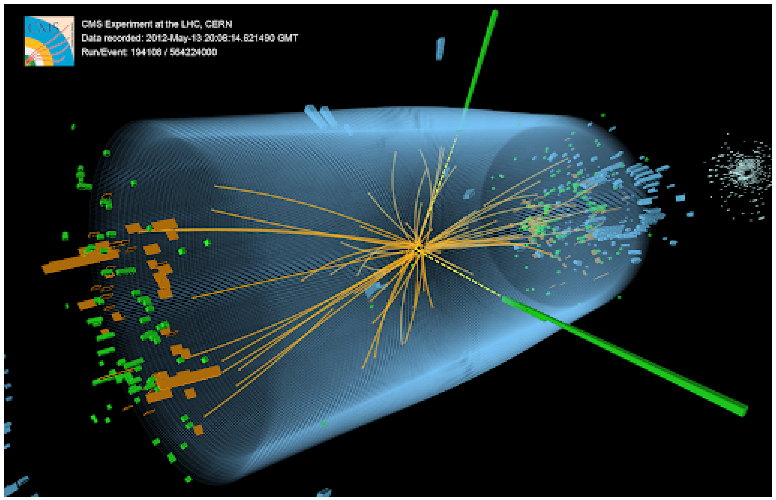
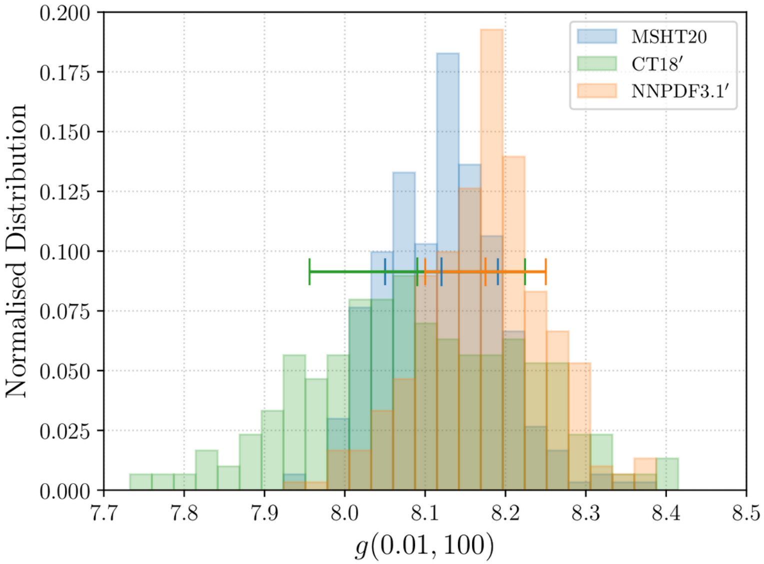
PDFs from EIC, lattice QCD, and the LHC

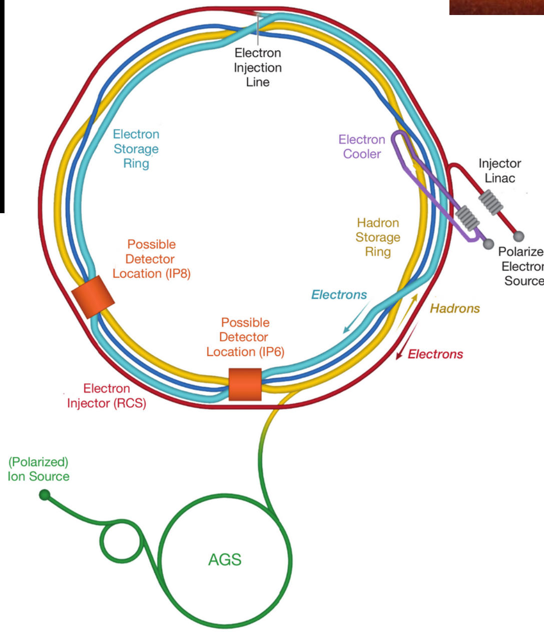
“or, making data work for you”

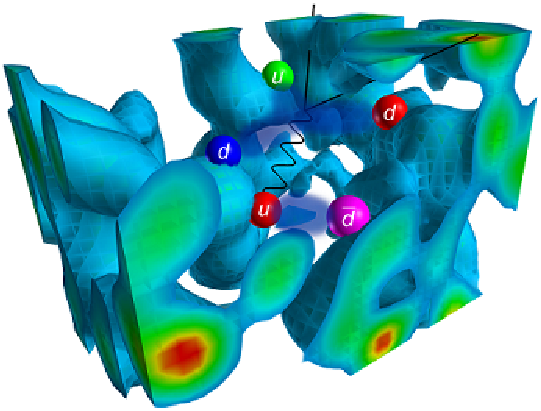
Tim Hobbs – Fermilab, IIT

30th August 2022









Fermilab

ILLINOIS INSTITUTE OF TECHNOLOGY

this talk: PDF activity key for 2 core needs in fundamental QCD

1: LHC-based SM tests limited by (incomplete) proton structure info

Boughezal, …

→ many **standard-candle HEP measurements PDF-limited**

Kaazde, Kotwal, …

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

this talk: high x

→ **PDF studies vital to nonpert. QCD**, mapping hadron structure

Metz, Sato, …

2: parallel developments likely to impact both areas

Wagman, …

→ lattice QCD: new opportunities to constrain inaccessible PDF behavior

→ EIC program, preparations have substantial PDF implications

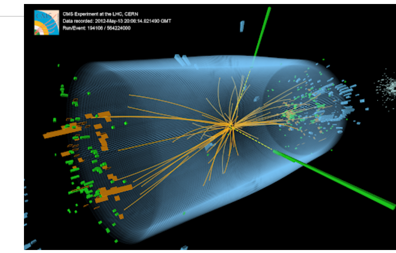
Arratia, …

highlight through:

i current status of PDFs; ii lattice QCD possibilities

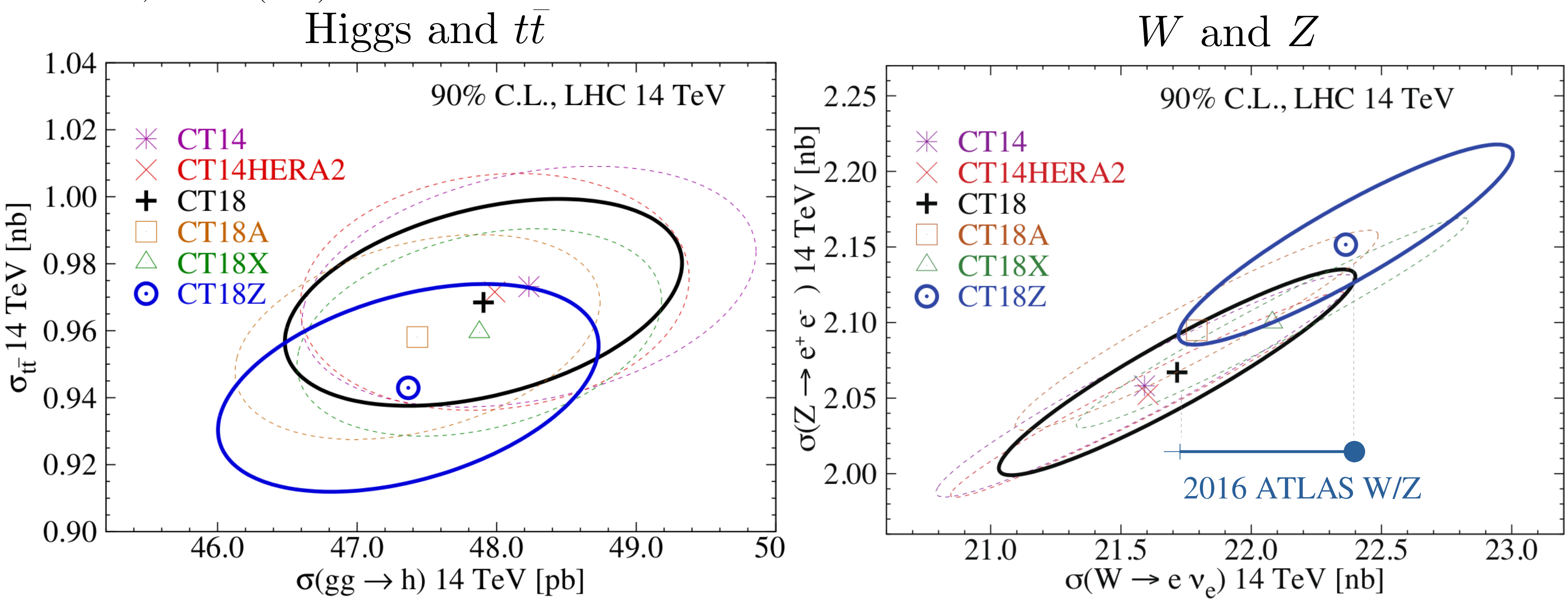
iii EIC projections; iv conclusion(s)

SM tests at LHC require high theory accuracy; precision



- 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 i

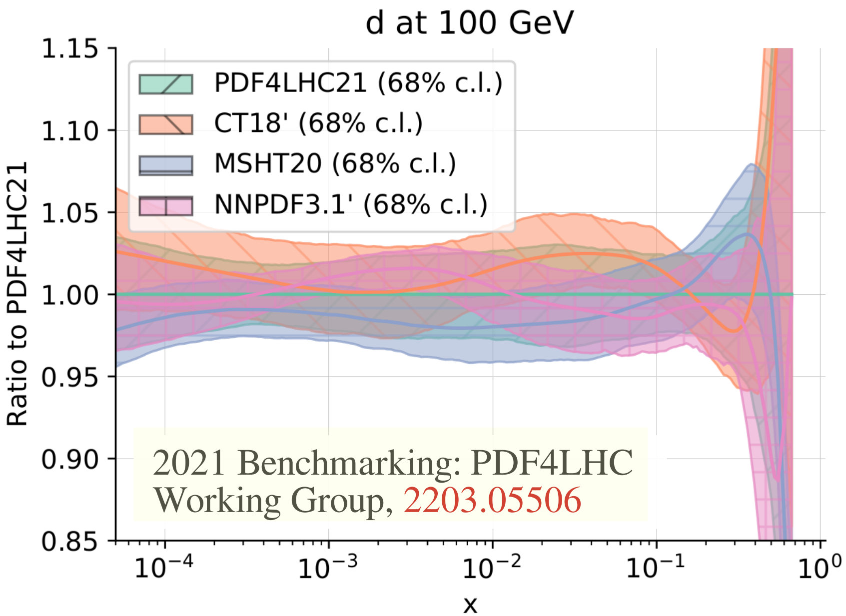
PDFs critical to next-generation precision

Snowmass21, Amoroso et al.: 2203.13923

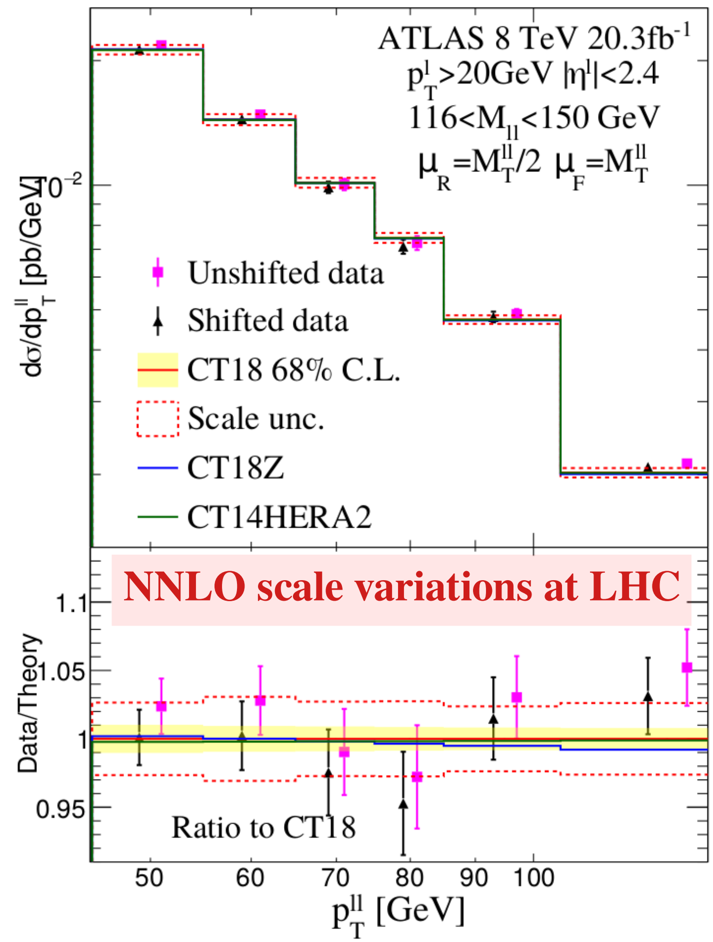
→ driven by marriage of high-energy data; **latest theory**

modern standard: NNLO

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



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



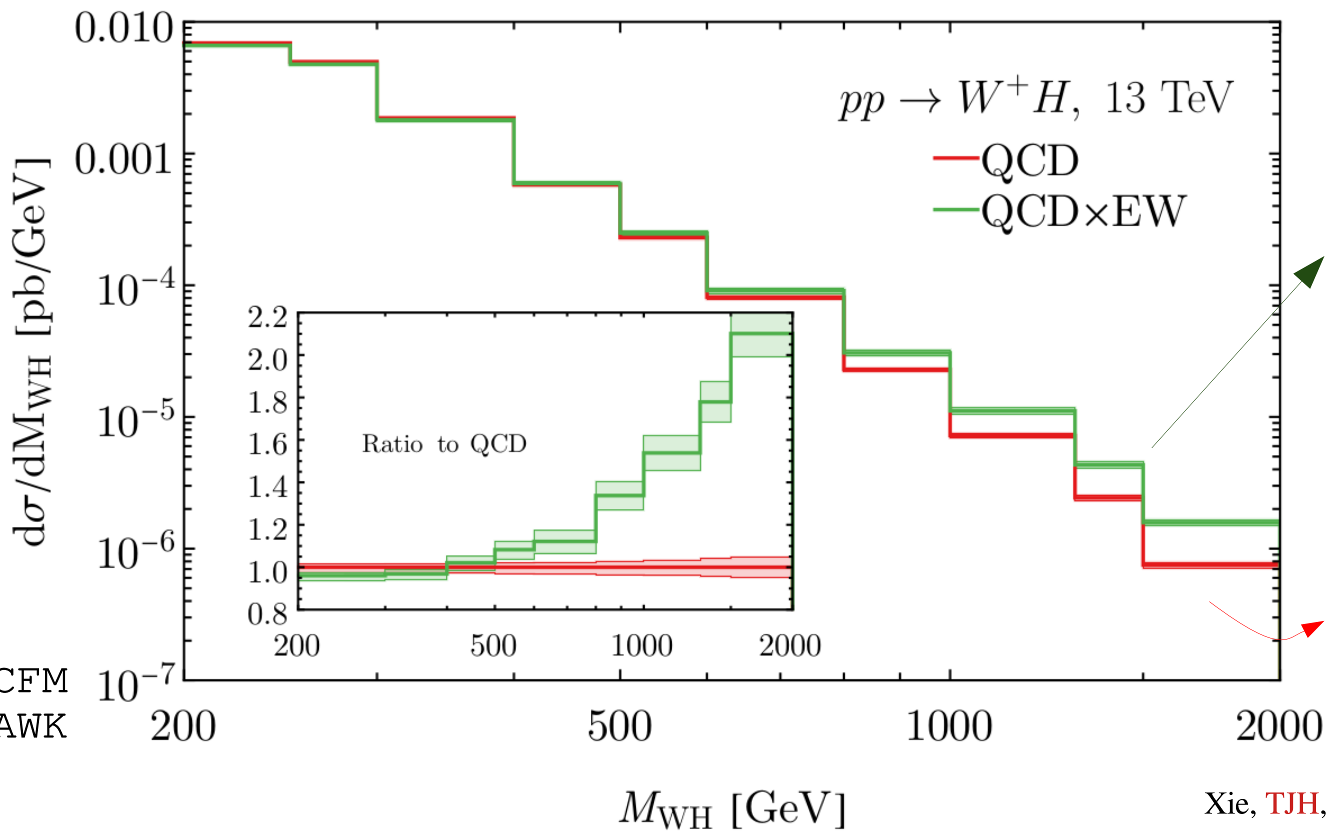
- periodic benchmarking (PDF4LHC21) valuable to cross-check treatment of data

→ intercompare theory choices; understand methodological dependence

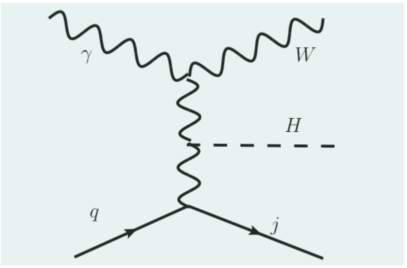
BSM searches in HEP also require EW theory accuracy

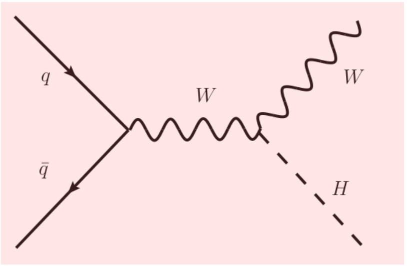
- non-standard physics may appear in tails of rapidity, inv. mass distributions

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



MCFM
HAWK





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

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

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

electroweak precision: photon, high-x PDFs; nonpert. QCD

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

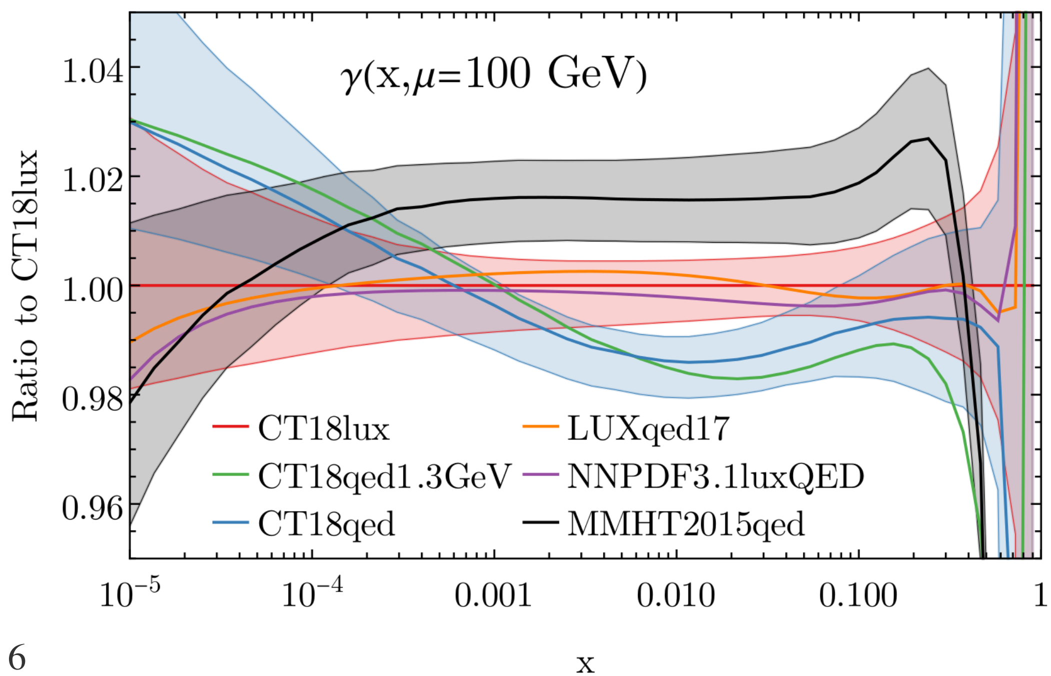
Xie, TJH, Hou, Schmidt, Yan, Yuan: PRD**105** (2022) 5, 054006.

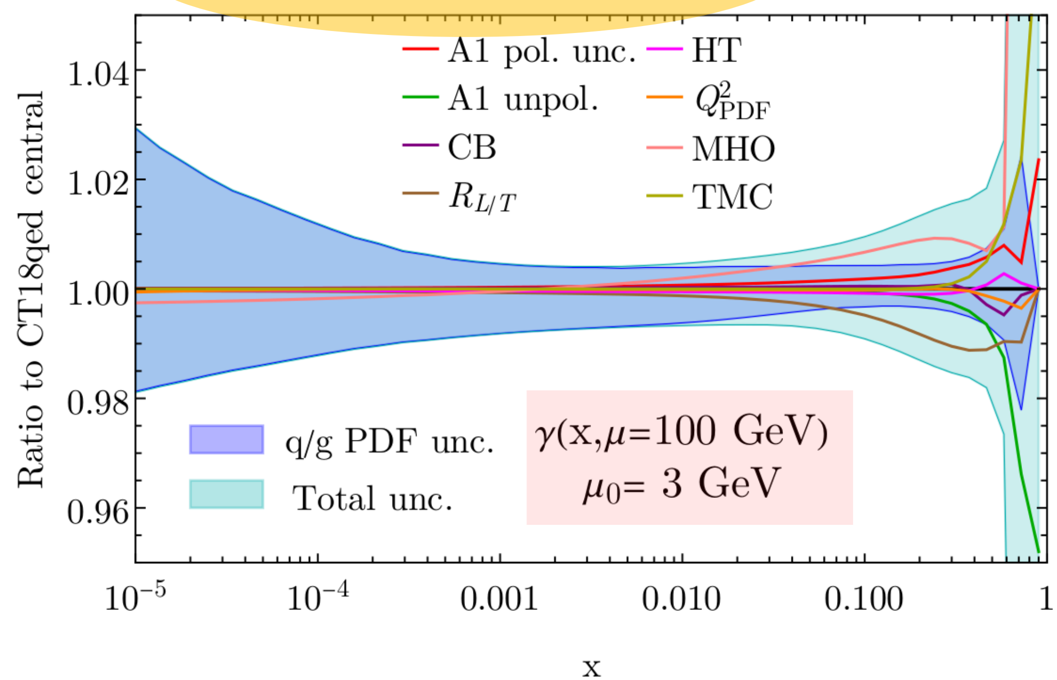
- following CT14QED, CT18QED now interfaces LUX formalism

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

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

[large-*x* physics...]

