Prospects for measurements of proton structure functions, proton parton densities and the strong coupling with the early running of the EIC

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Data assumptions and scenarios

Assumptions for EIC pseudo-data

- All studies have been done only with inclusive NC DIS reduced cross section pseudo-data generated for EIC
- We have assumed $\mathscr{L}_{\text{int}} = 1\ \text{fb}^{-1}$
- We have taken the so called "conservative" systematics, as for the early running best systematics might still not be available:

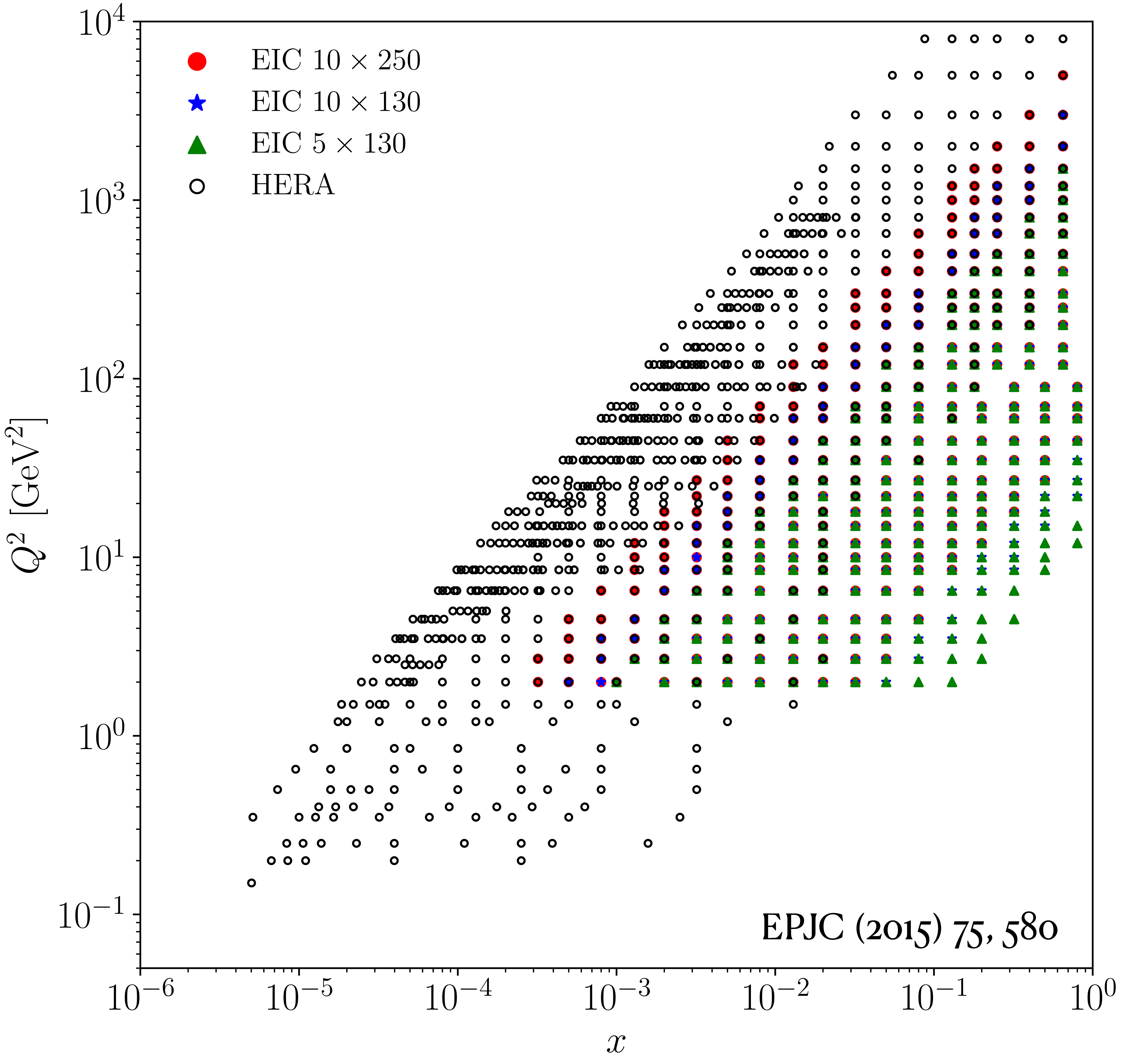
  1. Uncorrelated systematics of $1.9\ \%$
  2. Correlated systematics of $3.4\ \%$

The statistical uncertainty studies were calculated using the number of events from **PYTHIA**6.4. Events were reconstructed in each (x, Q^2) bins using electron-only reconstruction. The simulation of the ePIC detector was done in DD4hep and the reconstruction using the EICrecon framework.

Beam configurations and scenarios

- With 2 energies (10×130 and 10×250):
    1. Add HERA data (HERA + 2EIC)
    2. Error propagation method (2EIC)
- Adding a third energy (5×130):
    3. Add HERA data (HERA + 3EIC)
    4. Rosenbluth fit (3EIC)

We have considered all of them



We use the HERA DIS binning

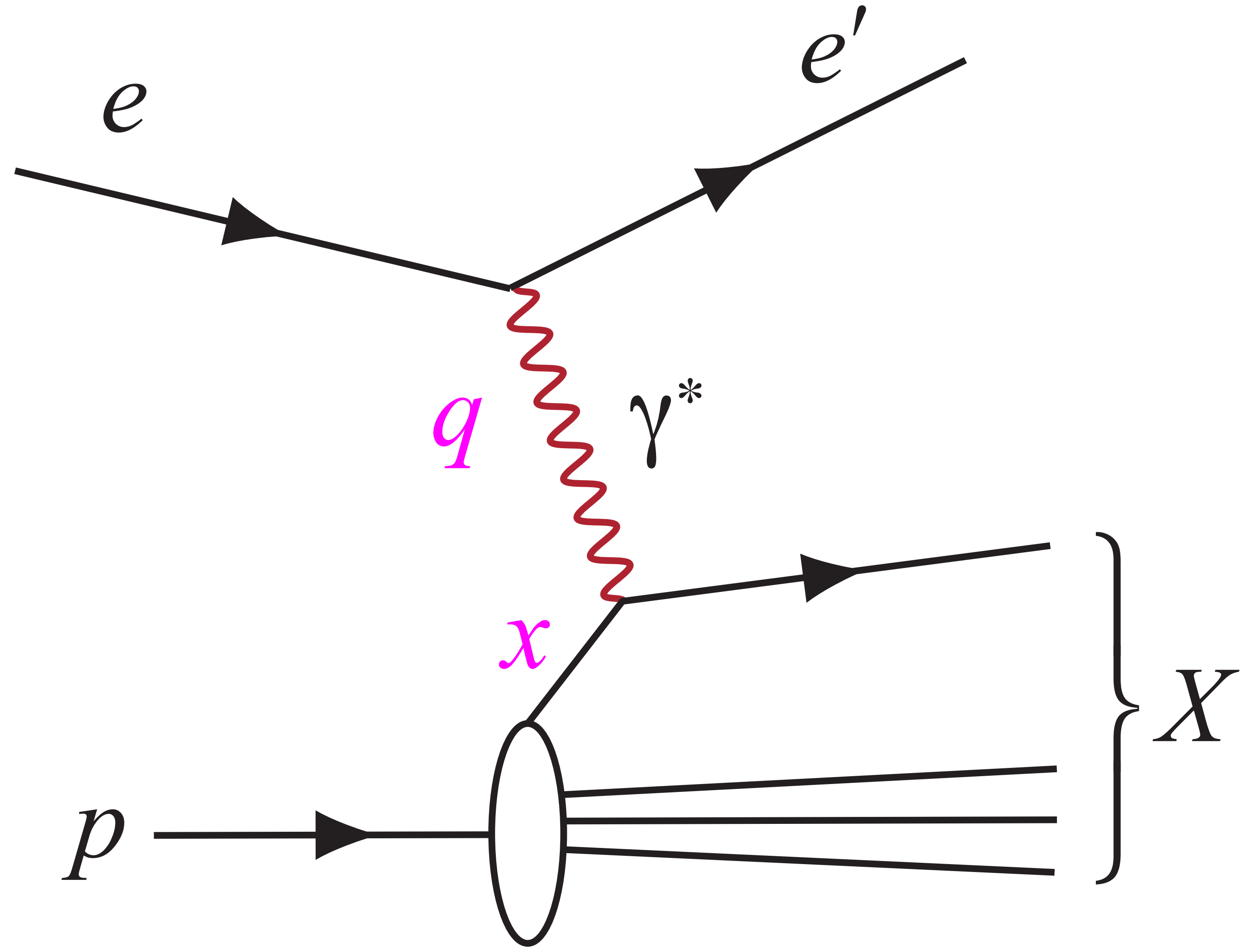
F_L extraction

The reduced cross-section of the $e^- p$ NC DIS for $Q^2 \ll M_Z^2$ is:

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

- x: Bjorken scaling variable
- y: inelasticity
- Q^2: virtuality
- $Y_+ = 1 + (1 - y)^2$

$$Q^2 = sxy$$



As x and Q^2 are known, F_2 and F_L can be extracted using a linear fit.

This is the well-known Rosenbluth-type separation method (*Rosenbluth., Phys. Rev.* **79**, 615).

