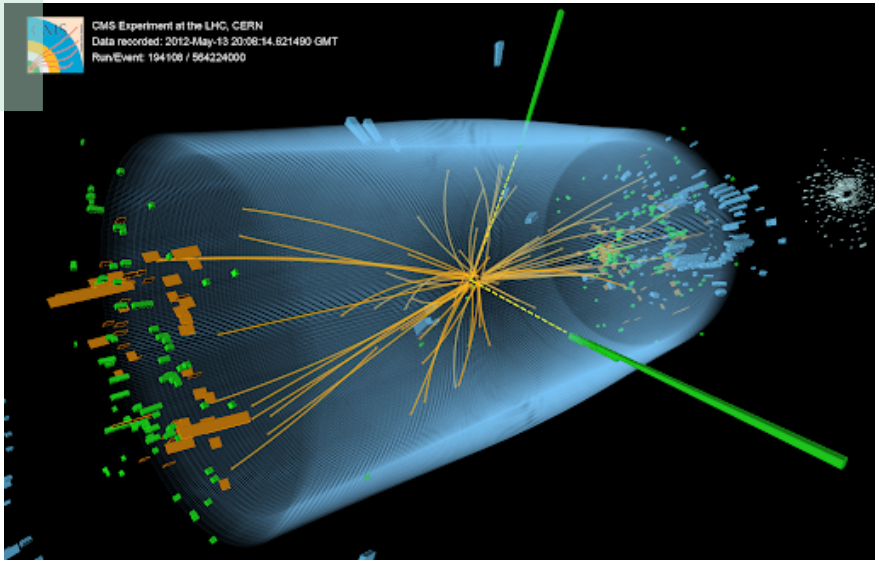
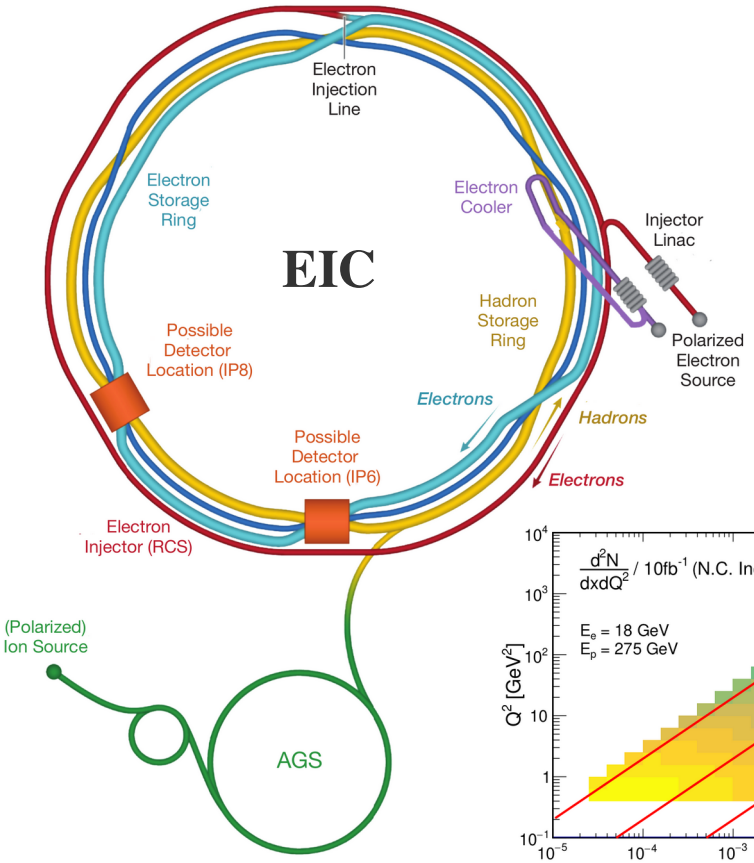
Reach and impact of the EIC: **collinear PDFs and MCEGs**

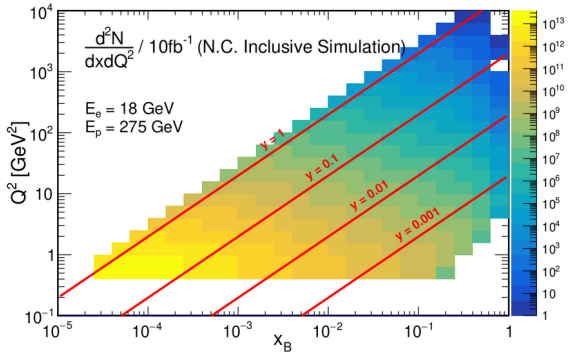
Tim Hobbs – Fermilab, IIT

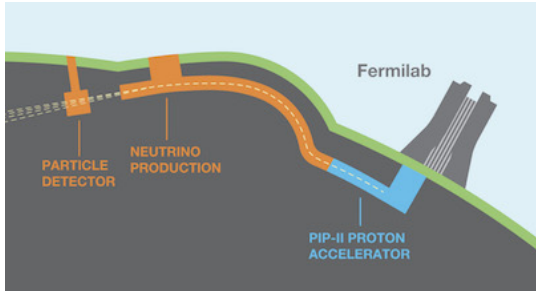
19th November 2021



EIC YR, arXiv: 2103.05419







Fermilab

ILLINOIS INSTITUTE OF TECHNOLOGY

MC and PDFs: bridging theory and experiment

- event generators direct theory, model predictions toward experimental analyses

  → EIC: inform detector design; efficiencies, backgrounds; syst. uncertainties

- generator predictions for colliders entail significant dependence on PDFs, theory choices

- PDF analyses are a complementary bridge: expt. data → QCD theory, model constraints

. . . . . .

- EIC design, preparation require DIS generator development; parallel refinements to PDF analyses

  → PDF improvements: theory accuracy, precision i

  → PDF scope of EIC program → LHC, νA ii

  → MC-dedicated PDF development iii

S. Gardiner

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**

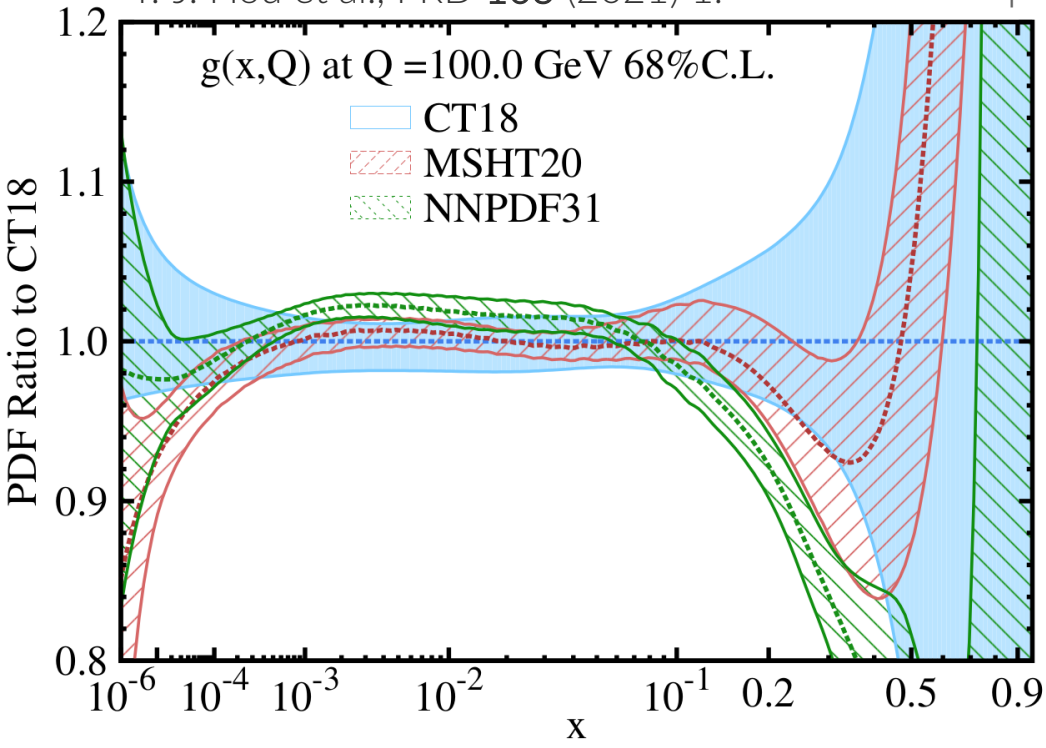
- heightened theory accuracy (HO, power corrections)
- novel measurements (EIC, LHC, νA)
- generator development

PDFs critical to next-generation precision

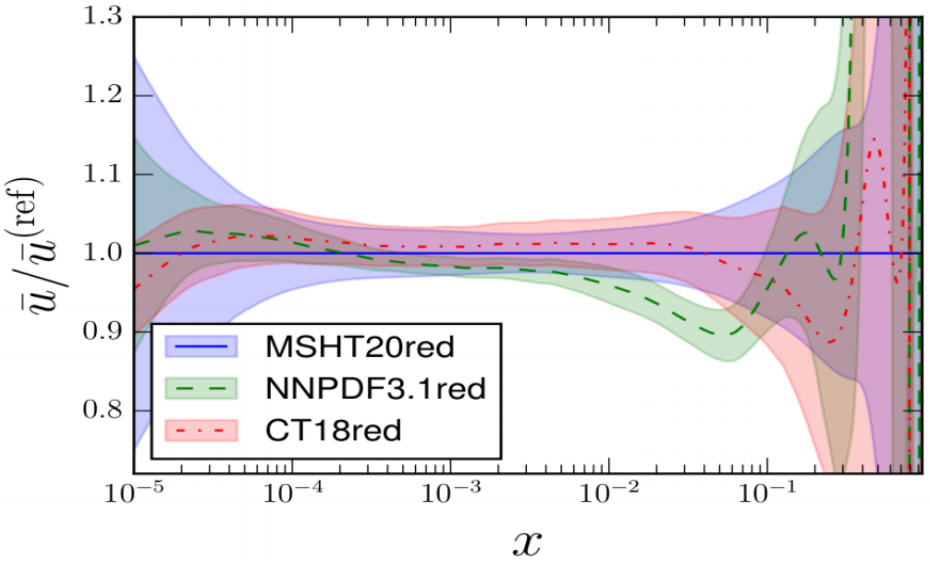
→ essential nonperturbative input for LHC predictions

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

T.-J. Hou et al., PRD 103 (2021) 1. contemporary NNLO QCD fits



…ongoing PDF4LHC21 benchmarking



- LHC program requires high-precision → reductions to PDF uncertainties

→ needed to match (N)NNLO theory accuracy; MC improvements

parametrization uncertainty: nonperturbative fitting forms

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

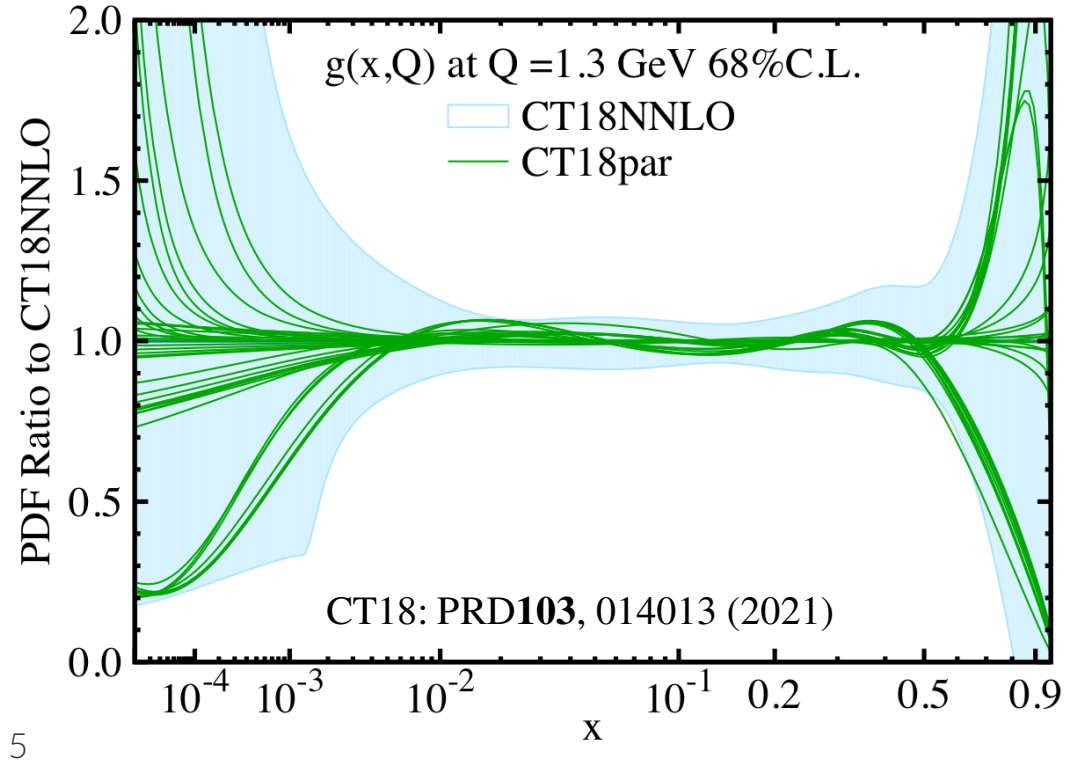
  → subject to complex nonperturbative dynamics

