the EIC as a Bridge to High Energy Physics

Lecture 2: higher precision at the LHC from PDFs and EIC science

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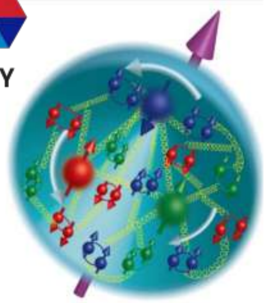
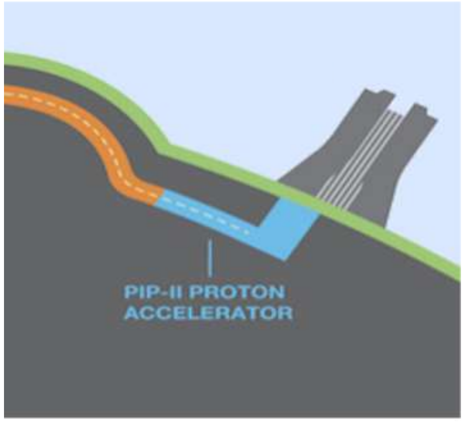
June 13th 2023

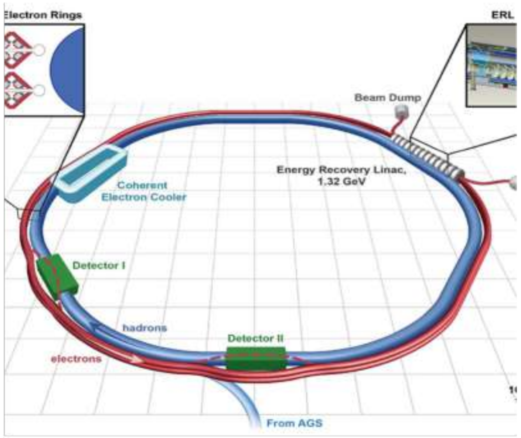
Argonne NATIONAL LABORATORY



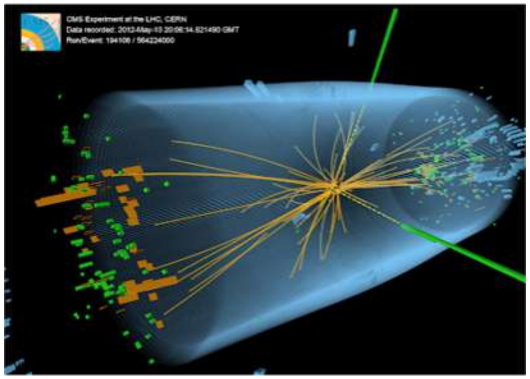
Fermilab



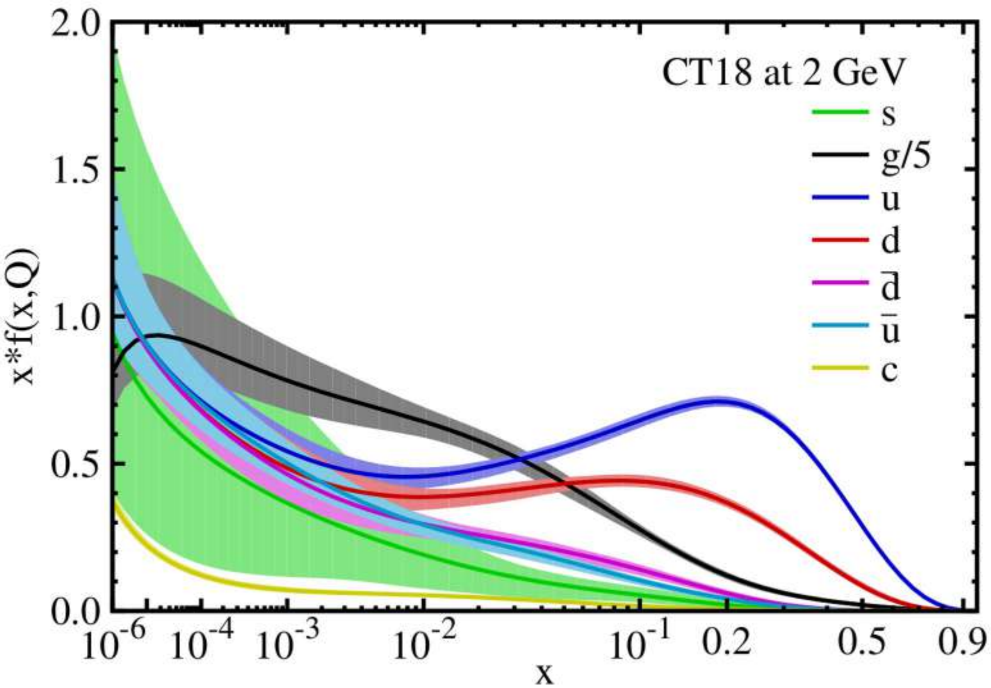
Electron-Ion Collider



Large Hadron Collider



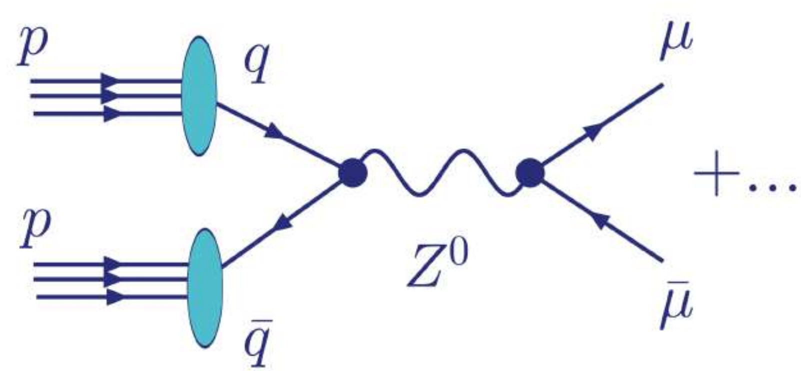
yesterday: PDFs transcend the HEP-nuclear divide



- Lecture 1 introduced PDFs from HEP perspective
  - stressed theory and methodology for determinations from hadronic data

- today: open PDF issues of EIC relevance; HEP implications

→ QCD factorization theorem; here, for Drell-Yan processes (e.g., LHC):

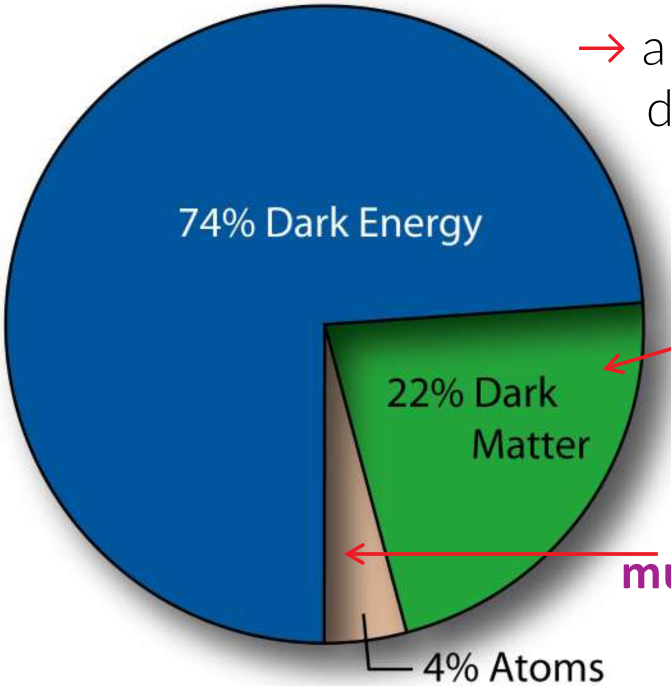


$$\sigma_{pp\to\ell\bar{\ell}X} = \sum_{a,b=q,\bar{q},g} \int_0^1 d\xi_1 \int_0^1 d\xi_2\, \widehat{\sigma}_{ab\to Z\to\ell\bar{\ell}} \left(\frac{x_1}{\xi_1}, \frac{x_2}{\xi_2}; \frac{Q}{\mu}\right) f_{a/p}(\xi_1,\mu^2) f_{b/p}(\xi_2,\mu^2)$$

$$+\,\mathcal{O}\left(\Lambda^2_{QCD}/Q^2\right)$$

QCD matter essential to HEP; e.g., BSM physics searches

→ a vast enterprise now in motion to identify dark matter (or test the Standard Model [SM]):

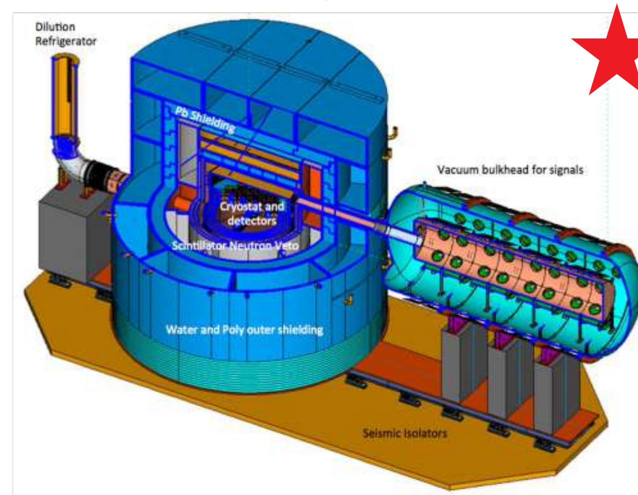


to find this

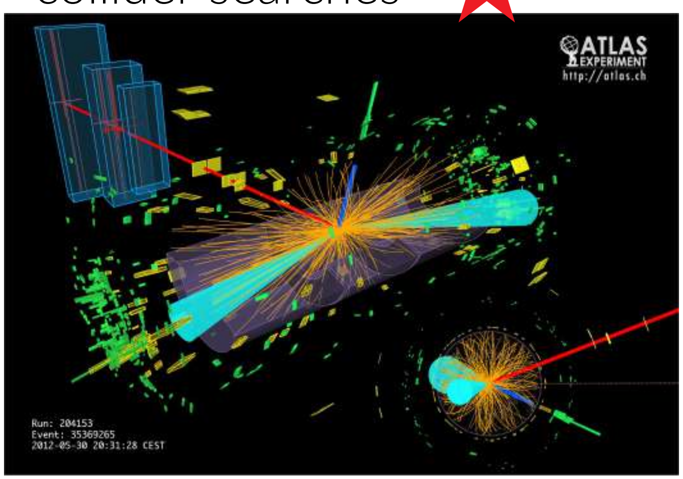
must understand this

Baryonic matter

“direct detection,” *e.g.*, SuperCDMS



collider searches



...look for the unexpected in SM processes

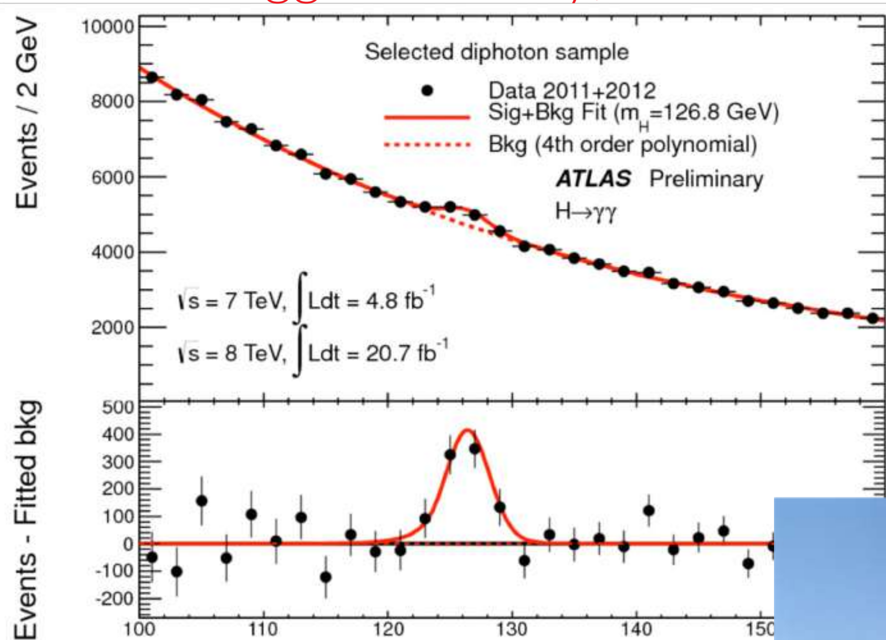
“indirect detection,” *e.g.*, AMS

searching for physics beyond the Standard Model (BSM)

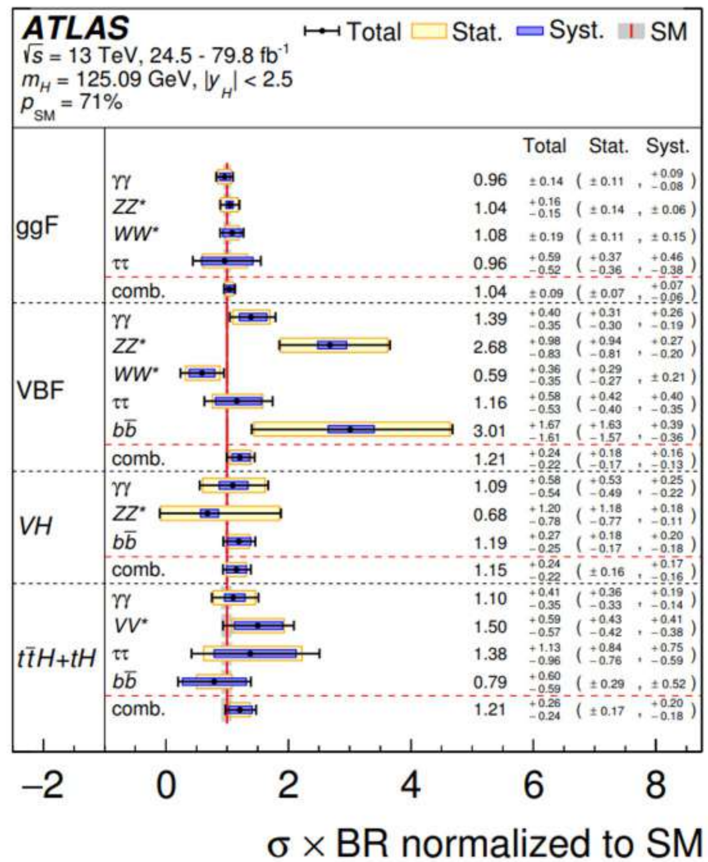
→ "discovery" searches

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!)

HEP measurements at the LHC depend on PDFs!

hadron collider theory predictions go like products of perturbative matrix elements and the PDFs to be measured at EIC

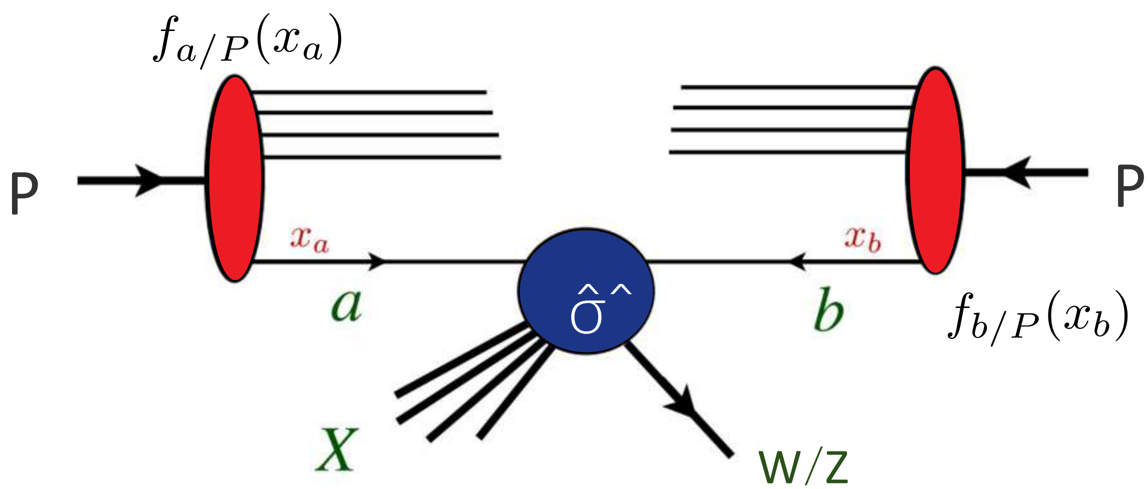
$$\sigma(PP \to W/Z+X) = \sum_n \alpha_s^n \sum_{a,b} \int dx_a dx_b$$

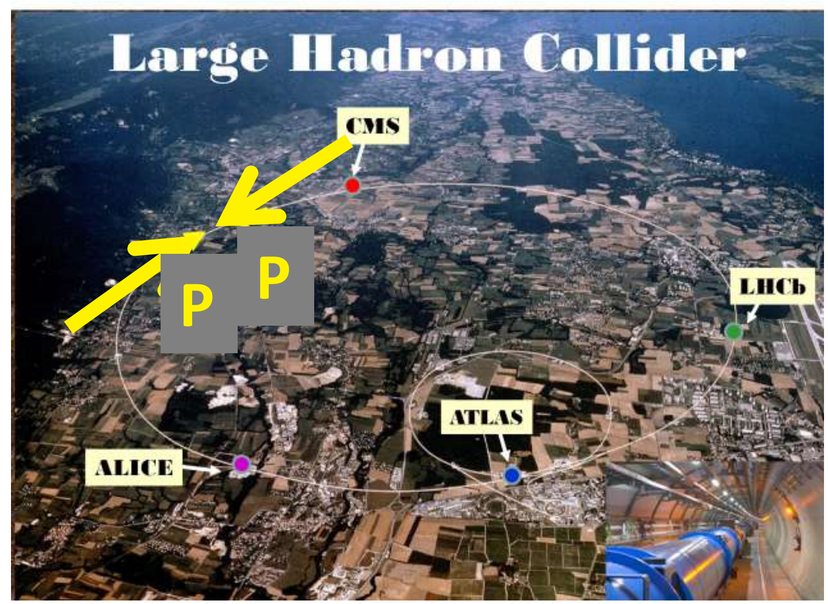
for EW boson pp production

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

pQCD matrix elements

unpolarized nucleon PDFs





BUT standard-candle measurements limited by PDF uncertainties

→ includes many observables: $\sigma_H, \ \sin^2\theta_W, \ m_W, \ \ldots$

→ this dependence NOT simply another 'theory uncertainty'

ATLAS, 1701.07240

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

→ recent CDF M_W measurement: significant PDF dependence

2205.03942 [hep-ph]

→ frontier efforts at the HL-LHC, LBNF, …, seek percent-level precision

→ confronting these effects will be a primary need of HEP

→ **importance only grows as SM tests become more systematics-dominated**

theory for (precision) electroweak observables: PDF dependence

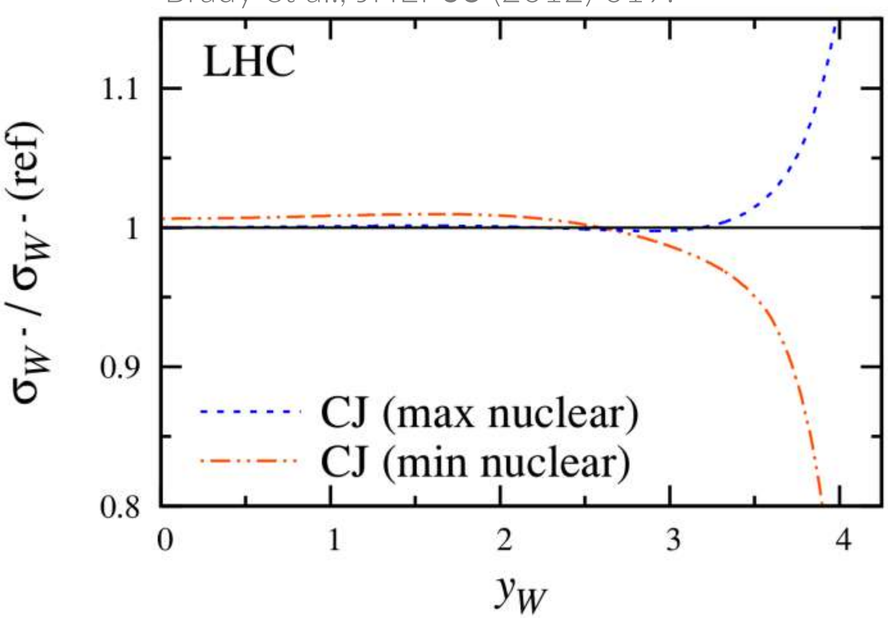
theory predictions for gauge-boson production quite sensitive to nucleon PDFs: *e.g.*, $d(x)$ at x **~ 1**, which is poorly constrained

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

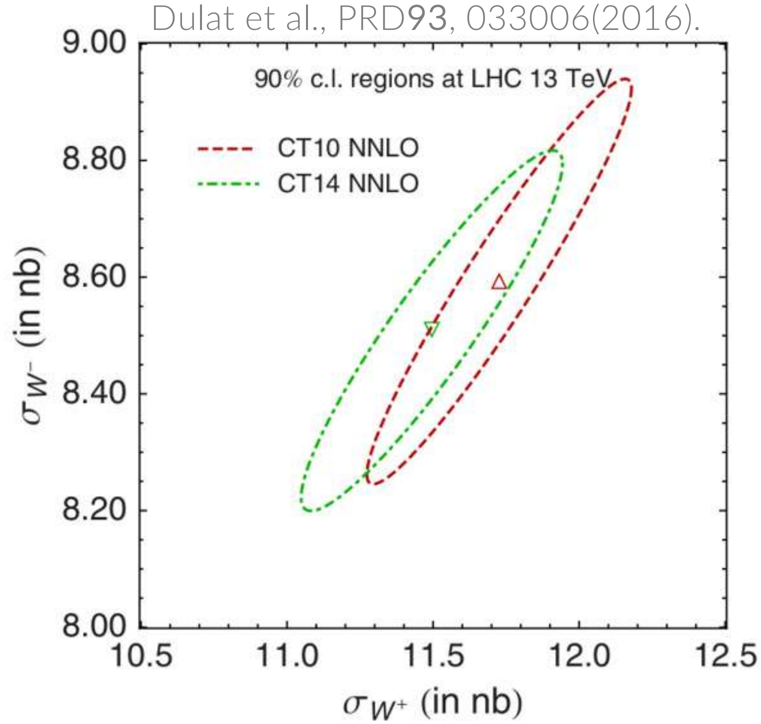
$$\frac{d\sigma}{dy}(pp \to W^- X) = \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \Big(\cos^2\theta_C \{ d(x_1)\bar{u}(x_2) + \bar{u}(x_1) d(x_2) \} + \sin^2\theta_C \{ s(x_1)\bar{u}(x_2) + \bar{u}(x_1) s(x_2) \} \Big)$$

d-type quark distributions are especially problematic

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

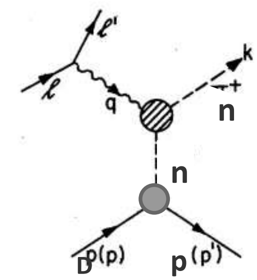


Dulat et al., PRD**93**, 033006(2016).

