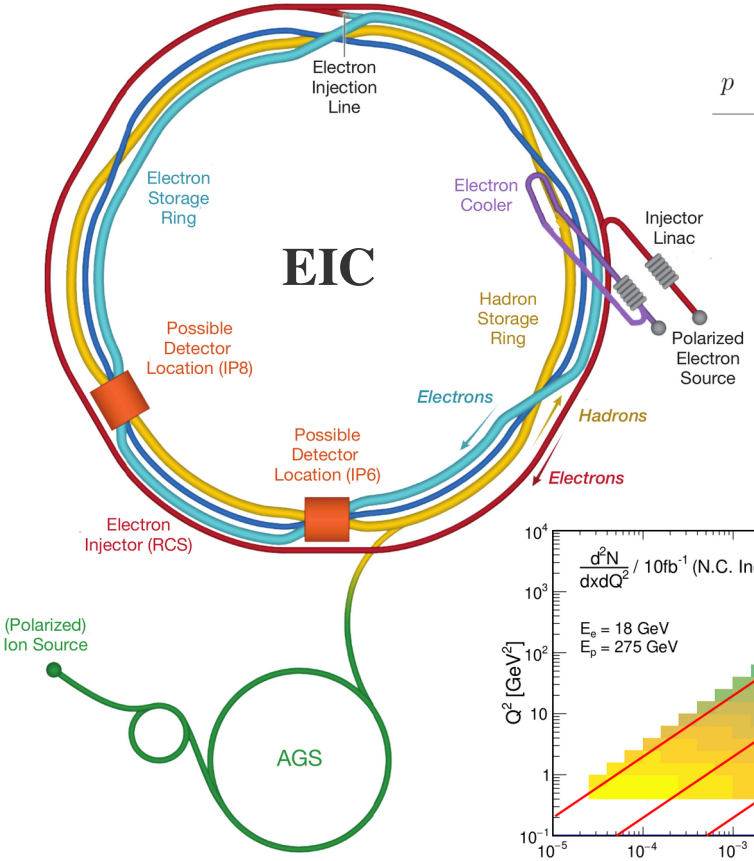
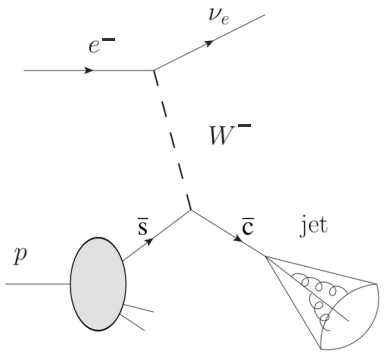
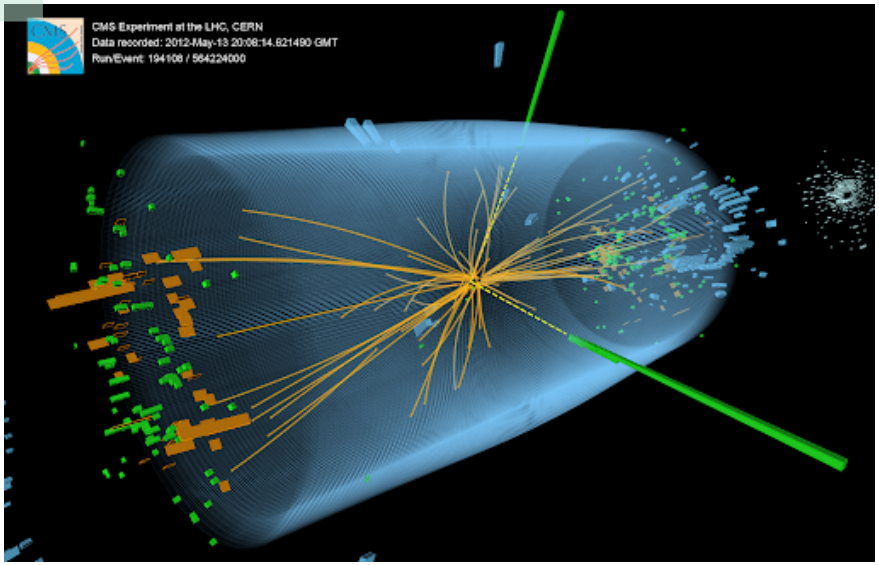
unpolarized PDFs and possibilities at (HL-)EIC

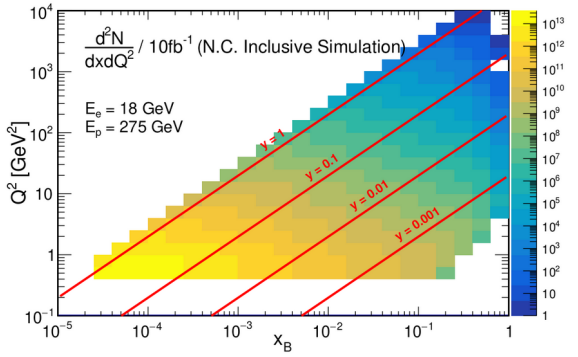
Tim Hobbs – Fermilab, IIT

22nd June 2022









Fermilab

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this talk: (HL-)EIC and 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 central to EIC mission of NP QCD, 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 recent/ongoing EIC studies; and

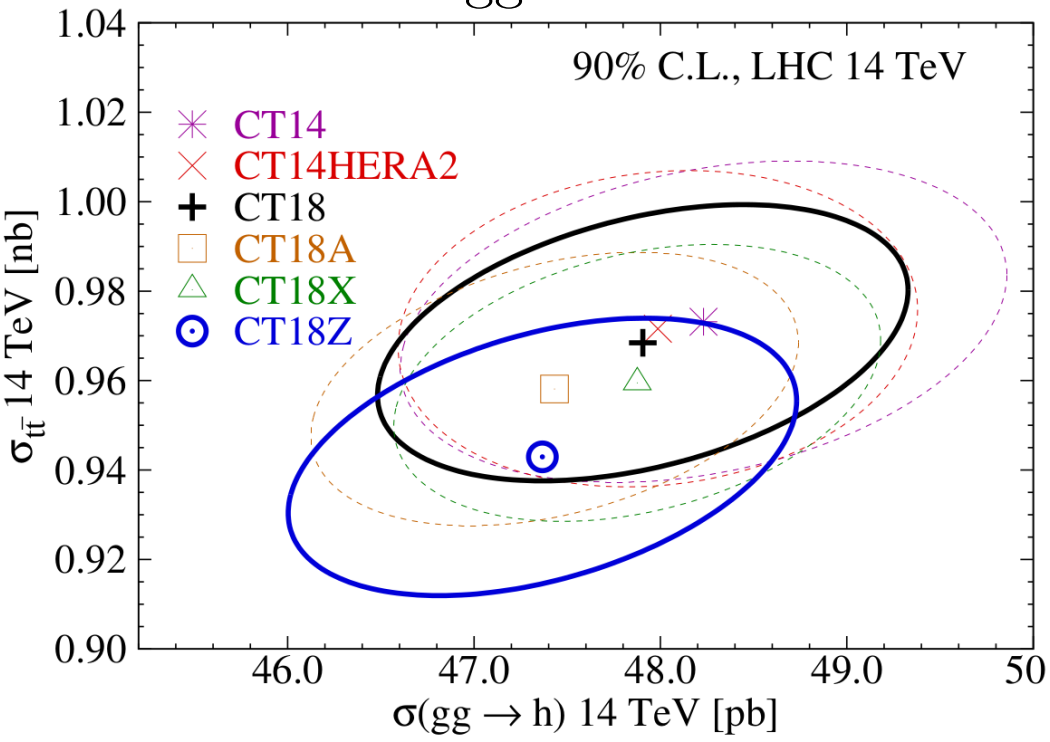
iii conclusion(s): thoughts on special opportunities with still higher luminosity

SM theory predictions from global analyses

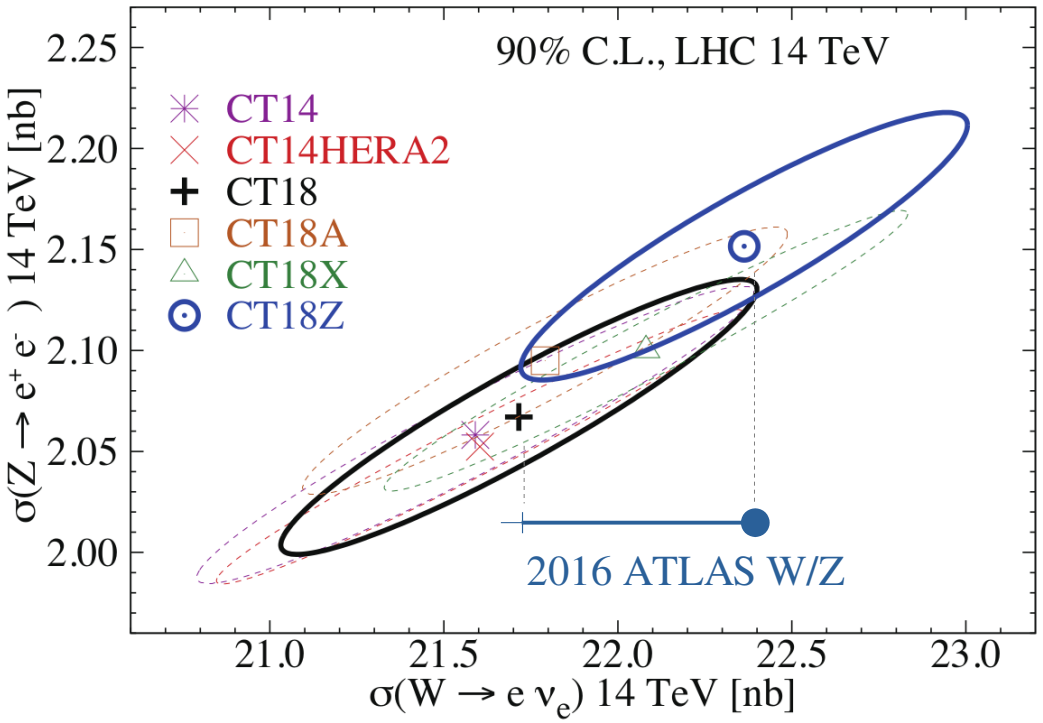
- from NNLO analyses, state-of-the-art predictions for fundamental LHC observables → *e.g.*, **total cross sections at 14 TeV**

CT18 NNLO, PRD 103 (2021) 1

Higgs and $t\bar{t}$



W and Z



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

for example:

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

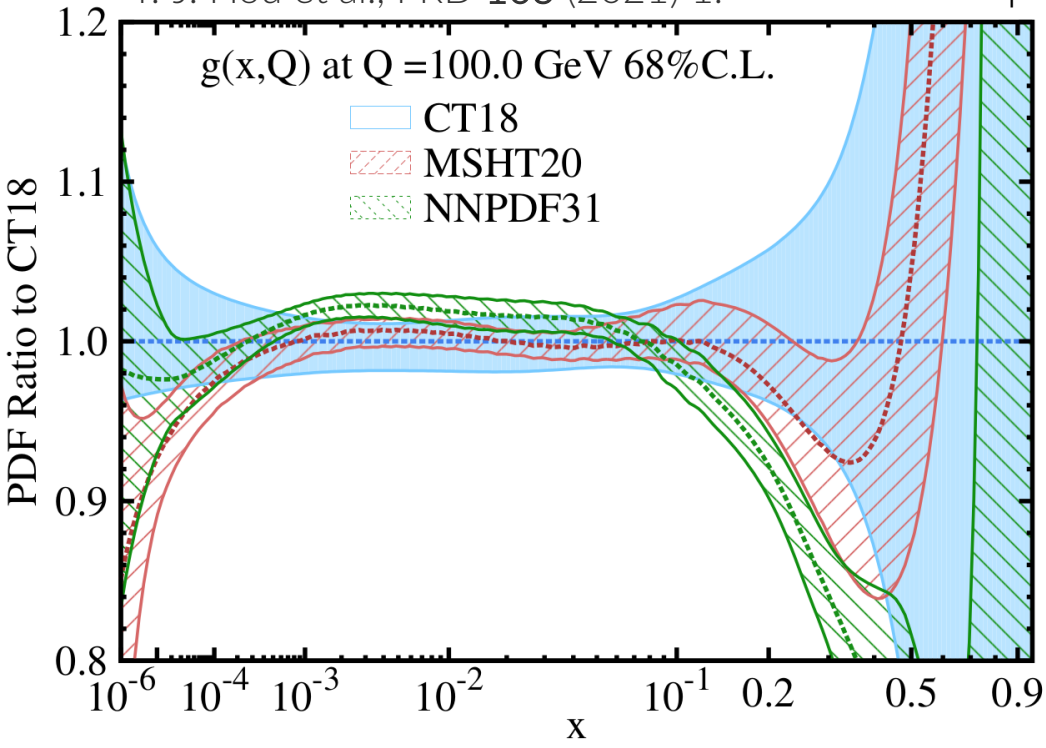
Snowmass21, Amoroso et al.: 2203.13923

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

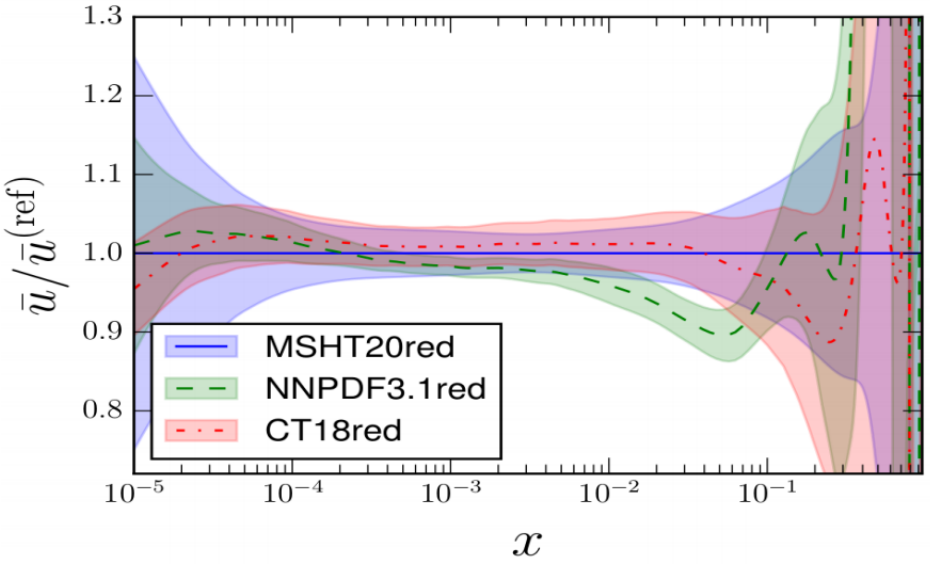
$$\sigma(AB \to W/Z+X) = \sum_n \alpha_s^n \sum_{a,b} \int dx_a dx_b \, f_{a/A}(x_a, \mu^2) \, \hat{\sigma}^{(n)}_{ab\to W/Z+X}(\hat{s}, \mu^2) \, f_{b/B}(x_b, \mu^2)$$

