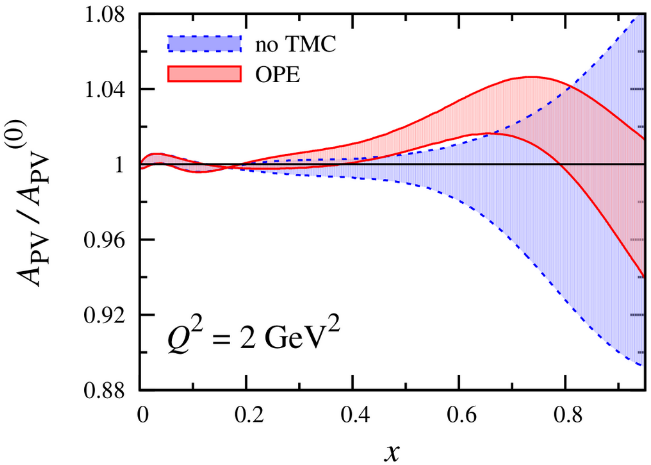
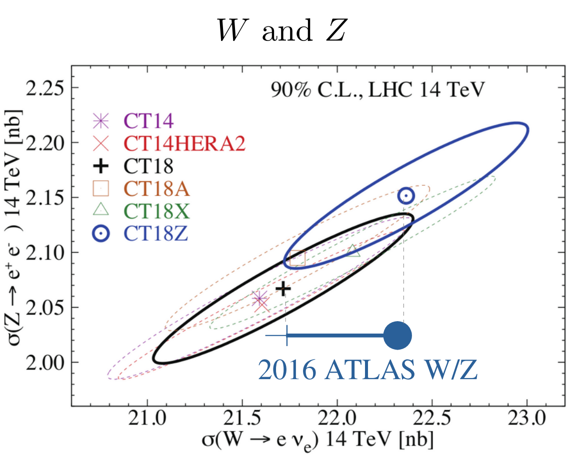
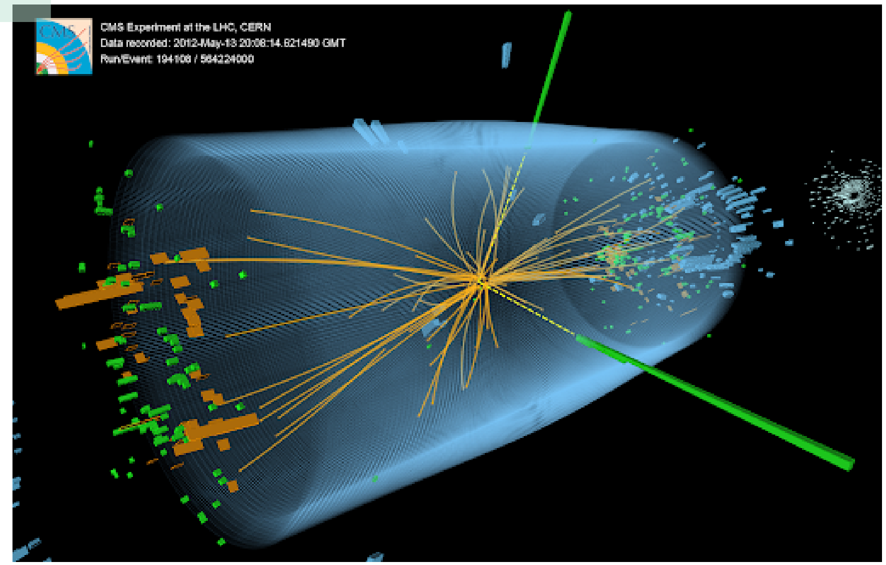
PDF implications and potential of PVDIS at JLab

Tim Hobbs – Fermilab, IIT

30th June 2022







i **PVDIS** and **PDF uncertainties**, **flavor dependence**

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

→ many standard-candle HEP measurements PDF-limited

... including very high x ...

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

→ PDF studies central to NP QCD at JLab12, maps of hadron structure

2: closely related: flavor separation generally needs numerous expts

→ controlling PDF uncertainties requires knowledge of flavor dependence

→ complementary measurements/analyses for $d/u,\ \bar{d}/\bar{u},\ s,\ \cdots$

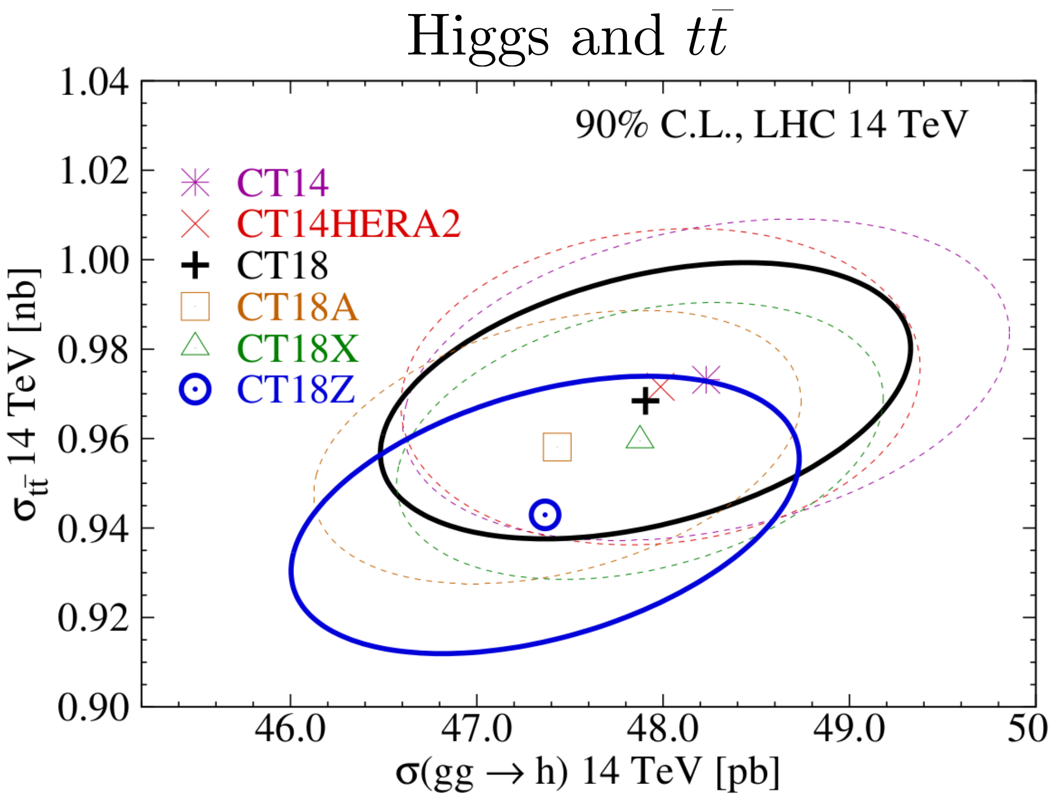
highlight through: i general status of HEP PDFs; ii flavor dependence issues

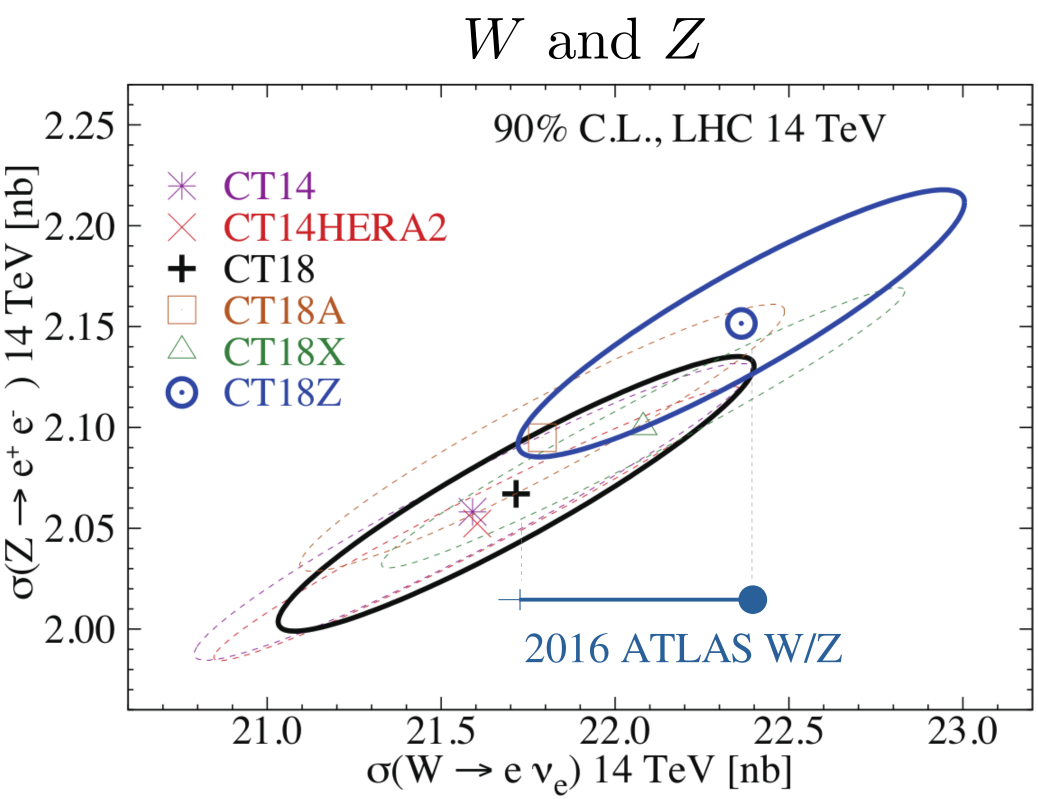
iii conclusion(s): implications for EW physics and PVDIS

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

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 (JLab12, EIC, LHC, νA)
- generator development

Snowmass21, Campbell et al.: 2203.11110

i

PDFs critical to next-generation precision

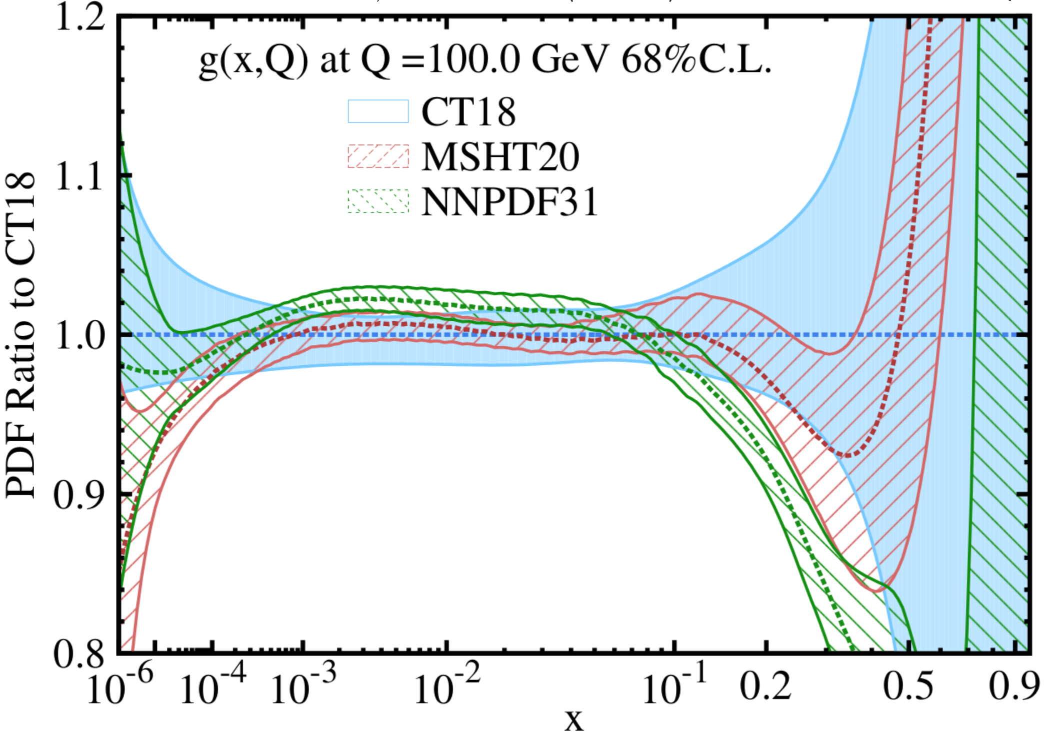
Snowmass21, Amoroso et al.: 2203.13923

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

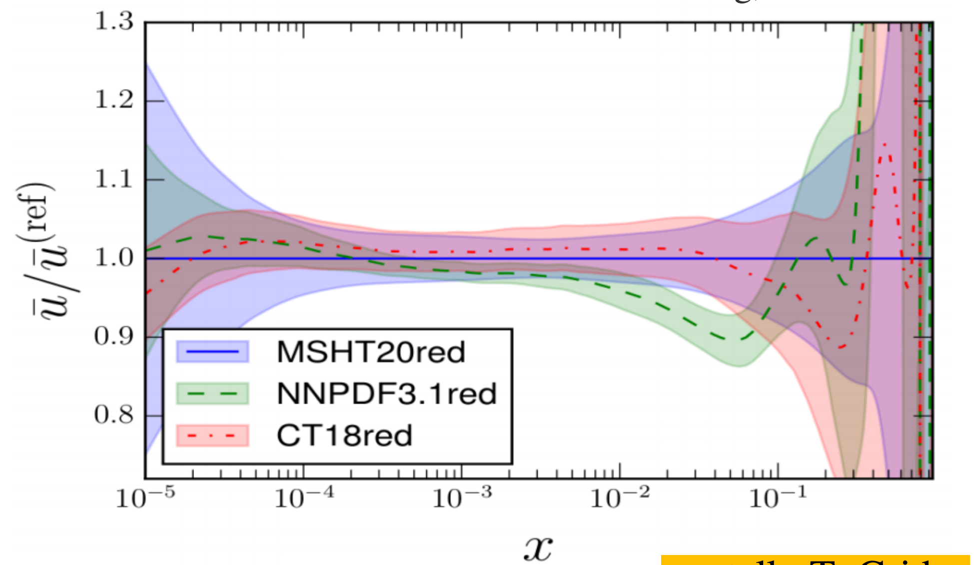
$$\sigma(AB \to W/Z+X) \;=\; \sum_n \alpha_s^n \sum_{a,b} \int dx_a dx_b\, f_{a/A}(x_a,\mu^2)\, \hat{\sigma}^{(n)}_{ab\to W/Z+X}(\hat{s},\,\mu^2)\, f_{b/B}(x_b,\mu^2)$$

