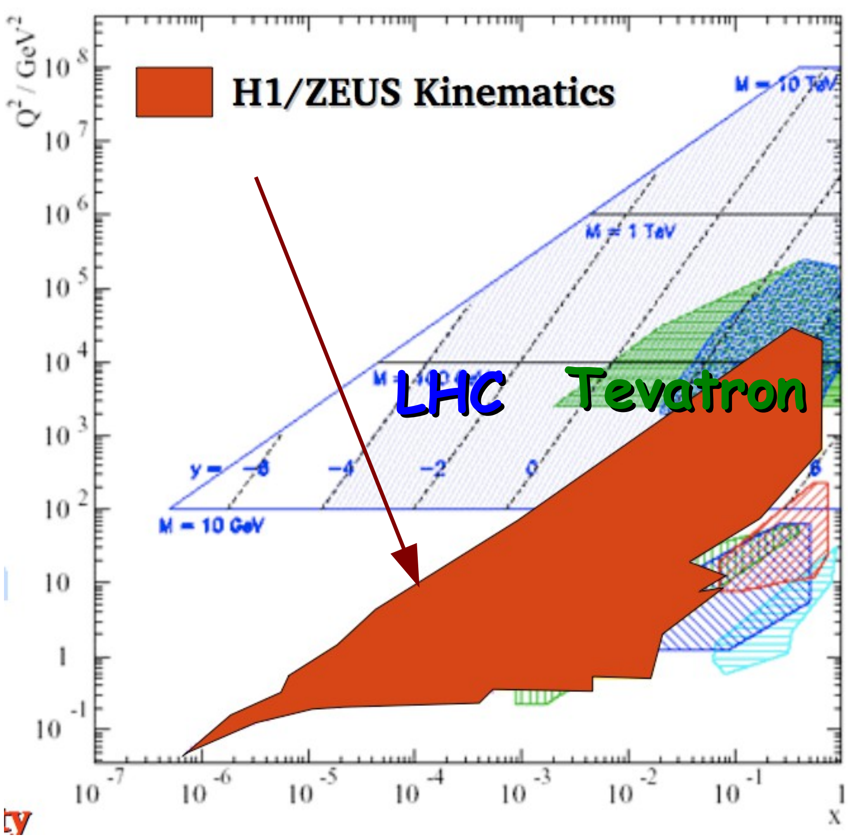
# PDFs from ep colliders:
# From current to ultimate picture


K. Wichmann

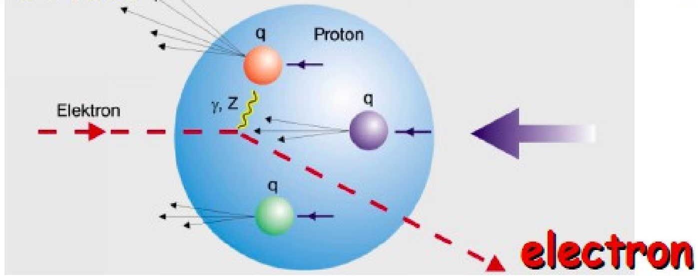
# Proton structure

- PDFs used in hadron interactions: LHC, Tevatron, HERA
- Precision of many measurements often limited by PDF uncertainty



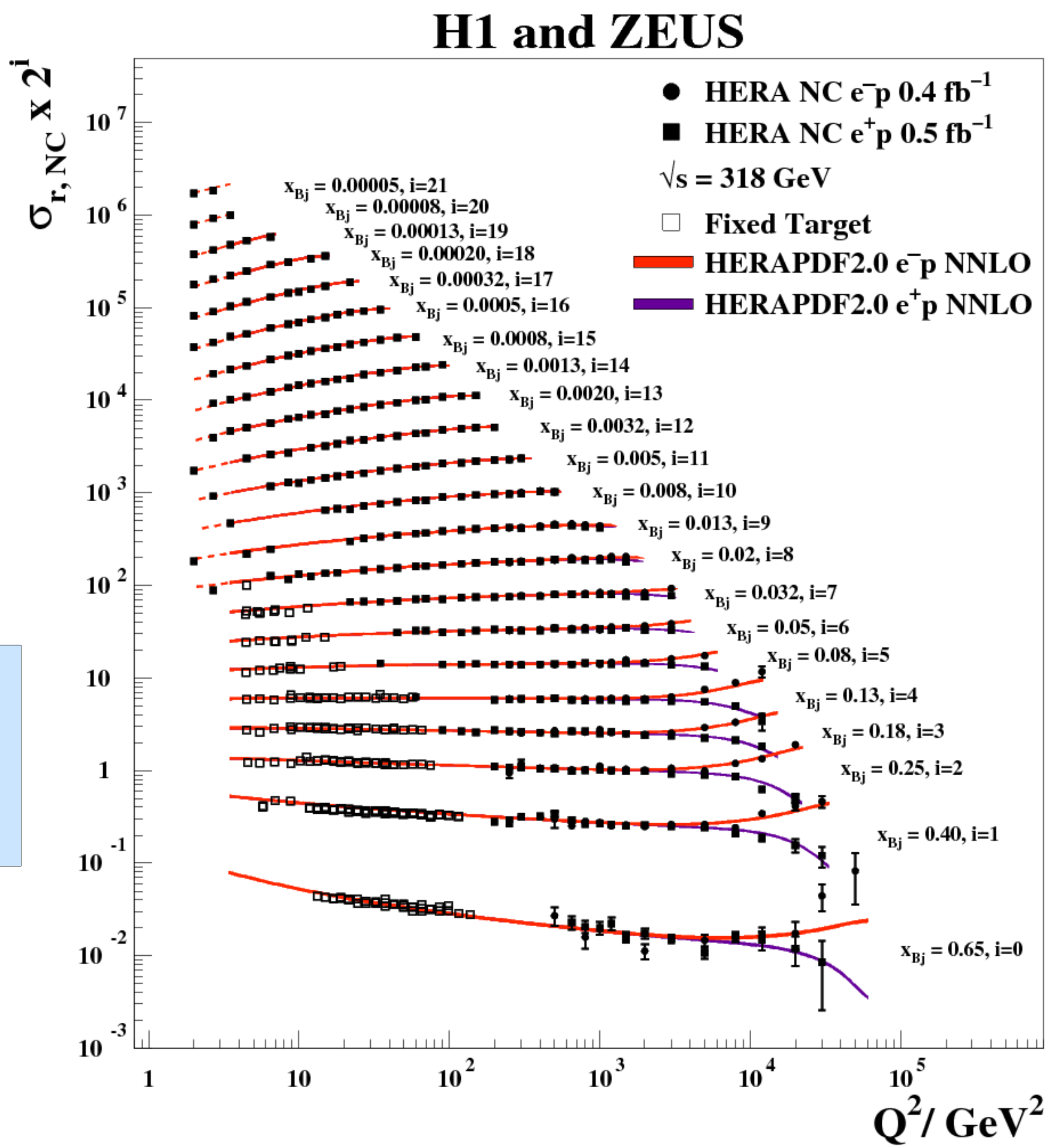

**Inclusive measurements from HERA are core of every parton density extraction**


K. Wichmann, Stony Brook 2025




# HERA combined inclusive DIS






## HERAPDF philosophy

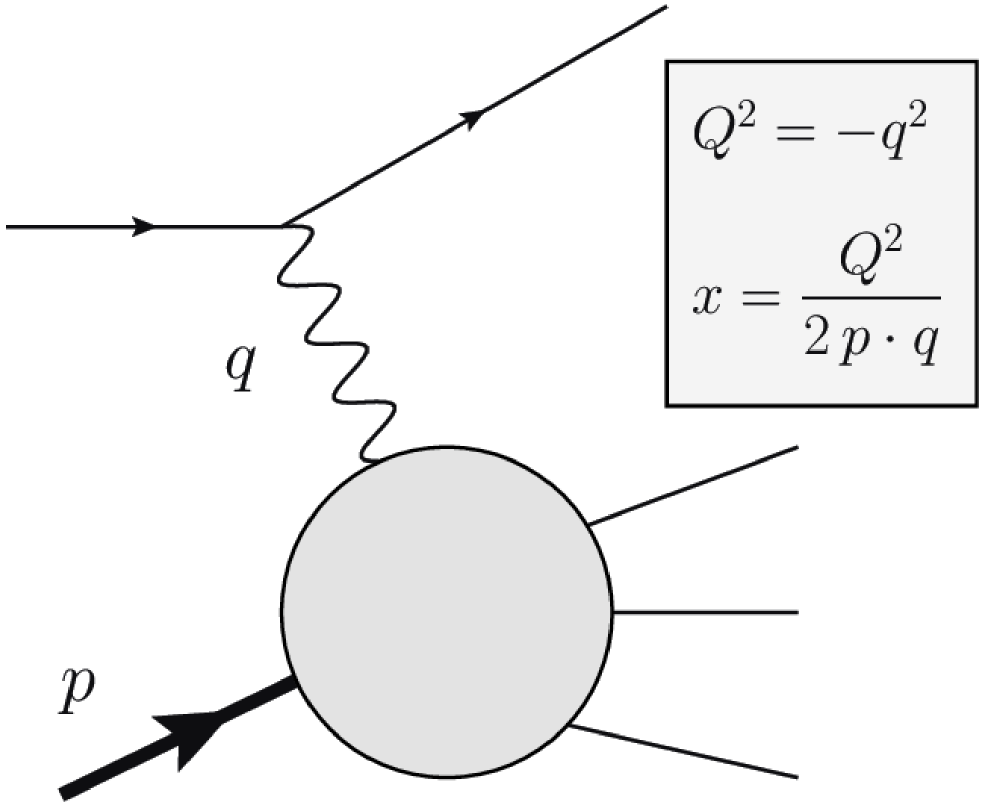
HERAPDF approach uses <u>only</u> HERA data in global QCD fit