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

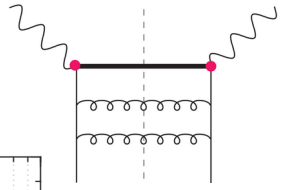
→ seek methodological independence in identifying data-driven PDF features

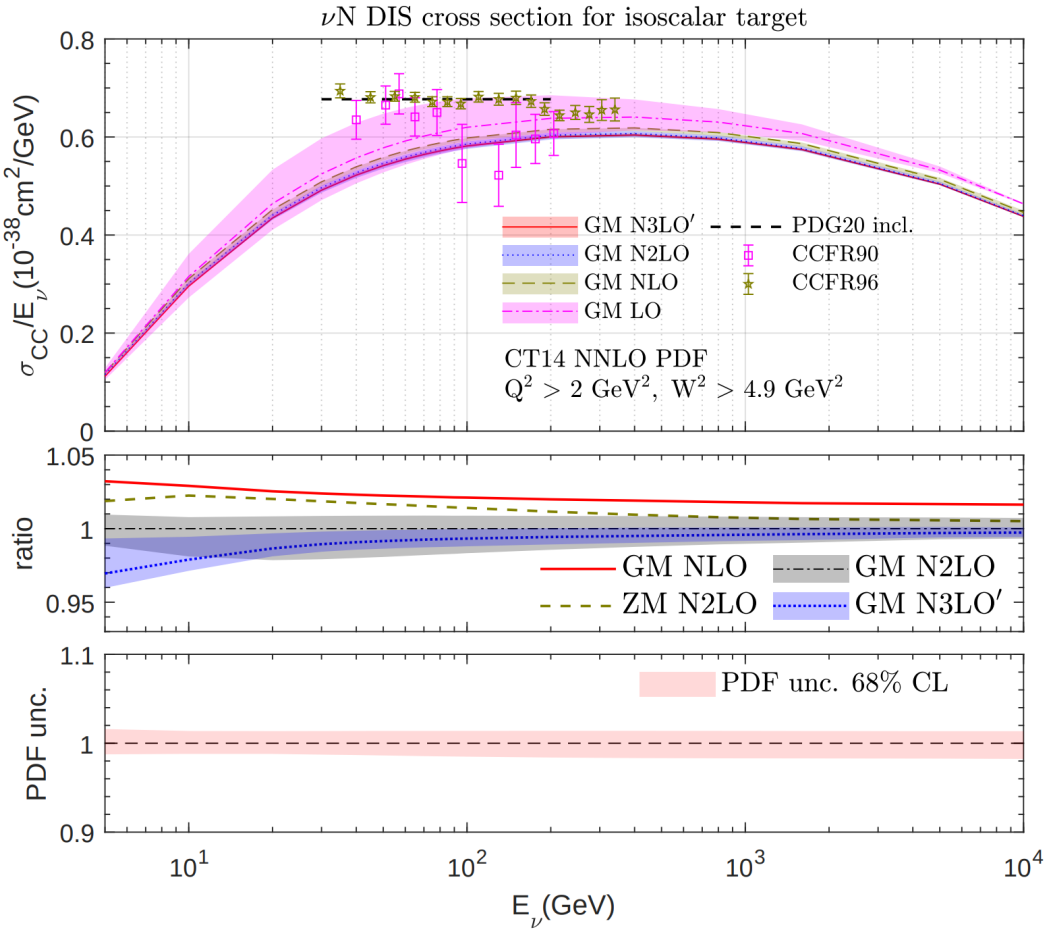
theory ingredients → higher pQCD accuracy

- future analyses will witness an interplay between pQCD & other dynamics
- NNLO+ necessary to stabilize scale uncertainties; especially over wide scales

charge-current DIS

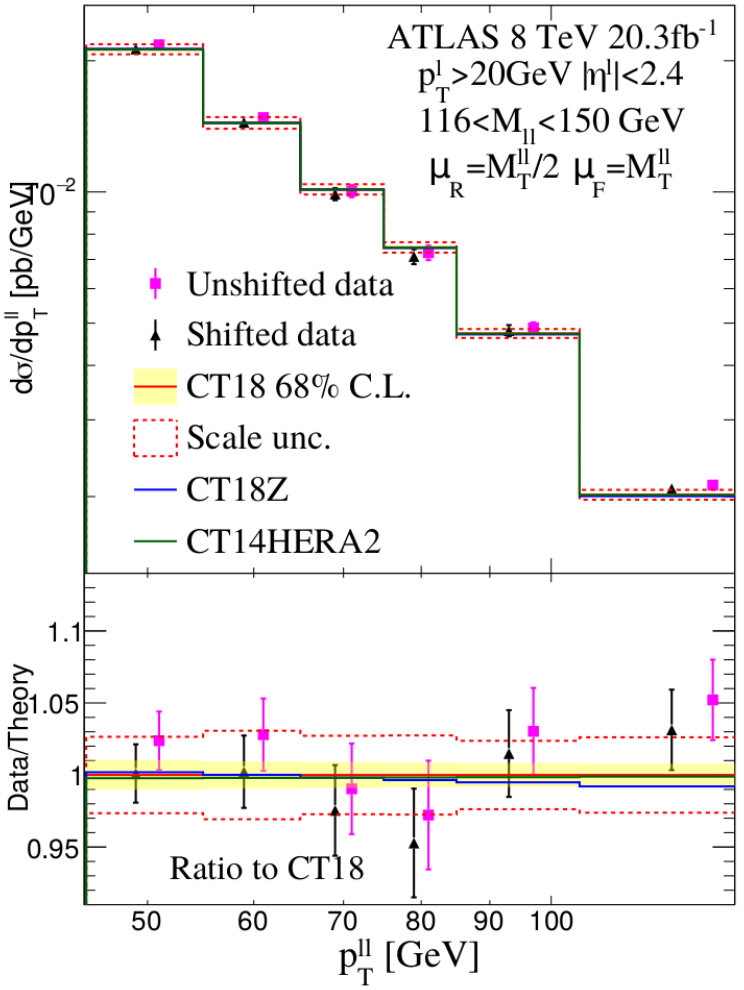
Gao, TJH, Nadolsky, Sun, Yuan: PRD105 (2022) 1, L011503





→ needed for DUNE, FASERν, EIC

NNLO scale variations at LHC



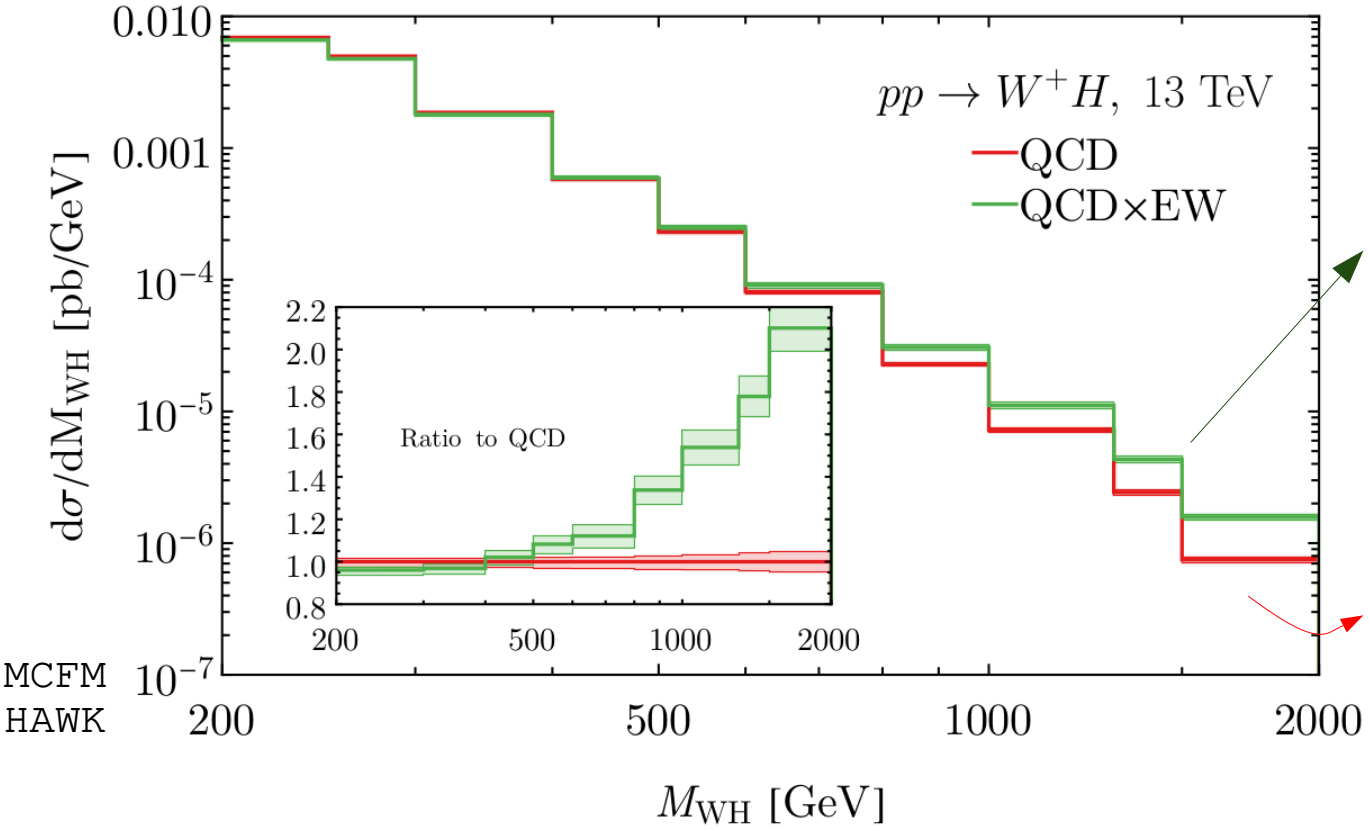
CT18 NNLO, PRD 103 (2021) 1

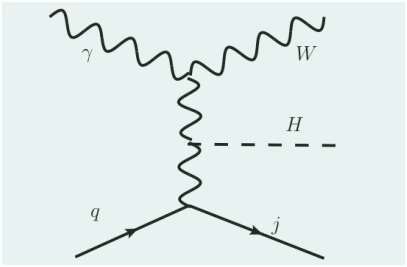
electroweak (EW) corrections also vital

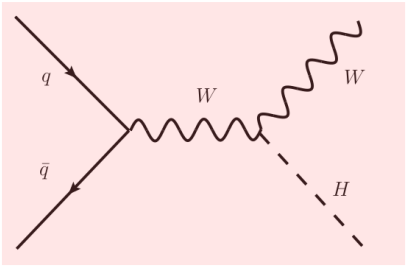
- at $\mathcal{O}(\alpha_s^2)$ accuracy, EW corrections and explicit $\gamma(x, \mu^2)$ needed

Xie, TJH, Hou, Schmidt, Yan, Yuan: PRD105 (2022) 5, 054006

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







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

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

i necessary for electroweak precision: photon PDF

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

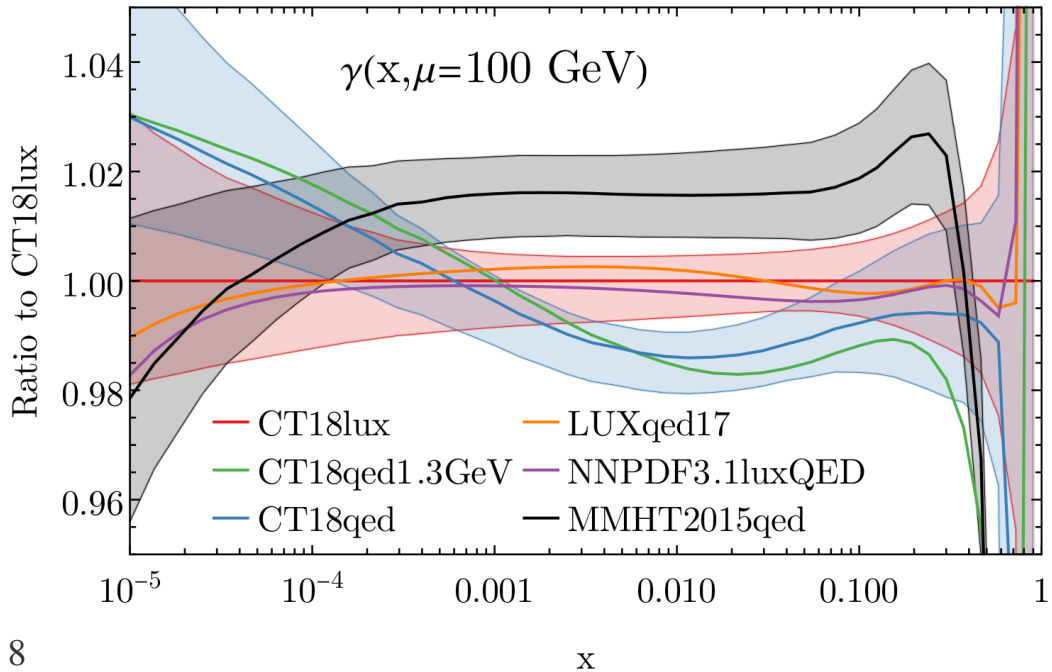
Xie, TJH, Hou, Schmidt, Yan, Yuan: PRD105 (2022) 5, 054006

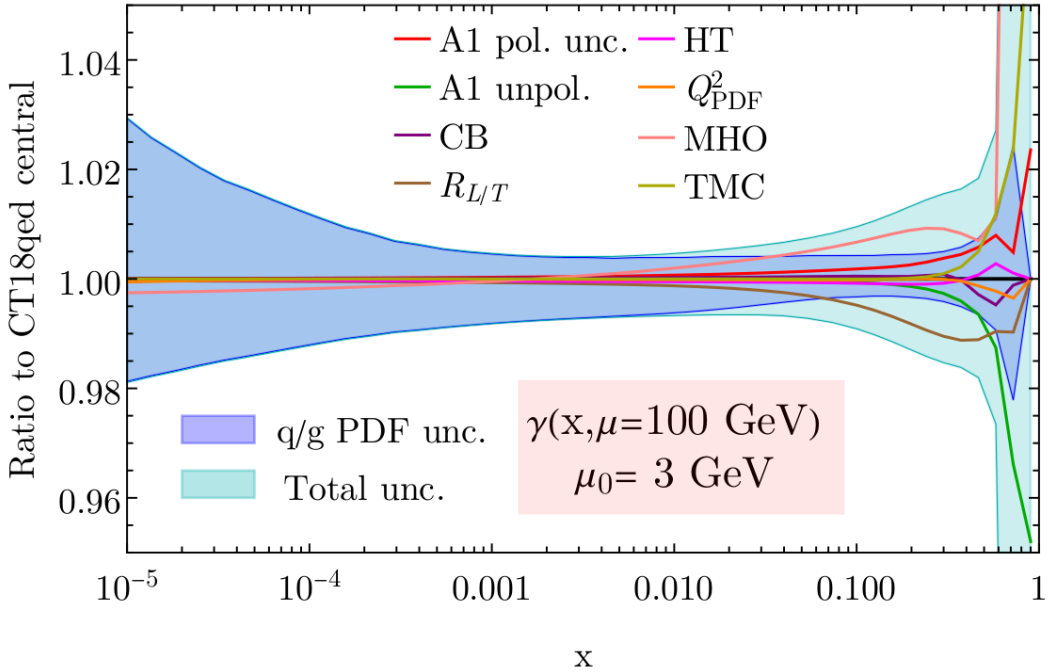
- following CT14QED, CT18QED now interfaces LUX formalism