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

contemporary NNLO QCD fits



PDF4LHC21 benchmarking, 2203.05506



see talk, T. Cridge

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

→ seek methodological independence in identifying data-driven PDF features

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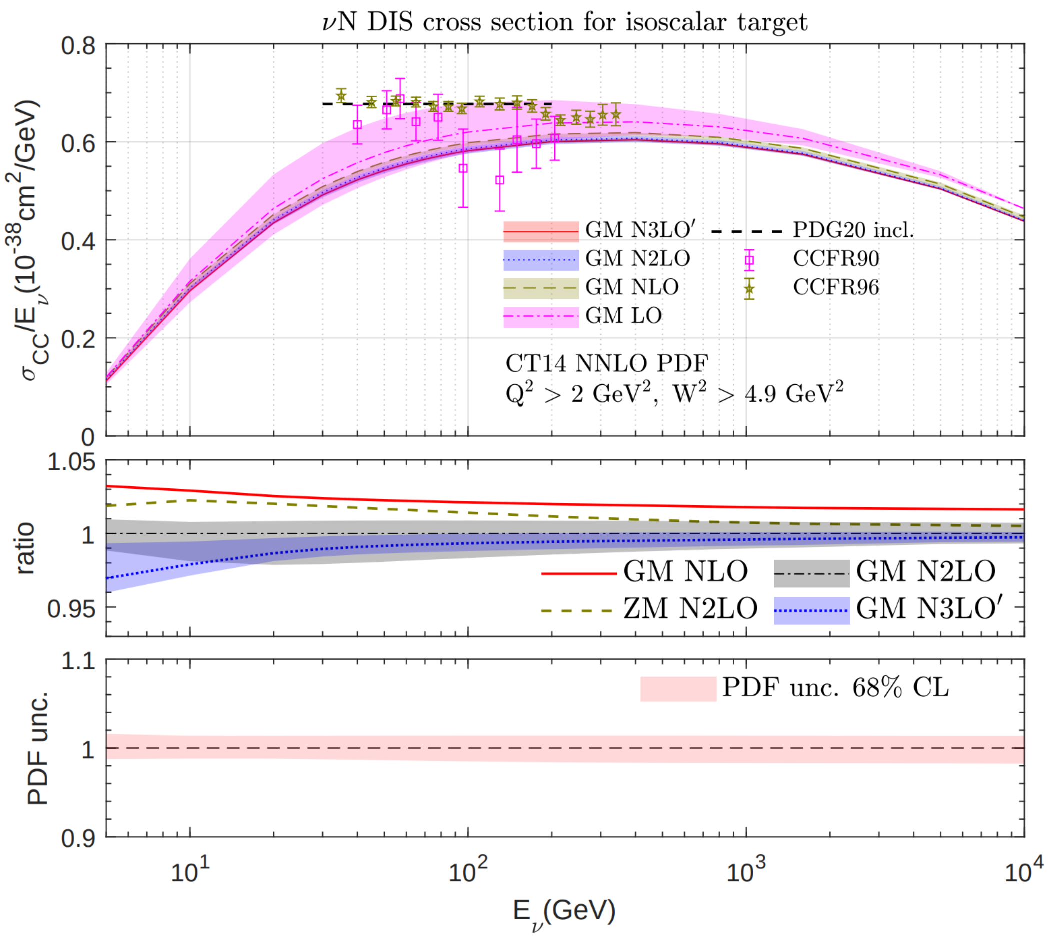
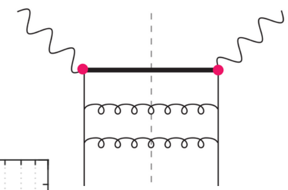
theory ingredients → higher pQCD accuracy

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

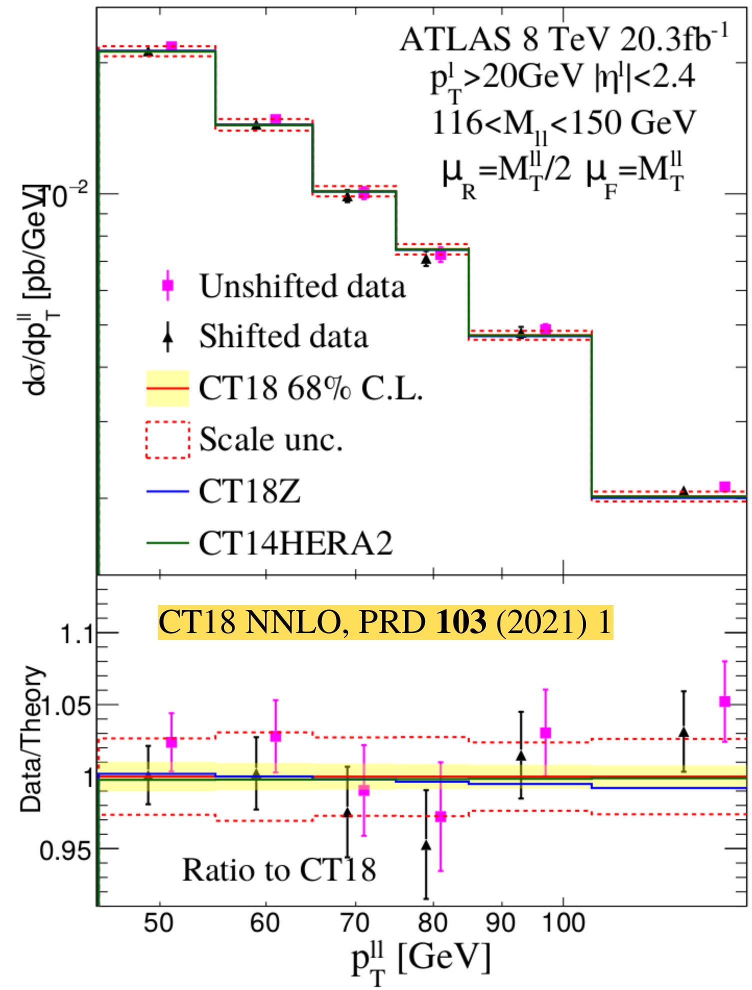
charge-current DIS

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





NNLO scale variations at LHC



→ essential to assess PDF dependence in parallel with HO corrections (beyond LO QPM)

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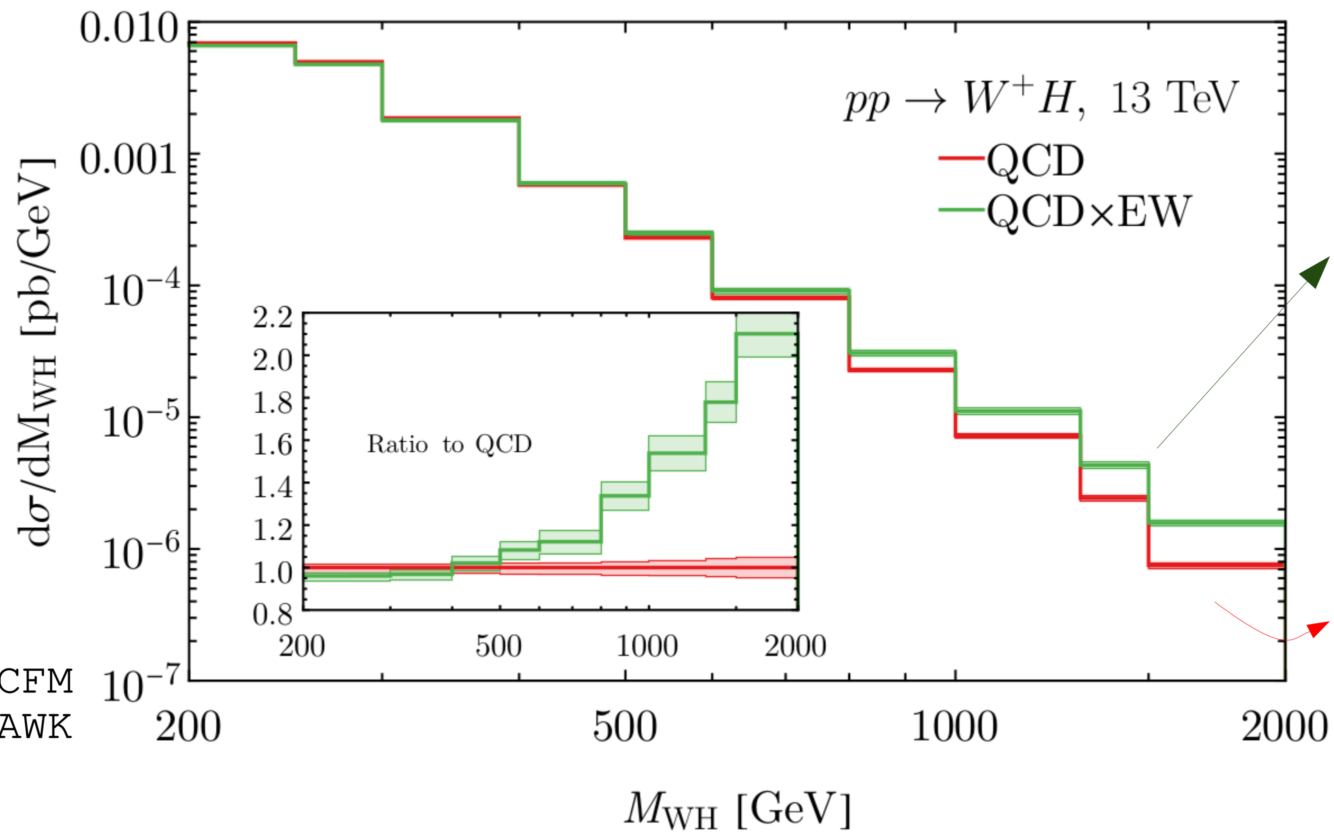
electroweak (EW) corrections also vital

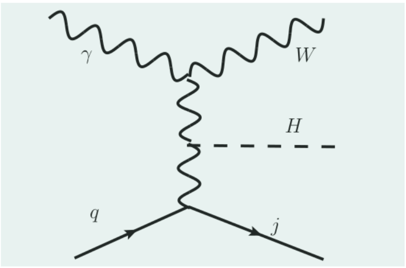
- at $\mathcal{O}(\alpha_s^2)$ accuracy, EW corrections and explicit $\gamma(x,\mu^2)$ needed

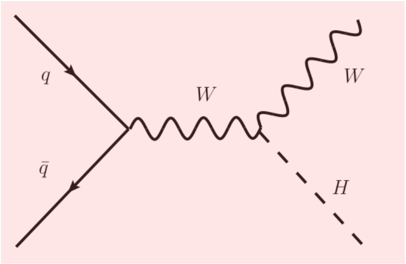
Xie, TJH, Hou, Schmidt, Yan, Yuan: PRD**105** (2022) 5, 054006

- 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

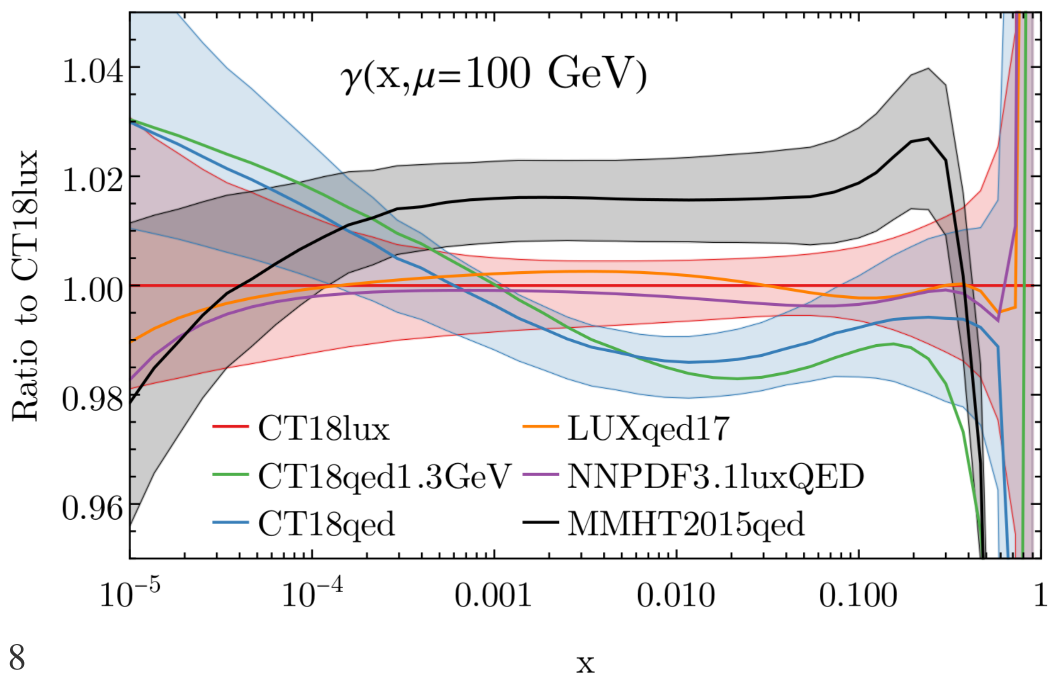
Xie, TJH, Hou, Schmidt, Yan, Yuan: PRD**105** (2022) 5, 054006

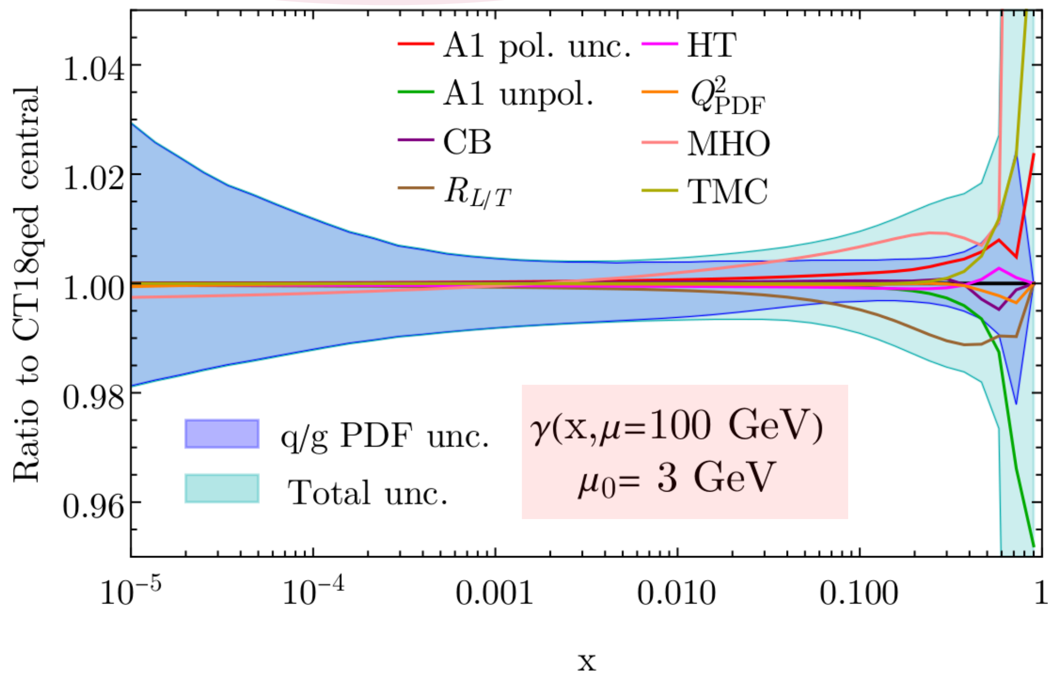
- following CT14QED, CT18QED now interfaces LUX formalism

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

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

[*i.e.*, 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...)