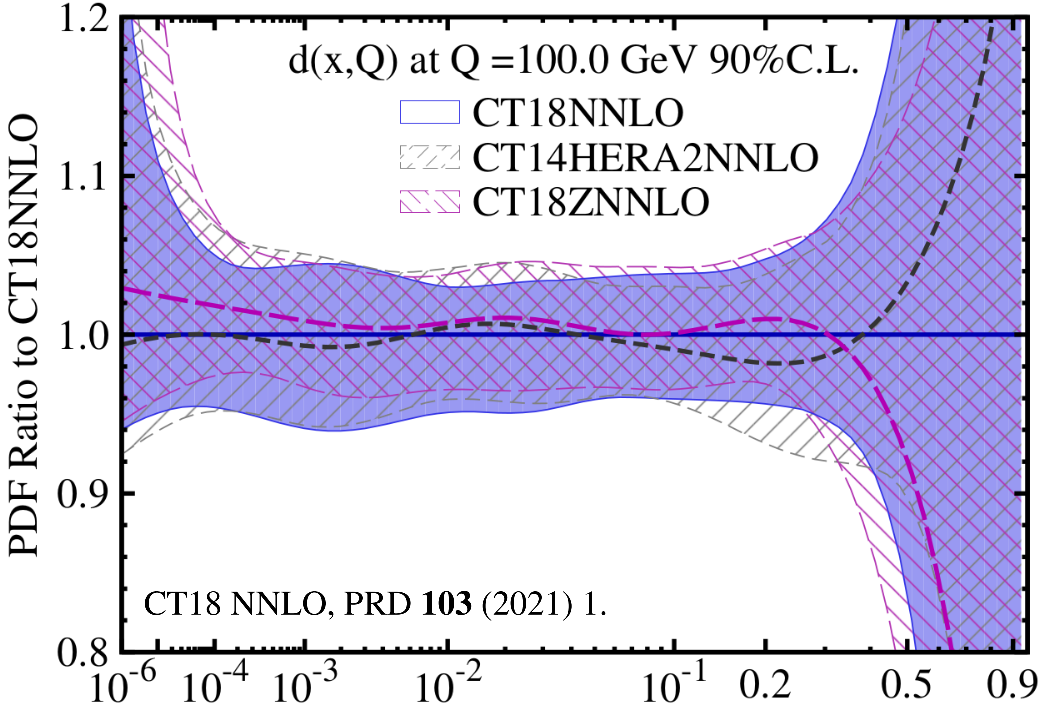


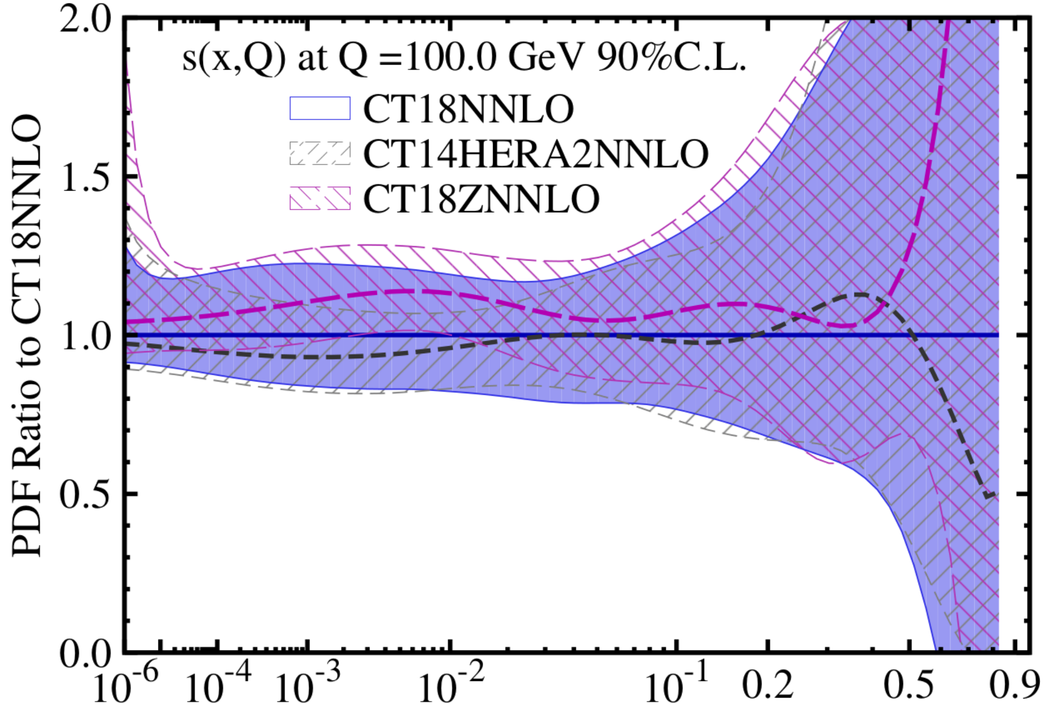


high-x PDFs remain dominated by large uncertainties

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

→ limited data → extrapolation → data tensions

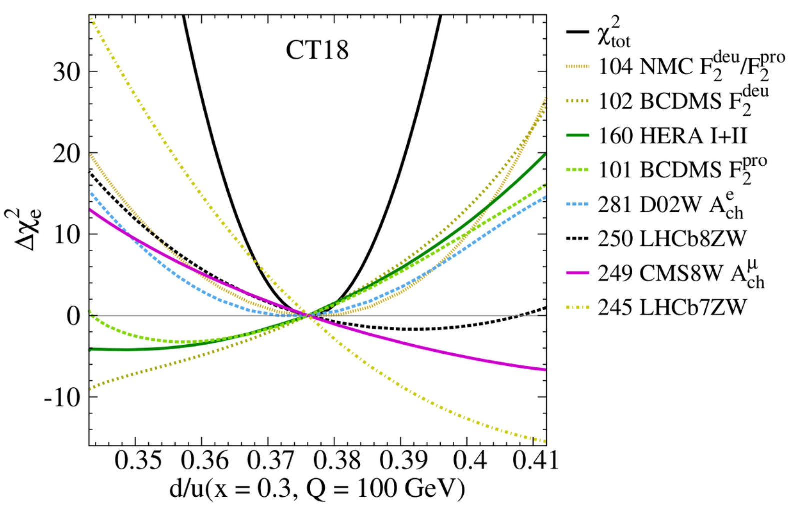




- competing pulls of fitted data at high-x also restrict precision; *e.g.*,

→ BCDMS, F_2^d

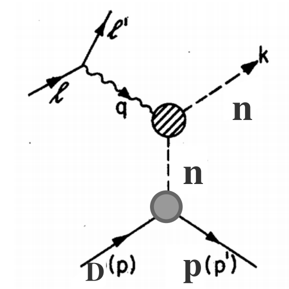
→ LHCb, W/Z 7 TeV



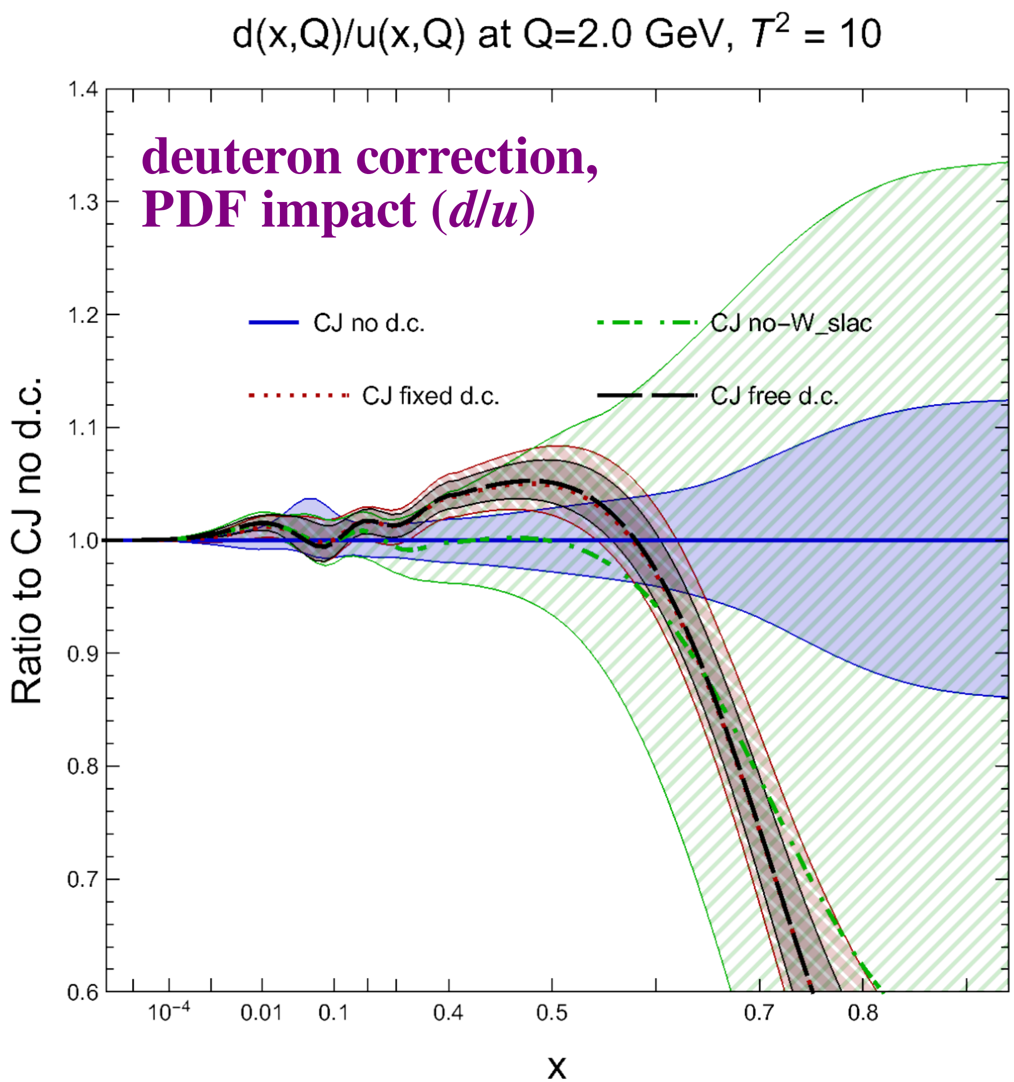
nuclear corrections: high-x PDFs and flavor separation

- 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

  → also, PDF correlations with gluon, other flavors

- impacts LHC observables; necessary for high precision

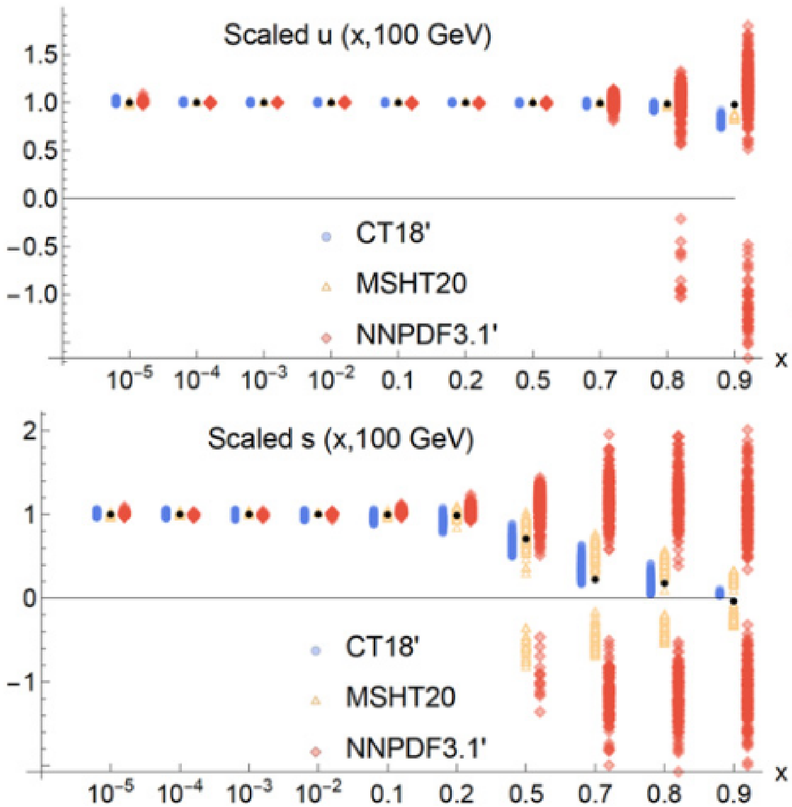
- analogous situation for **heavy-nuclear effects** in νA scattering → main (inclusive) source of **strangeness** info.

understanding PDFs and their uncertainties: high x

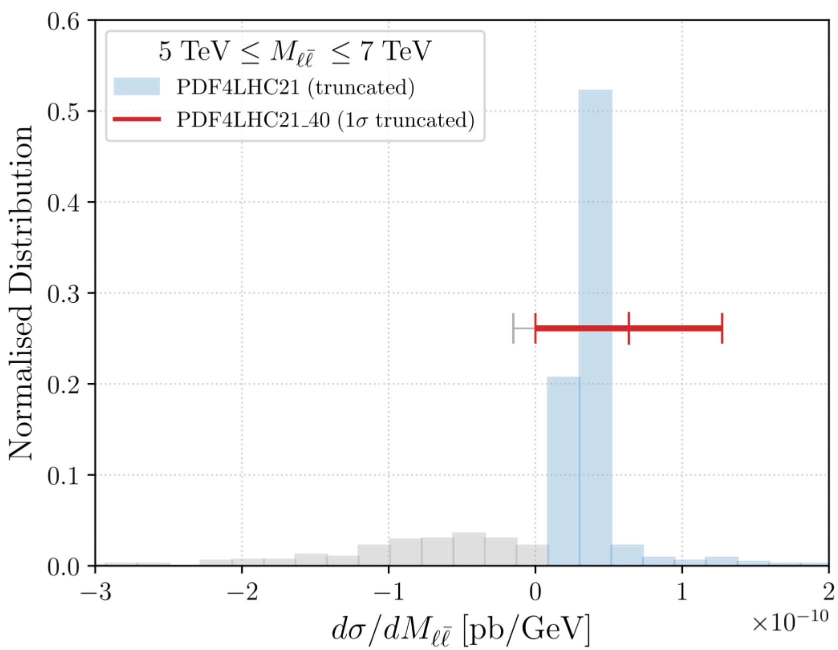
PDF4LHC21 benchmarking: J.Phys.G 49 (2022) 8, 080501.

- MC sampling of high-x PDFs can sometimes produce irregularities

  → *e.g.*, positive-definiteness not always guaranteed for $x \to 1$



→ can produce subtle but non-negligible phenomenological consequences:



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

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

PDF uncertainties: parametrization dependence

- initial PDFs still not generally calculable through rigorous QCD at $Q = Q_0 = m_c$ (more on this shortly...)

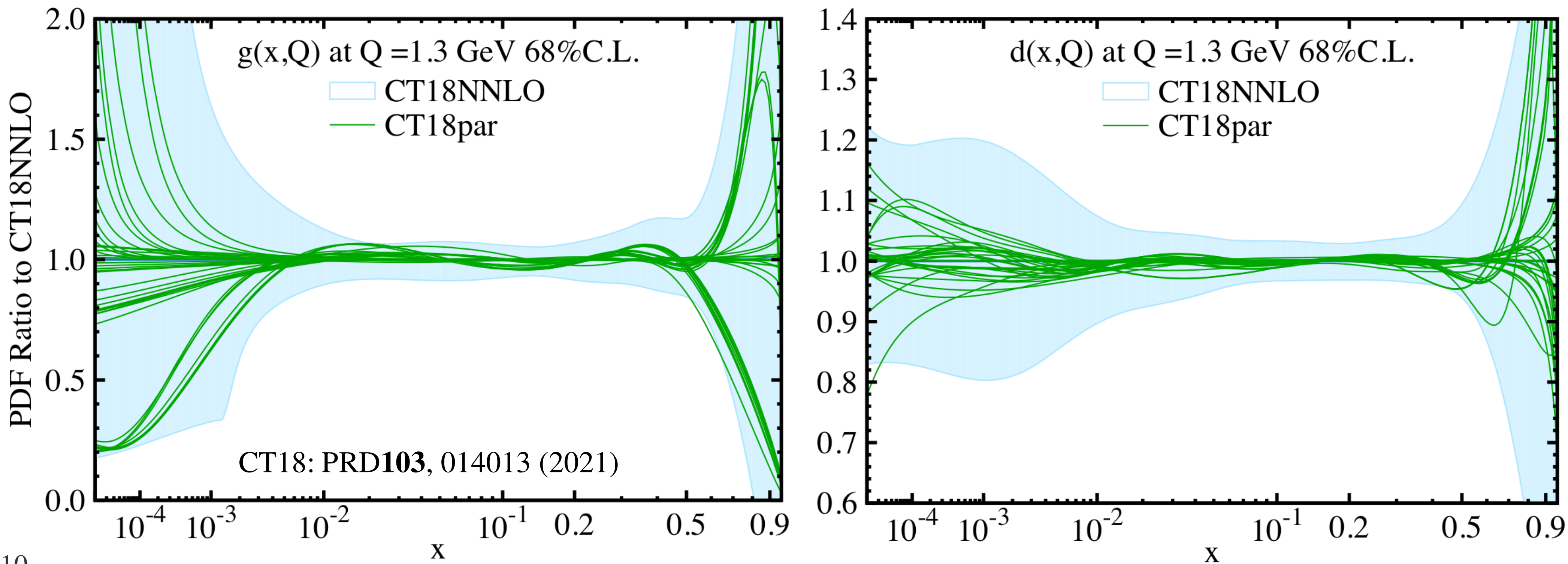
→ subject to complex nonperturbative dynamics

→ 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



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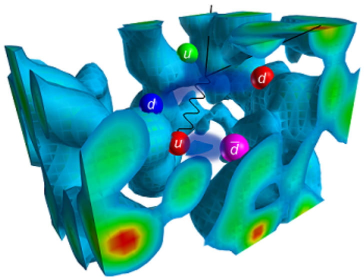
but, what about *ab initio* QCD methods (lattice QCD)?

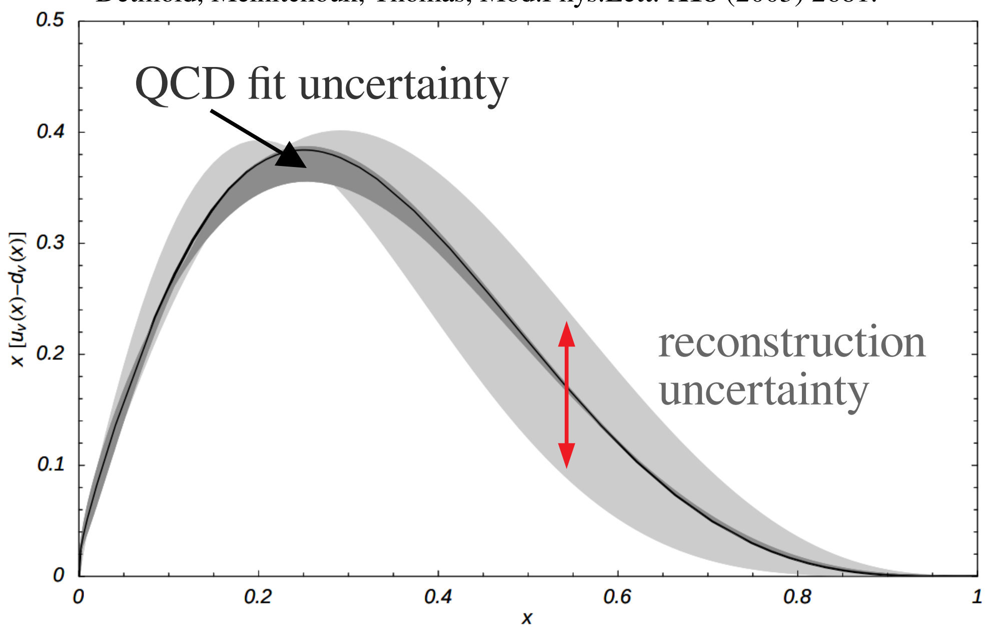
- PDF (Mellin) moments from lattice: **higher moments ↔ higher cov. derivatives**

$$\frac{1}{2}\sum_s \langle p, s|\mathcal{O}^q_{\{\mu_1,\cdots,\mu_{n+1}\}}|p, s\rangle = 2v_q^{n+1}\,[p_{\mu_1}\cdots p_{\mu_{n+1}} - \text{traces}]$$

$$v_q^{n+1}(Q) = \int_0^1 dx\, x^n\, q(x, Q)$$



Detmold, Melnitchouk, Thomas, Mod.Phys.Lett. **A18** (2003) 2681.



- higher moments sensitive to high-*x* PDFs
- historically, efforts to reconstruct PDFs from lattice-calculable moments (large uncertainties)

more recently

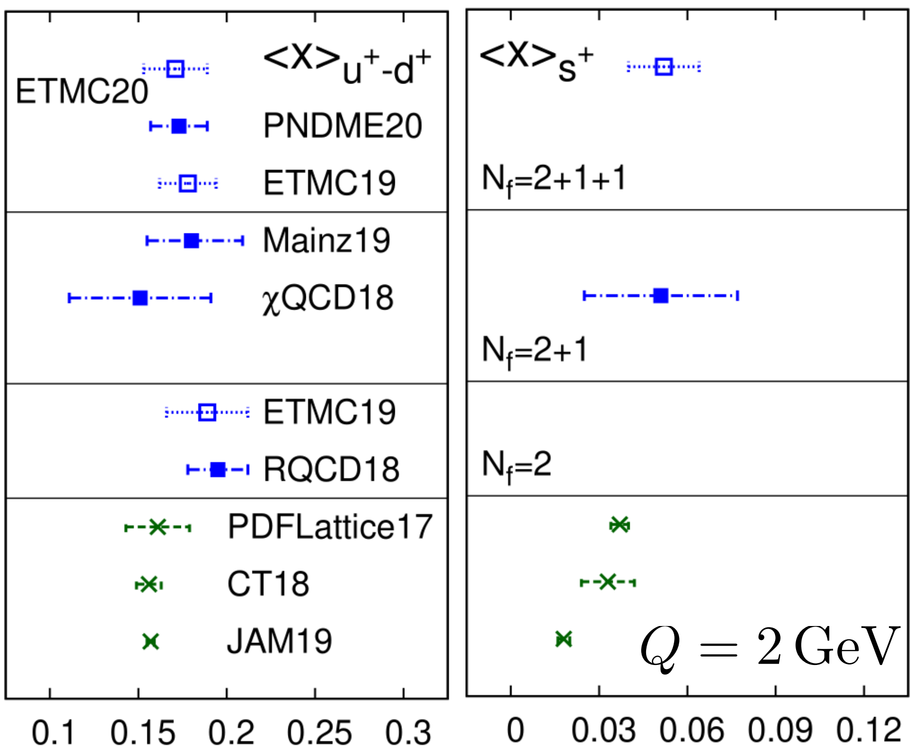
→ technical advances: more (and better) Mellin moment determinations

→ formal advances: quasi- and pseudo-PDFs ii

status of PDF moments on the lattice (2021)

PDF-Lattice whitepaper II – Constantinou et al., PPNP**121** (2021) 103908.

Moment	Collaboration	Reference	N_f	DE	CE	FV	RE	ES	Value
$\langle x \rangle_{u^+-d^+}$	ETMC 20	[235]	2+1+1	■	★	○	★	★	0.171(18)
	PNDME 20	[236]	2+1+1	★	★	★	★	★	0.173(14)(07)
	ETMC 19	[237]	2+1+1	■	★	○	★	★	0.178(16)
	Mainz 19	[238]	2+1	★	○	★	★	★	$0.180(25)(^{+14}_{-6})$
	χQCD 18	[239]	2+1	○	★	○	★	★	0.151(28)(29)
	ETMC 19	[237]	2	■	★	○	★	★	0.189(23)
	RQCD 18	[240]	2	★	★	○	★	★	0.195(07)(15)
$\langle x \rangle_{s^+}$	ETMC 20	[235]	2+1+1	■	★	○	★	★	0.052(12)
	χQCD 18	[239]	2+1	○	★	○	★	★	0.051(26)(5)



- depending on flavor, order – lattice moments have varying status (above, FLAG evaluations)

  → *e.g.*, the first isovector moment has been computed by numerous groups

- systematic lattice effects are similarly widely varied

- lattice precision lags QCD fits, but **higher moments would be informative**

- also, novel lattice methods available →

quasi-PDFs allow access to x dependence

- boost-dependent **quasi-PDF** can be matched to light-front PDF, up to power-suppressed corrections

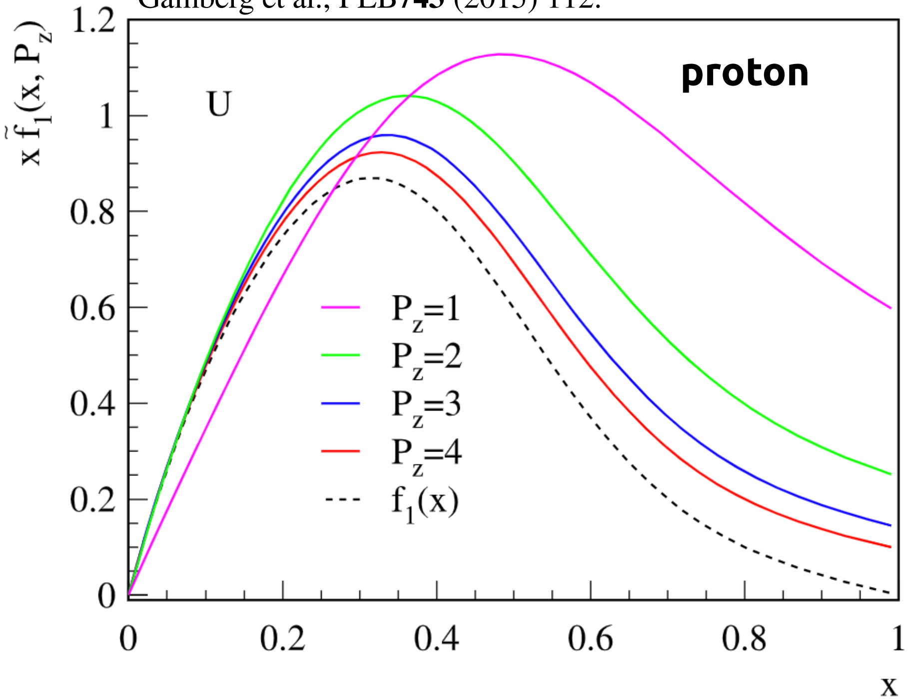
Ji, PRL**110**, 262002 (2013).

$$\sim \langle P|\overline{\psi}\gamma^{z,t}\psi|P\rangle \qquad \sim \langle P|\overline{\psi}\gamma^{+}\psi|P\rangle$$

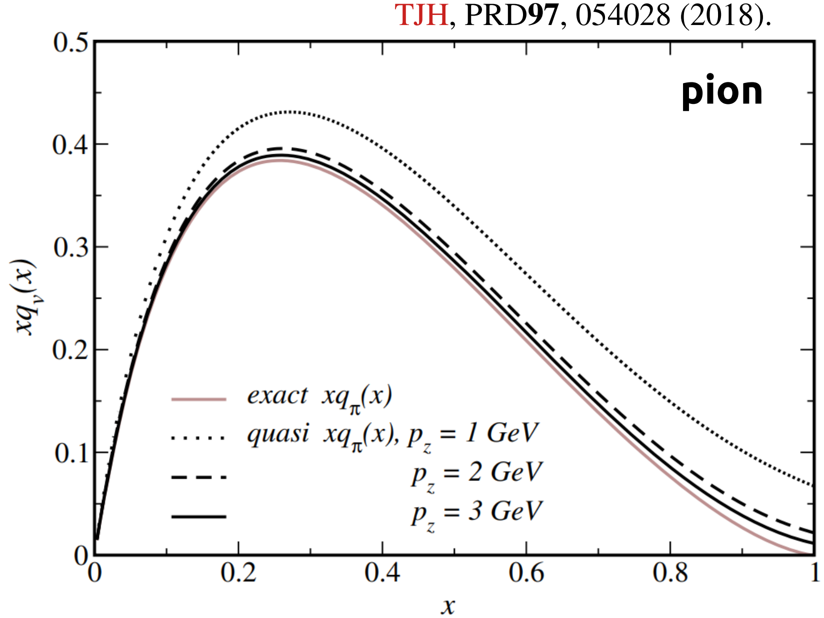
$$\widetilde{q}(x, P_z, \widetilde{\mu}) = \int dy\, Z\left(\frac{x}{y}, \frac{\Lambda}{P_z}, \frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{P_z^2}, \frac{M^2}{P_z^2}\right)$$

- yields x-dependent PDF information; limited by knowledge of perturbative matching, P_z dependence

Gamberg et al., PLB**743** (2015) 112.