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

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

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





parametrization uncertainty: nonperturbative fitting forms

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

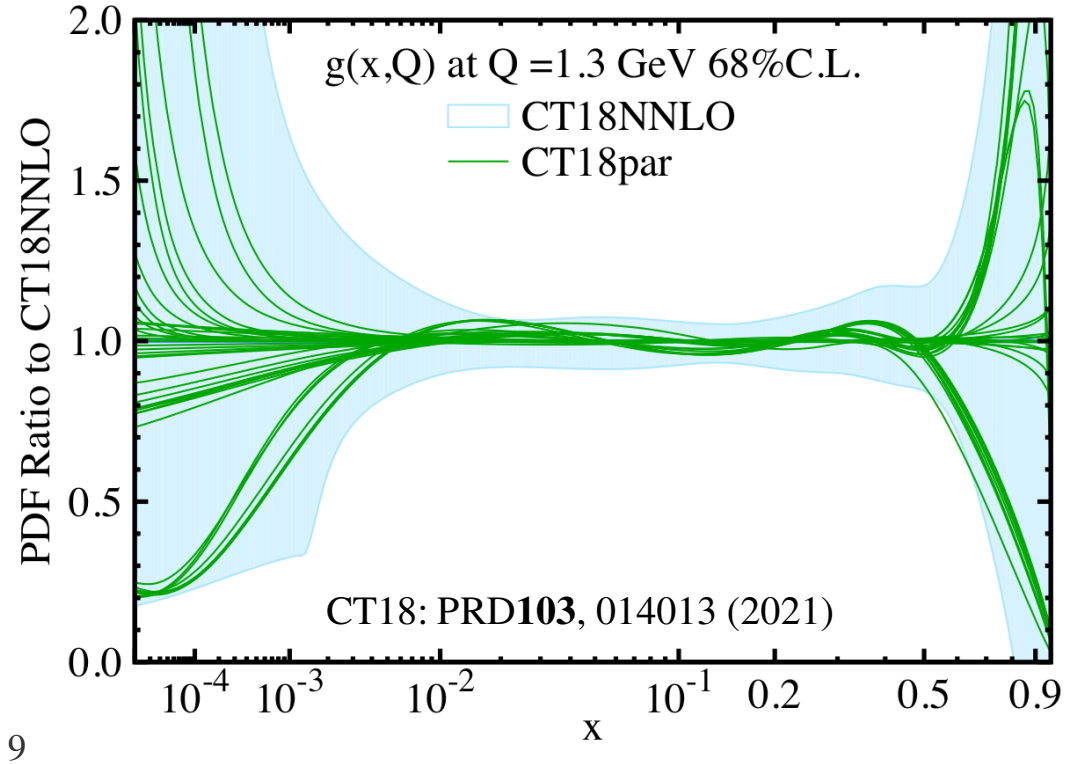
  → subject to complex nonperturbative dynamics

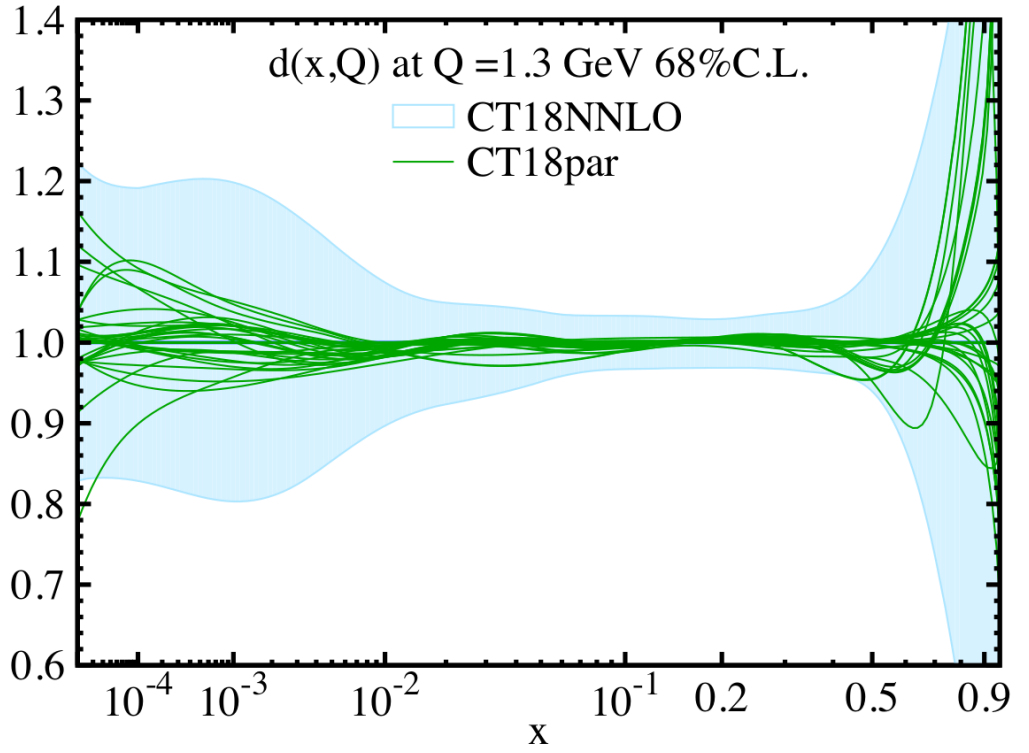
  → practice agnosticism w.r.t. initial parametrization

  (some guidance from QCD, QCD-inspired models)

  → explore model uncertainty with many forms

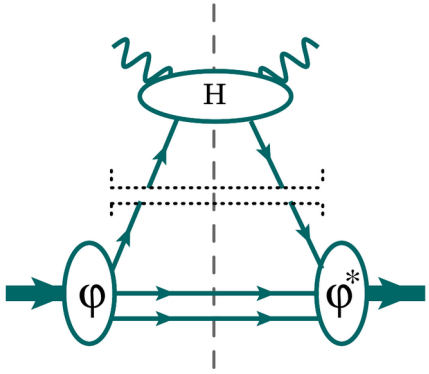
parametrization uncertainties largest in extrapolated regions



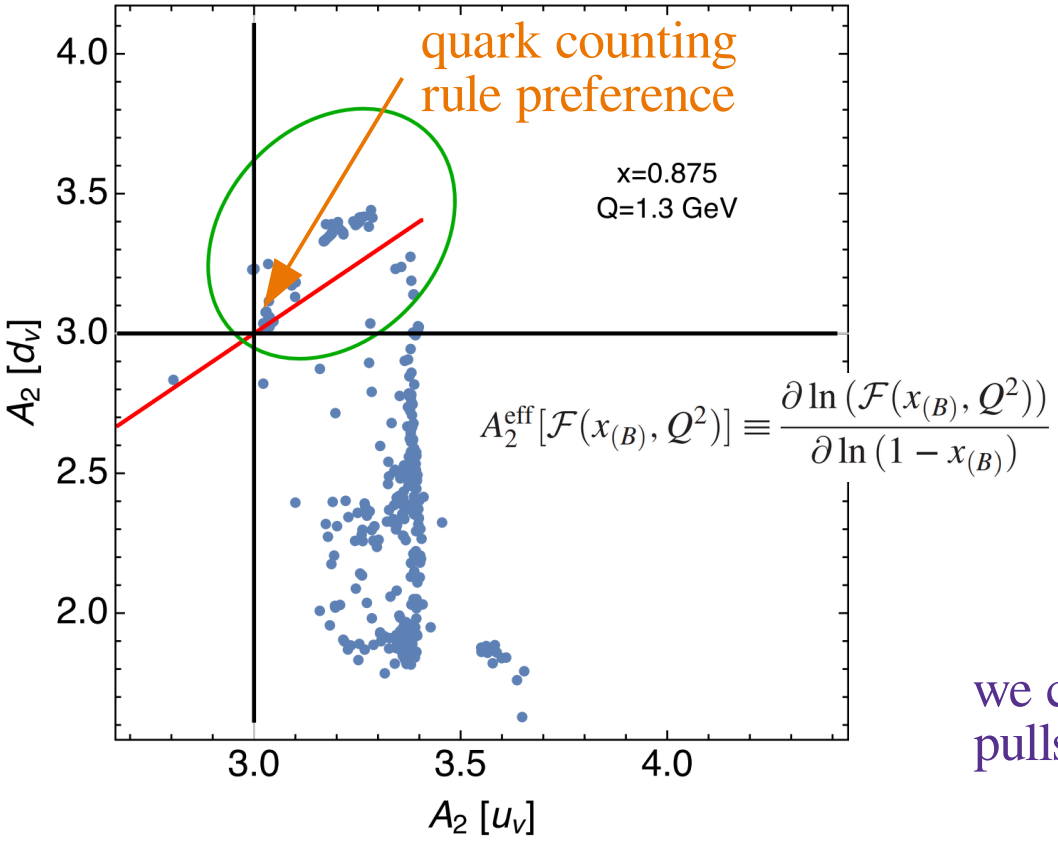


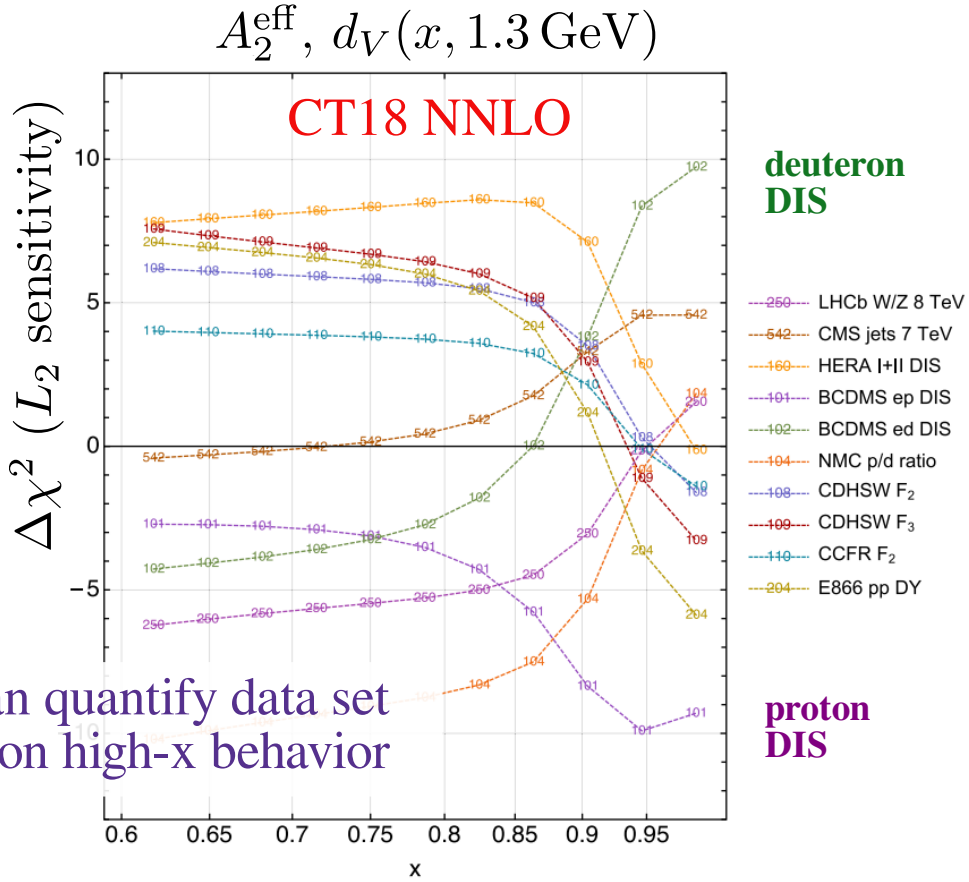
extracting high-x dependence in PDF fits

- 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, PRD103, 054029 (2021)