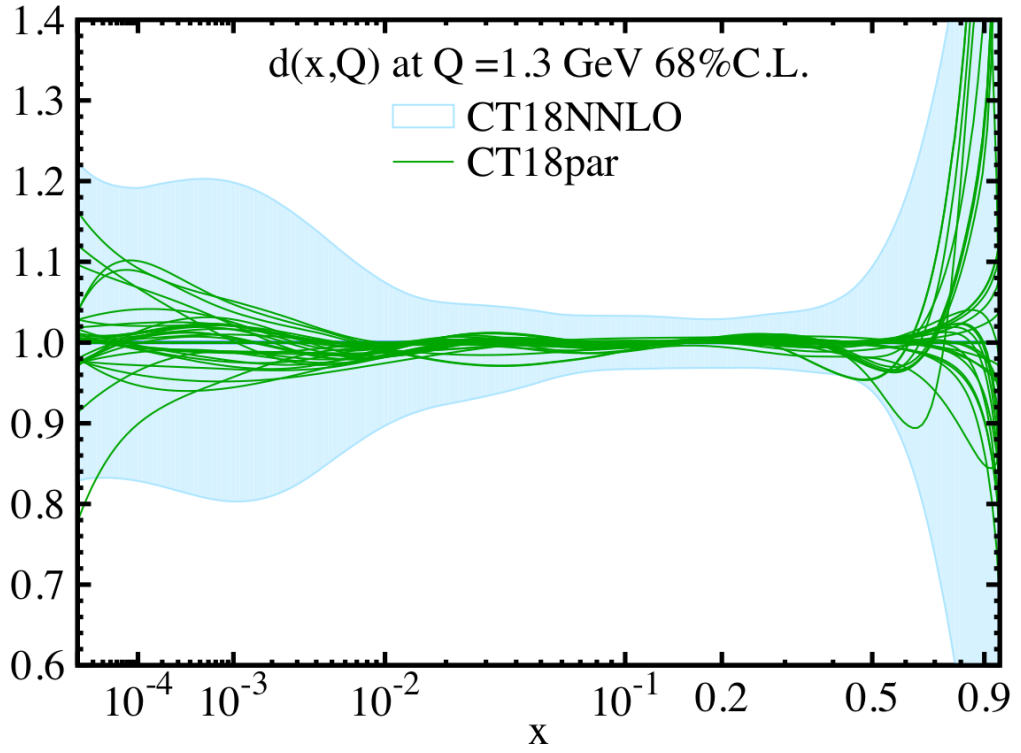
  → practice agnosticism w.r.t. initial parametrization

  (some guidance from QCD, QCD-inspired models)

  → explore model uncertainty with many forms

parametrization uncertainties largest in extrapolated regions

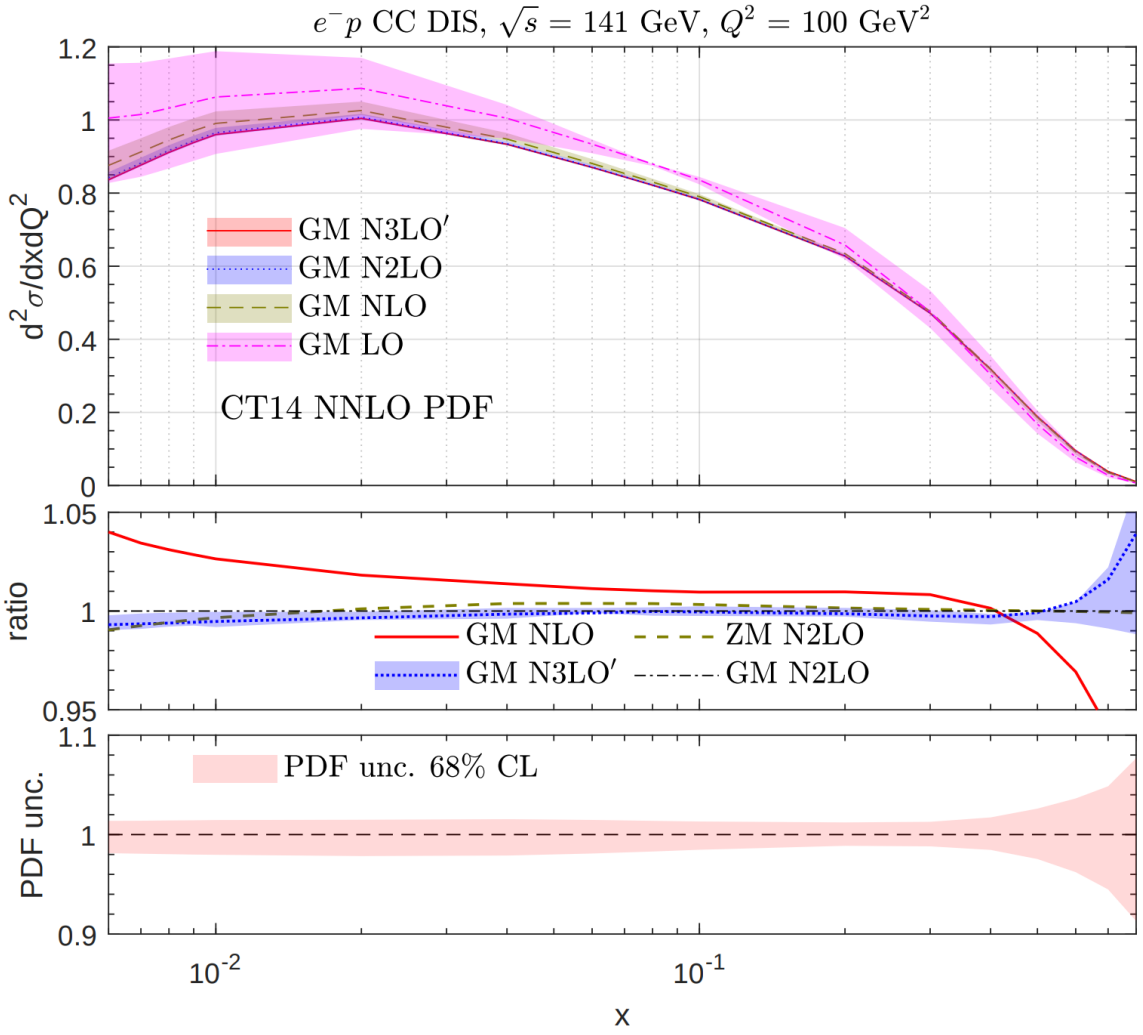




high perturbative QCD accuracy for EIC era

- treatment of heavy-quark masses at higher perturbative order non-trivial
- NNLO accuracy is necessary to stabilize scale uncertainties

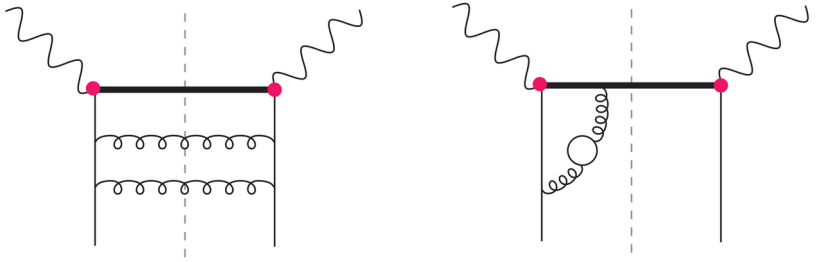
Gao, TJH, Nadolsky, Sun, Yuan: 2107.00460



- corrections enhance pQCD precision in CC DIS cross-section

→ higher energies: **EIC**, FASERν

→ analogous corrections influence DUNE few-GeV region



electroweak precision: photon PDF (i)

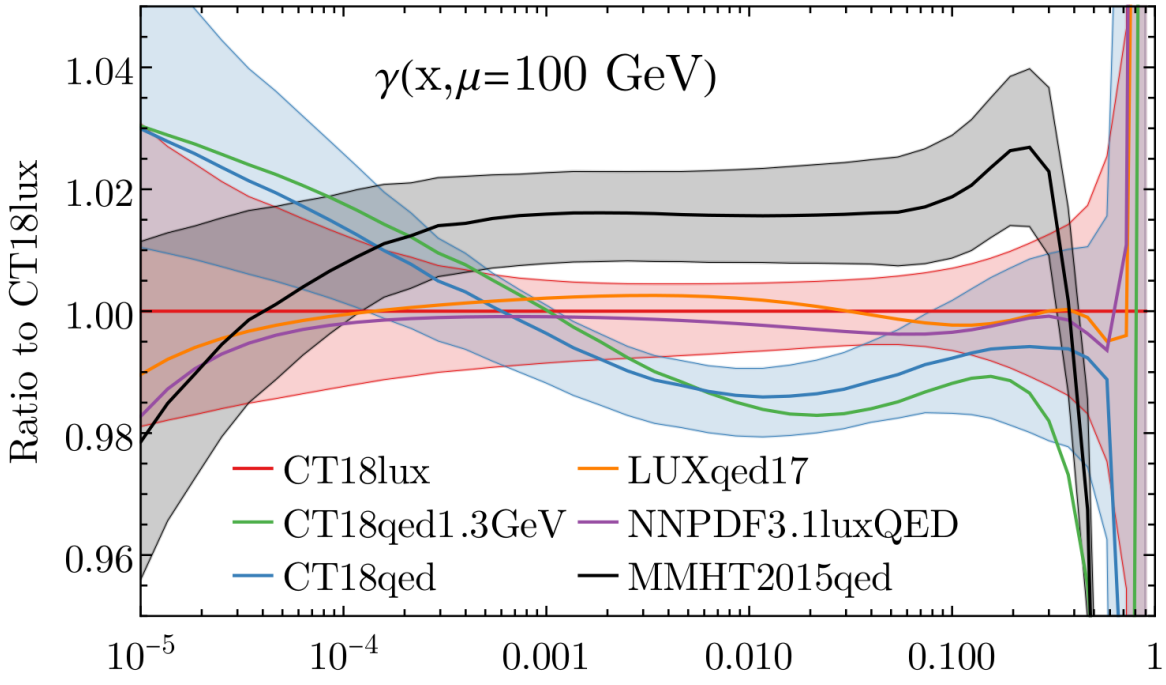
- at $\mathcal{O}(\alpha_s^2)$ accuracy, EW corrections and explicit $\gamma(x,\mu^2)$ needed