TJH, PRD**97**, 054028 (2018).



model calculations: qPDFs converge to exact for $P_z \to \infty$

- ultimately, the x- and P_z dependence of the qPDFs are informative of **hadronic wave functions**

lattice QCD output: basis for PDF-lattice synergy

there are (and will be) important synergies between PDF fitting and lattice QCD

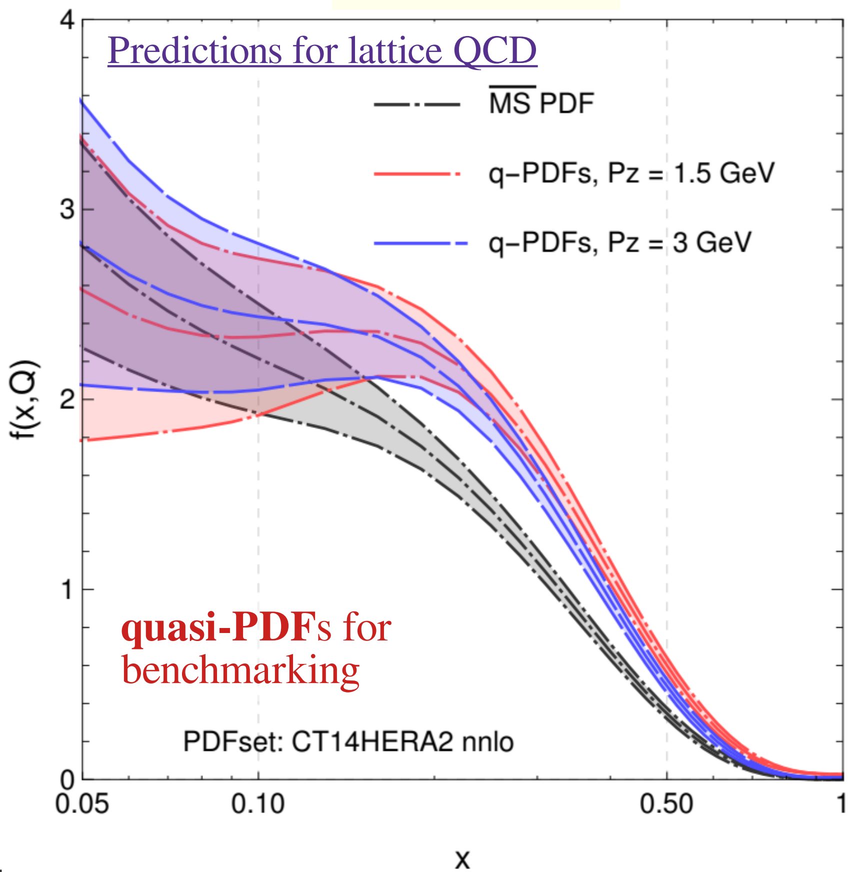
[overlaps with EIC; νDIS; LHC]

- PDF fits **benchmark** pQCD matching; lattice output can **constrain** QCD fits

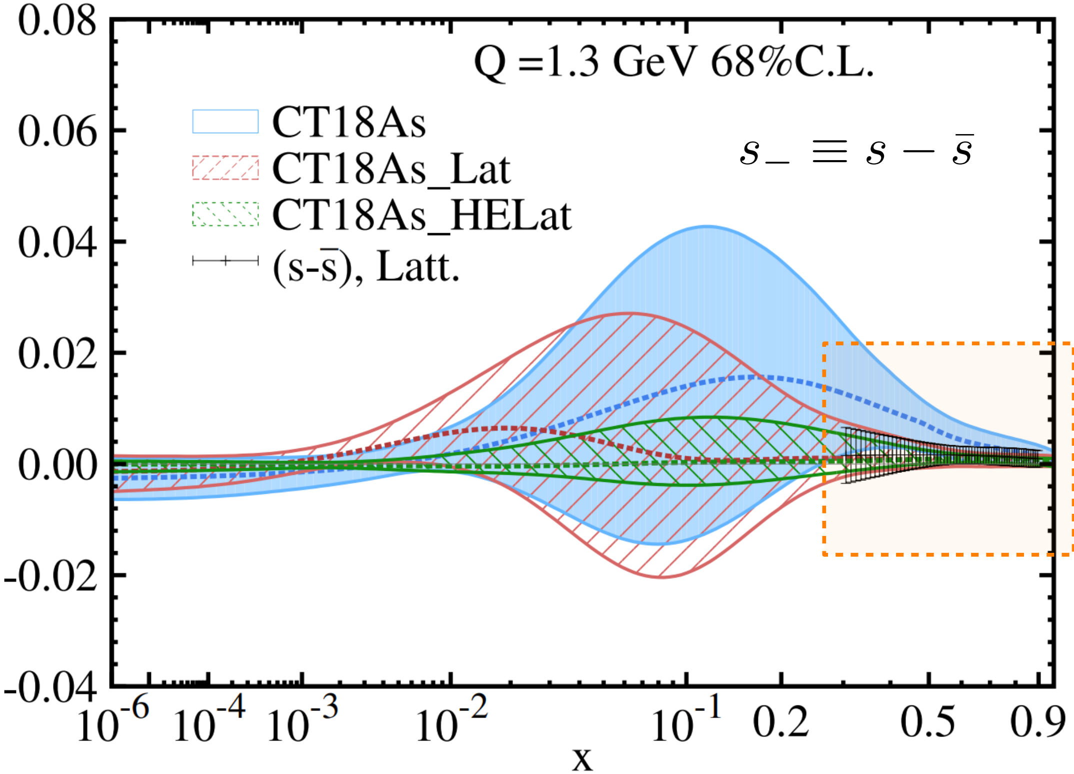
- lattice data can potentially inform high-x behavior of quark sea

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

u–d at μ_F = 3GeV



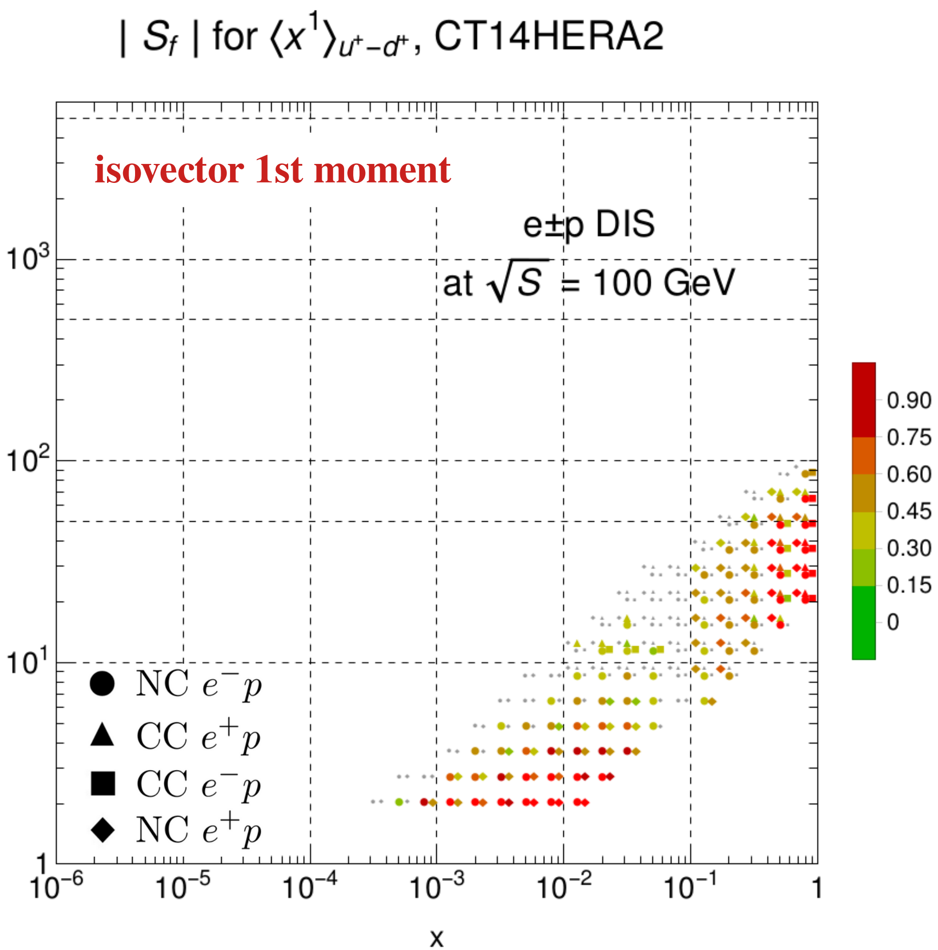
Hou et al., 2204.07944

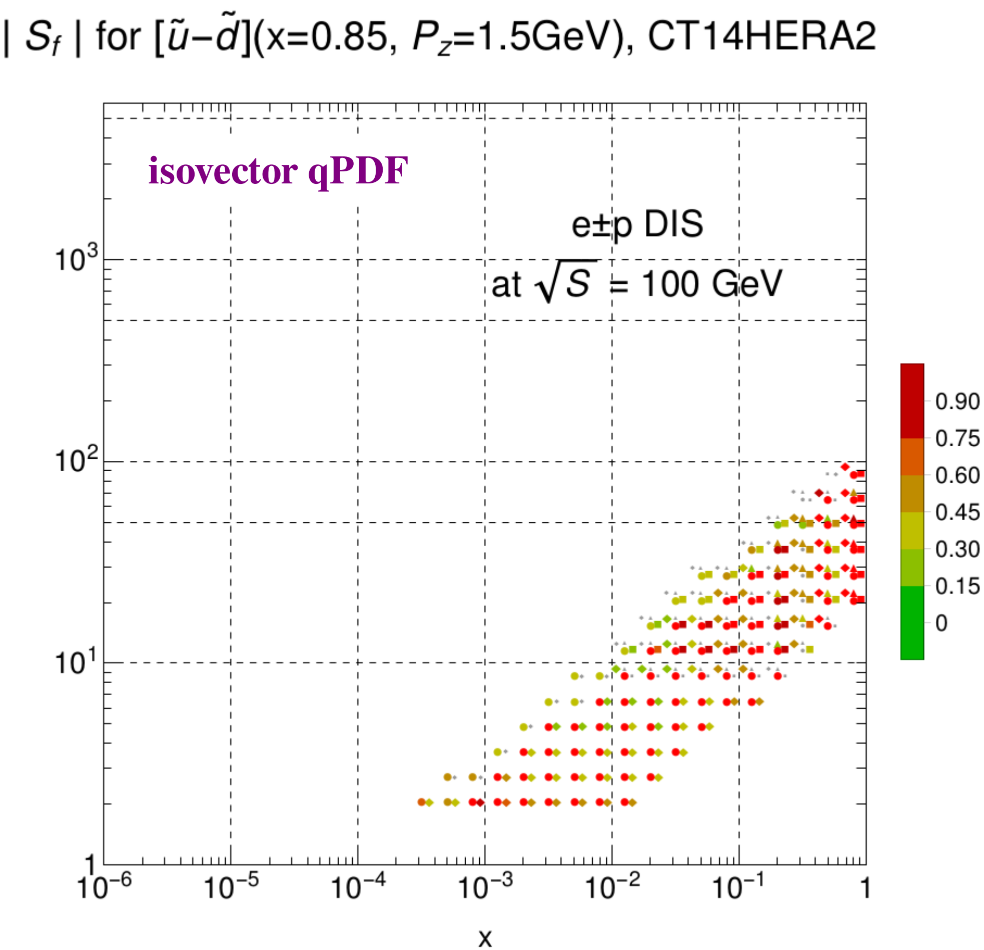


also: nuclear, spin-, transversity-, ..., PDFs

EIC: sensitivity to high-x; driver of lattice benchmarks

- EIC inclusive DIS data would already have strong PDF sensitivity to many lattice observables; below, the isovector first moment (left) and analogous qPDF (right)

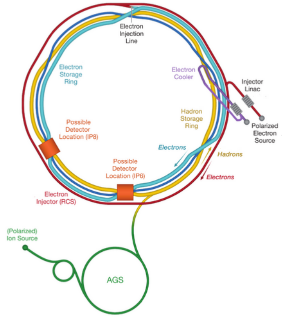




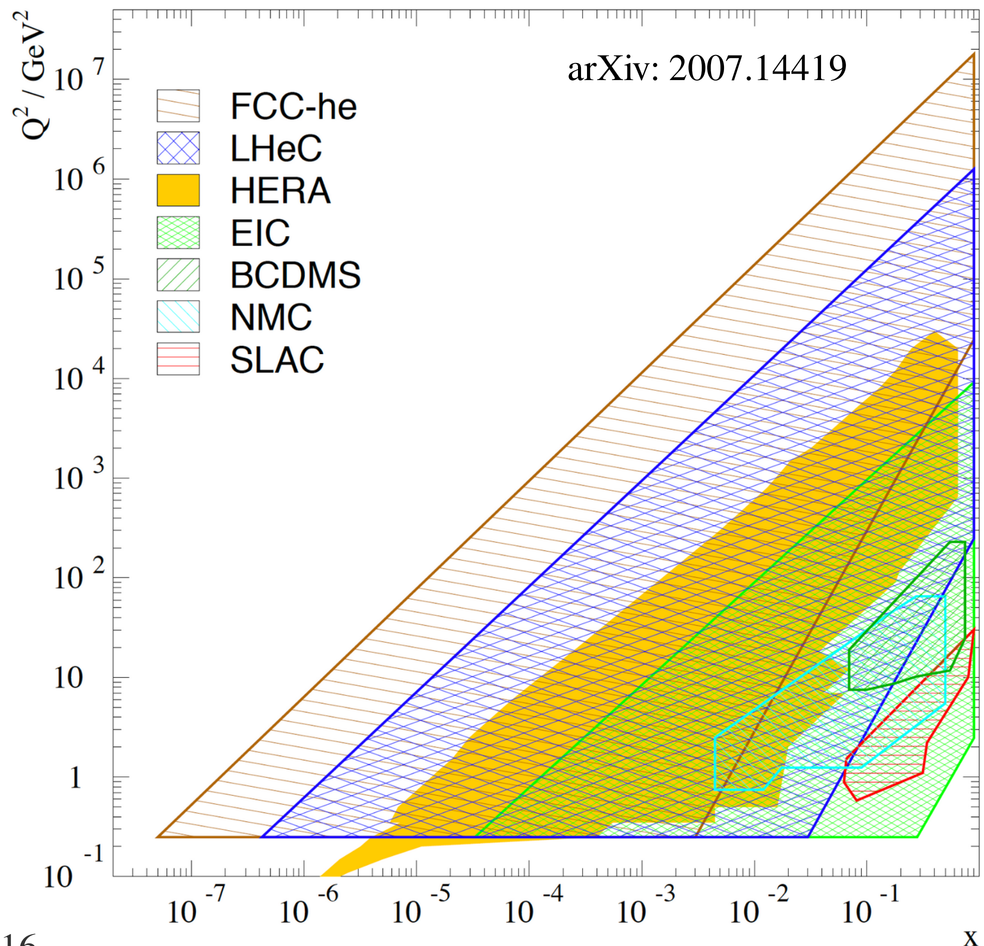
TJH, Wang, Nadolsky, Olness, PRD**100** (2019) 9, 094040.

- sensitivity (indicated in red) from broad range of x and scale Q; basis for reducing PDF uncertainties → benchmarking lattice calculations → further extrapolating to higher x

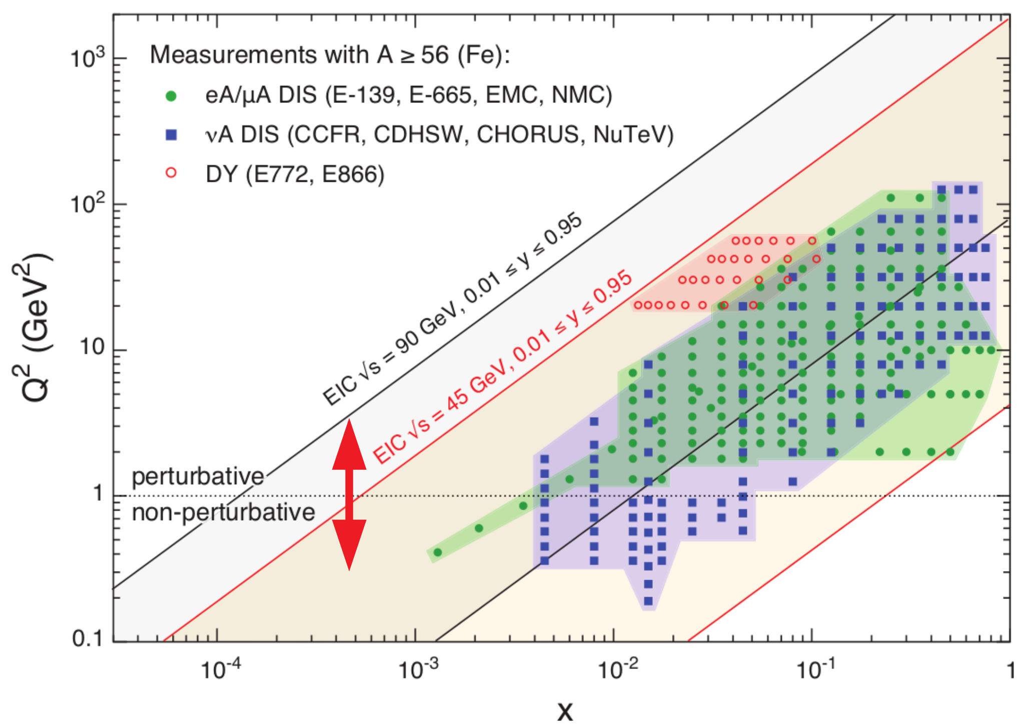
reach of the EIC program



- EIC explores unique region in $[x, Q^2]$; machine for HEP-NP intersections
  → strong coverage of quark-to-hadron transition region between HERA, JLab12
- even 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.

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PDF impacts compared to high-value fixed-target DIS

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

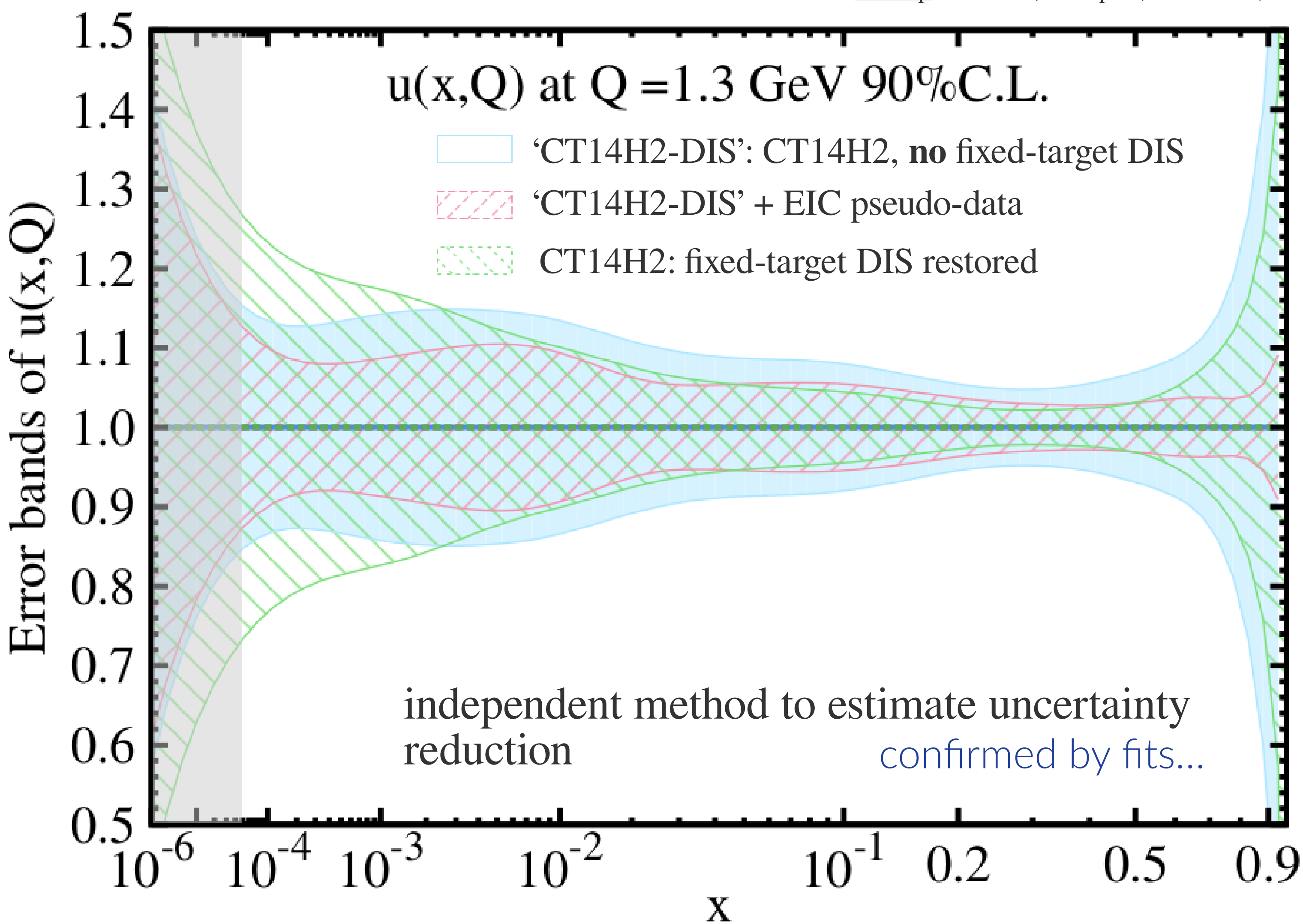


figure: S. Dulat

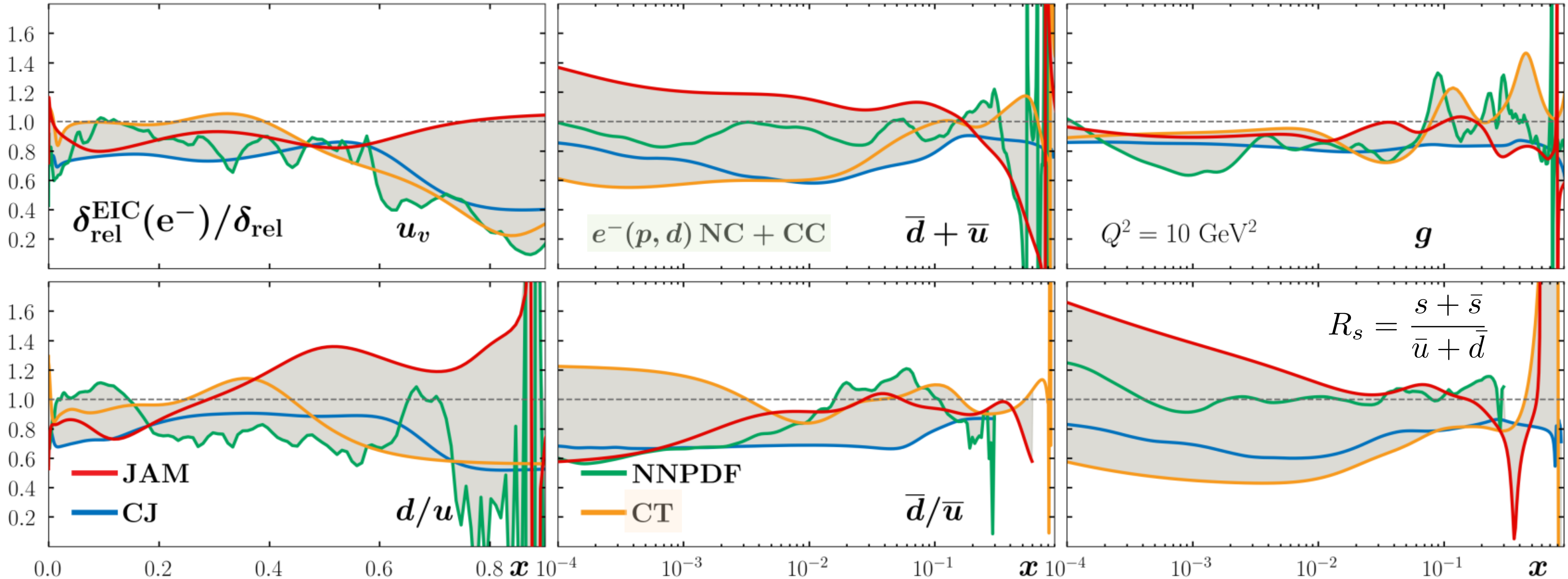
- **inclusive EIC may surpass total impact of fixed-target DIS in modern fits**