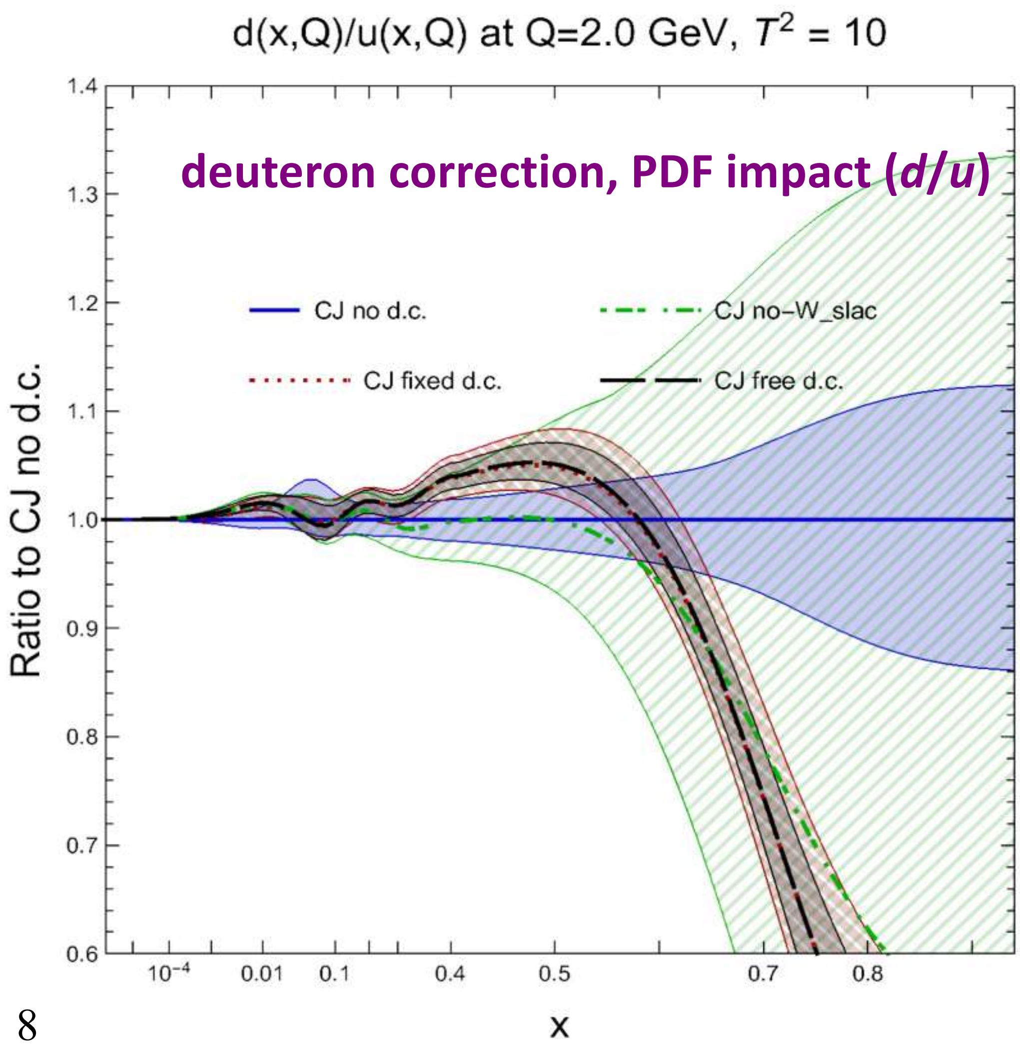


light nuclear corrections: high-*x* PDFs and flavor separation

d-PDF information from deuteron scattering; nuclear corrections relevant



$$f^d(x,Q^2) = \int \frac{dz}{z} \int dp_N^2\, \mathcal{S}^{N/d}(z,p_N^2)\, \widetilde{f}^N(x/z,p_N^2,Q^2)$$



Accardi, TJH, Jing, Nadolsky: EPJC**81** (2021) 7, 603.

corrections are generally ~percent-level, but can become larger, especially at <u>high *x*</u>

→ also, PDF correlations with gluon, other flavors

impacts LHC observables; necessary for high precision

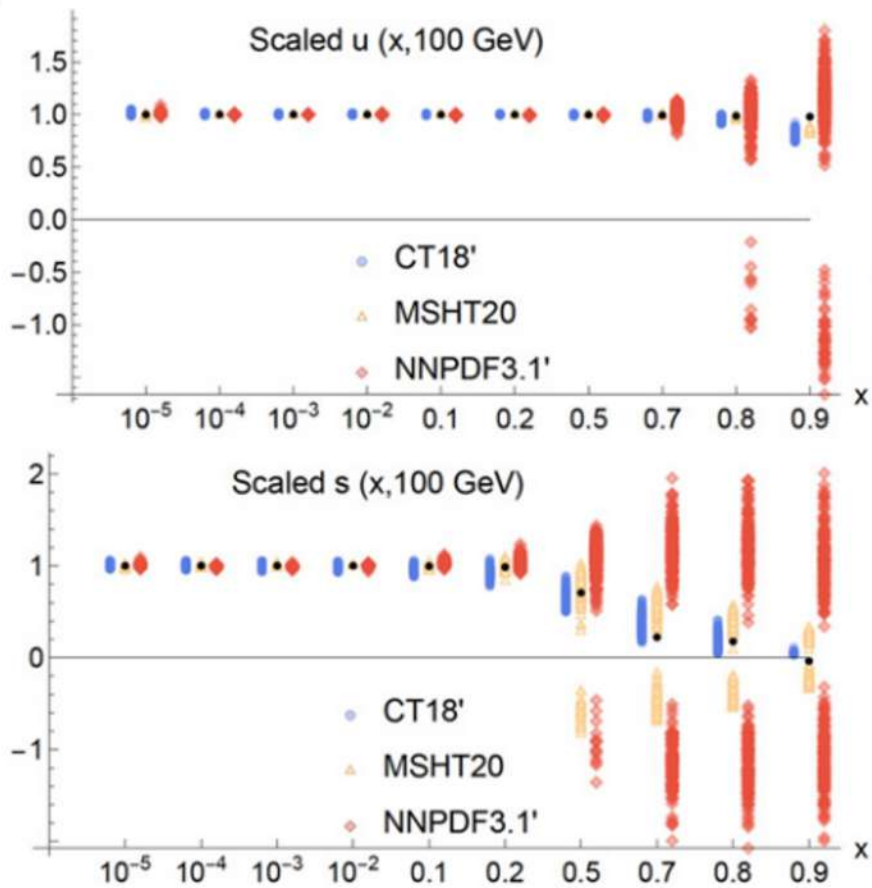
analogous situation for **heavy-nuclear effects** in νA scattering → main (inclusive) source of **strangeness** info.

understanding PDFs and their uncertainties: high x

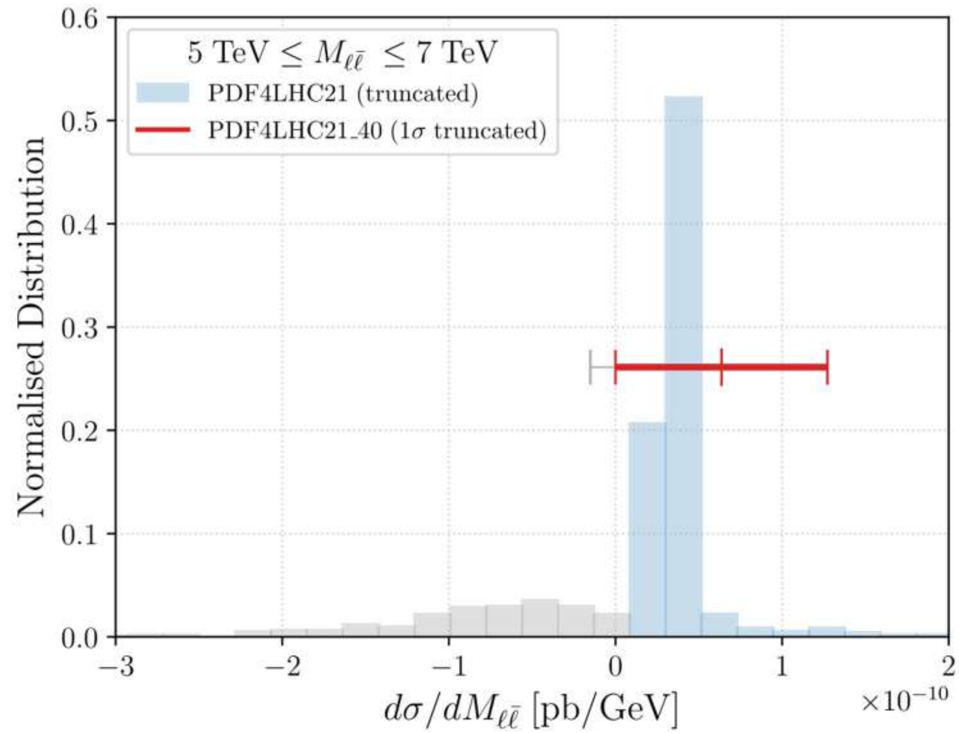
PDF4LHC21 benchmarking: J.Phys.G 49 (2022) 8, 080501.

MC sampling of high-x PDFs can sometimes produce irregularities

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



→ can produce subtle but non-negligible phenomenological consequences:



strong need for high-x sensitive data: (HL-)EIC

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

another example: PDF uncertainties in **Higgs physics**

→ Higgs phenomenology is significantly PDF-limited

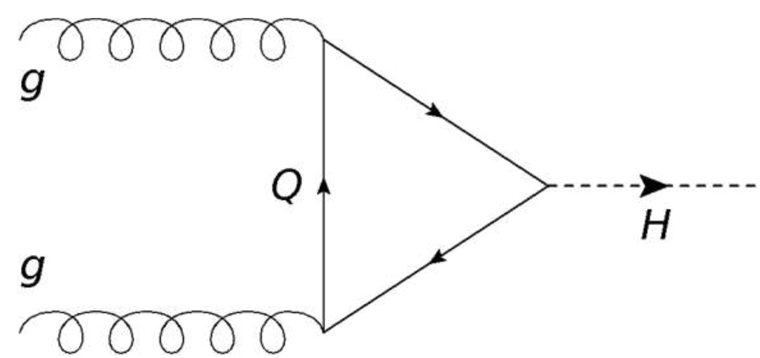
(i.e., predicted cross sections strongly vary with PDF parametrization)

→ similar for $\sin^2\theta_W,\ m_W,\ \ldots$

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

PDF sets	$\sigma(H)^{\mathrm{NNLO}}$ (pb) nominal $\alpha_s(M_Z)$
ABM12 [2]	39.80 ± 0.84
CJ15 [1][a]	$42.45^{+0.43}_{-0.18}$
CT14 [3][b]	$42.33^{+1.43}_{-1.68}$
HERAPDF2.0 [4][c]	$42.62^{+0.35}_{-0.43}$
JR14 (dyn) [5]	38.01 ± 0.34
MMHT14 [6]	$42.36^{+0.56}_{-0.78}$
NNPDF3.0 [7]	42.59 ± 0.80
PDF4LHC15 [8]	42.42 ± 0.78

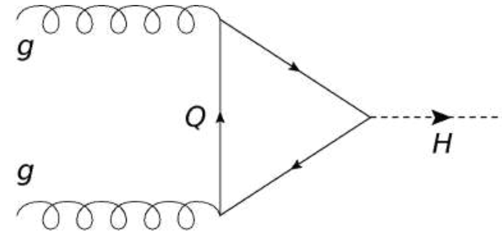
wide spread in predictions

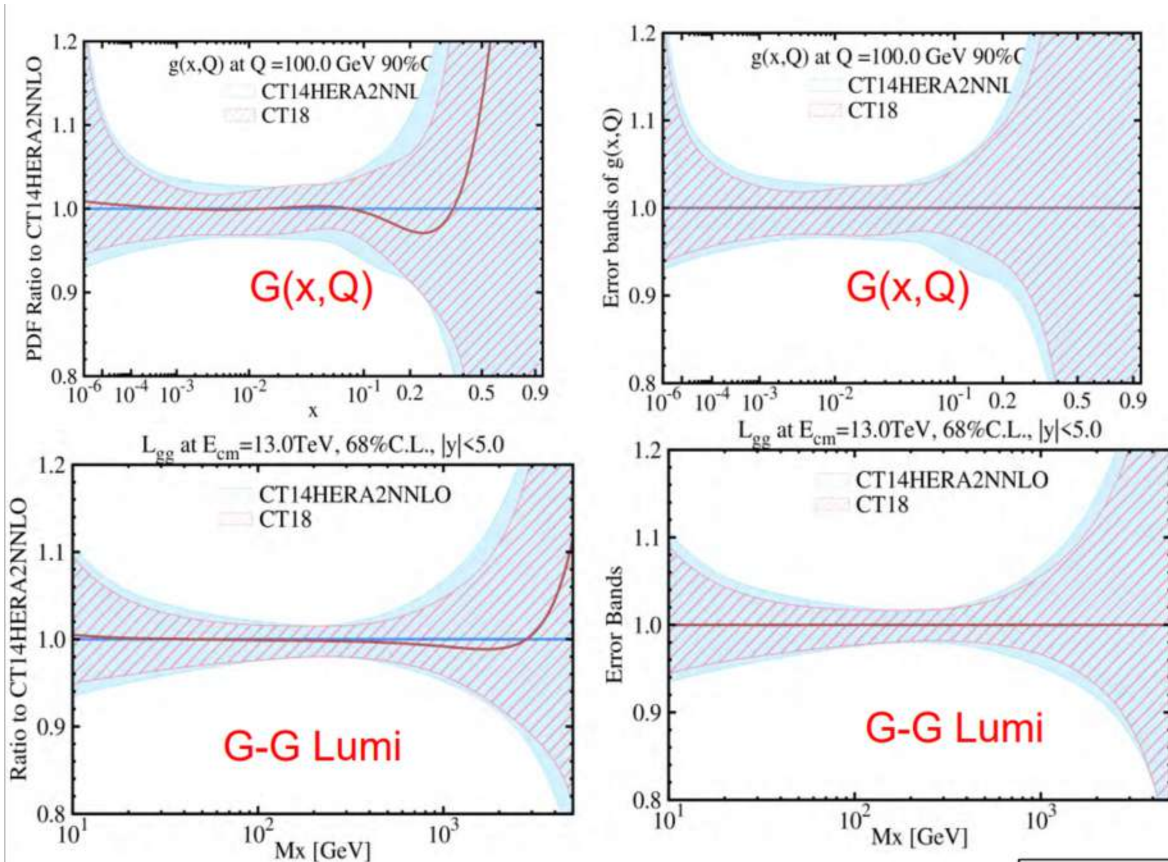


Higgs production dominated by gluon fusion (gluon PDF)

→ enhancing the discovery potential at LHC will require improving these uncertainties!

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





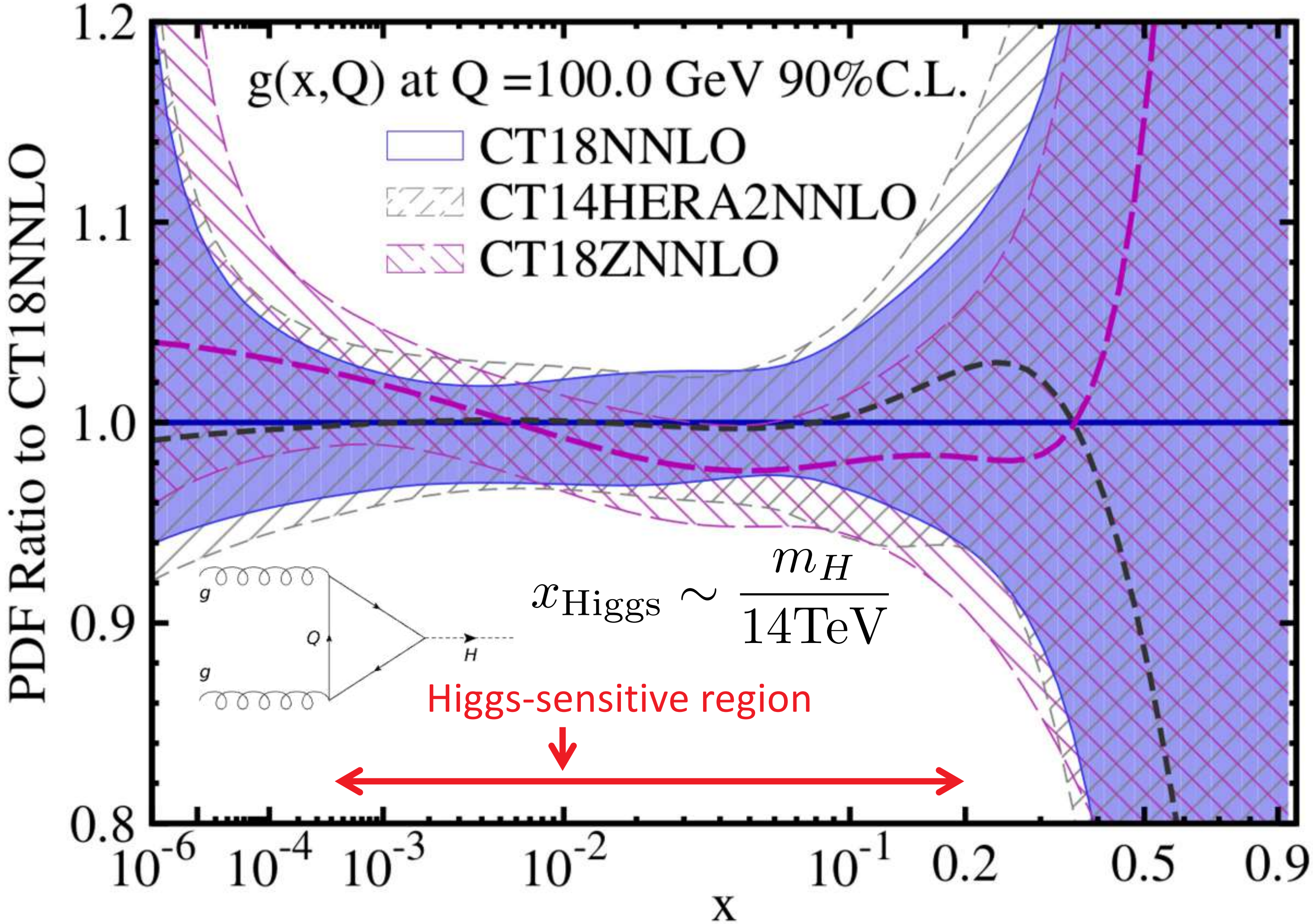
	σ(gg-h)	$\delta\sigma$ sym(90%C.L.)
7 TeV		
CT14NNLO	14.67	0.46
CT18	14.57	0.44
8 TeV		
CT14NNLO	18.70	0.57
CT18	18.45	0.55
13 TeV		
CT14NNLO	42.78	1.32
CT18	42.43	1.26
14 TeV		
CT14NNLO	48.23	1.50
CT18	47.91	1.42

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

$$\frac{1}{s}\frac{dL_{gg}}{d\tau} = \frac{1}{s}\int_{\tau}^{1}\frac{dx}{x}g(x)g(\tau/x)$$

