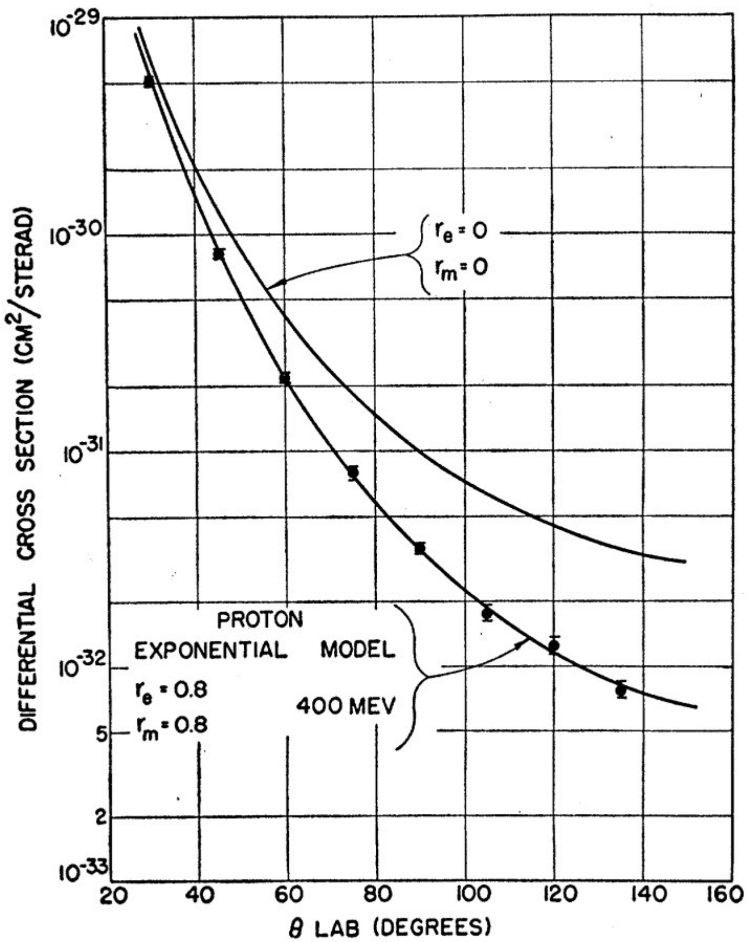
hadrons' collinear structure and the future EIC program

T.J. Hobbs

~1956

Hofstadter, RMP**28** (1956) no.3, 214.

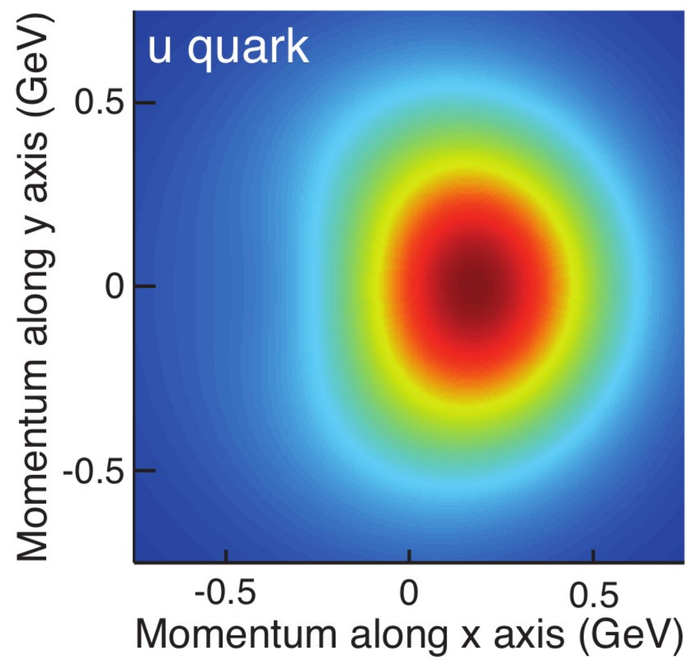


May 15th 2019

JLab Theory Center 'Cake Seminar'

~2020s

Accardi et al., EPJA**52** (2016) no.9, 268.



EIC Center@JLab **and** CTEQ@SMU

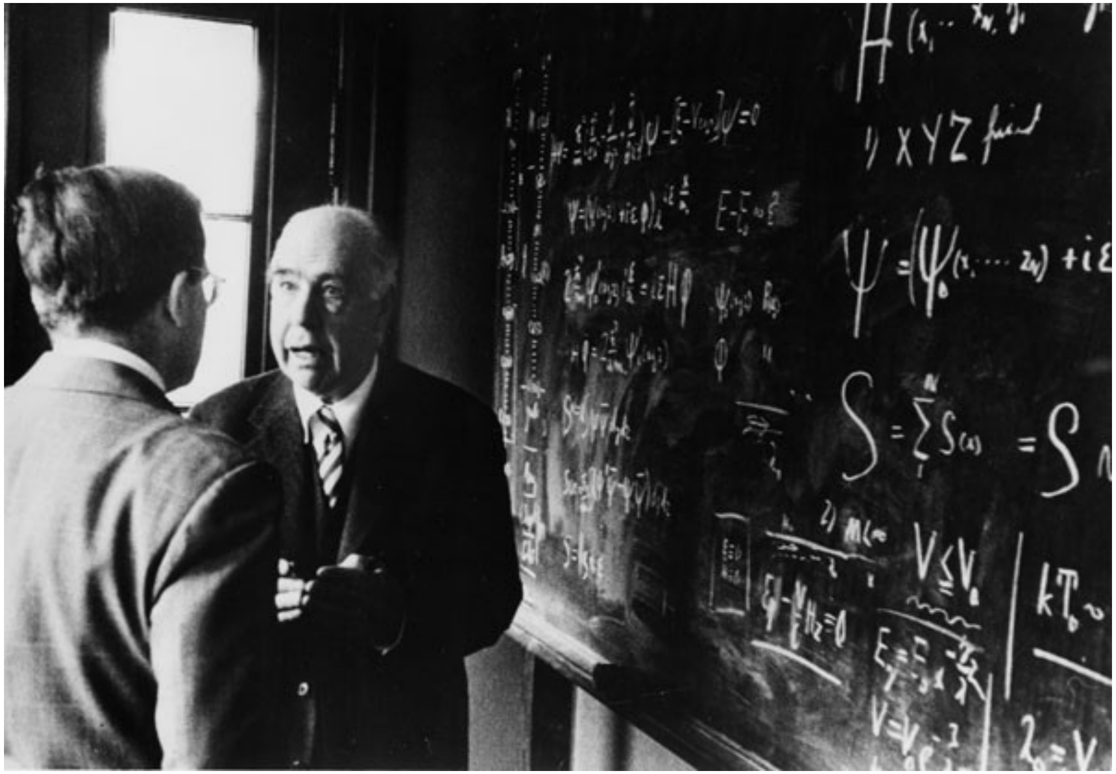
C T E Q

EIC²
EIC Center at Jefferson Lab

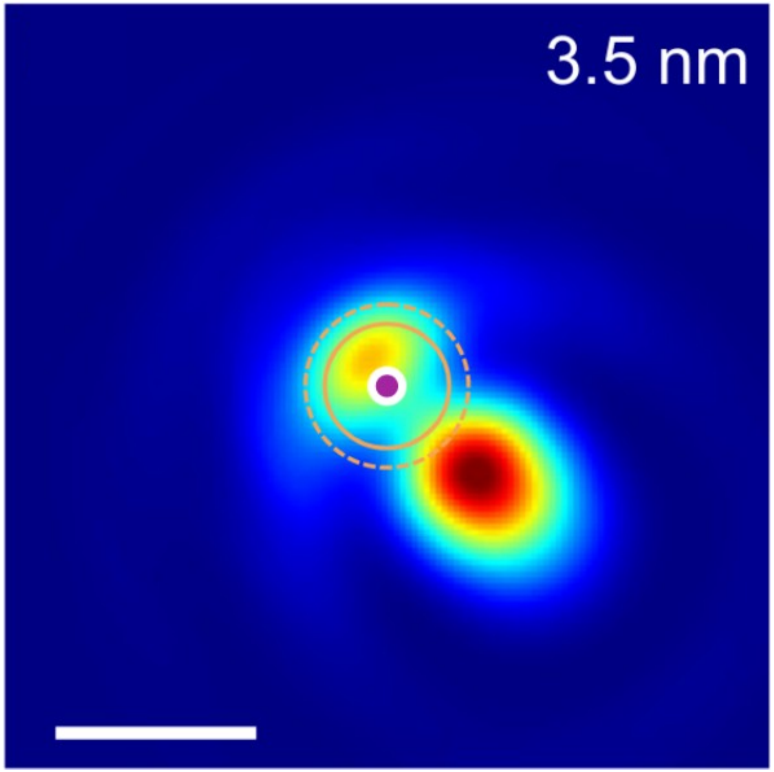
proton structure is increasingly becoming a precision field

- the present moment is in some ways reminiscent of progress made in atomic structure in the 20th Century:

Jeong et al., PRB93, 165140 (2016).



Niels with Aage at LANL.



Sr STEM simulated image

- much as the electronic structure of atomic matter has been mapped to high precision, we are entering an era of '**hadron tomography**'

… this is enshrined in the *2015 Nuclear Science Advisory Committee LRP*

→ AND motivation for JLab12, **EIC**, LHeC, collider data analyses

- lattice QCD calculations continue to improve and will be increasingly useful as inputs into QCD global analyses

PDF-Lattice whitepaper – Lin et al., PPNP100, 107 (2018); arXiv:1711.07916.

- the PDF-Lattice relationship will be *synergistic* :

→ PDF phenomenologists deliver improving benchmarks to challenge the Lattice

$\updownarrow$

→ Lattice calculations for PDF Mellin **moments** and **quasi-PDFs** can be theoretical priors for QCD global fits

PDFSense analysis – Hobbs, Wang, Nadolsky and Olness, arXiv:1904.00022.

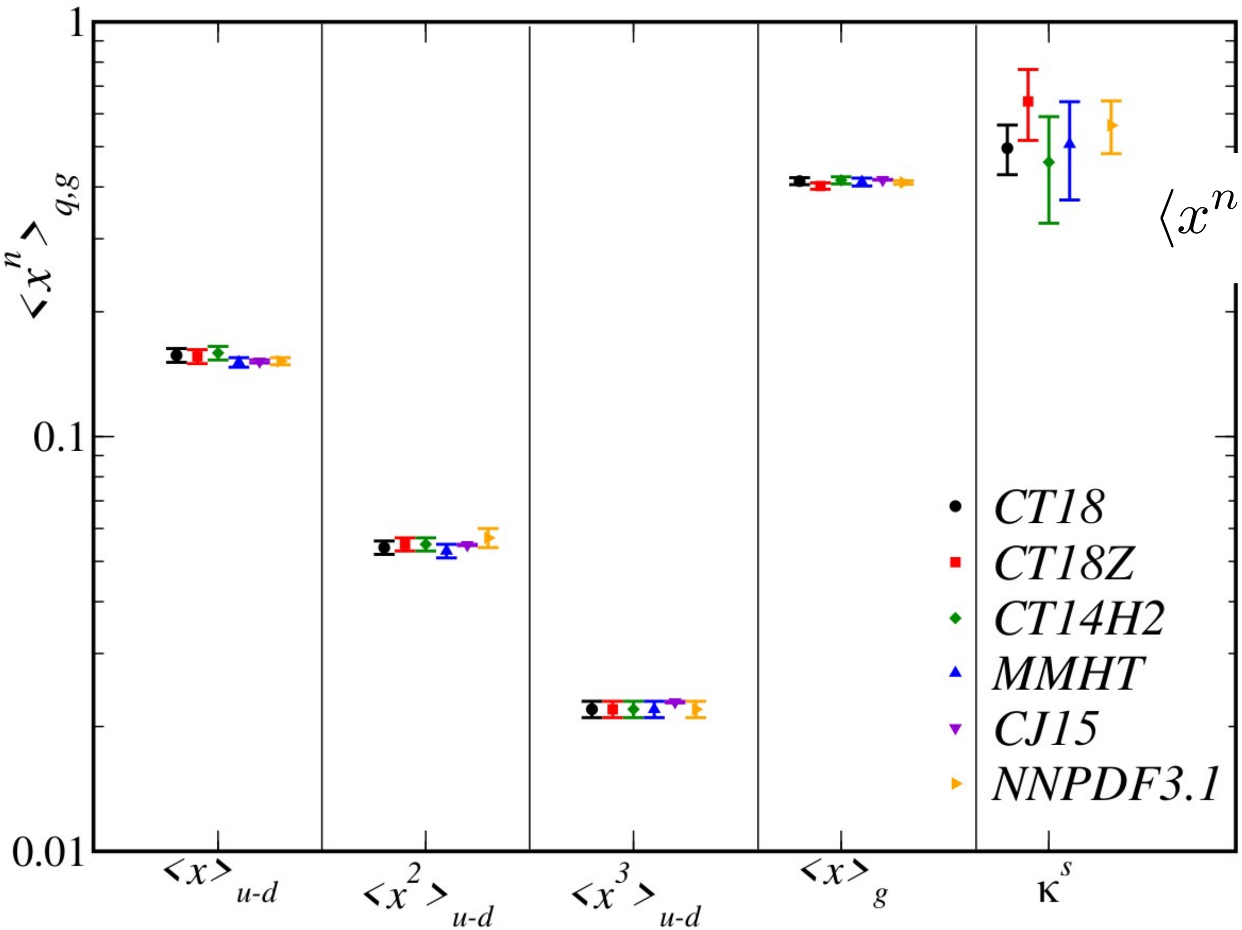
- moments from lattice can help unravel PDF flavor dependence, constrain phenom. PDFs:

(i) $$\langle x^n \rangle_q = \int_0^1 dx\ x^n \left[q(x) + (-1)^{n+1}\, \overline{q}(x)\right] \ \rightarrow \langle x^{1,3,\dots} \rangle_{q^+},\ \langle x^{2,4,\dots} \rangle_{q^-}$$

$$\mu_F = \mu^{\mathrm{lat.}} = 2\,\mathrm{GeV}$$

- lattice can also now compute x-dependent quantities – the quasi-PDFs (qPDFs):

(ii) $$\widetilde{q}(x, P_z, \widetilde{\mu}) = \int_{-\infty}^{\infty} \frac{dz}{4\pi} e^{ixP_z z} \langle P | \overline{\psi}(z) \gamma^z U(z,0) \psi(0) | P \rangle$$



PDF moments from CT18

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

- progress in lattice QCD is compelling PDF phenomenologists to sharpen their benchmarks – especially for lower moments of light quarks

➡ good agreement among phenom. predictions of isovector, gluon moments!

(...can discuss more in Q&A)

➡ constraints are significantly weaker for moments of the light quark sea distributions, *e.g.*, the strangeness suppression ratio, $\kappa^s \equiv \langle x \rangle_{s+\bar{s}} / \langle x \rangle_{\bar{u}+\bar{d}}$

preliminary
CT results

PDF moment	**CT18**	**CT18Z**	**CT14H2**
$\langle x \rangle_{u^+ - d^+}$	0.157(6)	0.156(6)	0.159(6)
$\langle x^2 \rangle_{u^- - d^-}$	0.054(2)	0.055(2)	0.055(2)
$\langle x^3 \rangle_{u^+ - d^+}$	0.022(1)	0.022(1)	0.022(1)
$\langle x \rangle_g$	0.413(8)	0.402(7)	0.415(8)
κ^s	0.496(68)	0.643(125)	0.459(132)

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

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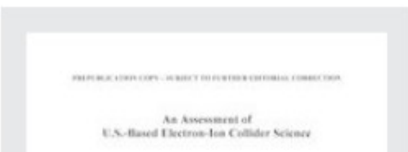
This PDF is available at http://nap.edu/25171

SHARE

- FY2020 proposed budget ➞ CD-0 by October 2019
- 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**

the capabilities that will allow EIC to address questions in QCD will also drive improvements in HEP

- EIC is a **very high luminosity** “femtoscope” – larger compared to HERA luminosities by a factor of $10^2 - 10^3$

- reach in center-of-mass energy, $10 \leq \sqrt{s} \leq \underline{100\,\mathrm{GeV}}$

  → upgradeable to $\sqrt{s} \leq \underline{140\,\mathrm{GeV}}$

- beam polarization of at least ~70% for e^-, p, light A

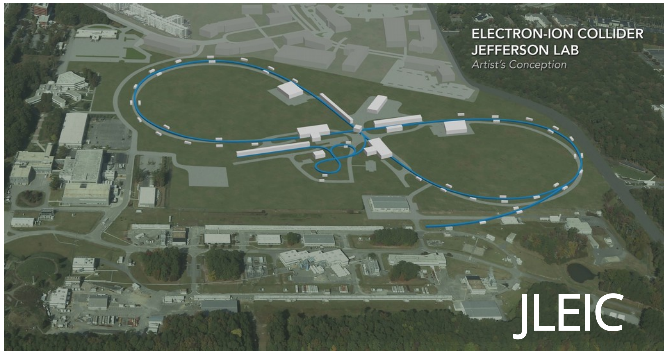
- as a generic scenario, we consider here the simulated impact of a machine with: $10\,\mathrm{GeV}\; e^{\pm}$ on $250\,\mathrm{GeV}\; p \quad (\sqrt{s} = 100\,\mathrm{GeV})$

~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

→ EIC will map the few GeV **quark-hadron transition** region

→ 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**)



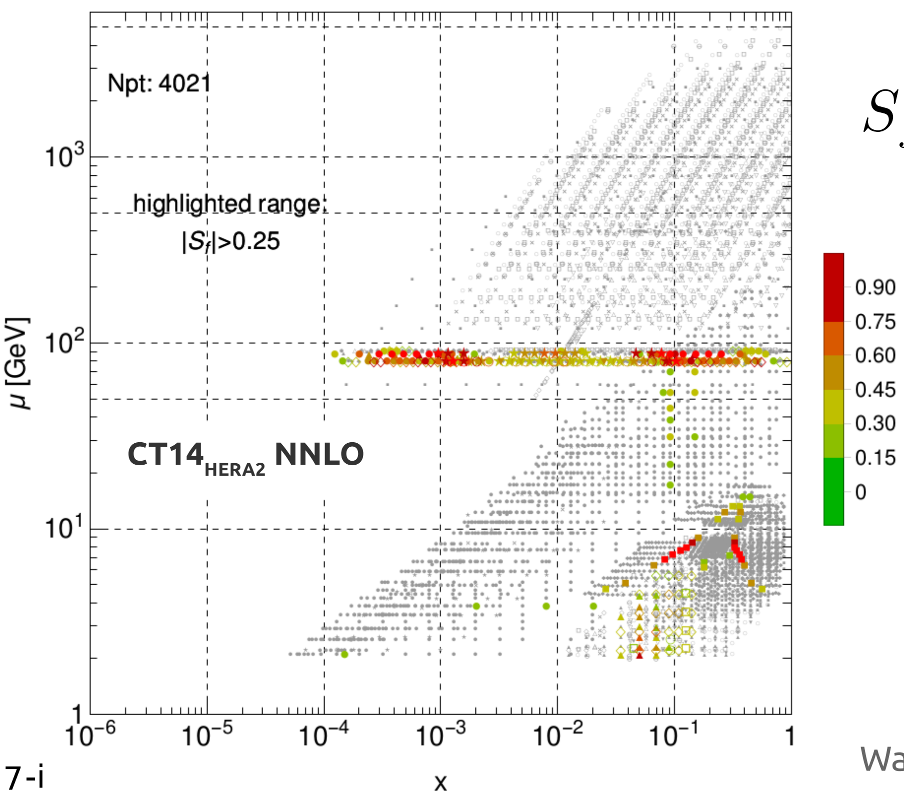
assessing/anticipating empirical constraints with PDFSense

- a QCD analysis produces an **ensemble of error PDFs** over which we may evaluate the fit quality (residual), and quantities derived from the PDF (e.g., the moments),

$$q^{j\in\{2N\}}(x,\mu^{\rm lat}) \;\longrightarrow\; \langle x^n\rangle^{j\in\{2N\}}_{q^\pm,\,\mu^{\rm lat}} = \int_0^1 dx\, x^n \left(q(x,\mu^{\rm lat}) \pm \overline{q}(x,\mu^{\rm lat})\right)_{j\in\{2N\}}$$

- define a generalized correlation – the **sensitivity** – as a statistical metric for the impact of the $i^{\rm th}$ datum to a PDF or PDF-derived quantity:

| S_f | for $\langle 1\rangle_{u^+-d^+}$



functional of the PDFs, $\langle x^n\rangle_{q^\pm,\mu^{\rm lat}}$

$$S_f = \frac{\Delta r_i}{\langle r_0\rangle_E}\,\mathrm{Corr}[\mathcal{F}\{q\}, r_i(x_i,\mu_i)]$$

the residual, $r_i = \dfrac{1}{s_i}\left(T_i - D_i^{sh}\right)$

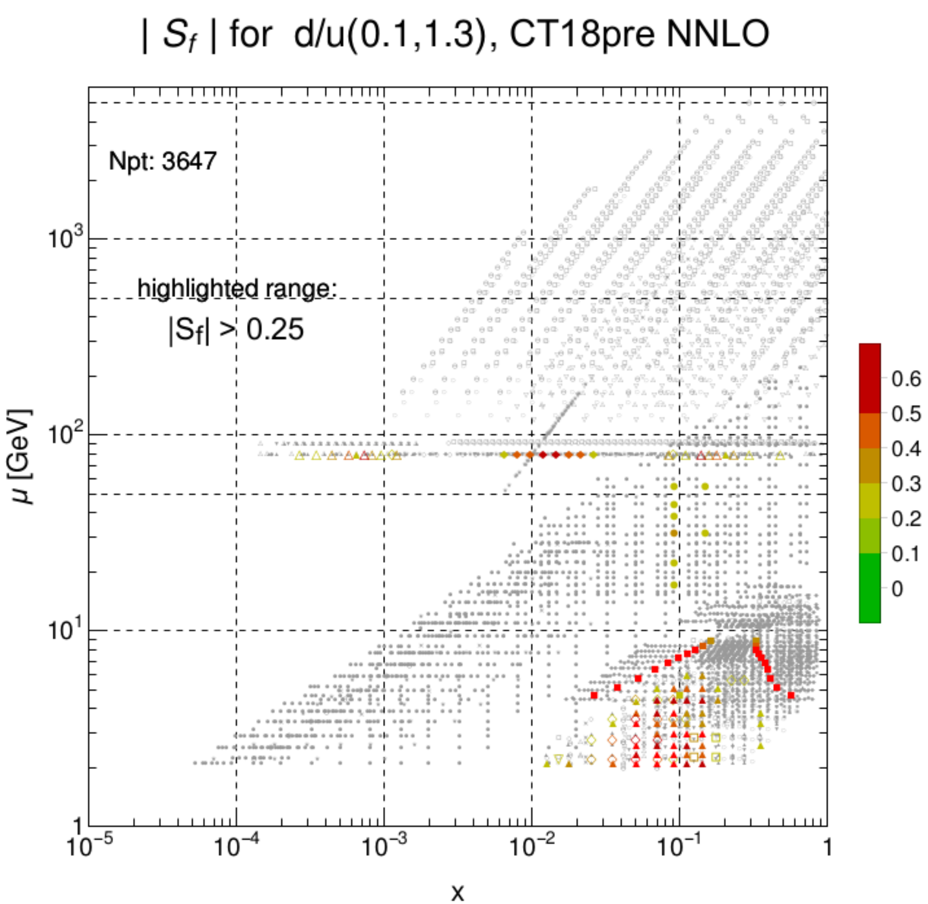
developed to quickly identify high-impact data in lieu of a full global analysis

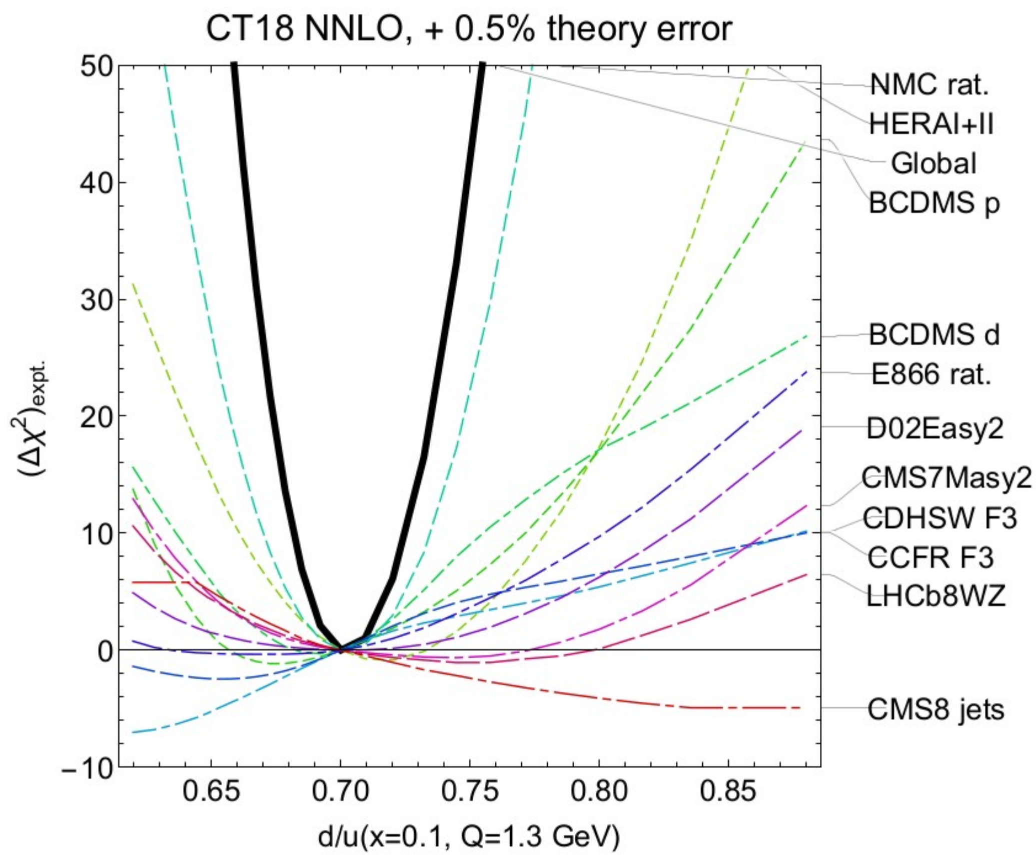
➡ allows kinematic **mapping** of PDF constraints

➡ avoids various ambiguities involved in fitting

Wang, TJH, Doyle, Gao, Hou, Nadolsky, Olness, PRD**98**, 094030 (2018).

