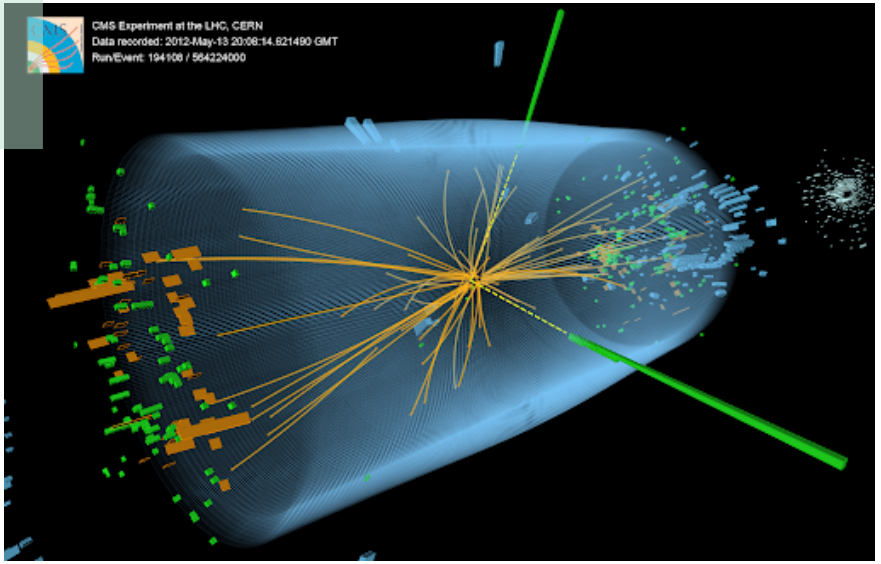
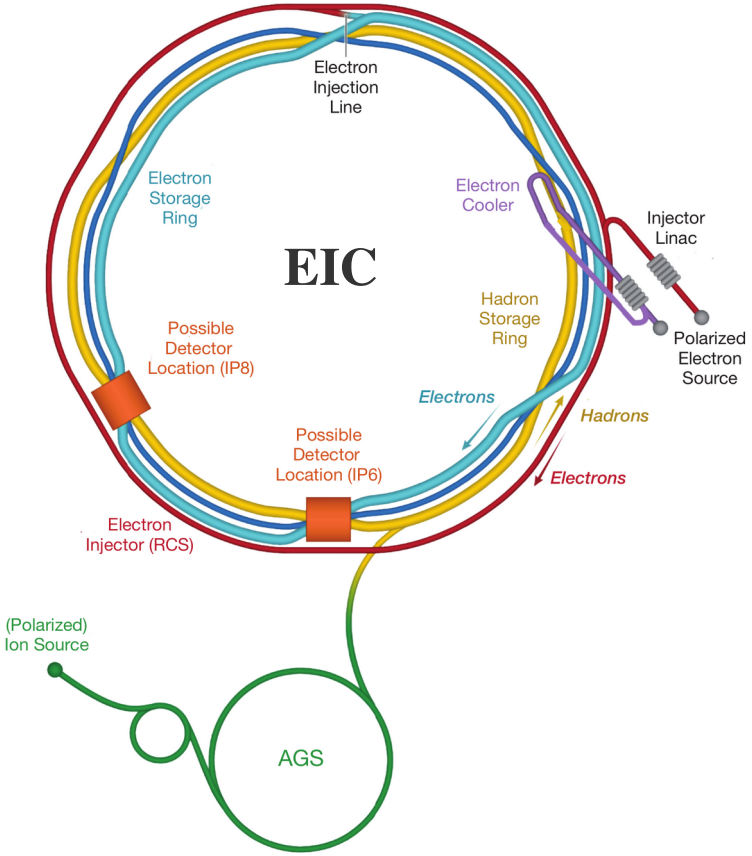
DIS (EIC/LHeC) physics connections to the LHC

Tim Hobbs, SMU, IIT, JLab EIC Center

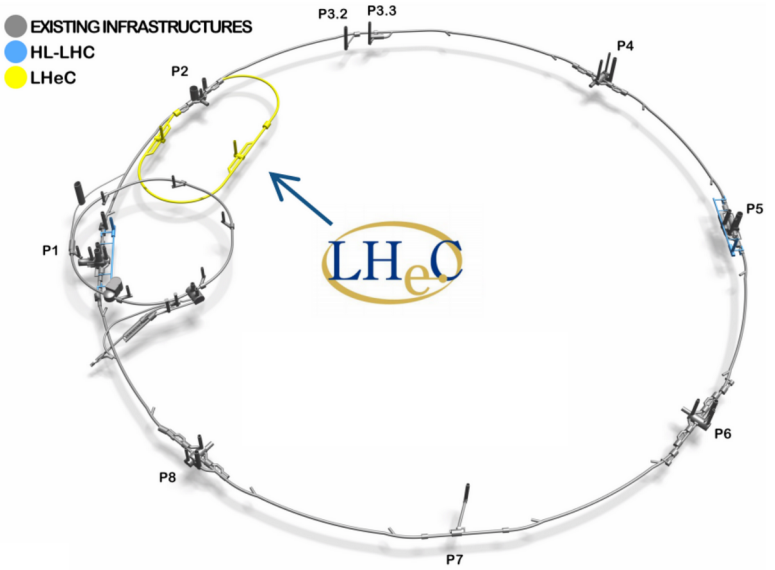
16th April 2021



EIC YR, arXiv: 2103.05419



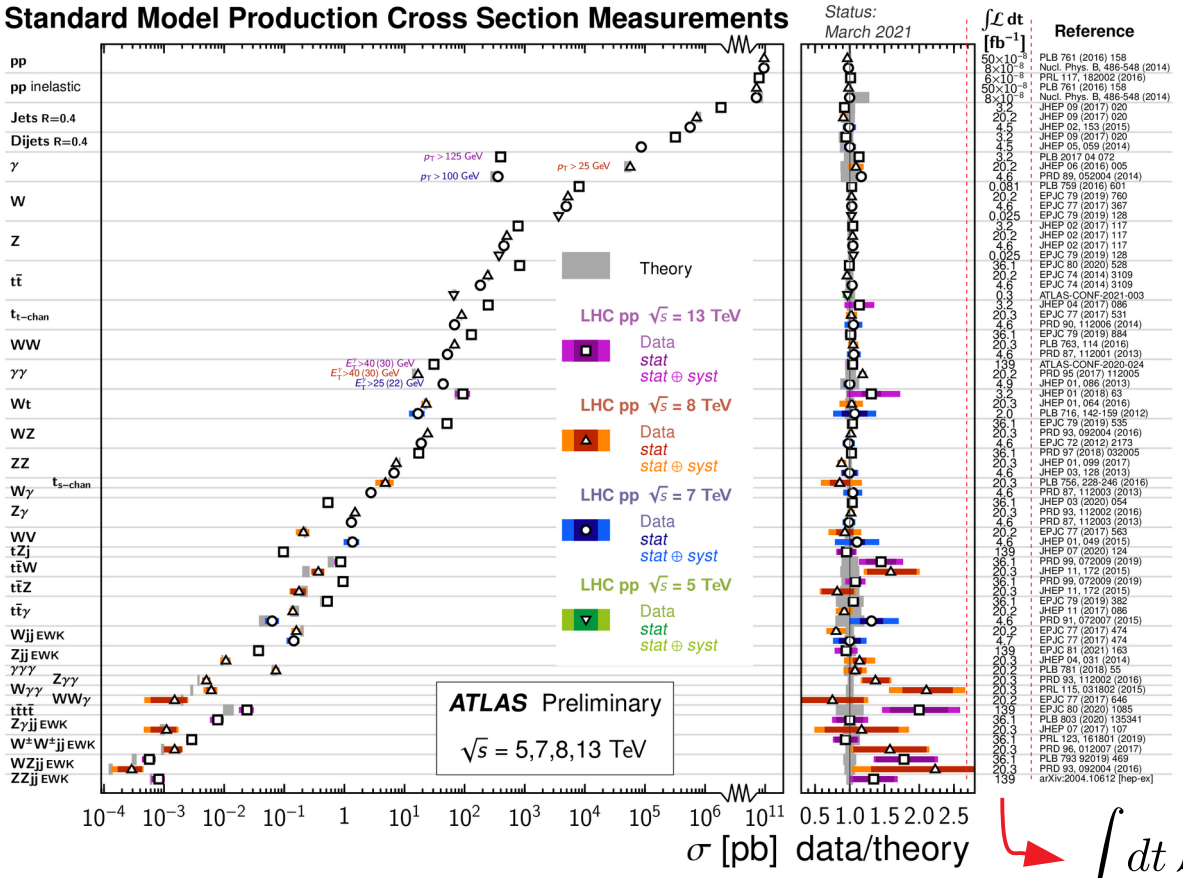
LHeC whitepaper, arXiv: 2007.14491



SMU

ILLINOIS INSTITUTE OF TECHNOLOGY

EIC² EIC Center at Jefferson Lab



LHC has logged large quantities of data; much more coming in HL-LHC era

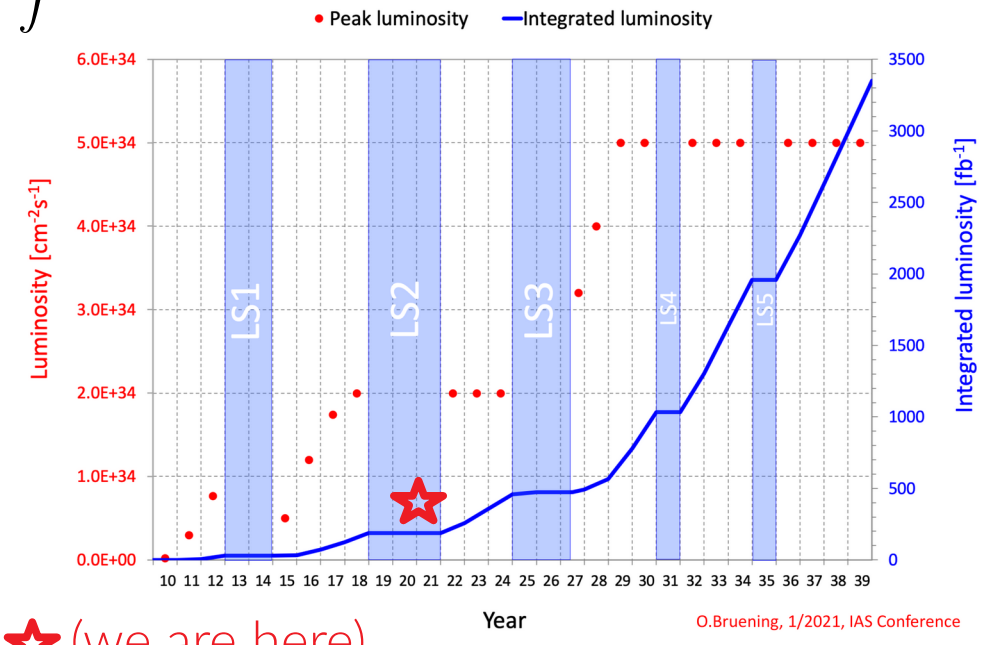
- LHC SM predictions have been very successful

  ...notwithstanding recent LHCb, FNAL muon g-2 anomalies...

[see talk, R. Boughezal]

- growing statistics → BSM searches become more systematics-limited

$$\int dt\,\mathcal{L} = 139\,\mathrm{fb}^{-1}$$



- improved discovery potential at HL-LHC requires improvement of **PDF, EW, nuclear, theory, …,** uncertainties

- input from future DIS experiments will be essential

★ (we are here)

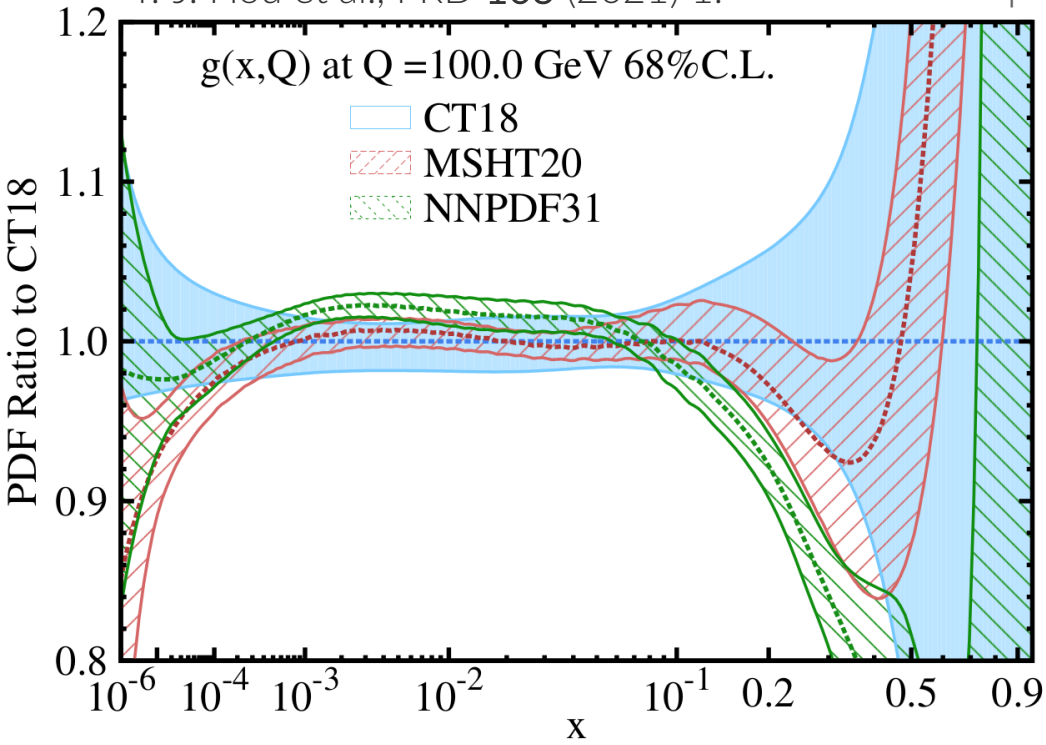
PDFs critical to next-generation precision at LHC