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

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

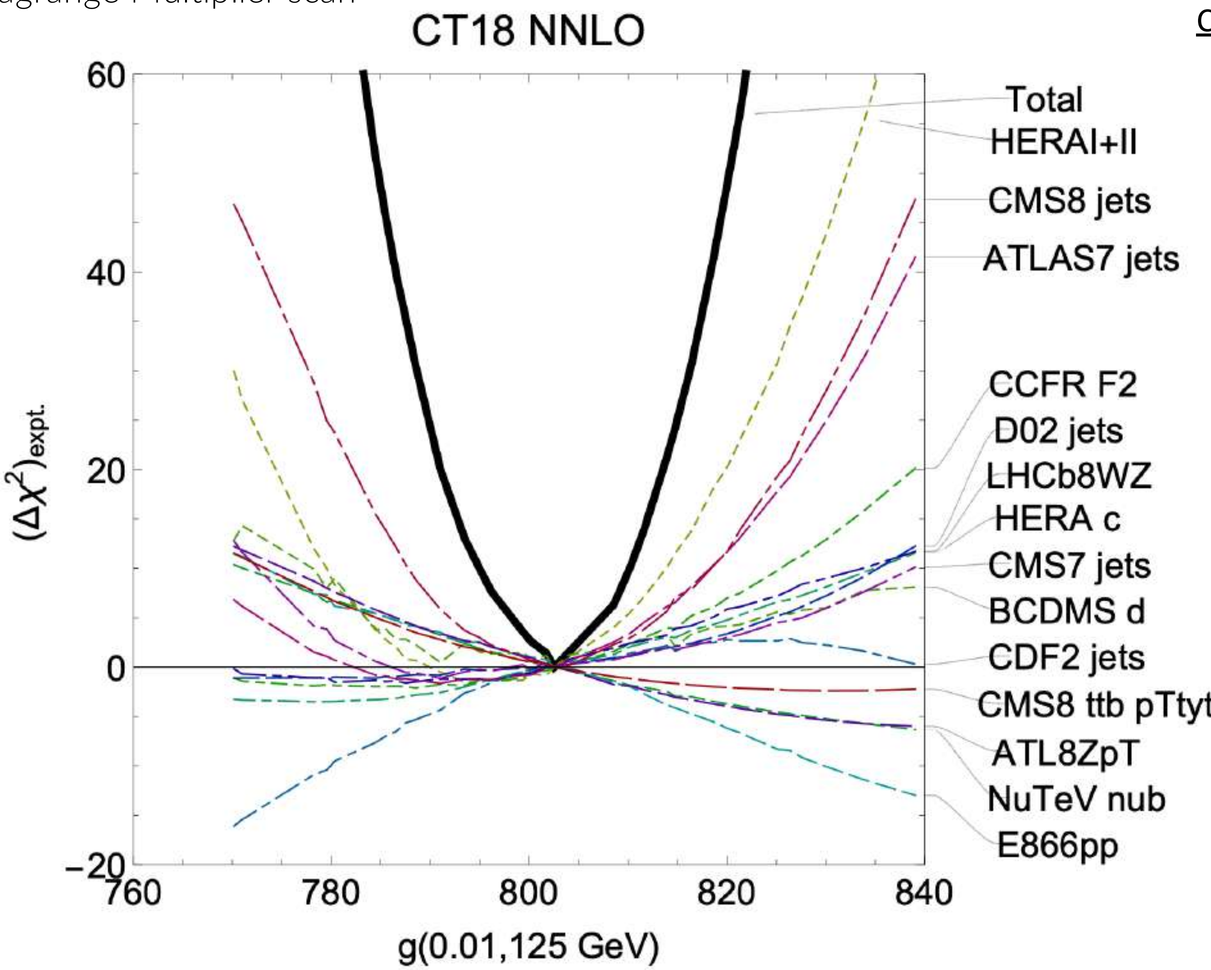


knowledge of the gluon content of the nucleon directly translates into constraints on SM Higgs production

compatibility of fitted data sets is a crucial question

tensions among individual fitted experiments drive a larger PDF uncertainty

Lagrange Multiplier scan



CT18: PRD**103** (2021) 1, 014013

examine change in χ^2 as PDF continuously varies away from fitted central value

larger gluon… and Higgs cross section… favored by some expts [like E866pp], but not others [like 8 TeV CMS jets]

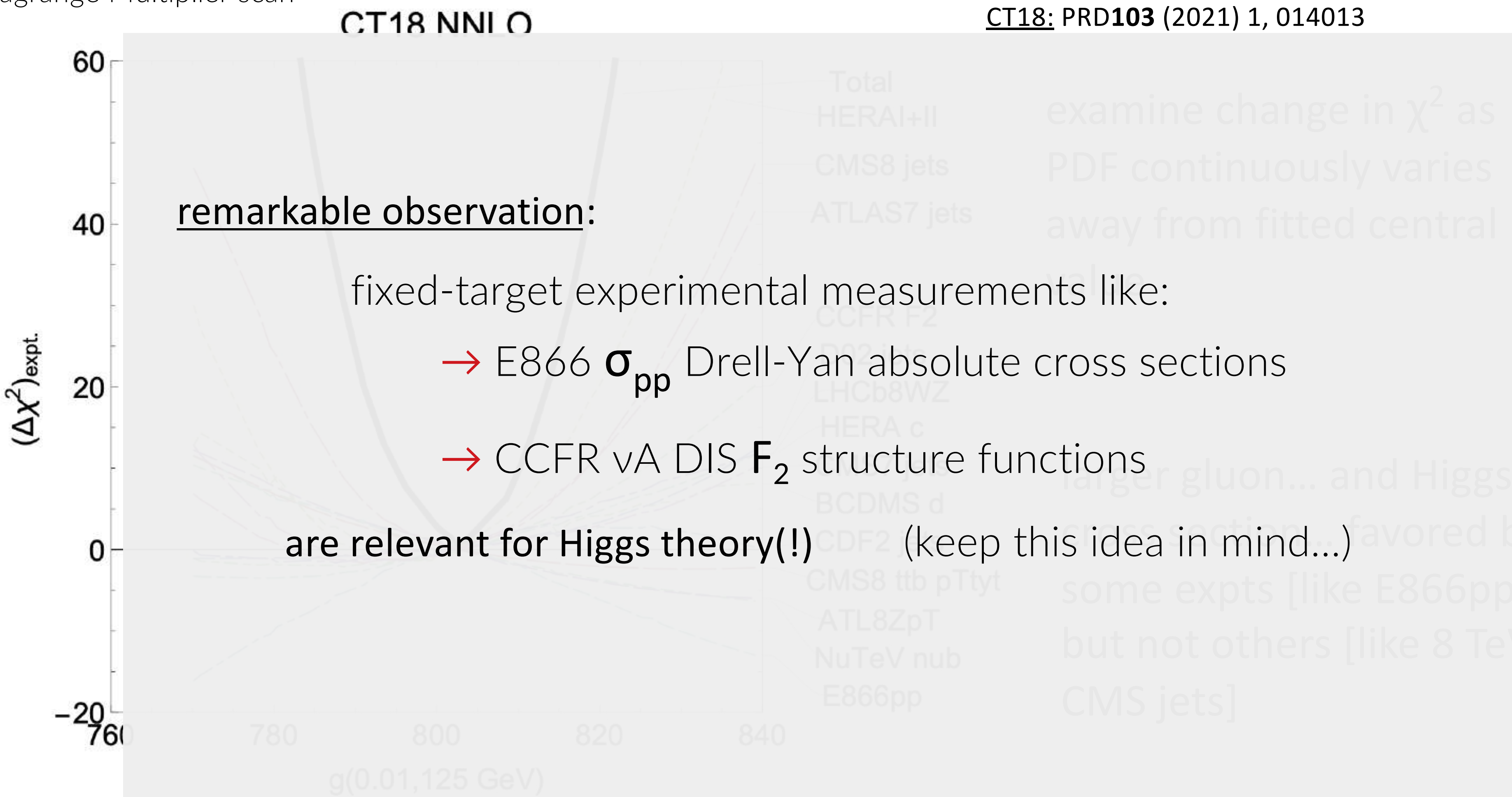
serious impediment to higher precision in PDFs and resulting theory predictions

compatibility of fitted data sets is a crucial question

tensions among individual fitted experiments drive a larger PDF uncertainty

Lagrange Multiplier scan

CT18: PRD**103** (2021) 1, 014013



remarkable observation:

fixed-target experimental measurements like:

→ E866 σ_{pp} Drell-Yan absolute cross sections

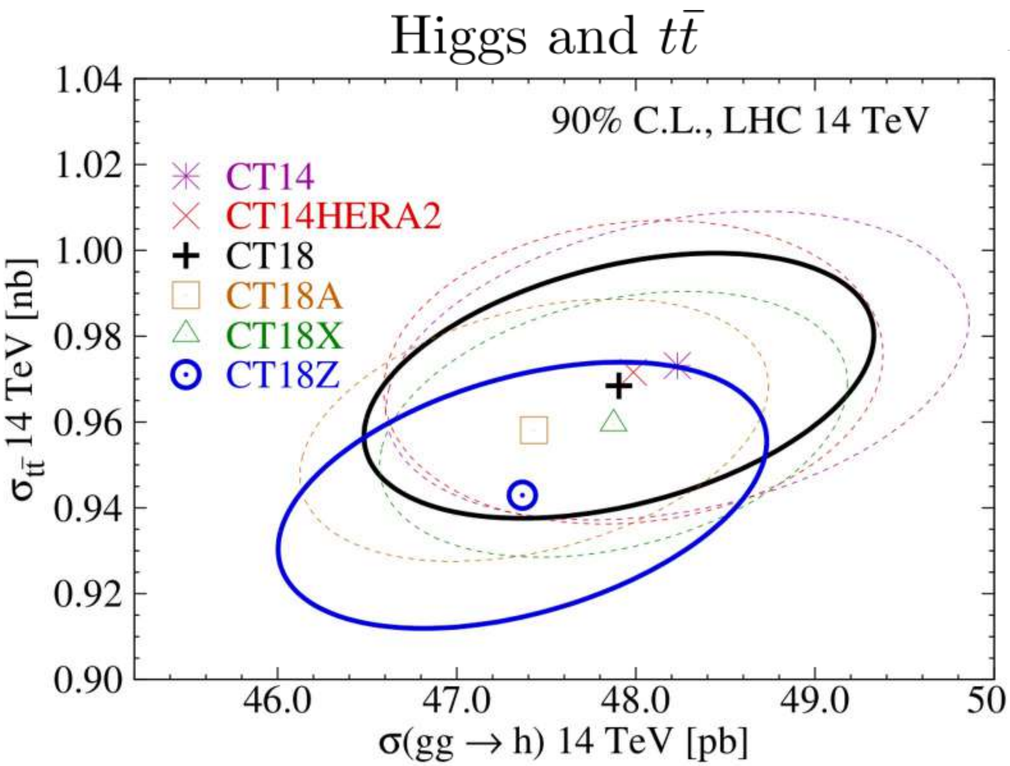
→ CCFR νA DIS F_2 structure functions

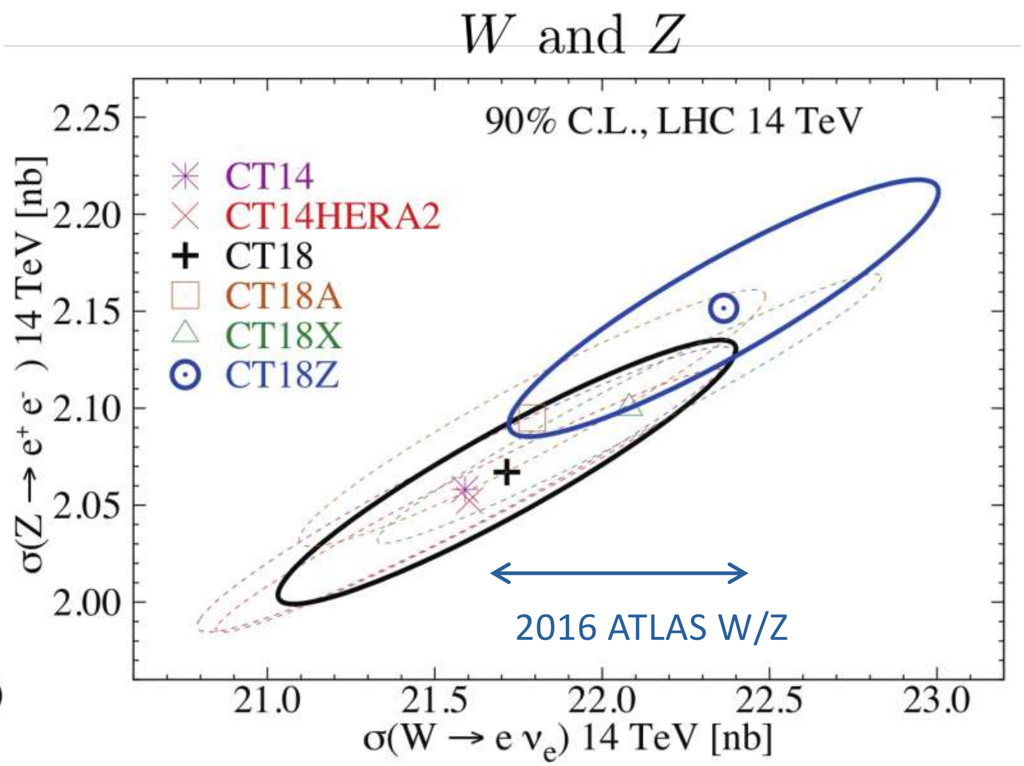
are relevant for Higgs theory(!) (keep this idea in mind...)

serious impediment to higher precision in PDFs and resulting theory predictions

SM theory predictions from global analyses

from (N)NNLO analyses, state-of-the-art predictions for fundamental LHC observables → *e.g.*, **total cross sections at 14 TeV**





Higs, NNLO QCD: iHixs v1.3

$t\bar{t}$, NNLO+NNLL: Top++ v2.0

$$\mu_R = \mu_F = m_t; m_{W,Z}; m_H$$

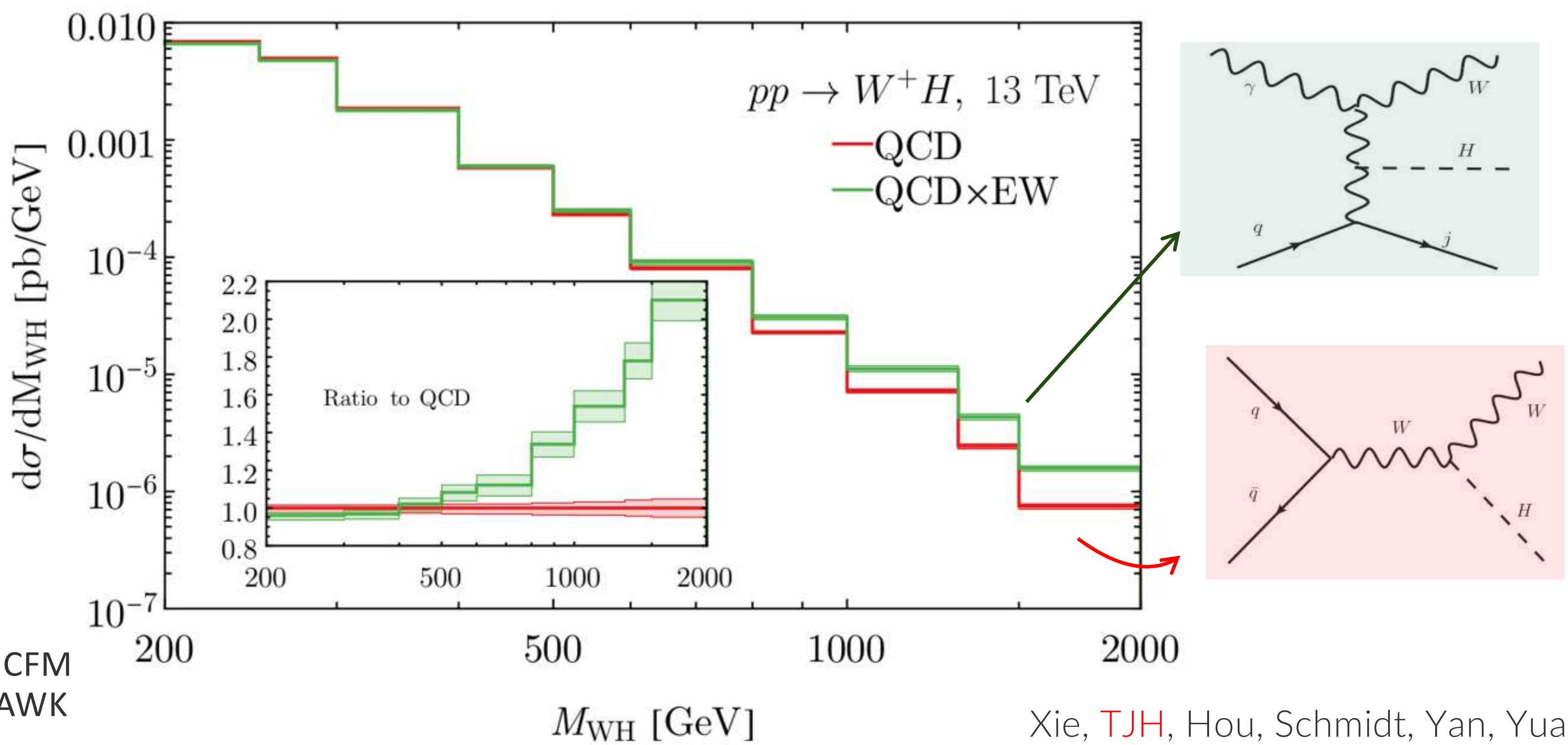
NNLO QCD: Vrap v0.9

significant PDF-driven uncertainties; also, systematic effects: W cross sections sensitive to inclusion of 2016 7 TeV ATLAS inclusive W/Z data

EW corrections for LHC processes

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

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



MCFM
HAWK

Xie, TJH, Hou, Schmidt, Yan, Yuan: 2106.10299

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

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

photon PDF for precision EW physics (i)

last night's recitation: photon as partonic degree-of-freedom; "what is a parton"

photon PDF calculable combination of factorization, hadronic tensor rep.:

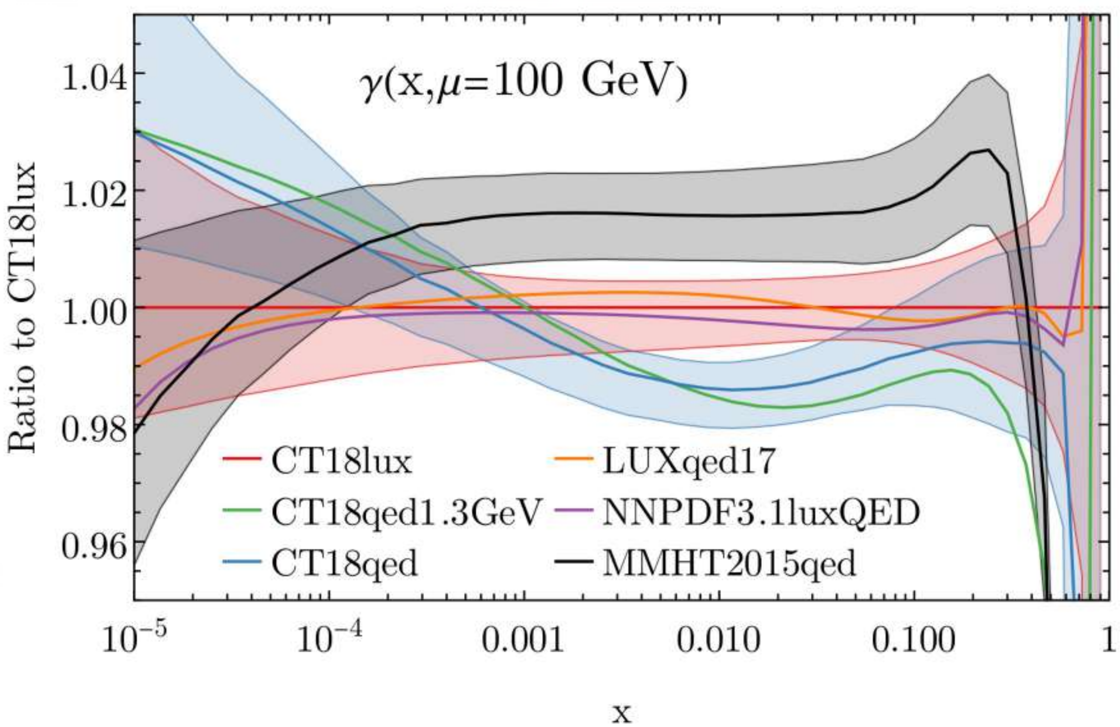
Xie, TJH, Hou, Schmidt, Yan, Yuan: 2106.10299

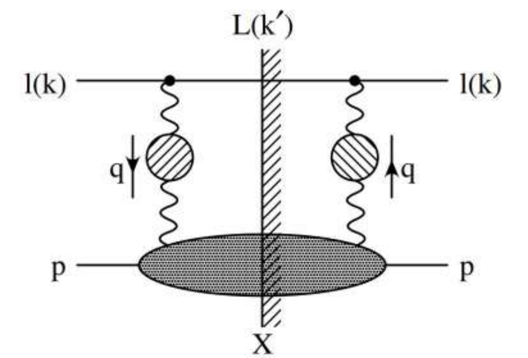
$$x\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{z}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{Q^2}{Q^2}\alpha_{\rm ph}^2(-Q^2)\left[\left(zp_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2)-z^2F_L(x/z,Q^2)\right]\right.$$

$$\left.-\alpha^2(\mu^2)z^2F_2(x/z,\mu^2)\right\}+\mathcal{O}(\alpha^2,\alpha\alpha_s)$$

Manohar, Nason, Salam, Zanderighi; JHEP12 (2017) 046

→ 2 complementary implementations: CT18lux, CT18qed





photon PDF for precision EW physics (ii)

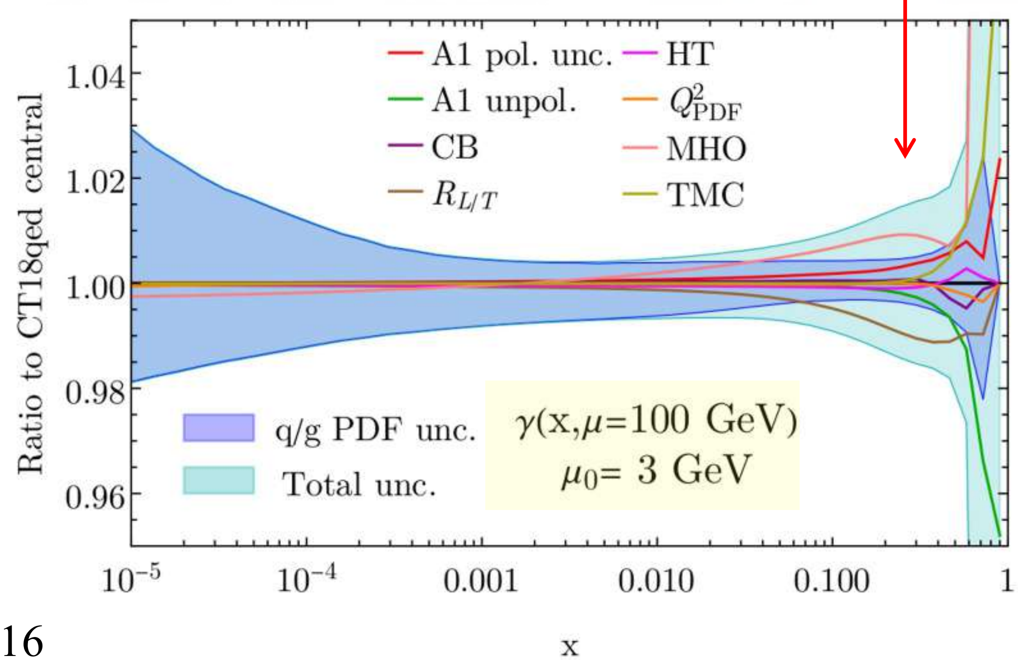
calculation depends on nonperturbative proton-structure inputs!

