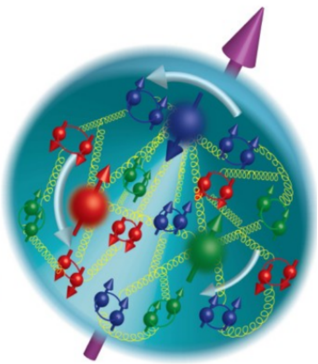
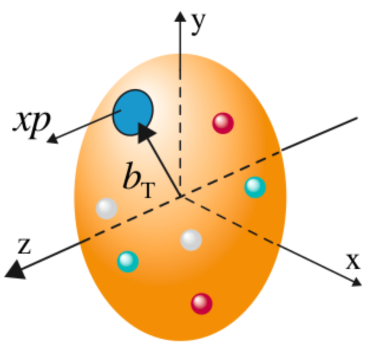
# Impacts of the EIC on LHC phenomenology

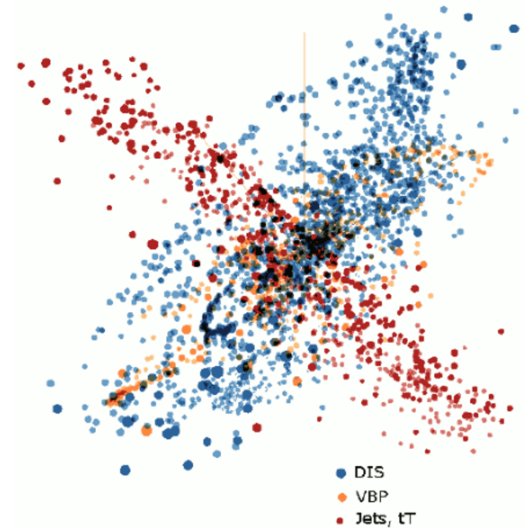
reducing uncertainties at the LHC with a DIS collider

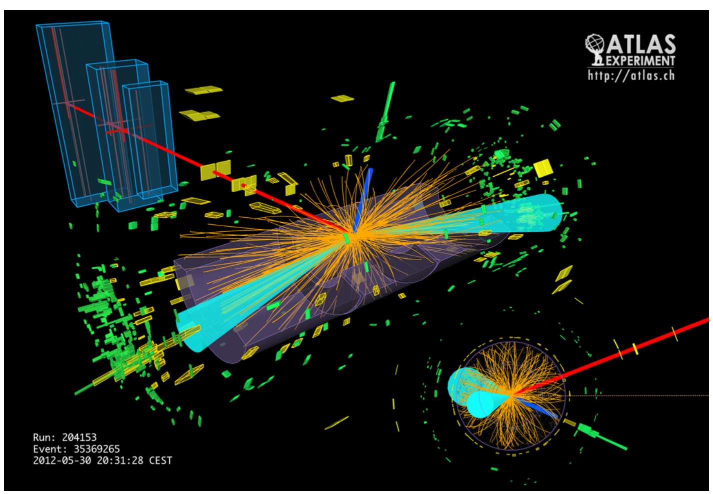
**Tim Hobbs**, **EIC Center@JLab and CTEQ@SMU**

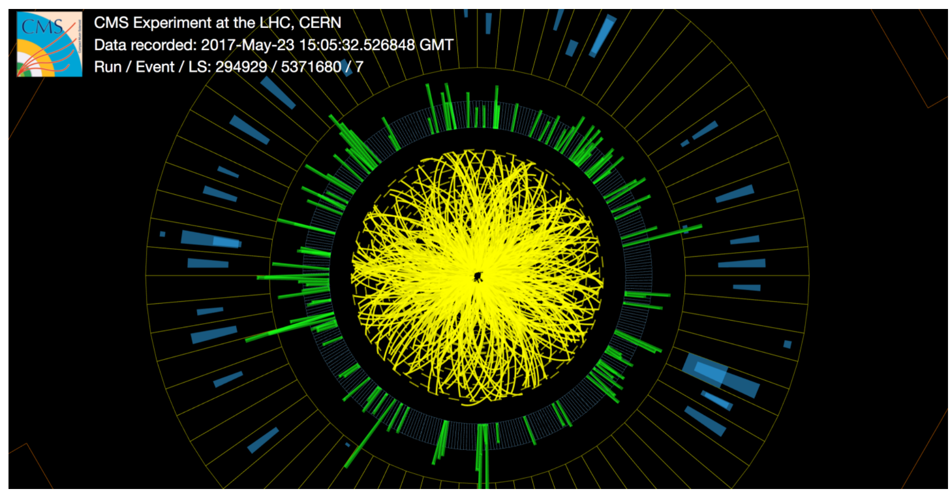
May 6th 2020





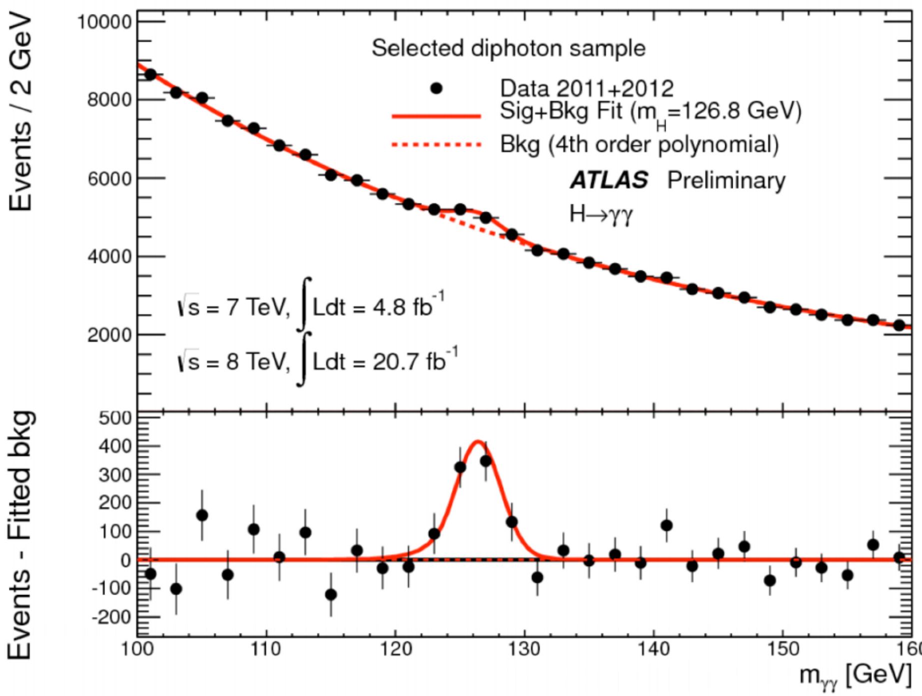

Electroweak and BSM physics at the EIC, CNFS, 6-7 May 2020

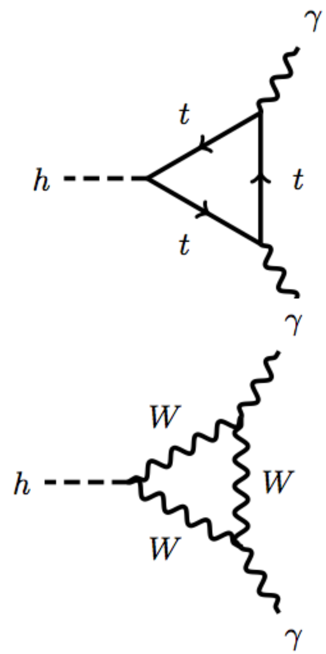
# collider searches for physics beyond the Standard Model (BSM)

→ "discovery" searches

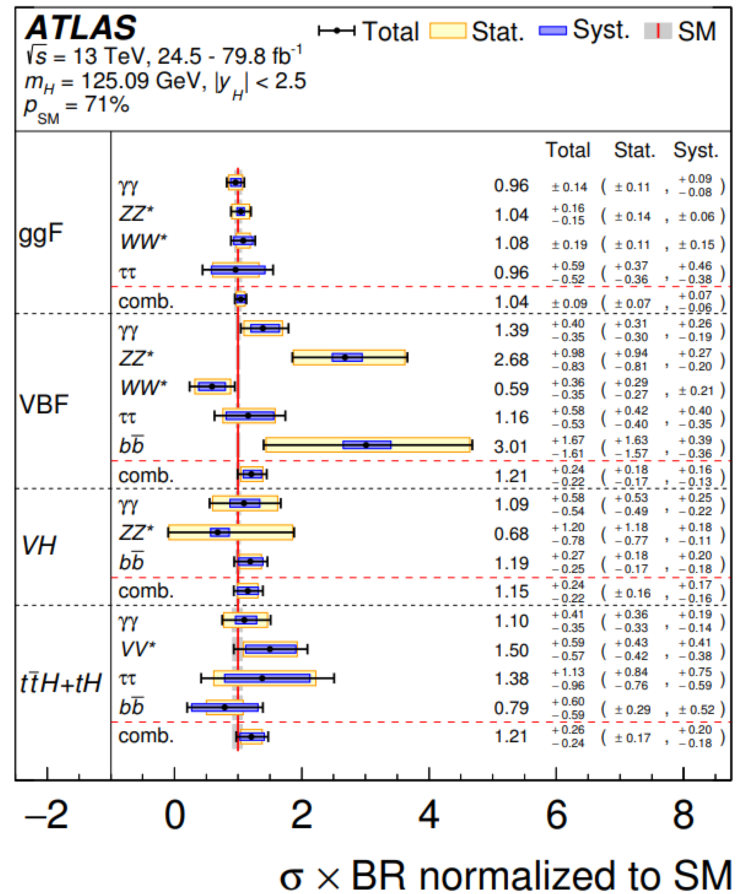
e.g., examining cross sections, etc., in previously unprobed kinematical regions

Higgs discovery, 2012




Higgs prod·decay/SM (PDG)

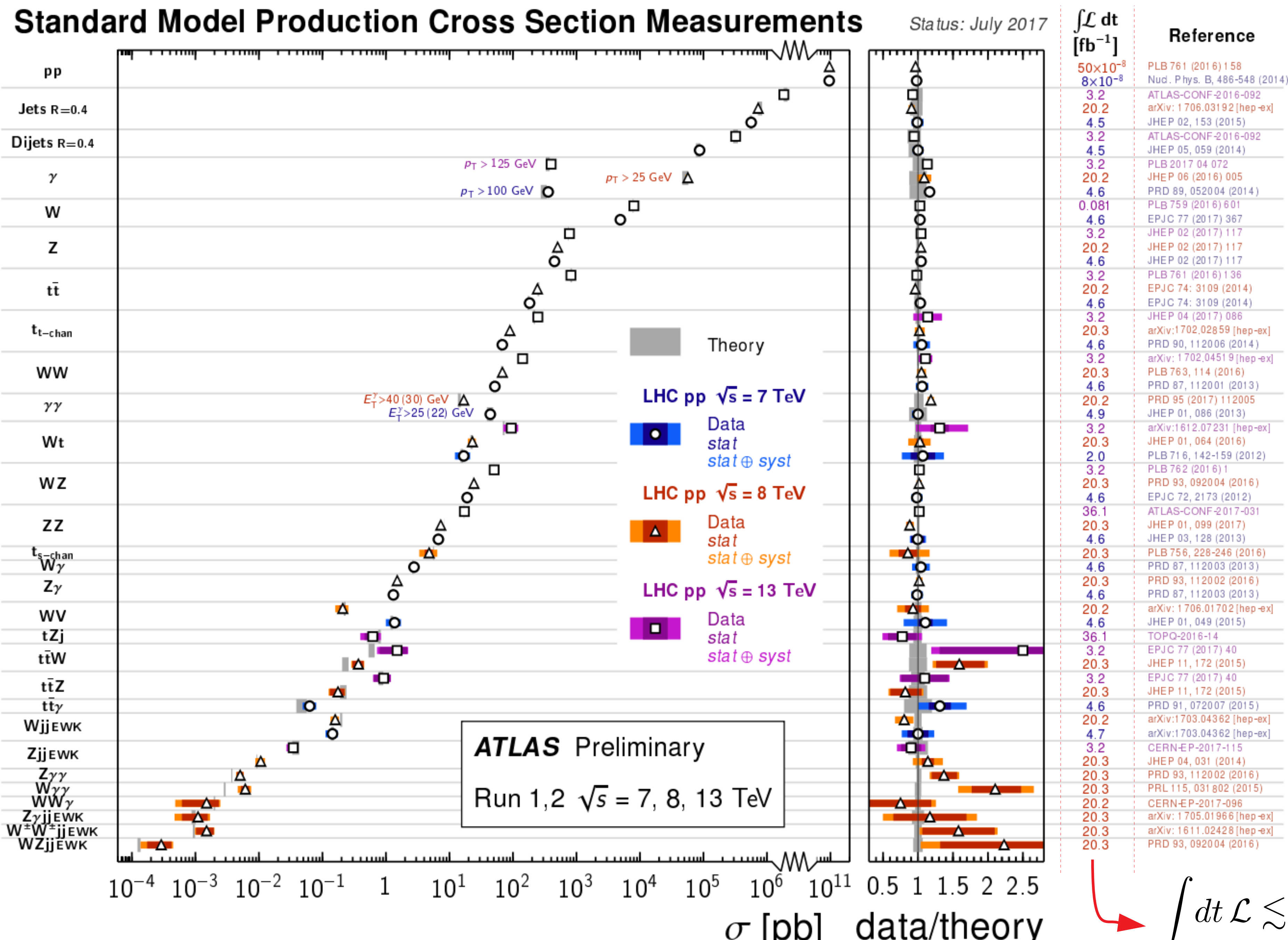



→ "precision" searches

testing the Standard Model through extremely fine measurements

**(deviations could reveal presence of new particles/interactions!)**

# circa 2020, the Standard Model has been phenomenally successful

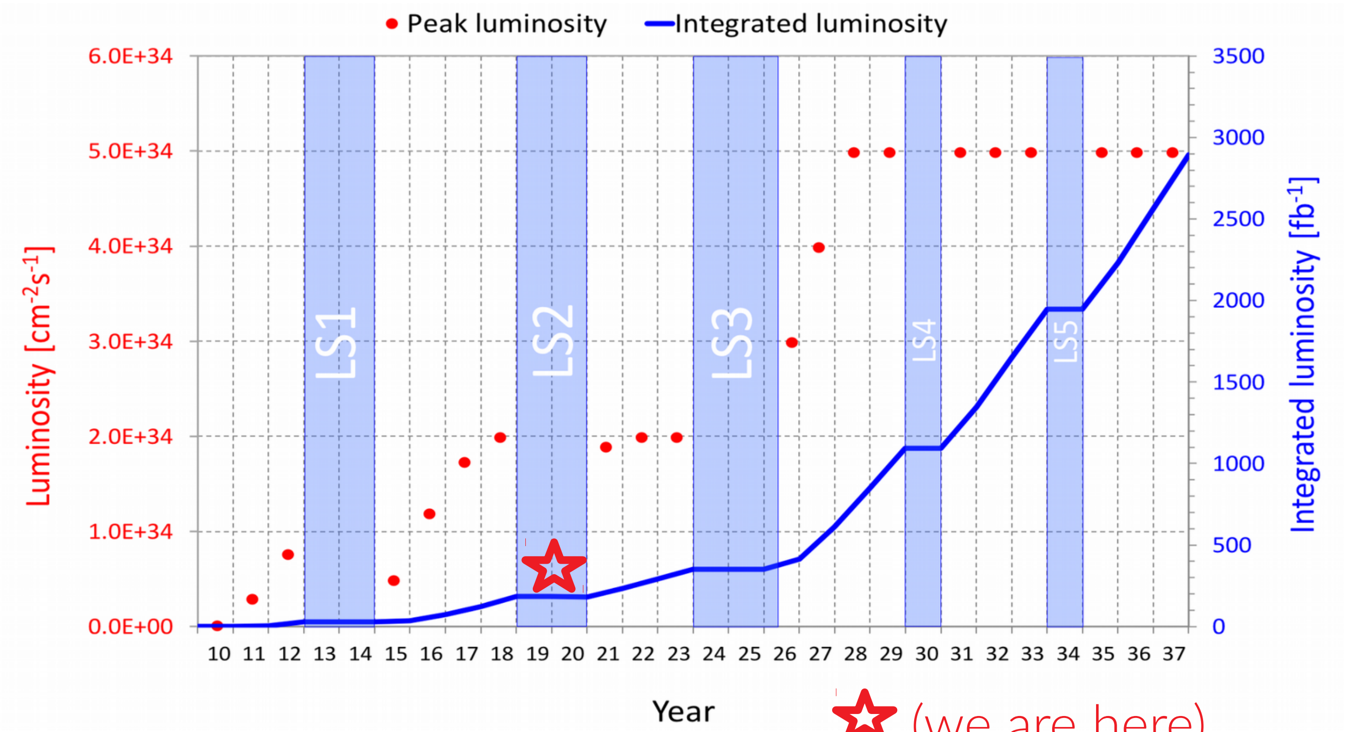



$$\int dt\,\mathcal{L} \lesssim 20\,\mathrm{fb}^{-1}$$

# the view from particle physics: the big data era has arrived.

- **with the completion of Run-2, LHC has accumulated copious data**

MUCH more is coming!




☆ (we are here)

- this data is an opportunity, but also a challenge

- as accumulated HEP data sets approach $\mathcal{O}(1\ \mathrm{ab}^{-1})$, sophisticated approaches required to leverage all the data & <u>deal with systematics</u>

  → advanced statistical/ML techniques

  → Lattice QCD

  → <u>experimental benchmarks (e.g., EIC – this talk)</u>

a holistic combination of approaches is preferred

# confronting high-energy data with (QCD) theory

→ a complex interplay of measurement, analysis, and **theoretical calculation**

computing a typical process at the LHC requires **perturbative matrix elements** *and* nonperturbative **parton distribution functions (PDFs)**

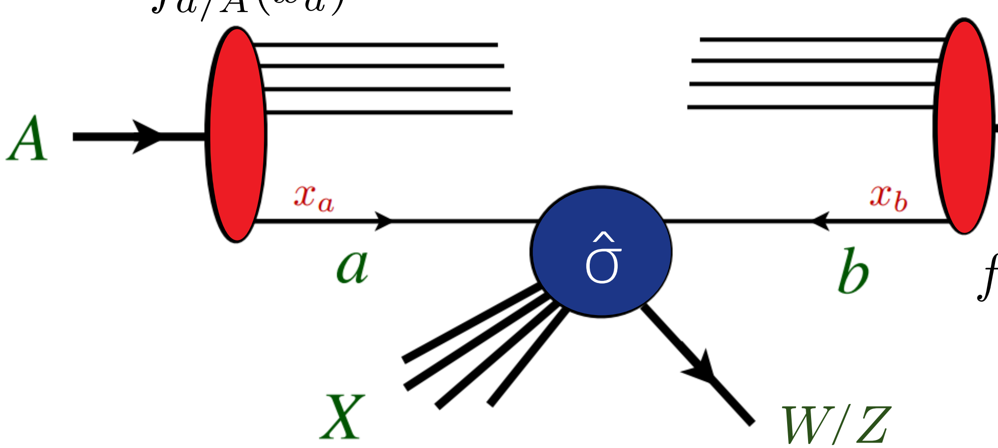
for EW boson pp production

$$\sigma(AB \to W/Z+X) = \sum_n \alpha_s^n(\mu_R^2) \sum_{a,b} \int dx_a dx_b$$

$$\times\, f_{a/A}(x_a,\mu^2)\, \hat{\sigma}^{(n)}_{ab\to W/Z+X}(\hat{s},\, \mu^2, \mu_R^2)\, f_{b/B}(x_b,\mu^2)$$

pQCD matrix elements

unpolarized nucleon PDFs




$f_{b/B}(x_b)$

|||

probability to find parton (quark/gluon) b carrying long. momentum $x_b$ of hadron B

NOTE! Any process involving identified hadrons depends on nonperturbative information – either PDFs or analogous functions

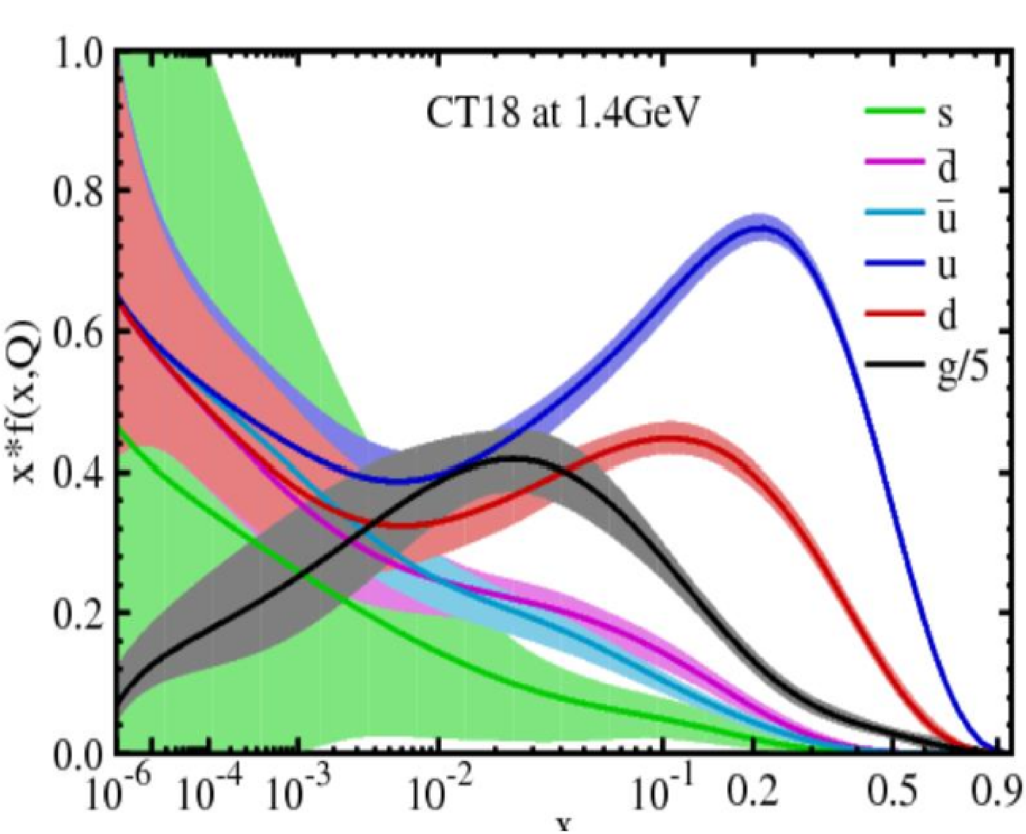
$$x_b \equiv \frac{p_b}{P_B}$$

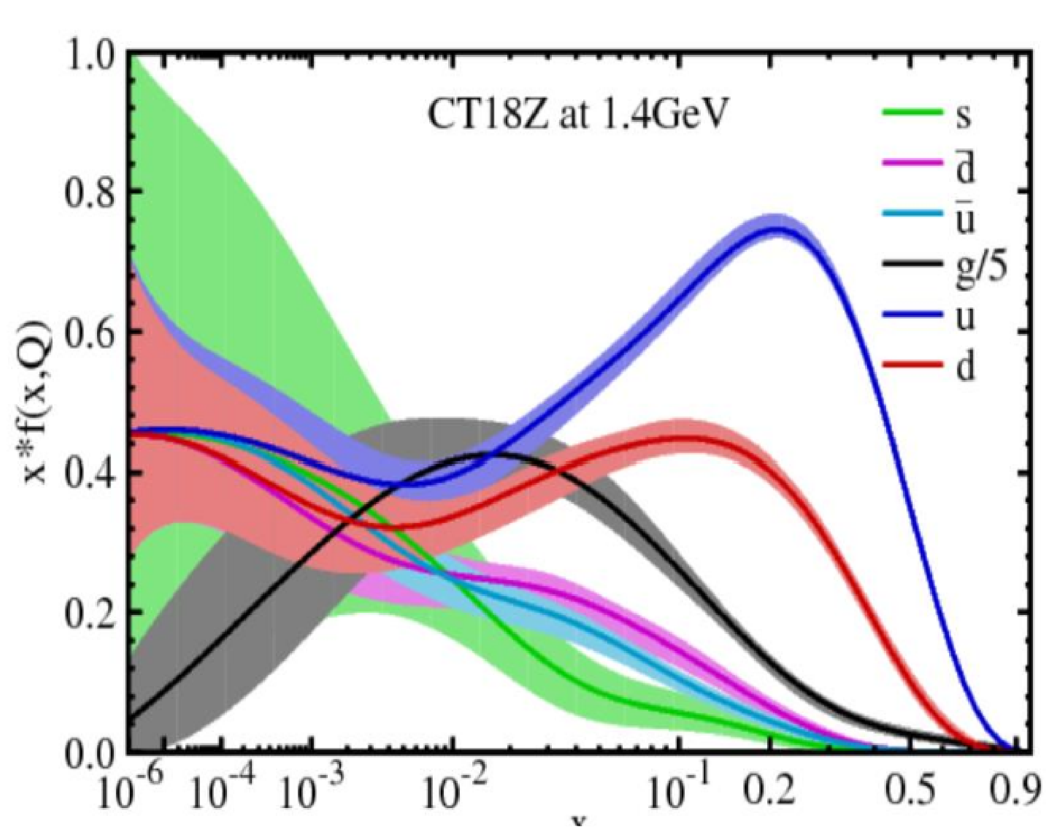
C T E Q

# CT18 parton distributions

PDF analyses are challenging! (theoretically, computationally, statistically, … )

CT18 main analysis → Hou, Gao, TJH, Xie et al., arxiv:1912.10053.