Pseudo-data simulation

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

- Cross sections are generated with HERAPDF2.0 NNLO
- The Gaussian smearing is done according to the conservative systematics: 1.9 % of uncorrelated + 3.4 % of correlated to give a total of 3.9 %
- No normalisation uncertainty across different beam configurations has been considered
- Predictions and fits are done using XFitter

Averaging over MC replicas

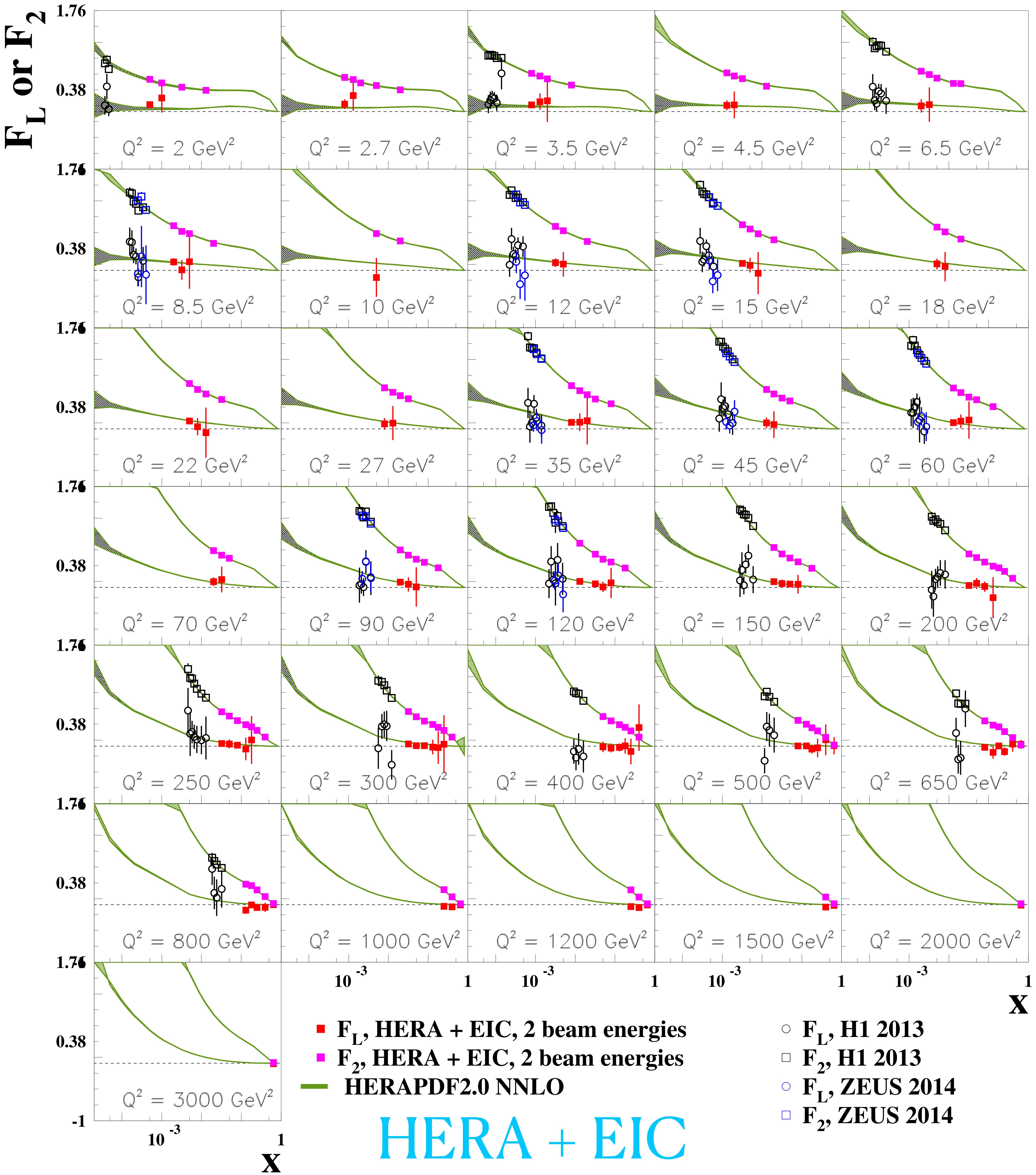
In order to get a final measurement of F_L and it's uncertainties, we apply the following averaging procedure (PRD 105, 074006 (2022), arXiv: 2112.06839):

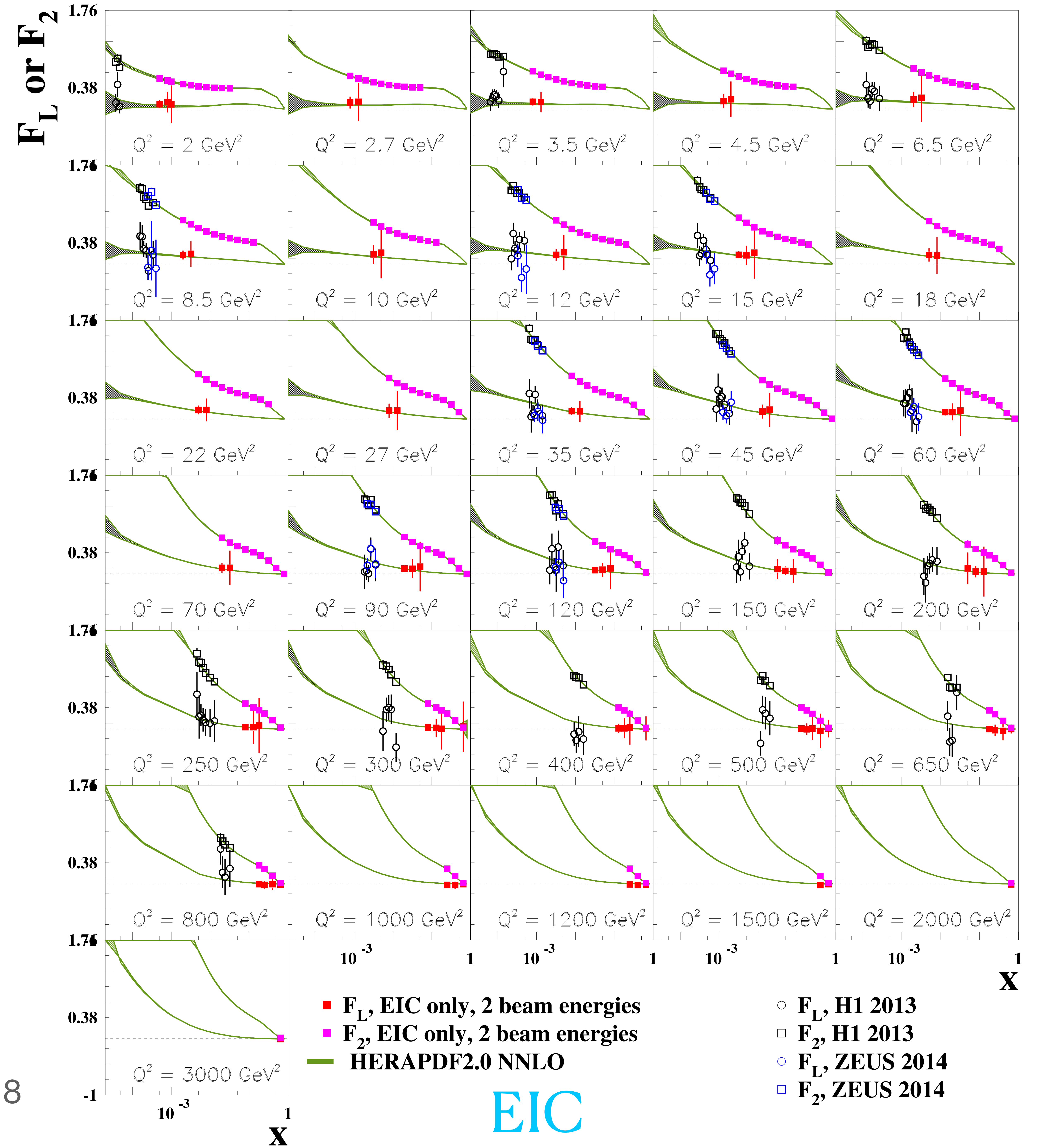
$$\bar{v} = \mathcal{S}_1/N \qquad (\Delta v)^2 = \frac{\mathcal{S}_2 - \mathcal{S}_1^2/N}{N-1}$$

where $\mathcal{S}_n = \sum_{i=1}^{N} v_i^n$ and v_i stands for the extracted value of F_L in the i-th MC replica.

This method allows the exploration of the distribution of possible outcomes for expected values and uncertainties on F_L

Note: for better visibility, only F_L points with an absolute uncertainty less than 0.5 will be displayed.