PDFSense predictions can be validated against actual fits





- PDFSense successfully predicts the highest impact data sets *before* fitting, as shown in this illustration for the large x PDF ratio d/u

- Lagrange Multiplier scans provide an independent test of which datasets most drive the global fit in connection with specific PDFs

HERA and fixed-target (BCDMS, NMC) data are dominant!

Higgs production is now dominated by PDF and α_s uncertainties

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

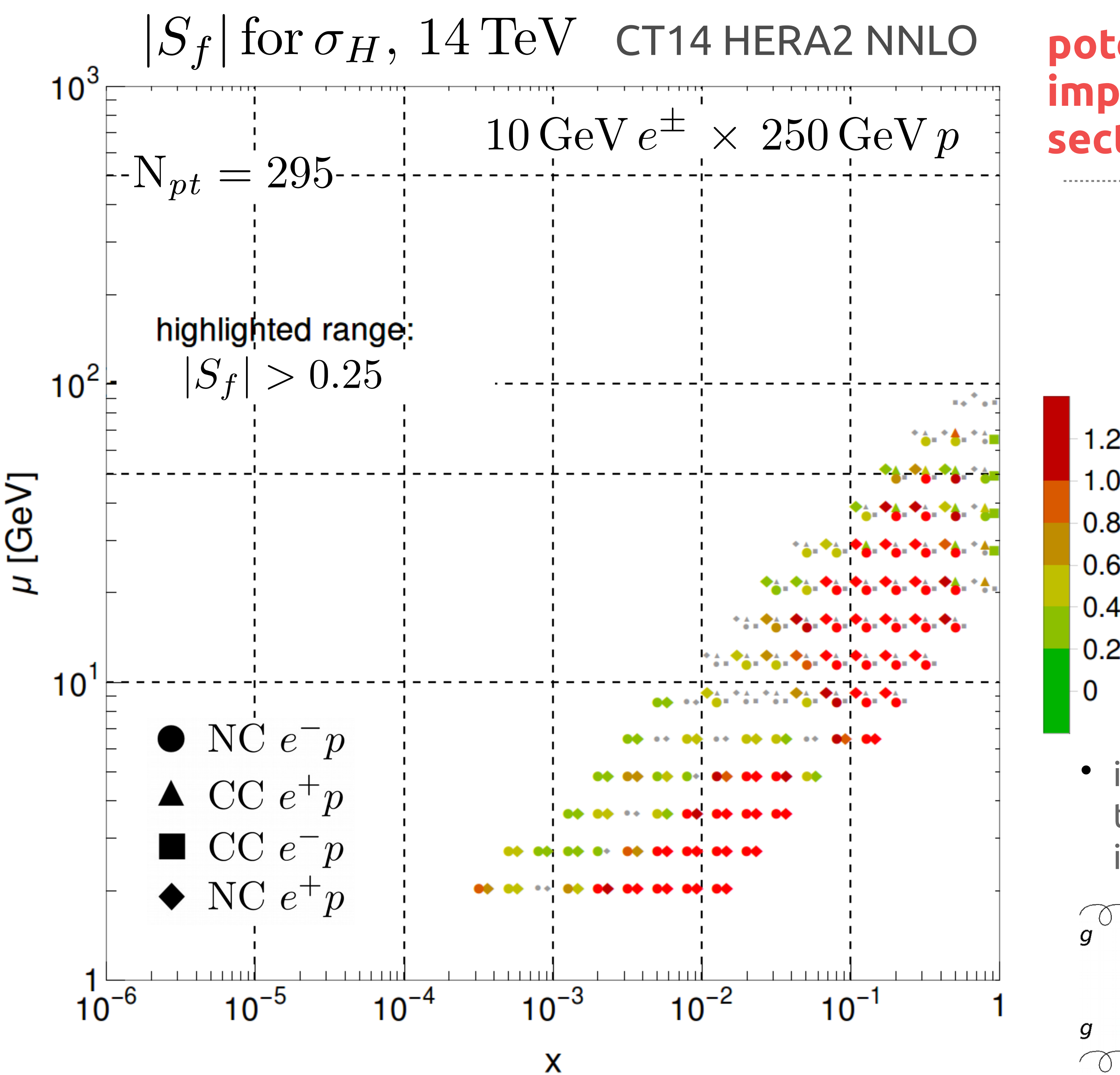
→ the situation is such that precision in Higgs phenom. is significantly **PDF-limited**

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

PDF sets	$\sigma(H)^{\rm NNLO}$ (pb) nominal $\alpha_s(M_Z)$	$\sigma(H)^{\rm NNLO}$ (pb) $\alpha_s(M_Z) = 0.115$	$\sigma(H)^{\rm NNLO}$ (pb) $\alpha_s(M_Z) = 0.118$
ABM12 [2]	39.80 ± 0.84	41.62 ± 0.46	44.70 ± 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 ± 0.34	39.34 ± 0.22	42.25 ± 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 ± 0.80	39.65 ± 0.74 (40.74 ± 0.88)	42.59 ± 0.80
PDF4LHC15 [8]	42.42 ± 0.78	39.49 ± 0.73	42.42 ± 0.78

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

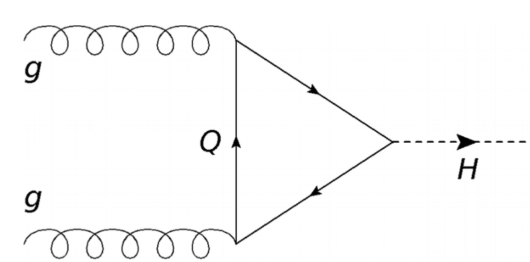
→ enhancing the discovery potential in the Higgs sector will require improving these uncertainties!



potentially strong 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:



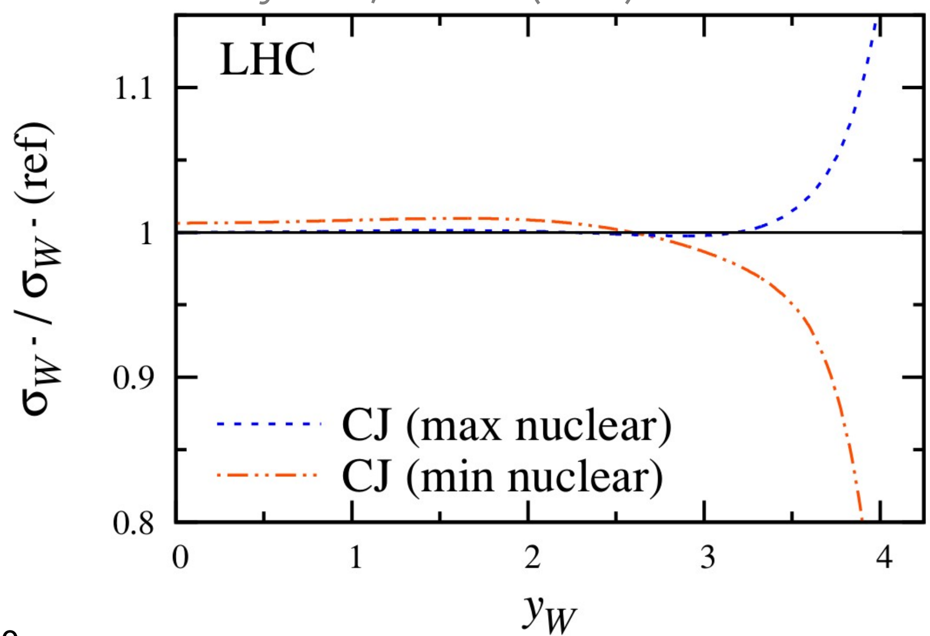
EIC and an era of (higher) precision **electroweak physics** (?)

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

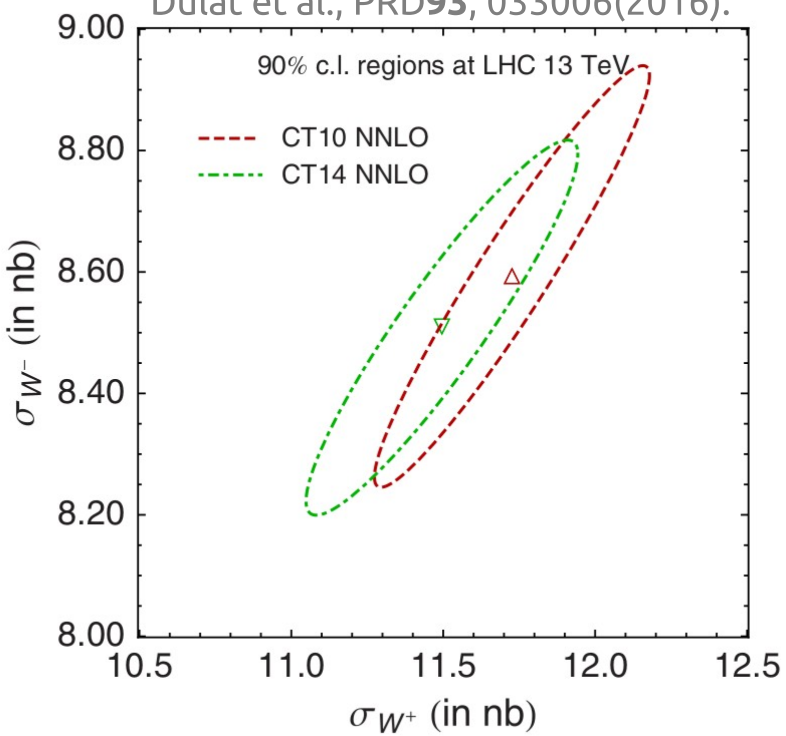
$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

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

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



Dulat et al., PRD**93**, 033006(2016).



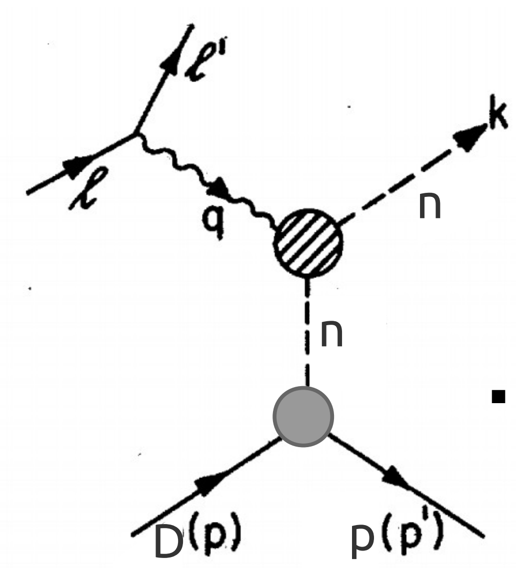
historically, extractions of $d(x),\ x \to 1$ have depended on nuclear targets (and corrections!)

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

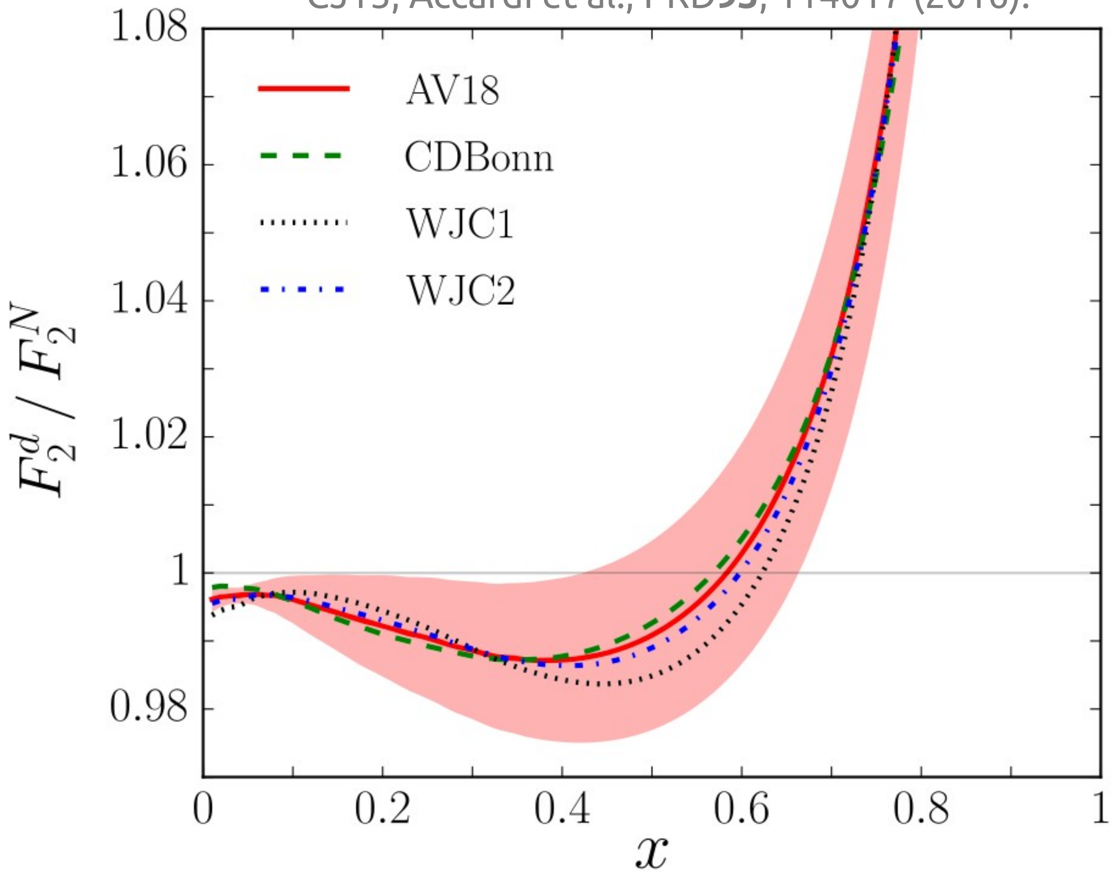
$$F_2^{e^- n} \sim x(4d + u)/9$$

vs

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



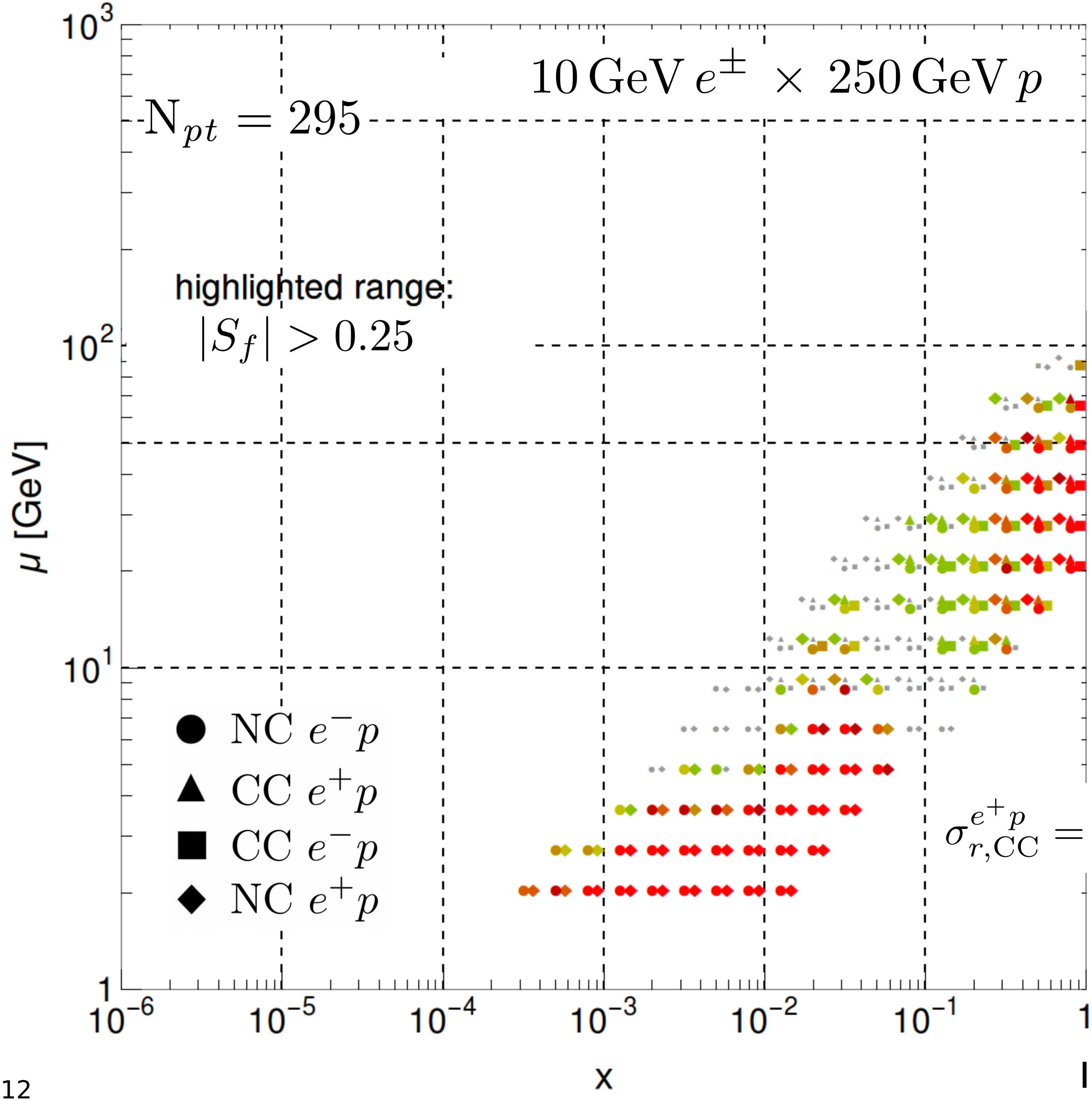
CJ15, Accardi et al., PRD**93**, 114017 (2016).

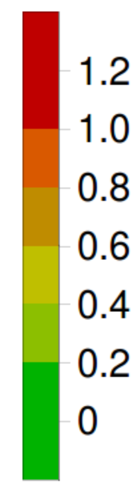


- **BUT**: in the absence of a free neutron target, scattering from nuclei (e.g., the deuteron) is necessary

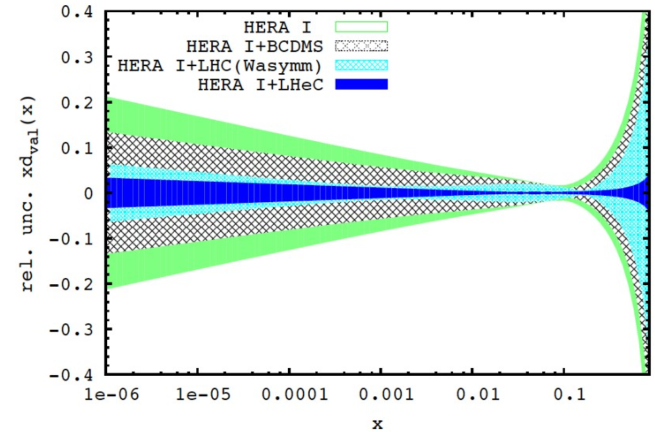
→ **nuclear corrections (Fermi motion) are sizable, especially for large x**

$|S_f|$ for $d(x,\mu)$ CT14 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 $x \to 1$

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

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

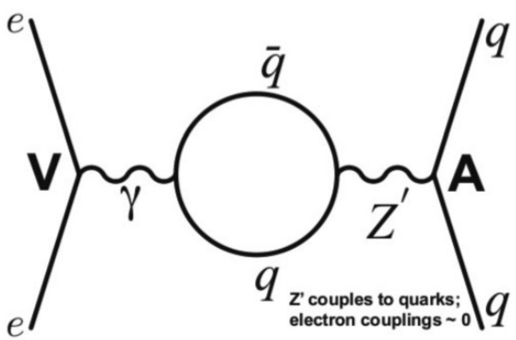
In the **LO quark-parton model**

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).

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

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

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

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

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

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

→ 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!