- a primary activity of the CTEQ collaborations (above, CT) is the determination of the proton and nuclear PDFs needed for HEP analyses

→ impacts on SM predictions are a central concern

# Unraveling PDFs' flavor dependence is challenging; **multiple channels/processes needed**

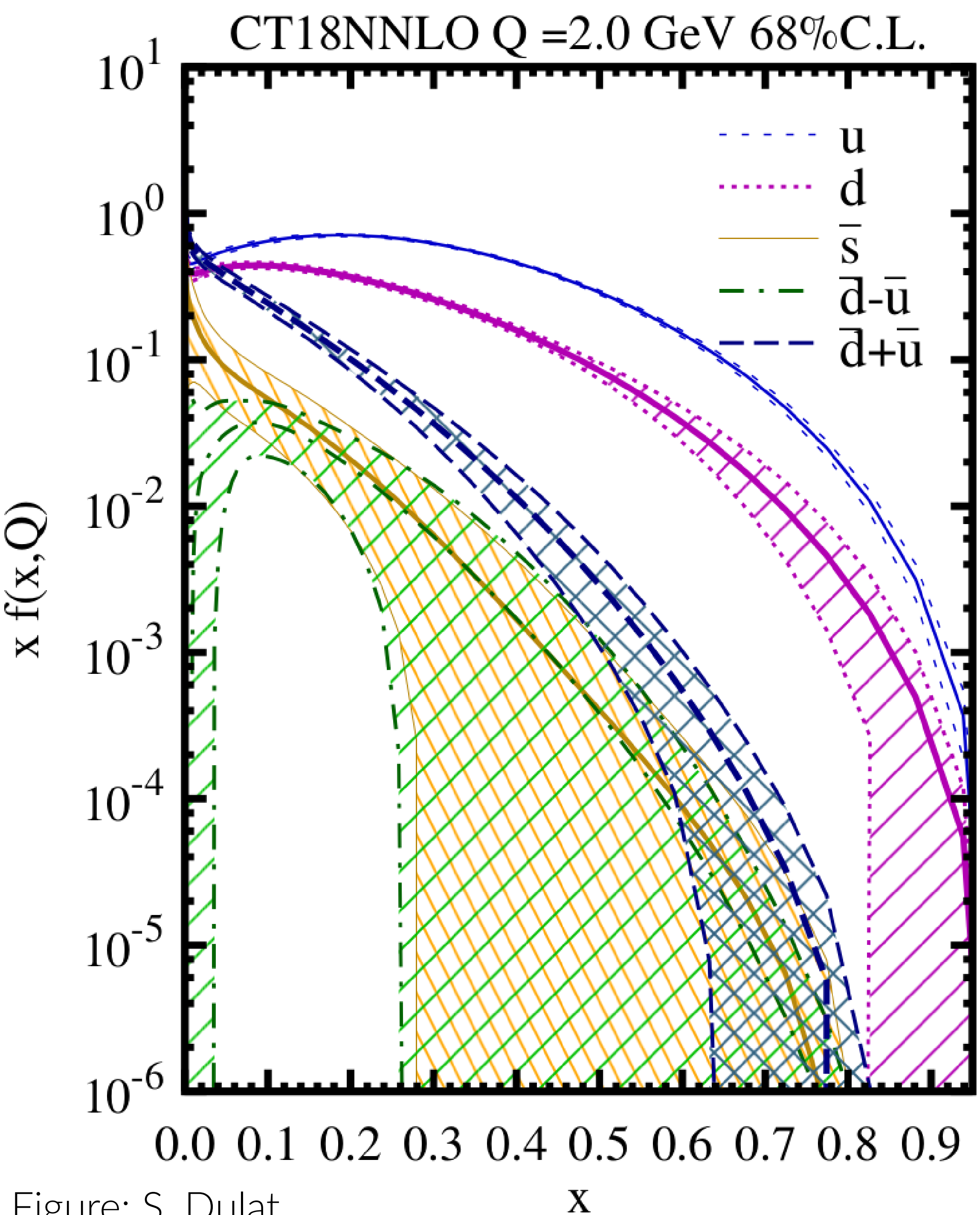



Figure: S. Dulat

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.)

high $x$ (>0.1) [re: BSM searches!]

→ $u$-quark dominates

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

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

...1% error on $u \rightarrow$ 50-100% error on $\bar{d} + \bar{u}$

→ 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 $\bar{u}, \bar{d}, \bar{s}$

# going forward, standard-candle quantities will be PDF-limited

→ this extends to, e.g., $\sigma_H, \ \sin^2\theta_W, \ m_W, \ \ldots$

→ the PDF uncertainties are NOT another 'theory uncertainty'

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 |

→ rather, they are fundamental gaps in empirical knowledge

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

→ this CANNOT be achieved without systematically dealing with these uncertainties.

→ **this must be a primary community objective**

# Higgs, g(x)

## a typical example: $\sigma_H$ and PDF, $\alpha_s$ uncertainties

- there remains considerable dependence (as large as ~13%) upon PDF paramatrization and running coupling

→ the situation is such that precision in Higgs phenom. is significantly **PDF-limited**

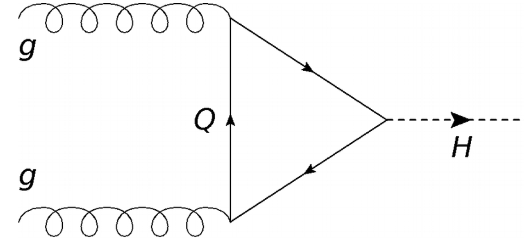
Accardi et al., EPJC**76**, 471 (2016).

| PDF sets | $\sigma(H)^{\mathrm{NNLO}}$ (pb) nominal $\alpha_s(M_Z)$ | $\sigma(H)^{\mathrm{NNLO}}$ (pb) $\alpha_s(M_Z) = 0.115$ | $\sigma(H)^{\mathrm{NNLO}}$ (pb) $\alpha_s(M_Z) = 0.118$ |
|---|---|---|---|
| ABM12 [2] | $39.80 \pm 0.84$ | $41.62 \pm 0.46$ | $44.70 \pm 0.50$ |
| CJ15 [1][a] | $42.45^{+0.43}_{-0.18}$ | $39.48^{+0.40}_{-0.17}$ | $42.45^{+0.43}_{-0.18}$ |
| CT14 [3][b] | $42.33^{+1.43}_{-1.68}$ | $39.41^{+1.33}_{-1.56}$ (40.10) | $42.33^{+1.43}_{-1.68}$ |
| HERAPDF2.0 [4][c] | $42.62^{+0.35}_{-0.43}$ | $39.68^{+0.32}_{-0.40}$ (40.88) | $42.62^{+0.35}_{-0.43}$ |
| JR14 (dyn) [5] | $38.01 \pm 0.34$ | $39.34 \pm 0.22$ | $42.25 \pm 0.24$ |
| MMHT14 [6] | $42.36^{+0.56}_{-0.78}$ | $39.43^{+0.53}_{-0.73}$ (40.48) | $42.36^{+0.56}_{-0.78}$ |
| NNPDF3.0 [7] | $42.59 \pm 0.80$ | $39.65 \pm 0.74$ $(40.74 \pm 0.88)$ | $42.59 \pm 0.80$ |
| PDF4LHC15 [8] | $42.42 \pm 0.78$ | $39.49 \pm 0.73$ | $42.42 \pm 0.78$ |

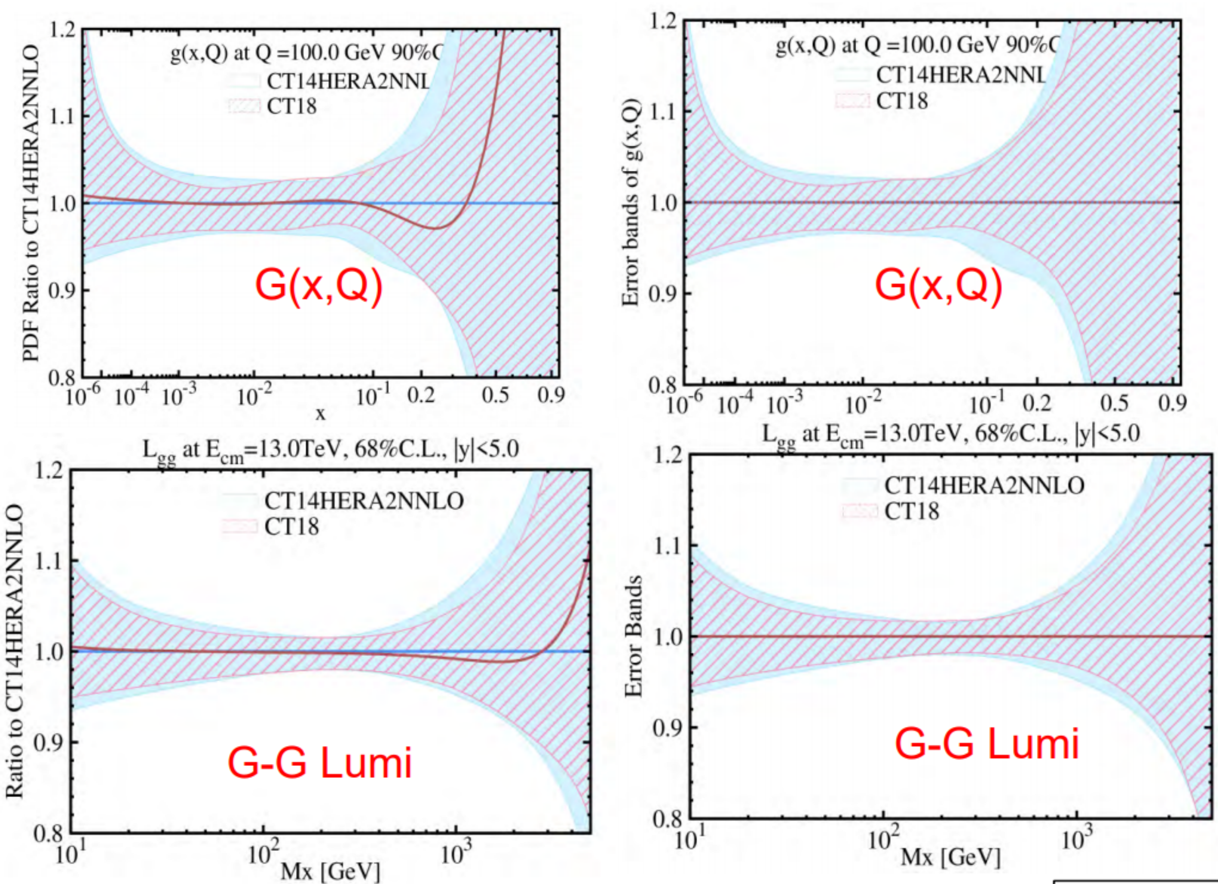
$$\sigma_H \text{ at NNLO and } \sqrt{s} = 13\,\text{TeV}; \;\; \mu_F = \mu_R = m_H$$

→ <u>enhancing the discovery potential in the Higgs sector will require improving these uncertainties!</u>

# Higgs cross section




## CT14 → CT18 modestly shifts Higgs cross sections and slightly reduces PDF uncertainties

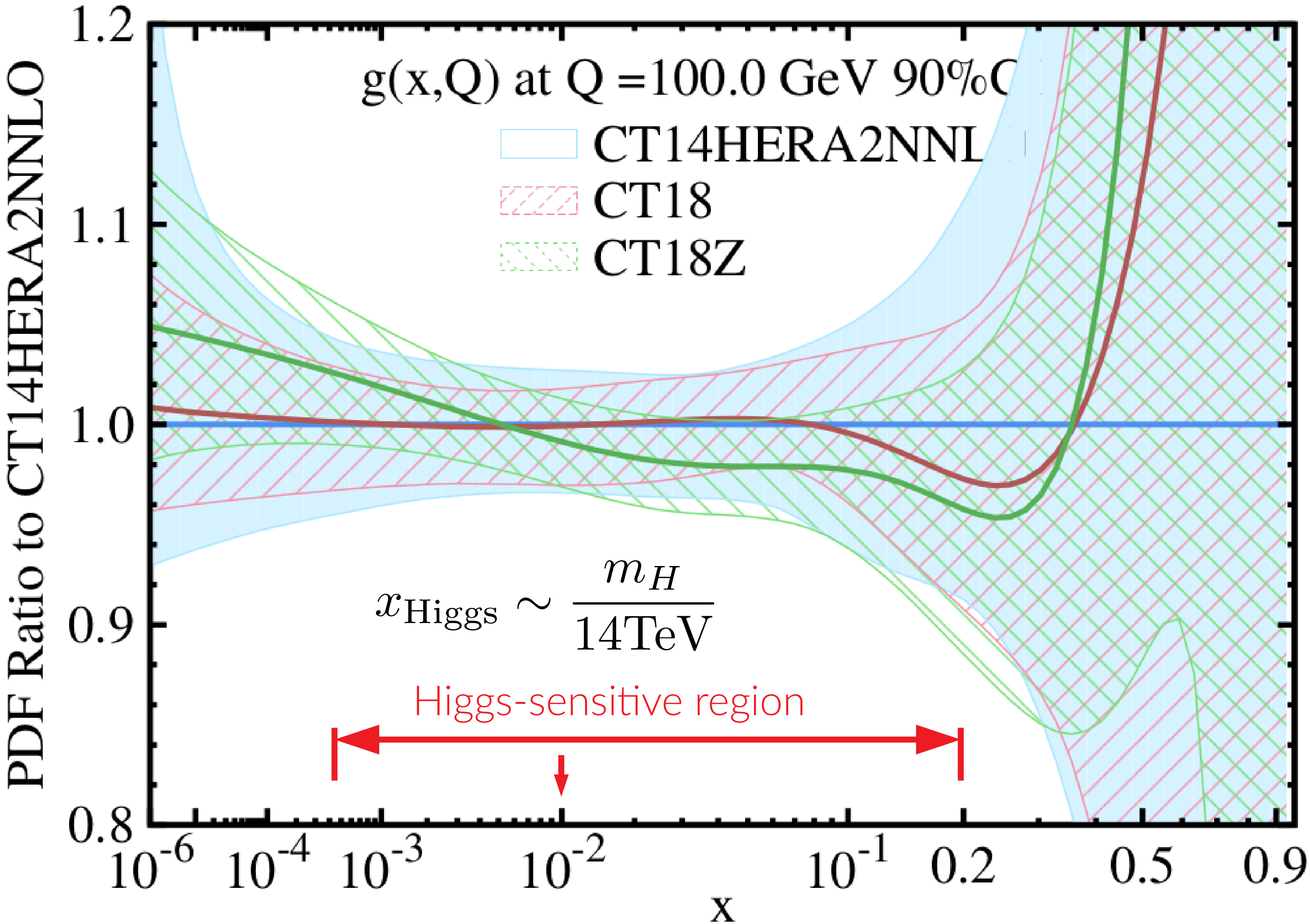



| | $\sigma$(gg-h) | $\delta\sigma$ sym(90%C.L.) |
|---|---|---|
| **7 TeV** | | |
| CT14NNLO | 14.67 | 0.46 |
| CT18 | 14.57 | 0.44 |
| **8 TeV** | | |
| CT14NNLO | 18.70 | 0.57 |
| CT18 | 18.45 | 0.55 |
| **13 TeV** | | |
| CT14NNLO | 42.78 | 1.32 |
| CT18 | 42.43 | 1.26 |
| **14 TeV** | | |
| CT14NNLO | 48.23 | 1.50 |
| CT18 | 47.91 | 1.42 |

PDF induced errors (at 90% CL) are reduced by about 5% as compared to CT14 predictions.

→ can we disentangle elements of the global analysis responsible for these improvements?

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

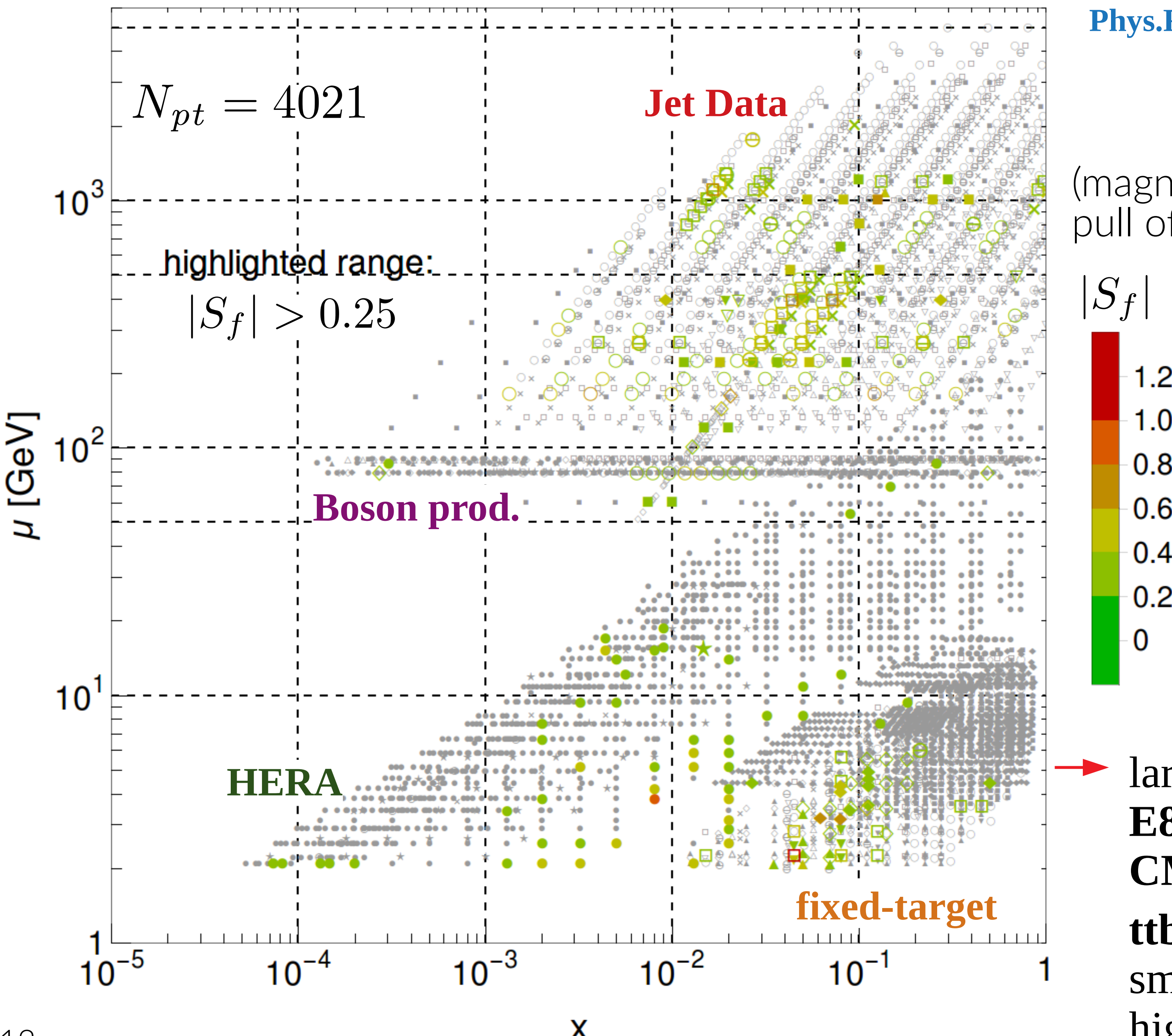



- while LHC Run-1 data drive important PDF improvements, including for the gluon at high-, low-$x$, the effect is relatively incremental

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

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

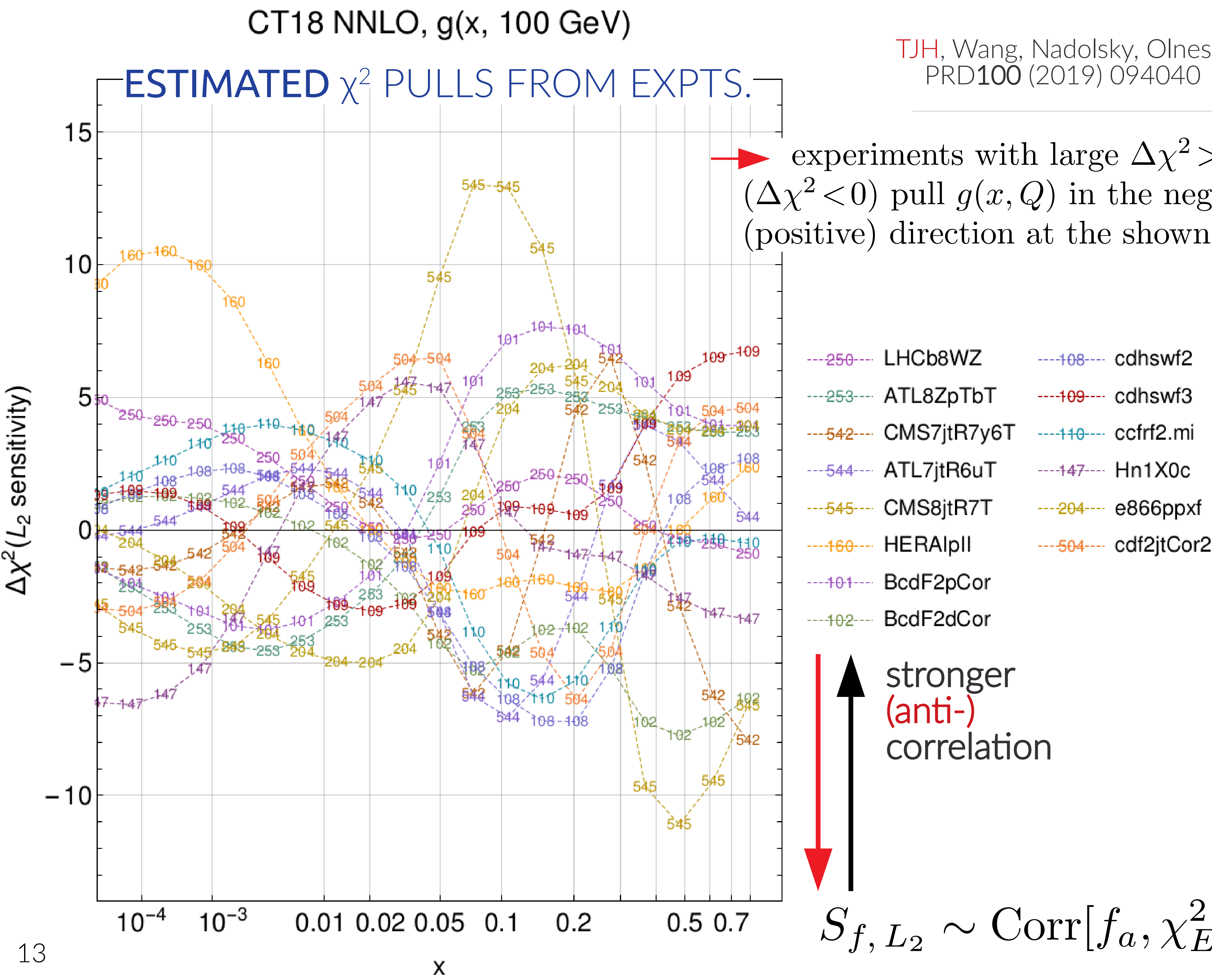
Phys.Rev. D98 (2018) 094030




(magnitude of PDF pull of each datum)

- 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

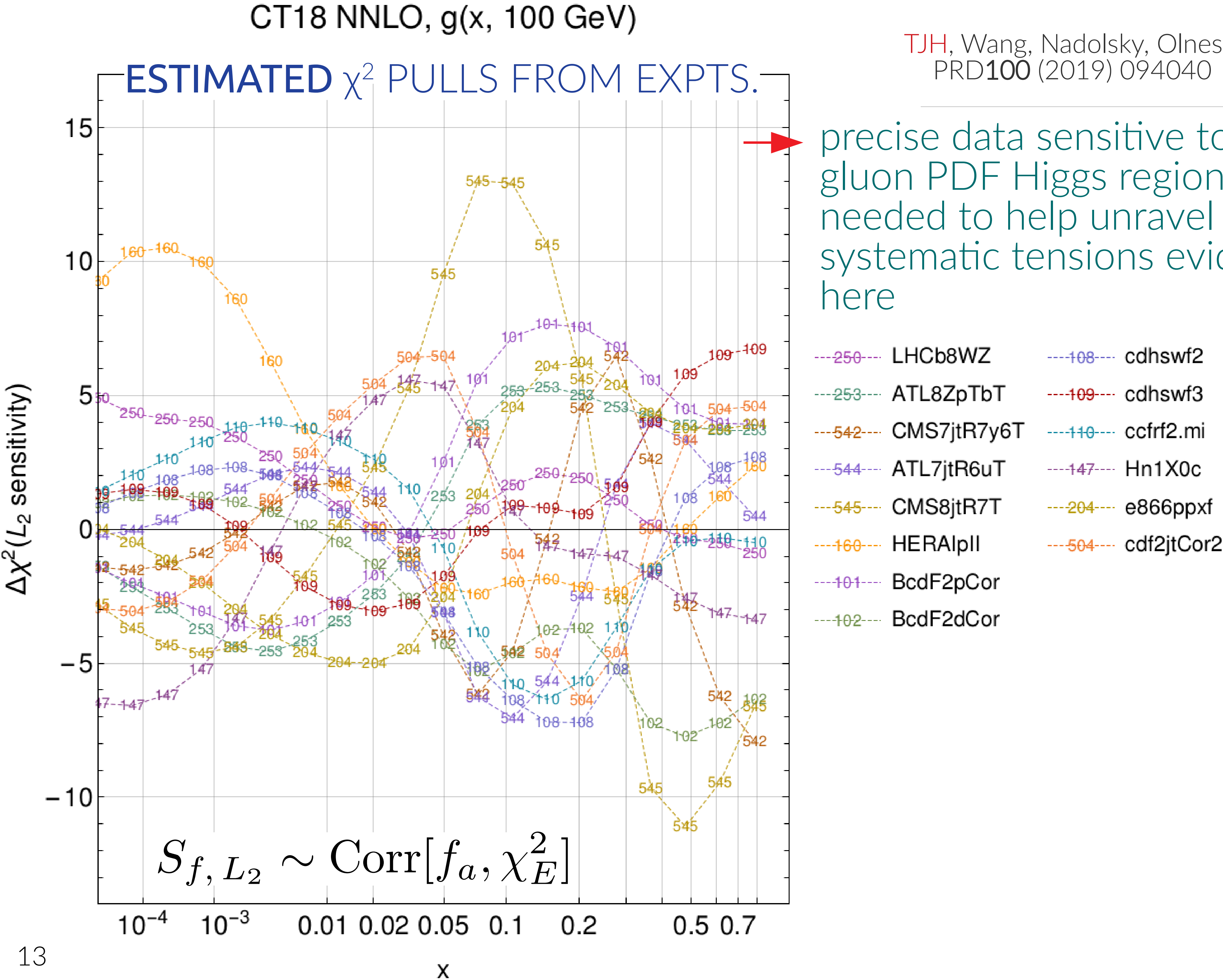



TJH, Wang, Nadolsky, Olness; PRD**100** (2019) 094040

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

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



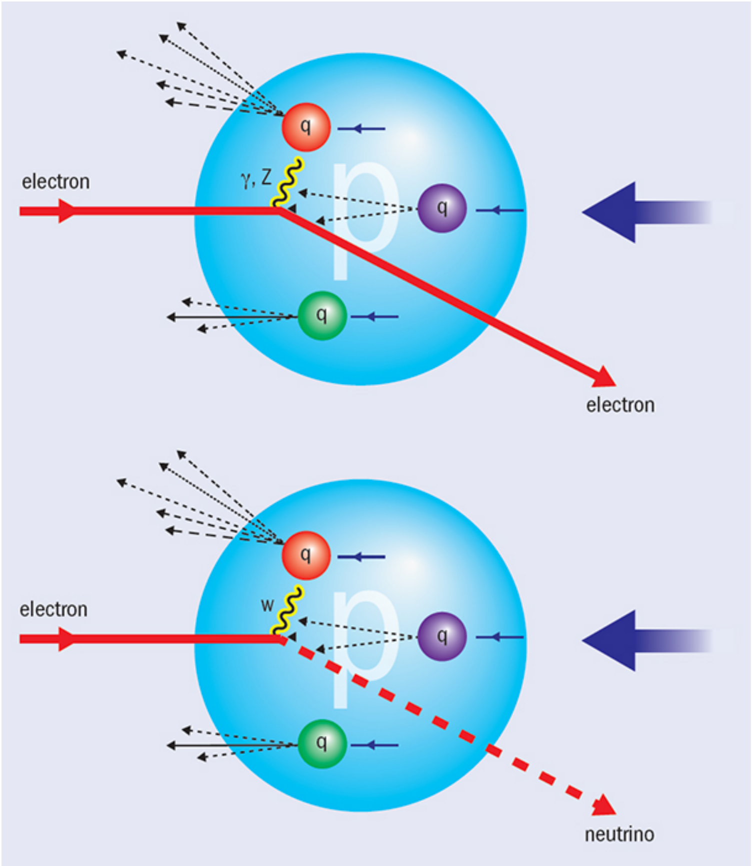

TJH, Wang, Nadolsky, Olness;
PRD**100** (2019) 094040

precise data sensitive to the gluon PDF Higgs region needed to help unravel the systematic tensions evident here