integrated proton SFs include contributions from **low *Q*, high *x***

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

dependence on Sachs EM **form factors**; twist-4 (HT), resonance prescriptions; target-mass corrections (TMC); …

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

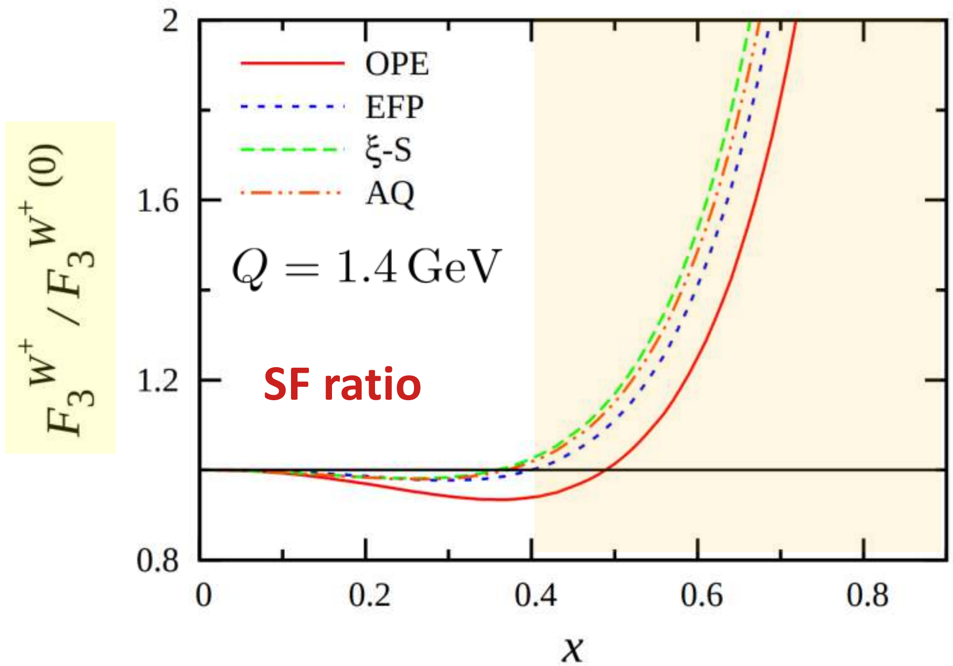


QCD effects induce uncertainties at LHC → *e.g.*, BSM-sensitive tails of rapidity distributions

for higher precision, future analyses must simultaneously incorporate and potentially fit these ingredients

EIC will help unravel these QCD effects

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



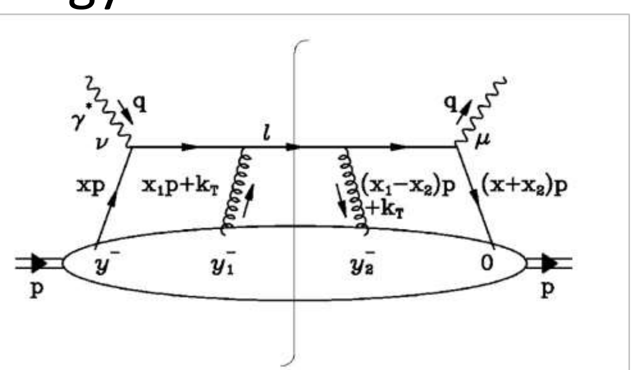
potentially large, $\sim 1/Q^2$ effects

crucial for precision in DIS

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

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

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



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

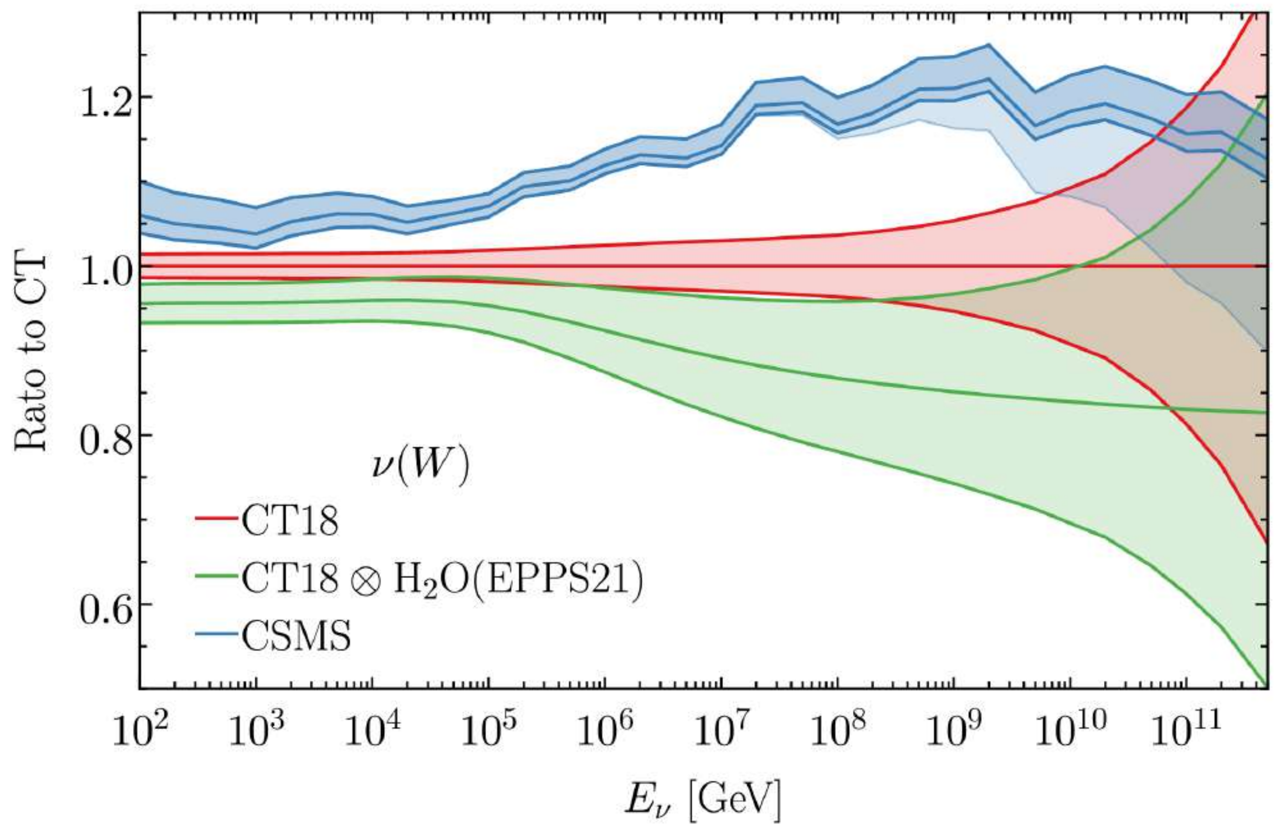
$$\Delta\langle p_T^2\rangle \equiv \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ep}$$ (jet pT broadening)

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

many observables at very high energies are (n)PDF dependent

- 'ultra-high energy' neutrinos have been proposed as having sensitivity to BSM scenarios (extra dimensions, …)

charged-current DIS neutrino cross section



2303.13607

- pervasive issue beyond LHC: neutrino cross sections similarly PDF-limited

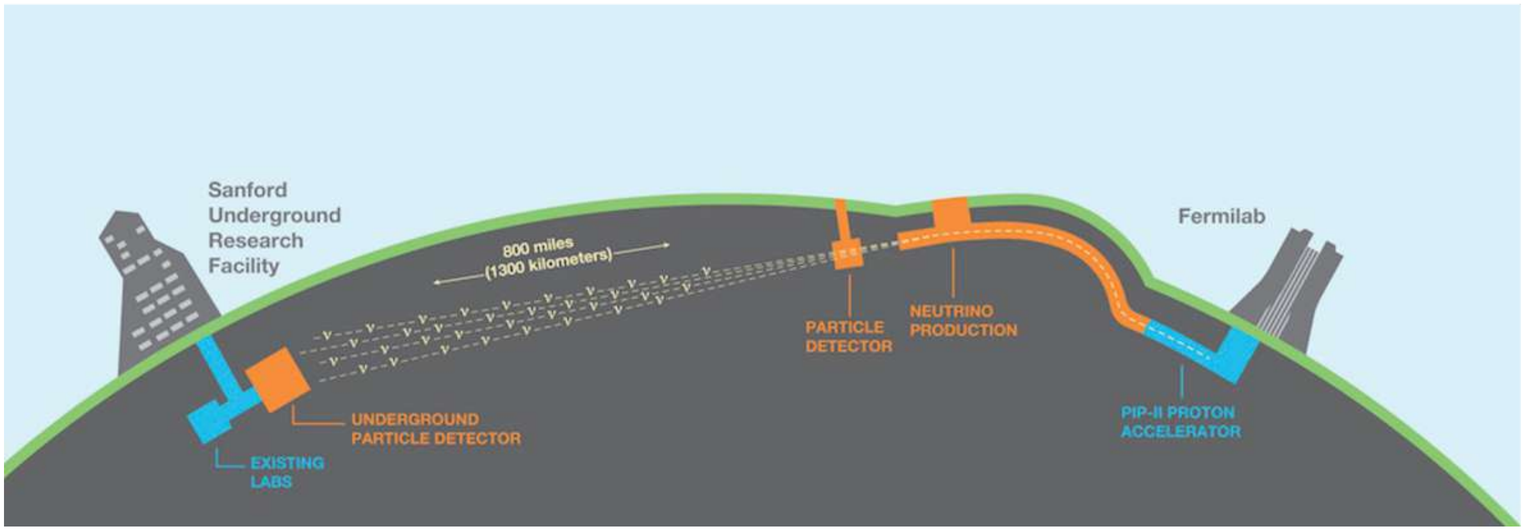
…above, for ν telescopes; analogous PDF uncertainties at low energies relevant for DUNE

interface with MC event generators, experimental interpretation

similar need: QCD for (lower-energy) neutrino efforts

Fermilab Intensity Frontier efforts: explore neutrino oscillation; search for **CP violation**

P5: flagship HEP activity and priority for US particle physics



↑ detector 2 ↑ detector 1

uncertainties:

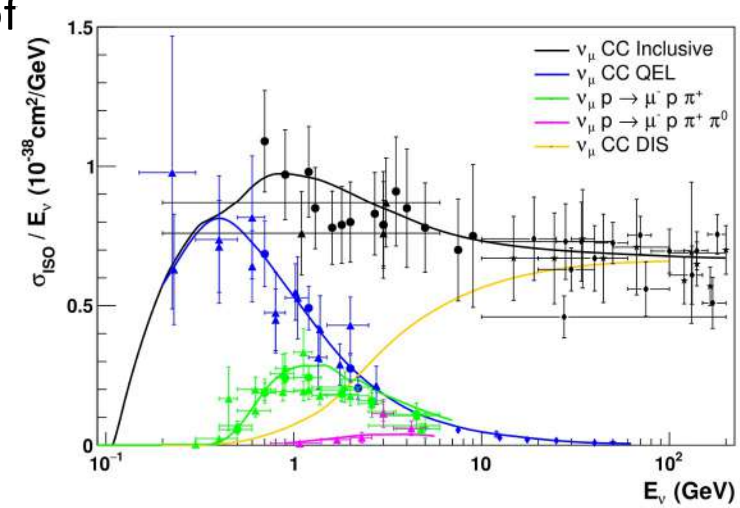
ν flux

νA cross section

→ νA cross section determined by complicated interplay of quasi-elastic, DIS, resonance contributions, …

precision in neutrino oscillation searches is limited by single-nucleon and nuclear structure uncertainties

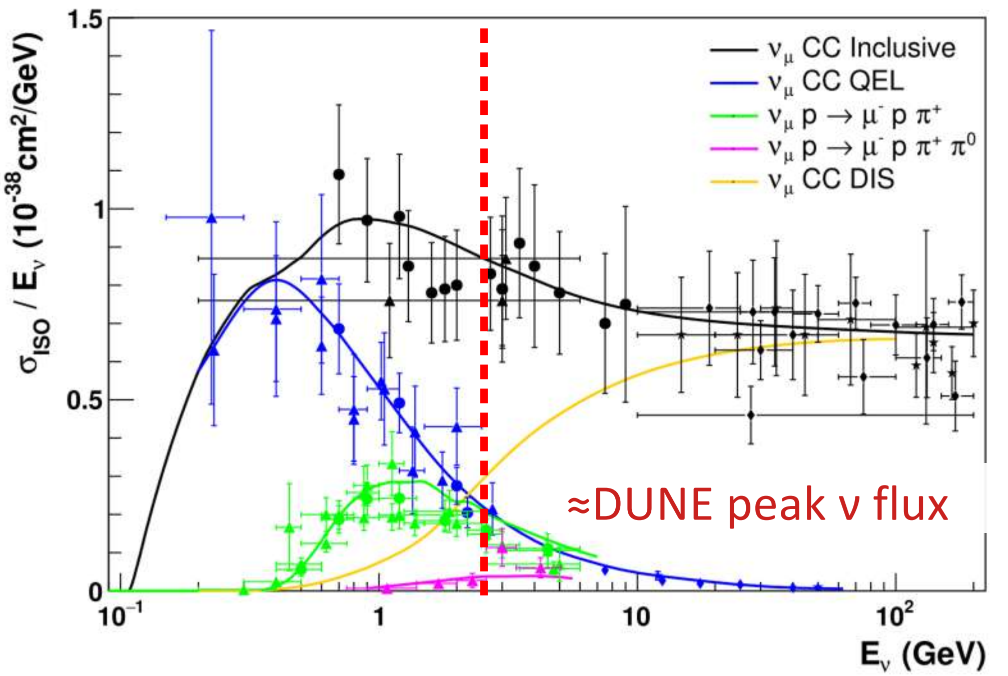
quasi-elastic	$G_A(Q^2)$
nuclear DIS	$f(x, \mu)$



few-GeV region will be critical for LBNF/DUNE

simulations for LBNF program involve neutrino generators (e.g., GENIE, GiBUU)

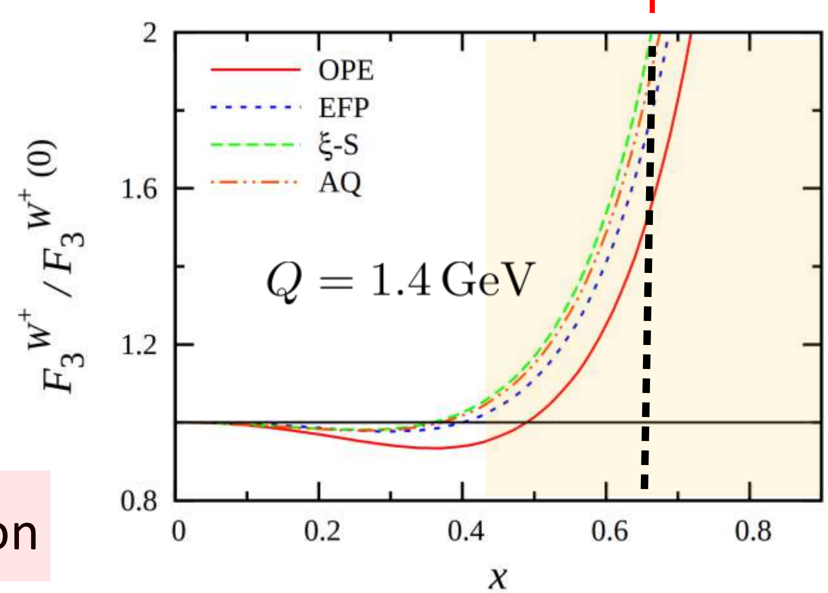
→ in complex *tunes* of physics models, **DIS is underdeveloped**



DUNE ν flux will peak around
$E_\nu \sim 2.5\,\mathrm{GeV}$

→ large share of DIS events!

(low *W* ↔ high *x*) $W \sim 2.4\,\mathrm{GeV}$



precisely where power-suppressed QCD effects are large (target-mass, higher-twist, ...): low *Q*, *W*

→ **must control**; serious challenge for νA precision

PDF fitting extendable beyond proton: nuclear PDFs

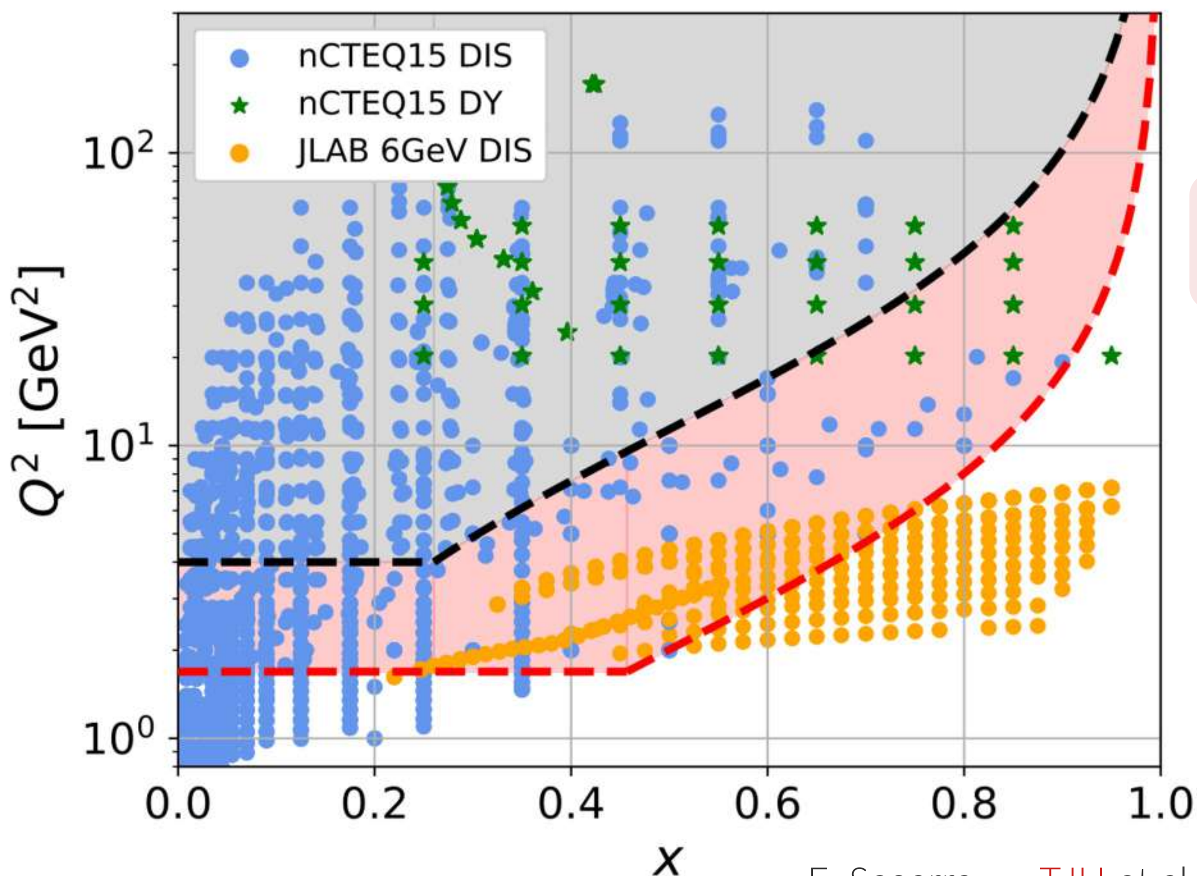
nCTEQ: parametrize and fit nuclear PDFs directly

$$f^A = \frac{Z}{A}\, f^{p/A} + \frac{(A-Z)}{A}\, f^{n/A}$$

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}$$
$$c_k \longrightarrow c_k(A) \equiv p_k + a_k(1 - A^{-b_k})$$

fit range of nuclear data; relax *W, Q* cuts

include TMC, HT prescriptions; deuteron correction

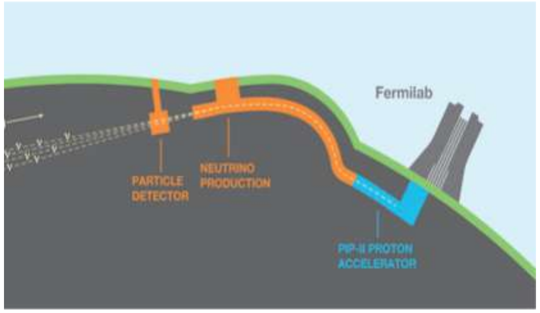


(dependence on proton baseline PDF)