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

reductions to PDF uncertainties: inclusive DIS data

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

EIC YR, 7.1.1 PDF uncertainty improvement ~1 year of [peak] data-taking



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

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

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

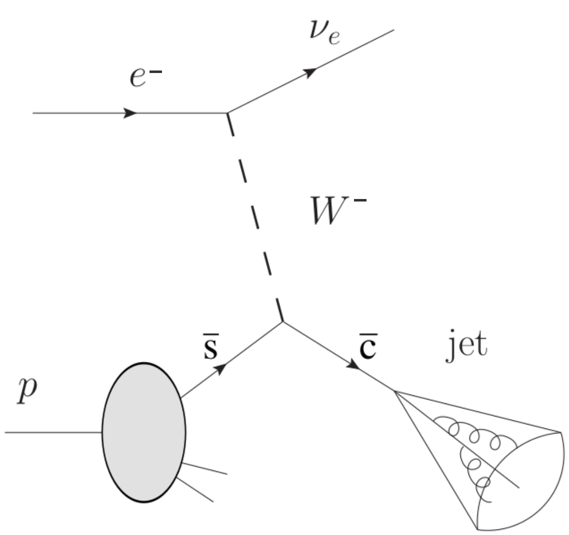
precision QCD through jet and heavy-flavor production

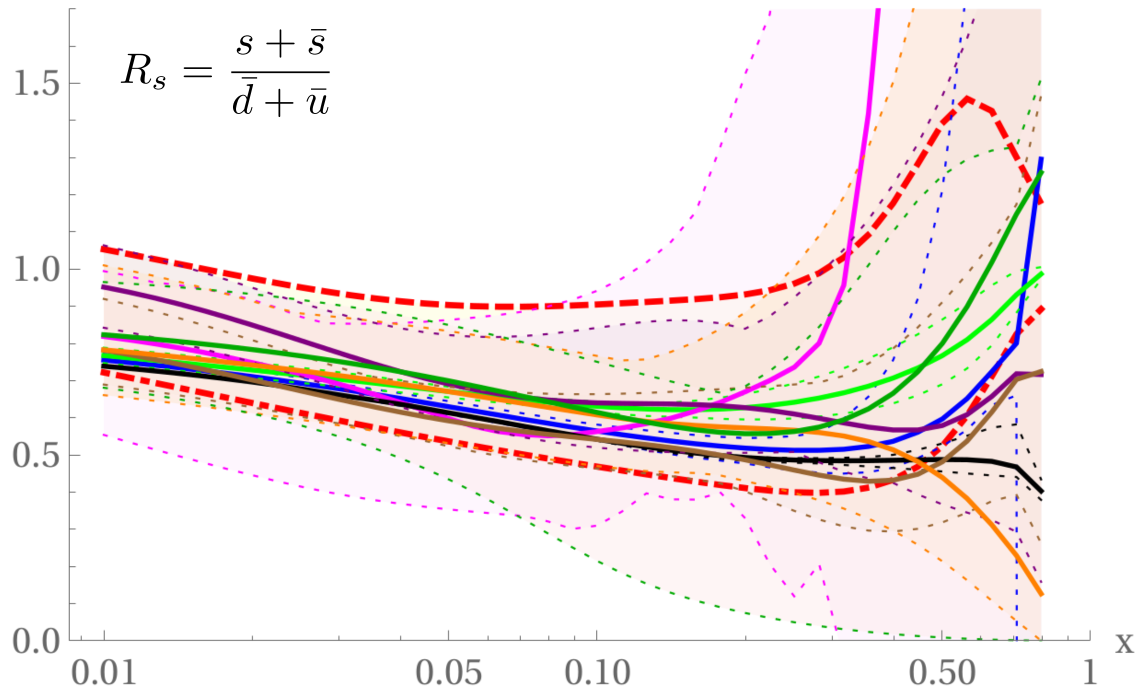
- DIS jet production, including through charge-current interactions, provides further access to quark-level information

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

R_s(x,Q) Q=10 GeV

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





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

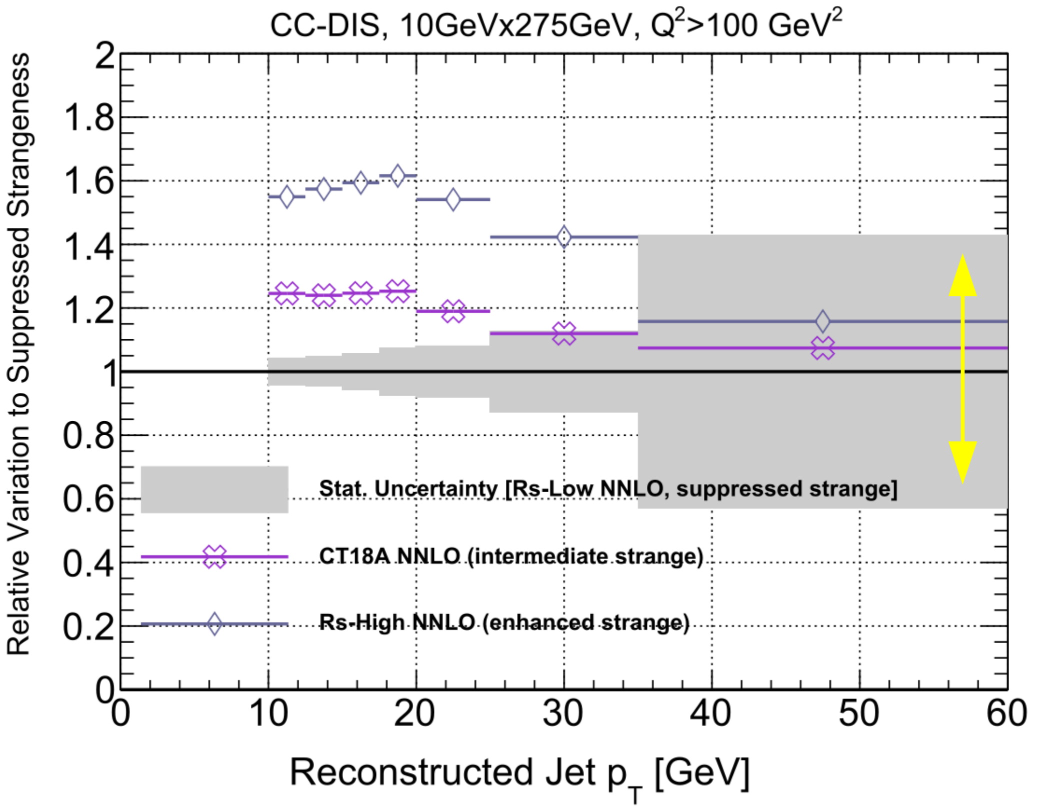
- n.b.: event generation, detector sim from PYTHIA8 + DELPHES; FASTJET reconstruction

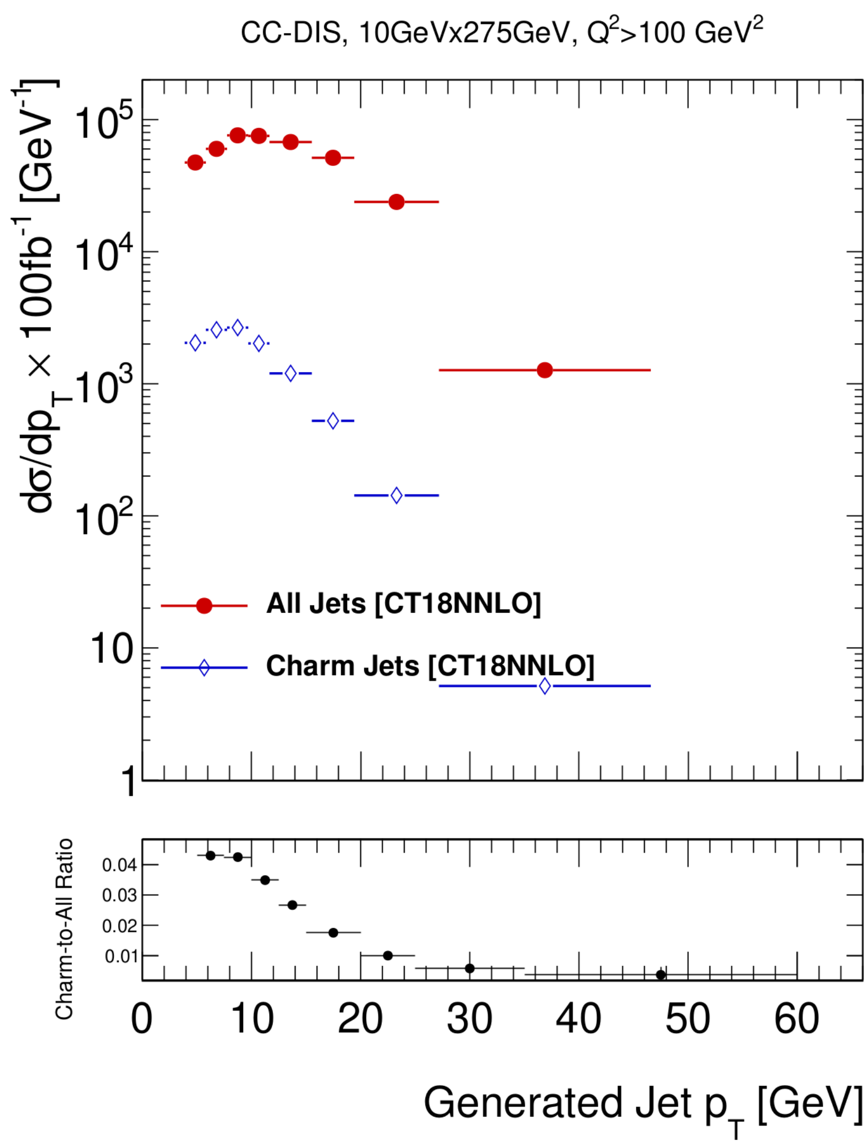
→ analogous jet measurements might be extended to nonperturbative heavy flavor

precision QCD through jet and heavy-flavor production

- challenging measurement: final-state flavor tagging; Jacquet-Blondel reconstruction

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



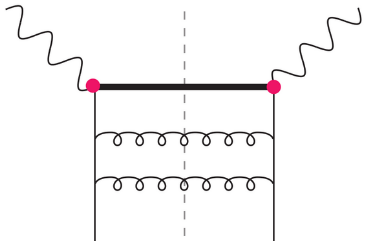


- charm production suppressed by >2 orders of magnitude; p_T cross section steeply falling

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

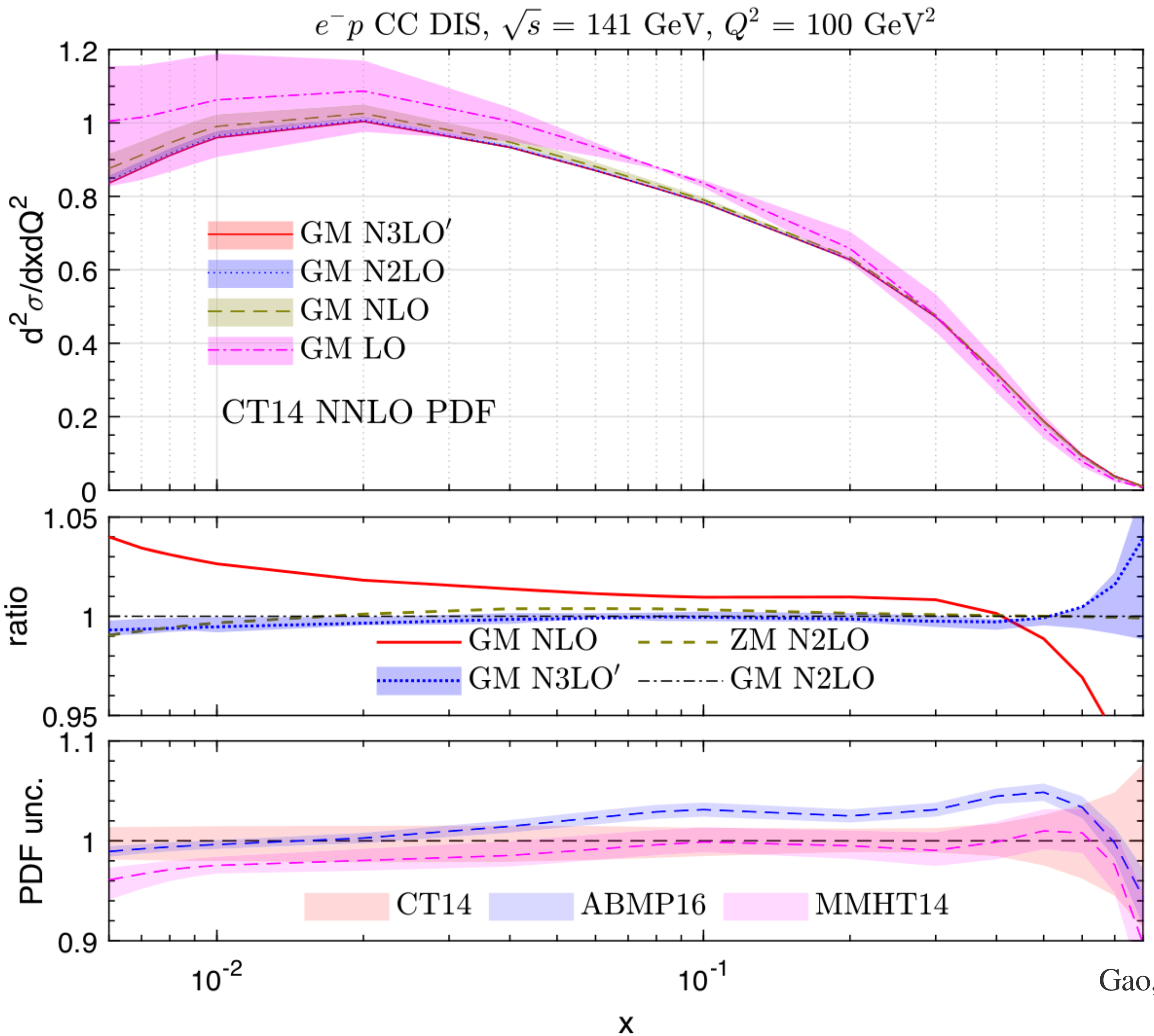
→ greater event rates may furnish enhanced discriminating power

(CC) DIS at NNLO and beyond



- extracting PDF information from CC DIS requires robust theory accuracy

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



- strong perturbative convergence

  → for N³LO´, scale variations generally contained to $\lesssim 0.5 - 1\%$

- significantly smaller than PDF-driven uncertainties, which can be as large as $\approx 2\%$

vital ingredient in EIC PDF program

- note improvements at high x: suggests possible synergy with high-luminosity measurements

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

precise EIC data impact high-energy predictions

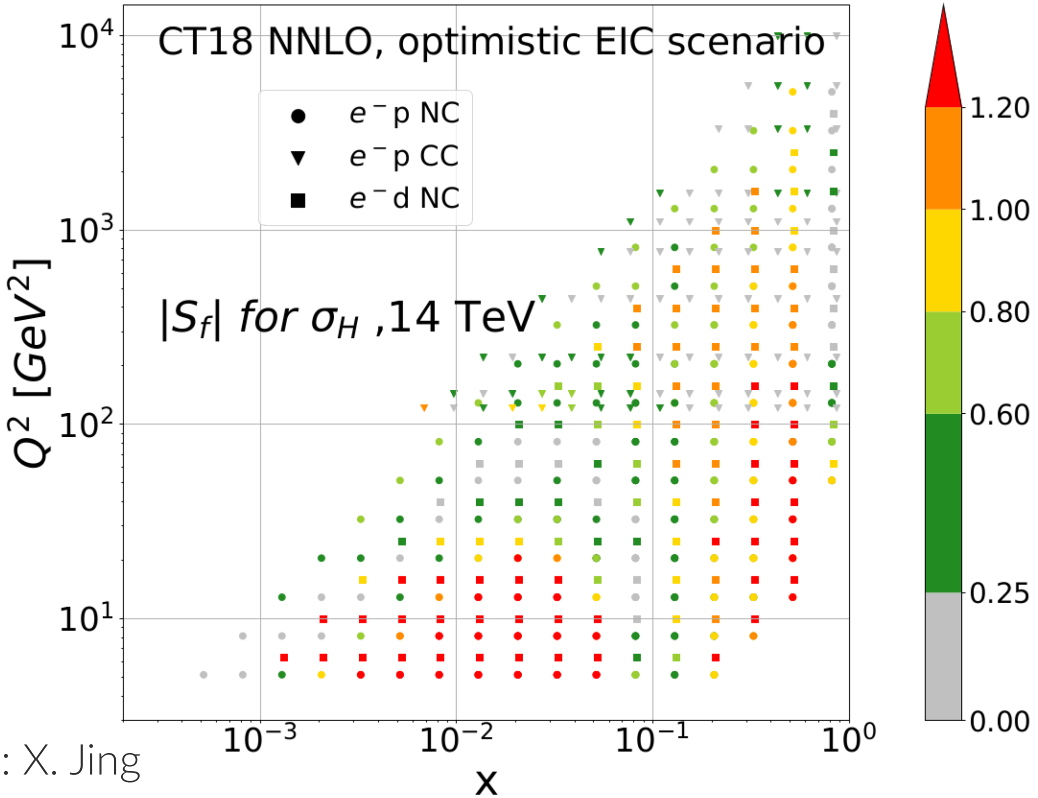
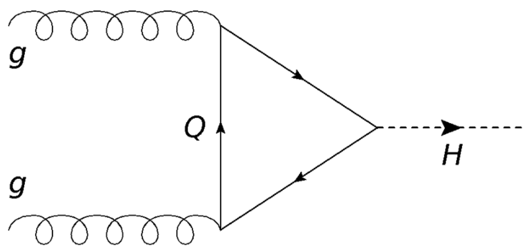


figure: X. Jing

example:

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



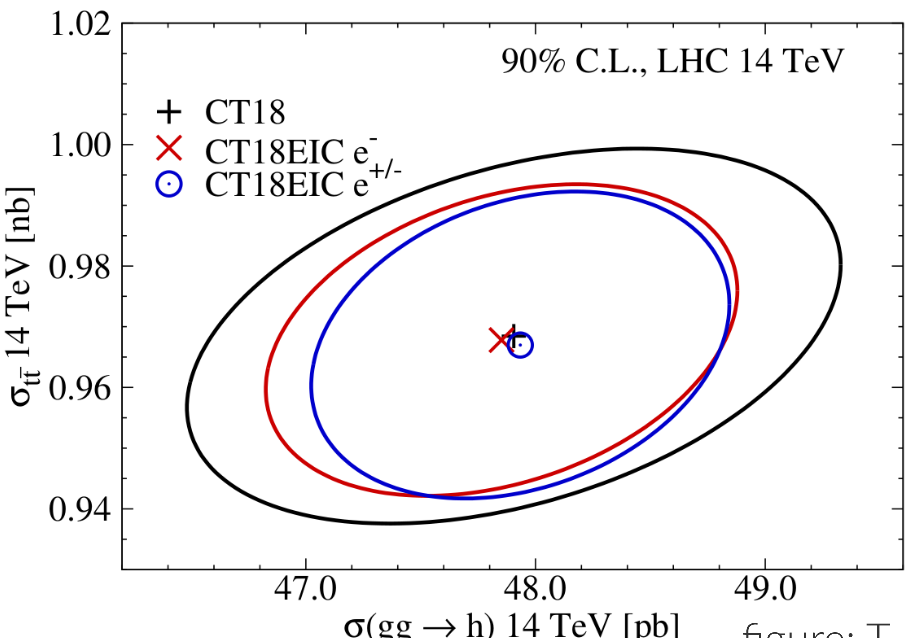


figure: T.-J. Hou

- impact closely tied to that of the integrated gluon PDF

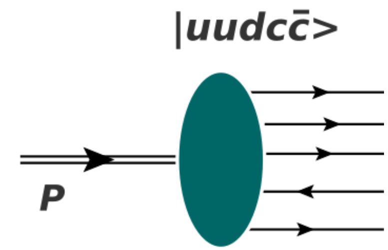
→ similar impacts on EW observables

coda: nonperturbative charm in the proton

- possible nonperturbative ('intrinsic') charm component of the nucleon long debated
- PDF valence-like *shape* predicted by various nonperturbative models

  → *normalization* has been challenging to determine

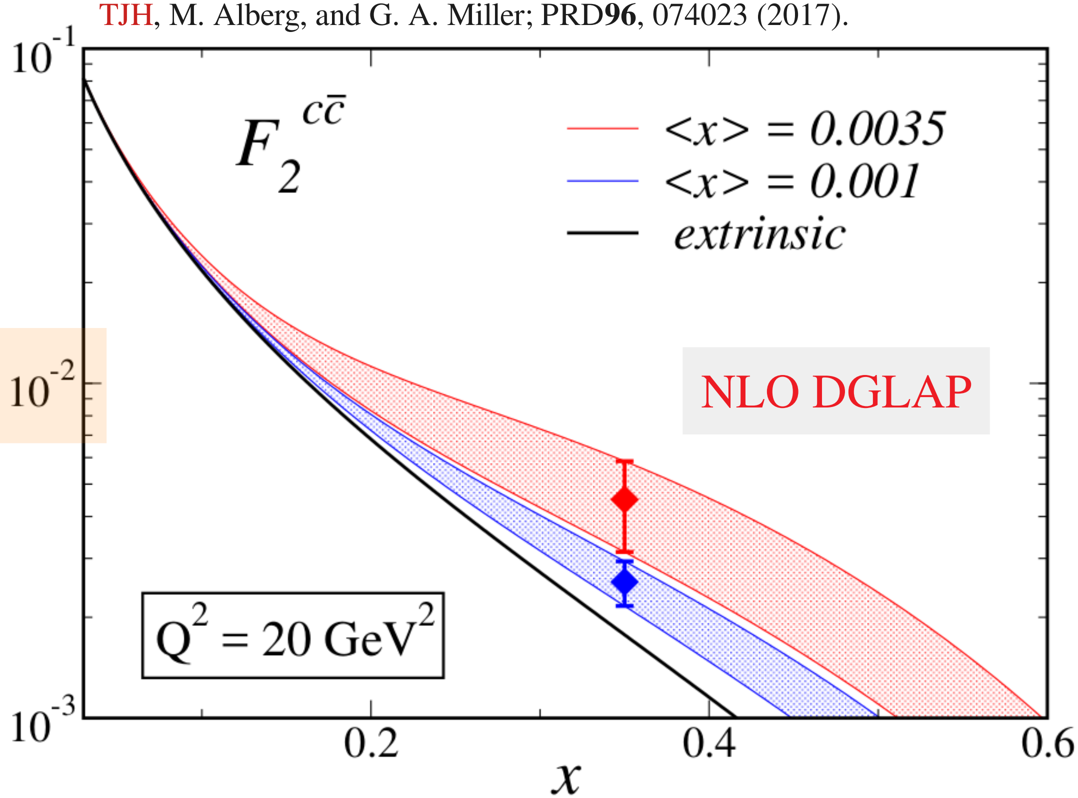
Brodsky et al.; PLB**93** (1980) 451.
TJH, Londergan, Melnitchouk; PRD**89** (2014) 7, 074008.



