high-energy predictions

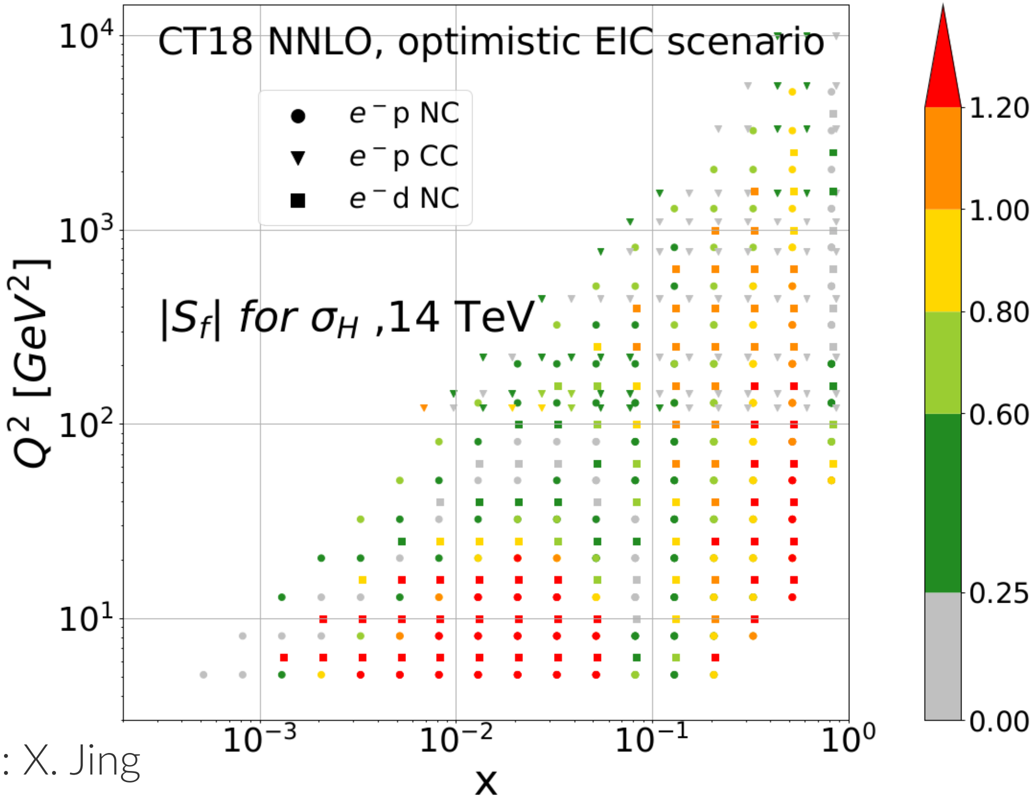
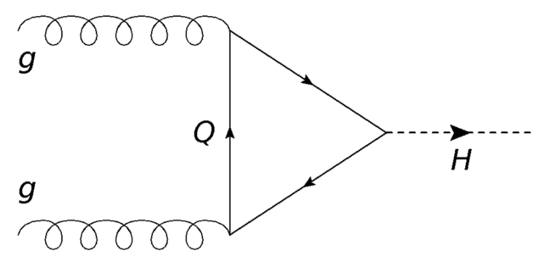


figure: X. Jing

example:

- PDF-driven improvement to **Higgs-production** cross section
- EIC impact on Higgs theory from broad region of the kinematical space it can access