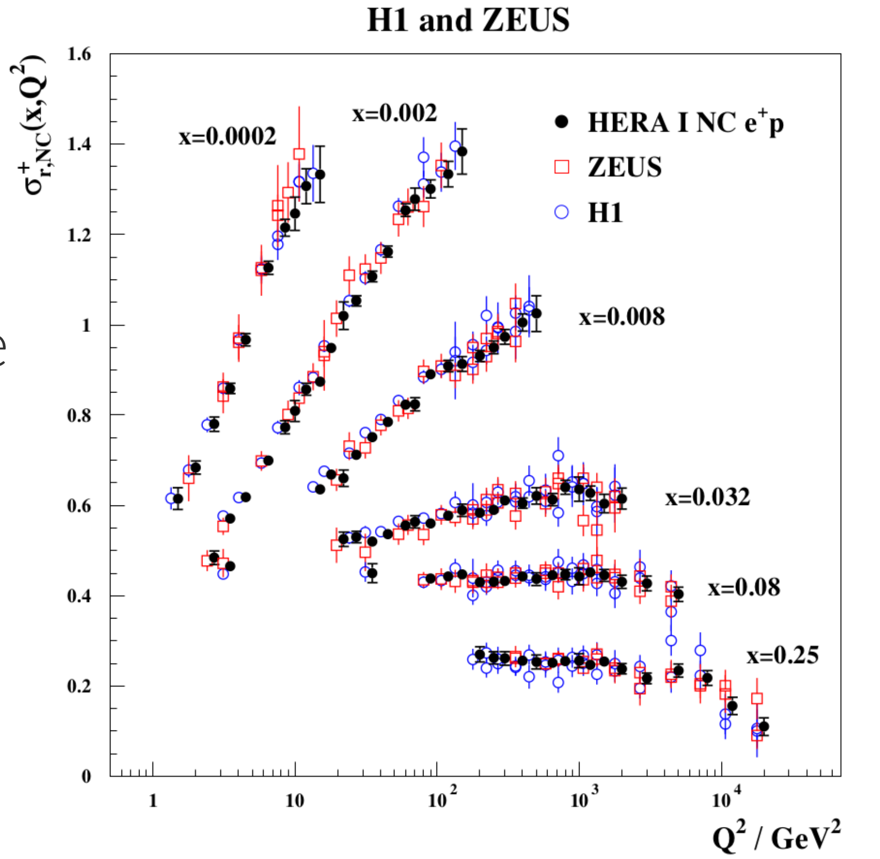
# we require a high-precision experimental arbiter

→ given the landscape of experiments with variable compatibility: **clean, high-statistics DIS collider data from the EIC would serve as an empirical anchor-point to negotiate tensions among data**

→ a historical antecedent exists for this: **HERA** – the only previous DIS collider




the need to describe a wide reach of DIS data provides a kinematical 'lever arm' on QCD evolution



# EIC is the **essential future tool** for hadron tomography and QCD

…following an expansive community effort

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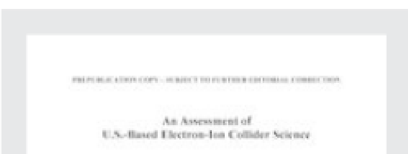
This PDF is available at http://nap.edu/25171 SHARE

**Summer 2018**



An Assessment of
U.S.-Based Electron-Ion Collider Science

An Assessment of U.S.-Based Electron-Ion Collider Science

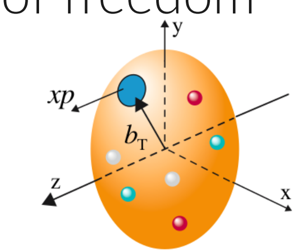
*“In summary, the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today.”*

“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 gluonic systems in the high-density limit

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



# update: “CD-0” and site-selection – BNL

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Department of Energy

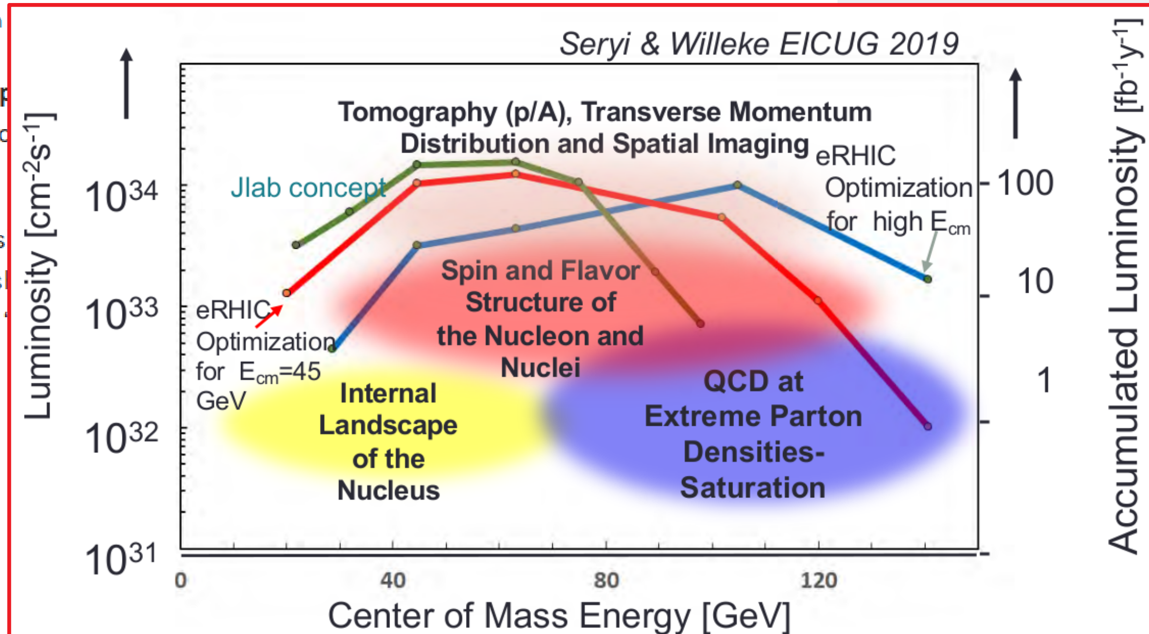
## U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JAN. 9th 2020

Home » U.S. Department of Energy Selects Brookhaven

**WASHINGTON, D.C.** – Today, the **U.S. Dep** Brookhaven National Laboratory in Uptc research facility.

The Electron Ion Collider (EIC), to be des between $1.6 and $2.6 billion, will smas effort to penetrate the mysteries of the




→ Hadrons up to 275 GeV

→ Electrons up to 18 GeV

# high-energy EIC design studies

- EIC is a **very high luminosity** "femtoscope"
- reach in center-of-mass energy, $20 \leq \sqrt{s} \leq \underline{140\,\mathrm{GeV}}$

→ 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

$$\left\{ \begin{array}{l} \mathcal{L} = 100\,\mathrm{fb}^{-1}\; e^{-}\;\text{pseudodata} \\ \mathcal{L} = 10\,\mathrm{fb}^{-1}\; e^{+}\;\text{pseudodata} \end{array} \right.$$

NC/CC

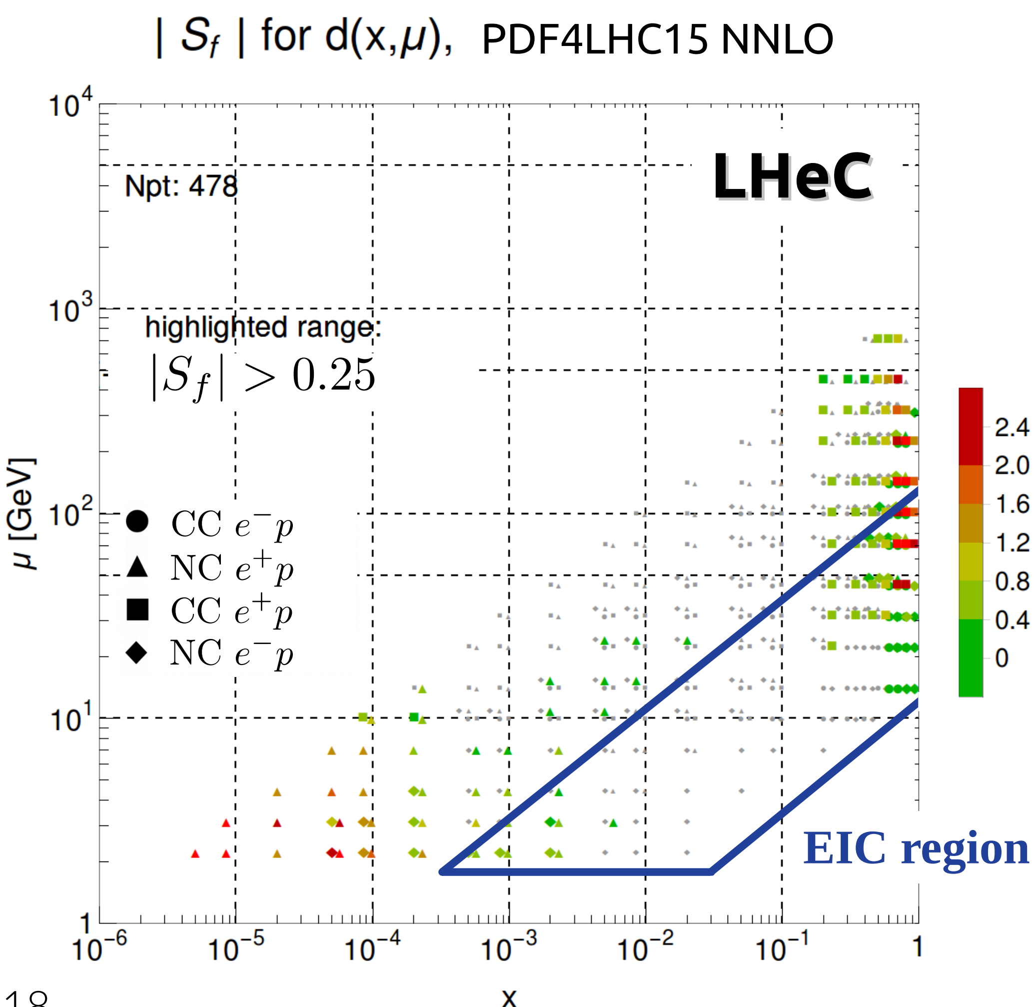
→ bootstrapped from CT14 HERA2 NNLO PDF fit

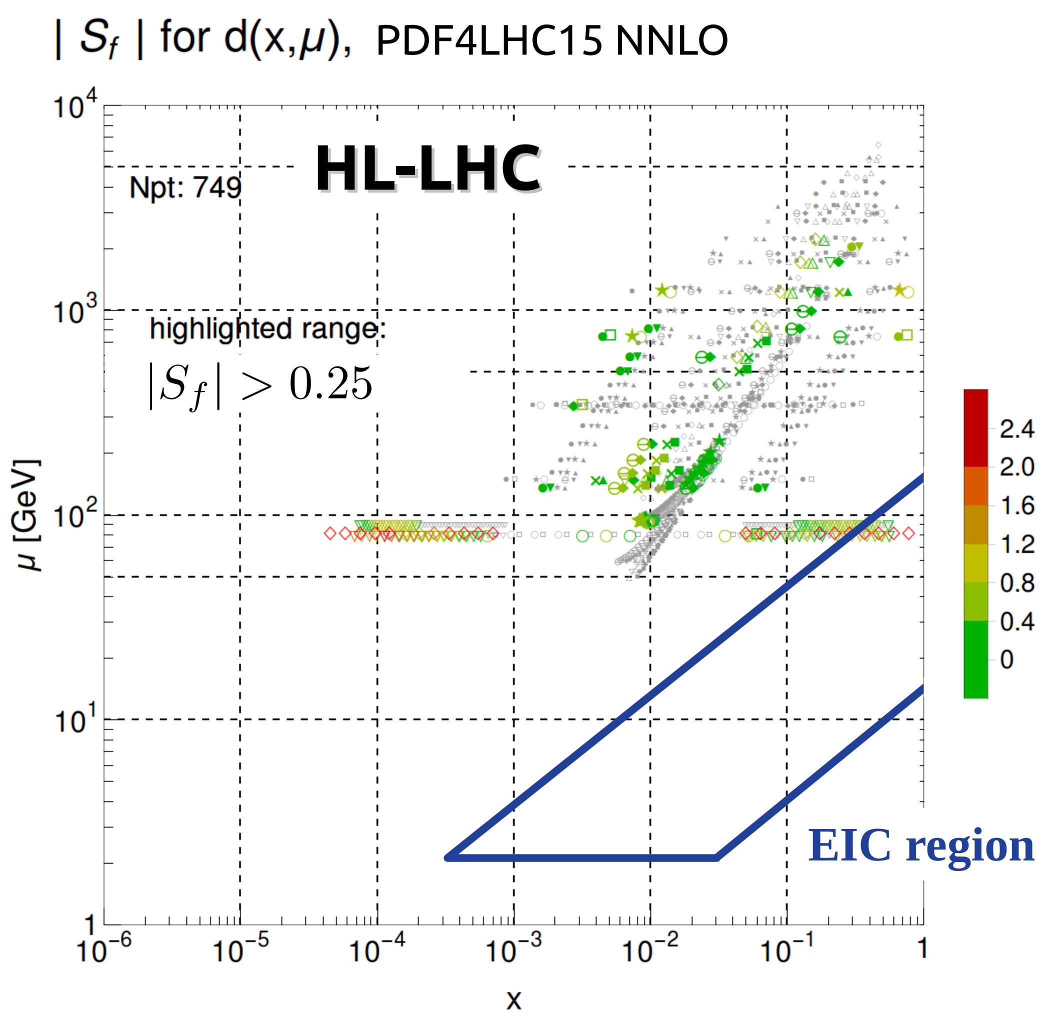
→ **need** rapid impact-study workflow for ongoing Yellow Report

# note: EIC will complement HL-LHC and LHeC

→ the EIC inhabits a unique kinematical region relative to the HL-LHC and LHeC

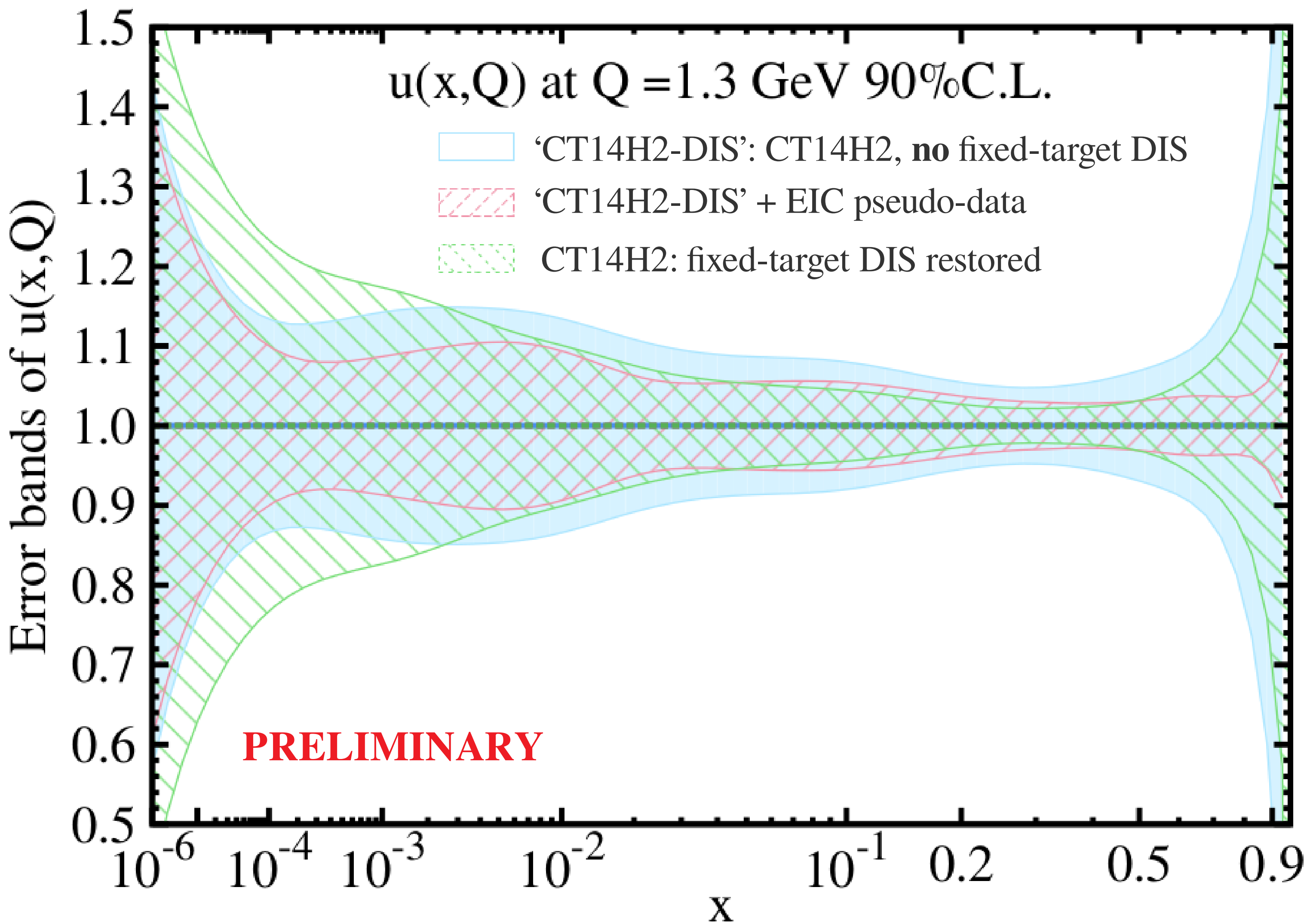
→ special coverage of lower-$\mu$ and high-$x$ quark-hadron transition regime



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

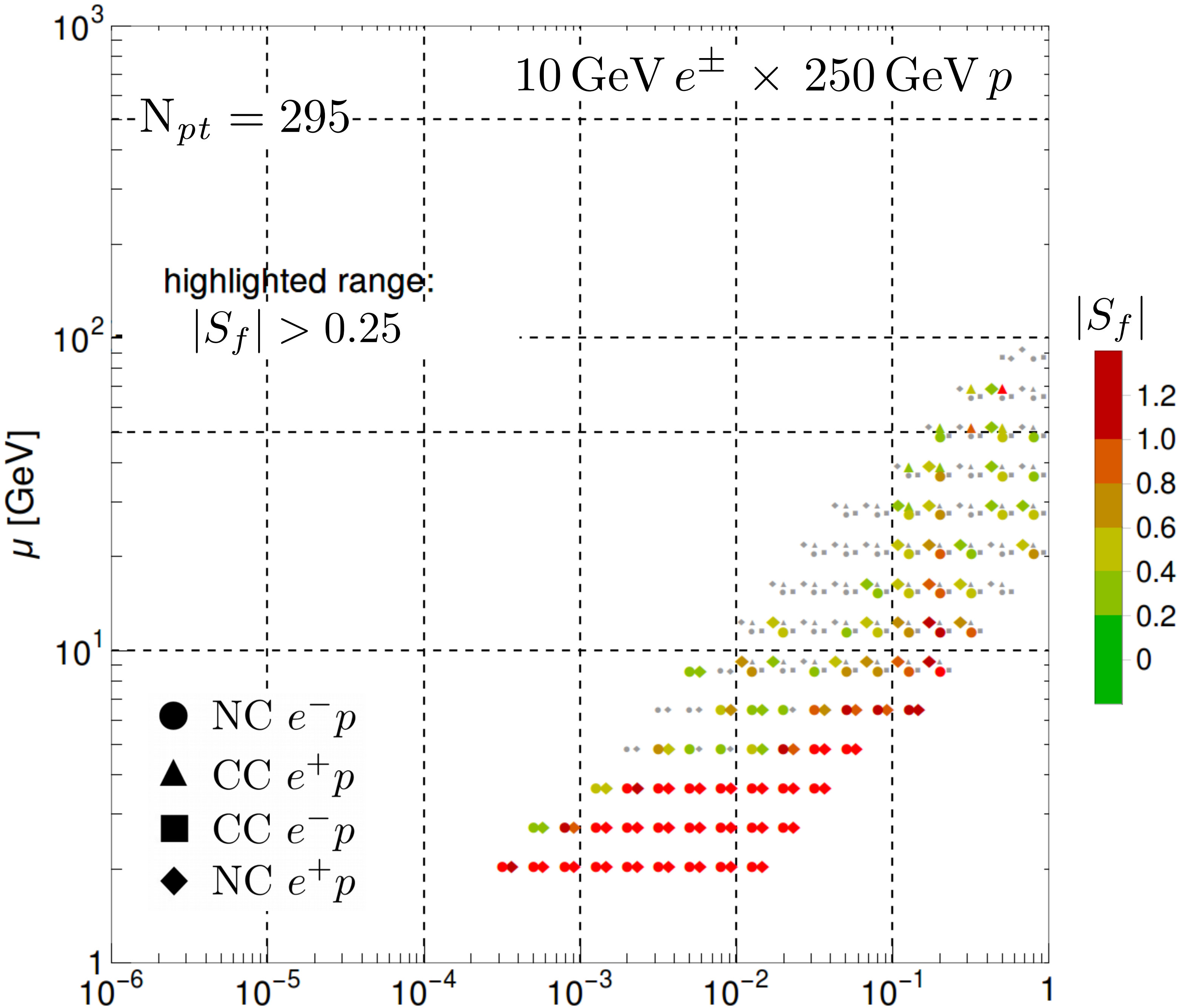
ePump: Schmidt, Pumplin, and Yuan; PRD98 (2018) no.9, 094005




- EIC pseudodata supersede fixed-target DIS information in CT fits
- reweighting strongly depends on parametrizations; other ambiguities

→ complementary approaches welcome!