F_L or F_2
1.76
0.38
-1
Q² = 2 GeV²
Q² = 2.7 GeV²
Q² = 3.5 GeV²
Q² = 4.5 GeV²
Q² = 6.5 GeV²
Q² = 8.5 GeV²
Q² = 10 GeV²
Q² = 12 GeV²
Q² = 15 GeV²
Q² = 18 GeV²
Q² = 22 GeV²
Q² = 27 GeV²
Q² = 35 GeV²
Q² = 45 GeV²
Q² = 60 GeV²
Q² = 70 GeV²
Q² = 90 GeV²
Q² = 120 GeV²
Q² = 150 GeV²
Q² = 200 GeV²
Q² = 250 GeV²
Q² = 300 GeV²
Q² = 400 GeV²
Q² = 500 GeV²
Q² = 650 GeV²
Q² = 800 GeV²
Q² = 1000 GeV²
Q² = 1200 GeV²
Q² = 1500 GeV²
Q² = 2000 GeV²
Q² = 3000 GeV²
10⁻³
1
x
F_L, HERA + EIC, 2 beam energies
F_2, HERA + EIC, 2 beam energies
HERAPDF2.0 NNLO
F_L, H1 2013
F_2, H1 2013
F_L, ZEUS 2014
F_2, ZEUS 2014
HERA + EIC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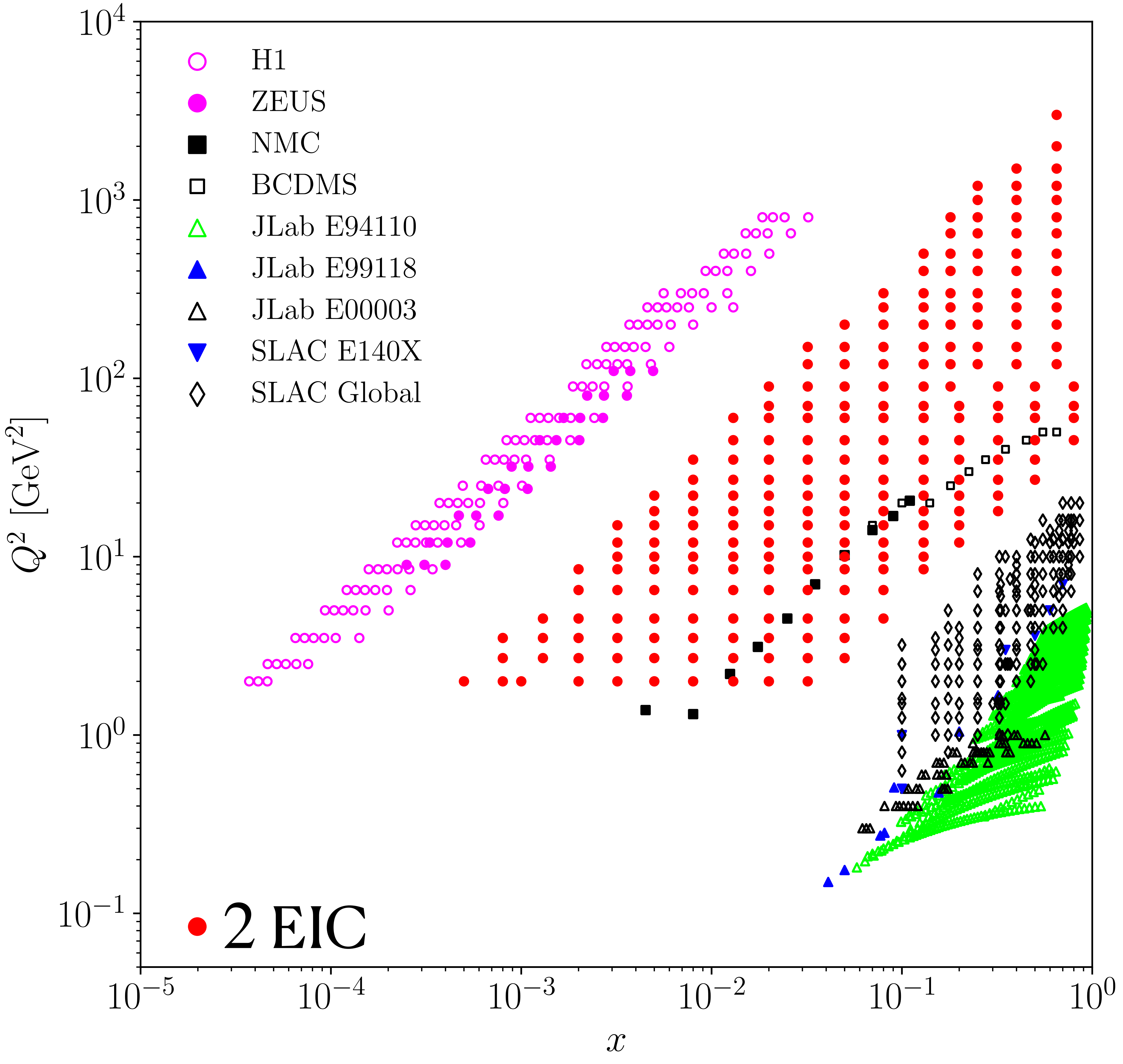
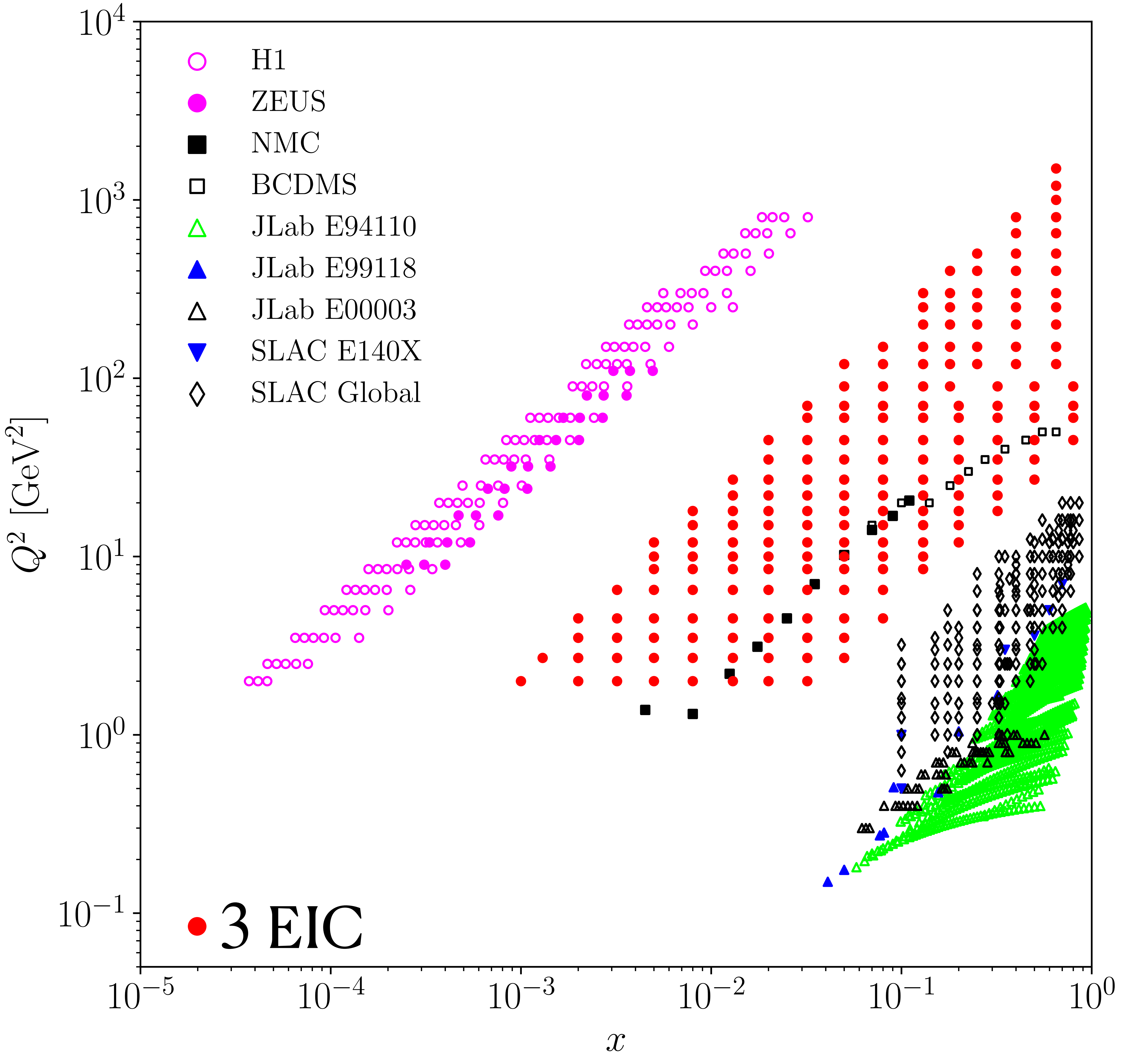
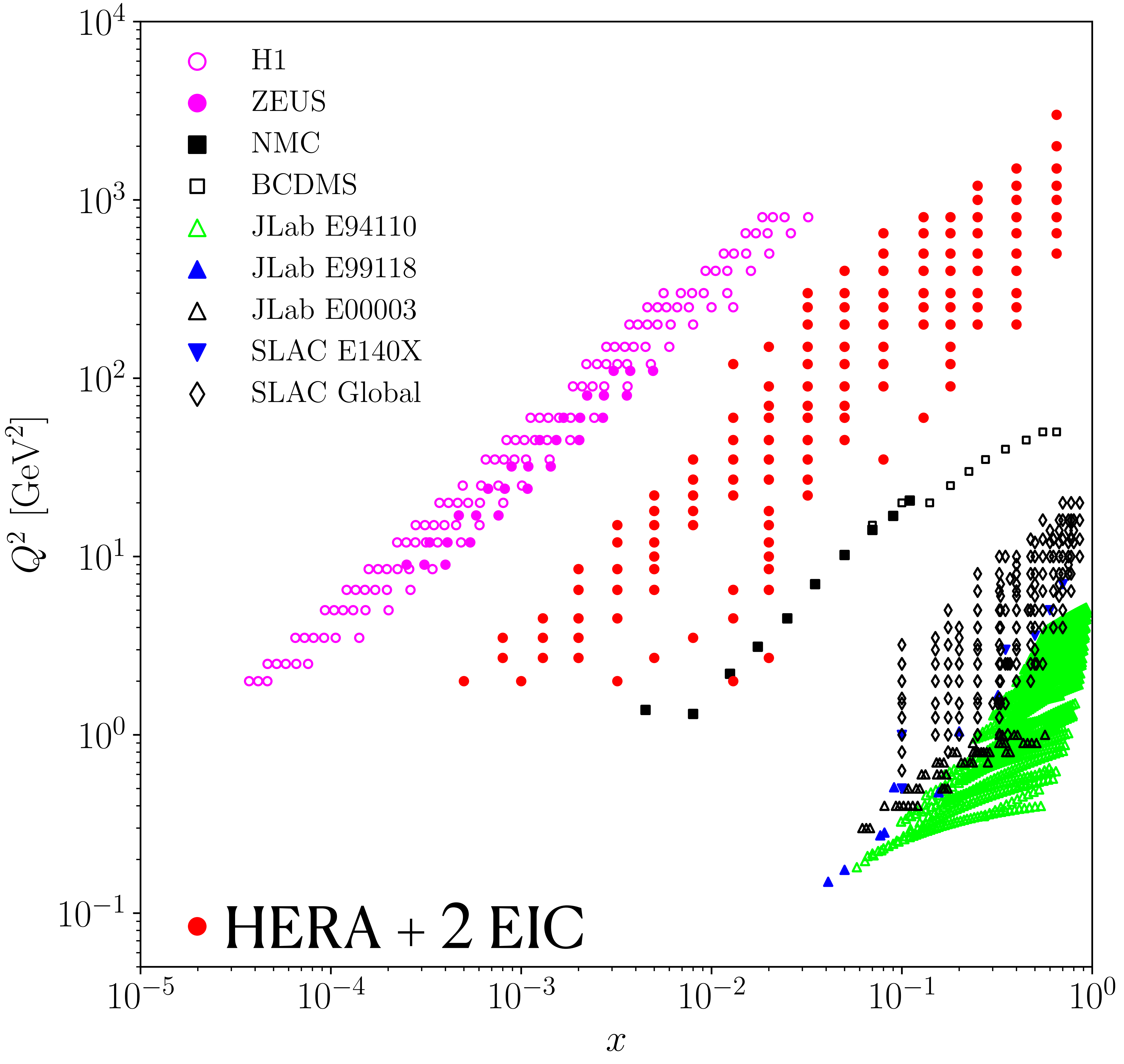
10⁻³
1
x
F_L, EIC only, 2 beam energies
F_2, EIC only, 2 beam energies
HERAPDF2.0 NNLO
F_L, H1 2013
F_2, H1 2013
F_L, ZEUS 2014
F_2, ZEUS 2014
EIC