Nature 608 (2022) 7923, 483.

- recent NNPDF analysis claims evidence; nominal size, $\langle x \rangle_{c^+}(Q = 1.51\text{ GeV}) = [0.62 \pm 0.28]\%$

TJH, M. Alberg, and G. A. Miller; PRD**96**, 074023 (2017).



- other recent analyses, different conclusions:

  → $\langle x \rangle_{\rm IC} < 0.1\%$ at 5σ

  Jimenez-Delgado, TJH, Londergan, Melnitchouk; PRL116 (2016).

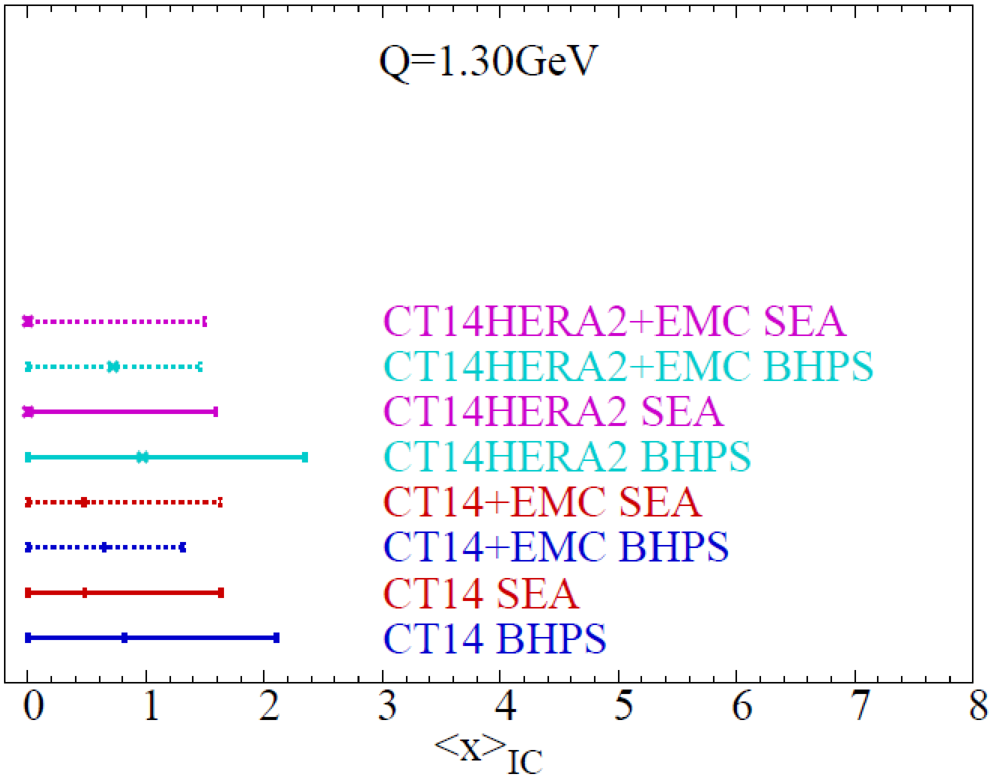
  → $\langle x \rangle_{\rm IC} \lesssim 2\%$ CT14IC, Hou et al., JHEP 02 (2018) 059.

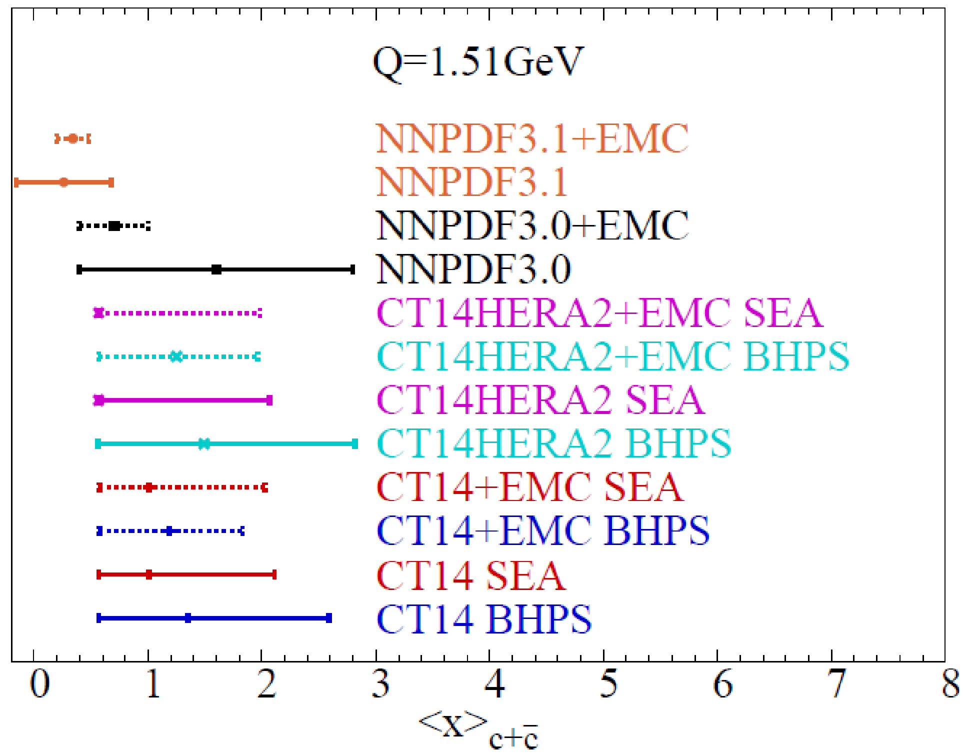
- subject remains unresolved!

  → 'IC' still lacks formal, universal def.

  → prime candidate for **EIC**; hard, but **lattice** might compute $\langle x \rangle_{c^+}$

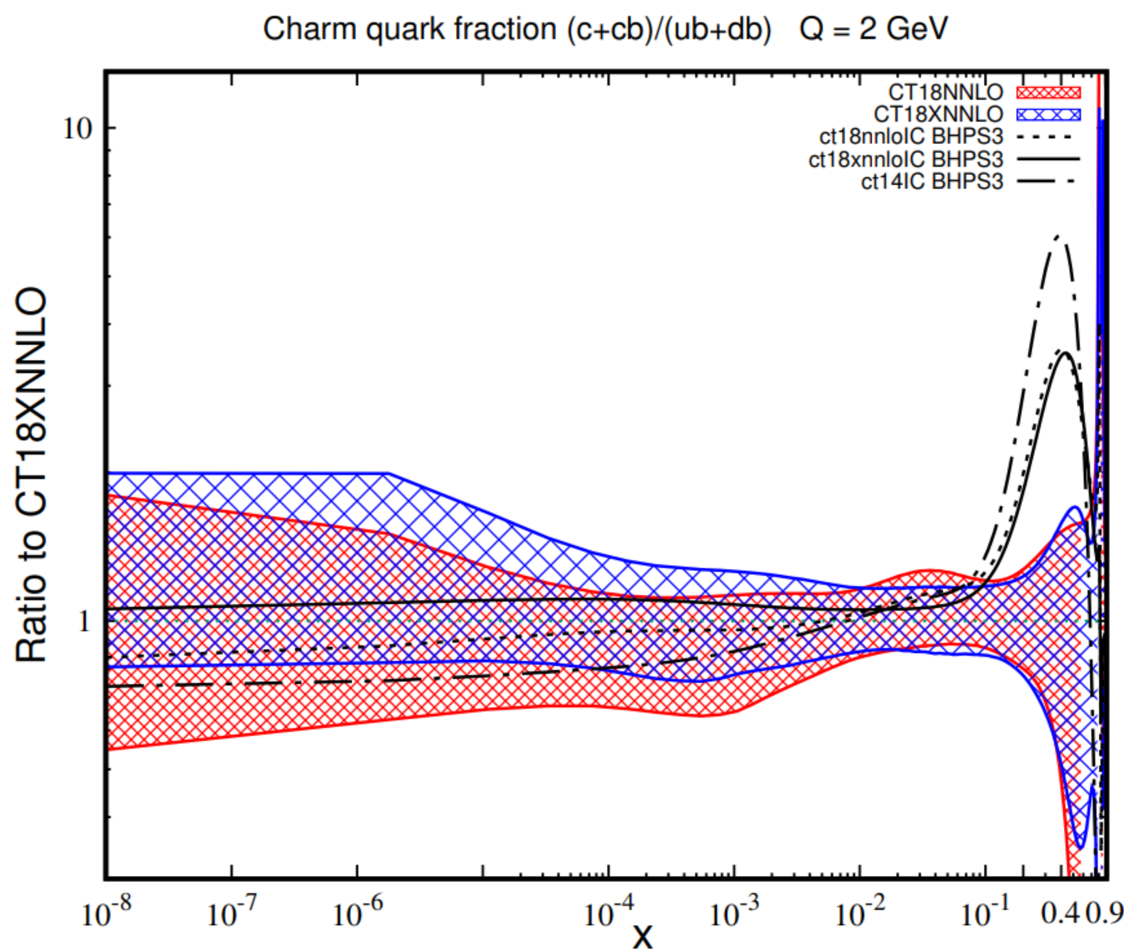
Allowed momentum fractions





Sources of differences	CT14 IC	NNPDF3.x
order	NNLO only	NLO, NNLO
Settings	90% c.l., GeV	68% c.l., GeV
LHC 8 TeV	Under validation; mild tension with HERA DIS data	Included; strong effect despite a smallish data sample
1983 EMC data included?	Only as a cross check (unknown syst. effects in EMC data)	Optional, strong effect on the PDF error

- lattice information on momentum fraction would enlighten this landscape, along with EIC



Forward Physics Facility whitepaper,

PR**968** (2022); 2109.10905

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conclusions: lattice/EIC for higher PDF precision

- PDFs **necessary for precision HEP measurements**

  → limit EW precision, sensitivity of collider-based BSM searches

  → active HEP program: higher theory accuracy; generator development

- parallel developments from **lattice, future EIC program will be instrumental**

  → lattice: challenging kinematics; flavor dependence; exotic matrix elements

  → EIC: comprehensive coverage of quark-hadron transition; QCD tests

  → must pioneer exciting synergies between QCD pheno./lattice

(this talk: mostly high-x; also opportunities at low x, high multiplicity)

- all core to understanding (nonpert.) QCD; nuclear systems

  → high-x: flavor-symmetry breaking ($\bar{d}/\bar{u}$); WF effects [$d(x \approx 1)$]

  → nuclear PDFs: EIC data; few-body moments, qPDFs from lattice

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

supplementary material

high-interest SM quantities are precision-limited by PDFs

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

ATLAS, 1701.07240

<u>for example</u>:

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

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

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

→ **large cross-cutting effort spanning theory/expt to improve**

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

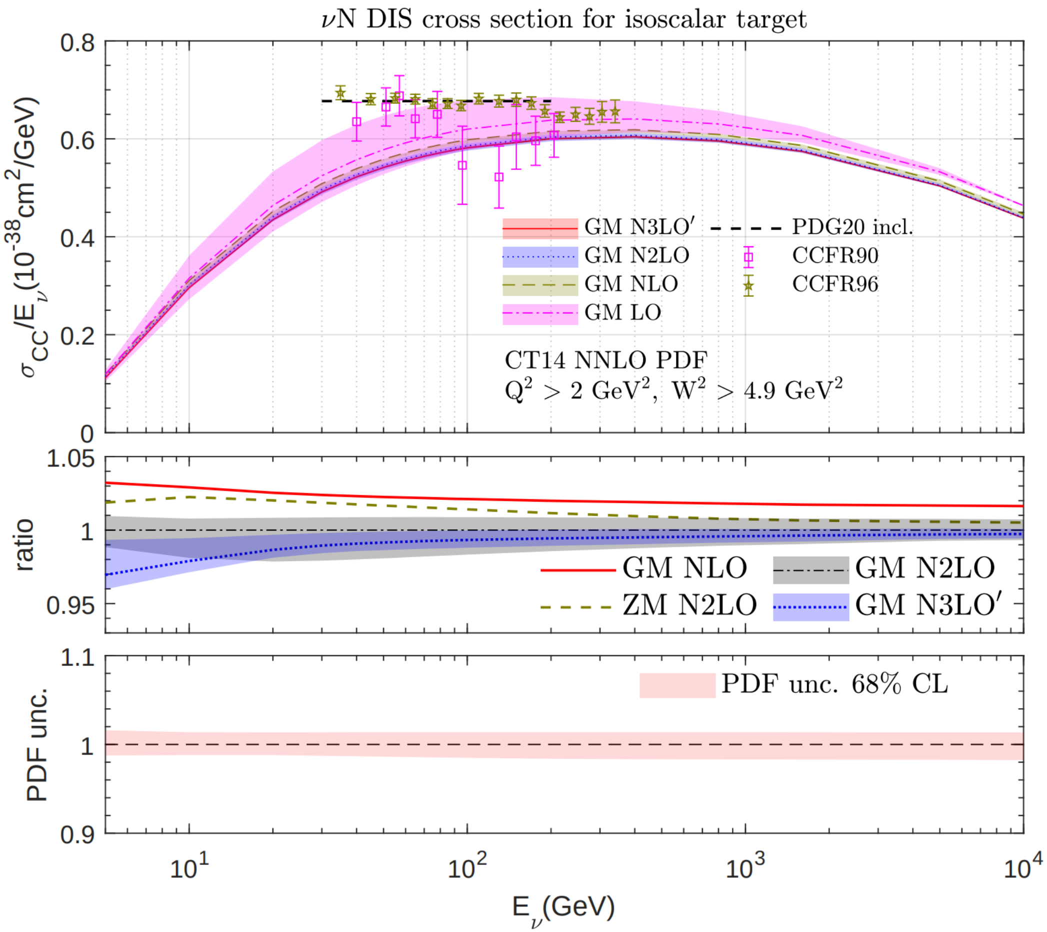
Snowmass21, Campbell et al.: 2203.11110

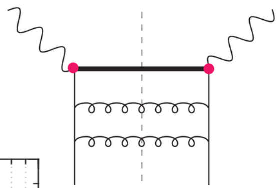
theory ingredients → higher pQCD accuracy

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

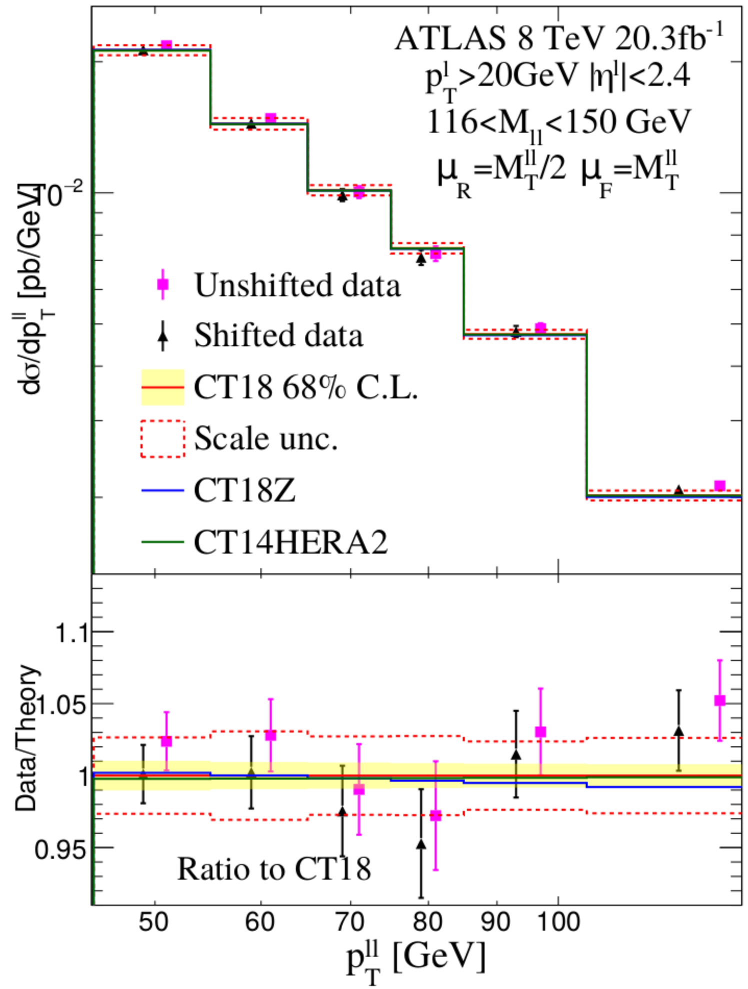
charge-current DIS

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





NNLO scale variations at LHC

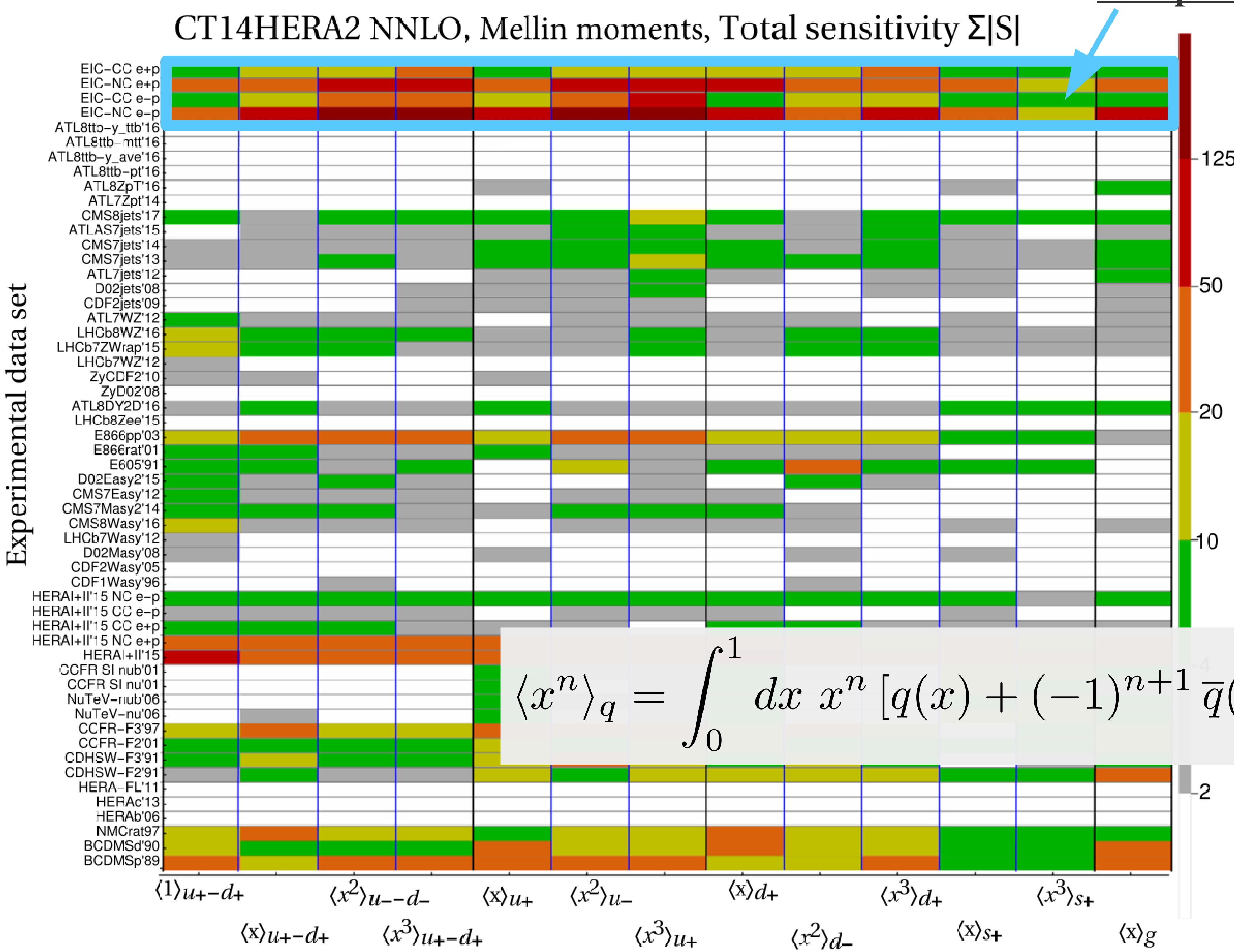


→ needed for DUNE, FASERν, EIC

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

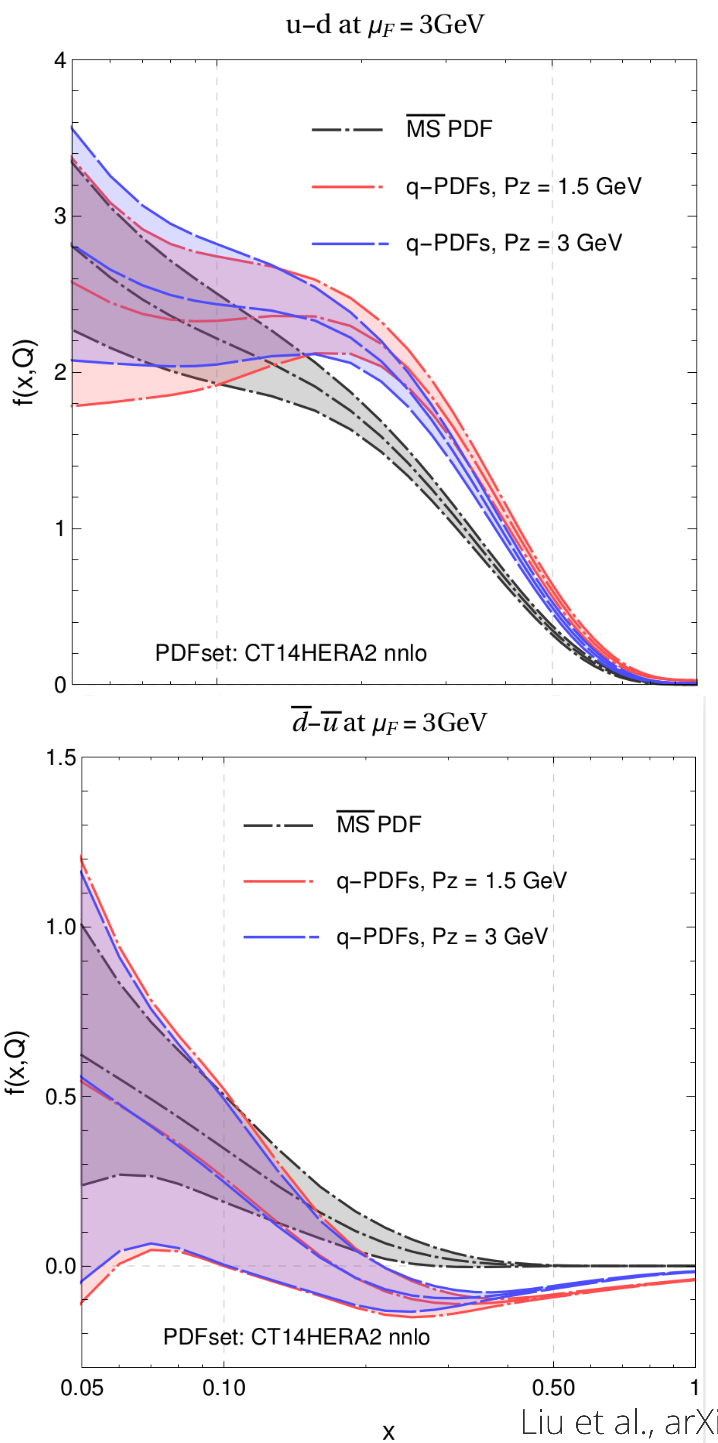
sensitivities can be aggregated for direct comparisons of exps

→ EIC stronly sensitive to PDF Mellin moments; lattice benchmarks



$$\langle x^n \rangle_q = \int_0^1 dx \; x^n \left[q(x) + (-1)^{n+1} \, \overline{q}(x) \right]$$