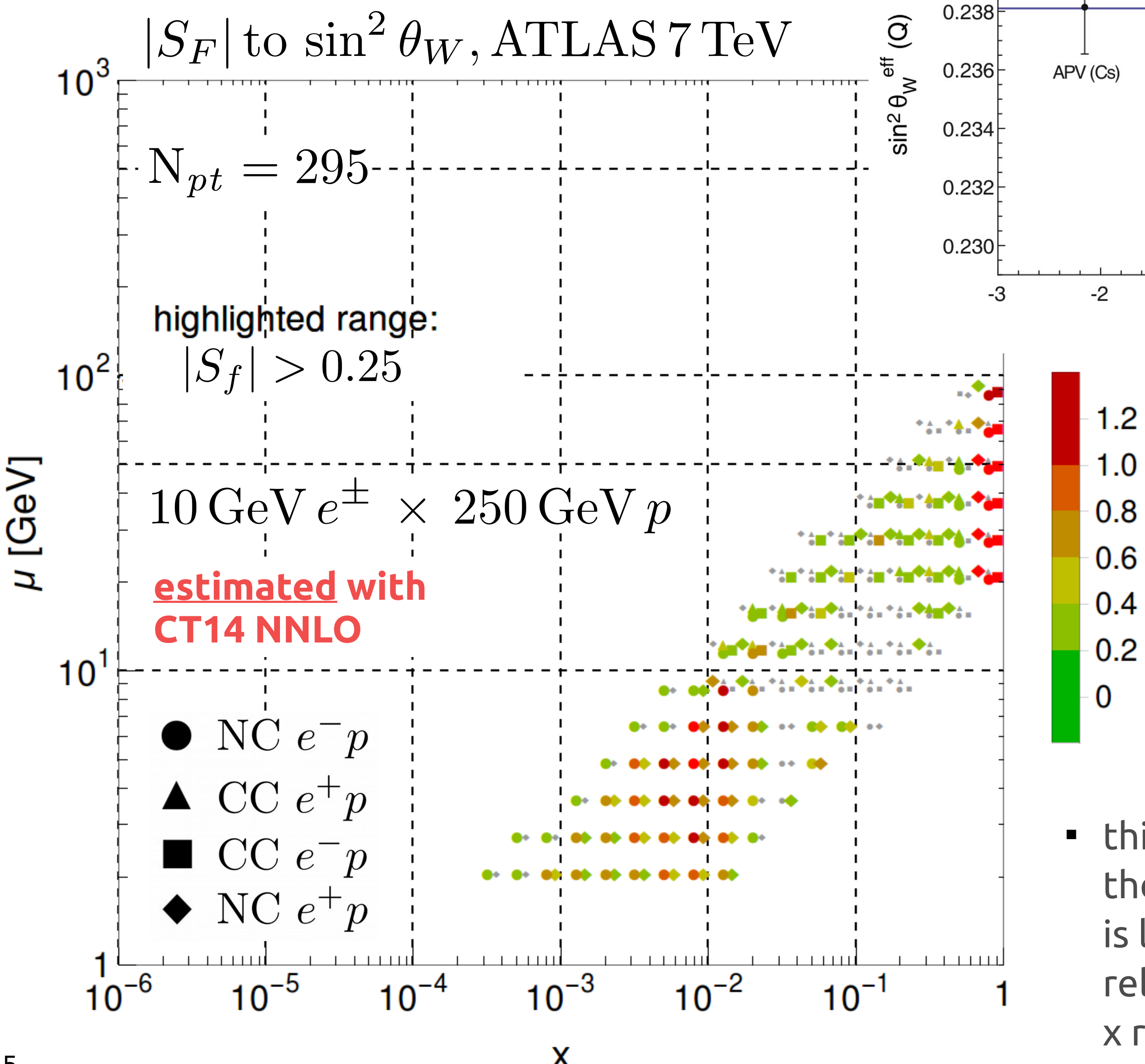
TJH and Melnitchouk, PRD**77**, 114023 (2008).

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

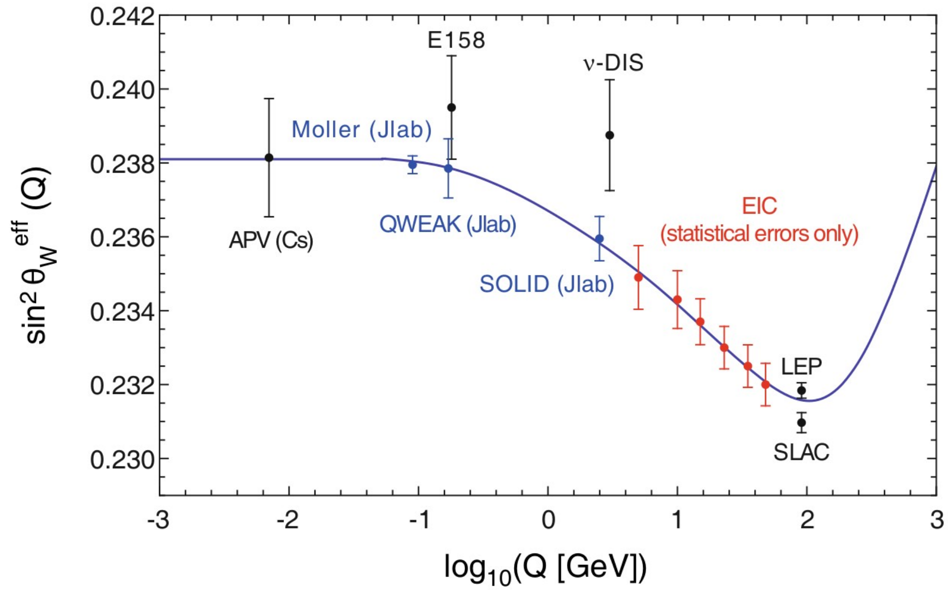
N.B.: extractions are dependent upon knowledge of the PDFs

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

an EIC will probe EW parameters and New Physics!



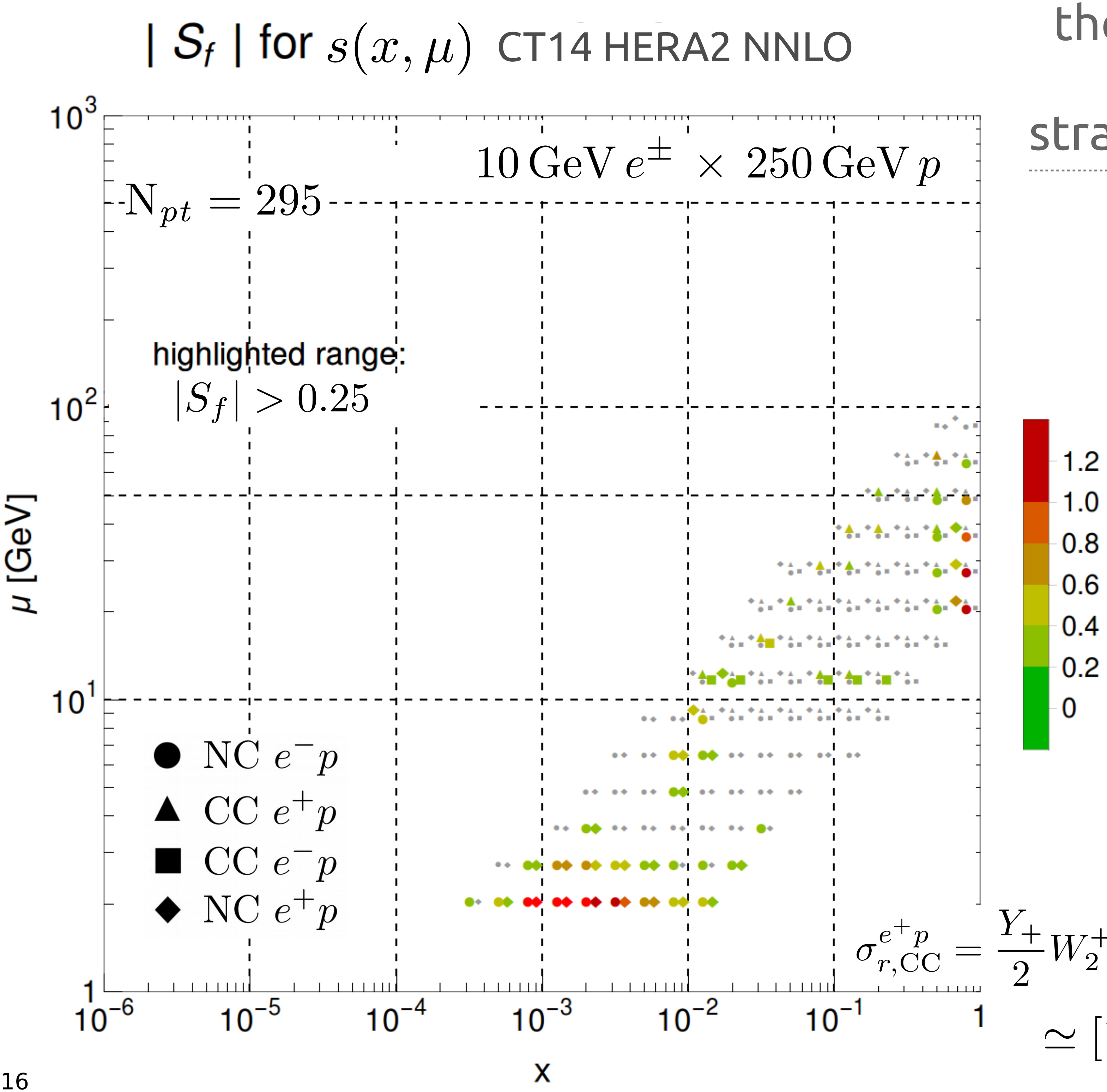
Accardi et al., EPJA**52**, 268 (2016).



- 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 $0.2 \lesssim x \lesssim 0.5$

the challenge of measuring strangeness at EIC



- while inclusive DIS cross sections have some sensitivity, charge-current **systematics** limitations (here, assumed ~5%) must be overcome

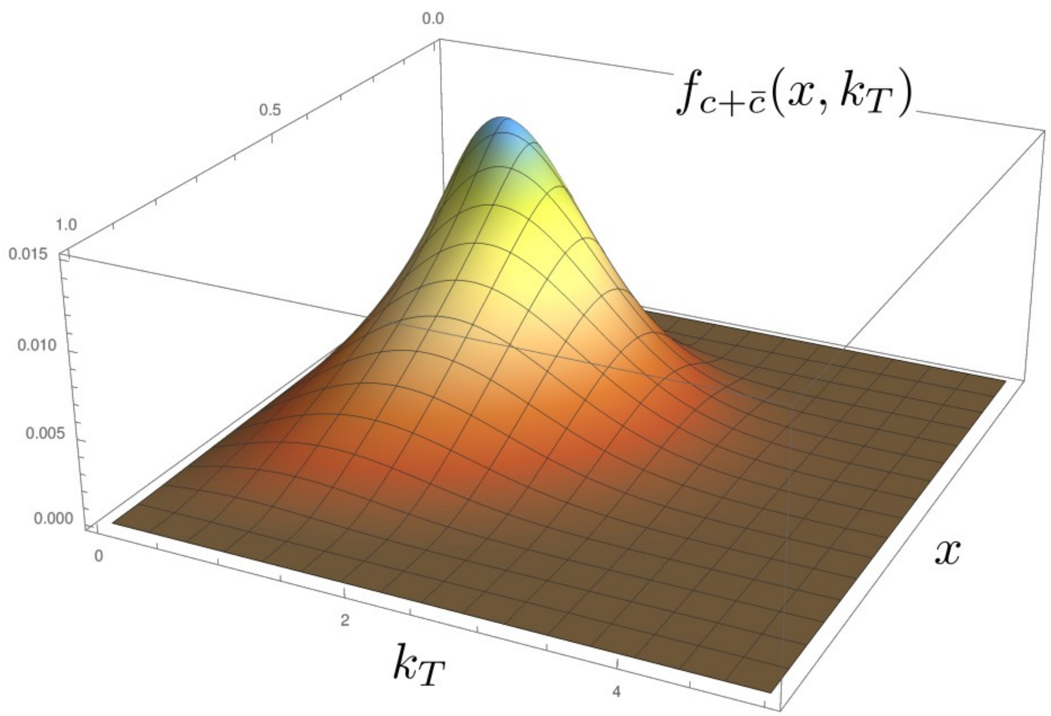
- **communication** among other processes will be crucial: e.g., SIDIS, final-state flavor tagging (W+c), ...

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

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

tomography probes the nucleon wave function

…the result will be important connections among nucleon observables (with HEP implications)



case studies:

i) nonperturbative charm

ii) nucleon strangeness

…flavor structure of the nucleon sea

iii) axial charge structure; neutrino phenom. (if time allows.)

nucleon strange/charm remain **very open** topics

- in spite of extensive effort and significant progess in recent years, ambiguities remain in both the magnitude and properties of the strange & charm components of the nucleon.

- the strangeness magnitude comparatively better constrained, $\langle x \rangle_{s\bar{s}} \sim 2\%$

  → **detailed x dependence remains uncertain, despite succession of historical improvements:**

increasing sensitivity to flavor asymmetries in the light quark sea

$$s(x) = \bar{s}(x) = \bar{u}(x) = \bar{d}(x)$$

$$s(x) = \bar{s}(x) \neq \bar{u}(x),\ \bar{d}(x)$$

$$s(x) \overset{?}{\neq} \bar{s}(x)$$

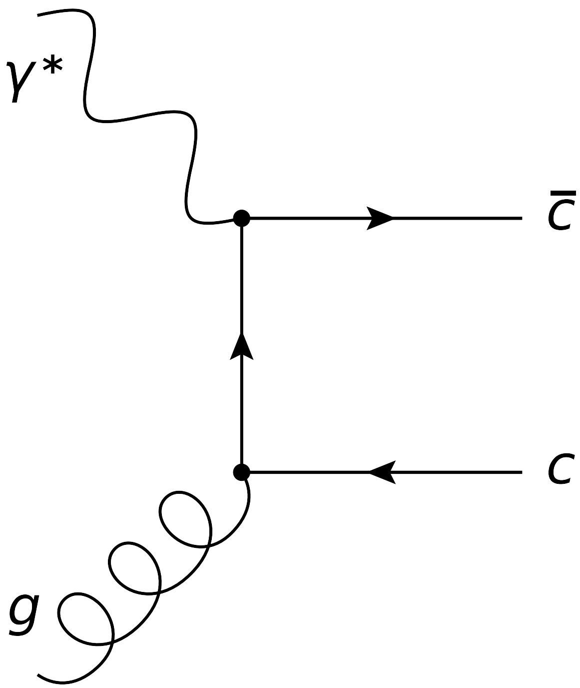
- there is much less clarity regarding the nucleon's charm content

  → in general, only upper limits to $\langle x \rangle_{c\bar{c}}$

  → very little agreement on the shape of the intrinsic "fitted dists.

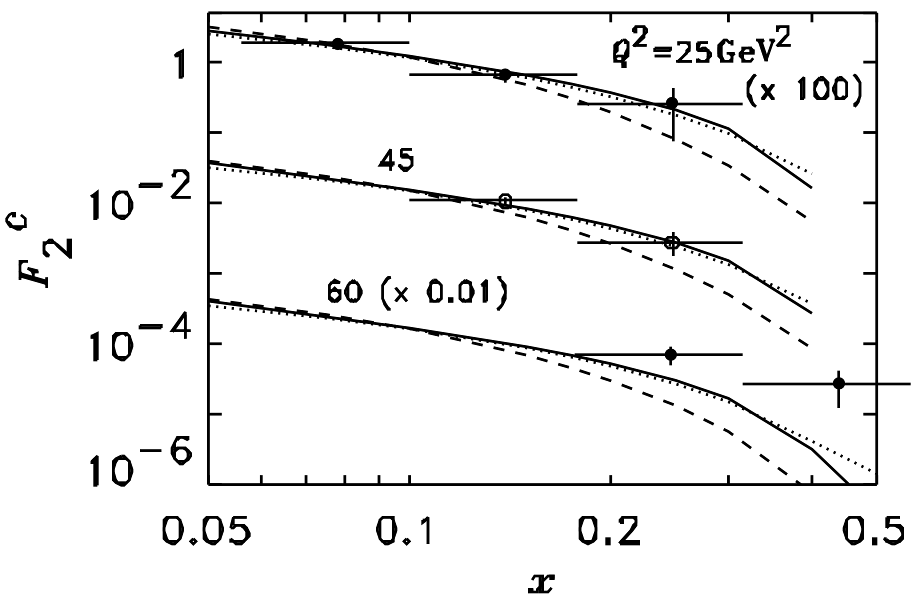
charm in *perturbative* **QCD** (pQCD)

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



$\rightarrow$

F. M. Steffens, W. Melnitchouk and A. W. Thomas, Eur. Phys. J. C **11**, 673 (1999) [hep-ph/9903441].



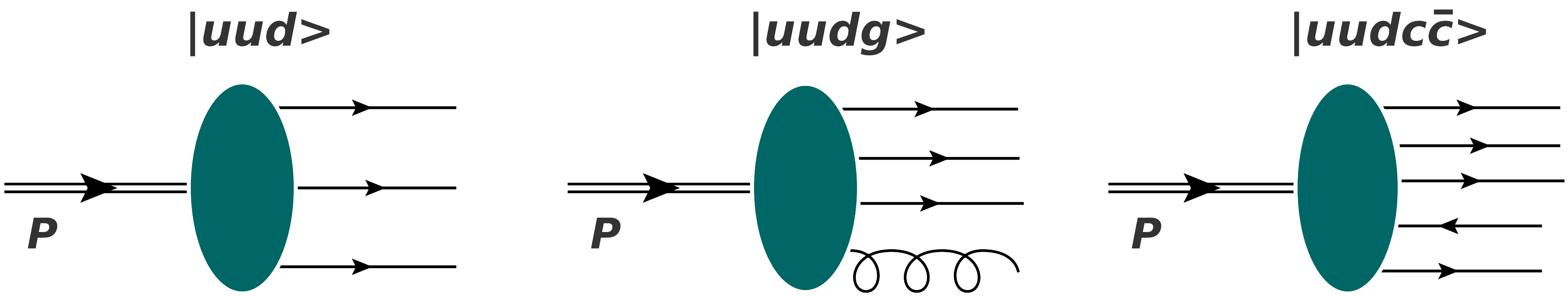
- *intermediate* Q^2:

$$F^c_{2,\ \mathrm{PGF}}(x, Q^2) \ = \ \frac{\alpha_s(\mu^2)}{9\pi} \ \int_x^{z'} \ \frac{dz}{z} \ C^{\mathrm{PGF}}(z, Q^2, m_c^2) \cdot xg\left(\frac{x}{z}, \mu^2\right)$$

- *high* Q^2:

massless **DGLAP** (i.e., *variable flavor-number* schemes)

simplest *nonperturbative* **model** calculations



$\rightarrow$ original models possessed *scalar* vertices...

- Brodsky et al. (1980):

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

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

- Blümlein (2015):

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

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

constraints from **global** fits...

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

26 sets:

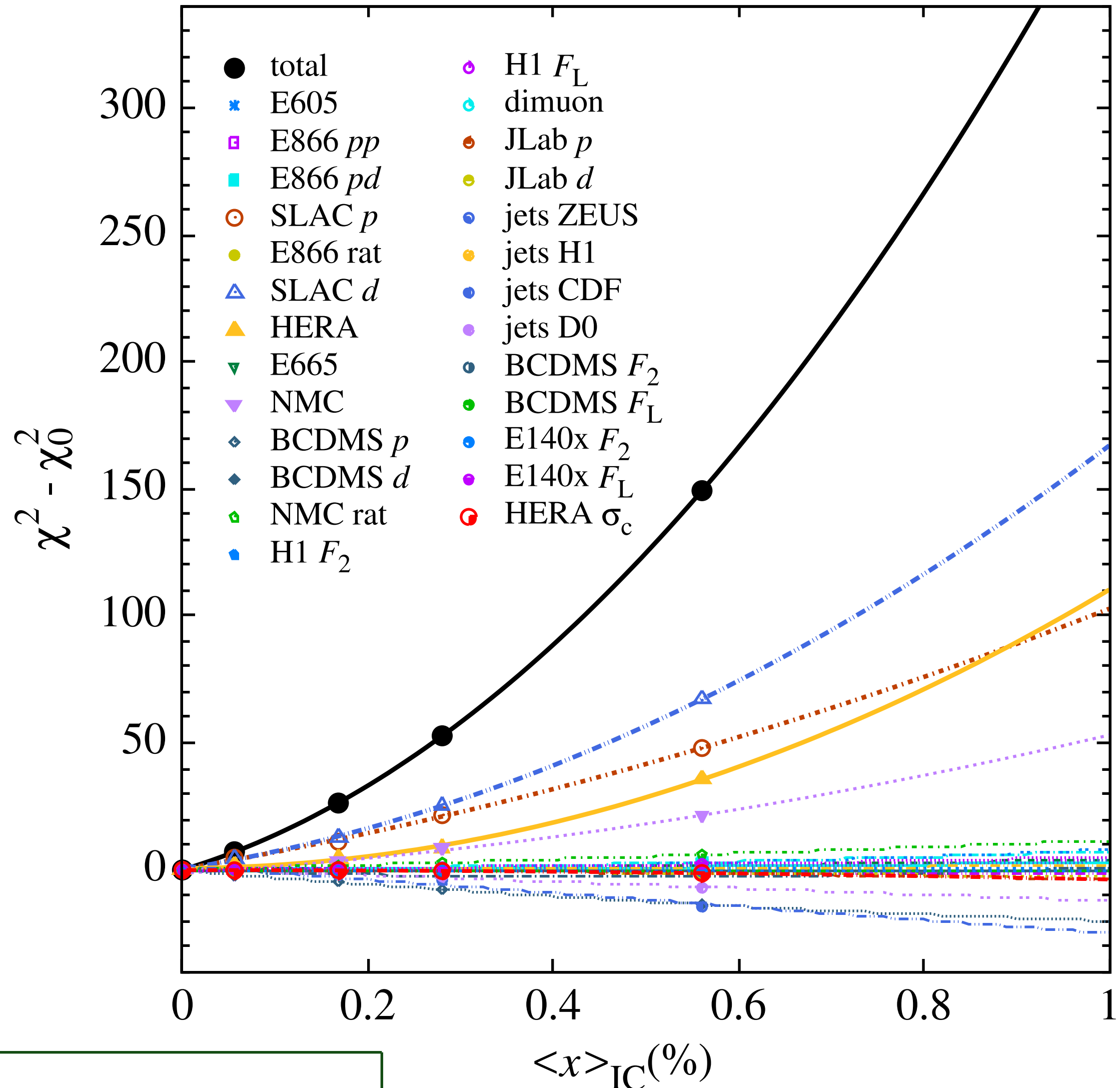
$$N_{dat} = 4296$$

$Q^2 \geq 1$ GeV^2

$W^2 \geq 3.5$ GeV^2

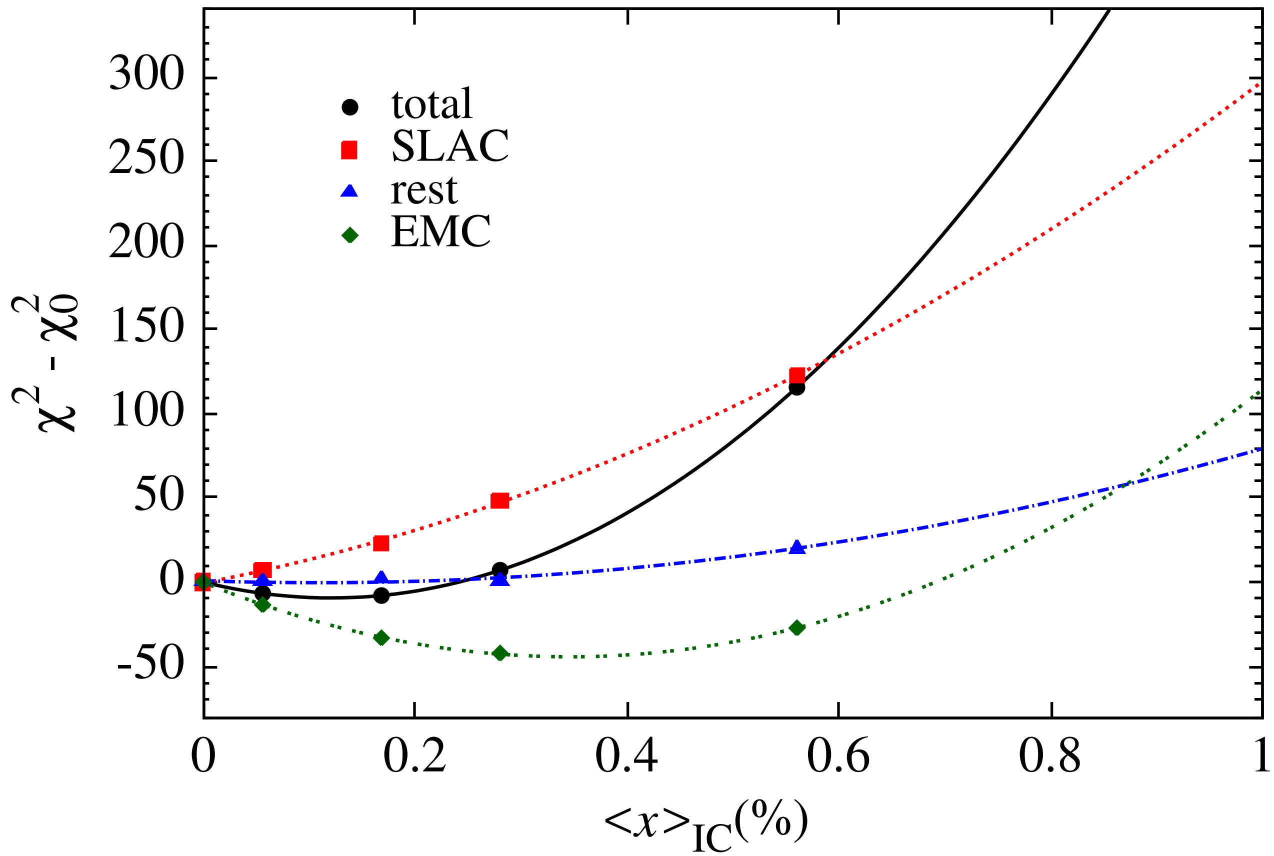
$\Longrightarrow$

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



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

...and constrained by EMC



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

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

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

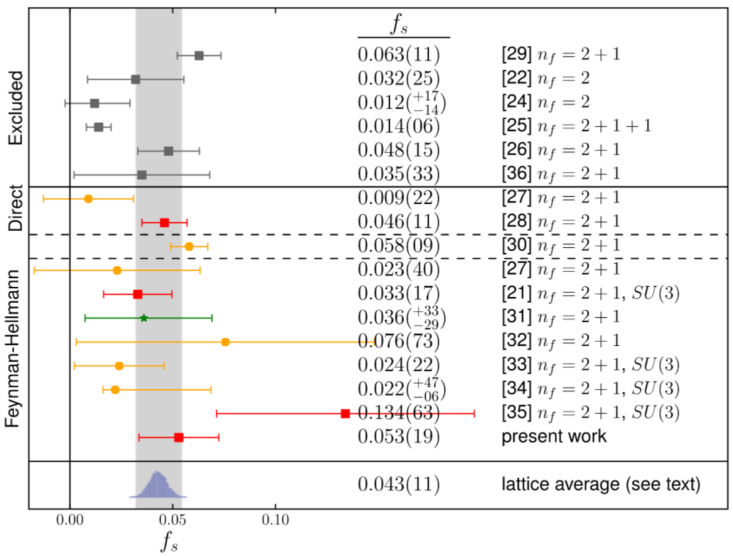
σ terms contribute to nucleon's mass, BSM cross sections

- the nucleon mass is a matrix element of the QCD energy-momentum tensor,

$$M\,\overline{\psi}_N \psi_N \;=\; \langle p \,|\, \theta_{\mu\mu} \,|p\rangle$$

$$\theta_{\mu\mu} \;\equiv\; \ldots + \sum_Q m_Q\, \overline{Q} Q + \ldots$$

Junnarkar, Walker-Loud; PRD 2013.