 extend it to only DIS data …

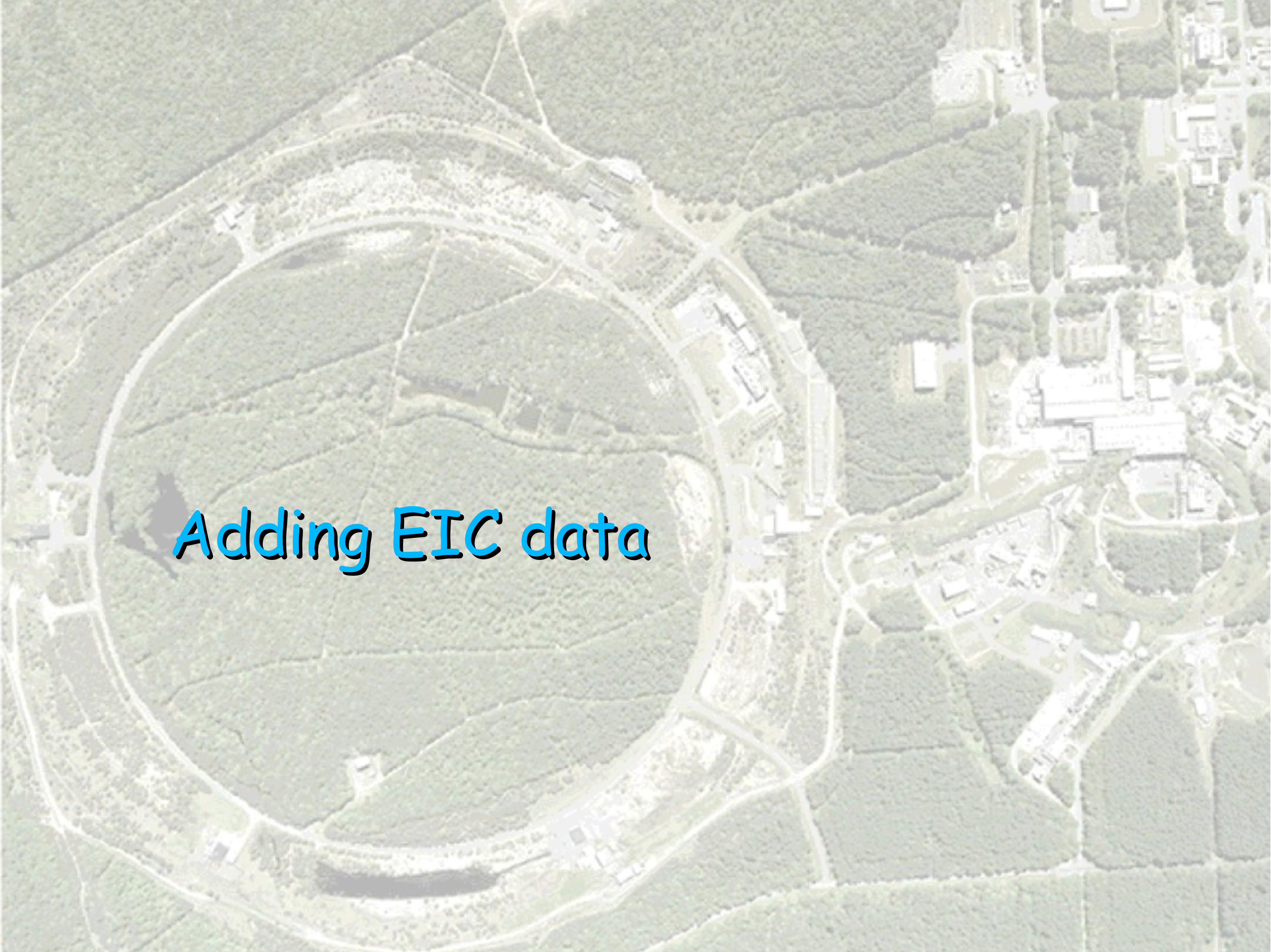
Eur. Phys. J. **C75** (2015), 12, 580

# Motivation

- The HERAPDF2.0 PDFs represent current state of the art in determining proton structure using data from DIS experiments alone
  - Their precision is at the few percent level at intermediate Bjorken x, but deteriorates fast for x > 1 and also below x of $10^{-3}$

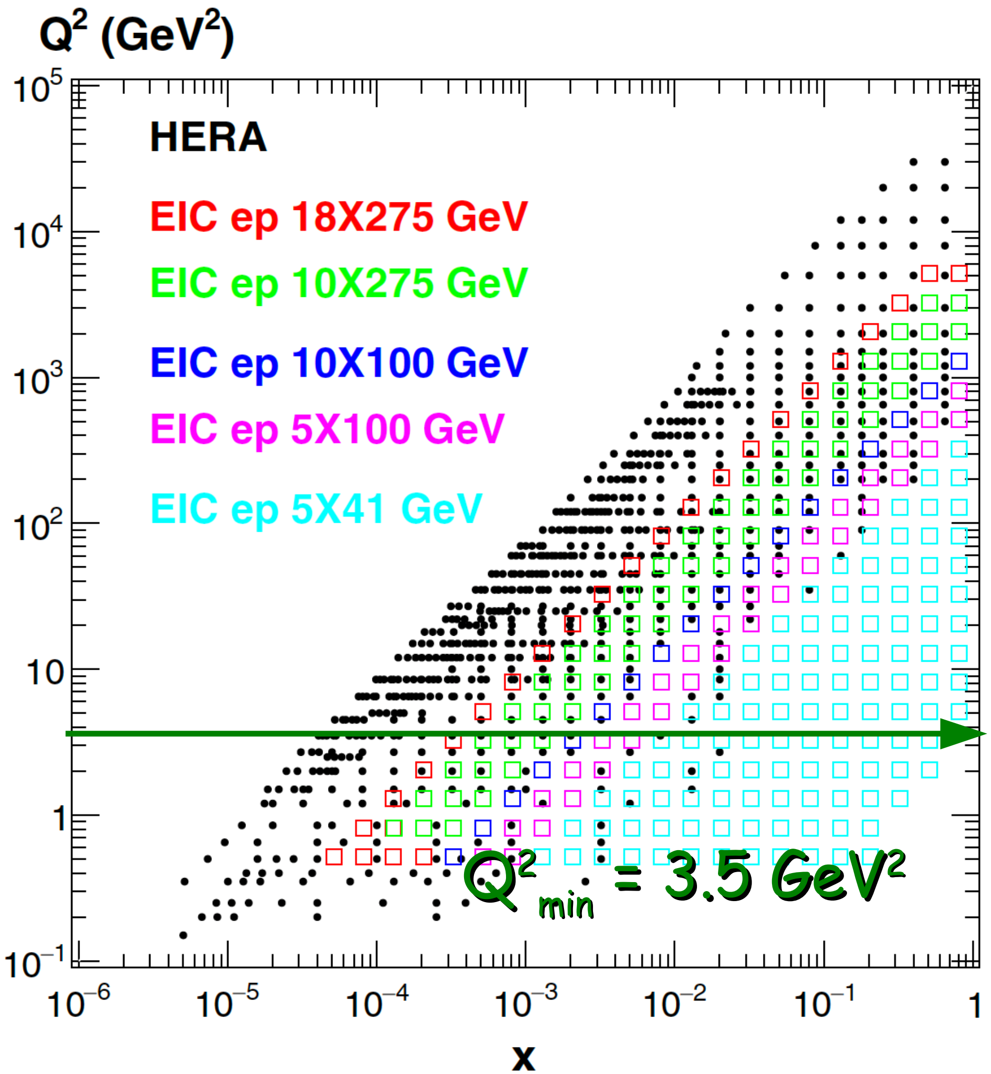



- Here study we investigate how this picture may evolve with time in the future by using only DIS ingredients in proton PDF fits
  - Adding EIC data (very!) soon
  - Adding Large Hadron electron Collider (LHeC)
  - Adding Future Circular Collider (FCC) in ep mode
  - → <u>Adding both!</u>



# Adding EIC data

# HERA & ATHENA phase-space




**PRD 109 (2024) 5, 054019**

High-x region not covered by HERA

 impact on high-x PDFs expected

| $e$-beam energy (GeV) | $p$-beam energy (GeV) | $\sqrt{s}$ (GeV) | Integrated lumi ($fb^{-1}$) |
|---|---|---|---|
| 18 | 275 | 141 | 15.4 |
| 10 | 275 | 105 | 100 |
| 10 | 100 | 63 | 79.0 |
| 5 | 100 | 45 | 61.0 |
| 5 | 41 | 29 | 4.4 |

# NNLO QCD analysis with DIS data

- EIC pseudo-data created using HERAPDF2NNLO with $\alpha_s(M_Z) = 0.118$
- HERAPDF procedure used

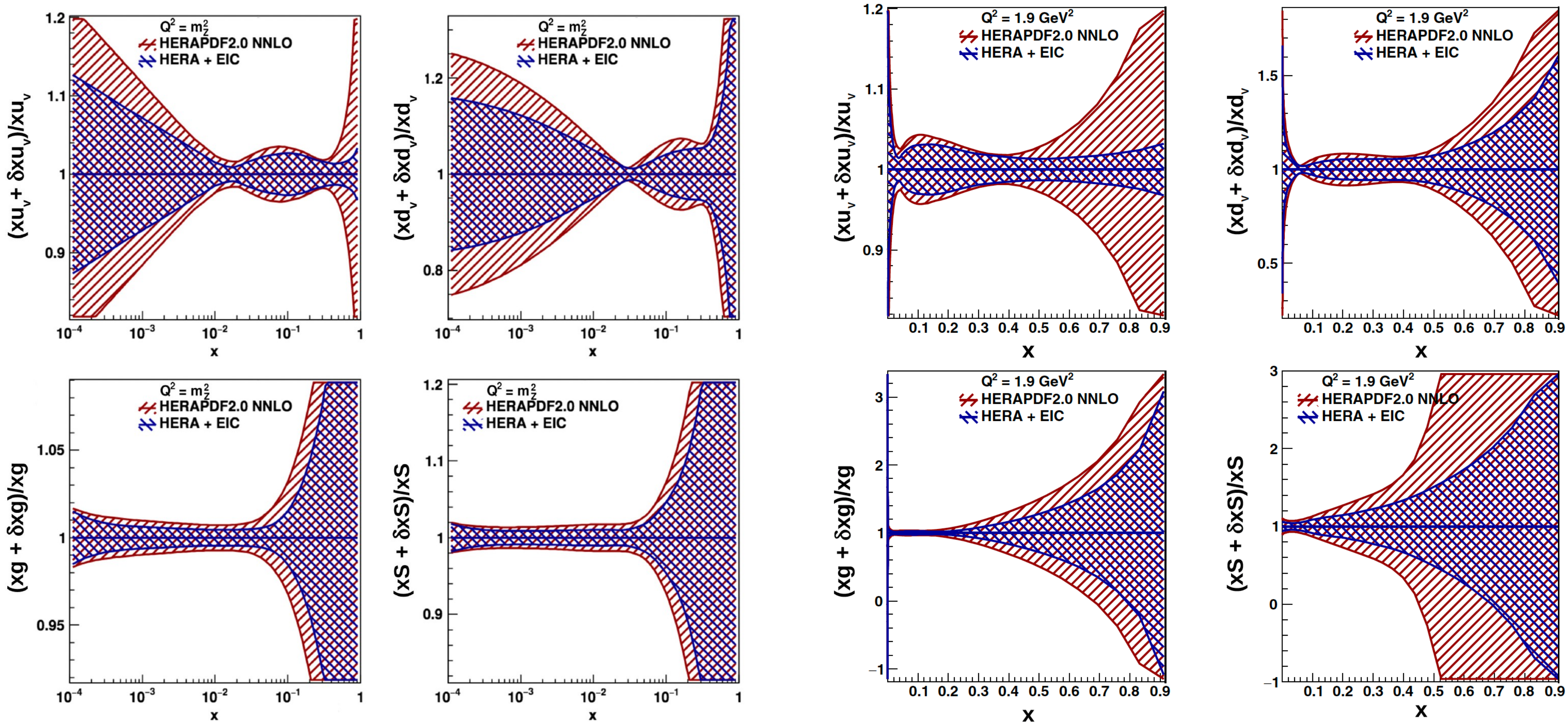
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25};\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right);\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}};\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x);\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

