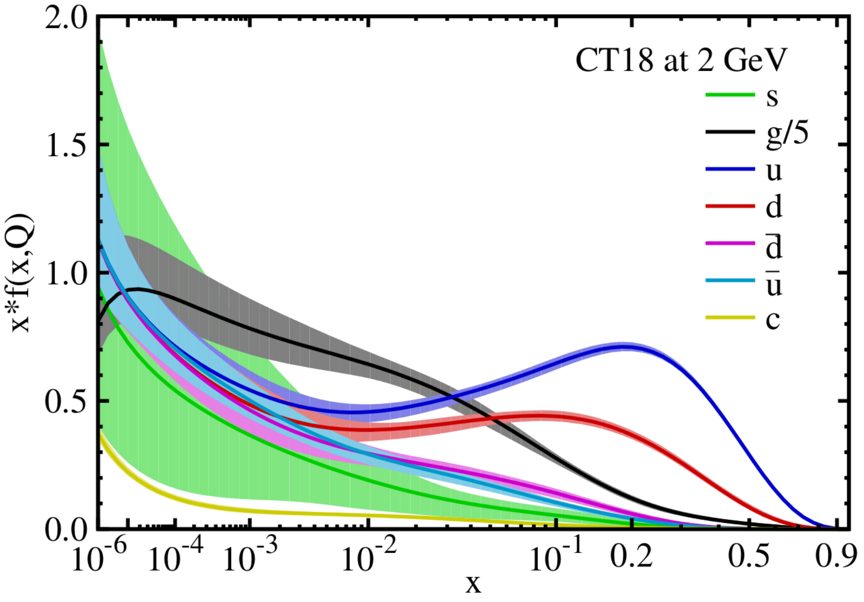
progress and prospects for nucleon PDF analyses

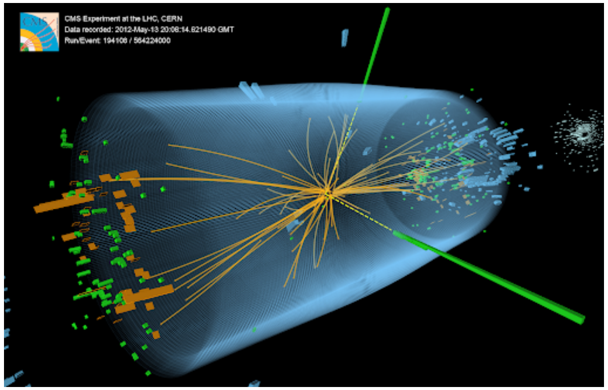
nonperturbative QCD and nuclear effects

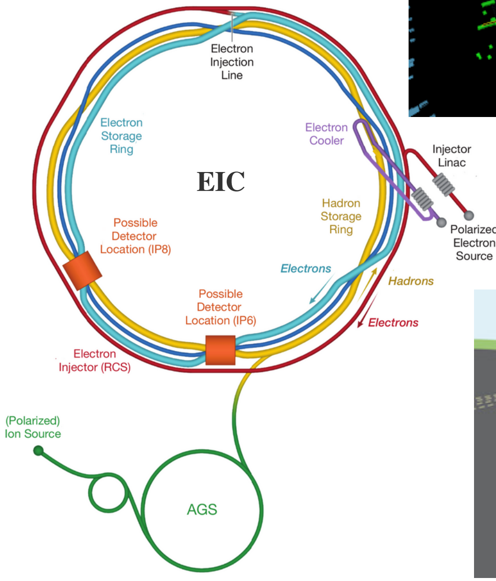
Tim Hobbs, Fermilab and IIT

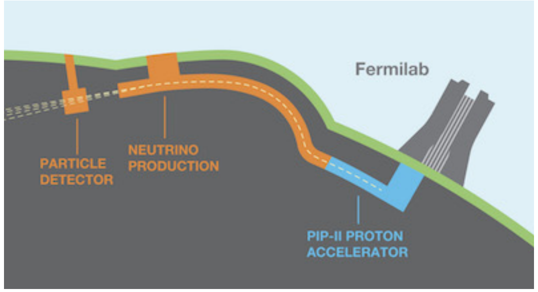
26th July 2021

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









Fermilab

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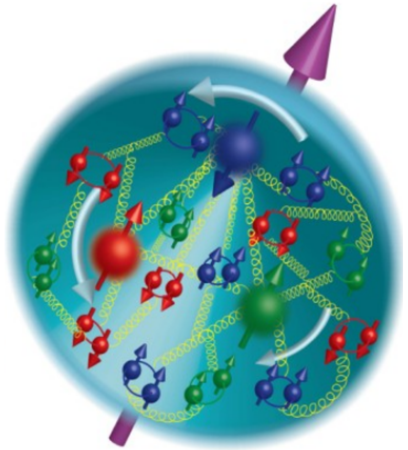
a *tour* of select nonpertubative issues in PDF analyses



- PDF global fits → crucial shuttle between nonperturbative, nuclear dynamics and high-energy phenomenology

  → nonpert. effects relevant to precision at higher energies

  → high-energy data sensitive to nonpert. physics

  → PDFs provide arena to explore patterns in nonpert. QCD

- highlight through illustrative examples from **CTEQ family** of QCD fits

  → CTEQ-TEA (CT): LHC emphasis · · · · · T.-J. Hou et al., PRD **103** (2021) 1, 014013

  → CTEQ-JLab (CJ): JLab physics-centric · · A. Accardi et al., PRD **93** (2016) 11, 114017

  → nuclear CTEQ (nCTEQ) · · · · · · · · · · · · · · · · E. Segarra et al., PRD **103** (2021) 11, 114015

CTEQ

SMU

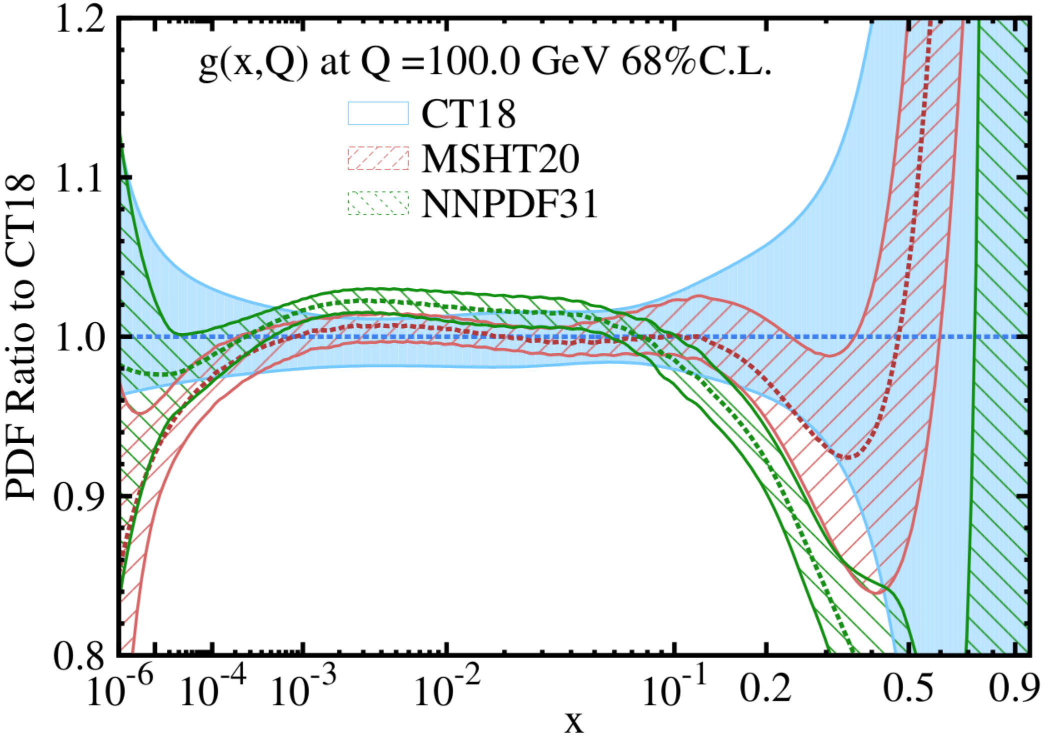
EIC[2] EIC Center at Jefferson Lab

PDFs critical to next-generation precision for hadronic expts

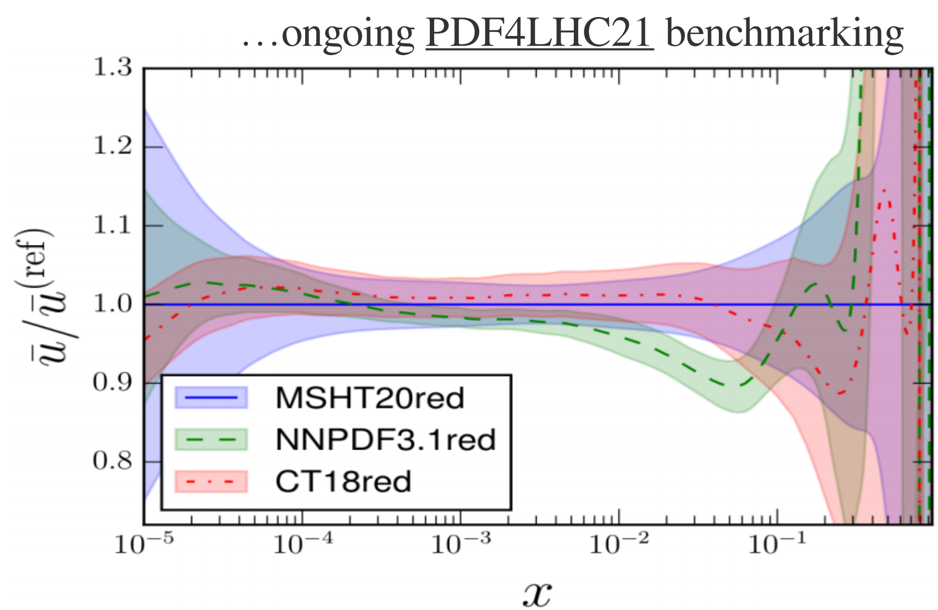
→ essential nonperturbative input for DIS, LHC predictions

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

T.-J. Hou et al., PRD **103** (2021) 1, 014013



contemporary NNLO QCD fits



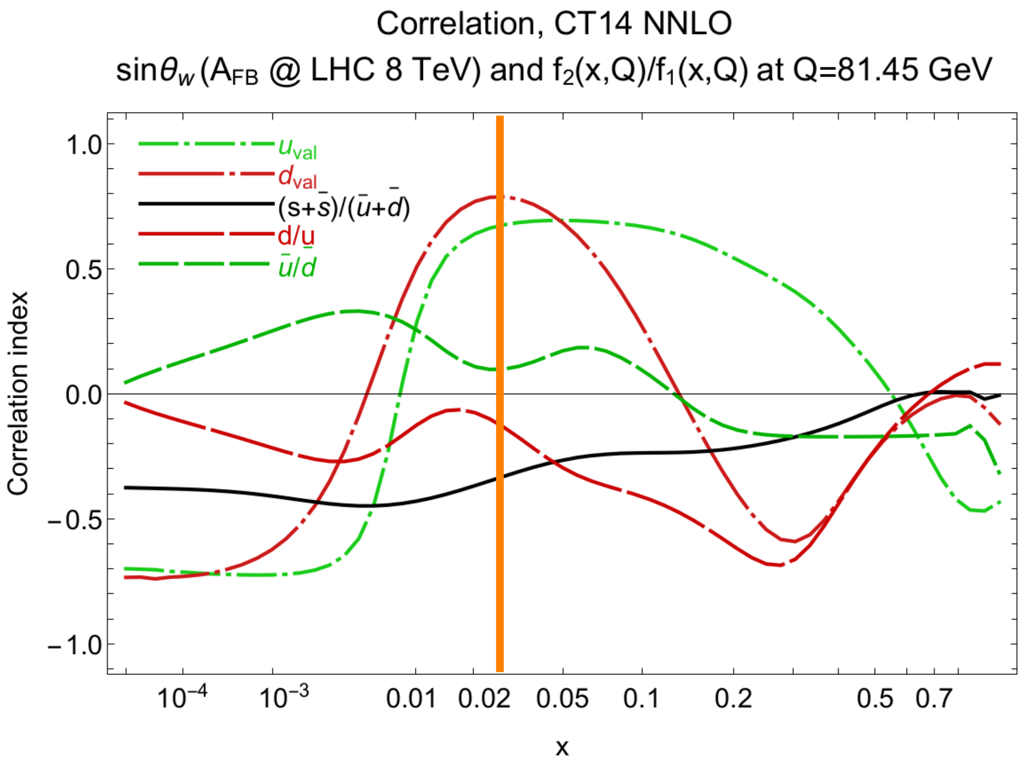
- upcoming programs need high-precision → reductions to PDF uncertainties

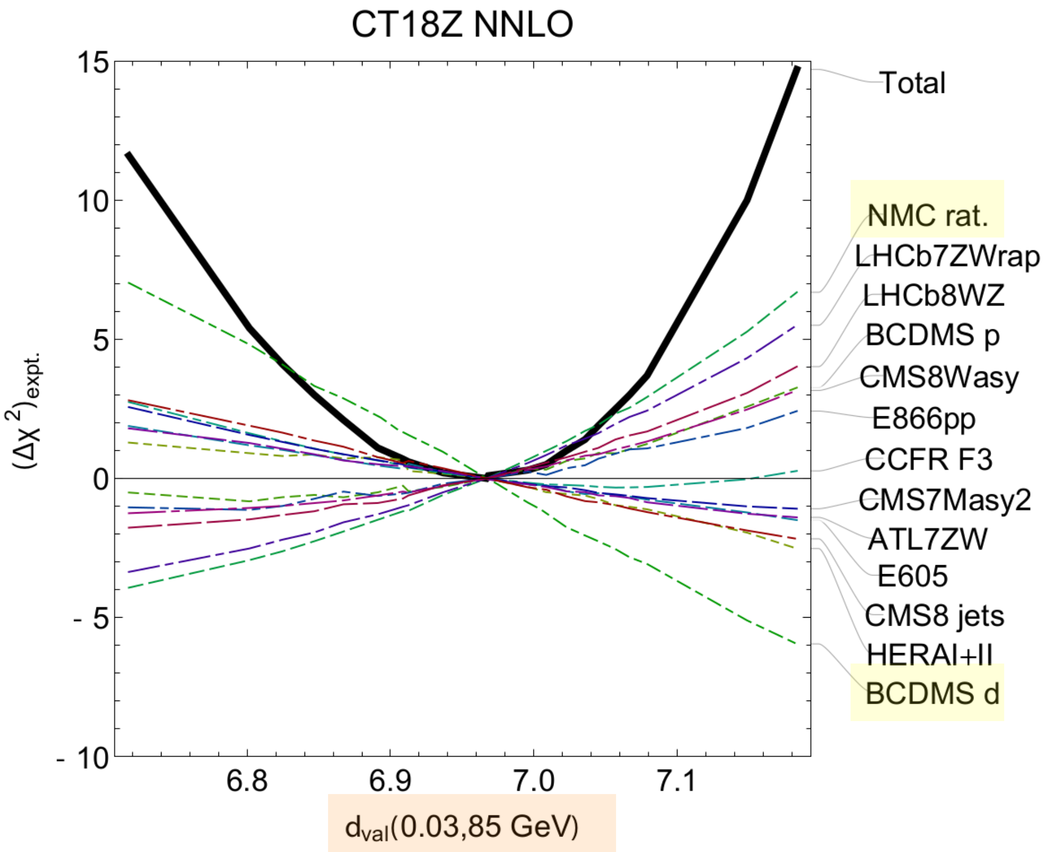
→ needed to match (N)NNLO theory accuracy; MC improvements

example: LHC measurement of the EW mixing angle

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

- significant correlations between EW quantities ($\sin^2\theta_W$) and valence *u*, *d* PDFs





- CTEQ-TEA: deuterium DIS experiments have strong pull on u_{val}, d_{val} for $x \sim 0.03$

more later

→ modified deuteron theory may have LHC EW precision implications!