# $|\, S_f \,|$ for $g(x,\mu)$ CT14 HERA2 NNLO

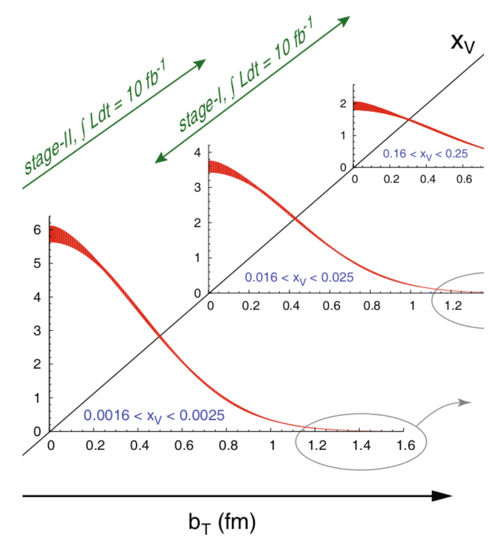


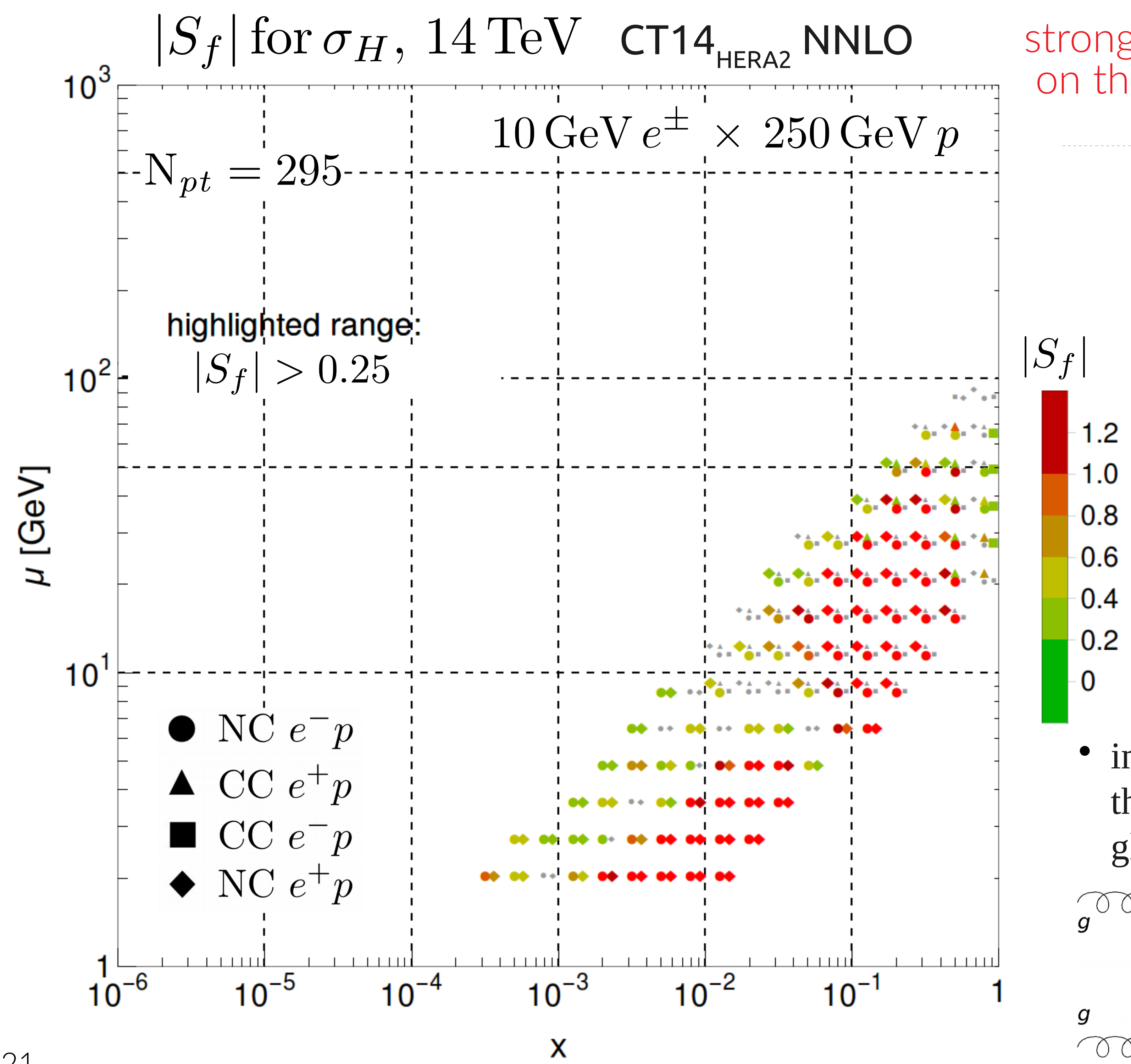

x

- 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 $\sigma_{r,\mathrm{NC}}^{e^{\pm}p}$

→ complement to tomography:

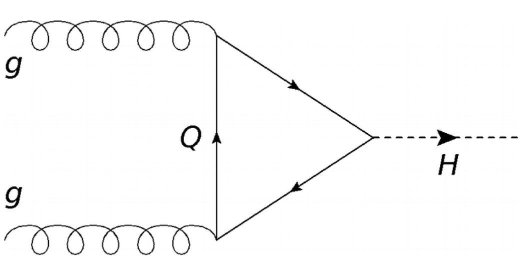





strong predicted impact on the Higgs sector

- 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 closely tied to that of the integrated gluon PDF:

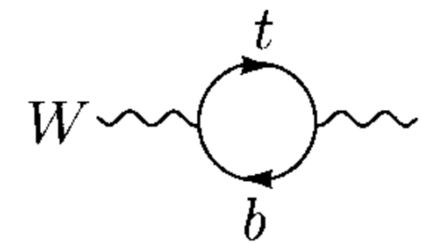


# $m_W$ as a sensitive window to BSM physics

- $m_W$ is sensitive to the gauge couplings and masses of heavy SM degrees of freedom, which enter a correction term, $\Delta r$

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

higher-order corrections




- extended theories **also** generate contributions to $\Delta r$ through BSM insertions

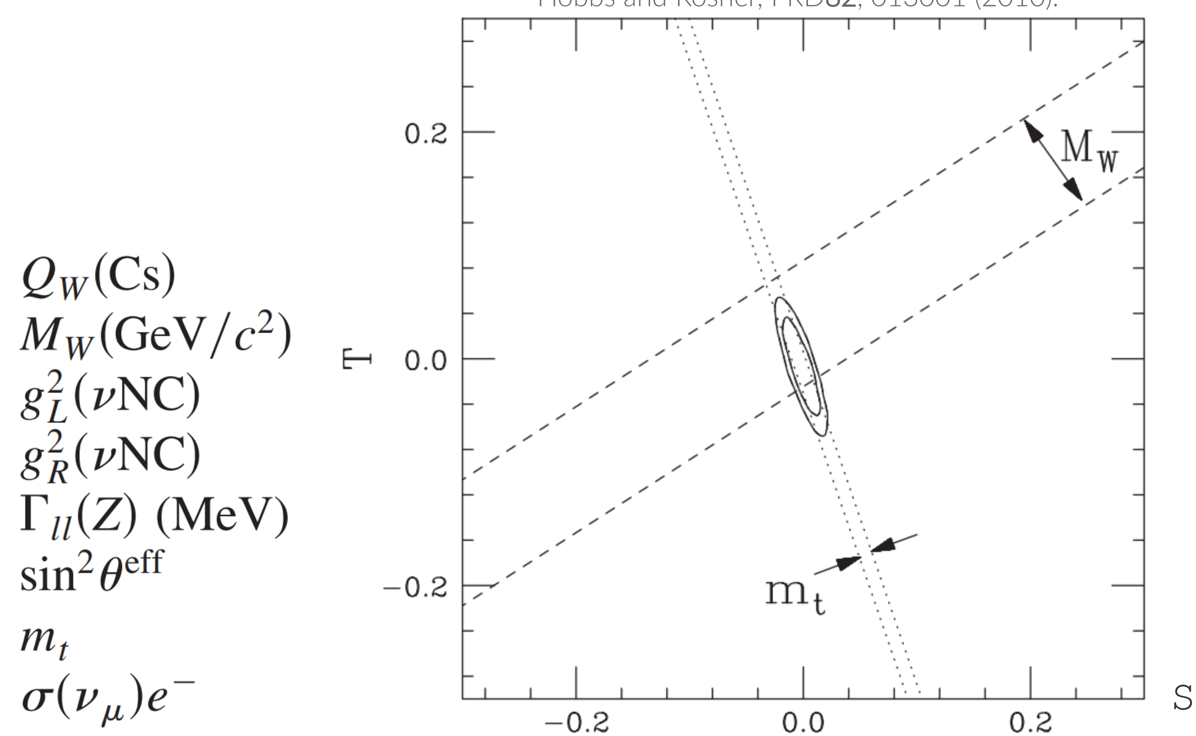
- **strategy**: careful comparison of precise measurements with theoretical SM predictions could reveal presence of BSM physics

  → constrain New Physics with a global fit of the electroweak sector:

  → $m_W$ is a crucial limitation

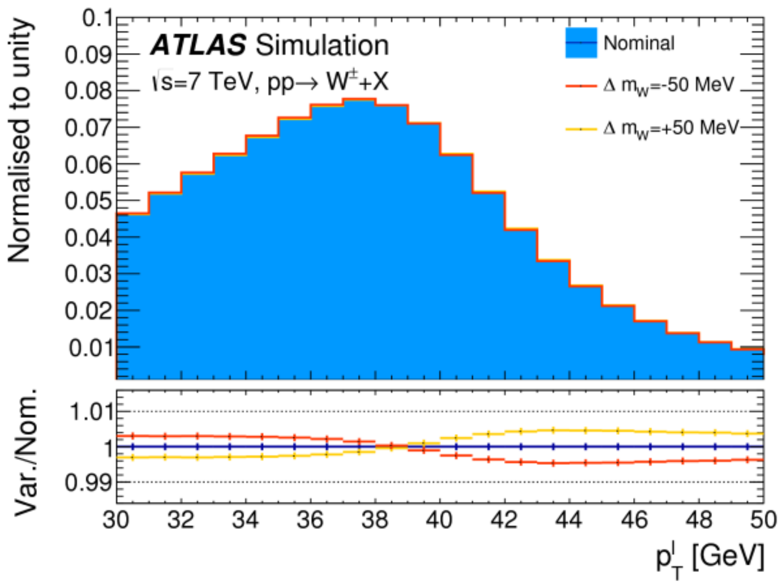
  → important interplay between *pp*, $\nu$ expts

Hobbs and Rosner, PRD**82**, 013001 (2010).



# strategy for experimentally extracting $m_W$

- Measurements of distributions sensitive to $m_W$:
  - Decay lepton $p_T$ (l), W transverse mass $m_T$, missing transverse energy $p_T$ ("neutrino pT") as cross check
- Template-Fit approach:
  - 1) vary $m_W$ in MC and predict the $p_T$(l) , $m_T$ , $p_T^{miss}$ distributions
  - 2) $m_W$ determination by $\chi 2$ minimization to data
- Imperfect QCD modelling distorts templates: significant uncertainty on $m_W$ measurement




- W mass is measured in $m_T$ and $p_T$(l) distributions in electron and muon channels for $W^+$, $W^-$ in different η bins and then these measurements are combined

| Decay channel | $W \to e\nu$ | $W \to \mu\nu$ |
|---|---|---|
| Kinematic distributions | $p_T^\ell$, $m_T$ | $p_T^\ell$, $m_T$ |
| Charge categories | $W^+$, $W^-$ | $W^+$, $W^-$ |
| $\lvert\eta_\ell\rvert$ categories | $[0, 0.6]$, $[0.6, 1.2]$, $[1.8, 2.4]$ | $[0, 0.8]$, $[0.8, 1.4]$, $[1.4, 2.0]$, $[2.0, 2.4]$ |

- Transfer of experimental calibration and QCD modeling from Z to W
  - Large and pure Z sample for detector calib., and well measured Z mass
  - Predictions are fit to Z data to improve modeling and then applied to W boson

# EIC and an era of (higher) precision electroweak physics

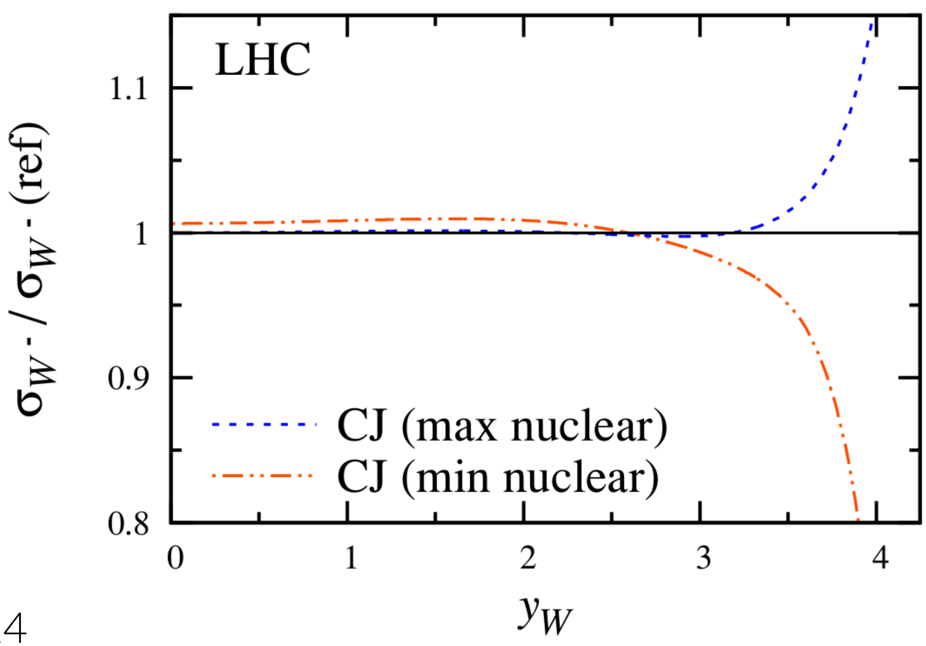
- theory predictions for the production of gauge bosons are quite sensitive to the nucleon PDFs: *e.g.*, $d(x)$ at $\boldsymbol{x}$ ~ **1**, which is poorly constrained

$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

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

$d$-type quark distributions are especially problematic

Brady et al., JHEP**06** (2012) 019.

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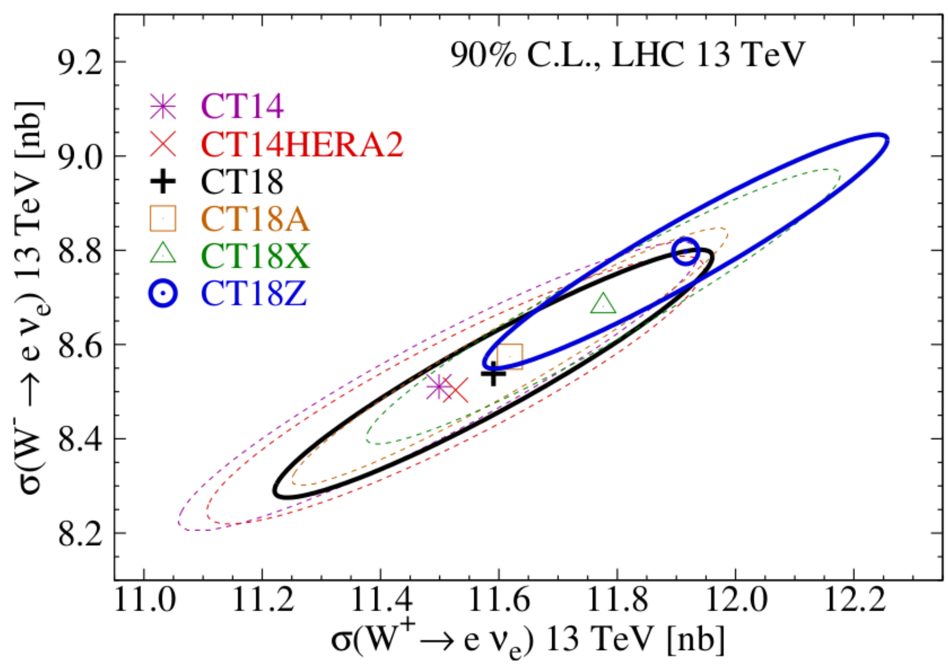


$m_W$

# historically, extractions of $d(x)$, $x \to 1$ have depended on nuclear targets

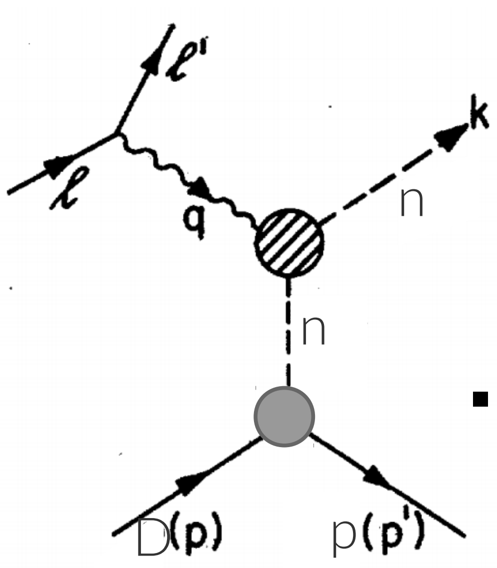
(and corrections!)

- in principle, a neutron target would allow the flavor separation needed to access $d(x, Q^2)$

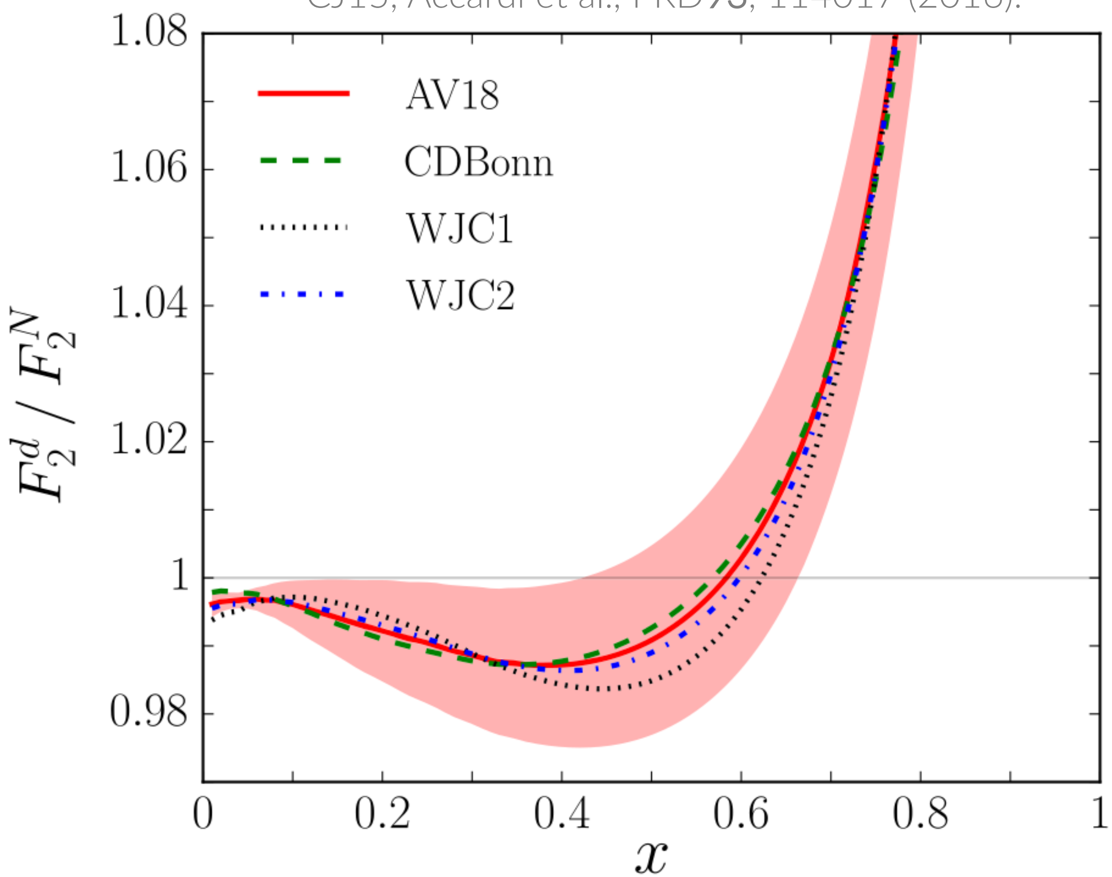
$$F_2^{e^- n} \sim x(4d + u)/9$$

$$vs$$

$$F_2^{e^- p} \sim x(4u + d)/9$$




CJ15, Accardi et al., PRD**93**, 114017 (2016).

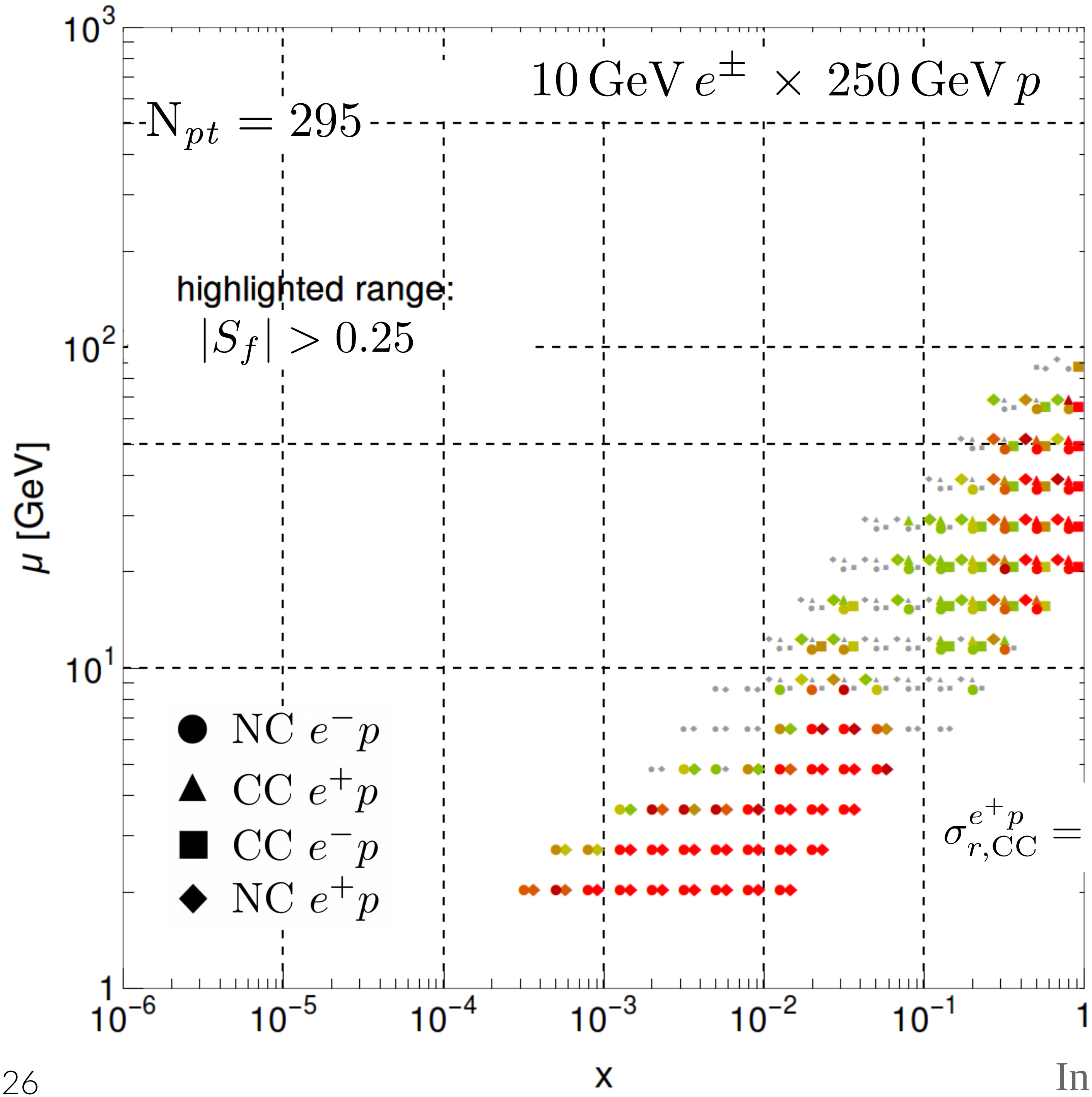


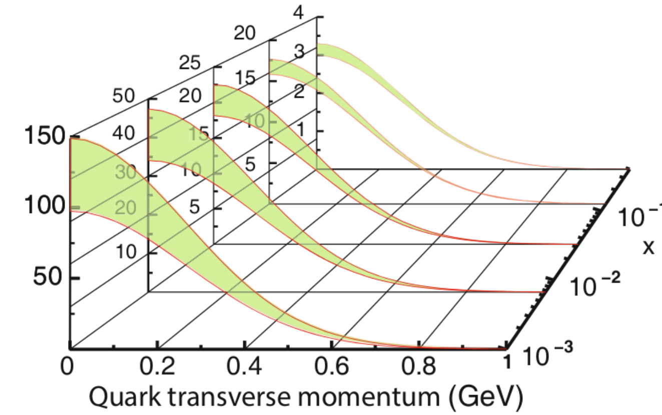

- **BUT**: in the absence of a free neutron target, scattering from nuclei (e.g., the deuteron) is necessary

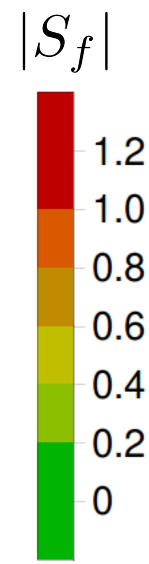
→ **nuclear corrections (Fermi motion) are sizable, especially for large $x$**