nCTEQ15HiX

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

nuclear DIS/PDFs impact νA predictions and experiments

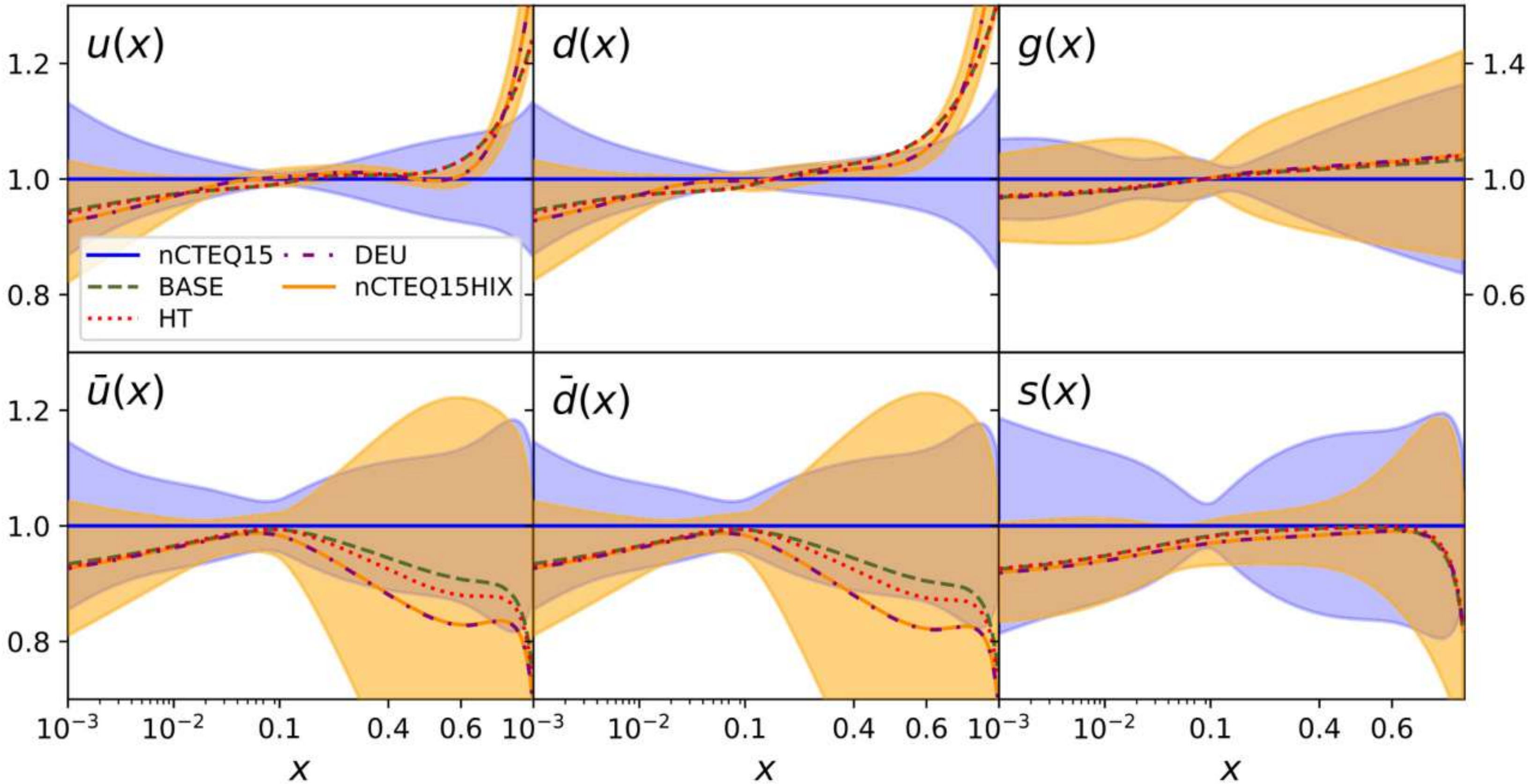


parametrization of *A* dependence allows predictions for ^{56}Fe
(cf. NuTeV, CCFR, ...)

→ low-*Q*, *W* effects sizable in nuclei; need simultaneous treatment with free-nucleon degrees-of-freedom

Iron PDF Ratios to nCTEQ15 ($Q = 2$ GeV)

...also for ^{40}Ar/DUNE...



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

→ nuclear and proton PDF fits often interdependent → <u>need simultaneous fits</u>

EIC: precision QCD, complementary to LHC/LBNF

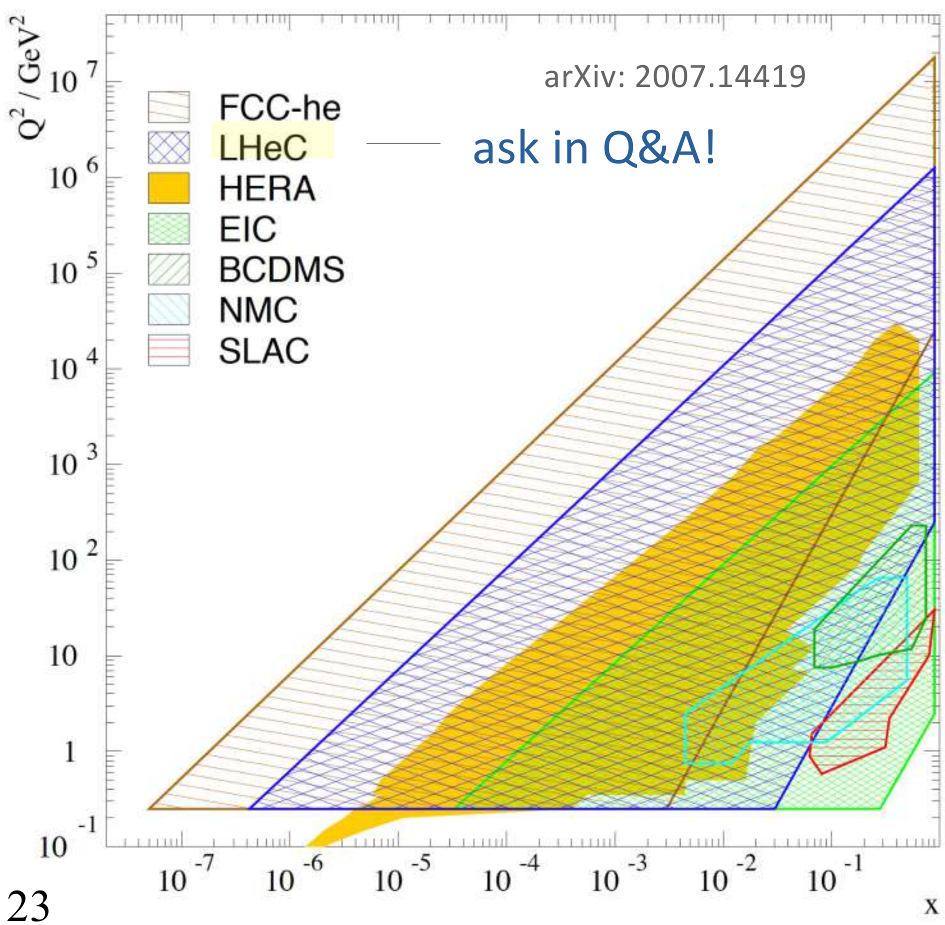
the EIC: a **high-luminosity** DIS collider: ~2-3 orders-of-magnitude cf. HERA

EIC will probe complementary kinematical space to LHC/LBNF in $[x, Q^2]$

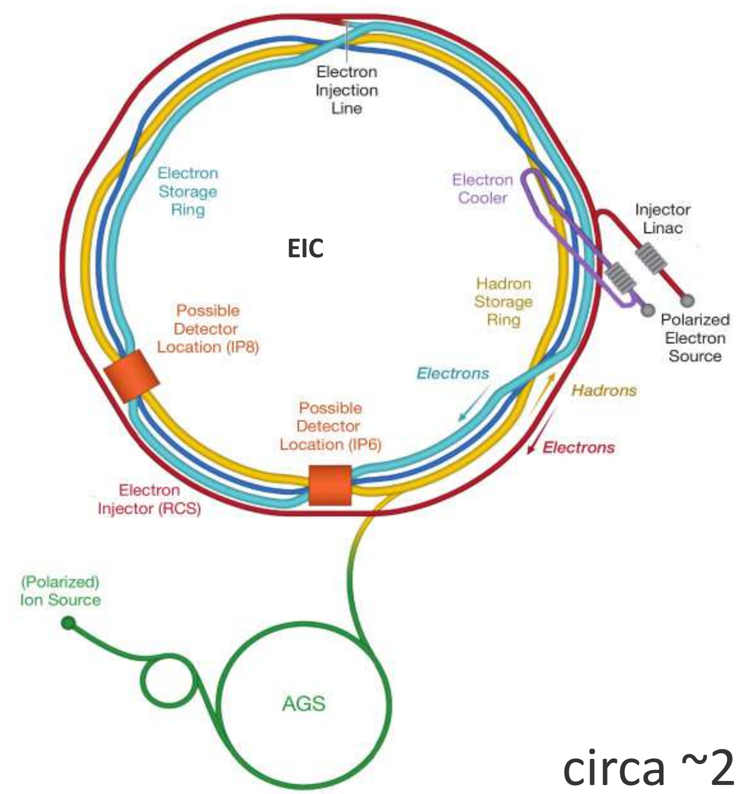
$20 \leq \sqrt{s} \leq 140\,\mathrm{GeV}$

wide battery of 'clean' **precision QCD measurements**

→ extensive probe(s) of the quark-to-hadron transition region (for PDFs)



ask in Q&A!



circa ~2030

CD-1; EIC Yellow Report: 2103.05419

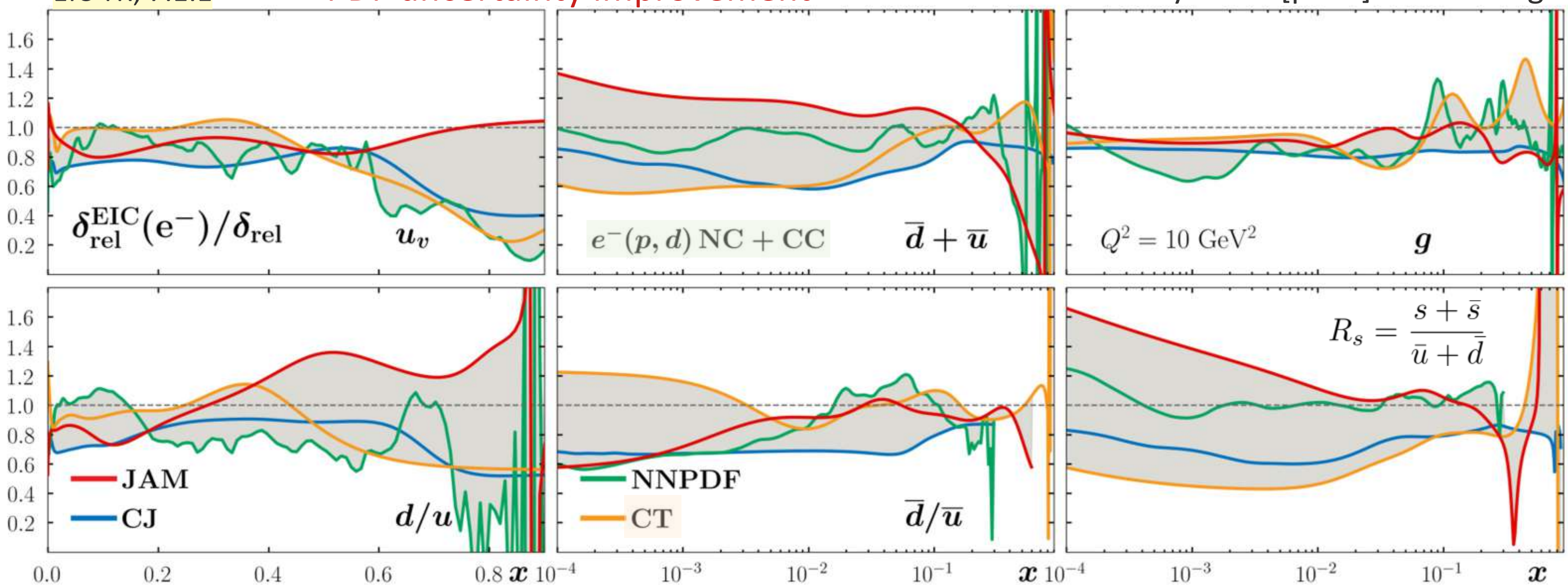
reductions to PDF uncertainties: inclusive DIS data

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

EIC YR, 7.1.1

PDF uncertainty improvement

~1 year of [peak] data-taking



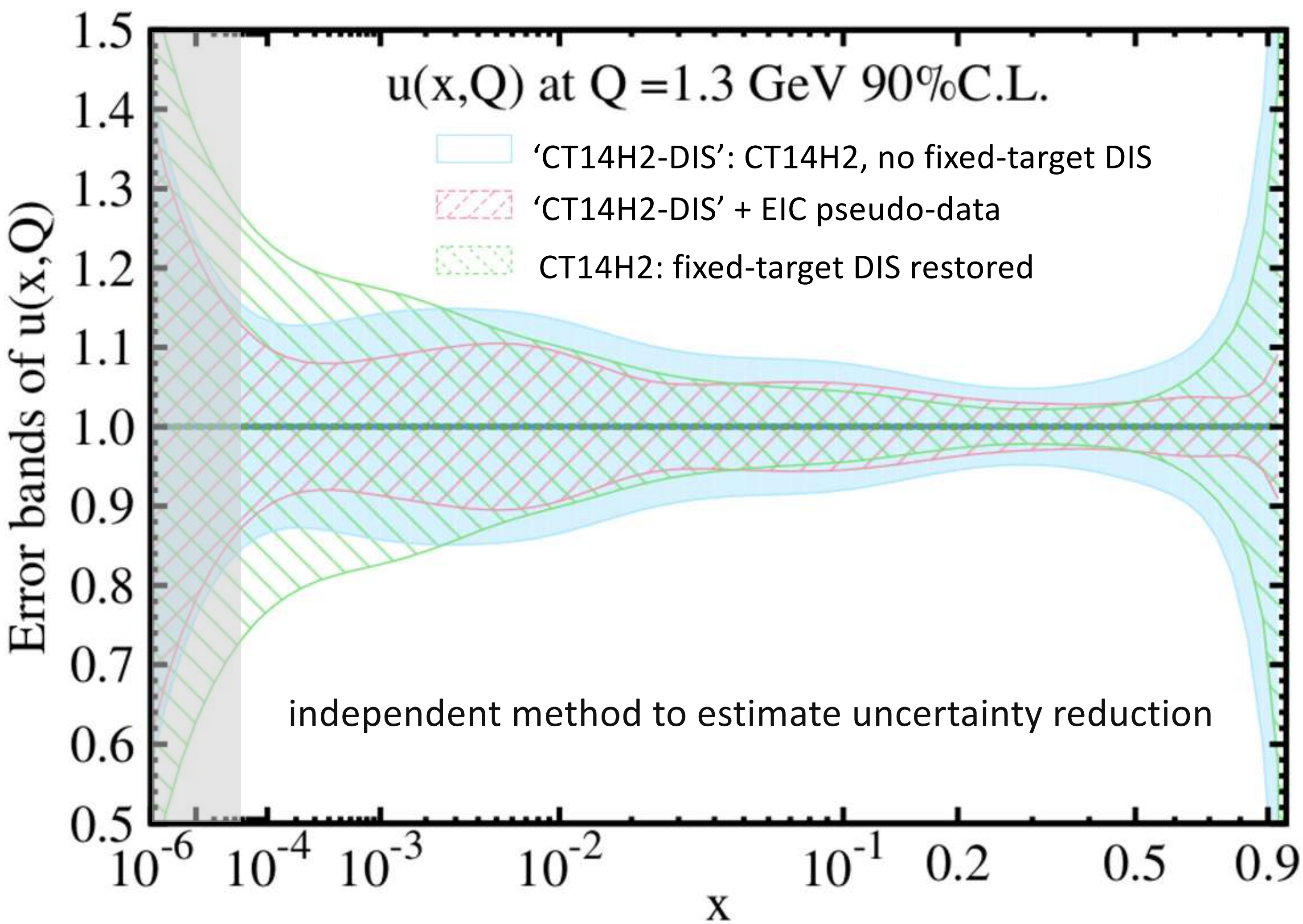
$\mathcal{L} = 100\,\mathrm{fb}^{-1}$

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

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

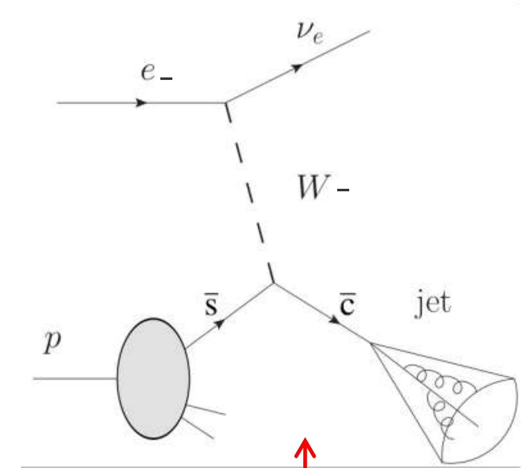
EIC sensitive to PDFs → strong HEP implications

[impact studies made with error profiling methods]



DIS charm-jet prod.

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



1-yr inclusive EIC dataset drives steep reductions in PDF uncertainties

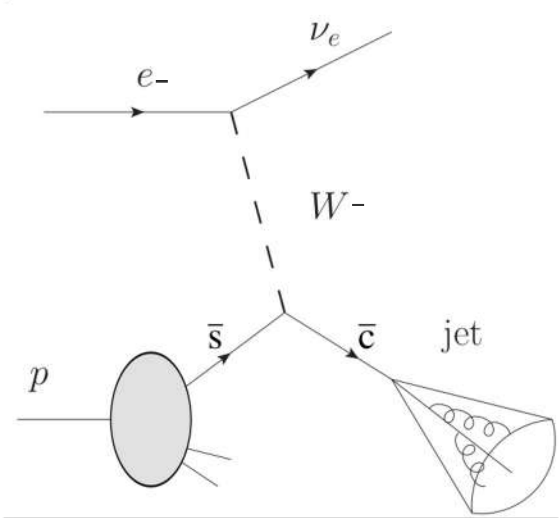
→ just inclusive DIS; many other channels with PDF sensitivity; precision QCD tests

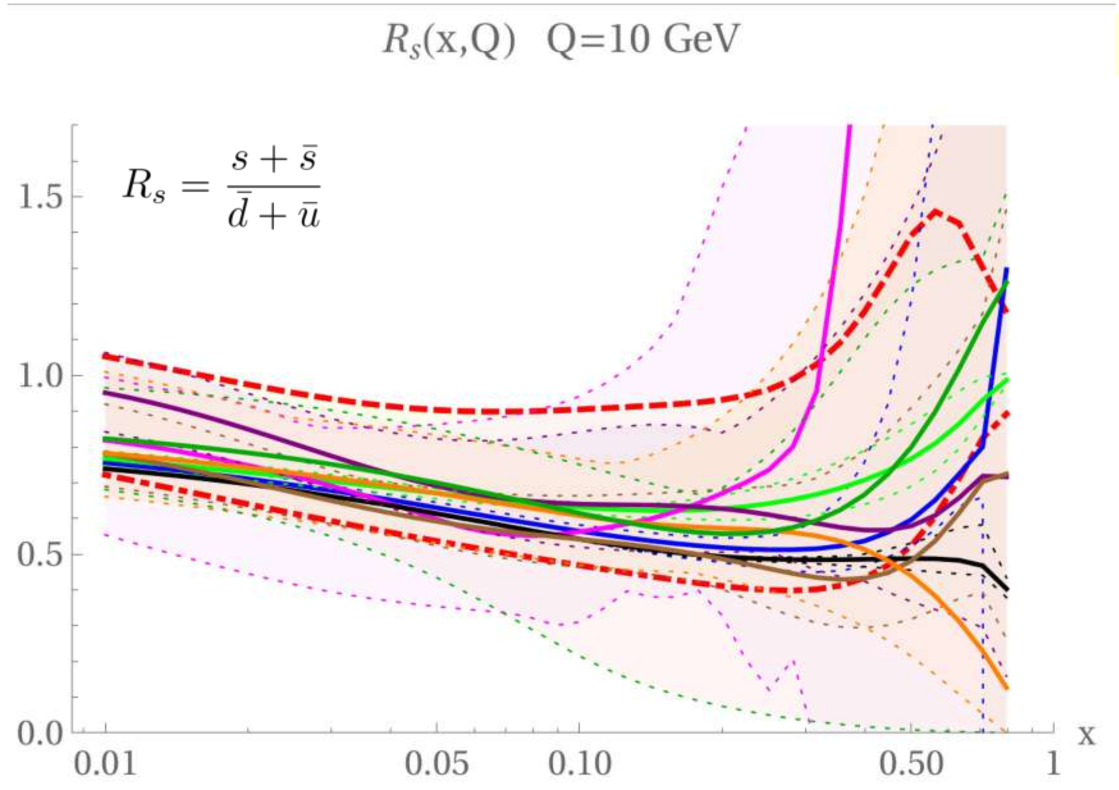
precision QCD through jet and heavy-flavor production