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

- following CT14QED, CT18QED now interfaces LUX formalism

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

→ 2 complementary implementations: CT18lux, CT18qed



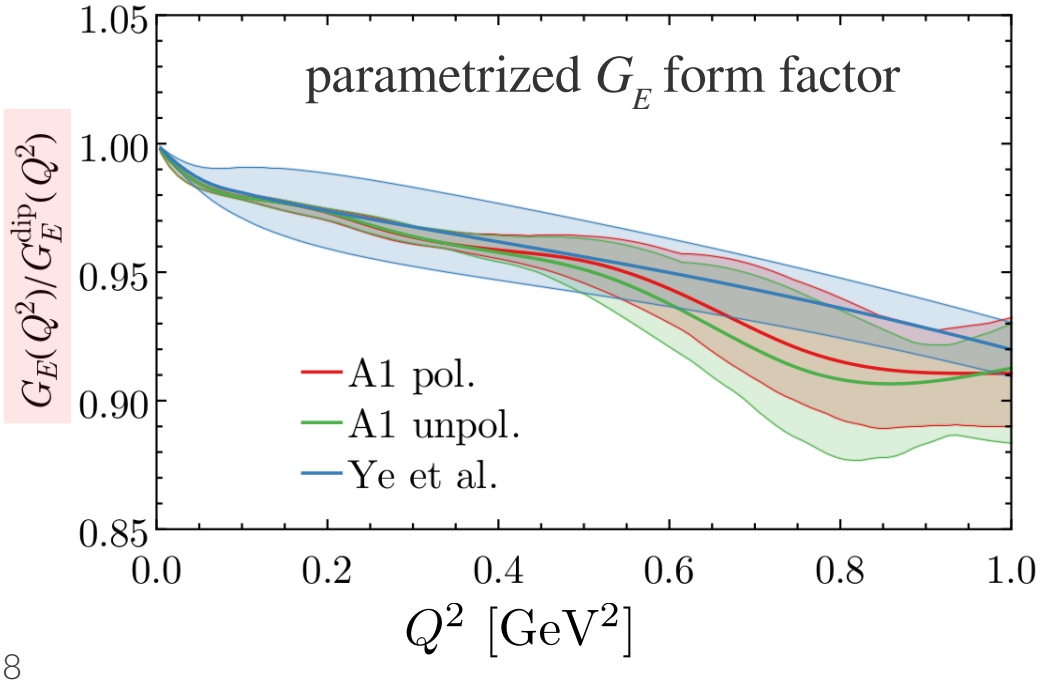
electroweak precision: photon PDF (ii)

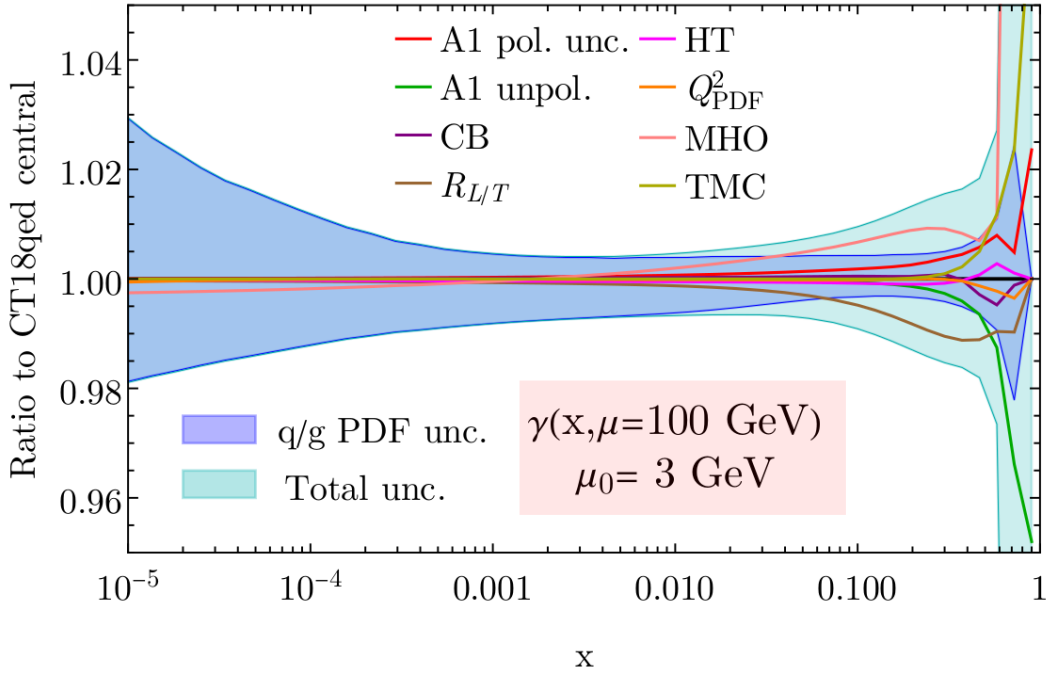
- depends on nonperturbative inputs [kinematical cuts alone can't avoid this]
- integrated proton SFs include contributions from low Q, moderate x

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

- dependence on Sachs EM form factors; twist-4, resonance prescriptions; …

[AND **quark-gluon PDFs**, uncertainties]

