Inclusive *e-p* measurement prospects for EIC Early Science

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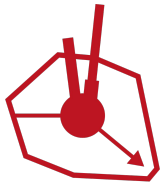
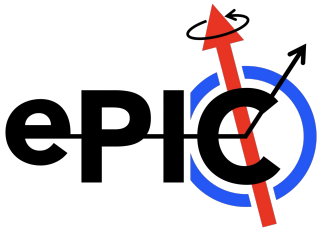
... with thanks to EIC and ePIC colleagues

UNIVERSITY OF BIRMINGHAM



DIS2026

33rd INTERNATIONAL WORKSHOP ON **DEEP INELASTIC SCATTERING AND RELATED SUBJECTS**



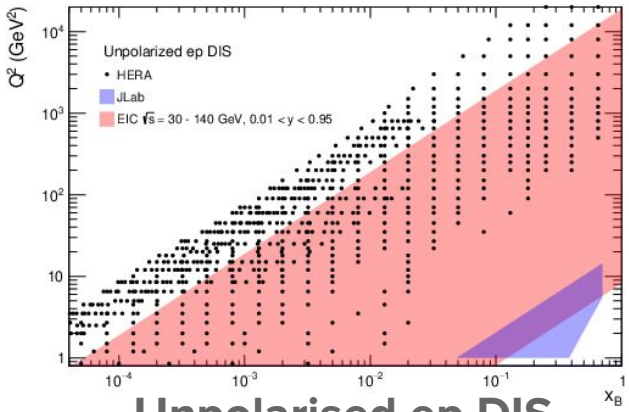
Inclusive Physics at the EIC

- The EIC will be the world's first:
  - ➢ *eA* collider
  - ➢ **High luminosity *ep* collider [focus of this talk]**
  - ➢ Polarised target collider

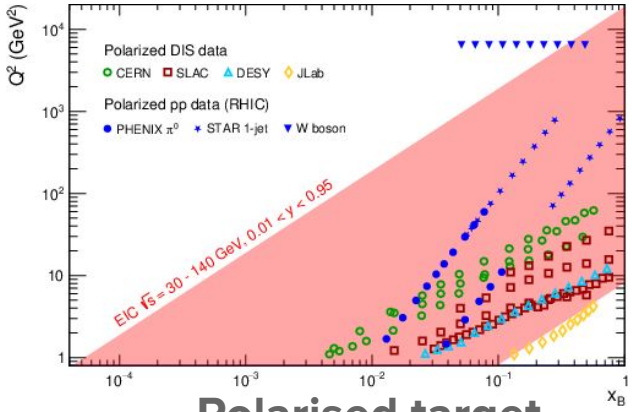
- Inclusive DIS at the EIC will allow us to explore:
  - ➢ Unpolarised collinear parton densities
  - ➢ Unpolarised proton/nuclear structure functions
  - ➢ Polarised nucleon/light-nuclear parton densities and structure functions

Talks by K. Wichmann, J. Jiménez-Lopez, W. Lin

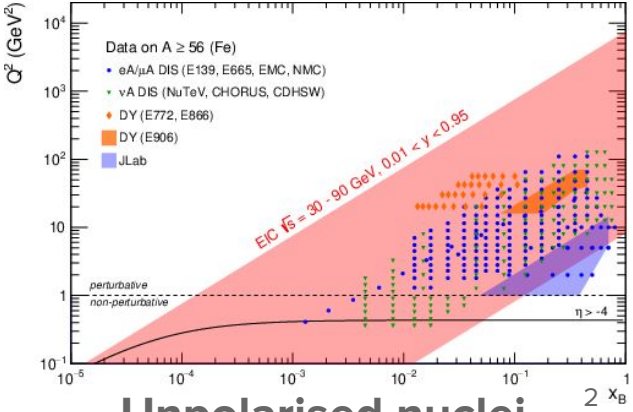
All over a wide range in x and Q^2!



Unpolarised ep DIS



Polarised target



Unpolarised nuclei

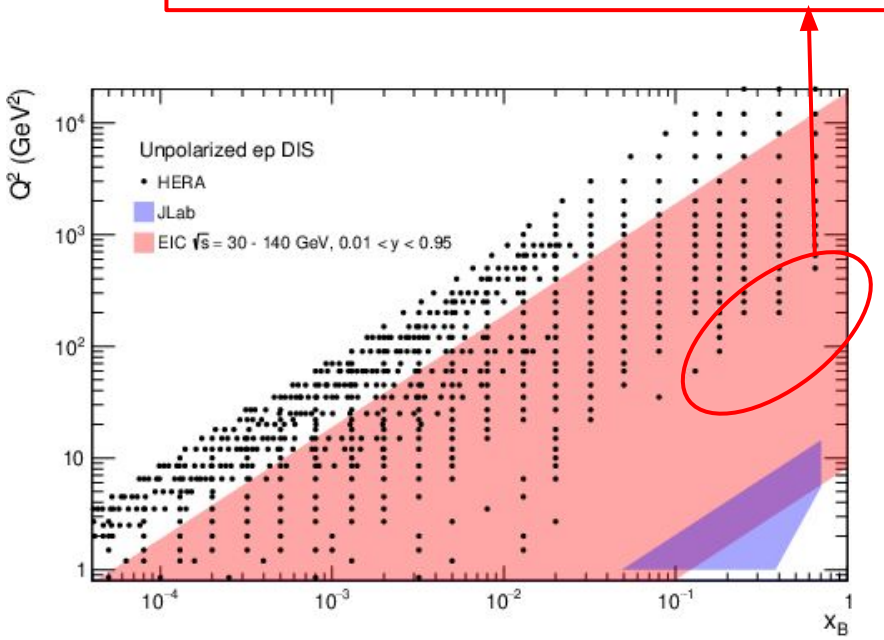
Inclusive unpolarised *ep* DIS at the EIC

- Inclusive *ep* DIS at the EIC will bridge the gap between fixed-target and HERA kinematics
- Here, the aim is to measure the inclusive reduced cross section σ_r over a wide range in x and Q^2

$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

- From σ_r measurements we may determine the proton structure functions, F_2 and F_L
- We can also use these measurements in fits to constrain collinear PDFs

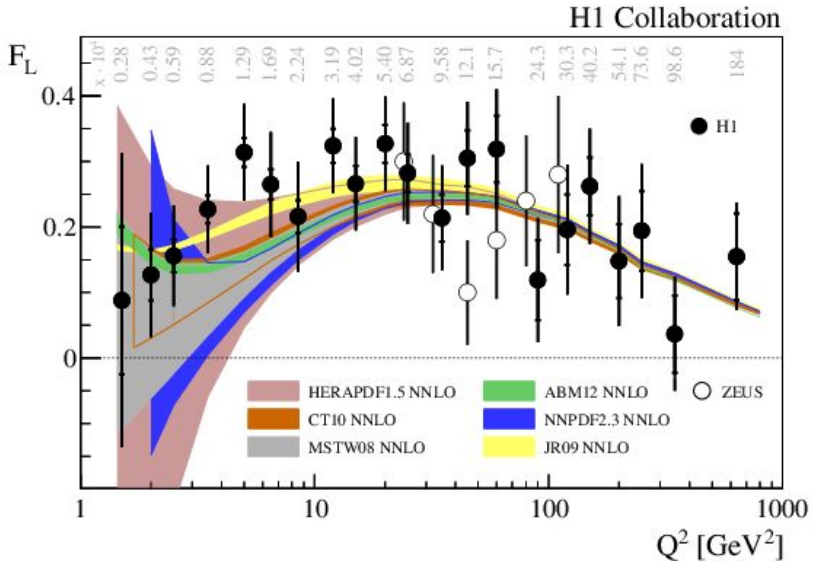
Limited high-x sensitivity for HERA data due to $1/Q^4$ factor in cross section