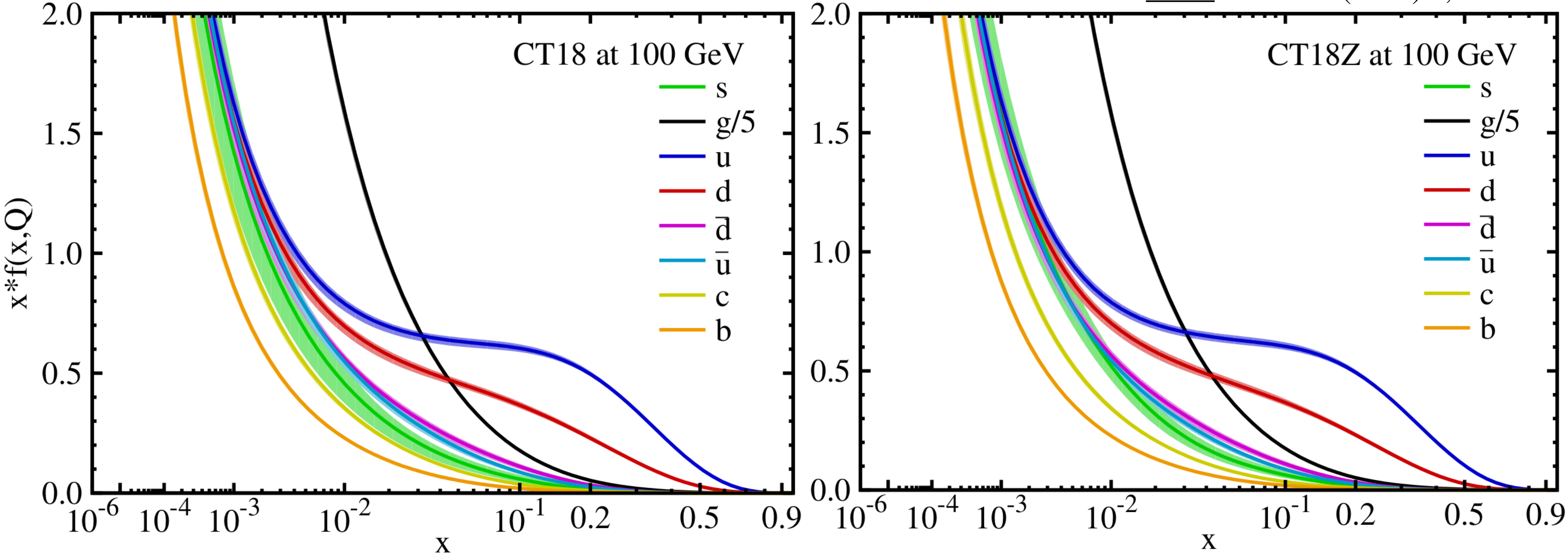
CTEQ

QCD global fits: nucleon structure from diverse data

- fit a wide assortment of data from various underlying processes; scales

$$f_{q/p}(x, \mu^2 = Q_0^2) = a_{q_0} x^{a_{q_1}} (1-x)^{a_{q_2}} \, P[x, \{a_{q_{n-3}}\}]$$

<u>CT18</u>: PRD**103** (2021) 1, 014013



- theory accuracy now/approaching (N)NNLO in α_s for typical processes

→ NLO EW corrections, especially for LHC data

invitation: photon PDF for precision EW physics (i)

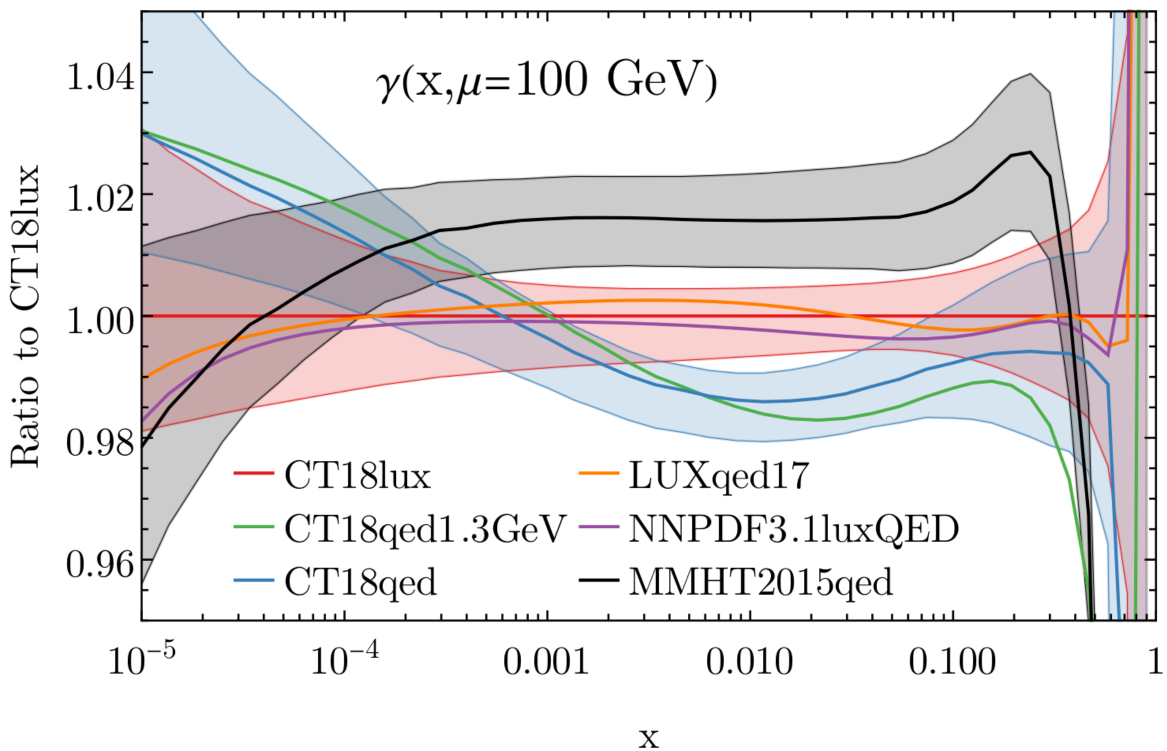
- at $\mathcal{O}(\alpha_s^2)$ accuracy, EW corrections and explicit $\gamma(x,\mu^2)$ needed

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

- following CT14QED, CT18QED now interfaces LUX formalism

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

→ 2 complementary implementations: CT18lux, CT18qed



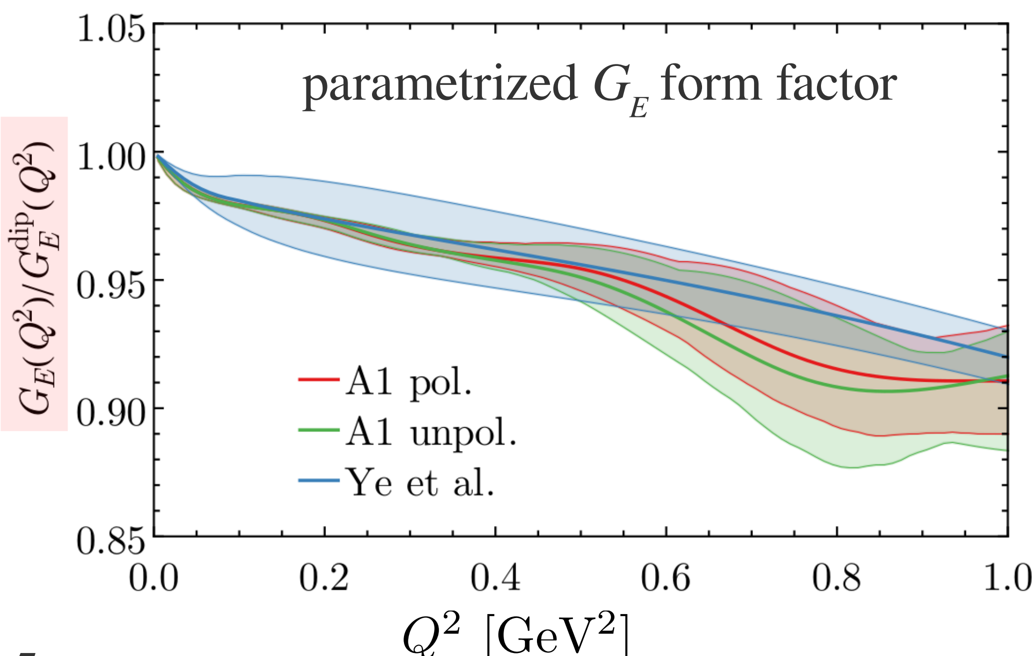
invitation: photon PDF for precision EW physics (ii)

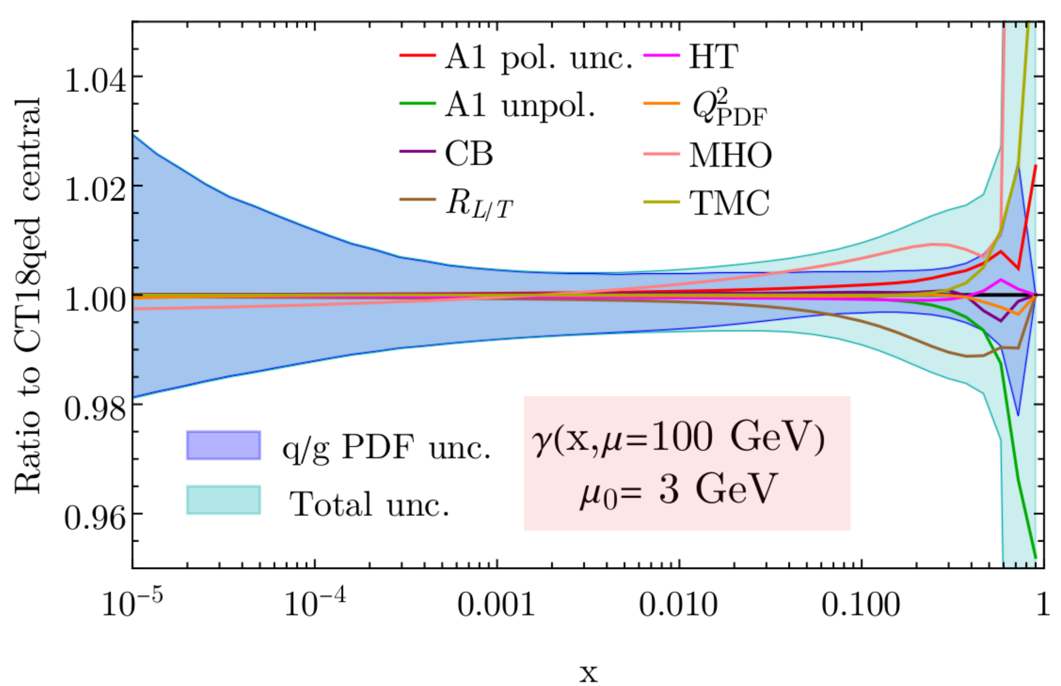
- calculation depends on nonperturbative proton-structure inputs!
- integrated proton SFs include contributions from low Q, moderate x

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

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

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





nonperturbative theory developments

many talks at this meeting

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

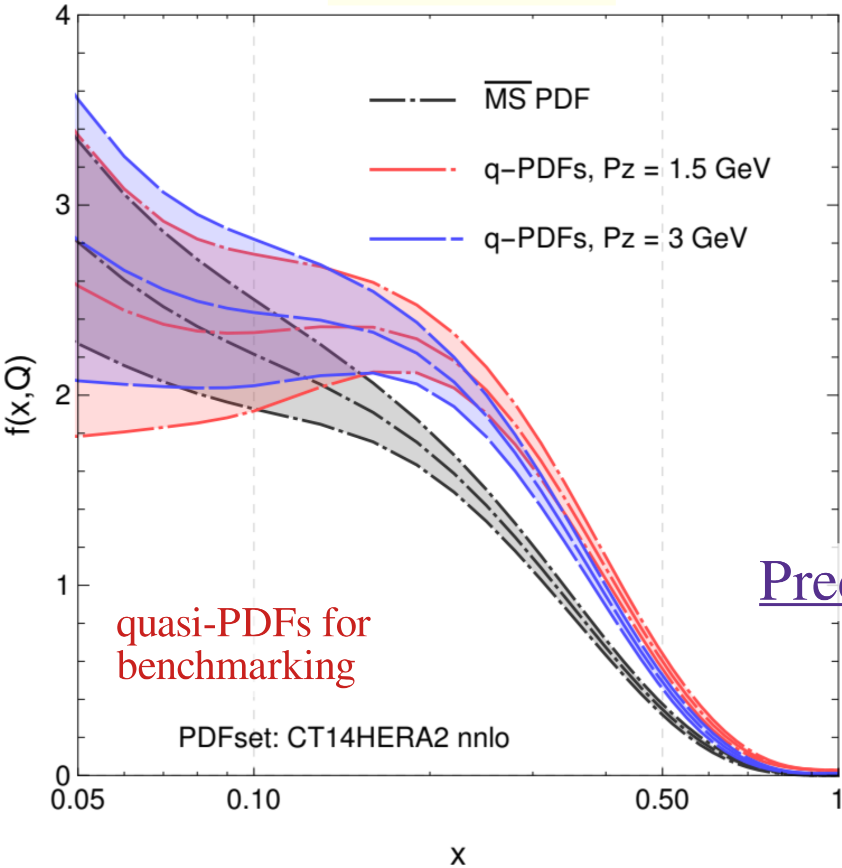
  → quasi-PDFs, pseudo-PDFs, quasi-TMDs, …