[many talks in SF WG1]

→ essential nonperturbative input for LHC predictions

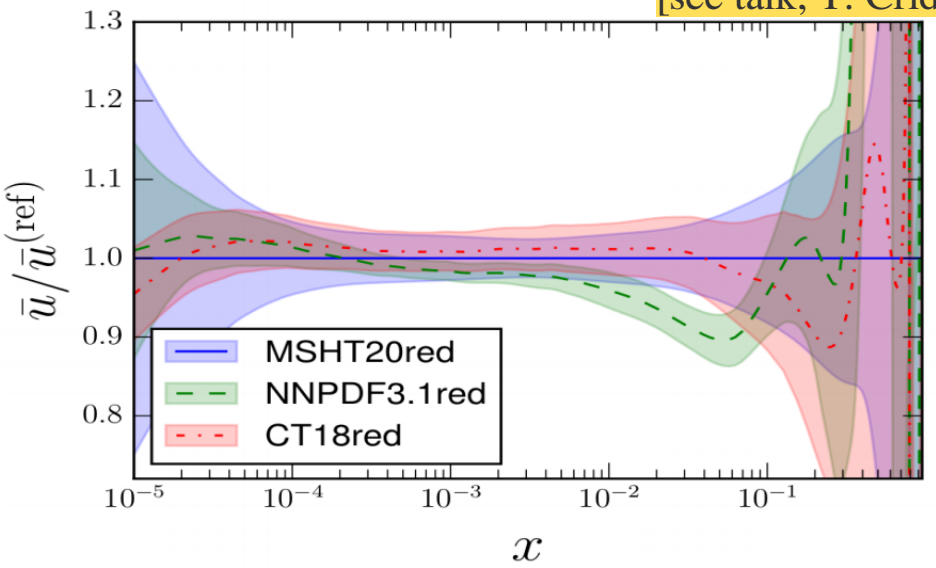
$$\sigma(AB \to W/Z+X) = \sum_n \alpha_s^n \sum_{a,b} \int dx_a dx_b \, f_{a/A}(x_a, \mu^2) \, \hat{\sigma}^{(n)}_{ab\to W/Z+X}(\hat{s}, \mu^2) \, f_{b/B}(x_b, \mu^2)$$

T.-J. Hou et al., PRD 103 (2021) 1. contemporary NNLO QCD fits



…ongoing PDF4LHC21 benchmarking

[see talk, T. Cridge]



- LHC program requires high-precision → reductions to PDF uncertainties

→ needed to match (N)NNLO theory accuracy; MC improvements

[see talk, S. Höche]

precise DIS data will impact many PDF-limited HEP quantities

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

ATLAS, 1701.07240

for example:

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

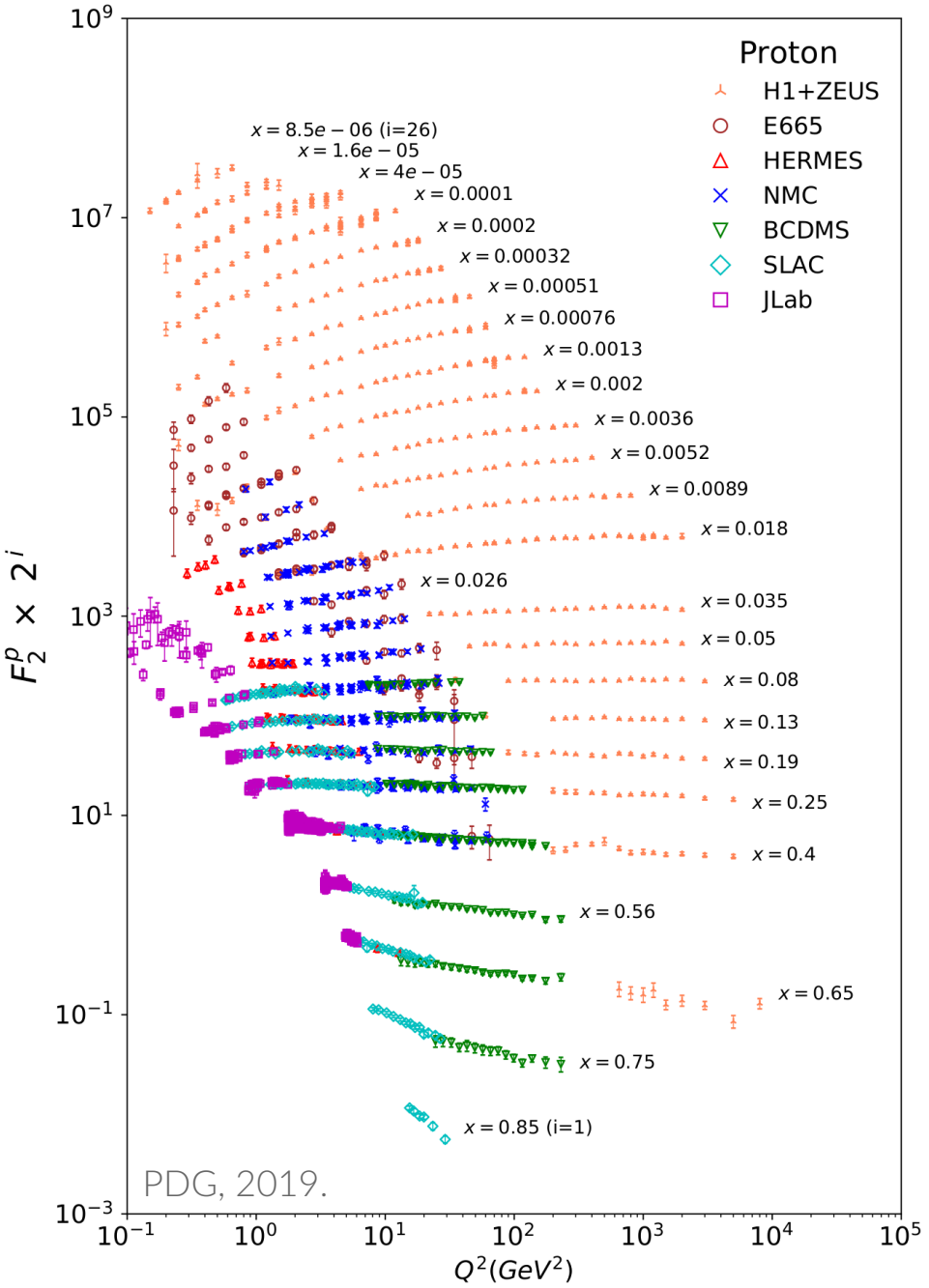
→ the PDF uncertainty can be a/the dominant uncertainty!

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

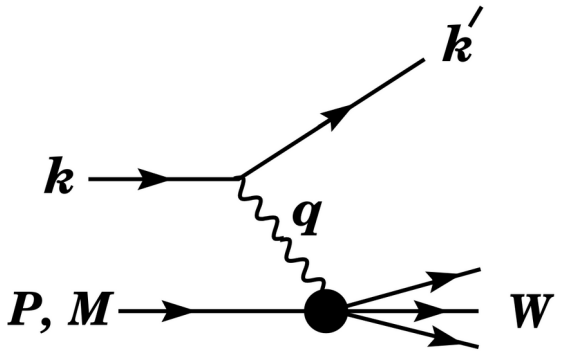
→ **DIS data helpful in resolving PDF limitations:**

- precise access to quark currents; QCD scaling violations
- negotiate tensions among legacy data
- (can be) independent of nuclear effects

DIS → sensitive probe of hadron structure; QCD



- **DIS provides experimentally "clean" access to internal hadron structure, dynamics**



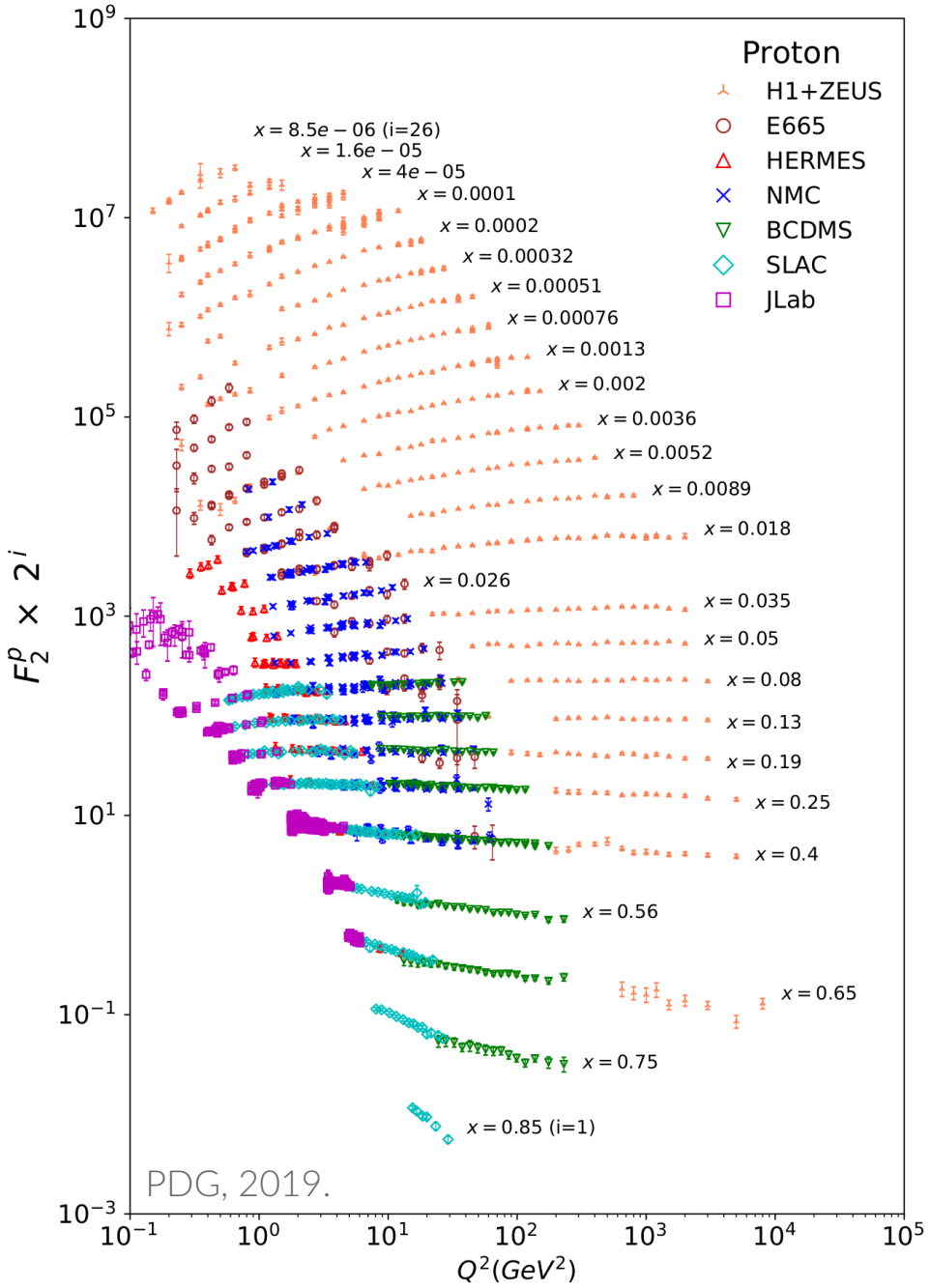
- extraction of quark-gluon information relies on established QCD factorization theorems
- perturbative sector known to N²LO/N³LO

- future experiments will provide valuable QCD 'lever-arm' for pQCD (α_s, m_Q); PDFs

[this talk]

EIC LHeC FCC-eh

DIS → sensitive probe of hadron structure; QCD



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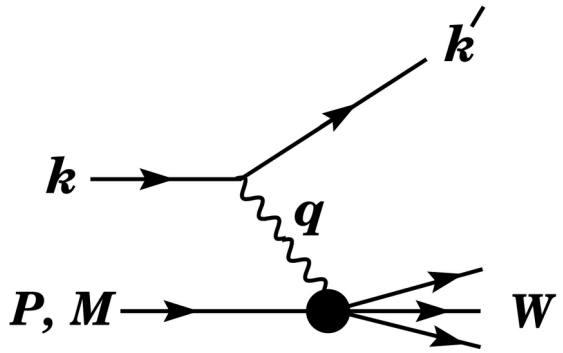

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N.B.: other complementary DIS facilities,