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

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

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





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

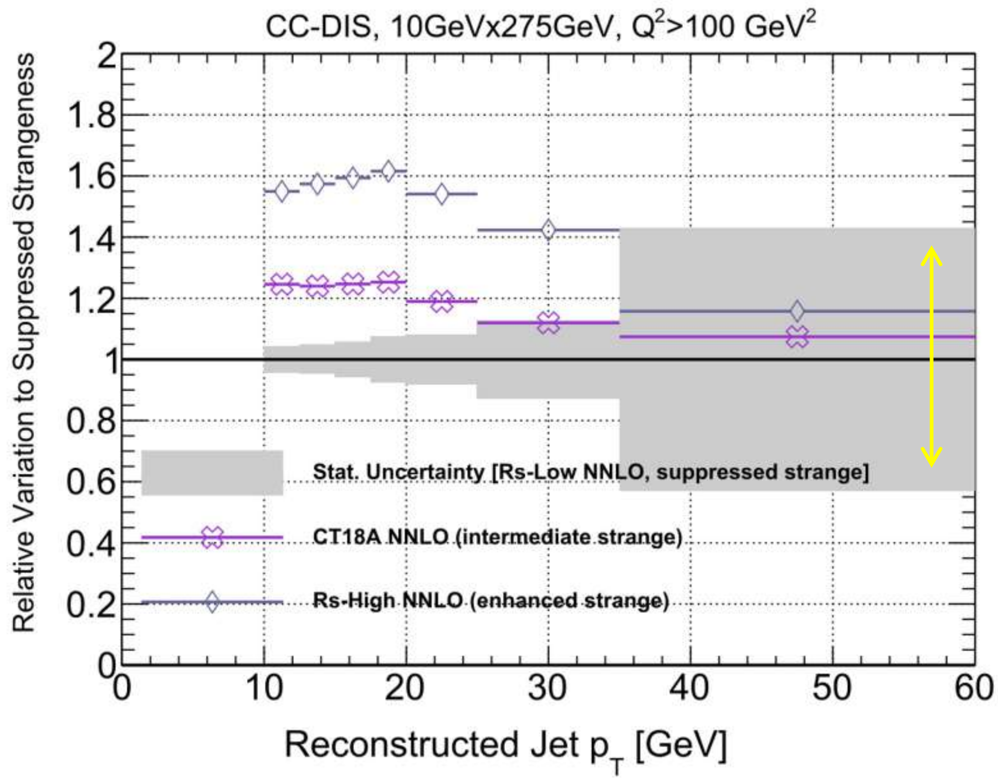
n.b.: event generation, detector sim from PYTHIA8 + DELPHES; FASTJET reconstruction

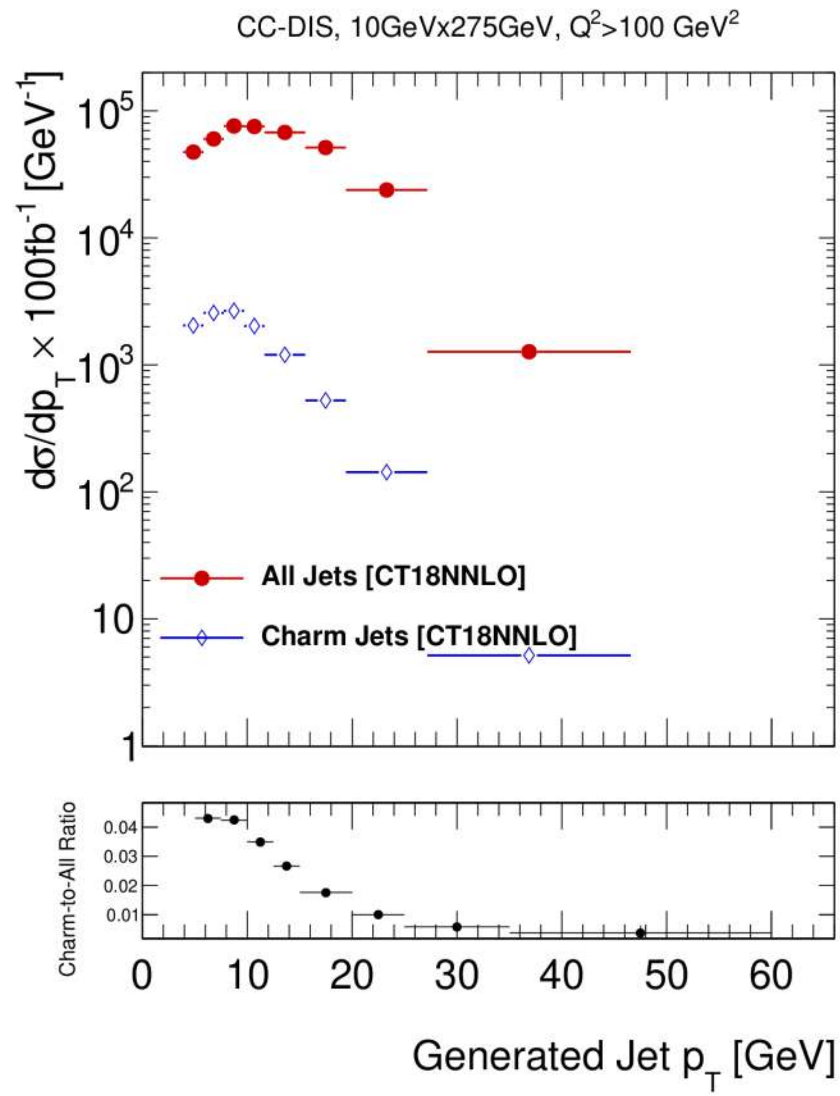
→ analogous jet measurements might be extended to nonperturbative heavy flavor

precision QCD through jet and heavy-flavor production

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

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





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

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

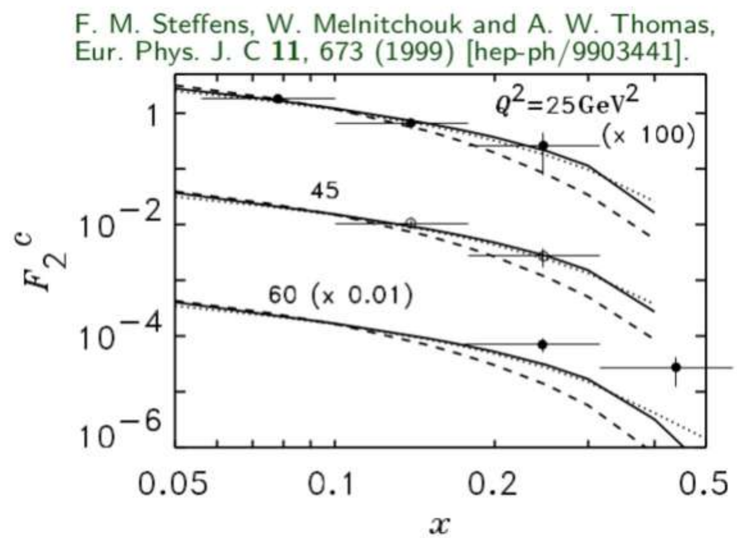
→ greater event rates may furnish enhanced discriminating power

…have seen how HQs are implemented *perturbatively* in QCD analyses

$$F_i = C_i \otimes f_{c/p}$$

what about *nonperturbative* charm;
not radiatively generated,

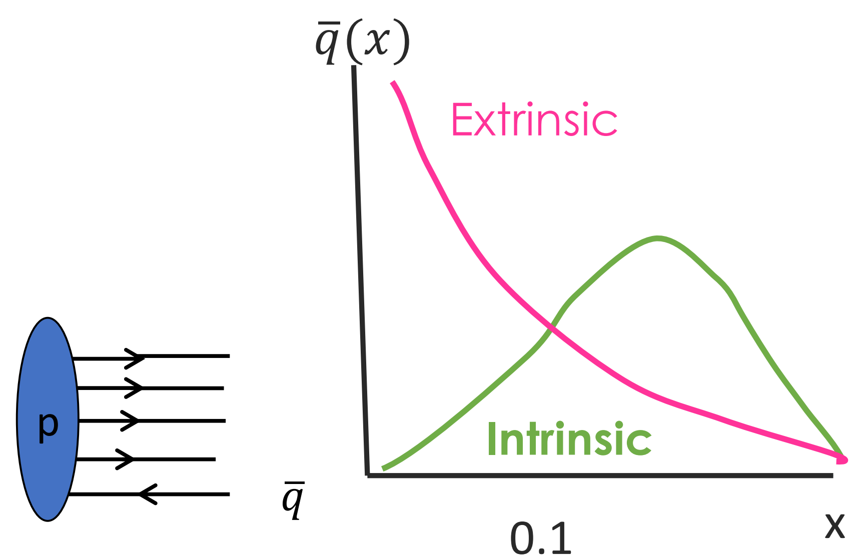
$$c(x, Q = m_c) = c^{\mathrm{IC}}(x) \neq 0$$



might PDF fits constrain "intrinsic" charm?

"Fitted charm" is a more direct term to describe the charm PDF found in the global QCD fit

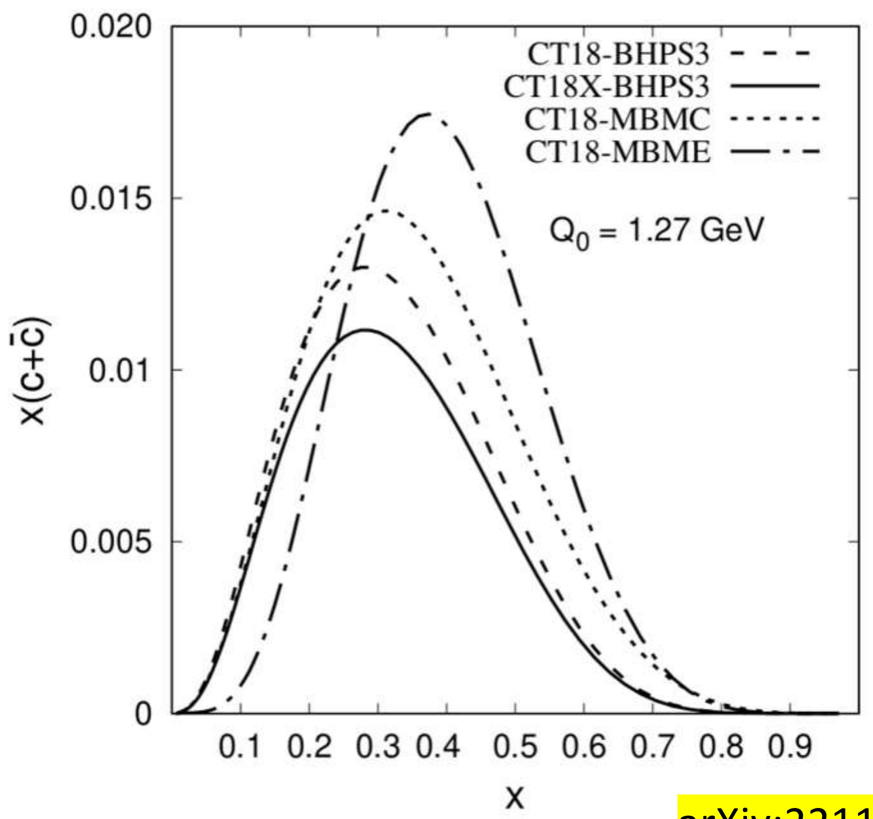
'smoking gun': valence-like high-x bump (or an (anti)charm asymmetry

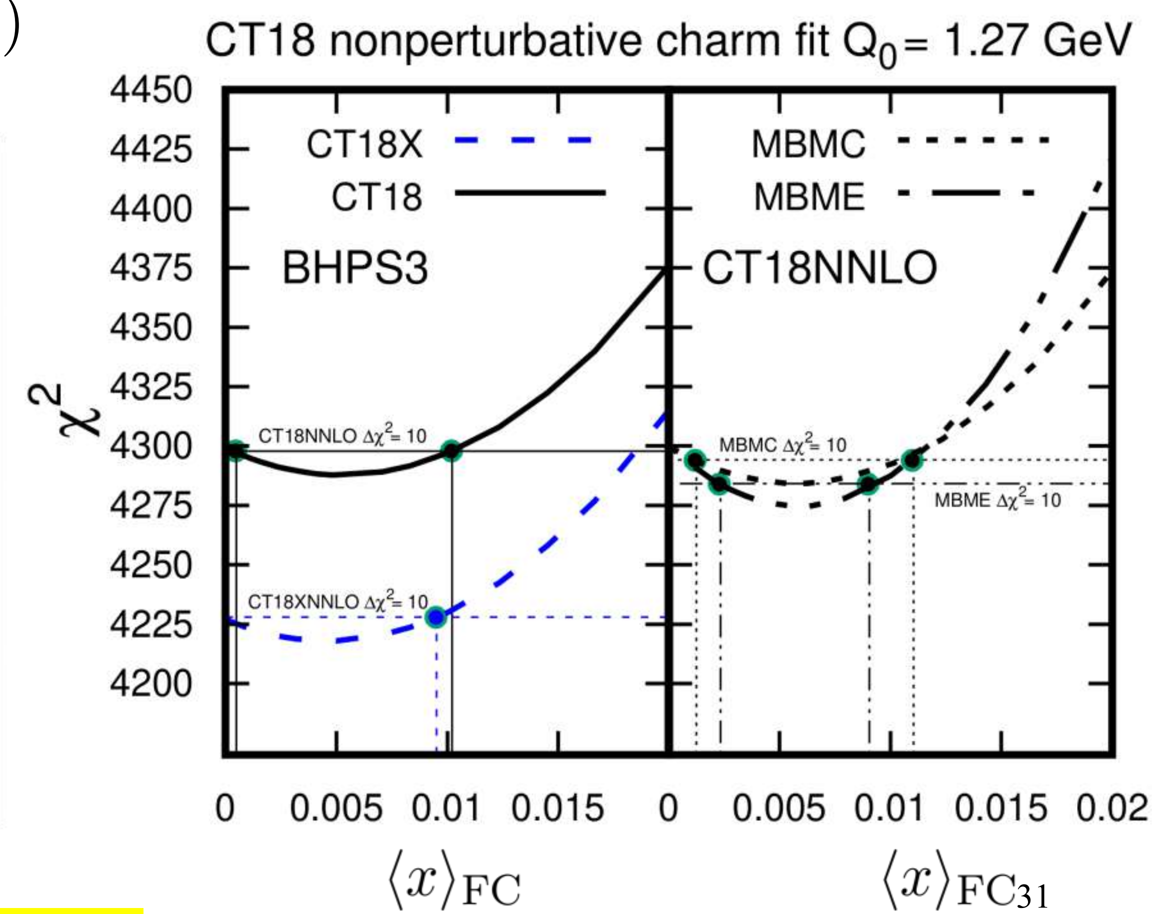


no clear signal for significant nonperturbative charm (CT)

- consider range of scenarios for fitted charm x dependence; fit normalization
  - → prediction of wave function models; distinct from typical, perturbatively-generated charm
  - → uncertainties remain large! need more information to resolve nonzero FC

$$\langle x \rangle_{\mathrm{FC}} = 0.0048^{+0.0063}_{-0.0048} \quad (\mathrm{BHPS3})$$





arXiv:2211.01387

Z+c at LHCb: intriguing new data; need theory development

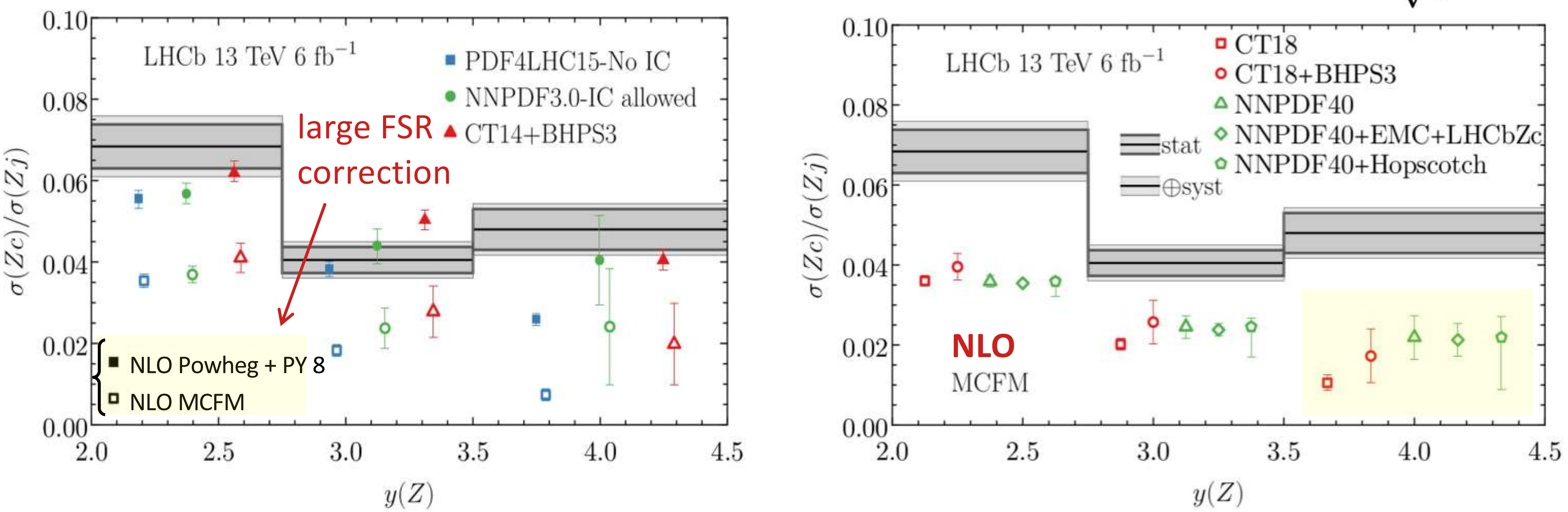
2022 LHCb 13 TeV data: (Z+c) / (Z+*jet*) ratios; 3 rapidity bins

R. Aaij, *et al*. (LHCb); arXiv: 2109.08084.

- FC slightly enhances ratio; not enough to improve agreement with data

  → meanwhile, significant theory uncertainties

$$x \sim \frac{Q}{\sqrt{s}} \exp y$$



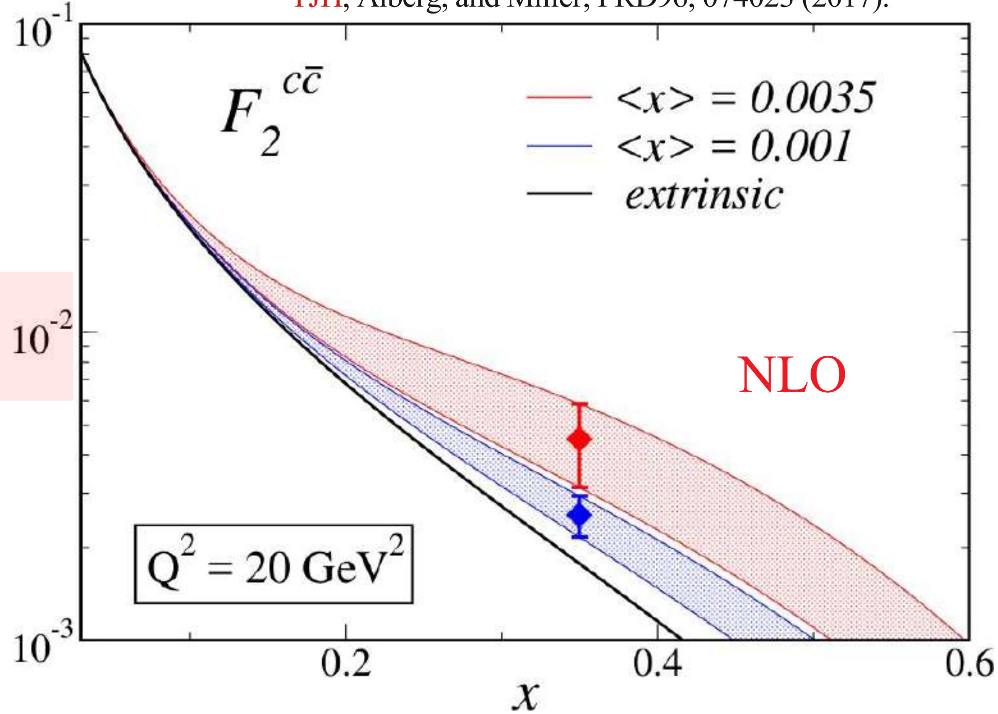
→ calculated **NLO** cross-section ratio similarly depends on showering, hadronization

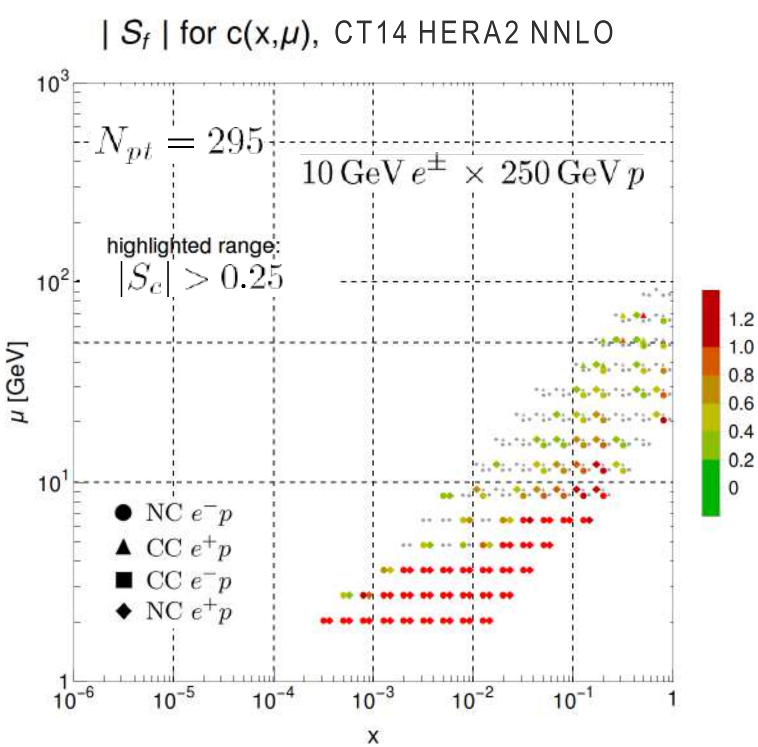
NNLO calculations recently available, but not implemented in PDF fits

R. Gauld, *et al*.; arXiv: 2005.03016; 2302.12844 M. Czakon, *et al*.; arXiv: 2011.01011.

EIC is an ideal experimental platform for the charm SF

TJH, Alberg, and Miller; PRD96, 074023 (2017).





