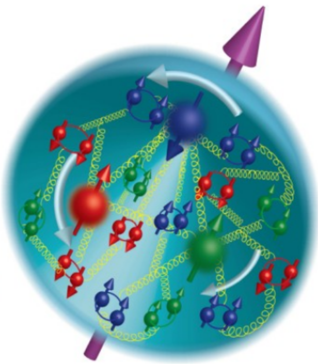
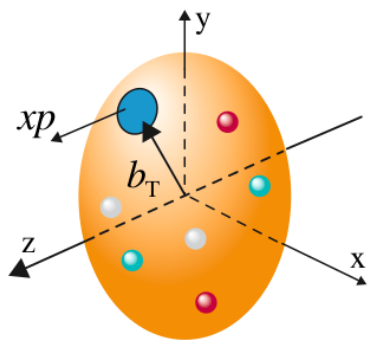
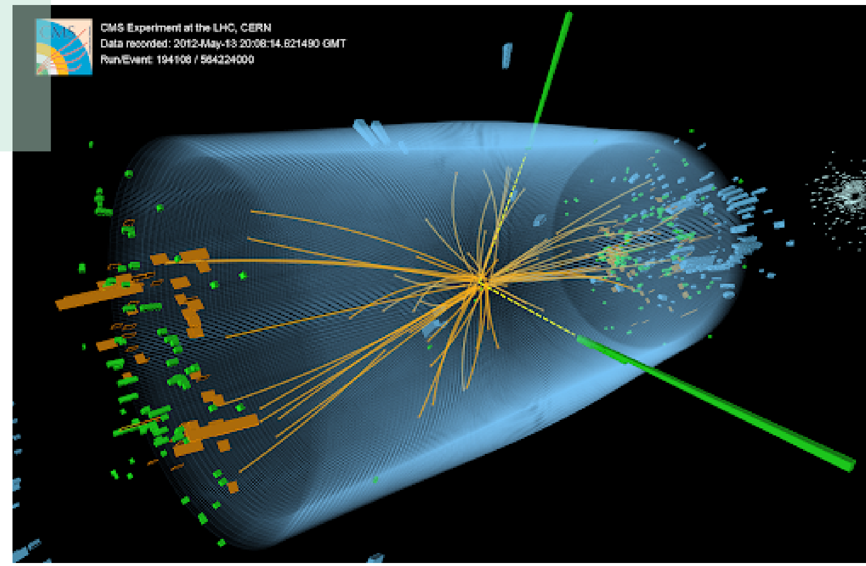
PDFs at/for the Electron-Ion Collider (EIC) and HEP implications

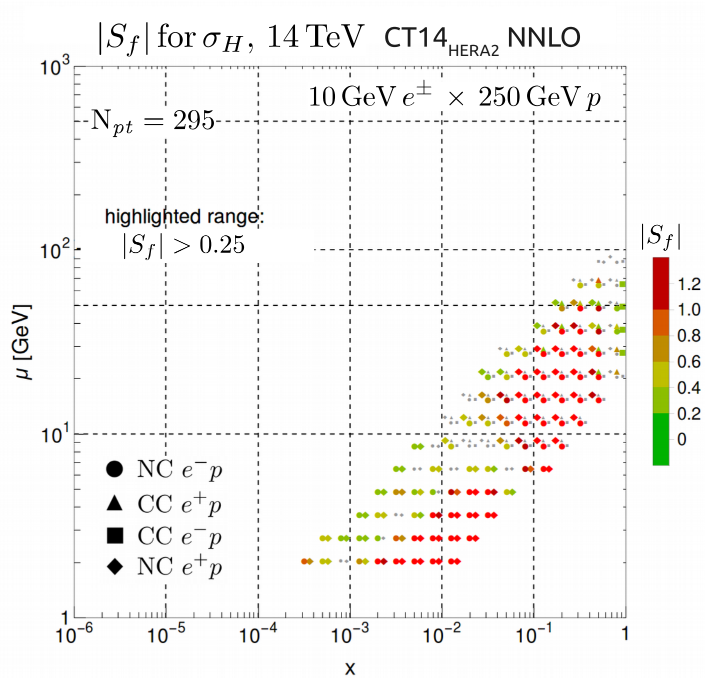
Tim Hobbs, CTEQ@SMU & JLab EIC Center

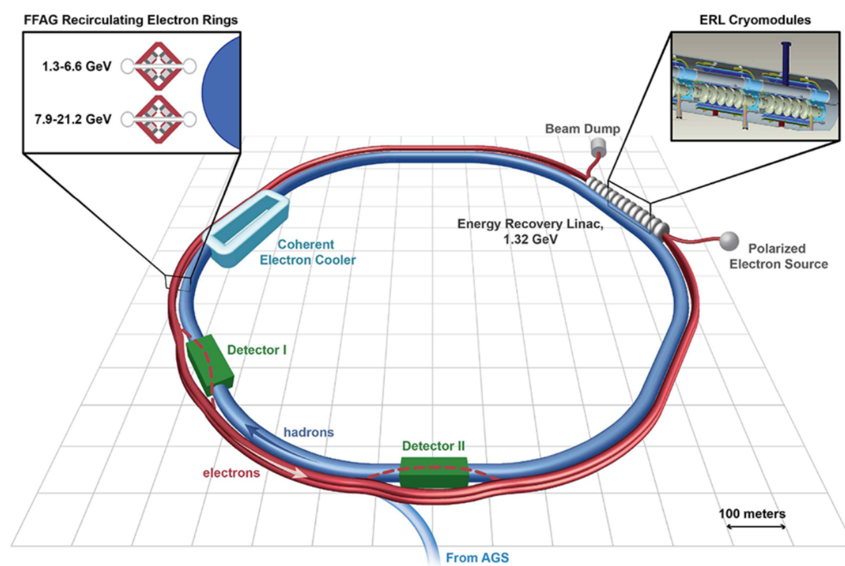
2nd October 2020











the Electron-Ion Collider (EIC)

- after ~20 years of investigation, the US nuclear community coalesced around the EIC as the definitive machine for hadronic/nuclear physics

The National Academies of SCIENCES ENGINEERING MEDICINE THE NATIONAL ACADEMIES PRESS

summer, 2018

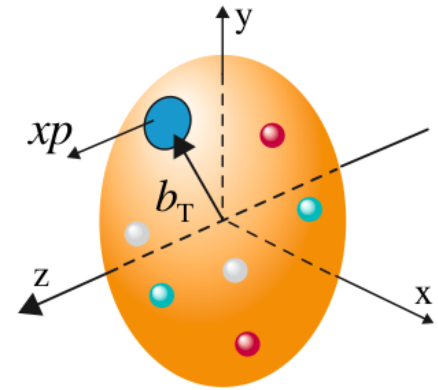
"Top-level" physics objectives – **connecting the bulk properties of hadrons to a parton-level description**:

→ the origin of nucleon mass and spin in partonic degrees of freedom

→ understanding nuclear medium effects

→ imaging the nucleon's **multi-dimensional structure**

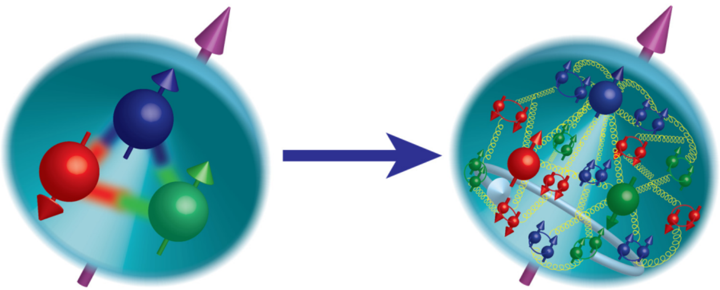
"In summary, the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."



principal physics objectives of the EIC

→ the EIC program dedicated to hadron/nuclear **tomography**

…measuring **multi-dimensional structure**



…resolving the complex quark-gluon landscape

- *e.g.*, can we unravel the flavor structure of the nucleon quark sea?

→ connecting this tomographic picture to hadronic bulk properties (spin, mass, charges, …)

essential to complete understanding of QCD!

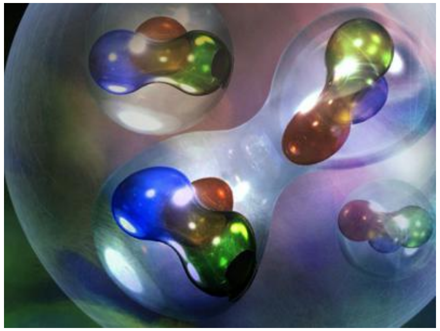
- *e.g.*, origin of hadronic spin from partonic degrees of freedom:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

(similar decompositions for mass, …)

→ understanding nuclear medium and properties

- *e.g.*, how does QCD generate nuclear binding and modify hadronic wave functions?



2020: recent movement on the EIC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Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JAN 2020

Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

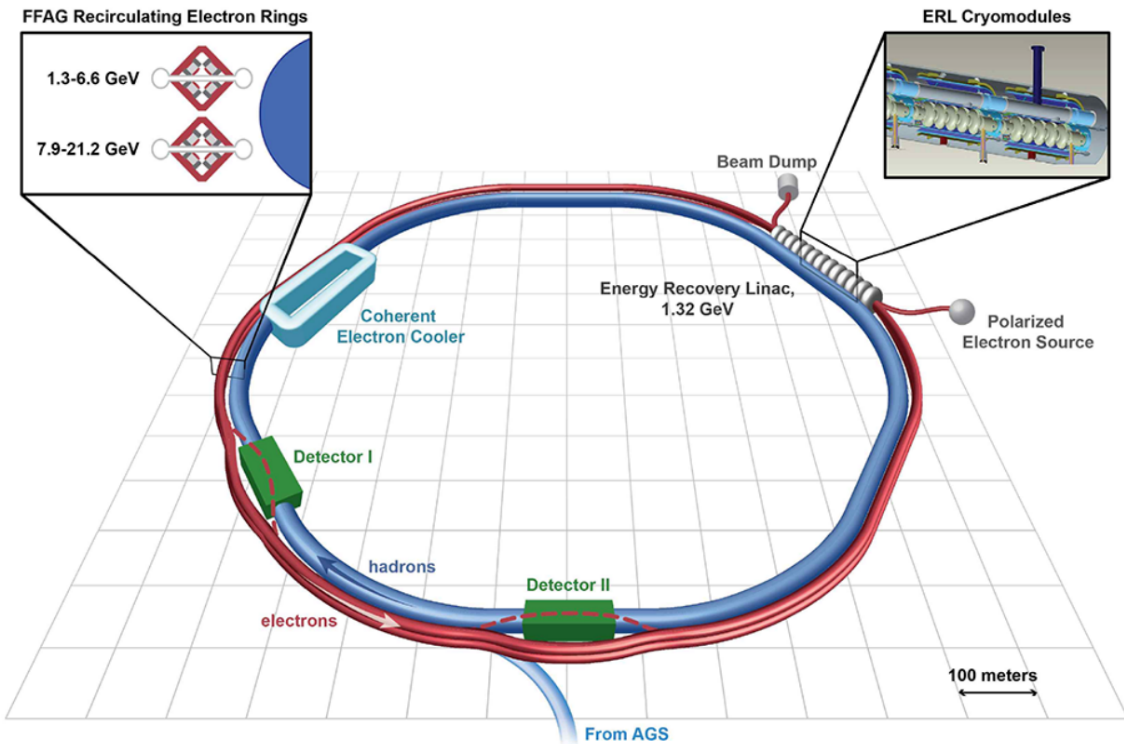
- CD-0: estimated construction cost: $1.6-2.6B over 10 years
- the only new collider planned in the US for the next half-century
- a centerpiece of American physics for the next few decades

- mix of theory, AI/Machine-Learning → peer deep inside hadrons

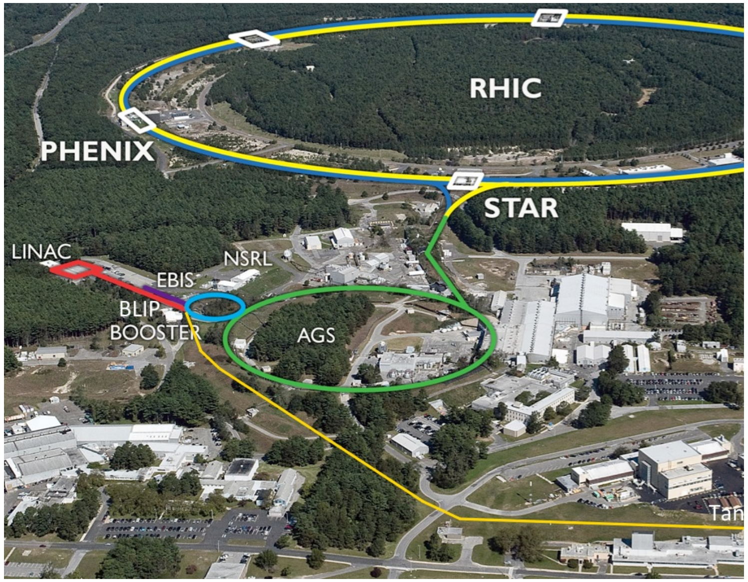
EIC: very high-luminosity DIS collider [$10^{2\text{-}3}$ times HERA]

selected Brookhaven concept, "eRHIC"