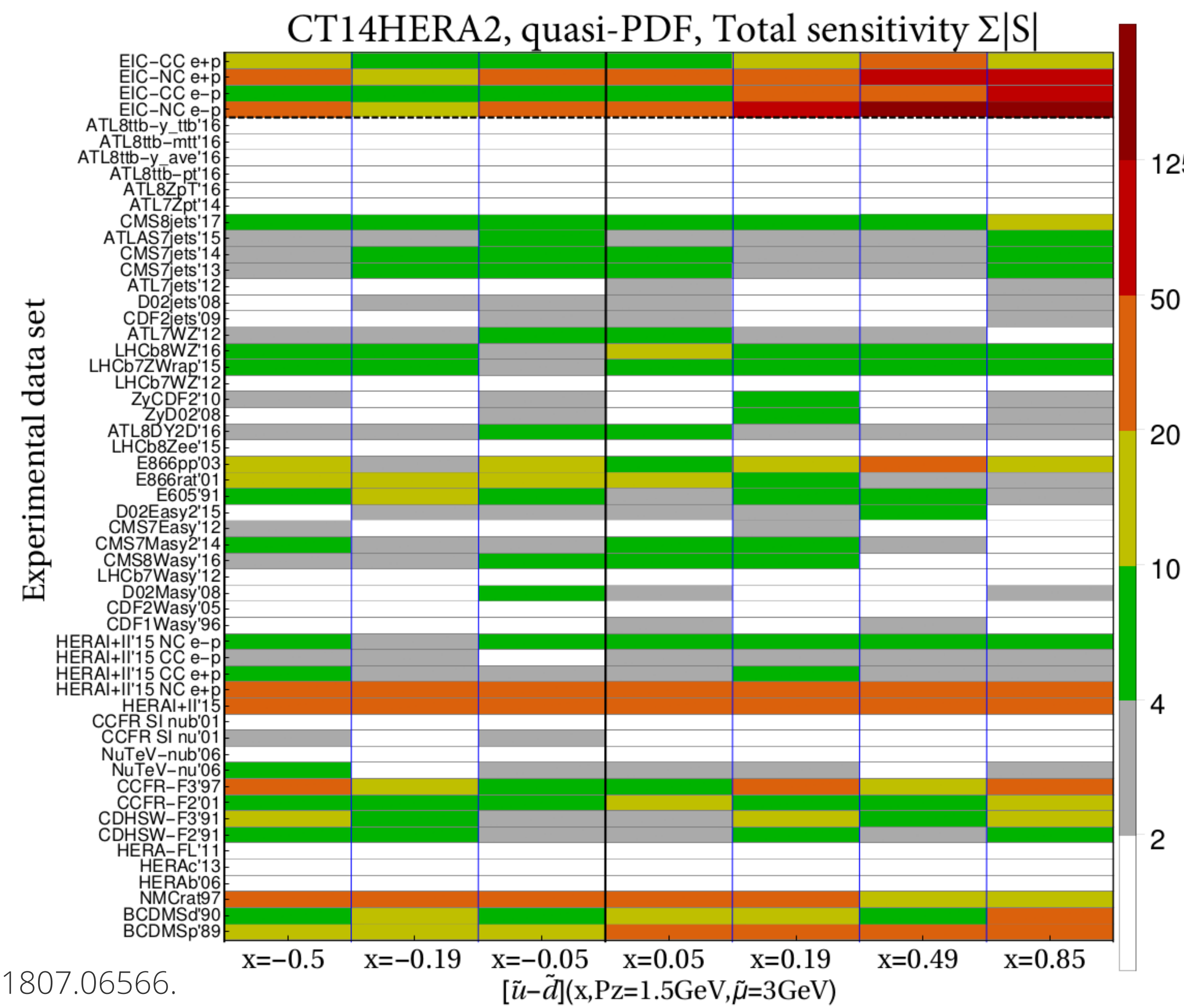
total sensitivity to matched quasi-PDFs



$$\bar{q}(x) = -q(-x) \;\rightarrow$$

$$q(x) \equiv \begin{cases} u(x) - d(x), & x > 0 \\ \bar{d}(|x|) - \bar{u}(|x|), & x < 0 \end{cases}$$

$$P_z = 1.5\,\text{GeV};\; \mu_F = 3\,\text{GeV}$$



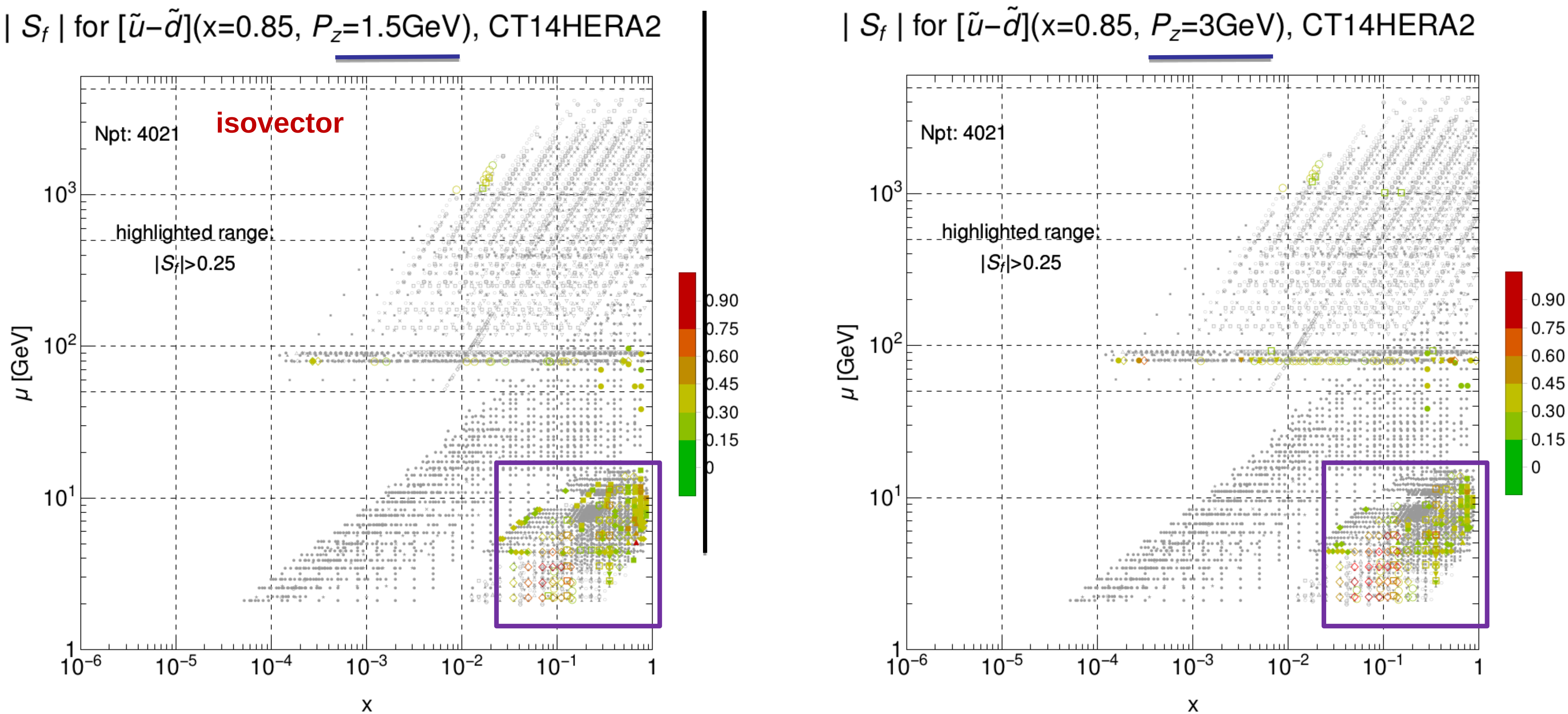
Liu et al., arXiv:1807.06566.

- Recovering PDFs from qPDFs requires the inversion of still-developing *matching relations*,

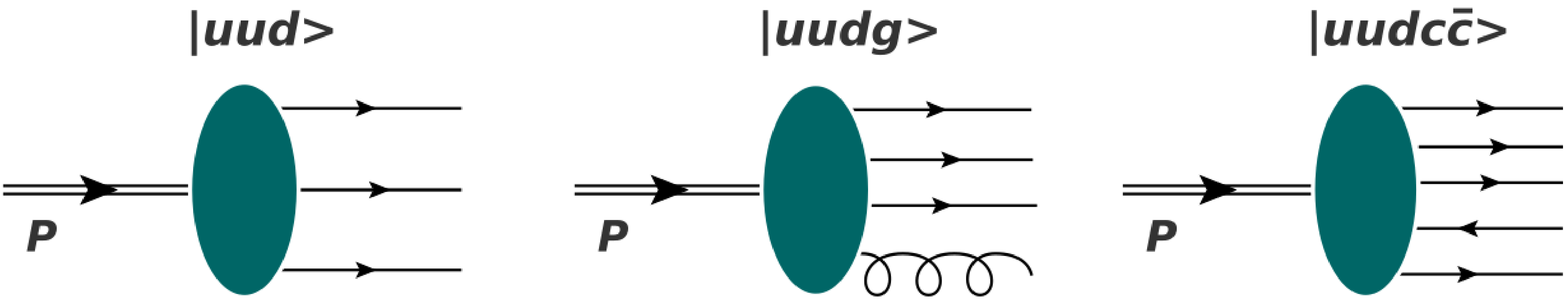
$$\widetilde{q}(x, P_z, \widetilde{\mu}) = \int dy\, Z\left(\frac{x}{y}, \frac{\Lambda}{P_z}, \frac{\mu}{P_z}\right) q(y, \mu) + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2}, \frac{M^2}{P_z^2}\right)$$

qPDF　　　　ordinary PDF

- The matching formalism depends crucially on the nucleon boost, P_z; fixed-target DIS data at high x_i are mildly sensitive to this P_z dependence, and can aid theory developments in qPDFs:



BUT: nonperturbative QCD can generate a low-scale charm PDF



→ original models possessed *scalar* vertices...

- Brodsky et al. (1980): intrinsic charm – 'BHPS' and other models

$$P(p \to uudc\bar{c}) \sim \left[M^2 - \sum_{i=1}^{5} \frac{k_{\perp i}^2 + m_i^2}{x_i}\right]^{-2}$$

→ produces *intrinsic* PDF, $c^{\rm IC}(x) = \bar{c}^{\rm IC}(x)$

Brodsky, Hoyer, Peterson, Sakai; Phys. Lett. **B93** (1980) 451.

- Blümlein (2015):

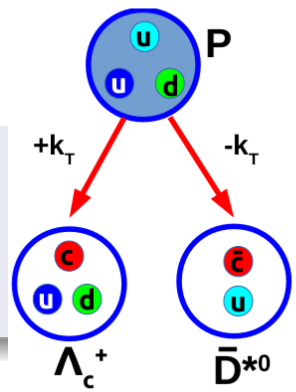
$$\tau_{life} = \frac{1}{\sum_i E_i - E} = \frac{2P}{\left(\sum_{i=1}^{5} \frac{k_{\perp i}^2 + m_i^2}{x_i} - M^2\right)}\Bigg|_{\sum_j x_j = 1} \quad \textbf{vs.} \quad \tau_{int} = \frac{1}{q_0}$$

→ comparison constrains $x - Q^2$ space over which IC is observable

Blumlein; Phys. Lett. **B753** (2016) 619.

meson-baryon models (MBM)

- we implement a framework which *conserves* **spin/parity**



- **nonperturbative** mechanisms are needed to break

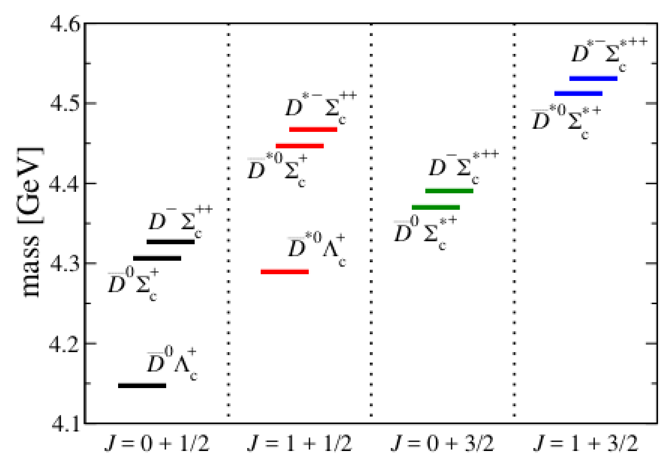
$$c(x, Q^2 \leq m_c^2) = \bar{c}(x, Q^2 \leq m_c^2) = 0!$$

We build an **EFT** which connects IC to properties of the hadronic spectrum: [**TJH, J. T. Londergan and W. Melnitchouk, Phys. Rev. D89, 074008 (2014).**]

- $|N\rangle \;=\; \sqrt{Z_2}\;|N\rangle_0 \;+\; \sum_{M,B} \int dy\, \boldsymbol{f_{MB}(y)}\, |M(y); B(1-y)\rangle$

$$y = k^+/P^+:\; k \text{ meson},\; P \text{ nucleon}$$

$$c(x) = \sum_{B,M} \left[\int_x^1 \frac{d\bar{y}}{\bar{y}}\, f_{BM}(\bar{y})\, c_B\left(\frac{x}{\bar{y}}\right) \right]$$



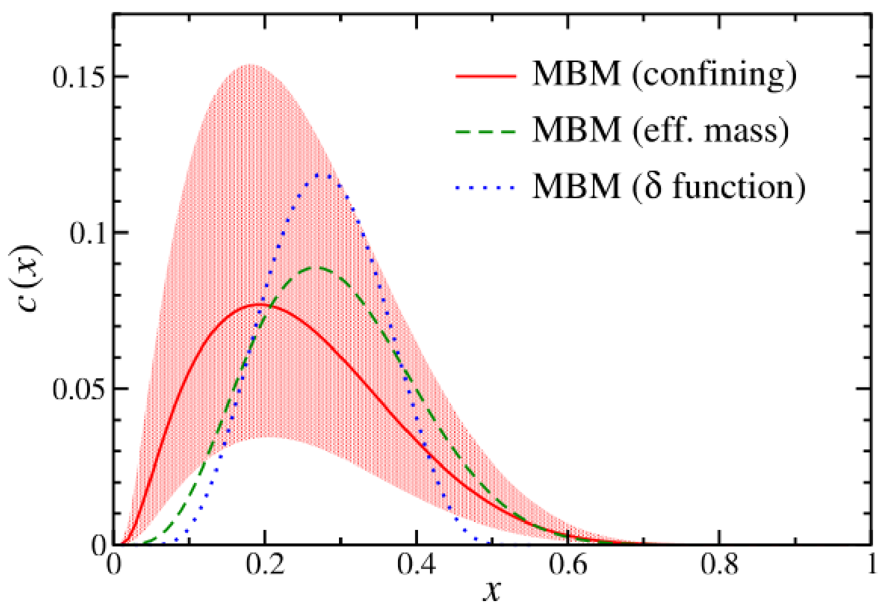
- a similar *convolution* procedure may be used for $\bar{c}(x)$ . . .

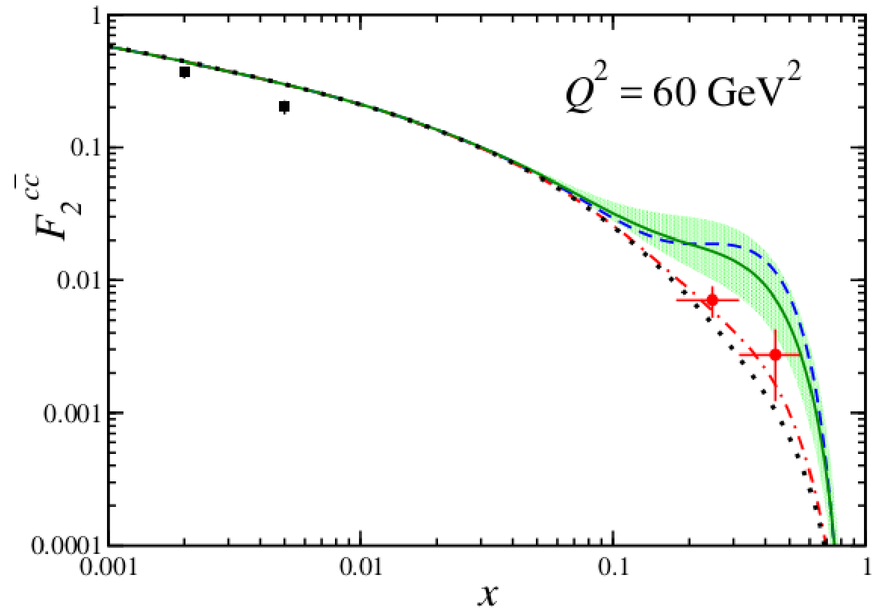
the resulting intrinsic charm depends on UV scales

- tune **universal** cutoff $\Lambda = \hat{\Lambda}$ to fit **ISR** $pp \to \Lambda_c X$ collider data

multiplicities, **momentum sum**:

$$\langle n \rangle_{MB}^{(\mathrm{charm})} = 2.40\% \,{}^{+2.47}_{-1.36}; \qquad P_c := \langle x \rangle_{\mathrm{IC}} = 1.34\% \,{}^{+1.35}_{-0.75}$$





$$F_2^{c\bar{c}}(x, Q^2) = \frac{4x}{9}\left[c(x,Q^2) + \bar{c}(x,Q^2)\right]$$

$\to$ evolve to EMC scale, $Q^2 = 60$ GeV^2

low-x H1/ZEUS data check *massless* **DGLAP** evolution

e.g., a 1st comprehensive fit including data on $F_2^{c\bar{c}}$

P. Jimenez-Delgado, TJH, J. T. Londergan and W. Melnitchouk; PRL 114, no. 8, 082002 (2015).

26 sets:

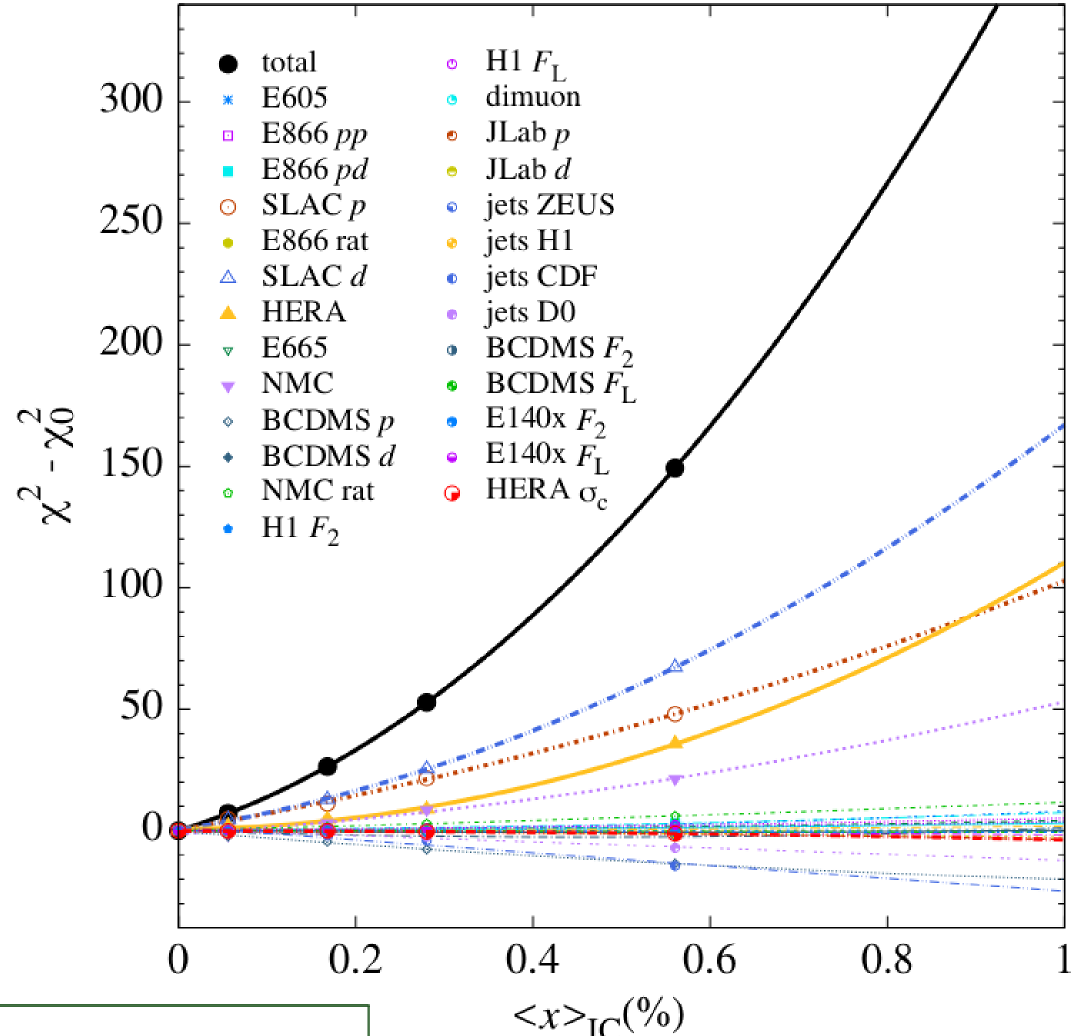
$$N_{dat} = 4296$$

$Q^2 \geq 1$ GeV^2

$W^2 \geq 3.5$ GeV^2

$\Longrightarrow$

** **HTs, TMCs, smearing...**



- constrain: $\boxed{\langle x\rangle_{\rm IC} = \int_0^1 dx\, x \cdot [c+\bar{c}](x)}$ ... '*total* IC momentum'

without the EMC data on $F_2^{c\bar{c}}$

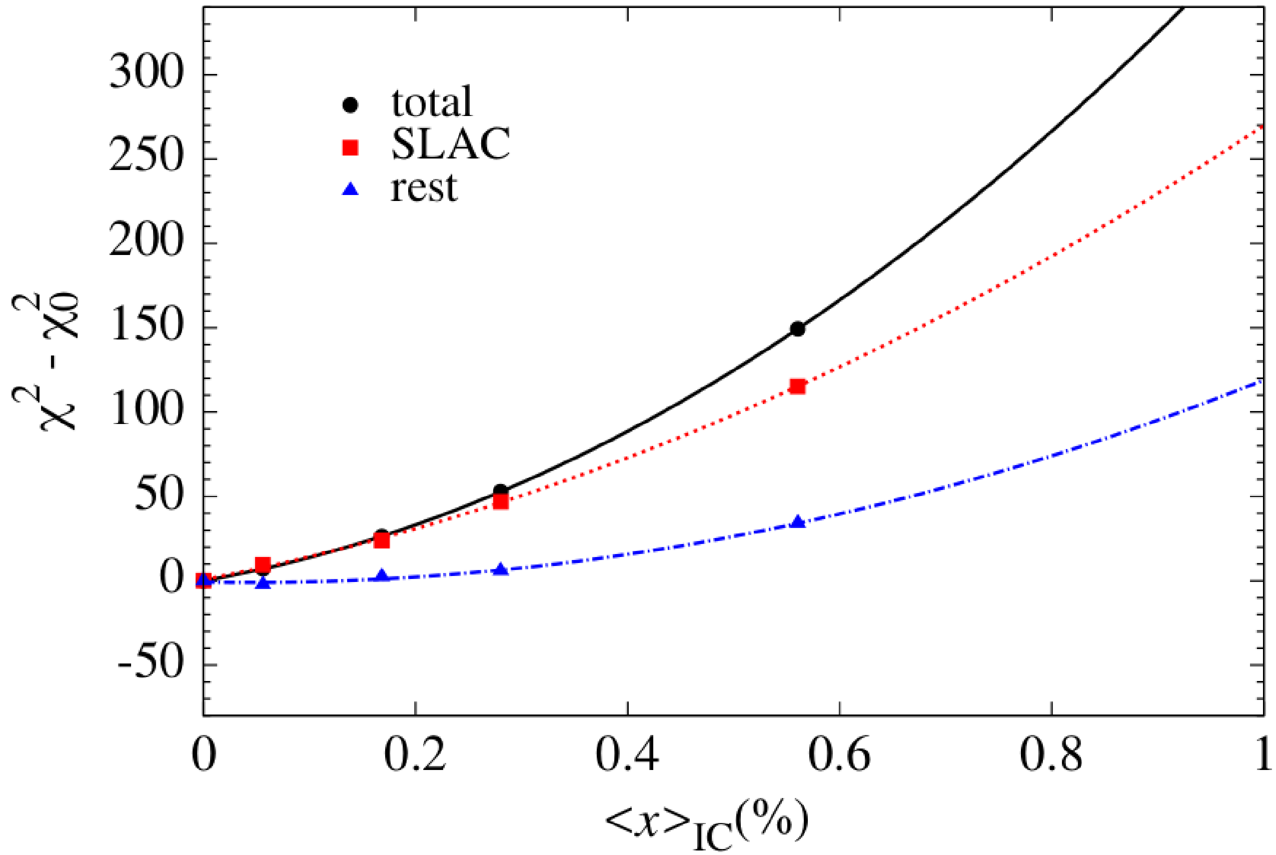
IC is severely constrained via mom. sum rule via light-quark degrees of freedom

SLAC ep, ed data!