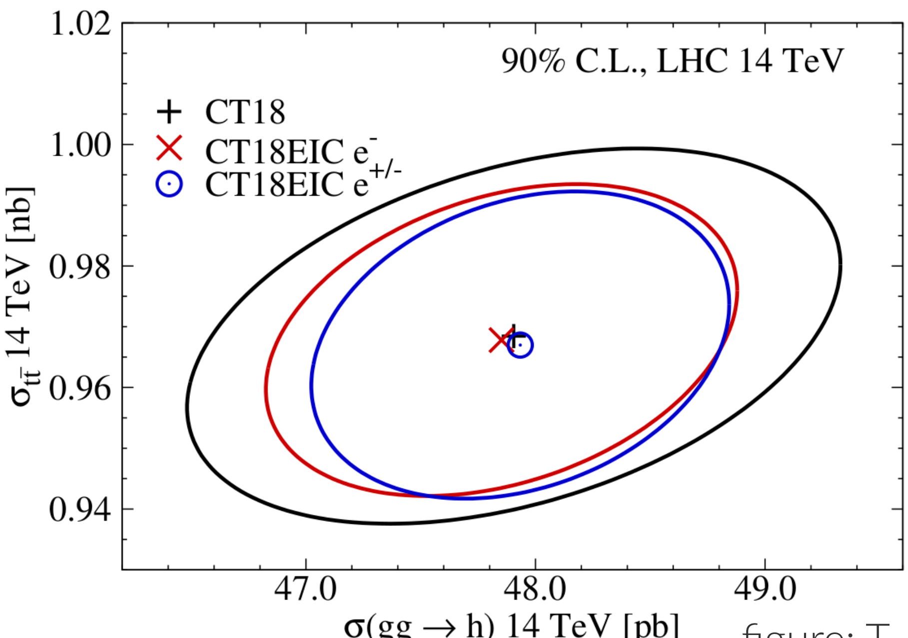
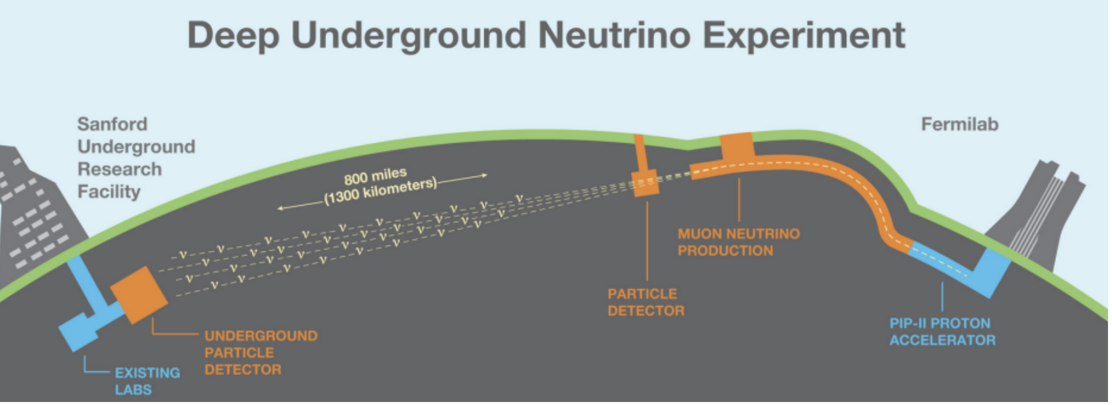