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



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



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

the EIC will cover an important kinematical region

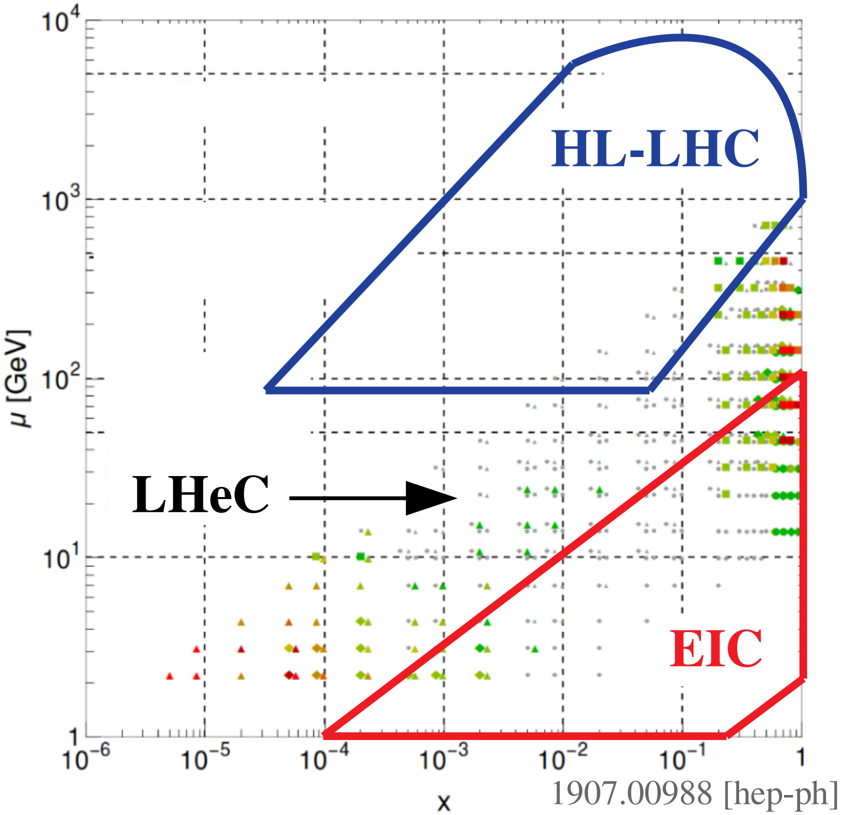
- *cf*. planned/proposed experiments, occupy complementary region of $[x, Q^2]$

[*e.g.*, LHeC, see talk, Gwenlan]

- kinematical overlap with many high-sensitivity fixed-target DIS experiments

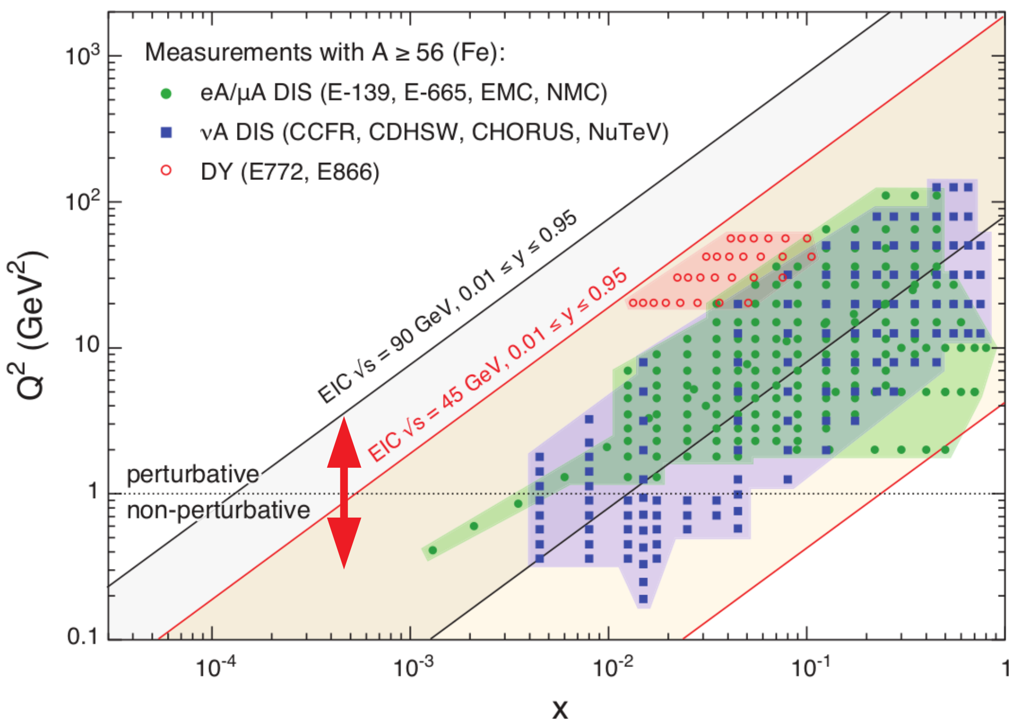
- extensive probe of the **quark-to-hadron transition** region

proton PDF: regions of sensitivity



1907.00988 [hep-ph]

analogous nuclear DIS coverage:



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

toward multi-dimensional structure at EIC

- EIC aspires to measure the unified wave function of the proton

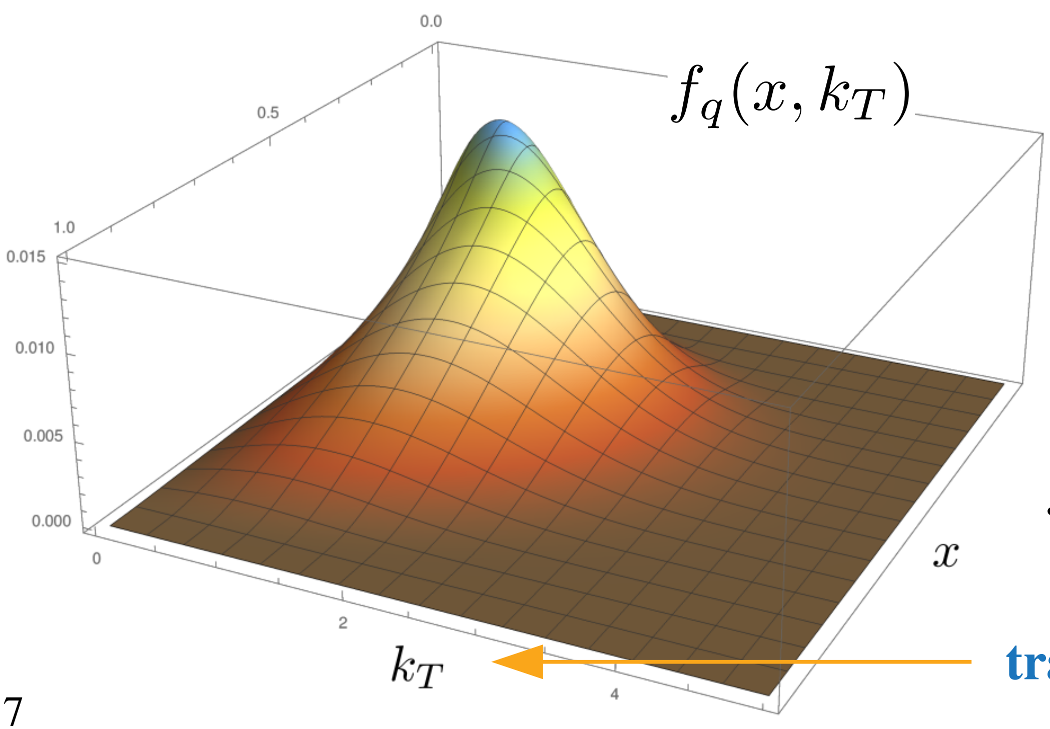
$W(x, \vec{k}_T, \vec{b}_T)$ the Wigner distribution

$$\int d\vec{b}_T\, W(x, \vec{b}_T, \vec{k}_T) = f(x, \vec{k}_T) \quad \text{TMD}$$

$$\int d\vec{k}_T\, f(x, \vec{k}_T) = f(x) \quad \text{PDF}$$

…ultimately, means learning about **PDFs** also!

TJH et al., PRD96 (2017) 7, 074023



→ developing QCD theory to guarantee **factorization theorems**: safely extract these quantities from data (à la PDF fits)

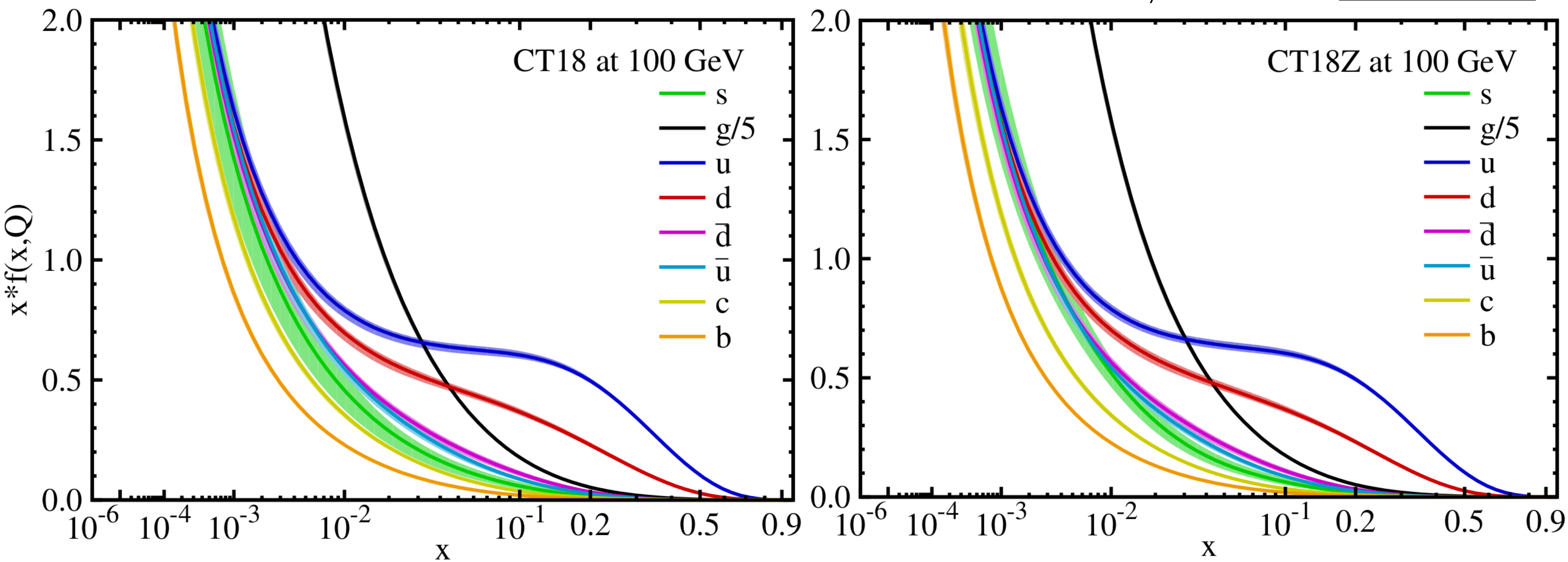
$$f_q(x) = \int dk_T\, f_q(x, k_T)$$

transverse momentum dependence (TMD)!

EIC will impinge on 1D PDF determinations

→ important to understand/anticipate the PDF implications of EIC

CT18 main analysis → arxiv:1912.10053.



- EIC program requires high-precision → reductions to PDF error

… also require precise PDFs, particularly in pQCD region

[see talks, Rojo/Nadolsky]

→ studying PDF pulls (in CT, ...) and phenomenlogical consequences

precise EIC DIS data will impact many PDF-limited HEP quantities

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

ATLAS, 1701.07240

for example:

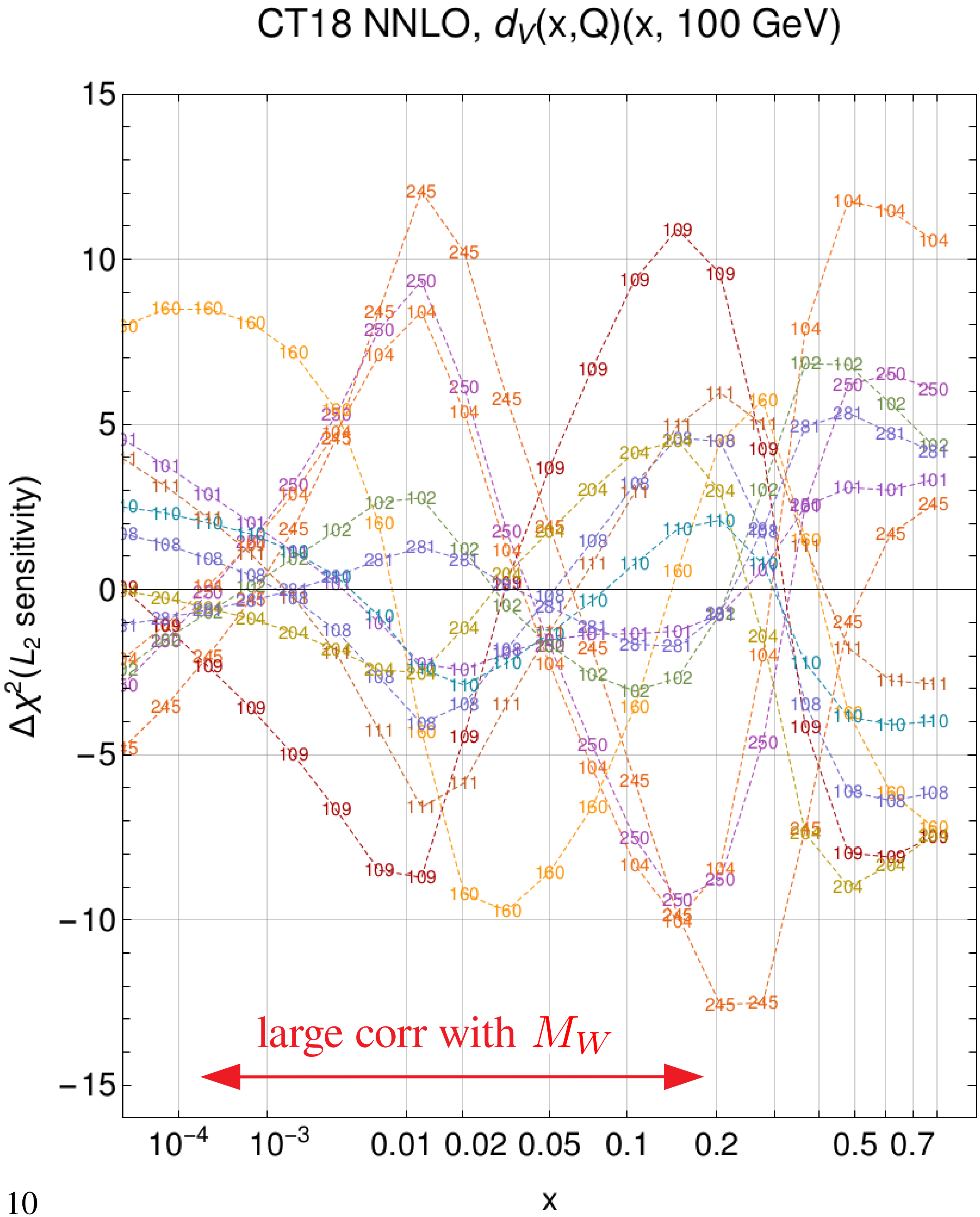
Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