- insights possible from continuum methods and model-building

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

2020 PDF-Lattice Report, 2006.08636

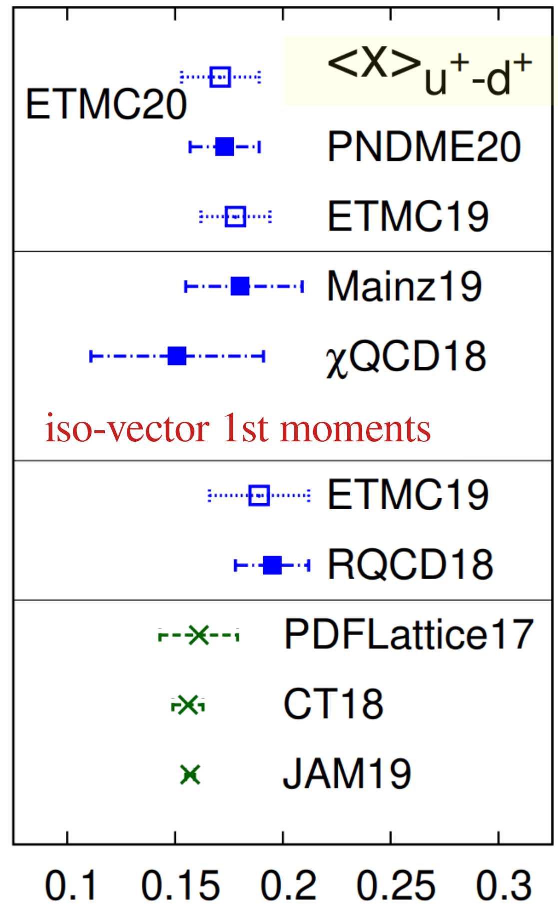
u–d at $\mu_F = 3$GeV



quasi-PDFs for benchmarking

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

Predictions for lattice QCD



parametrization uncertainty: nonperturbative fitting forms

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

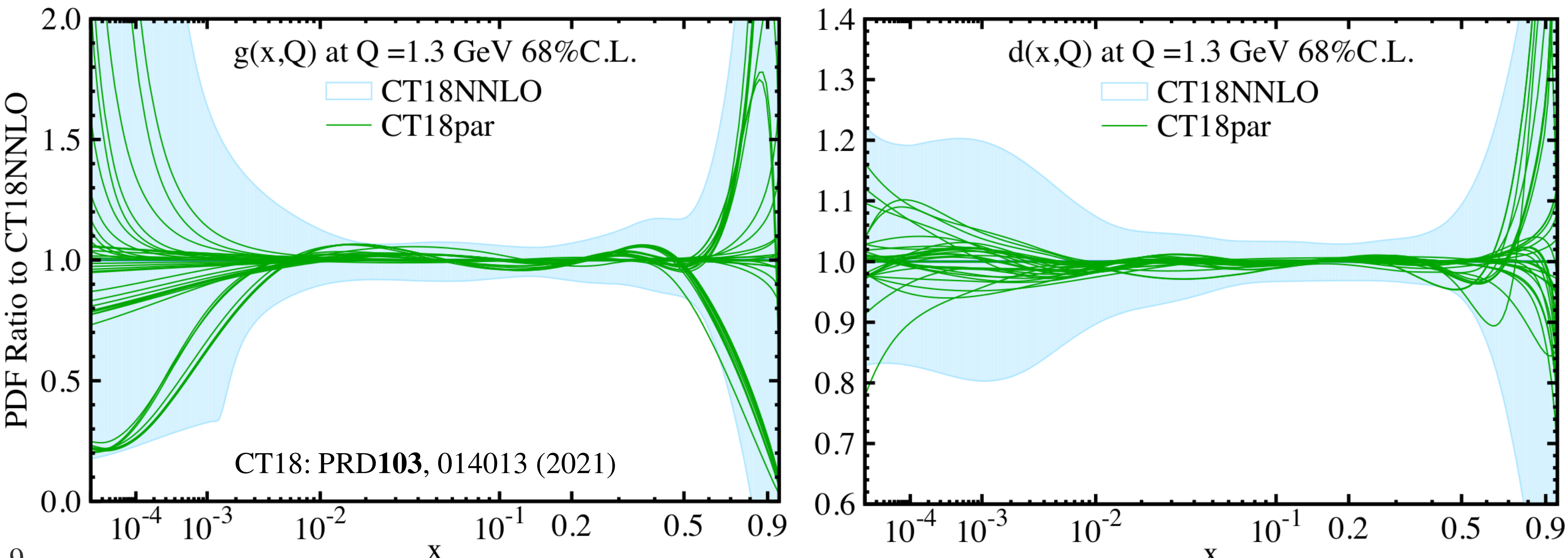
  → subject to complex nonperturbative dynamics

  → practice agnosticism w.r.t. initial parametrization

  (some guidance from QCD, QCD-inspired models)

  → explore model uncertainty with many forms

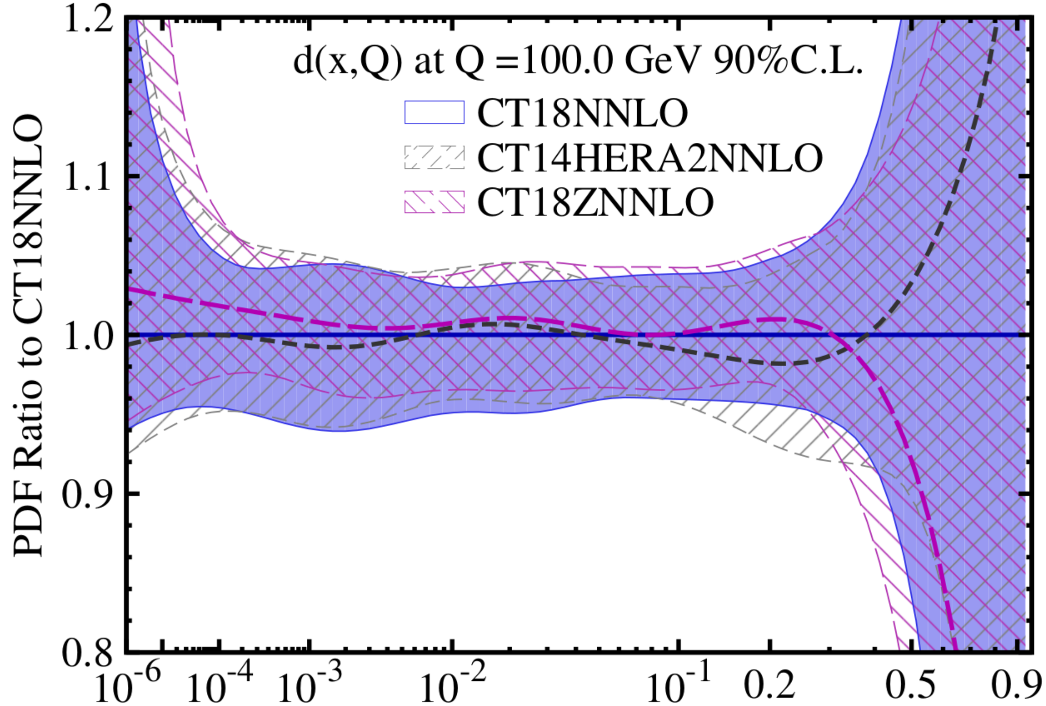
parametrization uncertainties largest in extrapolated regions

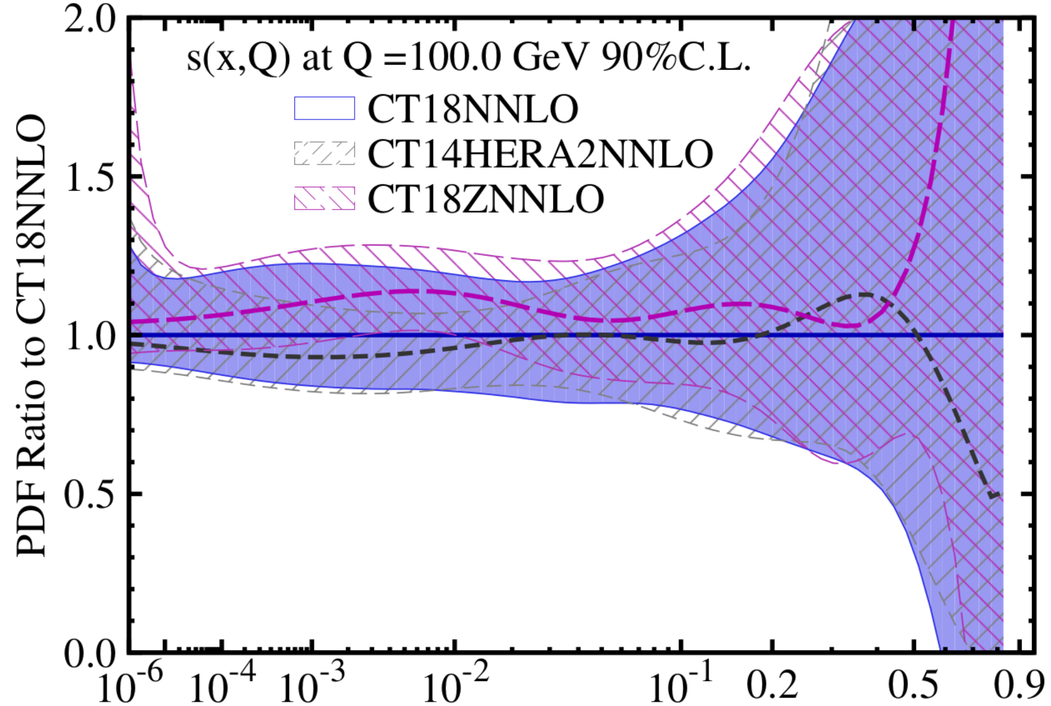


high-x PDFs remain dominated by large uncertainties

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

  → limited data → extrapolation → data tensions

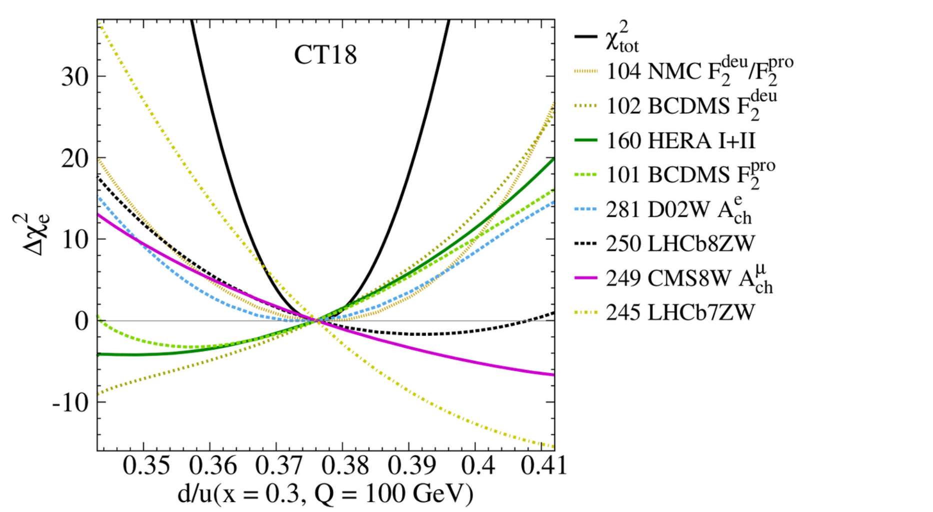




- competing pulls of fitted data at high-x also restrict precision; *e.g.*,

  → BCDMS, F_2^d

  → LHCb, W/Z 7 TeV



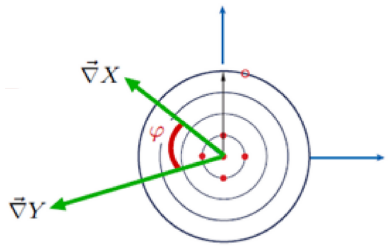
quantifying PDF preferences of fitted data: **the L_2 method**

$S_{f,L_2}(E)$: fast approximation of the Lagrange Multiplier scan of χ^2_E along direction of $f_a(x_i, Q_q)$.

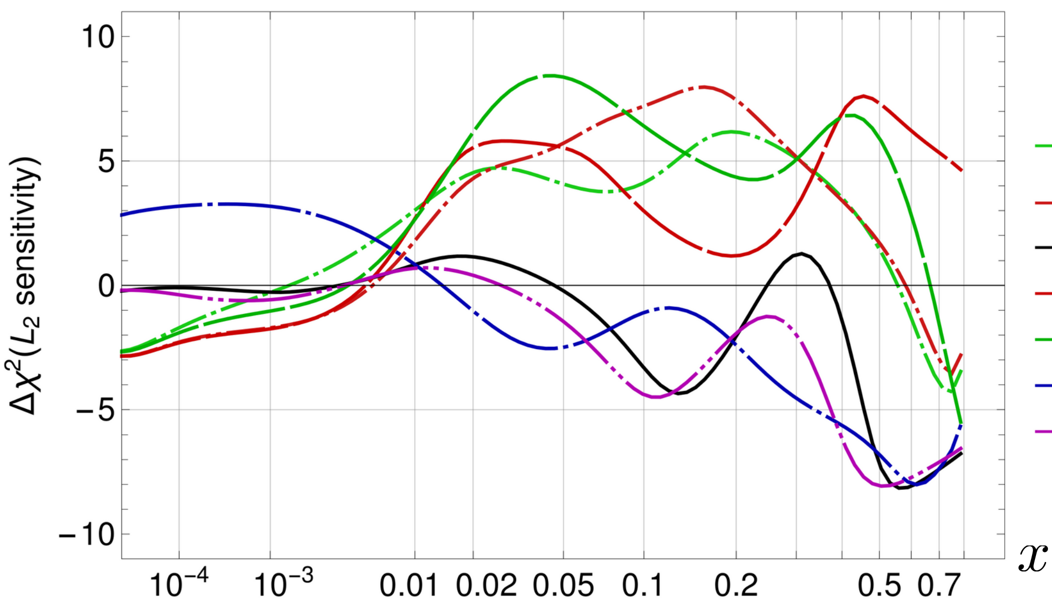
→ estimated $\Delta\chi^2_E$ for experiment E when $f_a(x_i, Q_i)$ increases by its $+68\%$ c.l. PDF uncertainty

$$Y = \chi^2_E \qquad X = f_a(x_i, Q_i) \qquad S_{f,L_2} \equiv \Delta Y(\vec{z}_{m,X}) = \vec{\nabla} Y \cdot \vec{z}_{m,X}$$

$$= \vec{\nabla} Y \cdot \frac{\vec{\nabla} X}{|\vec{\nabla} X|} = \Delta Y \cos\varphi$$



CT18 NNLO, BcdF2dCor (102), Q=2 GeV



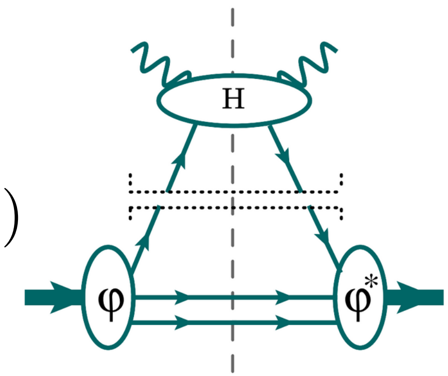
https://ct.hepforge.org/PDFs/ct18/figures/L2Sensitivity/