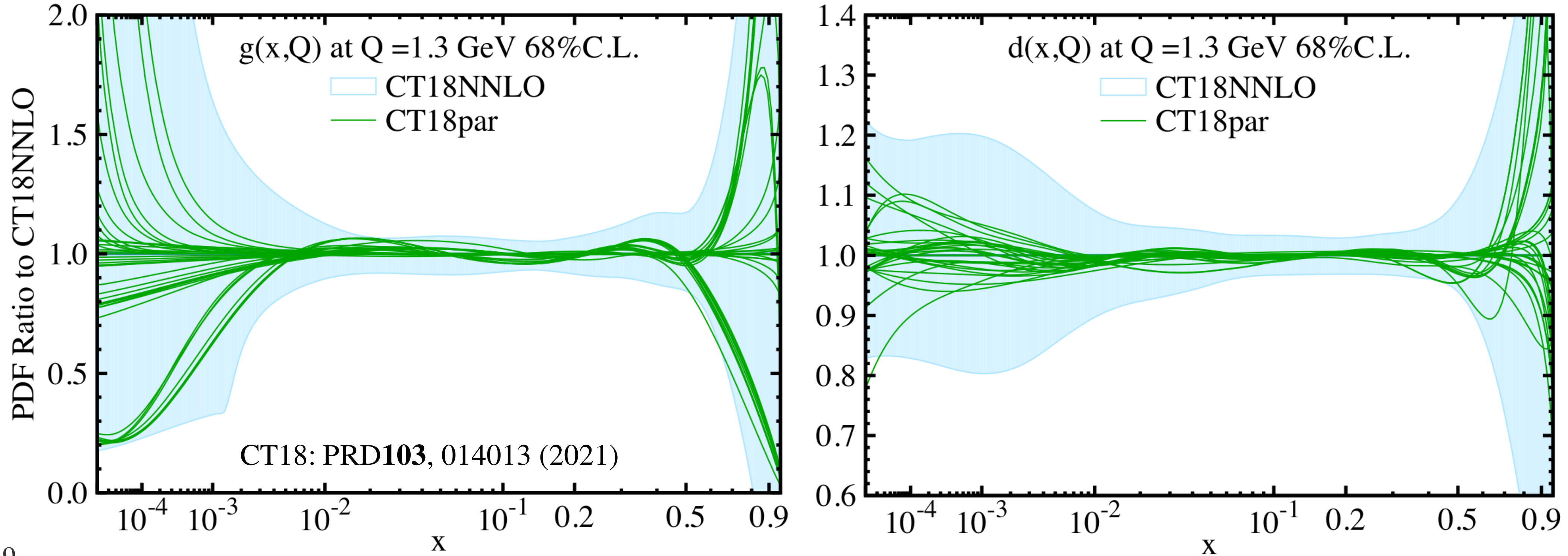
→ subject to complex nonperturbative dynamics

→ practice agnosticism w.r.t. initial parametrization

(some guidance from QCD, QCD-inspired models)

→ explore model uncertainty with many forms

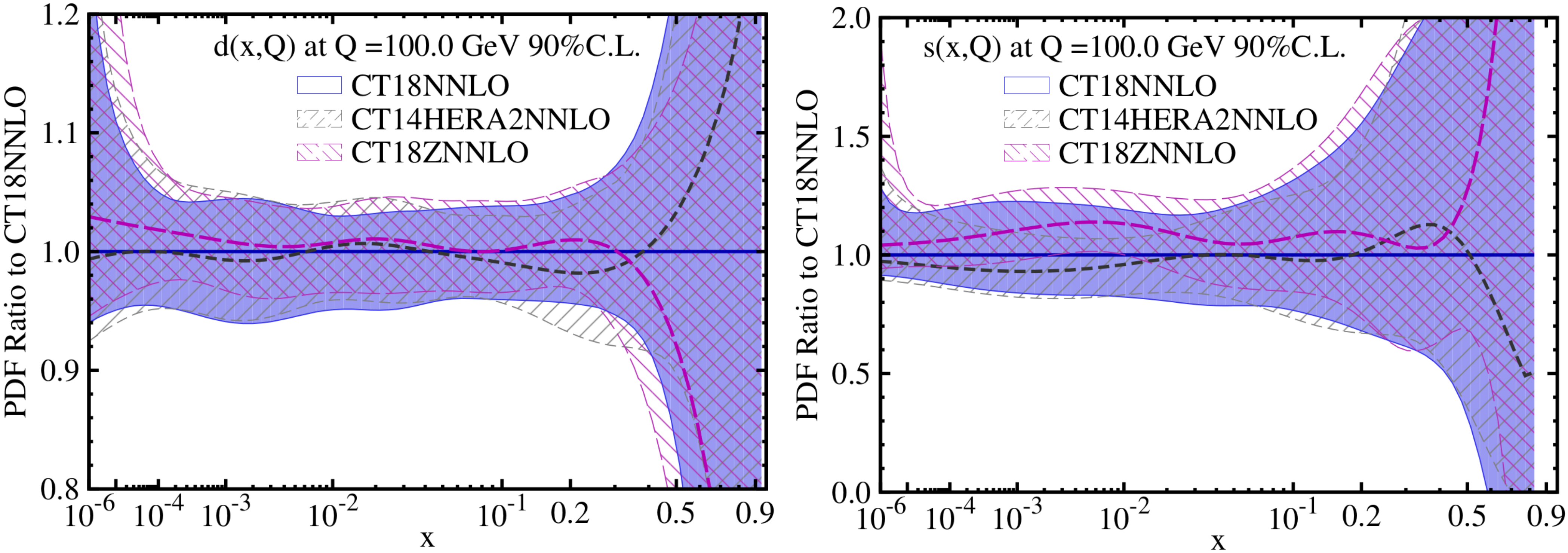
parametrization uncertainties largest in extrapolated regions



high-x PDFs remain dominated by large uncertainties

- much of the JLab12 (PVDIS) sensitivity probes high-x (low-W, Q) PDFs
- PDF (Hessian) uncertainties enlarge dramatically in high-x limit

→ limited data → extrapolation → data tensions

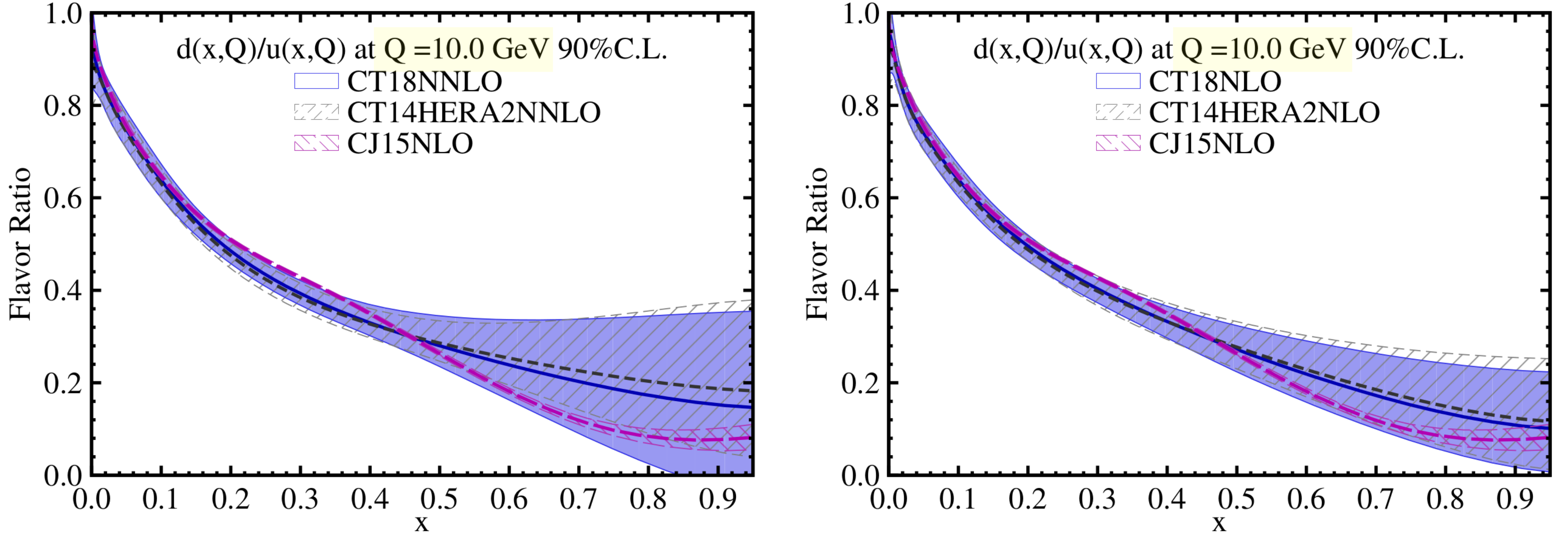


- flavor separation also challenging; parsing quark sea: various precision data

→ PVDIS γ-Z interference further complements standard data sets

ii

perturbative order (α_s), interplay of data sets relevant for high-x d/u



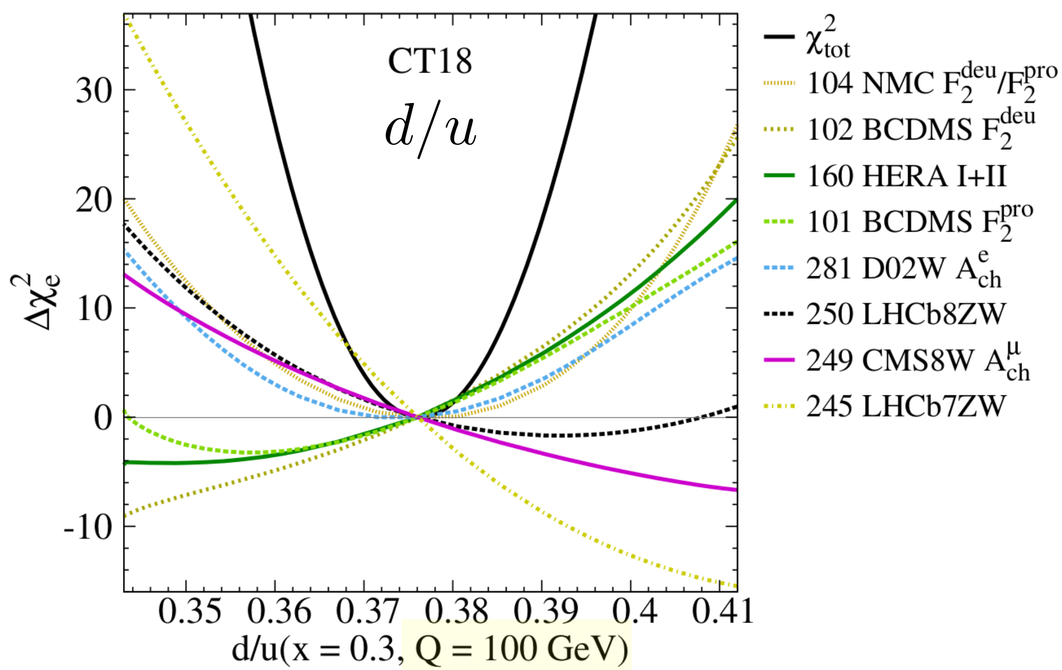
[see talk: C. Keppel]

- NNLO *vs.* NLO theory accuracy influences extrapolation region behavior

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

  → BCDMS, F_2^d

  → LHCb, W/Z 7 TeV



ii

light-nuclear corrections: **flavor dependence**, high-x PDFs

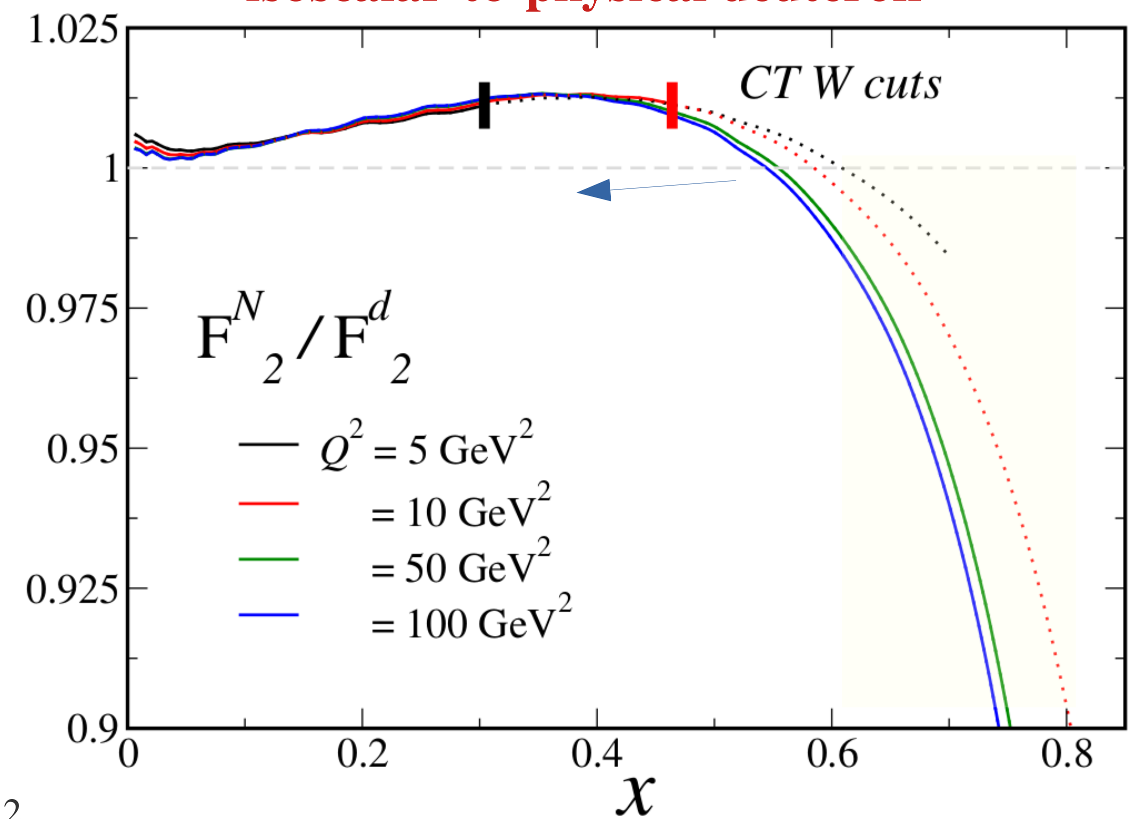
- d-PDF information from deuteron scattering; nuclear corrections relevant

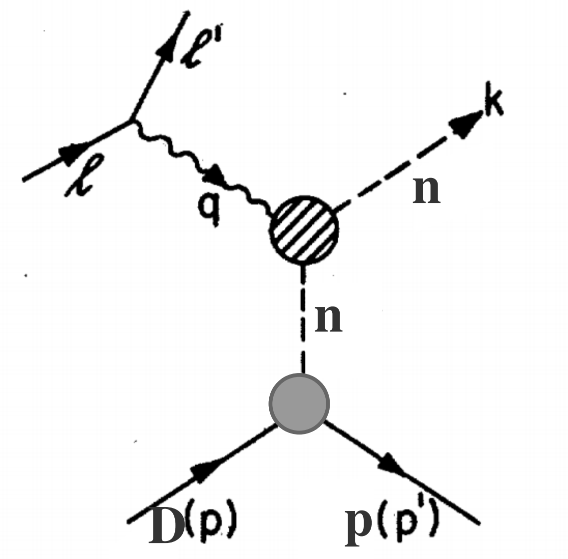
$$f^d(x, Q^2) = \int \frac{dz}{z} \int dp_N^2 \, \mathcal{S}^{N/d}(z, p_N^2) \, \widetilde{f}^N(x/z, p_N^2, Q^2)$$