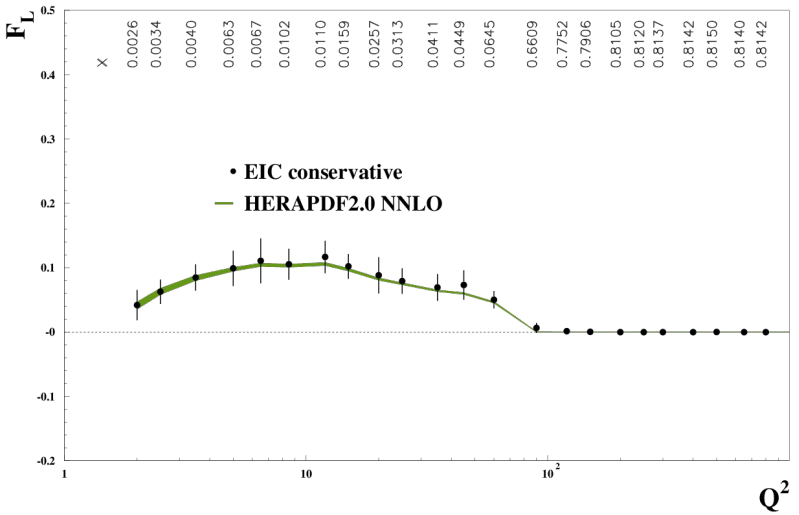
Note: y here is the usual inelasticity variable
x=Bjorken x and Q^2=virtuality

F_L prospects for full luminosity and five energies at EIC

- Variable √s over wide range offers a unique opportunity to constrain F_L



PRD 111, 056014 (2025), arXiv:2412.16123



Unprecedented precision for F_L measurement!

EIC Early Science

- "EIC Early Science" refers to the first 5 years of EIC operation
  - Luminosities will be lower compared to later operation **(but still high for an *ep* collider!)**
  - Options more restricted for beam energies and particle species
- Significant ongoing effort on the accelerator side ➜ specifics for what will be run and what luminosities will be achieved for Early Science are **not** final
  - For *ep*, the aim is to be capable of running ~5 and ~10 GeV electrons, and 130 and 250 GeV protons
- **A provisional Early Science programme is shown below:**

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	?	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	?	LONG	NO TRANS
YEAR 3	e+p	10 x 130	?	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	?	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	?	LONG	N/A TRANS and/or LONG
Note: the eA luminosity is per nucleon					

Specifics of the energies, species, and **luminosities** will depend on ongoing accelerator R&D, physics motivation, commissioning experience.
➜ For the following studies, we conservatively take 1fb^{-1} per *ep* beam energy configuration

EIC pseudo-data generation

- Pseudo-data generated for three potential EIC Early Science configurations

e-beam energy (GeV)	p-beam energy (GeV)	$\sqrt{s}$ (GeV)	Integrated lumi (fb^{-1})
10	250	100	1
10	130	72	1
5	130	51	1

Note: config not part of provisional ES programme

- Cross section central values calculated from HERAPDF2.0 NNLO
- Smeared according to estimated statistical and systematic uncertainties
  - **1.9% point-to-point uncorrelated systematics, 3.4% totally correlated normalisation → 3.9% total**
  - Normalisation uncertainty taken as totally uncorrelated between beam energy configs
  - Statistical uncertainties from full simulation of DIS events in the ePIC simulation framework
- For each pseudo-data point:
  - Smearing of pseudo-data performed 1000 times
  - Mean and variance calculated for N = 1000

$$\overline{v} = \frac{S_1}{N}, \quad (\Delta v)^2 = \frac{S_2 - S_1^2/N}{N-1}$$

See J. Jiménez-López talk

With $S_n = \sum_{i=1}^{N} v_i^n$ and v_i the extracted value of $F_{2,L}$ in MC sample i

Structure Functions

Rosenbluth separation method

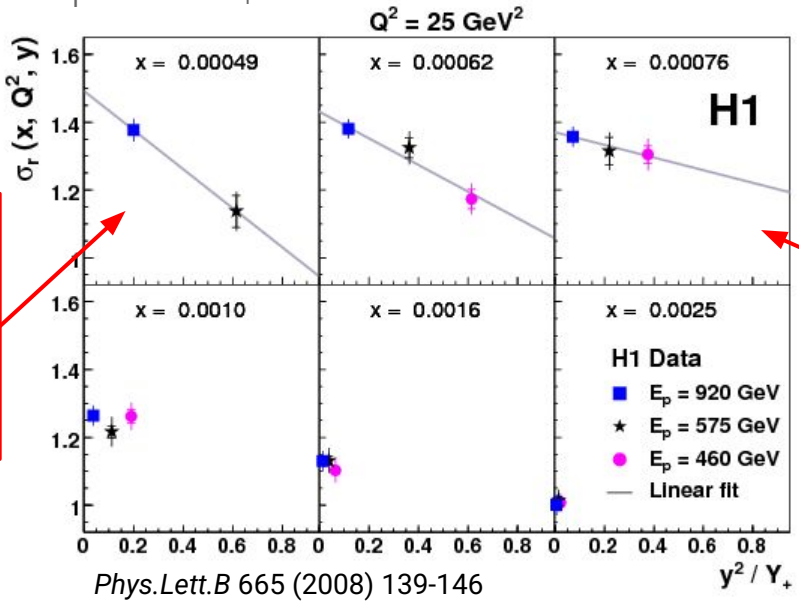
$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

- Linear relation between DIS cross section and structure functions ➡ plot σ_r vs y^2/Y_+!

$$Y_+ = 1 + (1 - y)^2$$

$$y \simeq \frac{Q^2}{sx}$$

y^2/Y_+ changes with √s!



Phys.Lett.B 665 (2008) 139-146

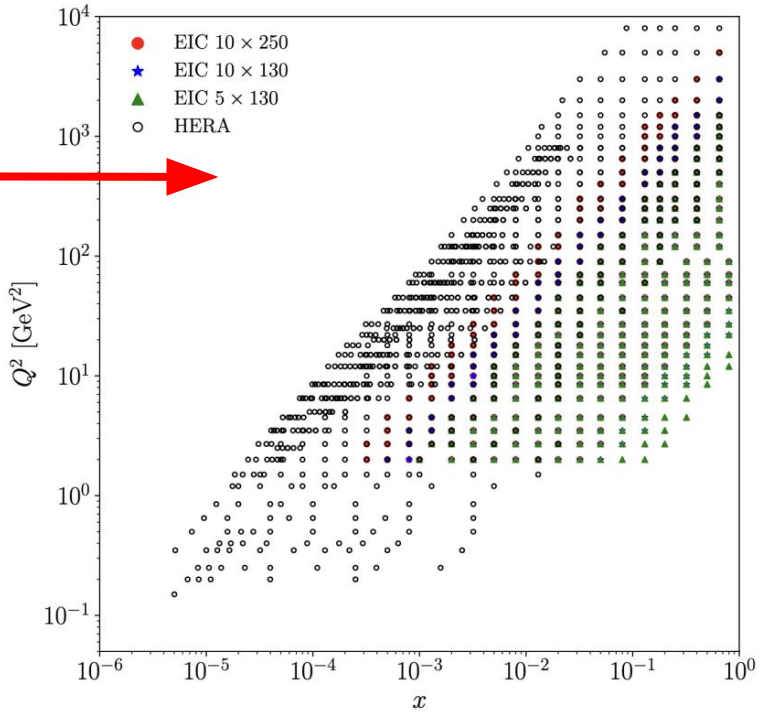
2 points needed to calculate slope and intercept