→ extension of L_1 sensitivity (PDFSense) method used to explore

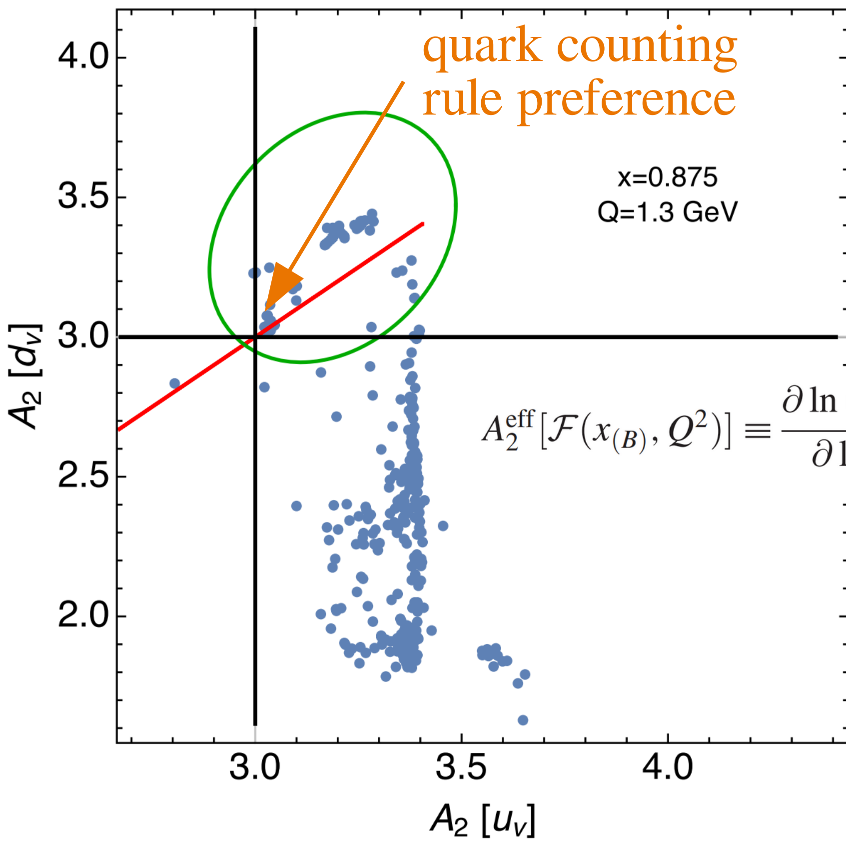
- HEP data pulls for CT18
  Phys.Rev.D 103 (2021) 1, 014013
- PDF-Lattice sensitivities
  Phys.Rev.D 100 (2019) 9, 094040
- EIC potential
  EIC YR, arXiv: 2103.05419

extracting high-x dependence in PDF fits

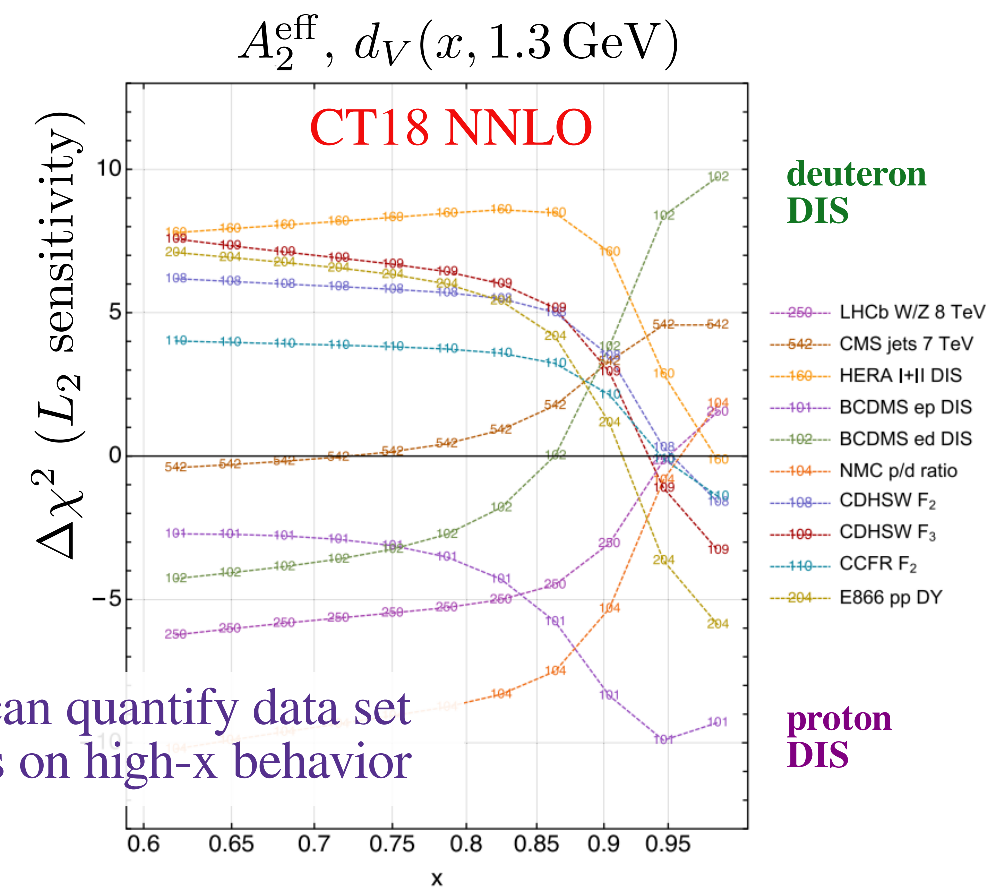
- high-x PDFs, ratios [e.g., d/u] connected to details of proton WF
- behavior at $x \to 1$ an important nonpert. discriminator
- CT18, parametrize $f_{a/A}(x, Q_0^2) = x^{A_{1,a}}(1-x)^{A_{2a}} \times \Phi_a(x)$



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

high-x d-PDF: information from light nuclei

- extracting d-type PDFs from proton targets only is challenging
- instead, e.g., **DIS on deuterium**: flavor separation by fitting *with* proton data

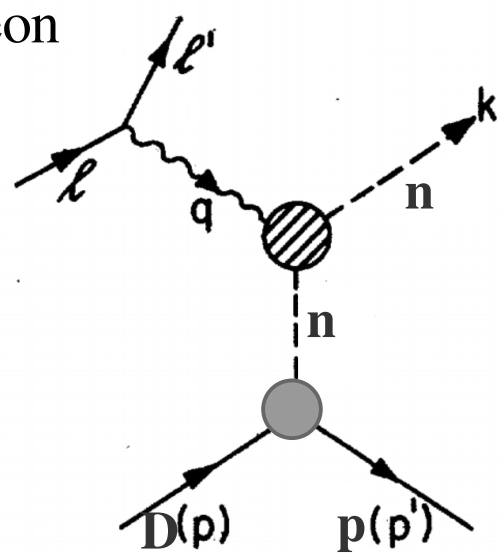
LO quark model: $F_2^{(p+n)/2} \sim \frac{5x}{9}(d+u)$ vs. $F_2^p \sim \frac{2x}{9}(4u+d)$

→ assumes *isoscalar* deuteron: *i.e.*, an incoherent superposition, $N = p + n$

- in actuality, the deuteron is a two-body nuclear bound state

→ binding modifies parton structure w.r.t. free nucleon

→ virtuality of struck (bound) nucleon
→ relativistic Fermi motion
→ details of the nuclear wave function

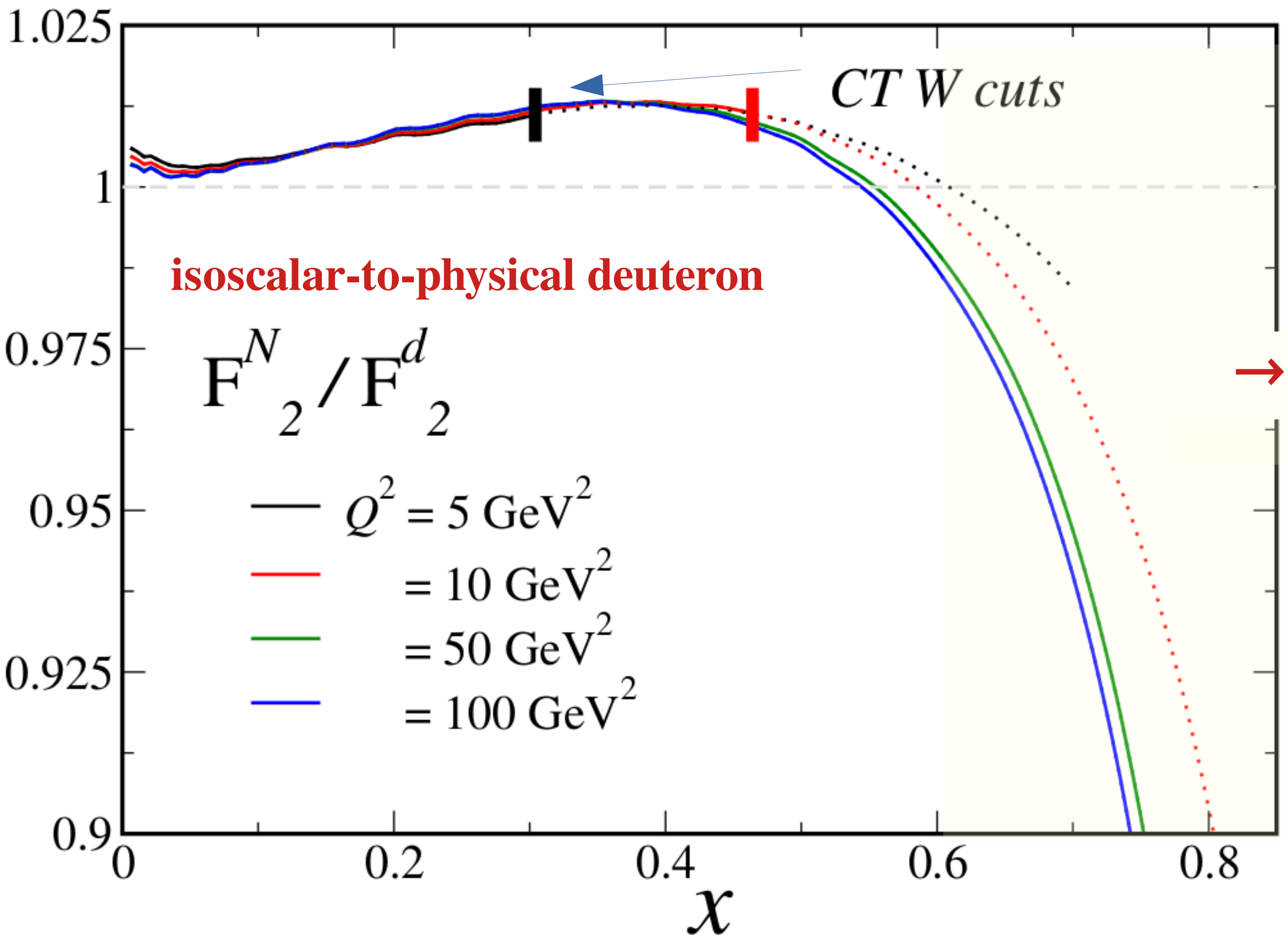


fixed isoscalar-to-physical deuteron correction

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

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

→ examine CT, CTEQ-JLab (CJ) fits with/out this correction: Accardi, TJH, Jing, Nadolsky EPJC81 (2021) 7, 603