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

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

isoscalar-to-physical deuteron





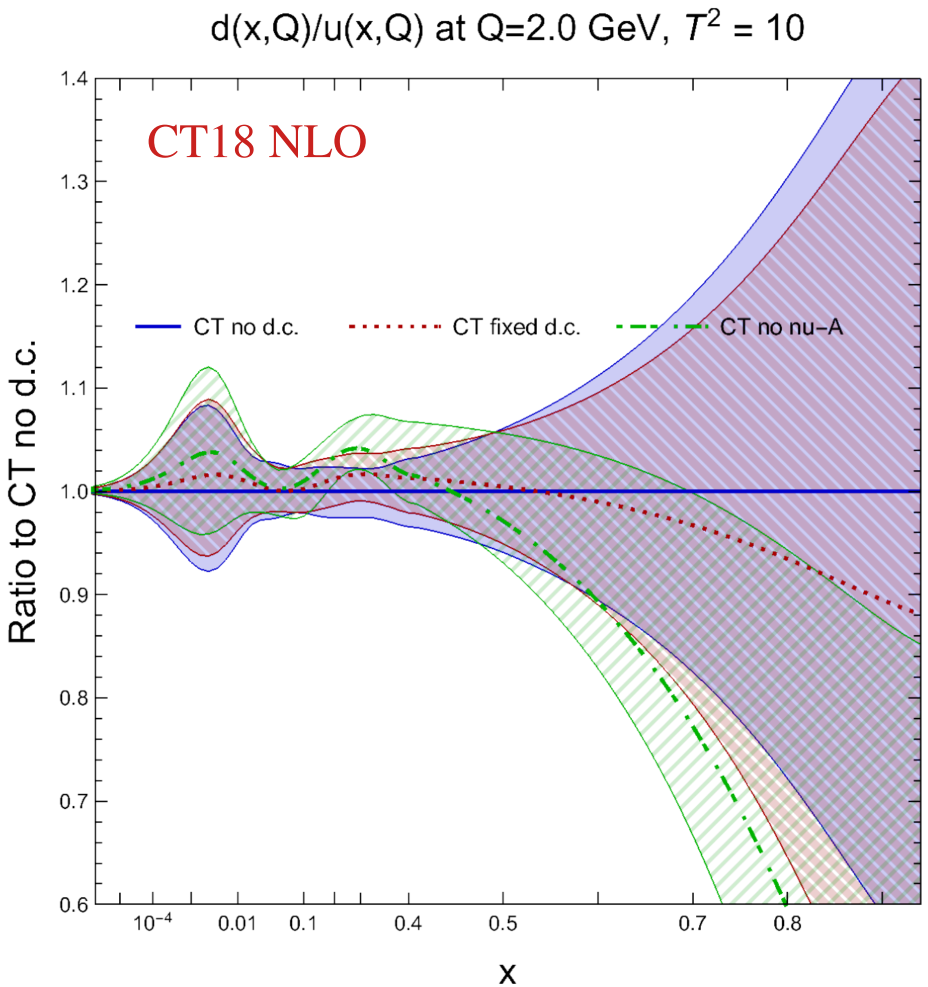
- impacts LHC observables; necessary for high precision

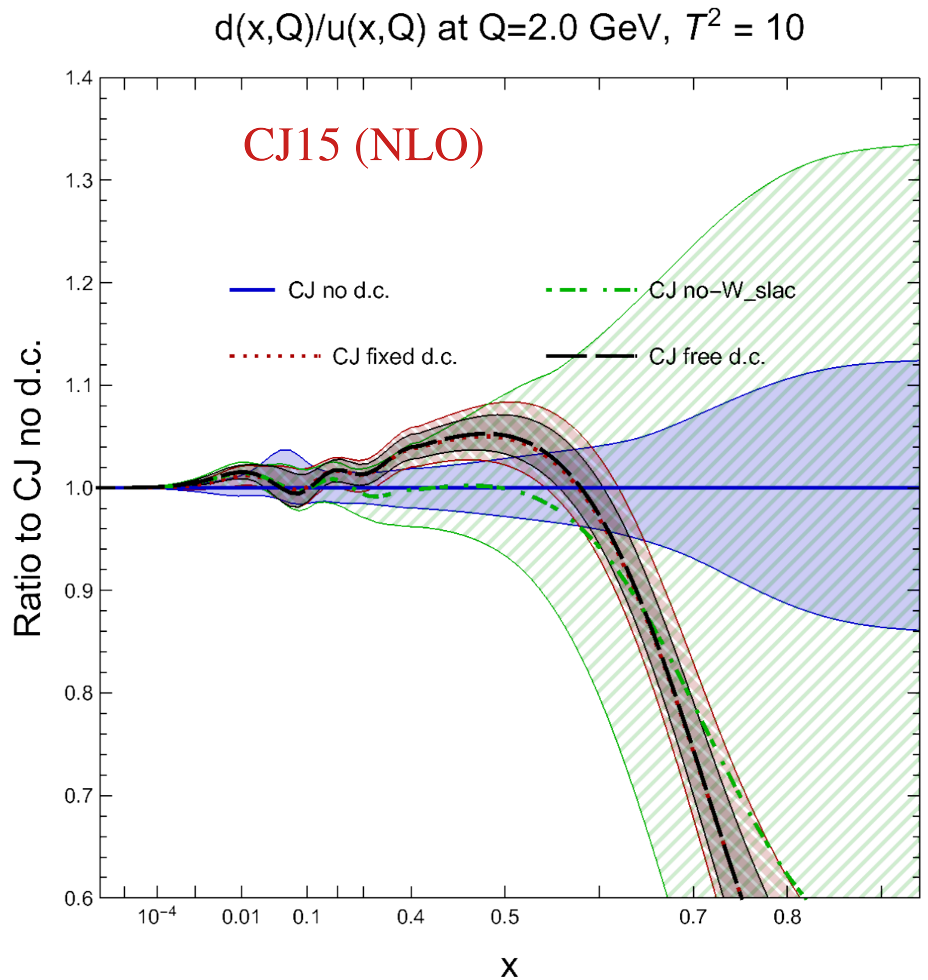
ii nuclear modifications of increasing importance with greater PDF precision

- example: nuclear effects in deuteron influence *d*-quark PDF $(x \geq 0.1)$

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

- comparative study: additonal effects at lower-*x;* gluon impacts (from flavor correlations)





- subtle interplay with **nuclear corrections** in large-*A* targets

→ demands more attention in future (free nucleon) PDF analyses [will revisit]

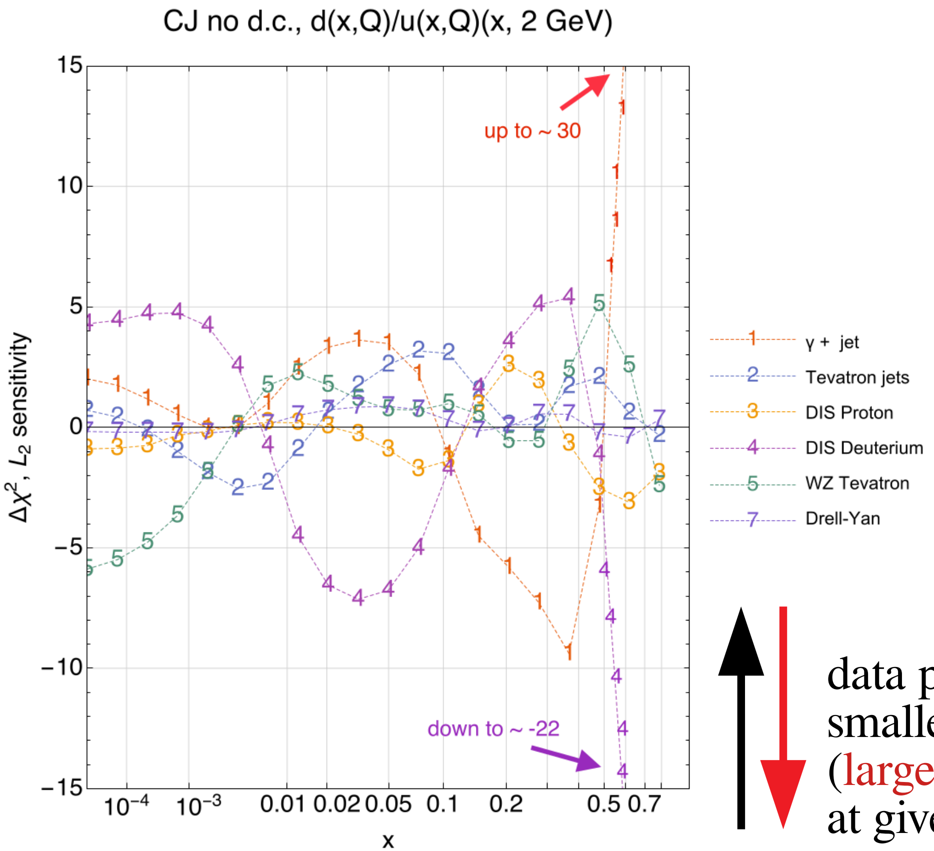
pulls of fitted data on d/u influenced by deuteron corrections

- L_2 sensitivity: quickly assess $\Delta\chi^2$ from upward shift of PDFs by 1σ uncertainty

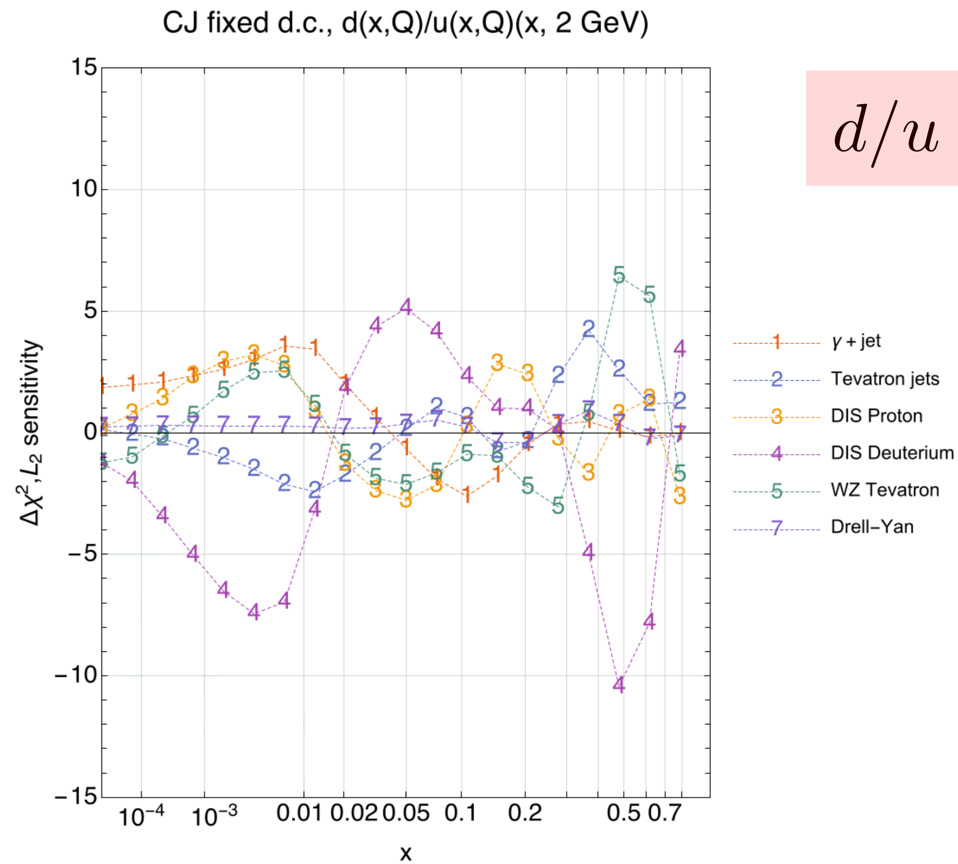
→ useful for apples-apples comparisons, especially among Hessian fits

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

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



data prefer smaller (larger) PDF at given x



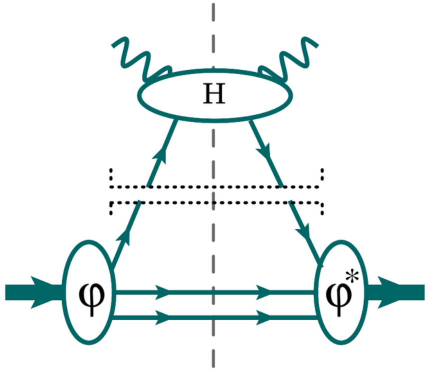
- in CJ fits *without* deuteron correction (left), large tensions at high x: γ-jet [1] vs. DIS-deuterium [4] data; especially at $x > 0.5$

→ with fixed correction (right), tensions relieved significantly

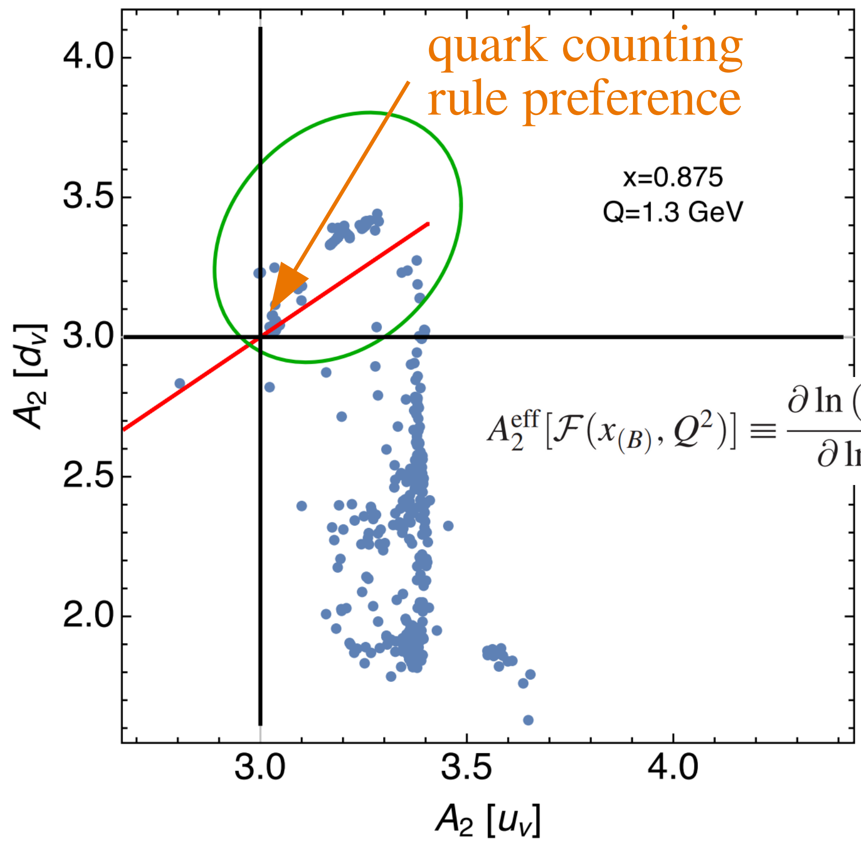
ii

extracting high-x dependence in PDF fits

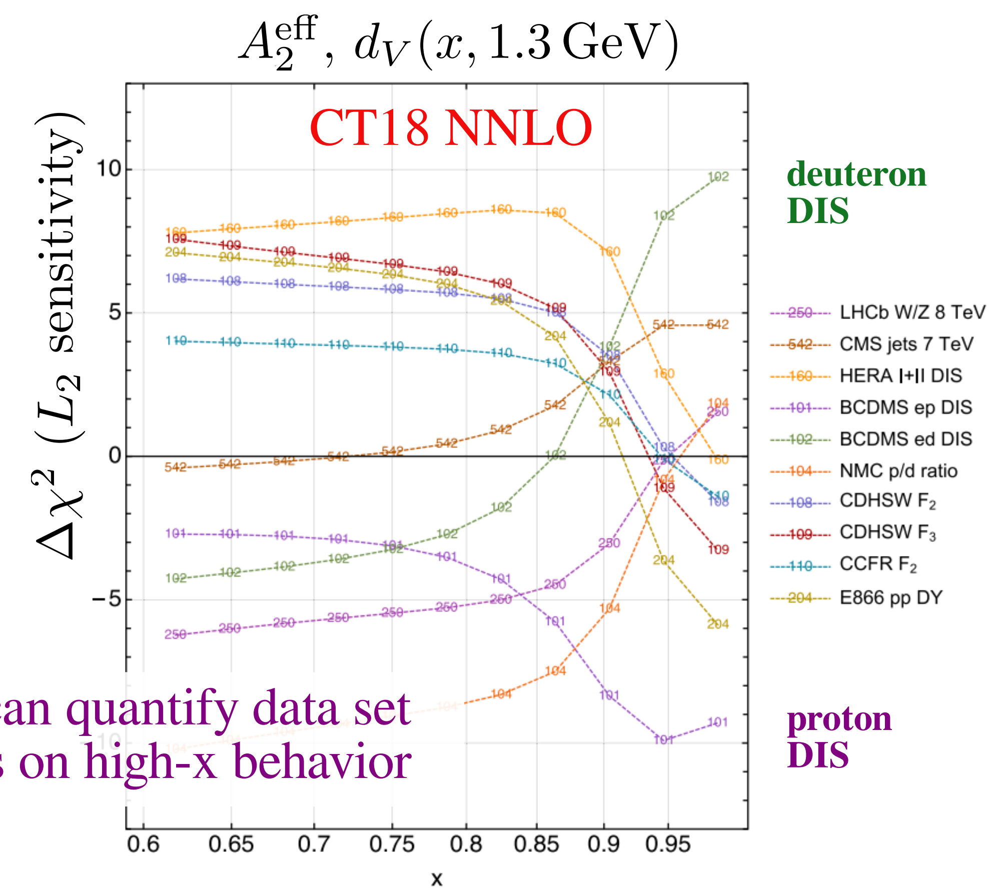
- high-x PDFs, ratios [e.g., d/u] connected to details of proton WF
- behavior at $x \to 1$ an important nonpert. discriminator
- CT18, parametrize $f_{a/A}(x, Q_0^2) = x^{A_{1,a}}(1-x)^{A_{2a}} \times \Phi_a(x)$