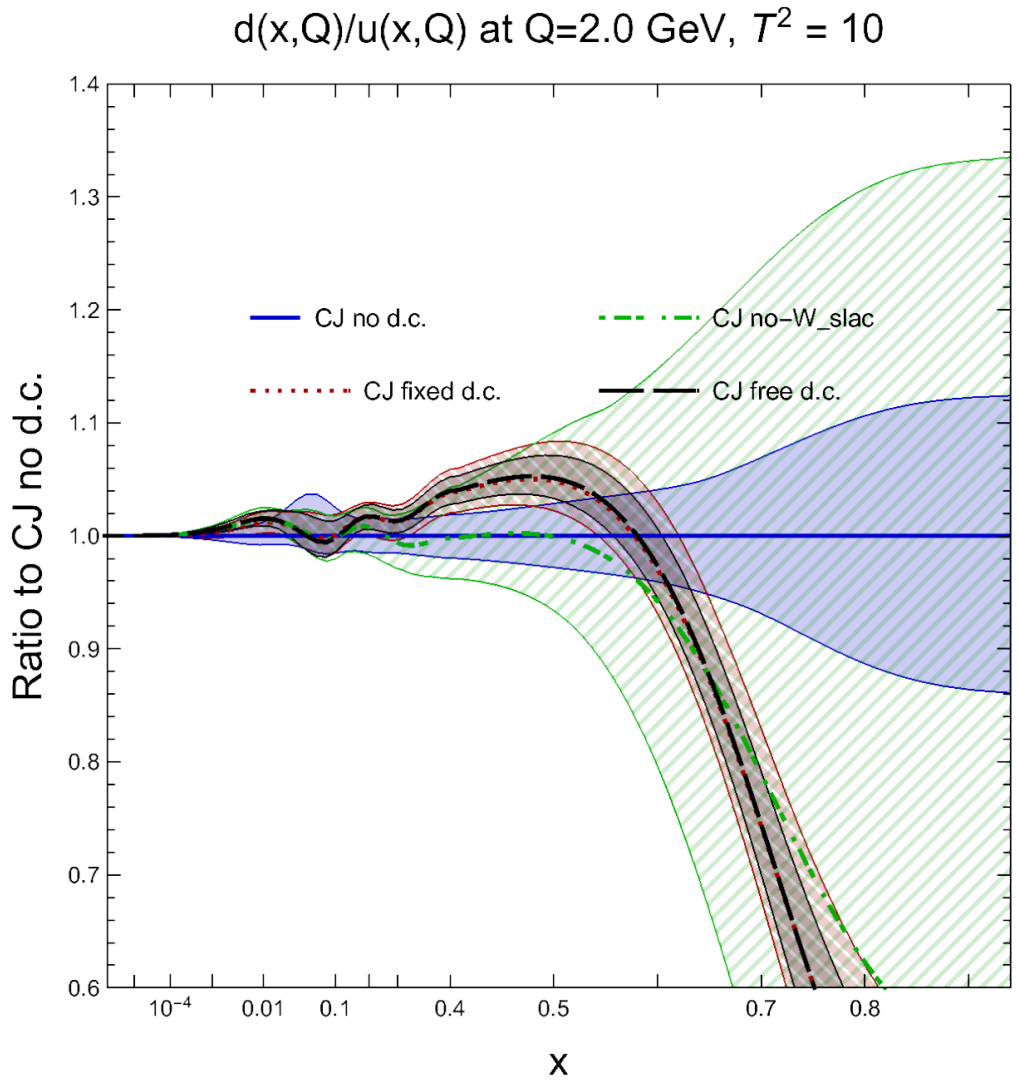


we can quantify data set pulls on high-x behavior

light-nuclear corrections: deuteron and high-x PDFs

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

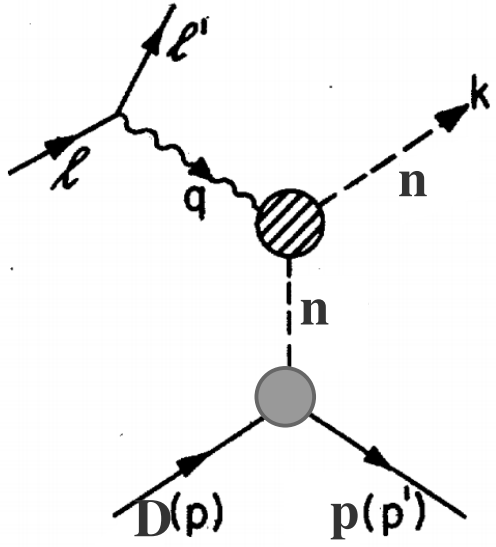
$$f^d(x,Q^2) = \int \frac{dz}{z} \int dp_N^2 \, \mathcal{S}^{N/d}(z,p_N^2)\, \widetilde{f}^N(x/z,p_N^2,Q^2)$$



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

- corrections are generally ~percent-level, but can become larger, especially at high x

- impacts LHC observables; necessary for high precision



heavy-nuclear effects relevant for proton structure studies

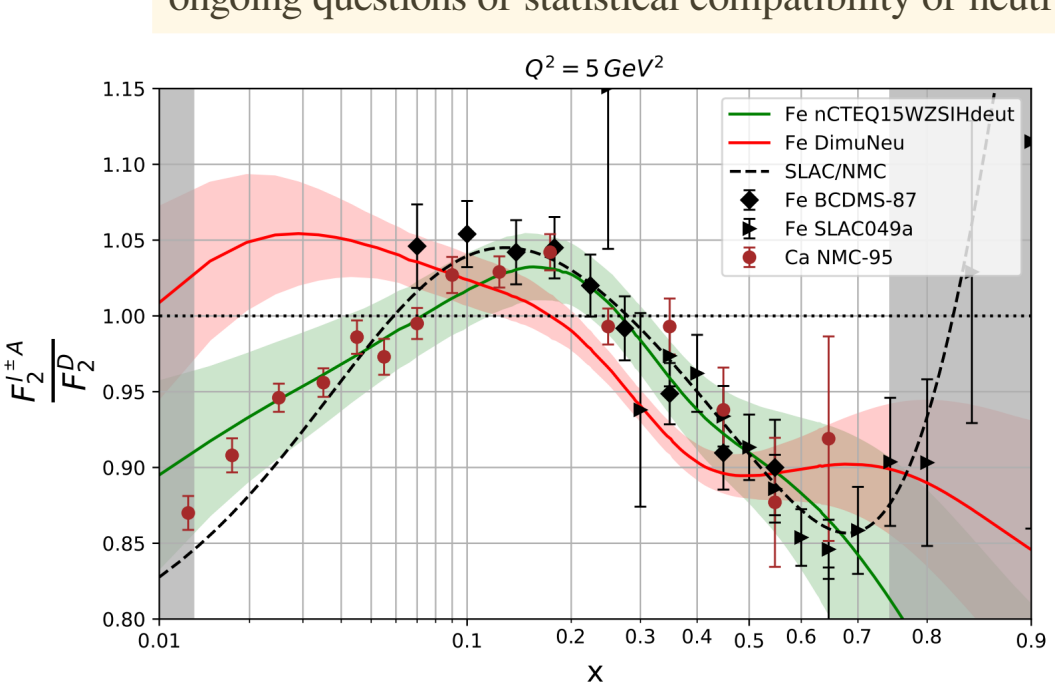
- beyond few-body systems, CT, other analyses use heavy-nuclei for flavor separation

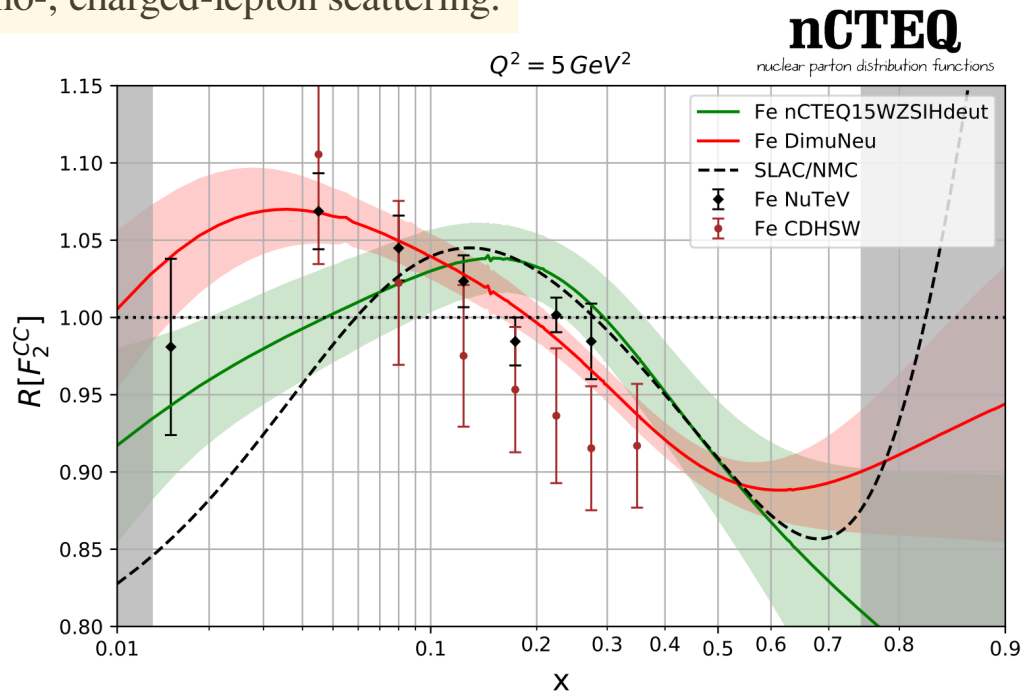
  [e.g., νA for strangeness]

- 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:





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

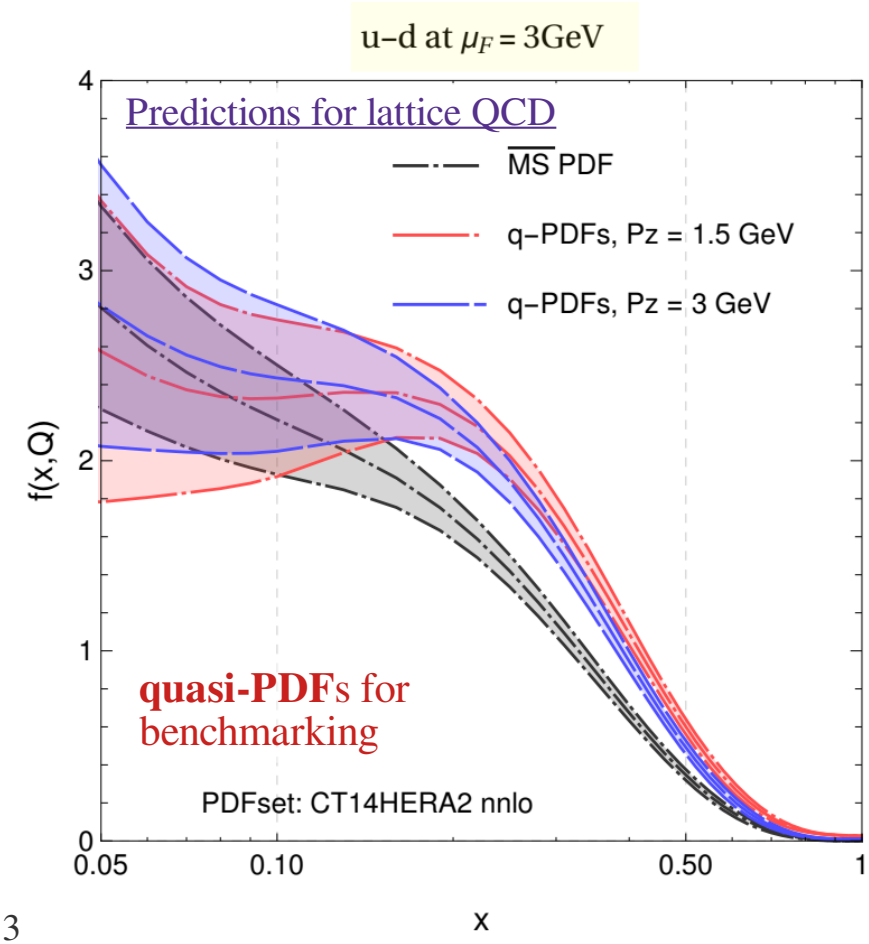
- recent years: progress in *ab initio* hadron-structure calculations from LQCD

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

there are be important synergies between PDF fitting and lattice QCD

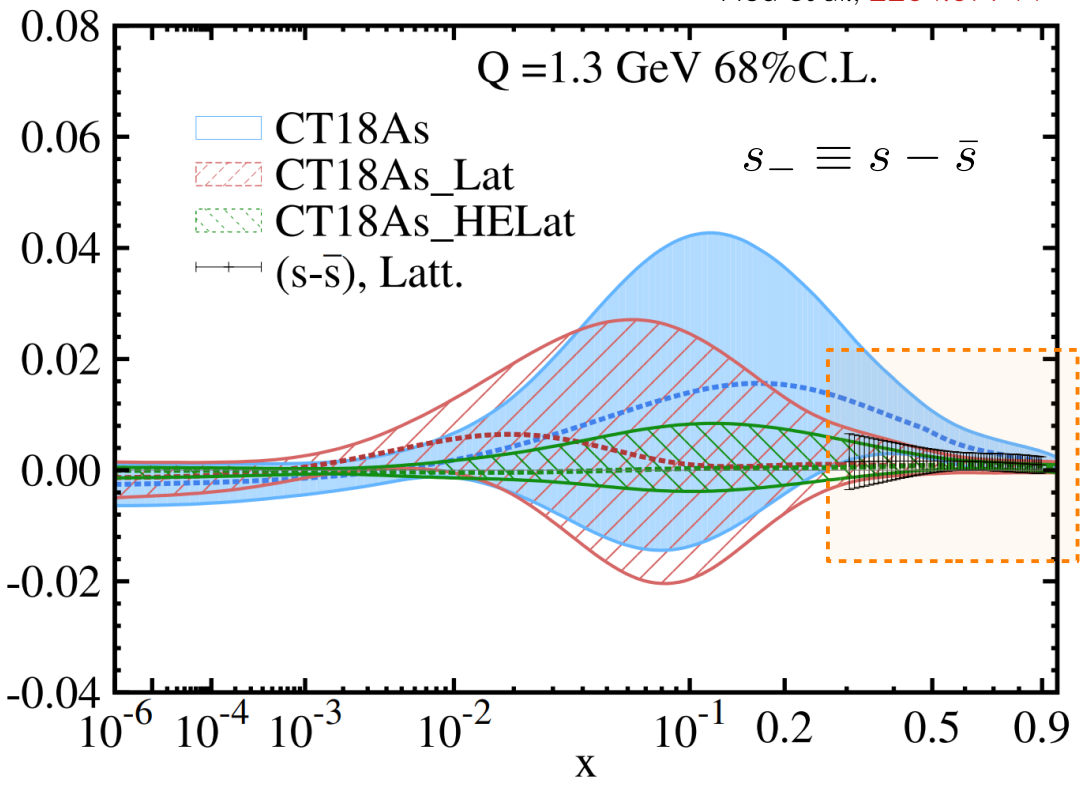
[possible overlap with HL-EIC]