- Cuts
  - $Q^2 > 3.5$ GeV$^2$
  - $W^2 = Q^2(1-x)/x > 10$ GeV
  - $0.001 < y < 0.95$

- Pseudodata uncertainties
  - Most data points have uncorrelated systematic uncertainty of 1.9%, extending to 2.75% at lowest y values
  - Additional normalisation uncertainty of 3.4% taken to be fully correlated between data at each CME, and fully uncorrelated between different CMEs

# DIS-only fits

- Dramatic improvement of valence quarks at large x
- Improvement also for gluons/sea




Log-x scale

Lin-x scale

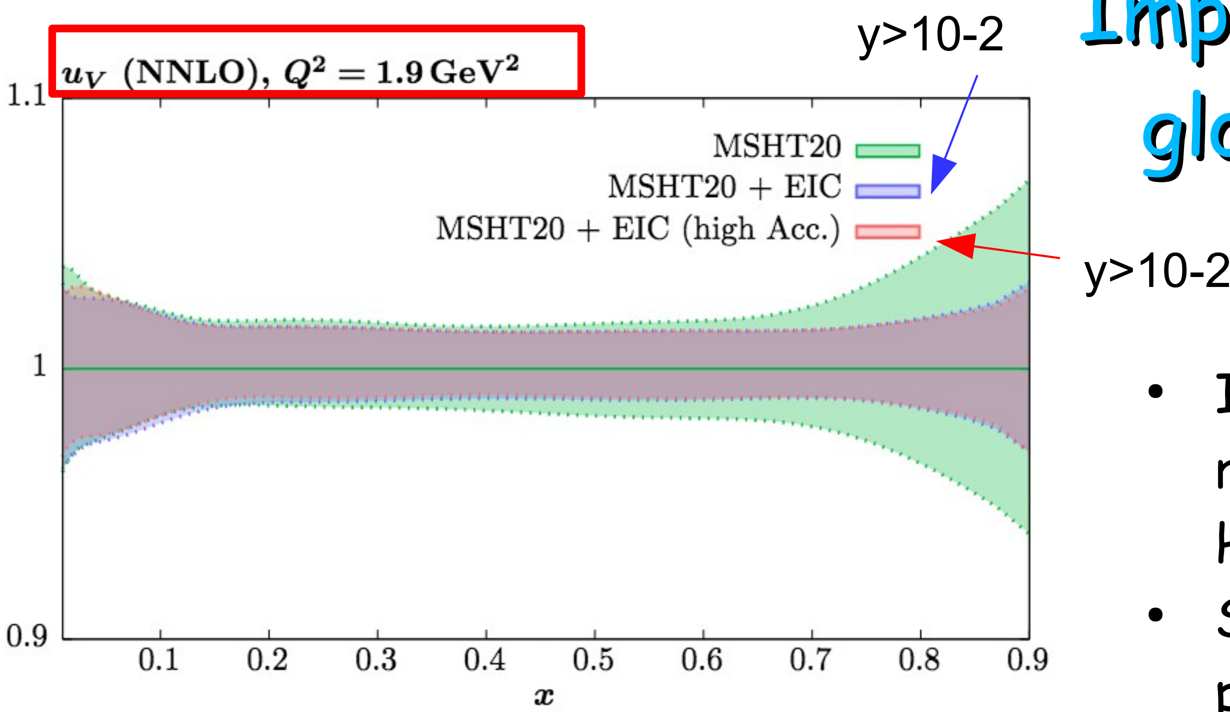
# Impact of EIC data on global fits

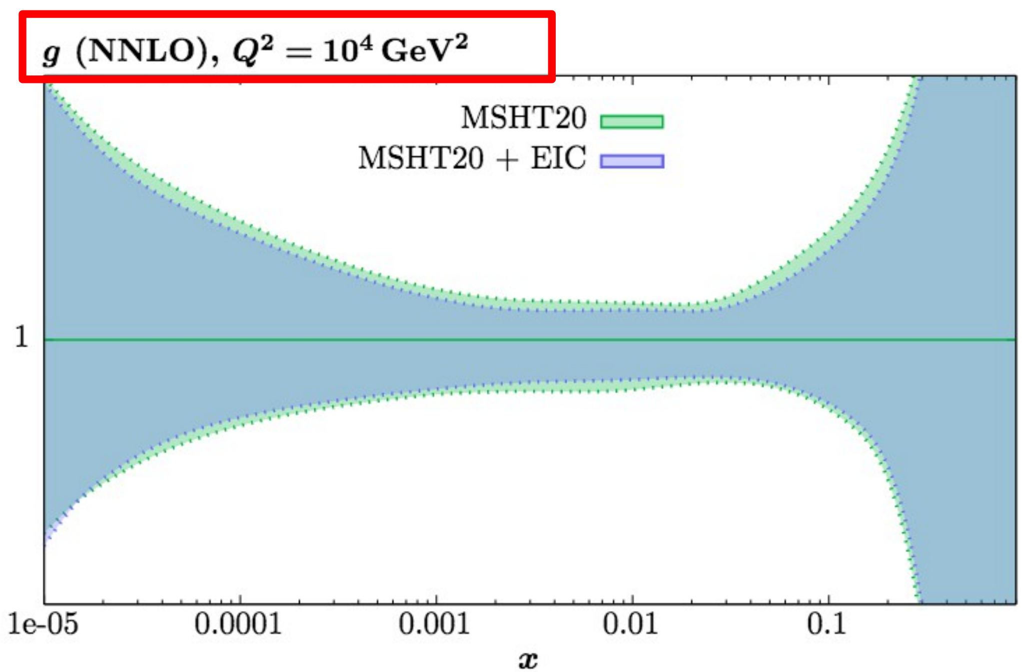
- Studies using MSHT20 approach
  - Parameterisations using Chebyshev polynomials (52 parameters in total)

$$xf(x,Q_0^2) = A(1-x)^\eta x^\delta \left(1+\sum_{i=1}^{n} a_i T_i^{\mathrm{Ch}}(y(x))\right)$$

  - Data with $Q^2 > 2$ GeV$^2$, $W^2 > 15$ GeV$^2$
- Pseudo-data created with MSHT20 with uncertainty assumptions
  - Most data points have uncorrelated systematic uncertainty of 1.9%, extending to 2.75% at lowest y values
  - Additional normalisation uncertainty of 3.4% taken to be fully correlated between data at each CME, and fully uncorrelated between different CMEs
- DIS data with $Q^2 > 2$ GeV$^2$, $W^2 > 15$ GeV$^2$

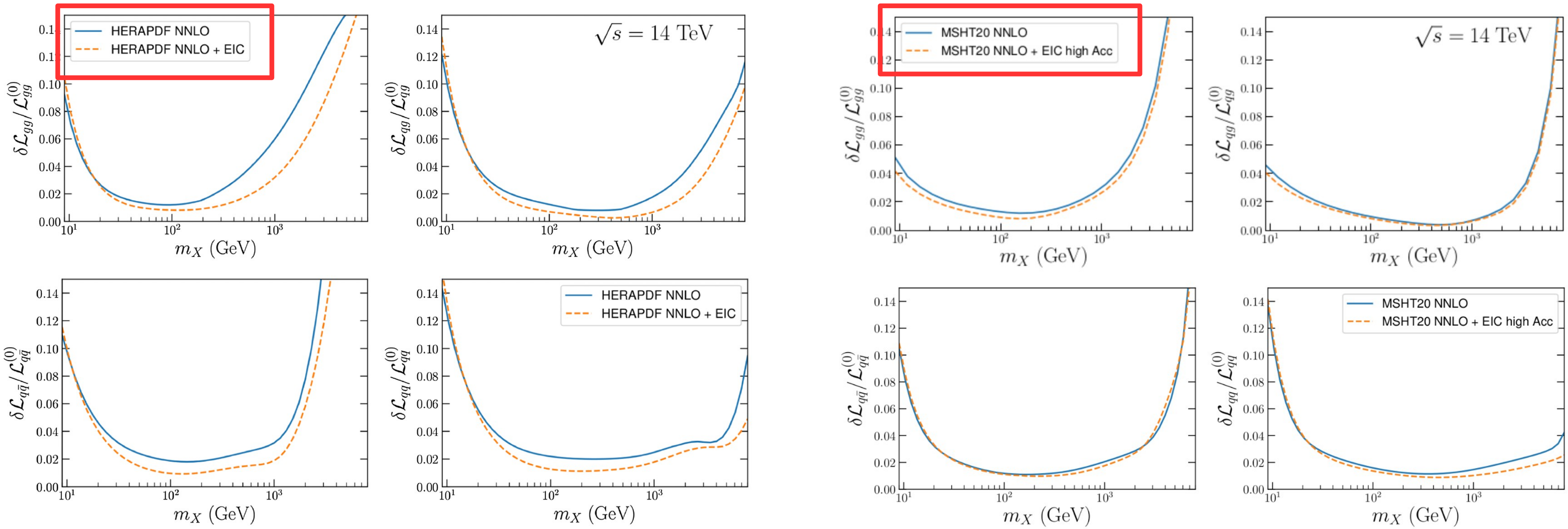
# Impact of EIC data on global fits @NNLO




- Improvement significantly reduced compared with HERAPDF2.0
- Still significant effects present
  → biggest impact on up-valence distribution
  → small but valuable improvement on all parton species visible at all x and $Q^2$ values

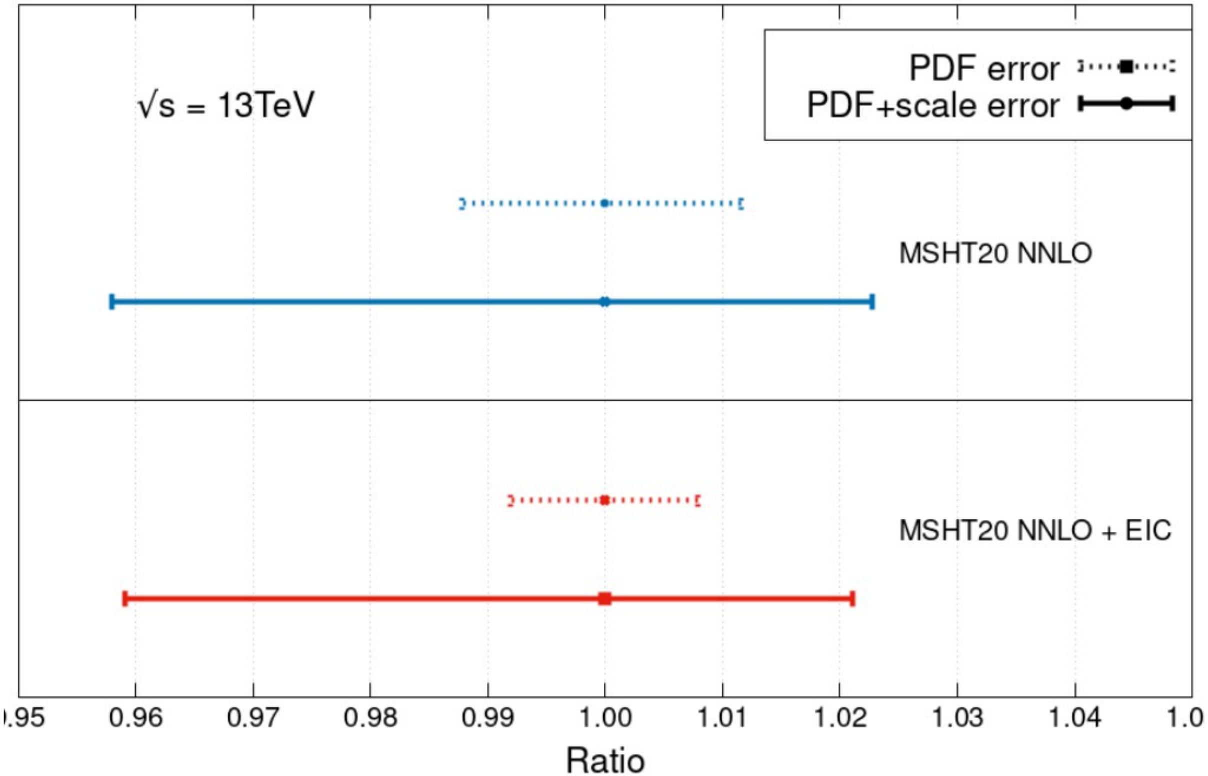
# Parton luminosities




- Reduced uncertainties
  - Largest impact at high $m_X$ coming from PDF constraints at high x
  - gluon-gluon luminosity shows largest reduction in uncertainty, up to ħ50% at larger invariant masses