→ νA programs: LBNF, KEK

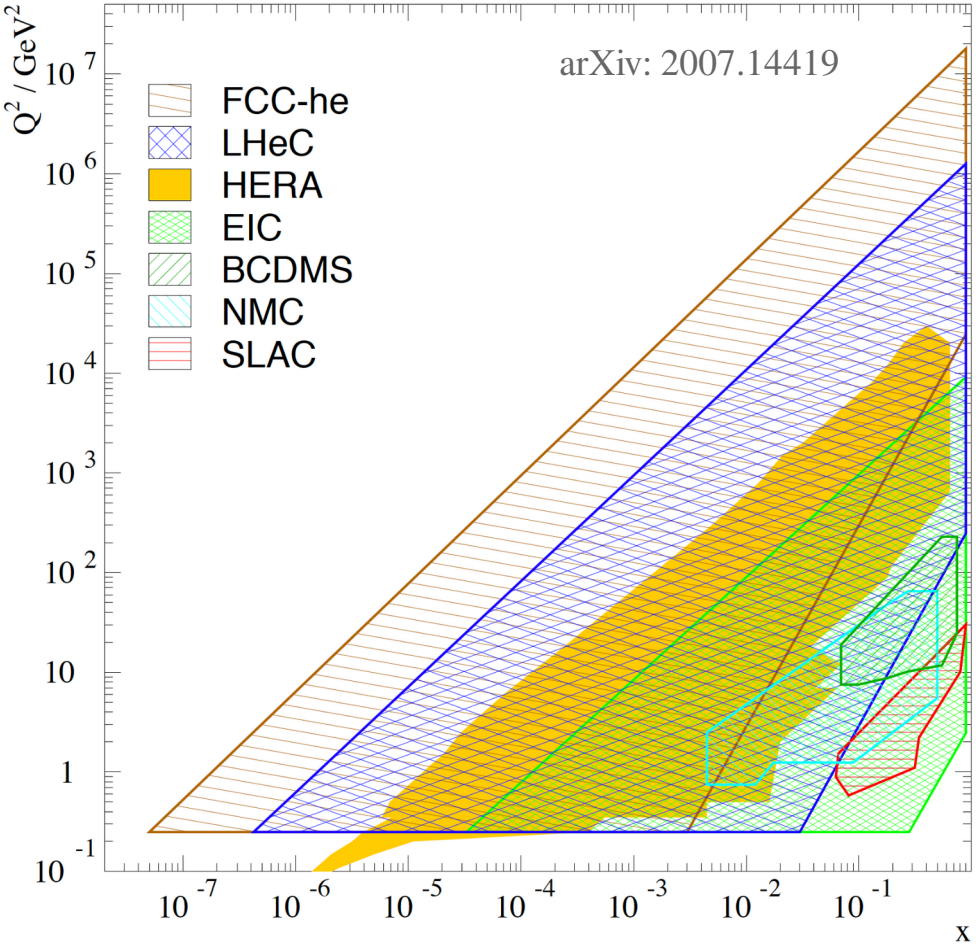
→ ongoing JLab12

→ EIC-China

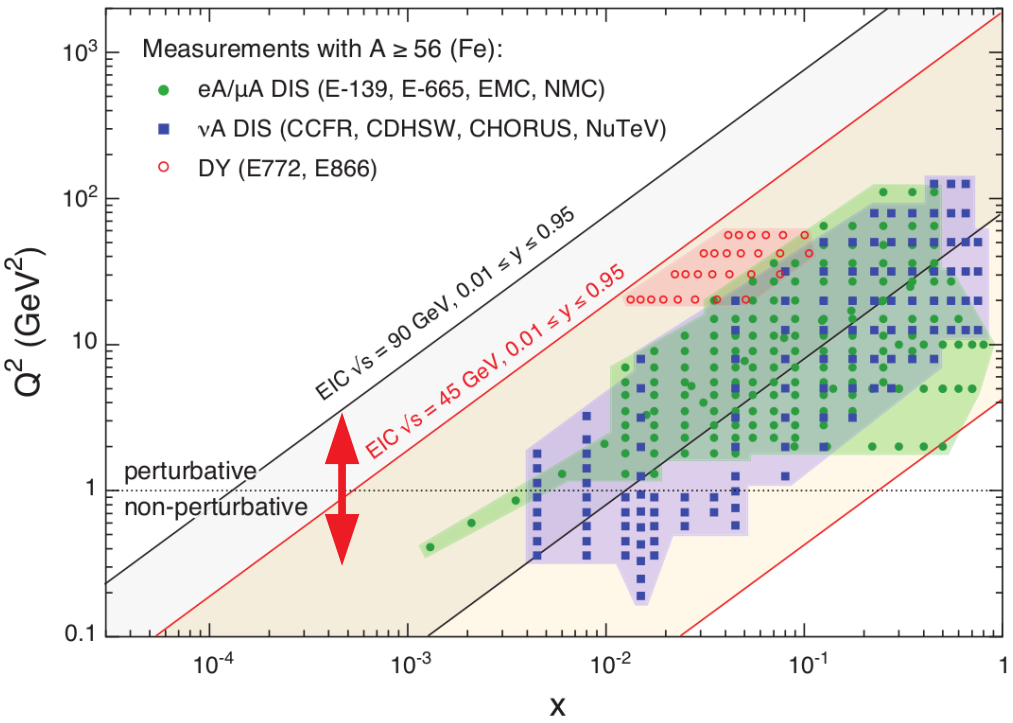
DIS programs of the future

- EIC and LHeC/FCC-eh pursue complementary physics studies in $[x, Q^2]$
- LHeC: push to very low *x*; broad coverage up to HL-LHC data
- EIC: overlap with high-sensitivity fixed-target DIS experiments

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



analogous nuclear DIS coverage:



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

2020-2021: movement toward the EIC

- CD-0: estimated construction cost: $1.6-2.6B over 10 years

  → dedicated machine for (non)perturbative QCD

  → precise 3D imaging of internal structure of nucleons, nuclei

[see talk, T. Hallman]

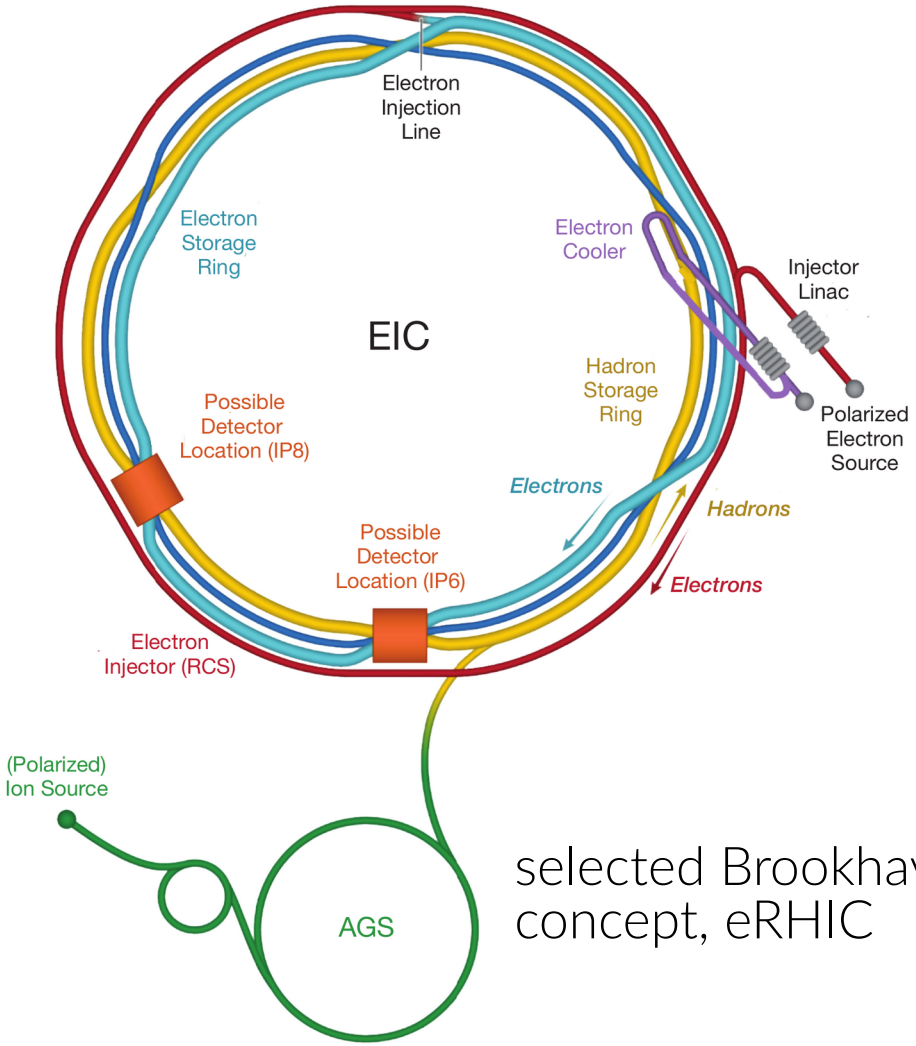
[see talk, B. Pasquini]

- recently completed extensive Yellow Report

  → Physics case; Detector design

arXiv: 2103.05419

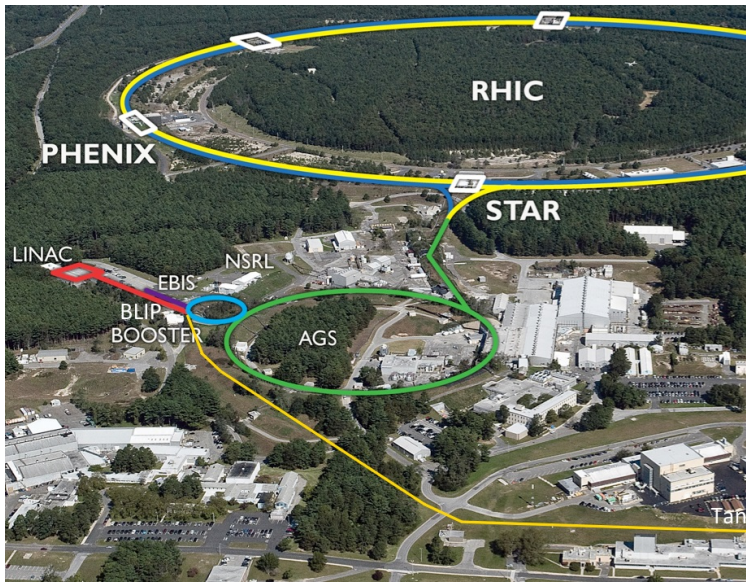
EIC: very high-luminosity DIS collider [$10^{2\text{-}3}$ times HERA]



selected Brookhaven concept, eRHIC

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

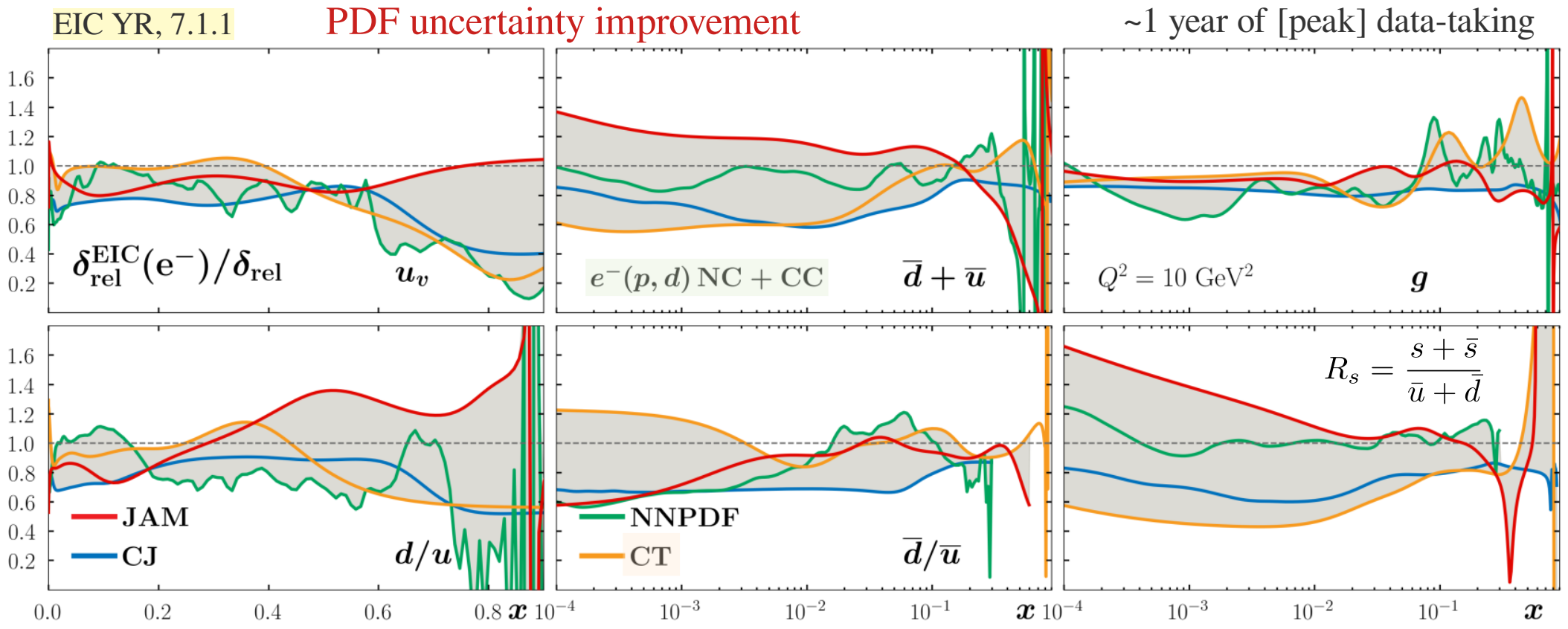
- add electron source, storage ring to existing heavy-ion collider complex (RHIC)