3 points needed for a <u>fit</u>

Options for early science measurements

If we optimise binning scheme to overlap HERA DIS measurements…

(Combined data: √s = 320, 300, 251, 225 GeV)

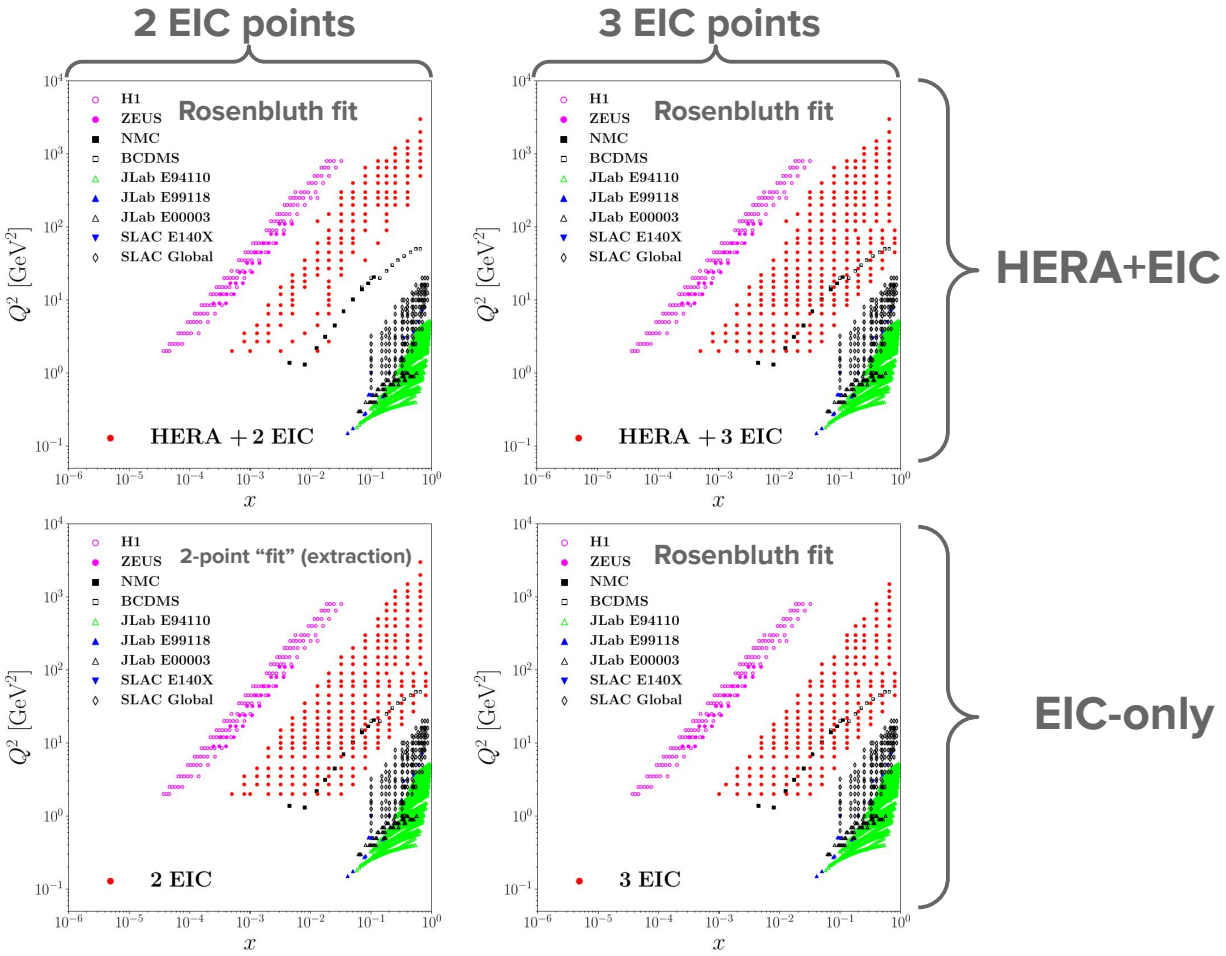


- **With only 2 energies: 10x130 and 10x250 GeV^2**
  1. **Fit** with HERA inclusive data ➔ 2 EIC + HERA
  2. Extraction (**not fit!**) from two EIC points and standard error propagation for uncertainties
- **With a third beam energy: 5x130 GeV^2**
  1. Fit 3 EIC + HERA
  2. EIC-only fit

Still ~5 bins per decade in x and Q^2

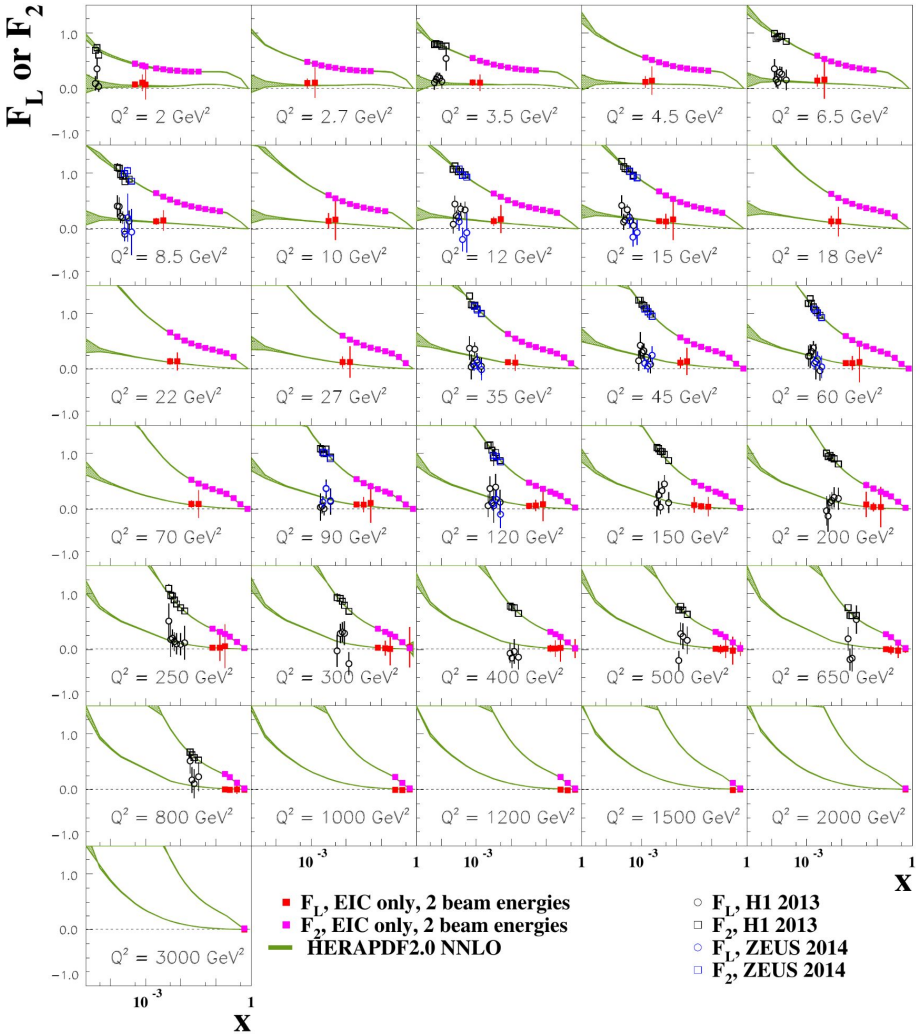
Phase space for the different scenarios

Note: we require 3 points for a proper Rosenbluth fit in all but the 2 EIC scenario