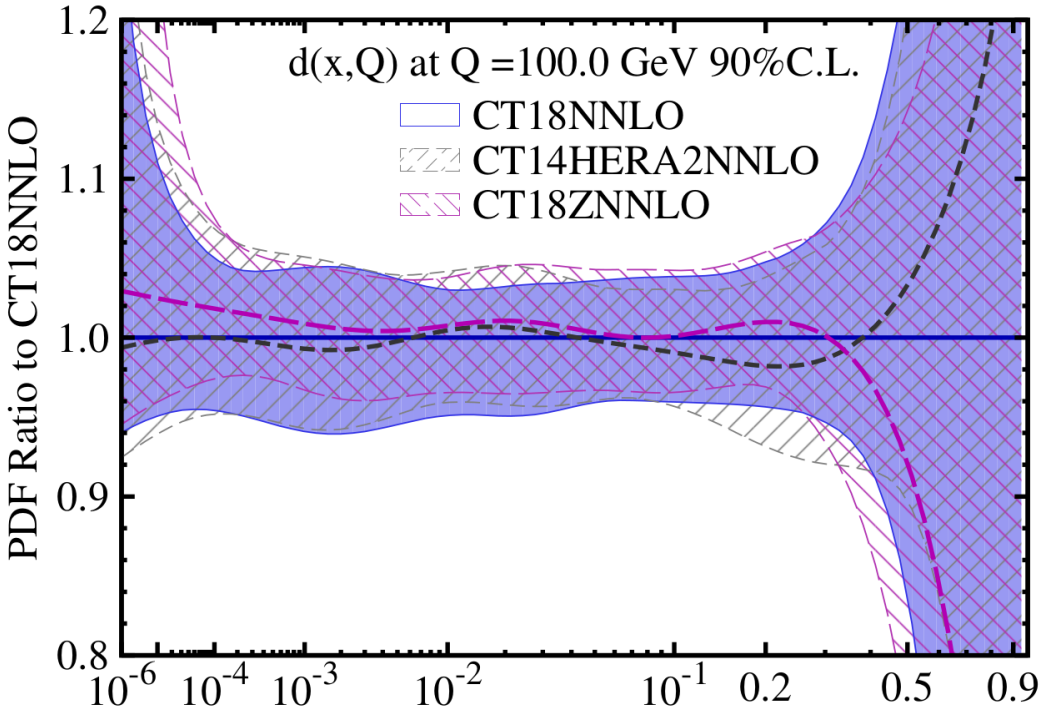


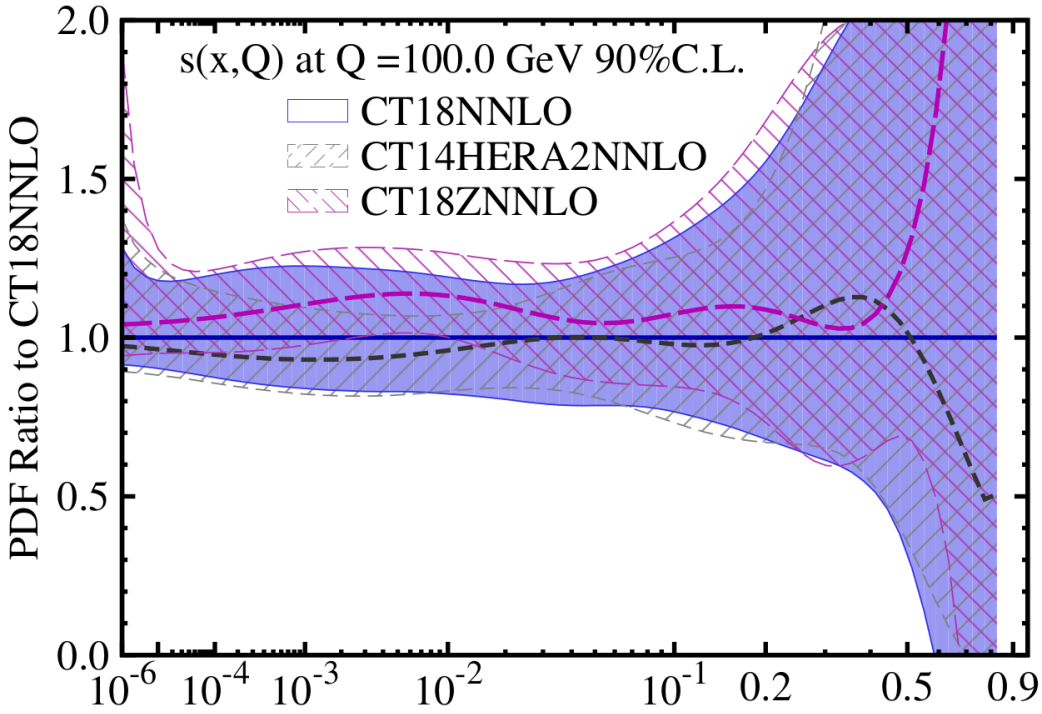


high-x PDFs remain dominated by large uncertainties

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

→ limited data → extrapolation → data tensions

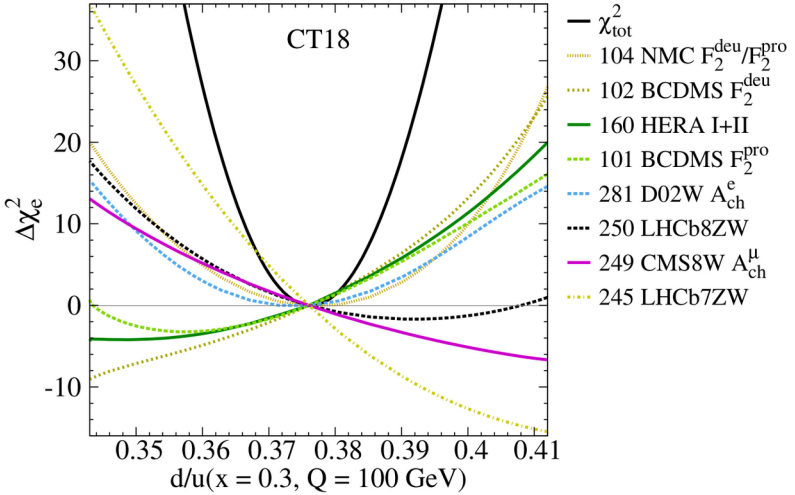




- competing pulls of fitted data at high-x also restrict precision; *e.g.*,

→ BCDMS, F_2^d

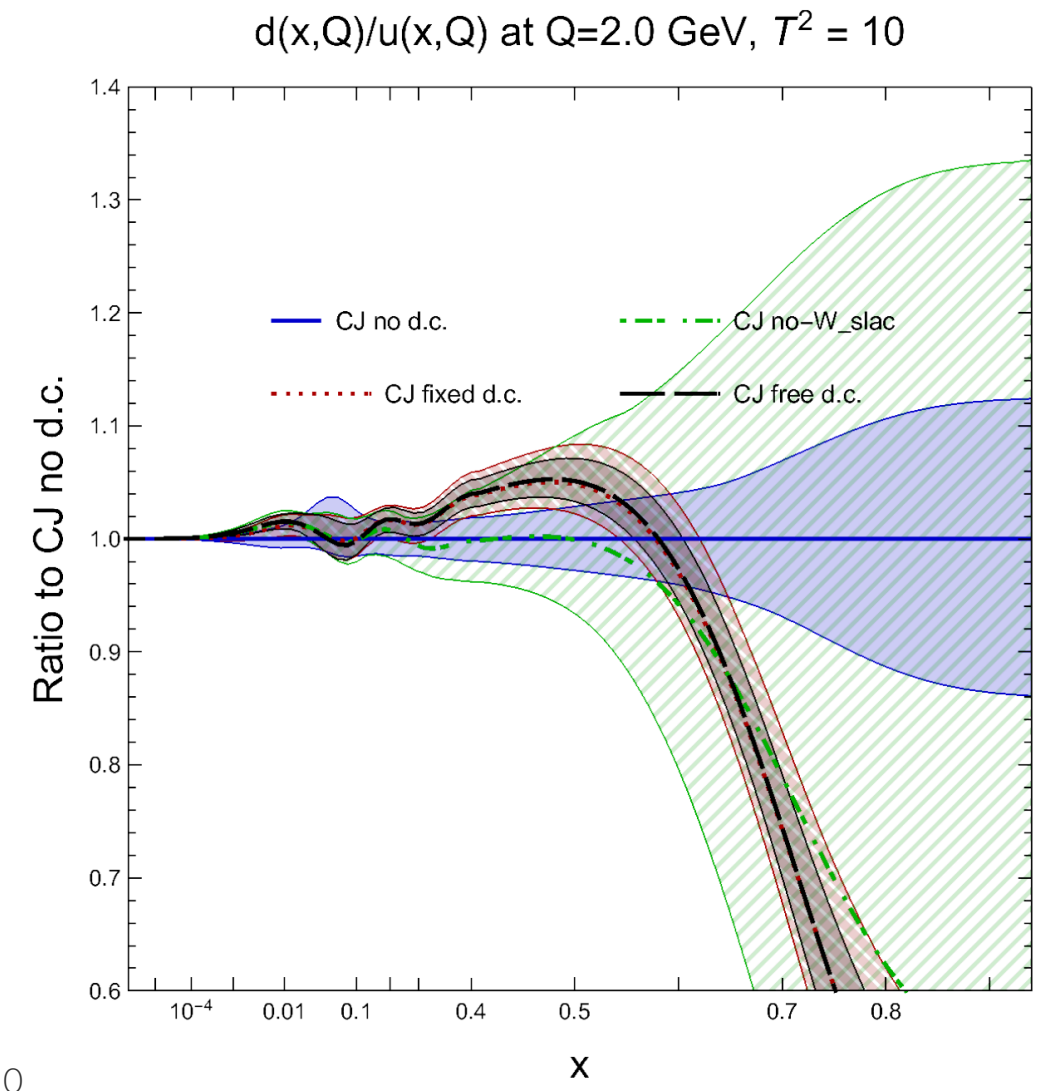
→ LHCb, W/Z 7 TeV



light-nuclear corrections: deuteron and high-x PDFs

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

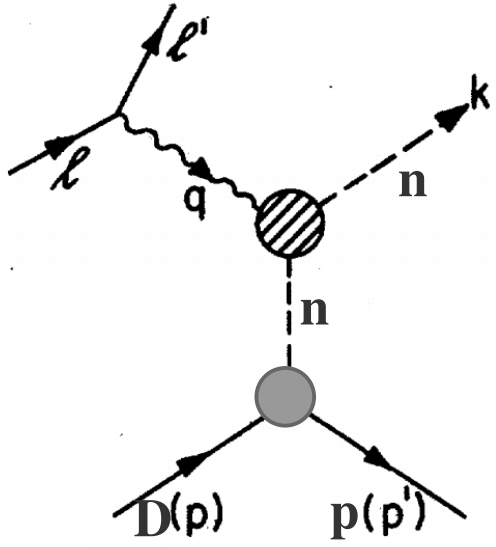
$$f^d(x,Q^2) = \int \frac{dz}{z} \int dp_N^2 \, \mathcal{S}^{N/d}(z,p_N^2)\, \widetilde{f}^N(x/z,p_N^2,Q^2)$$



Accardi, TJH, Jing, Nadolsky: EPJC81 (2021) 7, 603

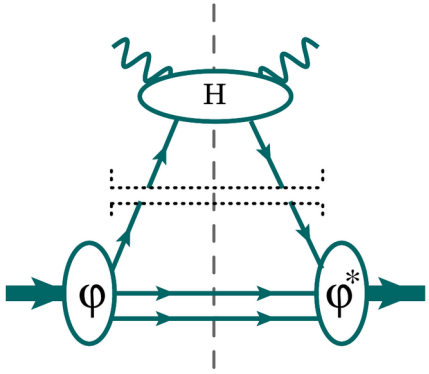
- corrections are generally ~percent-level, but can become larger, especially at high x

- impacts LHC observables; necessary for high precision

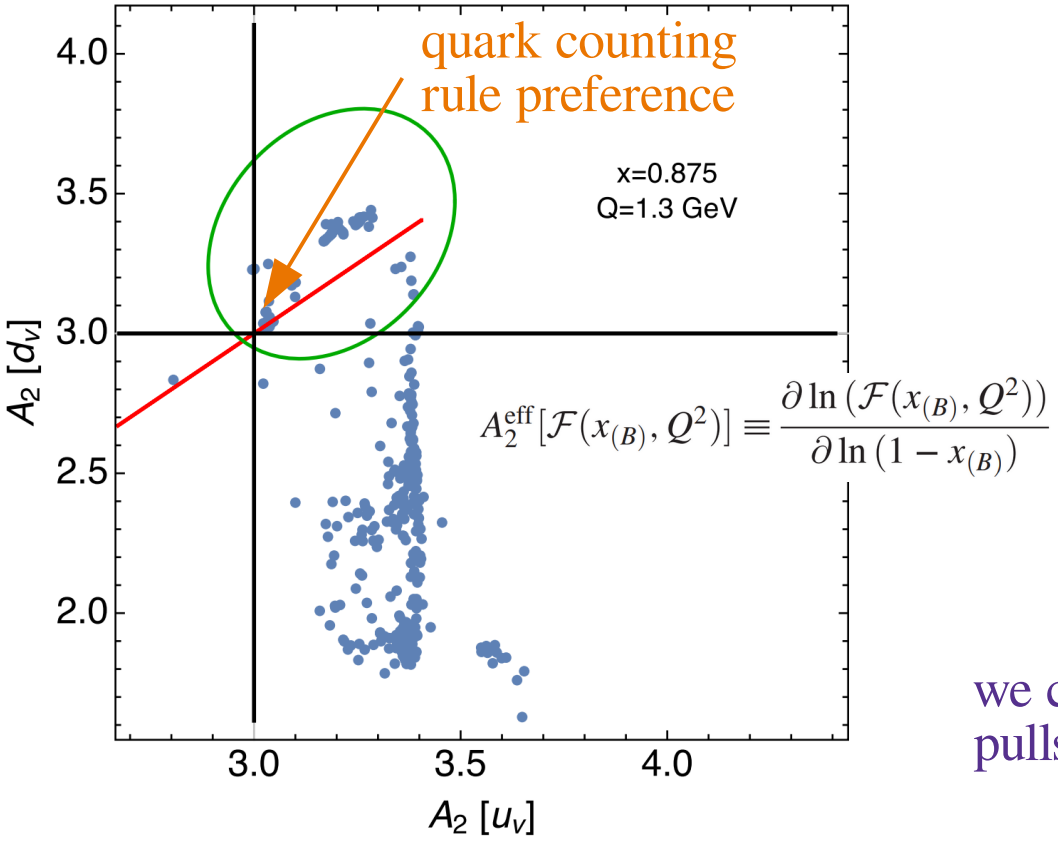


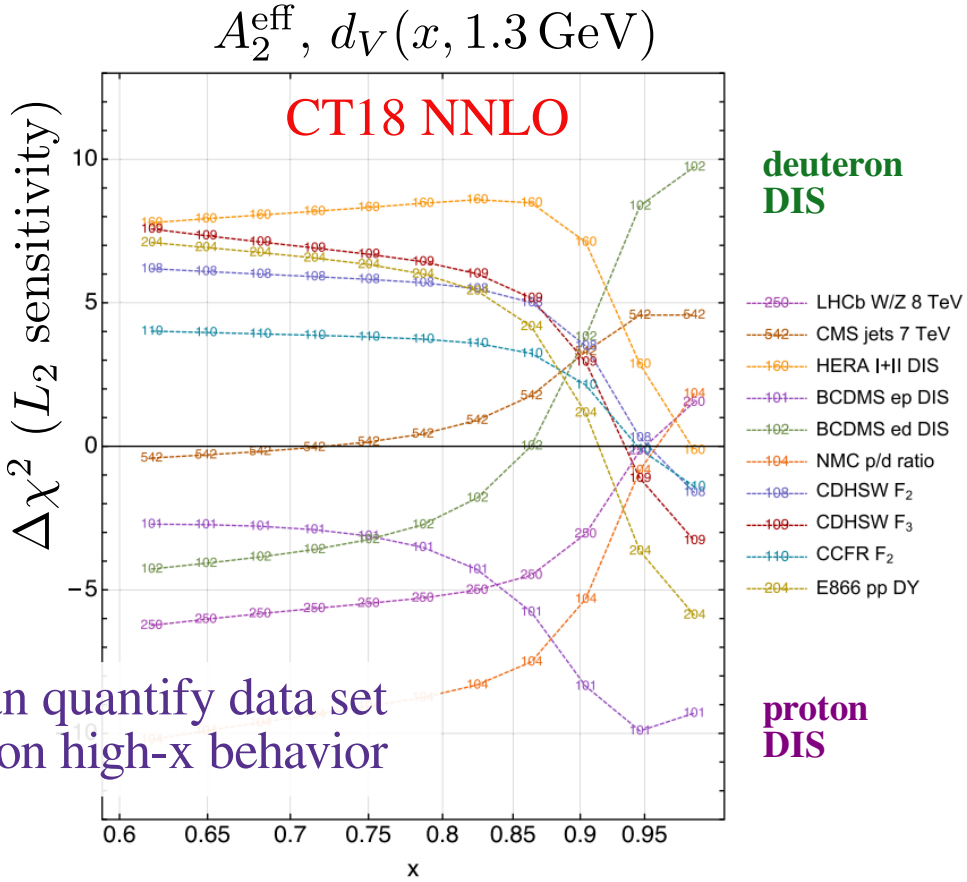
extracting high-x dependence in PDF fits

- 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

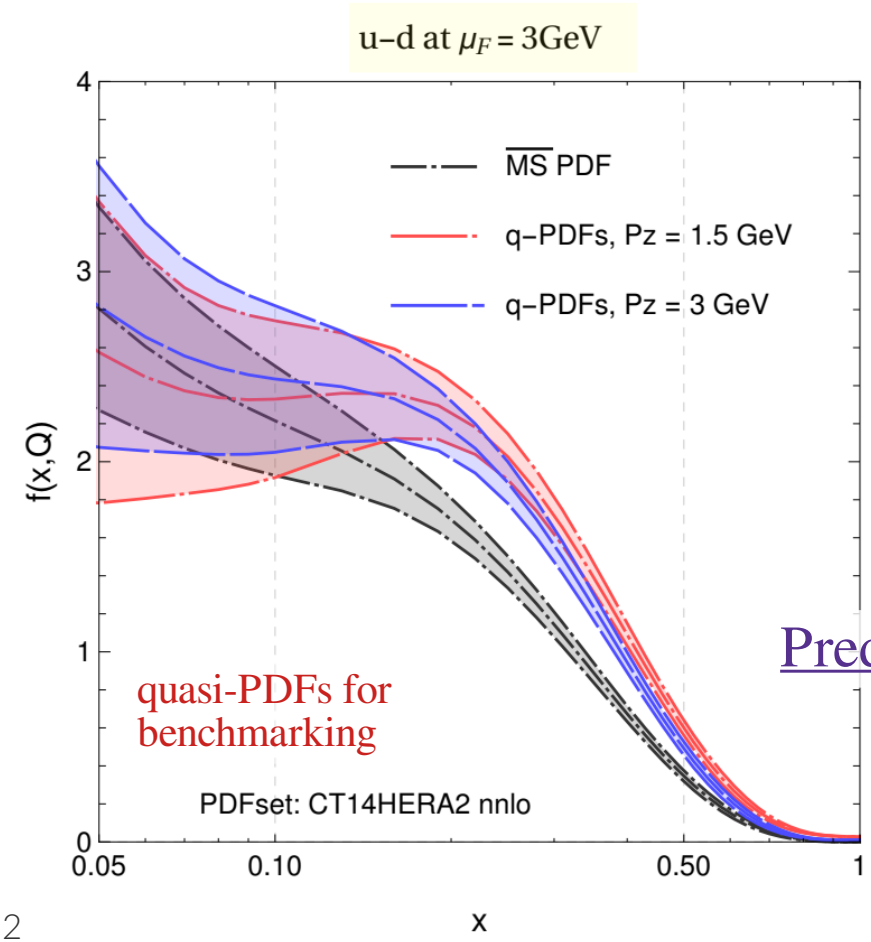
nonperturbative theory developments

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

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

- insights possible from continuum methods and model-building

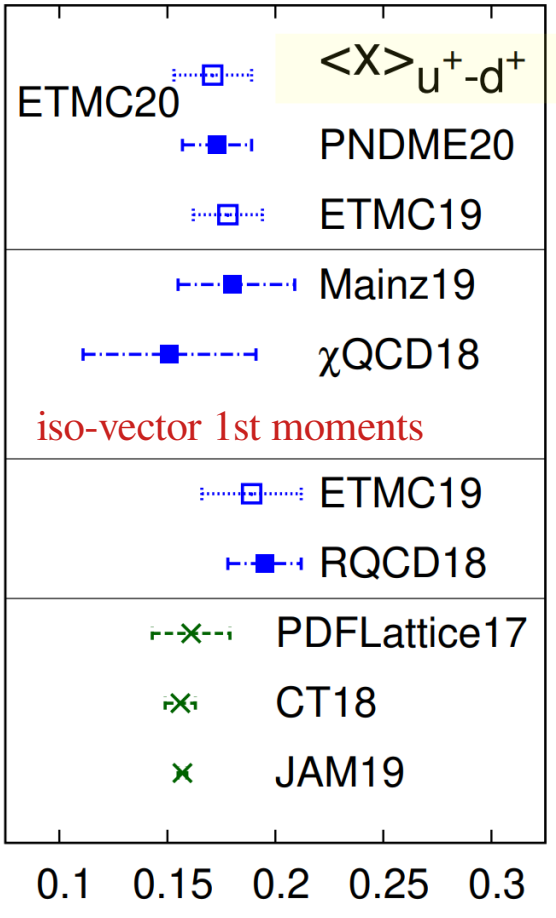
TJH, Wang, Nadolsky, Olness, PRD100 (2019) 9, 094040