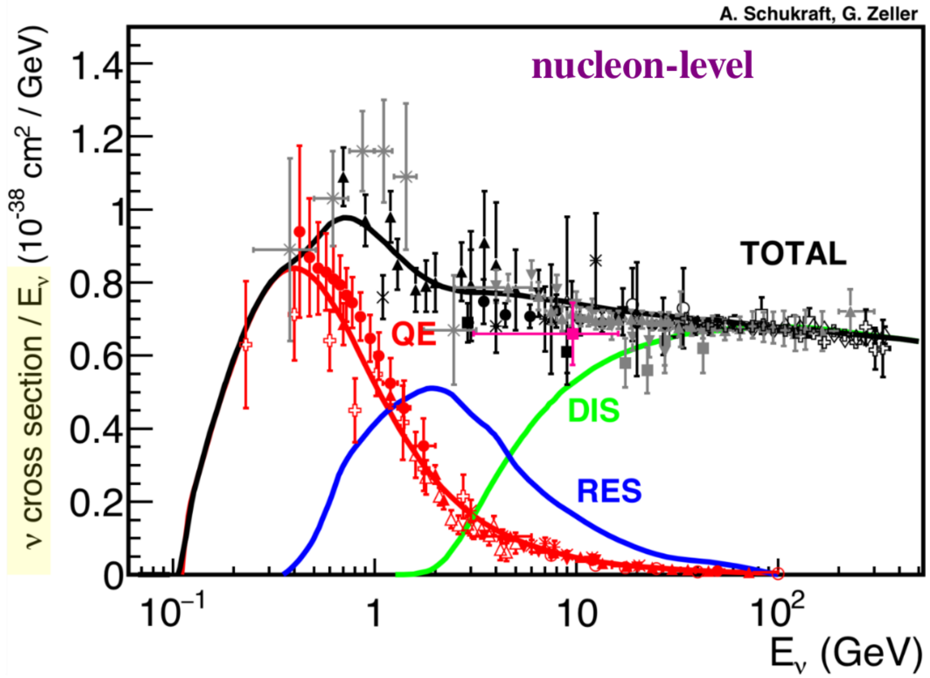
figure: T.-J. Hou

- impact closely tied to that of the integrated gluon PDF

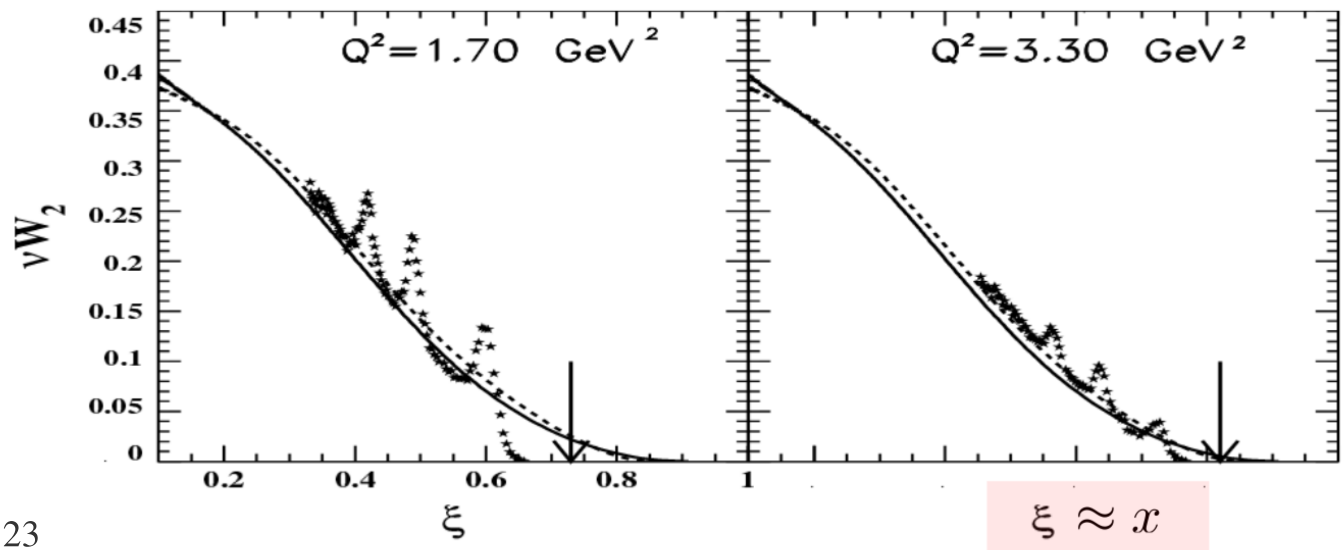
→ similar impacts on EW observables



nPDFs key to νDIS precision



- neutrino oscillation searches (e.g., DUNE) require accurate knowledge of νA interaction
  - → E_ν ~ few GeV dominated by RES/DIS
  - → DIS subject to finite-Q^2, nuclear effects
    (HTs; TMCs; few- and large-A)
  - → ν generators generally implement phenomenological models at LO; minimal error quant.



