PDFs and strong coupling from DIS only

Road from current to ultimate picture

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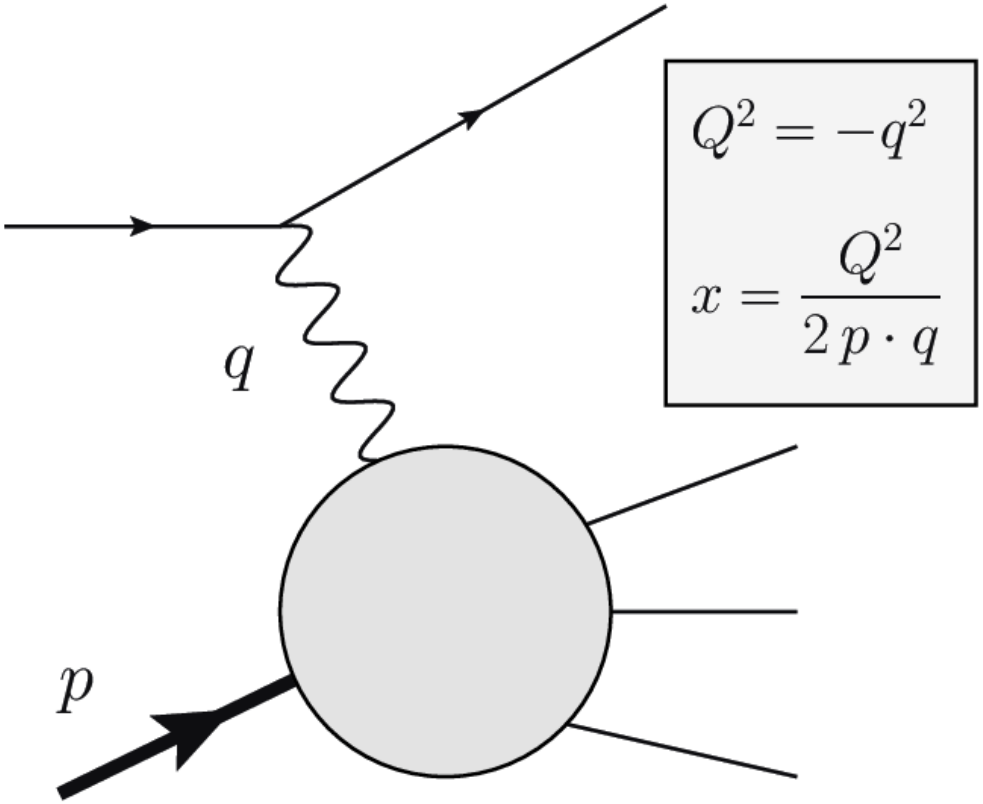
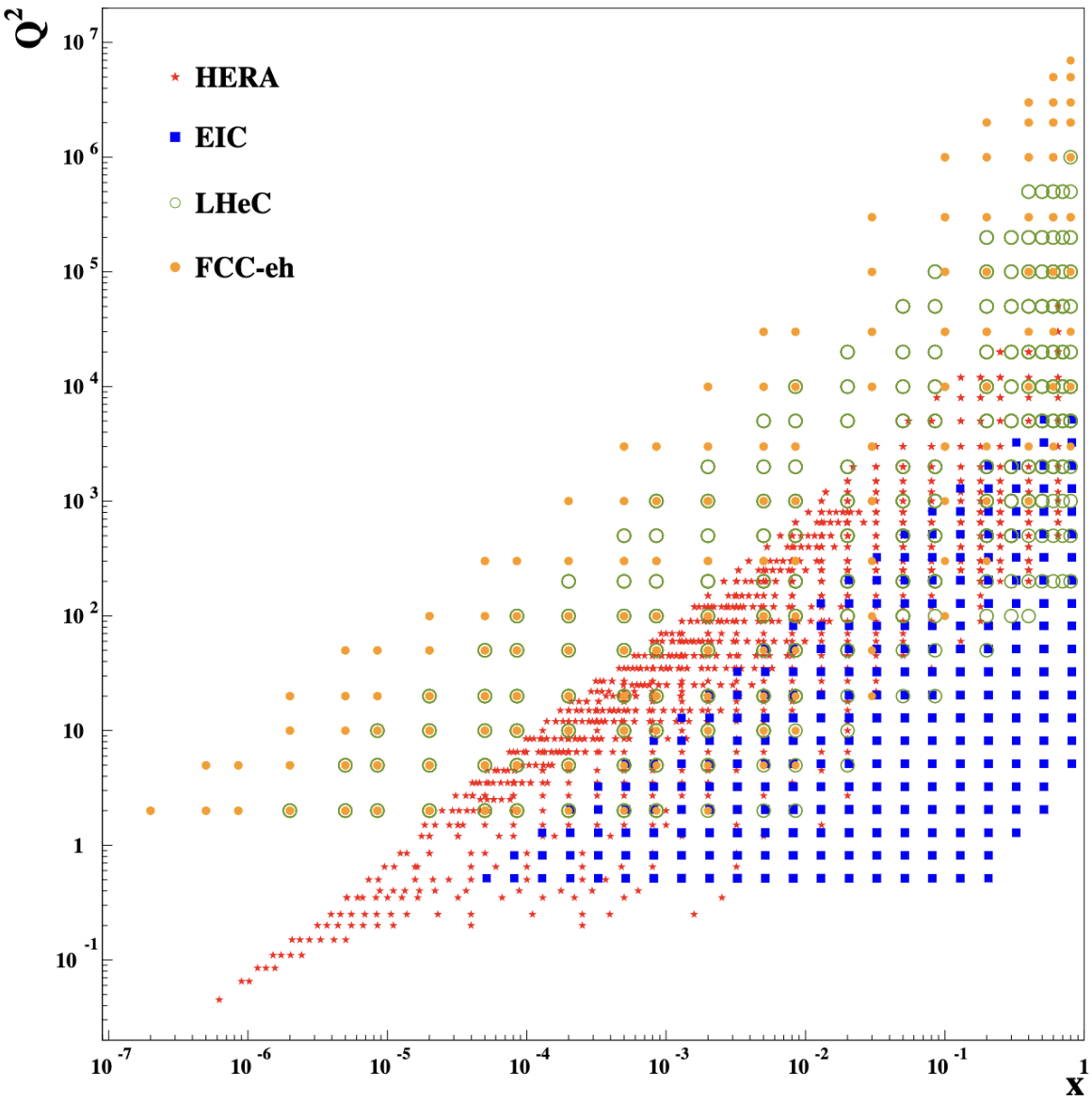
Motivation