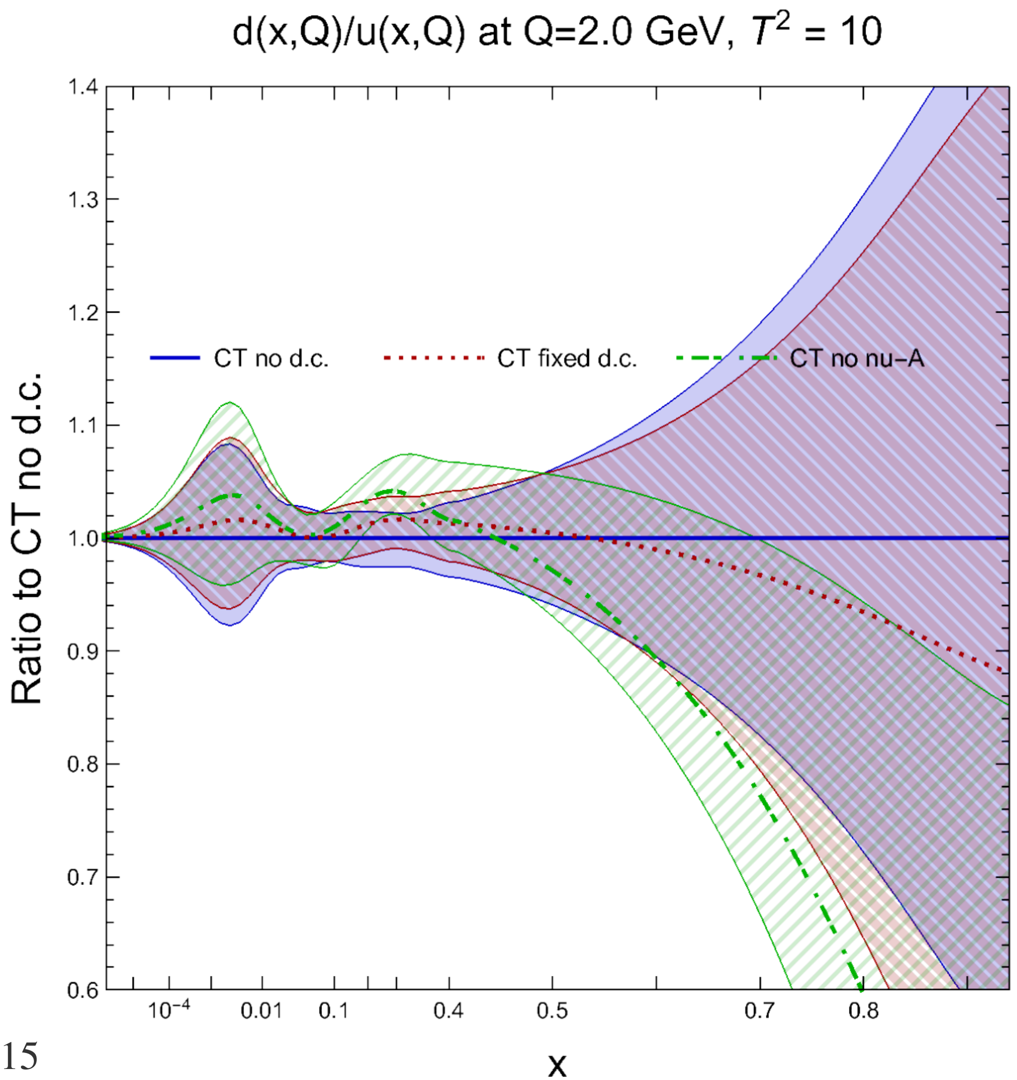
→ modest scale dependence at high x

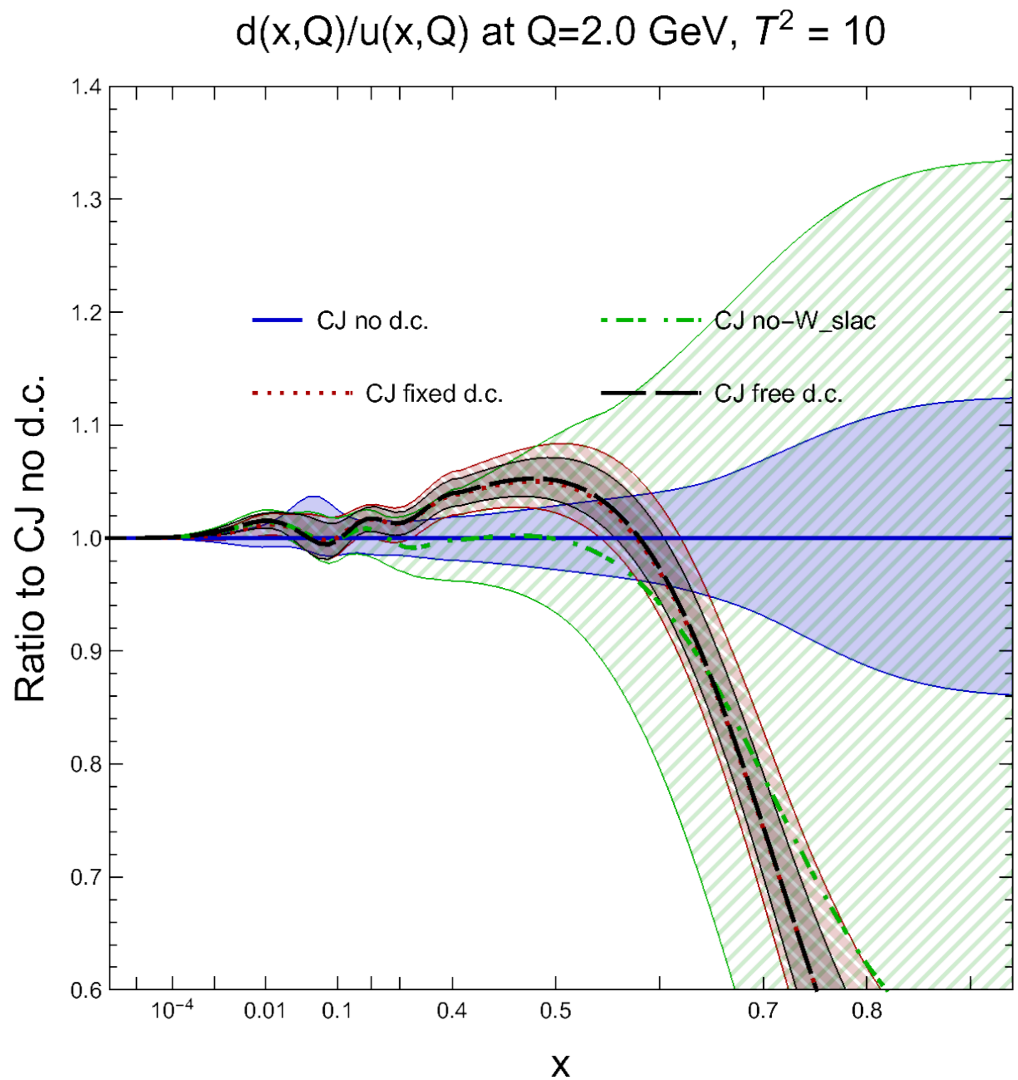
CT

CJ only

comparative analysis:
CJ and CT at **NLO**

1. Fits *without* deuteron corrections (`no d.c.`): `CT no d.c.`, `CJ no d.c.`;
2. Fits with the *fixed* CJ15 correction: `CT fixed d.c.`, `CJ fixed d.c.`;
3. A CJ fit in which the off-shellness correction is freely varied: `CJ free d.c.`;
4. Fits with the fixed CJ15 deuteron correction and variations in the fitted data sets: `CT no nu-A` (removing inclusive νA DIS experiments from CT), and `CJ no-W_slac` (removing Tevatron W production — the CDF [131] and DØ [132] W asymmetry data — and SLAC DIS [proton and deuteron] sets from CJ).

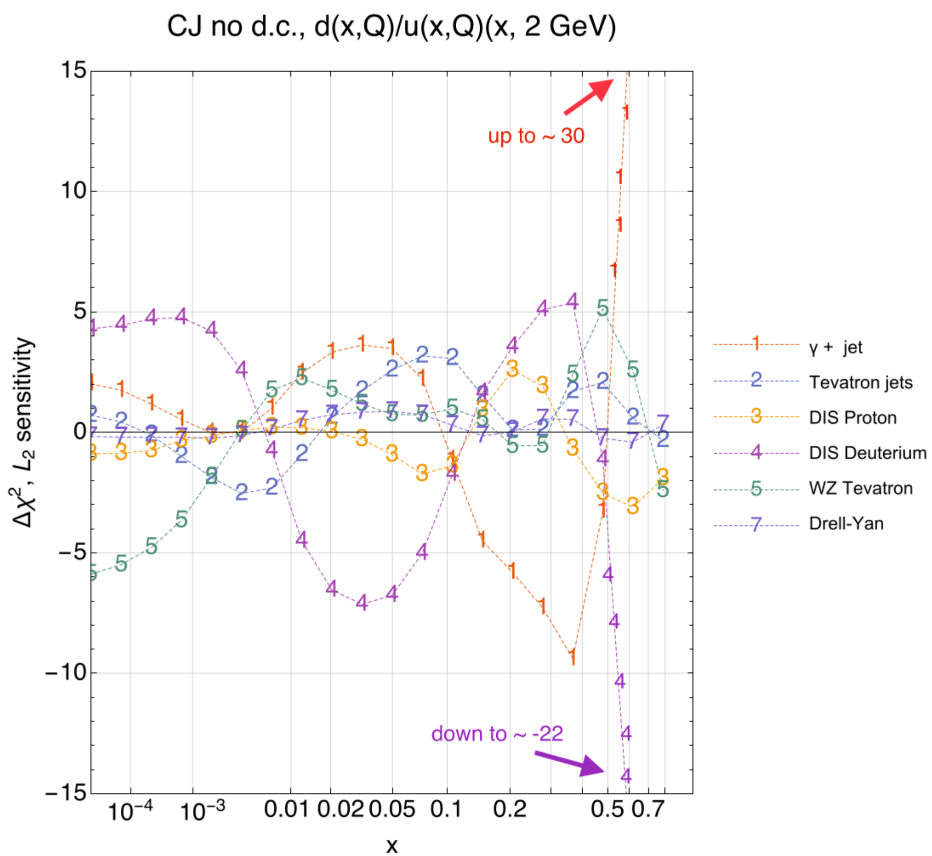


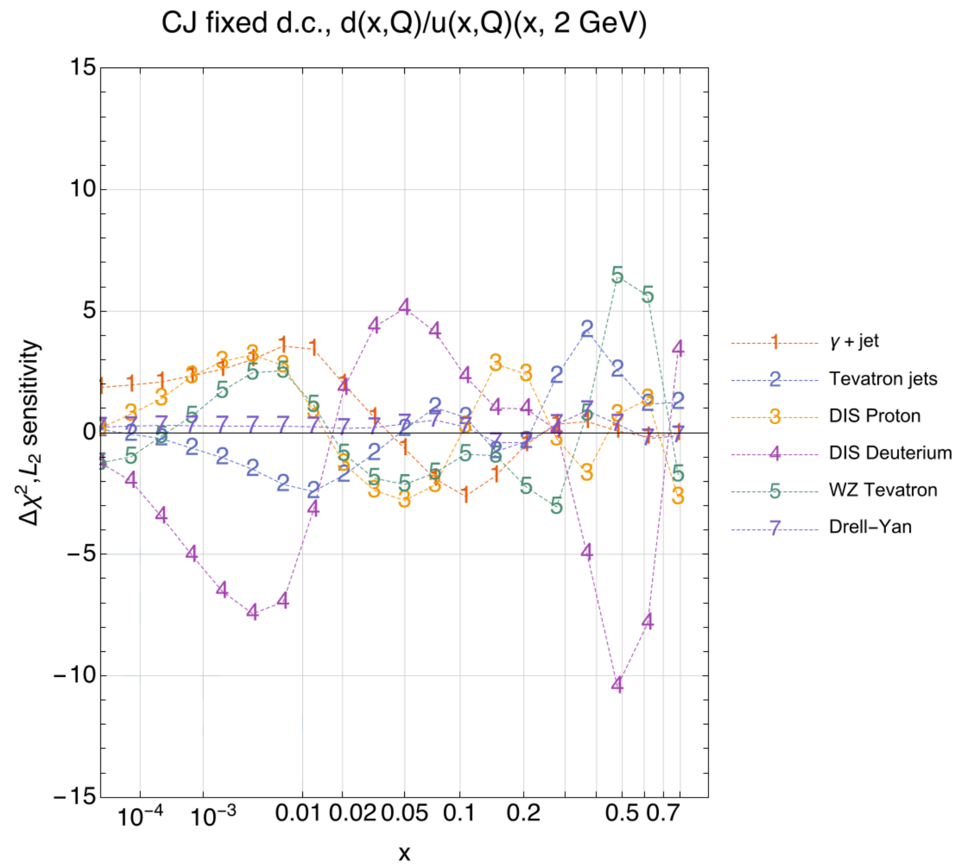


deuteron corrections: consequential for PDF pulls of fitted data

- in CJ fits without deuteron correction, large tensions at high x: γ-jet [1] vs. DIS-deuterium [4] data; especially at $x > 0.5$

d/u





- with fixed correction, tensions soften significantly; PDF pulls of DIS-deuteron [4] data flip sign over broad x range

→ reflects striking shift in *d*/*u* PDF with fixed deuteron correction

Article

The asymmetry of antimatter in the proton

Nature | Vol 590 | 25 February 2021 | 561

https://doi.org/10.1038/s41586-021-03282-z

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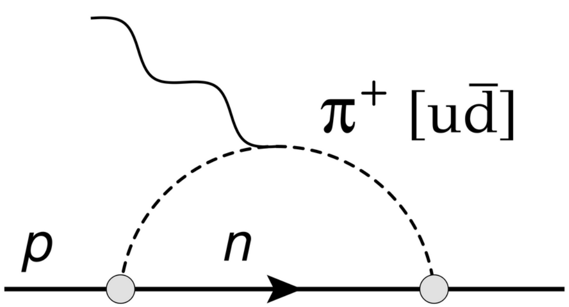
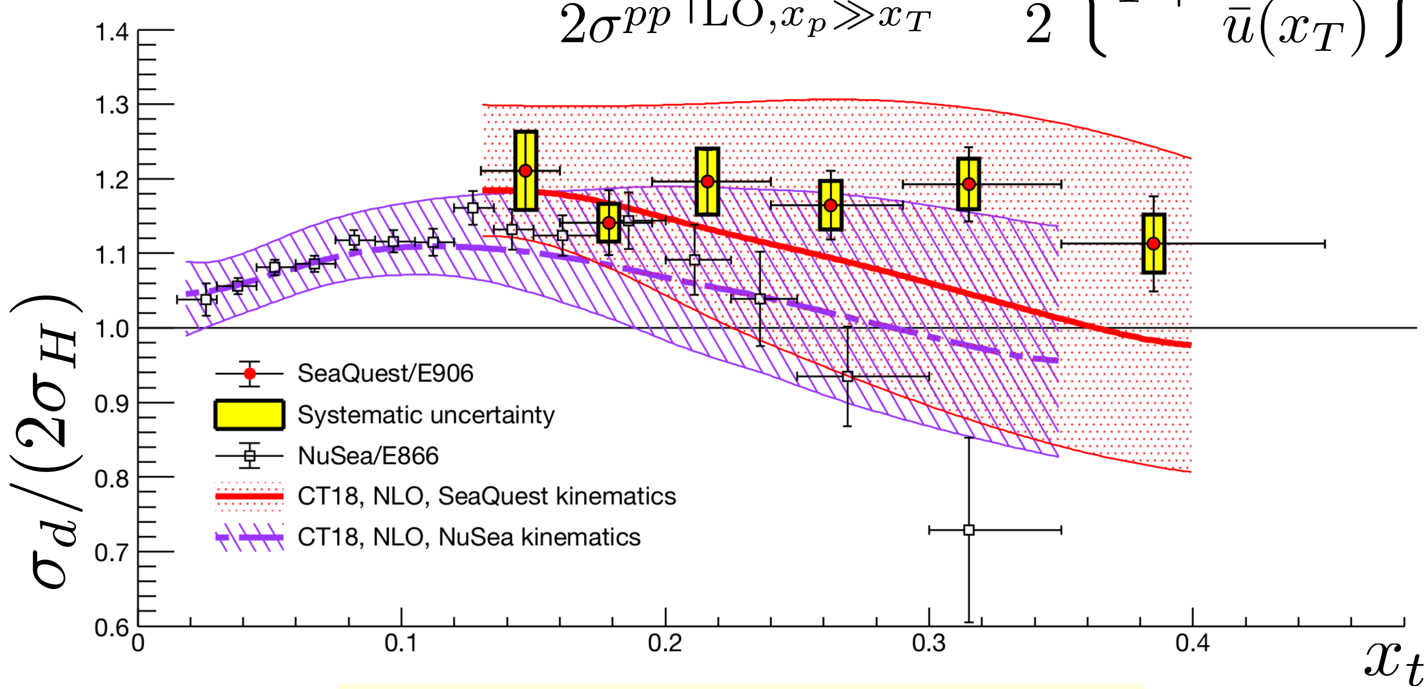
nonperturbative behavior of high-x PDFs

The Fermilab SeaQuest (E906) experiment may be sensitive to the high-x fraction of $\bar{d}$ vs. $\bar{u}$

→ many nonpert. models favor $\bar{d}/\bar{u} > 1$



$$\frac{\sigma^{pd}}{2\sigma^{pp}}\Big|_{\mathrm{LO},x_p \gg x_T} \sim \frac{1}{2}\left\{1+\frac{\bar{d}(x_T)}{\bar{u}(x_T)}\right\}$$

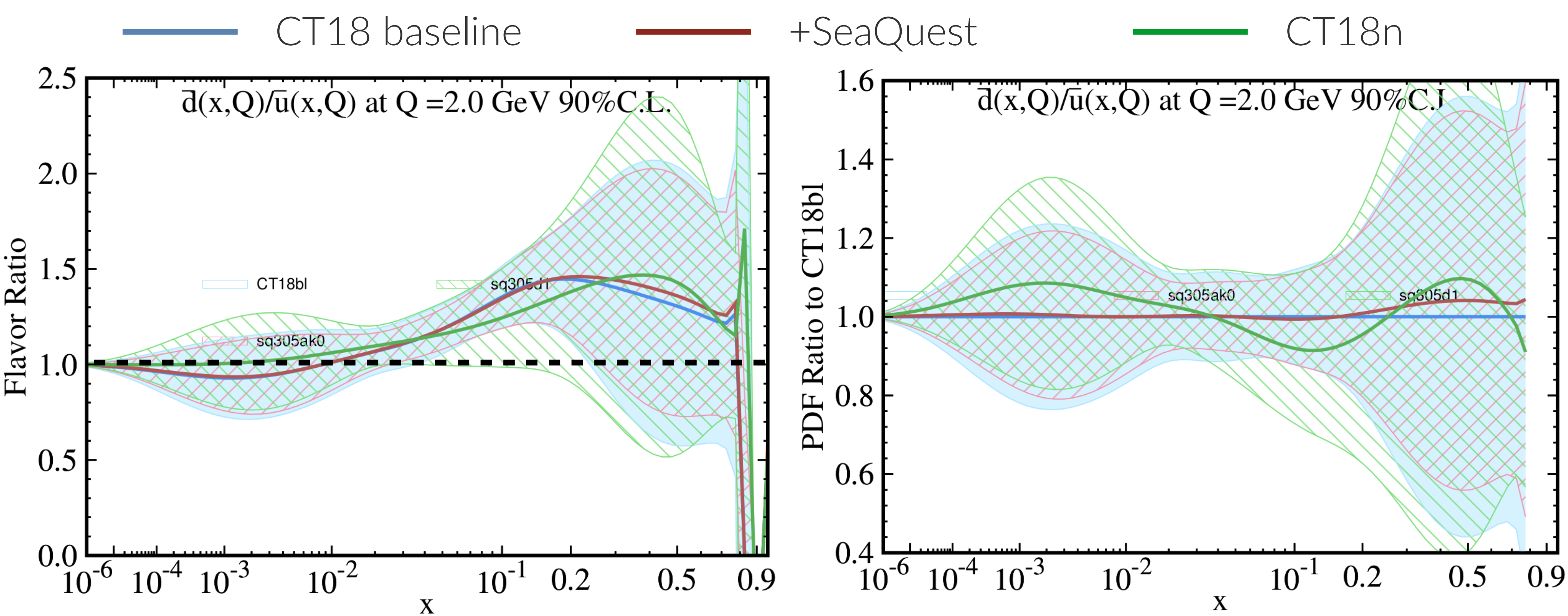


CT18 NNLO, $\chi^2_E/N_{pt} = 0.82$

What $\bar{d}/\bar{u}$ ratio do the other CT18 experiments prefer?