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



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



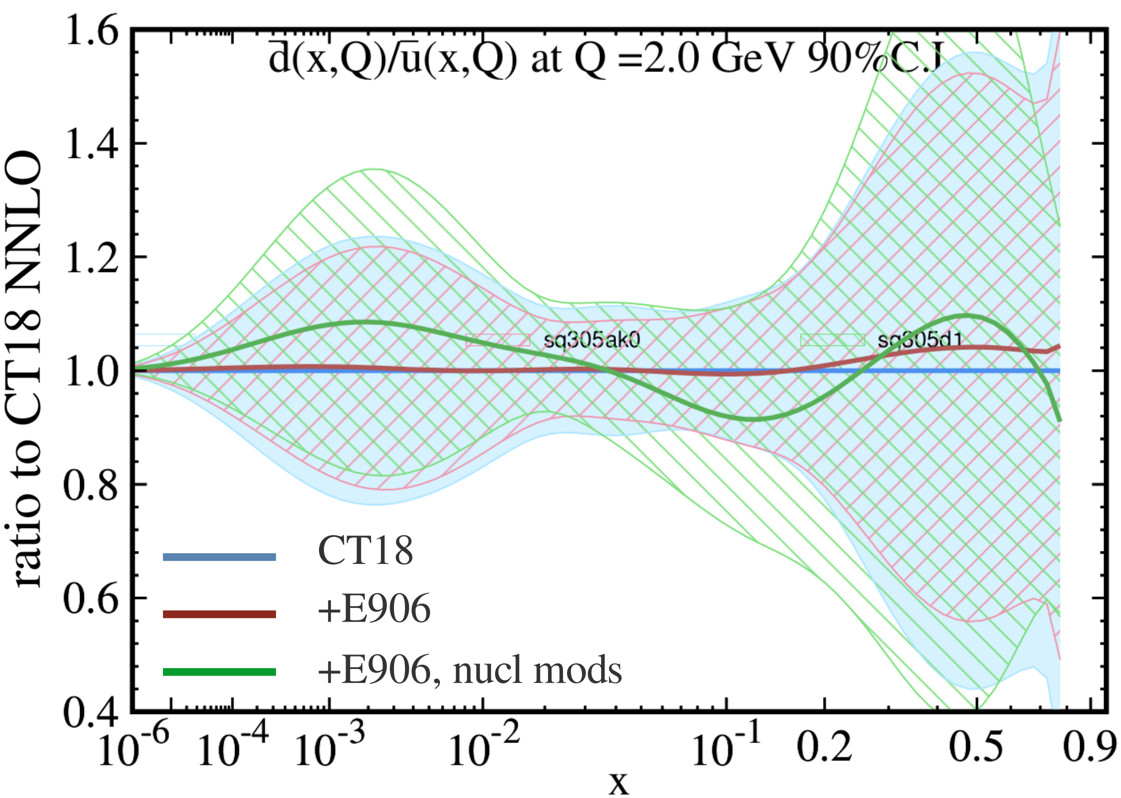
we can quantify data set pulls on high-x behavior

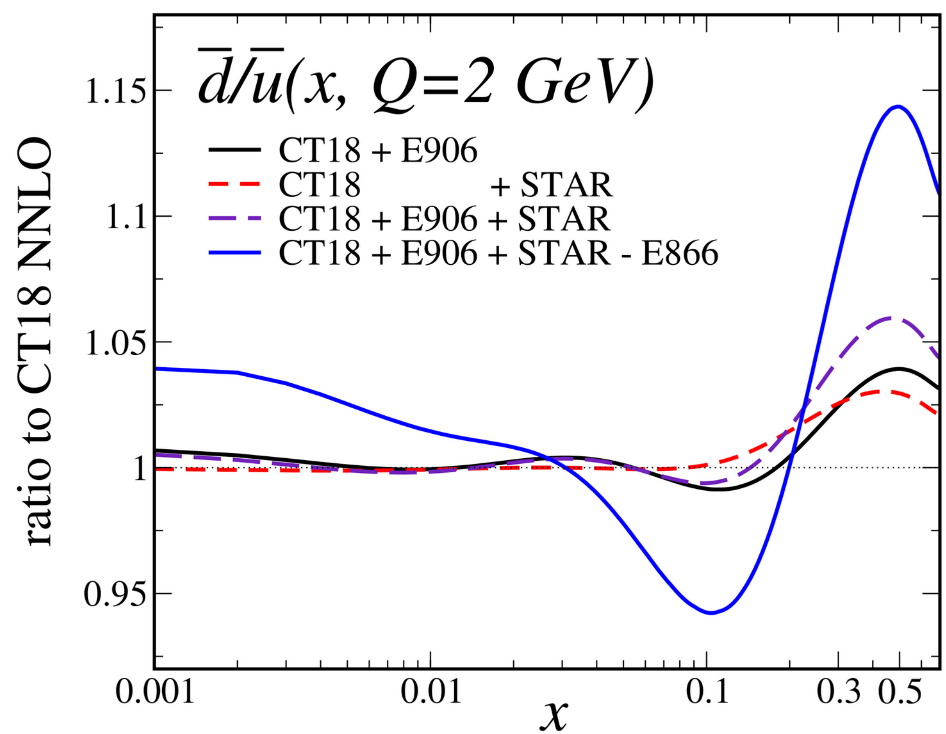
ii

high-x sea-quark asymmetries: SeaQuest (E906) and STAR Drell-Yan data

- potential overlap between PVDIS and PDF sensitivities of other high-x expts $\bar{d} > \bar{u}$
- recently-released SeaQuest data have **moderate sensitivity** to high-x

[see talk: A. Tadepalli]



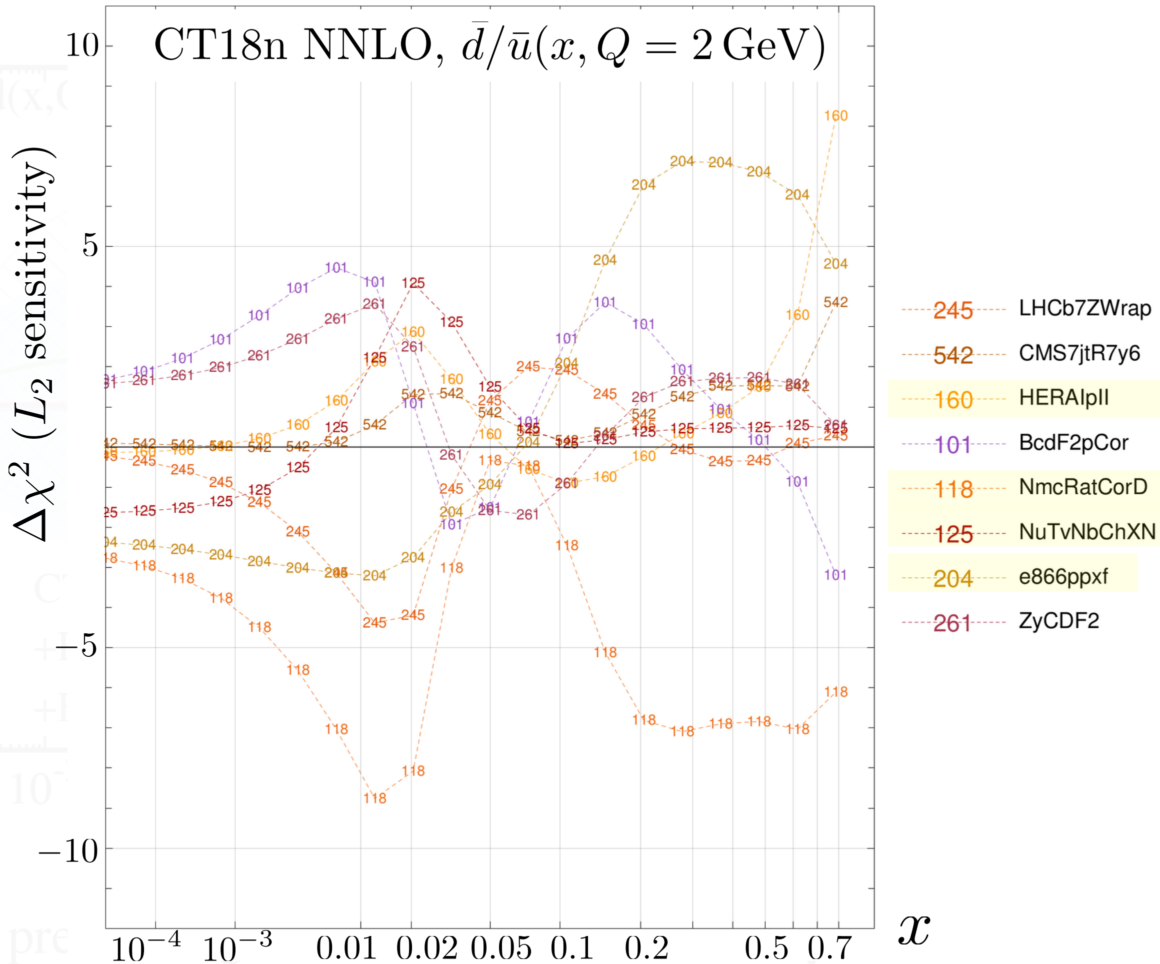


- SeaQuest prefers larger dbar/ubar at $x > 0.2$; may *somewhat* reduce strange-PDF uncertainty
- interplays: treatment of nucl. data (left); inclusion of STAR W-prod., E866 expts. (right)
  - → E906, STAR constructively enhance dbar/ubar; removing E866 augments this effect

ii

high-x sea-quark asymmetries: SeaQuest (E906) and STAR Drell-Yan data

- L_2 sensitivities: excluding E866, minimal tensions between E906, other sets

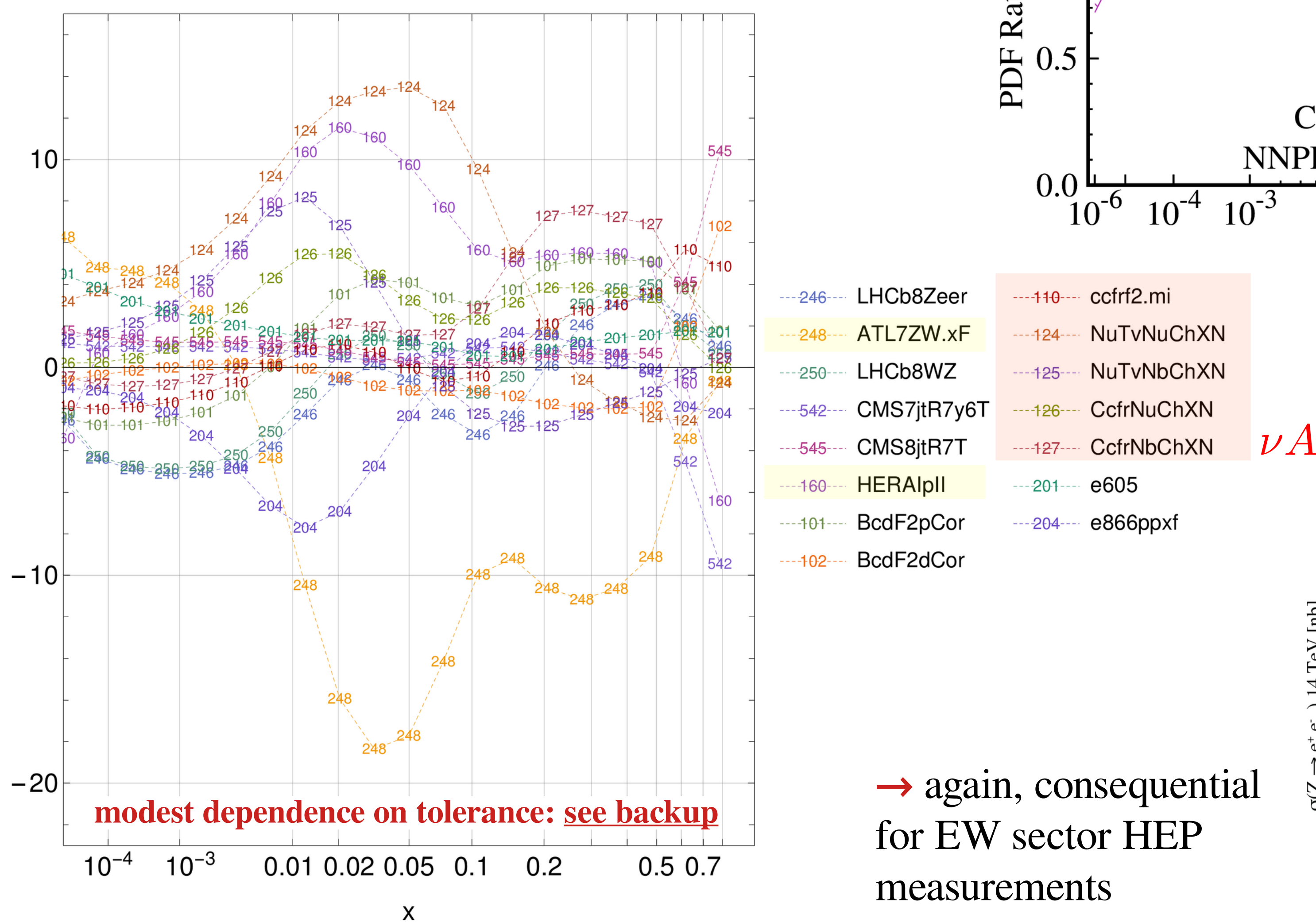


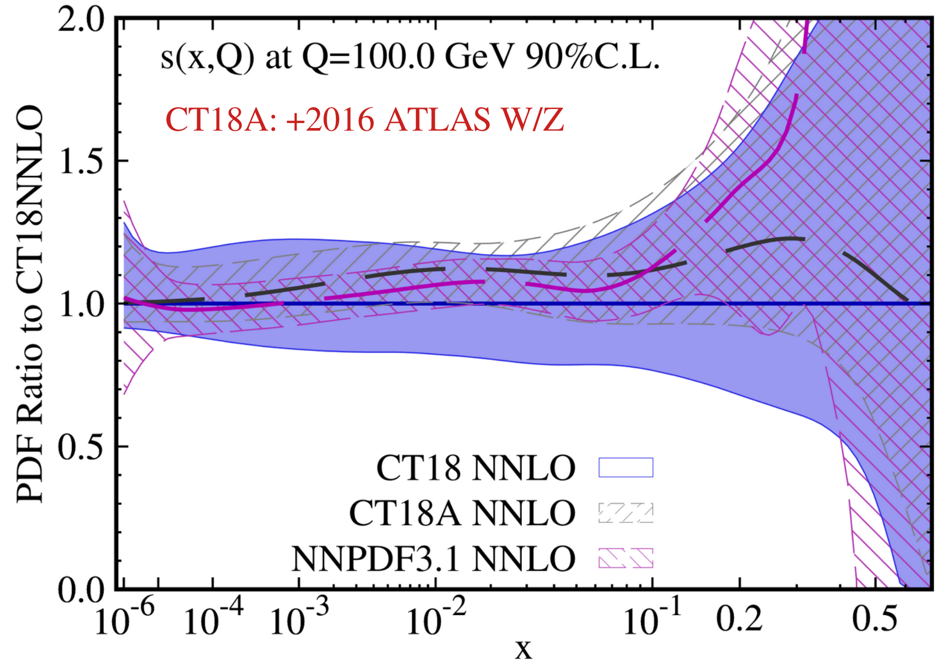
- forthcoming study: exploration of PDF pulls in post-E906 fits…

nucleon **strangeness** from neutrino and Drell-Yan data

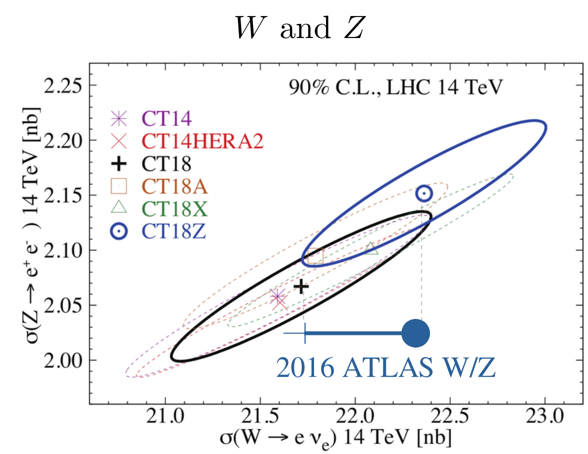
- strangeness PDF, breaking of flavor SU(3) remain highly uncertain
- CT18: indications of tension between neutrino (need nuclear corrections), precise LHC W/Z data