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

substantial reductions to PDF uncertainties

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



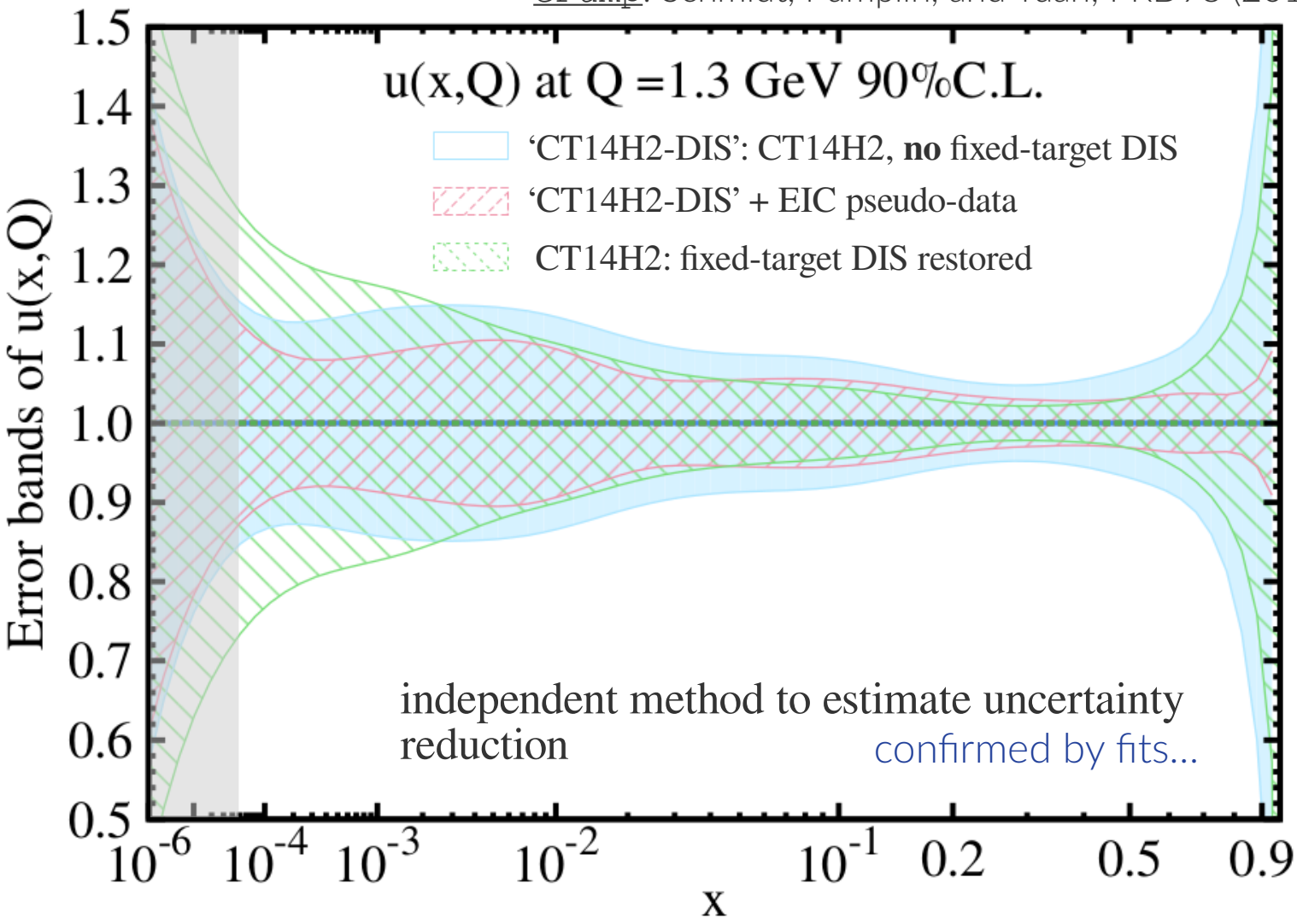
[see talk, F. Delcarro]

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

→ **final-state tagging; positron beams afford greater precision**

PDF impacts compared to high-value fixed-target DIS

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



S. Dulat

- **inclusive EIC may surpass total impact of fixed-target DIS in modern fits**

→ useful for negotiating among existing high-impact data

targeting nonperturbative QCD

- **beyond (inclusive) reduced cross sections, EIC complement of multi-dimensional QCD measurements**

  → higher-twist effects; low-W power-suppressed dynamics

  → generalized parton densities (GPDs), *e.g.*, from DVCS [see talks, W. Cosyn, H. Dutrieux]

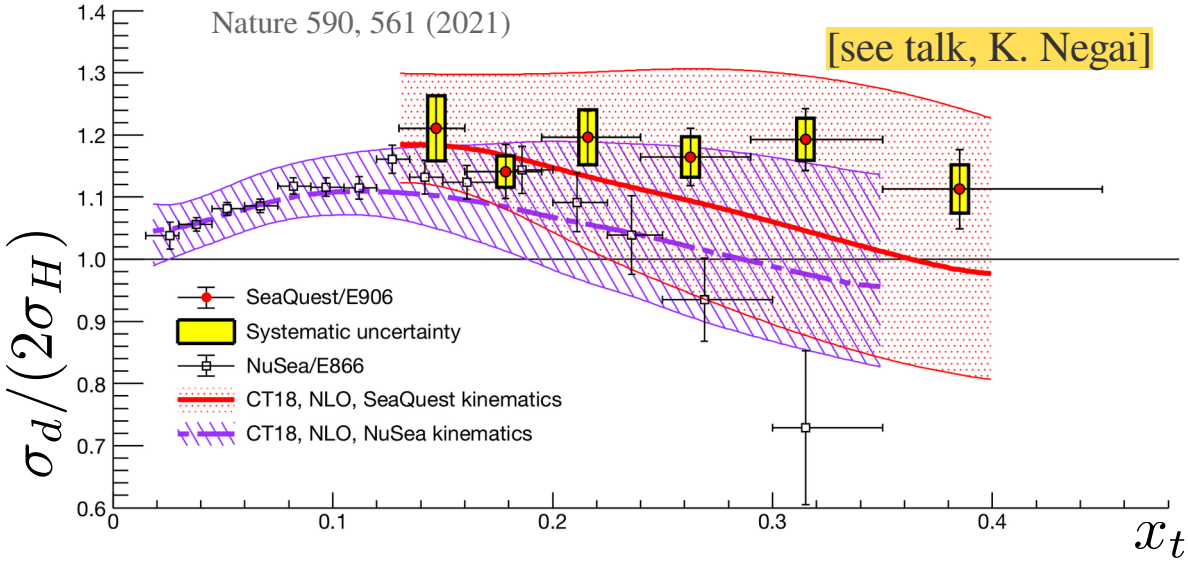
  → semi-inclusive DIS (SIDIS) for TMDs [see talk, P. Taels]

refine factorization theorems; additional access to parton flavor separation

$e.g.,\ \bar{u}(x), \bar{d}(x)$ from $e^- + p \to e^- + \pi^\pm + X$

NB: LHeC opportunities also

- interest following recent FNAL fixed-target Drell-Yan (SeaQuest) results



preliminary study, PDF4LHC March 2021

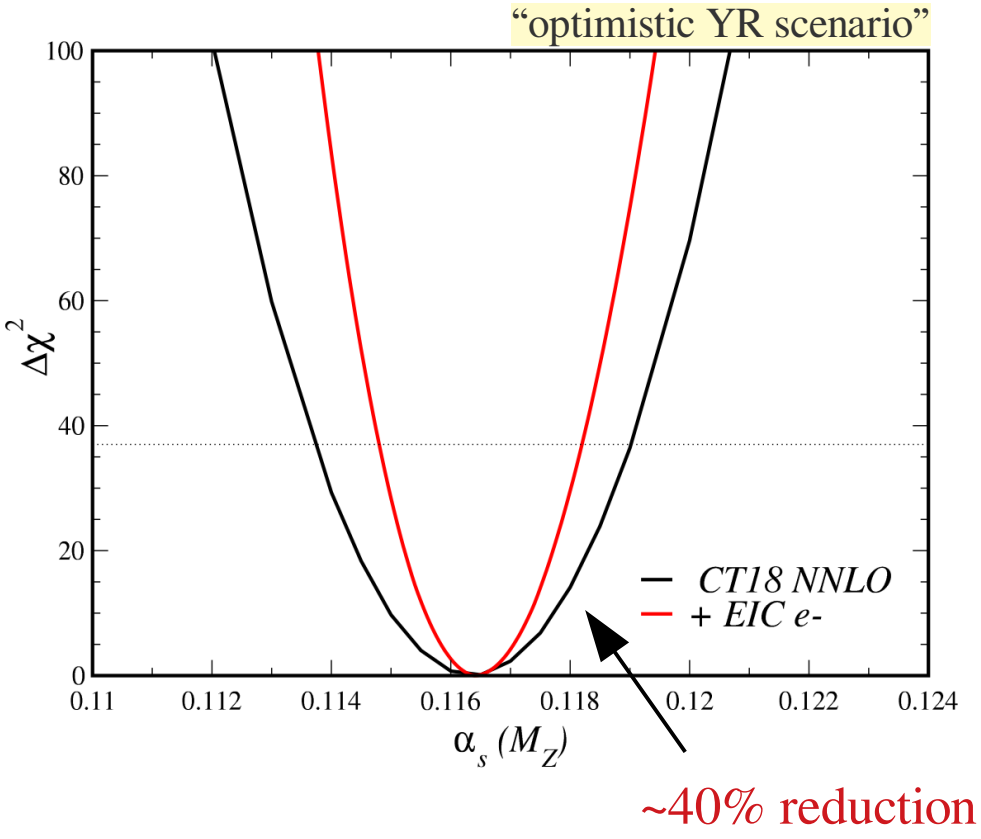
CT18 NNLO, $\chi^2_E/N_{pt} = 0.82$

EIC and SM inputs: α_s

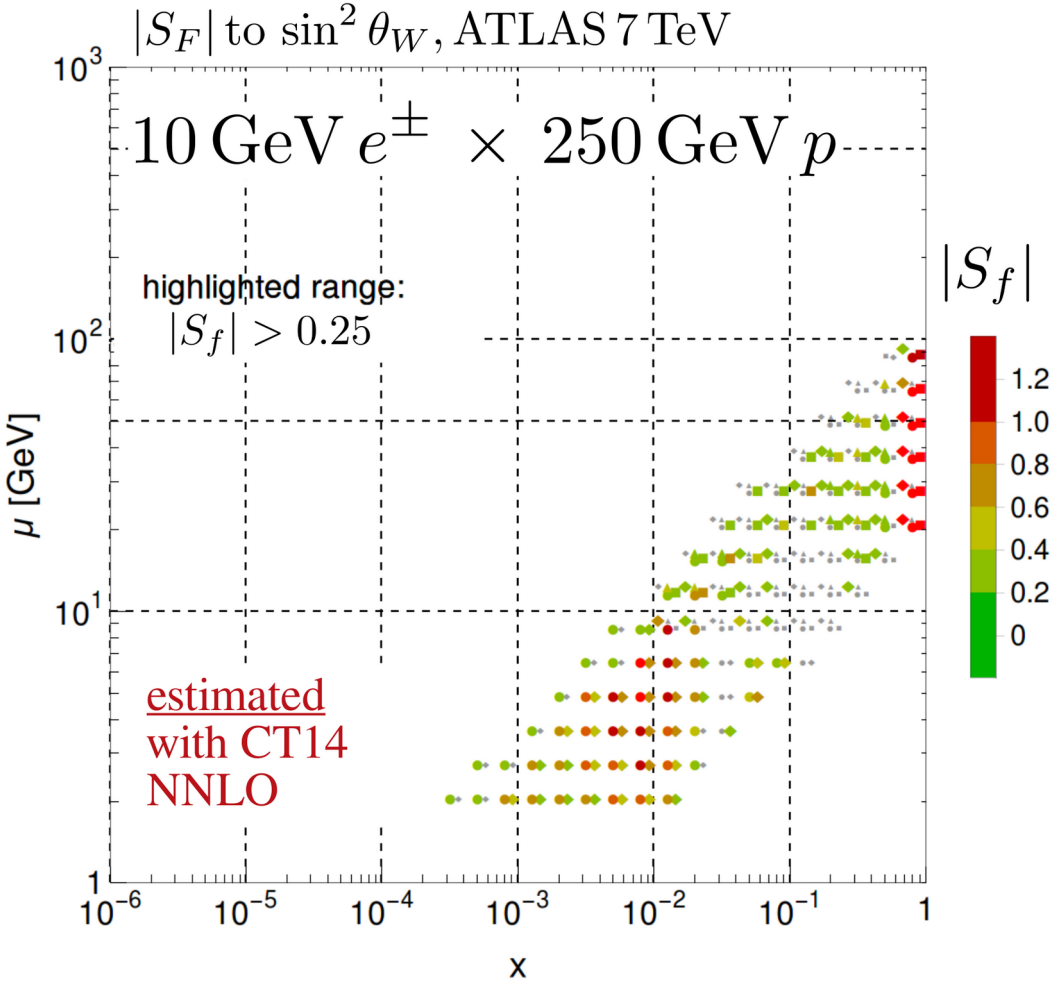
- part of moving toward N^{3}LO PDFs, precise determinations needed for α_s

similar argument for m_Q

from inclusive data alone

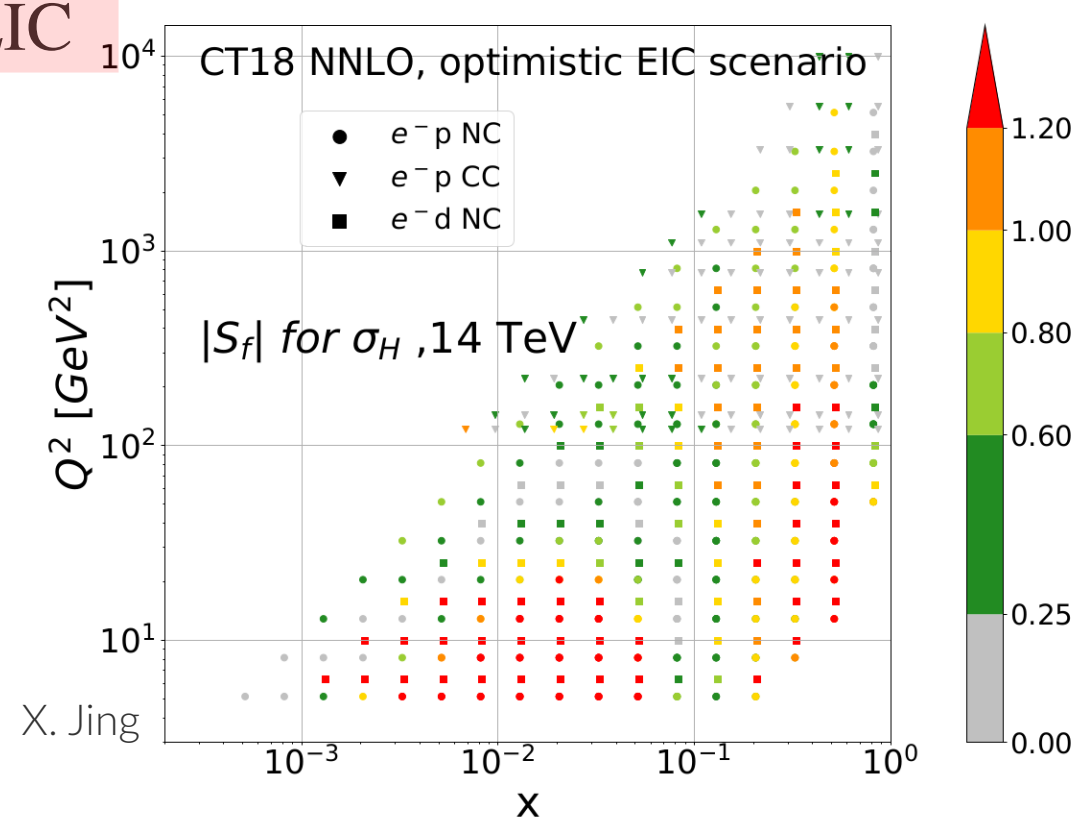


B.-T. Wang et al., PRD **98** (2018) 9.