EIC + lattice QCD will constrain FC scenarios

enhanced FC momentum implied by EMC data → small high-x effects in structure function; need high precision

- essential complementary input from LHC; CERN FPF

EIC will measure precisely in the few-GeV, high-x region where FC signals are to be expected

the EIC complements PDF-Lattice synergy

(see talk, H.-W. Lin)

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

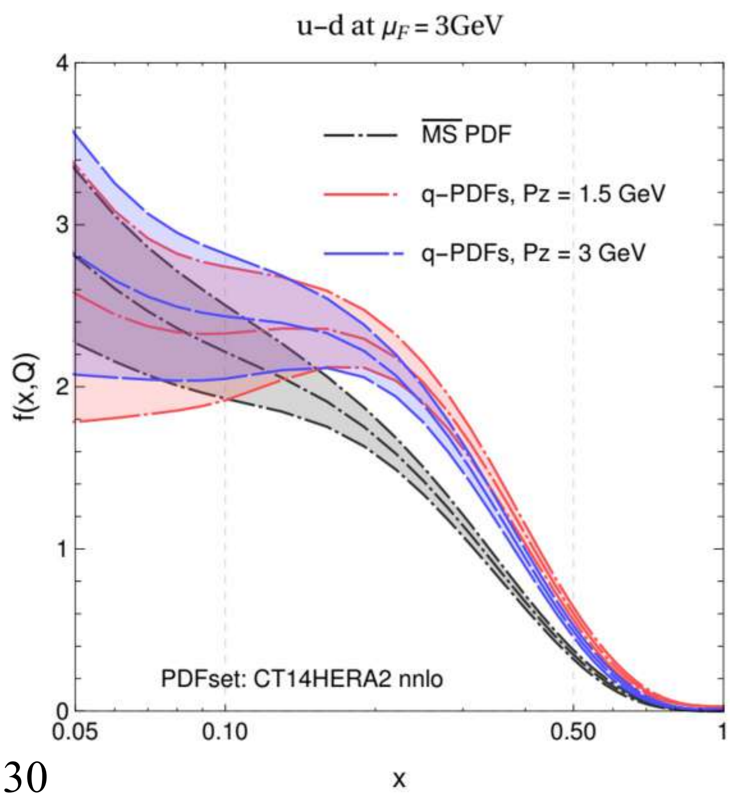
(compute QCD on discretized spacetime grid)

→ theory/models still being developed

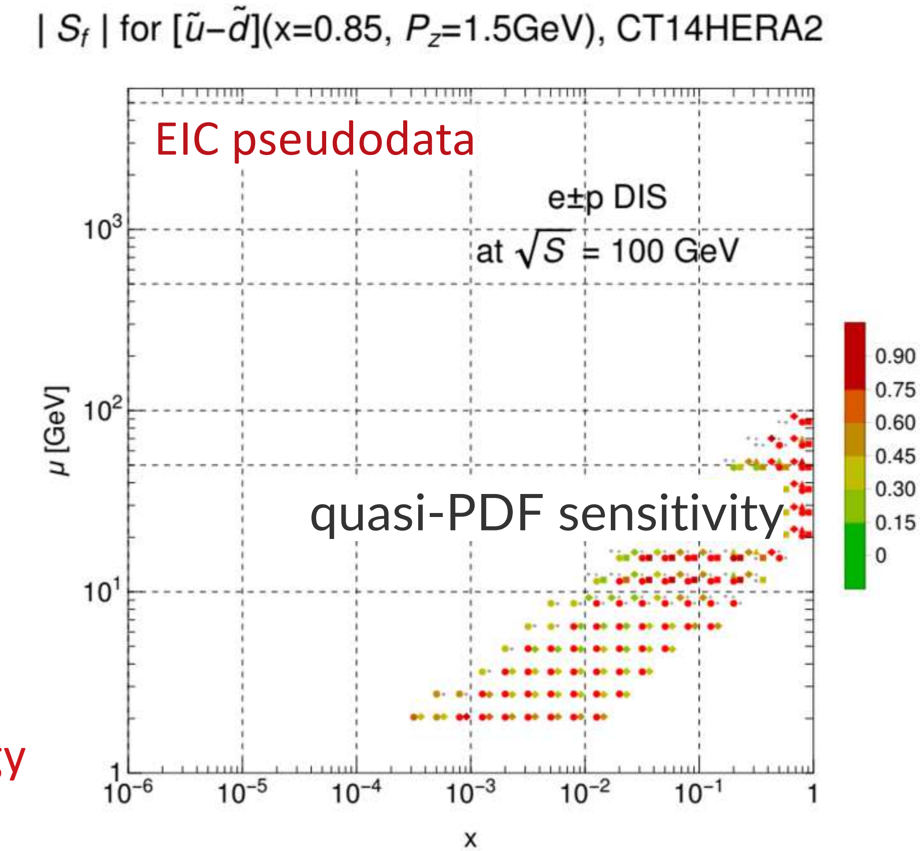
TJH, PRD97 (2018) 5, 054028

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

TJH et al., PRD100 (2019) 9, 094040



the EIC will drive a PDF-Lattice Synergy



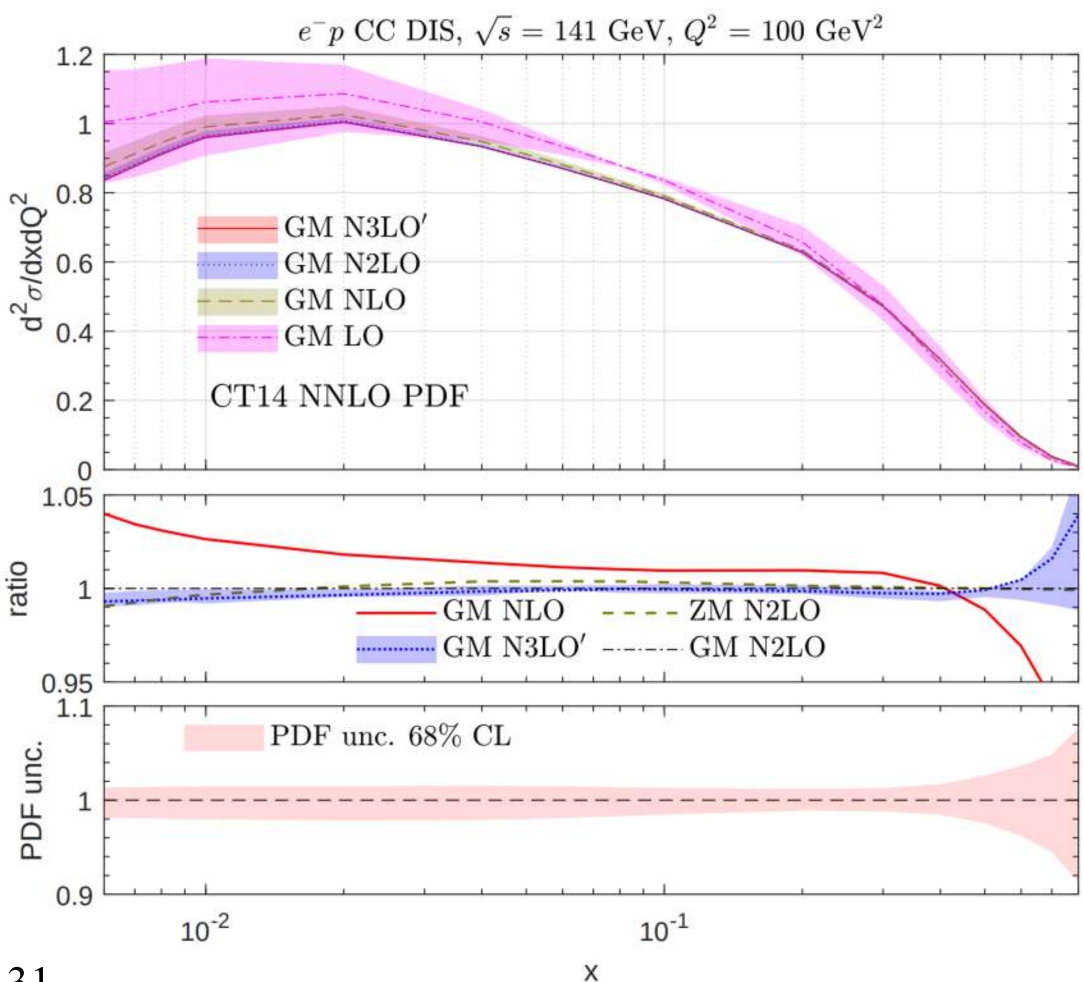
higher QCD accuracy necessary to leverage DIS data

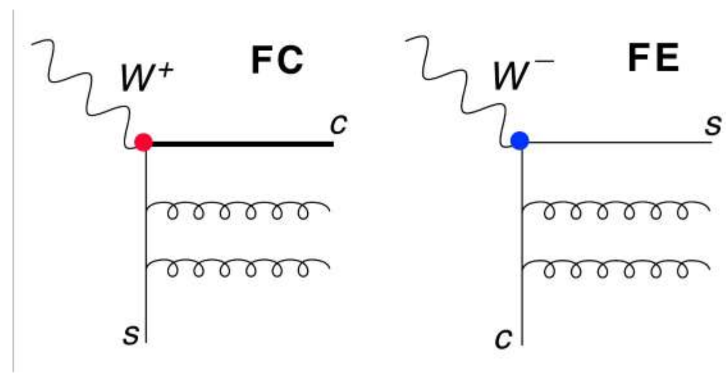
earlier, noted importance of (N)NNLO theory accuracy for collider phenomenology

→ applies also to **EIC CC DIS**, $e^- p \to \nu_e + X$

Gao, TJH, Nadolsky, Sun, Yuan: 2107.00460

tracing heavy-quark mass dependence also essential; range of scales → general-mass treatment





requires very careful treatment of flavor-creation, -excitation processes; delicate pattern of subtractions, *e.g.*,

$$C^{(2)}_{h,l} = H^{(2)}_l(z) - \Delta C^{(2)}_{h,l}$$

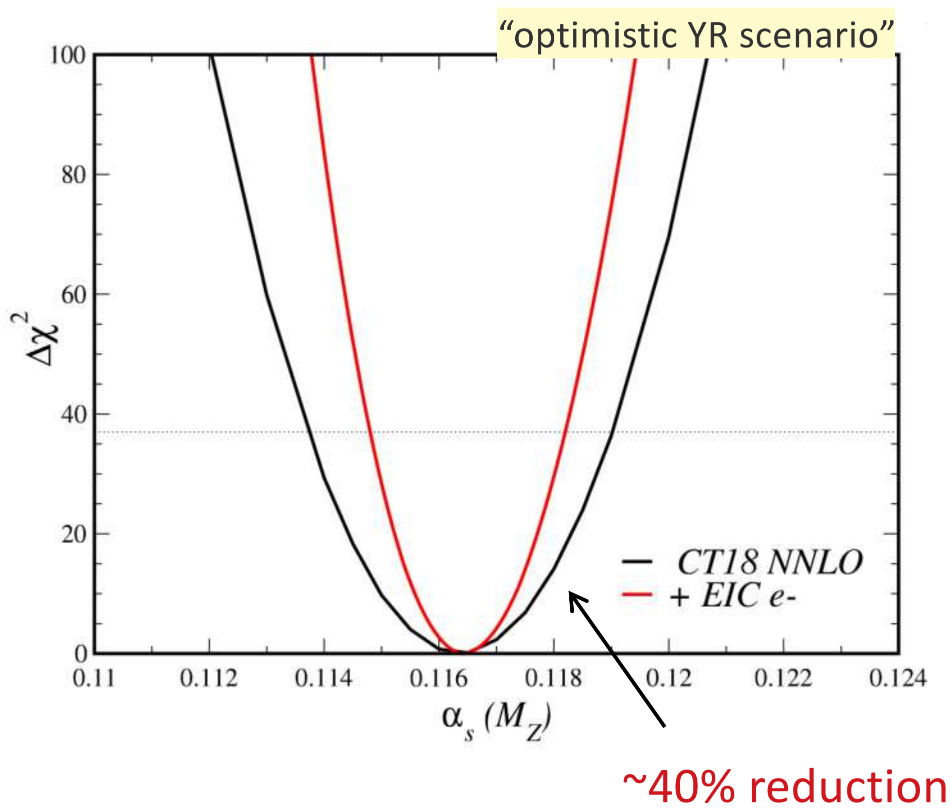
significantly reduces scale variations → critical for stability of PDF extractions

collider DIS and precision QCD: EIC and SM inputs: α_s

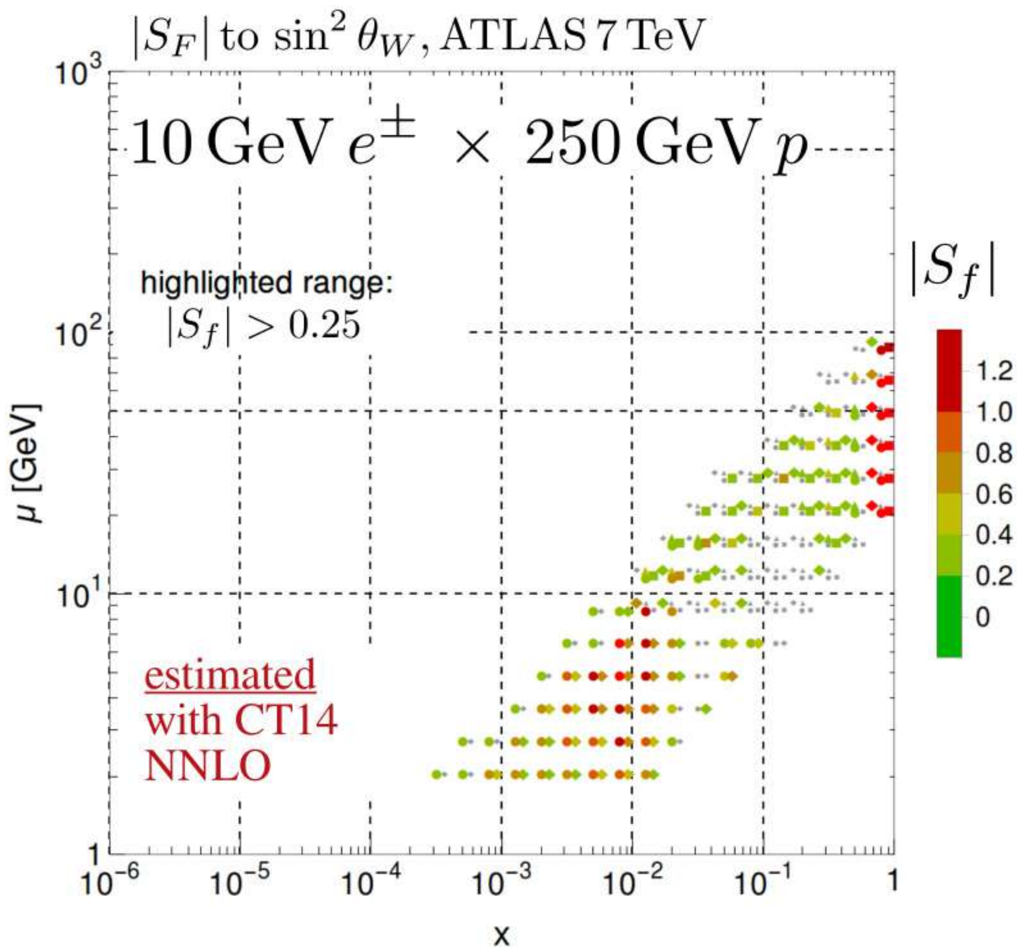
part of moving toward N^{3}LO PDFs, precise determinations needed for α_s

similar argument for m_Q

from inclusive data alone



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



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

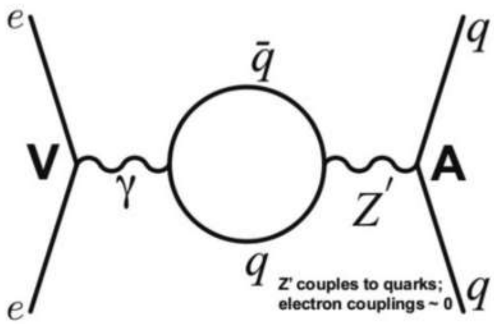
also: precise α_s extractions based on global event shapes; N-jettiness, τ_N

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

quark-level electroweak couplings may be sensitive to extended EW sector, *e.g.*, Z'

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

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



unique to EIC: combination of very high precision and **beam polarization**; allows observation of **parity-violating (PV) helicity asymmetries**:

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

TJH and Melnitchouk, PRD77, 114023 (2008).

EW measurements can be sensitive to TeV-scale physics

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

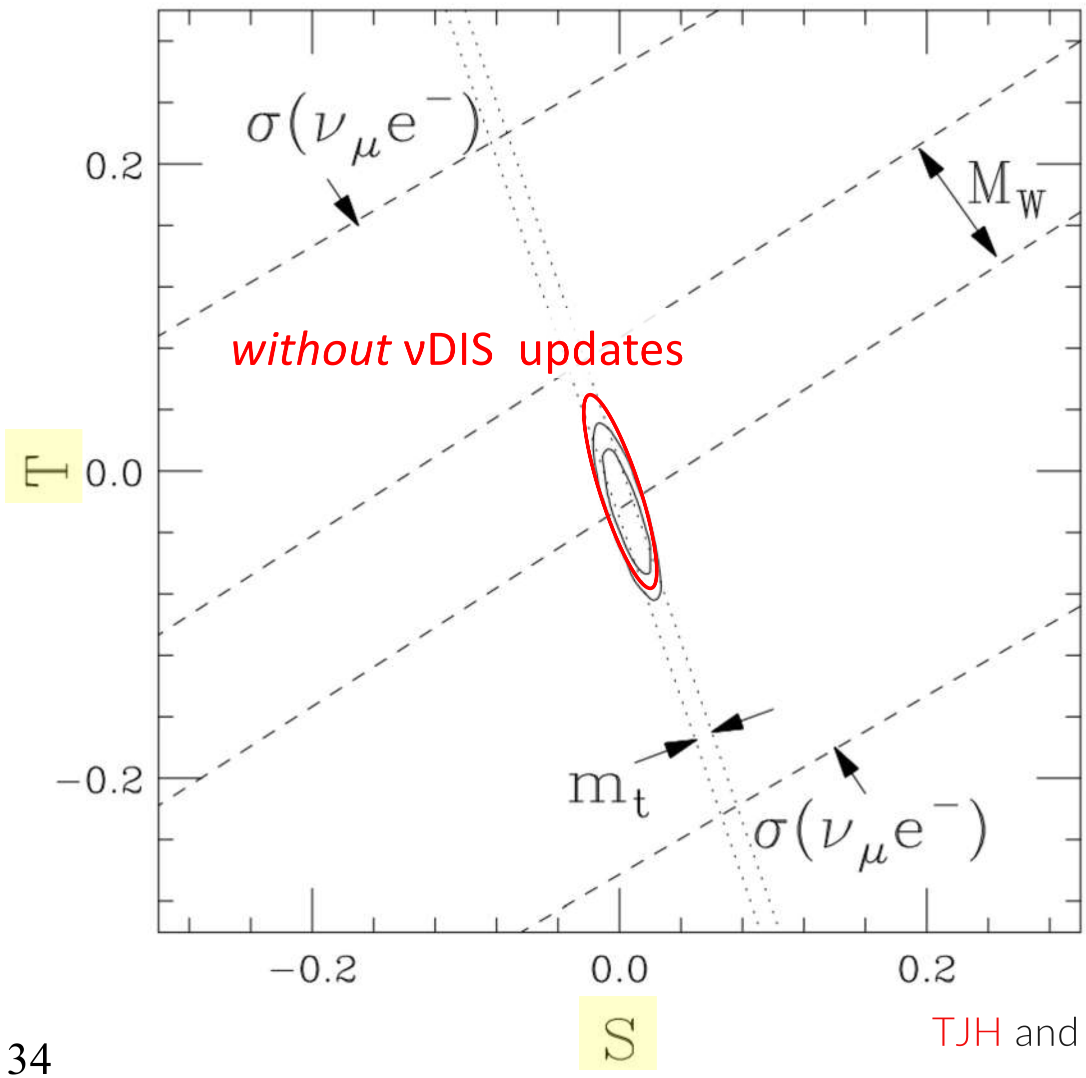
$$a_1 = \frac{2\sum_q e_q\ C_{1q}\ (q+\bar{q})}{\sum_q e_q^2\ (q+\bar{q})} \qquad a_3 = \frac{2\sum_q e_q\ C_{2q}\ (q-\bar{q})}{\sum_q e_q^2\ (q+\bar{q})}$$

separation of BSM signals from SM inputs

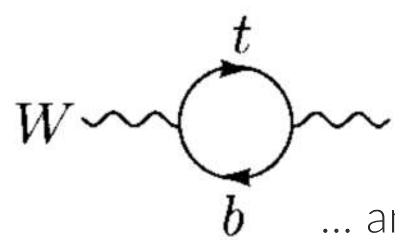
precise electroweak measurements can constrain potential BSM physics

→ *e.g.*, constrain (inner ellipses) oblique corrections through factor 3 improvement to $g^2_{L,R}$

(from νDIS measurements)



S,T parametrize BSM 'oblique' corrections to propagators:



… and BSM insertions

BUT:

extractions of SM parameters are entangled with QCD uncertainties which must be separated from BSM

TJH and J. Rosner: PRD**82** (2010) 013001

more systematically, EFT-based global analyses

(see talk, S. Dawson)

BSM searches and SMEFT suggest possible joint BSM-PDF analyses

"SM effective field theory"

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i^{N_{op}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)}$$

→ scale-suppressed BSM interactions

dependent upon Wilson cofficients for dim-6 operators:

$$\{c_i^{(k)}\}, \quad i = 1, \cdots, N_{op}, \quad k = 1, \cdots, N_{rep}$$

the Wilson coefficients, $\{c_i^{(k)}\}$, similarly fitted analogously to SM quantities (the PDFs)