$\xi \approx x$

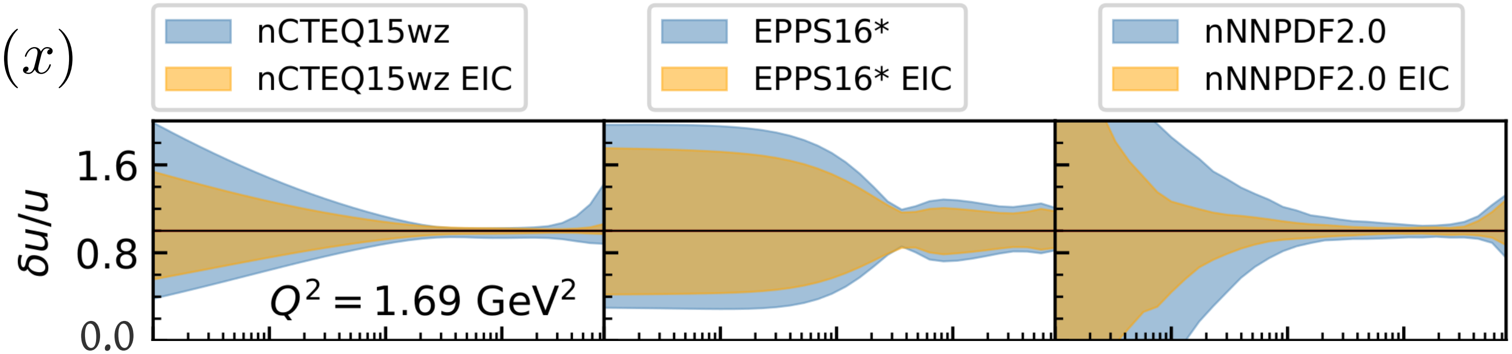
- nPDFs, QCD-based approaches to low-Q, W νDIS badly needed

- future near-detector ν expts may yield more QCD information

understanding nuclear effects

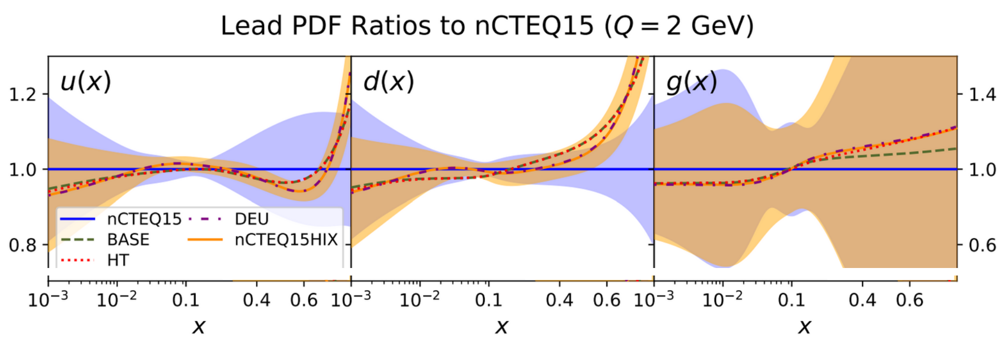
→ EIC: measure only "clean" DIS from hadrons; but also explore nuclear medium!

$u^{\mathrm{Au}}(x)$



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 essential**

conclusions: toward next-gen precision in nucleon PDFs

- signatures of nonperturbative QCD are etched upon the PDFs
  - → flavor-symmetry breaking ($\bar{d}/\bar{u}$); wave function effects [$d(x \approx 1)$]
  - → nuclear effects [$q(x)$, intermediate x]; description of deuterium data

closely linked to physics of confinement

- critical for understanding QCD; **necessary for precision HEP measurements**
  - → limit EW precision, sensitivity of BSM tests, neutrino programs
  - → closely related to challenge of flavor separation

- recent theory progress: pQCD now at (N)NNLO; interfacing with PDFs
  - → higher perturbative accuracy suggests parallel theory improvements
  - → EW higher-order accuracy; introduction of nuclear, nonpert. effects
  - → next-gen unraveling of statistical influence of fitted experiments

future experiments central: JLab12 → EIC, HL-LHC, LBNF, …