- Relatively mild improvement for luminosities
- Impact of EIC pseudodata on MSHT20 smaller than that of HERAPDF2.0
  □ consistent with changes seen in PDF uncertainties

# Impact of EIC data on Higgs production




• Reduction in gluon-gluon luminosity uncertainty directly affects precision of predictions for Higgs production from gluon-gluon fusion

- with EIC uncertainty in gg luminosity at $m_H$ 125 GeV goes from 1.2% to 0.8%
- same for PDF uncertainty
- however large scale variations make overall impact smaller

K. Wichmann, Stony Brook 2025

# Adding LHeC and FCC-ep data

# Data samples

- HERA: combined NC & CC, e+p & e-p, unpolarised
- EIC: NC for 5 center-of-mass energies e-p, CC for highest cms, following arXiv:2307.01183 (note: alphas = 0.116)
- LHeC NC + CC: arXiv:2007.14491

| Parameter | Unit | Data set | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
| Proton beam energy | TeV | 7 | 7 | 7 | 7 | 1 | 7 | 7 | 7 | 7 |
| Lepton charge | | −1 | −1 | −1 | −1 | −1 | +1 | +1 | −1 | −1 |
| Longitudinal lepton polarisation | | −0.8 | −0.8 | 0 | −0.8 | 0 | 0 | 0 | +0.8 | +0.8 |
| Integrated luminosity | $fb^{-1}$ | 5 | 50 | 50 | 1000 | 1 | 1 | 10 | 10 | 50 |

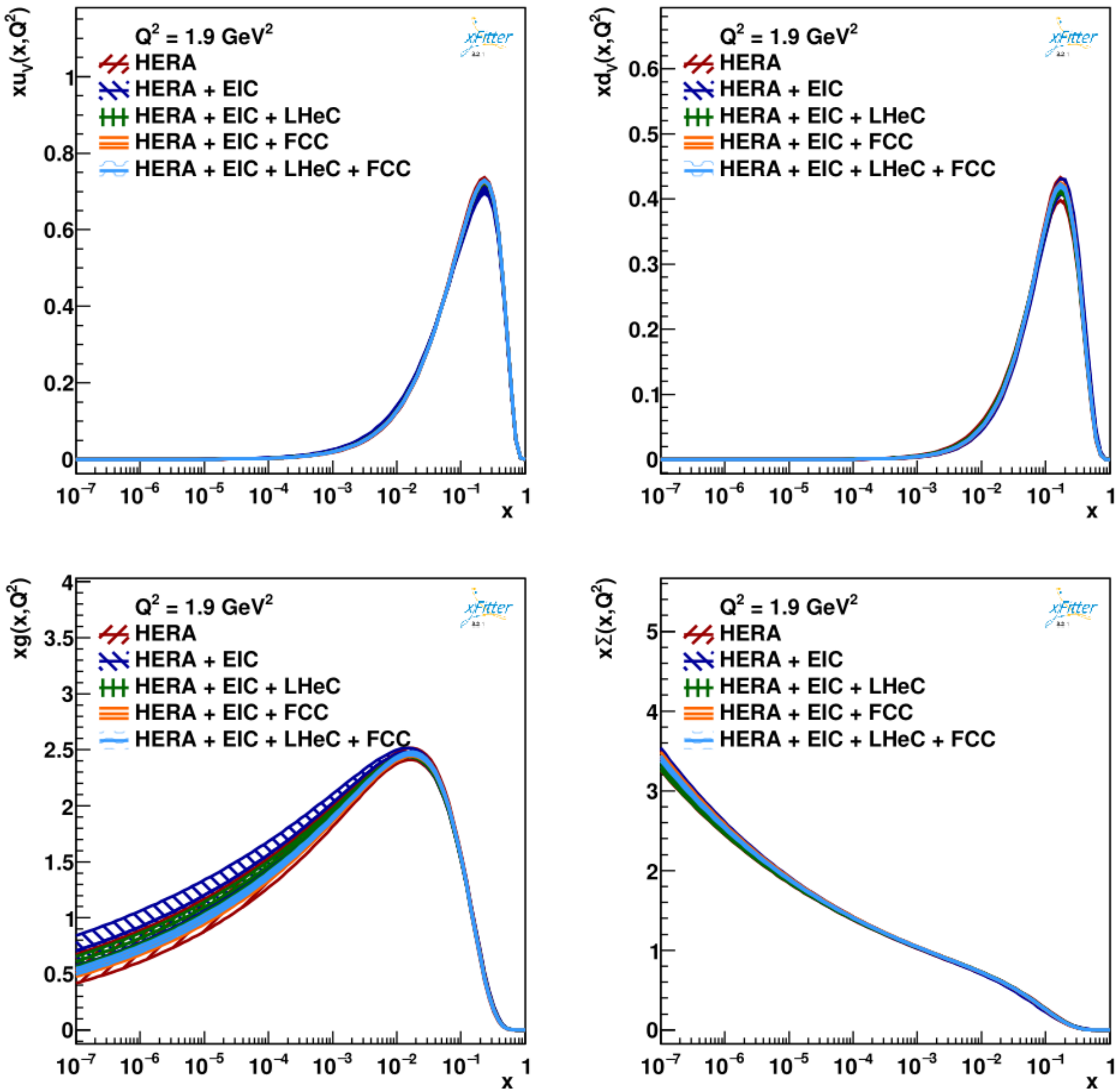
- FCC-eh NC + CC: arXiv:2007.14491

| Set | $E_e$/GeV | $E_p$/TeV | $P(e)$ | Charge(e) | Luminosity/$ab^{-1}$ |
|---|---|---|---|---|---|
| A: $e^-$ | 60 | 50 | −0.8 | −1 | 1 |
| B: $e^-$ | 60 | 50 | +0.8 | −1 | 0.3 |
| C: $e^+$ | 60 | 50 | 0 | +1 | 0.1 |
| D: low E | 20 | 7 | 0 | −1 | 0.1 |
| E: eA | 60 | 20 | −0.8 | −1 | 0.01 |

# Pseudo-data simulation

- Cross sections generated with HERAPDF2 NNLO style
  - without negative gluon term (characteristic for HERAPDF) – both LHeC and FCC go to very low-x
  - Available LHAPDF sets go only to $x = 10^{-6}$, not sufficient for FCC
  - alphas = 0.116 (following previous EIC studies, has no influence on conclusions)
- Smearing according to estimated statistical and systematic uncertainties (both correlated and uncorrelated) + 1% for lumi + 1% for polarisation (where applicable)
- Predictions and fits done using xFitter

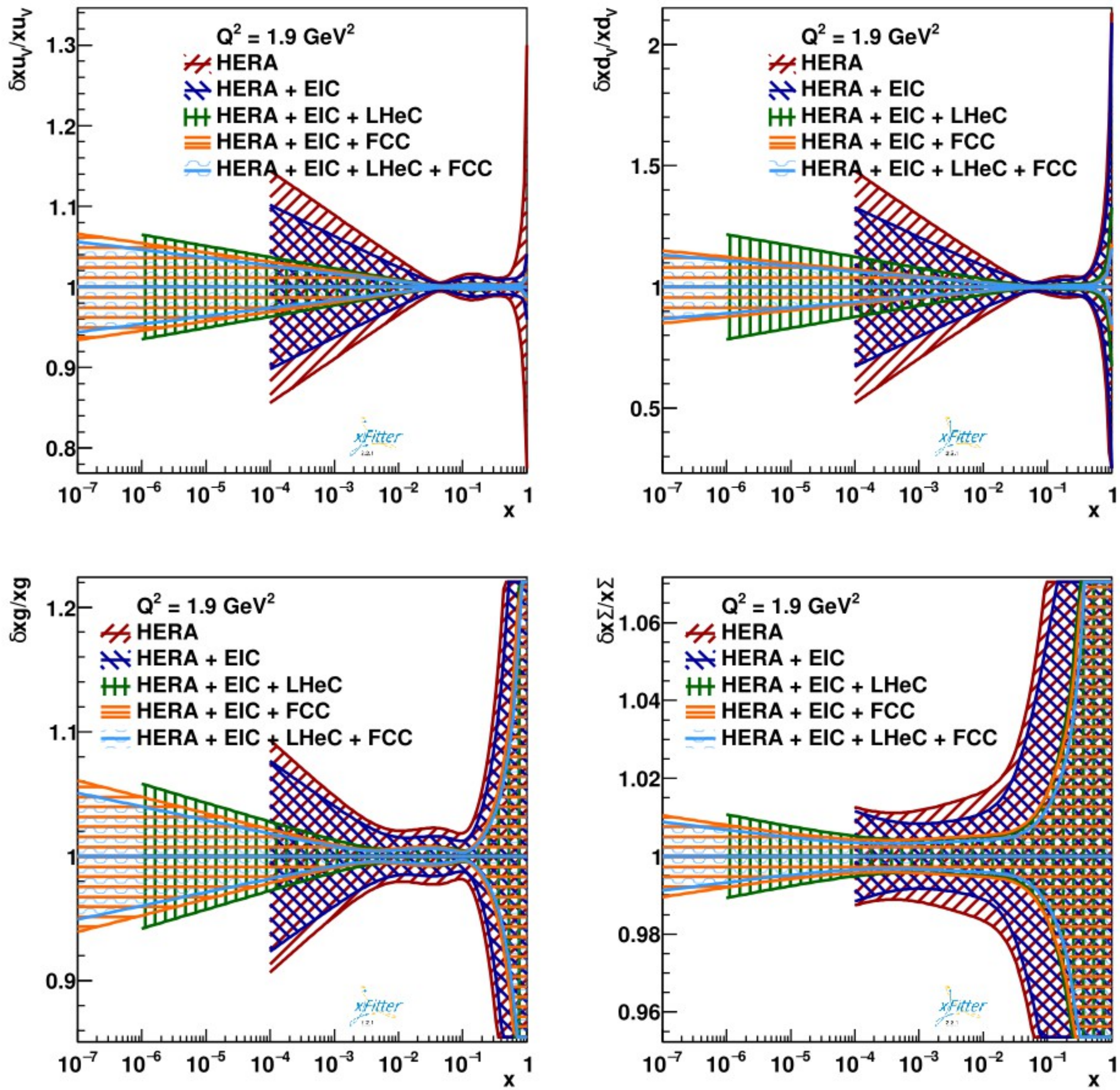
# Comparison of PDFs




- Well compatible by construction
- Note low x!