# $m_W$ | $S_f$ | for $d(x,\mu)$ CTI4 HERA2 NNLO

EIC Whitepaper:1206.2913




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

for $x \to 1$

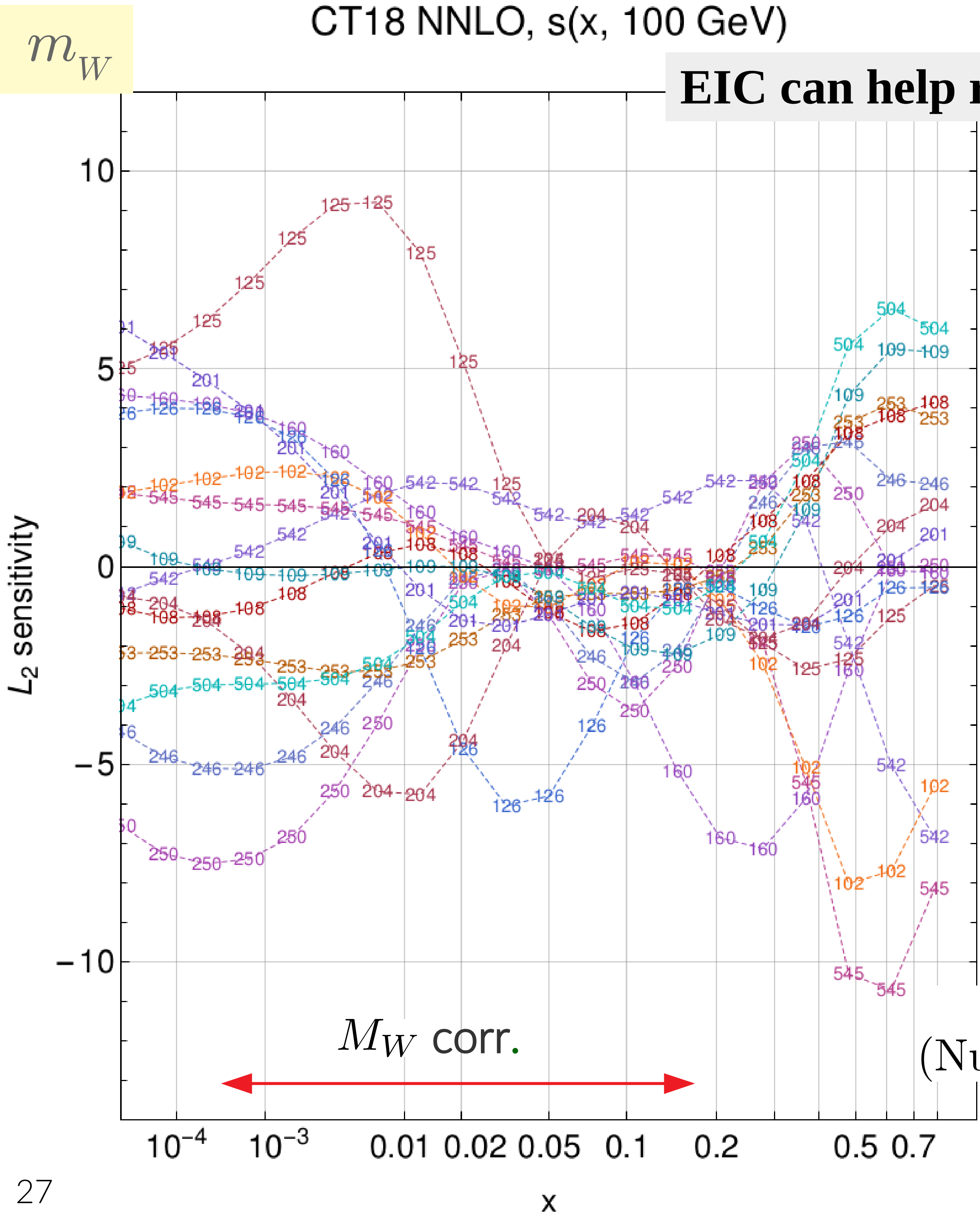
$$\sigma_{r,\mathrm{CC}}^{e^+p} = \frac{Y_+}{2} W_2^+ \mp \frac{Y_-}{2} x W_3^+ - \frac{y^2}{2} W_L^+$$

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

In the **LO quark-parton model**

$m_W$

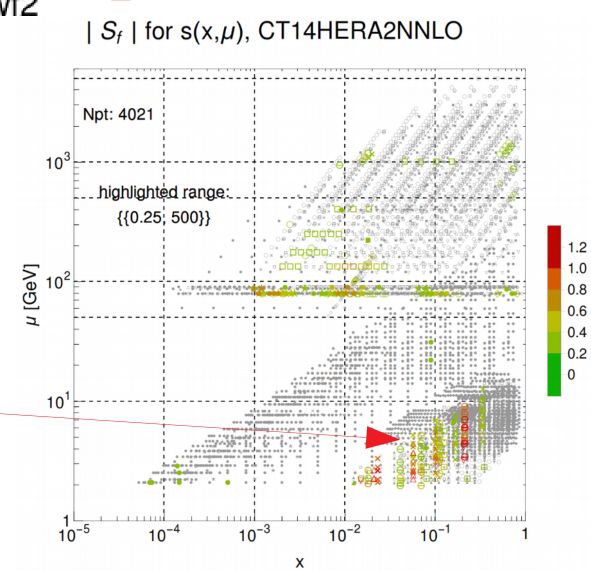
# EIC can help resolve nuclear uncertainties




neutrino-DIS data are used in single-nucleon fits

→ νA data play a vital role flavor-separation in contemporary global fits; e.g., for nucleon strangeness

$\nu$DIS (NuTeV, ...)

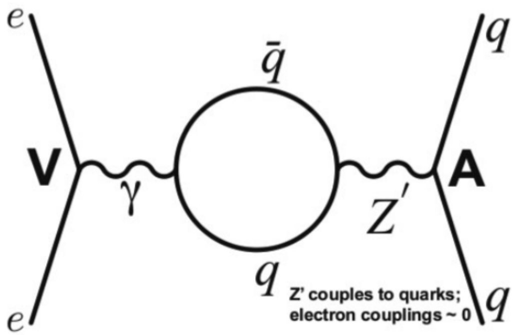


# electroweak sector and **BSM** searches at EIC

- 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**:

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

selects $\gamma$-Z interference diagrams!

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

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

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

$\sin^2\theta_W$

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

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

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

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

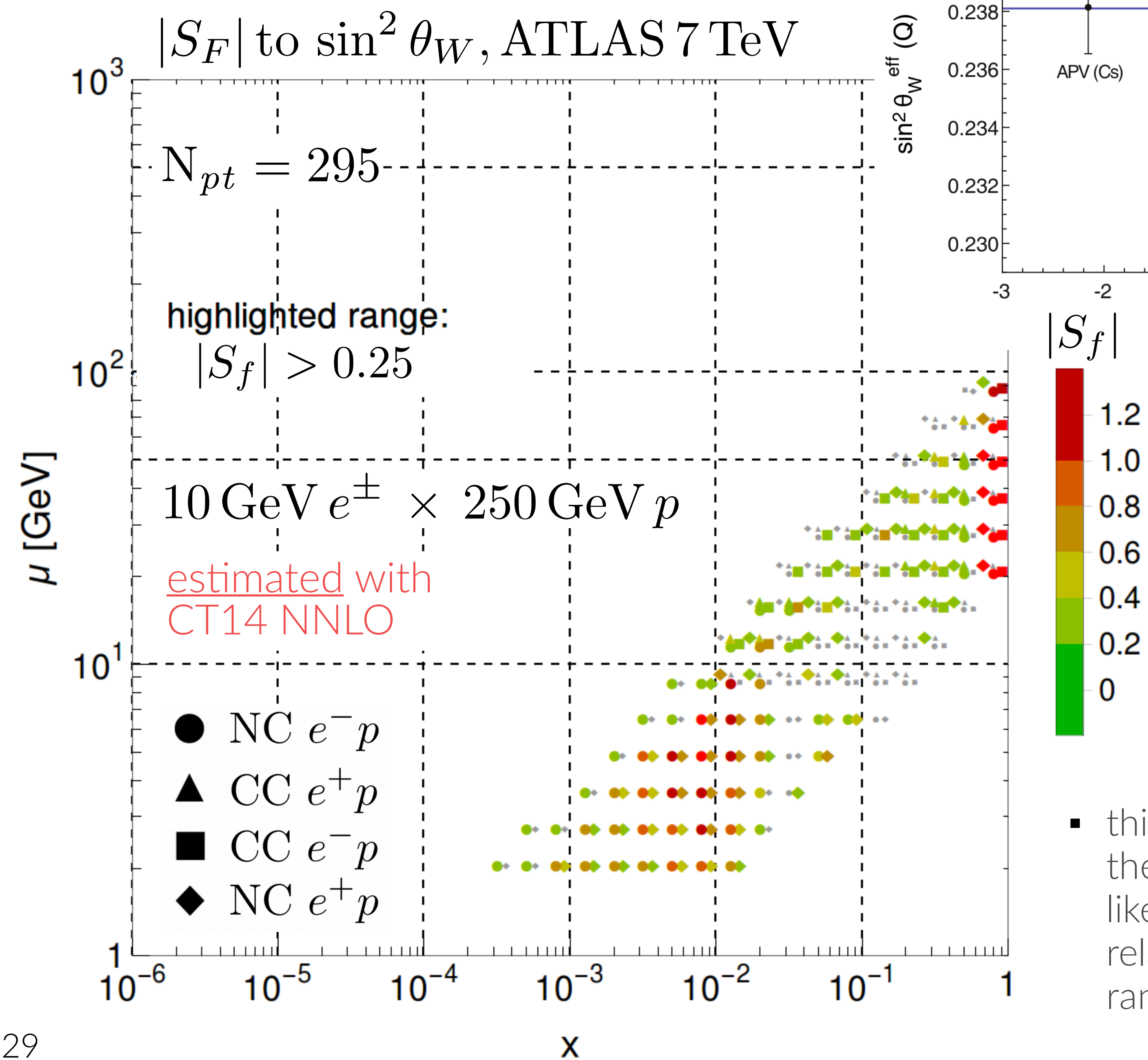
$$A^{\mathrm{PV}} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left(Y_1\ a_1 + Y_3\ a_3\right)$$

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

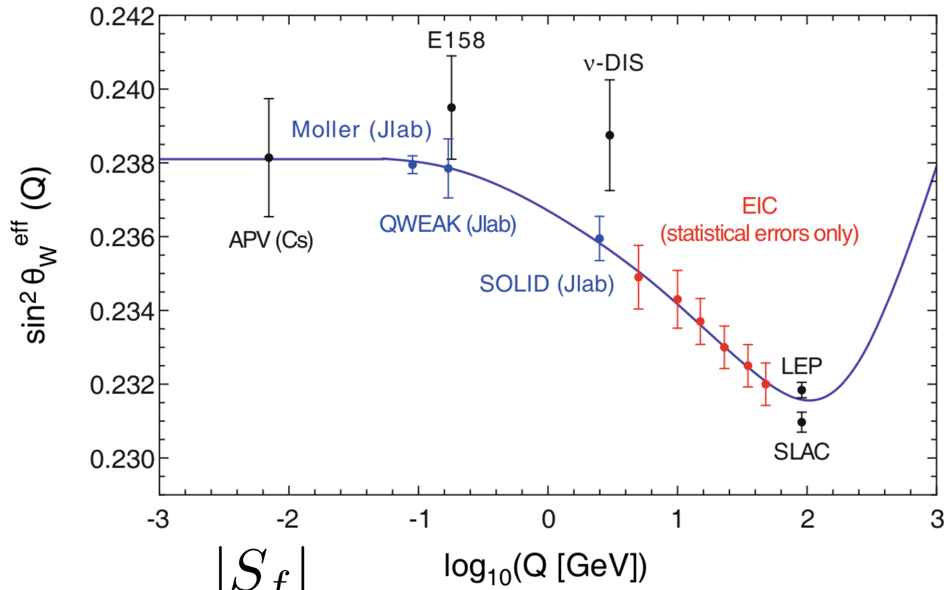
$$a_1 = \frac{2\sum_q e_q\ C_{1q}\ (q+\bar{q})}{\sum_q e_q^2\ (q+\bar{q})} \qquad a_3 = \frac{2\sum_q e_q\ C_{2q}\ (q-\bar{q})}{\sum_q e_q^2\ (q+\bar{q})}$$

$\sin^2\theta_W$

# EIC will probe BSM




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




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

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

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

# key points… & …recommendations.

- **numerous observables central to the LHC discovery program are limited by uncertainties associated with nucleon structure**

  → for the unpolarized PDFs, systematic tensions among modern world data are an impediment to higher precision for $\sigma_H$, $M_W$, …

  → an EIC will be ideally suited to perform measurements with the ability to unravel such systematic issues

- the EIC impact upon high-energy pheno will be pivotal

  → controlling PDFs/SM backgrounds for HL-LHC; neutrino pheno; event generators

- **it is imperative to inject these issues into EIC planning exercises**

  → for PDF issues: Phys. WG1 (IRG), WG3 (HQ/jets), …

  → access to $e^+$ beam important for full potential

  → critical decisions now will have long-term impact

# supplementary material

# there is a recent effort to explore these issues

## LPC Workshop on Physics Connections between the LHC and EIC

13-15 November 2019
Fermilab, Wilson Hall
America/Chicago timezone

https://indico.cern.ch/e/LHCEICPhysics

Search...

- Overview
- Call for Abstracts
- Timetable
- Registration
- Contribution List
- Participant List

**…whitepaper in preparation…**

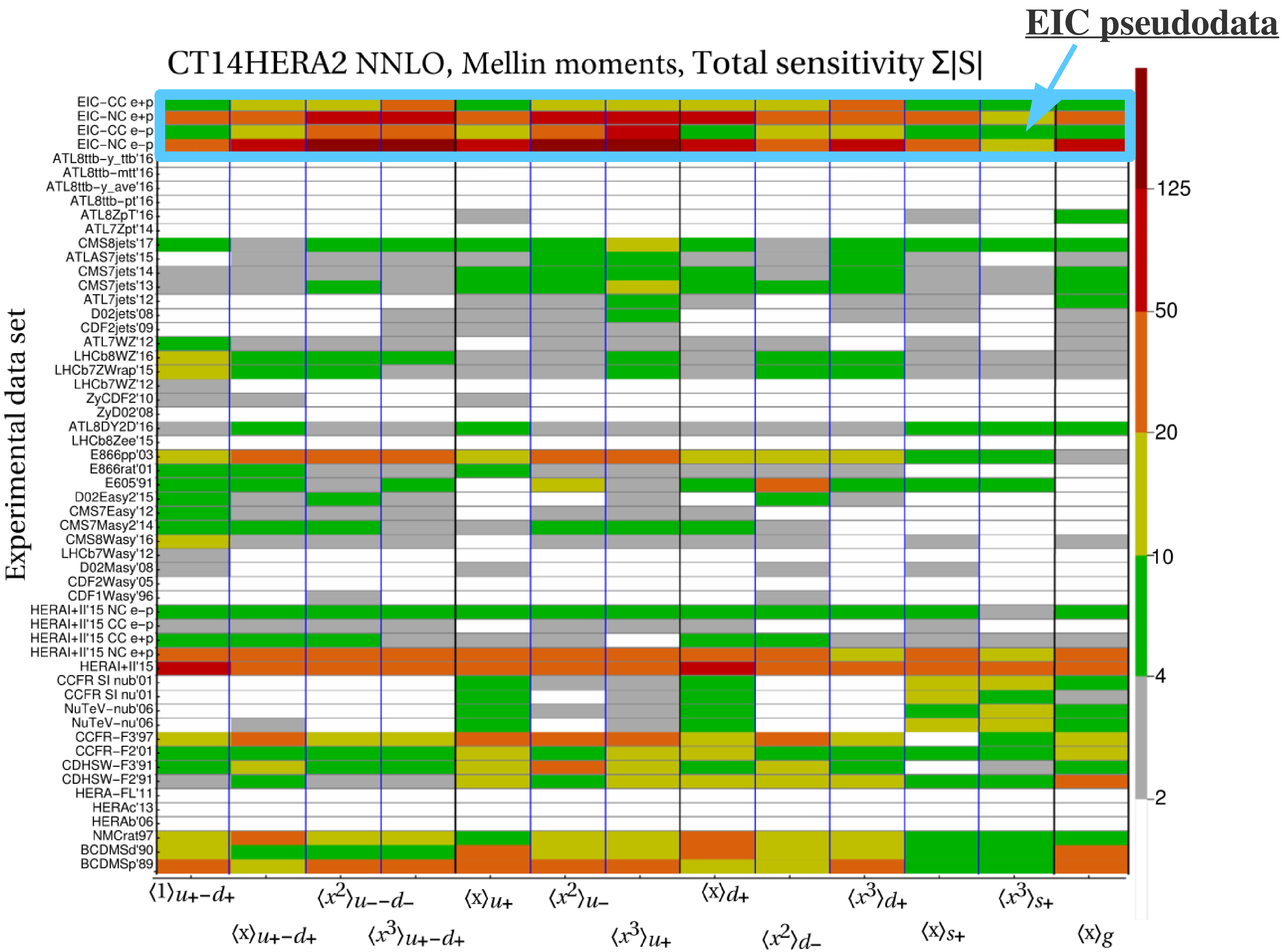
This 3-day workshop seeks to bring together members of the LHC and EIC communities under the auspices of the Fermilab LPC to explore possible synergies between the EIC program and LHC phenomenology. The areas of overlap to be discussed fall broadly along the lines of precision QCD, Monte Carlo event generators, lattice QCD and advanced computation, and opportunities in the electroweak sector, including potential improvements to neutrino phenomenology and BSM searches. The goal of this workshop is to identify and develop common working areas for which EIC science objectives can both inform and benefit from energy-frontier efforts at the LHC.

## Intellectual Health of the Field: QCD and Precision Physics - II

**JoAnne Hewett, talk to US HEP Advisory Panel**

- New ideas are emerging to exploit synergies, such as between the HL-LHC and the Electron-Ion-Collider (EIC) physics programs in the next decade. For example, a precision DIS experiment at the EIC will open a unique window to independently constrain the combination of parton distributions relevant for Higgs physics and high-mass resonance searches at the HL-LHC. At the same time, techniques developed to precisely predict hadronic jet properties and find rare events at the HL-LHC will also be of high value for the EIC community.

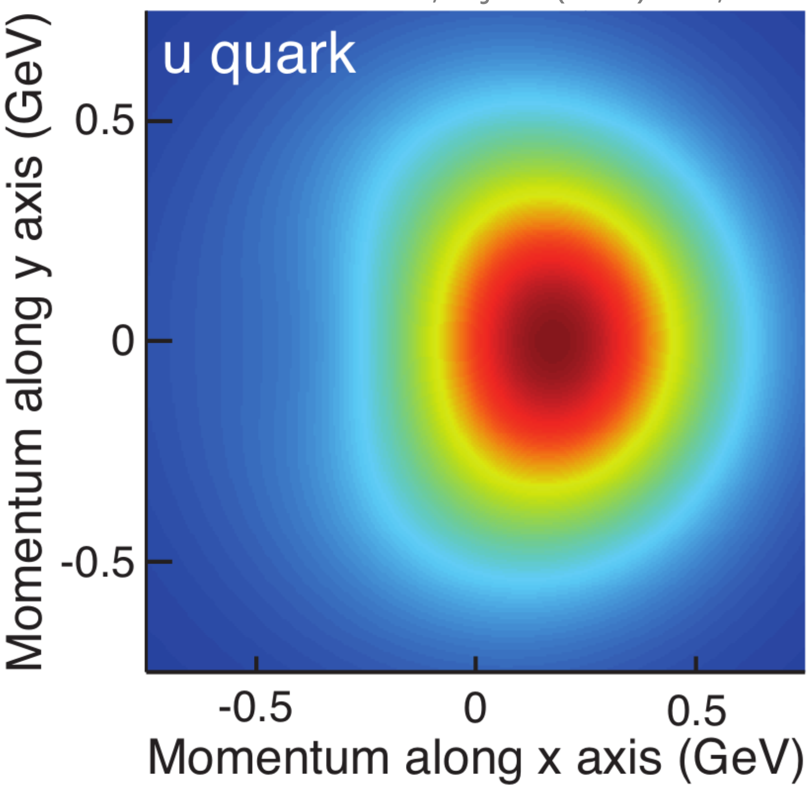
# sensitivities can be aggregated for direct comparisons of exps



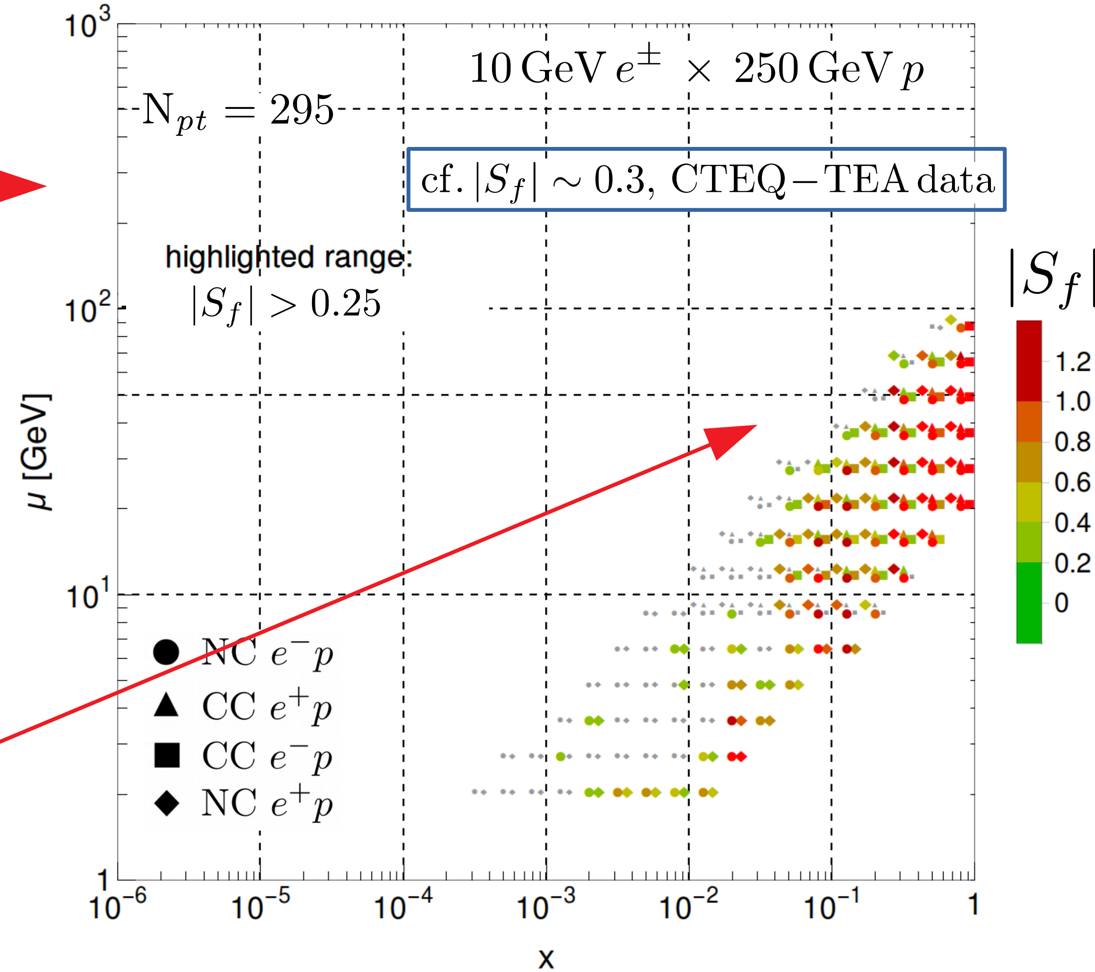
# the EIC tomography program will deliver high-precision DIS

- by measuring the nucleon's multi-dimensional wave function with high precision, the EIC will hugely constrain proton collinear structure

Accardi et al., EPJA52 (2016) no.9, 268.