- 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
  - → Adding both!

Enlarged kinematic phase-space



- EIC complements HERA at large x and moderate Q^2
  - high precision cross section measurements where HERA uncertainties become large (limited statistics)
- LHeC and FCC-eh extend Q^2 by two orders of magnitude
- LHeC and FCC-eh will reach unprecedented x values in the perturbative regime, down to 10^{-6} and 10^{-7}

Data samples

- HERA: combined NC & CC, e+p & e-p, unpolarised, 4 CMEs
- EIC: NC for 5 energies e-p, CC for highest CME: *arXiv:2307.01183*

E_p (GeV)	E_e (GeV)	$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})
275	18	141	15.4
275	10	105	100
100	10	63	79.0
100	5	45	61.0
41	5	29	4.4

- LHeC NC + CC: *https://doi.org/10.1088/1361-6471/abf3ba (arXiv:2007.14491)*

E_p (TeV)	E_e (GeV)	Charge (e)	$\sqrt{s}$ (GeV)	P_e	Luminosity (fb^{-1})
7	60	−1	1296	−0.8	1000
7	60	−1	1296	+0.8	50
7	60	+1	1296	0	1
1	60	−1	490	0	1

- FCC-eh NC + CC: *https://link.springer.com/article/10.1140/epjc/s10052-019-6904-3*

E_p (TeV)	E_e (GeV)	Charge (e)	$\sqrt{s}$ (GeV)	P_e	Luminosity (fb^{-1})
50	60	−1	3464	−0.8	1000
50	60	−1	3464	+0.8	300
50	60	+1	3464	0	100
7	20	−1	748	0	100