SeaQuest impact in CT18 at NNLO

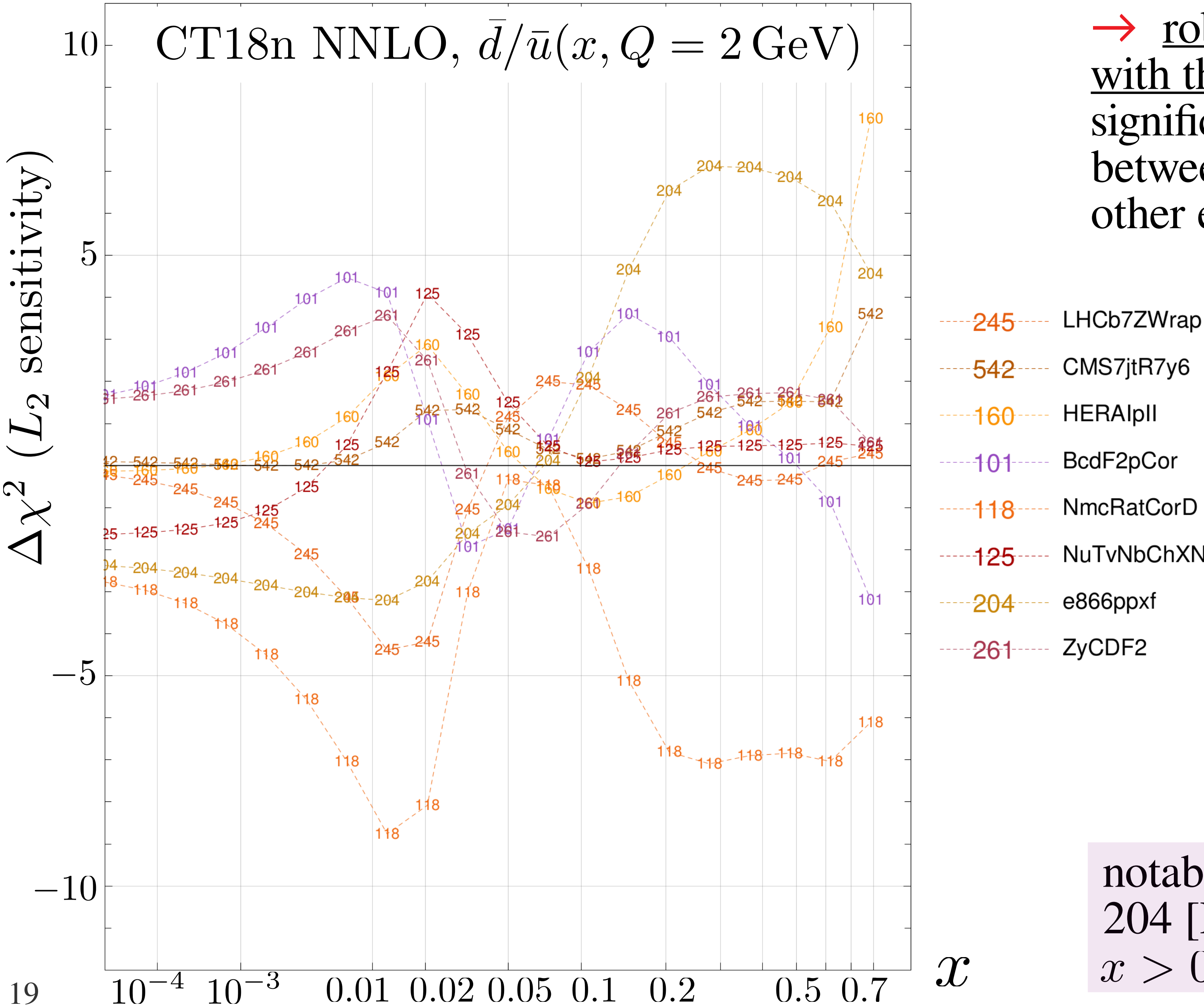
- **preliminary** NNLO fits:
  - → directly include SeaQuest on top of CT18 default sets, choices
  - → 'CT18n': replace E866 with SeaQuest; add deut. correction; no incl. νA; 5% E605 uncorr. unc. for nuclear effects on Cu



- SeaQuest pulls $\bar{d}/\bar{u}$ upward at high x; *may* reduce strangeness uncert.
- combined with other nuclear prescriptions: more complicated pattern of shifts

SeaQuest impact in CT18 at NNLO

- the nuclear choices in this latest fit affect PDF correlations, L_2 pulls



→ <u>robust agreement with theory</u>: no significant tension between SeaQuest and other expts

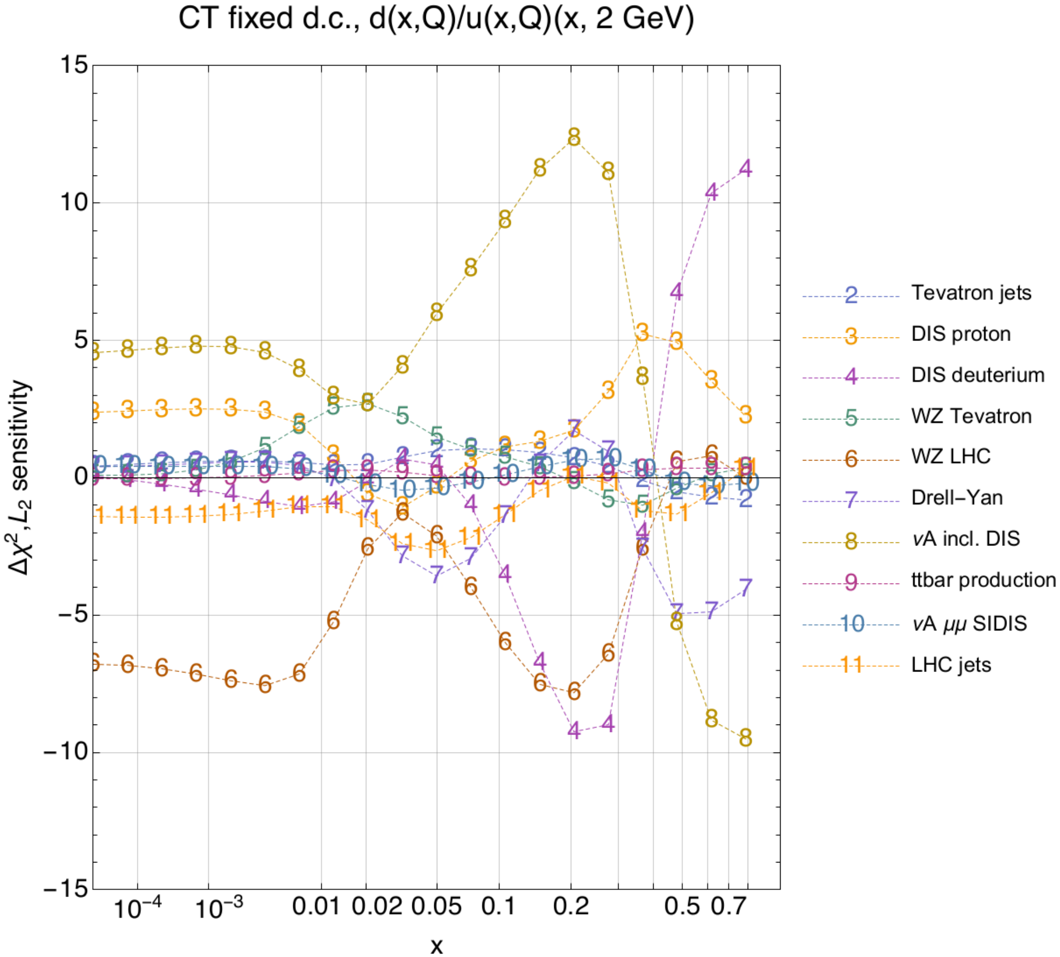
$\Delta\chi^2(\text{SeaQuest}) \lesssim 1$

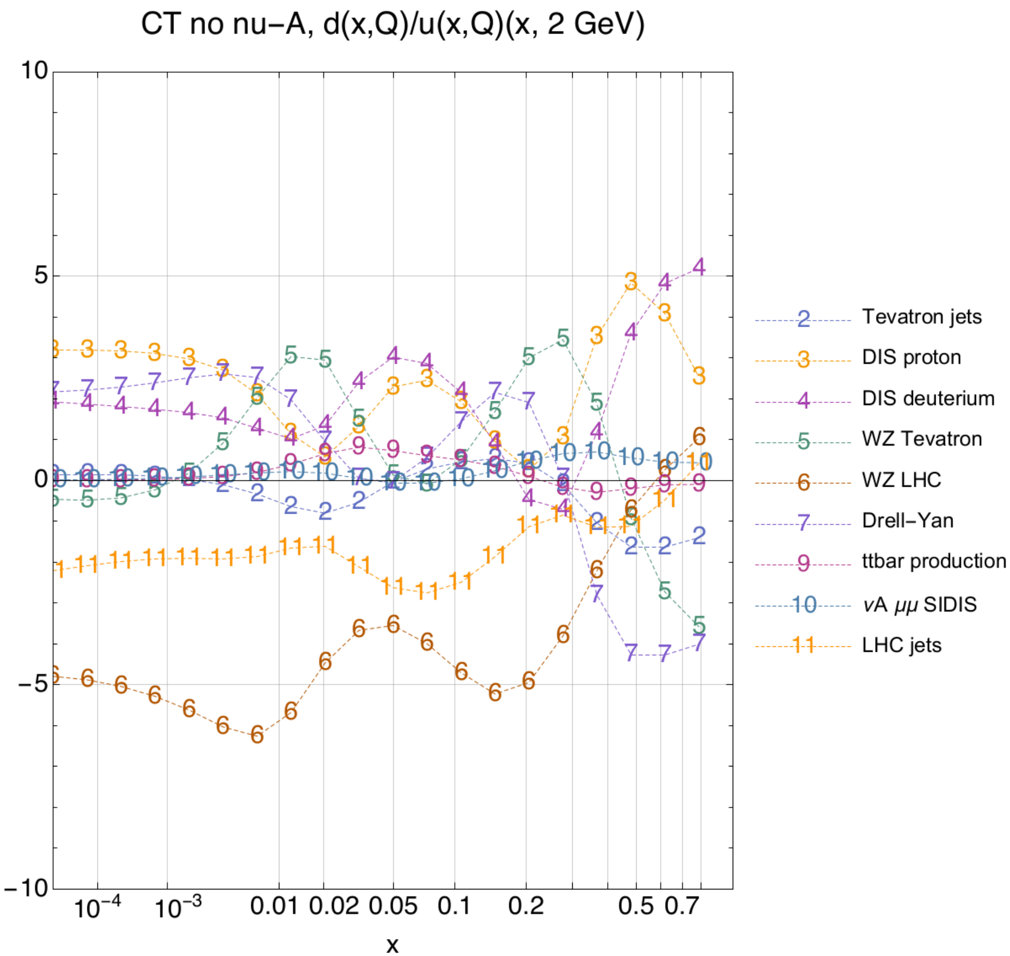
→ in fact, agreement among all expts markedly improved, generally showing $|S_f(E)| \lesssim 5$

notable pull from Expt 204 [E866 pp] at $x > 0.1$

important relationship between deuteron / heavy nucl. data

- indications of tensions between inclusive νA data and DIS-deut./*WZ*@LHC
- removing incl. νA improves agreement; enhances alignment of DIS *p*, *d* data





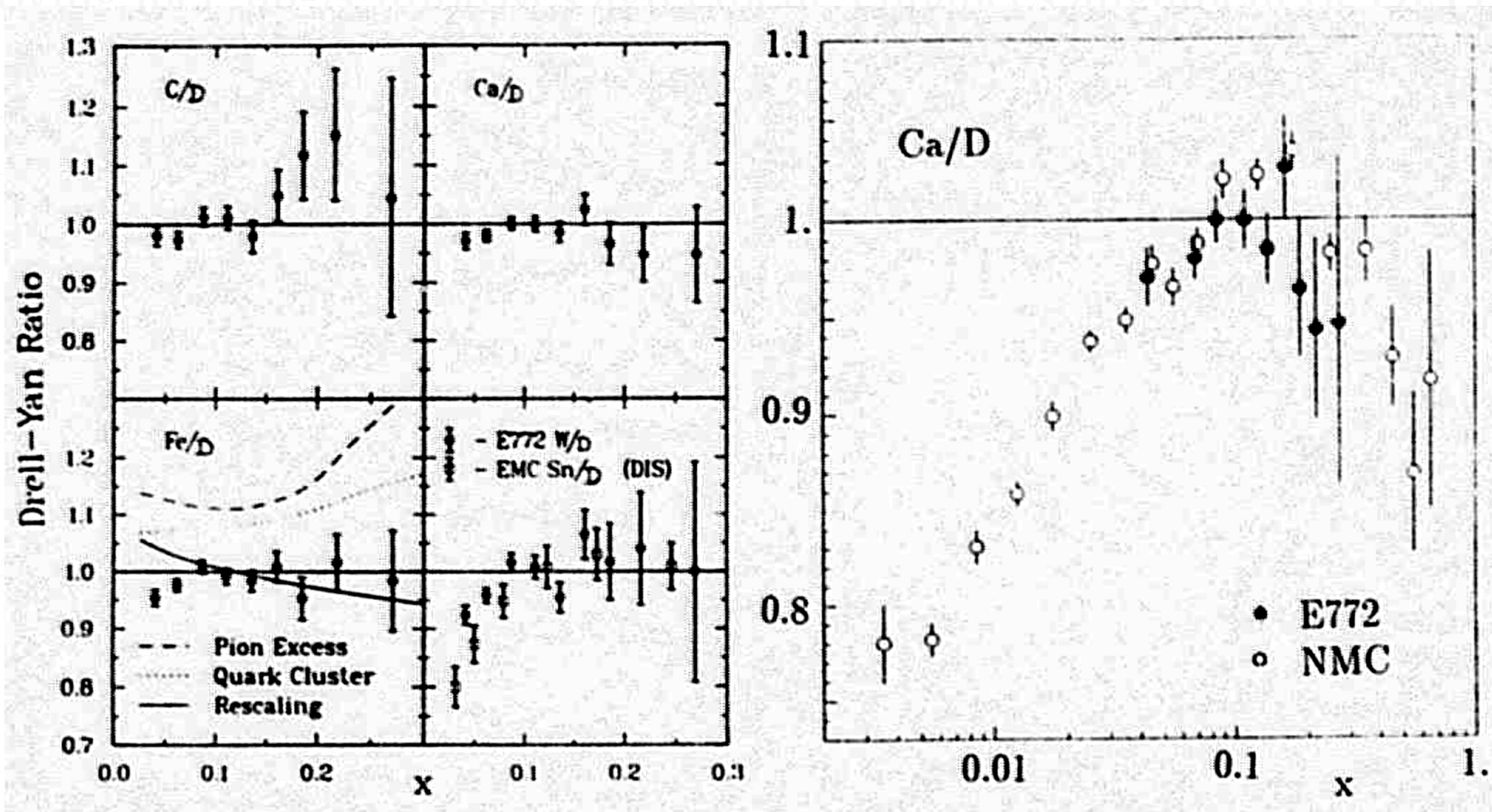
→ n.b.: $\Delta\chi^2$ can approach size of NNLO correction, scale-variation shifts