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

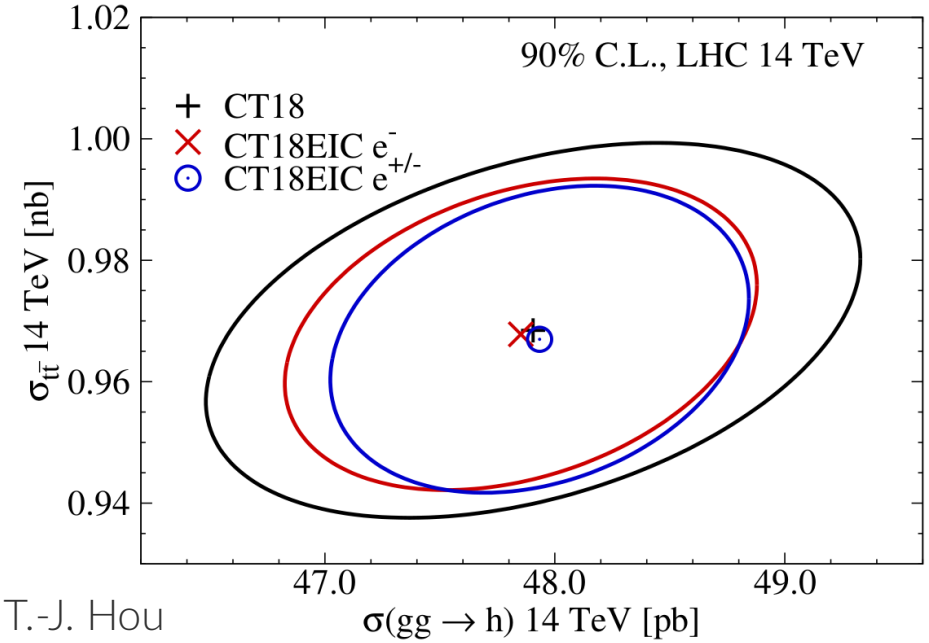
- robust PDF sensitivity to $\sin^2\theta_W$ from A_{FB}



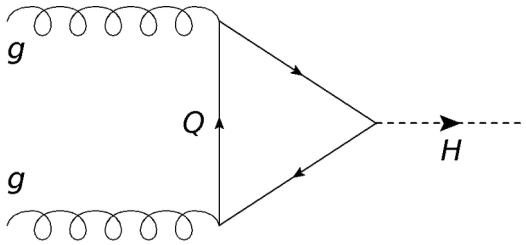
X. Jing

strong predicted impact on the Higgs sector

- PDF-driven improvement to Higgs-production cross section
- EIC impact on Higgs theory from broad region of the kinematical space it can access



T.-J. Hou



- impact closely tied to that of the integrated gluon PDF

→ added leverage from positron data…

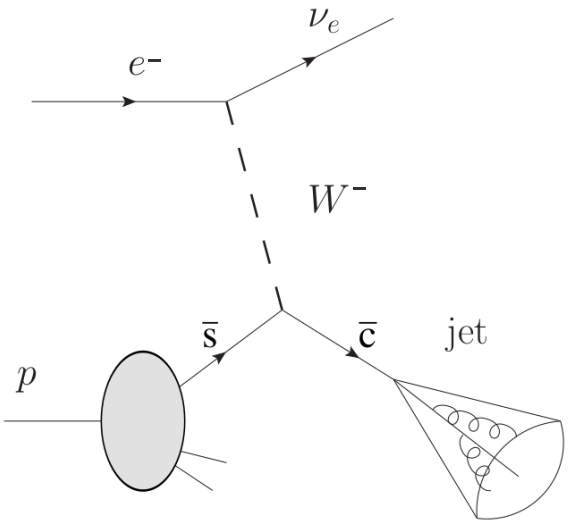
precision QCD through jet and heavy-flavor production

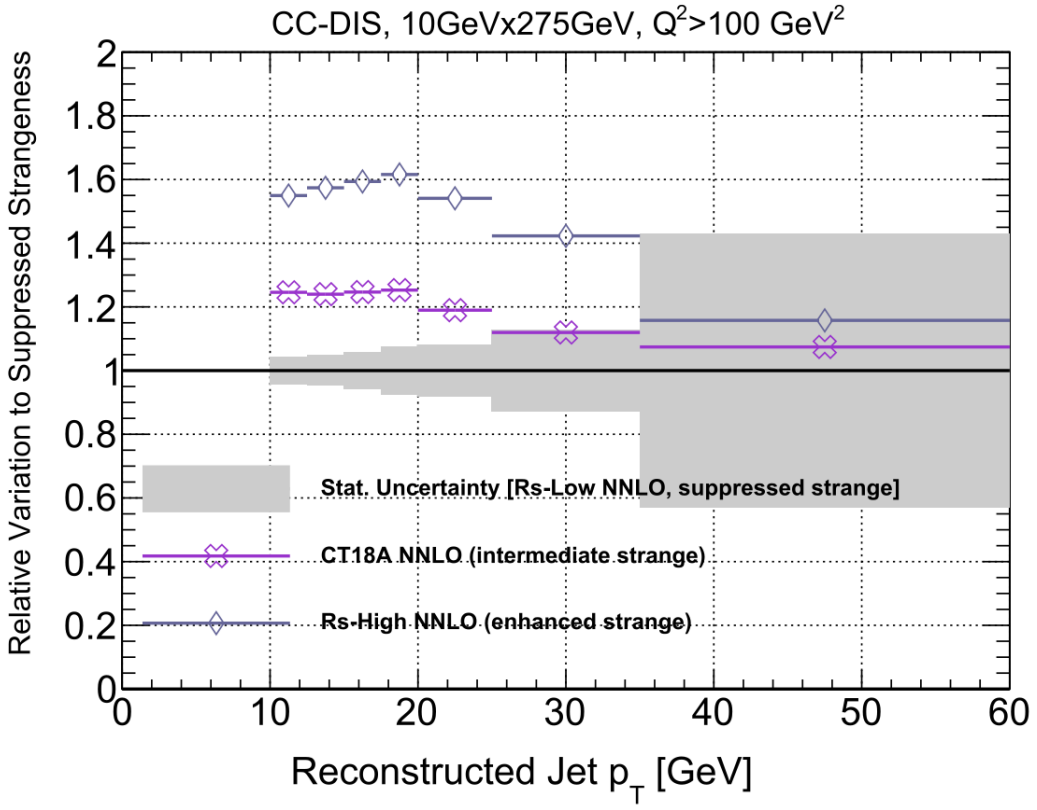
- DIS jet production, including through charge-current interactions, provides further access to quark-level information

PRD, to appear; arXiv: 2006.12520

Arratia, Furletova, TJH, Olness, Sekula

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)

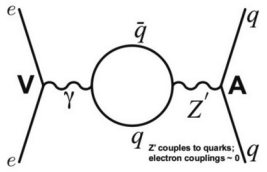
- many jet-based studies to explore perturbative QCD possible

[see talks, M. Arratia, M. Klasen]

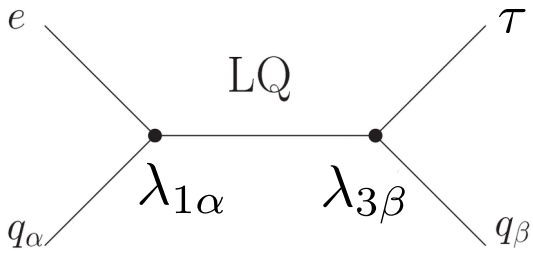
e.g., diffractive dijet production → tests of factorization

EW and BSM opportunities

- potentially BSM-sensitive extractions of EW quark couplings, $\sin^2\theta_W$ through **parity violation**

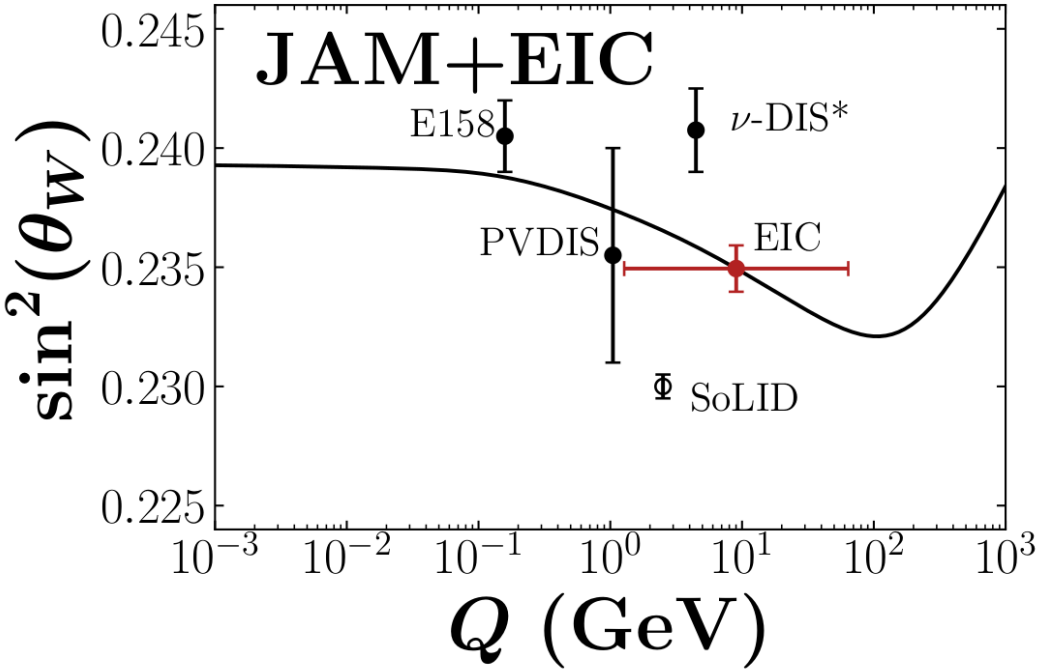


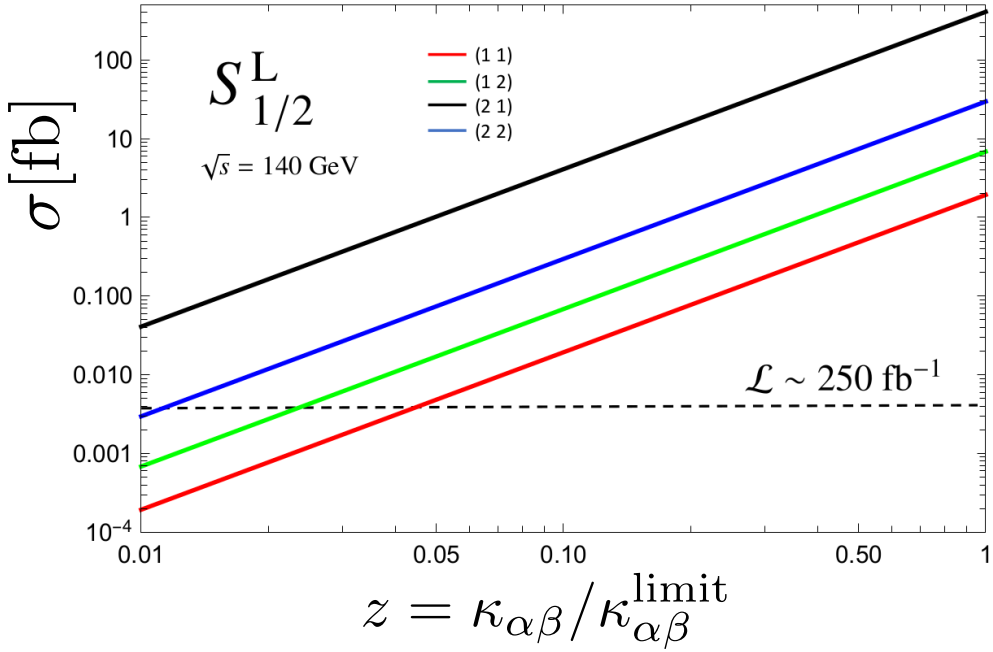
$$A_{\mathrm{PV}}^{e} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$