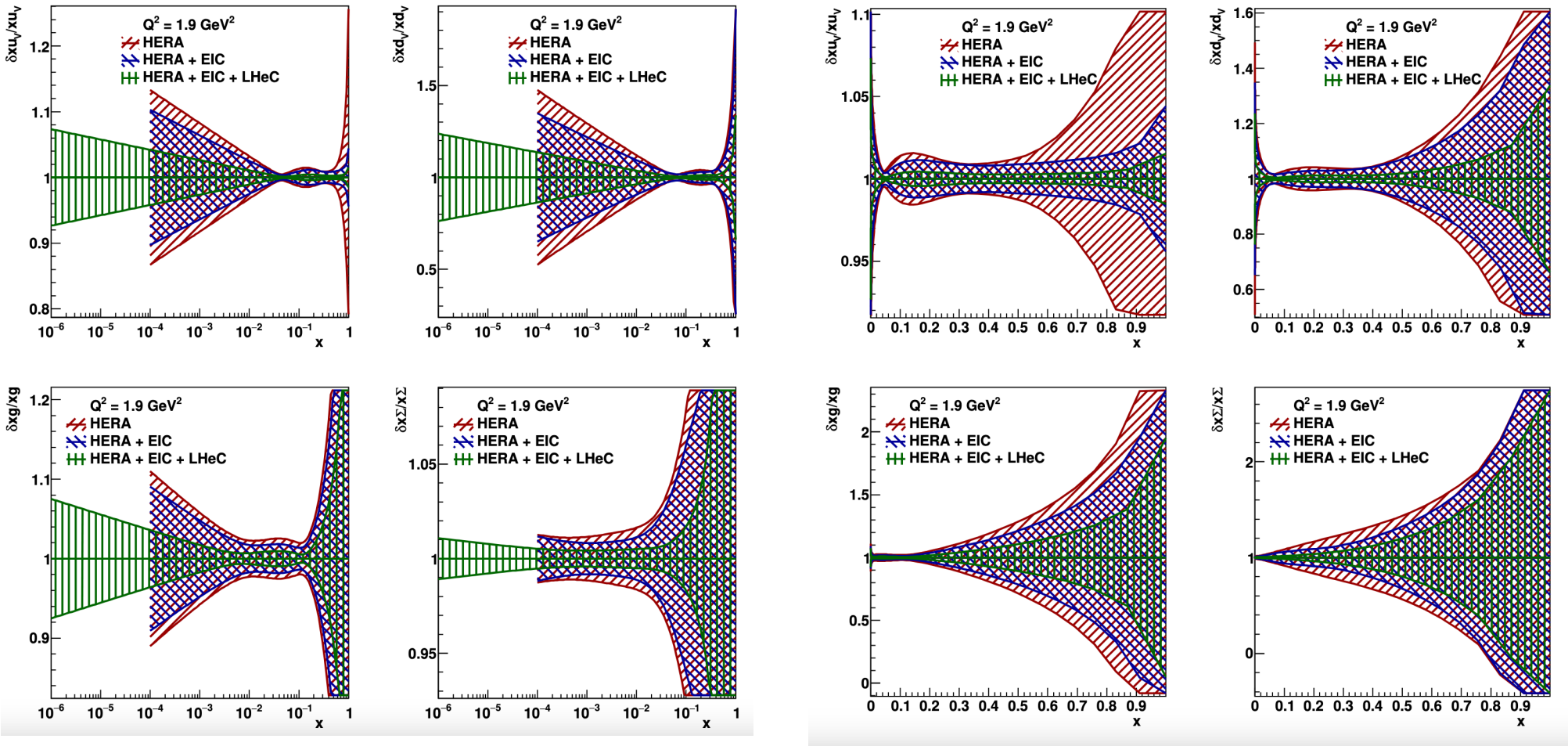
Pseudo-data simulation

- 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
  - $\alpha_s = 0.116$ (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
- Cuts on pseudo-data:
  - $Q^2 > 3.5\ GeV^2$, $W^2 > 10\ GeV^2$

First step: HERA and EIC and LHeC

By the time LHeC is in operation, EIC data are harvested:

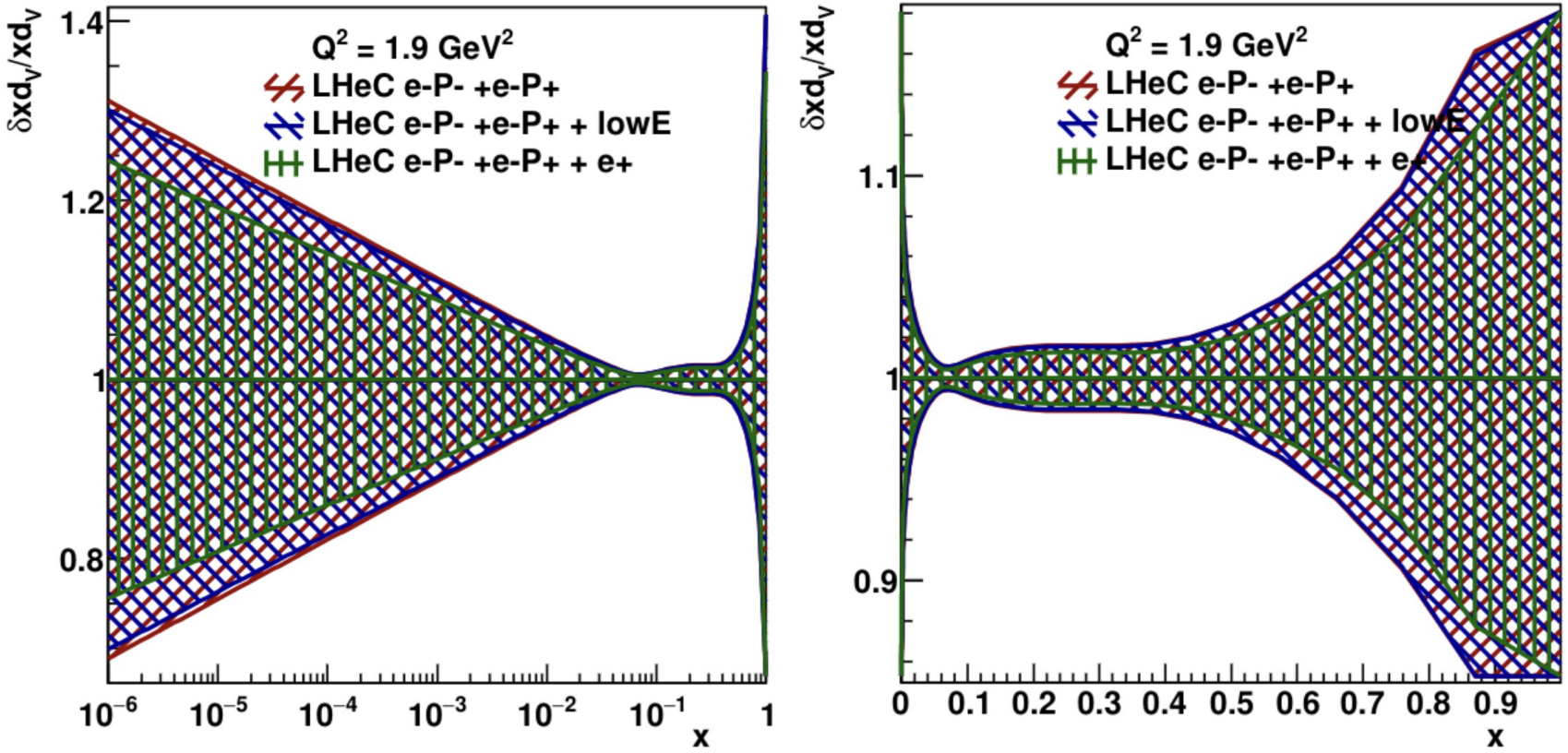
HERA + EIC is baseline



- Stunning improvements of uncertainties + extension of x range down to x^{-6} for LHeC

Are some LHeC data "better" than others?

Comparison for large x



- Positron bring improvement for d-valence quarks
- Too small samples to see more