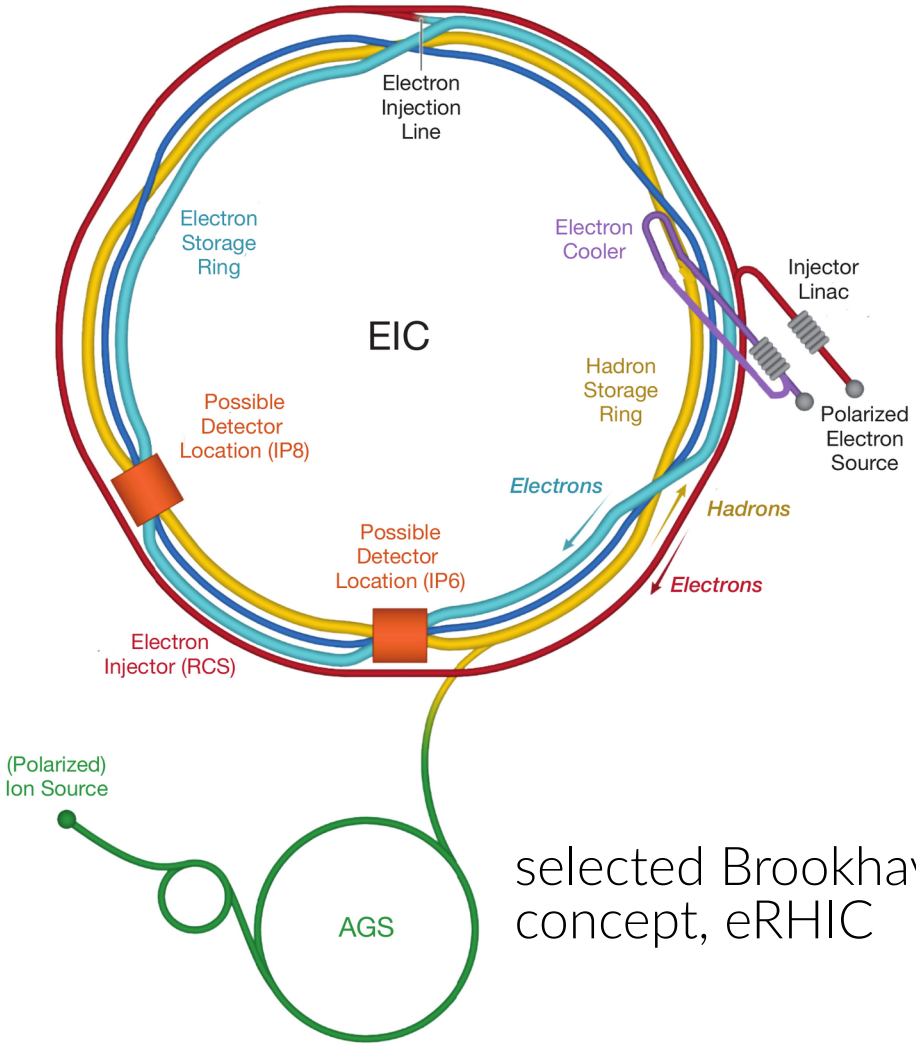
there are and will be important synergies between PDF fitting and, e.g., lattice QCD

Predictions for lattice QCD

2020 PDF-Lattice Report, 2006.08636



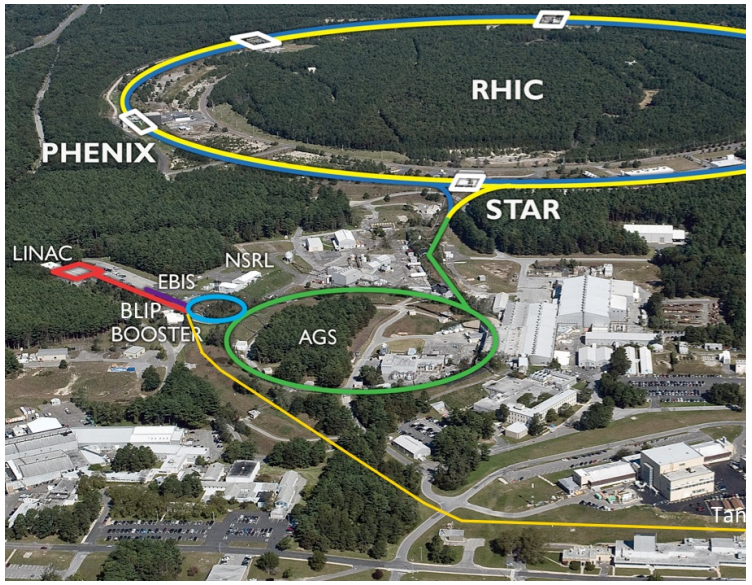
EIC: very high-luminosity DIS collider [$10^{2\text{-}3}$ times HERA]



selected Brookhaven concept, eRHIC

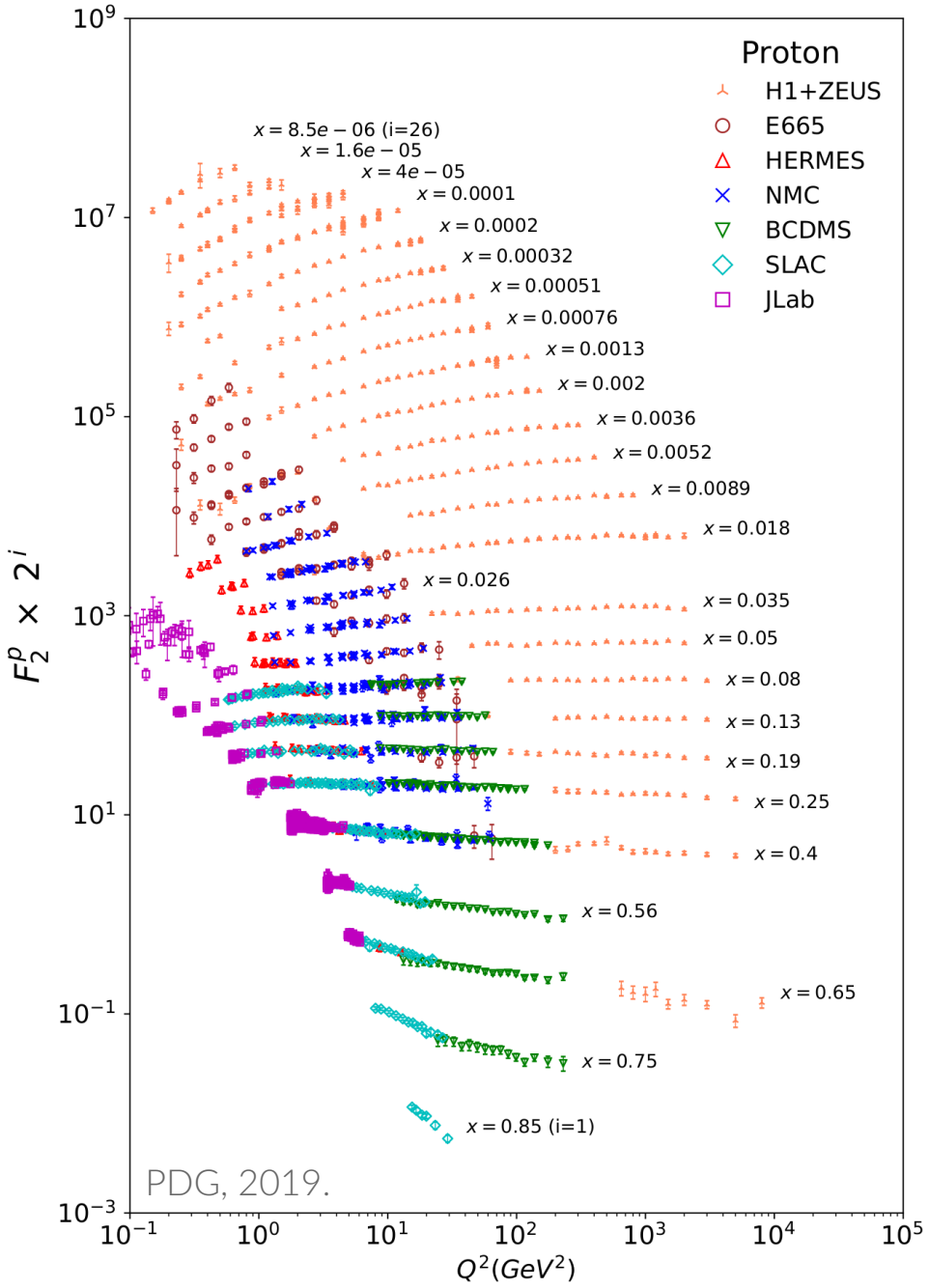
$$E_e < 18\,\text{GeV}$$
$$E_p < 275\,\text{GeV}$$
$$20 \leq \sqrt{s} \leq 140\,\text{GeV}$$

- add electron source, storage ring to existing heavy-ion collider complex (RHIC)

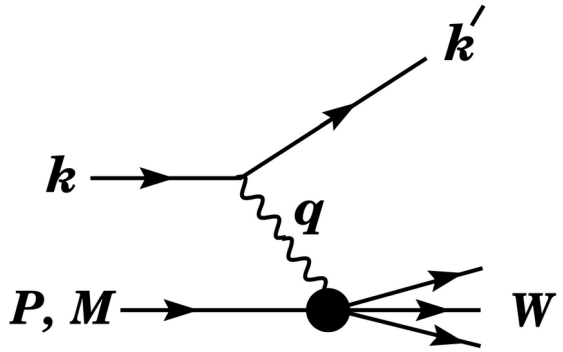


- collide electrons (and perhaps positrons) with:
  - → **(un)**polarized protons
  - → **(un)**polarized light nuclei [deuteron, ^{3}He]
  - → unpolarized heavy nuclei [up to Uranium]

DIS@EIC → sensitive probe of hadron structure; QCD



- **DIS provides experimentally "clean" access to internal hadron structure, dynamics**



- extraction of quark-gluon information relies on established QCD factorization theorems
- perturbative sector known to N²LO/N³LO