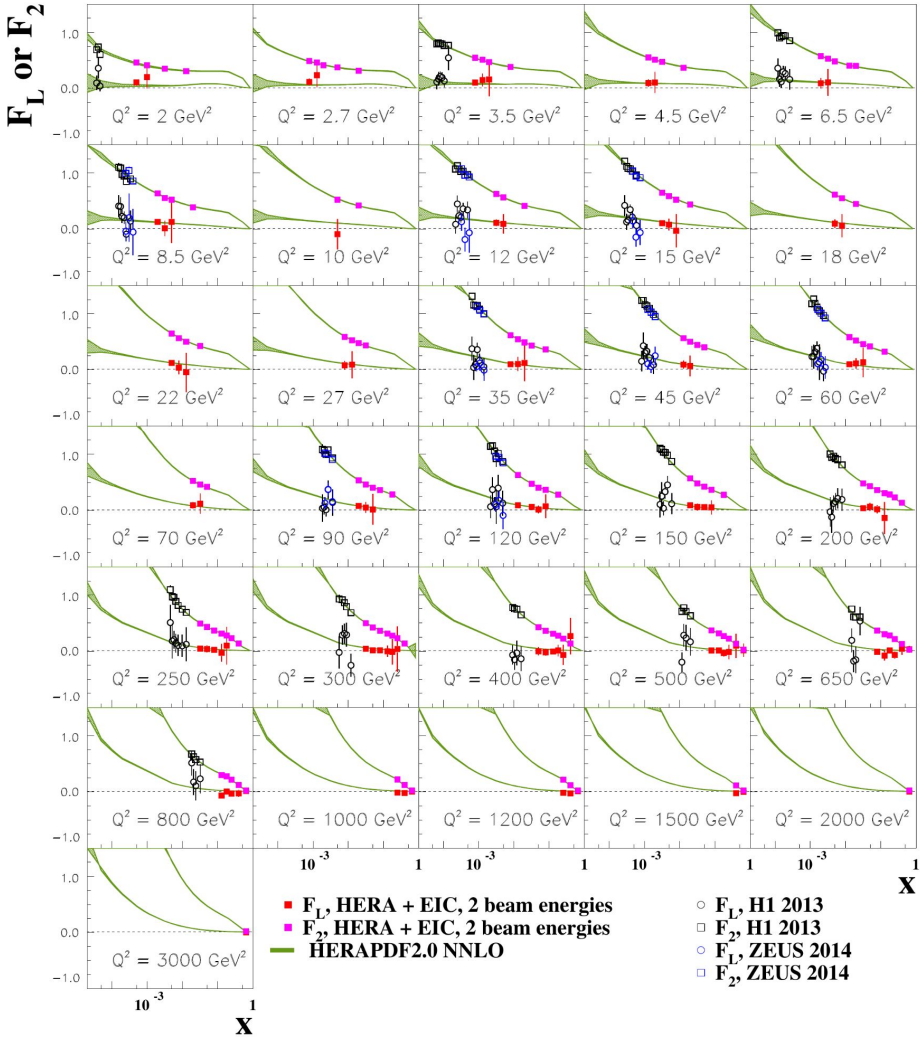
Structure Functions 2 EIC

- For visibility, only “good” F_L points with absolute uncertainty <0.5 are plotted - every F_2 point has an F_L at same x-Q^2 (error may be large)
- **EIC points at larger x than HERA points** - but <u>errors are large for all but a few F_L points</u>
- However, we obtain high precision (model-independent) F_2 extractions over a large range!



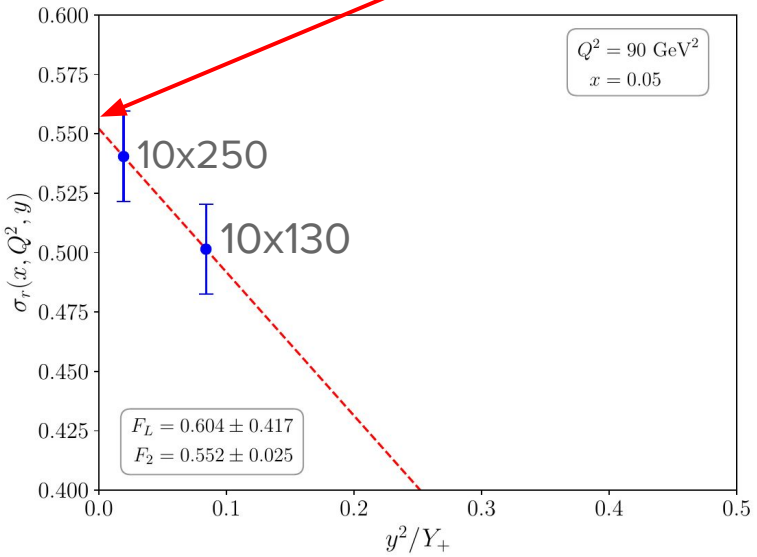
Structure Functions 2 EIC + HERA

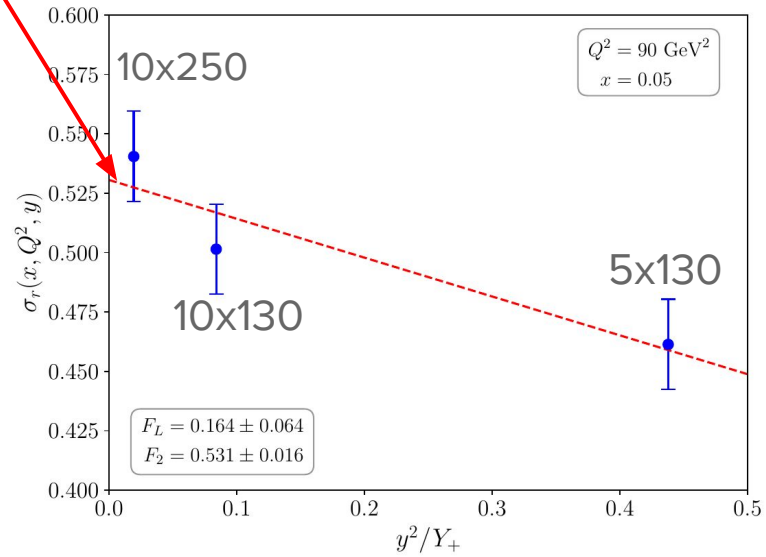
- Adding HERA data has two effects
  1. Fewer F_2 (and F_L) points as we require 3 points for the Rosenbluth fit (at least 1 point must come from HERA
  2. We gain in terms of **<u>F_L points with <0.5</u>** uncertainty, particularly at moderate to high Q^2
- Even with this improvement, the F_L points are often compatible with zero ➡ need more y^2/Y_+ lever arm