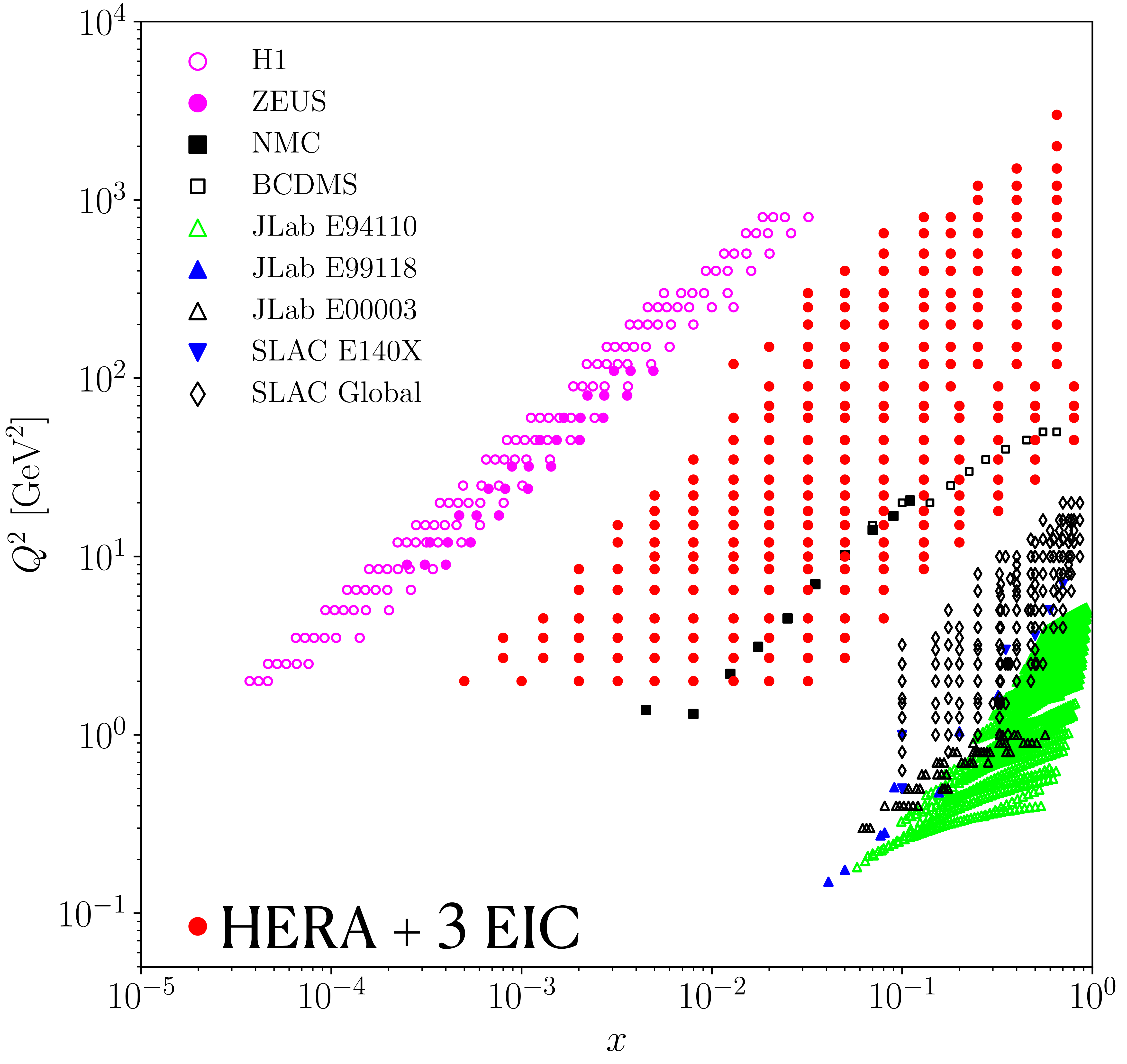
Phase space coverage for different scenarios





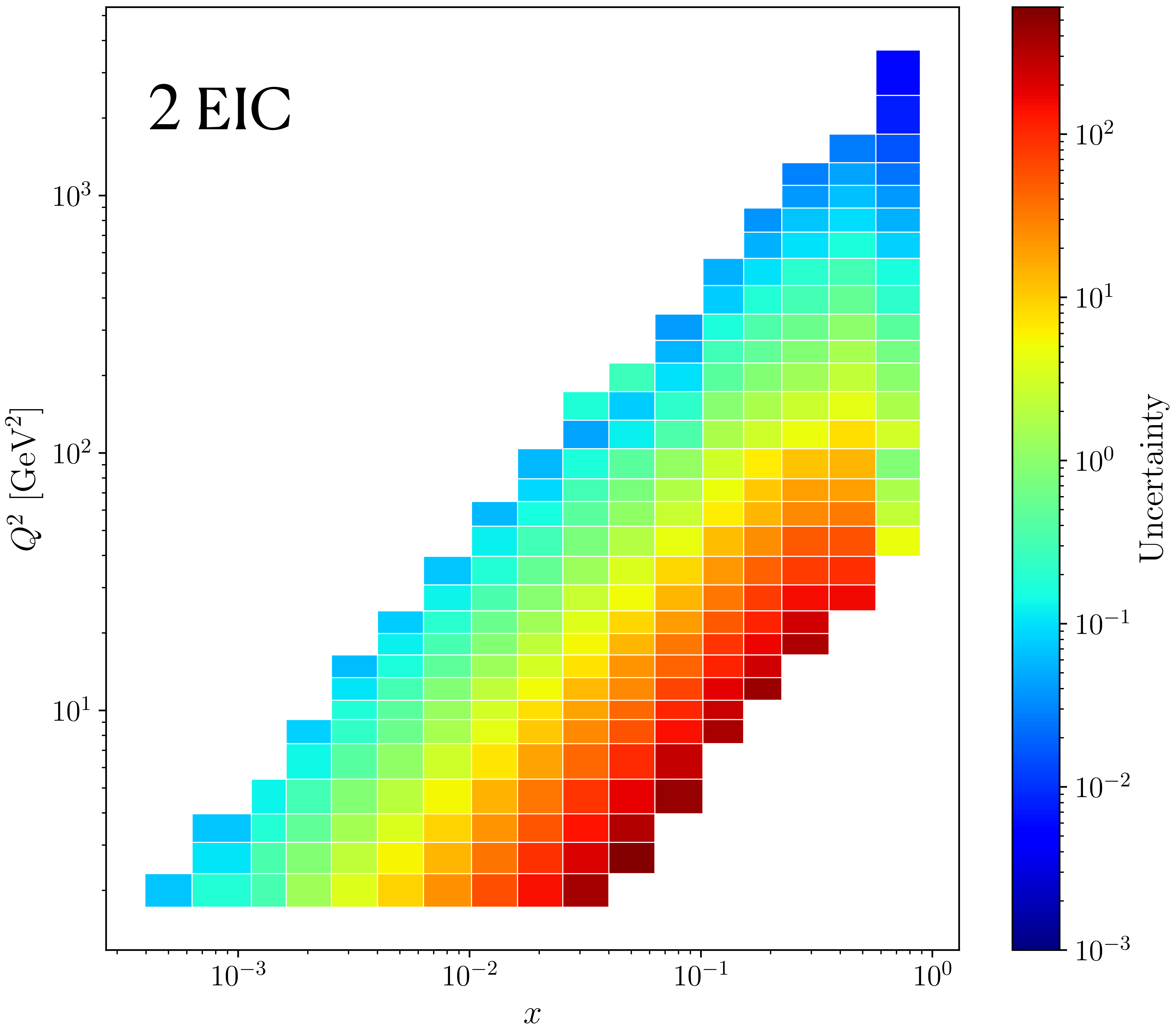
Phase space coverage for different scenarios

