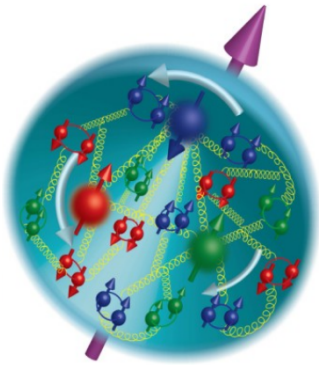
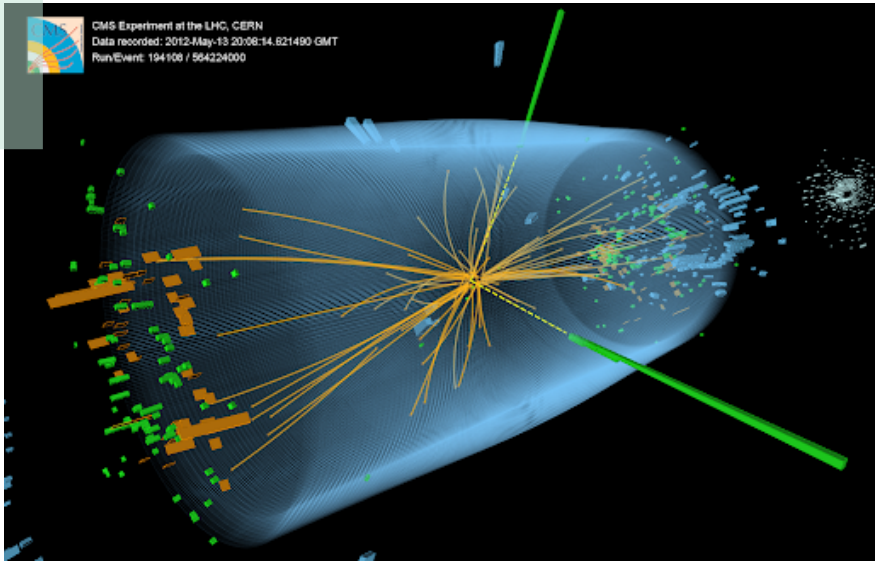
PDFs at the Electron-Ion Collider (EIC)

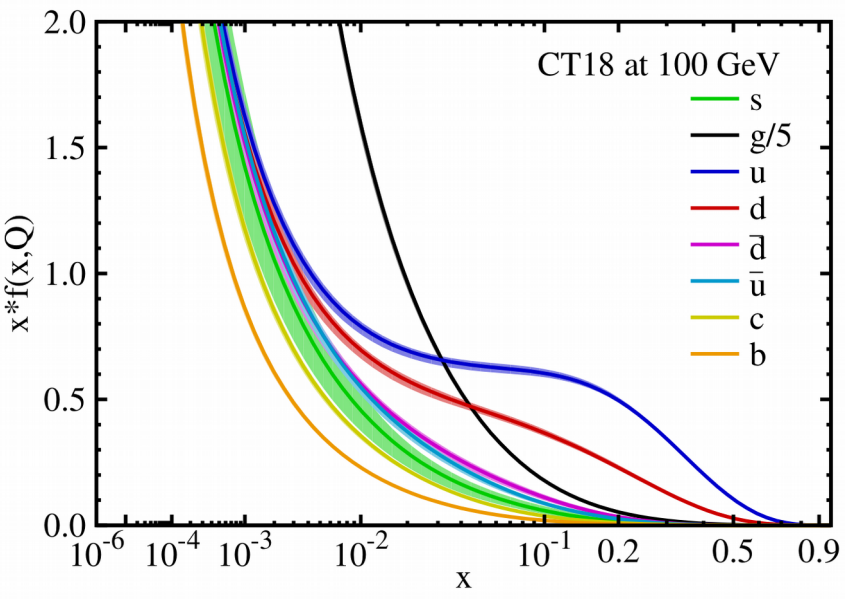
[and HEP implications]

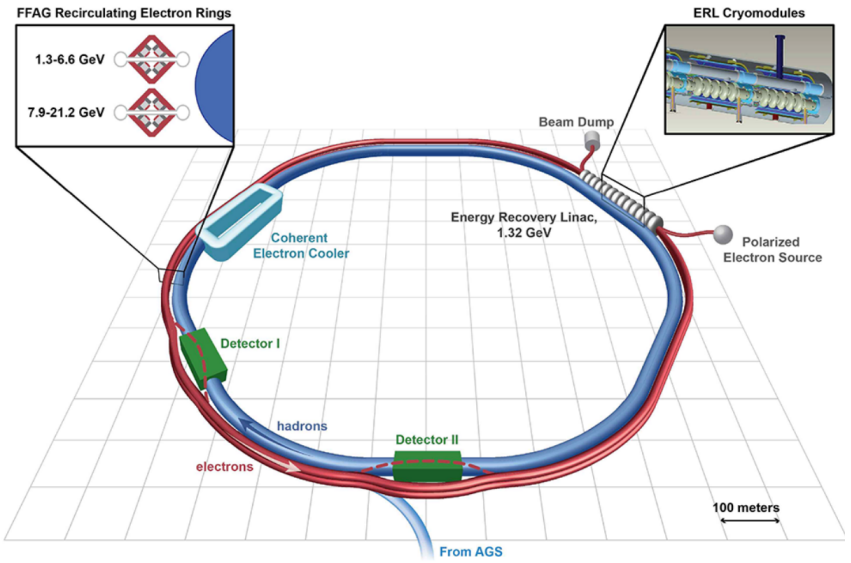
Tim Hobbs, CTEQ@SMU & JLab EIC Center

October 6th 2020









the Electron-Ion Collider (EIC)

- a next-generation **DIS collider**, to be built at BNL
- the only new collider planned in the US for the next half-century
- CD-0: estimated construction cost: $1.6-2.6B over 10 years

- a centerpiece of American physics for the next few decades
- **facility for precision QCD with HEP implications**

important feature of the physics landscape for Snowmass 2021!

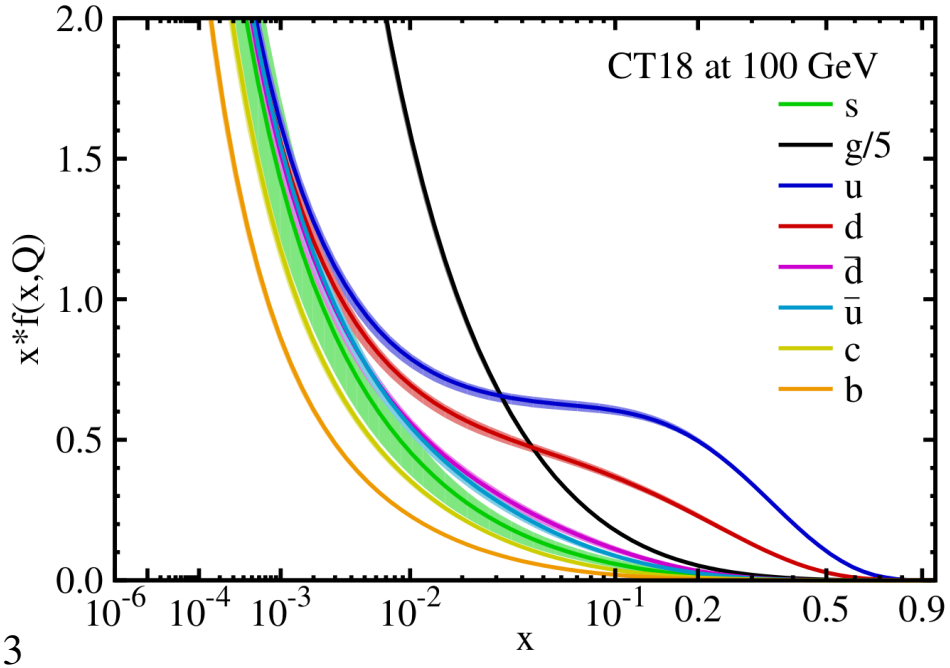
EIC: a machine for precision QCD

- EIC will record many measurements relevant to PDFs and HEP phenomenology:
  - **high-energy QCD** (DIS measurements; heavy quarks/masses, jets, α_s)
  - **gluonic structure/Higgs** (gluon PDF, improvements to gg→ 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)

LOI here

3D structure

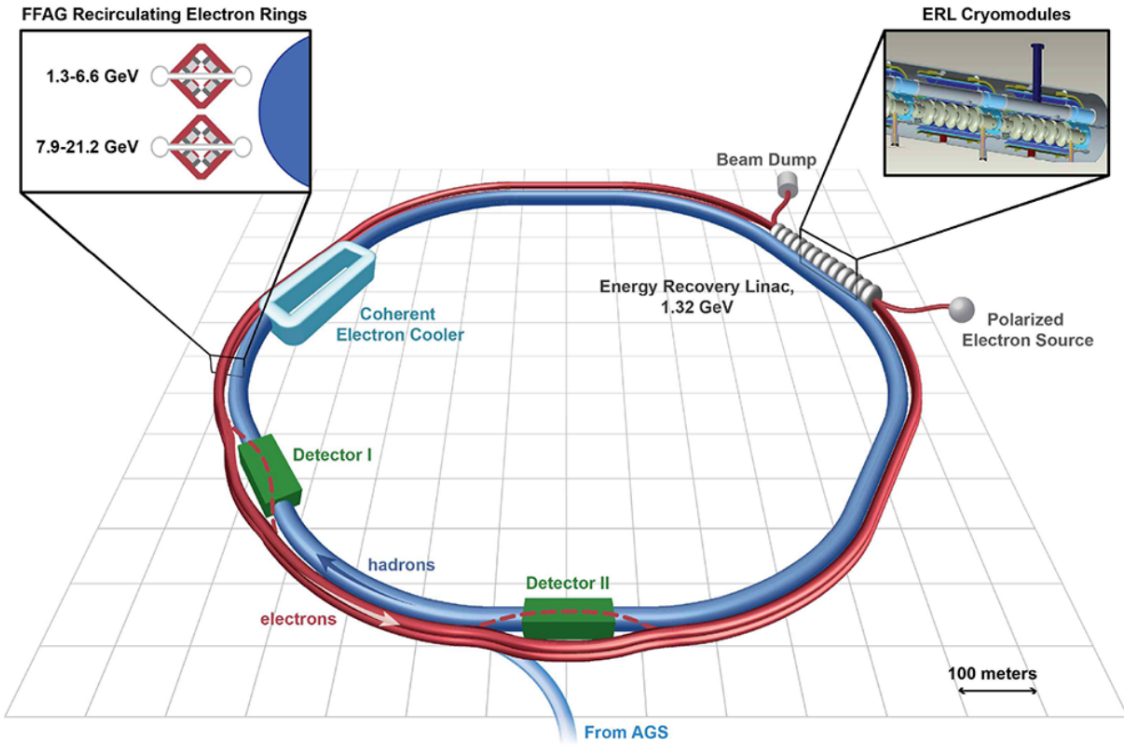
SnowMass2021



- PDF connections to other dedicated LOIs:
  - → heavy flavor (LOI)
  - → Electroweak and BSM (LOI)
  - → Jet production (LOI)
  - → low-x gluons, saturation

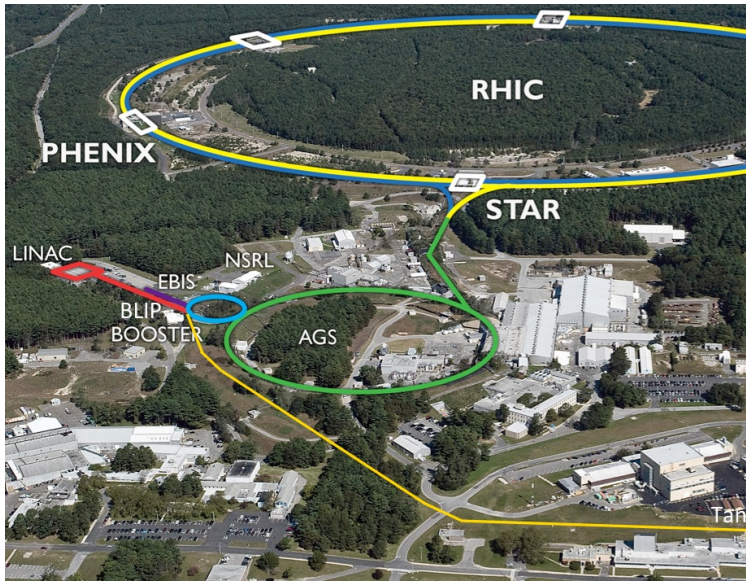
EIC: very high-luminosity DIS collider [$10^{2\text{-}3}$ times HERA]

selected Brookhaven concept, “eRHIC”



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

- 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 $[x, Q^2]$

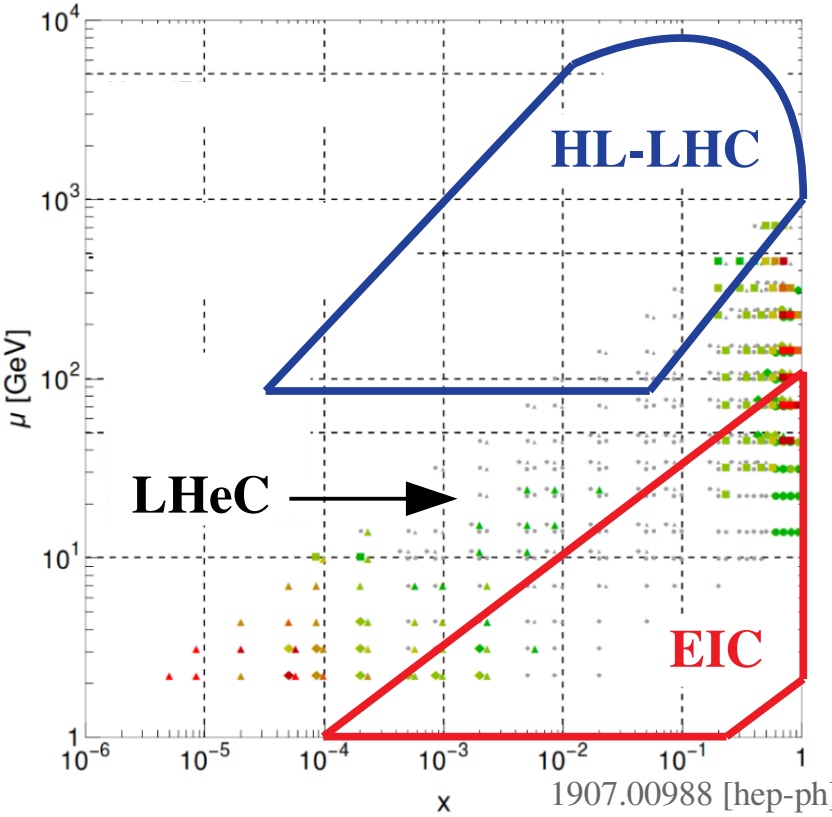
[see talks, Ubiali & Garzelli]