→ <u>PDFs</u>: frozen (or absent) theory ingredients (*e.g.*, photon PDF; nonpert. QCD corrections) can bias extraction

→ <u>SMEFT</u>: analogously, extracted Wilson coefficients may be biased if not simultaneously determined with PDFs

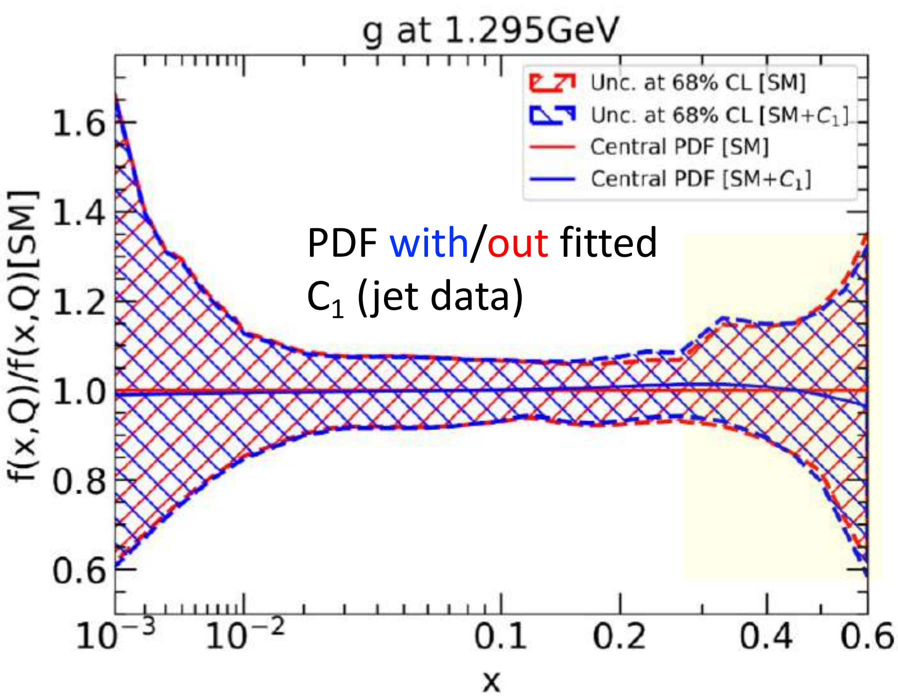
PDFs jointly fitted with SMEFT

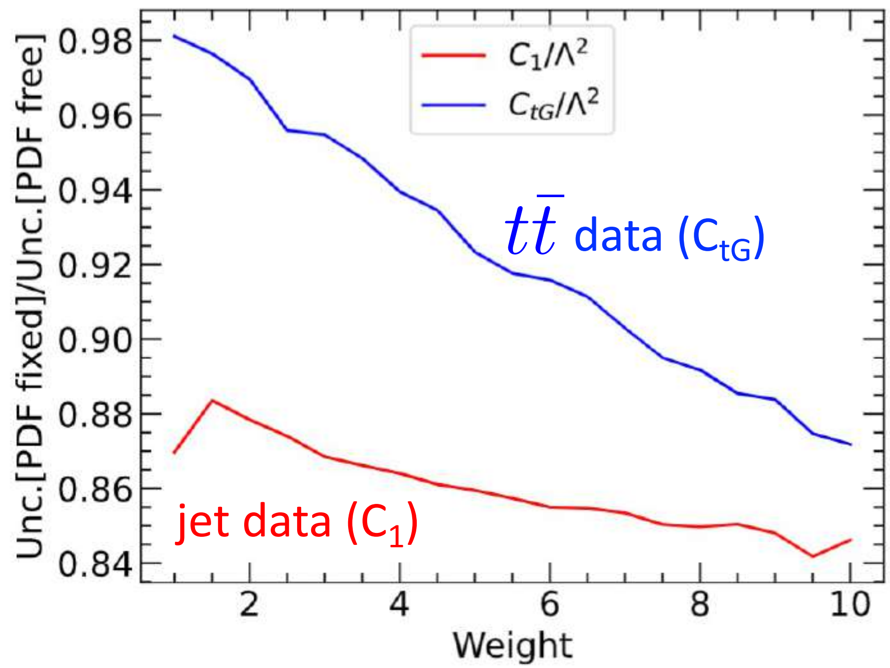
arXiv:2211.01094

- ongoing effort to constrain BSM model independently via EFT (SMEFT) global fits

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i O_i^{(6)}}{\Lambda^2} + \ldots$$

→ to minimize bias: jointly fit PDFs, SMEFT; examine PDF-SMEFT correlations





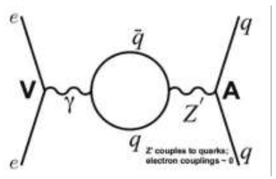
- PDF-SMEFT correlations (*e.g.*, with high-*x* gluon) are <u>mild</u> for jet, $t\bar{t}$ data

→ will likely be more severe with higher precision (HL-LHC); important future effort

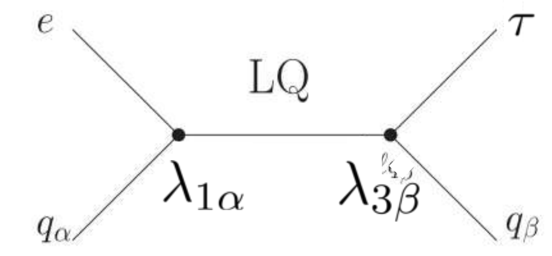
EW and BSM opportunities

potentially BSM-sensitive extractions of EW quark couplings, through **parity violation**

$\sin^2\theta_W$

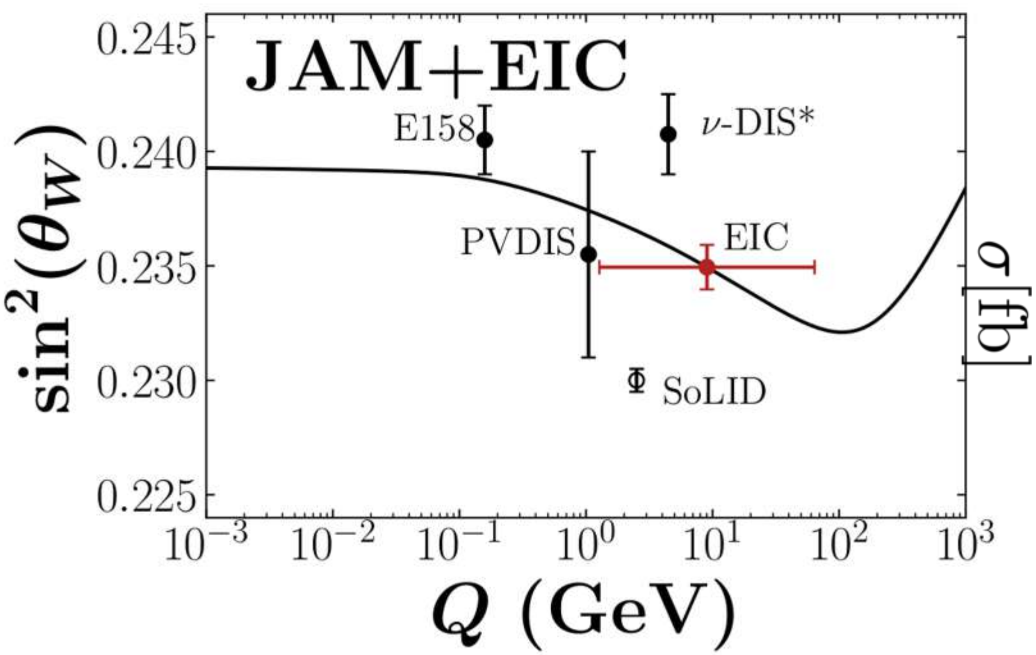


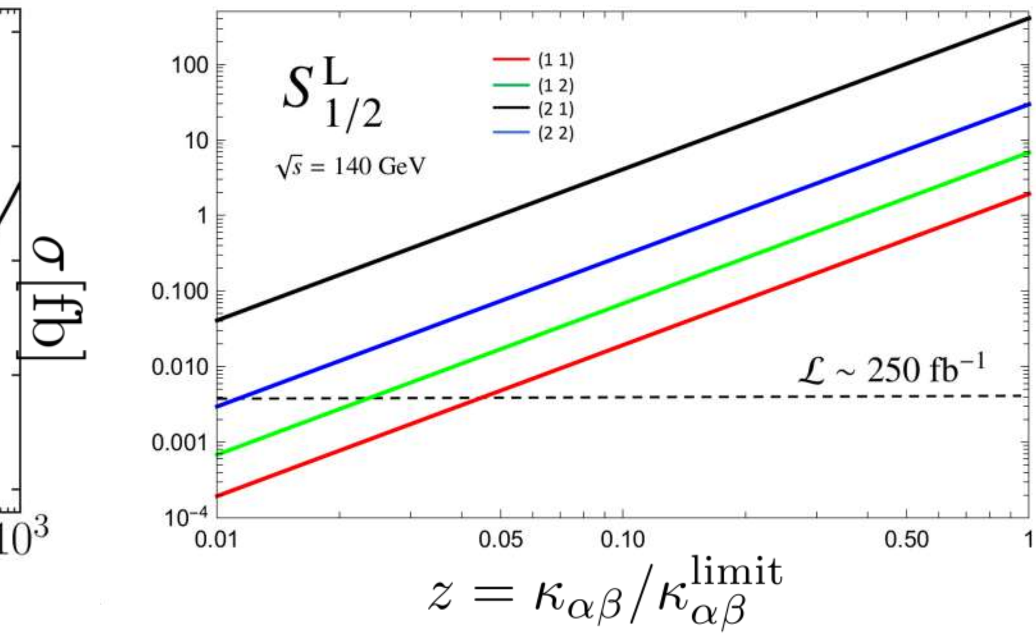
$$A^e_{\rm PV} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$



EIC YR, 7.5.1

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



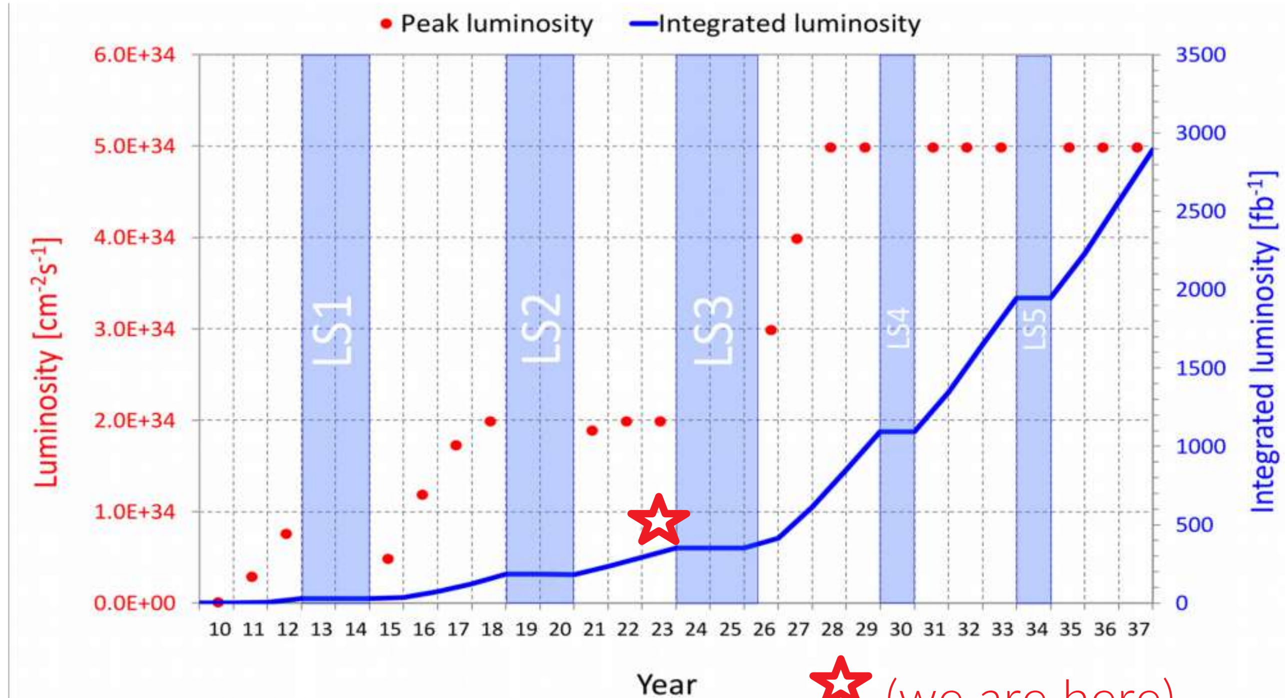


more direct SM tests also possible: searches for charged-lepton flavor violation (CLFV)

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

the big data era has arrived

from LHC and (soon) EIC, an enormous quantity of data



☆ (we are here)

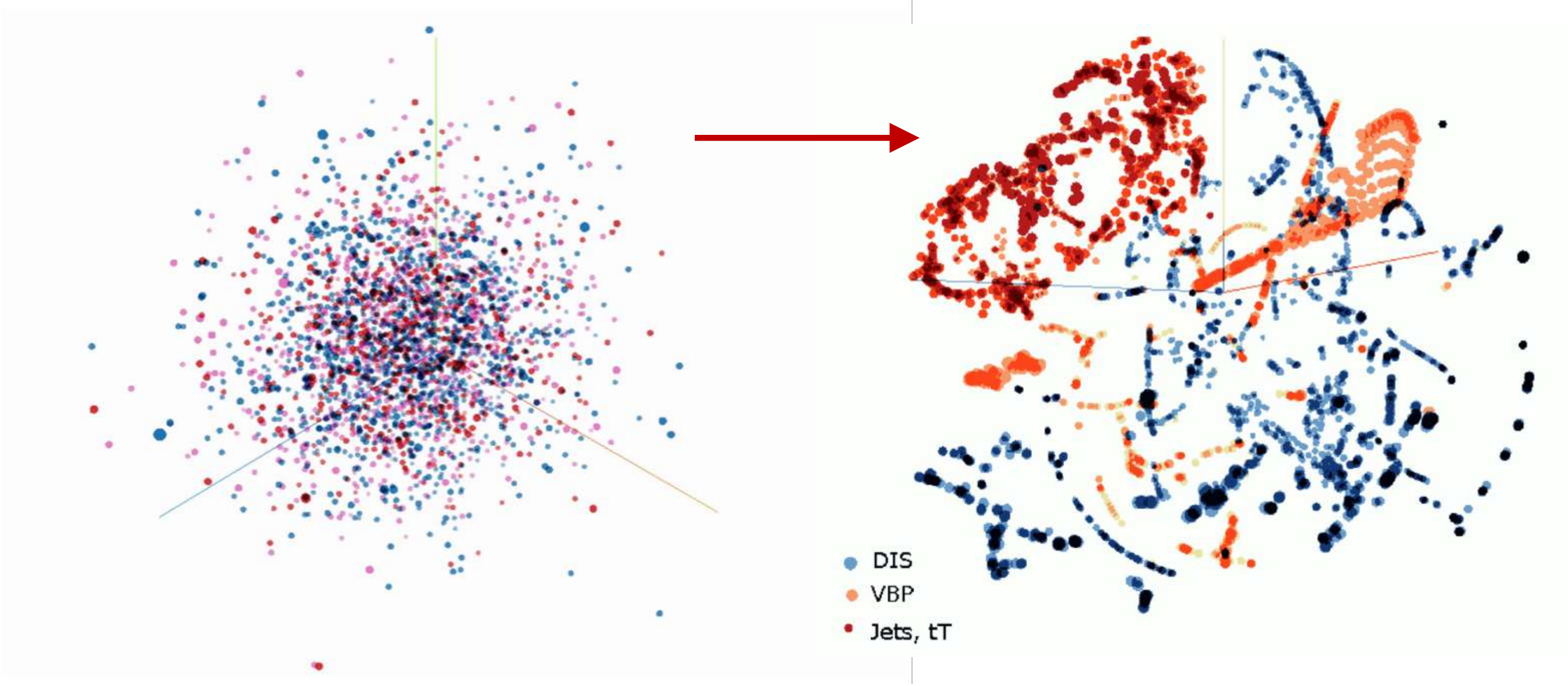
this data is both exciting and challenging

novel numerical methods for understanding HEP data

AI/ML tools valuable for dissecting pulls of hadronic data; *e.g.*, dimensionality reduction like t-SNE*: identify commonalities among HEP data in multi-dim. analyses

(**t-distributed stochastic neighbor-embedding*)

Wang, TJH, et al., PRD98 (2018) 9, 094030.



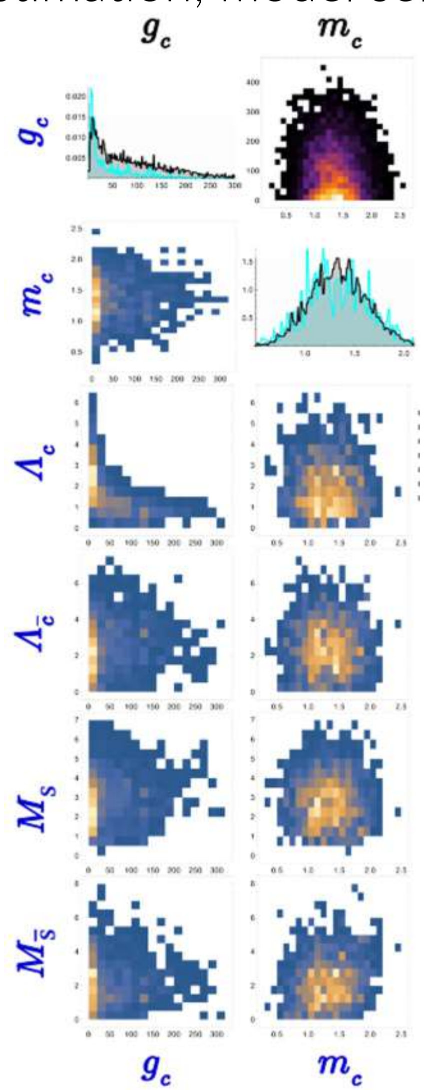
unsupervised learning: iteratively minimize KL divergence in lower-dimensional configuration space

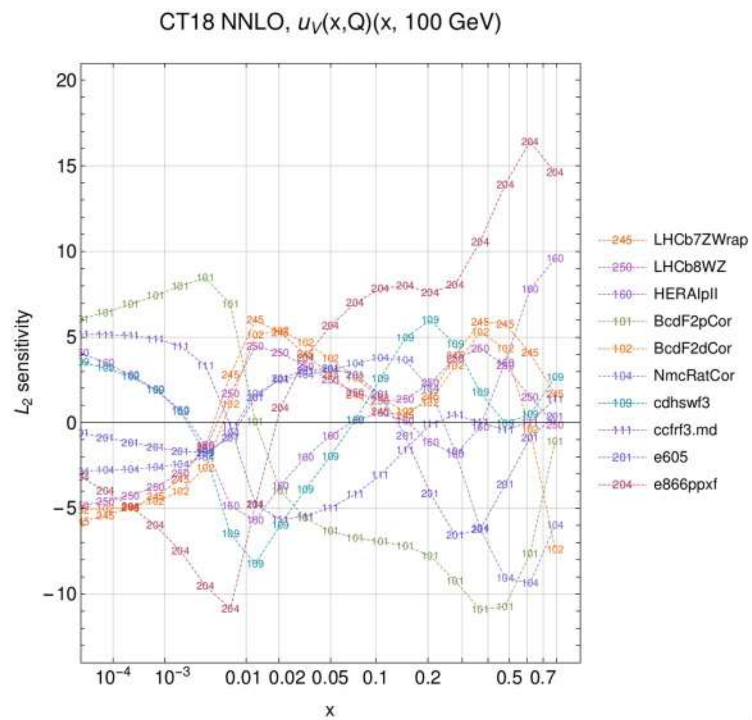
numerical tools, opportunities in AI/ML and Big Data

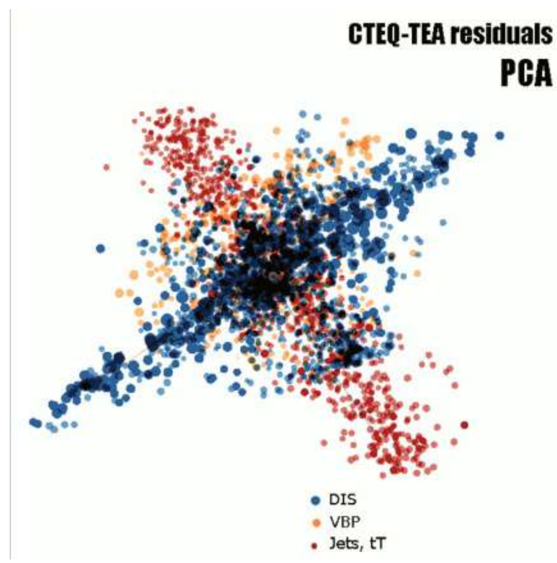
advanced parameter estimation; model selection

fast statistical methods

data embedding







→ techniques marry to computationally-intensive analyses

→ scale on computational clusters

→ improving reproducibility, interpretability are key

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

HEP and QCD are at an exciting moment

→ EIC will likely revolutionize understanding of QCD, PDFs

→ new theory, computational tools in development

→ developments will be felt throughout particle physics

numerous areas for engagement

→ PDFs are clearinghouse between theory, experiment, event gen

→ every issue here is a potential project, collaborative opportunity

tim@anl.gov ("don't be a stranger...")

conclusions …and **the future.**

HEP and QCD are at an exciting moment

→ EIC will likely revolutionize understanding of QCD, PDFs

→ new theory [illegible]

Thanks very much!

→ developments will be felt throughout particle physics

numerous areas for engagement

→ PDFs are clearinghouse between theory, experiment, event gen

→ every issue here is a potential project, collaborative opportunity

tim@anl.gov ("don't be a stranger…")