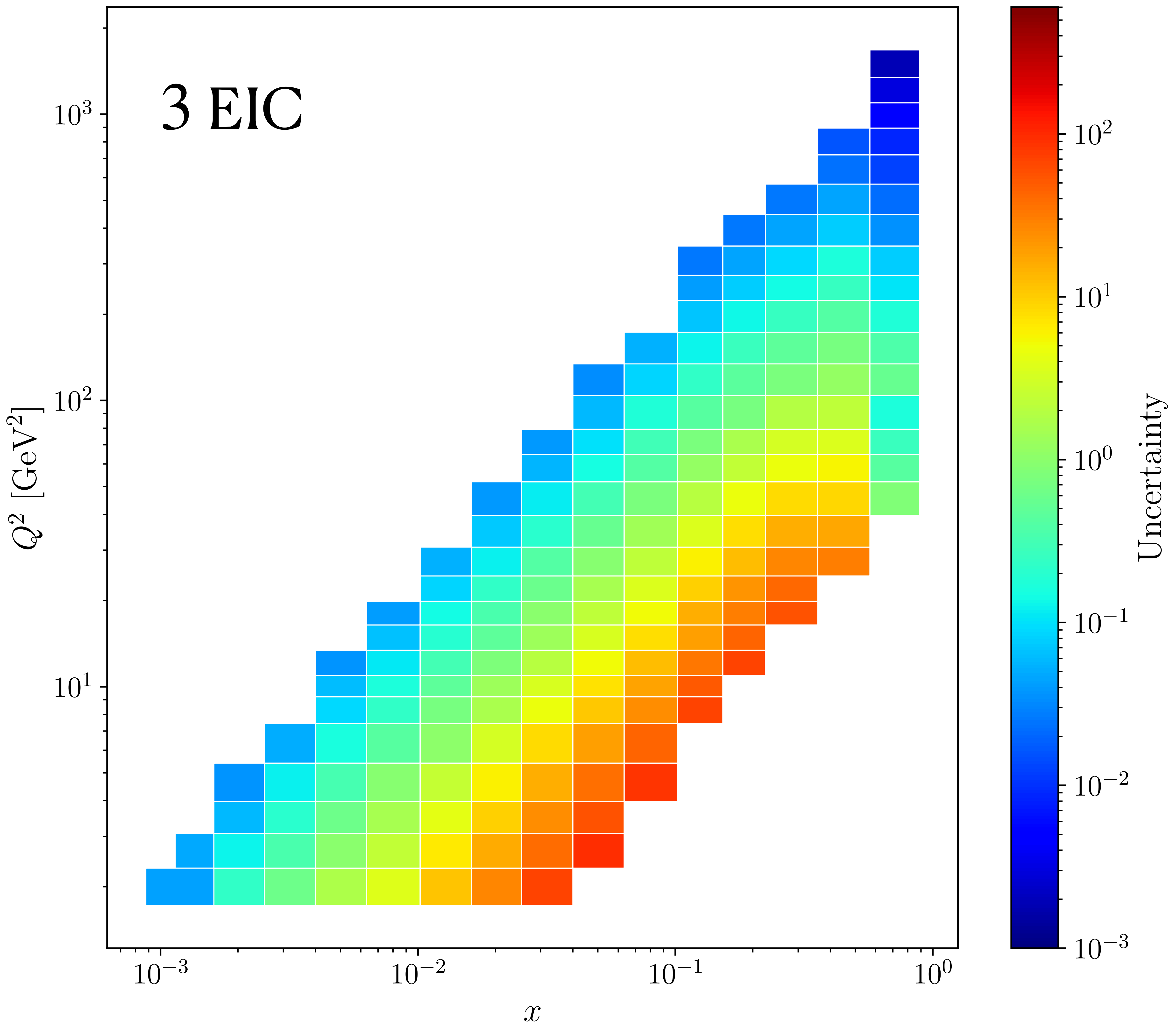




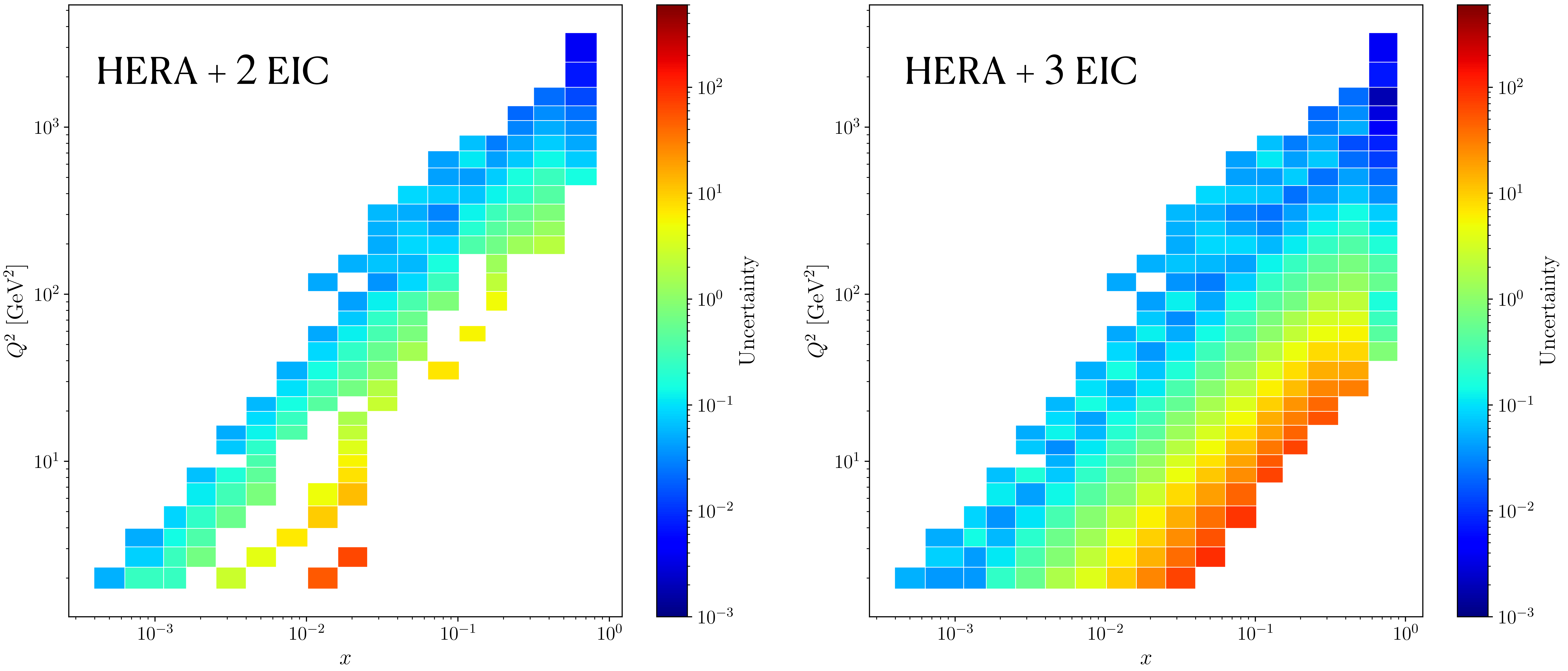
Uncertainties on F_L

EIC only results