Improving F_L uncertainties

HERA points down here

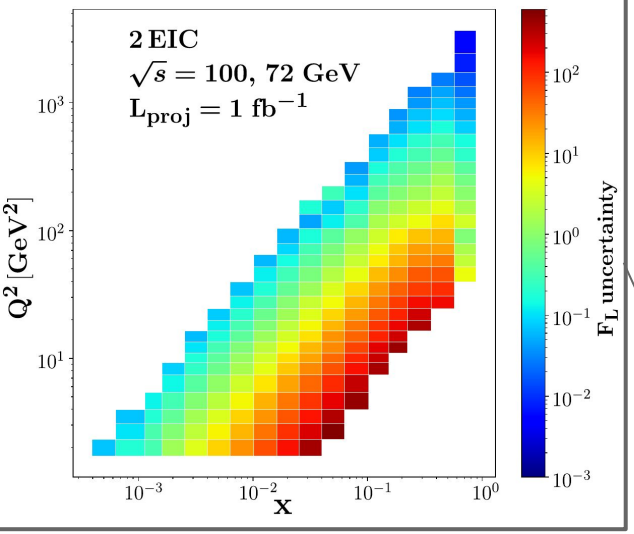


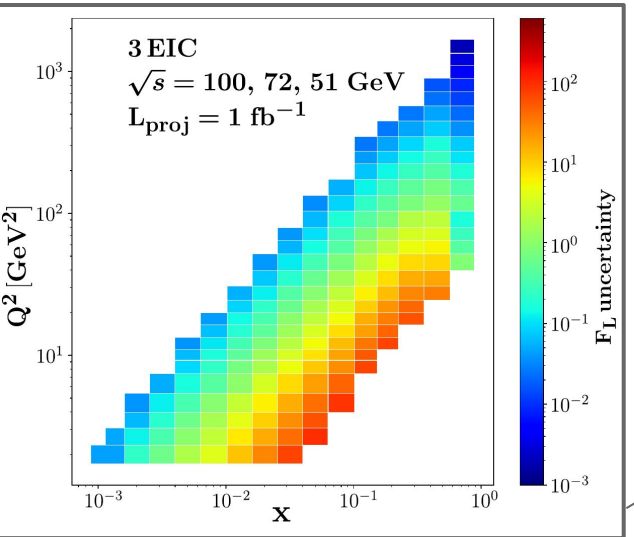


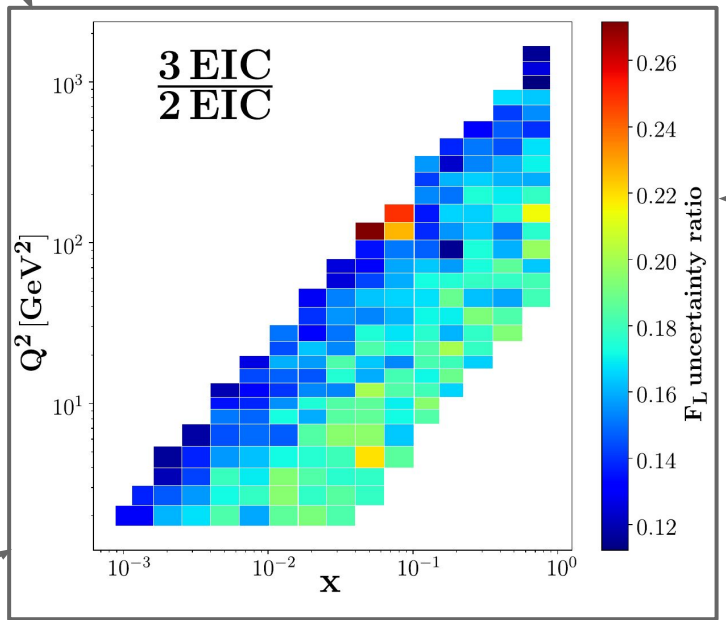
The precision on F_L benefits from high y (and therefore high y^2/Y_+) points → lower c.o.m. energy!

Uncertainties on F_L (EIC-only)

- Different extraction methods for 2 vs 3 energies, **phase-space for two-beam configuration = larger by definition**
- Difference in number of data points and y^2/Y_+ lever arm leads to different uncertainties for 2- and 3-beam F_L results







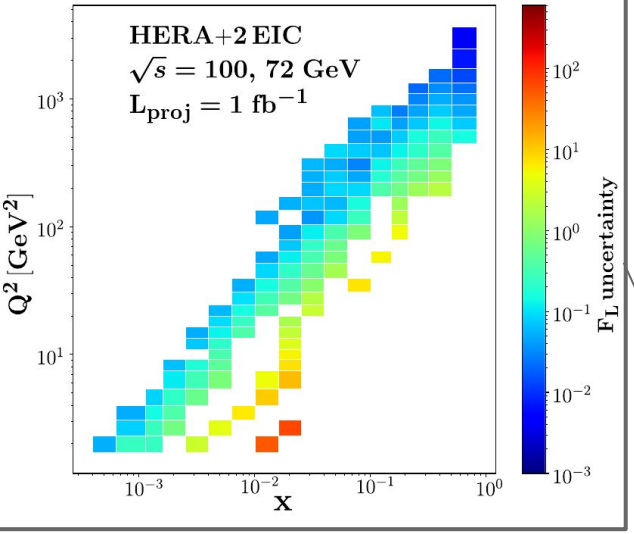
Ratio of uncertainties for 3- to 2-beam F_L results in common phase-space

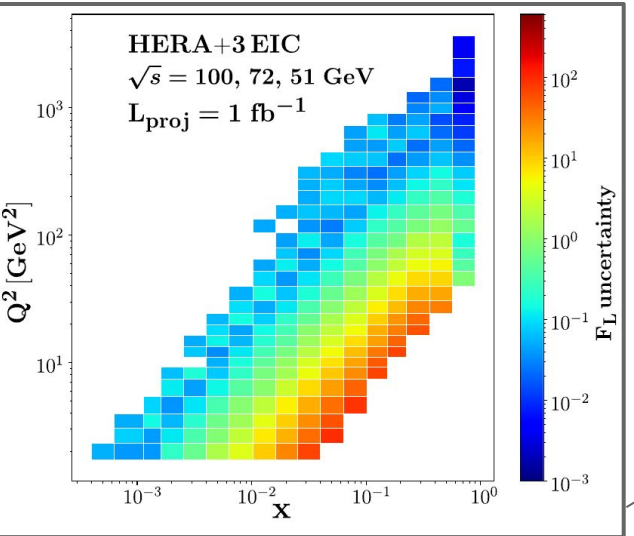
Ratio typically between 10% and 20% for most of phase-space and never over 30%

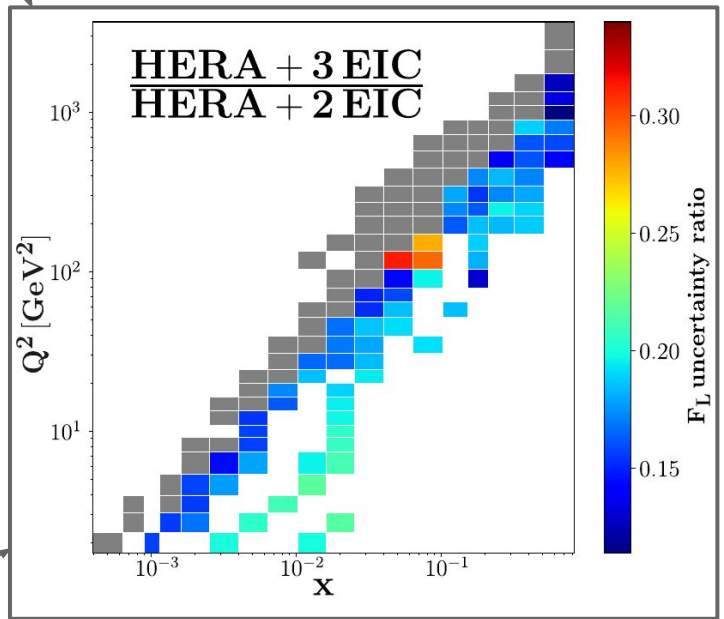
5-7x improvement!