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

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

→ **EIC data will be helpful to resolving PDF limitations:**

- negotiate tensions among legacy data
- independent of nuclear effects



- χ^2 pulls of CT18 experiments on the d_v PDF

→ opposing peaks indicate tension

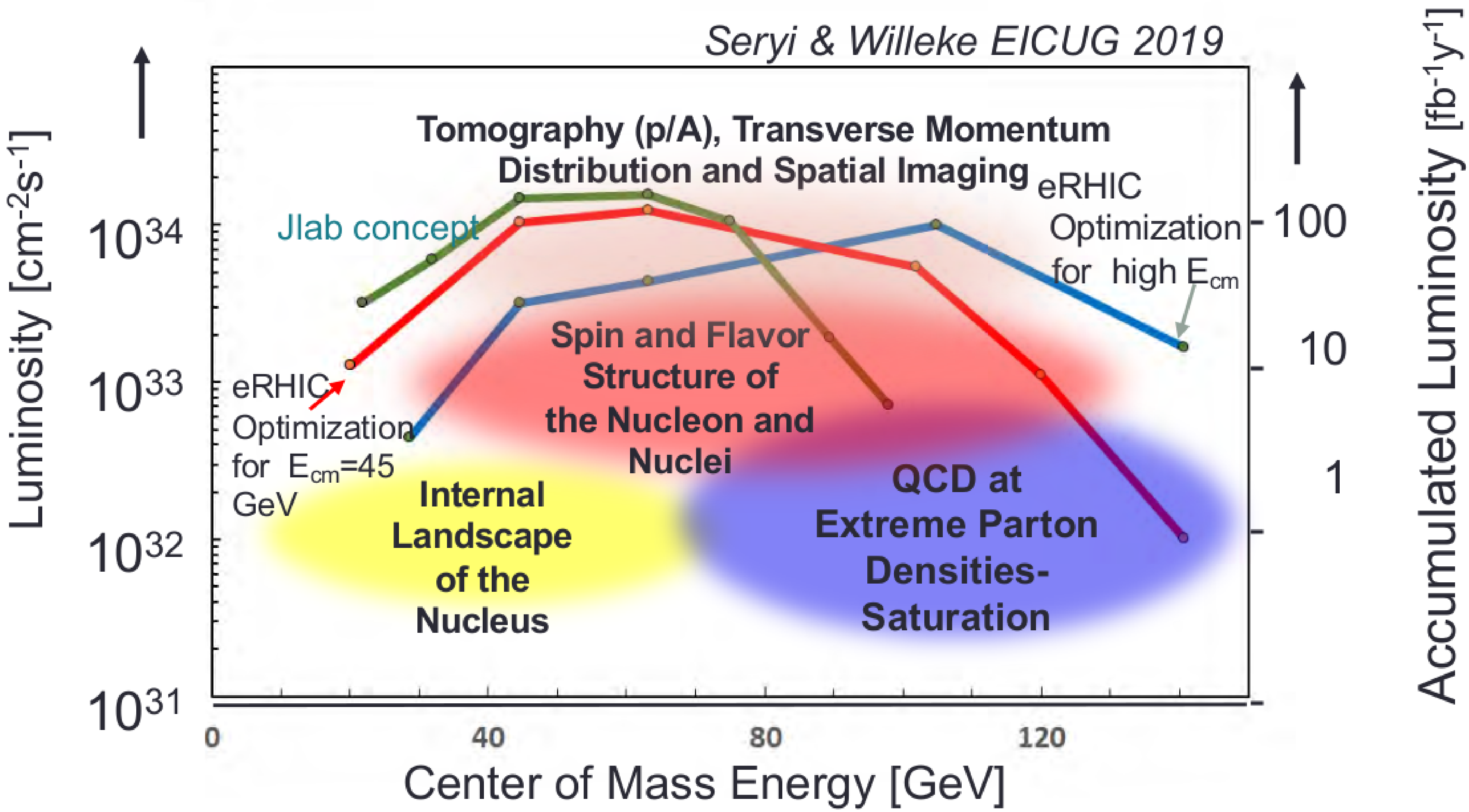
significant tensions in M_W correlated region

→ precise lepton-proton EIC data can help negotiate landscape of competing pulls, ameliorate tensions

EIC is now being designed/optimized

- we are rapidly working to ensure the highest-performance machine; **EIC Yellow Report**

→ **target to most impactful physics**



ongoing EIC **Yellow-Report** Initiative

- community-wide effort to prepare essential design details ↔ physics motivation

- divided between 2 working groups:

  → detector WG: detector concepts based on physics

  → physics WG: physics objectives, potential meas.:

    - **inclusive reactions** (reduced X-sect.; PDFs; PV asym., …)

      significant PDF-fitting involvement [NNPDF, JAM, CT, …]

    - **jets/heavy flavor**
    - **semi-inclusive reactions**
    - **exclusive reactions** (form factors; GPDs; …)
    - **diffractive reactions/tagging**

- areas of particular intersection with LHC/HEP emphases

- convergence: end-of-year, early 2021 [not so unlike Snowmass 2021 schedule...]

PDF-focused impact studies of the EIC (within **Yellow-Report**)

… to optimize physics output of the ultimate machine design

Collaborators and consultants

Pavel Nadolsky Fred Olness Bo-Ting Wang	Southern Methodist
Sayipjamal Dulat	Xinjiang Univ.
C.-P. Yuan	Michigan State
Alberto Accardi Yulia Furletova	Jefferson Lab

- the goal: use recently-developed tools for PDF global analyses to examine the PDF pulls of EIC pseudodata

1803.02777
1806.07950
1904.00022
1907.00988
2001.07862

tools and EIC apps

- needed for machine-design activities: quick, unambiguous PDF impact metrics

→ these can be incorporated into the impact-study workflows:

- iteratively, **machine/detector design** → **simulation** → **physics**

→ HEP-pheno implications are a key consideration in this process!

high-energy EIC pseudodata – **inclusive** studies

- reach in center-of-mass energy, $20 \leq \sqrt{s} \leq 140\,\mathrm{GeV}$

  → luminosities 2-3 decades greater than at HERA

  → á la HERA, the combination of precision & kinematic coverage provide constraining 'lever arm' on QCD evolution

  → QCD evolution: (**high x, low Q**) ↔ (**low x, high Q**)

- as a generic scenario, we consider here the simulated impact of a machine with: $10\,\mathrm{GeV}\ e^{\pm}\ \mathrm{on}\ 250\,\mathrm{GeV}\ p \quad (\sqrt{s} = 100\,\mathrm{GeV})$

~year of data-taking

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

$\mathcal{L} = 10\,\mathrm{fb}^{-1}\ e^{+}$ pseudodata

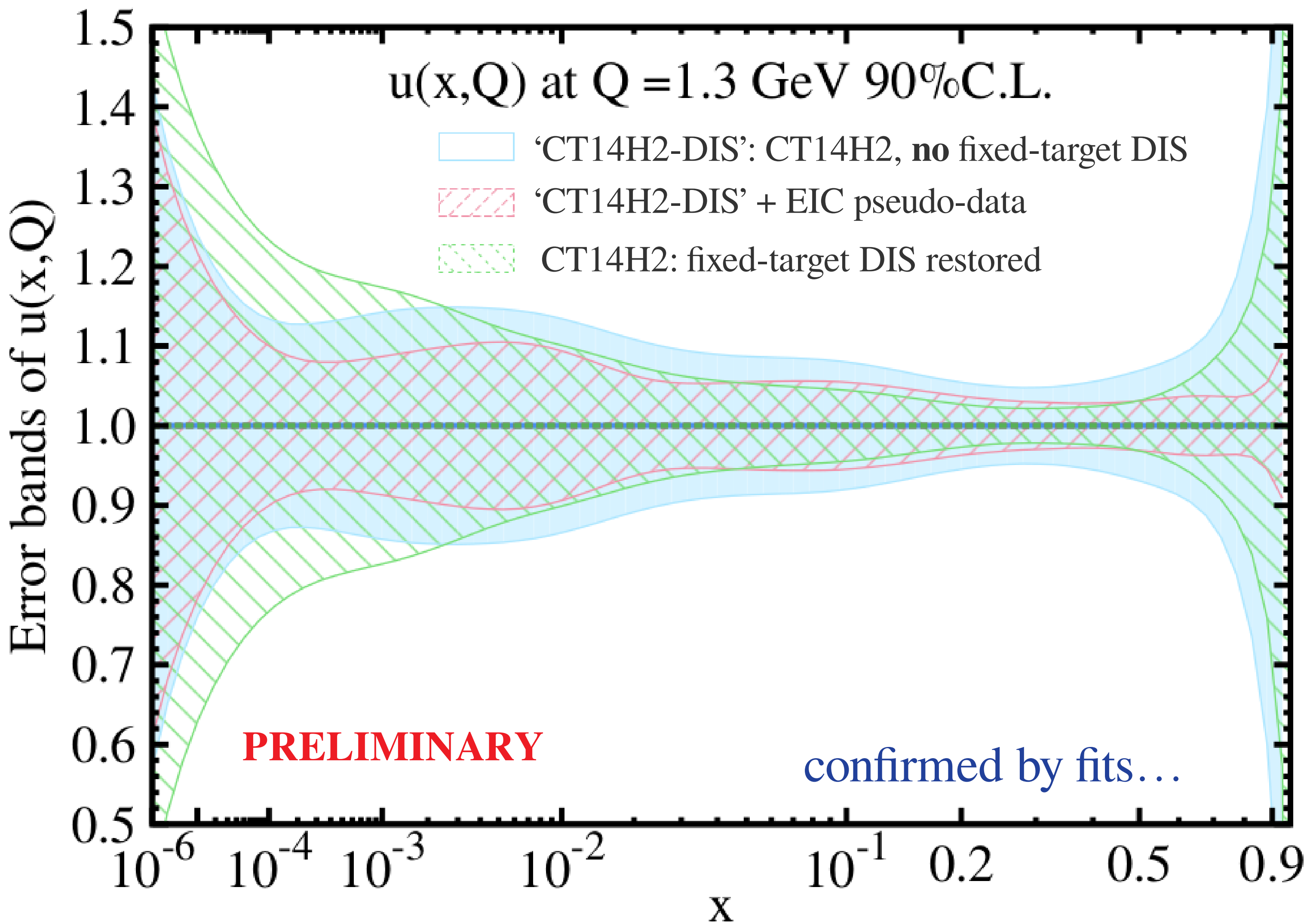
NC/CC

→ currently, proton scattering only

- generated based on CT14$_{\mathrm{HERA2}}$ NNLO PDF fit

Hessian profiling [ePump*] for EIC impacts on PDF errors

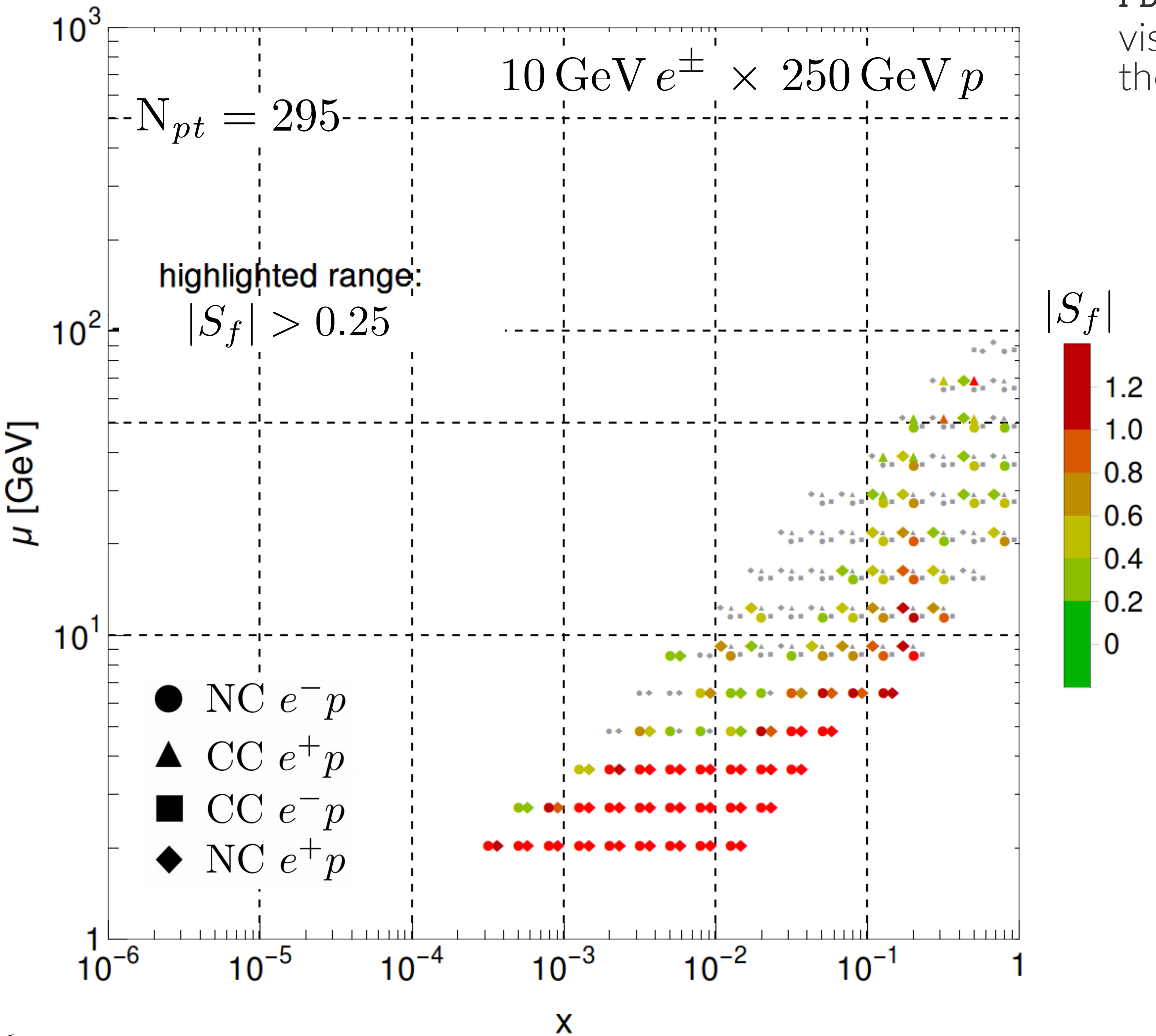
ePump: Schmidt, Pumplin, and Yuan; PRD98 (2018) no.9, 094005*



- **EIC pseudodata surpasses fixed-target DIS information in modern CT fits**
- reweighting strongly depends on tolerance def.; CT-like tolerance used here

→ complementary approaches welcome!