- EIC will provide valuable QCD 'lever-arm' for pQCD (α_s, m_Q); PDFs

N.B.: other complementary facilities,

→ HL-LHC

→ νA programs: LBNF

→ ongoing JLab12

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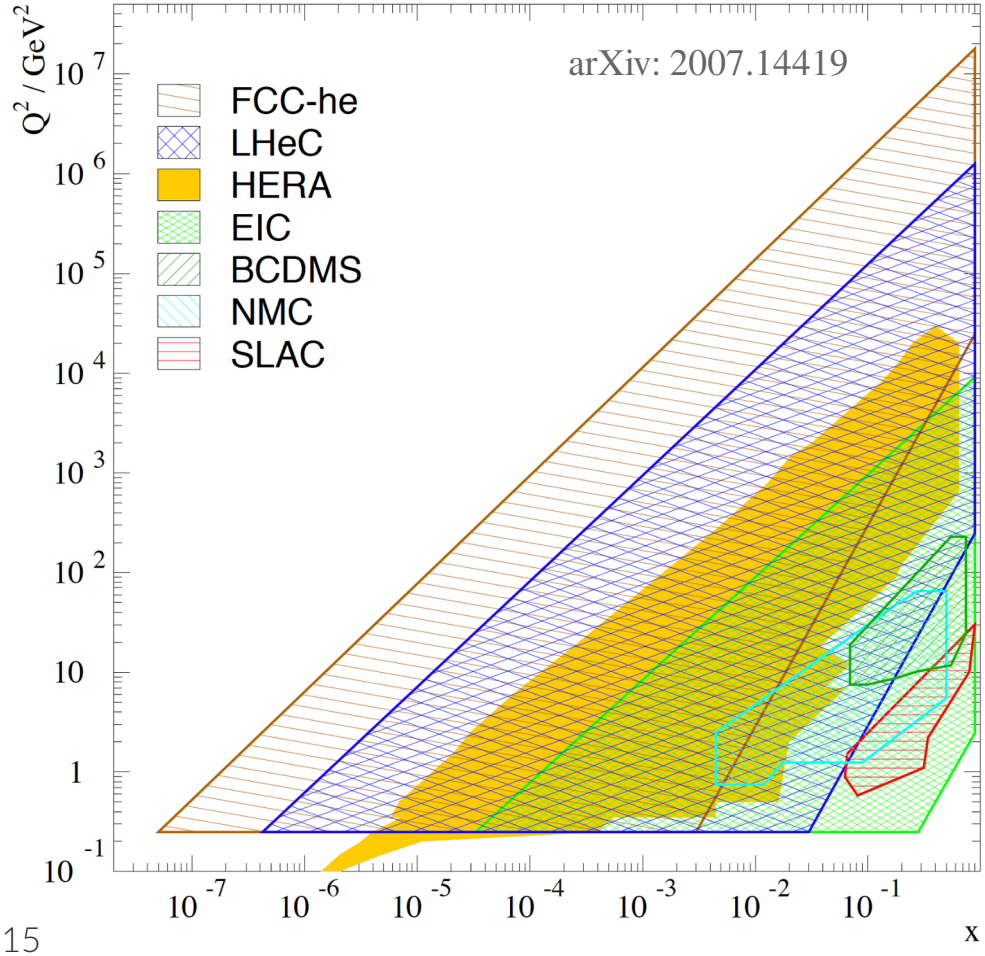
kinematic reach of the EIC program

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

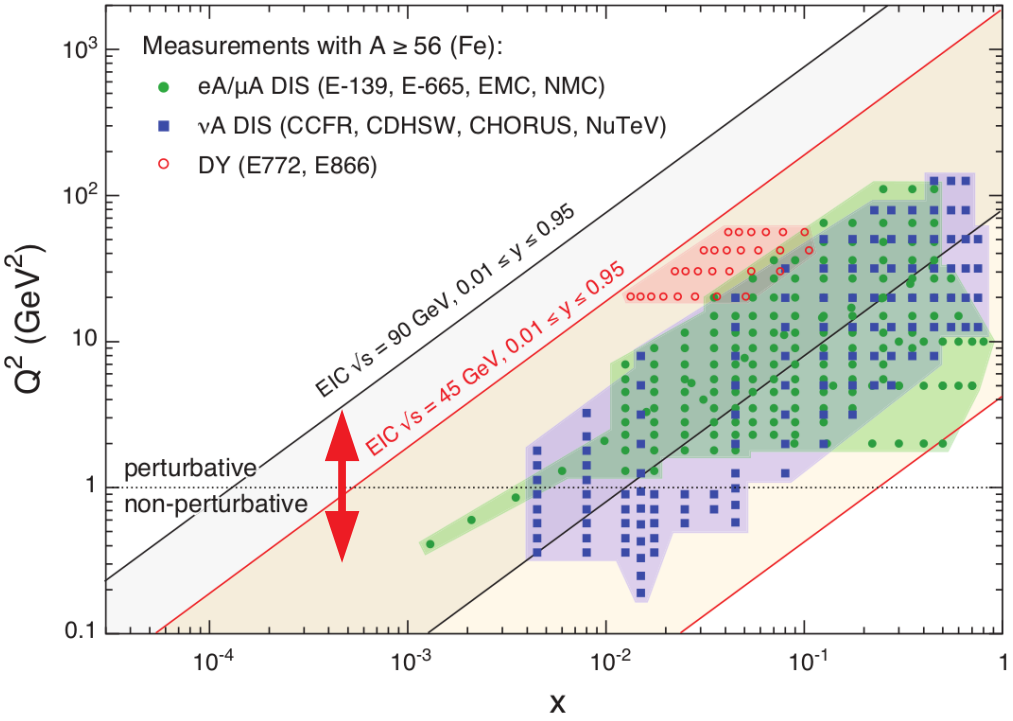
  → high-lumi coverage: intermediate region between HERA, JLab12

- overlap with high-sensitivity fixed-target DIS experiments

  → extensive probe(s) of the **quark-to-hadron transition** region



analogous nuclear DIS coverage:

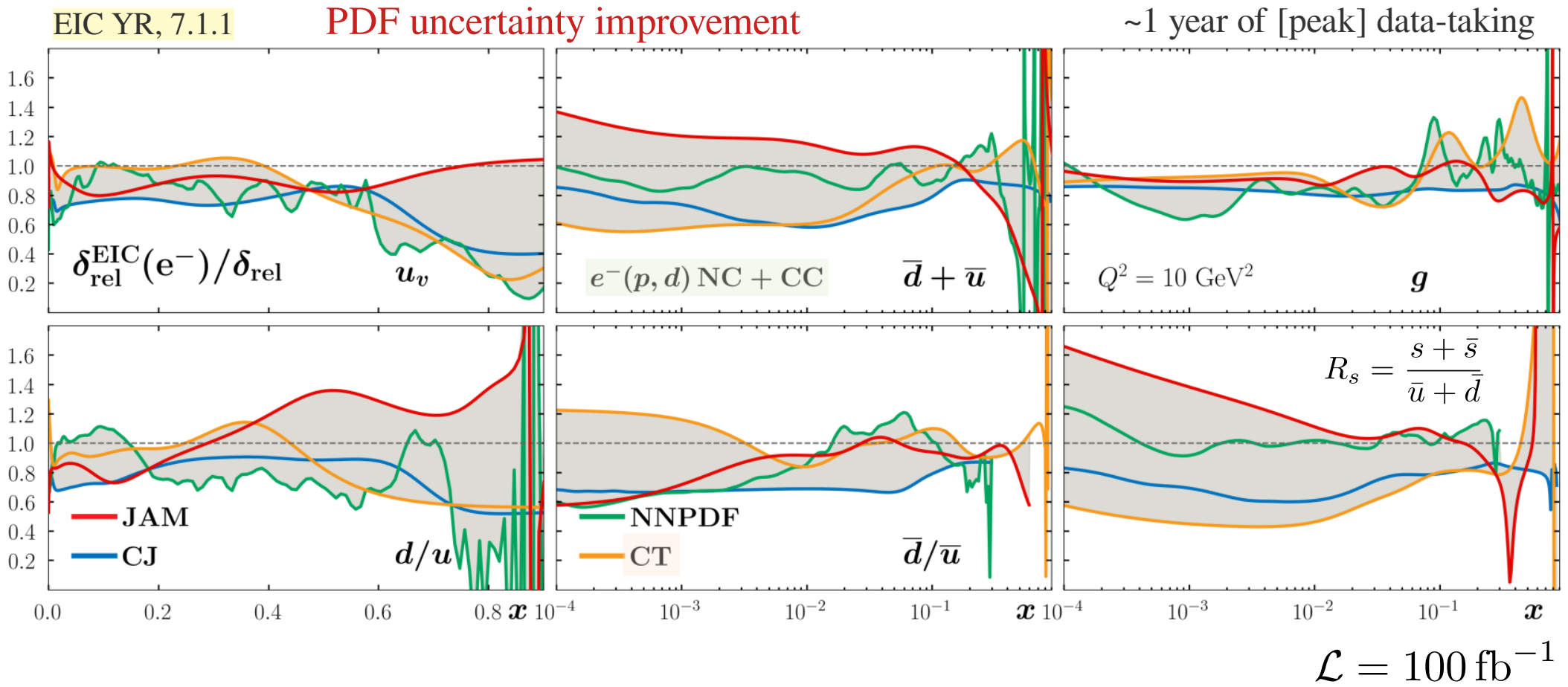


Eur. Phys. J. **A52** (2016) 9, 268.

ii

reductions to PDF uncertainties: inclusive DIS data

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

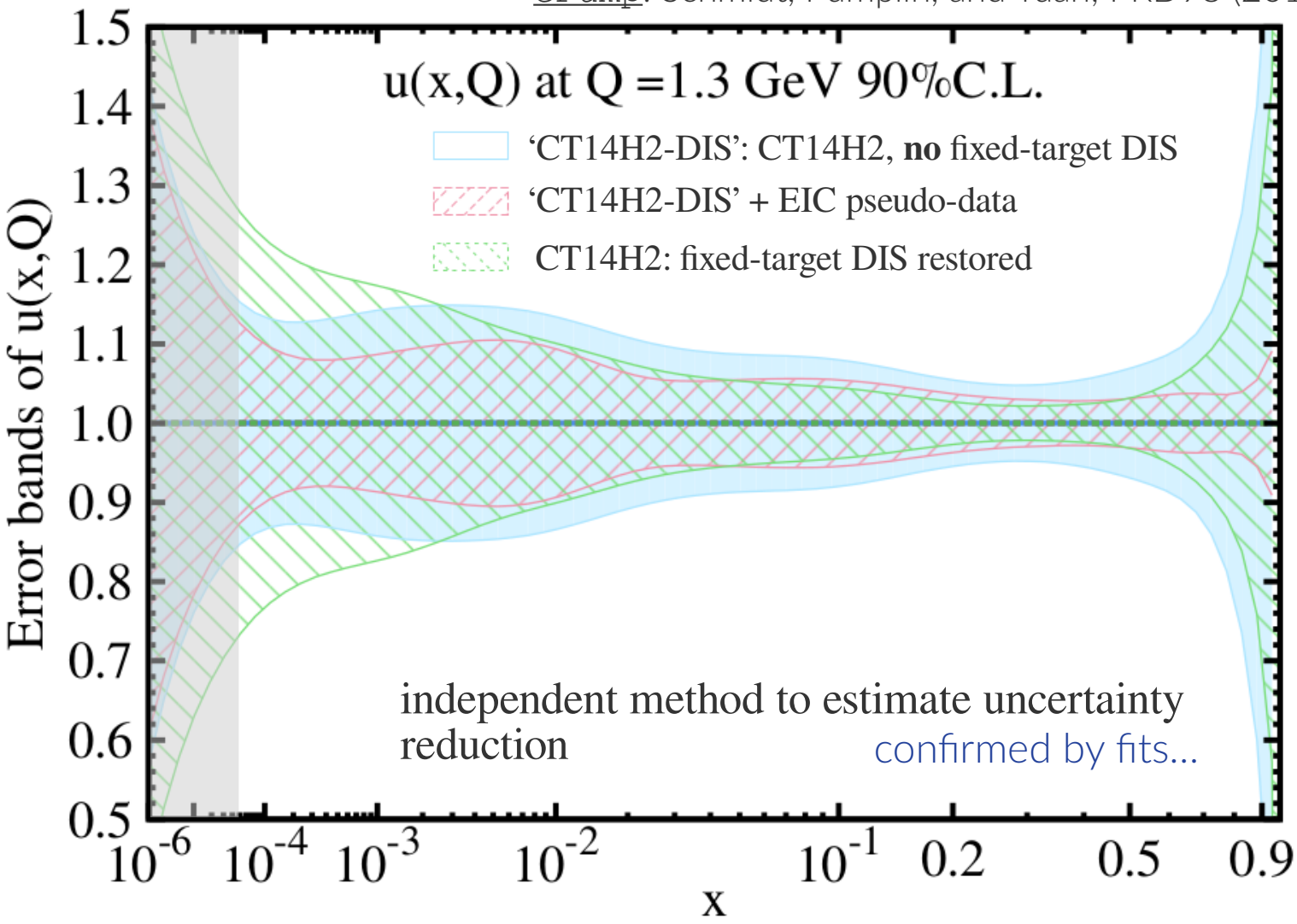


- broad impact, including on high-x u-, d-PDFs; probes of gluon, quark sea to low x