- for precision studies, important to understand heavy-nuclear corrections

important relationship between deuteron / heavy nucl. data

- since CTEQ6: phenomenological nuclear correction factors, *e.g.*,
- significant tensions between inclusive nu-A data and DIS-deut./WZ@LHC
- removing incl. nu-A improves agreement; enhances alignment of DIS p, d data

Rondio, Nucl. Phys. **A553** (1993) 615c-624c



8	nu-A incl. DIS	CDHSW F_2	108
		CDHSW xF_3	109
		CCFR F_2	110
		CCFR xF_3	111
9	ttbar production	CMS 8 TeV 19.7 fb^{-1} , $t\bar{t}$ norm. top p_T and y cross sec.	573
		ATLAS 8 TeV 20.3 fb^{-1}, $t\bar{t}$ p_T^t, $m_{t\bar{t}}$ abs. spectrum	580
10	nu-A dimuon SIDIS	NuTeV $\nu\mu\mu$ SIDIS	124
		NuTeV $\nu\bar{\mu}\mu$ SIDIS	125
		CCFR $\nu\mu\mu$ SIDIS	126
		CCFR $\nu\bar{\mu}\mu$ SIDIS	127

→ deserves dedicated, consistent study; heavy-nuclear corrections can be $\lesssim 5\%$

∴ dedicated nuclear PDF studies relevant for proton PDFs

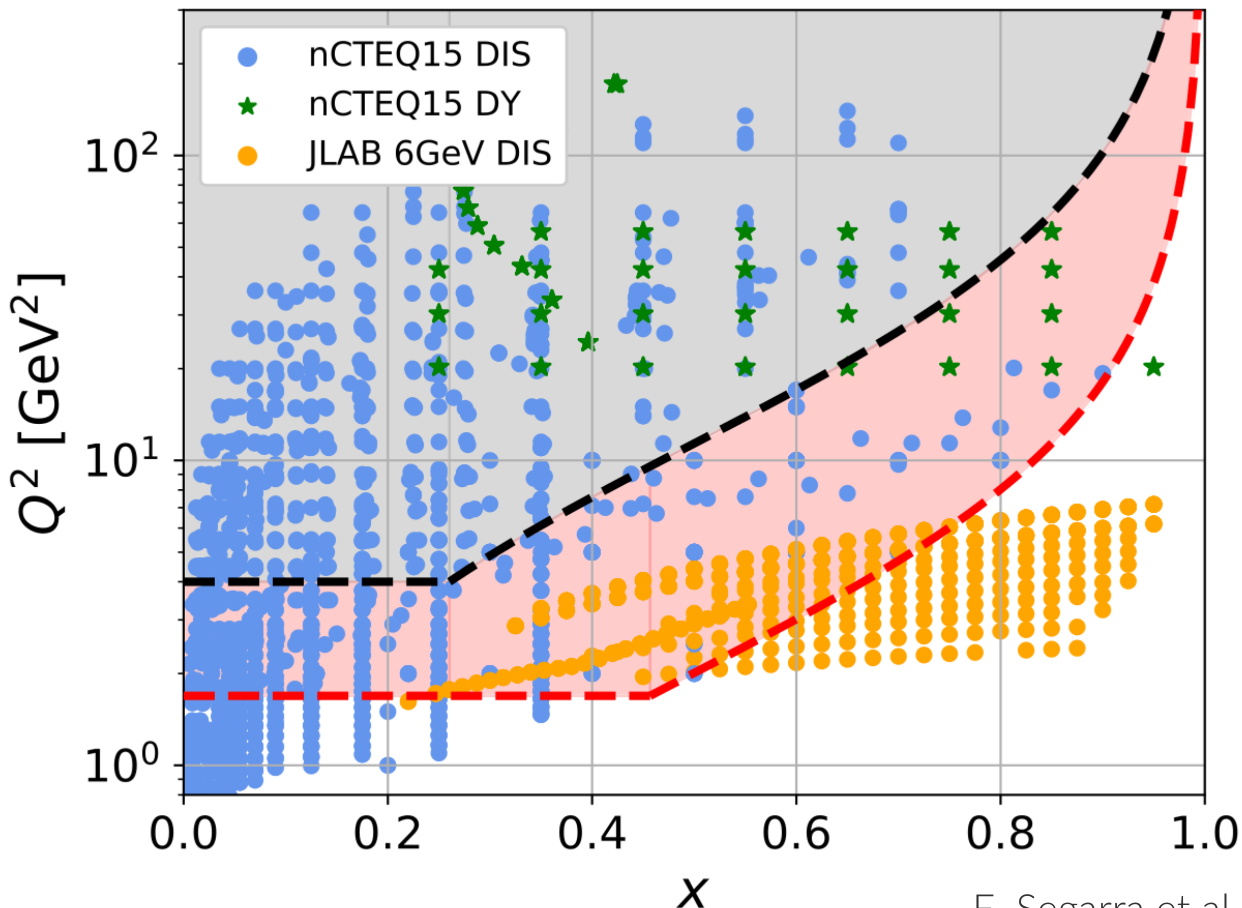
- nCTEQ: parametrize and fit nuclear PDFs directly

$$f^A = \frac{Z}{A}\, f^{p/A} + \frac{(A-Z)}{A}\, f^{n/A}$$

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}$$
$$c_k \longrightarrow c_k(A) \equiv p_k + a_k (1 - A^{-b_k})$$

- fit range of nuclear data; relax W, Q cuts with to fit 6 GeV JLab data

include TMC, HT prescriptions; CJ15 deuteron correction



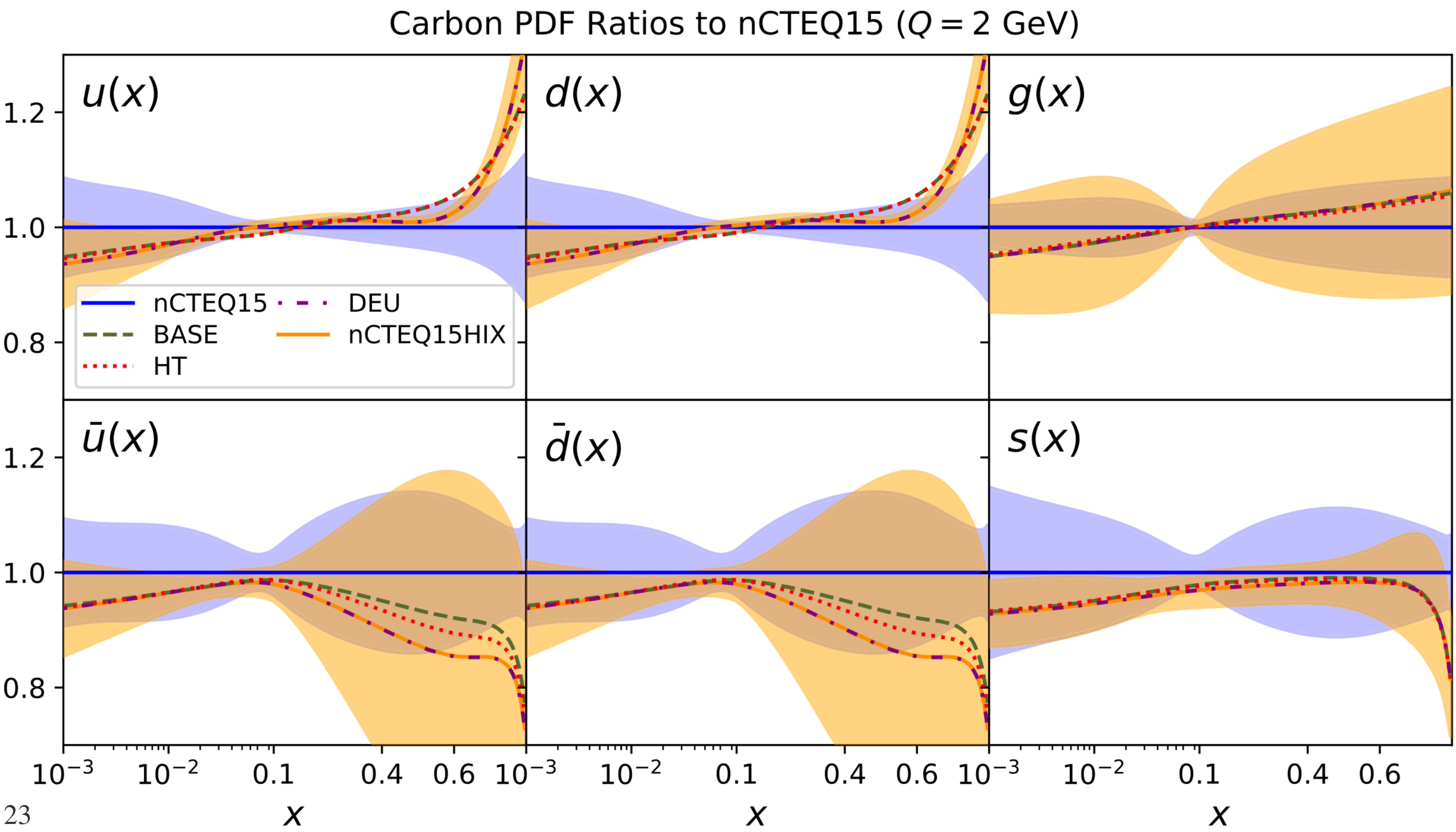
nCTEQ15HiX

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

dedicated nuclear PDF studies relevant for proton PDFs (i)

- ^{12}C PDFs, uncertainties sensitive to theory corrections, low-W data

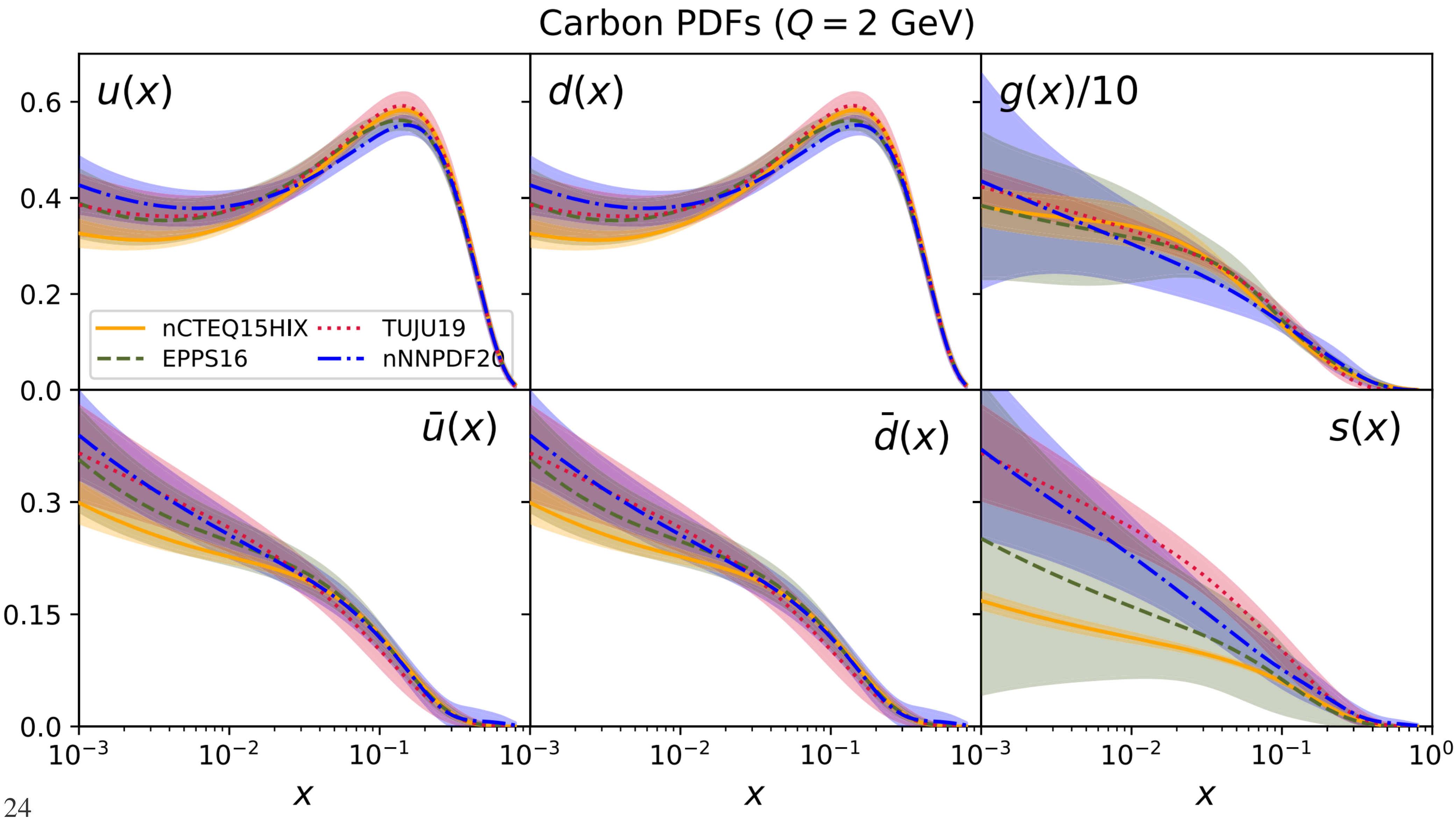
[nb: fitted at NLO…]



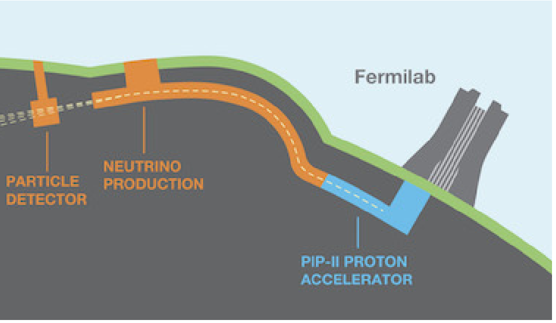
dedicated nuclear PDF studies relevant for proton PDFs (ii)