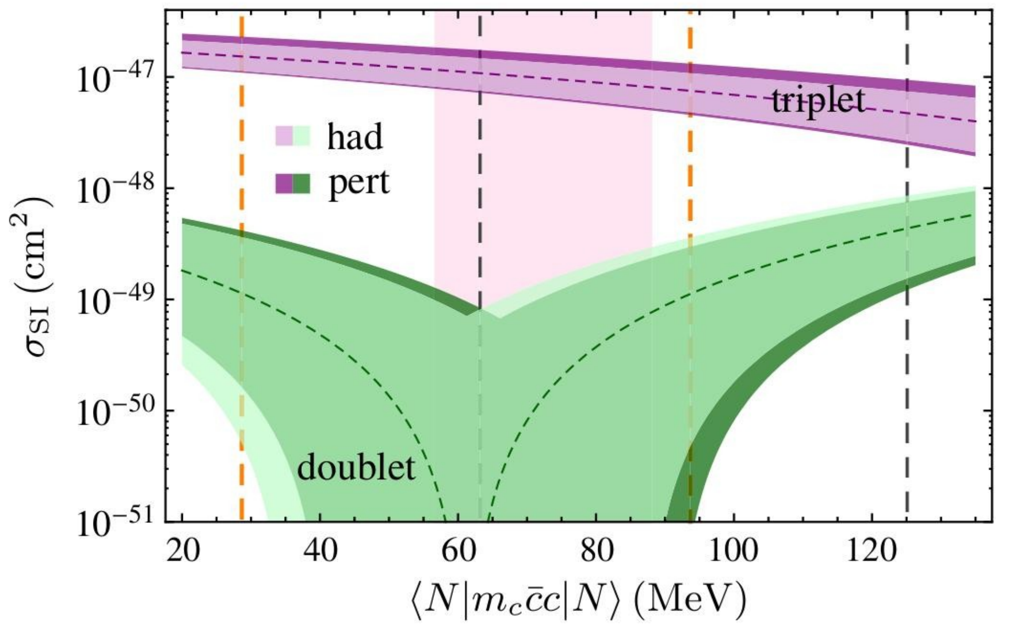


MANY more lattice determinations of σ_s

- ALSO: the **heavy quark sigma term** (esp. for charm) is important to WIMP direct searches :

$$\mathcal{L}_{\chi_\nu} \;=\; \frac{1}{M_W^3}\overline{\chi}_\nu \chi_\nu \left(\sum_q c_q^{(0)} \left(m_q \bar{q} q\right) + c_g^{(0)} \left(G^A_{\mu\nu}\right)^2 \right)$$

Hill and Solon, Phys. Rev. Lett. **112**, 211602 (2014).



… relatively few for σ_c

- in principle, with knowledge of the wave function, there may be a way to correlate σ-terms and DIS-derive quantities, e.g., $\langle x \rangle_{c\bar{c}}$

… need models for *both* the charm PDF *and* $\sigma_{c\bar{c}}$

- **light-front wave functions (LFWFs)** are one such approach
- they deliver a **frame-independent** description of hadronic bound state structure

  - the light front represents physics *tangent* to the light cone:

$$x^\mu = (x^0, \mathbf{x}) \longrightarrow (x^+, x_\perp, x^-)$$

$$x^\pm = x^0 \pm x^3, \quad x_\perp = (x^r)\,; \quad r = \{1,2\}$$

- with them, many matrix elements (GPDs, TMDs) are calculable via the same **universal** objects:

$$c(x) \sim \langle \bar{c}\,\gamma^+ c \rangle \longleftrightarrow \sigma_{c\bar{c}} \;=\; m_c \,\langle p \big| \bar{c}c \big| p \rangle$$

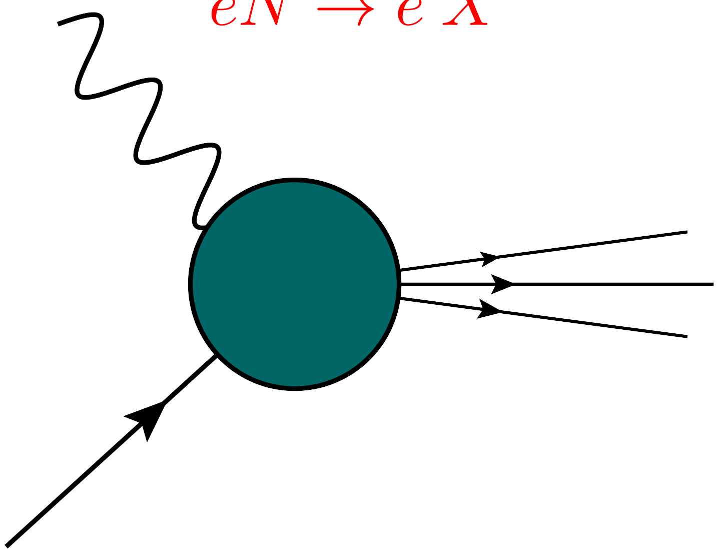
- in fact, have already developed this technology for **nucleon strangeness**!

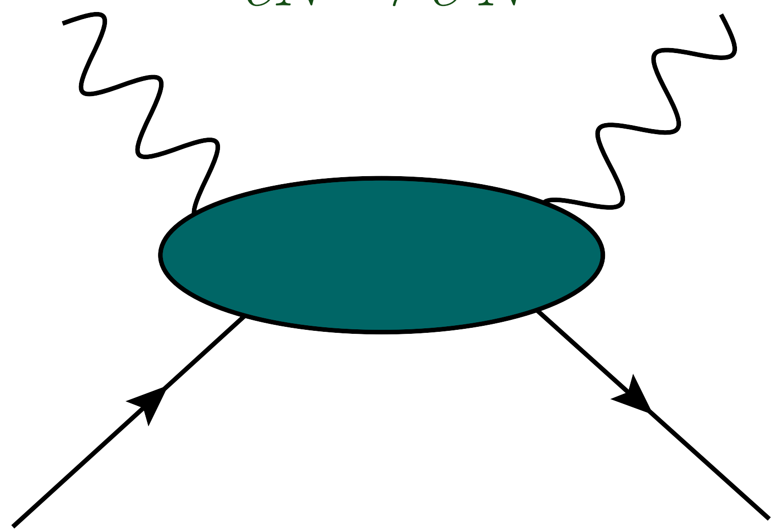
TJH, M. Alberg, and G. A. Miller; PRC91, 035205 (2015).

DIS and elastic strangeness

- *predict* inelastic and elastic observables?

  $\rightarrow$ requires knowledge of quark-level proton **wave function**





$$xS^+ = \int_0^1 dx\ x[s(x) + \bar{s}(x)]$$

$$xS^- = \int_0^1 dx\ x[s(x) - \bar{s}(x)]$$

$$F_1(Q^2) \sim \langle P', \uparrow | J^+_{EM} | P, \uparrow \rangle$$

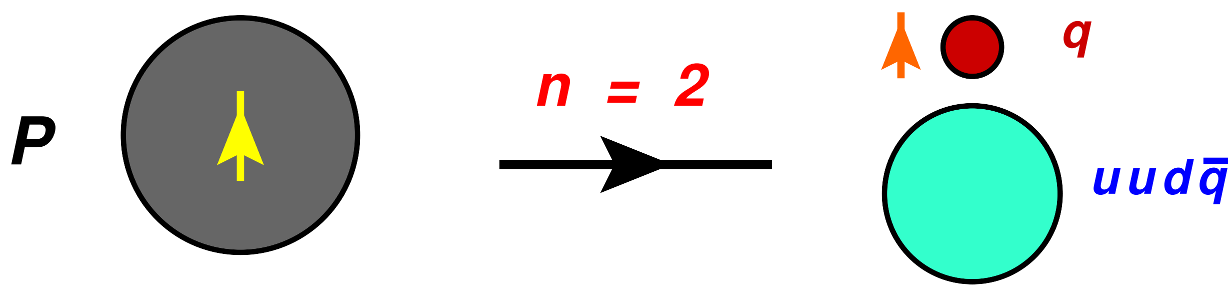
$$F_2(Q^2) \sim \langle P', \downarrow | J^+_{EM} | P, \uparrow \rangle$$

$$\boxed{J^\mu_{EM} = \gamma^\mu F_1(Q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2M} F_2(Q^2)}$$

hadronic **light-front** wave functions **(LFWFs)**

- **S. J. Brodsky, D. S. Hwang, B. Q. Ma and I. Schmidt; Nucl. Phys. B 593, 311 (2001).**

$$|\Psi_P^\lambda(P^+,\mathbf{P}_\perp)\rangle = \sum_n \int \prod_{i=1}^n \frac{dx_i d^2\mathbf{k}_{\perp i}}{\sqrt{x_i}(16\pi^3)} 16\pi^3 \, \delta\left(1-\sum_{i=1}^n x_i\right) \times \delta^{(2)}\left(\sum_{i=1}^n \mathbf{k}_{\perp i}\right) \psi_n^\lambda(x_i,\mathbf{k}_{\perp i},\lambda_i) \, |n; k_i^+, x_i\mathbf{P}_\perp + \mathbf{k}_{\perp i}, \lambda_i\rangle$$



$$|\Psi_P^\lambda(P^+,\mathbf{P}_\perp)\rangle = \frac{1}{16\pi^3}\sum_{q=s,\bar{s}} \int \frac{dx d^2\mathbf{k}_\perp}{\sqrt{x(1-x)}} \psi_{q\lambda_q}^\lambda(x,\mathbf{k}_\perp) \times |q; xP^+, x\mathbf{P}_\perp + \mathbf{k}_\perp\rangle$$

$\rightarrow$ **3D** helicity WF $\psi_{q\lambda_q}^\lambda(x,\mathbf{k}_\perp)$; **light-front fraction**: $x = k^+/P^+$

electromagnetic form factors

- the quark q contribution from any 5-quark state is then:

$$F_1^q(Q^2) \;=\; e_q \int \frac{dx d^2\mathbf{k}_\perp}{16\pi^3} \sum_{\lambda_q} \psi^{*\lambda=+1}_{q\lambda_q}(x,\mathbf{k}'_\perp)\; \psi^{\lambda=+1}_{q\lambda_q}(x,\mathbf{k}_\perp)$$

$$F_2^q(Q^2) \;=\; e_q \frac{2M}{[q^1+iq^2]} \int \frac{dx d^2\mathbf{k}_\perp}{16\pi^3} \sum_{\lambda_q} \psi^{*\lambda=-1}_{q\lambda_q}(x,\mathbf{k}'_\perp)\; \psi^{\lambda=+1}_{q\lambda_q}(x,\mathbf{k}_\perp)$$

- for strangeness, $q \to s$; total strange: $s+\bar{s}$

$$F_{1,2}^{s\bar{s}}(Q^2) \;=\; F_{1,2}^{s}(Q^2) \;+\; F_{1,2}^{\bar{s}}(Q^2) \quad\Longrightarrow$$

Sachs form :

$$G_E^{s\bar{s}}(Q^2) \;=\; F_1^{s\bar{s}}(Q^2) - \frac{Q^2}{4M^2} F_2^{s\bar{s}}(Q^2)$$

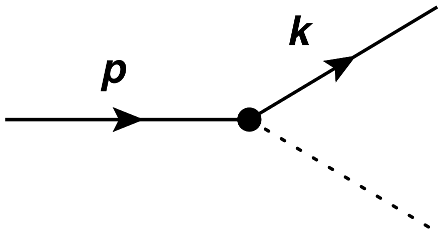
$$G_M^{s\bar{s}}(Q^2) \;=\; F_1^{s\bar{s}}(Q^2) + F_2^{s\bar{s}}(Q^2)$$

$$\boxed{\mu_s \;=\; G_M^{s\bar{s}}(Q^2=0)} \qquad \boxed{\rho_s^D \;=\; \left.\frac{dG_E^{s\bar{s}}}{d\tau}\right|_{\tau=0}}$$

where $\tau \;=\; Q^2 \big/ 4M^2$

strangeness **wave functions**

- require a **proton** $\rightarrow$ **quark** + **scalar tetraquark** LFWF:



I. C. Cloët and G. A. Miller; Phys. Rev. C 86, 015208 (2012).

$$\boxed{\psi^{\lambda}_{\lambda_s}(k,p) \;=\; \bar{u}^{\lambda_s}_s(k)\; \phi(M_0^2)\; u^{\lambda}_N(p)}$$

$\phi(M_0^2)$: scalar function $\rightarrow$ quark-spectator interaction

(M_0^2 = quark-tetraquark invariant mass^2!)

e.g., $$\psi^{\lambda=+1}_{s\lambda_s=+1}(x,\mathbf{k}_\perp) \;=\; \frac{1}{\sqrt{1-x}} \left(\frac{m_s}{x} + M\right)\; \phi_s$$

$$\text{gaussian}:\;\; \phi_s \;=\; \frac{\sqrt{N_s}}{\Lambda_s^2} \exp\left\{-M_0^2(x,\mathbf{k}_\perp,\mathbf{q}_\perp)\Big/ 2\Lambda_s^2\right\}$$

$$F_1^s(Q^2) \;=\; \frac{e_s N_s}{16\pi^2 \Lambda_s^4} \int \frac{dx\,dk_\perp^2}{x^2(1-x)} \left(k_\perp^2 + (m_s + xM)^2 - \frac{1}{4}(1-x)^2 Q^2\right)$$

$$\times\;\; \exp(-s_s/\Lambda_s^2) \qquad \boxed{s_s = (M_0^2 + M_0'^2)/2} \qquad \textit{sim. for } F_2^s(Q^2)!$$

$s\bar{s}$ distribution functions

- s quark distribution $\equiv$ x-**unintegrated** $F_1^s(Q^2=0)$ form factor (up to e_s!):

$$s(x) \ = \ \int \frac{d^2\mathbf{k}_\perp}{16\pi^3} \sum_{\lambda_s} \psi^{*\lambda=+1}_{s\lambda_s}(x,\mathbf{k}_\perp) \ \psi^{\lambda=+1}_{s\lambda_s}(x,\mathbf{k}_\perp)$$

$\rightarrow$ again inserting **helicity wave functions** $\psi^{\lambda=+1}_{q\lambda_q}(x,\mathbf{k}_\perp)$ ($Q^2=0 \implies \mathbf{k'}_\perp = \mathbf{k}_\perp$):

$$\boxed{s(x) \ = \ \frac{N_s}{16\pi^2\Lambda_s^4} \int \frac{dk_\perp^2}{x^2(1-x)} \Big(k_\perp^2 + (m_s + xM)^2\Big) \ \exp(-s_s/\Lambda_s^2)}$$

$$s_s \ = \ \frac{1}{x(1-x)}\Big[k_\perp^2 + (1-x)m_s^2 + x m_{S_p}^2 + \frac{1}{4}(1-x)^2 Q^2\Big]$$

$\rightarrow$ total of **eight** model parameters!

(N_s, Λ_s, m_s, and m_{S_p} ... **AND** anti-strange)

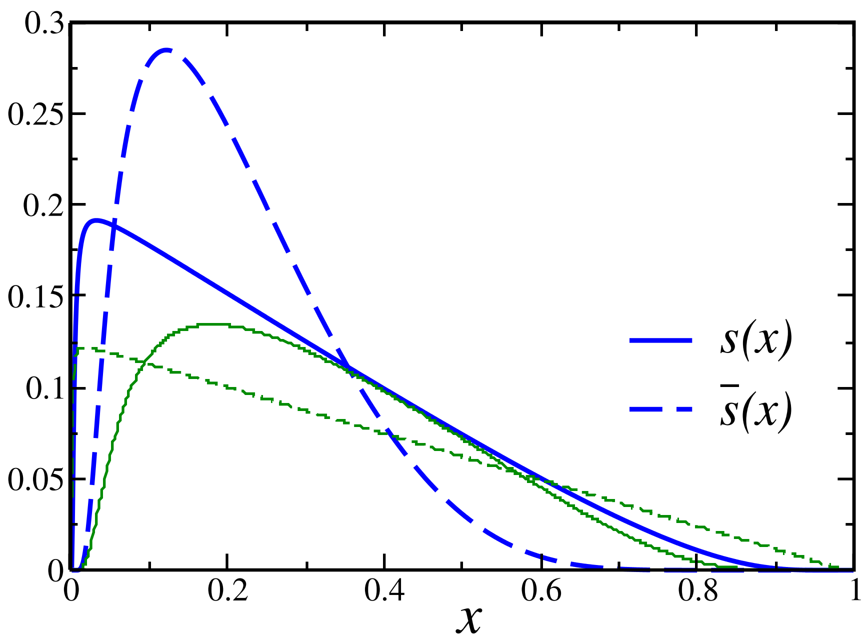
limits from **DIS** measurements

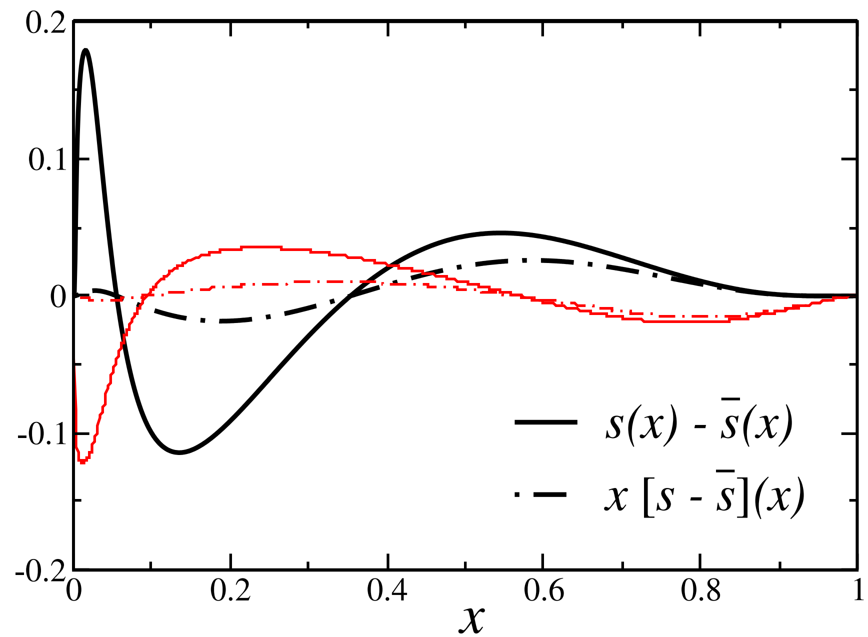
- DIS measurements have placed limits on the PDF-level total strange momentum xS^+ and asymmetry xS^-

CTEQ6.5S:

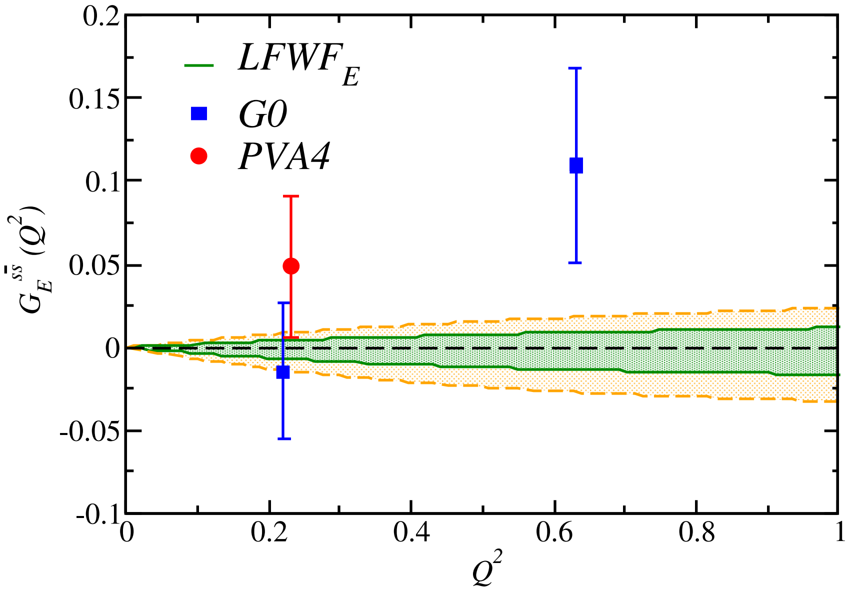
$$\boxed{0.018 \leq xS^+ \leq 0.040} \qquad \boxed{-0.001 \leq xS^- \leq 0.005}$$

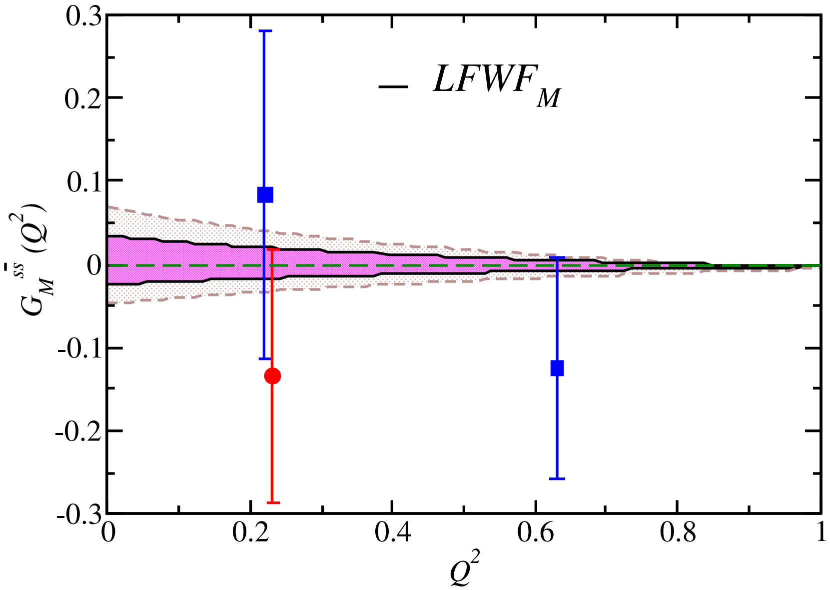
- **SCAN** the available parameter space subject to the DIS limits; **SEARCH** for extremal values of μ_s, ρ_s^D