TJH, Wang, Nadolsky, Olness, PRD100 (2019) 9, 094040



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

Hou et al., 2204.07944



ii

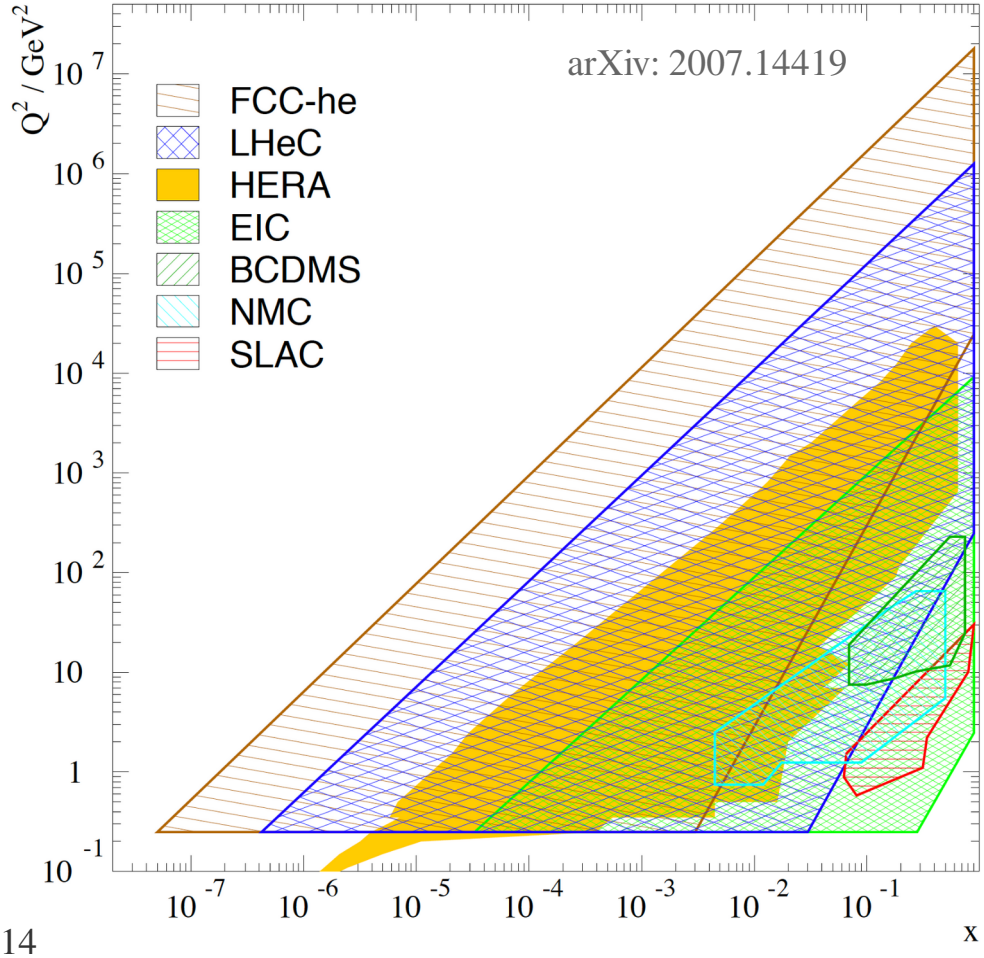
kinematic reach of the (HL-)EIC program

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

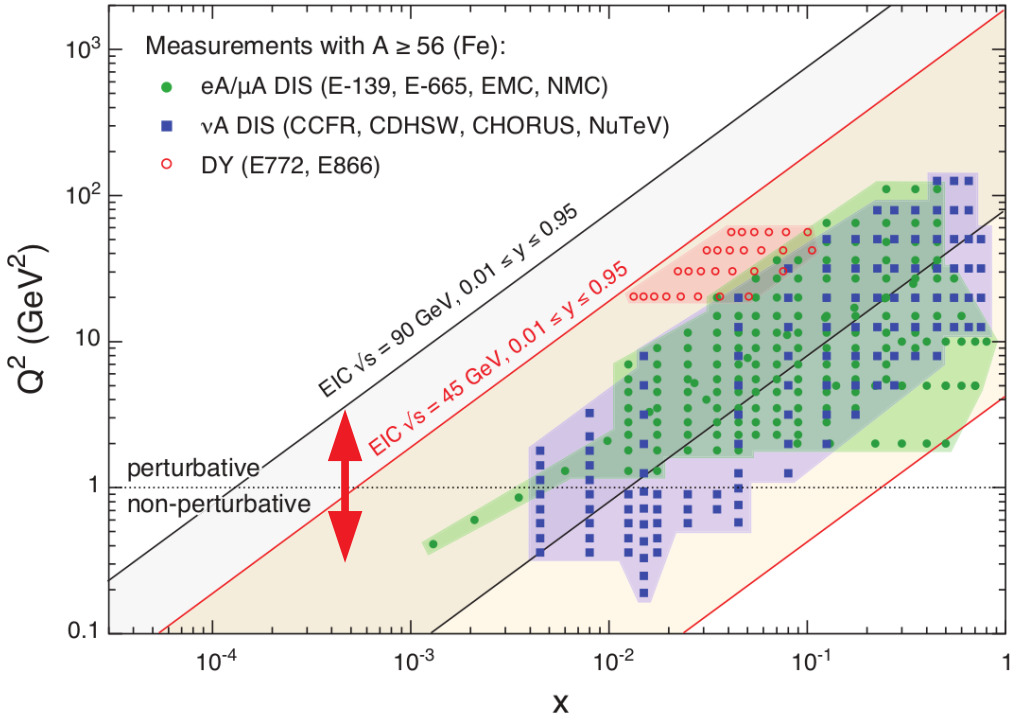
  → strong coverage of quark-to-hadron transition region between HERA, JLab12

- higher luminosity would enhance EIC's coverage at periphery of nominal [x, Q^2] space

  → strengthen overlaps with other experiments; enable more scaling studies



analogous nuclear DIS coverage:



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

ii

PDF impacts compared to high-value fixed-target DIS

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

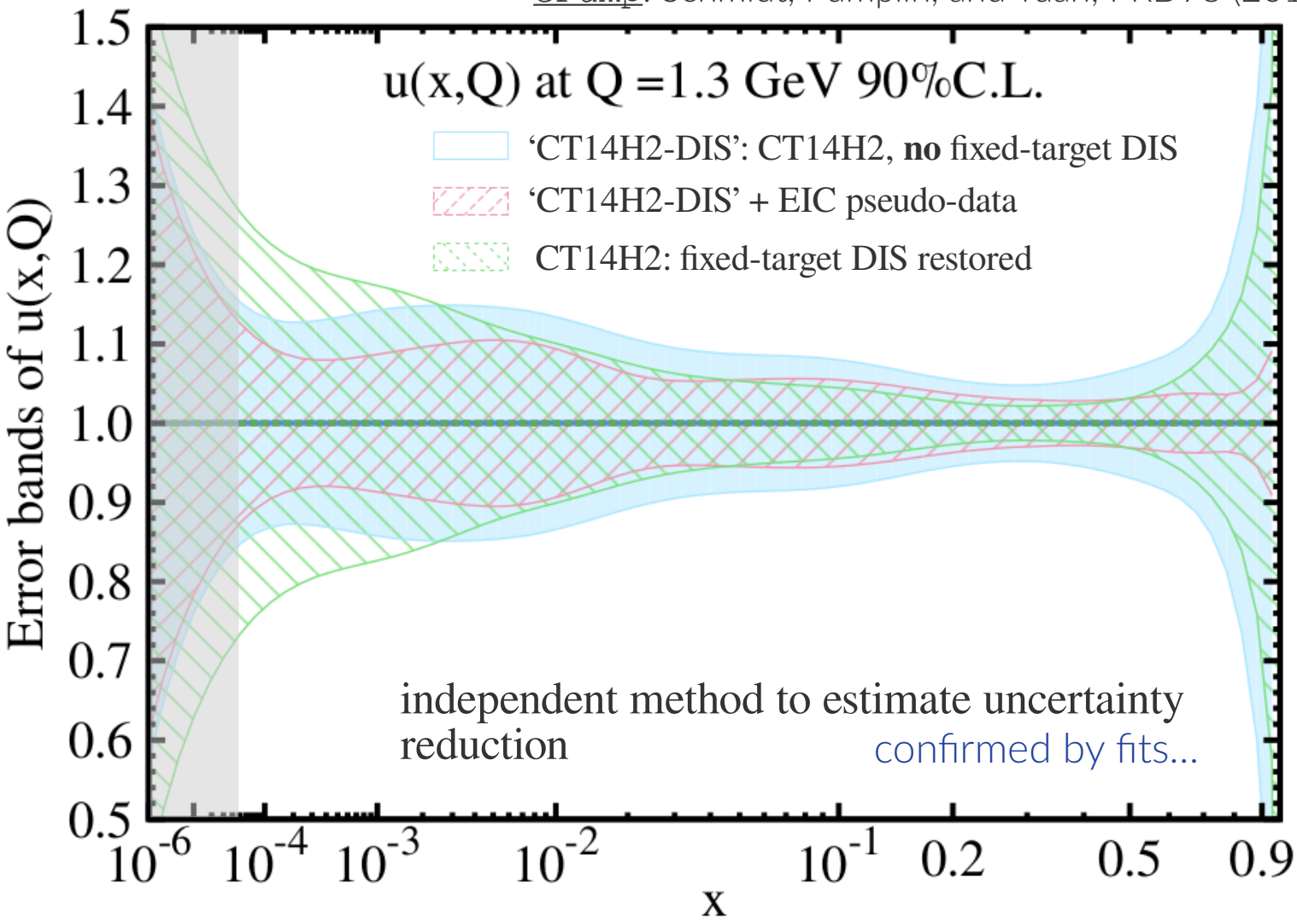


figure: S. Dulat

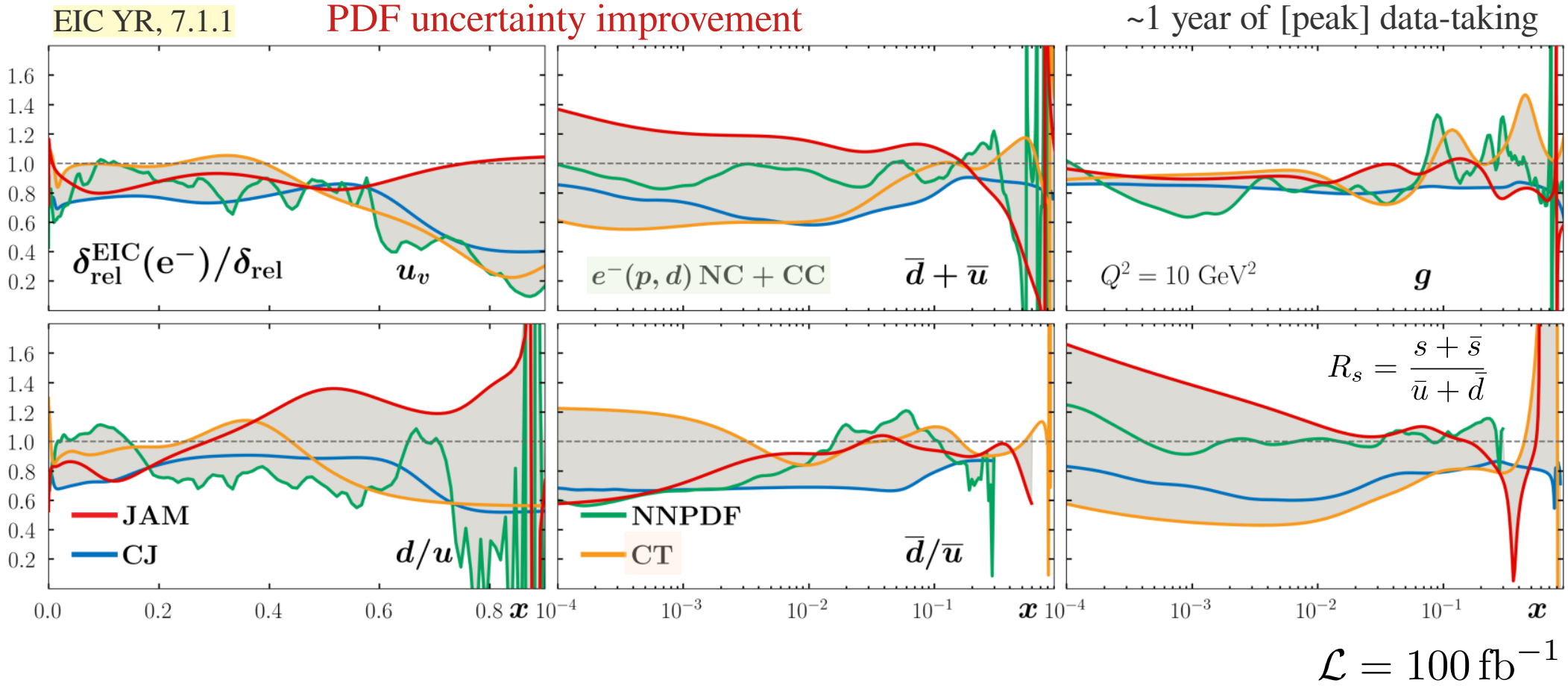
- **inclusive EIC may surpass total impact of fixed-target DIS in modern fits**

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

ii

reductions to PDF uncertainties: inclusive DIS data

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



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

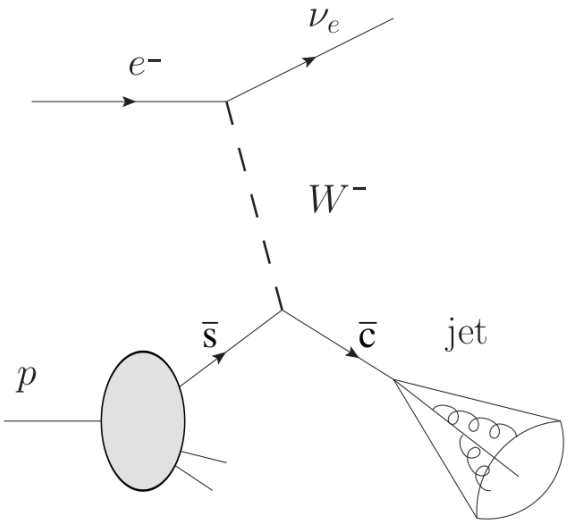
→ inclusive studies – indications of systematics limitations; **must also investigate**

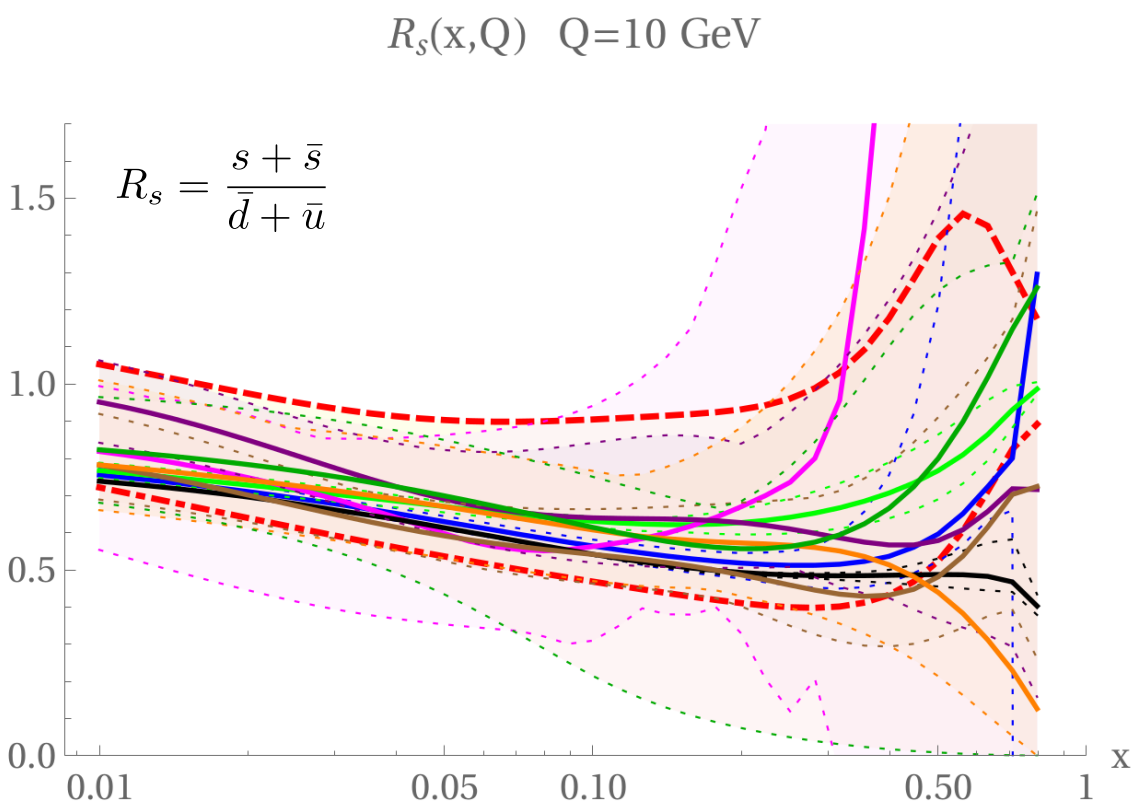
precision QCD through jet and heavy-flavor production