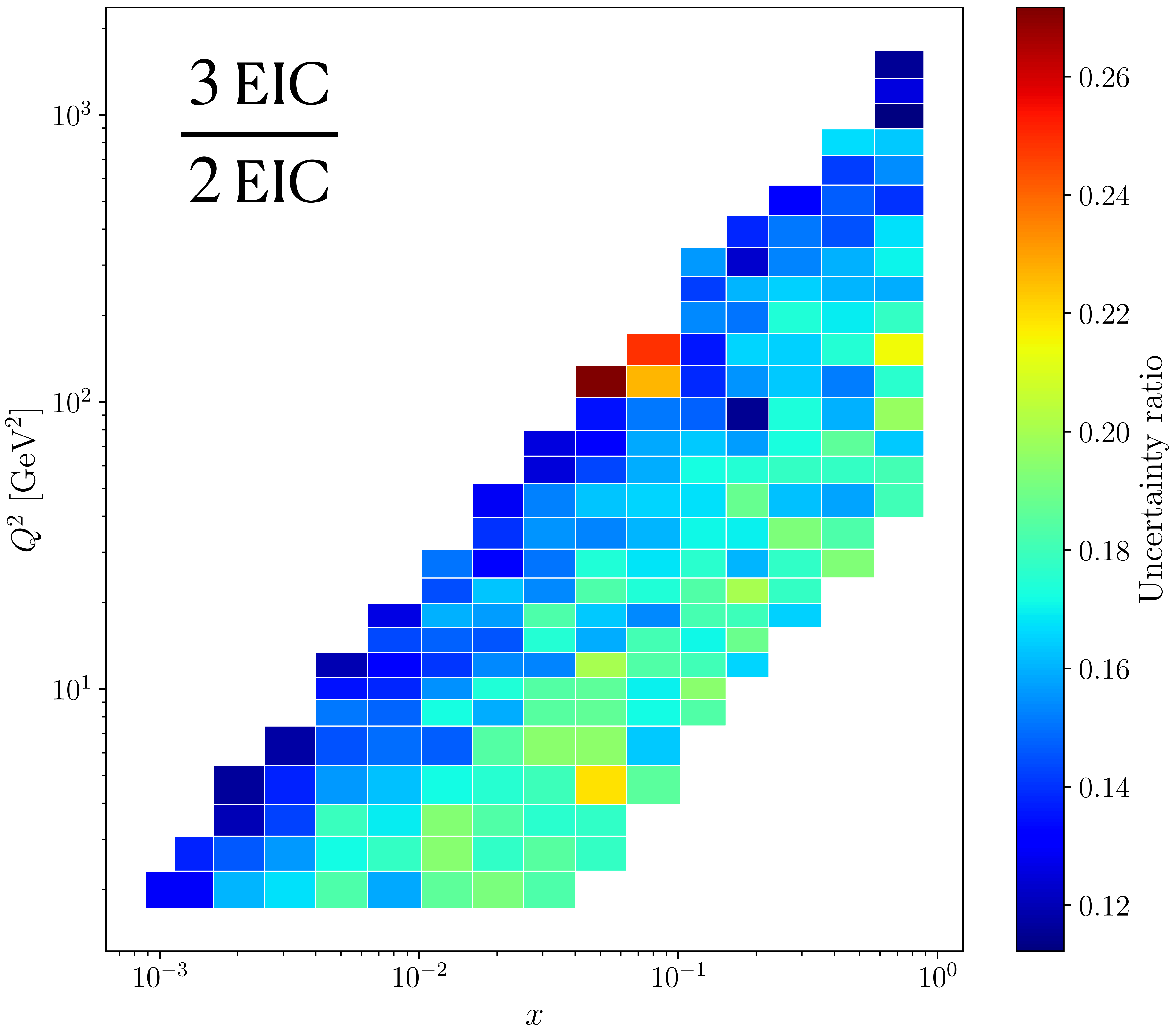


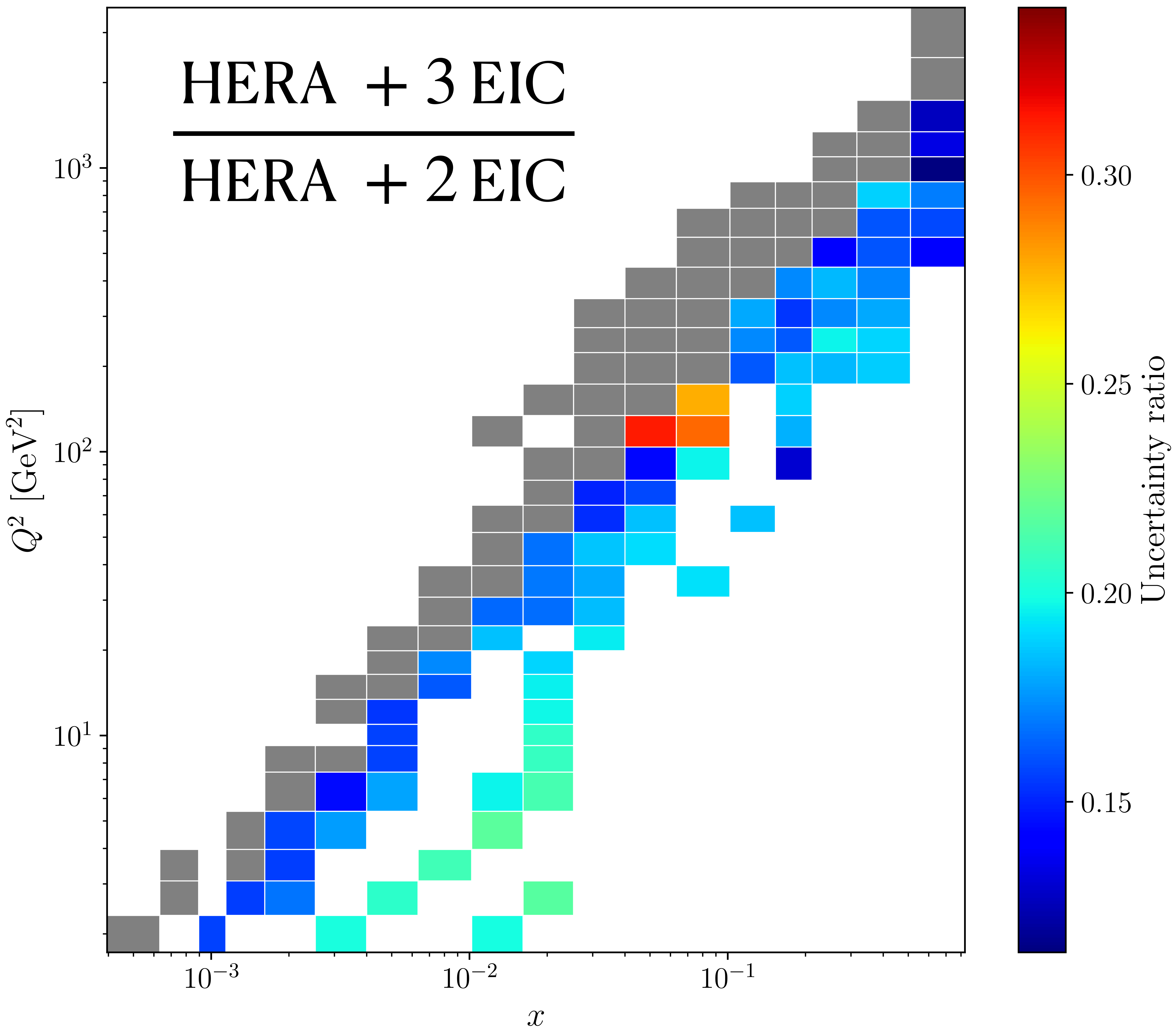


HERA + EIC results



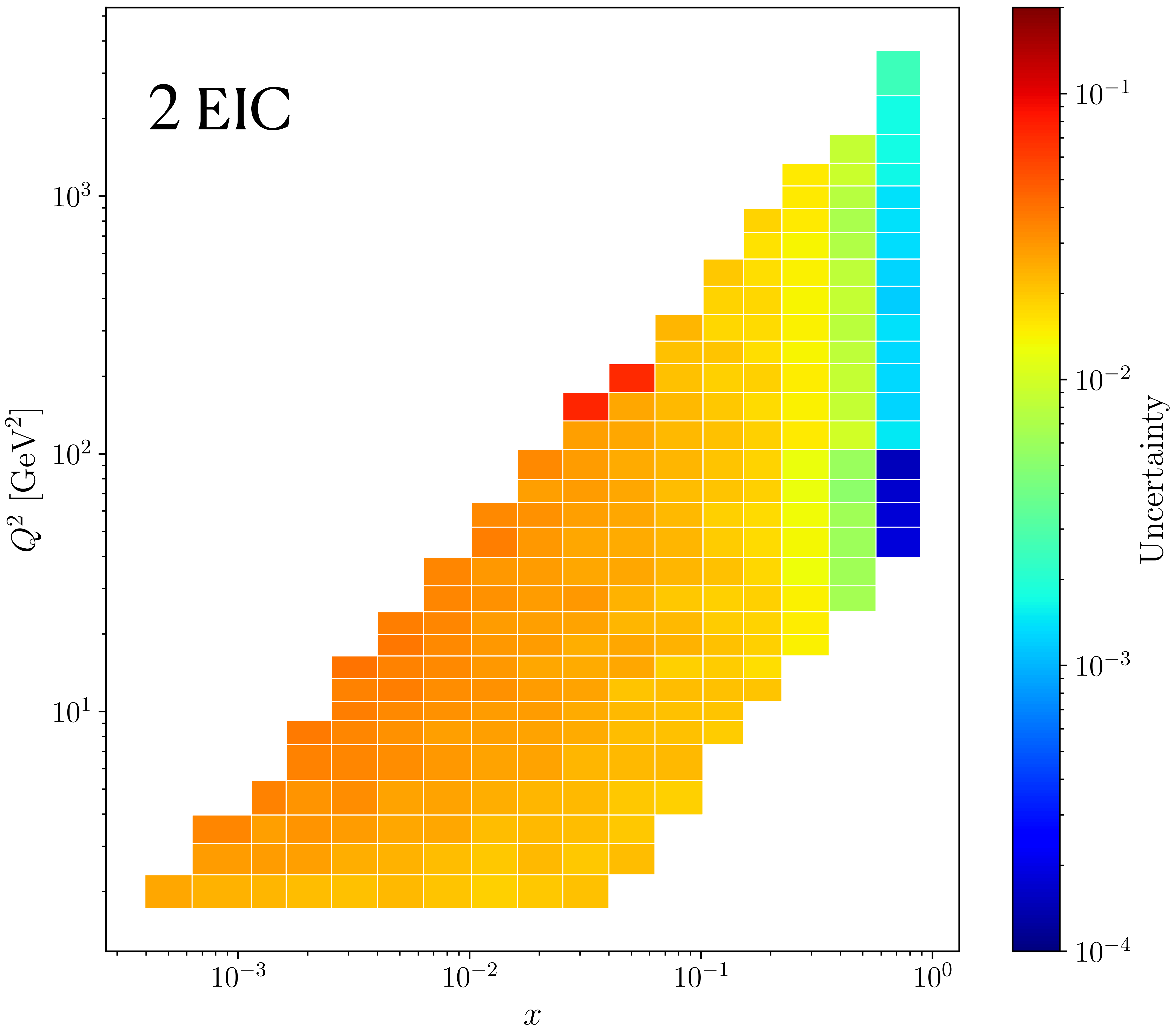
Uncertainty ratios