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

[PDF impact exceeds legacy CT fixed-target data important for key LHC processes]

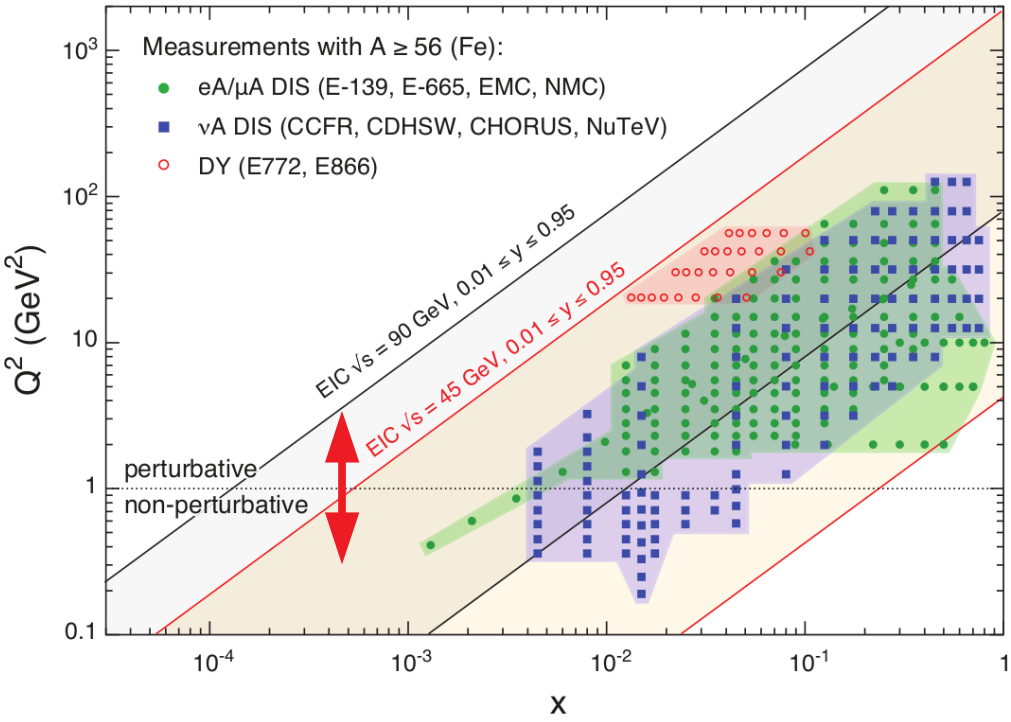
- extensive probe of the **quark-to-hadron transition** region

proton PDF: regions of sensitivity



1907.00988 [hep-ph]

analogous nuclear DIS coverage:



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

precision HEP phenomenology is PDF-limited

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

for m_W :

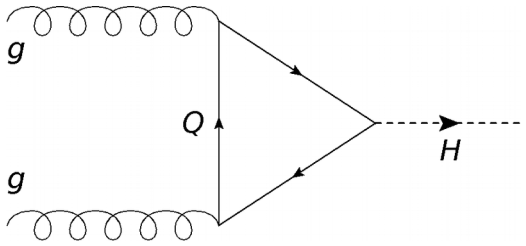
ATLAS, 1701.07240

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

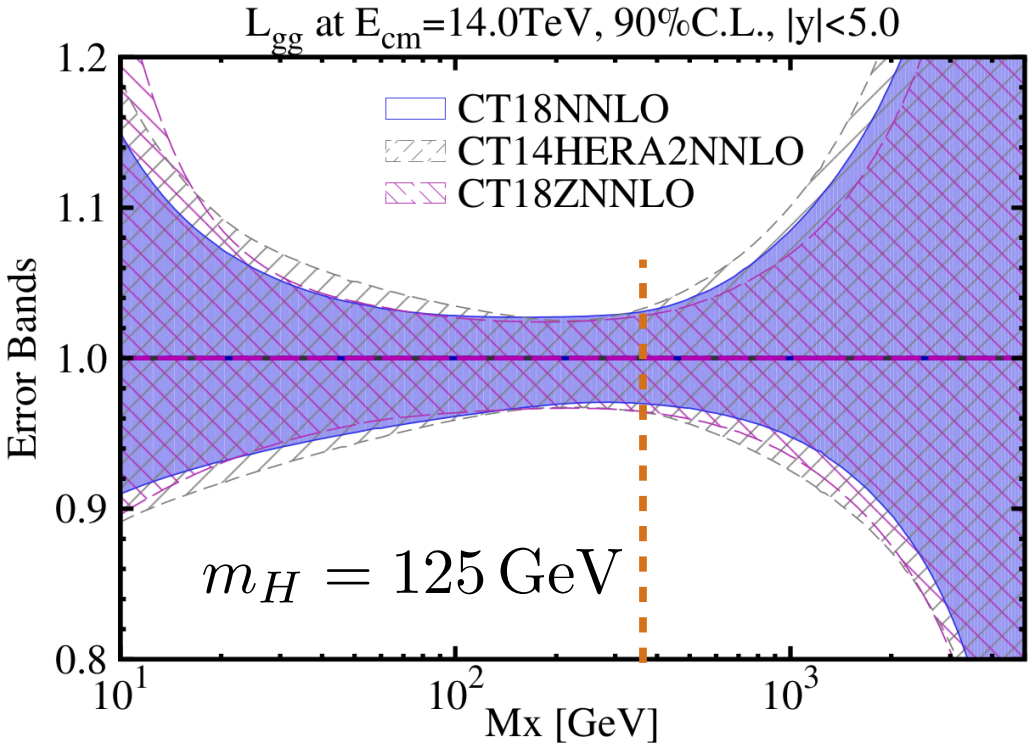
→ **the PDF uncertainty can be a dominant uncertainty!**

for σ_H :

- Higgs production limited by knowledge of proton's gluon content:



- hadron colliders will be challenged to resolve this alone



toward next-generation PDFs

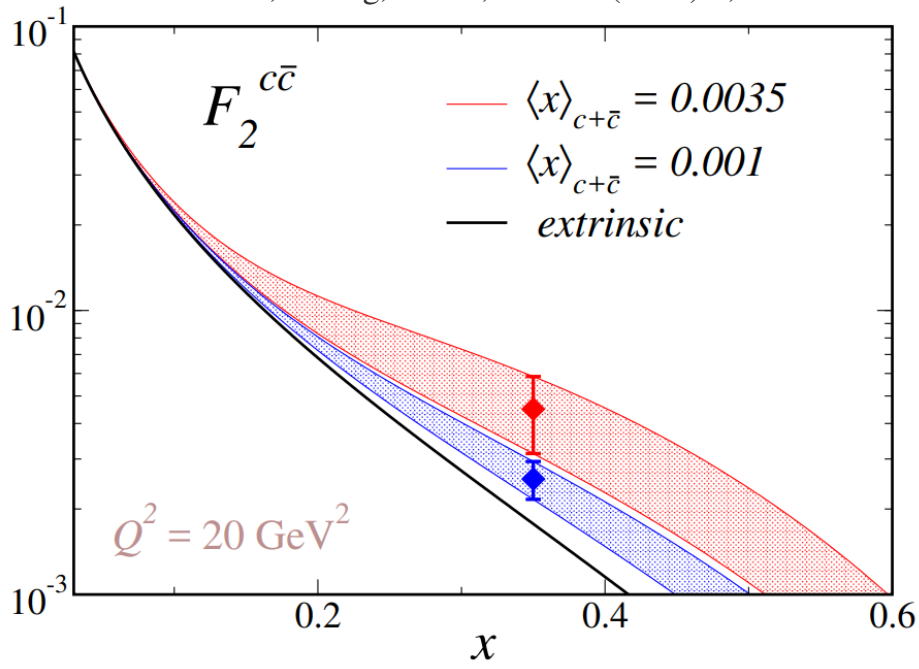
- EIC will be a machine for nonperturbative PDFs & QCD dynamics
  - → high-lumi measurements near the PDF starting scale, $Q \sim Q_0$
  - → data traversing few-GeV region: control **HTs, TMCs, multi-parton correlations**
  - → nuclear considerations

    (nuclear-free PDF extractions; nuclear-medium effect studies)

- AND precision QCD in perturbative regime
  - → extensive DIS data a la HERA
  - → needed for (N)NNLO PDF extractions

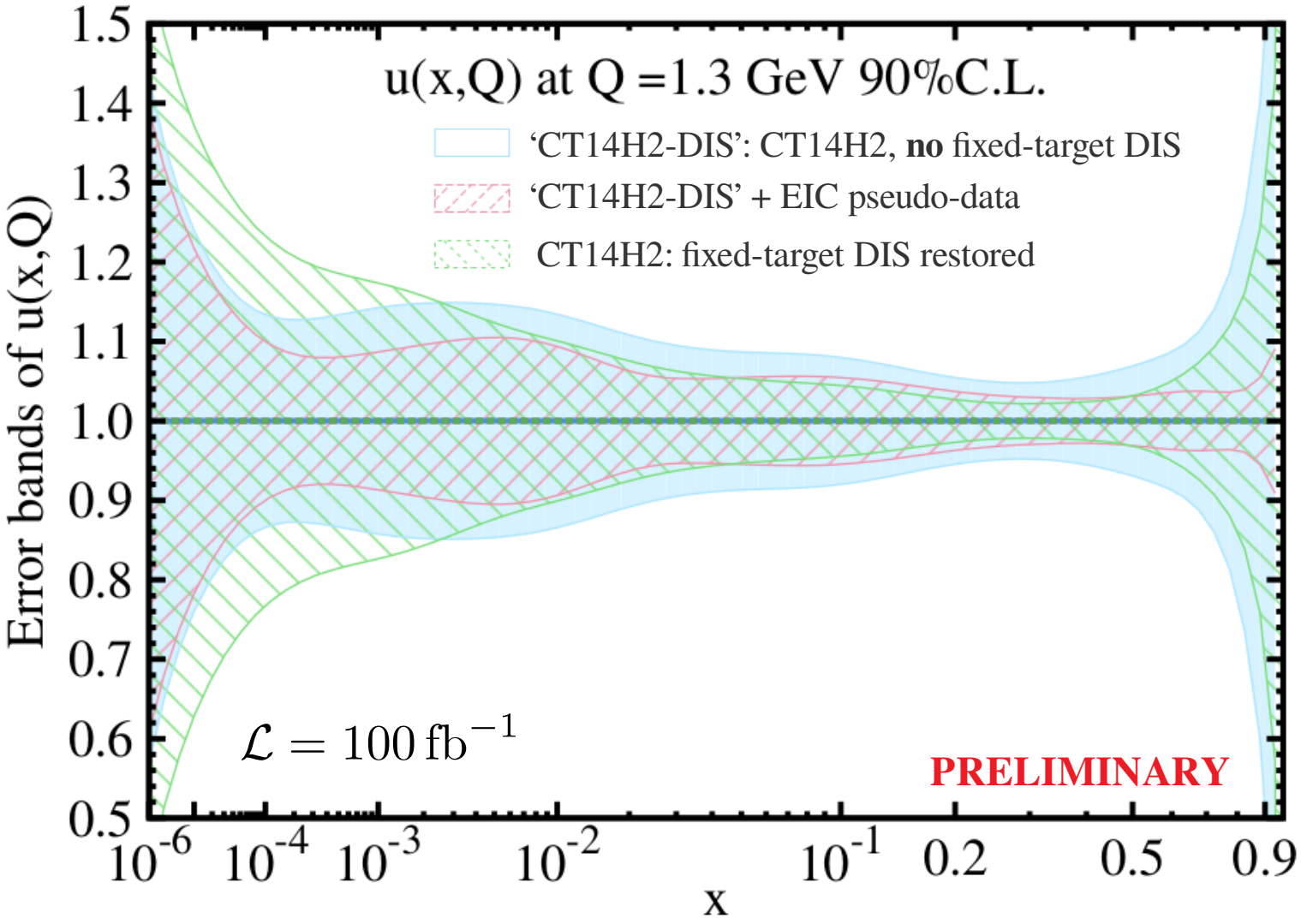
    require improved showering; MCEGs
- (non)perturbative hybrid issues
  - → resolve intrinsic/fitted charm (*right*)
  - → benchmark lattice-PDF calculations

TJH, Alberg, Miller, PRD**96** (2017) 7, 074023.