- 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

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





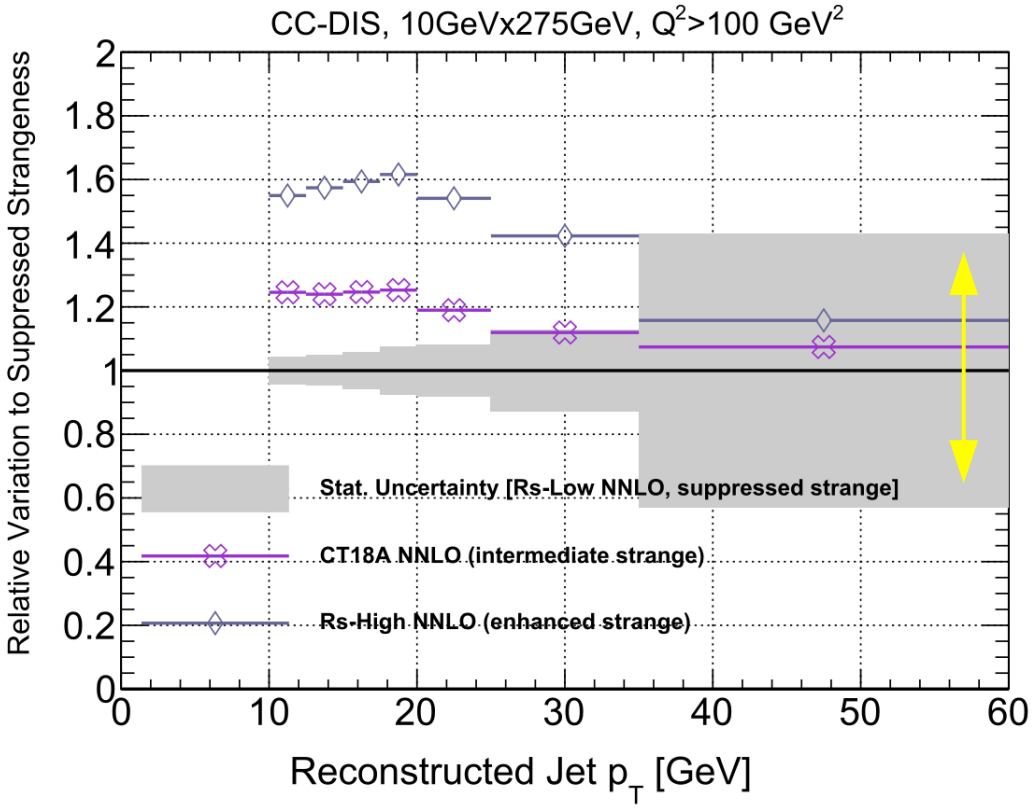
final-state tagging provides lever arm for flavor separation (here, strangeness)

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

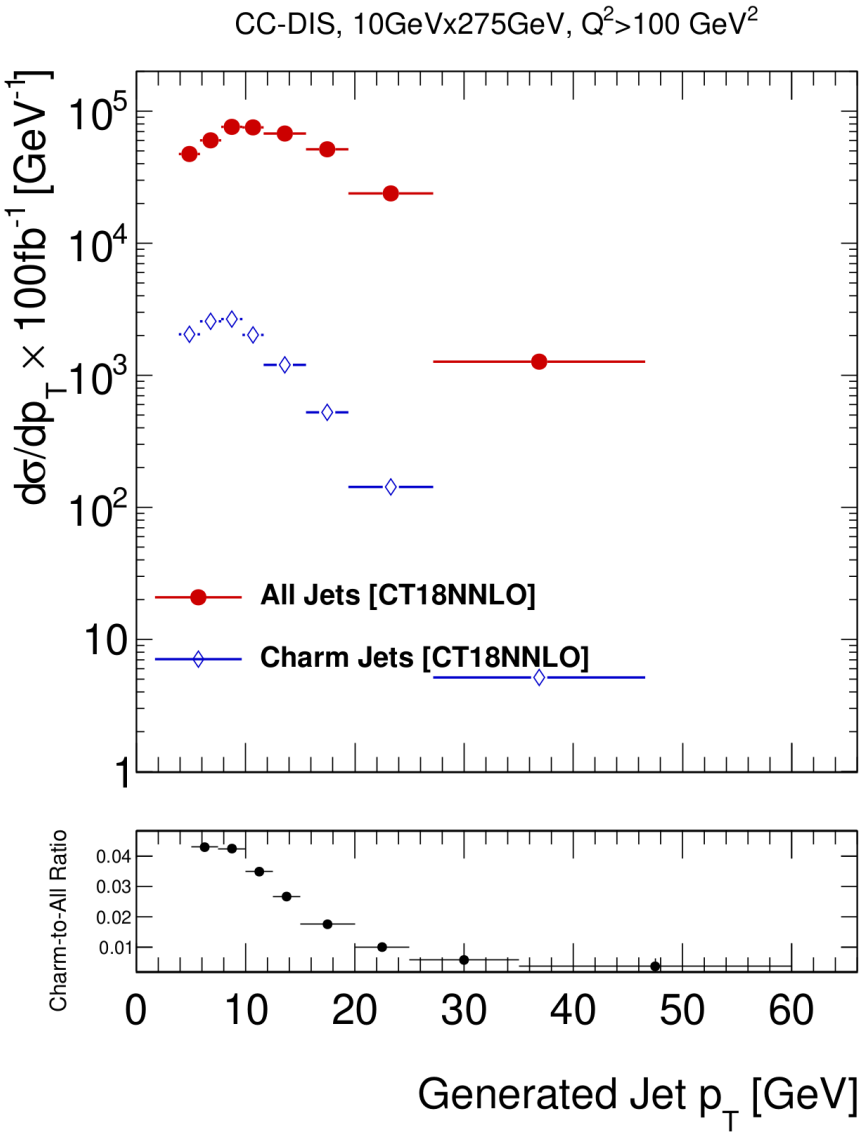
→ analogous jet measurements might be extended to nonperturbative heavy flavor

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

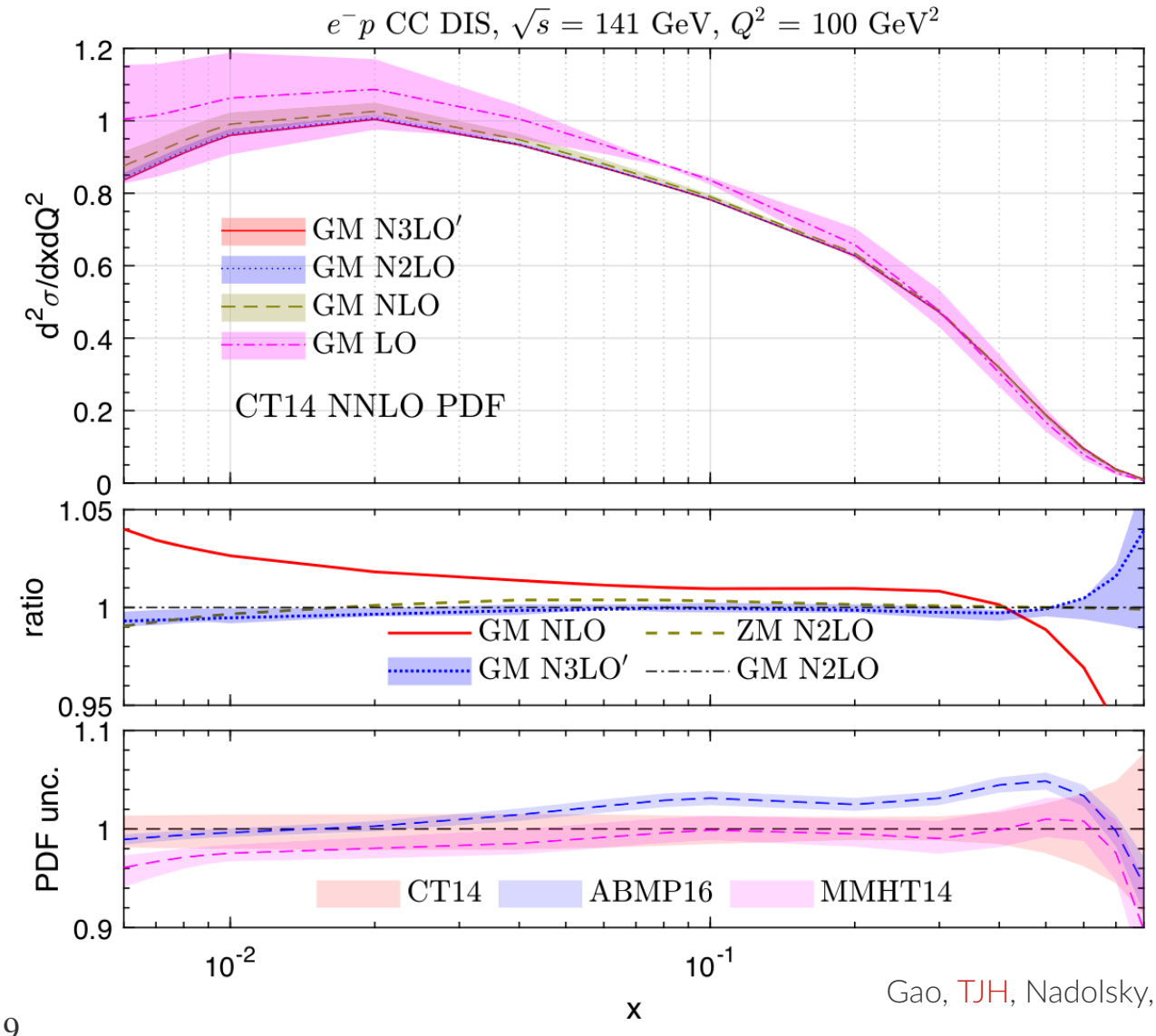
- reduced $\delta_{\rm stat}$ could significantly enhance knowledge of p_T dependence

→ 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 N^{3}LO corrections for highest energies at EIC



- strong perturbative convergence

  → for N^{3}LO′, 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

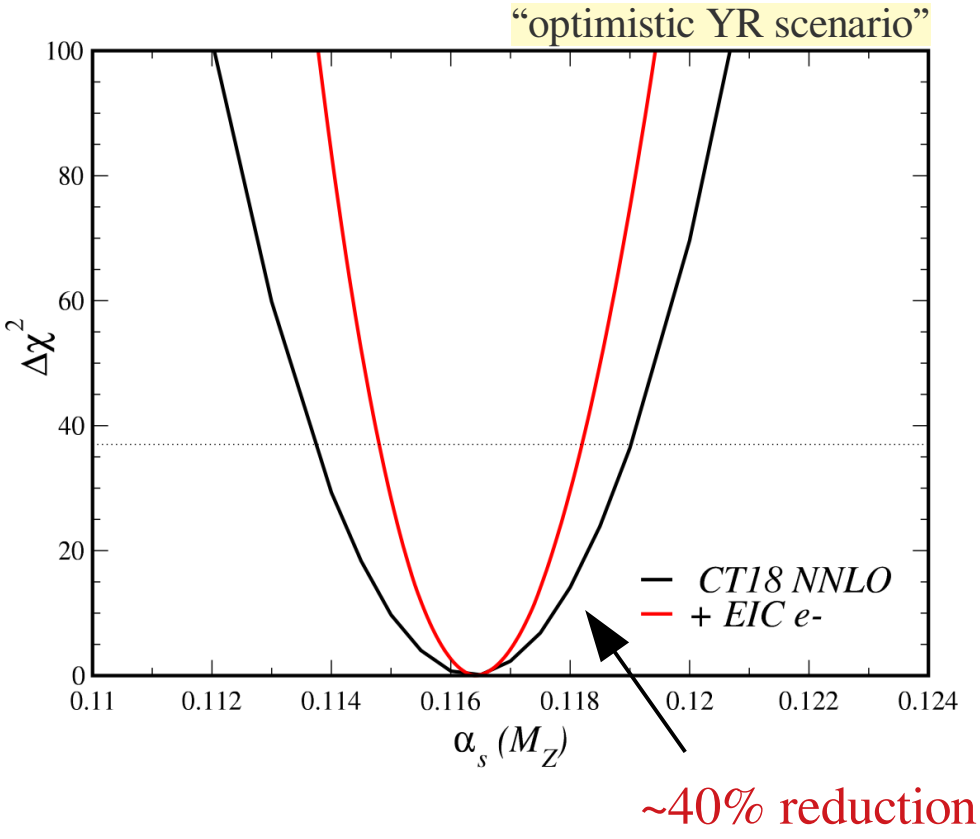
Gao, TJH, Nadolsky, Sun, Yuan: PRD105 (2022) 1, L011503