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



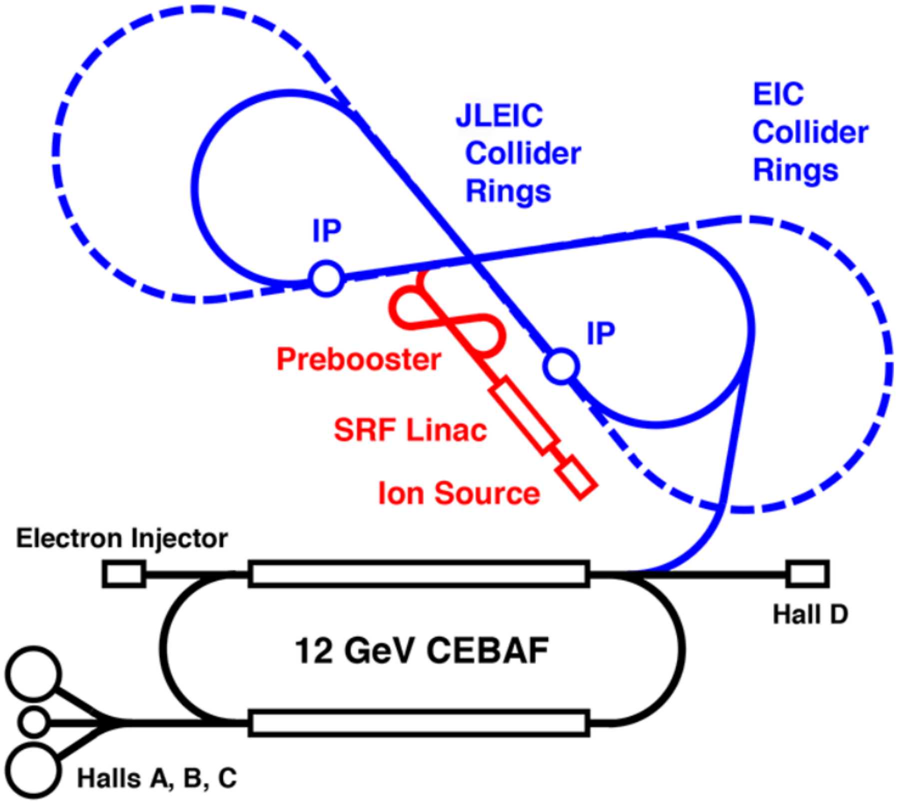

PROJECTED IMPACT OF EIC PSEUDO-DATA VERY LARGE – RED SIMULATED MEASUREMENTS

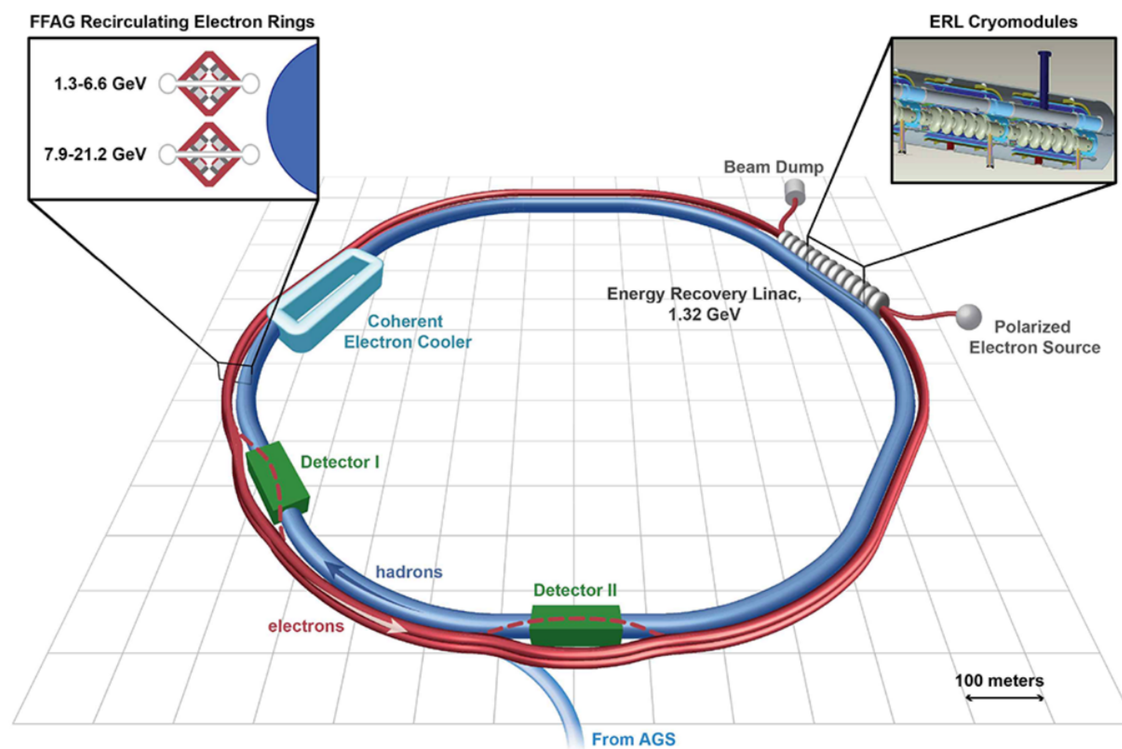
DIS cross sections from EIC will supercede the bulk of fixed-target information in contemporary QCD fits; provide an 'anchor-point' to resolve systematic PDF tensions

# the EIC will be a very high-luminosity DIS collider

Jefferson Lab concept, JLEIC

Brookhaven concept, eRHIC




→ add Ion source, collider rings to existing electron accelerator (CEBAF)

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

these designs share many essential features

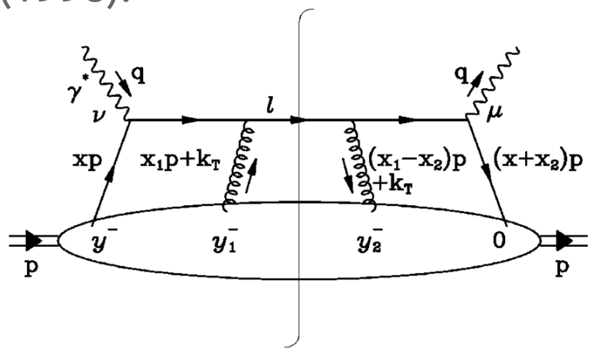
# interactions with multiple partons at EIC: **nuclear case**

- **consider jet production in electron-nucleus vs. electron-nucleon DIS**

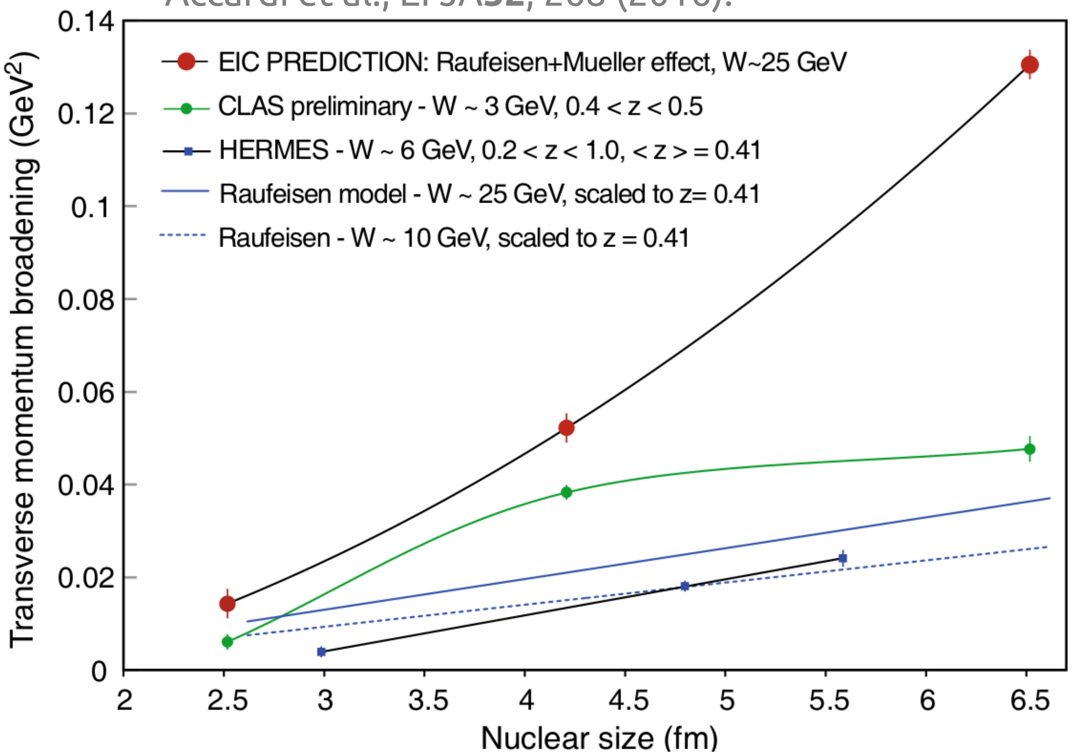
X. Guo, PRD**58**, 114033 (1998).

$$\Delta\langle p_T^2\rangle \equiv \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ep}$$

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




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



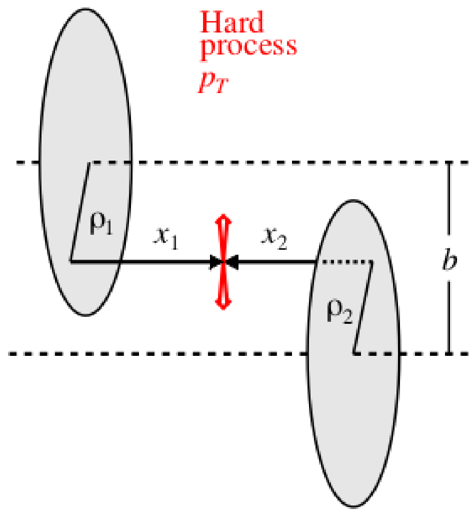

- multi-parton interactions in nuclear scattering:

  → multiple scatterings of produced quark with nuclear medium

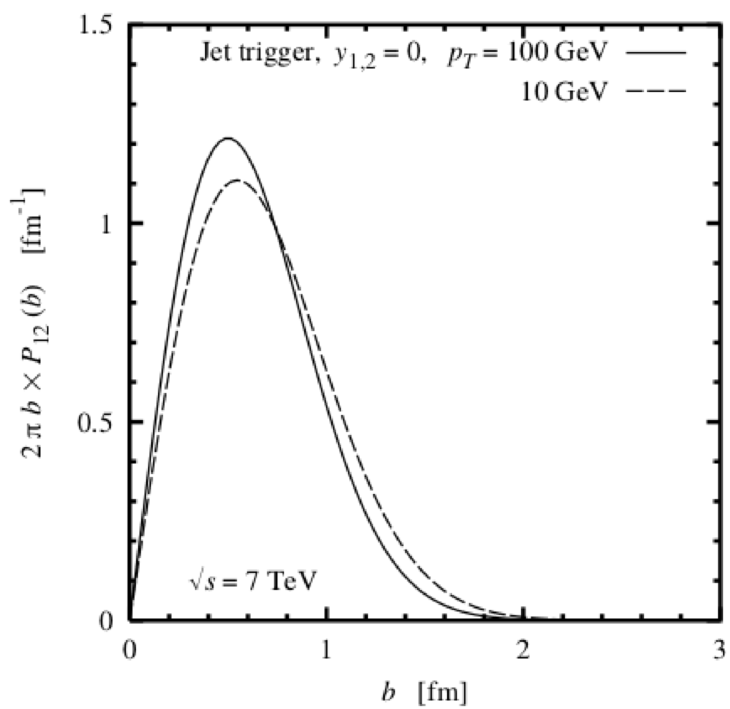
  → **qualitatively different dependence on nuclear size predicted at EIC energies**

  → more phase space for radiation, larger $\Delta\langle p_T^2\rangle$

# Transverse geometry in pp: Hard processes




Thanks to Christian Weiss!




- Hard process from parton-parton collision

  Local in transverse space $p_T^2 \gg (\text{transv. size})^{-2}$

- Cross section as function of $pp$ impact par

$$\sigma_{12}(b) \;=\; \int d^2\rho_1\, d^2\rho_2\, \delta(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) \times G(x_1, \rho_1)\, G(x_2, \rho_2)\, \sigma_{\text{parton}}$$

$\rightarrow$ precise GPDs furnished by EIC will be crucial!

Calculable from known transverse distributions
Integral $\int d^2 b$ reproduces inclusive formula

Normalized distribn $P_{12}(b) = \sigma_{12}(b)/[\int \sigma_{12}]$

- New information available

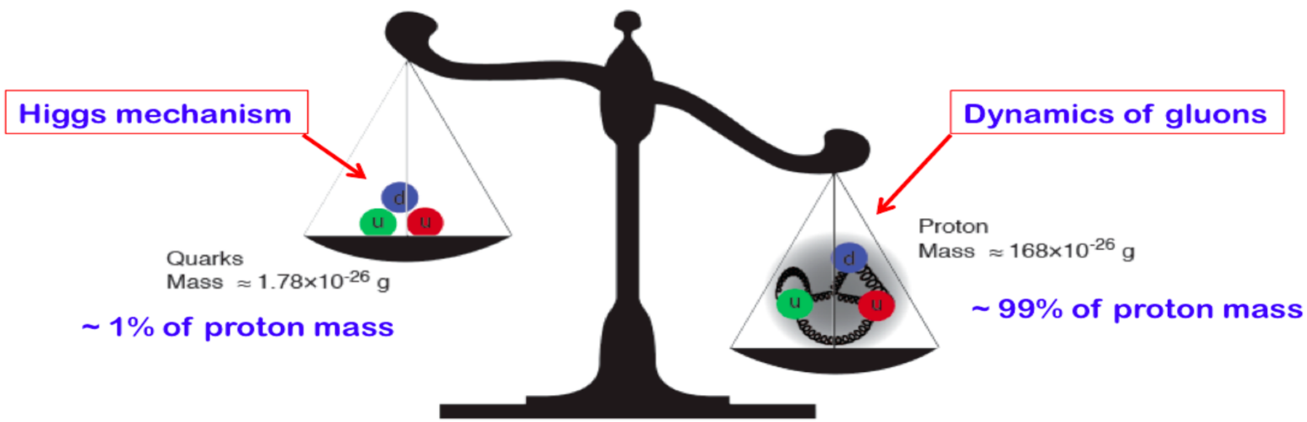
  Model spectator interactions depending on $b$
  Underlying event

  Predict probability of multiple hard processes
  Dynamical correlations? FSW04

  Diffraction: Gap survival probability
  Determined largely by transverse geometry FHSW 07

# a full understanding of QCD bound states is still forthcoming

→ e.g., the Higgs mechanism accounts for **very little** of the mass of the visible universe



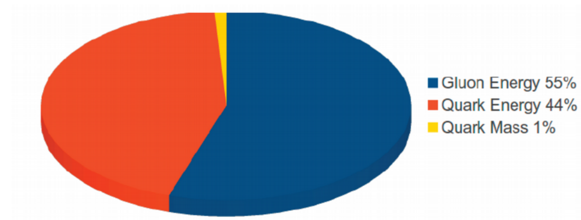
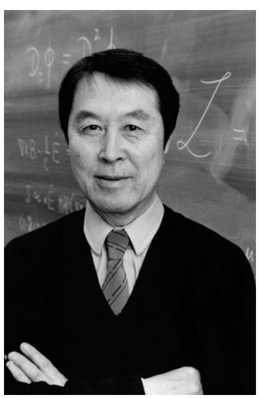
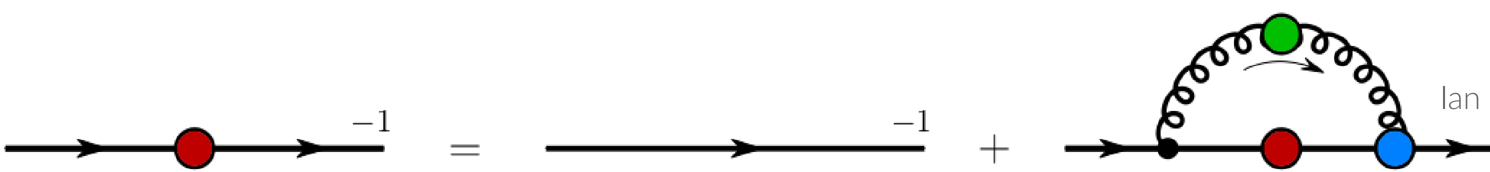



Fig. 2.1 NAS Report


Y. Nambu

QCD has a gap equation through which the dynamics of chiral symmetry breaking generate large masses, e.g., of the bound quark



Ian Cloët

→ the full mass decomposition involves multiple contributions,

$$M_p = E_q + E_g + \chi_{m_q} + T_g$$

...direct measurement can resolve contribution from quark-gluon motion

# QCD analyses operationalize this physics into global fits

- PDFs (& analogous distributions) are nonpertubative hadronic matrix elements,

$$f_{q/p}(x,\mu^2) = \int \frac{d\xi^-}{4\pi} e^{-i\xi^- k^+} \langle p \,|\overline{\psi}(\xi^-)\gamma^+ \mathcal{U}(\xi^-,0)\psi(0)\,|p\rangle$$

'The Big Bang Theory'

challenging to compute from QCD!

there are lattice QCD developments

```
Amy: Maybe you could make your
new field of study the
calculation of nuclear matrix
elements.

Sheldon: Oh, please!
```

philosophy: lacking a first-principles calculation, fit a flexible parametrization at a suitable boundary condition for QCD evolution:

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

→ perturbatively-calculable evolution then specifies dependence on $\mu^2 > Q_0^2$

→ fit the world's data from a diverse range of scales and processes

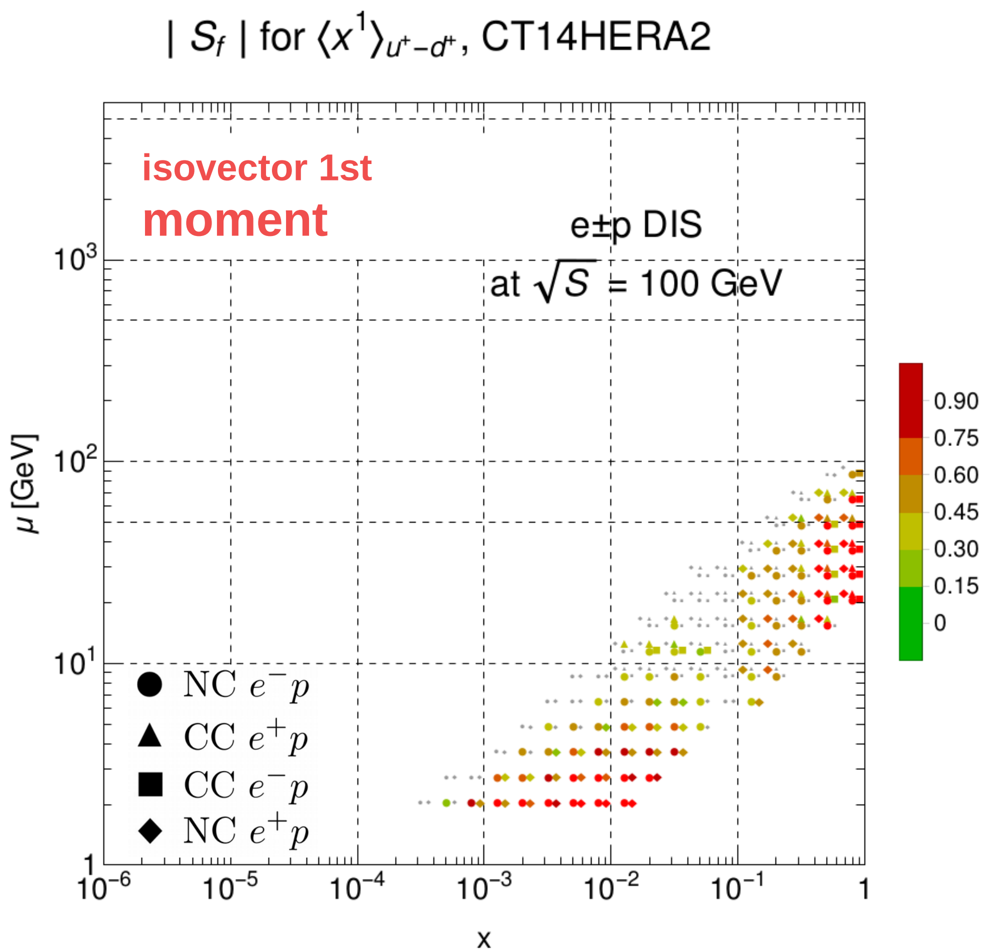
# An EIC would drive lattice phenomenology

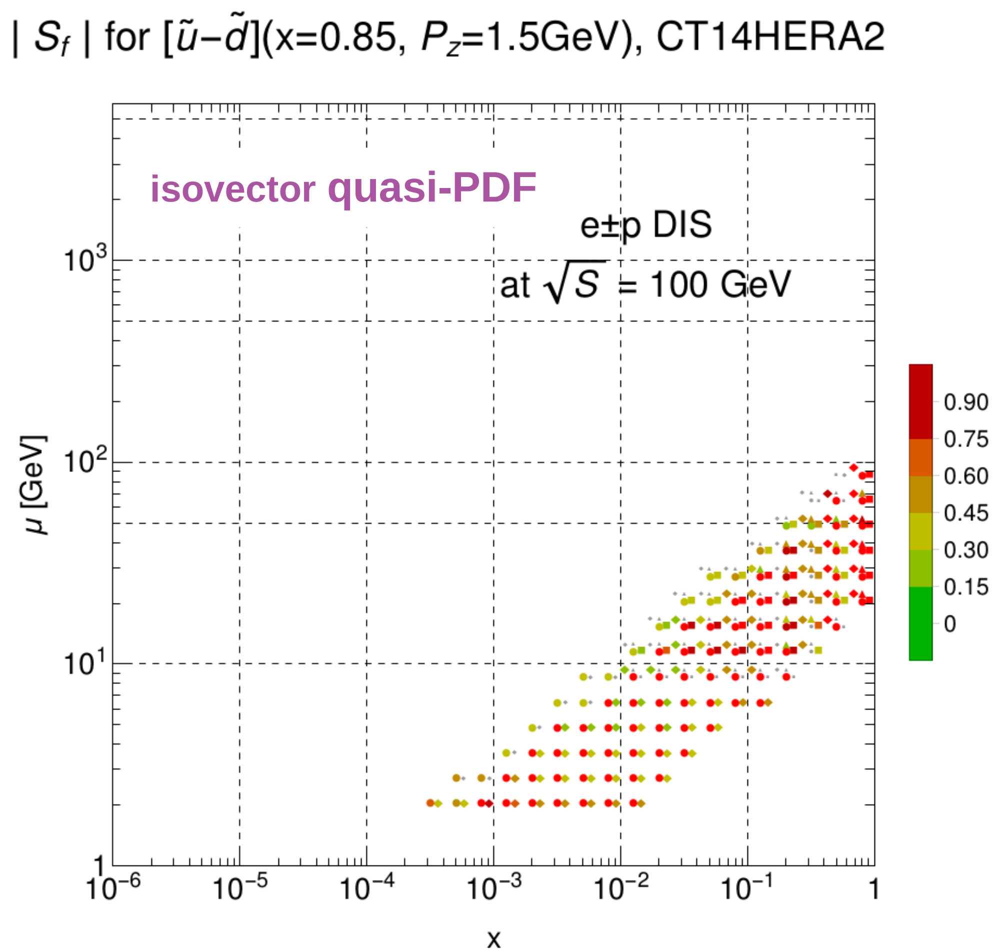
arXiv:1904.00022 [hep-ph] (PRD, to appear)

- A high-luminosity lepton-hadron collider will impose very tight constraints on many lattice observables; below, the isovector first moment and qPDF; this is crucial for benchmarking!
- Many of the experiments most sensitive to PDF Mellin moments and qPDFs involve nuclear targets → eA data from EIC would sharpen knowledge of nuclear corrections

$$\langle x^n \rangle_{q,g} = \int dx\, x^n f_{q,g}(x, \mu = 2\,\mathrm{GeV})$$

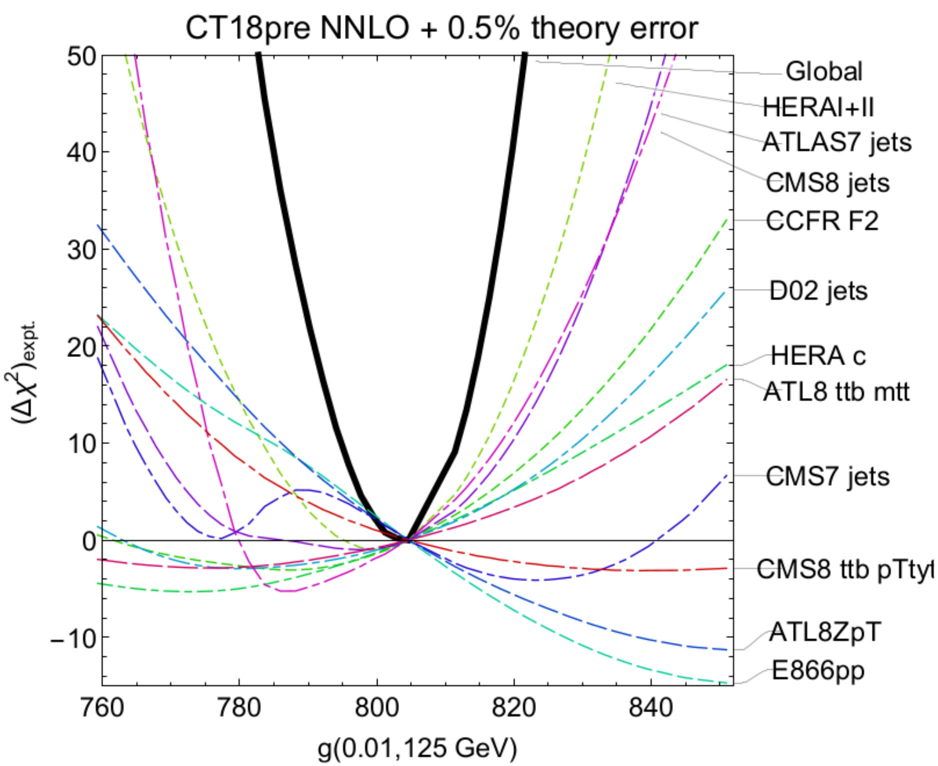
$$\widetilde{q}(x, P_z, \widetilde{\mu}) = \int dy\, Z\left(\frac{x}{y}, \frac{\Lambda}{P_z}, \frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{P_z^2}, \frac{M^2}{P_z^2}\right)$$



# we use the Higgs region g(x) to validate PDFSense

...for the gluon PDF in the Higgs region, $g(0.01, m_H)$




| $g(x=0.01, \mu=125$ GeV$)$ | | |
|---|---|---|
| PDFSense | | LM scan |
| CT14HERA2 | CT18pre | CT18pre |
| HERAI+II'15 | HERAI+II'15 | HERAI+II'15 |
| CMS8jets'17 | CMS8jets'17 | CMS8jets'17 |
| CMS7jets'14 | CMS7jets'14 | ATL8ZpT'16 |
| ATLAS7jets'15 | E866pp'03 | E866pp'03 |
| E866pp'03 | ATLAS7jets'15 | ATLAS7jets'15 |
| BCDMSd'90 | BCDMSd'90 | CCFR-F2'01 |
| CCFR-F3'97 | BCDMSp'89 | D02jets'08 |
| D02jets'08 | D02jets'08 | HERAc'13 |
| NMCrat'97 | NMCrat'97 | NuTeV-nub'06 |
| BCDMSp'89 | CDHSW-F2'91 | CCFR-F3'97 |