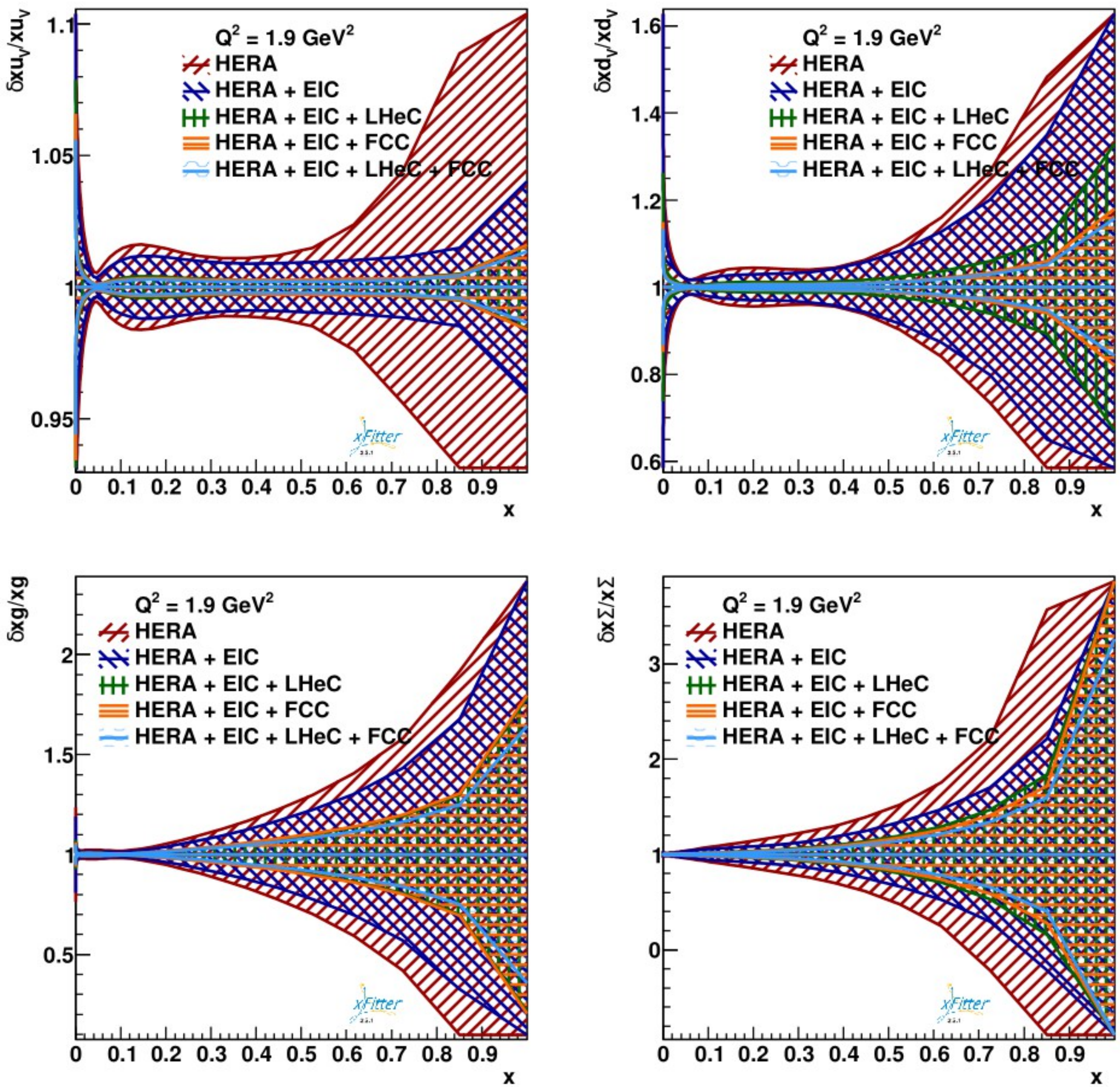
K. Wichmann, Stony Brook 2025

# Comparison of experimental uncertainties




- Stunning improvements of uncertainties + extension of x range down to $x^{-6}$ for LHeC and $x^{-7}$ for FCC-eh