$\langle Q^2 \rangle \sim 15$ GeV^2

$0.06 \leq x \leq 0.9$

$(\chi^2/N_{dat} \sim 1.25)$



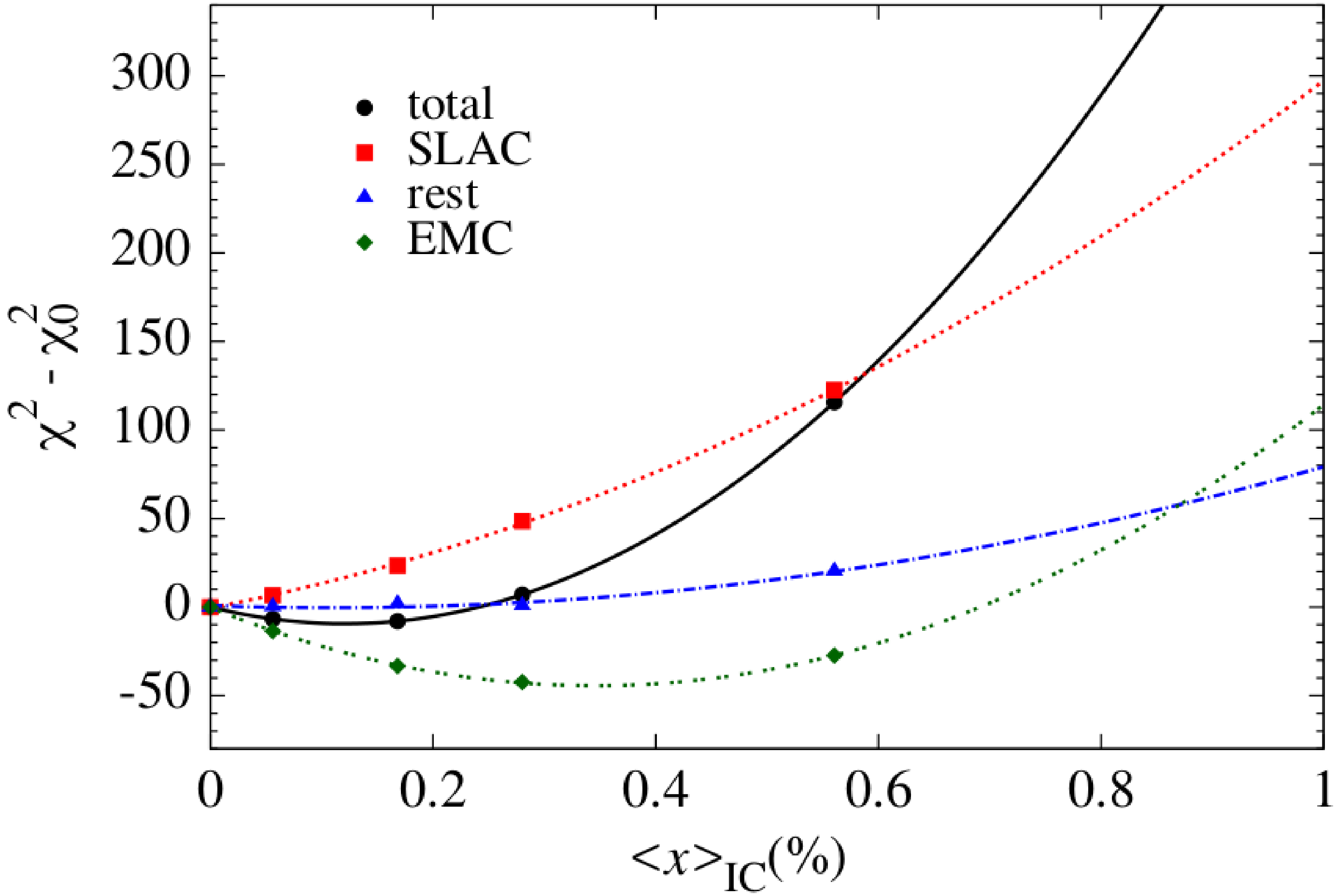
'SLAC + REST' $\Longrightarrow$ $\langle x \rangle_{\rm IC} < 0.1\%$; at 5σ !

'REST' only $\Longrightarrow$ $\langle x \rangle_{\rm IC} < 0.1\%$; at 1σ

cf. $\langle x \rangle_{\rm IC} \lesssim 2\%$ CT14 fits with IC [Hou et al., arXiv:1707.00657]

N.B.: different *tolerances*: $\Delta\chi^2 = 1$ vs. $\Delta\chi^2_{CT} = 100$

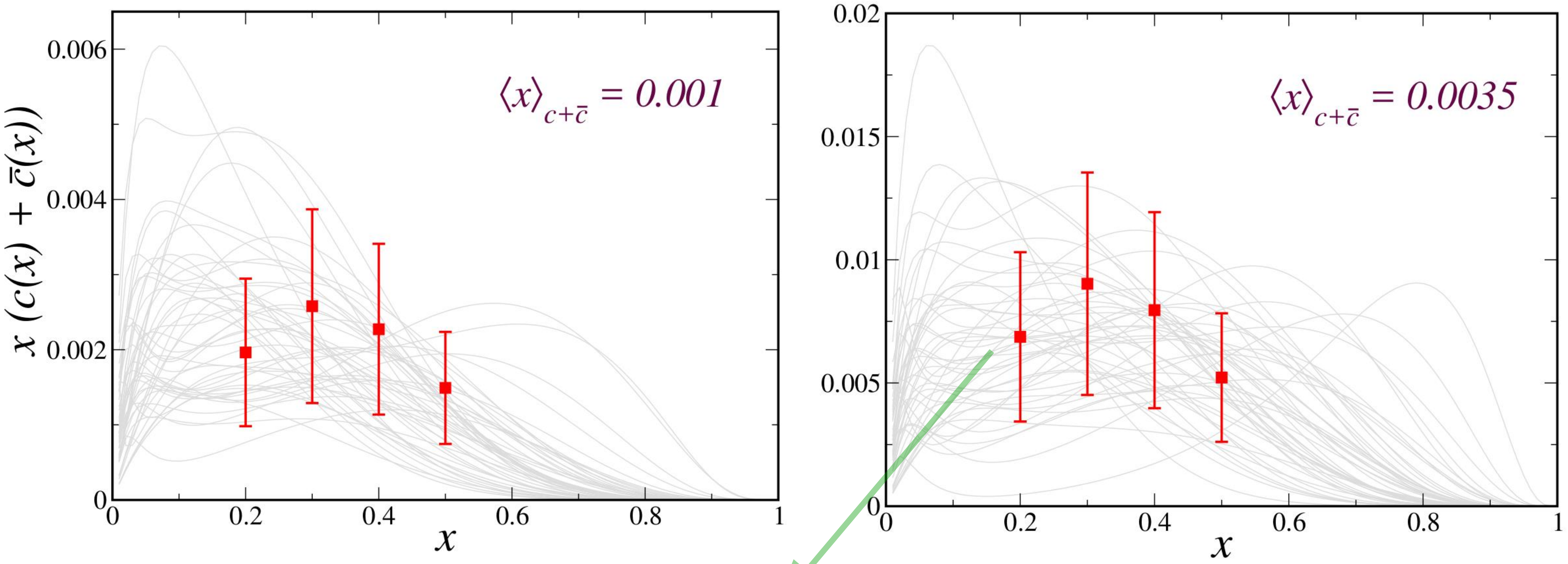
the EMC data prefer modest IC, but do not fit well...



EMC alone: $\langle x \rangle_{\mathrm{IC}} = 0.3 - 0.4\%$

+ SLAC/'REST': $\langle \boldsymbol{x} \rangle_{\mathbf{IC}} = \mathbf{0.13 \pm 0.04\%}$

...but $F_2^{c\bar{c}}$ poorly fit — $\chi^2 \sim 4.3$ per datum!

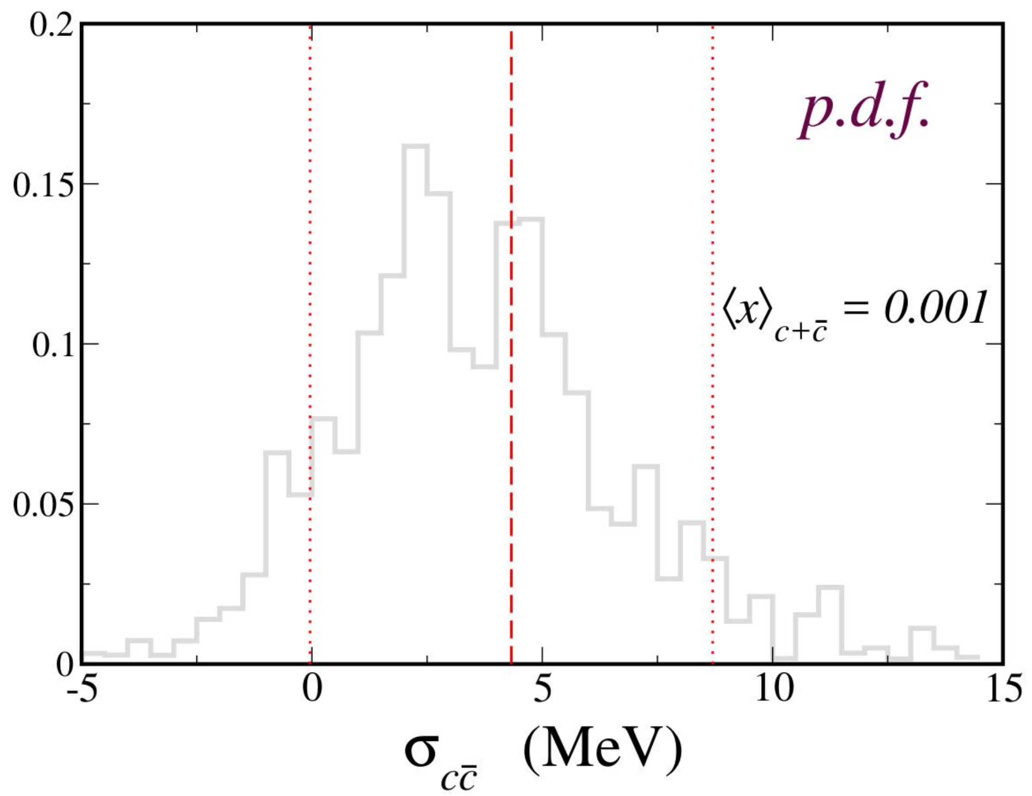


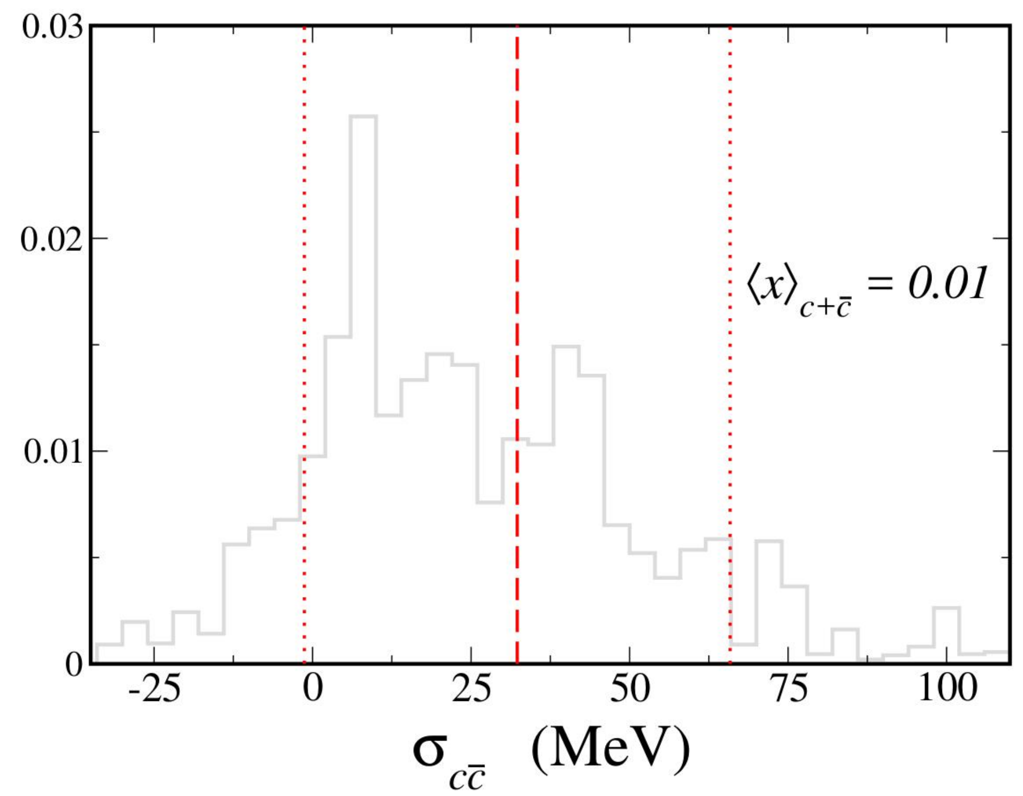
- we constrain the model with hypothetical **pseudo-data** (taken from the \`confining' MBM) of a given $\langle x \rangle_{\mathrm{IC}} \pm 50\%$

(input data normalizations are inspired by the just-described global analysis)

$$\begin{cases} \langle x \rangle_{\mathrm{IC}} = 0.001 & \text{[upper limit tolerated by the full fit/dataset]} \\ \langle x \rangle_{\mathrm{IC}} = 0.0035 & \text{[central value preferred by EMC data alone]} \end{cases}$$

- rather than traditional χ^2 minimization, the model space is instead explored using **Bayesian methods**





$$\sigma_{c\bar{c}} = 4.3 \pm 4.4\,\mathrm{MeV} \quad (\gamma = 3 \text{ interaction}) \quad \sigma_{c\bar{c}} = 32.3 \pm 33.6\,\mathrm{MeV}$$

- we find better concordance cf. existing lattice determinations, for somewhat larger IC magnitudes; also, close correlation with the DIS sector –

$$\sigma_{c\bar{c}} = 94\,(31)\,\mathrm{MeV}$$ (χQCD)

$$= 67\,(34)\,\mathrm{MeV}$$ (MILC)

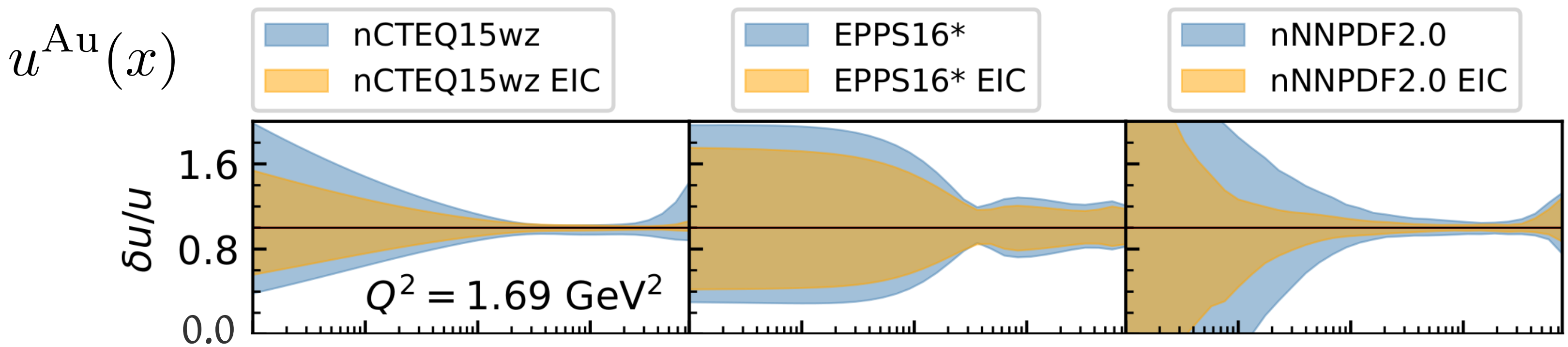
$$\sigma_{c\bar{c}} = 79\ (21)\binom{12}{8}\,\mathrm{MeV}$$ (AR)[1]

[1]Abdel-Rehim et al., Phys. Rev. Lett. **116**, 252001 (2016).

<u>bigger point</u>: lattice calculations can directly inform the IC PDF question

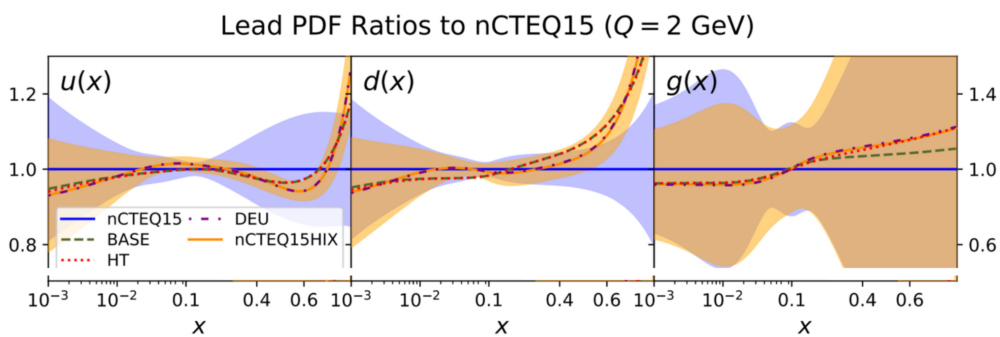
understanding nuclear effects

→ 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*:



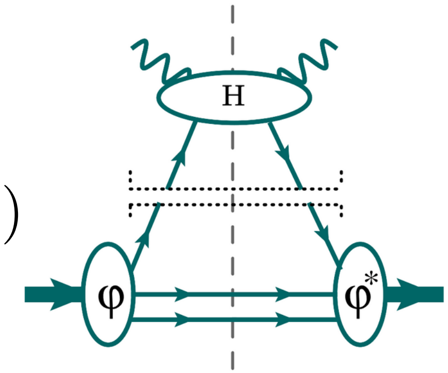
Segarra et al., PRD **103** (2021) 11, 114015

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

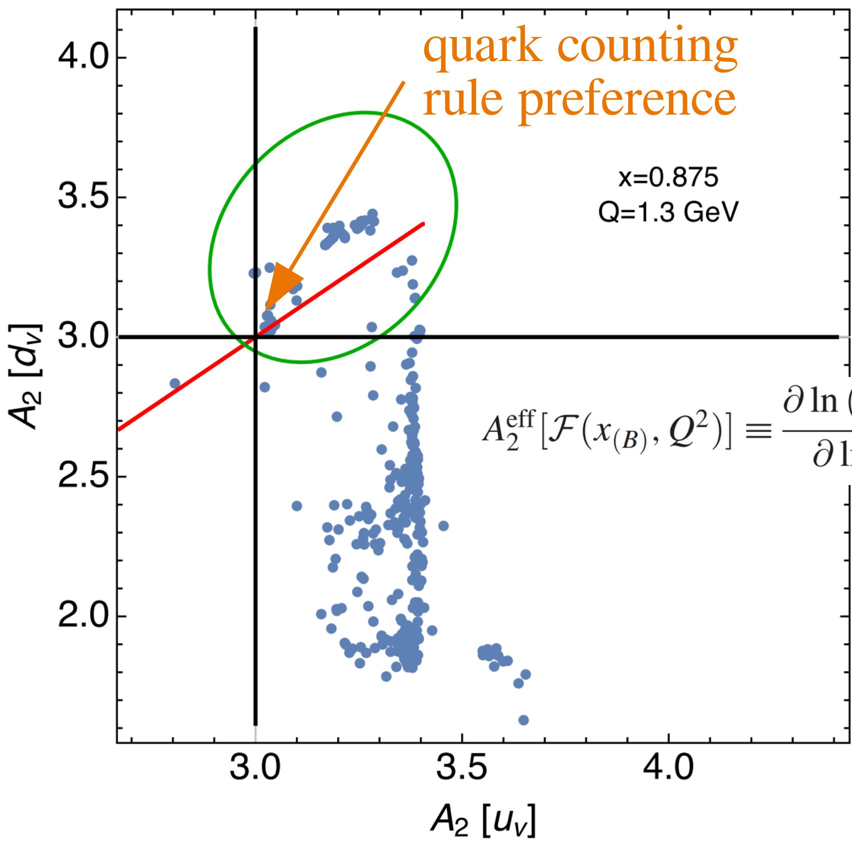
- nuclear *A* dependence requires copious data: **high luminosity essential**

extracting high-x dependence in PDF fits

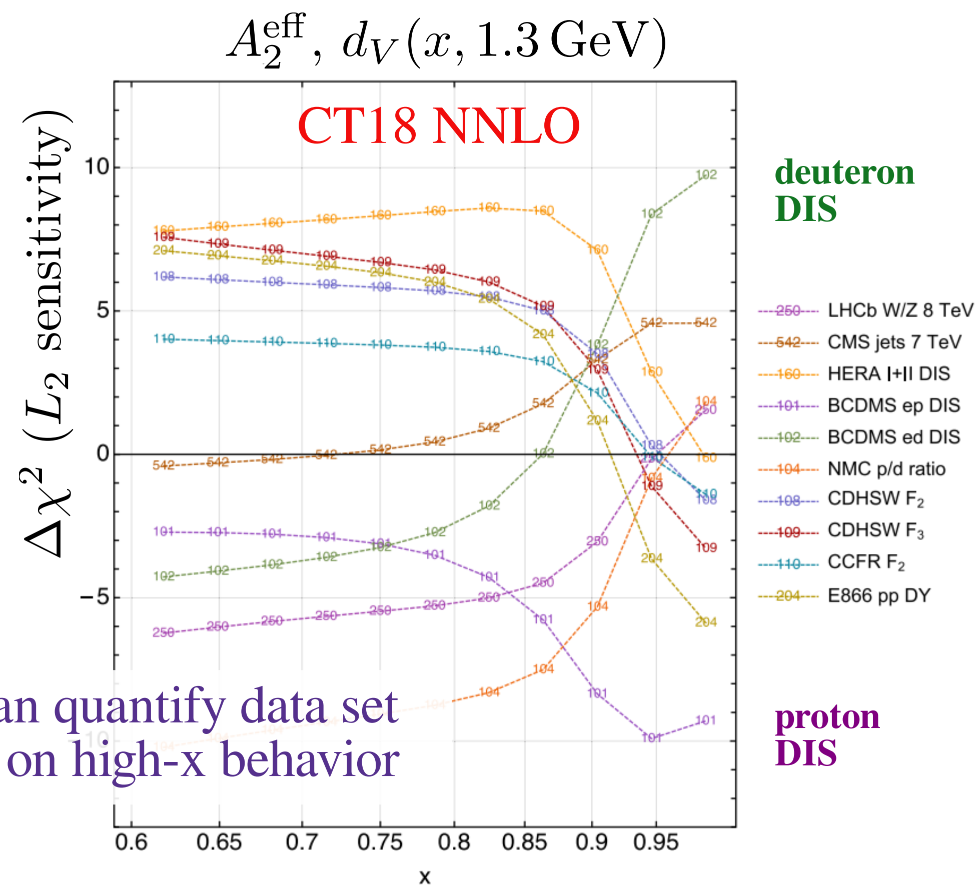
- high-x PDFs, ratios [e.g., d/u] connected to details of proton WF
- behavior at $x \to 1$ an important nonpert. discriminator
- CT18, parametrize $f_{a/A}(x, Q_0^2) = x^{A_{1,a}}(1-x)^{A_{2a}} \times \Phi_a(x)$