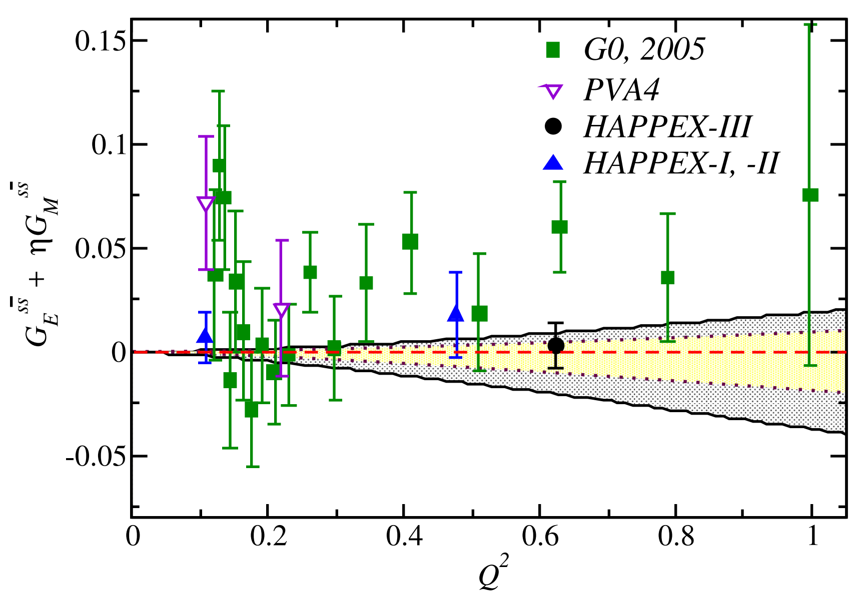
constraints on **elastic** form factors





- **DIS-driven limits** to elastic FFs are significantly **more stringent** than current experimental precision

$$\boxed{\eta(Q^2) \sim 0.94\ Q^2} \rightarrow$$

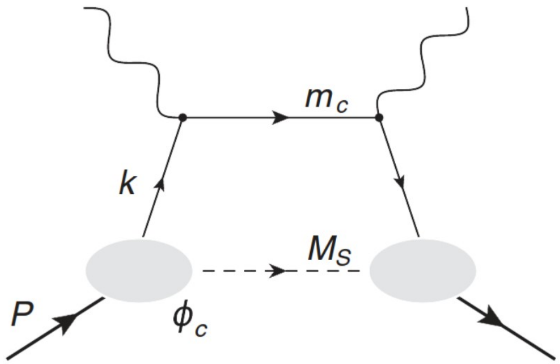


we build a model for the charm wave func^{n}… 1st the **PDF**

- use a scalar spectator picture; details in helicity wave func^{n}s :

$$|\Psi_P^\lambda(P^+,\mathbf{P}_\perp)\rangle \;=\; \frac{1}{16\pi^3}\sum_{q=c,\bar{c}}\int\frac{dx\,d^2\mathbf{k}_\perp}{\sqrt{x(1-x)}}$$

TJH, Alberg and Miller,
Phys. Rev. D**96** (2017) no.7, 074023.



$$\times\,\psi_{q\lambda_q}^\lambda(x,\mathbf{k}_\perp)\,|q;xP^+,x\mathbf{P}_\perp+\mathbf{k}_\perp\rangle$$

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

$$c(x)\;=\;\frac{1}{16\pi^2}\int\frac{dk_\perp^2}{x^2(1-x)}\left[\frac{k_\perp^2+(m_c+xM)^2}{(M^2-s_{cS})^2}\right]\left|\phi_c(x,k_\perp^2)\right|^2$$

use a power-law (γ=3) covariant vertex function, $\phi_c(x,k_\perp^2)\;=\;\sqrt{g_c}\left(\frac{\Lambda_c^2}{t_c-\Lambda_c^2}\right)^\gamma$

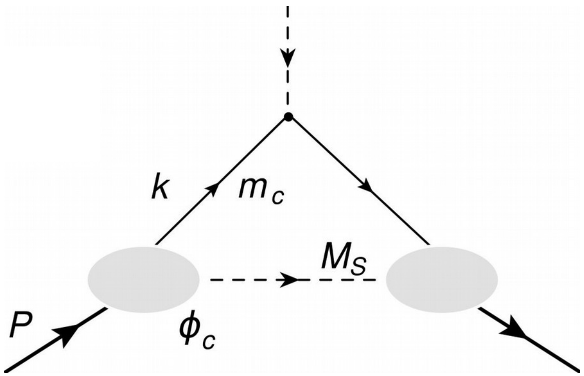
$$\begin{cases} s_{cS}\left(x,k_\perp^2\right)\;=\;\dfrac{1}{x\,(1-x)}\left(k_\perp^2+(1-x)\,m_c^2+x\,M_S^2\right) & \textbf{invariant mass}\\[2ex] t_c\left(x,k_\perp^2\right)\;=\;\dfrac{1}{1-x}\left(-k_\perp^2+x\left[(1-x)M^2-M_S^2\right]\right) & \textbf{covariant } \mathrm{k}^2\end{cases}$$

then, a covariant formalism gives the **sigma term**:

- IF the LFWFs can be constrained with information from the DIS sector, we may evaluate $\sigma_{c\bar{c}}$

$$\sigma_c = \frac{ig_c}{2M}\int \frac{d^4k}{(2\pi)^4}\,\overline{u}(p)\left(\frac{1}{\not{k}-m_c+i\epsilon}\right)[m_c\mathcal{I}_4]\left(\frac{1}{\not{k}-m_c+i\epsilon}\right)u(p)$$

$$\times\left(\frac{1}{[p-k]^2-M_S^2+i\epsilon}\right)\left(\frac{\Lambda^2}{k^2-\Lambda_c^2+i\epsilon}\right)^{2\gamma}$$



$$\sigma_{c\bar{c}} = \sigma_c + \sigma_{\bar{c}}$$

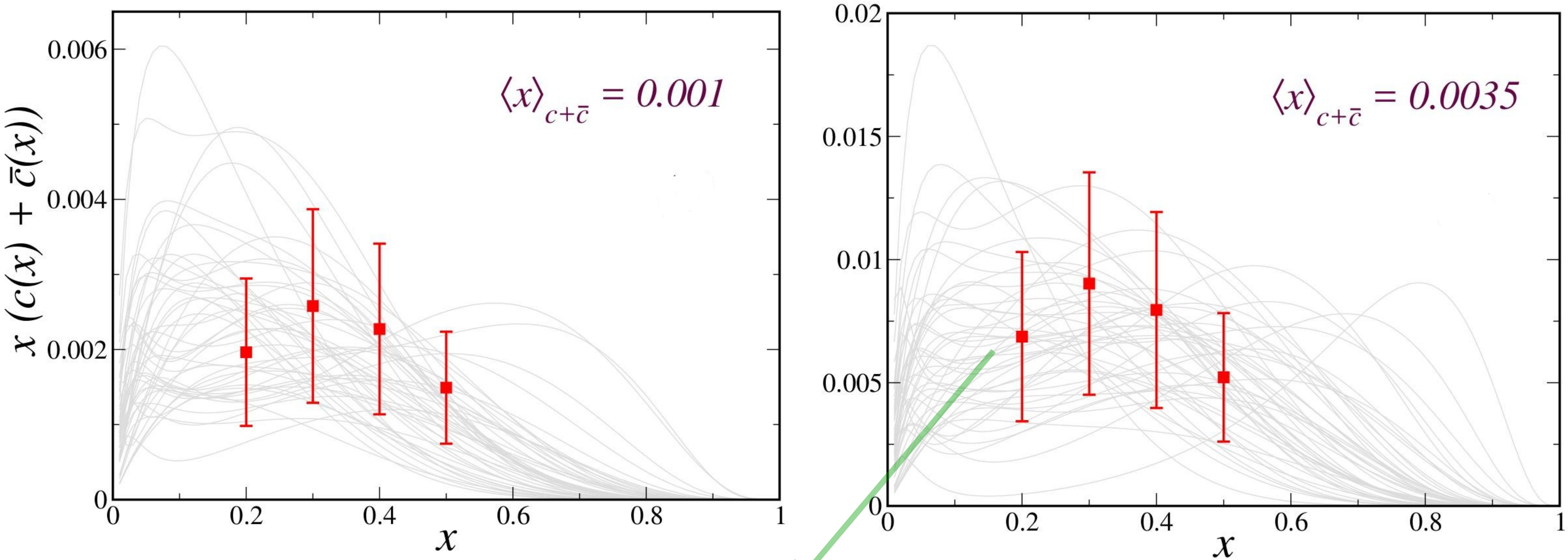
…we determine **probability distribution functions** (p.d.f.s) for this quantity

- this formalism is required because the LFWFs contain noncovariant parts:

$$i\frac{\sum_\lambda u_\lambda(k)\,\overline{u}_\lambda(k)}{k^2-m^2+i\epsilon} = \frac{i}{\not{k}-m+i\epsilon} - i\frac{\gamma^+}{2k^+}$$

- **it remains to determine the (free) *parameters* of the light-front model,**

$$\left(g_c,\ m_c,\ \Lambda_c,\ \Lambda_{\bar{c}},\ M_S,\ M_{\bar{S}}\right)$$



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

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

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

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

model simulations with **m**arkov **c**hain **m**onte **c**arlo (MCMC)

- specifically, use a **D**elayed-**R**ejection **A**daptive **M**etropolis (DRAM) algorithm

Haario et al., Stat. Comput. (2006) **16**: 339–354.

construct a Markov chain consisting of $n_{sim} \approx 10^5 - 10^6$ simulations, sampling the ***joint posterior distribution***

$$p(\vec{\theta}\,|x) \;\sim\; p(x|\vec{\theta}\,)\, p(\vec{\theta}\,)$$

x	: input data
$\vec{\theta}$	: parameters

BROAD gaussian priors

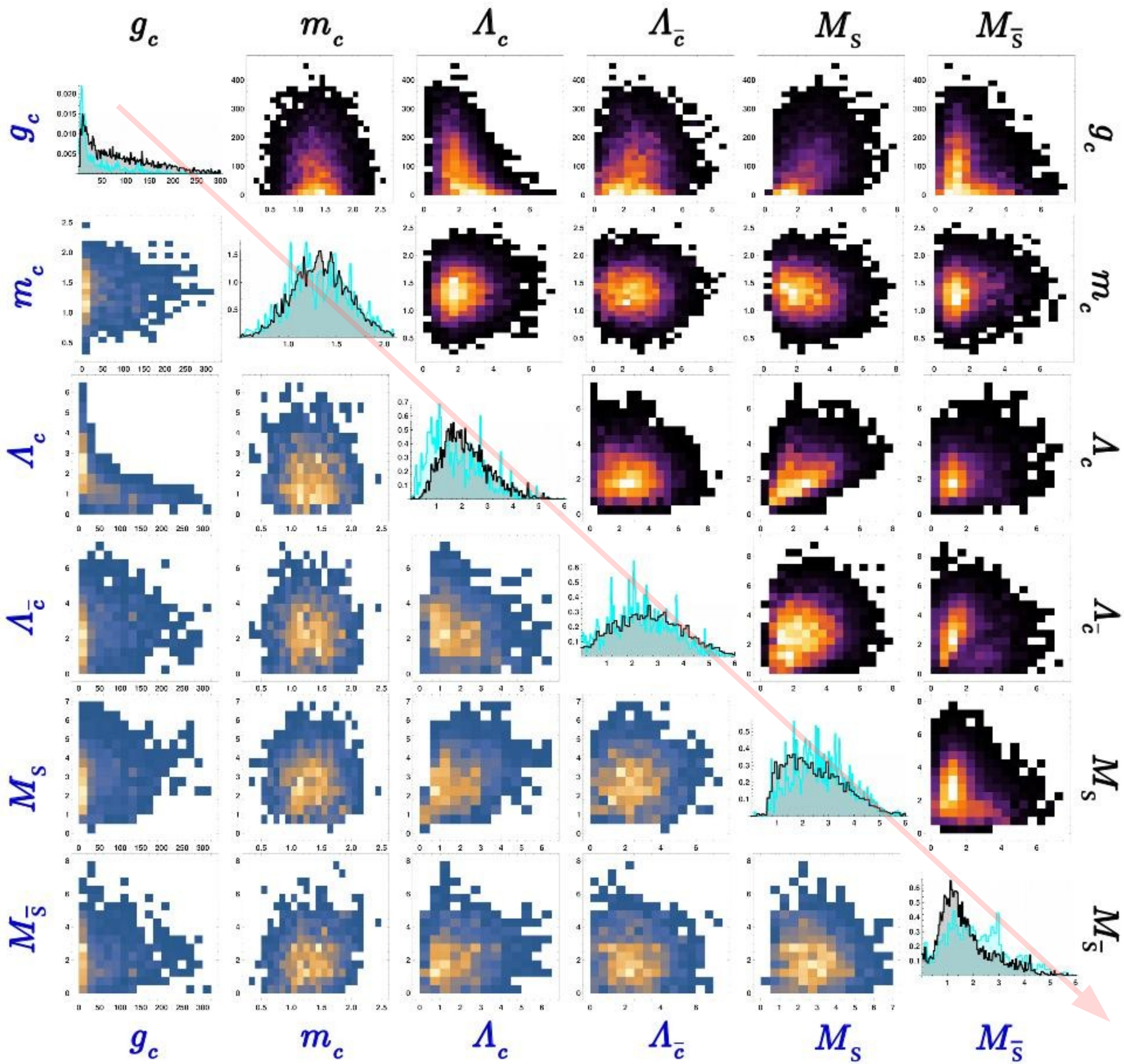
likelihood function $p(x|\vec{\theta}\,) \;=\; \exp\left(-\chi^2/2\right)$

$$\chi^2 = \sum_i \left(\frac{1}{\sigma_i^{data}}\right)^2 \left| F_2^{c\bar{c}}(x_i, \vec{\theta}\,) - F_2^{c\bar{c},\,data}(x_i)\right|^2$$

- asymptotically, the MCMC chain fully explores the joint posterior distribution

✔ from this, we extract **probability distribution functions (p.d.f.s)** for the model parameters and derived quantities, **including $\sigma_{c\bar{c}}$**

MCMC Joint posterior distribution



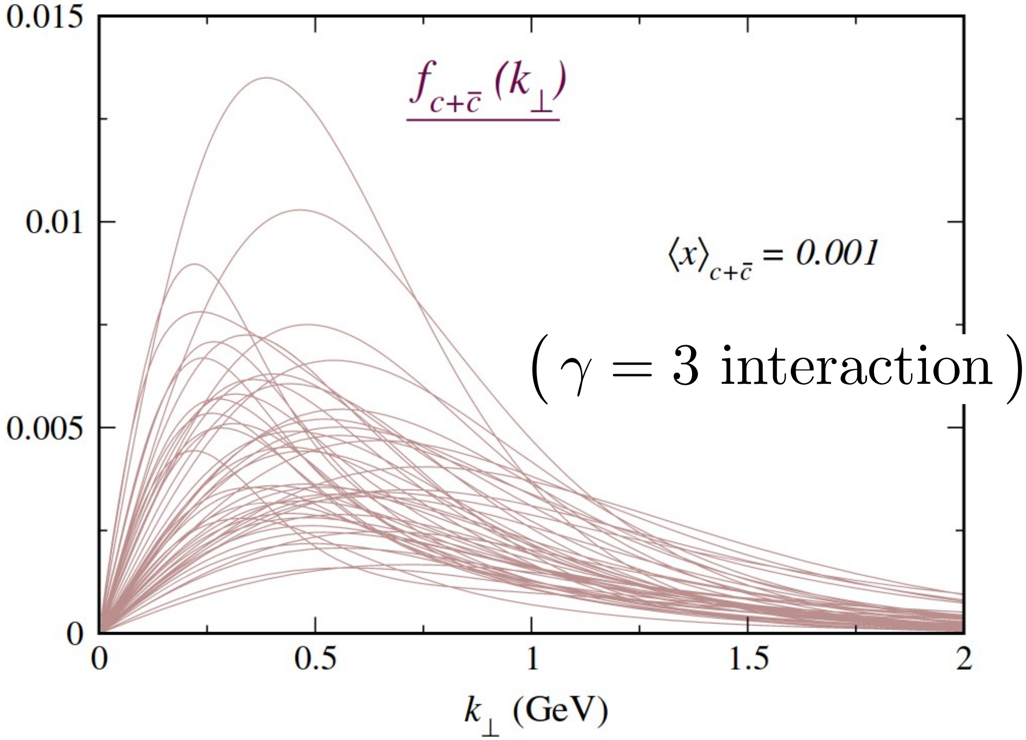
$\gamma = 3$ interaction

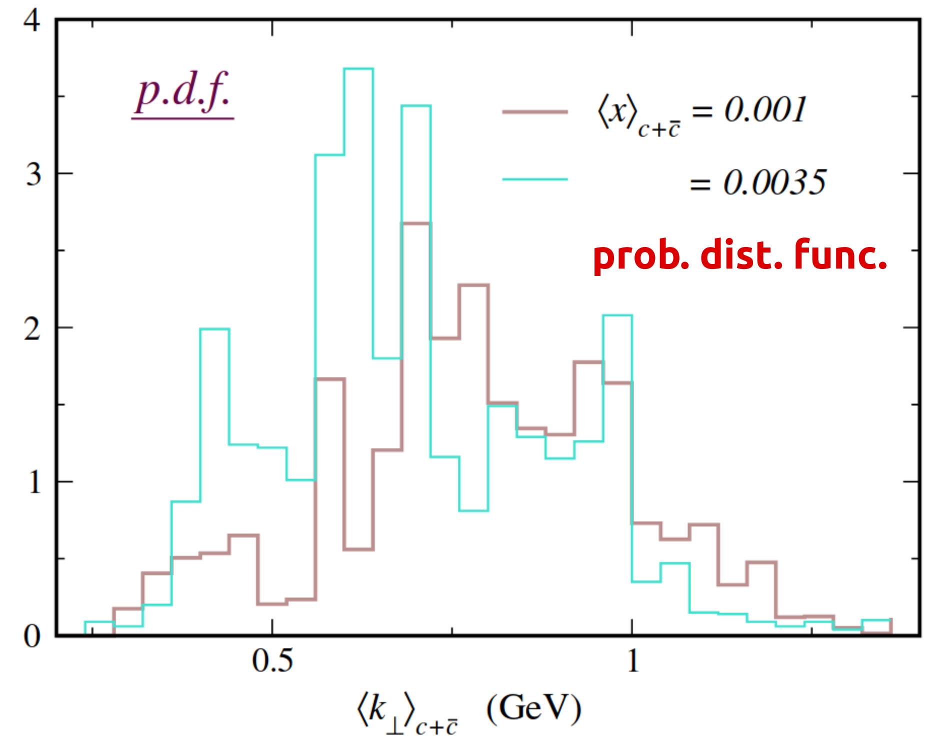
correlations

$\gamma = 1$ interaction

p.d.f.s

the **charm TMD** is consistent with deeply internal quarks





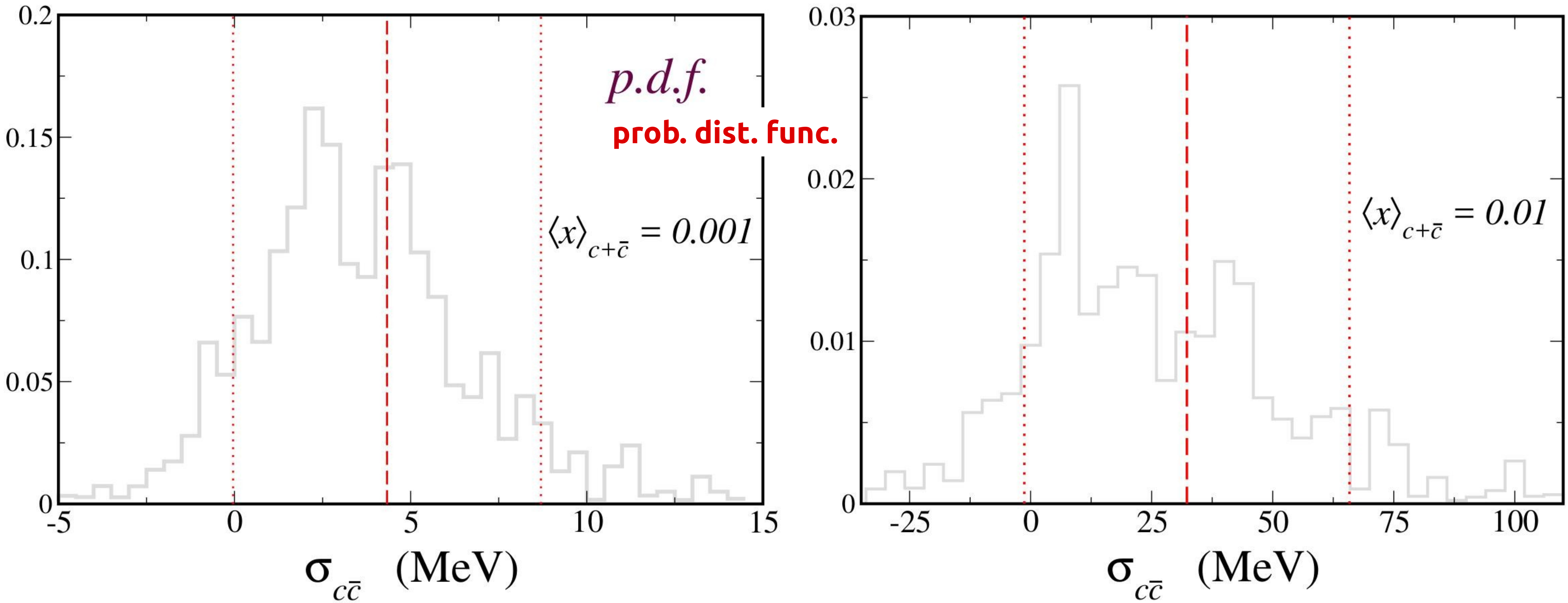
$$\langle k_\perp \rangle_c \equiv \frac{1}{n_c} \int dx\, dk_\perp^2\, k_\perp\, f_{c/p}(x, k_\perp)$$

$$\langle k_\perp \rangle_{c+\bar{c}} = 0.75 \pm 0.20\,\mathrm{GeV} \qquad f_{c/p}(x, \boldsymbol{b}_\perp) = \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^2}\, e^{-i\boldsymbol{k}_\perp \cdot \boldsymbol{b}_\perp}\, f_{c/p}(x, \boldsymbol{k}_\perp)$$

$$\longrightarrow \quad \langle b_\perp \rangle_{c+\bar{c}} \ll 1\, fm$$

- knowledge of the wave function may help with building a give-and-take between efforts to describe collinear PDFs and TMDs for detailed tomography

$F_{2,\mathrm{IC}}^{c\bar{c}}$ and $\sigma_{c\bar{c}}$ are directly correlated.



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

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

$$\sigma_{c\bar{c}} = 94\,(31)\,\mathrm{MeV} \quad (\chi\mathrm{QCD})^{1}$$

$$= 67\,(34)\,\mathrm{MeV} \quad (\mathrm{MILC})^{2}$$

$$\sigma_{c\bar{c}} = 79\;(21)\binom{12}{8}\,\mathrm{MeV} \quad (\mathrm{AR})^{3}$$

[1]Gong et al., Phys. Rev. **D88**, 014503 (2013).