Uncertainties on F_L (HERA+EIC)

- Here we **always require 3+ data points** → proper Rosenbluth fit
  - Phase-space for HERA + 2 EIC beam energies energies is therefore considerably smaller than for HERA + 3 EIC
- **Measurements in 3-beam scenario are more precise, but at similar level to 3 EIC-only → the lower √s EIC point has largest impact**



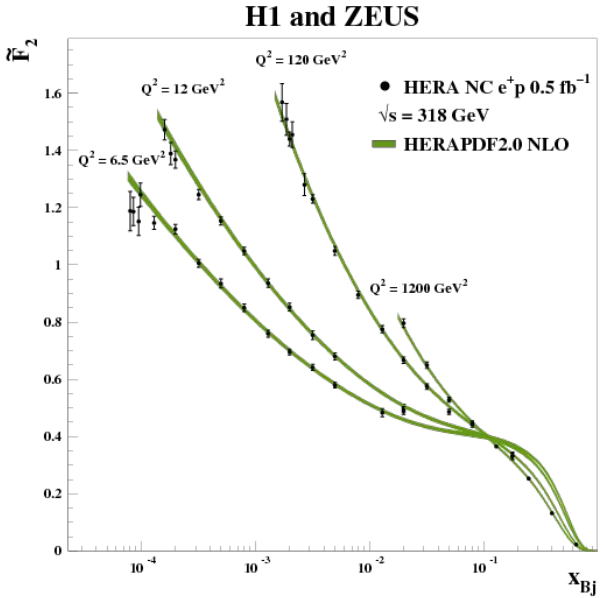




Grey = no EIC points → ratio = 1

Calculations of the F_2 uncertainty

- In HERA publications on inclusive cross sections with F_2 extraction, the uncertainty derives from the cross sections ➔ models used to determine the size of F_L contribution to cross section
  - ➢ **F_2 either quoted without uncertainty or uncertainty is simply taken as relative total uncertainty of the cross section**
  - ➢ **No model uncertainties calculated**



- Here, the F_2 are model-independent (using Rosenbluth Method)
  - No model uncertainties introduced
  - Only uncertainties are on the cross sections used to measure structure functions

Comparison of F_2 extraction methods

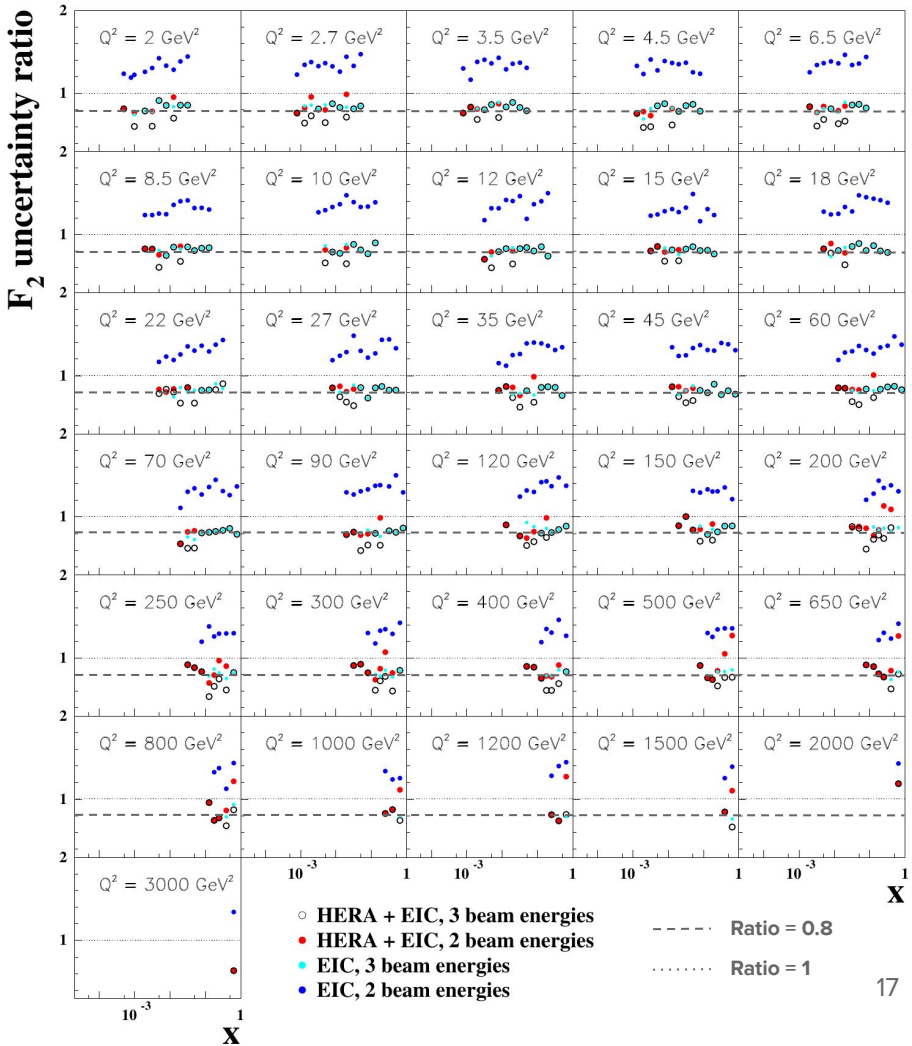
- Only for EIC-only fits with 2 energies is model-dependent extraction better
- For the rest uncertainties obtained in model-independent way are almost* always lower

$$\text{Ratio} = \frac{\text{model-independent } F_2}{\text{model-dependent } F_2}$$

If Ratio < 1 then Rosenbluth fit gives better F_2 precision

We see R≈0.8 for except for 2 EIC!

*model independent uncertainties are worse only for HERA + EIC fits for bins with only one EIC point



Collinear Proton PDFs and α_s

(...in HERAPDF style)

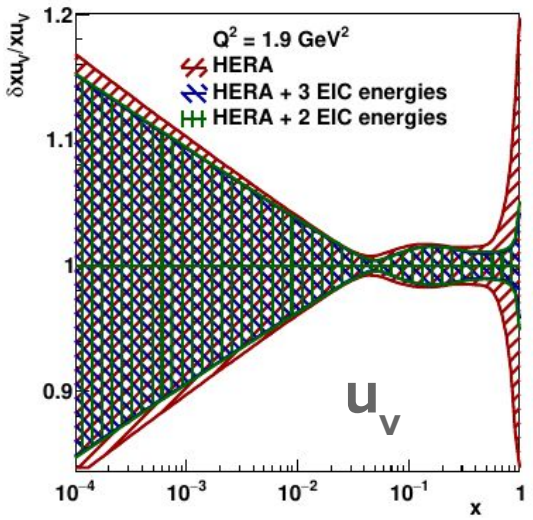
Collinear PDFs (Early Science)

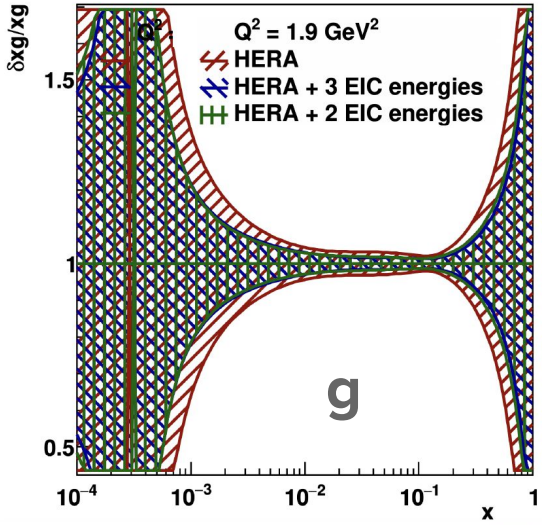
- Fit pseudo-data alongside HERA data in HERAPDF parametrisation using xFitter
- Same pseudo-data as for F_2 & F_L studies
  - W > 10 GeV
- **Modest improvement for low-to-mid x** for the **u_v quarks and gluons**
- **Large improvement for x > 0.1** for gluons and u_v