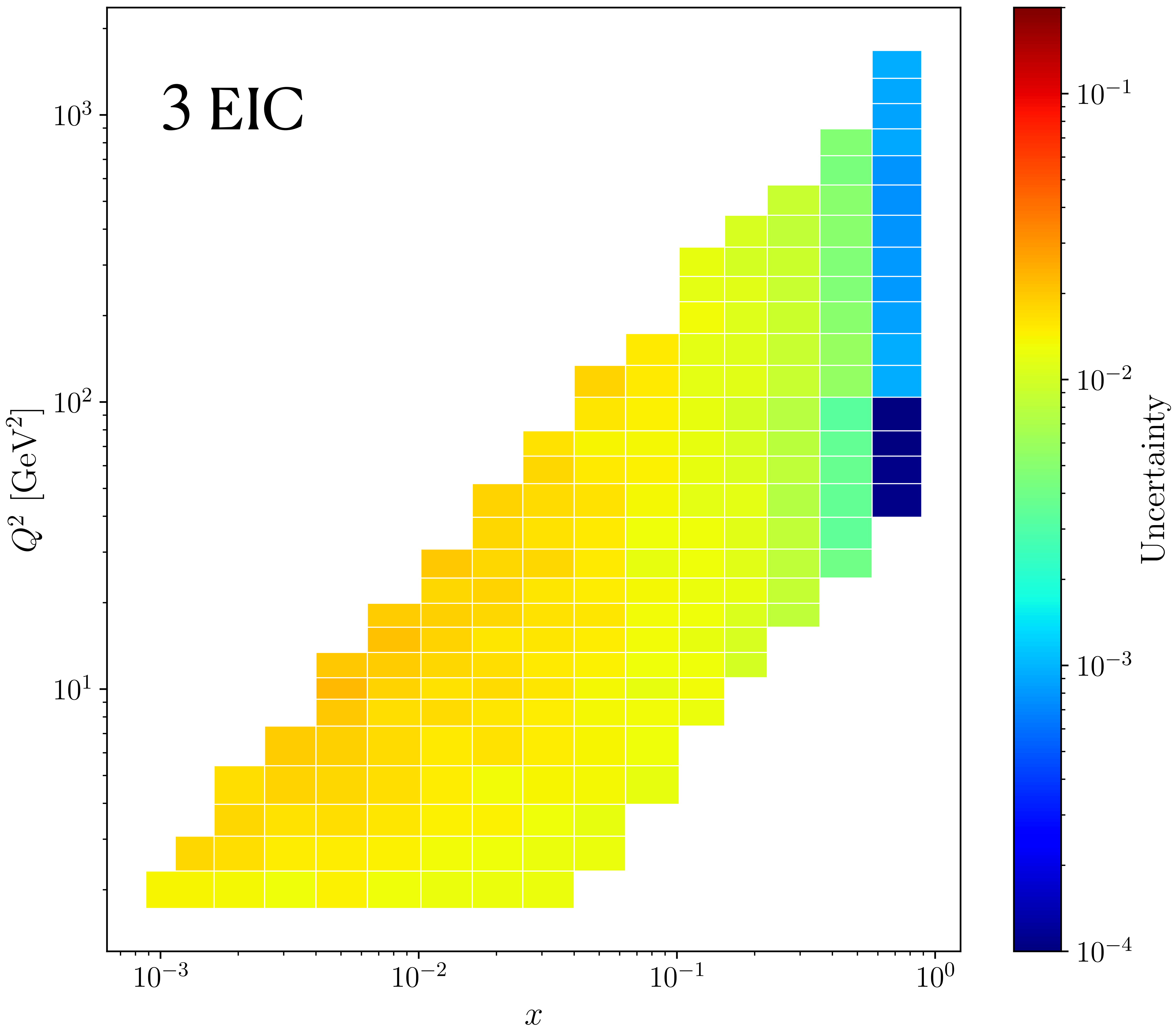




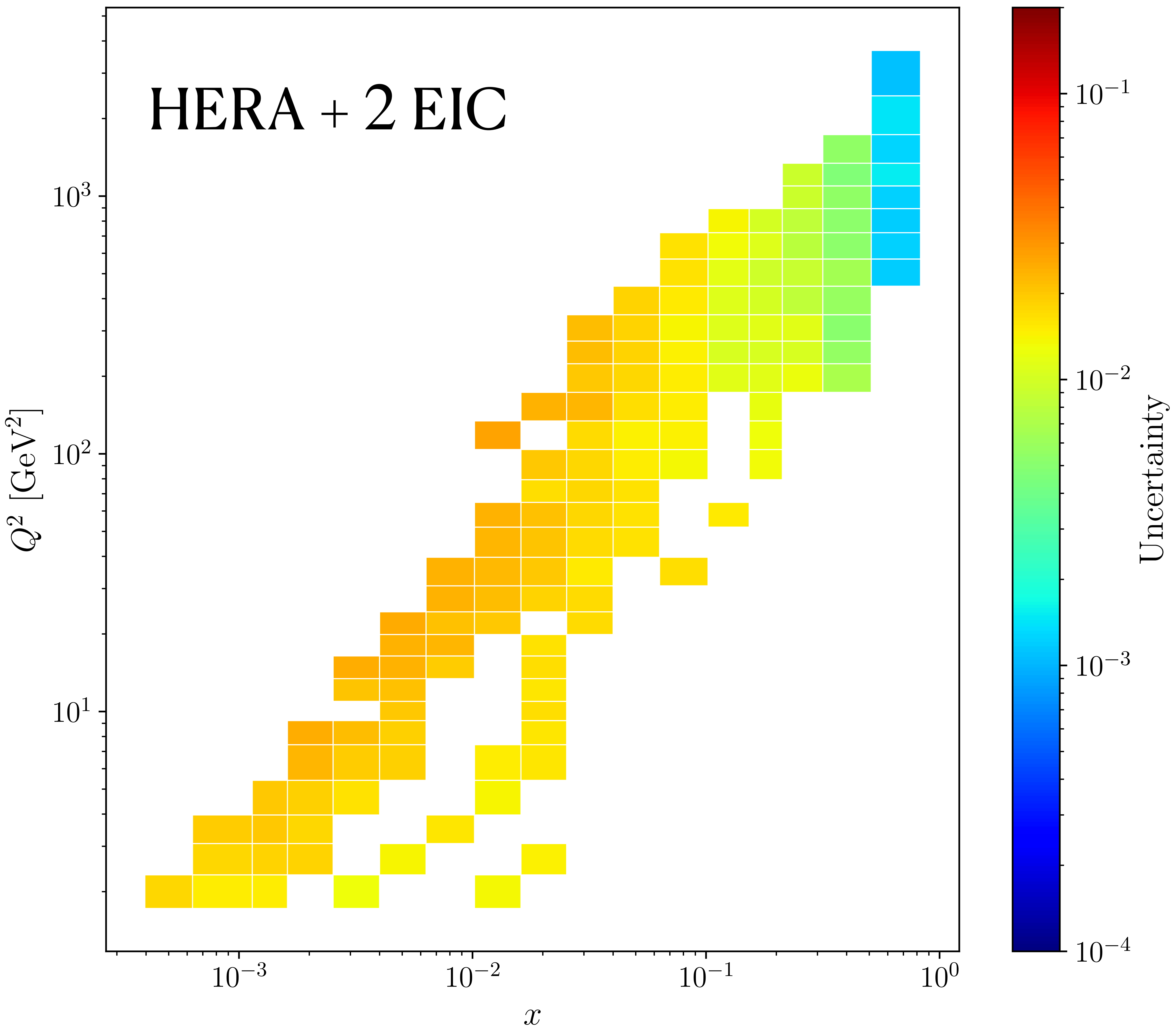
Uncertainties on F_2

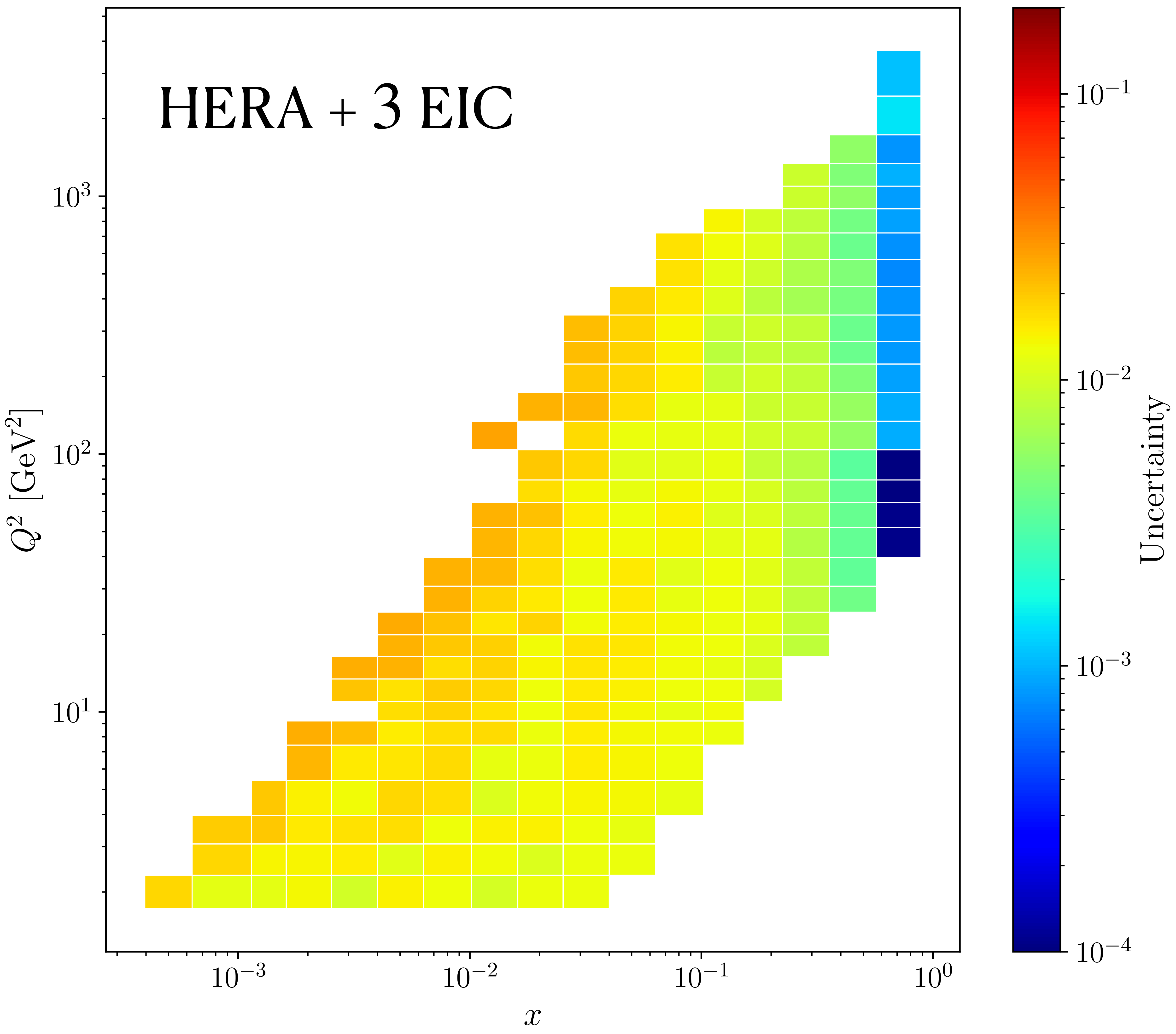