[2]Freeman and Toussaint, Phys. Rev. **D88**, 054503 (2013).

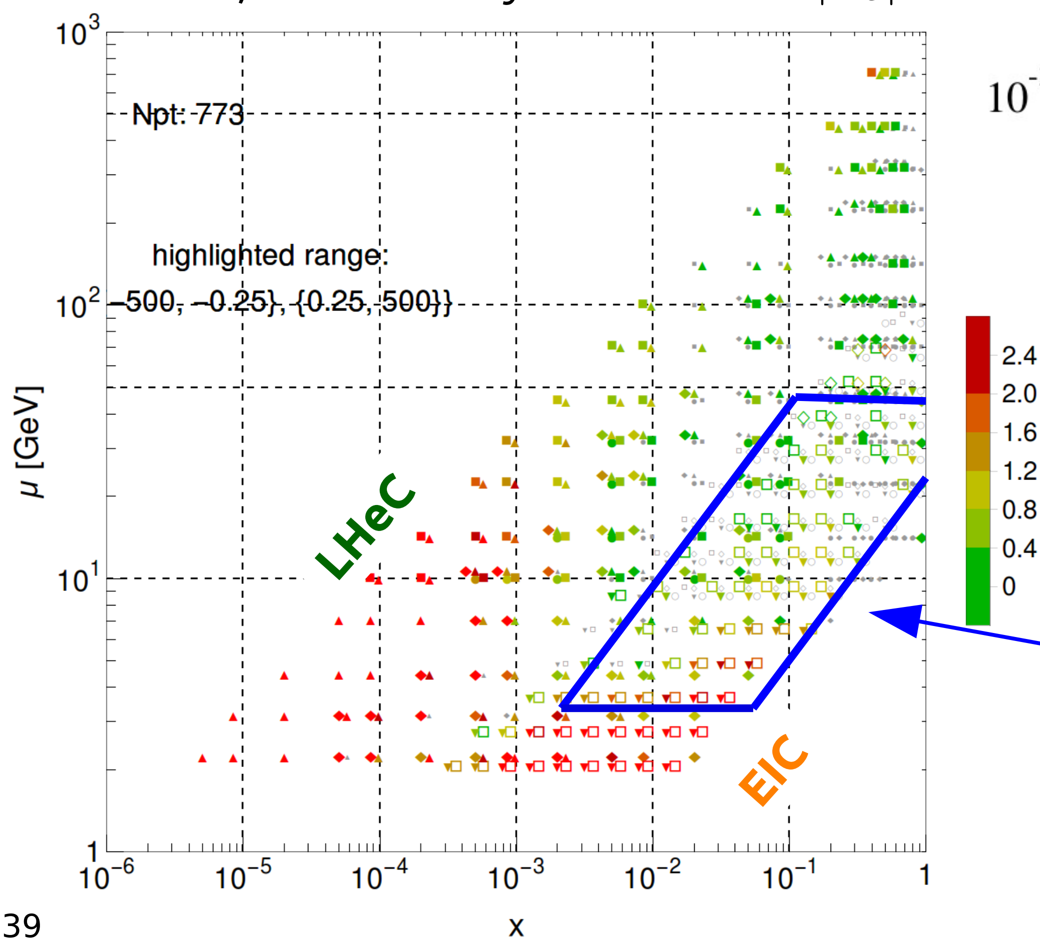
[3]Abdel-Rehim et al., Phys. Rev. Lett. **116**, 252001 (2016).

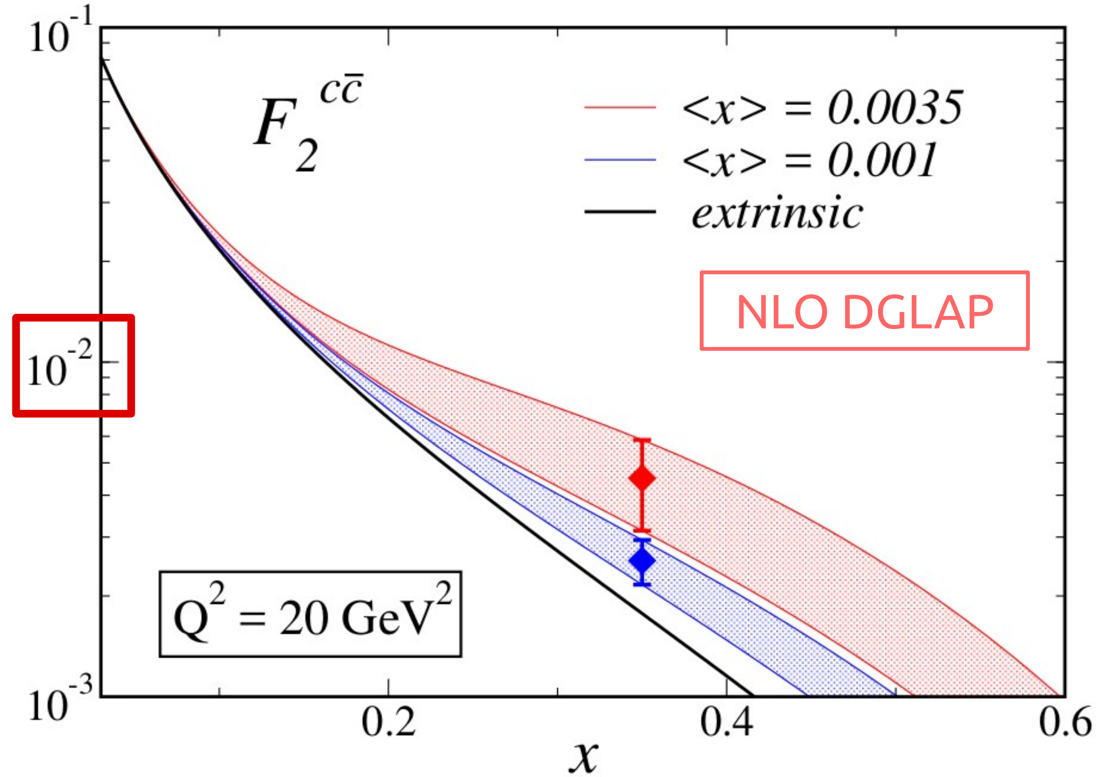
an intrinsic charm component with a small normalization is would likely need very substantial precision to unambiguously disentangle…

… but an EIC would be well-adapted to try.

EIC Whitepaper, Eur. Phys. J. A (2016) **52**: 268

LHeC, EIC sensitivity to charm PDF $|S_c|$





- e.g., for a 'generic' (slightly higher energy) EIC scenario, $\sqrt{s} \sim 100\,\mathrm{GeV}$

- EIC can access the crucial nonpert. region of the charm distribution!

with knowledge of the wave function, can also compute **helicity-odd M.E.s** (Δq)

$$\sigma_i(\epsilon) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_{Vi}^2 + 5c_{Ai}^2\right)$$

elastic total cross section, $\nu N \to \nu N$

$i = (p, n)$

ϵ : inc. neutrino energy

$$c_{Vp} = \frac{1}{2} - 2\sin^2\theta_W \,, \qquad c_{Vn} = -\frac{1}{2}$$

$$c_{Ap} = +\frac{g_A}{2} \,, \qquad c_{An} = -\frac{g_A}{2}$$

THE ASTROPHYSICAL JOURNAL LETTERS, 808:L42 (8pp), 2015 August 1 doi:10.1088/2041-8205/808/2/L42

delayed neutrino flux from PNS can heat the post-shock region; re-energize shock front:

NEUTRINO-DRIVEN EXPLOSION OF A 20 SOLAR-MASS STAR IN THREE DIMENSIONS ENABLED BY STRANGE-QUARK CONTRIBUTIONS TO NEUTRINO–NUCLEON SCATTERING

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Received 2015 April 28; accepted 2015 June 30; published 2015 July 30

$$c_{Ai} = \frac{1}{2}\left(\pm G_A(0) - G_A^{s\bar{s}}(0)\right) = \frac{\pm g_A - \Delta s}{2}$$

$$\boxed{\left(c_{An}^{(\Delta s \leq 0)}\right)^2 \leq \left(c_{An}^{(\Delta s = 0)}\right)^2}$$

- $\Delta s = -0.2$ **increases (decreases)** $\nu p \; (\nu n)$ **opacity!**

… **BUT**, how *realistic* is Δs = −0.2? … input from a **light-front model.**

- in coordinate space, the light front represents physics *tangent* to the light cone:

$$x^\mu = (x^0, \mathbf{x}) \longrightarrow (x^+, x_\perp, x^-)$$

$$x^\pm = x^0 \pm x^3, \quad x_\perp = (x^r); \quad r = \{1,2\}$$

- **Fock-state expansion:** $\boxed{|p\rangle \to |uuds\bar{s}\rangle}$

$$\left|\Psi_P^\lambda(P^+, \mathbf{P}_\perp)\right\rangle = \frac{1}{16\pi^3}\sum_{q=s,\bar{s}}\int \frac{dx\, d^2\mathbf{k}_\perp}{\sqrt{x(1-x)}}\psi^\lambda_{q\lambda_q}(x,\mathbf{k}_\perp)\left|q; xP^+, x\mathbf{P}_\perp + \mathbf{k}_\perp\right\rangle$$

e.g., Brodsky, Pauli, and Pinsky, Phys. Rep. **301**, 299 (1998).

- **given a choice for the *light-front wave function*, $\psi^\lambda_{q\lambda_q}(x,\mathbf{k}_\perp)$, may compute desired quark-level matrix elements:**

$$\Delta s = G_A^{s\bar{s}}(Q^2=0) \sim \frac{1}{P^+}\langle P|\bar{s}\,\gamma^+\gamma_5\, s|P\rangle$$

quark + scalar spectator spin decomposition

$$= \frac{N_s}{16\pi^2\Lambda_s^4}\int \frac{dx\,dk_\perp^2}{x^2(1-x)}\Big(-k_\perp^2 + (m_s + xM)^2\Big)\exp(-s_s/\Lambda_s^2) + \Big\{s \longleftrightarrow \bar{s}\Big\}$$

TJH, M. Alberg, and G.A. Miller, Phys. Rev. C **93**, 052801 (2016).

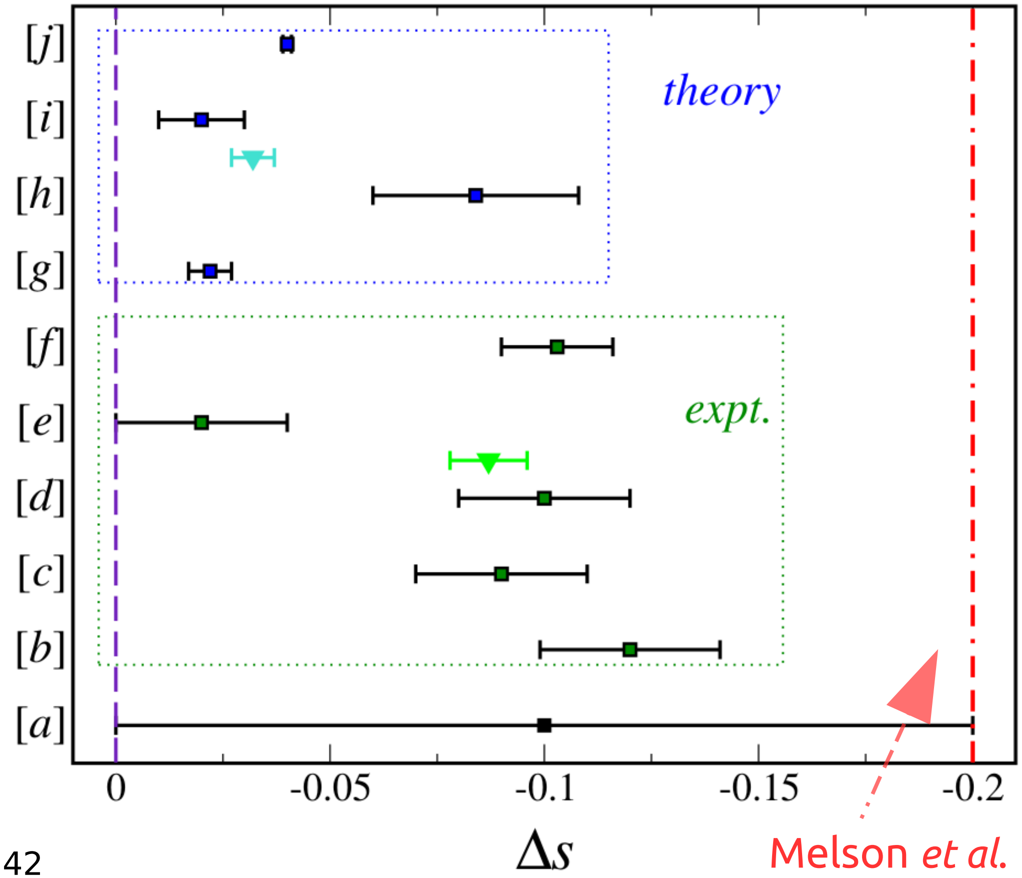
$$\Delta s \;=\; (g_A^{(0)} - g_A^{(8)})/3 \;=\; -0.02 \pm 0.01 \qquad \text{(cloudy bag)}$$ [i]

Bass & Thomas, Phys. Lett. B**684**, 216 (2010).

$$= \; -0.022 \pm 0.005 \qquad \text{(lattice avg.)}$$ [g]

QCDSF; Babich *et al.*; Engelhardt; Abdel-Rahim *et al.*; Chambers *et al.*

$$= \; -0.084 \pm 0.024 \qquad (\chi\text{QCD collab.})$$ [h]



$$\boxed{\Delta s \overset{\text{avg.}}{=} -0.032 \pm 0.005}$$

... theory suggests: $\Delta s \gtrsim -0.04$

theory sets a more stringent constraint
than current experimental extractions

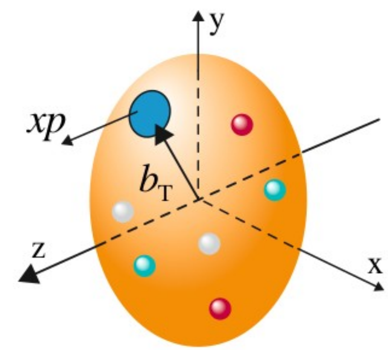
$$\boxed{\Delta s \overset{\text{avg.}}{=} -0.087 \pm 0.009}$$

... expt. suggests: $\Delta s \gtrsim -0.1$

conclusions... ...and **the future.**

- comprehensive tomography (as typified by JLab12/EIC) is now the priority of the US nuclear and hadronic physics communities

→ the dedicated aim of this effort will be the resolution of long-standing issues in QCD, and the precise determination of the nucleon's multi-dimensional structure



→ ultimately, we will learn the nucleon's wave function.

→ the impact of this work will **NOT** be relegated purely to hadronic/nuclear physics!

rather, the expected impact upon high energy physics is substantial

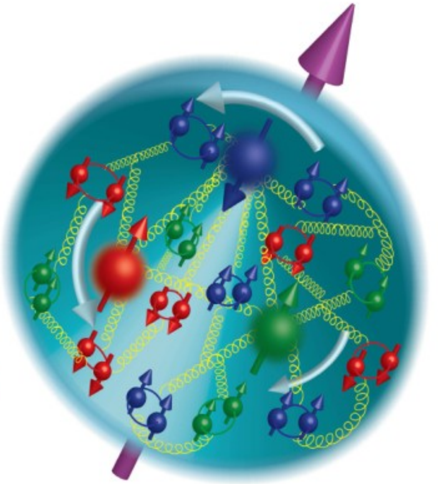
→ controlling SM backgrounds; BSM searches; neutrino pheno.; heavy quark schemes; MPIs; ...

- exploring the physics implications of EIC (including in HEP) requires a **community effort**, esp. to optimize the output of the eventual program

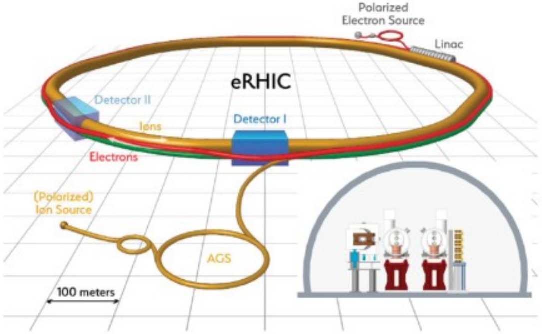
... many opportunities to get involved.

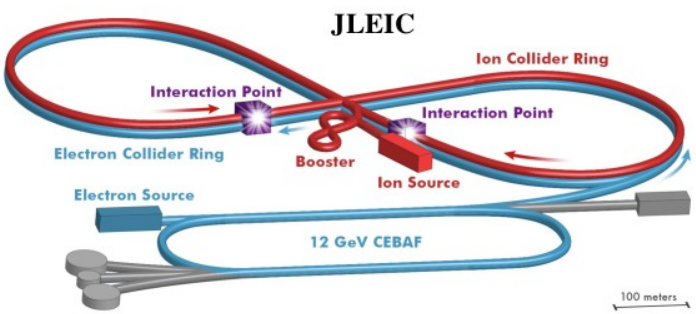
Join APS GHP!

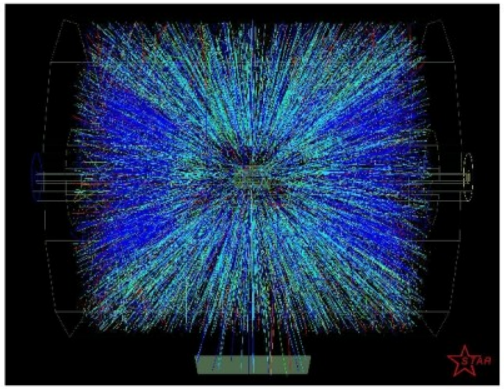
Benefits of GHP Membership



- The *Topical Group on Hadronic Physics (GHP)* is the dedicated organization that advocates for the science of QCD within the APS; and therefore to the broader physics community, funding agencies, and general public [www.aps.org/units/ghp/]
- Effectiveness of this advocacy and its impact is strongly coupled to the number of GHP members. Importantly, membership determines:
  - Number of APS Fellows the GHP can nominate — *250 members $\simeq$ 1 APS Fellow per-year*
  - Number of plenary and invited parallel talks at the APS April Meeting
- Hadron Physics is a vibrant field, with upgrades at Jefferson Lab and RHIC, and the proposed \$1.5 billion EIC — this growth should also be apparent in the GHP
  - GHP helps reward and highlight the world-class research in our field through, e.g., the Dissertation award and APS Fellows — very important for hires, grants, and promotions
- Please consider joining the GHP — \$10/yr with APS membership







supplementary material

(i) PDF moments can be evaluated on the QCD lattice

- in lattice gauge theory, the accessible moments are C-odd/even combinations,

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

$$\langle x^n \rangle_{q^+} = \langle x^n \rangle_q \quad \text{for} \quad n = 2\ell - 1$$

$$\langle x^n \rangle_{q^-} = \langle x^n \rangle_q \quad \text{for} \quad n = 2\ell \qquad\qquad \ell \in \mathbb{Z}^+$$

- the PDF moments are related to hadronic matrix elements of twist-2 operators:

PDF Mellin moments

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

$$\mathcal{O}^q_{\{\mu_1, \cdots, \mu_{n+1}\}} = \left(\frac{i}{2} \right)^n \bar{q}(x) \gamma_{\mu_1} \overleftrightarrow{D}_{\mu_2} \ldots \overleftrightarrow{D}_{\mu_{n+1}} q(x)$$

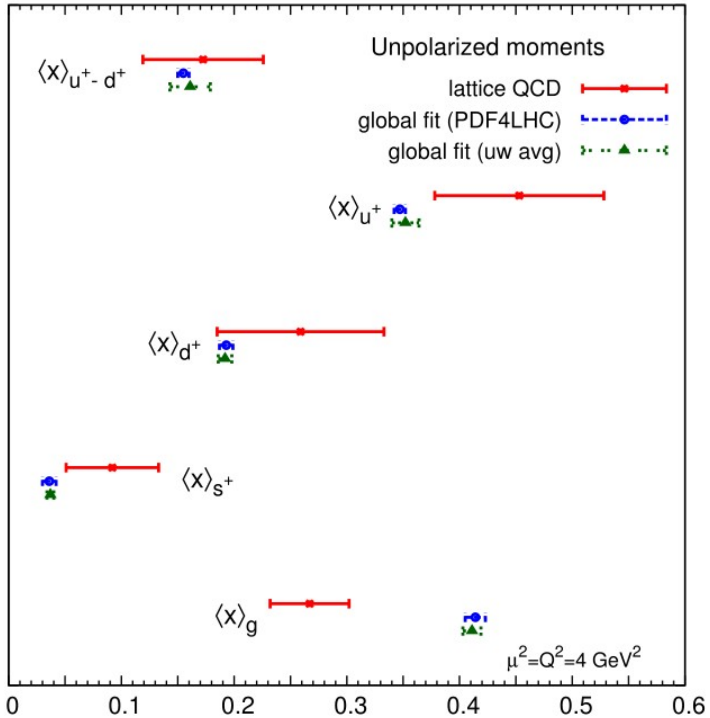
gauge-covariant derivatives

the status of lattice QCD calculations

PDF-Lattice whitepaper – Lin et al., Prog. Part. Nucl. Phys. **100**, 107 (2018).

Mom.	Collab.	Ref.	N_f	Status	Disc [fm]	QM	FV	Ren	ES
$\langle x\rangle_{u^+-d^+}$	ETMC 15	[263]	2+1+1	P	0.06, 0.08	–	■, ★	★, ★	■, ★
	ETMC 15	[263]	2	P	0.06–0.09	–	○	★	■
	RQCD 14	[251]	2	P	0.06–0.08	–	○	★	○

Mom.	Collab.	Ref.	N_f	Status	Disc	QM	FV	Ren	ES	
$\langle x^2\rangle_{u^--d^-}$	LHPC and SESAM 02	[279]	2	P	■	■	■	○	■	0.145(69)
	QCDSF 05	[93]	0	P	■	■	■	★	■	0.083(17)
	LHPC and SESAM 02	[279]	0	P	■	■	■	○	■	0.090(68)



- depending upon flavor and order, lattice extractions of Mellin moments have varying status (above, FLAG evaluations)
  - → e.g., the first isovector moment has been computed by numerous groups
  - → but the second, by relatively few
- systematic lattice effects are similarly widely varied

however, improvements are being made rapidly!

toward a PDF-lattice working relationship

- what are the prospects for actually building a lattice-PDF synergy --- i.e., what must be done (aside from lattice improvements in the [unpolarized] moments)?

> *"Although the studies presented here are still in an initial exploratory phase, they provide strong motivation for global fitters to begin consider incorporating lattice-QCD constraints into their global analyses."*
>
> – Prog. Part. Nucl. Phys. **100**, 107 (2018).