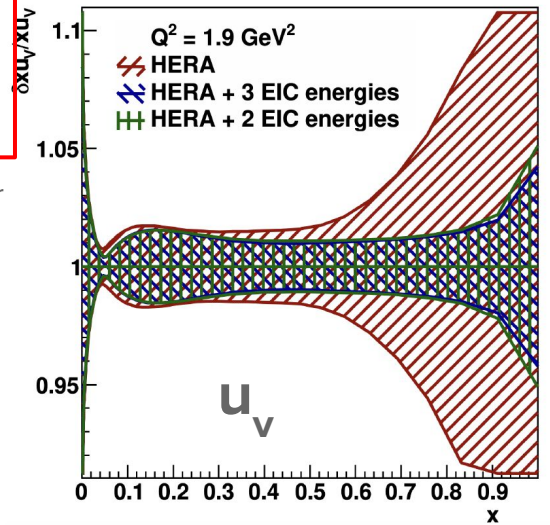
➢ **Shown:** relative experimental uncertainties for u_v and g (no parametrisation//theory)

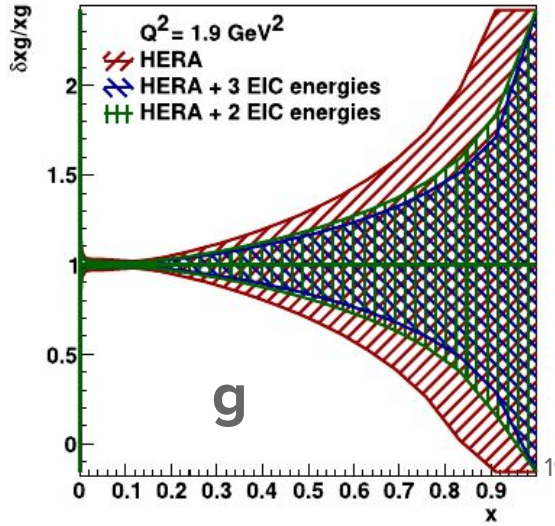
➢ **Not shown:** no significant improvement for d_v quarks and only minor improvement for the mid-x total sea

➢ **Only small difference between two- and three- beams scenarios**









Simultaneous fits of PDFs and α_s (full EIC running)

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

- **Simultaneous PDF and $\alpha_s(M_Z)$ fit** with **ONLY** inclusive DIS data
  - α_s kept as free parameter in fit
  - α_s extraction possible thanks largely to EIC high-x region
- For 1 year each at **design luminosities and 5 energies** → very precise results expected

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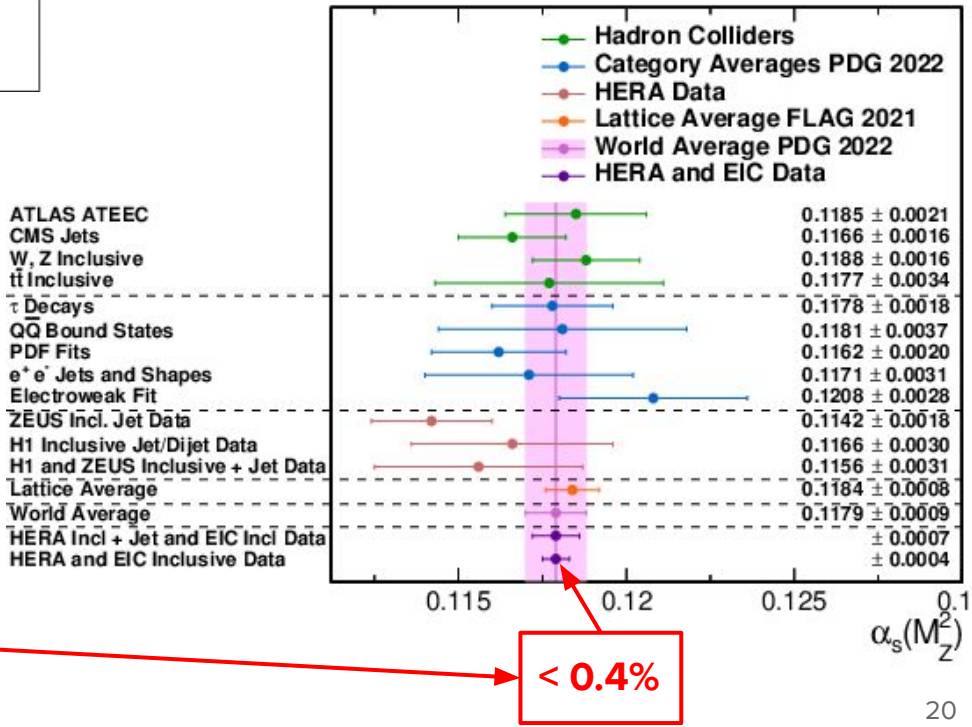
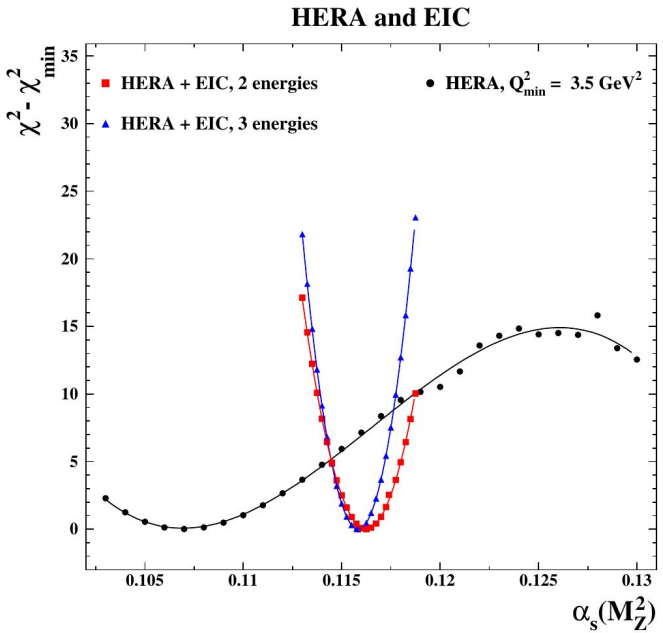


Early Science prospects for strong coupling

- For 2 EIC beam energies $\alpha_s(M_Z^2) = 0.1162 \pm 0.0008\ (\text{exp})$

For 3 EIC beam energies $\alpha_s(M_Z^2) = 0.1158 \pm 0.0006\ (\text{exp})$

- **Measurement is already very precise with 2 EIC Early Science beam configurations**
- **Comparable to lattice QCD determinations and present world average**



➢ Parametrisation & model uncertainties expected to be small

➢ Method for determining theoretical uncertainties uncertain

Summary

- Inclusive DIS cross section/structure function measurements can be made early on in EIC running
  - Measurements for proton target bridge the gap between fixed target and HERA kinematics
- We can extract F_2 and F_L via measurements at different √s
  - If only 2 EIC *ep* runs in early science ➔ combine with HERA data to improve SF extraction
  - Addition of a third, low(er) √s EIC ep config significantly imrproves F_L extractions in all cases
  - Determine F_2 in model-independent way and improve precision compared to model-dependent approach if 3+ points in fit
- EIC can constrain u_v and gluon PDFs in first 5 years ➔ further improve all PDFs when full design capabilities
- Strong coupling can be determined at level competitive with current world and lattice averages within the first 5 years ➔ also improved when full design capabilities reached
- **Details of this work in arXiv:2602.00860**