→ **final-state tagging; positron beams afford greater precision**

PDF impacts compared to high-value fixed-target DIS

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



S. Dulat

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

→ useful for negotiating among existing high-impact data

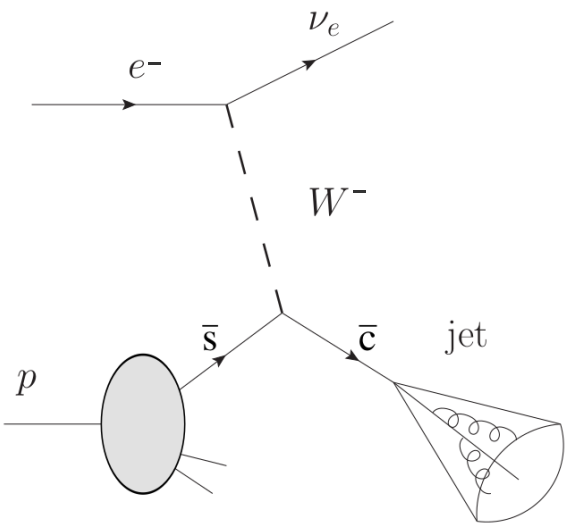
precision QCD through jet and heavy-flavor production

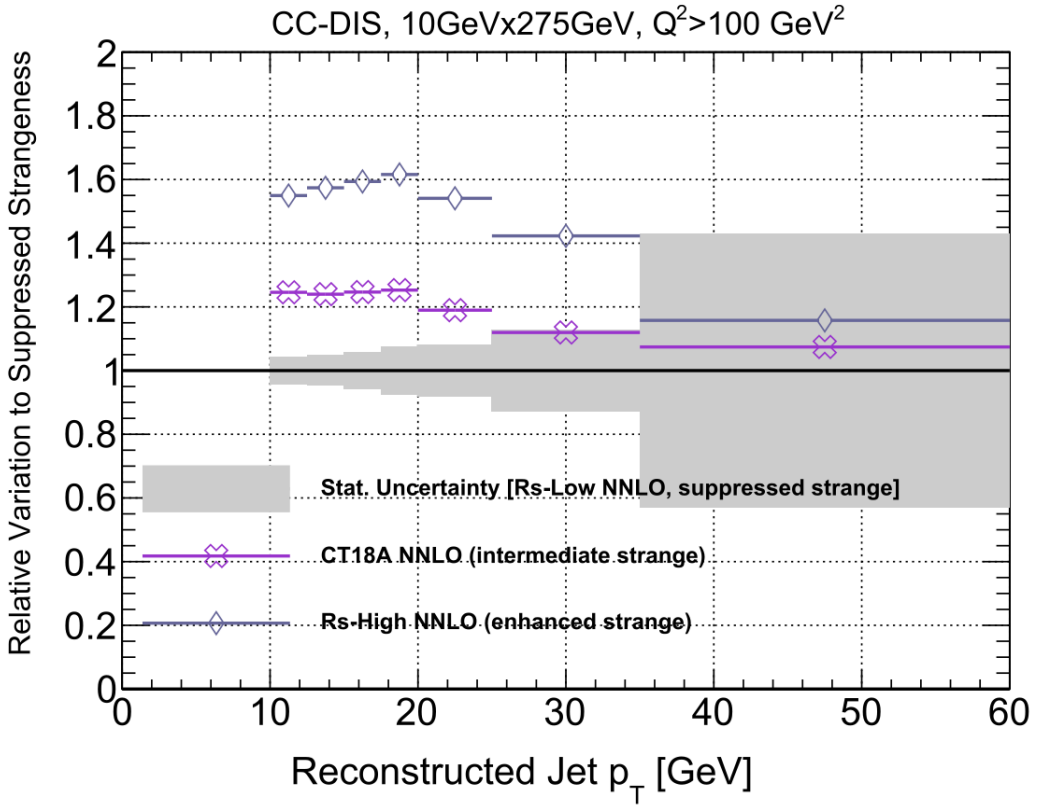
- DIS jet production, including through charge-current interactions, provides further access to quark-level information

PRD **103** (2021) 7, 074023

Arratia, Furletova, TJH, Olness, Sekula

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

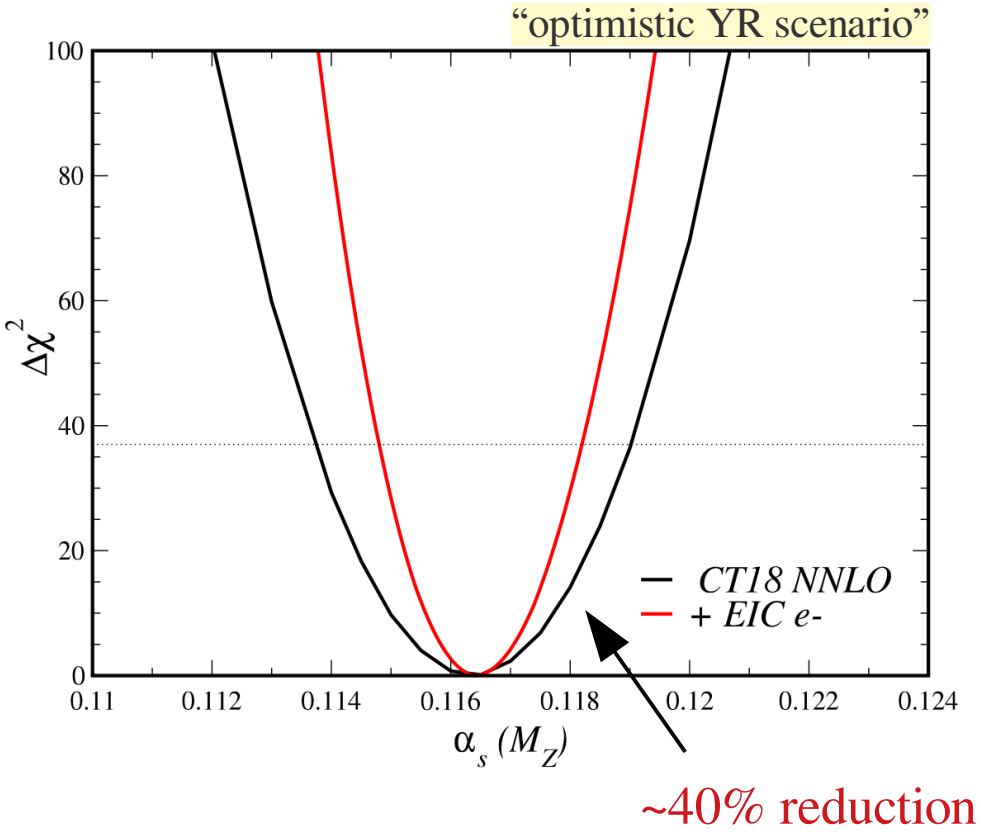
→ further development of MC jet-production studies needed, including HO effects

EIC and SM inputs: α_s

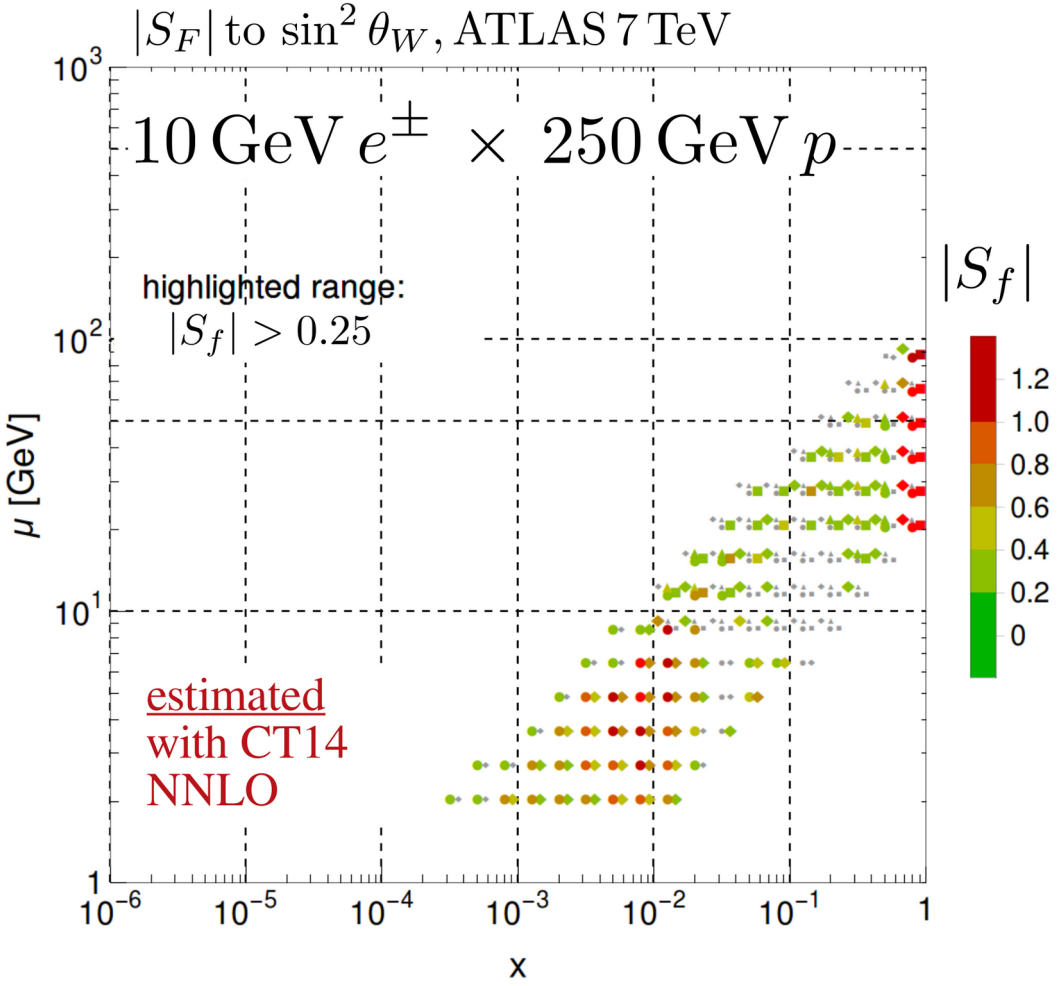
- part of moving toward N^{3}LO PDFs, precise determinations needed for α_s