substantial reductions to PDF uncertainties

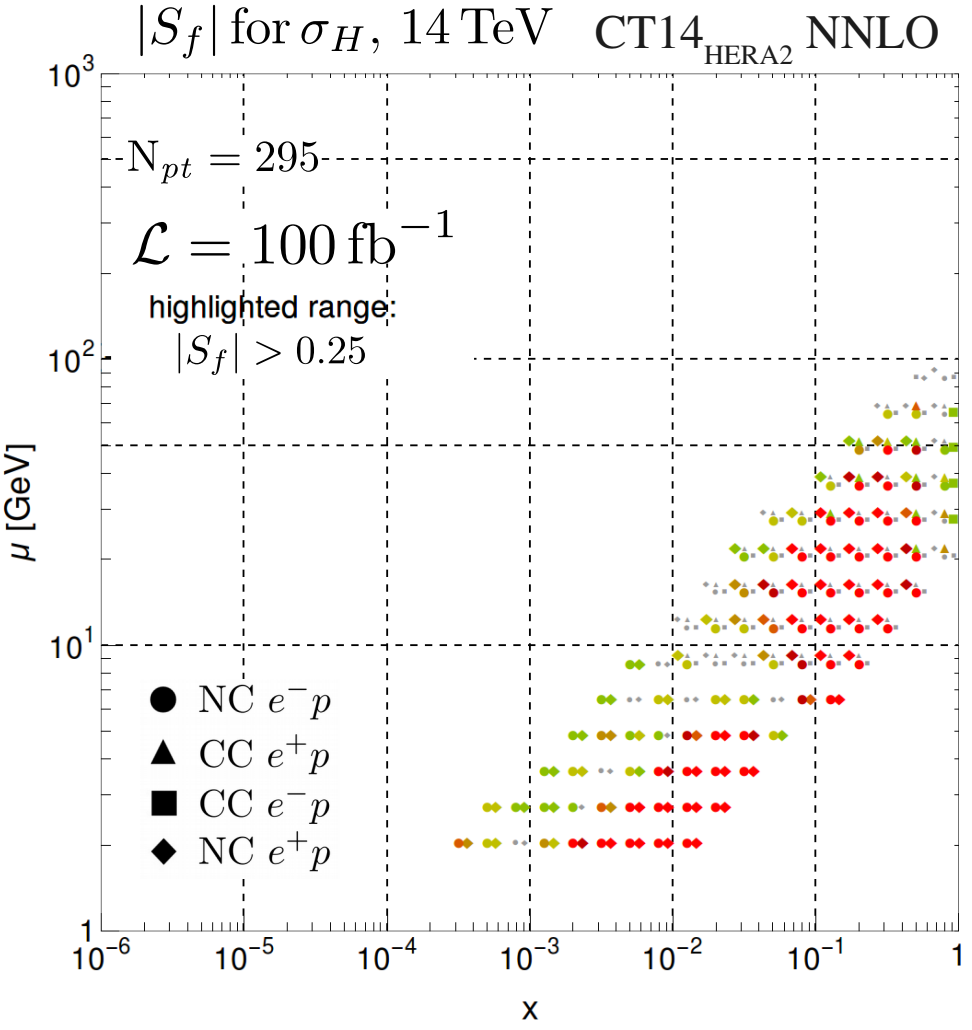
(1 approximate year of data-taking)

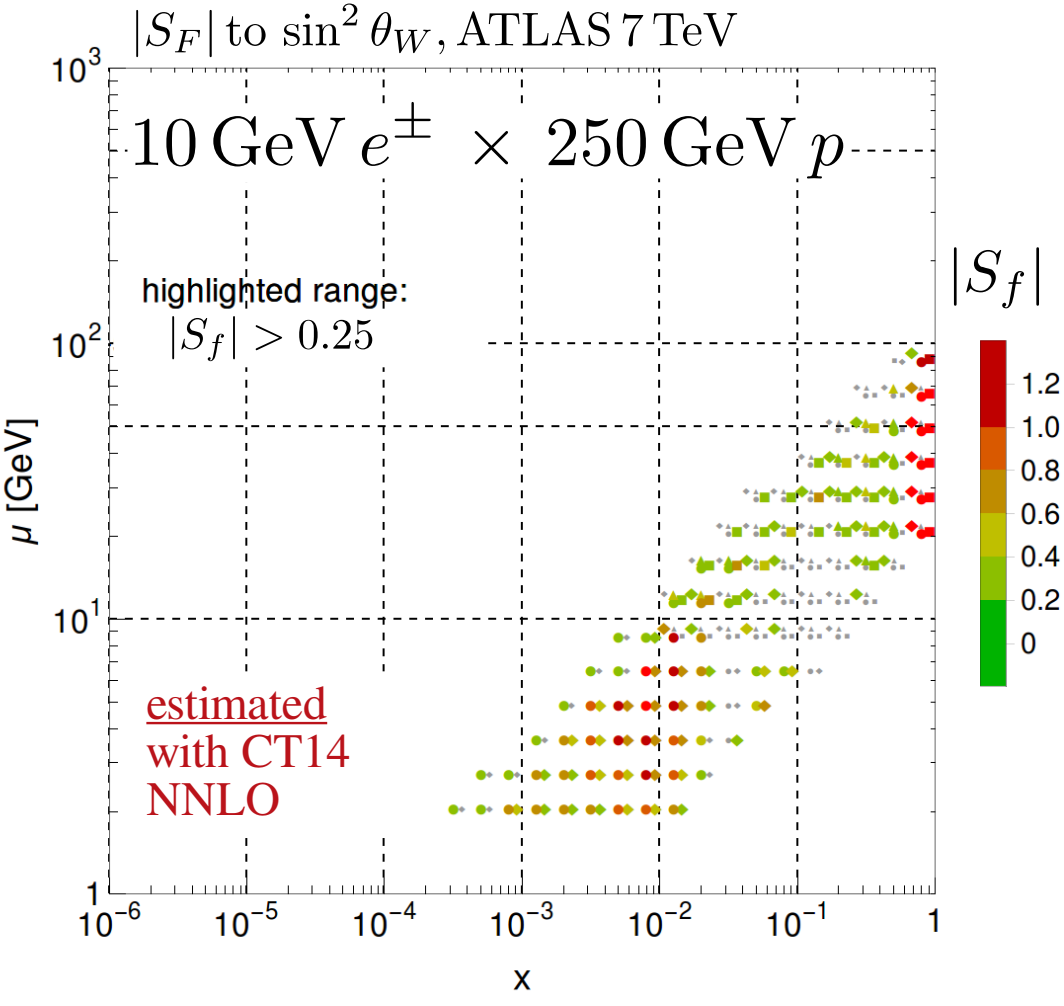


- **EIC pseudodata surpasses fixed-target DIS information in modern CT fits**
- in addition to powerful constraints, can resolve tensions in legacy data

significant PDF sensitivity to key HEP observables

- inclusive $e^{\pm}$ NC/CC reduced X-sections: reduce PDF uncertainties of SM quantities
  - gluon constraints $\leftrightarrow$ strong sensitivity to Higgs cross section (*left*)
  - *d*-type PDF $\leftrightarrow$ significant pull on weak-mixing angle (*right*)



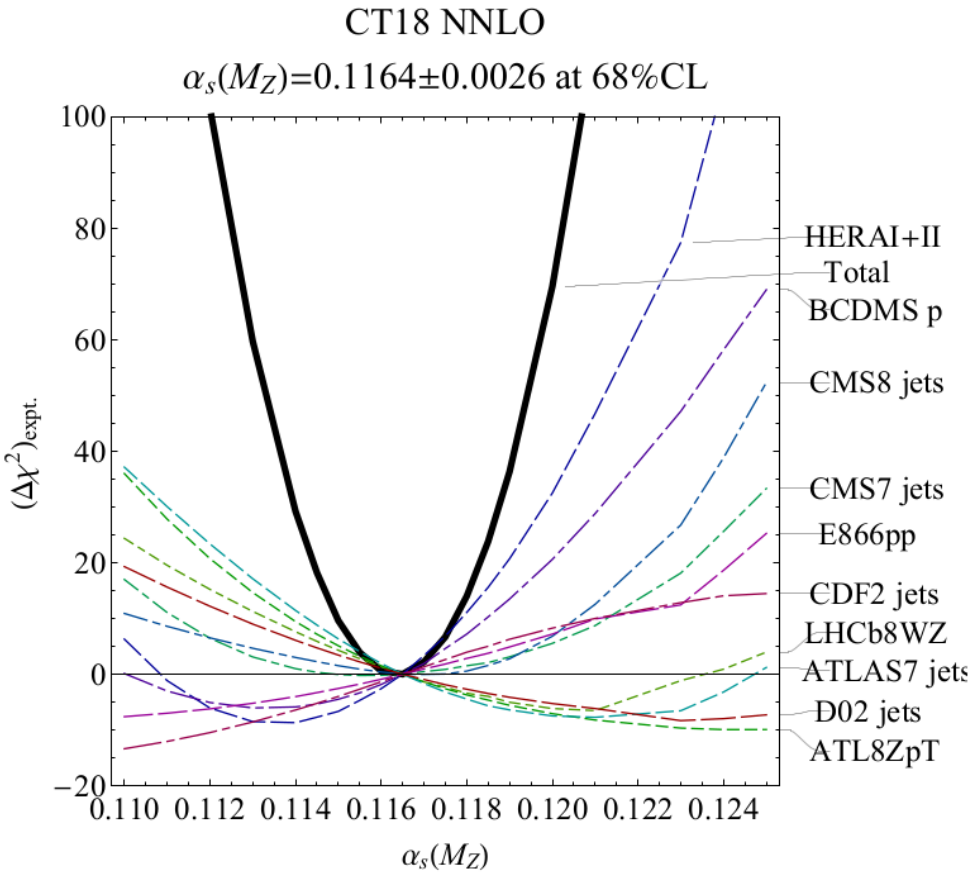


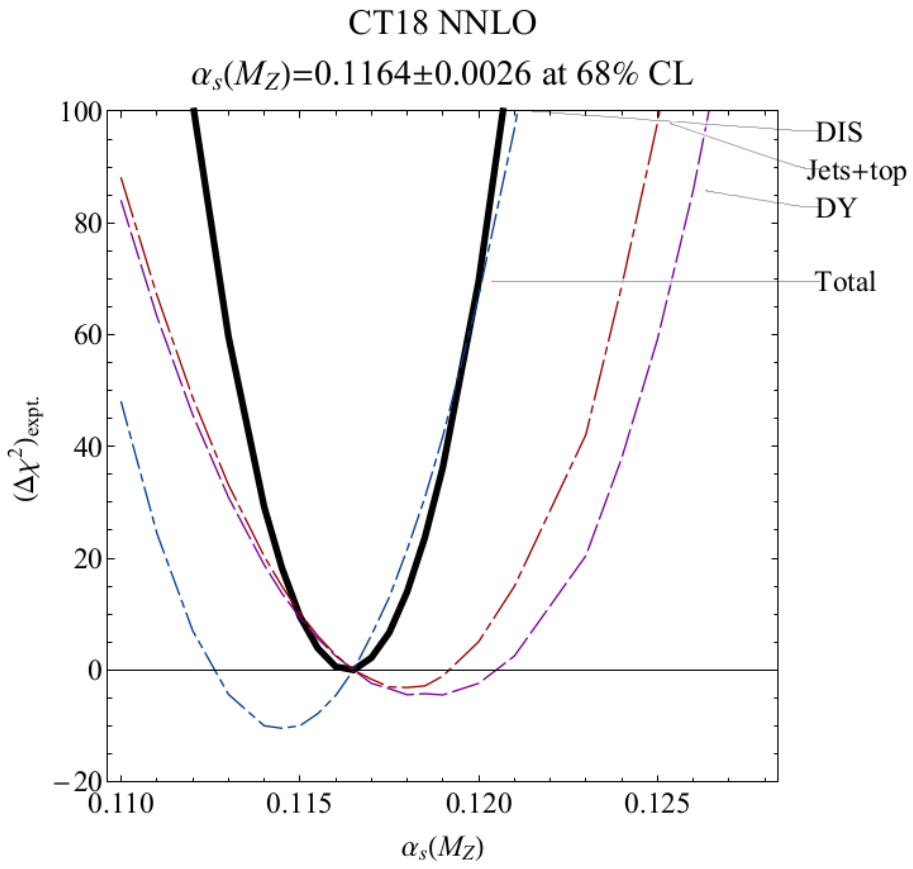
EIC and SM inputs: α_s

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

[see talk, Huston]

- in CT18, strong DIS (and HERA) pulls → dominant role of DIS colliders like EIC





- EIC can drive simultaneous PDF/SM parameter extractions for HL-LHC

BSM and EW possibilities

- alternative extractions of Weinberg angle at EIC: PVDIS

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

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

(accessible from the parity-violating lepton helicity asymmetry, A_e^{PV})

- improve upon HERA limits in charged-lepton flavor violation,

$$eN \to \tau X$$

- SMEFT: move toward simultaneous fits of PDFs, higher-dimensional operator M.E.s

see dedicated LOI: Electroweak and BSM (LOI)

conclusions, recommendations

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

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

  → will drive development for **next-gen PDFs, theory**

  [requires base (N)NNLO calculations; better showering]