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

EIC YR, 7.5.1

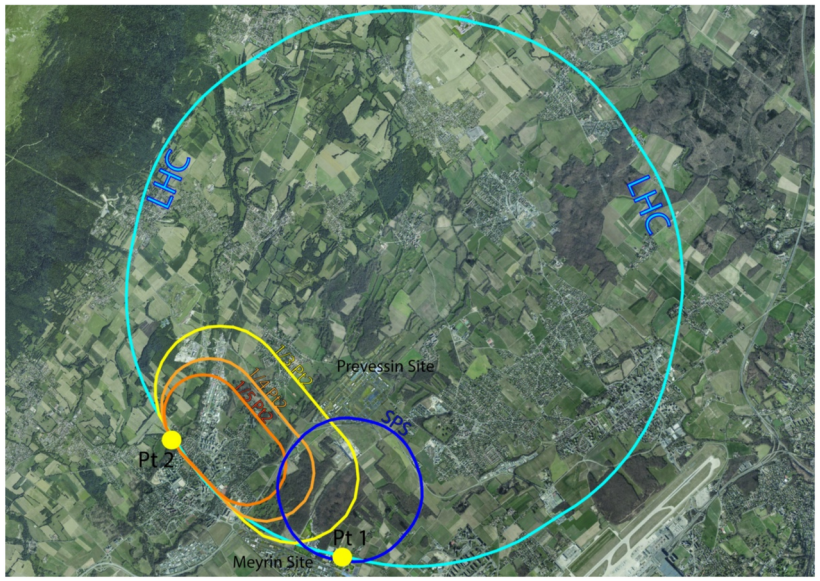




- more direct SM tests also possible: searches for charged-lepton flavor violation (CLFV)

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

DIS at the LHC: LHeC and FCC-eh



DIS with LHC kinematics:

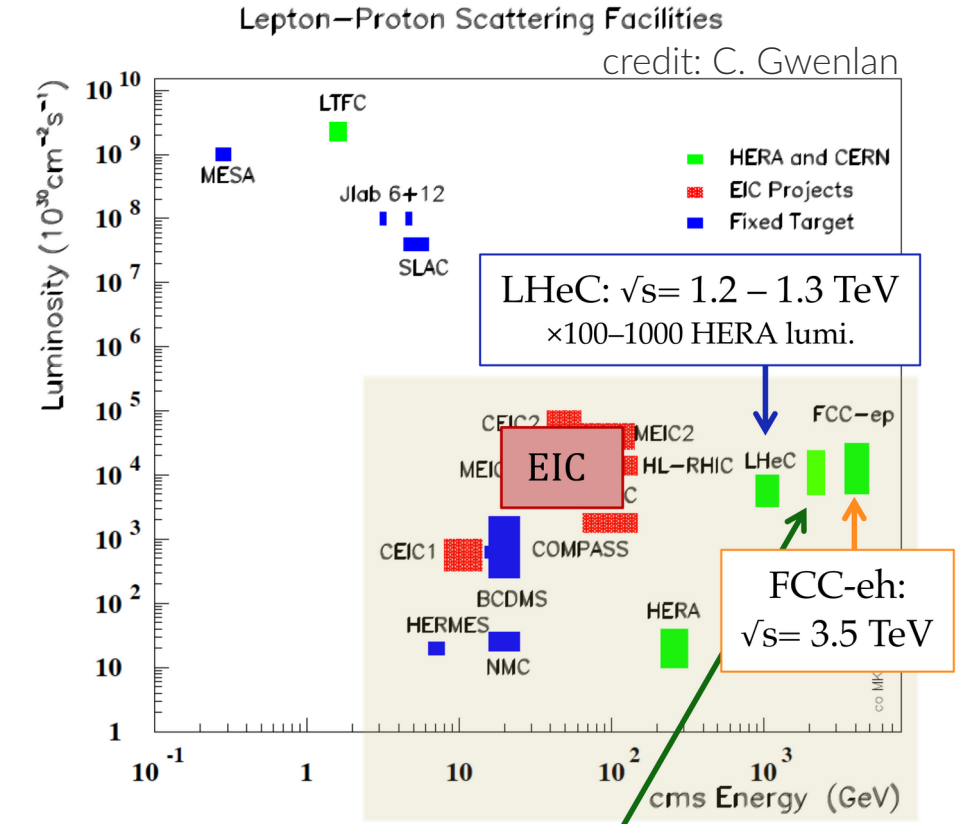
$$E_e = 50, 60\,\text{GeV}$$
$$E_p = 7\,\text{TeV}$$
$$\sqrt{s} = 1.2,\ 1.3\,\text{TeV}$$

$$\int dt\,\mathcal{L} = 1\text{–}2\,\text{ab}^{-1}$$
$$P_e = \pm 0.8$$

- **build an Energy Recovery LINAC (ERL) to supply electron beam to HL-LHC… or FCC**

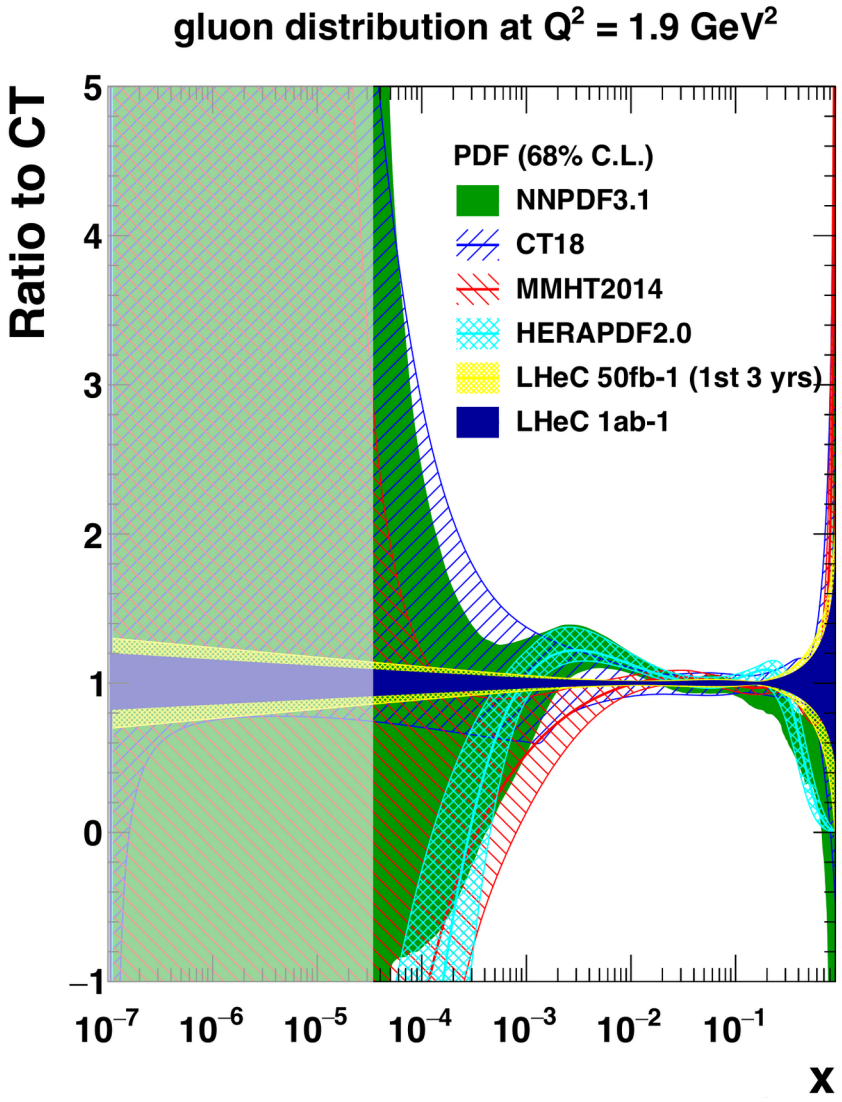
→ further developed in recent LHeC whitepaper, arXiv: 2007.14491

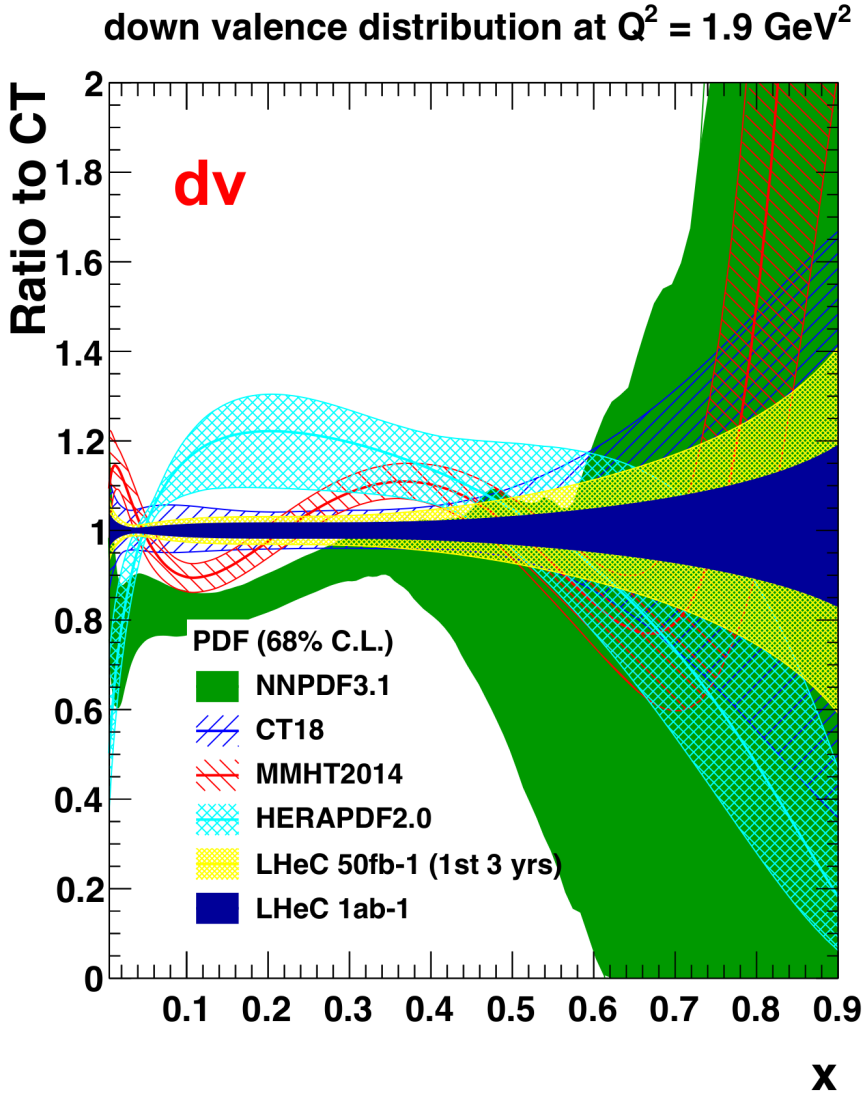
→ **extensive** opportunities to probe QCD, test the SM



LHeC can probe PDFs to high precision

LHeC band from xFitter analysis; detailed study in arXiv: 2007.14491 [see talk, C. Gwenlan]





- **sensitivity to low-x dynamics**

  → saturation; onset of BFKL scaling

[see talk, A. Stasto]

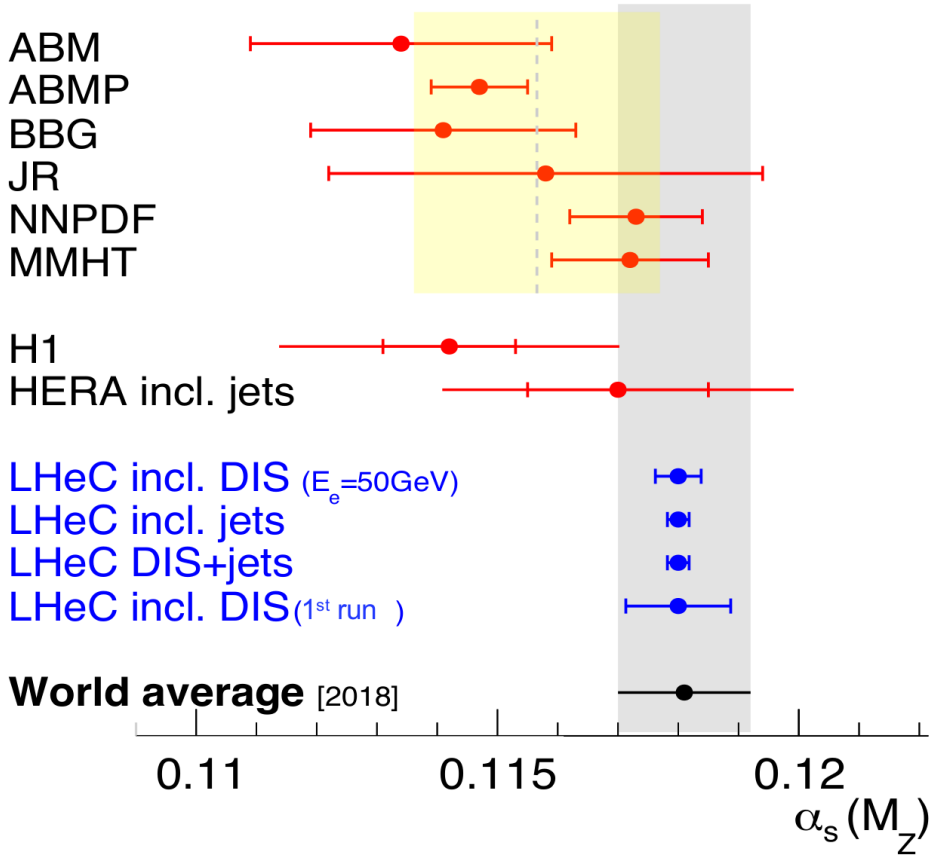
- **reductions of high-x quark PDF errors**

  → critical for BSM searches

LHeC can probe PDFs to high precision

[see talk, U. Klein]

αs determinations at NNLO QCD:



LHeC simultaneous **PDF+αs** fit:

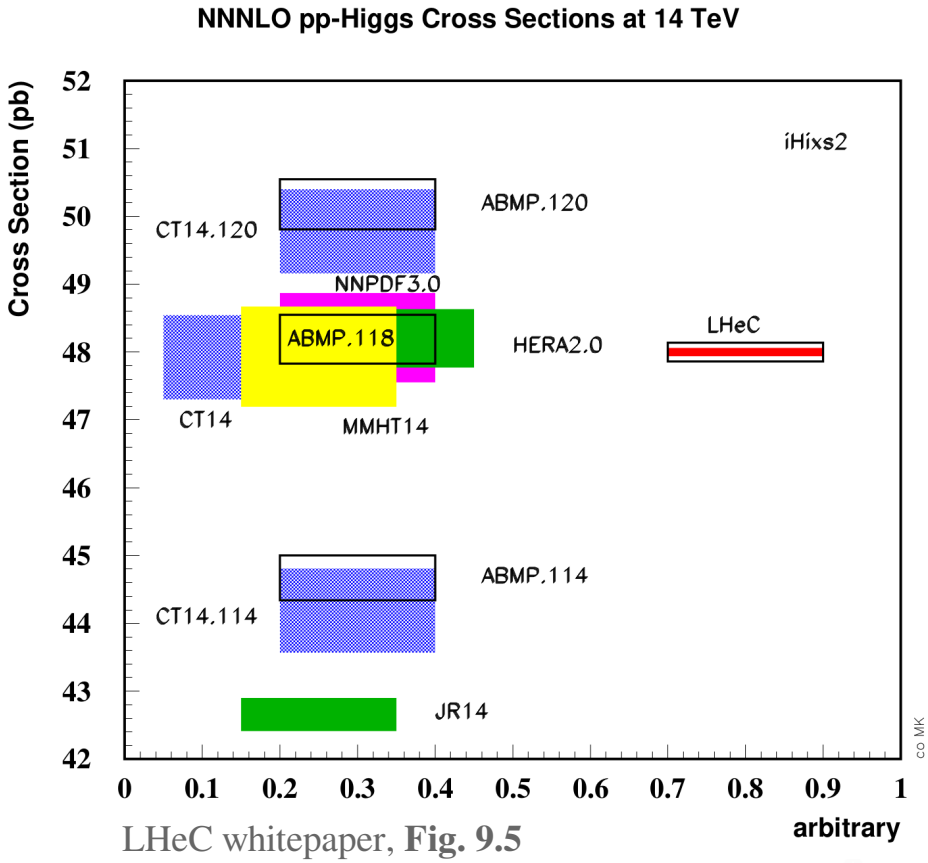
Δαs(MZ) (exp.+pdf) = **±0.00022** (inclusive DIS)

Δαs(MZ) (exp.+pdf) = **±0.00018** (incl. DIS & jets)

[see talk, C. Gwenlan]

- achievable precision $\mathcal{O}(0.1\%)$

- substantial achievable precision in N³LO Higgs cross sections:



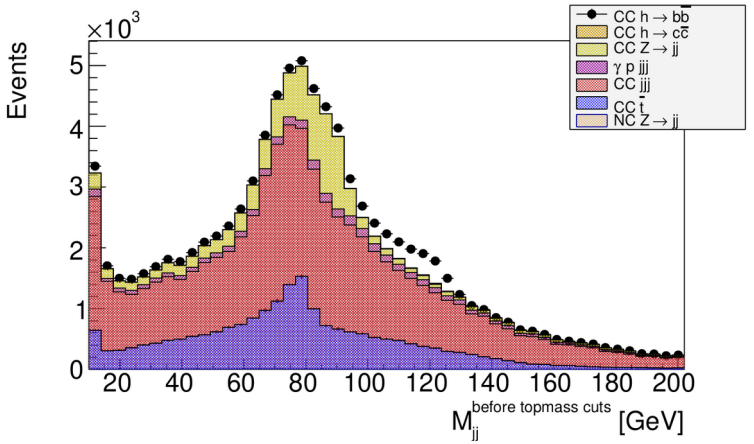
LHeC whitepaper, **Fig. 9.5**

precision capabilities in the Higgs Sector

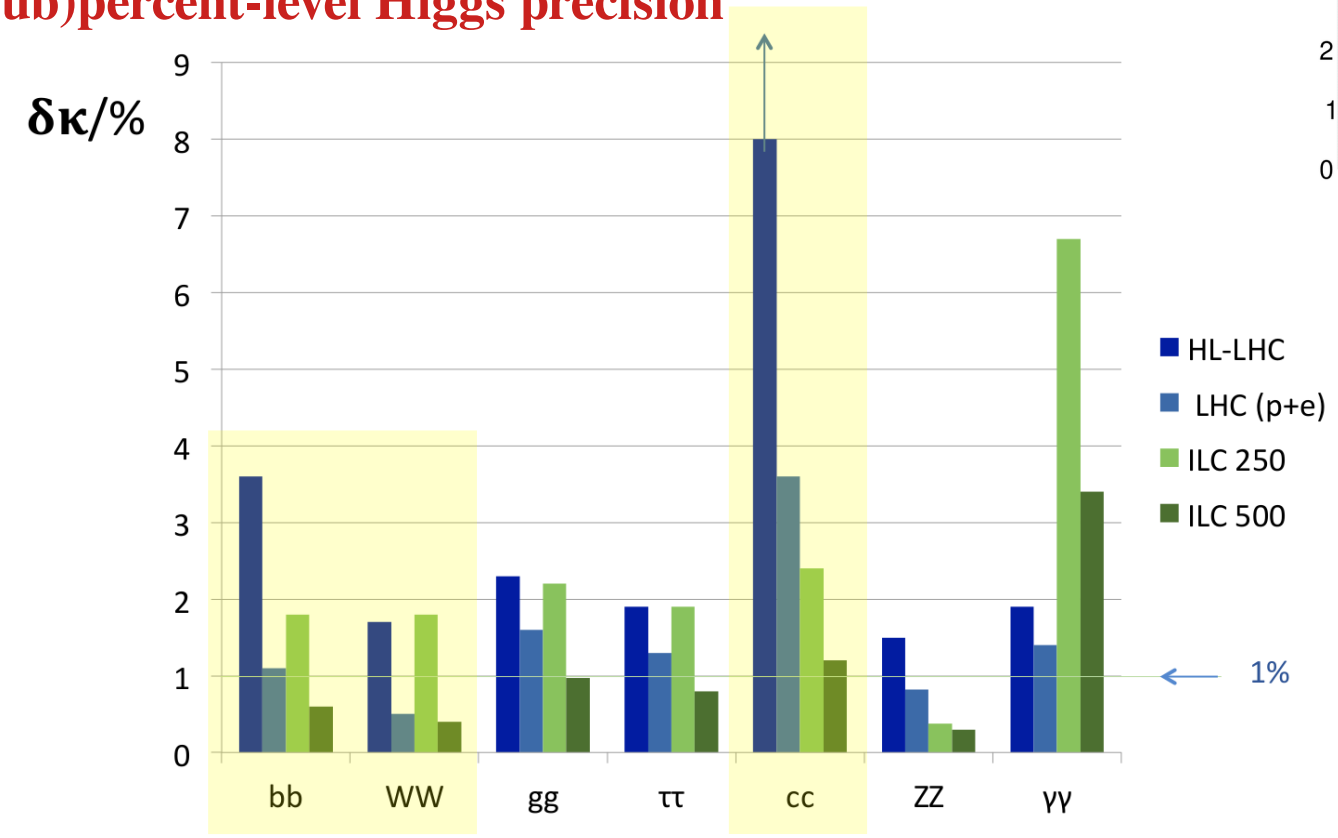
[see talk, U. Klein]

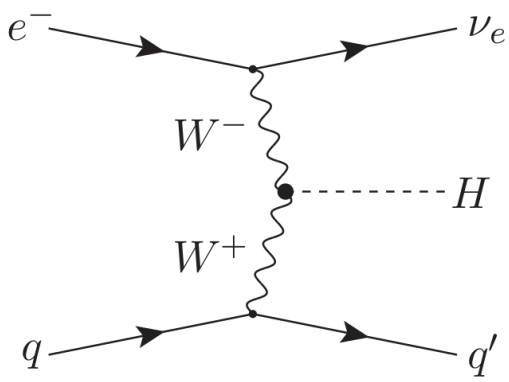
- availability of TeV-scale energies at LHeC opens direct DIS Higgs production channels

...fertile territory for possible BSM signals...



(sub)percent-level Higgs precision





- in line with tight limits in $t\bar{t}$ sector, α_s

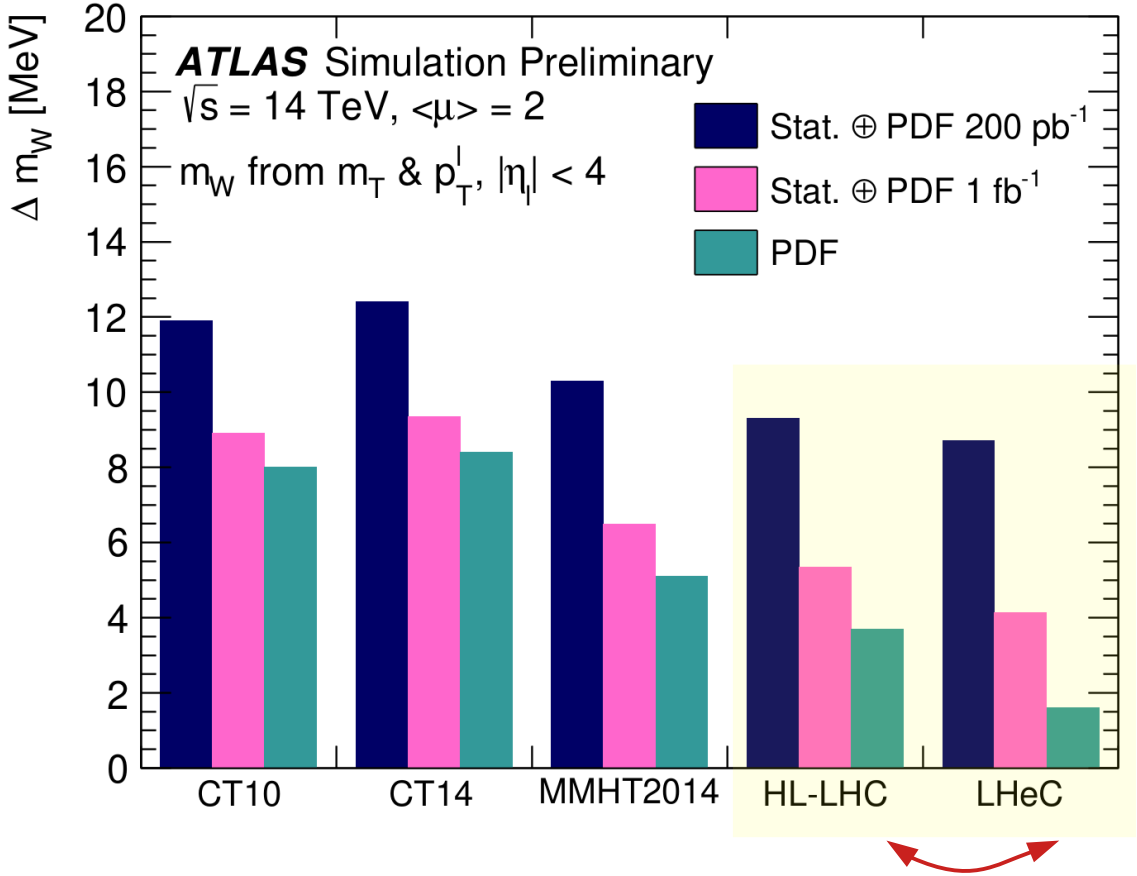
[see talks, M. Kumar, C. Gwenlan]

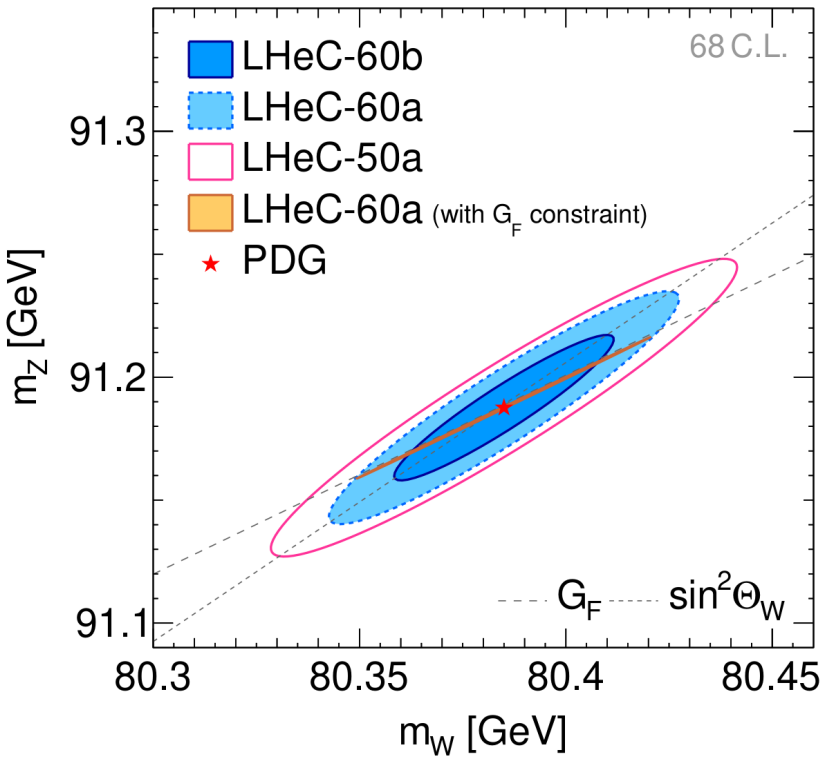
improved sensitivity to gauge boson masses

[see talks, L. Aperio Bella, D. Britzger]