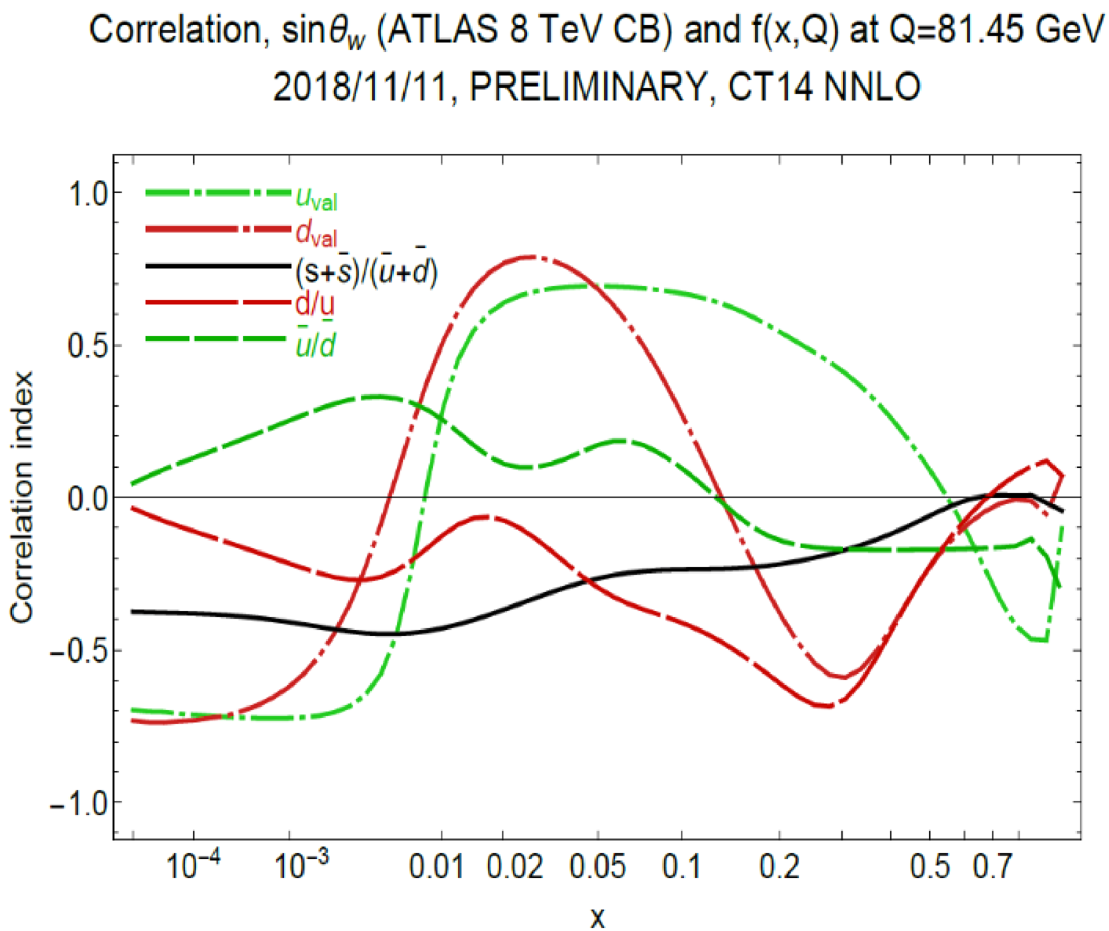
- PDFSense identifies the most sensitive experiments with high confidence and in accord with other methods such as the LM scans. It works the best when the uncertainties are nearly Gaussian, and experimental constraints agree among themselves [arXiv:1803.02777]

$\sin^2\theta_W$ (and, eventually, $M_W$)

...as a follow-on to Alesandro's EW-focused overview:

important PDF correlations for the ATLAS extraction of $\sin^2\theta_W$

# Example: $\sin^2\theta_{weak} \equiv s2w$ measured by ATLAS 8 TeV




Strongest correlations of s2w with $u_{val}$, $d_{val}$ at

$$0.005 \lesssim x \lesssim 0.2$$

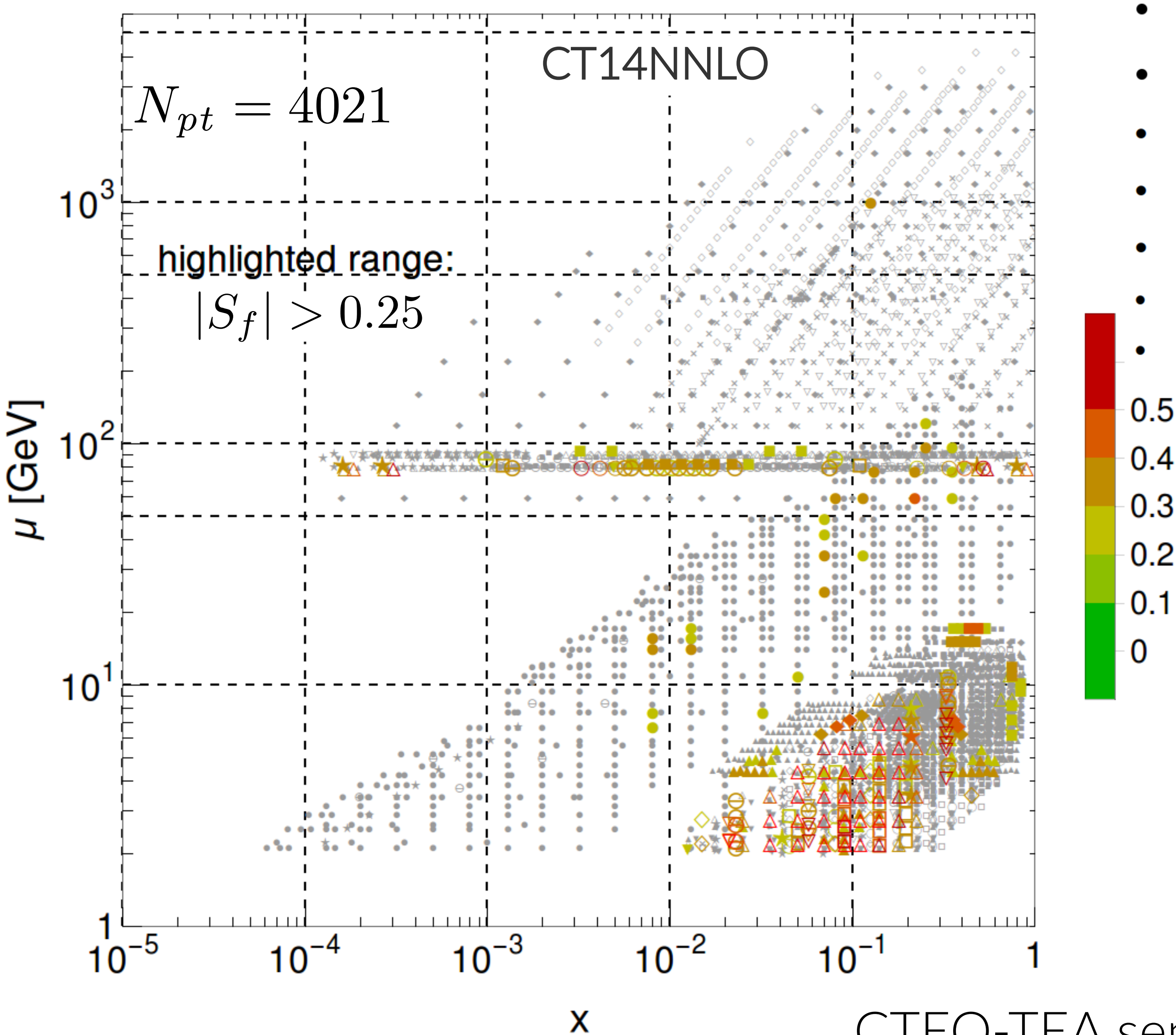
weak correlations with $\bar{u}$, $\bar{\mathrm{d}}$, $\bar{s}$, $g$

$u_{val}$, $d_{val}$ changed between CT10 and CT14
**[1506.07433, Sec. 2B]**

It is instructive to explore the data pulls on $u_{val}$, $d_{val}$

$\sin^2\theta_W$

PDF sensitivity of $\sin^2\theta_W$ from 7 TeV ATLAS data

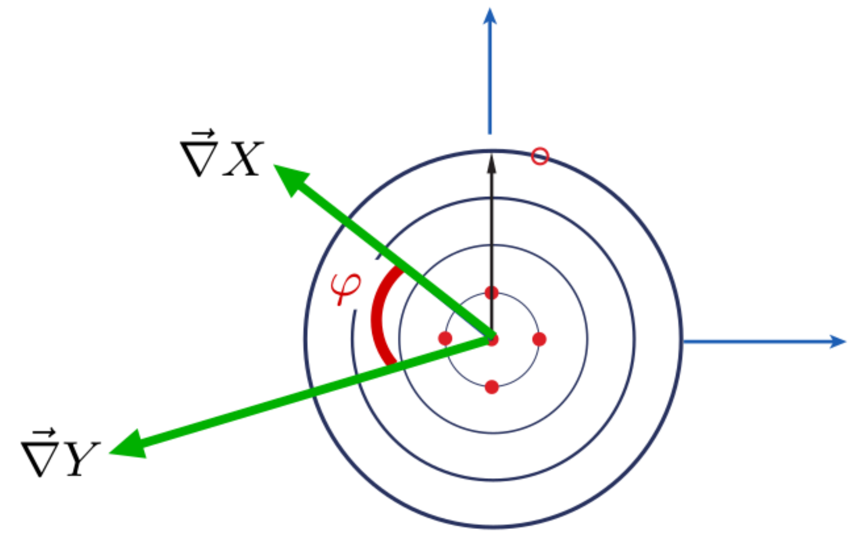



- **combined HERA1 DIS [most sensitive]**
- CCFR $\nu p$ DIS $F_{3,2}$
- BCDMS $F_2^{p,d}$
- NMC $ep$, $ed$ DIS
- CDHSW $\nu A$ DIS
- NuTeV $\nu A \to \mu\mu X$
- CCFR $\nu A \to \mu\mu X$
- E866 $pp \to \ell^+\ell^- X$
- ATLAS 7 TeV W/Z (35 $pb^{-1}$)

CTEQ-TEA sensitivities to $\sin^2\theta_W$

rather than the costly LM scans, we can examine a “cheaper” measure which yields comparable information

the *L2 sensitivity*



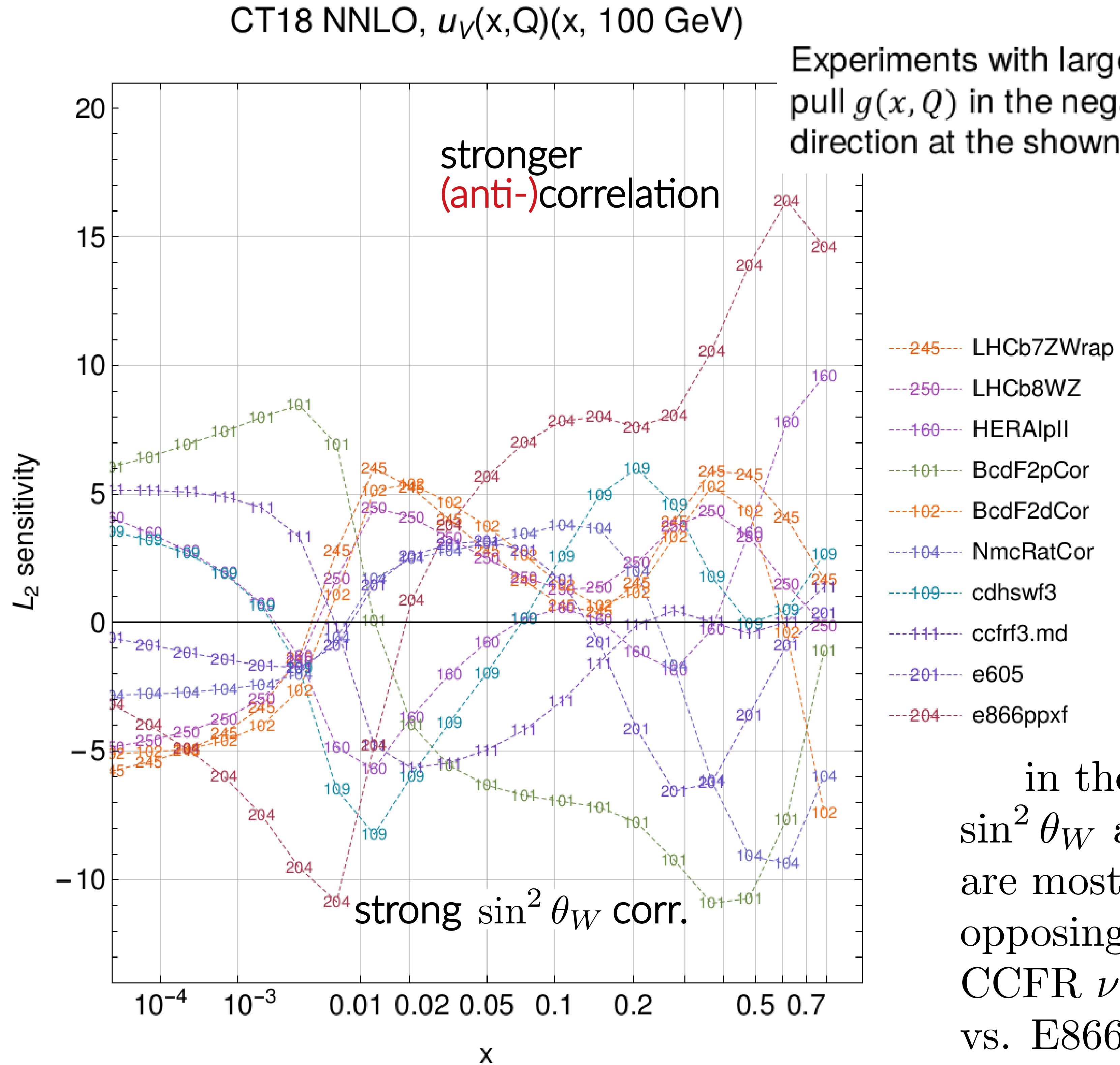

$L_2$ sensitivity. Take $X = f_a(x_i, Q_i)$ or $\sigma(f)$; $Y = \chi^2_E$ for experiment $E$. Find $\Delta Y(\vec{z}_{m,X})$ for the displacement $|\vec{z}_{m,X}| = 1$ along the direction $\vec{\nabla}X / \left|\vec{\nabla}X\right|$ (corresponding to $\Delta\chi^2_{tot} = T^2$ and $X(\vec{z}) = X(0) + \Delta X$):

$$S_{f,L_2} \equiv \Delta Y(\vec{z}_{m,X}) = \vec{\nabla}Y \cdot \vec{z}_{m,X} = \vec{\nabla}Y \cdot \frac{\vec{\nabla}X}{|\vec{\nabla}X|}$$

$$= \Delta Y \, \cos\varphi$$

or, $\sim \mathrm{Corr}[f_a, \chi^2_E]$

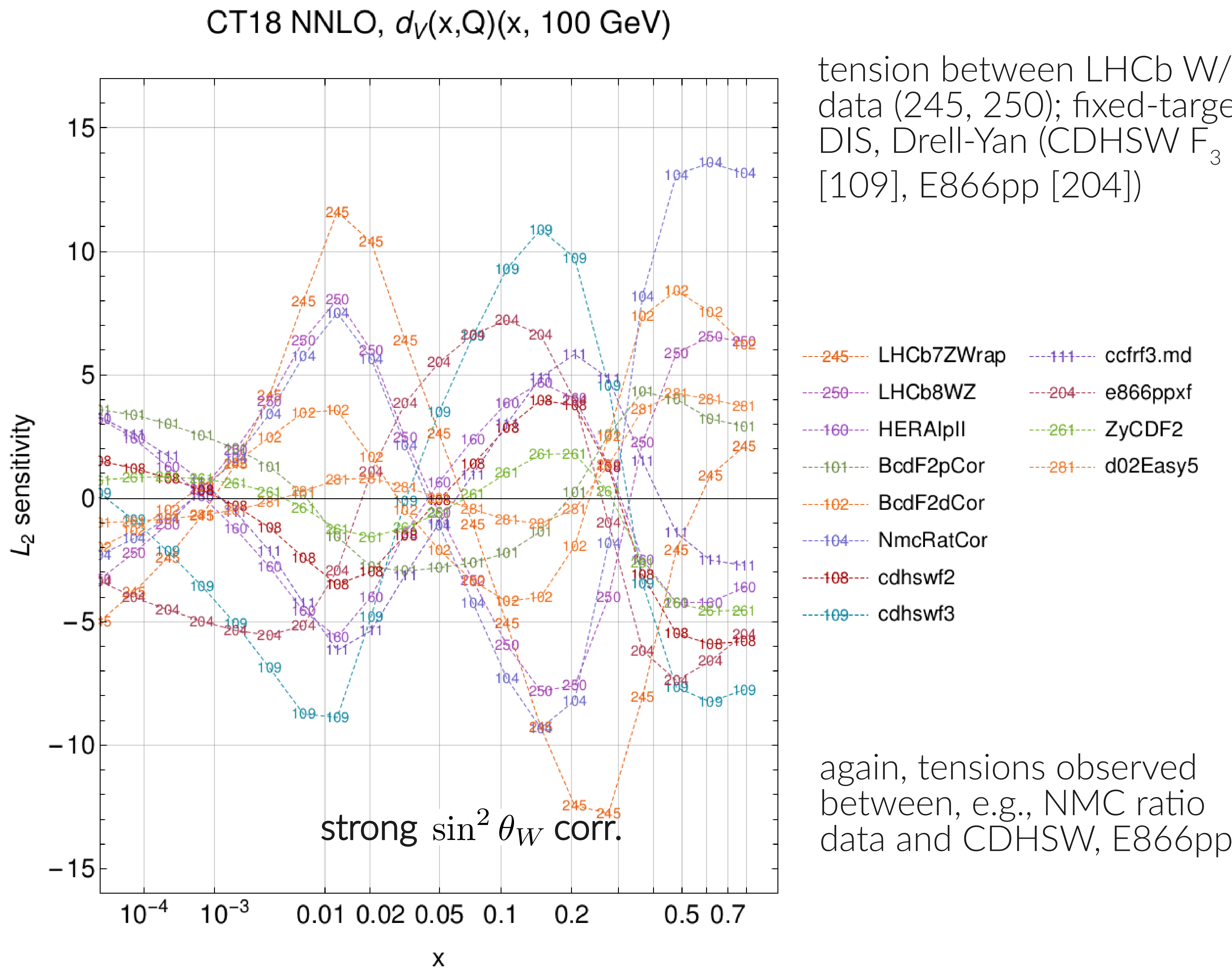
...extent to which total $\chi^2_E$ of specific expts. correlates with $x$-dep. of PDFs




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

tension between LHCb W/Z data (245, 250); fixed-target DIS, Drell-Yan (CDHSW $F_3$ [109], E866pp [204])

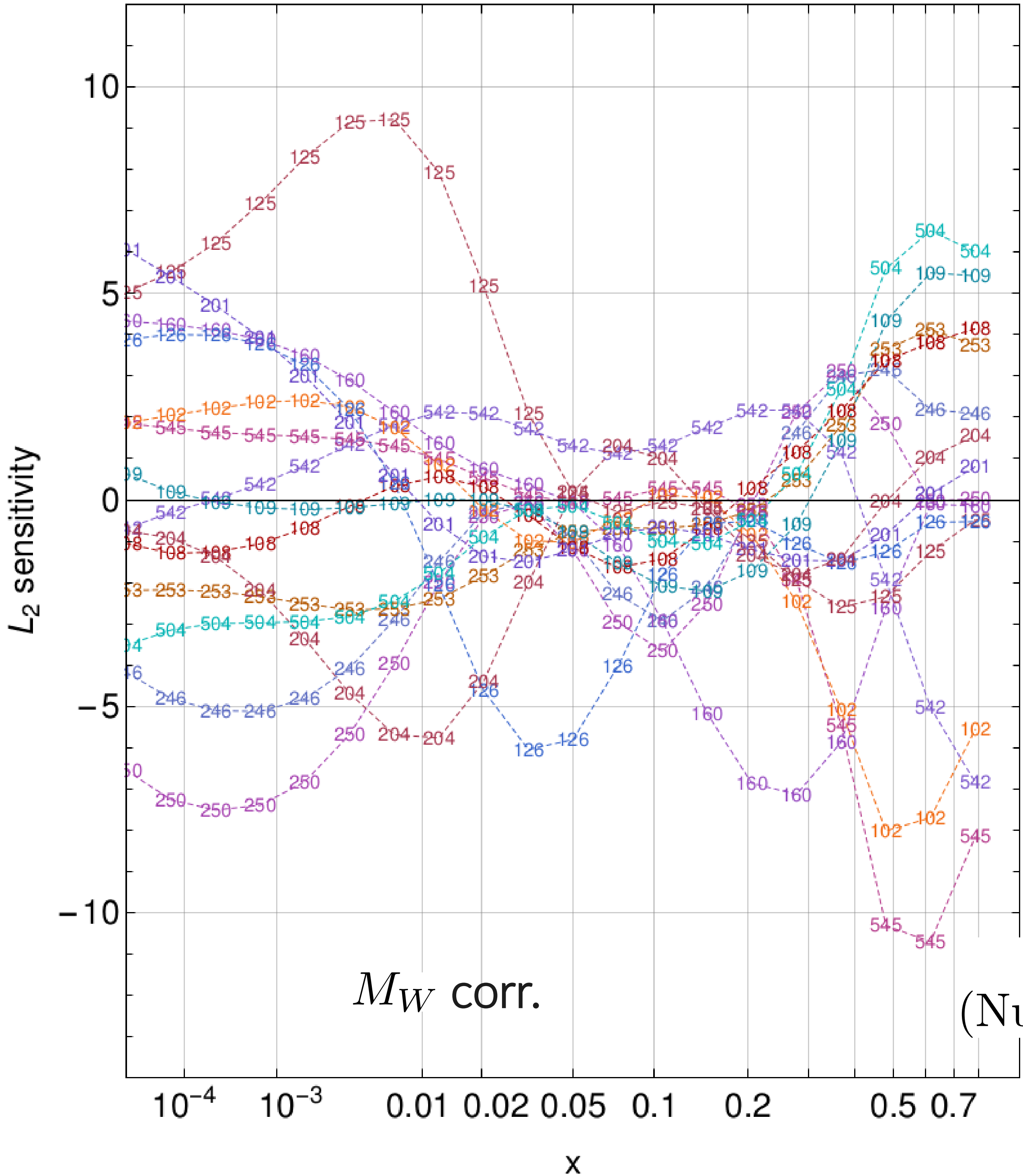
in the region where $\sin^2\theta_W$ and $u_v$ are most correlated, opposing pulls from CCFR $\nu$DIS, BCDMS vs. E866 $pp$, NMC rat.




tension between LHCb W/Z data (245, 250); fixed-target DIS, Drell-Yan (CDHSW $F_3$ [109], E866pp [204])

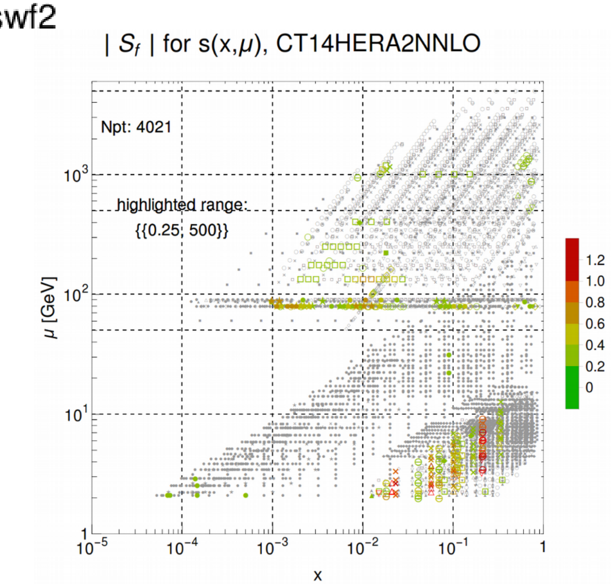
again, tensions observed between, e.g., NMC ratio data and CDHSW, E866pp

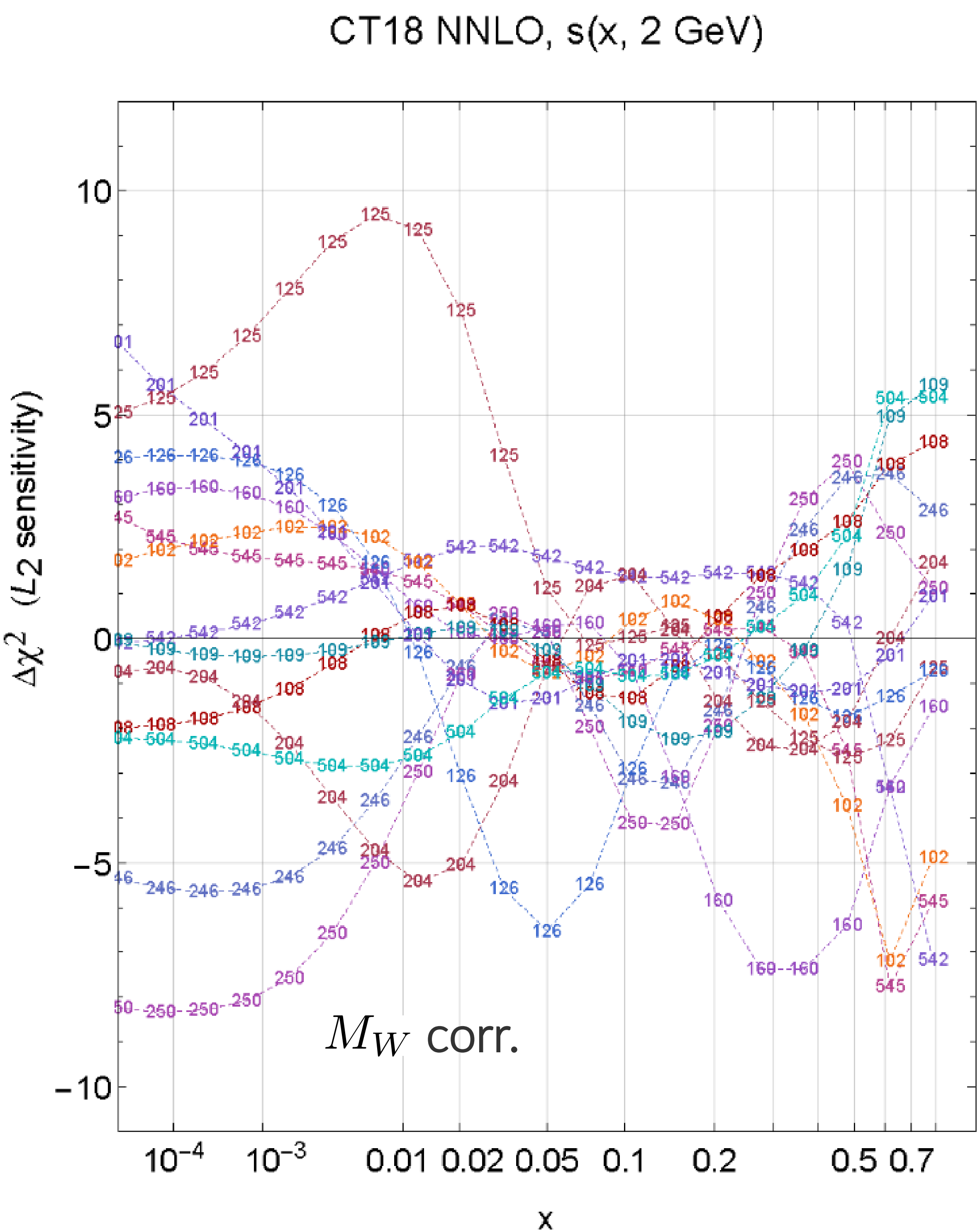
$M_W$




...this analysis can be extended to $M_W$, extractions of which are dependent upon s(x), through Z-calibration

$\nu$DIS (NuTeV, ...)