  → PDF improvements will propagate to SM quantities; EW tests, BSM searches

- 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

  → coordinate with dedicated PDF, QCD theory LOIs/initiatives

supplementary material

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**

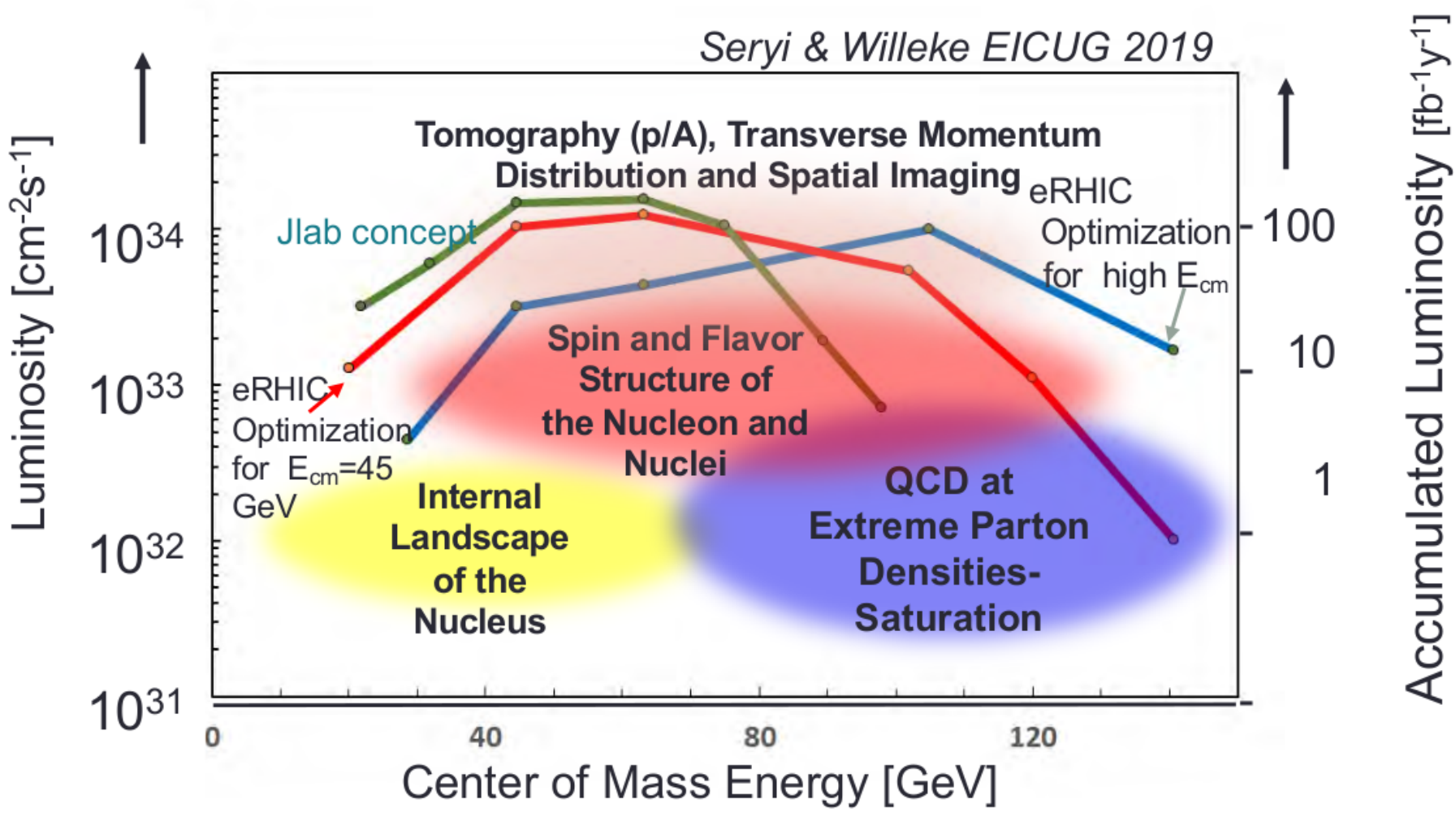
- areas of particular intersection with LHC/HEP emphases

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

EIC is now being designed/optimized

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

→ target to most impactful physics



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

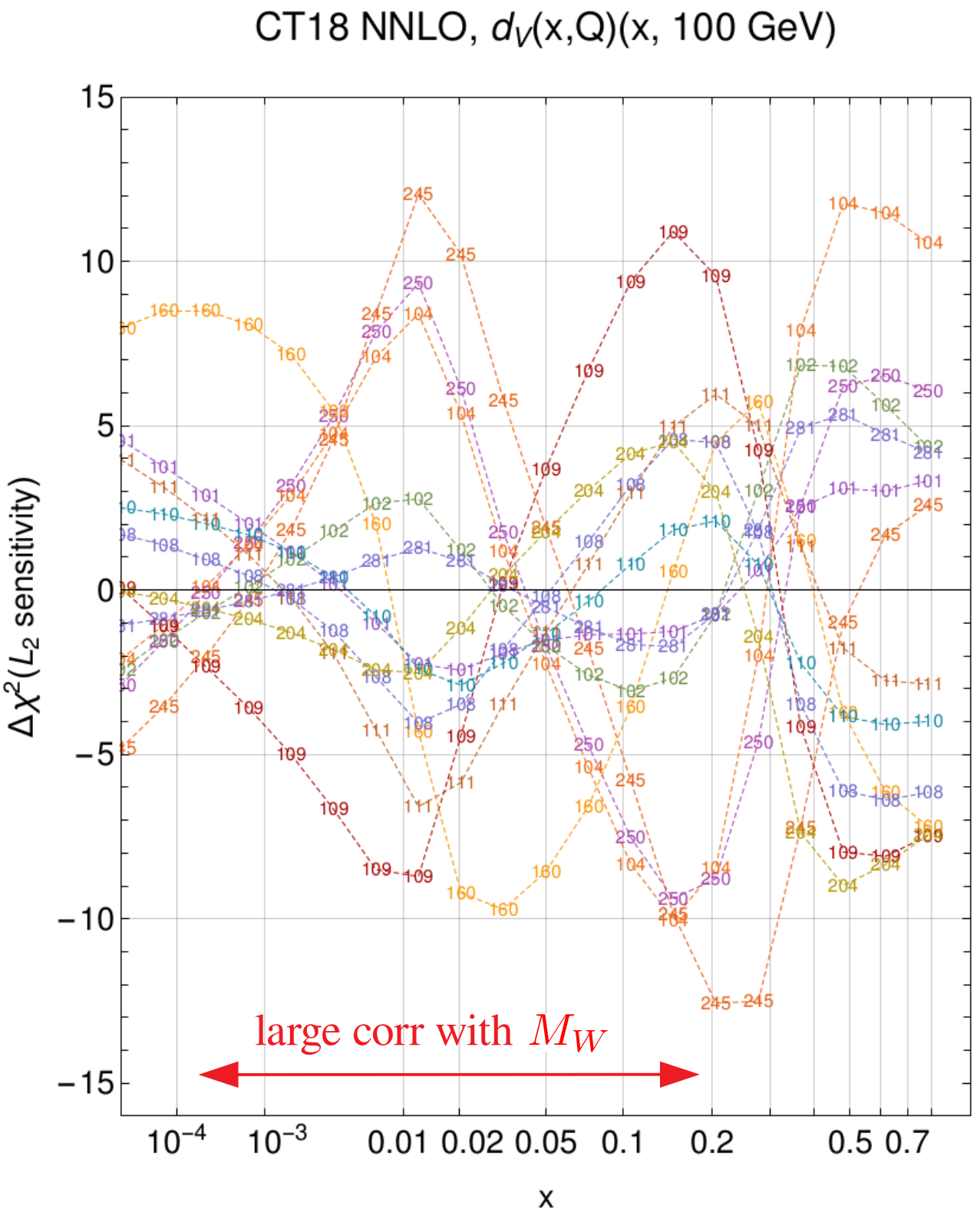
tools and EIC apps

- 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!



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

→ opposing peaks indicate tension

245 LHCb7ZWrap
250 LHCb8WZ
160 HERAIpII
101 BcdF2pCor
102 BcdF2dCor
104 NmcRatCor
108 cdhswf2
109 cdhswf3
110 ccfrf2.mi
111 ccfrf3.md
204 e866ppxf
281 d02Easy5

significant tensions in M_W correlated region

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

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: $10\,\mathrm{GeV}\ e^{\pm}$ on $250\,\mathrm{GeV}\ p$ $\quad(\sqrt{s} = 100\,\mathrm{GeV})$

~year of data-taking

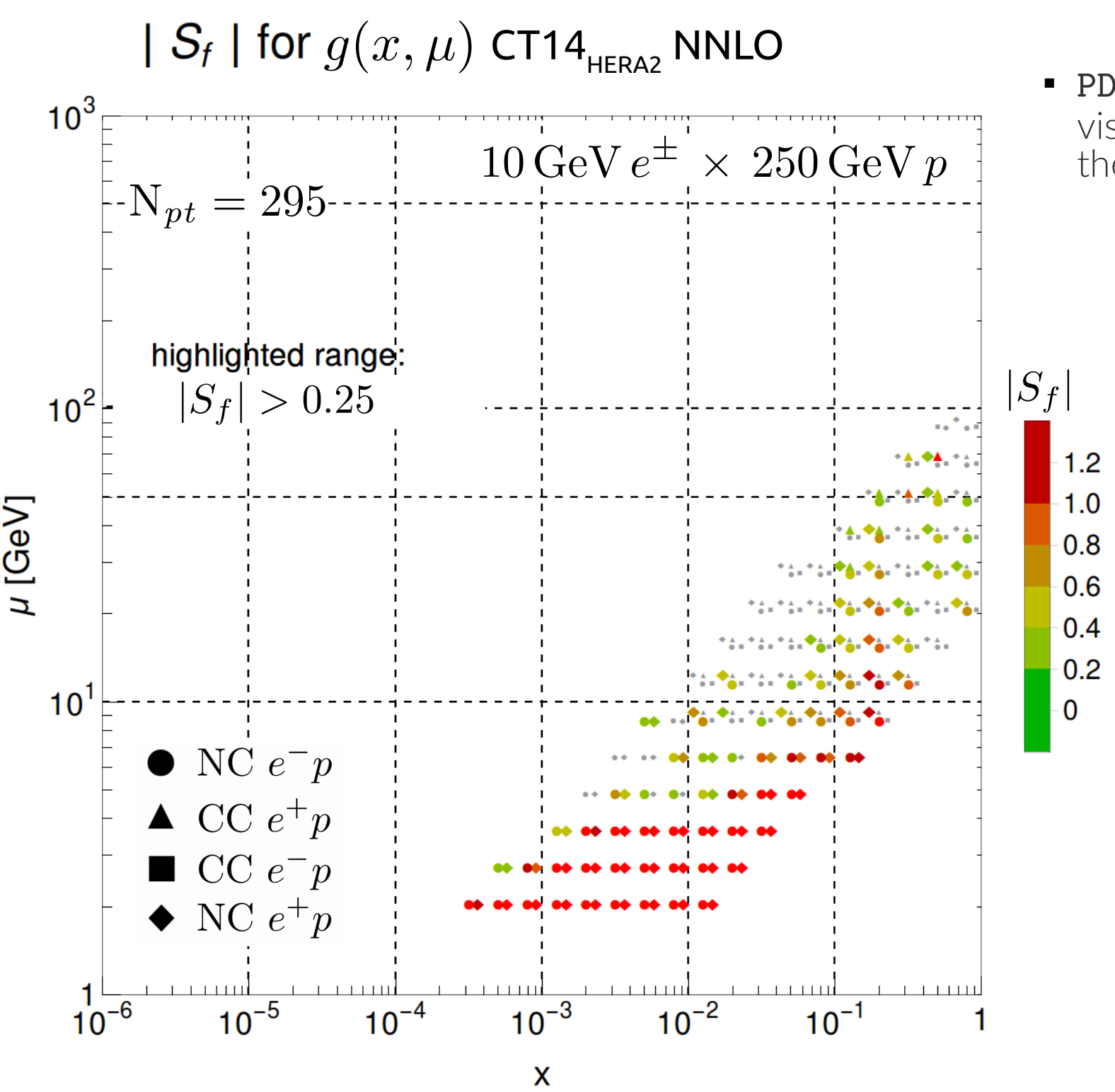
$\mathcal{L} = 100\,\mathrm{fb}^{-1}\ e^{-}$ pseudodata

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

→ NC/CC

→ currently, proton scattering only

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



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

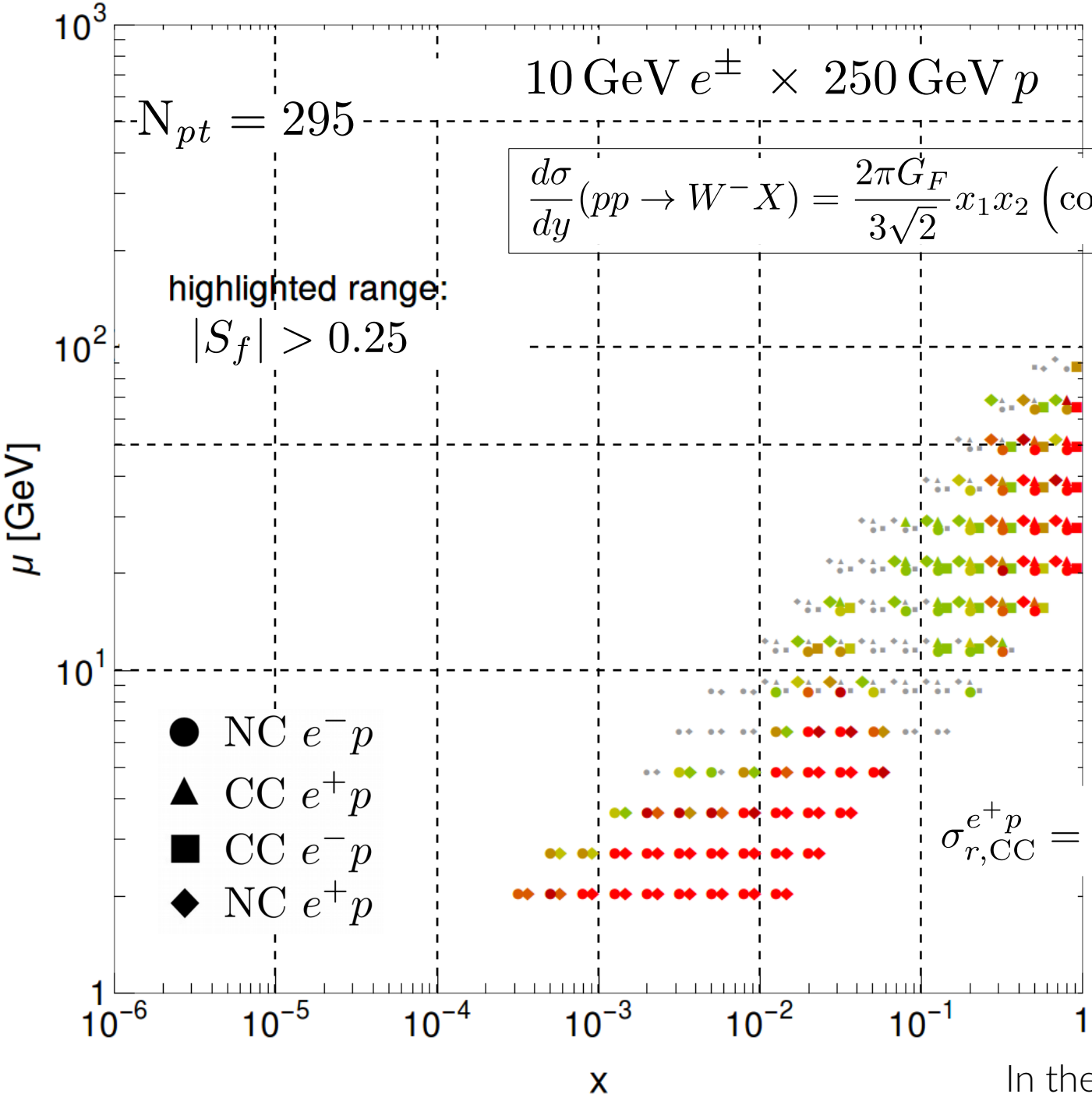
cf. $|S_f| \sim 0.3$-0.5, typical CT18 expts.