$|S_f|$ for $g(x, \mu)$ CT14$_{\mathrm{HERA2}}$ NNLO



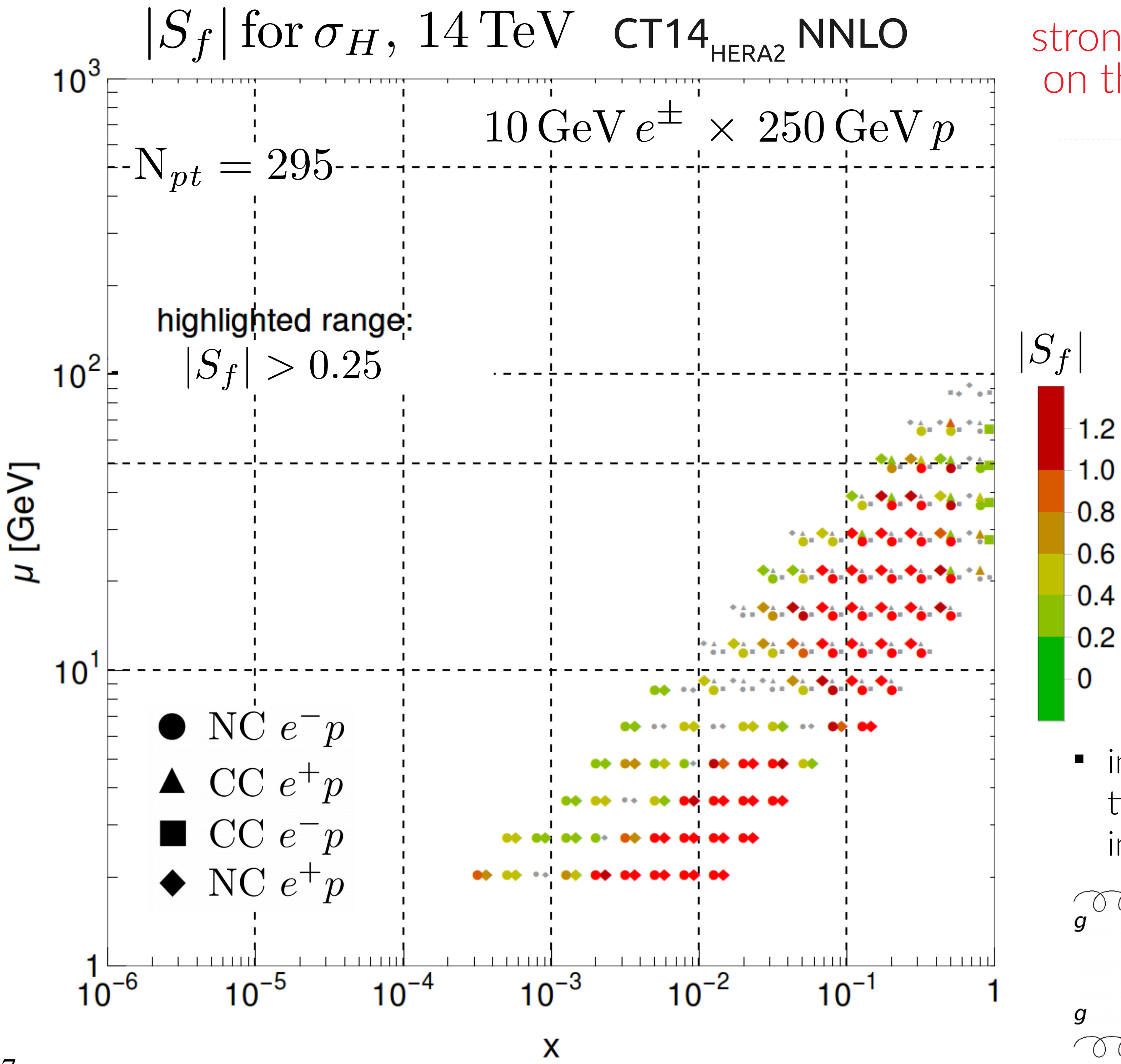
- **PDFSense** quickly visualizes the pulls of the EIC pseudodata

cf. $|S_f| \sim$ 0.3-0.5, typical CT18 expts.

- an EIC will provide a sensitive probe to the gluon distribution – especially at low x

$$x \gtrsim 3 \times 10^{-4}$$

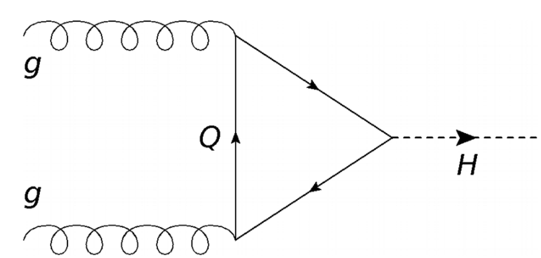
- these constraints arise from high statistics neutral current data on $\sigma_{r,\mathrm{NC}}^{e^{\pm}p}$



strong predicted impact on the Higgs sector

- the impact of an EIC upon the theoretical predictions for inclusive Higgs production arises from a very broad region of the kinematical space it can access

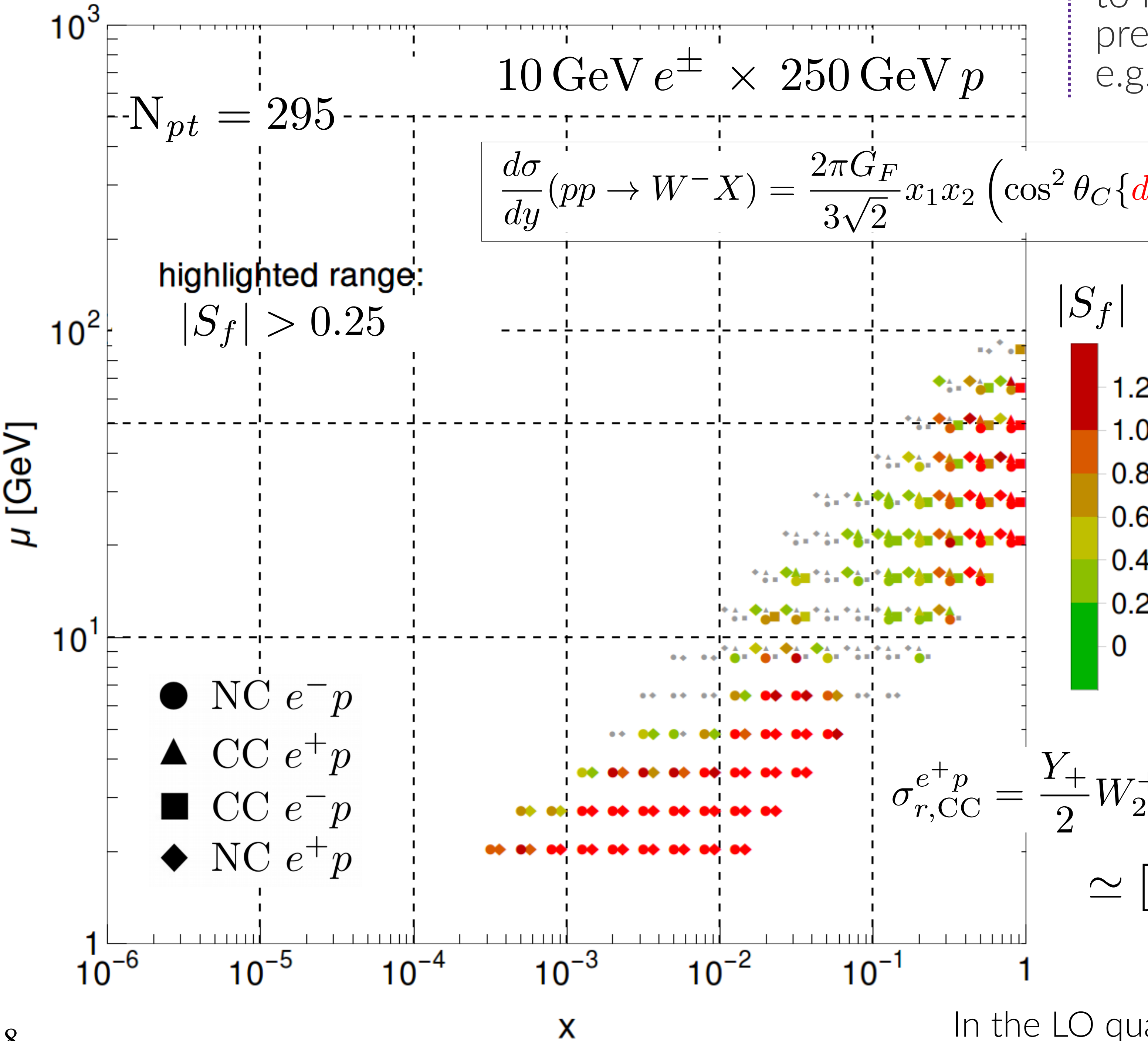
- impact rather closely tied to that of the integrated gluon PDF:



$|S_f|$ for $d(x,\mu)$ CT14$_{\text{HERA2}}$ NNLO

this message translates to PDFs needed for precision EW physics, e.g., M_W and $d(x)$

$$\frac{d\sigma}{dy}(pp \to W^- X) = \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \left(\cos^2\theta_C \{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)\}\right.$$



- an EIC affords **strong sensitivities without a nuclear target**; here, at both very high and low x

for $x \to 1$

$$\sigma_{r,\text{CC}}^{e^+p} = \frac{Y_+}{2} W_2^+ \mp \frac{Y_-}{2} x W_3^+ - \frac{y^2}{2} W_L^+$$

$$\simeq [1-y]^2\, x(d+s)$$

In the LO quark-parton model

EIC and PDF-Lattice synergy

Constantinou *et al.*; 2006.08636

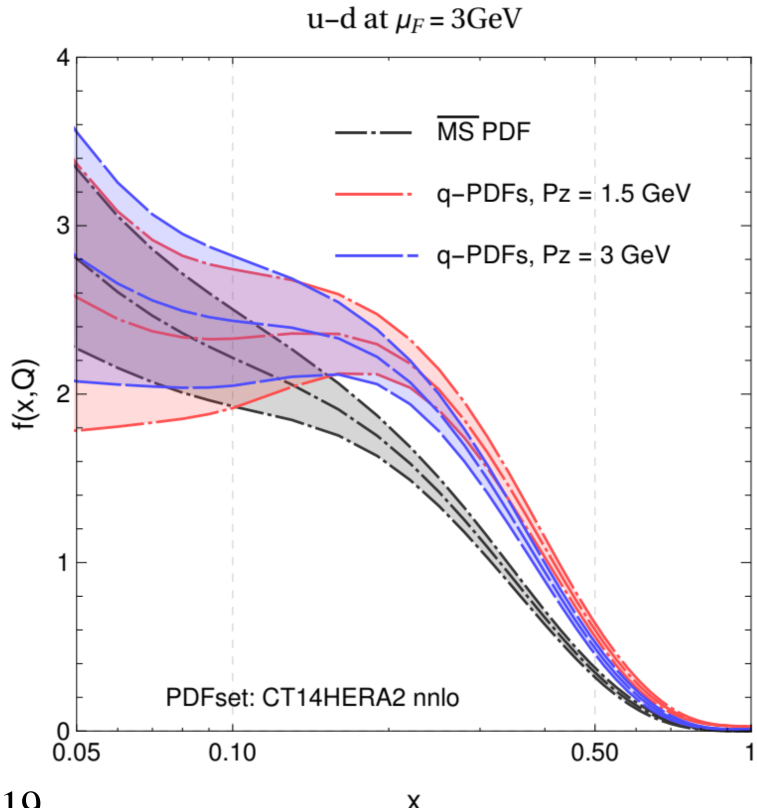
- techniques for x-dependent PDFs from **lattice QCD** now available

  (compute QCD on discretized spacetime grid)

  → theory/models still being developed

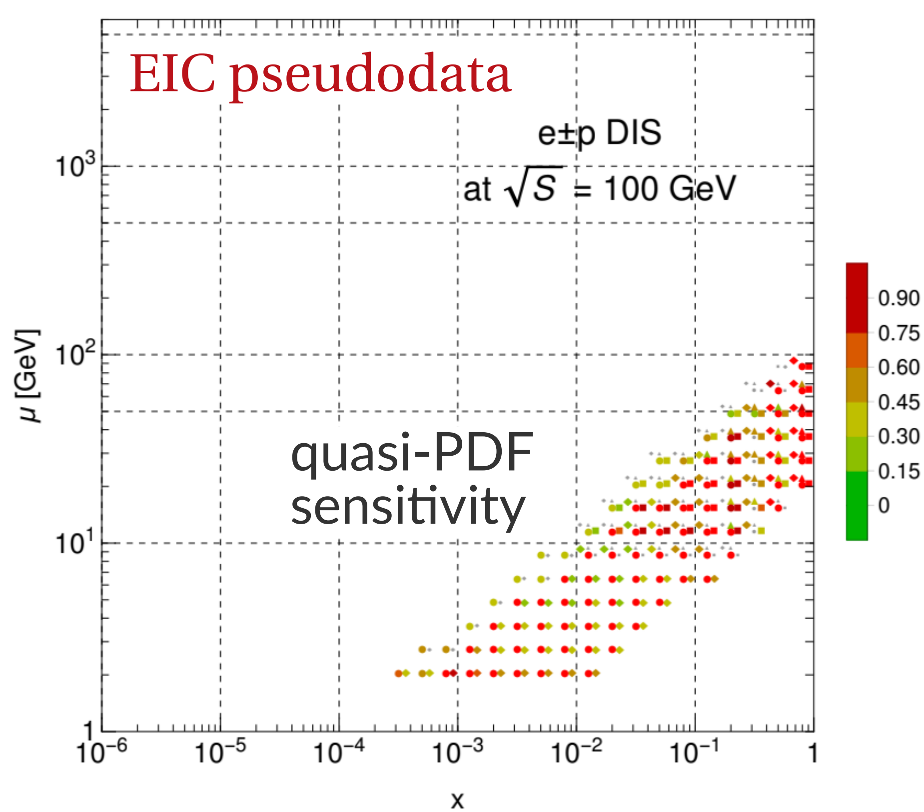
- can be used for *experimentally inaccessible* regions of PDFs (combine w/ fits)

TJH, Wang, Nadolsky, Olness: Phys. Rev. D100 (2019) 9, 094040.