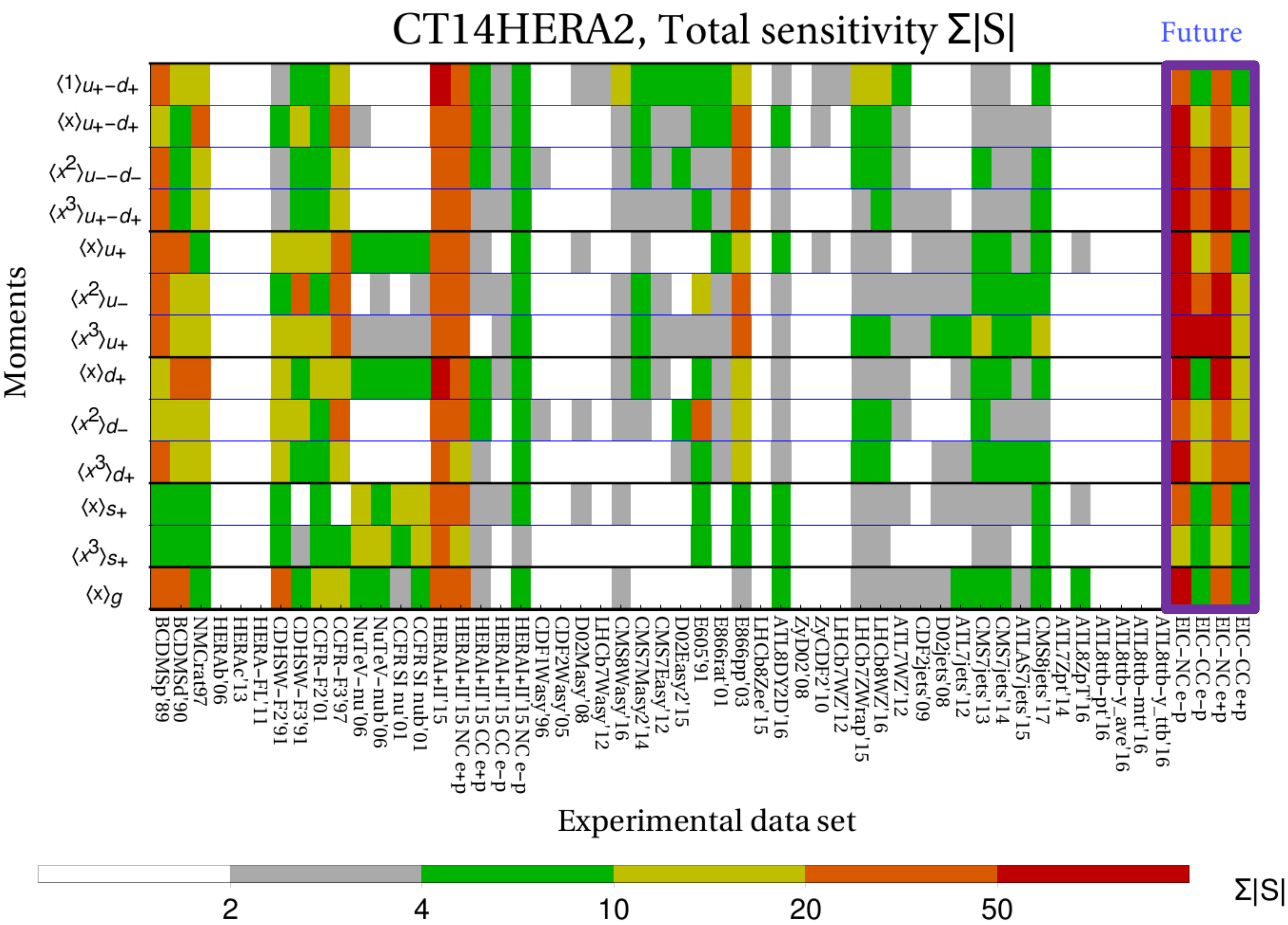
→ PDF phenomenologists must understand which lattice output would be most beneficial – and where the greatest impact would be felt

for this, a detailed accounting of how phenomenological knowledge of lattice-calculable moments is derived will be essential

The problem with a seesaw is you're always off balance.

→ this understanding must be communicated to lattice practitioners, who must continue building a common framework for assessing lattice systematics/artifacts

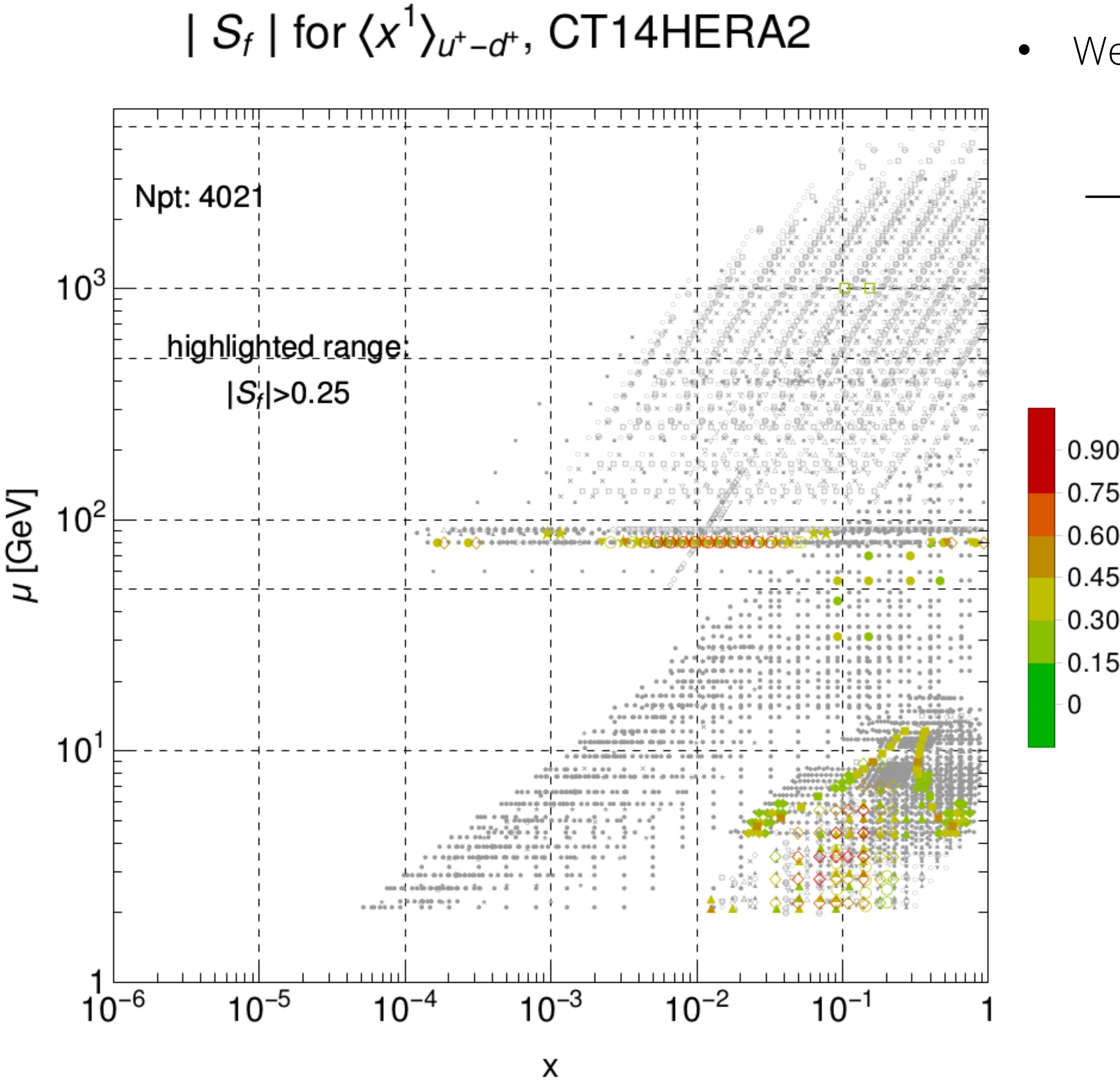
sensitivity to Mellin moments



we show Mellin moments computable on the lattice at the scale $\mu_F = 2\,\mathrm{GeV}$

HERA, BCDMS, NMC, E866 DY pair production are most sensitive to the moments

sensitivity maps: isovector moments



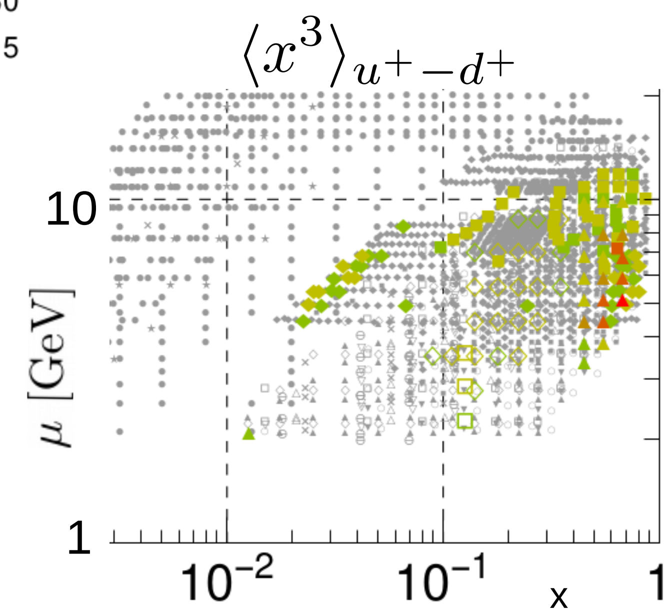
$$\overline{x}_{|S_f|} = \sum_i x_i |S_f^i| \Big/ \sum_i |S_f^i|$$

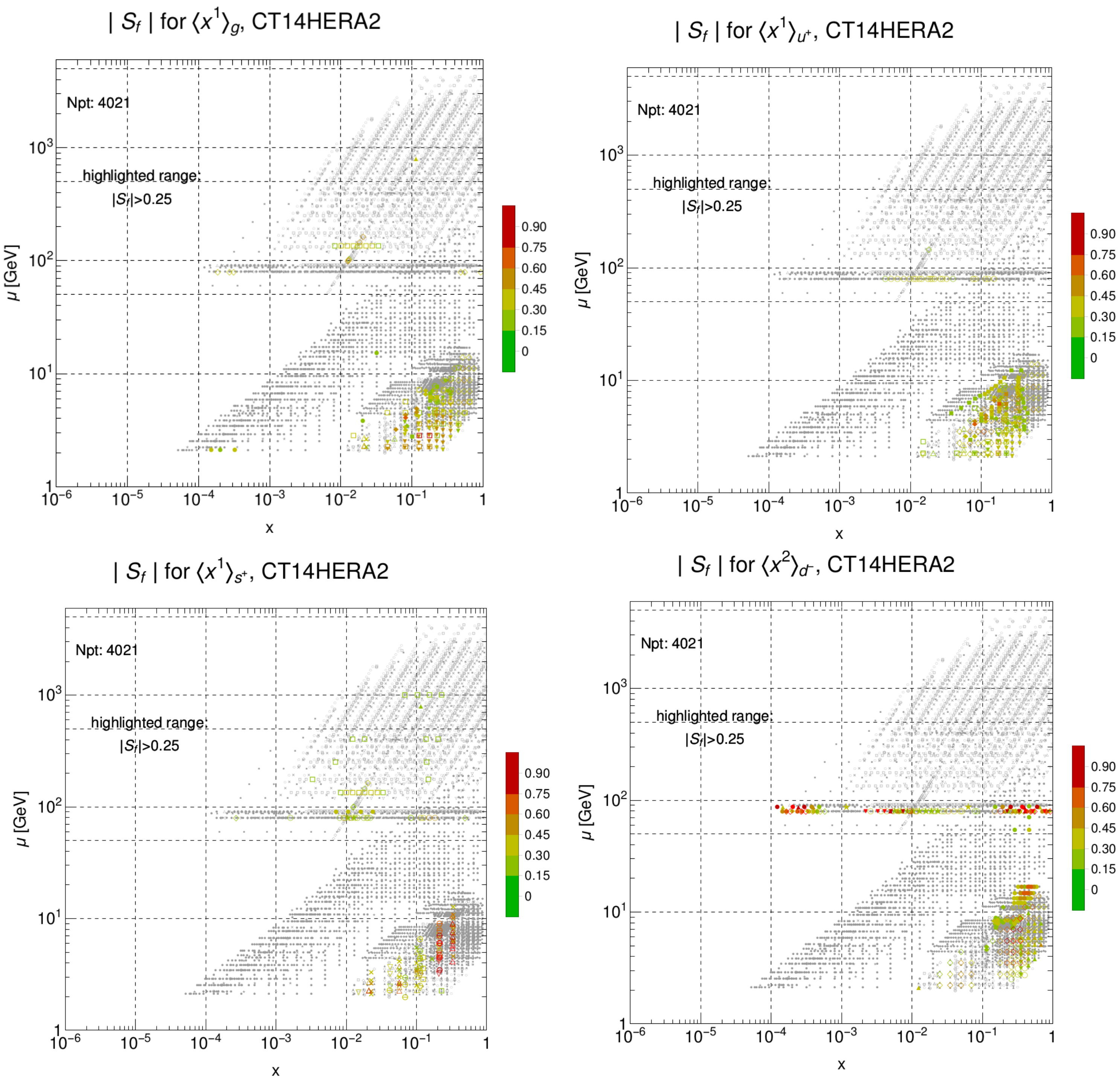
(grows with moment order, n)

- We focus on **isovector** (u-d) PDF combinations

→ on the lattice, these are more readily computed since flavor non-singlet combinations do not receive disconnected insertions

- Moments of higher order are constrained by higher x_i fixed-target data:





➡ the pulls for most PDF moments are dominated by small clusters of experiments, with a roughly power-law falloff in their impact when ranked in descending order

➡ data from fixed-target DIS and Drell-Yan [often on nuclear targets] are crucial!

(ii) quasi-PDFs allow access to PDFs' x dependence

- still, resolving the P_z dependence of qPDFs remains an important theoretical issue

Ji, PRL110, 262002 (2013).

$\sim \langle P|\overline{\psi}\gamma^{z,t}\psi|P\rangle$ matching kernel (pQCD) higher-twist corrections

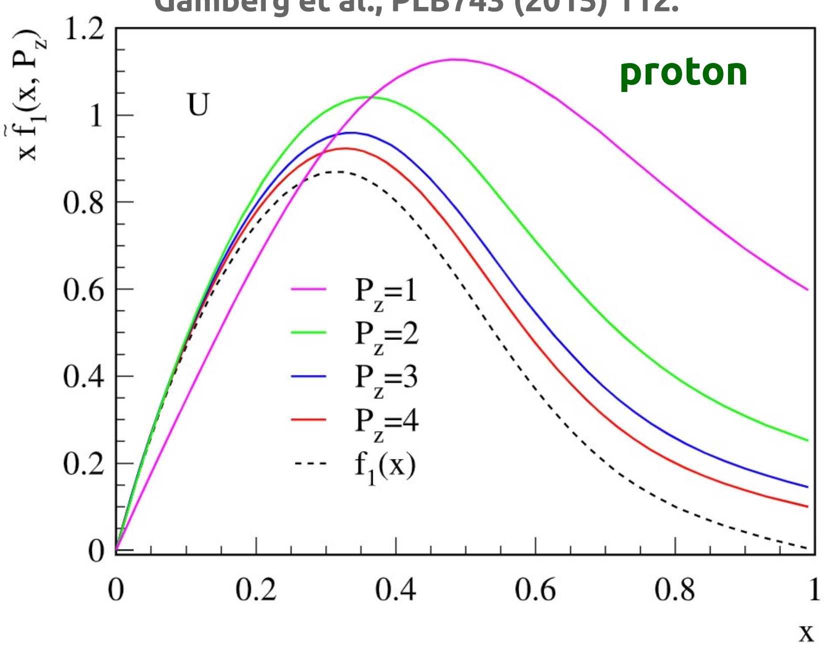
$$\widetilde{q}(x,P_z,\widetilde{\mu}) = \int dy\, Z\left(\frac{x}{y},\frac{\Lambda}{P_z},\frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{P_z^2},\frac{M^2}{P_z^2}\right)$$

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

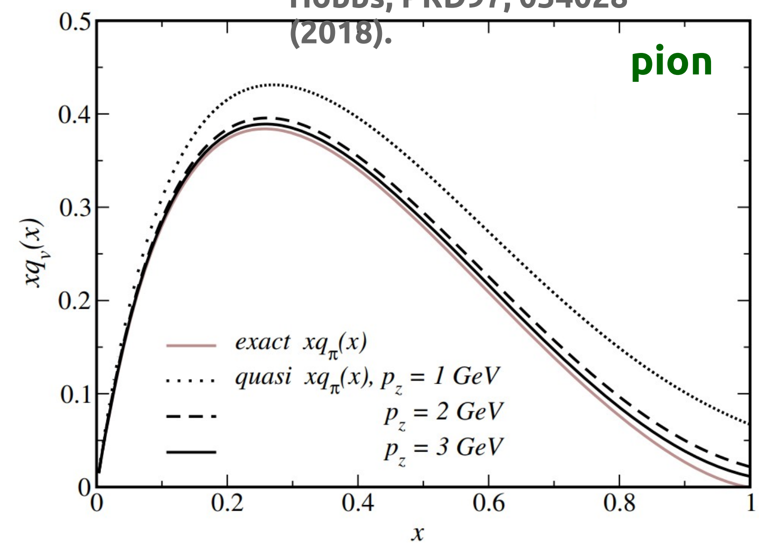
$\sim \langle P|\overline{\psi}\gamma^{+}\psi|P\rangle$

➡ this can be demonstrated with simplified models for the nucleon...

Gamberg et al., PLB743 (2015) 112.

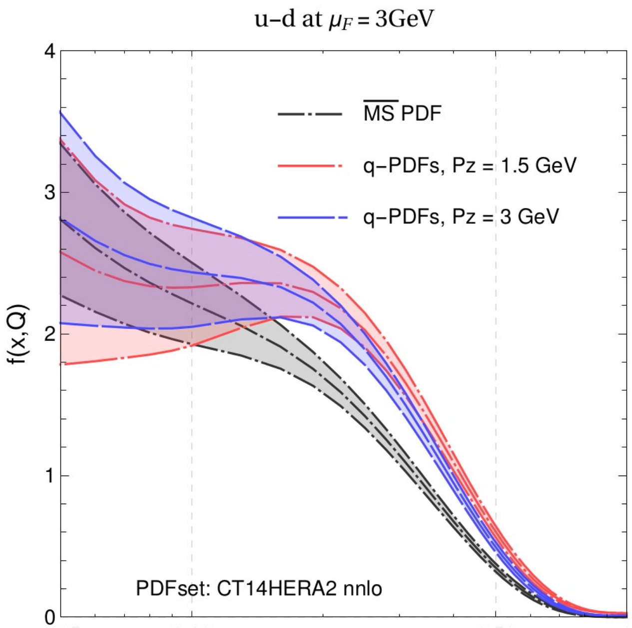


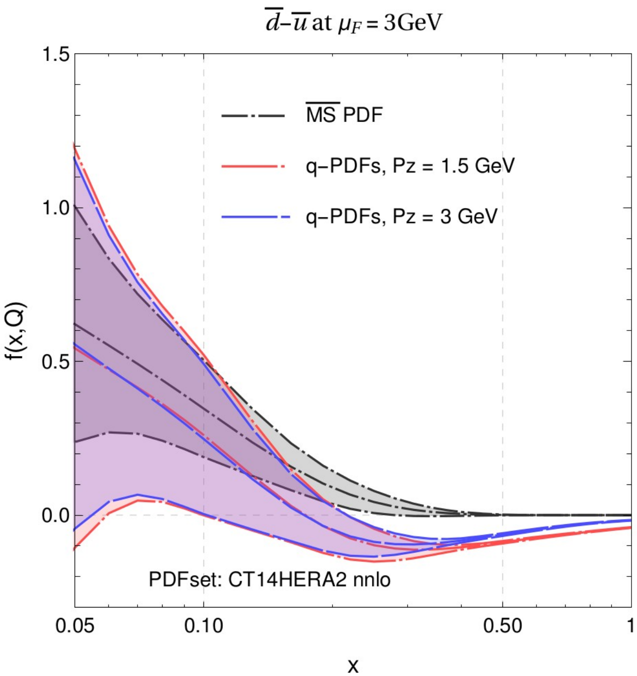
Hobbs, PRD97, 054028 (2018).



... and similar considerations hold for the pion.

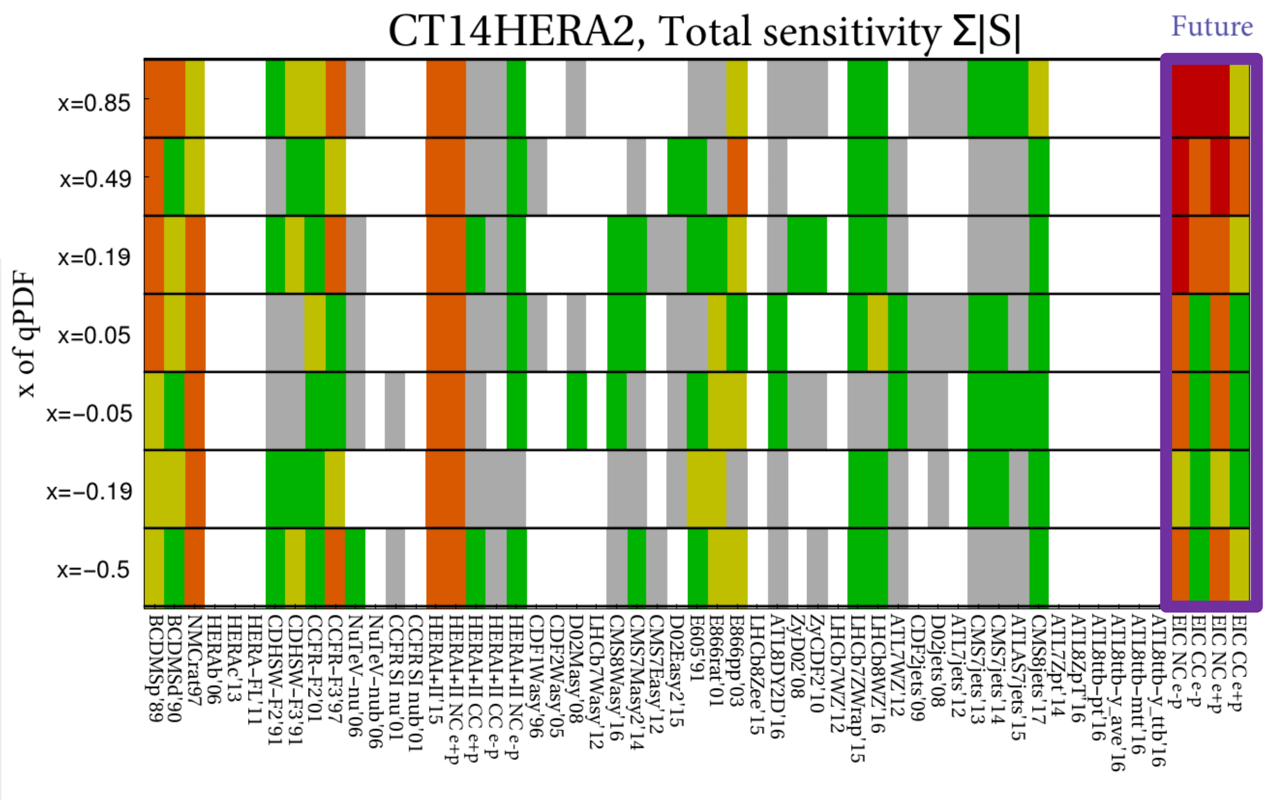
total sensitivity to matched quasi-PDFs





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

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



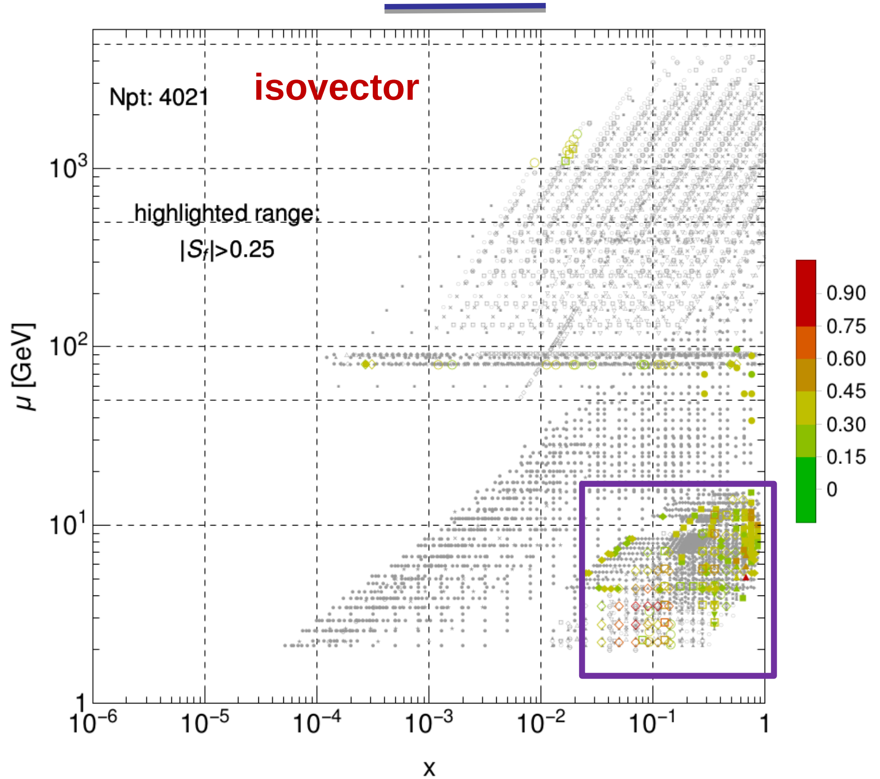
Liu et al., arXiv:1807.06566.