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

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

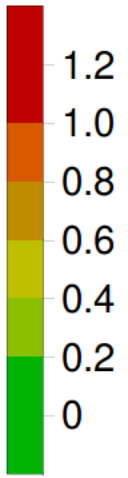
- these constraints arise from high statistics neutral current data on $\sigma^{e^{\pm}p}_{r,\text{NC}}$

$|S_f|$ 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 $x \to 1$

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

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

In the LO quark-parton model

EIC and PDF-Lattice synergy

Constantinou *et al.*; 2006.08636

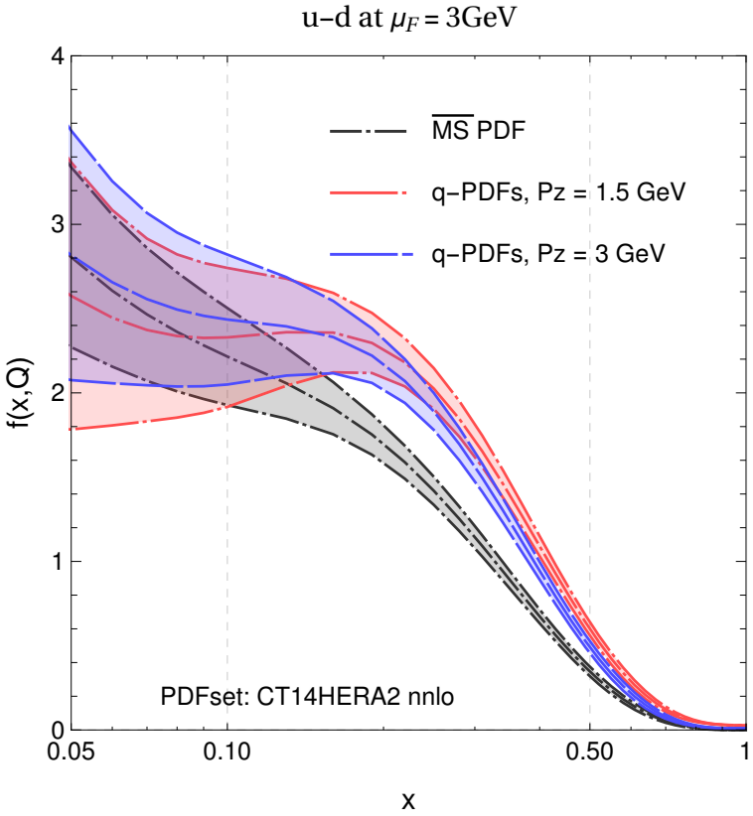
- techniques for x-dependent PDFs from **lattice QCD** now available

  (compute QCD on discretized spacetime grid)

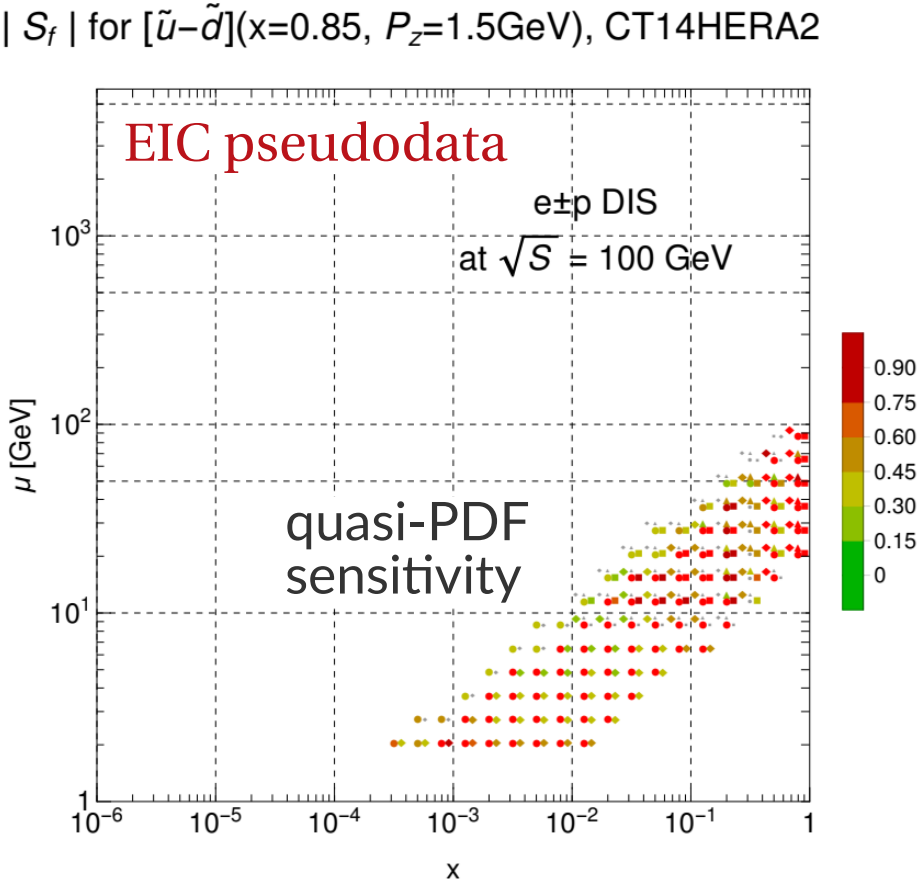
  → theory/models still being developed

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

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

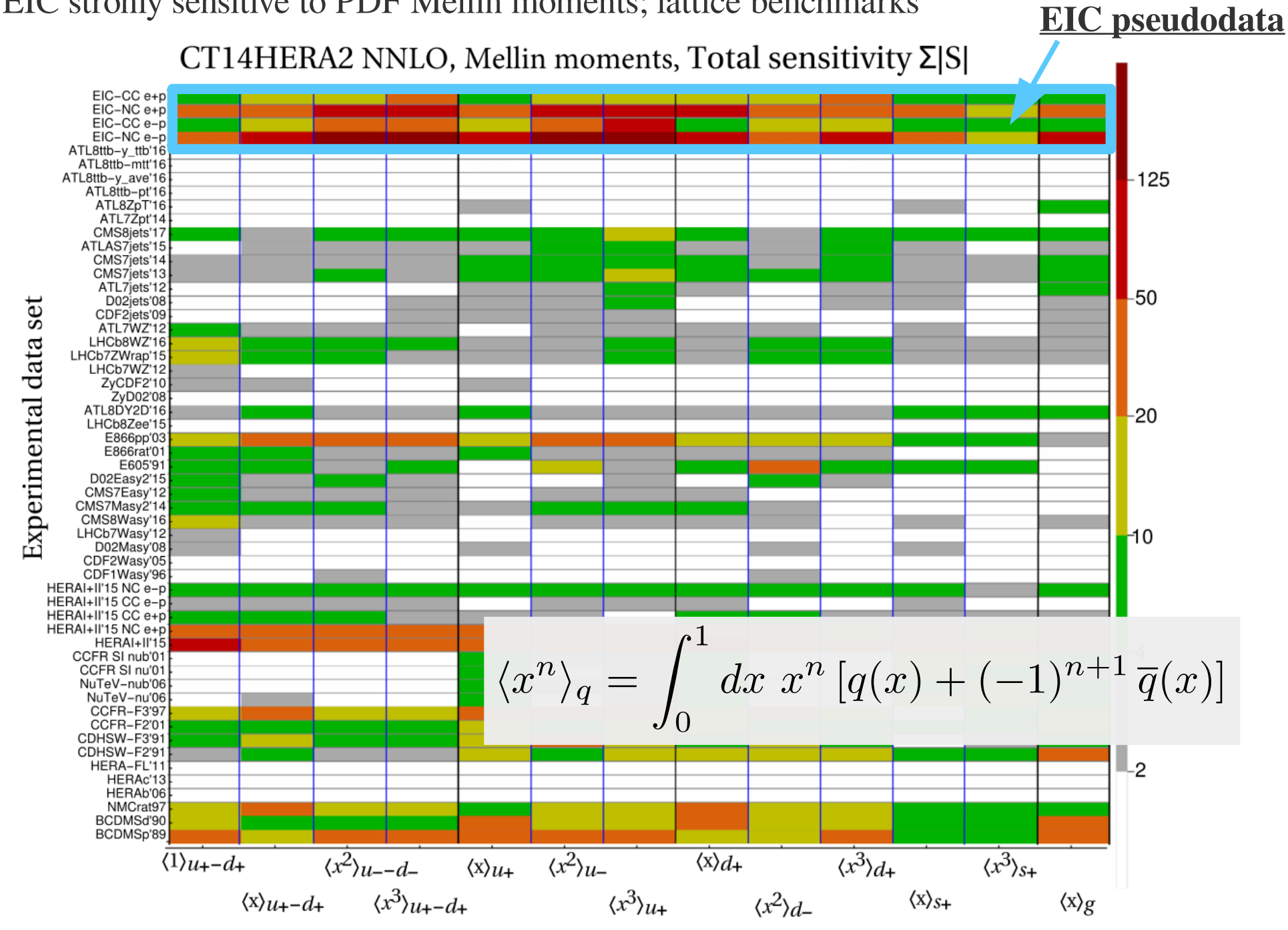


the EIC will drive a PDF-Lattice Synergy



sensitivities can be aggregated for direct comparisons of exps

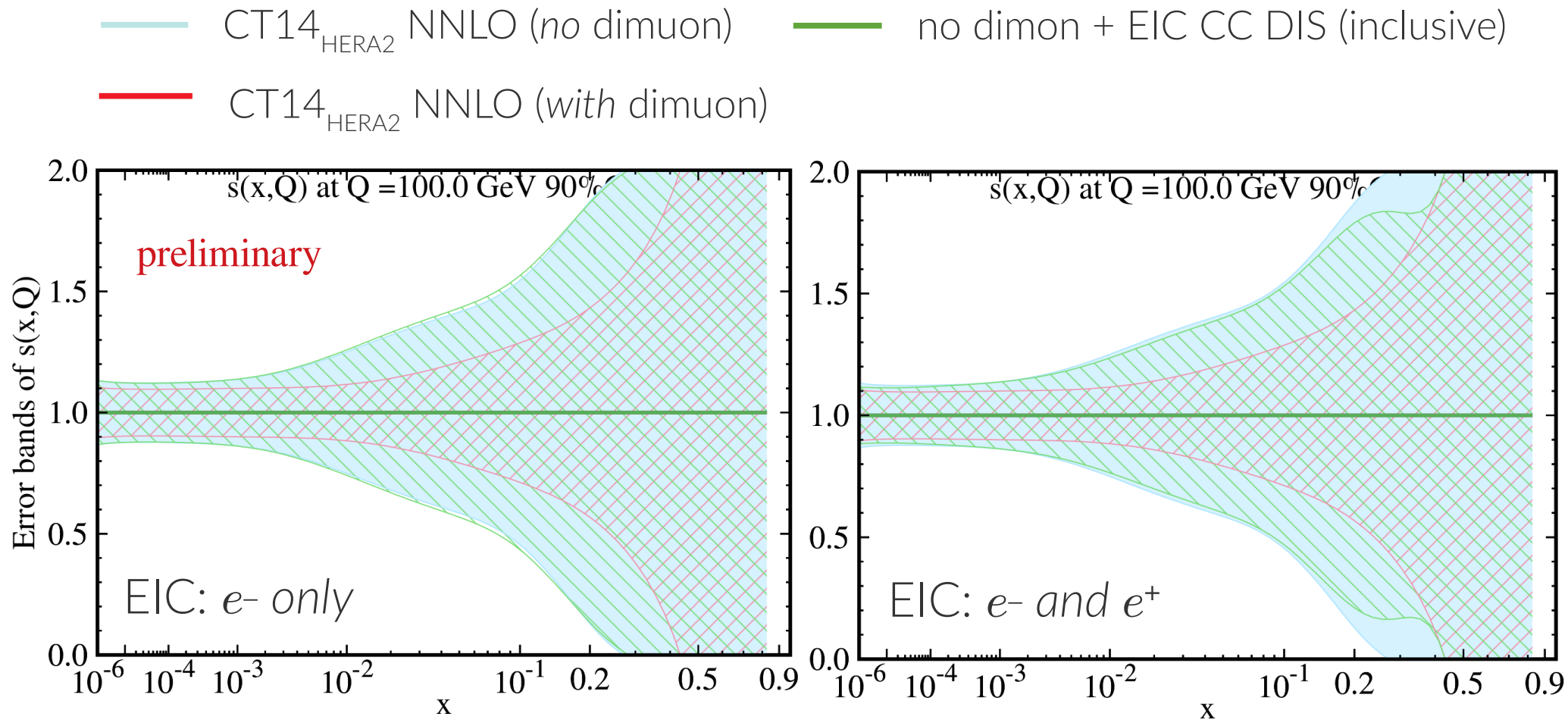
→ EIC stronly sensitive to PDF Mellin moments; lattice benchmarks



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

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!