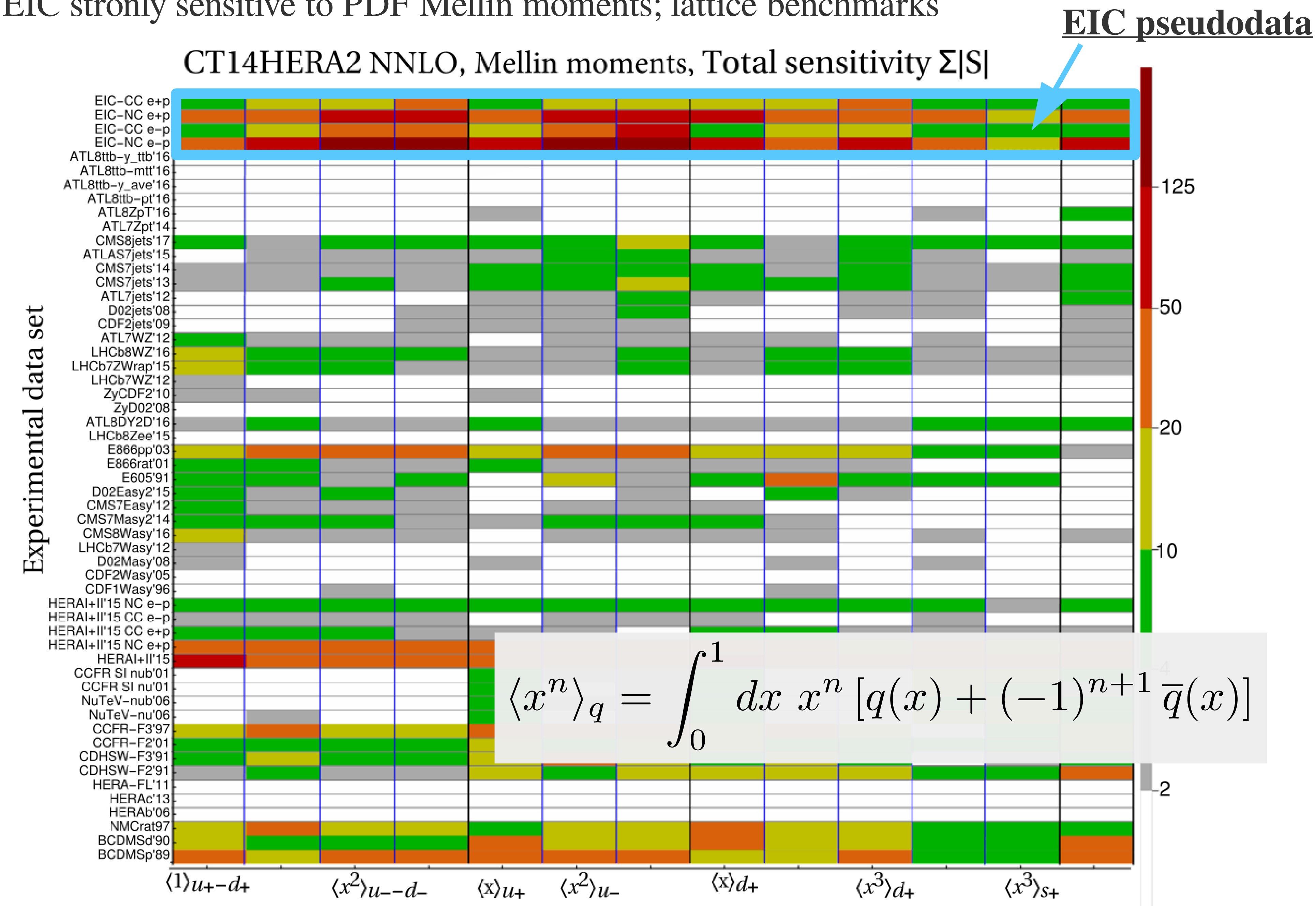
the EIC will drive a PDF-Lattice Synergy

| S_f | for $[\tilde{u}-\tilde{d}]$(x=0.85, P_z=1.5GeV), CT14HERA2



sensitivities can be aggregated for direct comparisons of exps

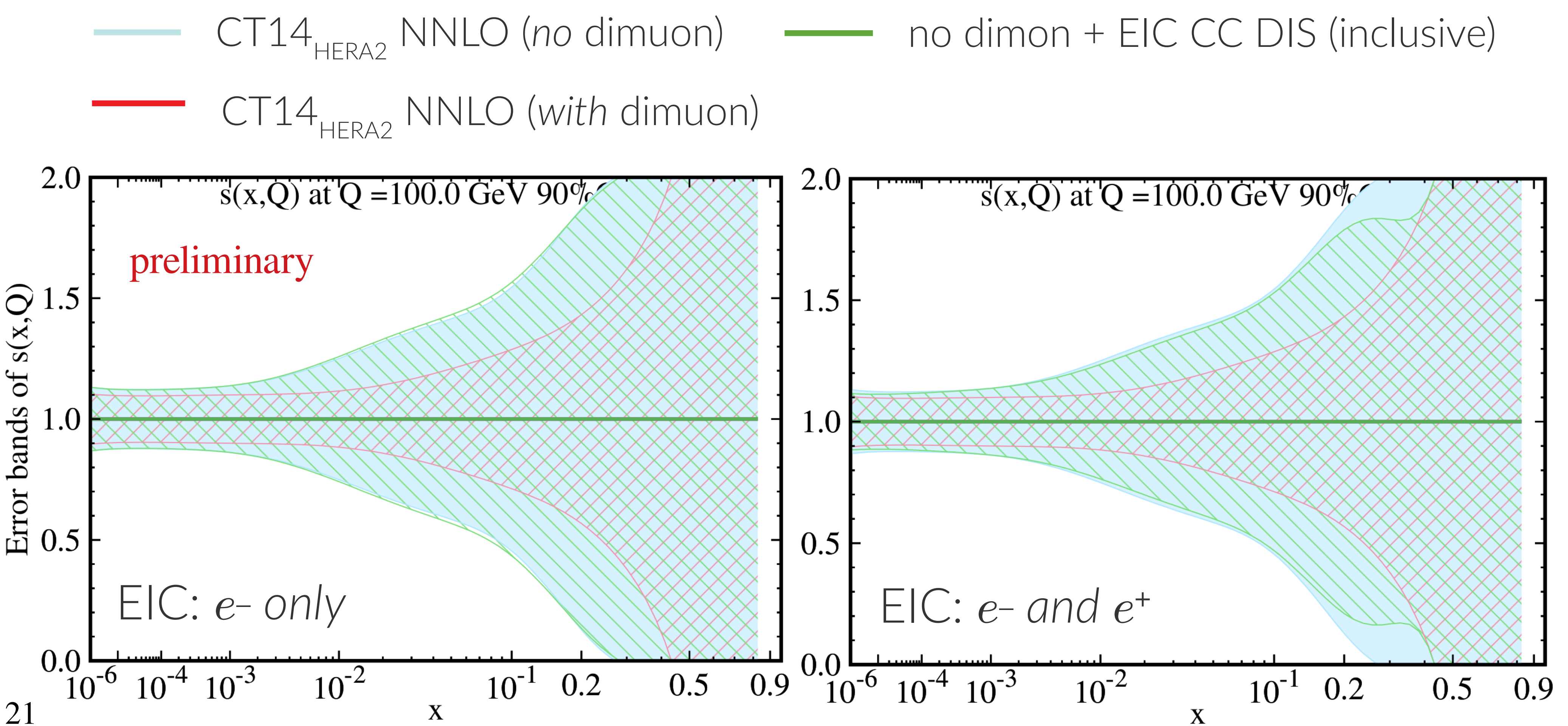
→ EIC stronly sensitive to PDF Mellin moments; lattice benchmarks



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

limitations of inclusive measurements: accessing strangeness

- EIC inclusive pseudodata comparisons with legacy data are instructive
- in CT, νFe dimuon production (NuTeV, CCFR) are important constraints on $s(x,Q)$
- **especially without e^+, EIC CC inclusive DIS data struggle to compete**



flavor structure only from inclusive data is challenging!

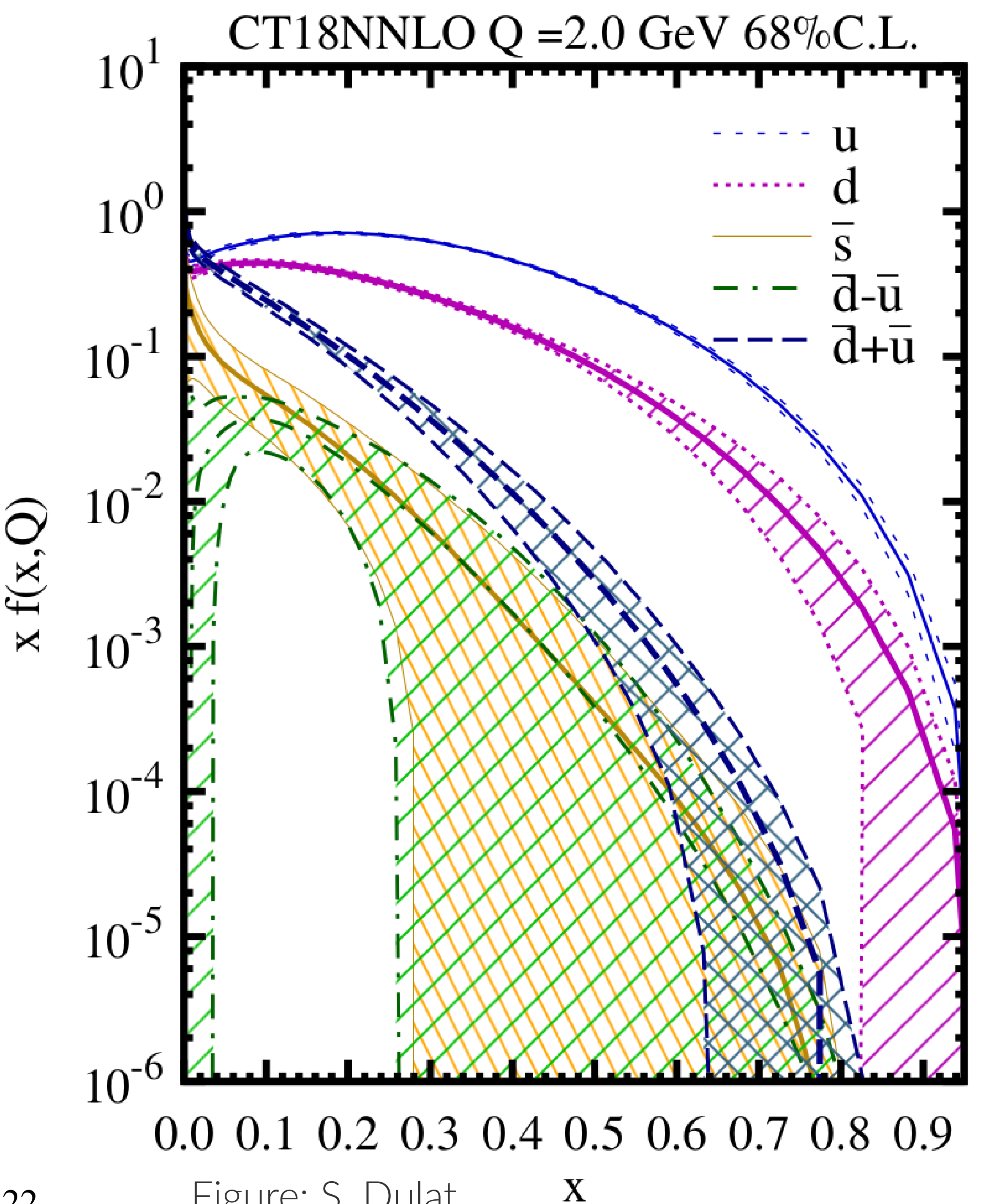


Figure: S. Dulat

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 $\bar{u}, \bar{d}, \bar{s}$

unraveling flavor structure is challenging!

the point: unraveling the flavor structure of the quark sea is challenging through purely inclusive measurements!

require input from additional channels

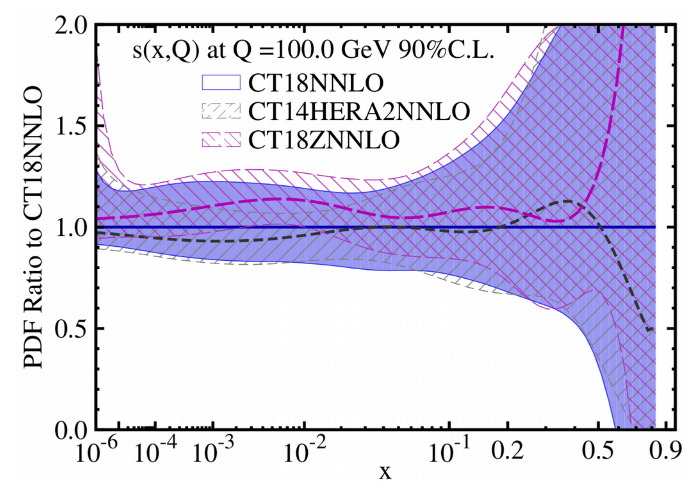
Figure: S. Dulat

case study: accessing nucleon strangeness in (tagged) CC processes

→ final-state tagging can help unravel flavor structure

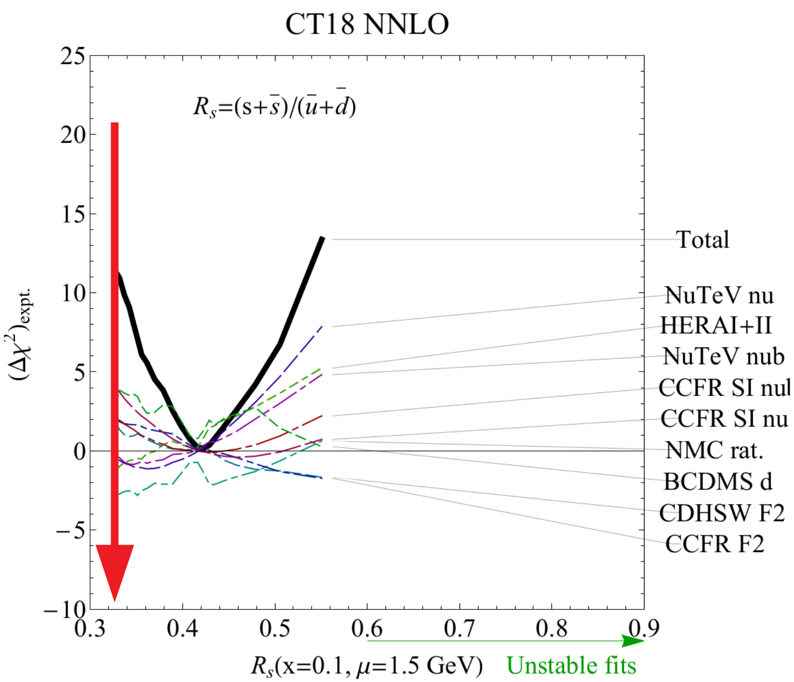
→ study: strange suppression ratio, $R_s = \dfrac{s + \bar{s}}{\bar{u} + \bar{d}}$