E_p (TeV)	E_e (GeV)	Charge (e)	$\sqrt{s}$ (GeV)	P_e	Luminosity (fb^{-1})
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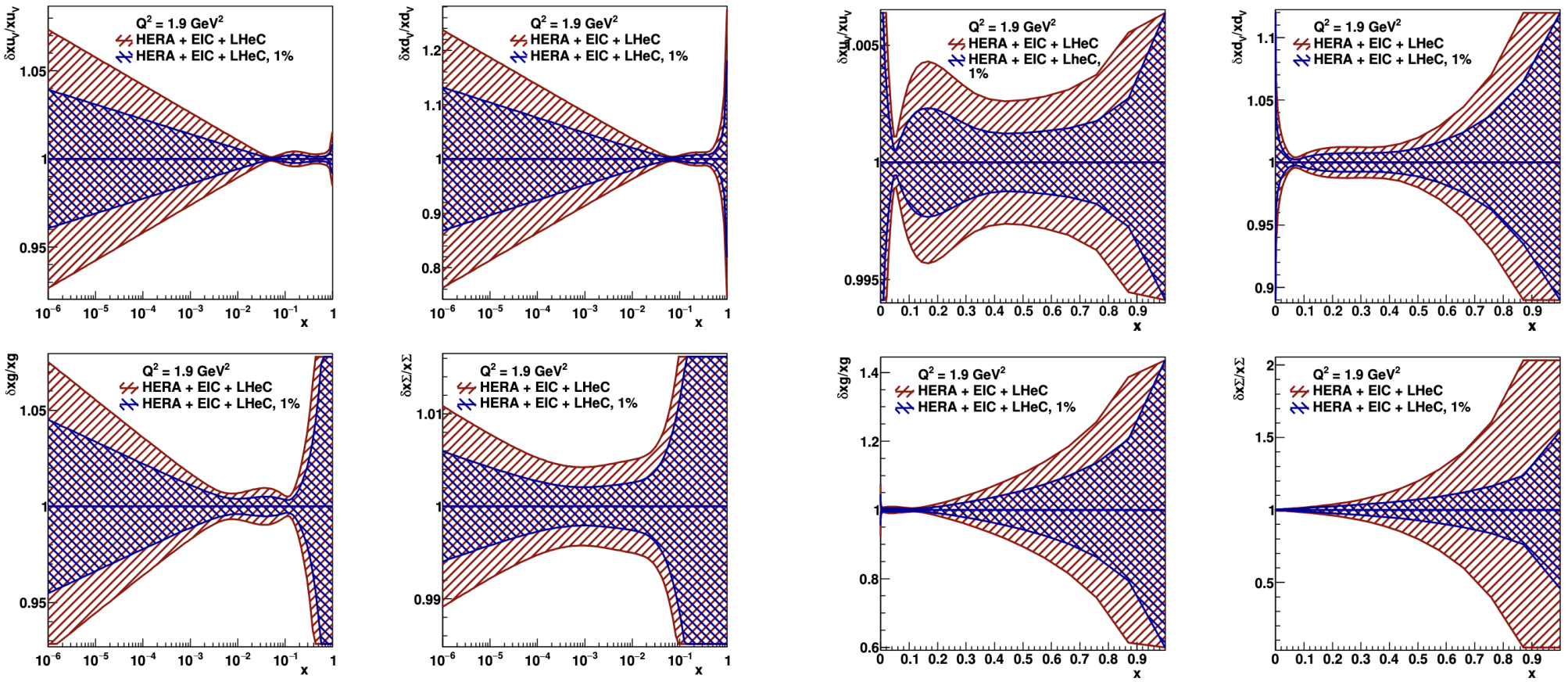
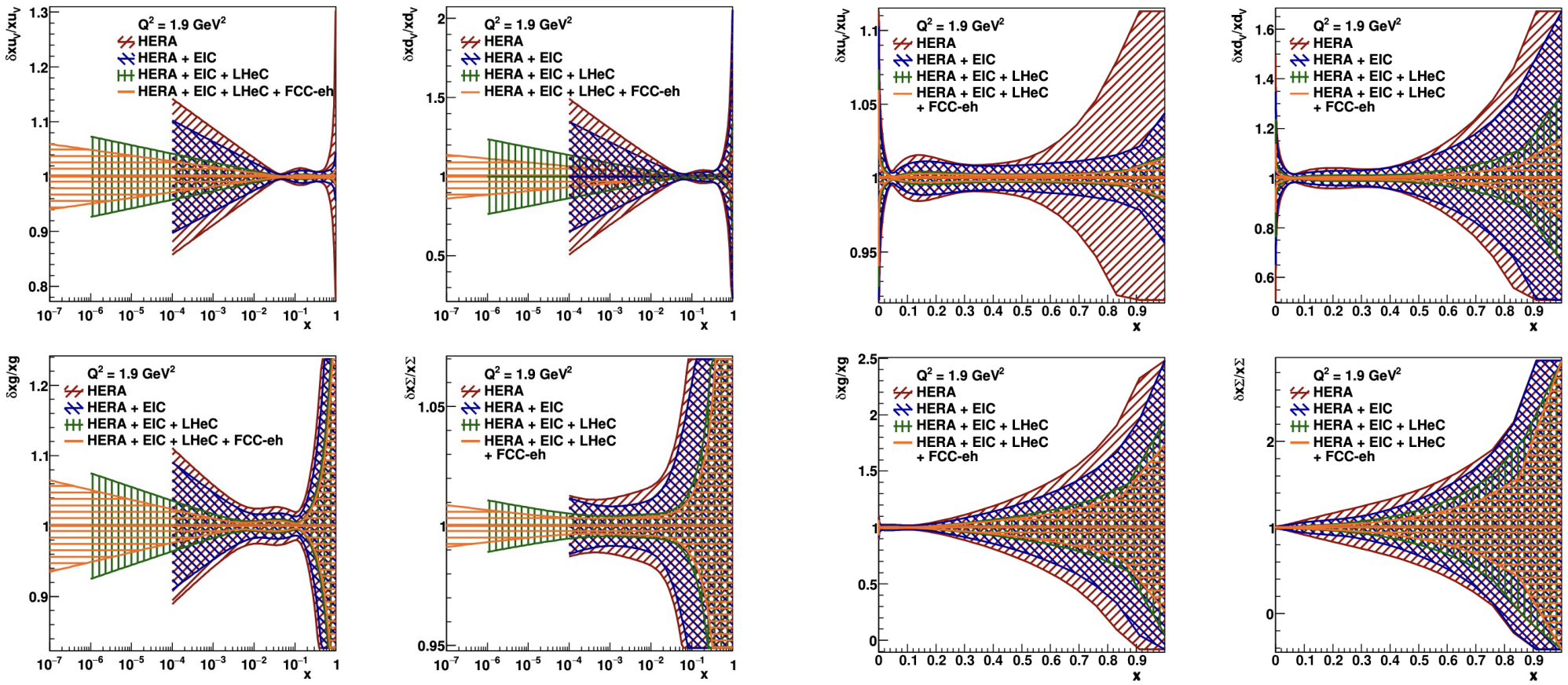
Ultimate precision

- We test optimistic version of total systematic uncertainties for EIC and LHeC: 1% (including lumi) + 1% polarisation