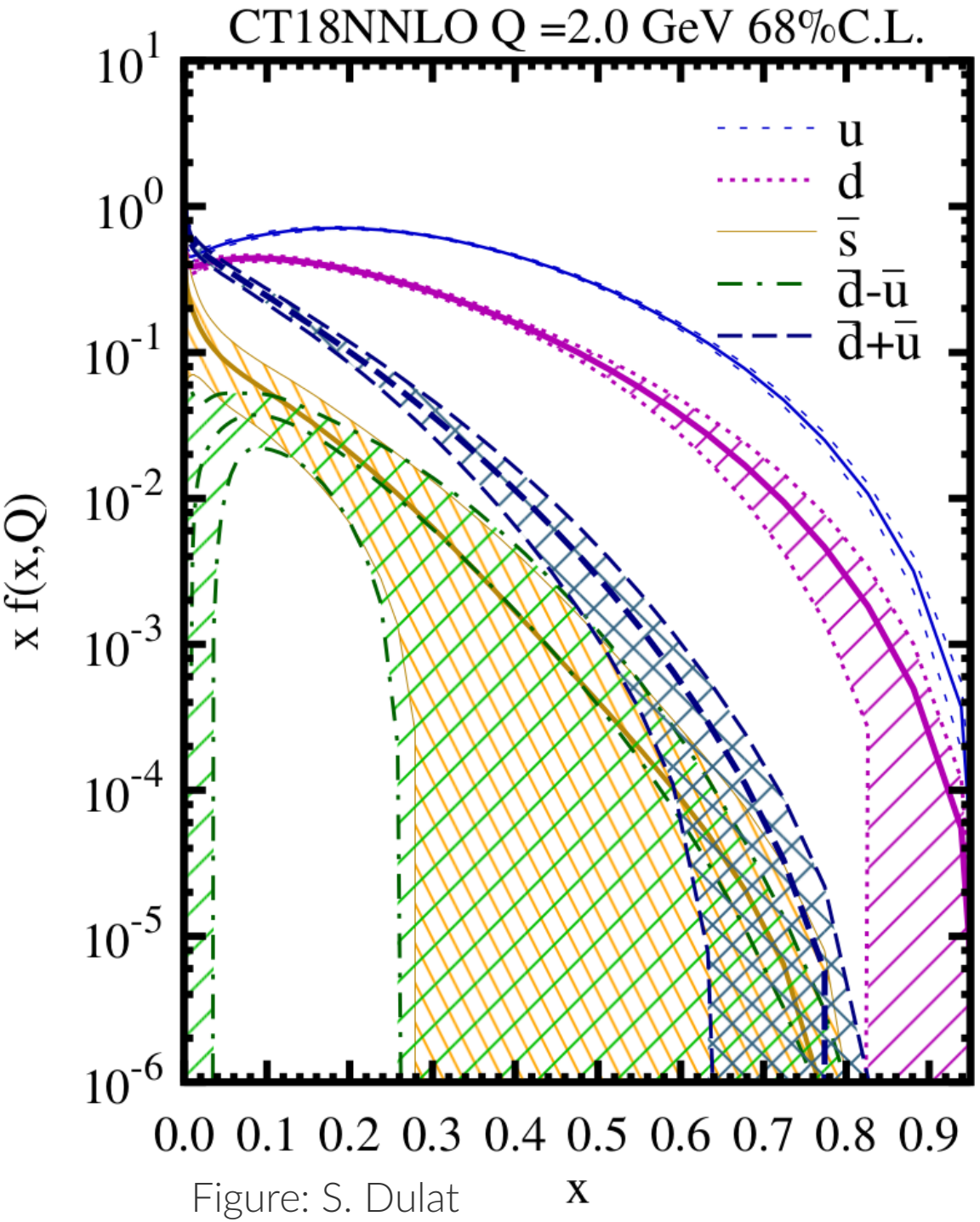


Figure: S. Dulat

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

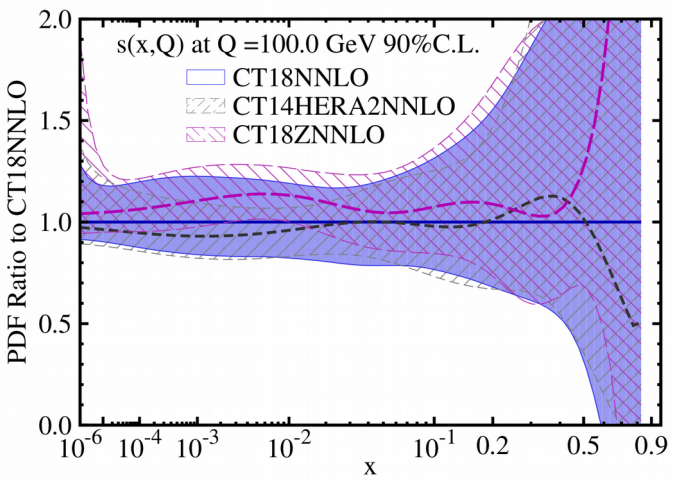
<u>case study:</u> accessing nucleon strangeness in (tagged) CC processes

→ final-state tagging can help unravel flavor structure

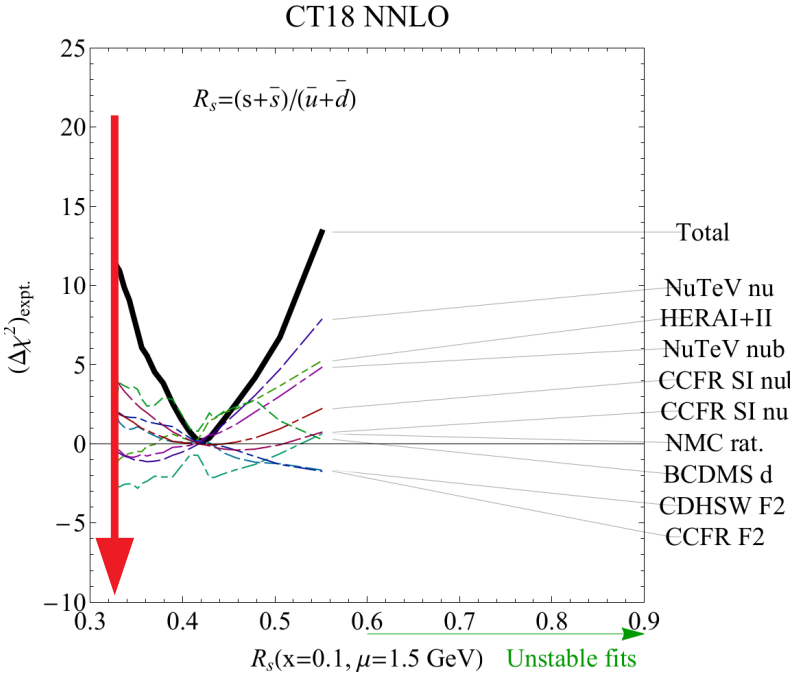
→ study: strange suppression ratio, $R_s = \dfrac{s+\bar{s}}{\bar{u}+\bar{d}}$

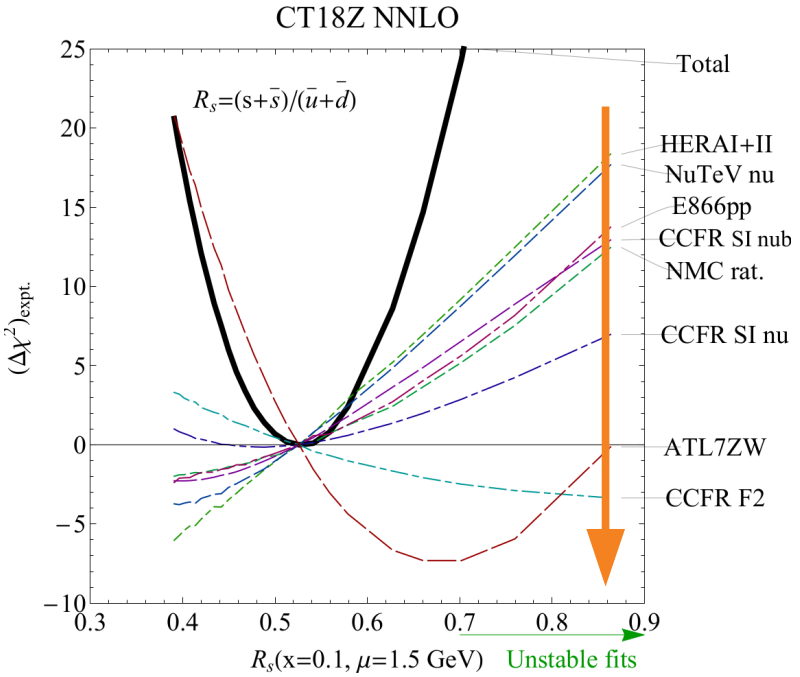
→ ν-A data often favor $R_s \sim 0.5$; ATLAS W/Z production favors $R_s \sim 1$

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



take 2 extreme PDF sets for R_s :



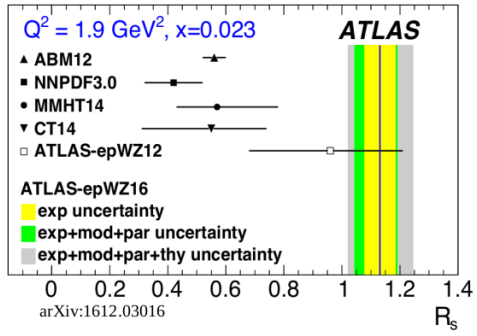


<u>theory inputs:</u> for

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

* $R_s = 0.325$ (CT18)

* $R_s = 0.863$ (CT18Z)



arXiv: 1912.10053 [hep-ph]

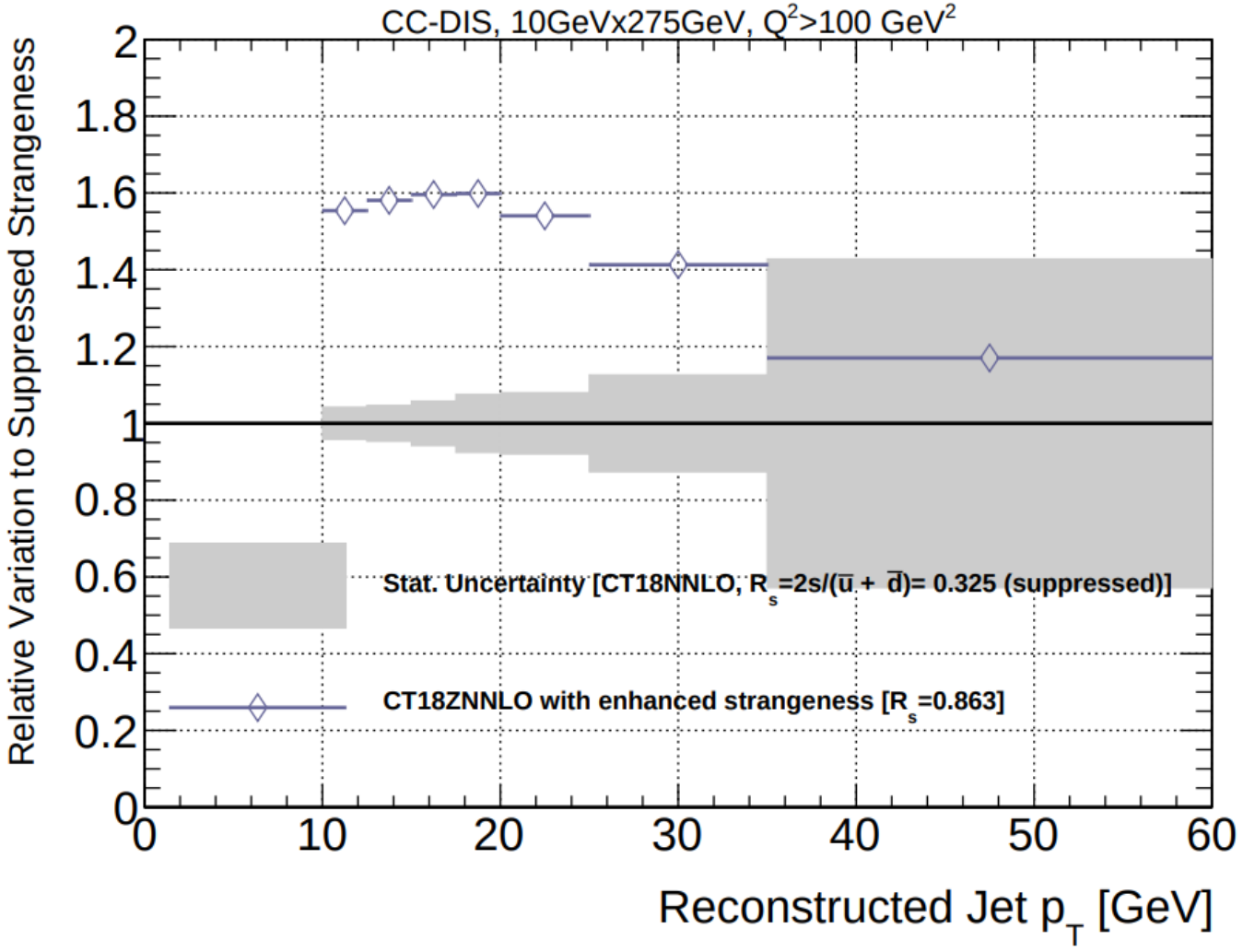
sensitivity of CC charm jet production to strange suppression

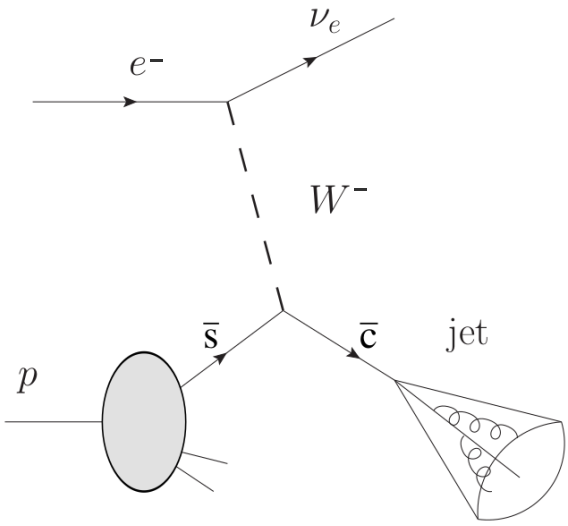
Arratia, Furletova, TJH, Olness, Sekula

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

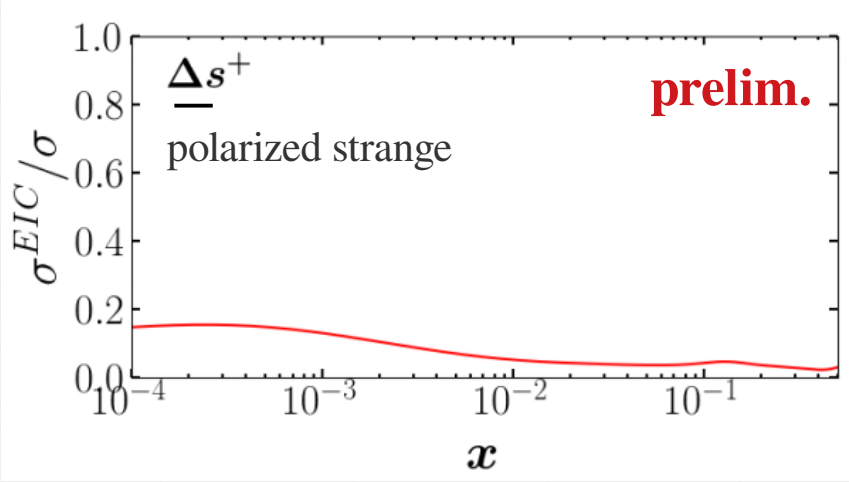
Arra

-
-

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

another, A^{PV}:

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



some impact on unpol strange as well

JAM, C. Cocuzza et al.