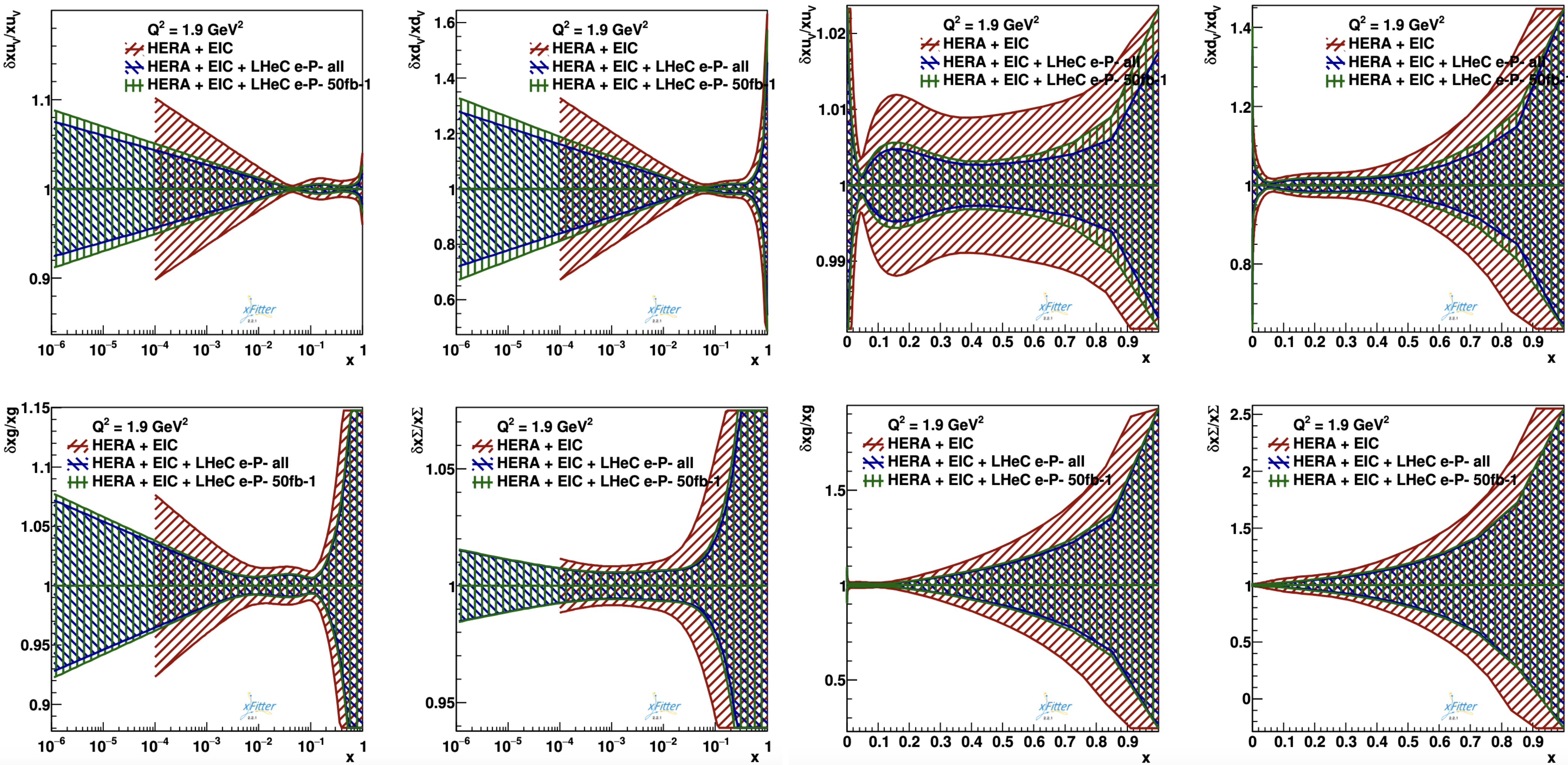
# Comparison for large x




- Improvement also for large x, especially valence quarks and gluon

## Can we make a quick meaningful measurement?

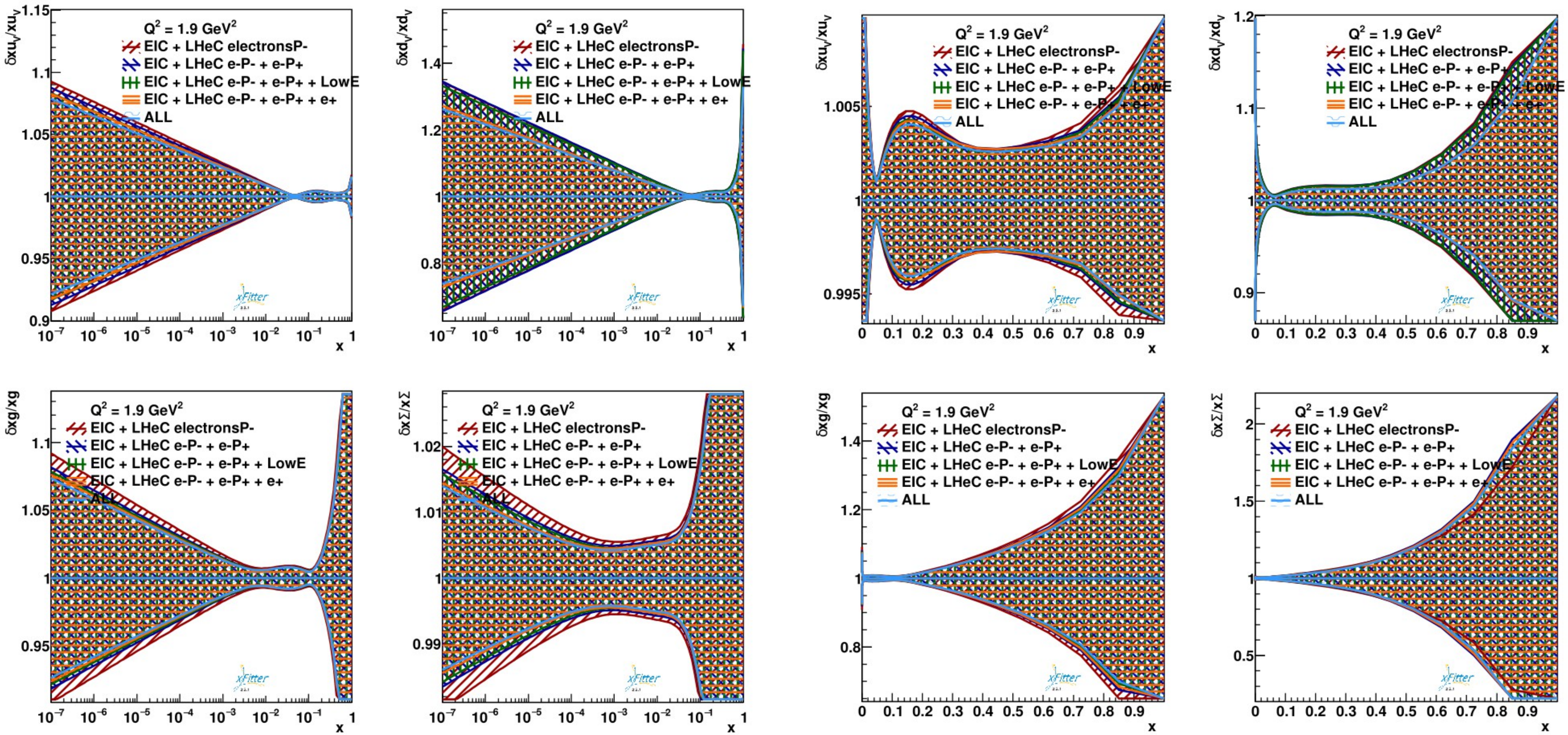
# "Only" 50 fb$^{-1}$ lumi for LHeC




- Only 50 fb$^{-1}$ instead of 1000 fb$^{-1}$ for LHeC enough for vastly improving uncertainties (especially at large x almost no difference)

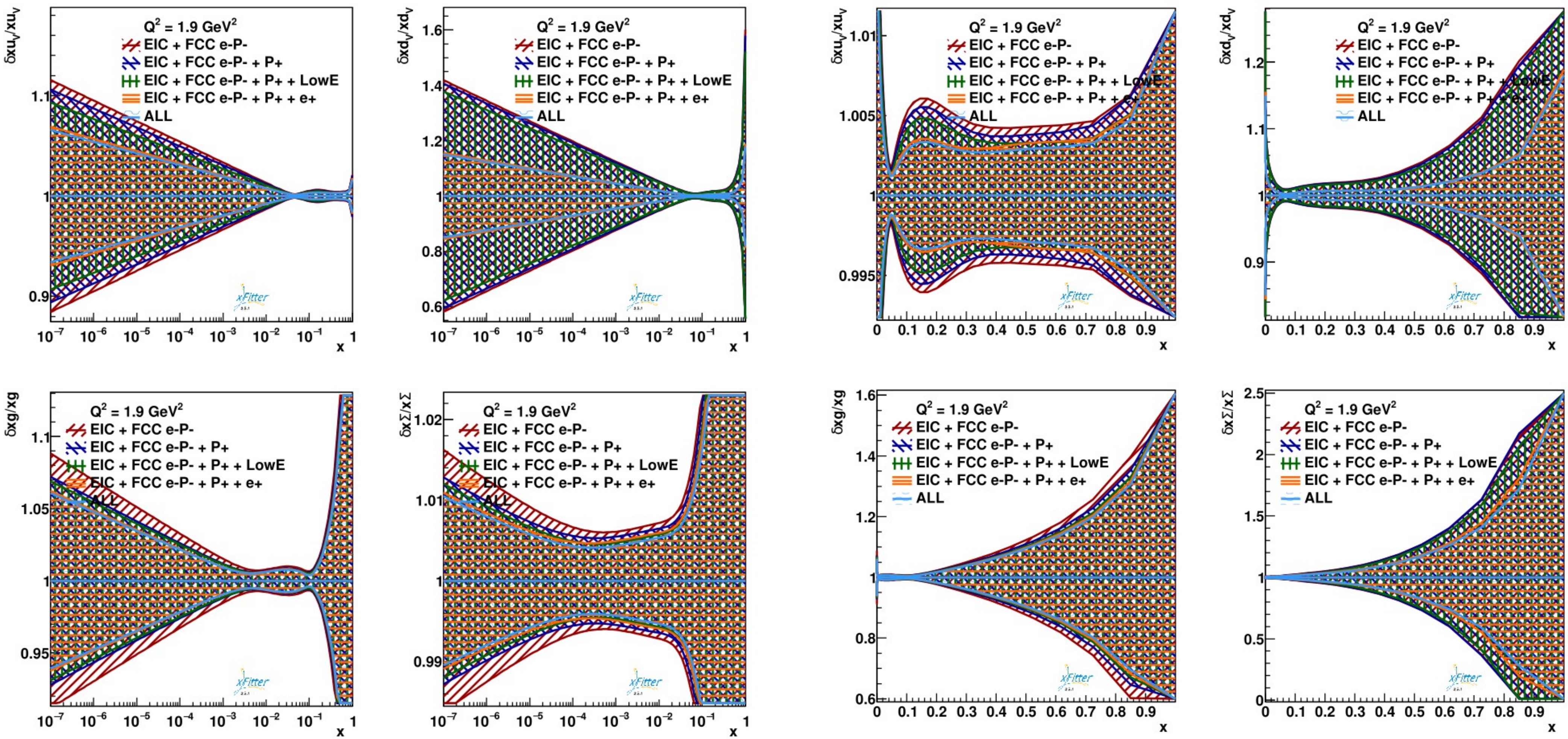
# Are some processes better than others?

# LHeC stacked: which samples matter most?




- Essentially all precision brought already by the main $e^-P^-$ sample

# FCC stacked: which samples matter most?




- More complicated picture here: e⁻P⁻ most important …
- … but positrons seem to play a role as well (maybe others as well)

# Strong coupling determination with DIS only

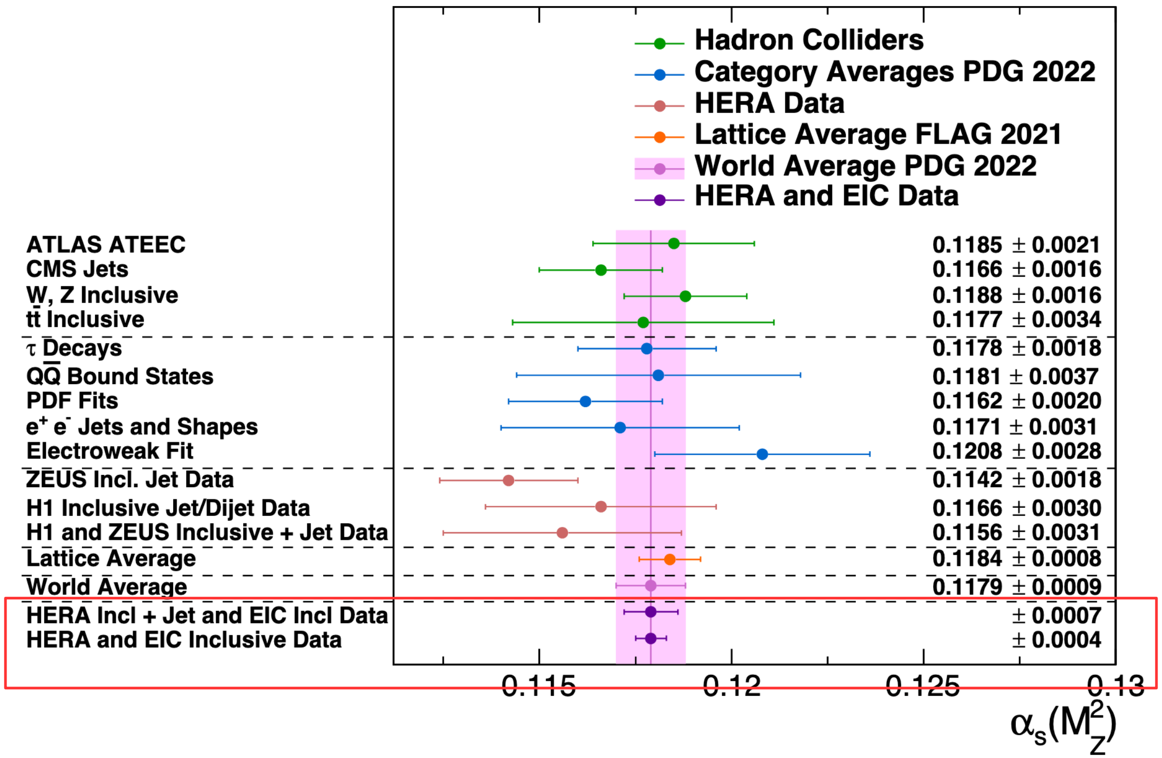
# Strong coupling can be determined with DIS only

- Previous studies of alphas estimation with HERA+EIC DIS data only arXiv:2307.01183

Extraction of the strong coupling with HERA and EIC inclusive data

Salim Cerci[1], Zuhal Seyma Demiroglu[2,3], Abhay Deshpande[2,3,4], Paul R. Newman[5], Barak Schmookler[6], Deniz Sunar Cerci[1], Katarzyna Wichmann[7]

- Mainly due to EIC large-x region strong coupling can be estimated from DIS data only (no jets/etc needed), with very good precision, competitive to all present measurements and lattice calculations (no large scale variation uncertainties
- Can this be extended further with LHeC and FCC?