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

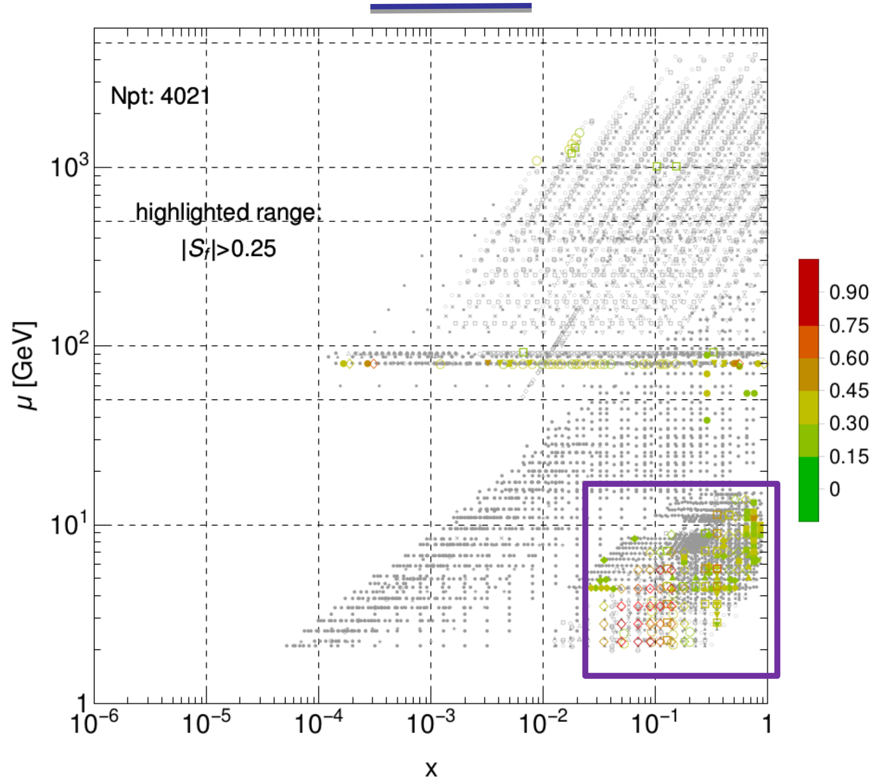
$$\underbrace{\widetilde{q}(x, P_z, \widetilde{\mu})}_{\text{qPDF}} = \int dy\, Z\left(\frac{x}{y}, \frac{\Lambda}{P_z}, \frac{\mu}{P_z}\right) \underbrace{q(y,\mu)}_{\text{ordinary PDF}} + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2}, \frac{M^2}{P_z^2}\right)$$

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

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

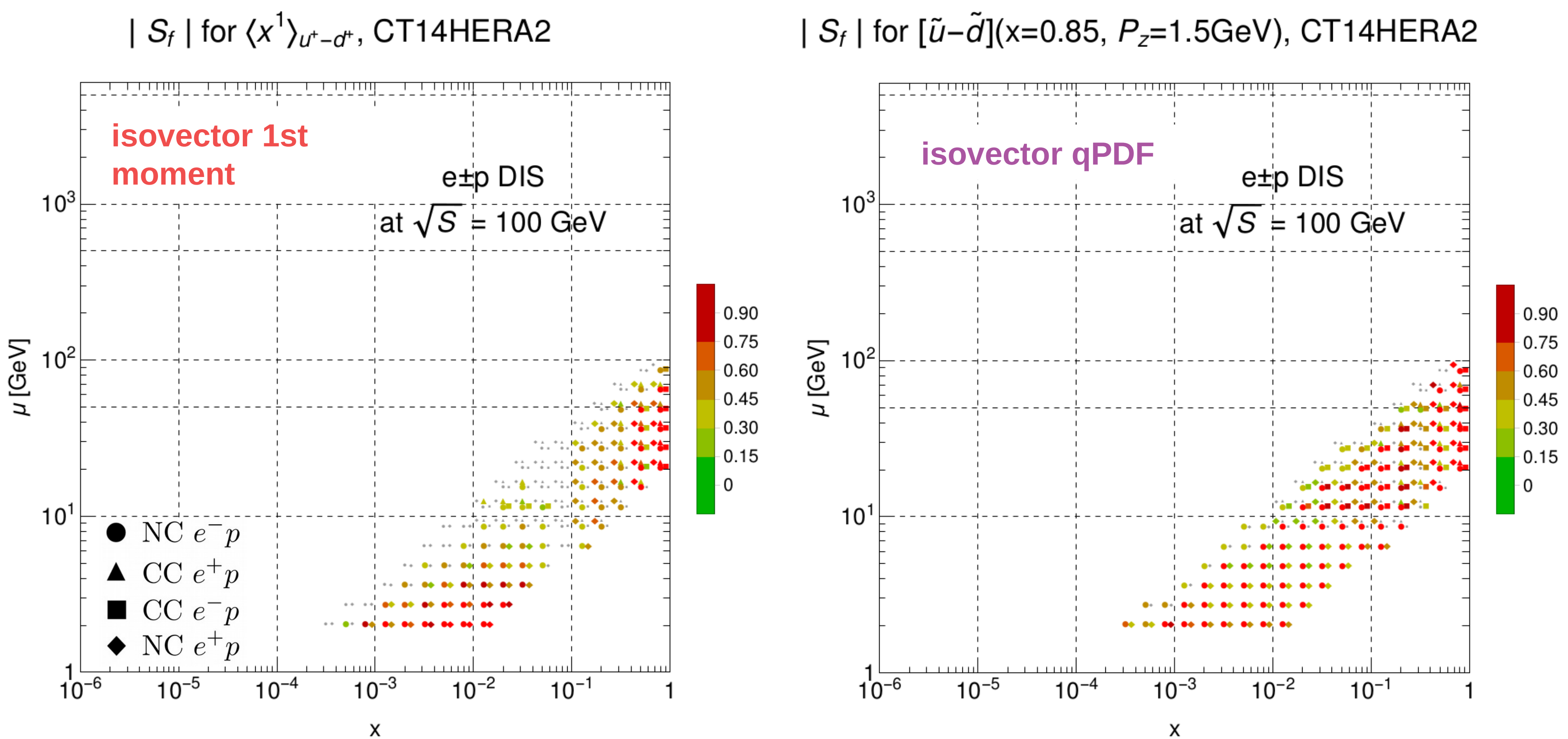


| S_f | for $[\tilde{u}-\tilde{d}](x=0.85,\ P_z=3\text{GeV})$, CT14HERA2



An EIC would drive lattice phenomenology

- A high-luminosity lepton-hadron collider will impose very tight constraints on many lattice observables; below, the isovector first moment and qPDF
- 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**



the goal is to quantify the strength of the constraints placed on a particular set of PDFs by both individual and aggregated measurements *without direct fitting*

- for single-particle hadroproduction of gauge bosons at, e.g., LHC, factorization gives

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

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

PDFs determined by fits to data; e.g., "CT14H2"

pQCD matrix elements – specified by theoretical formalism in a given fit

- *idea* : study the statistical correlation between PDFs and the quality of the fit at a measured data point(s); fit quality encoded in a (Theory) – (shifted Data) *residual* :

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

s_i : uncorrelated uncert. | $\vec{a}$: PDF parameters

a brief statistical aside, i

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

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

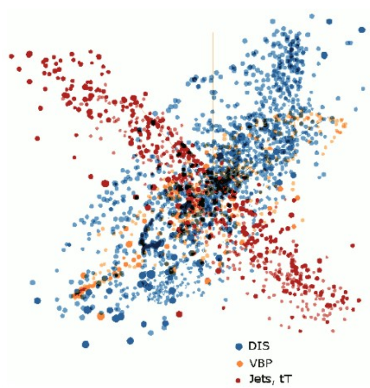
nuisance parameters to handle correlated errors

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

these result in systematic shifts to data central values:

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

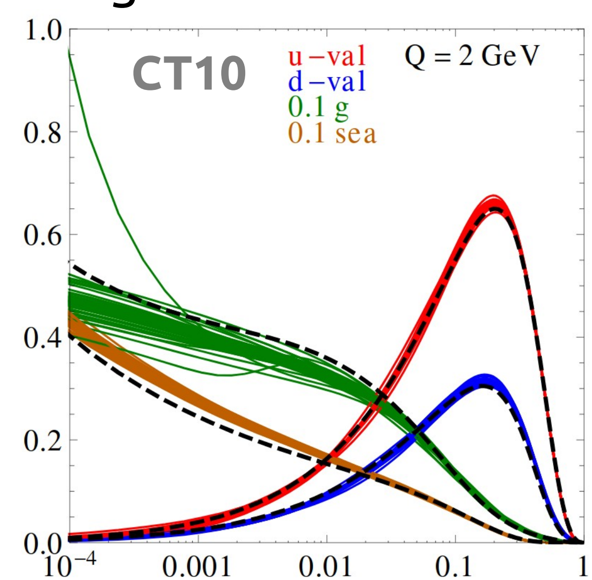
- a 56-dimensional parametric basis $\vec{a}$ is obtained by diagonalizing the Hessian matrix H determined from χ^2 **(following a 28-parameter fit)**



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

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

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

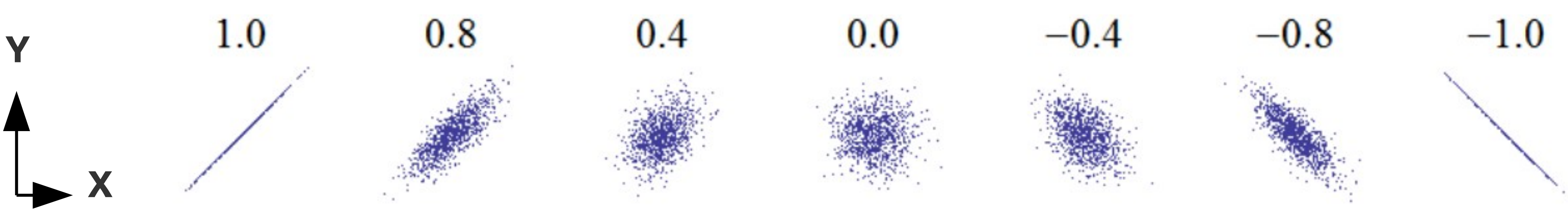


a brief statistical aside, ii

- **… 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



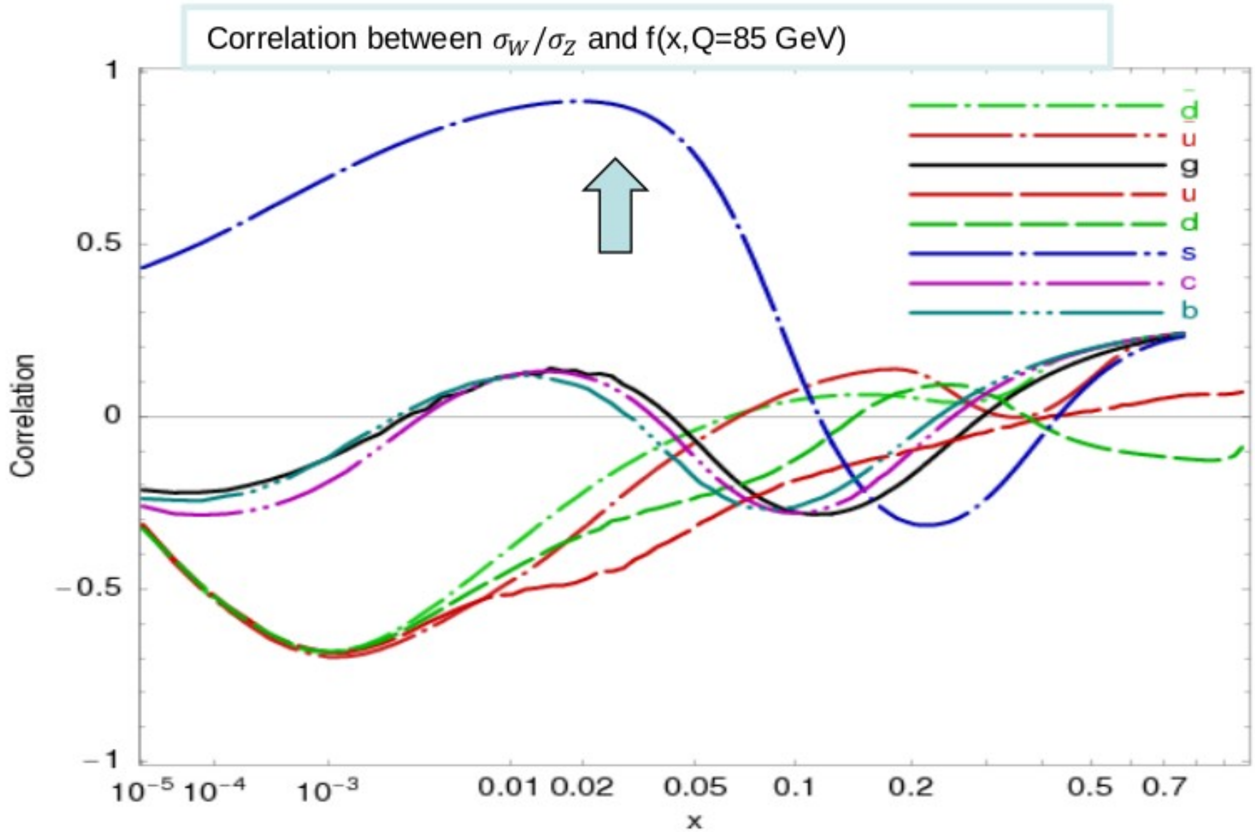
[X,Y] are exactly (anti-)correlated at the far (right) left above.

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

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

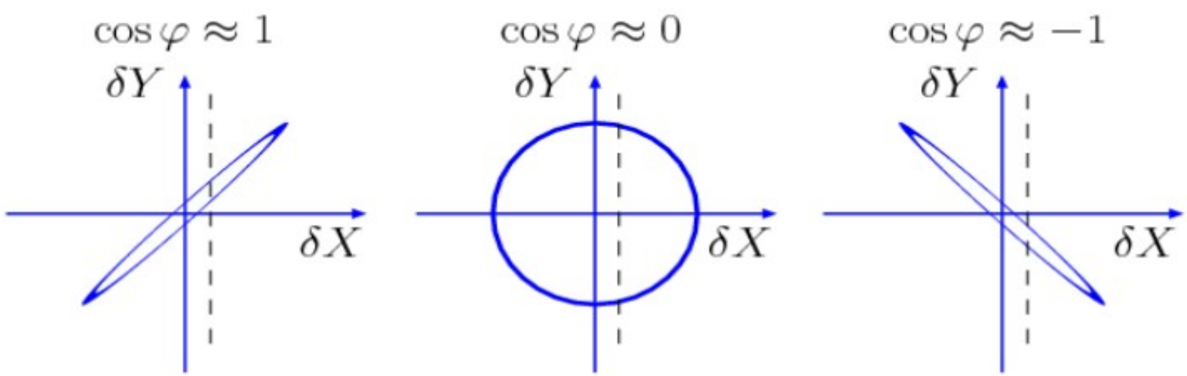
...we may turn to the Pearson correlations between PDFs and δ_i, but we first note

Correlations carry useful, but limited information



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

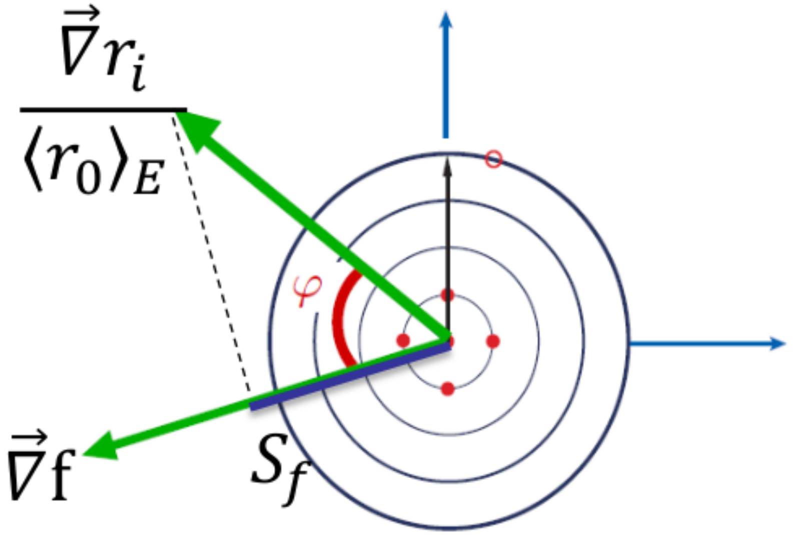
$\cos\varphi \approx \pm 1$ suggests that a measurement of X **may** impose tight constraints on Y



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

$$x_i \ : \ \text{parton mom. fraction}$$

$$\mu_i \ : \ \text{factorization scale}$$

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

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

etc...

Sensitivity ranking tables

… to assess the impact of separate experiments

No.	Expt.	N_{pt}	Rankings, **CT14 HERA2 NNLO PDFs**													
			$\sum_f \lvert S_f^E \rvert$	$\langle \sum_f \lvert S_f^E \rvert \rangle$	$\lvert S_{\bar d}^E \rvert$	$\langle \lvert S_{\bar d}^E \rvert \rangle$	$\lvert S_{\bar u}^E \rvert$	$\langle \lvert S_{\bar u}^E \rvert \rangle$	$\lvert S_g^E \rvert$	$\langle \lvert S_g^E \rvert \rangle$	$\lvert S_u^E \rvert$	$\langle \lvert S_u^E \rvert \rangle$	$\lvert S_d^E \rvert$	$\langle \lvert S_d^E \rvert \rangle$	$\lvert S_s^E \rvert$	$\langle \lvert S_s^E \rvert \rangle$
1	HERAI+II'15	1120.	620.	0.0922	B		**A**	3	**A**	3	**A**	3	B		C	
2	CCFR-F3'97	86	218.	0.423	C	**1**	C	**1**		3	B	**1**	C	2		
3	BCDMSp'89	337	184.	0.0908			C		C		B	3	C			
4	NMCrat'97	123	169.	0.229	C	2					C	2	B	2		
5	BCDMSd'90	250	141.	0.0939	C				C	3	C	3	C	3		
6	CDHSW-F3'91	96	115.	0.199	C	2	C	2		3	C	2	C	3		
7	E605'91	119	113.	0.158	C	2	C	2				3				
8	E866pp'03	184	103.	0.0935		3	C	3			C	3				
9	CCFR-F2'01	69	89.1	0.215		3		3	C	2		3		2		3
10	**CMS8jets'17**	185	87.6	0.0789					C	3						
11	CDHSW-F2'91	85	82.4	0.162		3		3		3		3	C	3		
12	CMS7jets'13	133	63.8	0.0799					C	3						
13	NuTeV-nu'06	38	58.9	0.259		3		3				3		3	C	**1**
14	**CMS7jets'14**	158	57.5	0.0606					C	3						
15	CCFR SI nub'01	38	49.4	0.217		3		3				3		3	C	**1**
16	**ATLAS7jets'15**	140	48.2	0.0574						3						
17	CCFR SI nu'01	40	48.	0.2		3		3				3		3	C	**1**

Experiments are listed in the descending order of the summed sensitivities to $\bar d, \bar u, g, u, d, s$

For each flavor, A and 1 indicate the strongest total sensitivity and strongest sensitivity per point

C and 3 indicate marginal sensitivities; low sensitivities are not shown

new/ongoing global analyses

- **NNPDF3**: not anchored to specific parametrizations/models

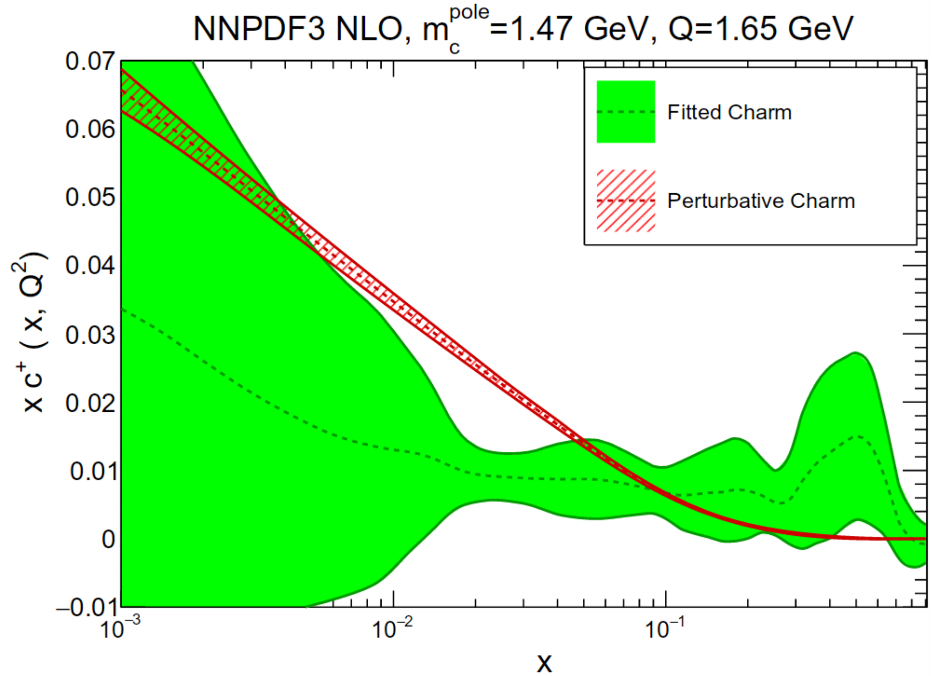
  see: Ball *et al.* Eur. Phys. J. **C76** (2016) no.11, 647

- *included* EMC:

$\langle x \rangle_{\rm IC} = 0.7 \pm 0.3\%$ at $Q \sim 1.5$ GeV

$\rightarrow$ drove a **very** hard $c(x) = \bar{c}(x)$ distribution

- peaked at $x \sim 0.5$
- AND, required a *negative* IC component to describe EMC $F_2^{c\bar{c}}$!



- recent CTEQ-TEA IC analysis, extending **CT14**

  see: T. J. Hou *et al.* JHEP**02** (2018) 059.

$\rightarrow$ found $\langle x \rangle_{\rm IC} \lesssim 2\%$; examined $m_c^{\rm pole}$ dependence

future experimental prospects?

- jet hadroproduction: $pp \to (Zc) + X$ at **LHCb**

  e.g., Boettcher, **Ilten**, Williams, PRD**93**, 074008 (2016).

$\to$ a "direct" measure in the forward region, $2 < \eta < 5$

. . . sensitive to $c(x)$, $x \sim 1$ for *one* colliding proton

$\to$ can discriminate $\langle x \rangle_{\mathrm{IC}} \gtrsim 0.3\%$ ("valencelike"), 1% ("sealike")

- prompt atmospheric neutrinos?

  see: **Laha** & Brodsky, 1607.08240 (2016).

  $\to$ IceCube ν spectra may constrain IC normalization

- possible impact upon hidden charm **pentaquark**, P_c^+?

  e.g., Schmidt & Siddikov, PRD**93**, 094005 (2016).

- AFTER@LHC? . . . fixed-target pp at $\sqrt{s} = 115$ GeV

  Brodsky *et al.* Adv. High Energy Phys. **2015**, 231547 (2015). **[Signori]**