similar argument for m_Q

from inclusive data alone



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



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

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

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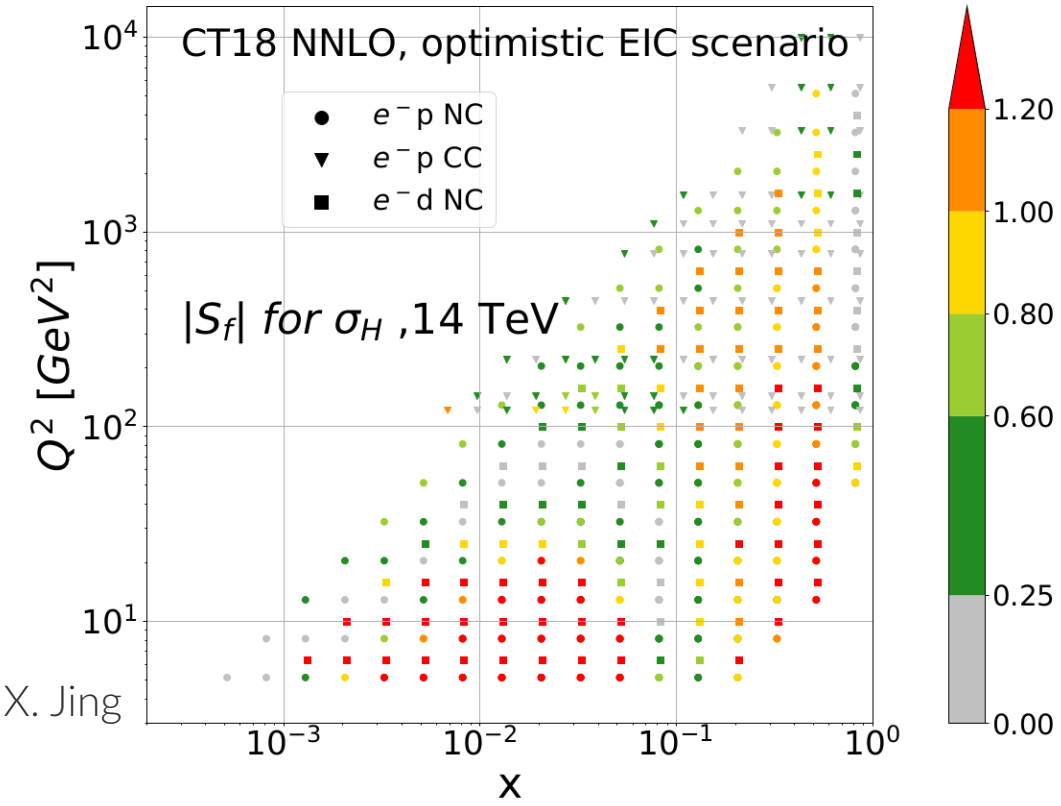
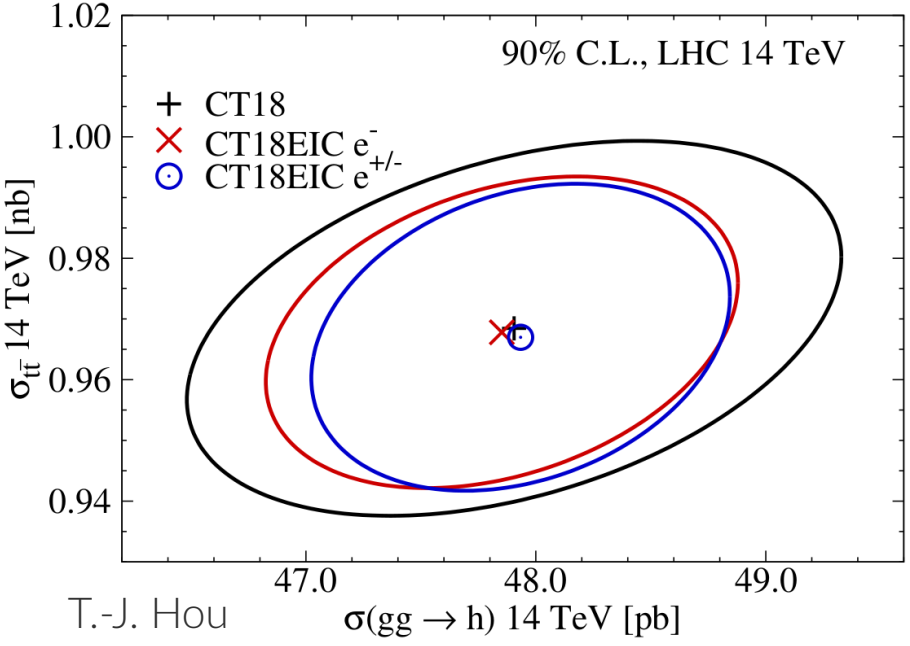


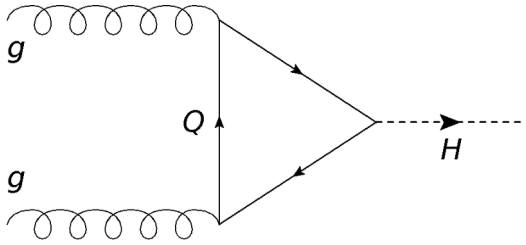
X. Jing

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



T.-J. Hou



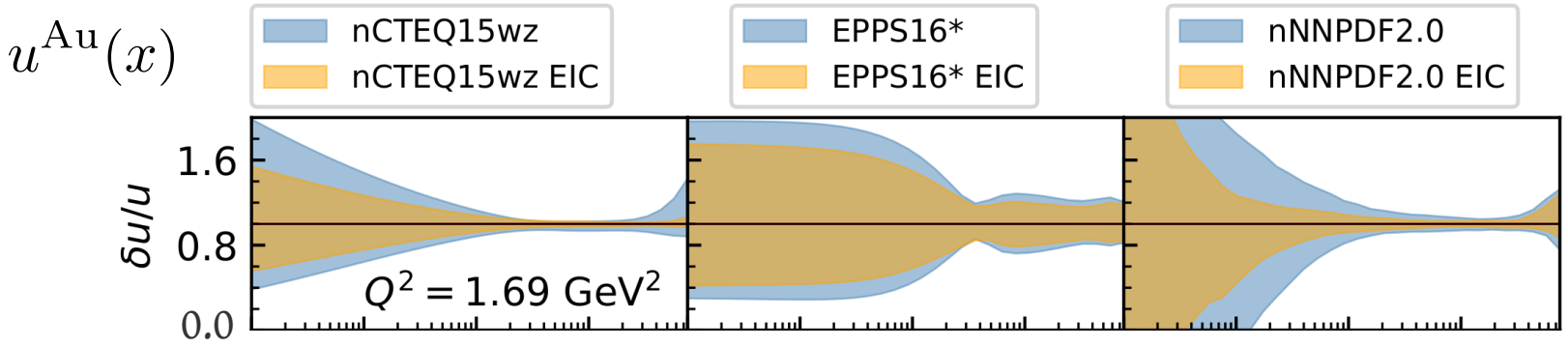
- impact closely tied to that of the integrated gluon PDF

→ added leverage from positron data…

understanding nuclear effects

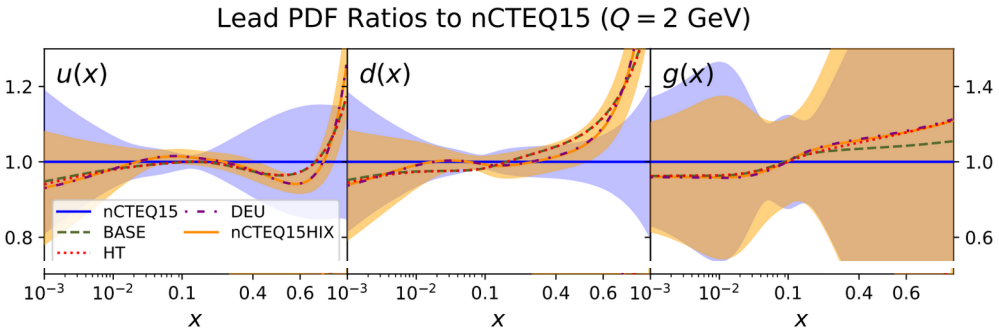
see talk: P. Paakkinen

→ 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*:



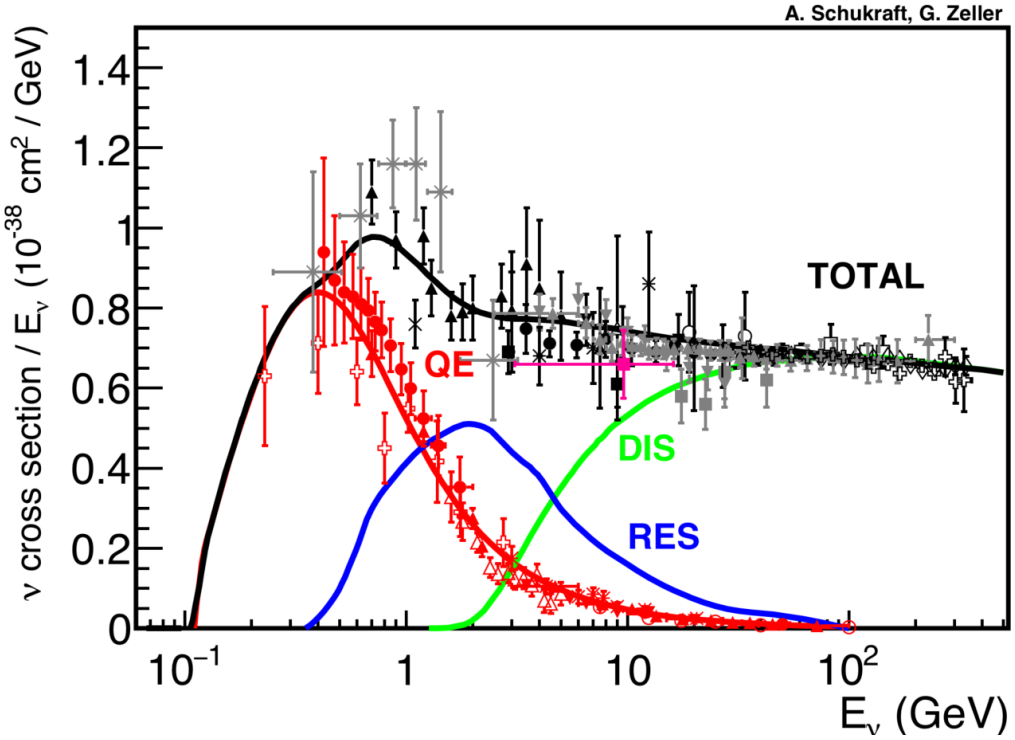
Segarra et al., PRD 103 (2021) 11, 114015

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

- need for further DIS MC development with nuclear effects

cross-cutting aspects of EIC, νA MC development

- neutrino generators (e.g., `GENIE`, `NuWro`, `GiBUU`): complex tunes of physics models accounting for interplay of nuclear processes, effects



- at higher neutrino energies, inceasingly DIS/(n)PDF dominated

  → DIS remains significant down to few-GeV region

- producing comprehensive EG tunes with futuristic DIS data is large undertaking

- EIC will probe few-GeV transition region of interest

  → build upon JLab12

  → inform follow-up e4ν activities

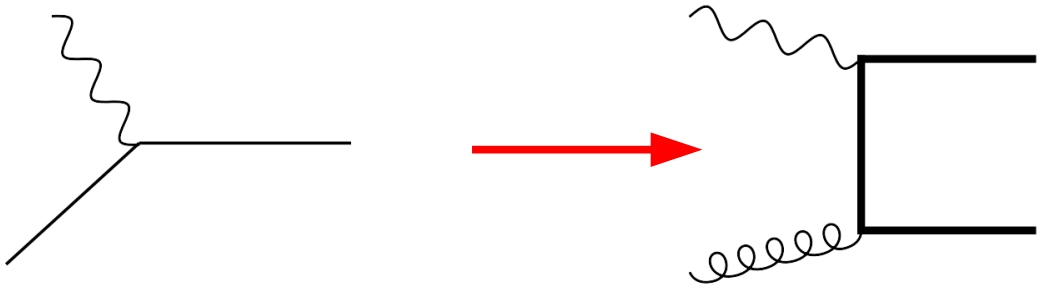
  → intersections with Forward Physics Facility

toward next-generation PDFs for EIC MCs

- generators are special use-case for PDFs, have a number of unique considerations
- in EIC era, particular attention needed given high statistical precision, syst. domination
- perturbative order central issue

  → MCEGs historically LO; future need for specialized NLO/NNLO PDFs?

  → for DIS at NLO, important diagrams appear in, *e.g.*, heavy-quark production



  → important implications for acceptance, interpretation of generated events

- consistency of theoretical choices in PDF analyses → generators implementing PDFs
- shared numerical techniques

  → ML techniques (e.g., BDTs) for multidimensional integrations; analysis for tunes

iii MC, PDFs and HEP planning (Snowmass)

SnowMass2021

- Snowmass 2021: multiple initiatives explore intersections presented here

Letters Of Interest,

- for the EIC
  - → tomography – [includes PDFs] (LOI)
  - → heavy flavor, …
- PDFs at N^3LO accuracy and related issues
  - → dedicated PDF4LHC effort
- global survey of Monte Carlo generators; needs

see intro: Abhay, discussion

- improved tuning in neutrino generators: NF

conclusion

- precision reach of EIC can be expected to greatly reduce PDF uncertainties
  - → strong implications for HL-LHC, νA, other HEP activities
- systematics will be of increasing importance
  - → *e.g.*, hadronic final-state effects on PDFs from SIDIS see talk: A. Signori
- MC development for DIS needed in parallel with next-generation PDFs
  - → PDFs must increasingly tackle various (non)perturbative effects
  - → cross-cutting DIS MC aspects shared with other generators
- possibilities for machine learning
- coordination (as with Snowmass) needed to develop physics results

Many thanks to colleagues throughout the PDF, EIC, MC communities