- **like the EIC, LHeC could dramatically enhance constraints to m_W**

$$\Delta^{\mathrm{PDF}} m_W \lesssim 2\,\mathrm{MeV}$$



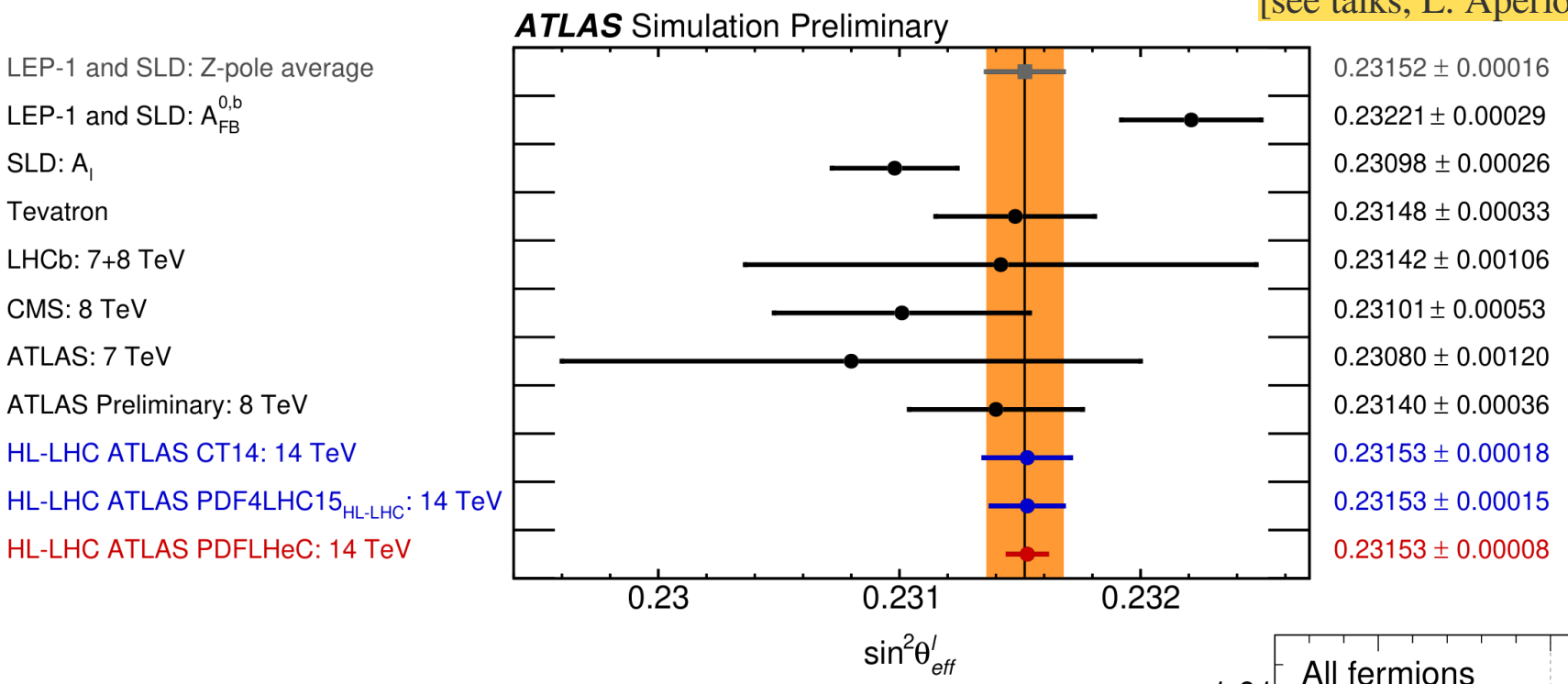


> factor 2 PDF improvement

- m_W measurement uncertainty from 200 pb^{-1} and 1 fb^{-1}, low pile-up m_T and p^l_T HL-LHC data

constraints on fundamental interactions

[see talks, L. Aperio Bella, D. Britzger]

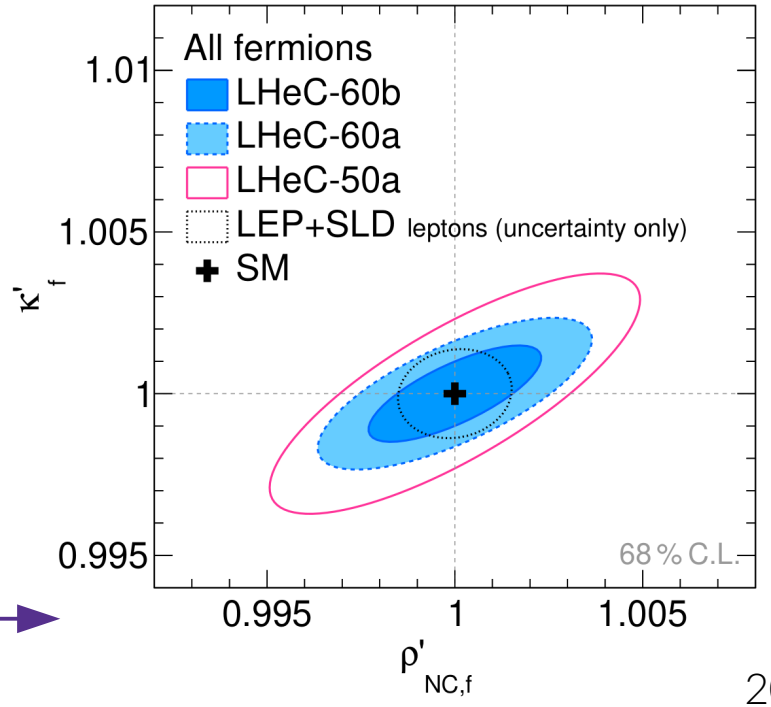


- PDF constraints produce significant (factor 2) improvement in effective weak mixing angle

$$\sin^2\theta^{\text{eff}}_{W,f}(\mu^2) = \kappa'_f(\mu^2)\,\kappa_f(\mu^2)\,\sin^2\theta_W$$

$$g_A^f = \sqrt{\rho'_{\text{NC},f}\,\rho_{\text{NC},f}}\,I^3_{\text{L},f}$$

- precision extends to limits on anomalous couplings

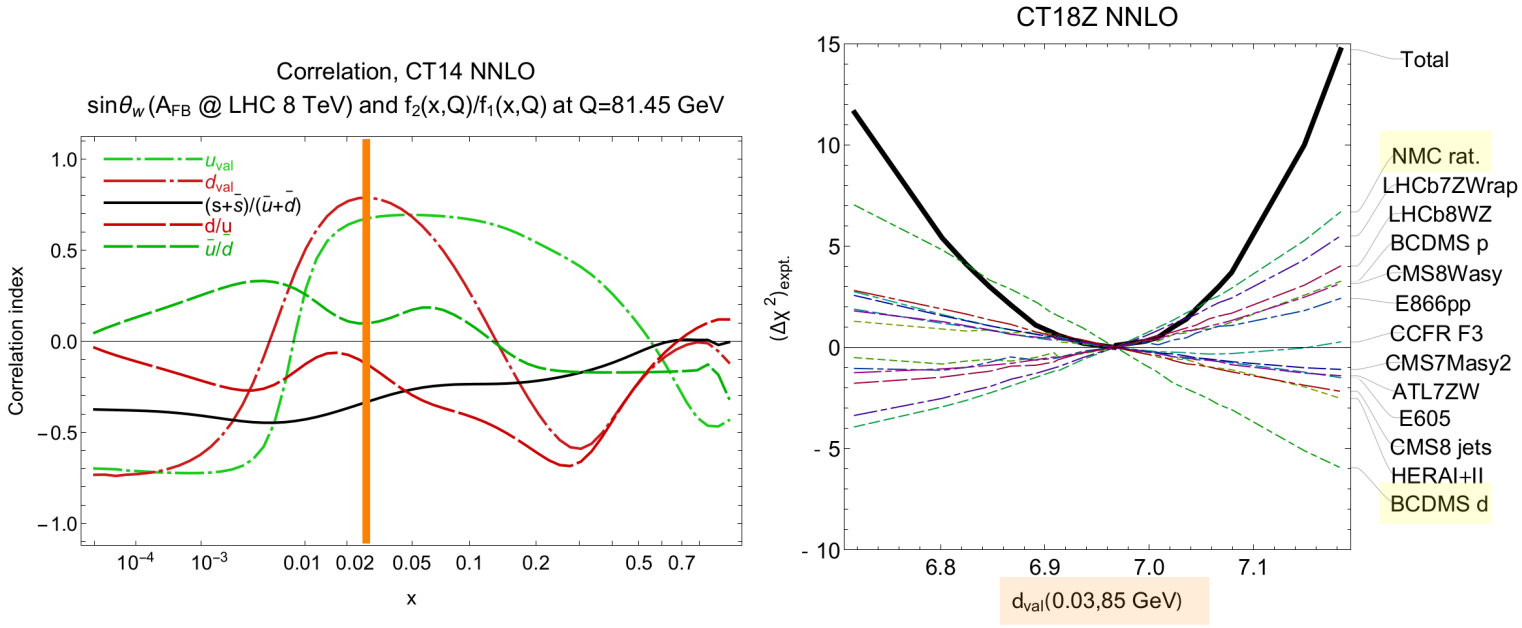


progress in resolving nuclear ambiguities

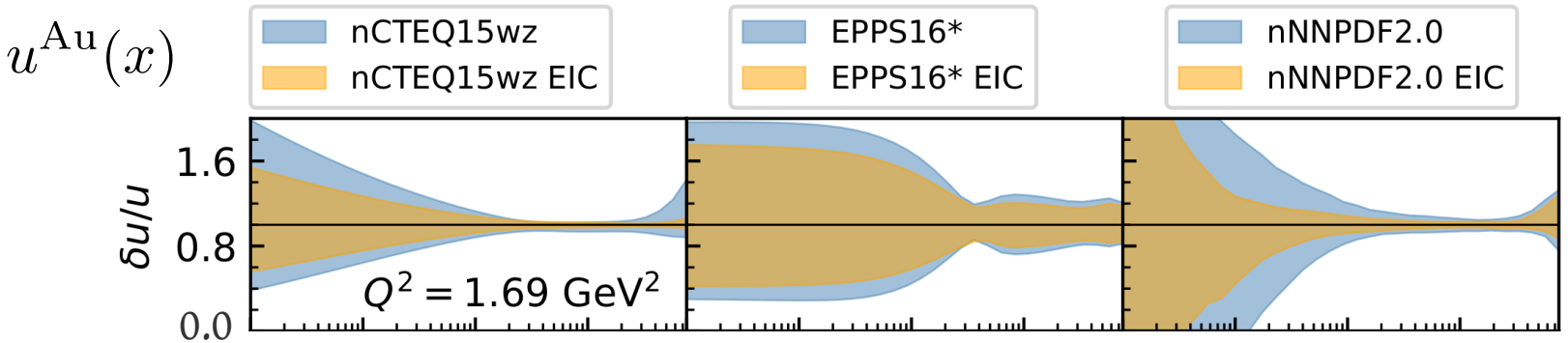
[see talks, X. Jing, R. Pearson]

Accardi, TJH, Jing, Nadolsky; arXiv: 2102.01107

- understand deuteron structure: *e.g.*, important for valence *u*, *d* PDFs; $\sin^2\theta_W$



→ measure only "clean" DIS from hadrons; but also explore nuclear medium!



[see talks, C. Keppel, R. A. Khalek, T. Lappi, H. Mäntysaari, I. Vitev, ...]

similar message for LHeC

EIC YR, 7.3.3

→ nuclear effects: jet production, hadronization; implications for AA, UPC programs

future DIS experiments in Snowmass 2021 community planning

SnowMass2021

- Snowmass 2021: inputs to P5, HEPAP; recommendations for particle physics, including LHC activities

Letters Of Interest,

- for the EIC
  - → tomography – [includes PDFs] (LOI)
  - → heavy flavor (LOI)
  - → Electroweak and BSM (LOI)
  - → Jet production (LOI)

...as well as others.

- LHeC, FCC-eh studies
  - → small-x physics (LOI)
  - → PDFs, α_s (LOI)
  - → joint *hh*/*eh* analyses (LOI)

e.g., other LHeC/FCC-eh LOIs:

- Top-Quark and Electroweak Physics at LHeC and FCC-eh (EF4)
- Detector solutions for Lepton-hadron Scattering based on the LHCand FCC (general, IF9)
- LHeC and FCC-he: Dark Matter (EF10)
- LHeC and FCC-he: More general explorations (EF09)
- LHeC and FCC-he: Model specific c explorations (EF08)
- Energy Frontier eh Scattering - LHeC and FCC-eh (general)
- Physics at High Energy eh and hh Experiments (general)
- LHeC and FCC-eh: Small-x Physics at Energy FrontierElectron-Proton and Electron-Nucleus Colliders (EF6, EF7)
- PDFs, alphas and Low-x Physics and at Future DIS FacilitiesLHeC/FCC-eh: Future (EF) ep and eh Colliders (EF5)
- PERLE a 'Stepping Stone' for the Next Generation ERLs (AF6,AF7)

conclusion

- the future for DIS – experiment and theory – is bright indeed

  HERA, JLab12, … → EIC; LHeC [FCC-eh]

- these DIS programs will be central to realizing precision goals at HL-LHC

  …while settling long-standing puzzles in QCD; exploring Higgs, BSM, …

- community planning (à la Snowmass) needed to leverage physics results

Many thanks to colleagues throughout these intersecting communities

- EIC: A. Deshpande, Y. Furletova, D. Higinbotham, R. Yoshida
- LHeC/FCC-eh: L. Aperio Bella, C. Gwenlan, M. Klein, U. Klein
- CTEQ groups [CT; nCTEQ; CJ]: S, Dulat, T.-J. Hou, P. Nadolsky, C.-P. Yuan; C. Keppel, O. Kusina, F. Olness; A. Accardi, X. Jing

…and others!