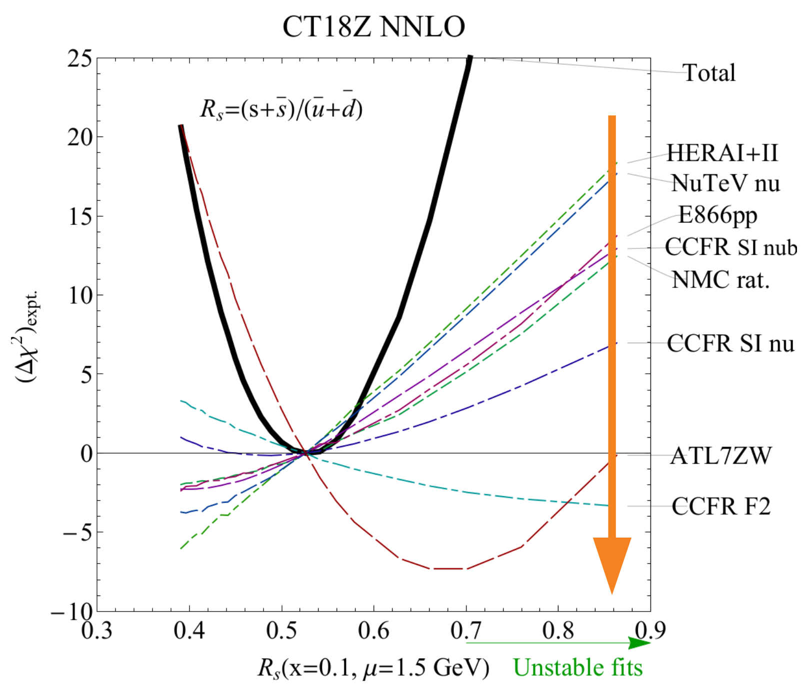
→ ν-A data often favor $R_s \sim 0.5$; ATLAS W/Z production favors $R_s \sim 1$



→ ***question*: can CC charm jet production off proton distinguish small from large R_s?**

take 2 extreme PDF sets for R_s :



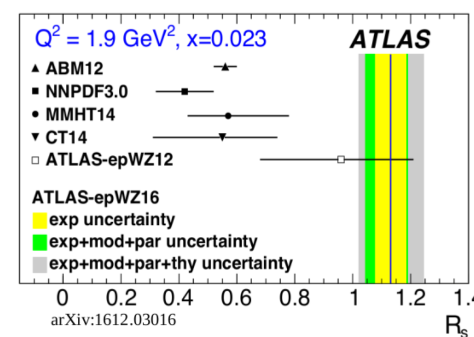


theory inputs: for

$x = 0.1, \;\; \mu = 1.5\,\text{GeV}$

* $R_s = 0.325$ (CT18)

* $R_s = 0.863$ (CT18Z)



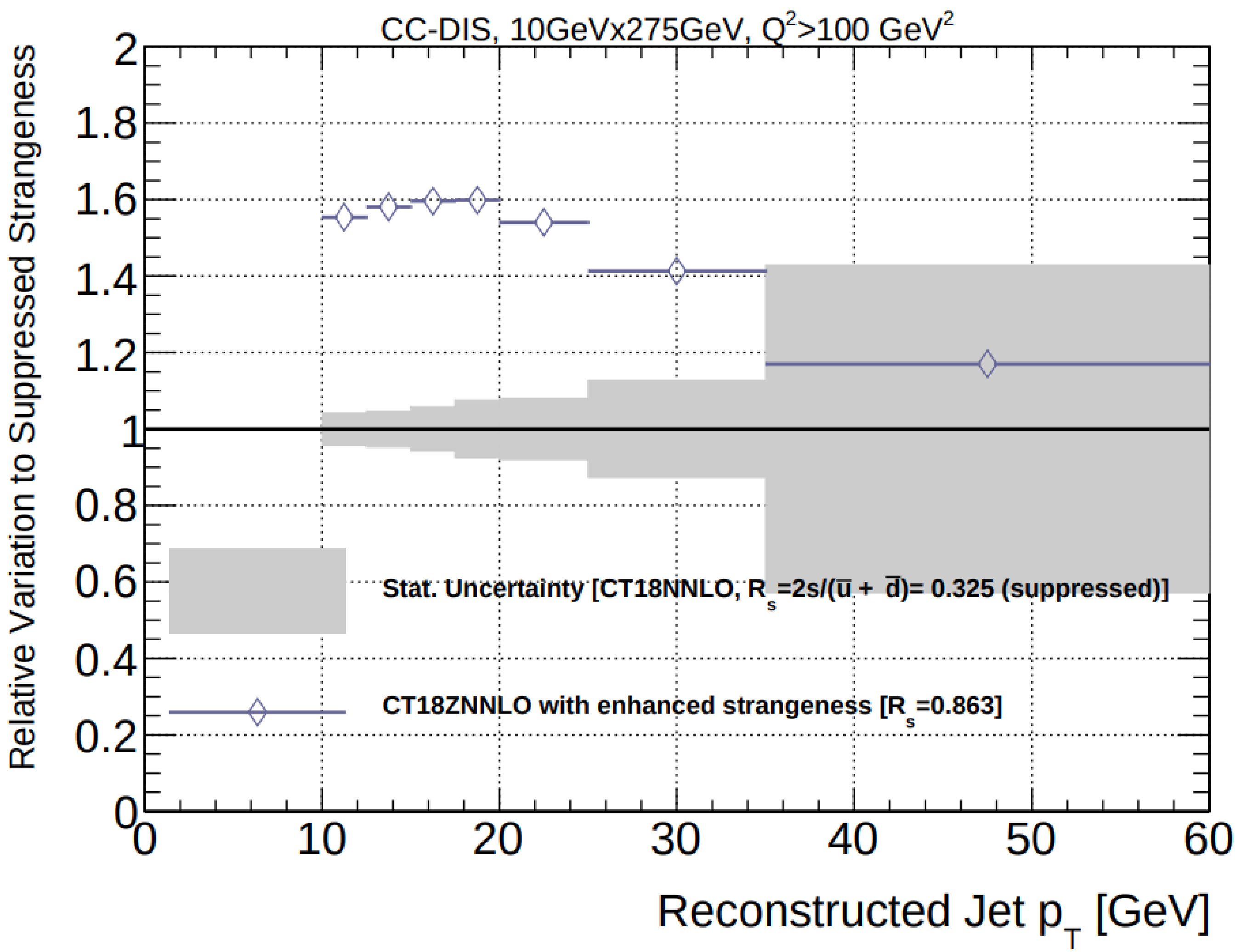
arXiv: 1912.10053 [hep-ph]

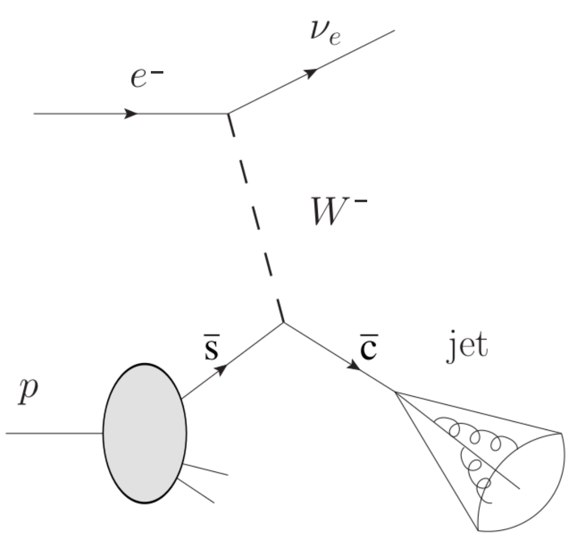
sensitivity of CC charm jet production to strange suppression

Arratia, Furletova, TJH, Olness, Sekula

arXiv: 2006.12520

- 100 fb^{-1} CC DIS (10M simulated events), at 10x275 GeV (e^- on p); Q^2 > 100 GeV^2
- **even assuming conservative charm-tagging efficiency, event-level discrimination potential is substantial, relative to statistical uncertainties**





final-state tagging will provide a critical lever arm for flavor separation

sensitivity of CC charm jet production to strange suppression

Arratia, Furletova, TJH, Olness, Sekula

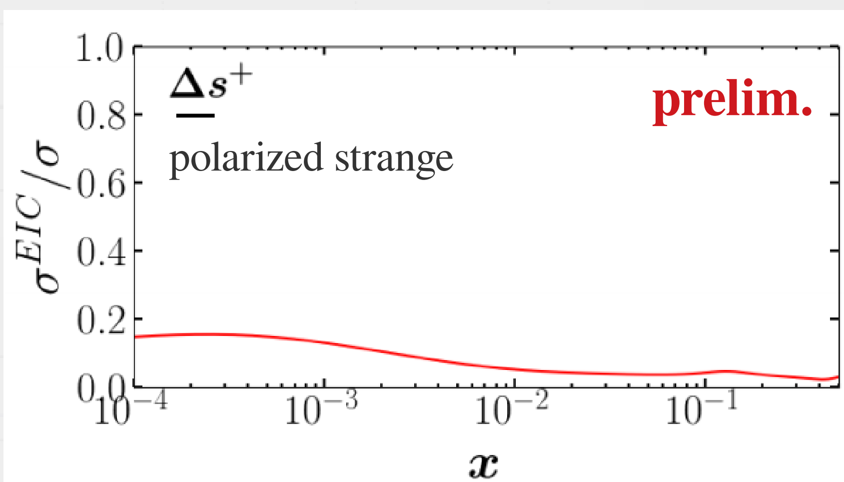
arXiv:2006.12520

- 100 fb^{-1} CC DIS (10M simulated events), at 10x275 GeV (e^- on p); $Q^2 > 100$ GeV^2
- **even assuming conservative charm-tagging efficiency, event-level discrimination potential is significant…**

this is one example; the full impact of EIC program will derive from many channels/processes in combination!

another, A^{PV}:

$$A^{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



some impact on unpol strange as well

JAM, C. Cocuzza et al.

Relative Variation to Suppressed Strangeness

Reconstructed Jet p_T [GeV]

final-state tagging will provide a critical lever arm for flavor separation

EIC and Snowmass `21

EIC@Snowmass21 LOI: Hadronic Tomography at the EIC and the Energy Frontier

Editors: Salvatore Fazio, TJH, Alexei Prokudin, Alessandro Vicini

160+ coauthors/signers

- tomography encompasses a wide range of EIC ↔ HEP topics
- EIC determinations of partonic distributions (PDFs, TMDs, GPDs)

- **high-energy QCD** (DIS measurements; heavy quarks/masses, jets, α_s)
- **gluonic structure/Higgs** (gluon PDF, improvements to $gg \rightarrow h$ production)
- **QED effects** (photon PDF; improved EW corrections)
- **TMD measurements, precision EW physics** (TMDs and M_W extractions)
- **nuclear structure** (nuclear PDFs, connections to heavy-ion UPCs)

select topics

- progress will depend on various methods

→ phenomenological studies; global analyses

→ continuum QCD approaches

→ lattice QCD input

→ AI/machine-learning and MCEGs

- completed LOI available here

SnowMass2021

the EIC has an extended presence in Snowmass planning

SnowMass2021

- tomography – most 'immediate' center for PDF-related activity (LOI)

- other complementary areas (in Energy Frontier):

  → heavy flavor (LOI)

  → Electroweak and BSM (LOI)

  → Jet production (LOI)

  → low-x gluons, saturation

- going forward, need to coordinate these with PDF studies

- many other related, independent initiatives/submissions

conclusions, recommendations

- EIC will run contemporaneously with HL-LHC; take copious high-precision DIS data instrumental to improving SM predictions

  → EIC PDF program rests within larger tomography emphasis

  → strong kinematic complementarity with HL-LHC, LHeC, …

  (see talk, Gwenlan)

  → motivation for **next-gen PDFs**, **theory**

  (Rojo/Nadolsky)

- this talk: PDFs/implications; full HEP impact of EIC intersects many areas

  → recent meetings have canvassed these issues:

  - LPC Workshop, LHC-EIC Physics Connections, https://indico.cern.ch/event/853569/
  - EW/BSM Physics at the EIC, https://indico.bnl.gov/event/8110/

- Snowmass21, EIC Yellow-Report proceedings run in parallel; should be exploited

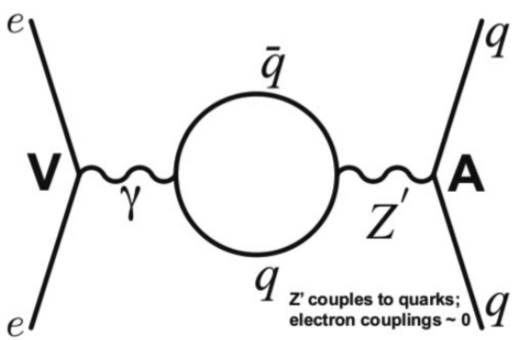
  → significant EIC@Snowmass effort, associated LOIs supplementary material

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).