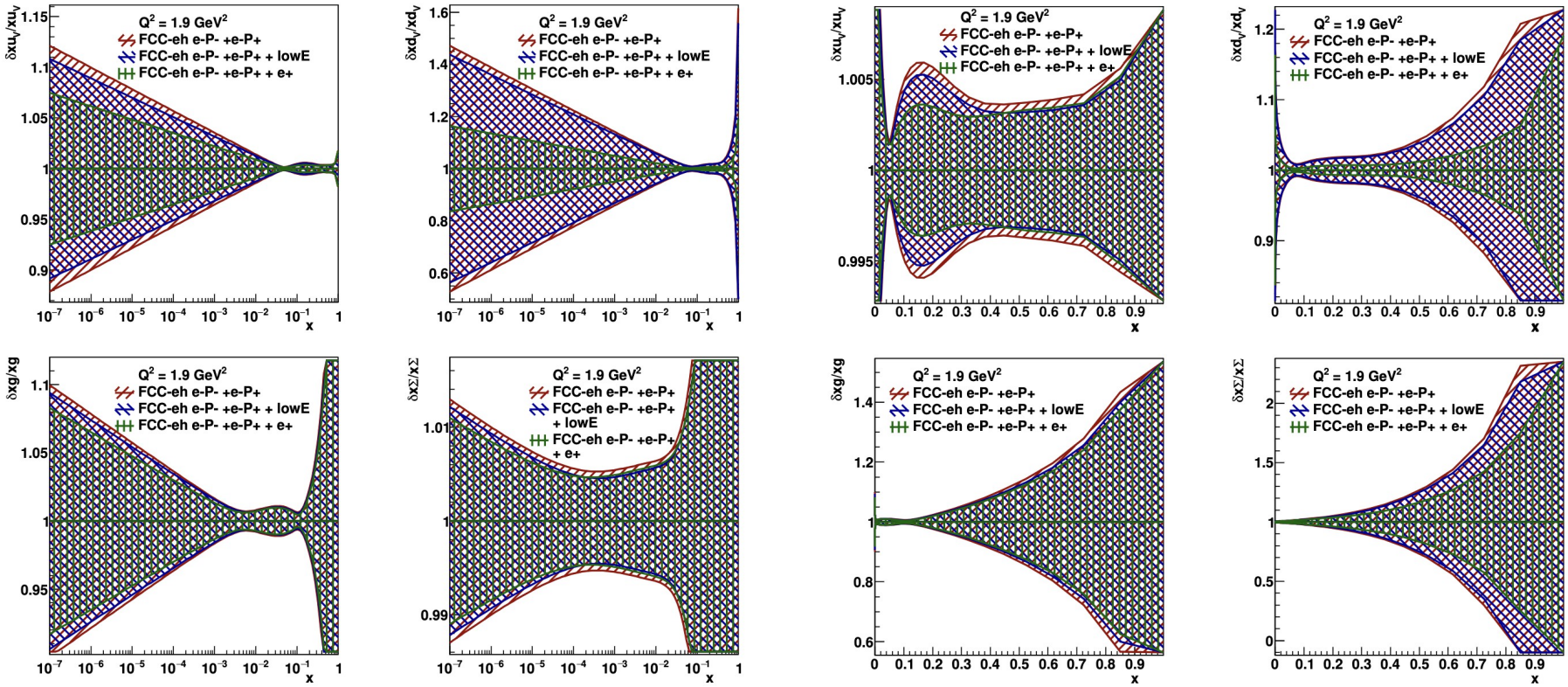
- Big improvement with 1% systematic uncertainties of EIC and LHeC

Ultimate picture: adding FCC-eh



- FCC-eh extends x range to 10^{-7}
- Improvements in precision, especially for low x and for u-valence quarks for high x

Testing impact of various FCC-eh samples



- Positrons have substantial effect
- Some effects seen also for low energy sample
- Larger samples that for LHeC case

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Strong coupling determination with DIS data only