CT18Z NNLO, s(x, 2 GeV)





→ again, consequential for EW sector HEP measurements



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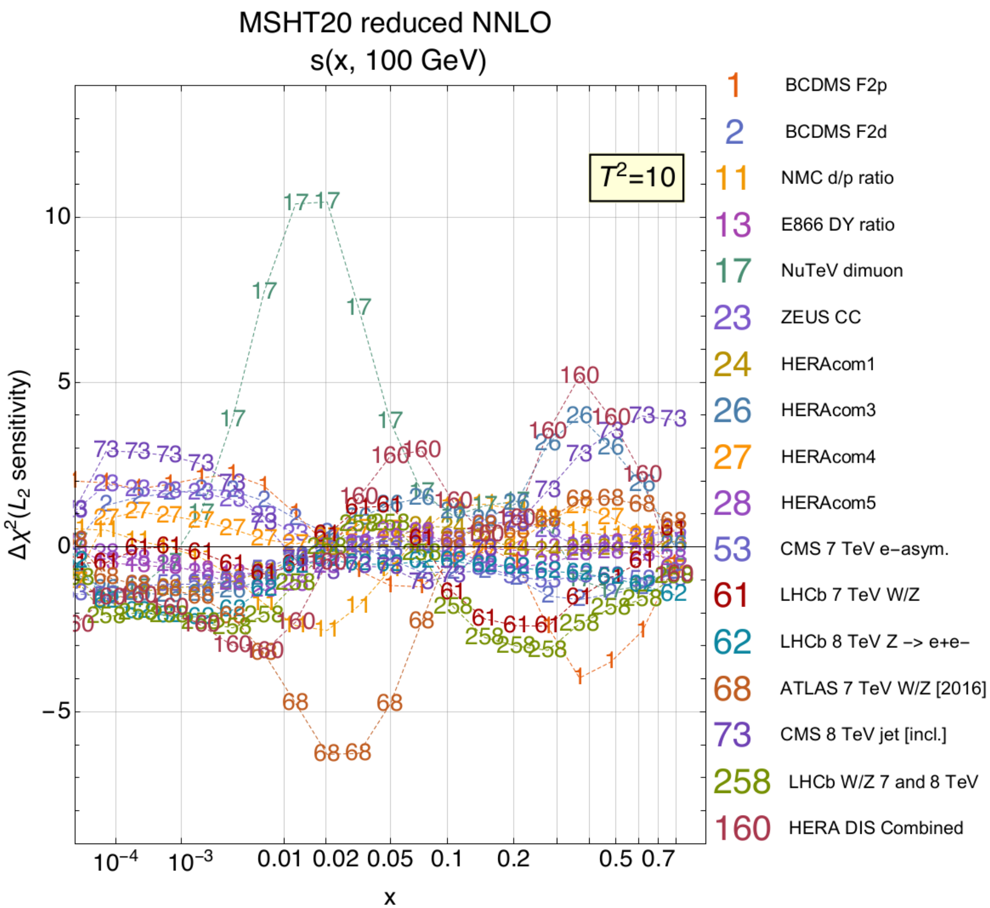
nucleon **strangeness** from neutrino and Drell-Yan data

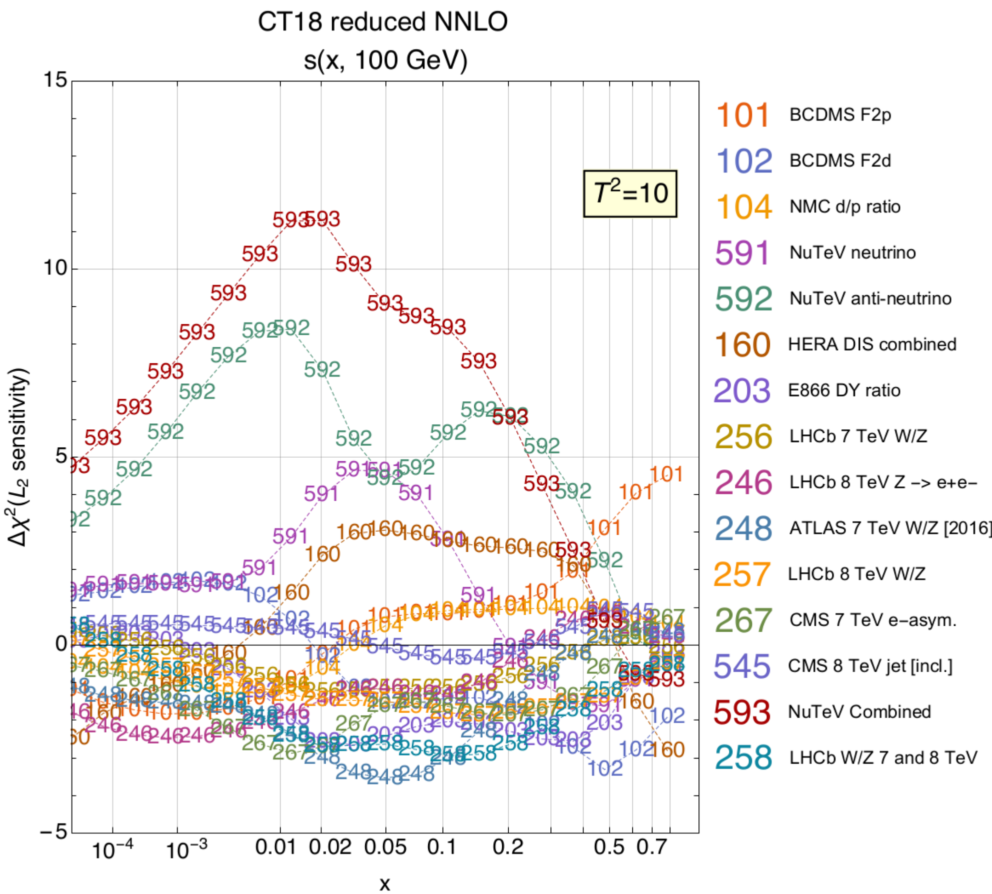
[again, see talk: T. Cridge]

- explored in PDF4LHC21 benchmarking studies, especially for *reduced* PDF fits

PDF4LHC21 benchmarking: 2203.05506, App. D

(common tolerance, theory choices)





- dominant experiments exert qualitatively similar pulls on strangeness in CT, MSHT

NuTeV neutrino scattering; 2016 ATLAS W/Z; HERA combined DIS data; …

ii

heavy-nuclear effects relevant for proton structure studies

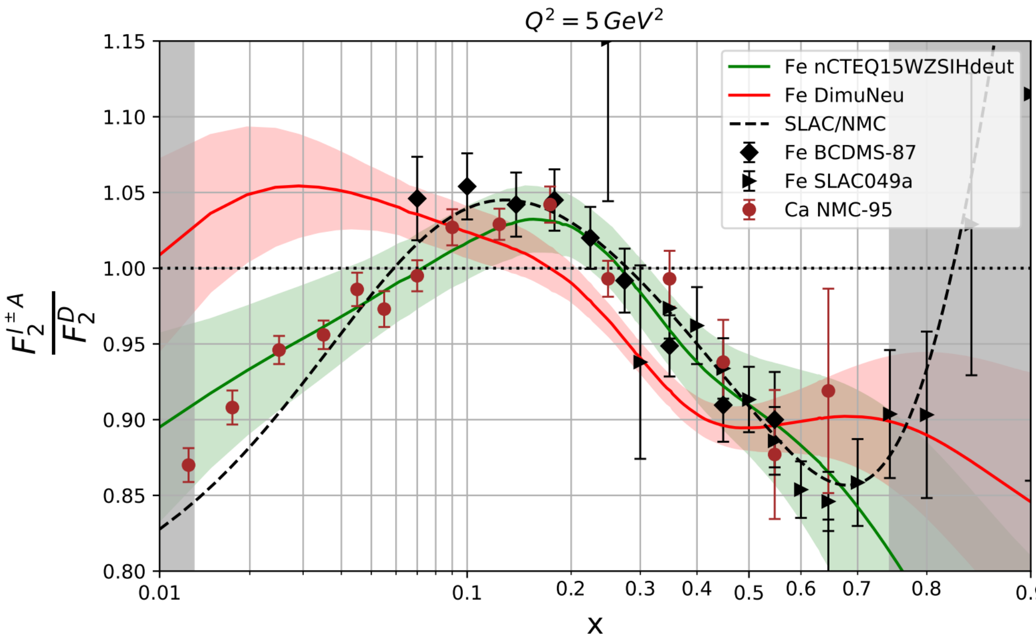
- beyond few-body systems, CT, other analyses use heavy-nuclei for flavor separation

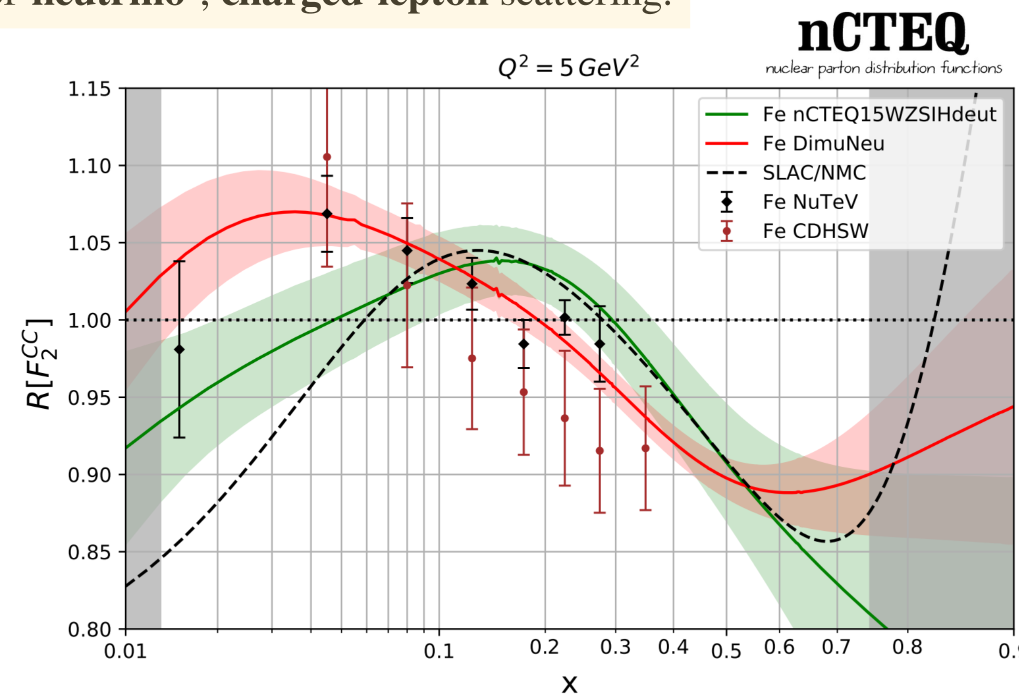
- requires knowledge of nuclear corrections; these directly fitted by nPDF analyses

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

[see talk: B. Ramson]

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





Muzakka, Duwentäster, TJH et al., 2204.13157

- more systematic studies of interdependence of nucleon, nuclear analyses needed

→ high-x PVDIS from proton, nuclei helpful to building this picture

nonperturbative theory developments: lattice QCD inputs

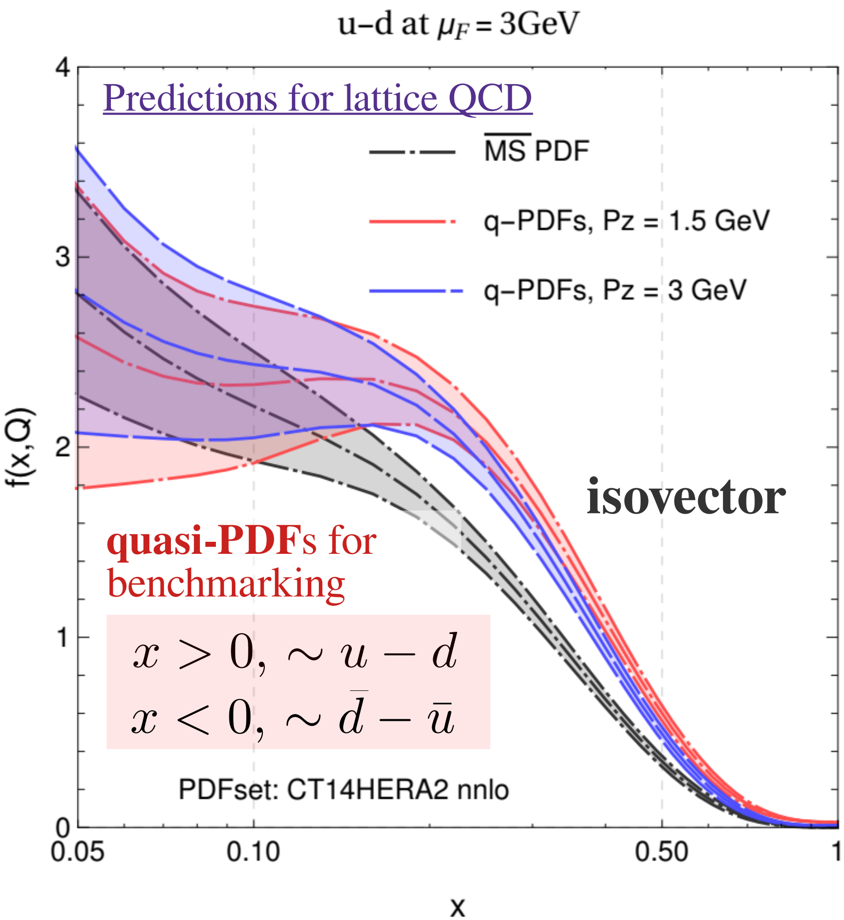
- recent years: progress in *ab initio* hadron-structure calculations from LQCD