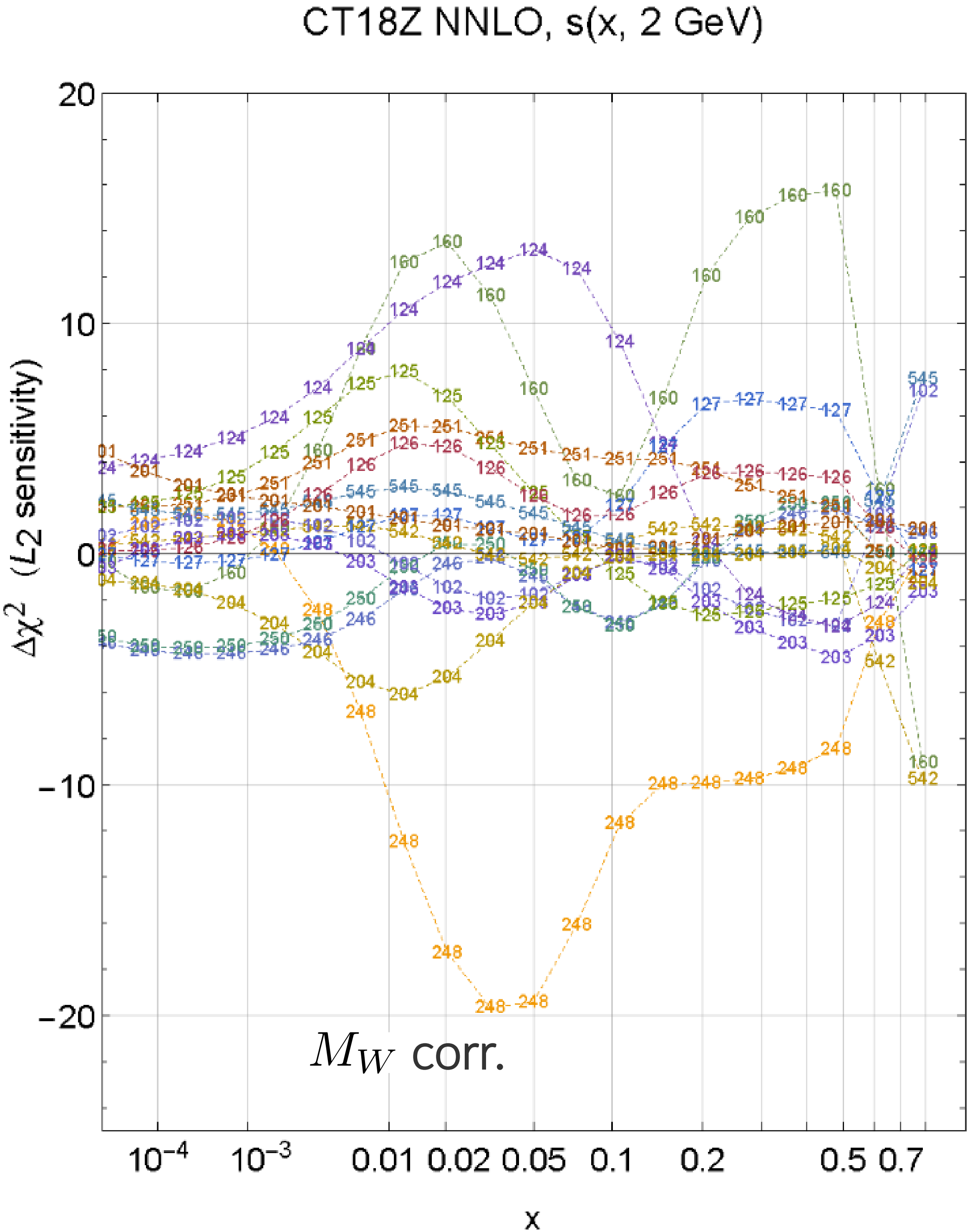



# $L_2$ sensitivity, strangeness: CT18

Most sensitive experiments

| | | | |
|---|---|---|---|
| 246 | LHCb8Zeer | 125 | NuTvNbChXN |
| 250 | LHCb8WZ | 126 | CcfrNuChXN |
| 542 | CMS7jtR7y6T | 201 | e605 |
| 545 | CMS8jtR7T | 204 | e866ppxf |
| 160 | HERAIpII | 504 | cdf2jtCor2 |
| 102 | BcdF2dCor | | |
| 108 | cdhswf2 | | |
| 109 | cdhswf3 | | |

A tension trend between DIS (HERA I+II, CCFR, NuTeV) and Drell-Yan (ATLAS 7 Z/W, LHCb W/Z, E866 pp, …) experiments




# $L_2$ sensitivity, strangeness: CT18Z

## Most sensitive experiments

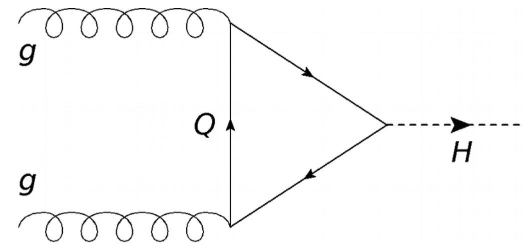
- 246 LHCb8Zeer
- 248 ATL7ZW.xF
- 250 LHCb8WZ
- 251 ATL8DY
- 542 CMS7jtR7y6T
- 545 CMS8jtR7T
- 160 HERAIpII
- 102 BcdF2dCor
- 124 NuTvNuChXN
- 125 NuTvNbChXN
- 126 CcfrNuChXN
- 127 CcfrNbChXN
- 201 e605
- 203 e866f
- 204 e866ppxf

A tension trend between DIS (HERA I+II, CCFR, NuTeV) and Drell-Yan (ATLAS 7 Z/W, LHCb W/Z, E866 pp, …) experiments

pronounced effect of ATLAS 7 TeV Z/W data!

# **QCD at high energies**: an EIC and control over the gluon

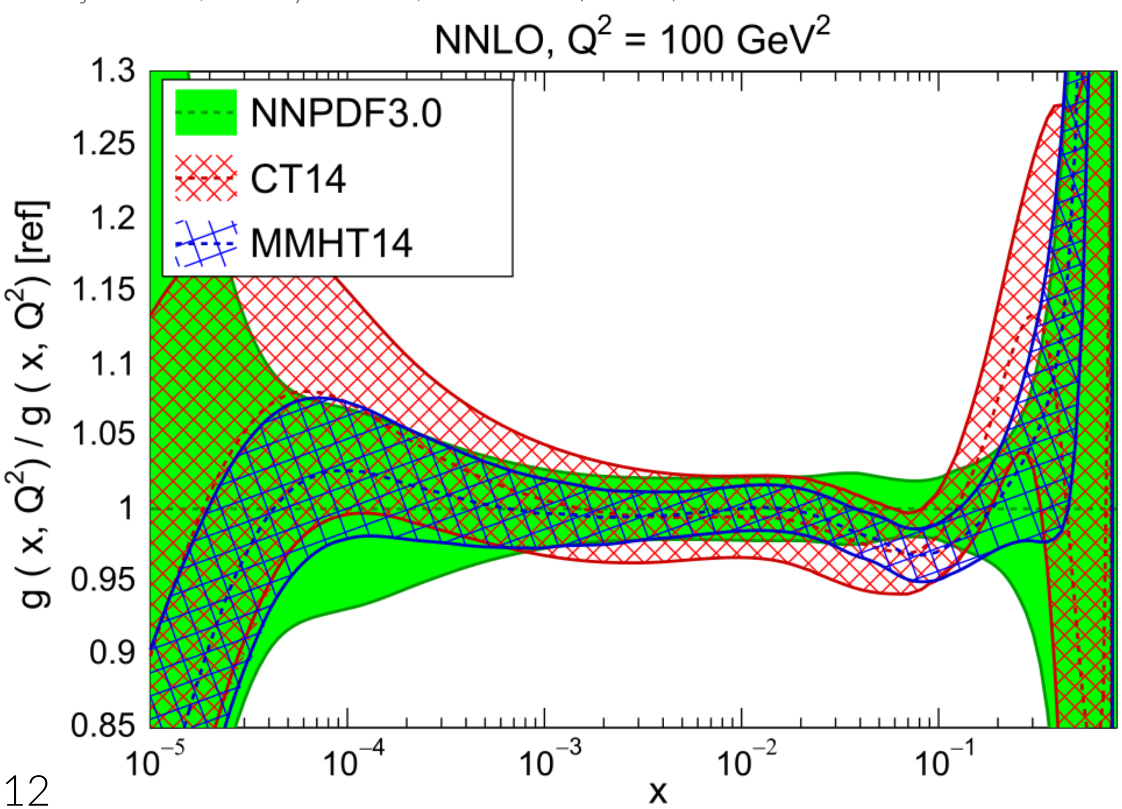
- the gluon is crucial to the mass of hadronic bound states, and $gg \to H$ is the dominant channel in Higgs production



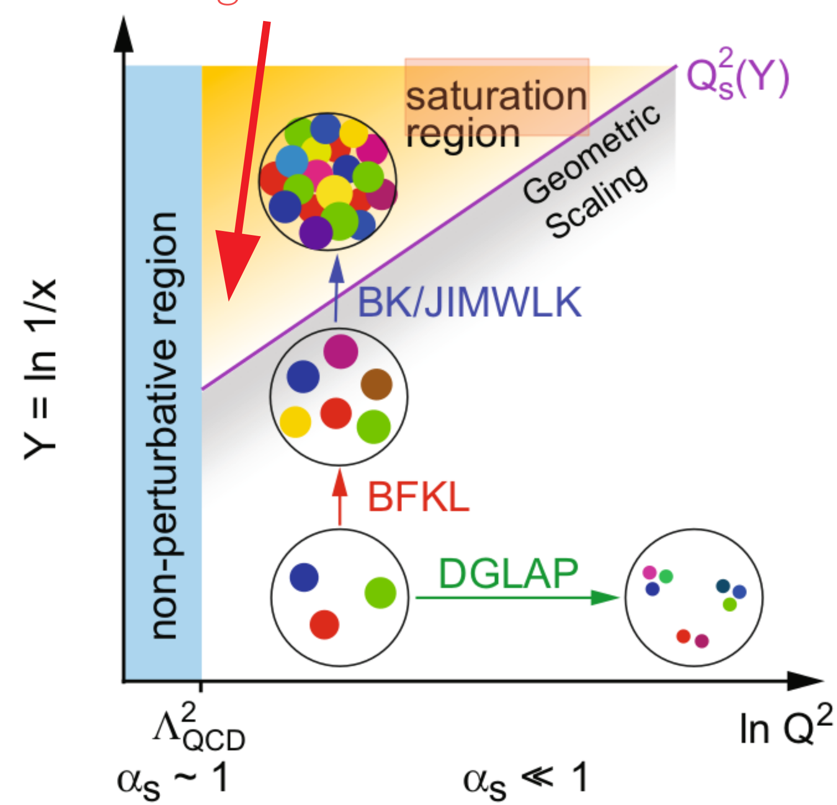

BUT

- while under better control at intermediate $x$, the collinear gluon PDF is poorly known toward the distribution endpoints, *i.e.*, $g(x,\mu)$ for $x \to 0,\, 1$

Rojo et al., J. Phys. G**42**, 103103 (2015).




can we begin to observe this transition?



# a brief statistical aside, i

- **the CTEQ-TEA global analysis relies on the Hessian formalism for its error treatment**

$$\chi^2_E(\vec{a}) = \sum_{i=1}^{N_{pt}} r_i^2(\vec{a}) + \sum_{\alpha=1}^{N_\lambda} \overline{\lambda}_\alpha^2(\vec{a})$$

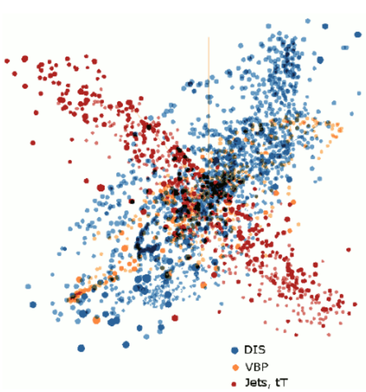
nuisance parameters to handle correlated errors

$$r_i(\vec{a}) = \frac{1}{s_i}\left(T_i(\vec{a}) - D_{i,sh}(\vec{a})\right)$$

these result in systematic shifts to data central values:

$$D_i \to D_{i,sh}(\vec{a}) = D_i - \sum_{\alpha=1}^{N_\lambda} \beta_{i\alpha}\overline{\lambda}_\alpha(\vec{a})$$

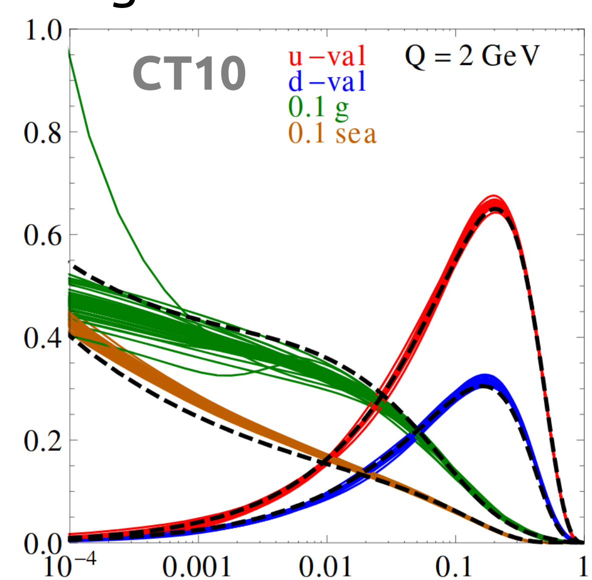
- a 56-dimensional parametric basis $\vec{a}$ is obtained by diagonalizing the Hessian matrix H determined from $\chi^2$ **(following a 28-parameter fit)**




**use this basis to compute 56-component "normalized" residuals :**

$$\delta^{\pm}_{i,l} \equiv \left(r_i(\vec{a}_l^{\pm}) - r_i(\vec{a}_0)\right) / \langle r_0 \rangle_E$$

where $\langle r_0 \rangle_E \equiv \sqrt{\dfrac{1}{N_{pt}} \sum_{i=1}^{N_{pt}} r_i^2(\vec{a}_0)}$

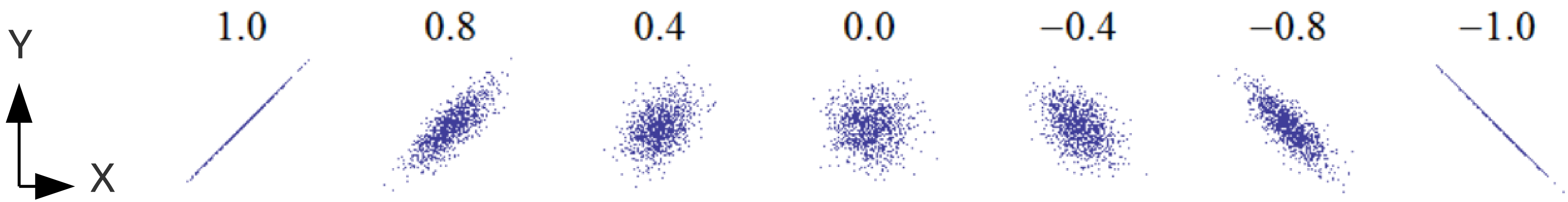


# a brief statistical aside, ii

- **... but how does the behavior of these residuals relate to the fitted PDFs and their uncertainties?**

for example, how does the PDF uncertainty (at specific $x$, μ) correlate with the residual associated with a theoretical prediction at the same $x$, μ?

**examine the Pearson correlation over the 56-member PDF error set between a PDF of given flavor and the residual**



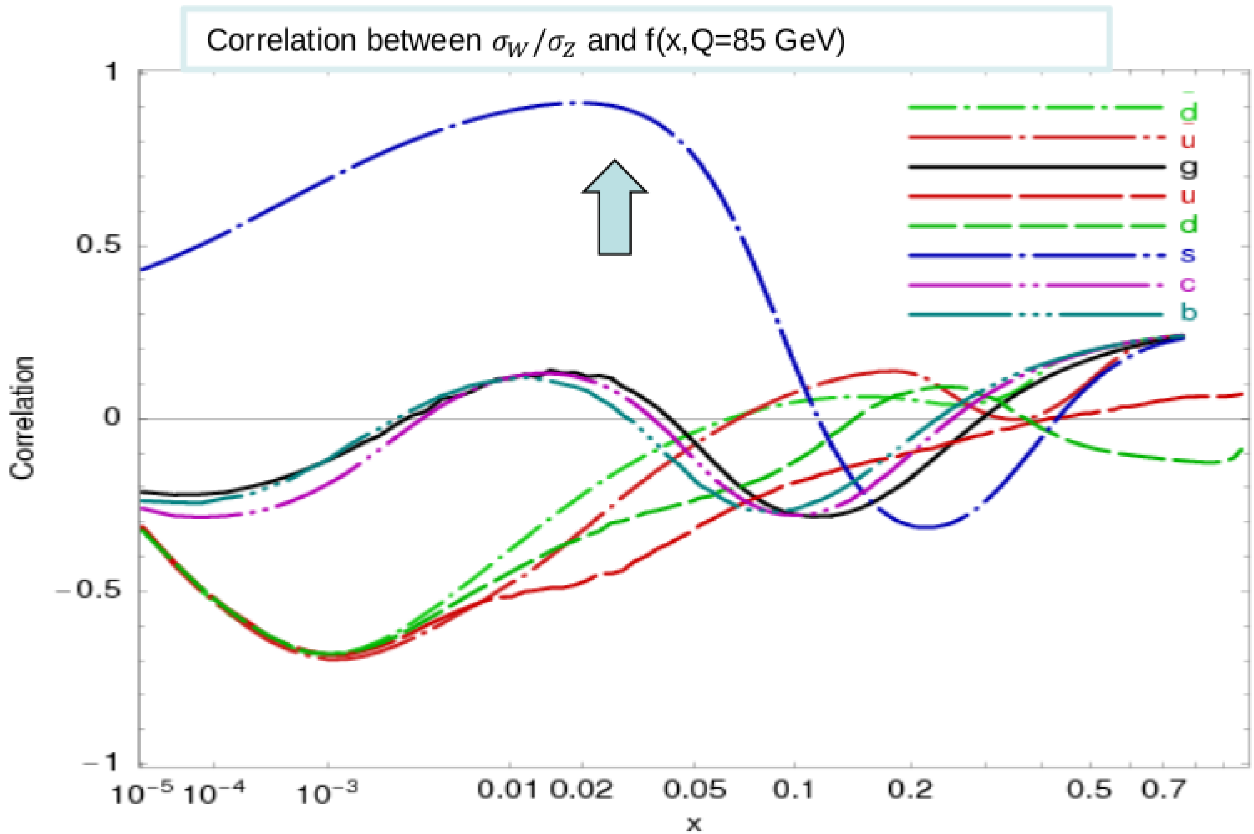

[X,Y] are exactly (anti-)correlated at the far (right) left above.

- we may then evaluate correlations between arbitrary PDF-derived quantities over the ensemble of error sets ([X,Y] may be PDFs, cross sections, residuals,... ):

$$\mathrm{Corr}[X,Y] = \frac{1}{4\Delta X \Delta Y}\sum_{j=1}^{N}(X_j^+ - X_j^-)(Y_j^+ - Y_j^-) \qquad \Delta X = \frac{1}{2}\sqrt{\sum_{j=1}^{N}(X_j^+ - X_j^-)^2}$$

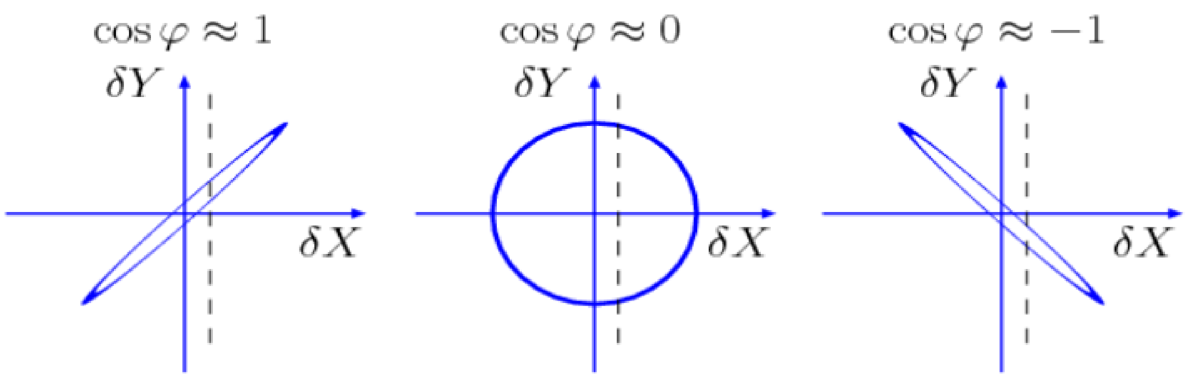
...we may turn to the Pearson correlations between PDFs and $\delta_i$, but we first note

# Correlations carry useful, but limited information




**CTEQ6.6 [arXiv:0802.0007]:**
$\cos\varphi > 0.7$ shows that the ratio $\sigma_W/\sigma_Z$ at the LHC must be sensitive to the strange PDF $s(x,Q)$

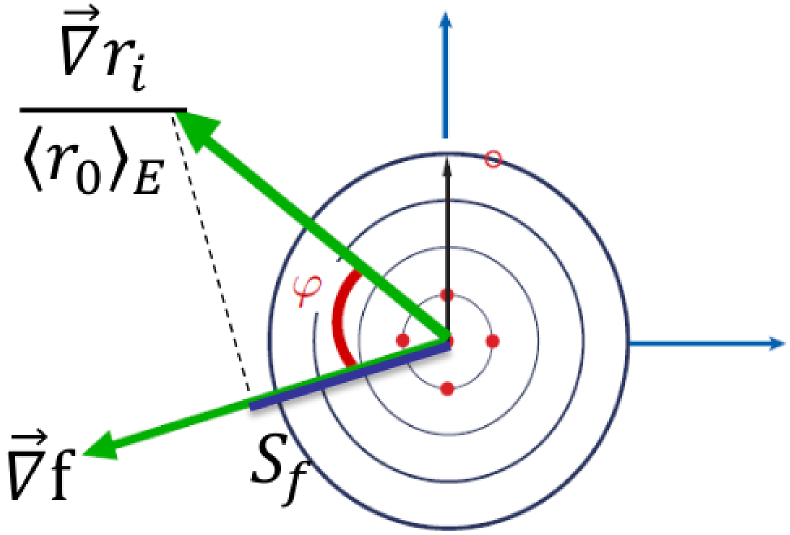
$\cos\varphi \approx \pm 1$ suggests that a measurement of $X$ **may** impose tight constraints on $Y$




But, Corr[X,Y] between **theory** cross sections $X$ and $Y$ does not tell us about **experimental** uncertainties

# Correlation $C_f$ and sensitivity $S_f$

The relation of data point $i$ on the PDF dependence of $f$ can be estimated by:




- $C_f \equiv \mathrm{Corr}[\rho_i(\vec{a})), f(\vec{a})] = cos\varphi$

$\vec{\rho}_i \equiv \vec{\nabla} r_i / \langle r_0 \rangle_E$ -- gradient of $r_i$ normalized to the r.m.s. average residual in expt E;

$$\left(\vec{\nabla} r_i\right)_k = \left(r_i(\vec{a}_k^+) - r_i(\vec{a}_k^-)\right)/2$$

$$\mathrm{Corr}[X,Y] = \frac{1}{4\Delta X \Delta Y} \sum_{j=1}^{N} (X_j^+ - X_j^-)(Y_j^+ - Y_j^-)$$

$C_f$ is **independent** of the experimental and PDF uncertainties. In the figures, take $|C_f| \gtrsim 0.7$ to indicate a large correlation.

- $S_f \equiv |\vec{\rho}_i| cos\varphi = C_f \frac{\Delta r_i}{\langle r_0 \rangle_E}$ -- projection of $\vec{\rho}_i(\vec{a})$ on $\vec{\nabla} f$

$S_f$ is proportional to $\cos\varphi$ and the ratio of the PDF uncertainty to the experimental uncertainty. We can sum $|S_f|$.

In the figures, take $|S_f| > 0.25$ to be significant.

# $2^{nd}$ aside: **kinematical matchings**

- residual-PDF correlations and sensitivities are evaluated at parton-level kinematics determined according to leading-order matchings with physical scales in measurements

$x_i$ : parton mom. fraction

$\mu_i$ : factorization scale

deeply-inelastic scattering:

$$\mu_i \approx Q\big|_i \,, \;\; x_i \approx x_B\big|_i$$

hadron-hadron collisions:

$AB \to CX$

$$\mu_i \approx Q\big|_i \,, \;\; x_i^{\pm} \approx \frac{Q}{\sqrt{s}} \exp(\pm y_C)\Big|_i$$

single-inclusive jet production: $Q = 2p_{Tj}, \;\; y_C = y_j$

$t\bar{t}$ pair production: $Q = m_{t\bar{t}}, \;\; y_C = y_{t\bar{t}}$

etc...

$d\sigma/dp_T^Z$ measurements: $Q = \sqrt{(p_T^Z)^2 + (M_Z)^2}, \;\; y_C = y_Z$