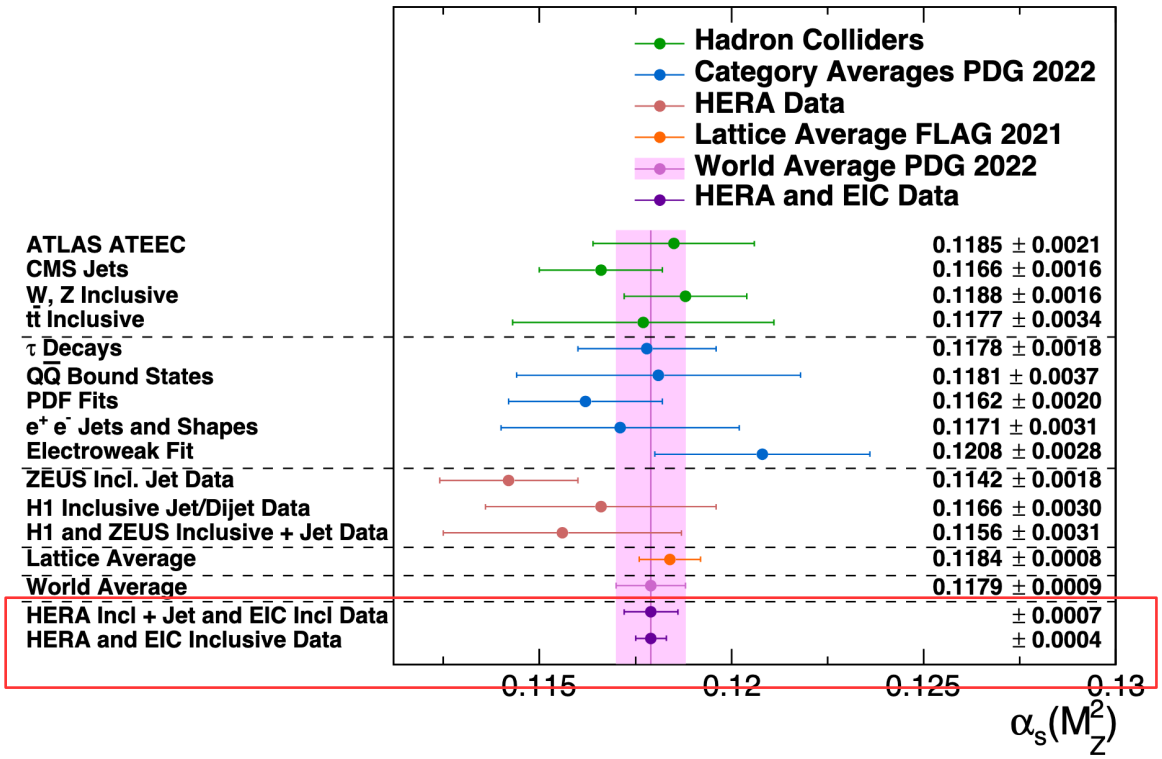
Strong coupling can be determined with DIS only

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

- 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?

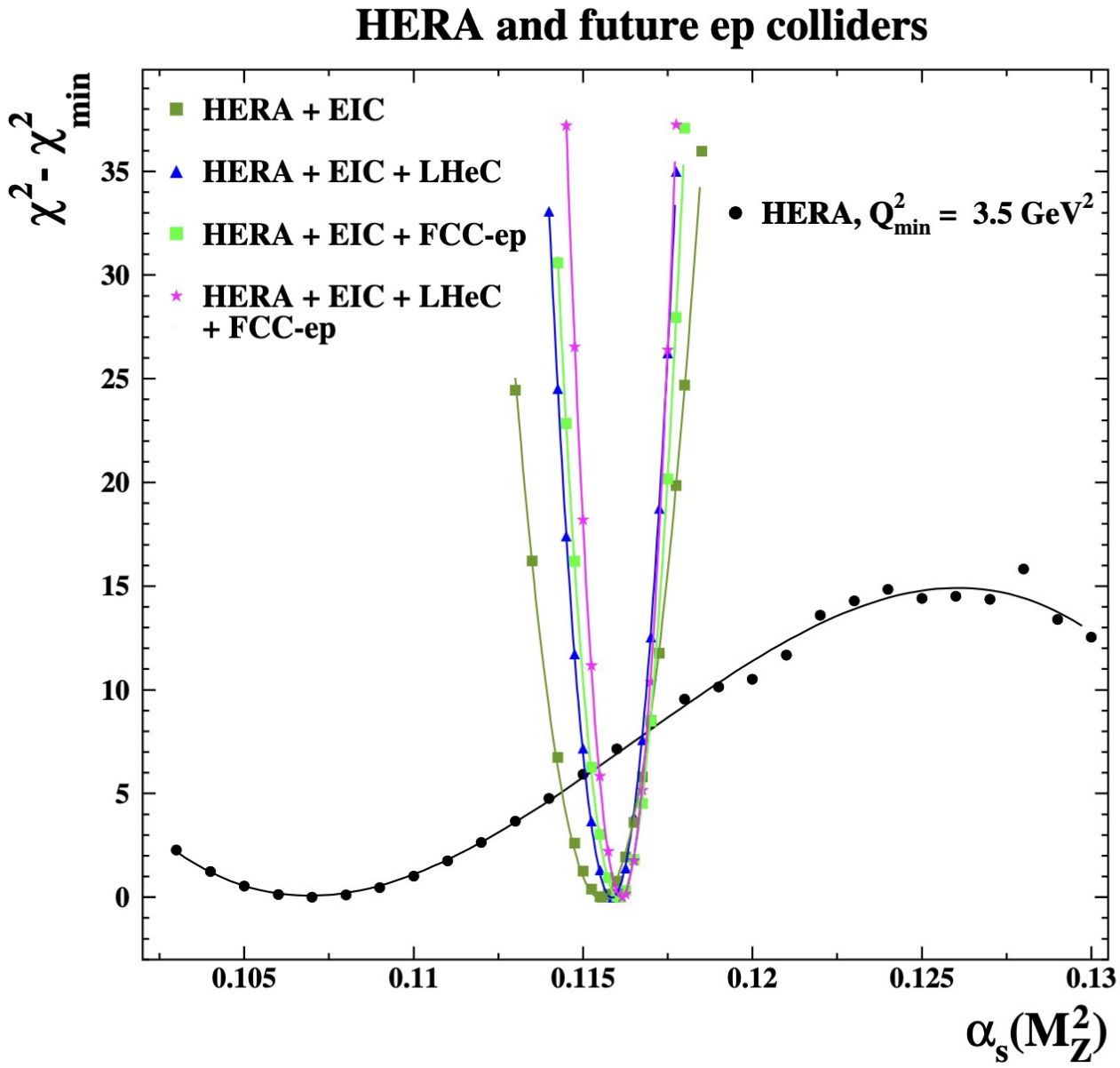
Extraction of the strong coupling with HERA and EIC inclusive data