Relative Variation to Suppressed Strangeness

toward multi-dimensional structure at EIC

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

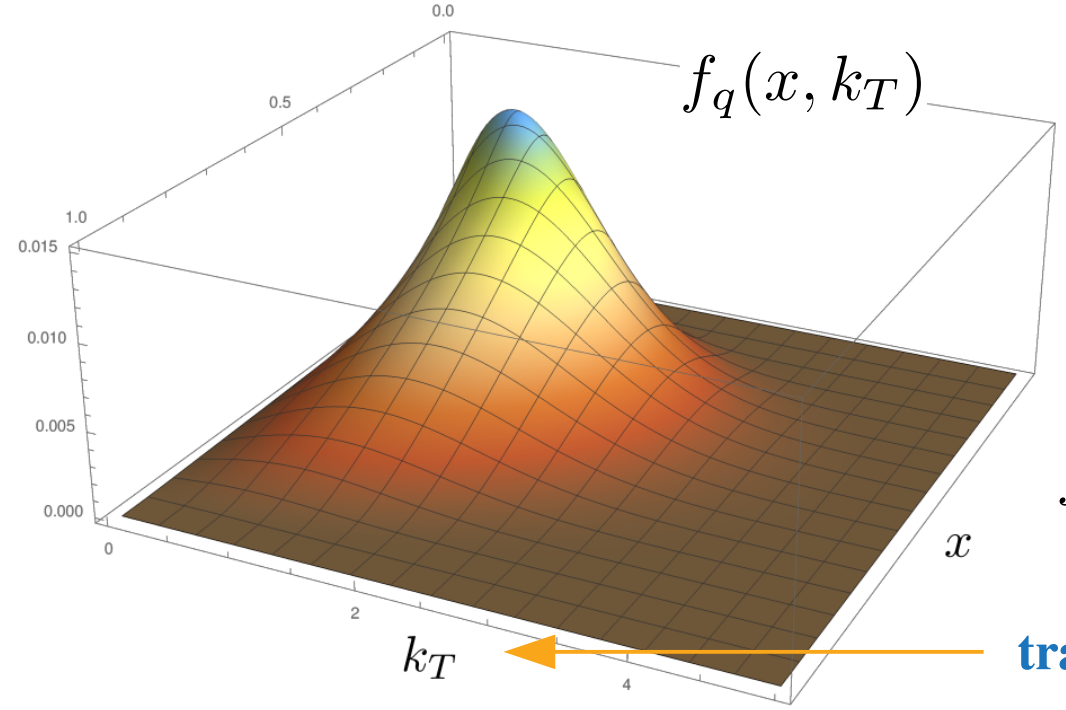
$W(x, \vec{k}_T, \vec{b}_T)$ the Wigner distribution

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

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

…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)

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

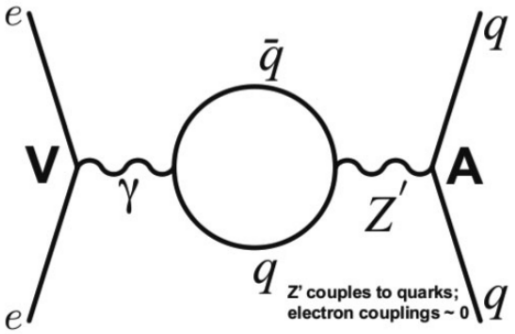
transverse momentum dependence (TMD)!

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).

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

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

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

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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).

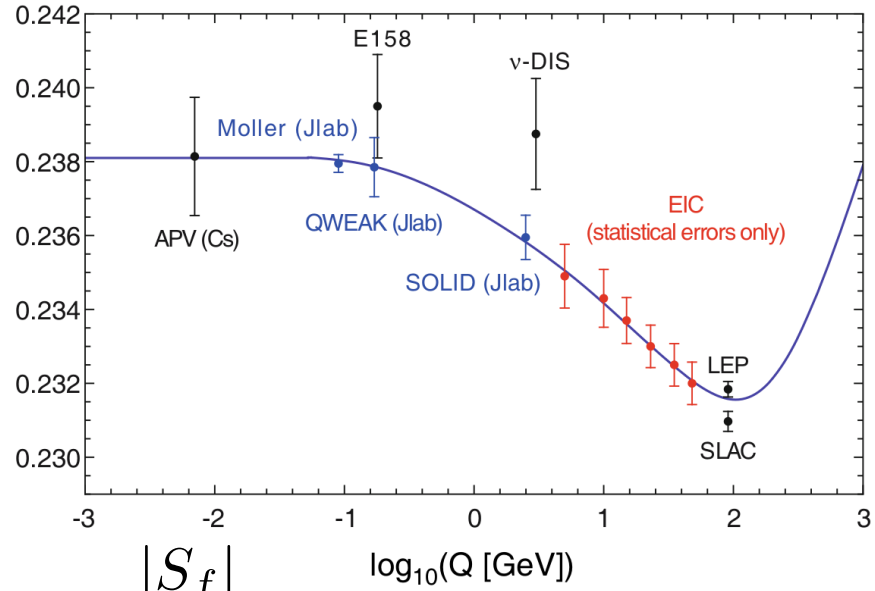
$$A^{\rm PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left(Y_1\ a_1 + Y_3\ a_3\right)$$

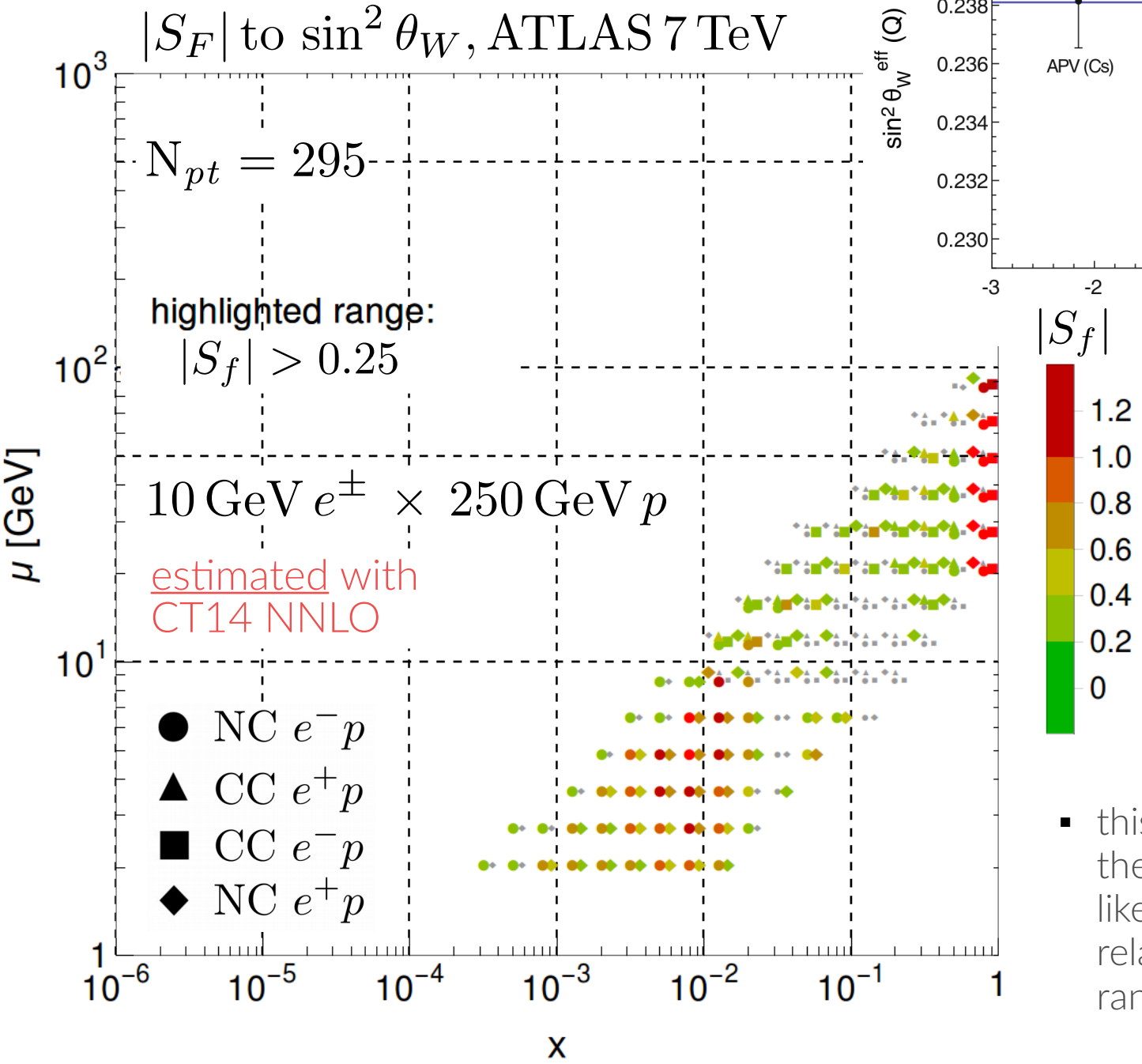
N.B.: extractions are dependent upon knowledge of the PDFs

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

an EIC will probe EW parameters and New Physics!

Accardi et al., EPJA52, 268 (2016).





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

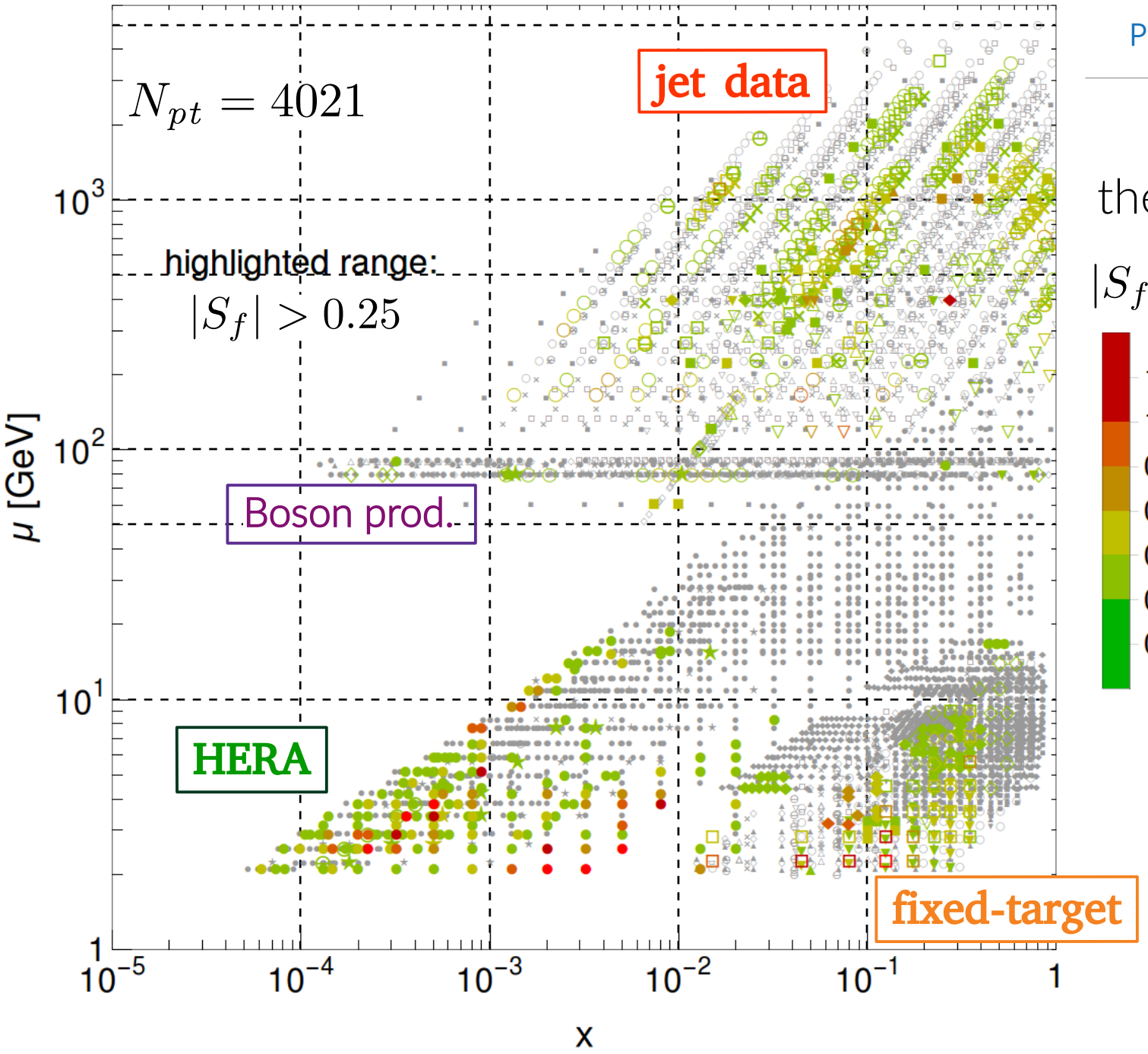
$$\mathcal{L} = 100\mathrm{fb}^{-1}$$

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

$$0.2 \lesssim x \lesssim 0.5$$

II) visualizing impacts with PDFSense

Phys.Rev. D98 (2018) 094030



the PDF *sensitivity*

$|S_f|$

(magnitude of PDF pull of each datum)