- these improvements can be assessed in the context of other nPDF determinations

  → nCTEQ uncertainties significantly narrower



extendable to large A; relevant for νA experiments



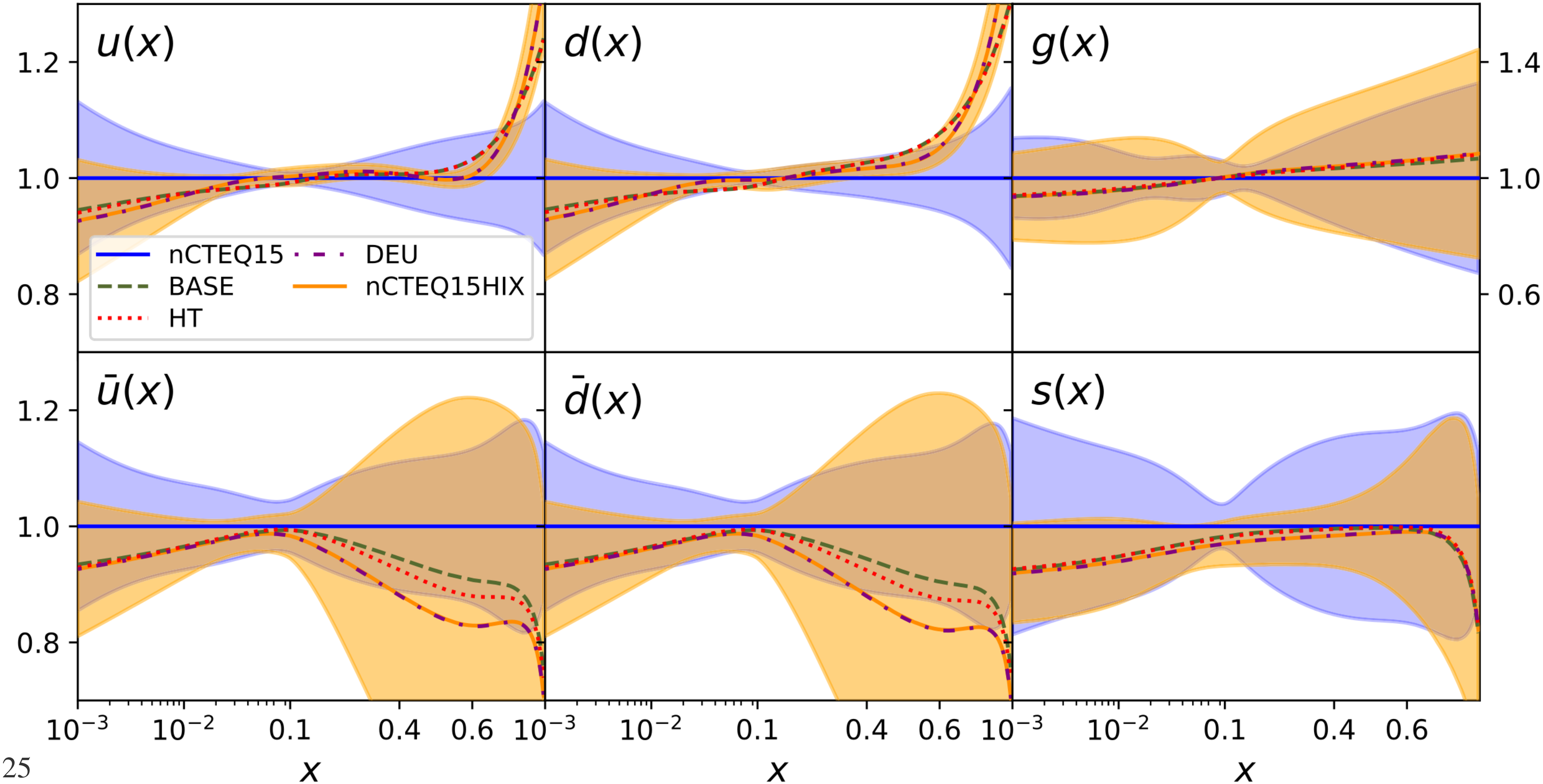
- parametrization of A dependence allows predictions for ^{56}Fe

(cf. NuTeV, CCFR, ...)

→ valuable for LBNF measurements (Ar)

(useful for accessing unique flavor currents)

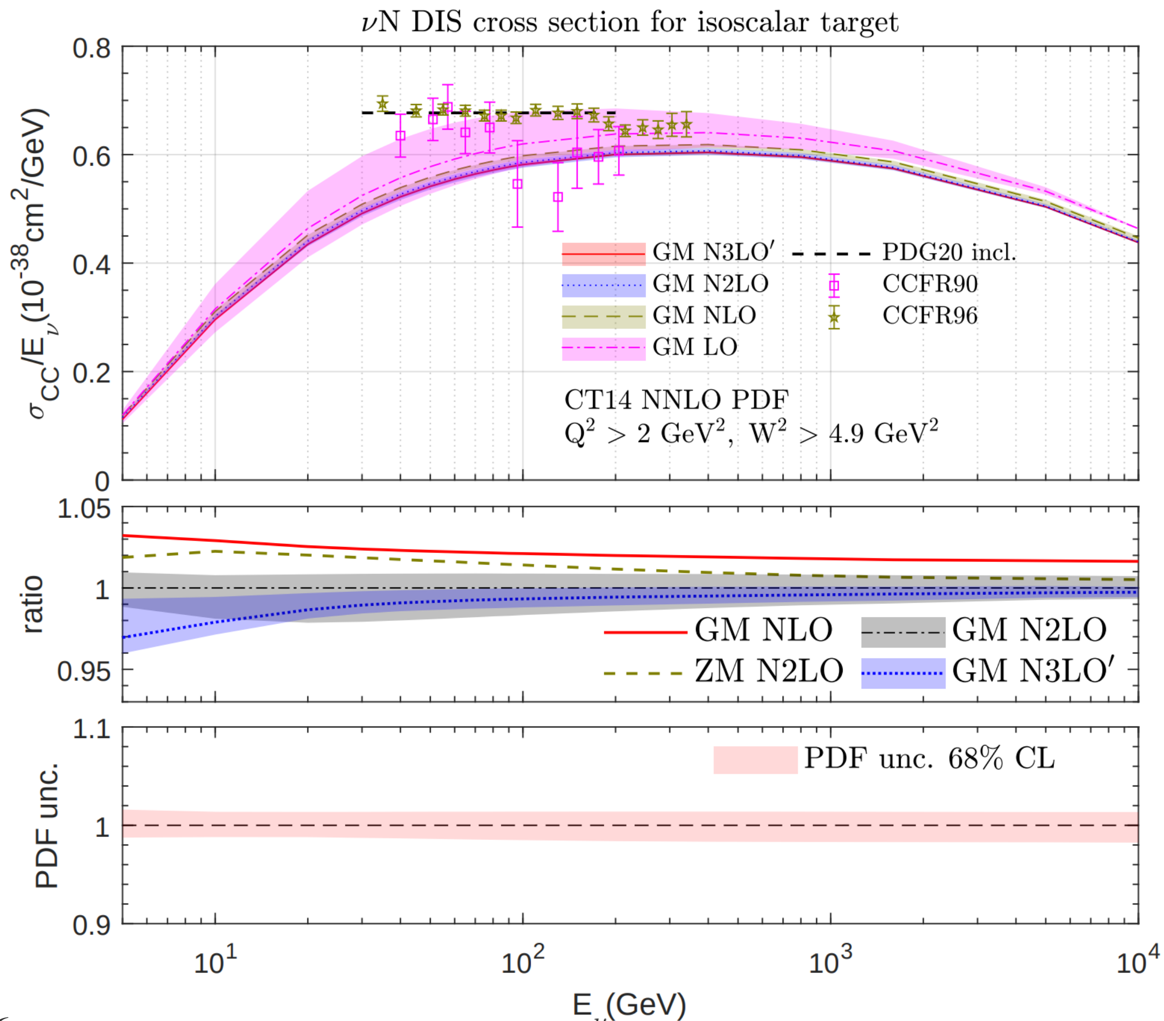
Iron PDF Ratios to nCTEQ15 ($Q = 2$ GeV)



precision QCD will also be necessary for νA

- future analyses will witness an interplay between pQCD and nuclear effects
- NNLO accuracy is necessary to stabilize scale uncertainties

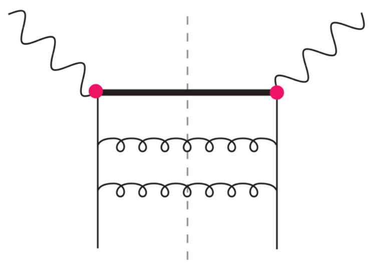
Gao, TJH, Nadolsky, Sun, Yuan: 2107.00460

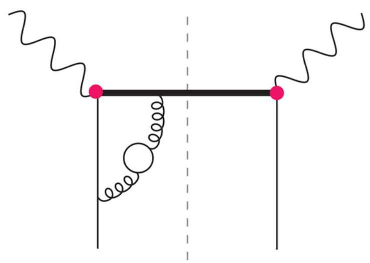


- corrections enhance pQCD precision in CC DIS cross-section

→ DUNE few-GeV region

→ higher energies: EIC, FASERν



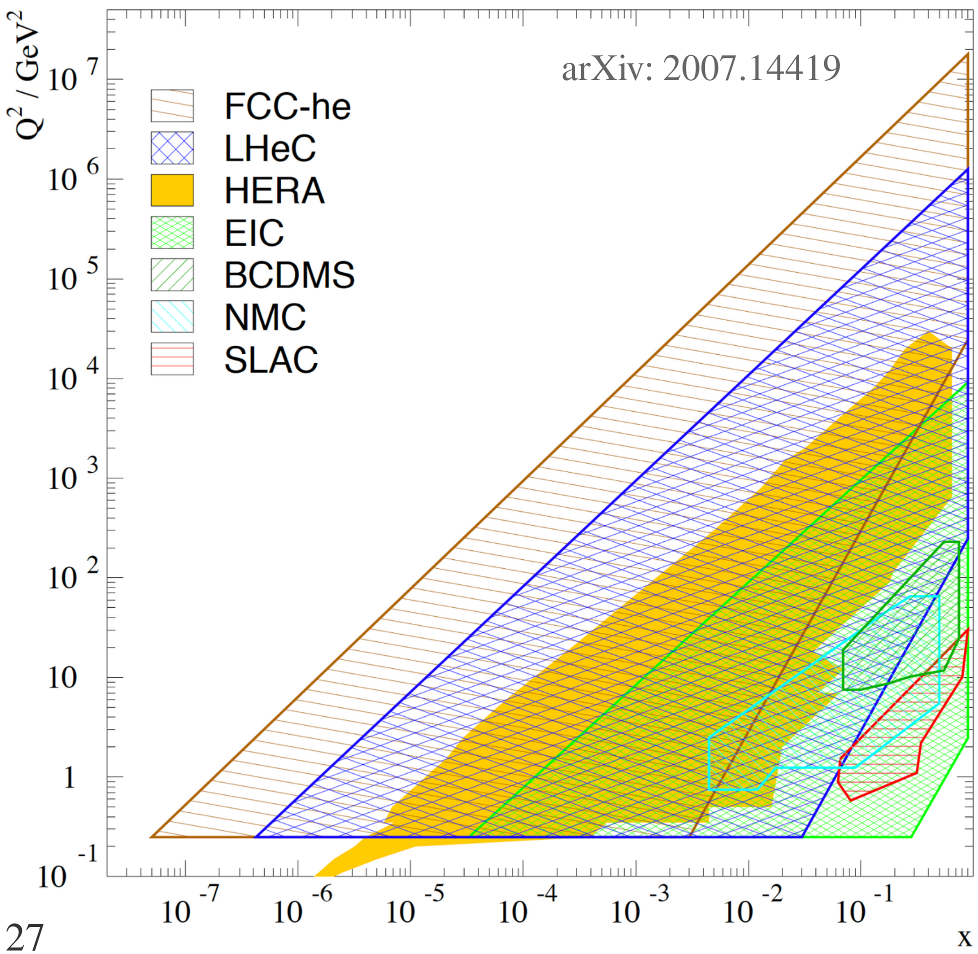


the future: many complementary experiments

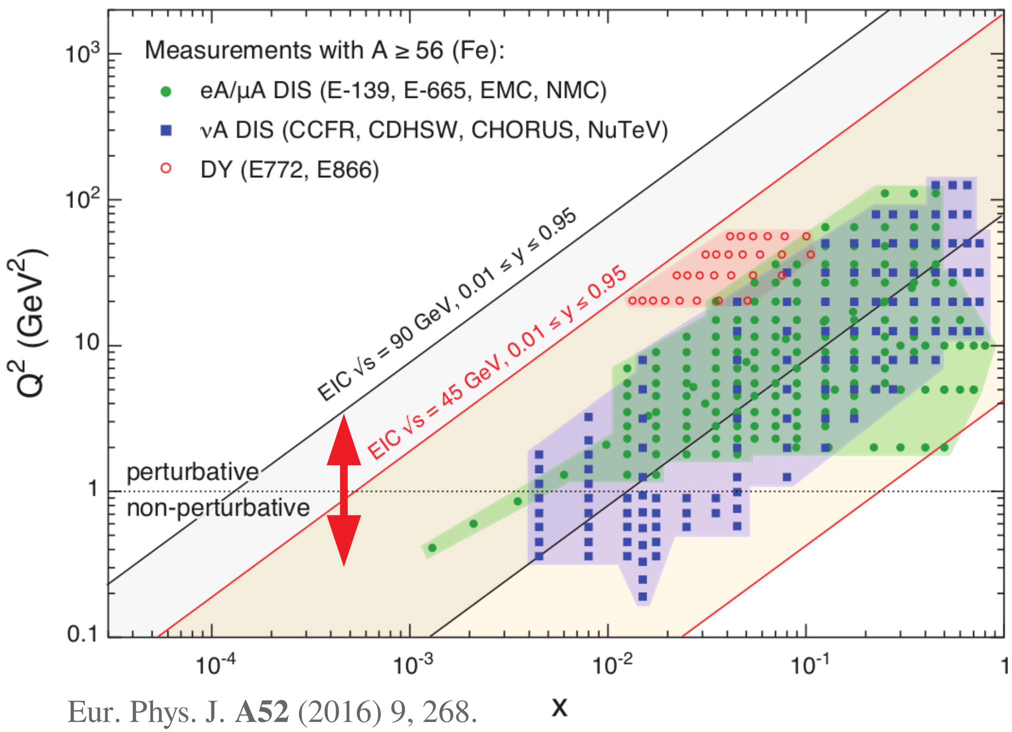
- experiments beyond JLab12, LHC, FNAL νA program
- EIC and LHeC pursue complementary physics studies in $[x, Q^2]$
- EIC: overlap with high-sensitivity fixed-target DIS experiments

see talk, E. Aschenauer

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



analogous nuclear DIS coverage:



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

CD-1; EIC Yellow Report: 2103.05419

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

- critical for understanding QCD; necessary for precision HEP measurements

- future analyses: leverage interplay among ingredients explored here

(higher pQCD theory accuracy; model exploration; nuclear effects; ...)

.. .. AS WELL AS .. ..

- input from other nonperturbative, theoretical methods
- connections to larger tomography program

→ projections: $\int d\vec{k}_T \, d\vec{b}_T \, W(x, \vec{b}_T, \vec{k}_T) = f(x)$

- future experiments: JLab12 → EIC, HL-LHC, <u>LBNF</u>, …