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]



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

Improvements in alphas estimation



Improvements in alphas estimation

Nominal result: no negative gluon term

DIS data/pseudo-data	$\alpha_s(M_Z^2)$	Experimental uncertainty
HERA + EIC	0.11556	± 0.00049 (0.42%)
HERA + EIC + LHeC	0.11587	± 0.00032 (0.27%)
HERA + EIC + FCC-eh	0.11607	± 0.00032 (0.28%)
HERA + EIC + LHeC + FCC-eh	0.11615	± 0.00027 (0.23%)

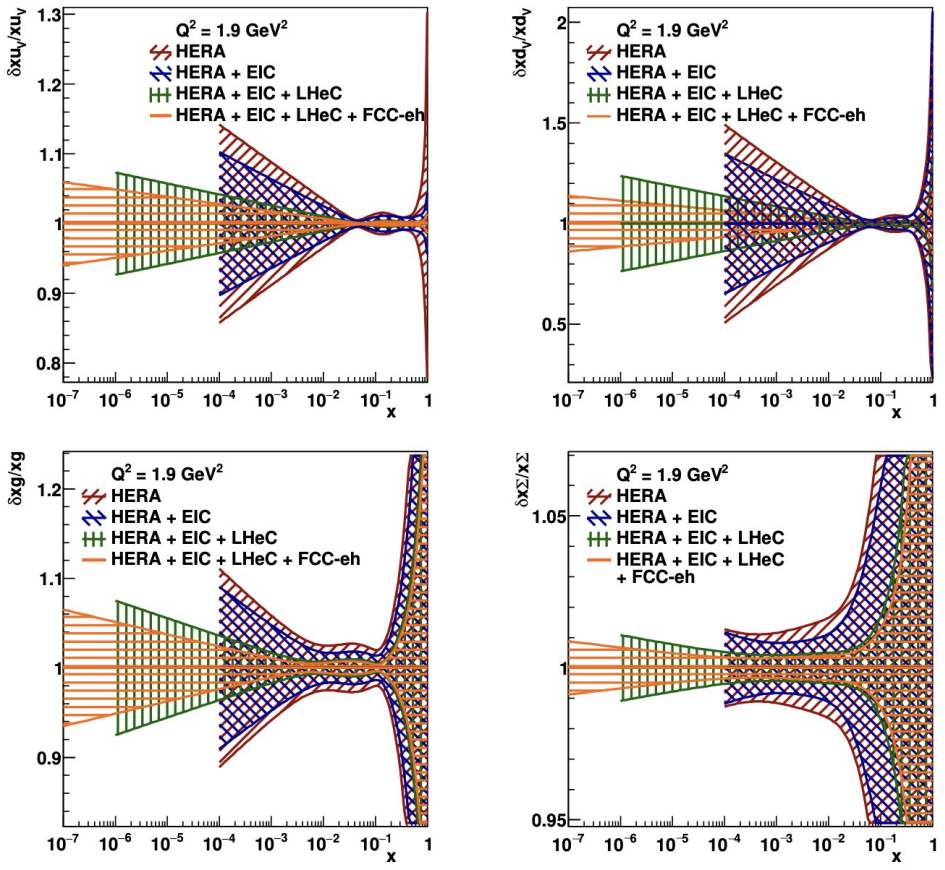
- Present world average: ± 0.76%
- Present QCD Lattice estimate: ± 0.6%

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

→ Question about theoretical uncertainties of such DIS-only determinations still remains open *EPJC 86 (2026) 3, 216*

Message to remember

- Ultimate DIS sample HERA + EIC + LHeC + FCC-eh will bring huge extension of low-x region in PDF estimation
  - Both for covering "unknown" regions and improving greatly uncertainties
  - FCC-eh 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



It all started at HERA in 1992 …

On 30.06.2007 last HERA data taking

After 20 years SAVE THE DATE: 30.06-02.07 2027

HERA Symposium, Hamburg Germany