**Above studies repeated with addition of LHeC and FCC pseudo-data**

# Improvements in alphas estimation

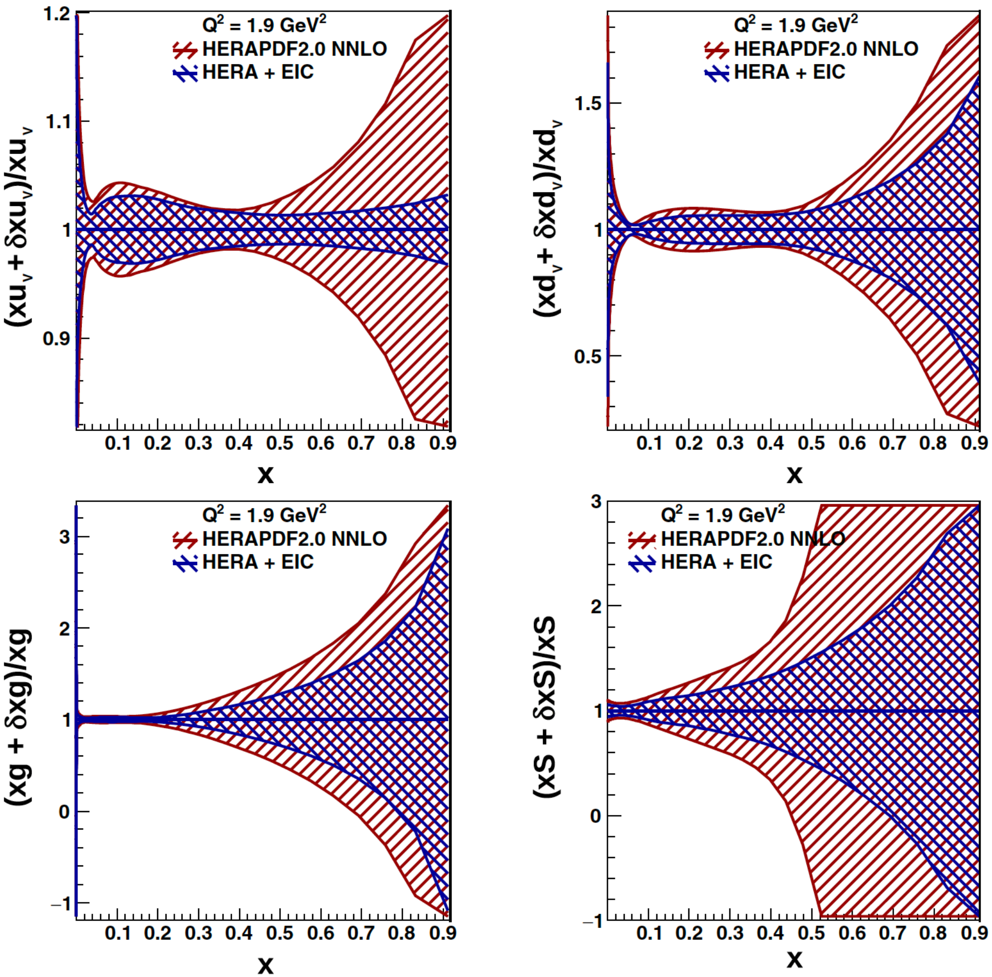
Nominal result: no negative gluon term

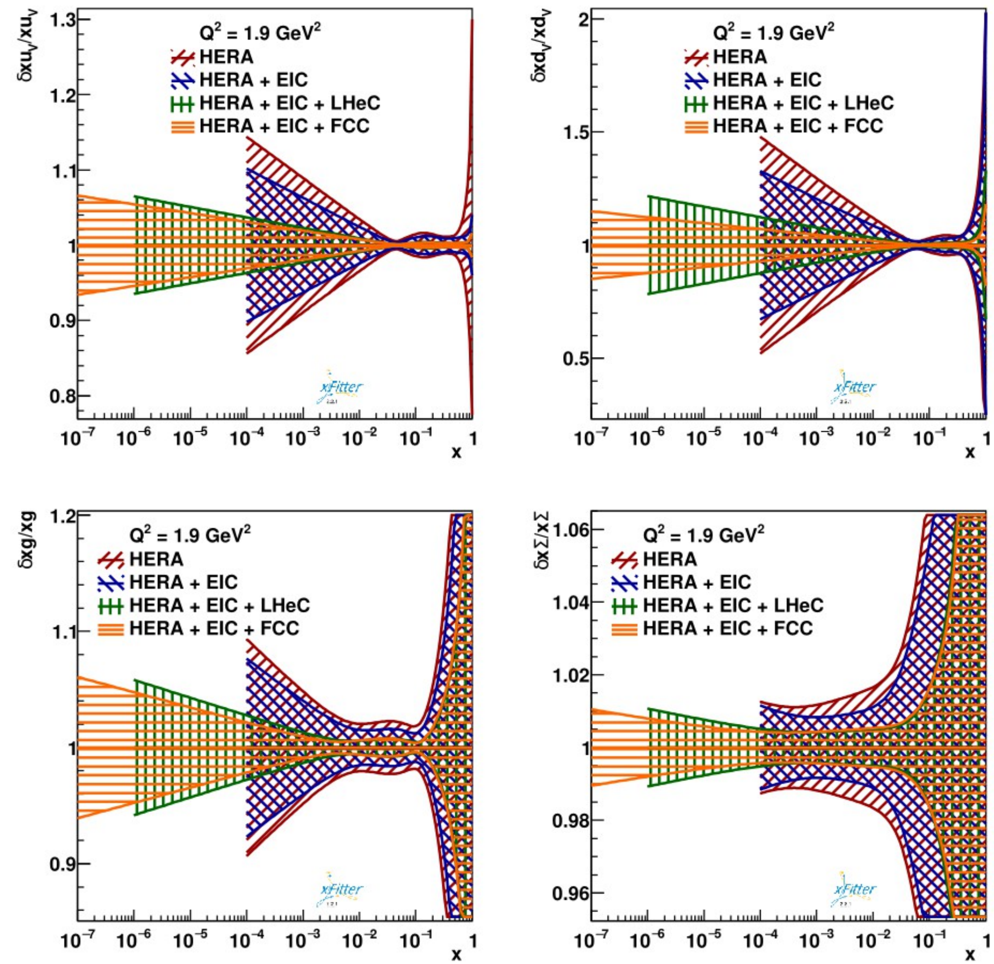
| | |
|---|---|
| • EIC: | as = 0.11561 +- 0.00047 |
| • EIC + LHeC: | as = 0.11573 +- 0.00030 |
| • EIC + FCC: | as = 0.11587 +- 0.00025 |
| • EIC + LHeC +FCC: | as = 0.11589 +- 0.00022 |

Observed high potential to improve strong coupling determination from DIS data only

- Question about theoretical uncertainties of such DIS-only determinations still remains open

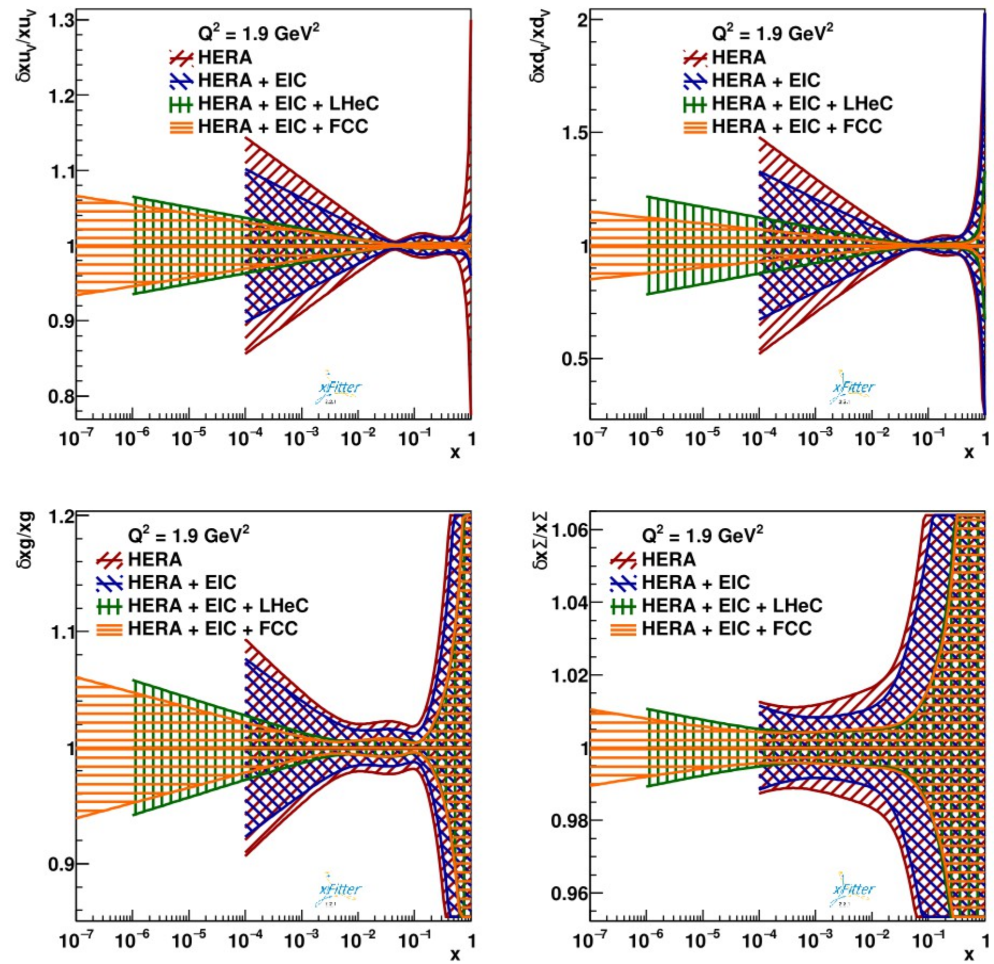
# Two plots to remember



# Two plots to remember

- Ultimate DIS sample HERA+EIC+LHeC+FCC will bring huge extension of low-x region in PDF estimation
    - Both for covering "unknown" regions and improving greatly uncertainties
    - FCC reaches to lower $x > 10^{-7}$
- Also for mid- and large-x PDF uncertainties will be hugely decreased
- Studies of strong coupling estimation show promise of more precise determination with DIS data only



# Impact of inclusive electron ion collider data on collinear parton distributions

Néstor Armesto,[1] Thomas Cridge,[2,*] Francesco Giuli,[3] Lucian Harland-Lang,[4] Paul Newman,[5] Barak Schmookler,[6] Robert Thorne,[4] and Katarzyna Wichmann[2]

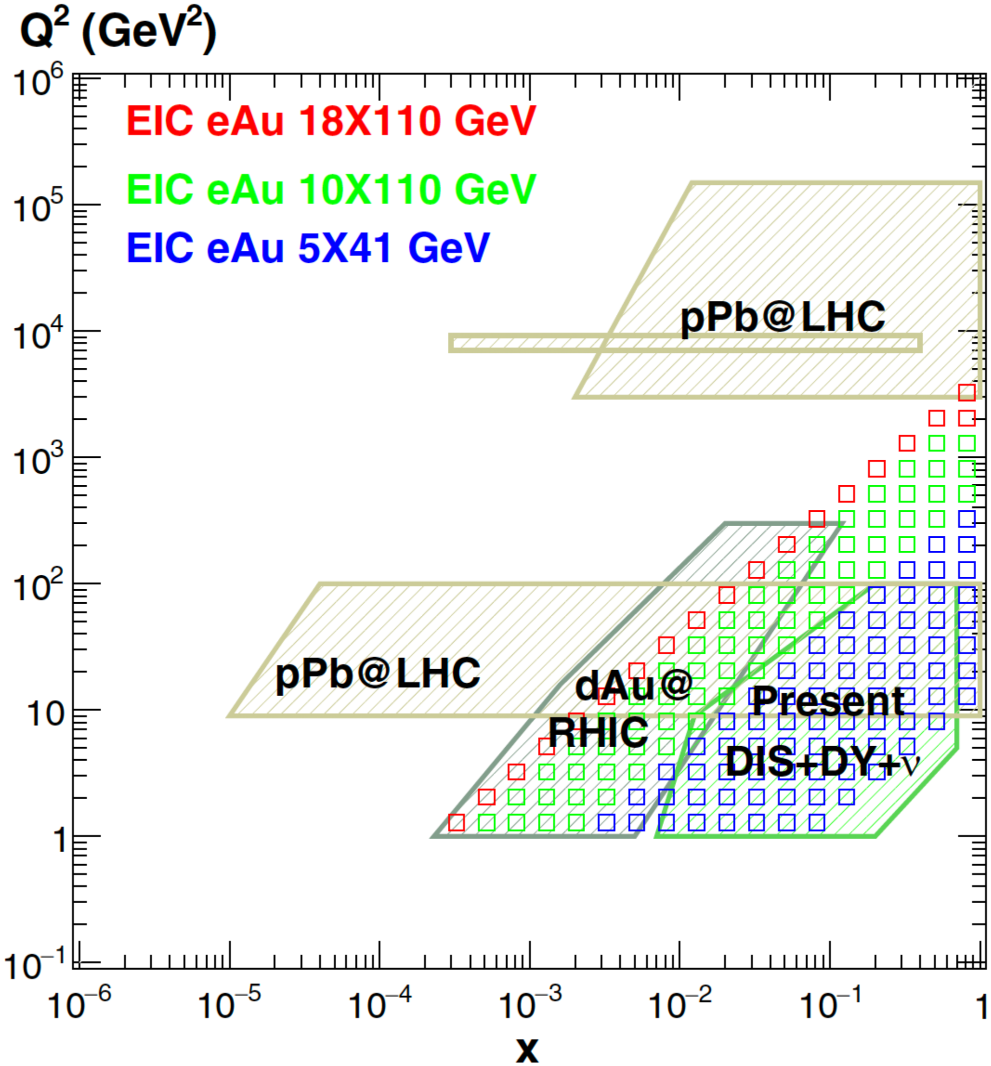
[1]*Departamento de Física de Partículas and IGFAE, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain*
[2]*Deutsches Elektronen-Synchrotron DESY, Germany*
[3]*CERN, CH-1211 Geneva, Switzerland*
[4]*Department of Physics and Astronomy, University College, London, WC1E 6BT, United Kingdom*
[5]*School of Physics and Astronomy, University of Birmingham, B15 2TT, United Kingdom*
[6]*Department of Physics and Astronomy, University of California, Riverside, California 92521, USA*