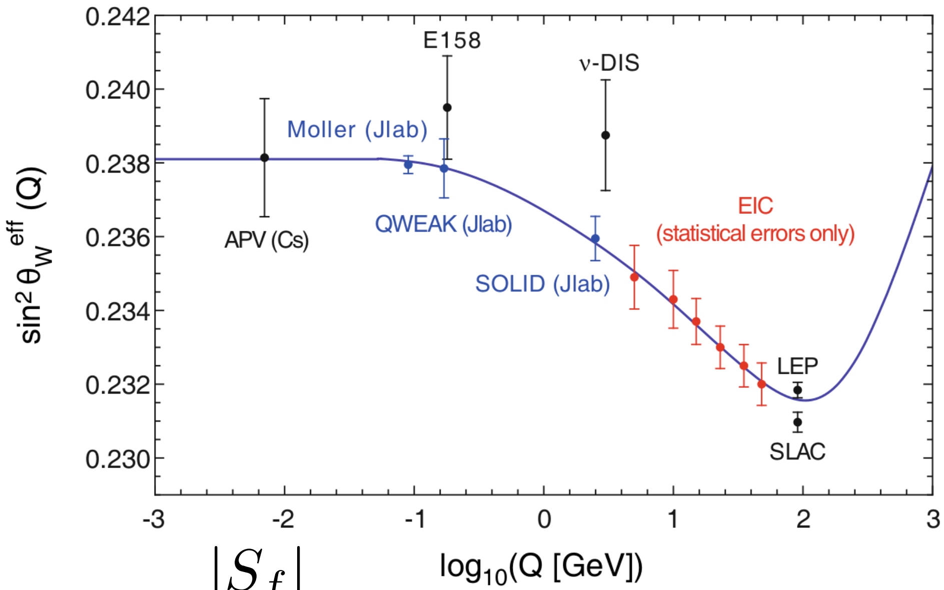
$$A^{\rm PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left(Y_1\, a_1 + Y_3\, a_3\right)$$

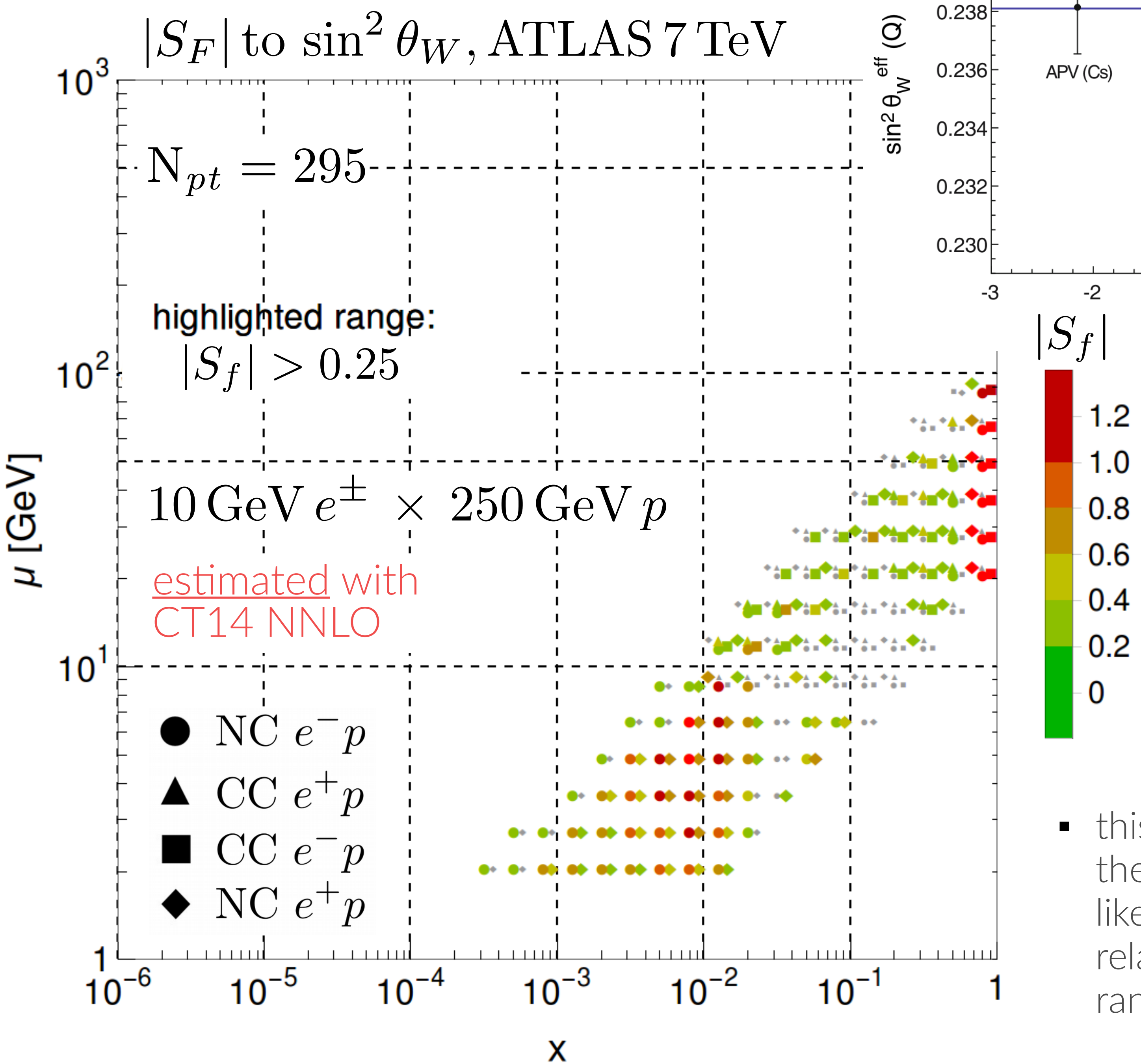
N.B.: extractions are dependent upon knowledge of the PDFs

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

an EIC will probe EW parameters and New Physics!

Accardi et al., EPJA**52**, 268 (2016).



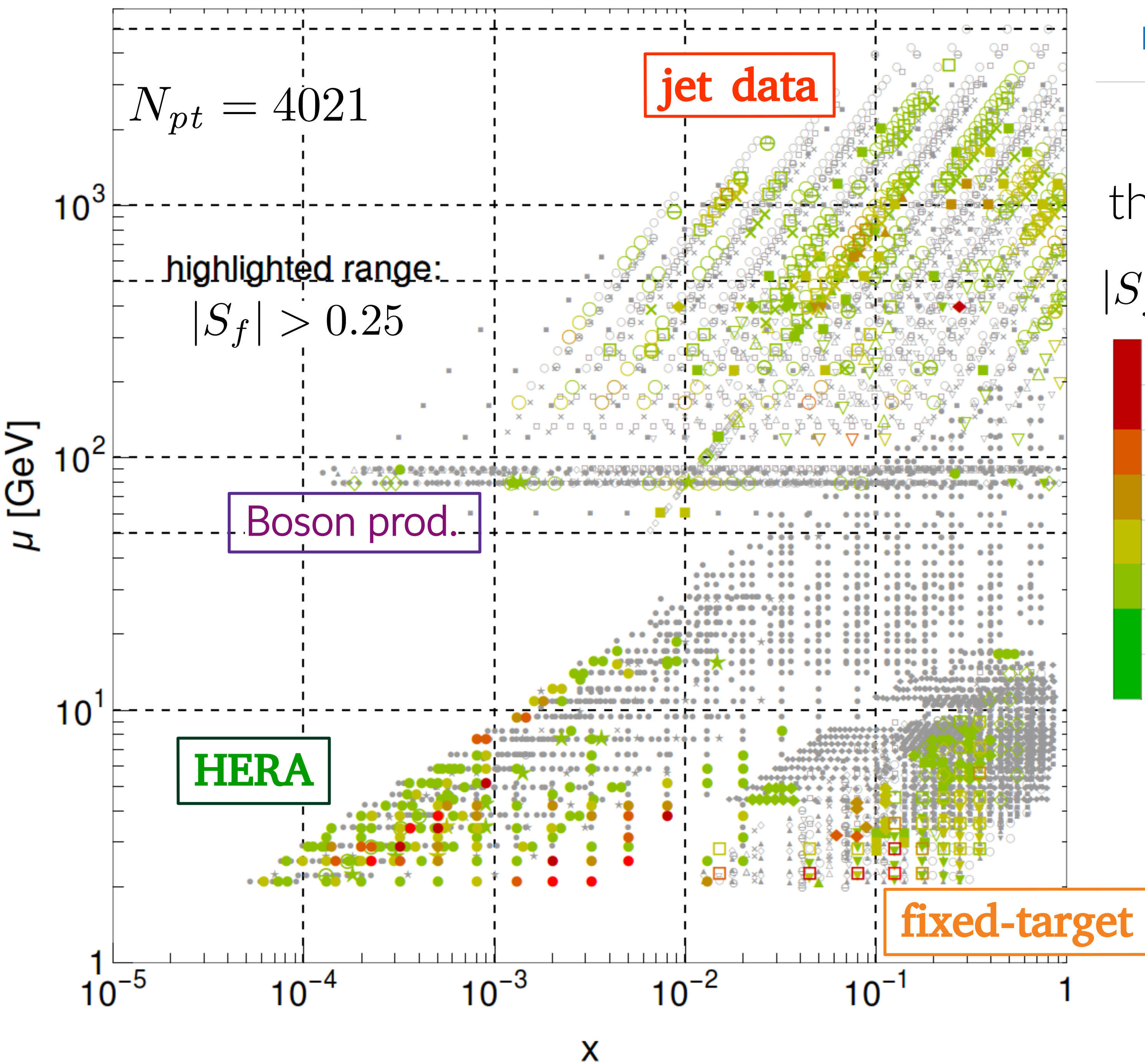


- observe a pronounced sensitivity to the Weinberg angle, especially low and high x, **even at**

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

- this corresponds closely to the kinematics at which EIC is likely to measure A^{PV} — relatively large Q^2 and in the x range $0.2 \lesssim x \lesssim 0.5$

| S_f | for g(x,μ), CT14$_{HERA2}$ NNLO



II) visualizing impacts with PDFSense

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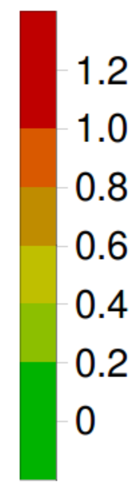
the PDF *sensitivity*

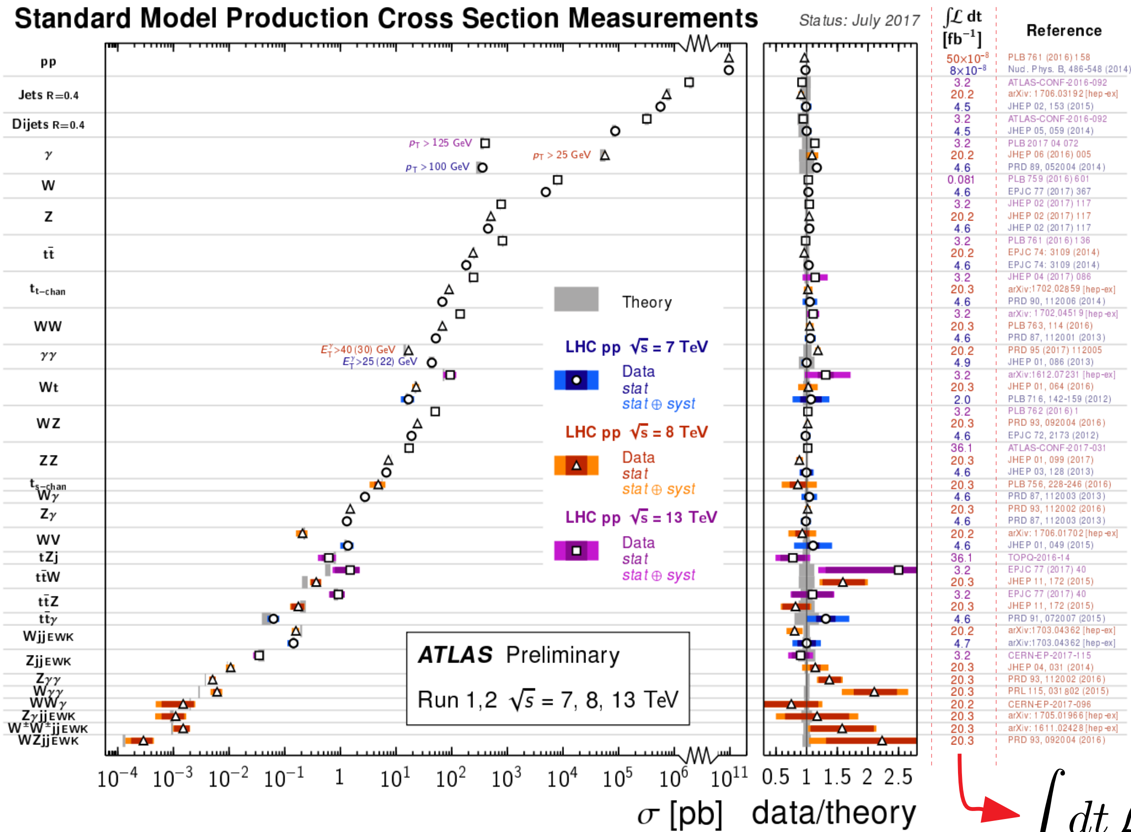
$|S_f|$



(magnitude of PDF pull of each datum)