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



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



we can quantify data set pulls on high-x behavior

electroweak precision: photon PDF

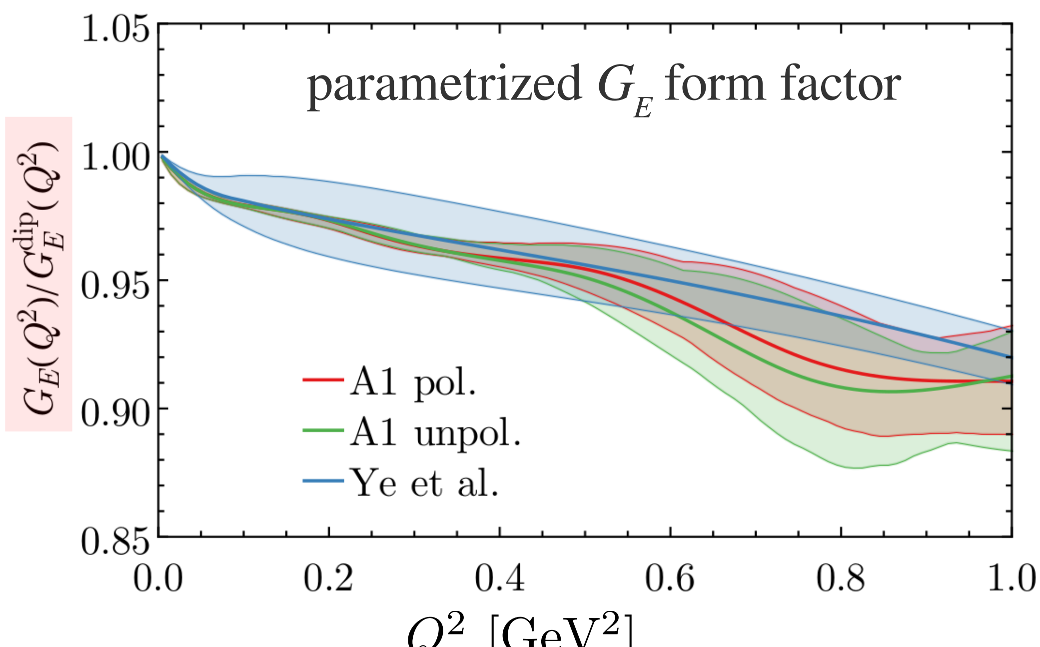
- depends on nonperturbative inputs [kinematical cuts alone can't avoid this]

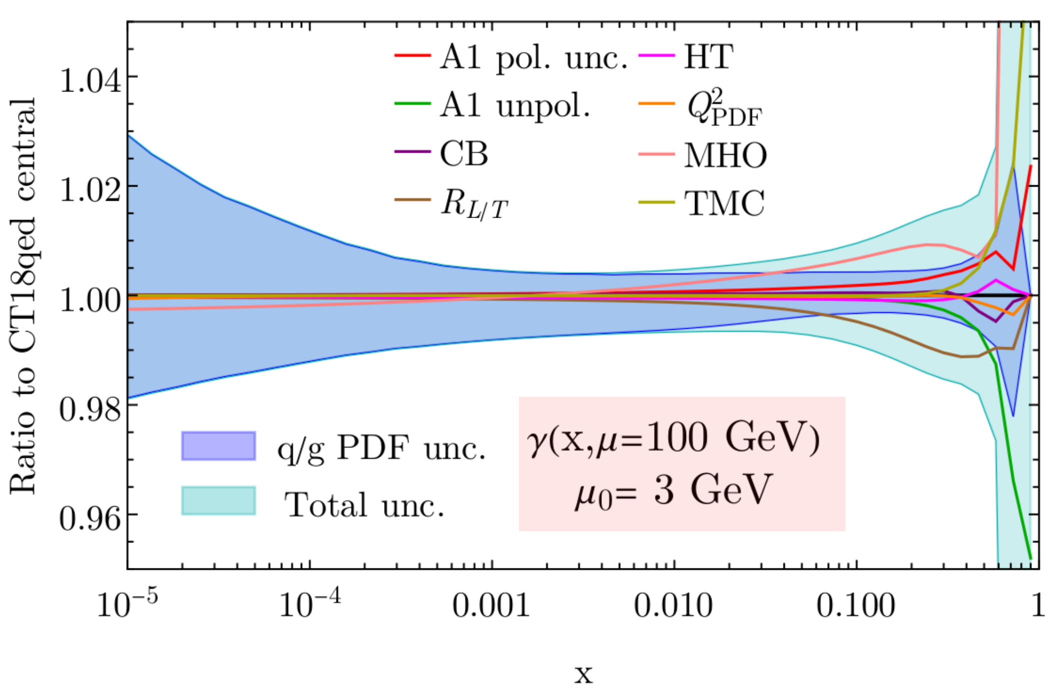
- integrated proton SFs include contributions from low Q, moderate x

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

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

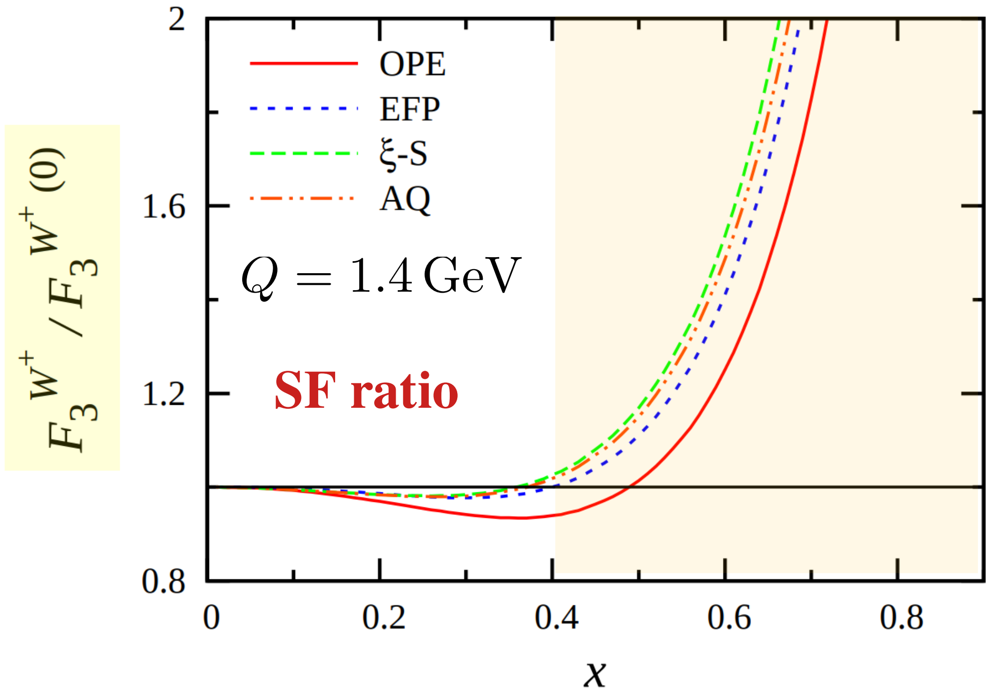
[AND **quark-gluon PDFs**, uncertainties] →





higher luminosity: understand power-suppressed QCD corrections

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



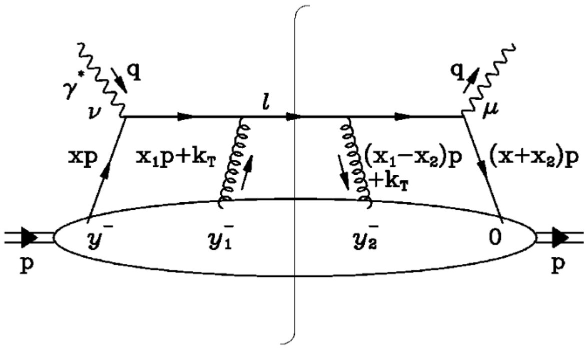
potentially large, $\sim 1/Q^2$
large-x effects

crucial for precision in DIS

Brady, Accardi, TJH, Melnitchouk:
PRD**84** (2011) 9, 074008

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

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



X. Guo, PRD**58**, 114033 (1998).

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

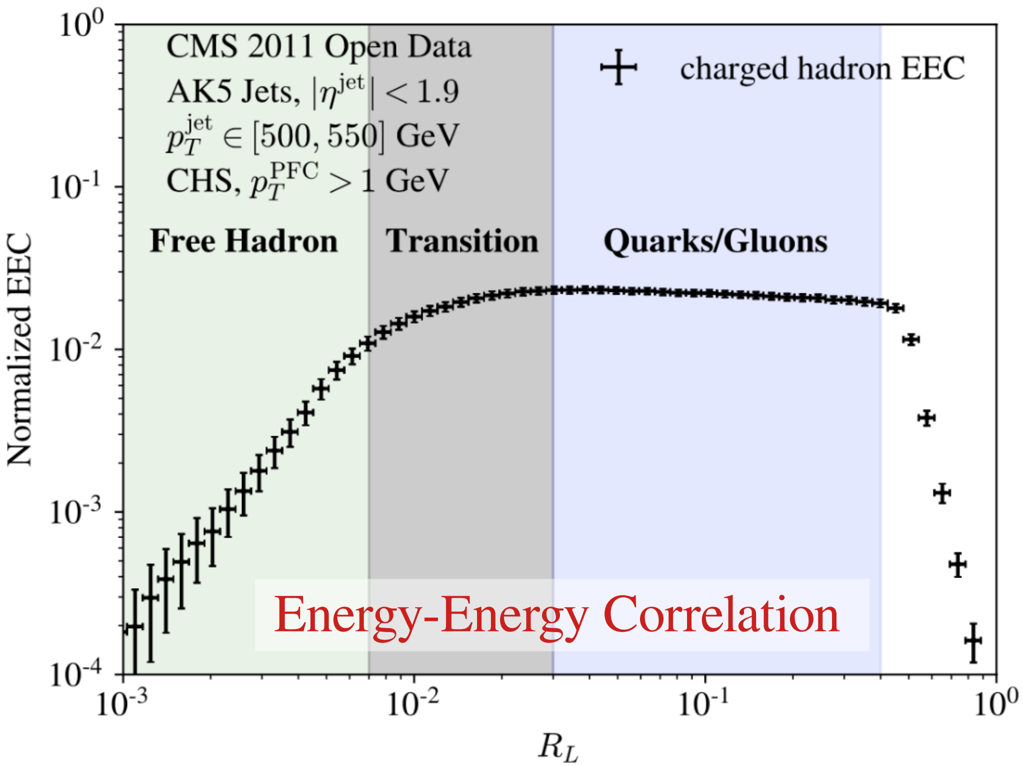
$$\langle p_T^2\rangle = \int dp_T^2 p_T^2 \frac{d\sigma}{dx_B dQ^2 dp_T^2} \Big/ \frac{d\sigma}{dx_B dQ^2}$$

sensitivity to possible ‘new’ QCD measurements

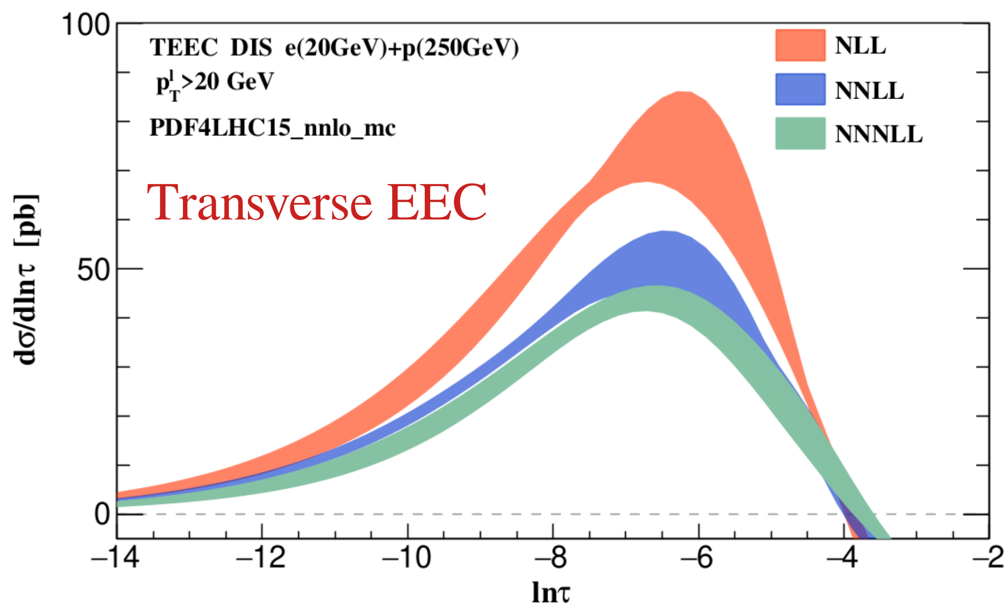
- strong interest in measurements connecting event-level observables to fundamental QCD
- e.g., QCD jets (various observables, constructions)

  → 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

EIC and SM inputs: α_s

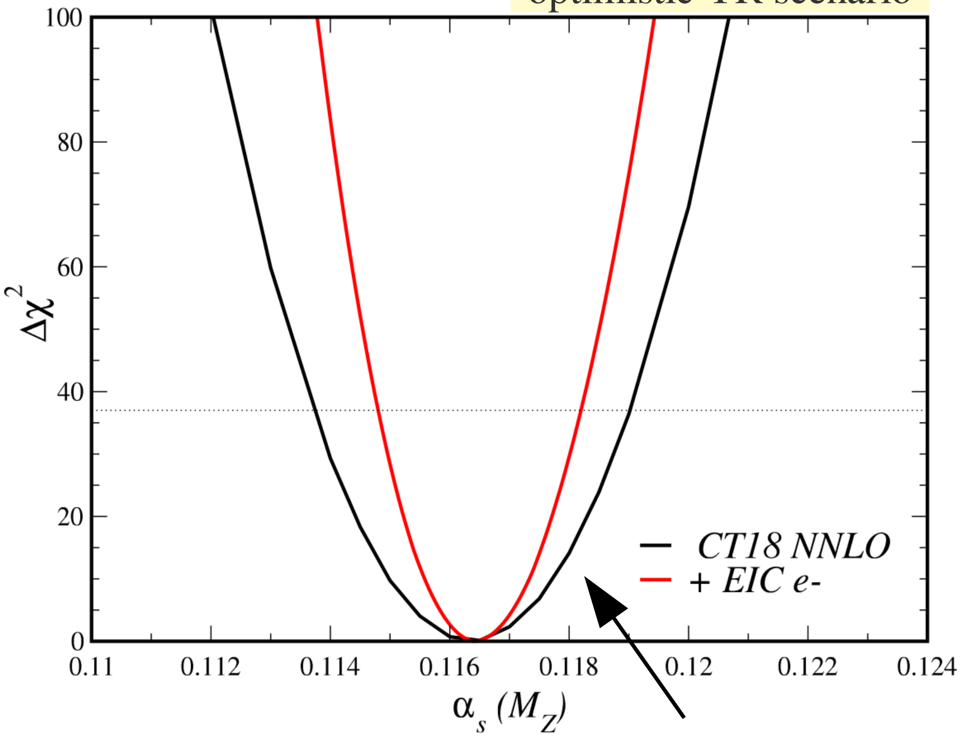
- part of moving toward N^{3}LO PDFs, precise determinations needed for α_s

similar argument for m_Q

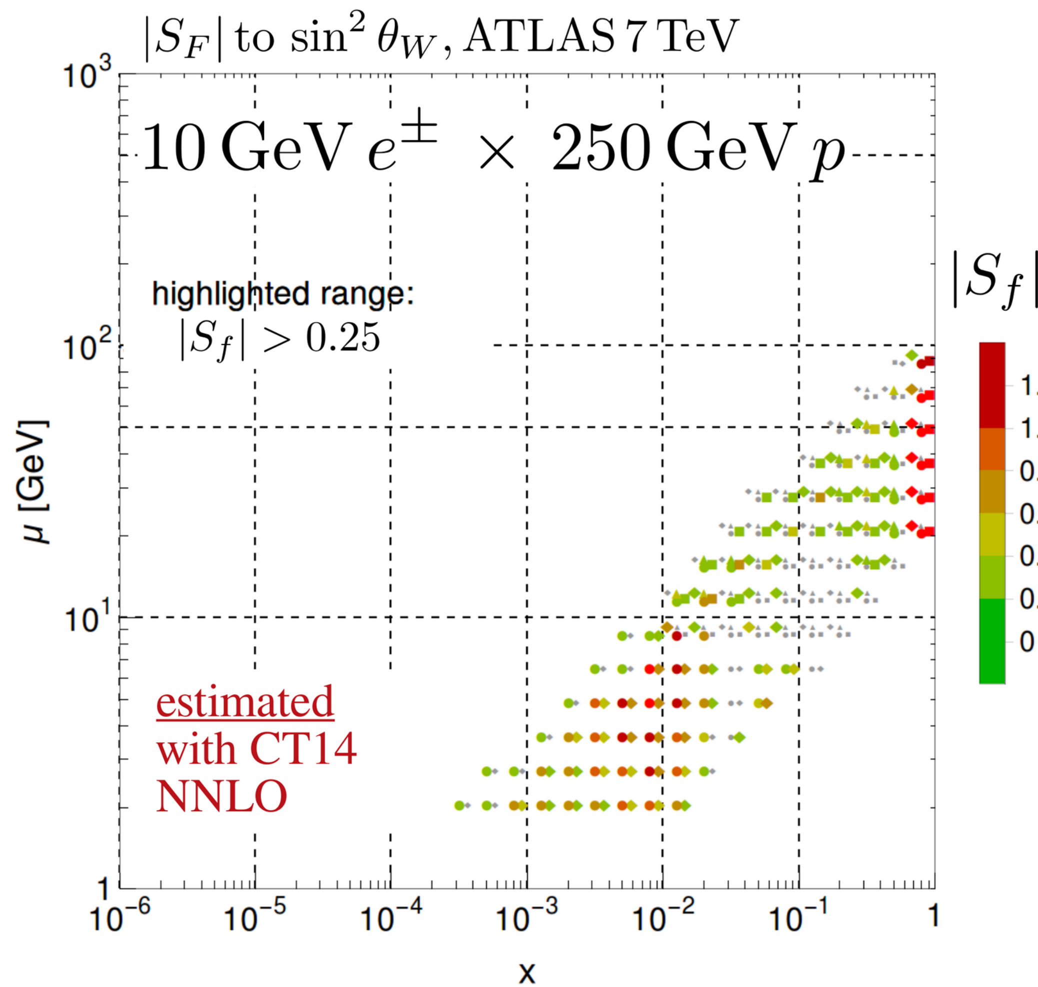
from inclusive data alone

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

"optimistic YR scenario"



~40% reduction

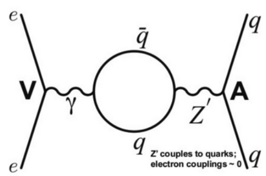


- also: precise α_s extractions based on global event shapes; N-jettiness, ${}_N$

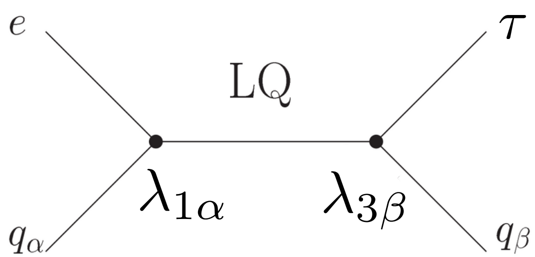
- robust PDF sensitivity to $\sin^2\theta_W$ from A_{FB}

EW and BSM opportunities

- potentially BSM-sensitive extractions of EW quark couplings, $\sin^2\theta_W$ through **parity violation**

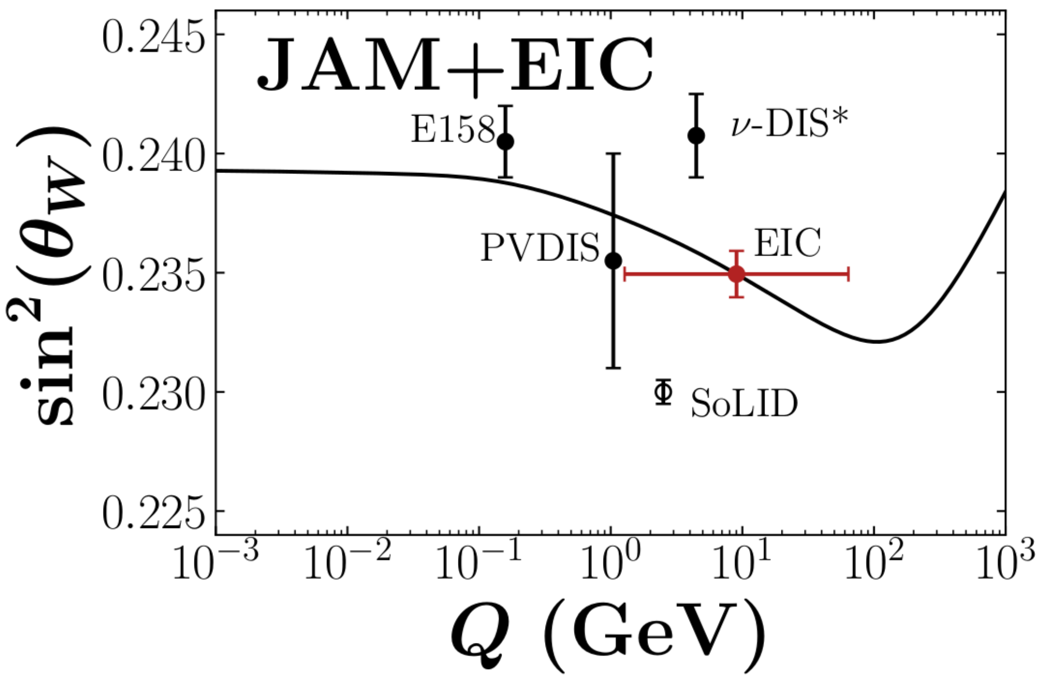


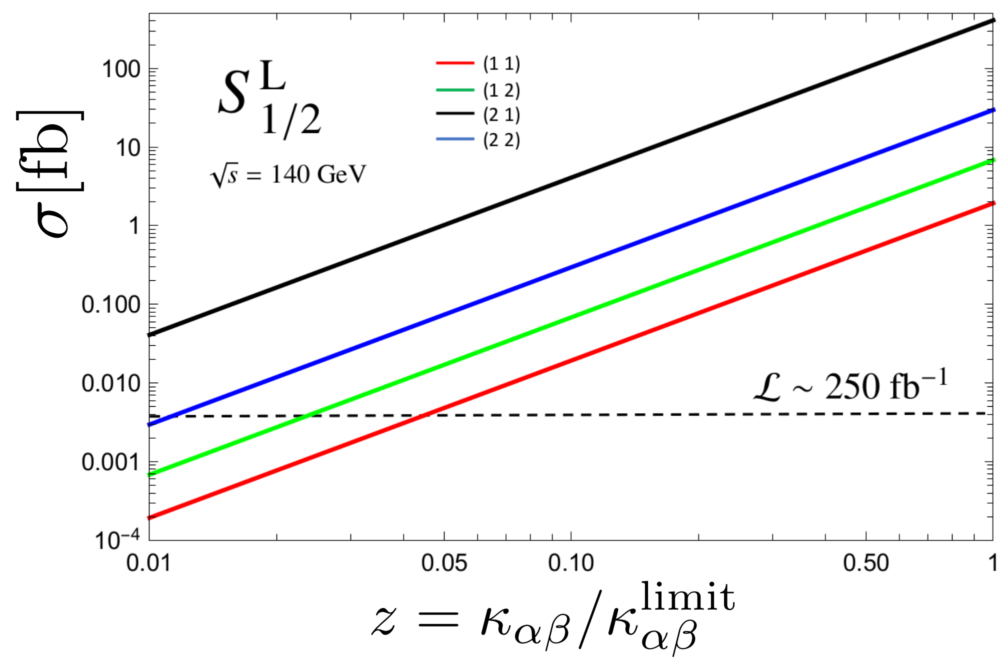
$$A^e_{\mathrm{PV}} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$



$$\kappa_{\alpha\beta} = \lambda_{1\alpha}\lambda_{3\beta}/M^2_{LQ}$$

EIC YR, 7.5.1





- more direct SM tests also possible: searches for charged-lepton flavor violation (CLFV)

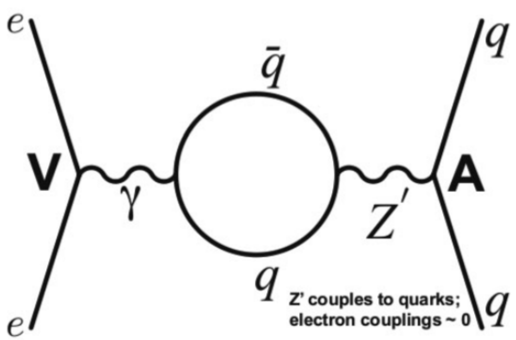
$$e^- + N \to \tau^- + X$$

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'

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

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



- 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**:

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

selects γ-Z interference diagrams!

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

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

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

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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).

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

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

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