(Received 24 November 2023; accepted 15 February 2024; published 11 March 2024)

A study is presented of the impact of updated simulated inclusive electron ion collider deep inelastic scattering data on the determination of the proton and nuclear parton distribution functions (PDFs) at next-to-next-to-leading and next-to-leading order in QCD, respectively. The influence on the proton PDFs is evaluated relative to the HERAPDF2.0 set, which uses inclusive HERA data only, and also relative to the global fitting approach of the MSHT20 PDFs. The impact on nuclear PDFs is assessed relative to the EPPS21 global fit and is presented in terms of nuclear modification ratios. For all cases studied, significant improvements in the PDF uncertainties are observed for several parton species. The most striking impact occurs for the nuclear PDFs in general and for the region of high Bjorken $x$ in the proton PDFs, particularly for the valence quark distributions.

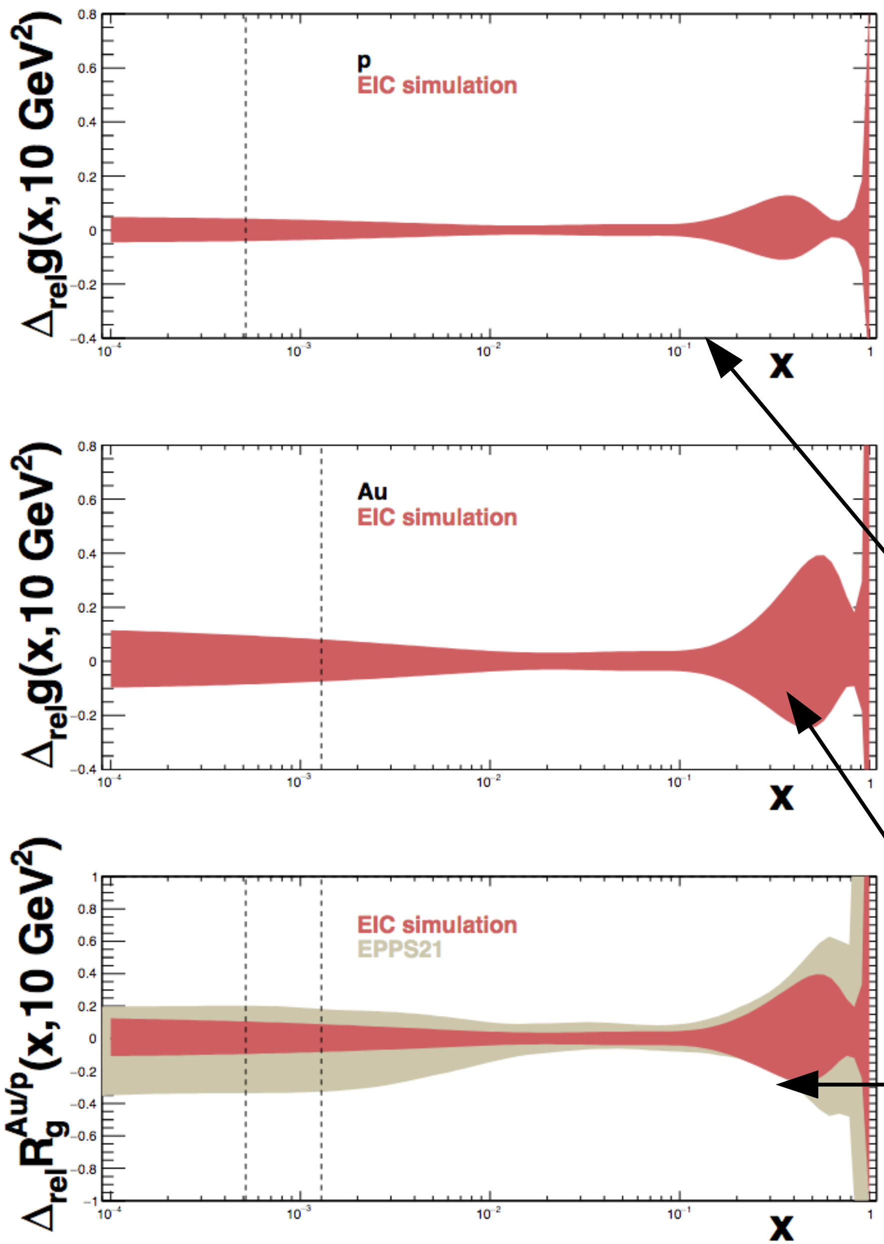
DOI: 10.1103/PhysRevD.109.054019

# Nuclear PDFs from EIC




- EIC will have revolutionary impact on eA phase space  most promising environment to observe novel low-x effects
- Studies performed @ NLO in xFitter & HERAPDF framework to assess sensitivity of EIC relative to EPPS21 (representative current global fit)
  - EPPS21 includes
    -  Fixed target DIS and DY
    -  p+A at LHC
    -  $g^0$ from PHENIX

# Impact on Nuclear PDFs: Gluon

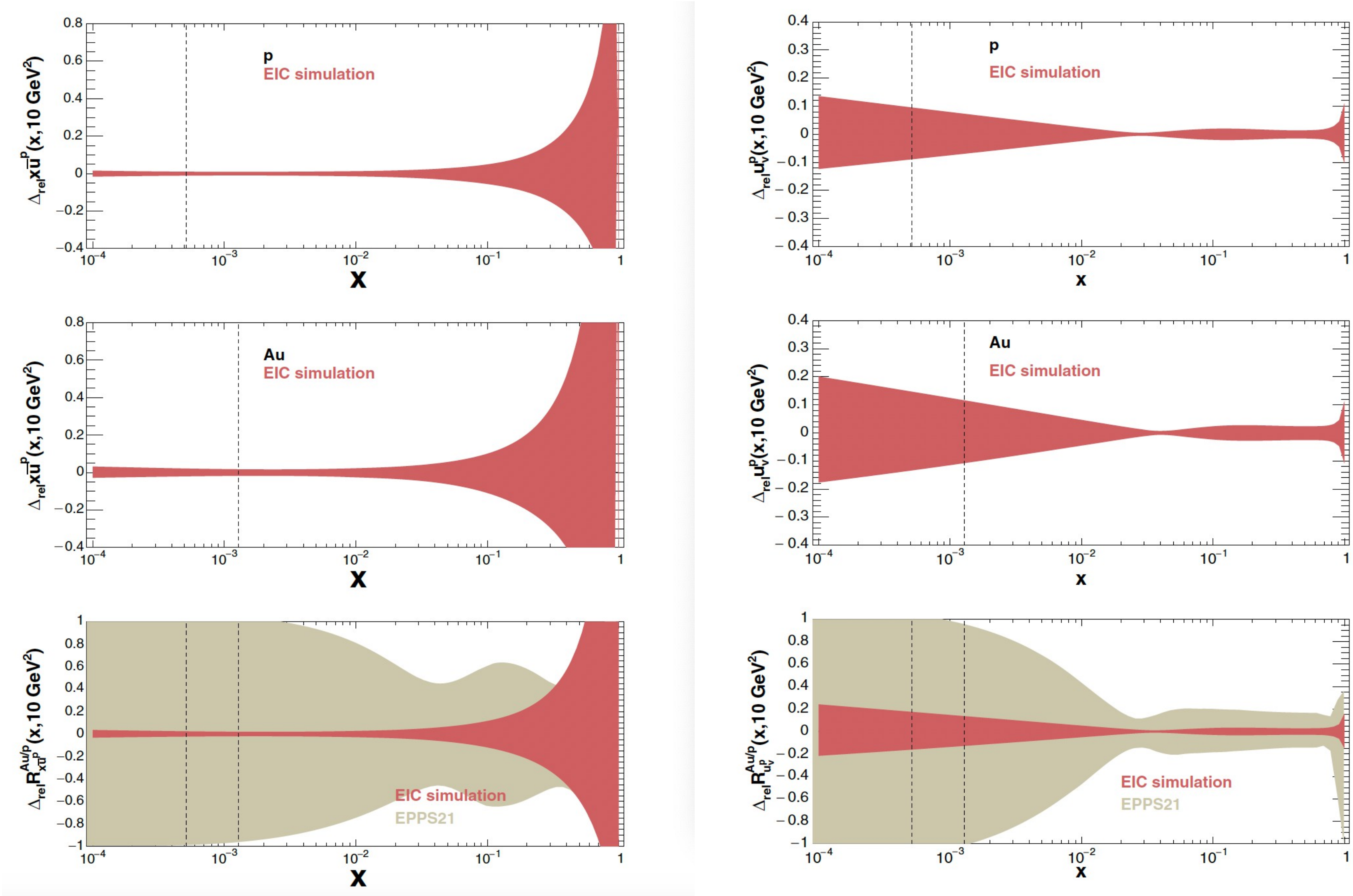



- Nuclear PDFs studied in terms of nuclear modification factor R:

  It encodes deviations of nPDFs from simple scaling of free nucleon PDFs with atomic mass A after accounting for varying proton-to-neutron ratios using isospin symmetry

- Relative uncertainty of gluon in proton EIC-only fits
- Uncertainty of gluon in gold nucleus
- Nuclear modification factor formed from ratio of gluon in gold and proton

# Impact on Nuclear PDFs: sea and valence u quarks




Precision largely improved <u>with EIC data only</u>

factor of 2 @ x ~ 0.1

K. Wichmann, Stony Brook 2025