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

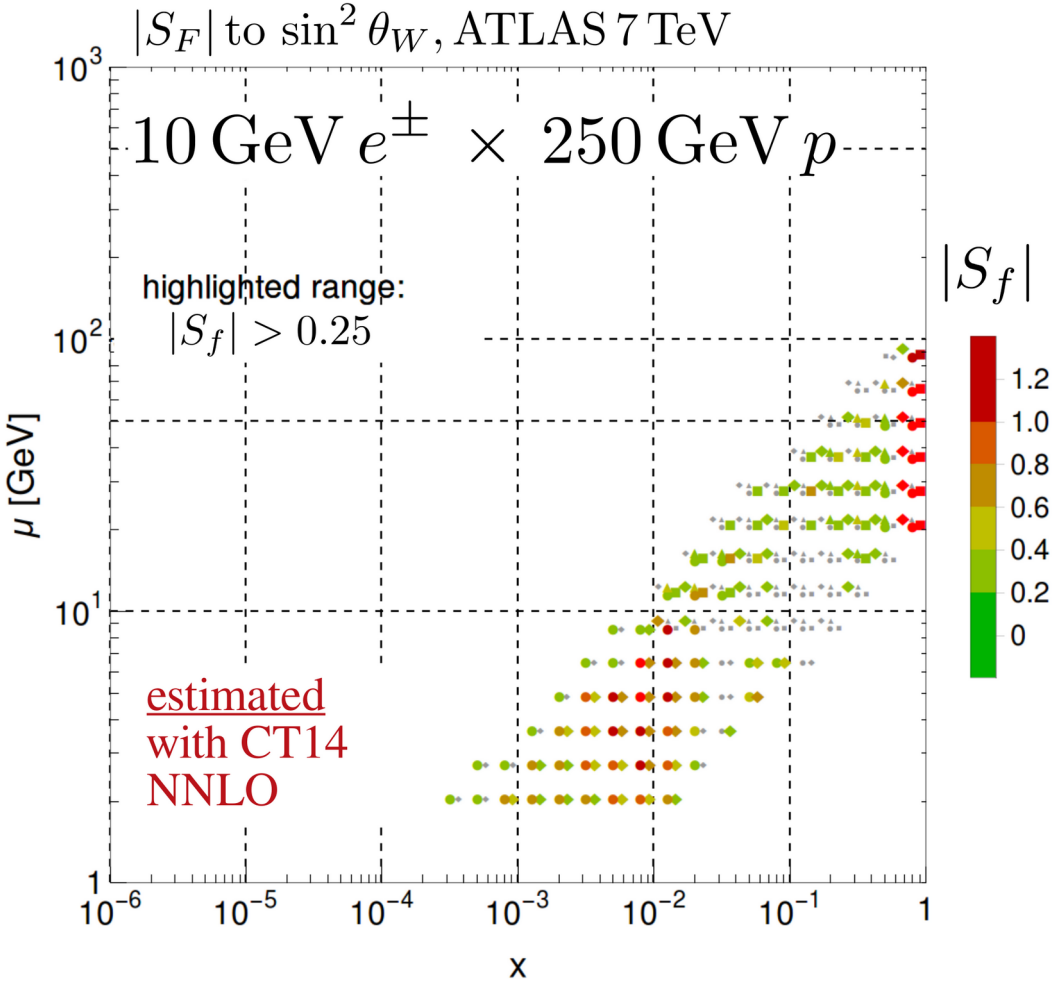
from inclusive data alone



~40% reduction

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

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



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

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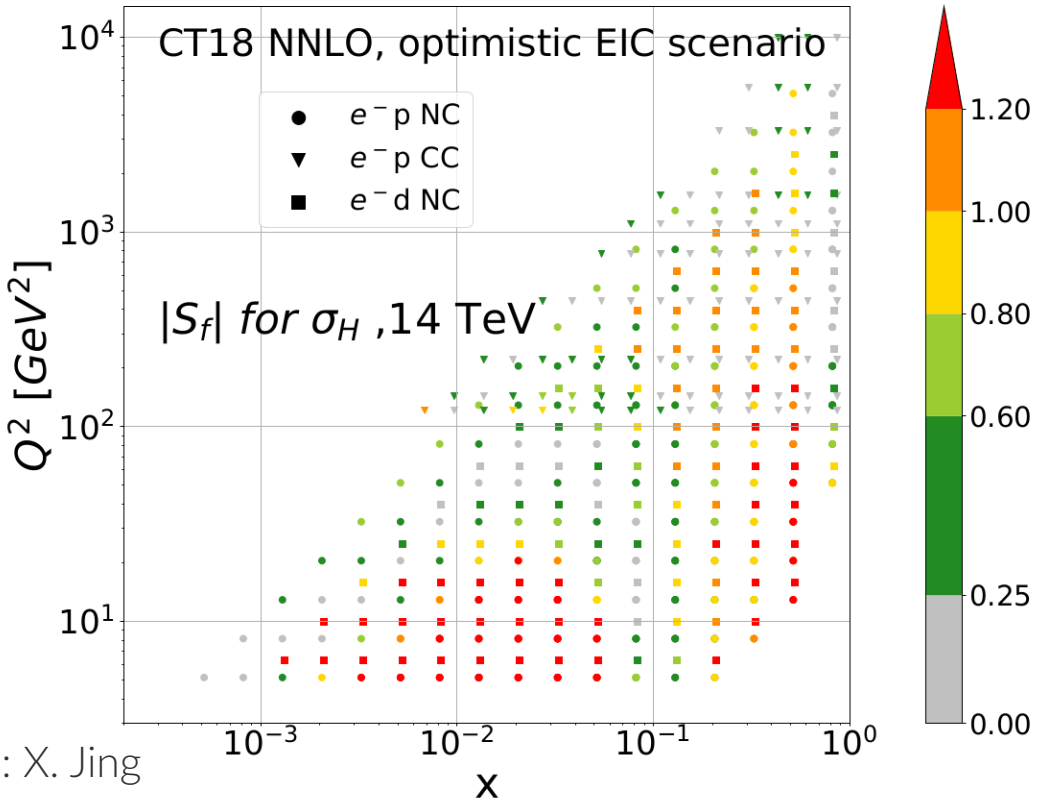


figure: X. Jing

strong predicted impact on the Higgs sector

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

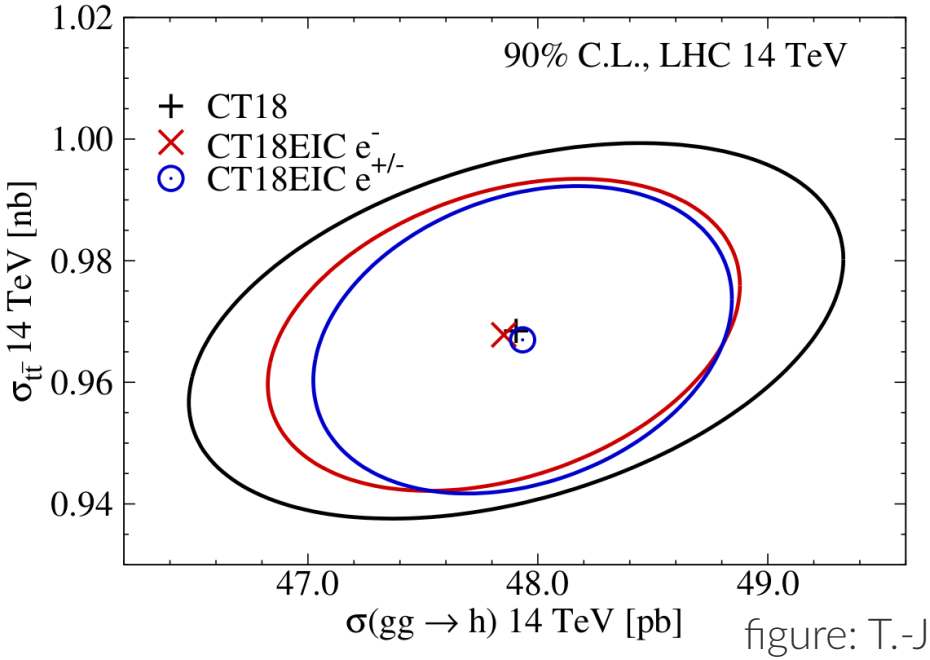
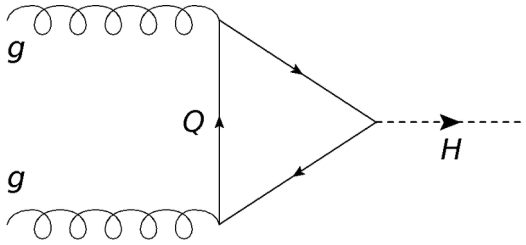


figure: T.-J. Hou

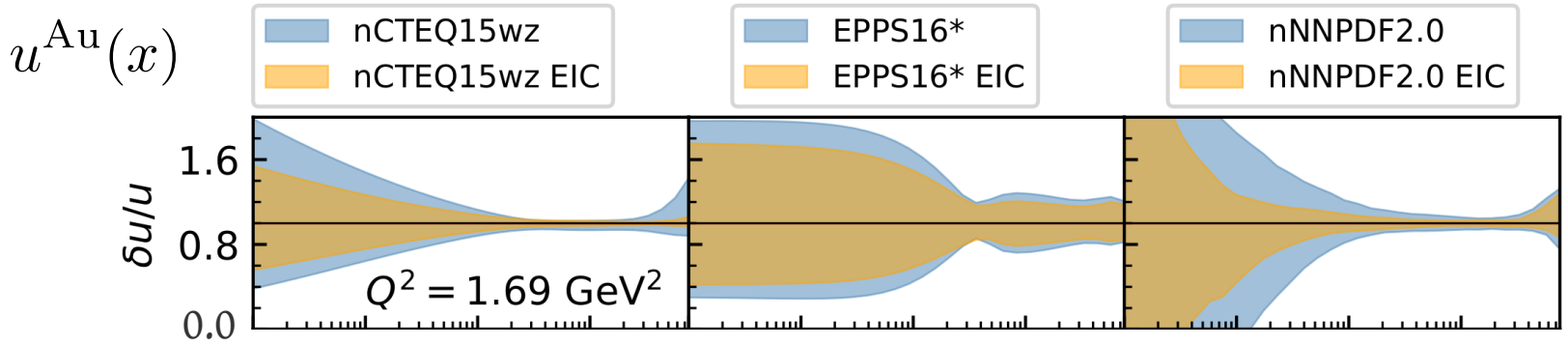


- impact closely tied to that of the integrated gluon PDF

→ added leverage from positron data…

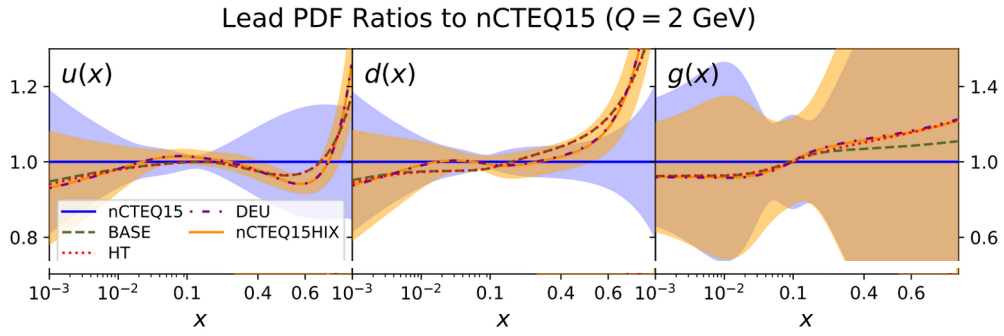
understanding nuclear effects

→ 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: higher luminosities would help

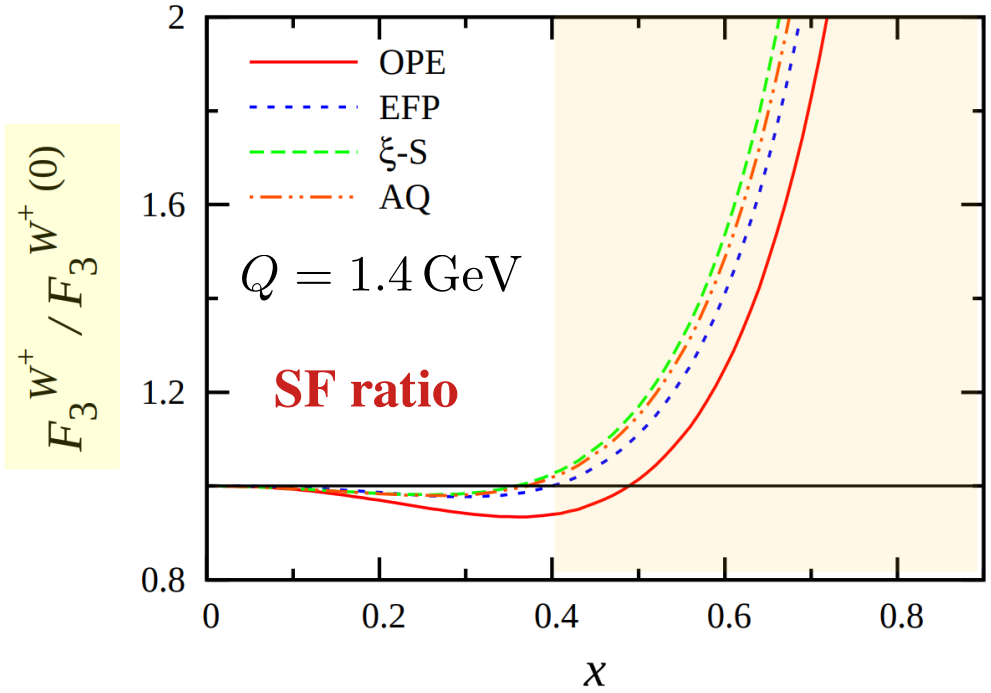
high-luminosity possibilities

Snowmass21, Abdul Khalek et al.: 2203.13199

- have highlighted examples of EIC impact on PDFs, high-energy QCD
  - → in the process, already alluded to possibilities with higher luminosity
- in general, may open or extend new channels
  - → especially those hindered by low(er) event rates
    - these suggest a number of other potential avenues

higher luminosity: understand power-suppressed QCD corrections

- aside from higher-order corrections in α_s : higher-twist, target-mass corrections



potentially large, $\sim 1/Q^2$
large-x effects

crucial for precision in DIS

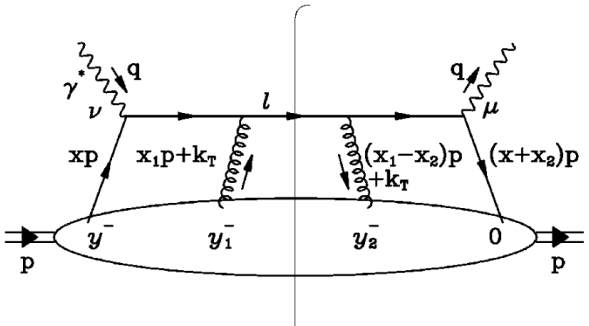
Brady, Accardi, TJH, Melnitchouk:
PRD84 (2011) 9, 074008

- closely-related to **multi-parton interactions** at high energy:

(jet production in electron-nucleus vs. electron-nucleon DIS)

$$\Delta\langle p_T^2\rangle \equiv \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ep} \qquad \text{(jet pT broadening)}$$

$$\langle p_T^2\rangle = \int dp_T^2 p_T^2 \frac{d\sigma}{dx_B dQ^2 dp_T^2} \Big/ \frac{d\sigma}{dx_B dQ^2}$$