→ measurements with strong PDF correlations AND high precision have high $|S_f|$

- used to identify high-impact data for CT18

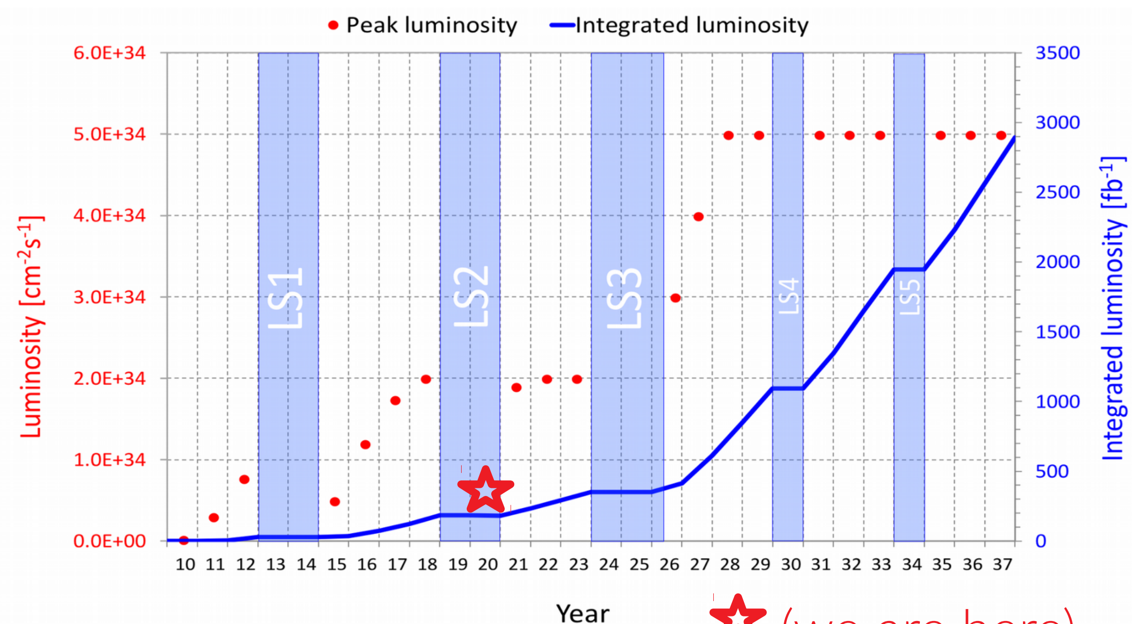


$$\int dt\, \mathcal{L} \lesssim 20\,\mathrm{fb}^{-1}$$

LHC has logged large quantities of data, with much more to come in the High-Lumi. era

- SM predictions have been very successful
- as accumulated statistics grow, systematics limitations in BSM searches, SM tests will become more acute

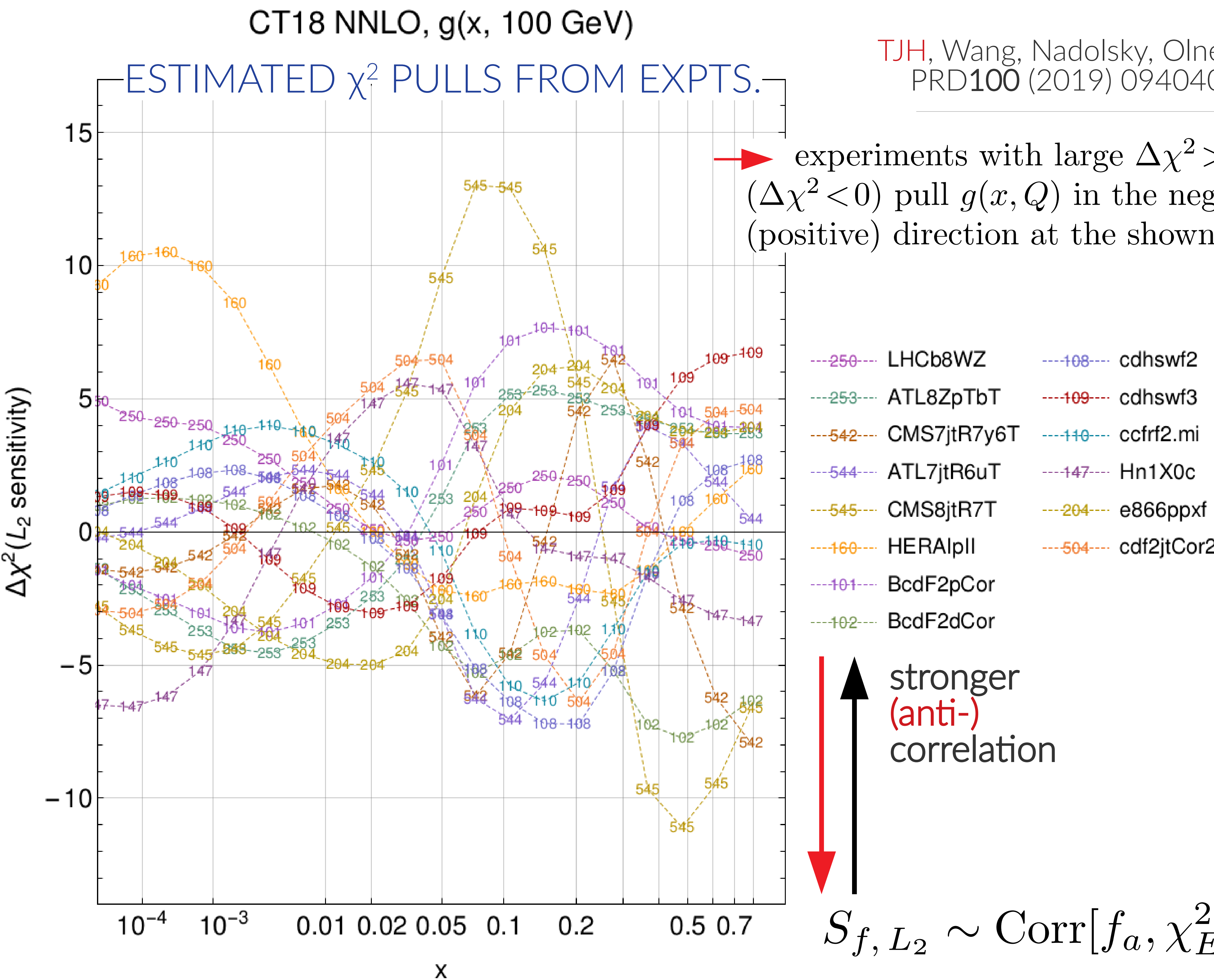
- improved discovery potential at HL-LHC requires reduction of PDF and theory uncertainties
- negotiating the large amount of data from HL-LHC will require theory improvements, computation, and additional experiments



☆ (we are here)

ESTIMATED χ^2 PULLS FROM EXPTS.

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



→ experiments with large $\Delta\chi^2 > 0$ ($\Delta\chi^2 < 0$) pull $g(x, Q)$ in the negative (positive) direction at the shown x

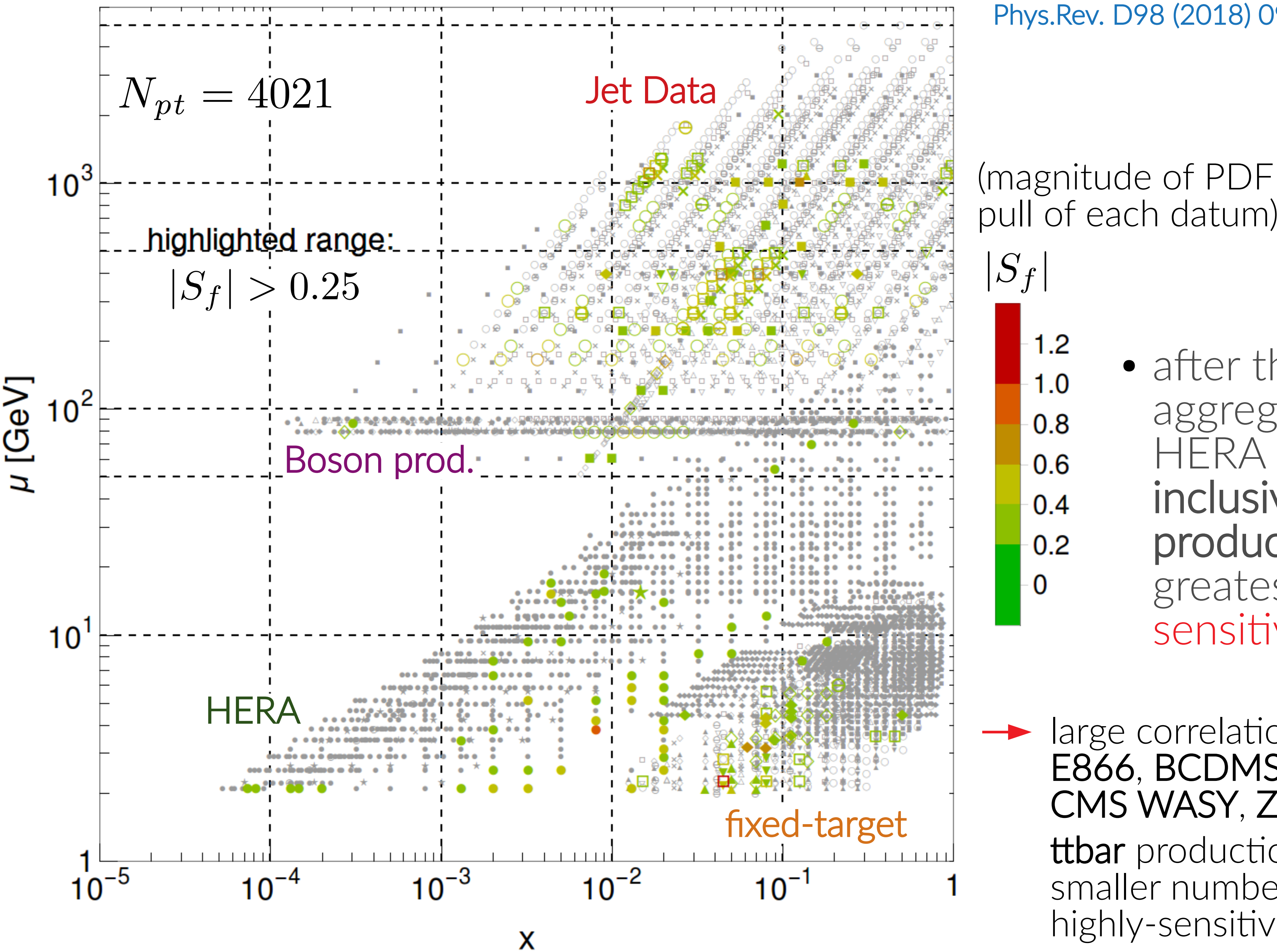
stronger (anti-) correlation

$$S_{f,\,L_2} \sim \mathrm{Corr}[f_a, \chi^2_E]$$

| S_f | for σ_{H^0} 14 TeV, CT14$_{HERA2}$ NNLO

B.-T. Wang, TJH, S. Doyle, J. Gao, T.-J. Hou, P. M. Nadolsky, F. I. Olness

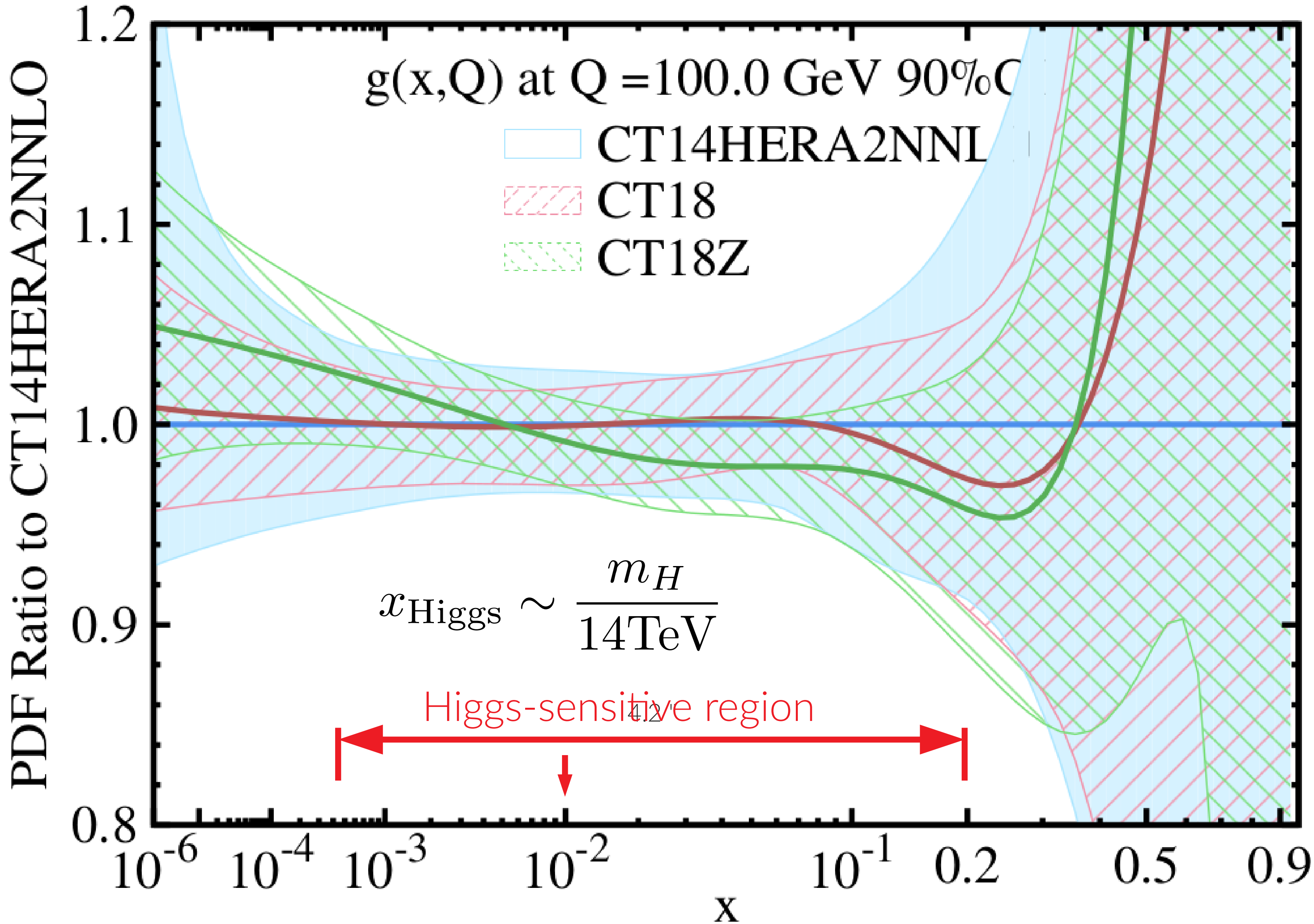
Phys.Rev. D98 (2018) 094030



- after the aggregated HERA data, **inclusive jet production** – greatest total sensitivity!

→ large correlations for **E866**, **BCDMS**, **CCFR**, **CMS WASY**, **Z p_T** and **ttbar** production, but smaller numbers of highly-sensitive points

LHC Run-1 gluon PDF impact in CT14 → CT18(Z)



- while LHC Run-1 data drive important PDF improvements, including for the gluon at high-, low-x, the effect is relatively incremental