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

there are be important synergies between PDF fitting and lattice QCD

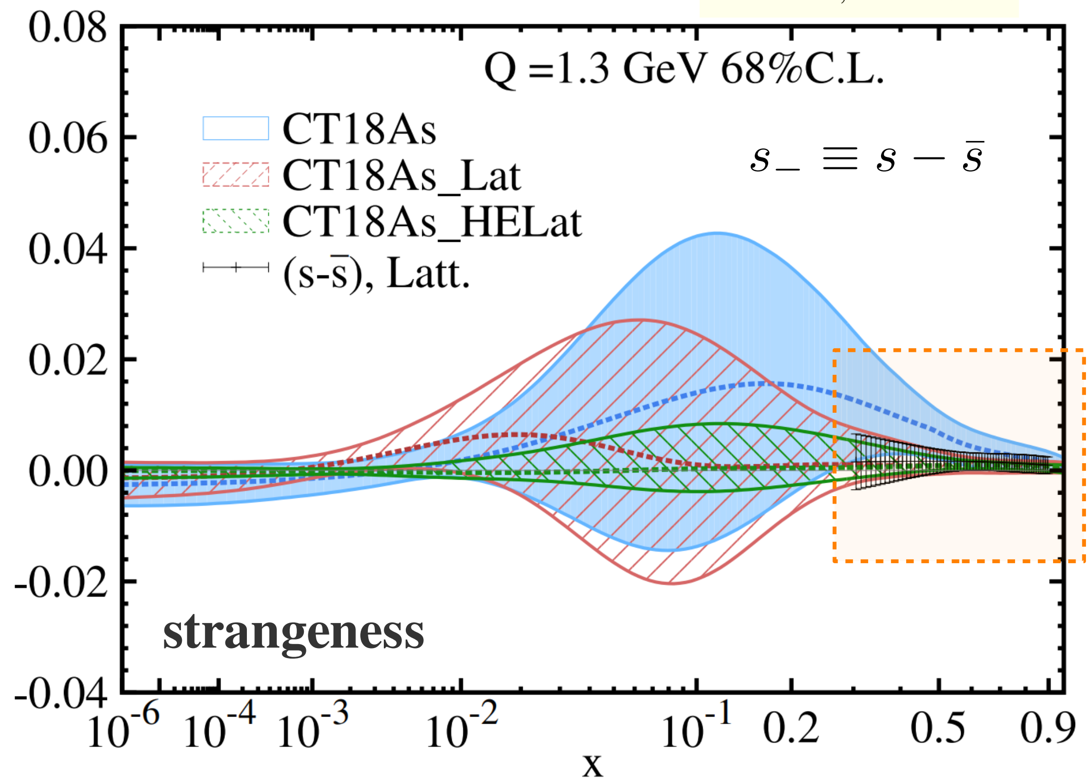
[overlaps with PVDIS]

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



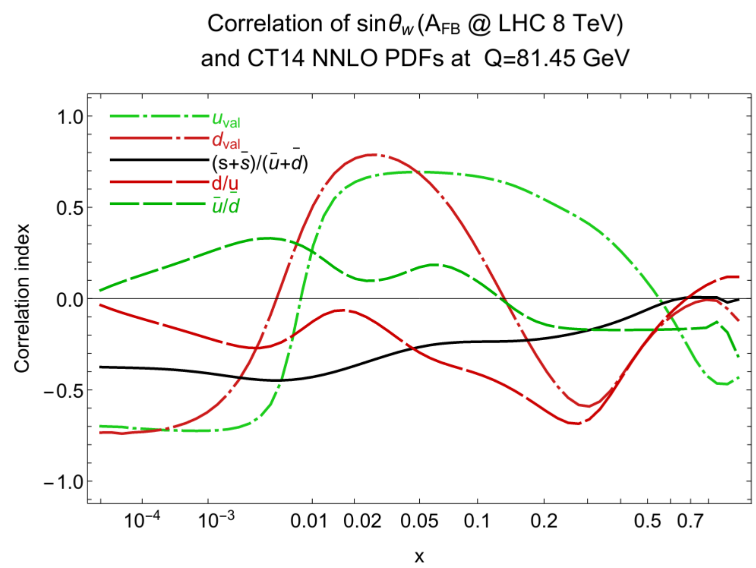
- lattice data can potentially inform high-x behavior of quark sea

Hou et al., 2204.07944



PVDIS and HEP PDF fits

- have illustrated: PDF flavor dependence, including high x, is an HEP frontier



→ array of (non)overlapping experiments with sensitivity

→ PVDIS, JLab12 should have unique flavor access

- BUT: HEP-focused PDF analyses typically exclude very low Q^2, high x

(in CT, standard cut of $W > 3.5$ GeV, $Q > 2$ GeV...)

→ future impact studies, though challenging, may be helpful

→ meanwhile, a few observations

iii

achieving highest (PDF) impact of PVDIS: mastery of small Q

TJH and Melnitchouk, PRD**77**, 114023 (2008)

→ γ-Z interference accesses unique flavor currents in nucleon

$$A^{\mathrm{PV}} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left[g_A^e\, Y_1\, \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + \frac{g_V^e}{2}\, Y_3\, \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

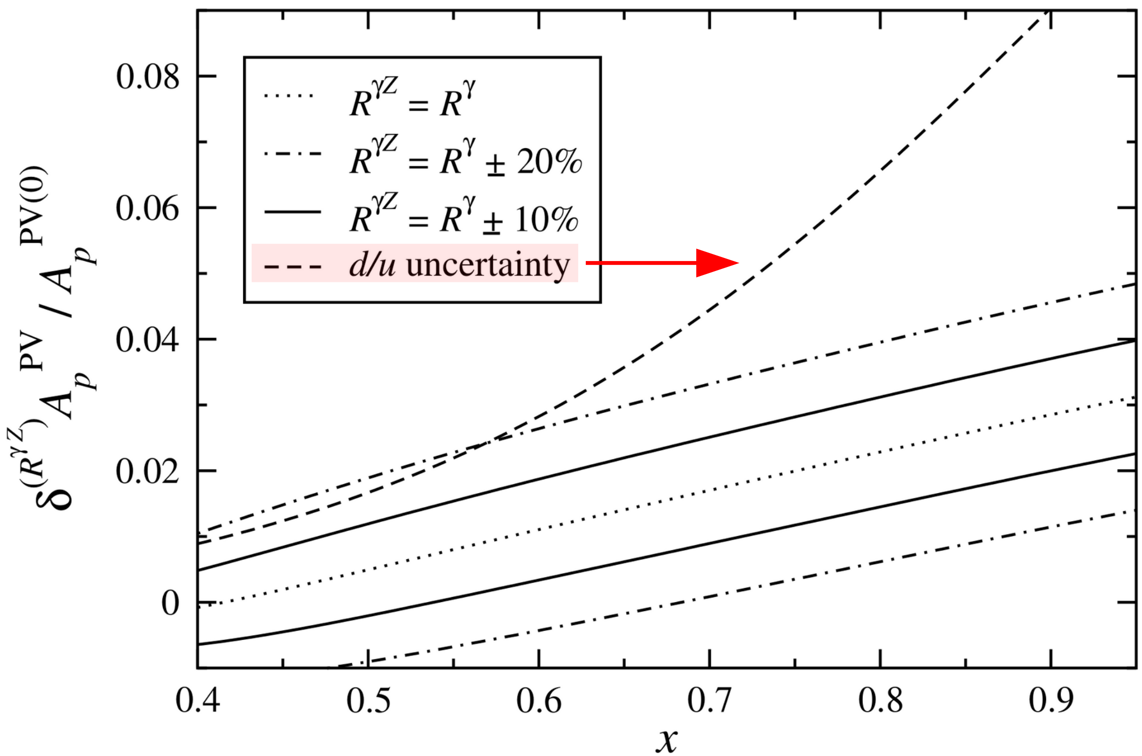
A^{PV} potentially subject to finite-Q^2 corrections

$$Y_1 = \frac{1+(1-y)^2 - y^2(1-r^2/(1+R^{\gamma Z})) - xyM/E}{1+(1-y)^2 - y^2(1-r^2/(1+R^{\gamma})) - xyM/E}\left(\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right)$$

$R = \sigma_L/\sigma_T \neq 1$

$(= 1,\ \text{Callan-Gross})$

- in principle, could complicate PDF sensitivity of PV asymmetry
- effectively, proxy for various low-Q^2 corrections which must be investigated/controlled
- substantial theory, phenomenological progress over intervening years



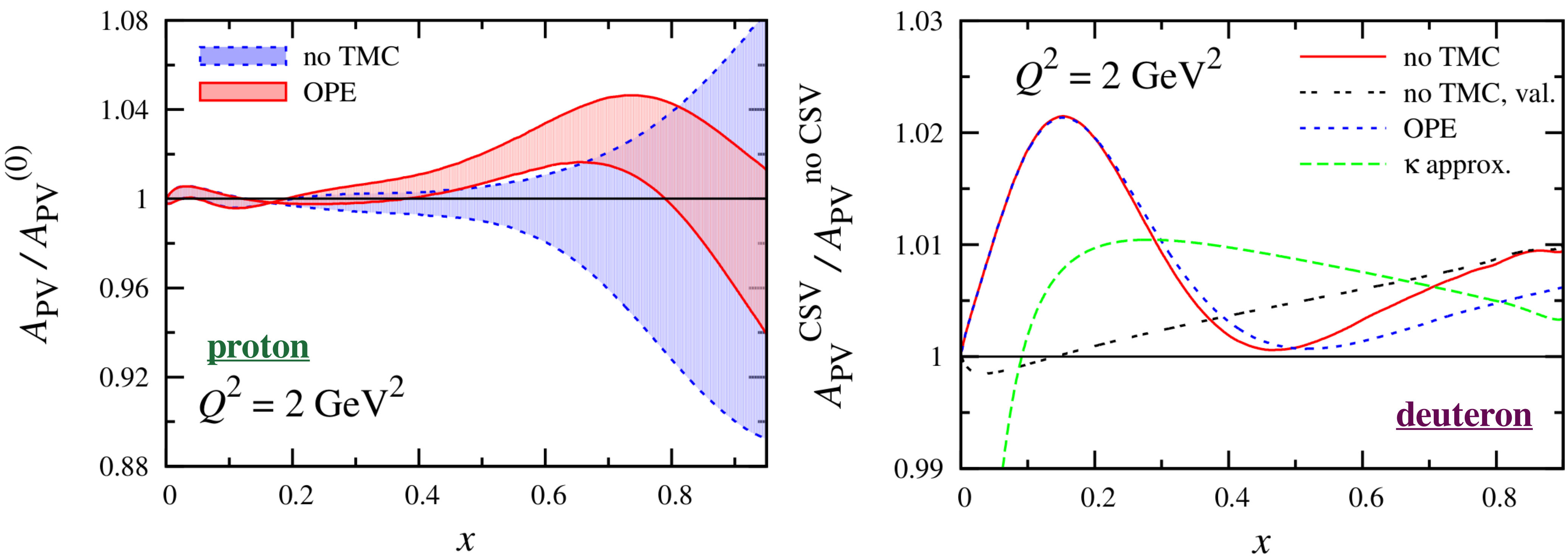
iii

PVDIS will have subtle relationship with HTs, TMCs, …

[see talks: A. Accardi, S. Li, N. Sato, ...]

Brady, Accardi, TJH, and Melnitchouk, PRD**84**, 074008 (2011)

- at lowest Q^2, TMCs (and HTs) can represent multi-percent **proton** A^{PV} corrections
  - → as precision effect, ~comparable to deuteron corrections shown earlier



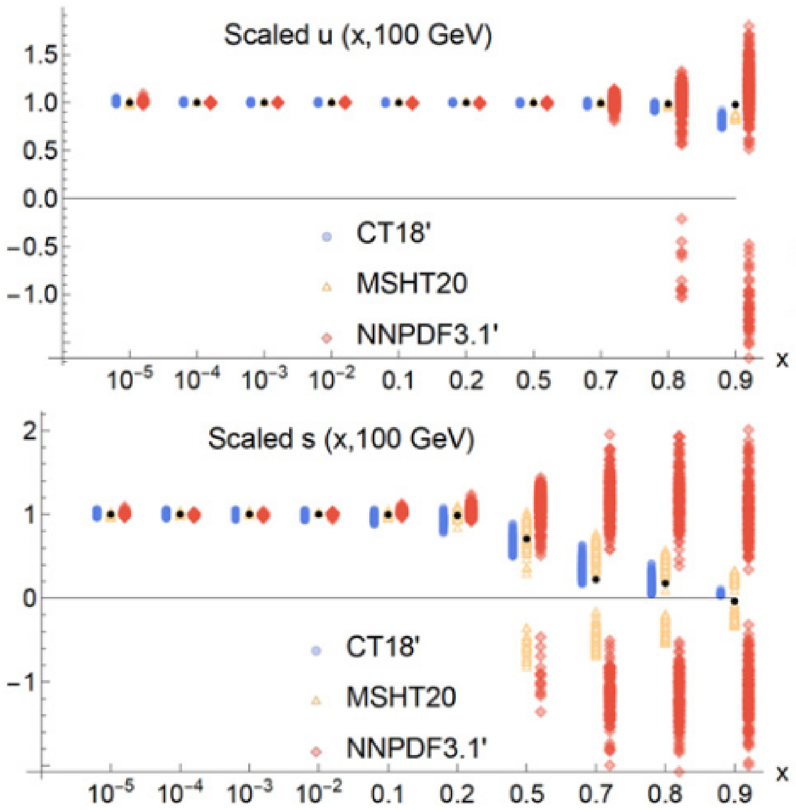
- TMC prescription dependence mild; deuteron A^{PV} (mostly) insulated from effects
  - → BSM, SMEFT analyses based on deuteron have much weaker PDF dependence [see talk: K. Simsek]
  - → A^{PV} deuteron more sensitive to charge-symmetry violation (complement EIC)
  - → TMCs more relevant for CSV; consequential for $\gamma(x)$, CT EW phenomenology

understanding PDFs and their uncertainties: high x

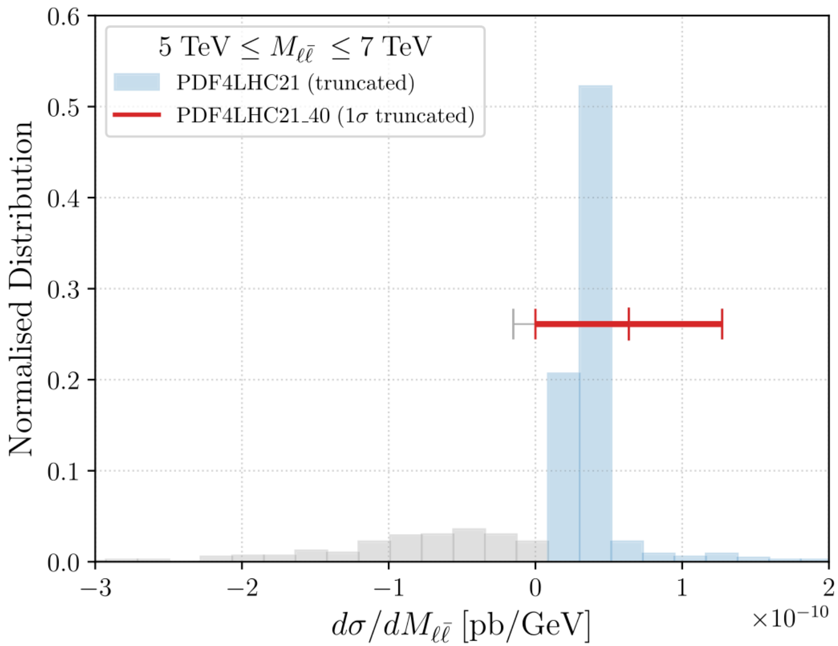
PDF4LHC21 benchmarking: 2203.05506

- 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:



- high-x PVDIS data: perhaps explore PDF uncertainties with representative sampling

→ discriminating power

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

conclusions

- HEP analyses increasingly confront problem of taming high-x uncertainties
  - → limit to EW precision, sensitivity of BSM tests
  - → closely related to challenge of flavor separation

- QCD analysis progress: mix of theory corrections, pheno considerations

  [higher-order QCD, EW; light, heavy nuclear effects; power-suppressed corrections; …]

- PVDIS, EW measurements at JLab12 hold intriguing possibilities
  - → significant PDF (proton), BSM/EW (deuteron) sensitivity
  - → extending HEP fits past kinematical cuts nontrivial but may be worthwhile

    meanwhile, could play valuable benchmarking role

  - → clear complementarity to EIC (both PV and positron) measurements

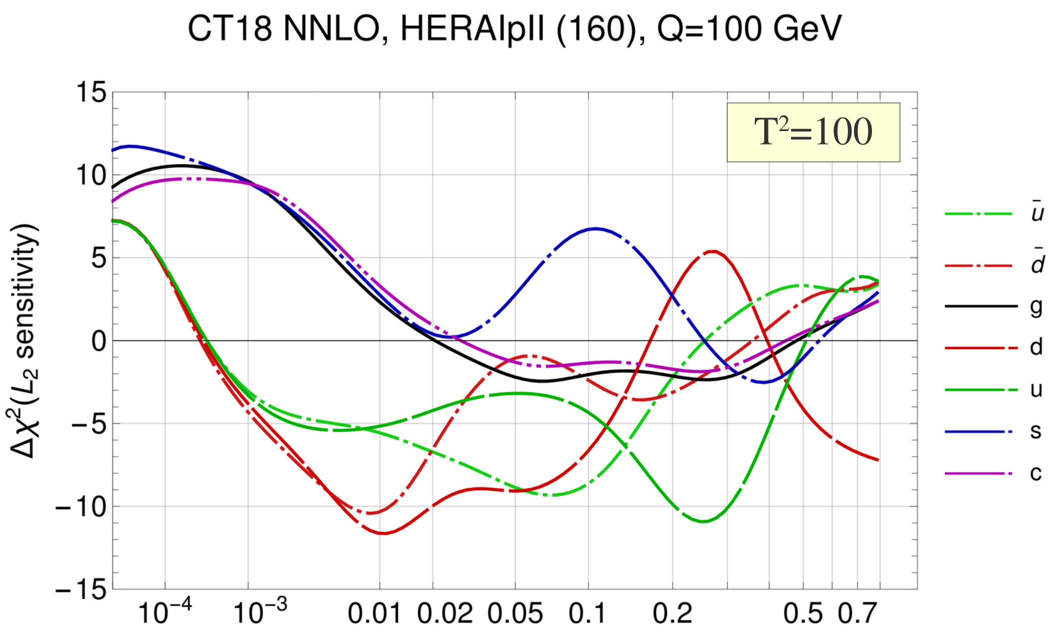
EIC YR, 2103.05419

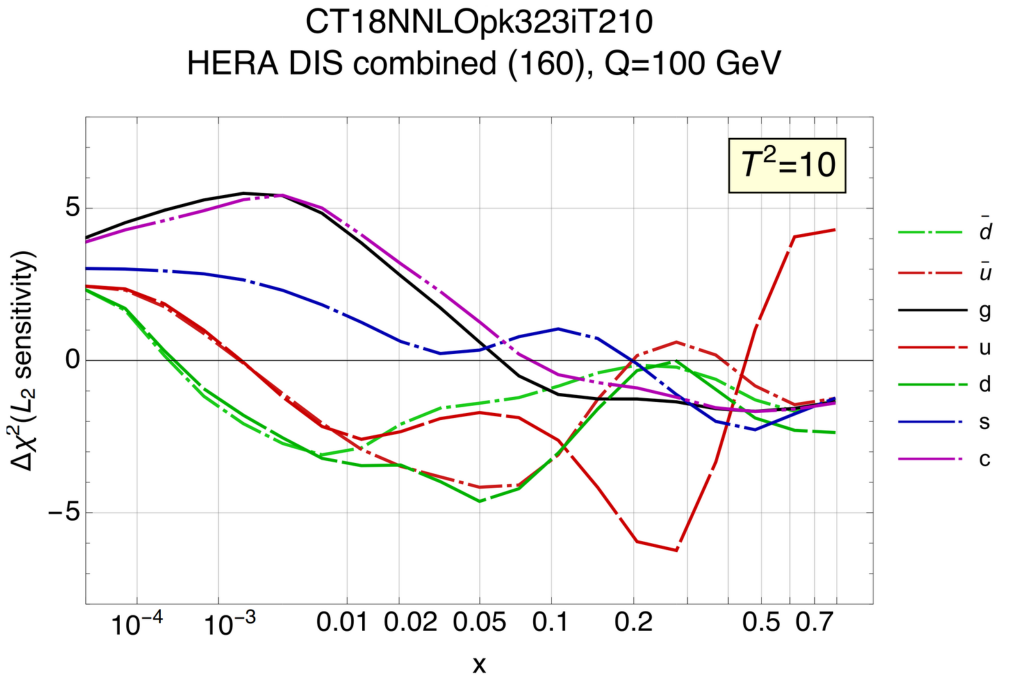
TJH, Londergan, Murdock, Thomas, PLB**698**, 123 (2011)

supplementary material

strangeness (and other) PDF pulls have modest tolerance dependence

CT & MSHT groups, in preparation.



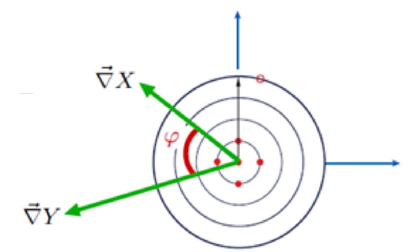


quantifying PDF preferences of fitted data: **the L_2 method**

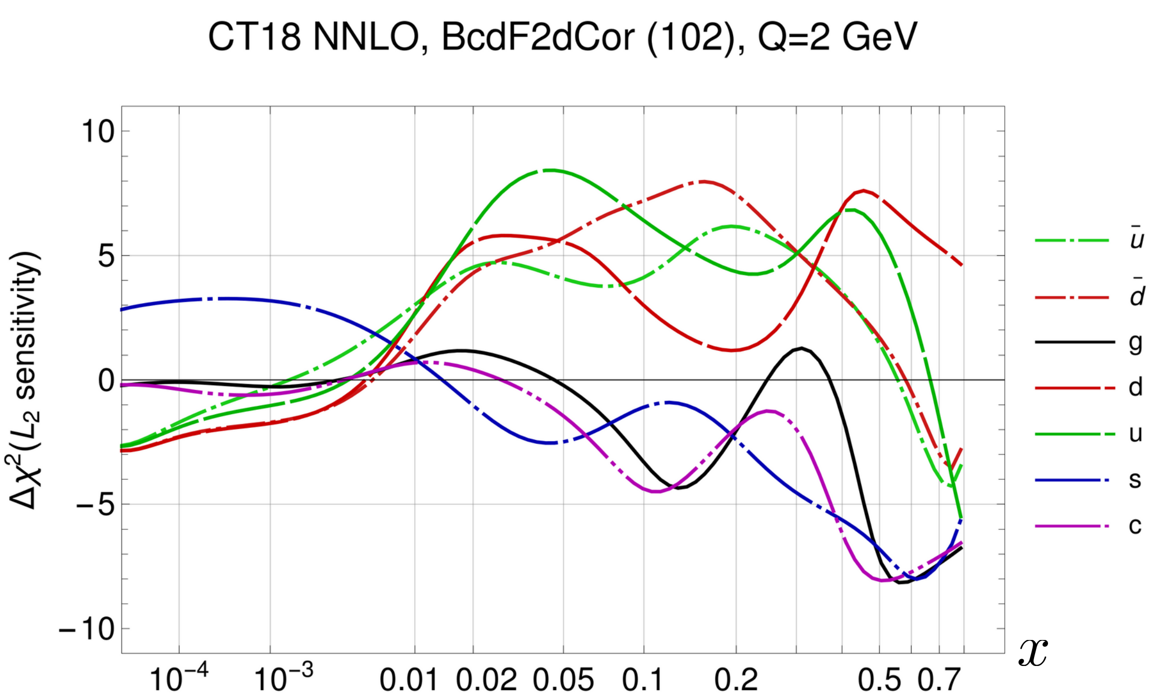
$S_{f,L_2}(E)$: fast approximation of the Lagrange Multiplier scan of χ^2_E along direction of $f_a(x_i, Q_q)$.

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

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



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



→ 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

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

flavor structure only from inclusive data is challenging!

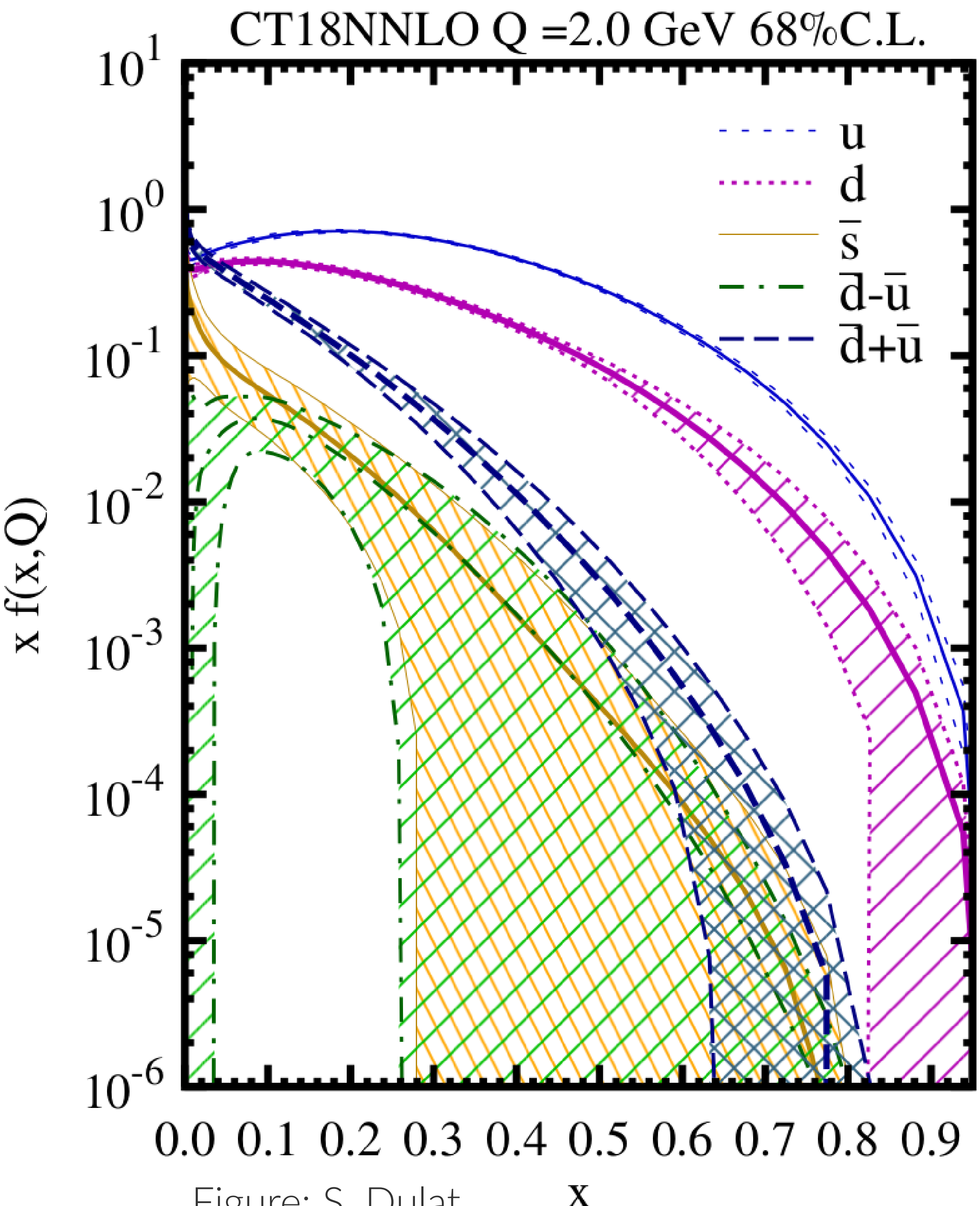


Figure: S. Dulat

note PDFs' different orders-of-mag.!

NC DIS: sensitivity to d-type quarks ¼ that of u-type

$$\sigma \propto \frac{4}{9}(u_+ + c_+) + \frac{1}{9}(d_+ + s_+ + b_+)$$

CC DIS: lower accuracy (1/10 lumi.)

→ u-quark dominates

→ d-quark ½ of u, but harder to access in NC DIS (above)

→ $\bar{d} + \bar{u} \sim$ few percent of u

→ for x~0.1,

$$s \approx \bar{s} \approx \bar{d} - \bar{u} < 0.1(\bar{d} + \bar{u})$$

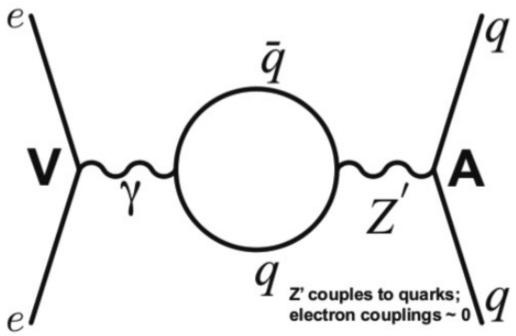
→ at x>0.5, no separation for $\bar{u}, \bar{d}, \bar{s}$

the electroweak sector and **New Physics** searches at EIC

- if measured to sufficient precision, the quark-level electroweak couplings may be sensitive to an extended EW sector, e.g., Z'

$$\mathcal{L}^{\rm PV} = \frac{G_F}{\sqrt{2}} \left[\bar{e}\gamma^\mu\gamma_5 e \left(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d \right) + \bar{e}\gamma^\mu e \left(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d \right) \right]$$

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W$$



- a unique strength of an EIC is its combination of very high precision and **beam polarization**, which allows the observation of **parity-violating helicity asymmetries**:

$$A^{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad (\mathrm{R/L} : e^- \ \text{beam helicities})$$

selects γ-Z interference diagrams!

TJH and Melnitchouk, PRD**77**, 114023 (2008).

$$A^{\rm PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left(Y_1\ a_1 \ + \ Y_3\ a_3\right)$$

$$a_1 = \frac{2\sum_q e_q\ C_{1q}\ (q+\bar{q})}{\sum_q e_q^2\ (q+\bar{q})} \qquad a_3 = \frac{2\sum_q e_q\ C_{2q}\ (q-\bar{q})}{\sum_q e_q^2\ (q+\bar{q})}$$

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$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W$$

→ with sufficient precision, an EIC (which will be statistics-limited in these measurements) can extract $\sin^2\theta_W$

- **this measurement is potentially sensitive to the TeV-scale in a complementary fashion to energy-frontier searches!**

TJH and Melnitchouk, PRD**77**, 114023 (2008).

$$A^{\mathrm{PV}} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \right) \left(Y_1\, a_1 + Y_3\, a_3 \right)$$

N.B.: extractions are dependent upon knowledge of the PDFs

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