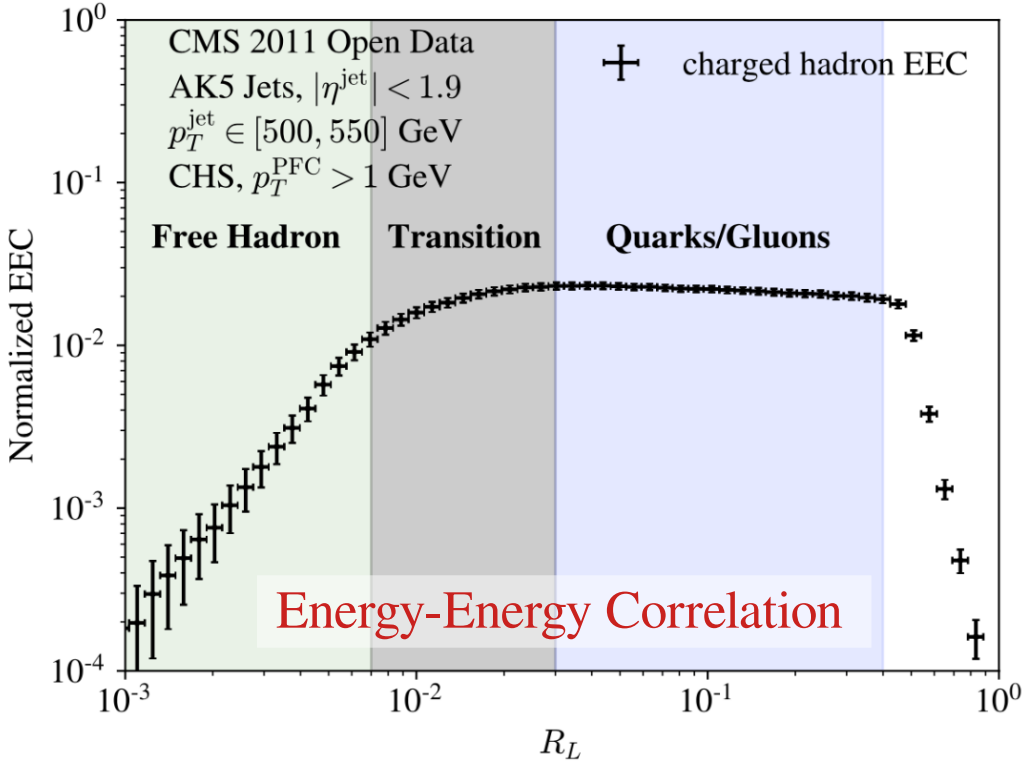
X. Guo, PRD58, 114033 (1998).

sensitivity to possible 'new' QCD measurements

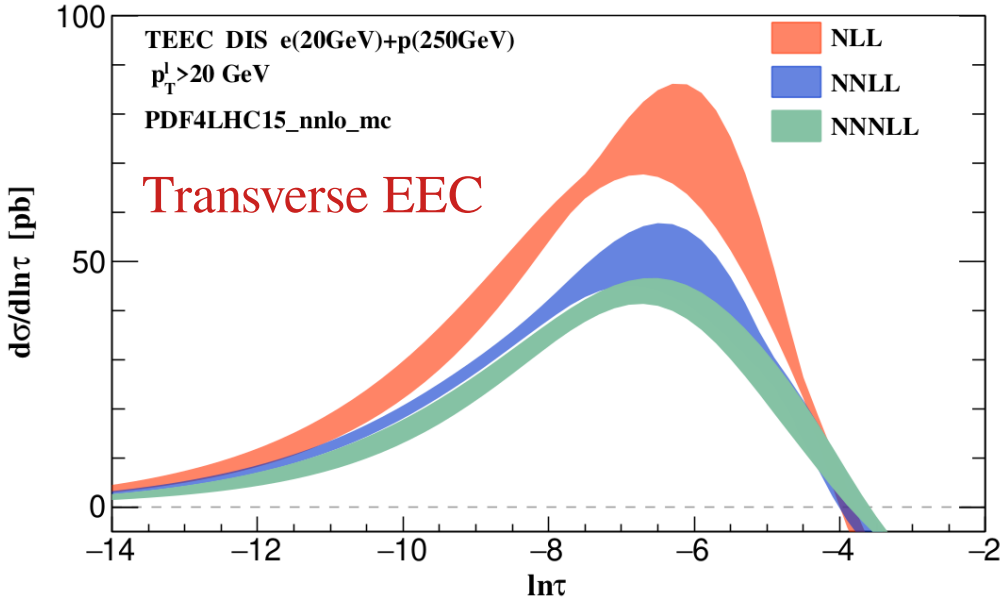
- strong interest in measurements connecting event-level observables to fundamental QCD
- e.g., QCD jets (various observables, constructions)

  → closely related to tests of QCD factorization

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



→ explore scaling to EIC kinematics



→ further understanding of TMD physics

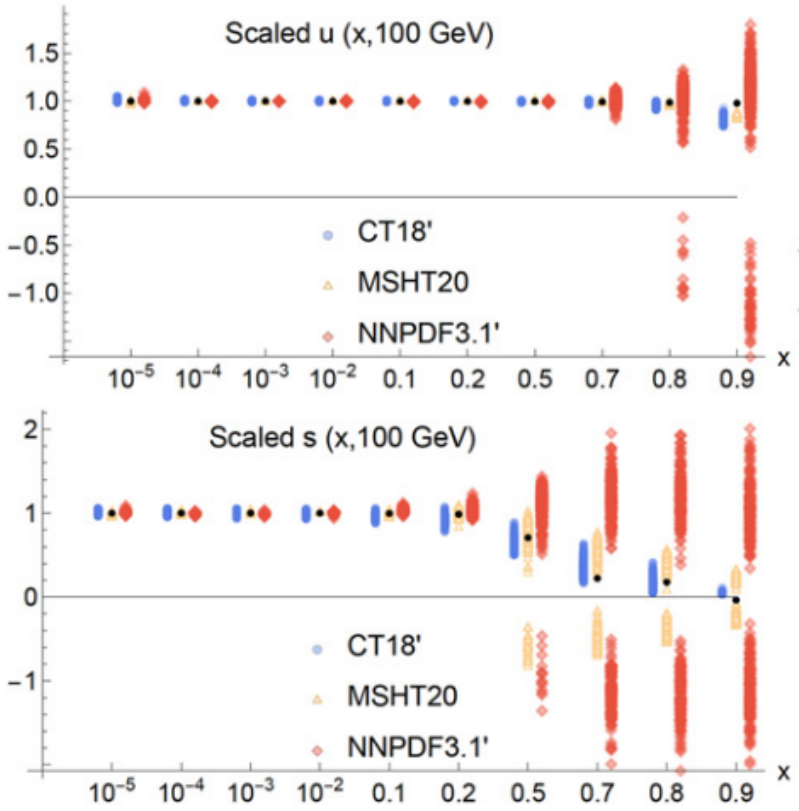
- higher luminosity significantly increases relevant cross sections

understanding PDFs and their uncertainties: high x

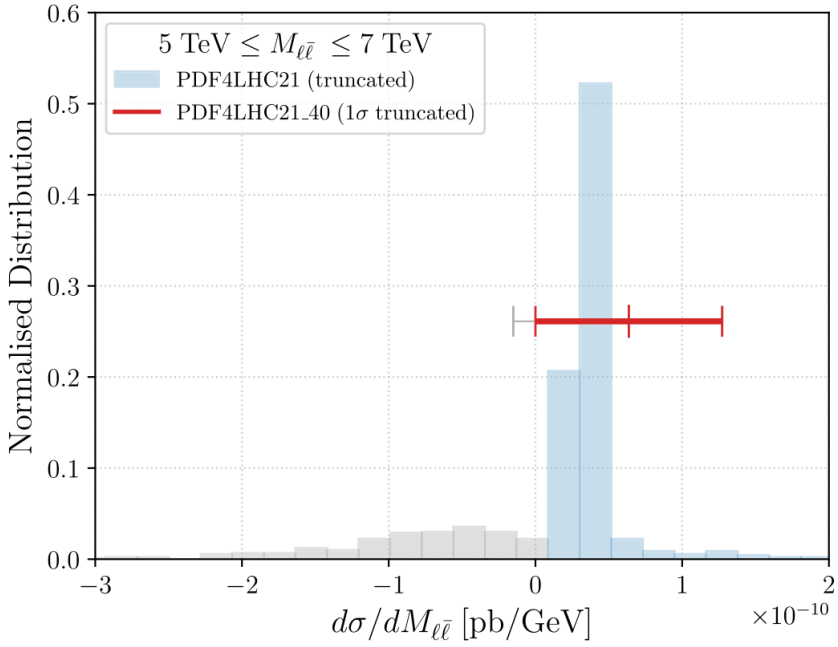
PDF4LHC21 benchmarking: 2203.05506

- 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:



- HL-EIC would allow exploration of PDF uncertainties with representative sampling

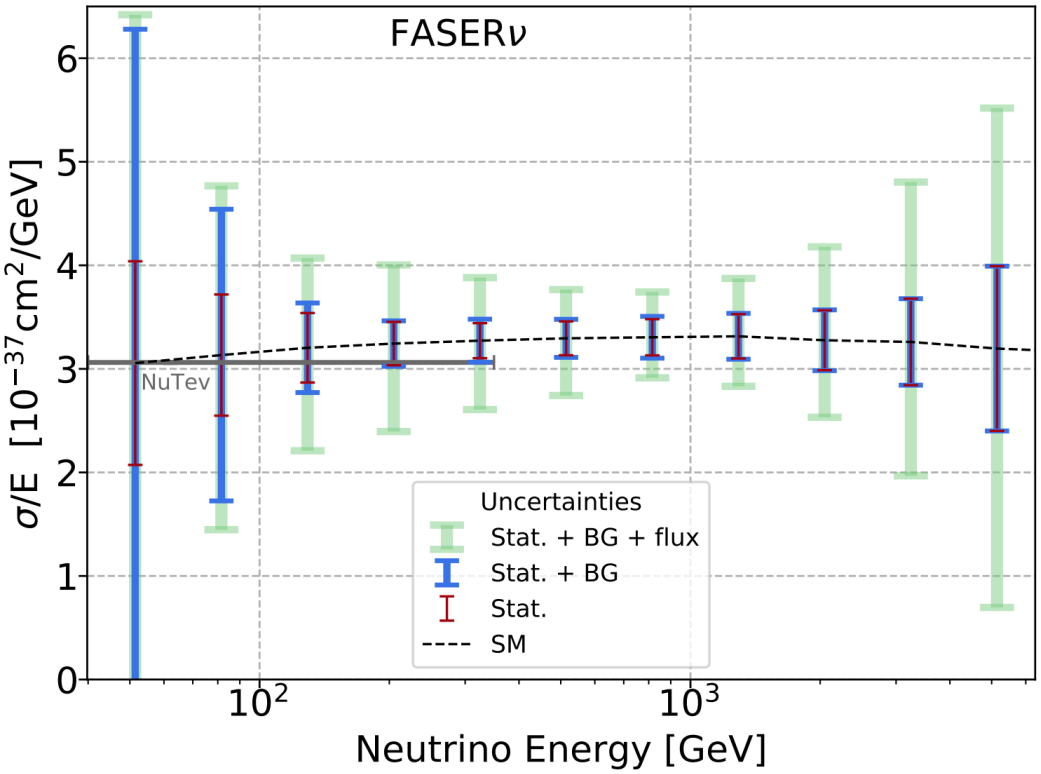
Courtoy, Huston Nadolsky, Xie, Yan, Yuan: 2205.10444

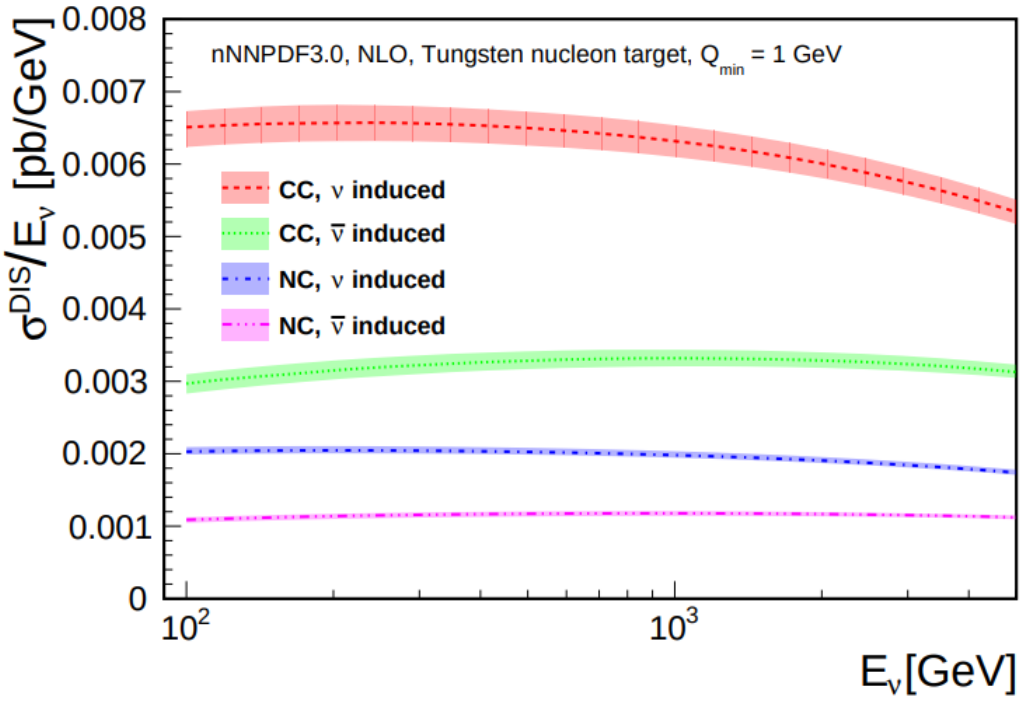
enhanced intersections with other/new facilities

- increased luminosity at EIC: greater synergies with very forward measurements

  → *e.g.*, FASERν at FPF could extract complementary nucleon/nuclear information

Feng et al., 2203.05090





- opportunity: multiple complementary expts; challenge: realistic impact studies

conclusions

- ultimately, higher EIC luminosity could open range of new measurements
  - → more sensitive interrogation of sea PDFs; subtler tests of QCD; …

- reach of (HL-)EIC can further reduce PDF uncertainties
  - → strong implications for HL-LHC, νA, other HEP activities, facilities
  - → PDFs must further tackle various (non)perturbative effects

- **systematics** important to weigh simultaneously
  - → *e.g.*, hadronic final-state effects on PDFs from SIDIS
  - → must understand relationship with **higher luminosity**

...needs careful assessment of priorities...

  - → YR often focused on latter; must explore more impact studies

Thanks to colleagues throughout the PDF, EIC communities