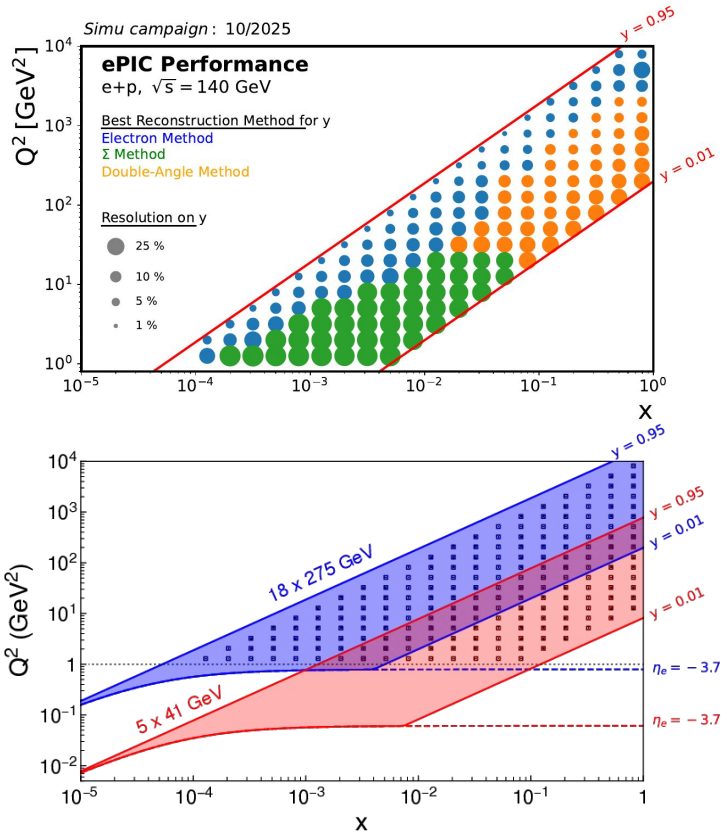
Takeaway

- Inclusive *ep* measurements at the EIC offer a fantastic opportunity to continue and significantly expand on the *ep* collider story that started with HERA. Impactful measurements can be made in the first 5 years, and beyond.

Backup

EIC pseudo-data generation

- The following studies use only **inclusive NC DIS** reduced cross section pseudo-data generated for EIC
  - Kinematic resolutions in ePIC allow ~5-8 bins per decade in x, Q^2
- Use conservative systematics estimates ➔ “best systematics” may not be available for early science
  - **1.9% uncorrelated systematics 3.4% and correlated systematics**
- Statistical uncertainties from full simulation of DIS events in the ePIC simulation framework
  - Efficiency and resolution effects introduced at a level that might be expected for the start of EIC operation
  - For $1fb^{-1}$ integrated luminosity per *ep* beam configuration, statistical uncertainties are negligible compared to systematic uncertainties in all but the largest x and Q^2 bins



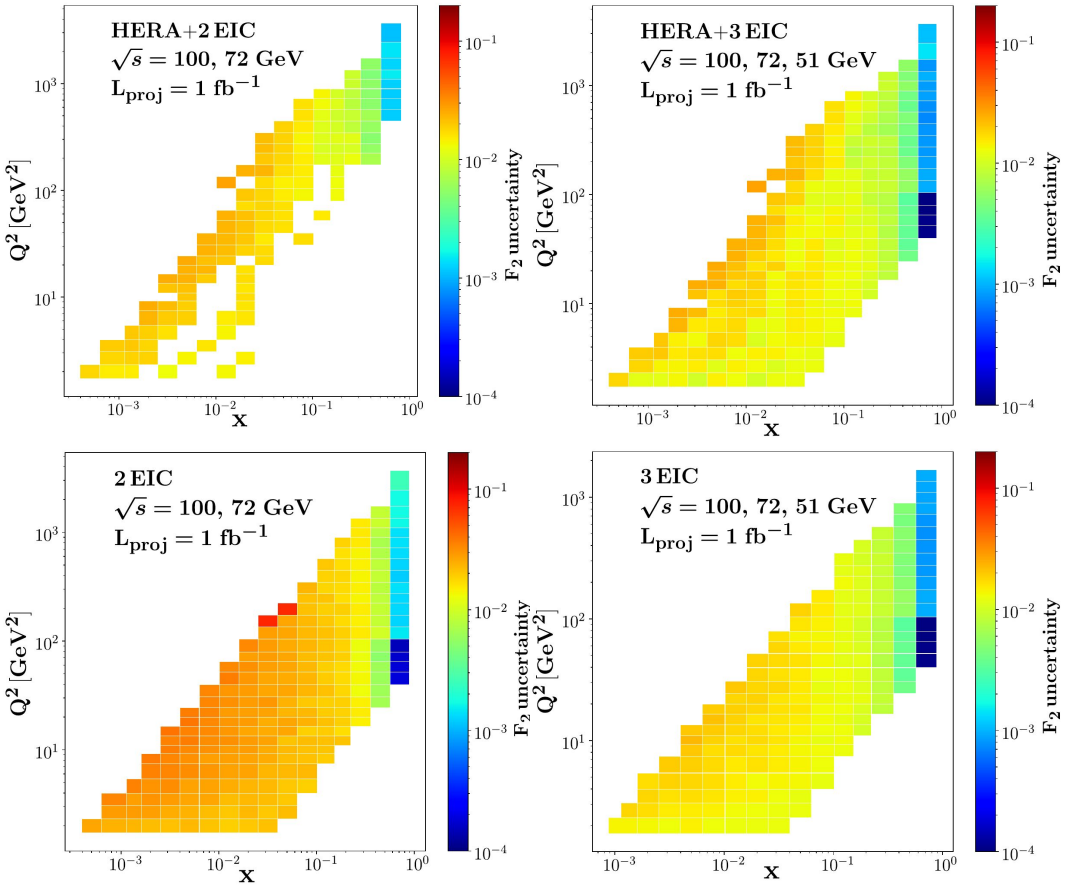
MC replica method

- To sample distribution of possible outcomes for expected values and uncertainties on F_L in statistically meaningful way MC replicas are used
- Method adapted from PRD 105, 074006, 2022:
  - “Diffractive longitudinal structure function at the Electron Ion Collider”, N. Armesto, P. R. Newman, W. Słomiński, and A. M. Staśto
- For each pseudo-data point:
  - Smearing of pseudo-data performed 1000 times
  - Mean and variance calculated for N = 1000

$$\overline{v} = \frac{S_1}{N}, \quad (\Delta v)^2 = \frac{S_2 - S_1^2/N}{N-1}$$

With $S_n = \sum_{i=1}^{N} v_i^n$ and v_i the extracted value of $F_{2,L}$ in MC sample i

Absolute uncertainties on F_2



- Phase-space for F_2 scenarios exactly the same as for F_L
- Uncertainties for F_2 are small
  - **around 10^{-2} for most of accessible kinematic plane**
- 3-beam scenario offers higher precision, for both EIC-only and HERA+EIC measurements

HERAPDF2.0 Parametrisation

- In HERAPDF, the proton PDFs, xf(x) , are generically parametrised at starting scale μ_{f0}^2 as:

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

- The central parametrisation is:

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

- Additional Constraints:
  - A_{uv}, A_{dv}, A_g constrained by quark number sum rules and momentum sum rule
  - $B_{\bar{U}} = B_{\bar{D}}$
  - $x\bar{s} = f_s x\bar{D}$ at starting scale, $f_s = 0.4$
  - Charm and beauty from HERA HF data