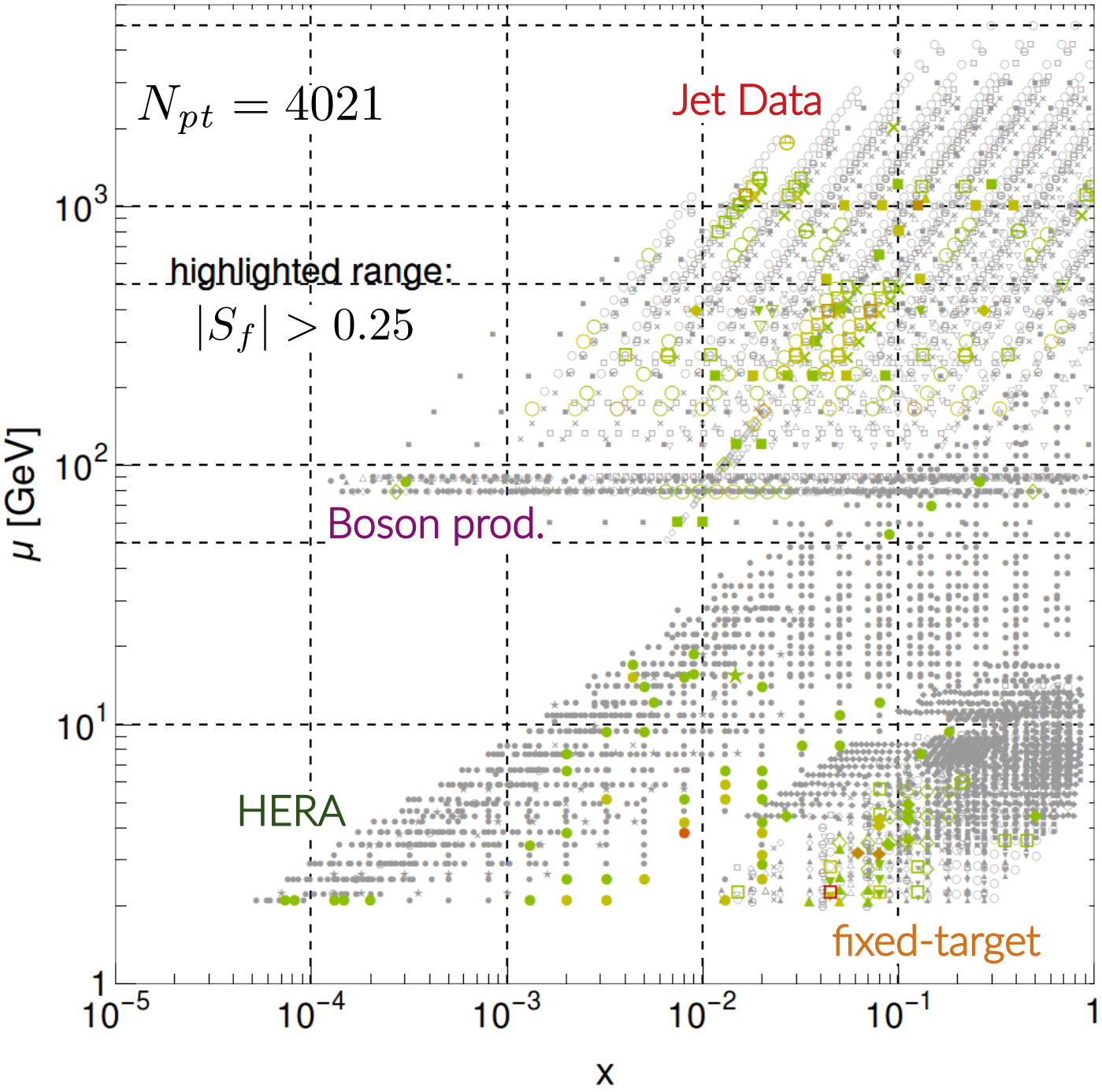
→ measurements with strong PDF correlations AND high precision have high $|S_f|$

- used to identify high-impact data for CT18

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

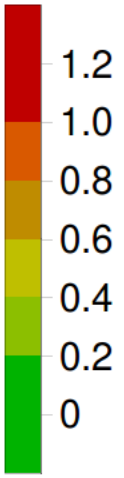
B.-T. Wang, TJH, S. Doyle, J. Gao, T.-J. Hou, P. M. Nadolsky, F. I. Olness

Phys.Rev. D98 (2018) 094030



(magnitude of PDF pull of each datum)

$|S_f|$

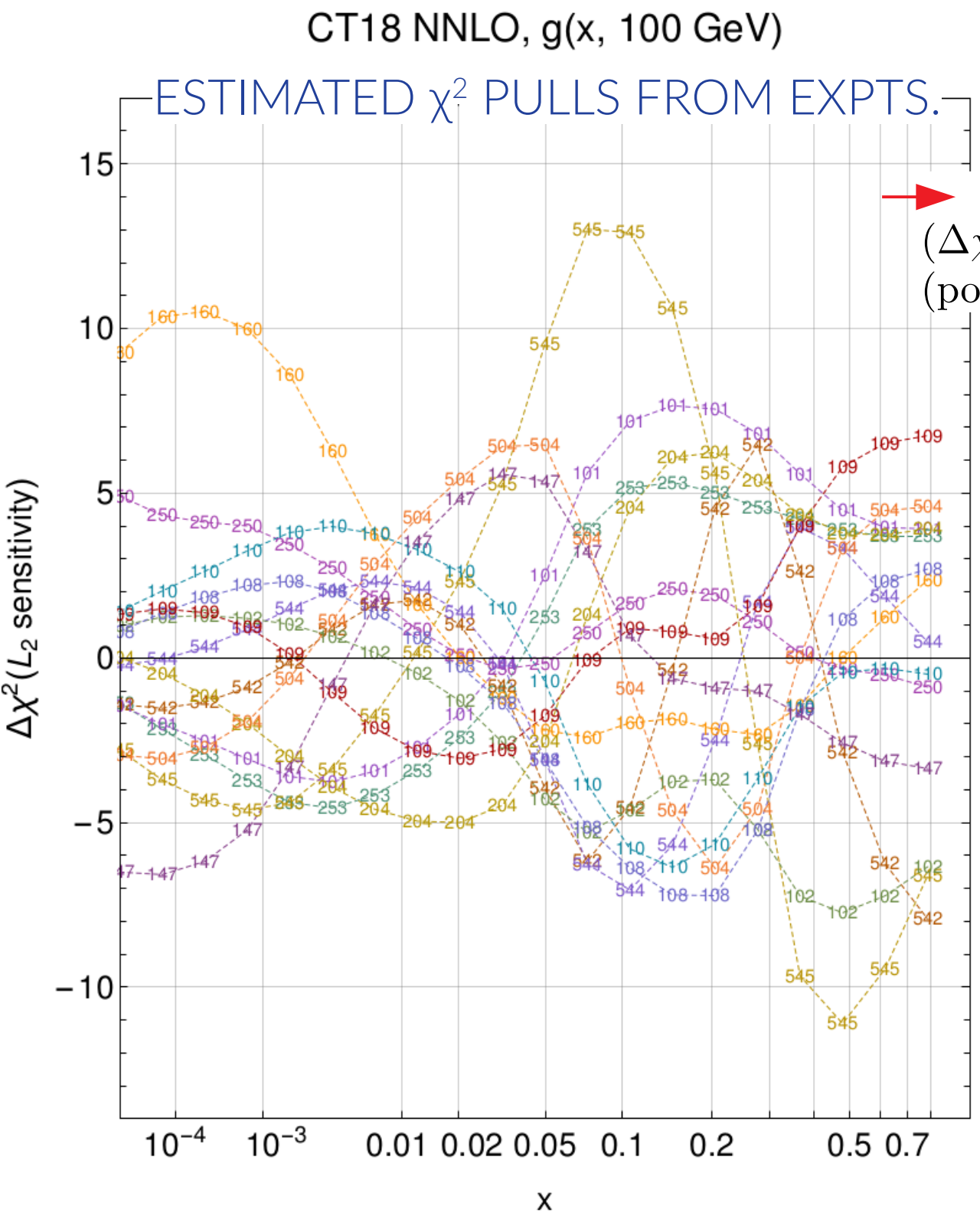


- after the aggregated HERA data, **inclusive jet production** – greatest total sensitivity!

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

ESTIMATED χ^2 PULLS FROM EXPTS.

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



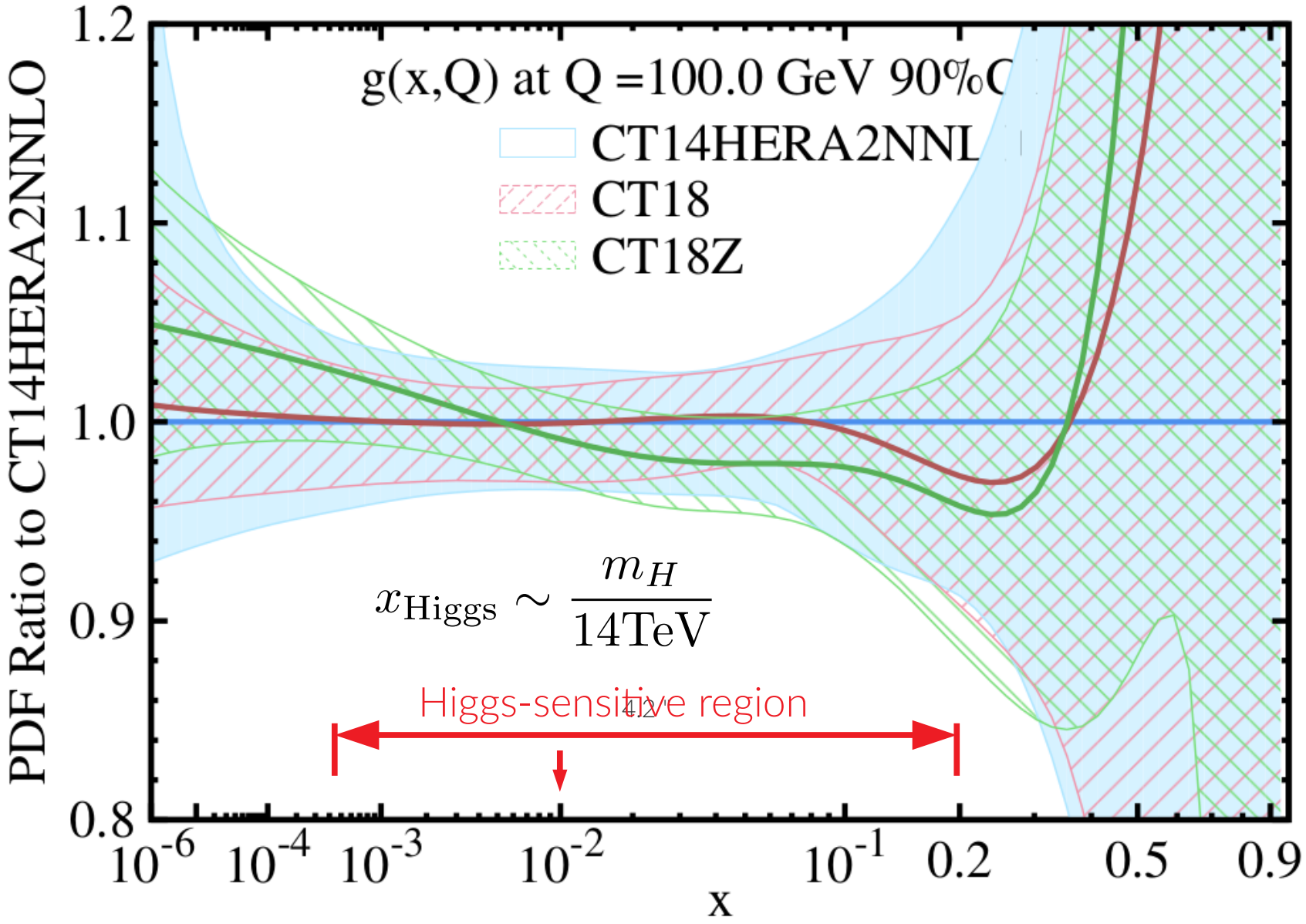
experiments with large $\Delta\chi^2 > 0$ ($\Delta\chi^2 < 0$) pull $g(x, Q)$ in the negative (positive) direction at the shown x

250 LHCb8WZ	108 cdhswf2
253 ATL8ZpTbT	109 cdhswf3
542 CMS7jtR7y6T	110 ccfrf2.mi
544 ATL7jtR6uT	147 Hn1X0c
545 CMS8jtR7T	204 e866ppxf
160 HERAIpII	504 cdf2jtCor2
101 BcdF2pCor	
102 BcdF2dCor	

stronger (anti-) correlation

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

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