EIC only results



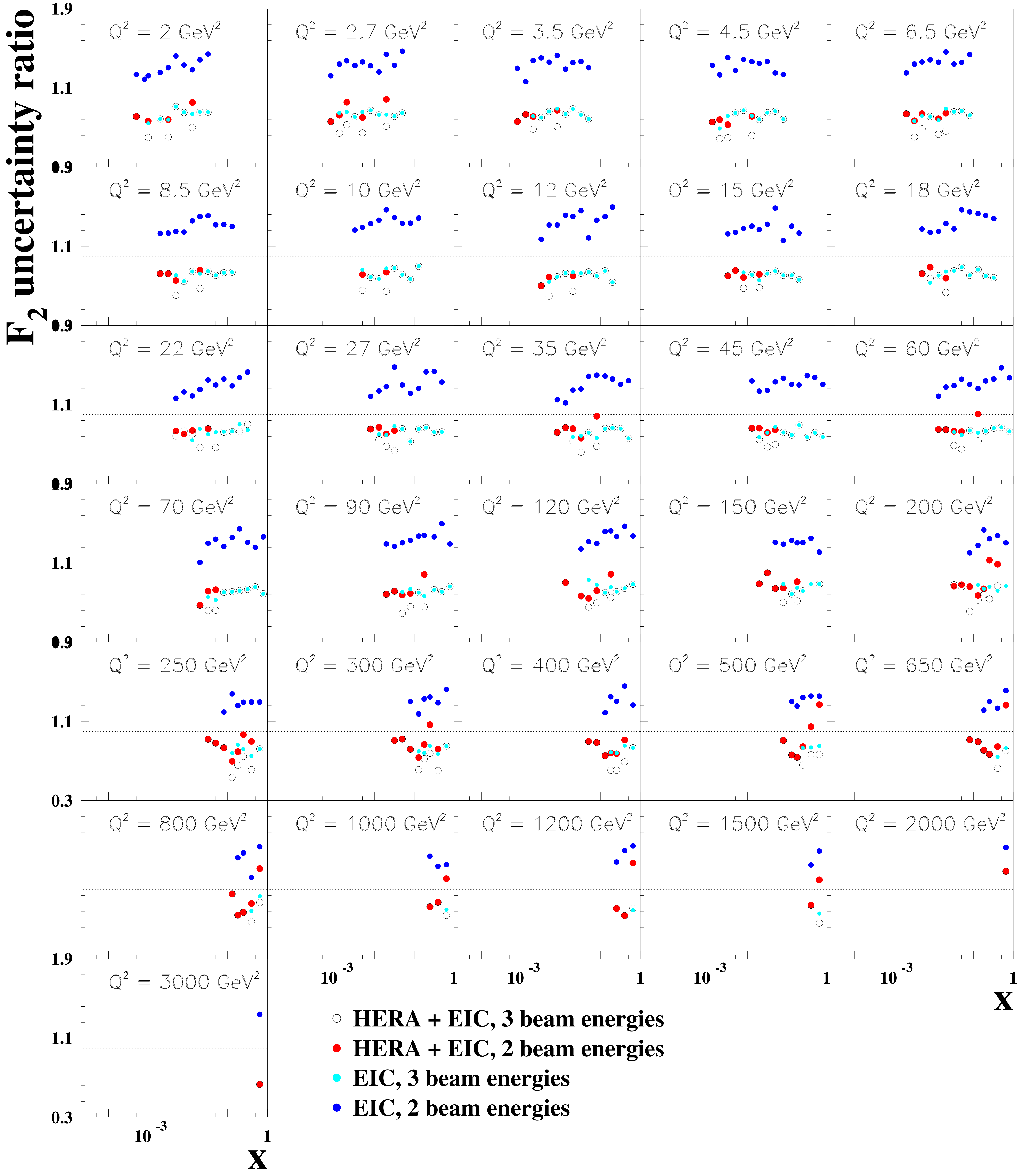


HERA + EIC results



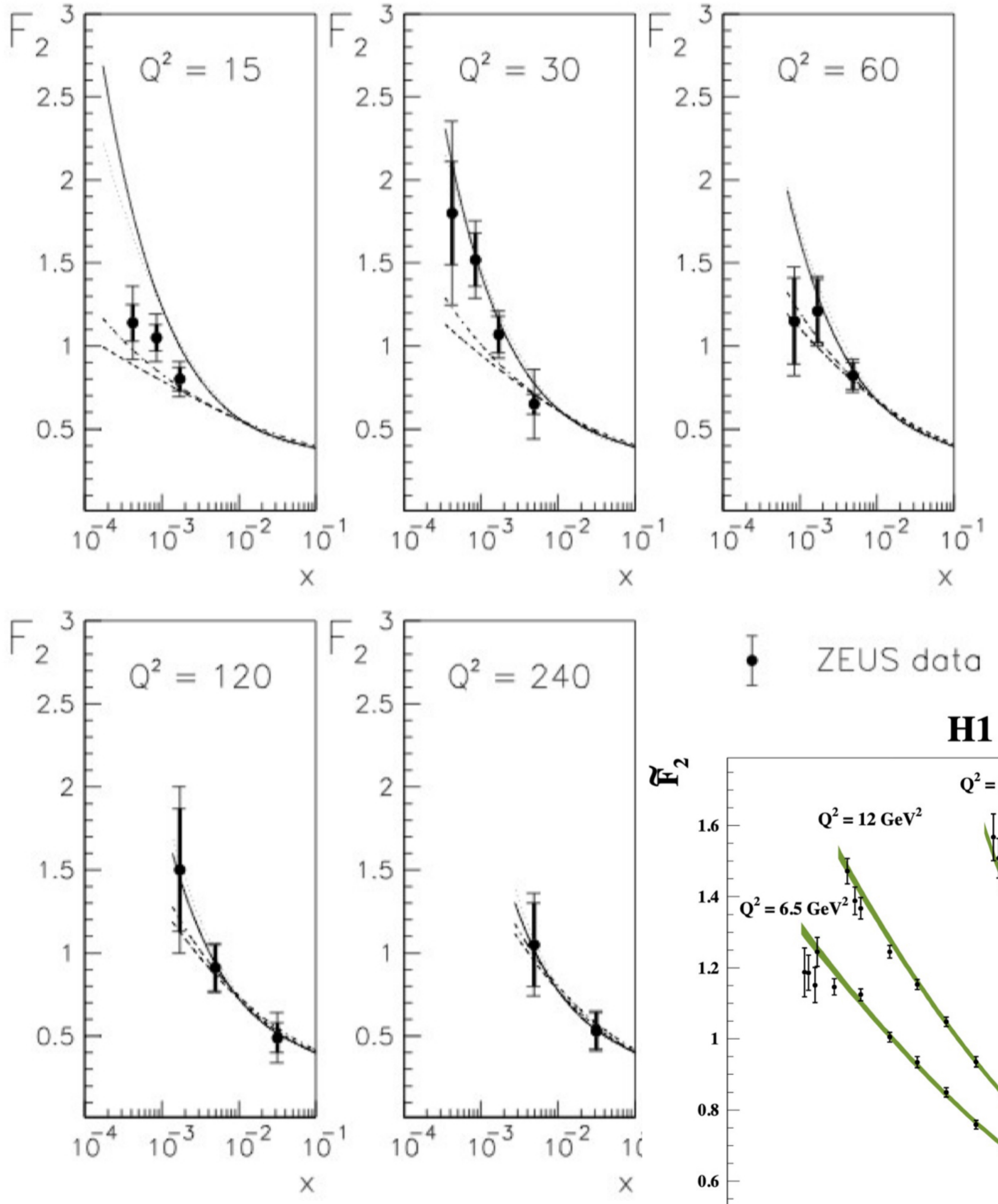


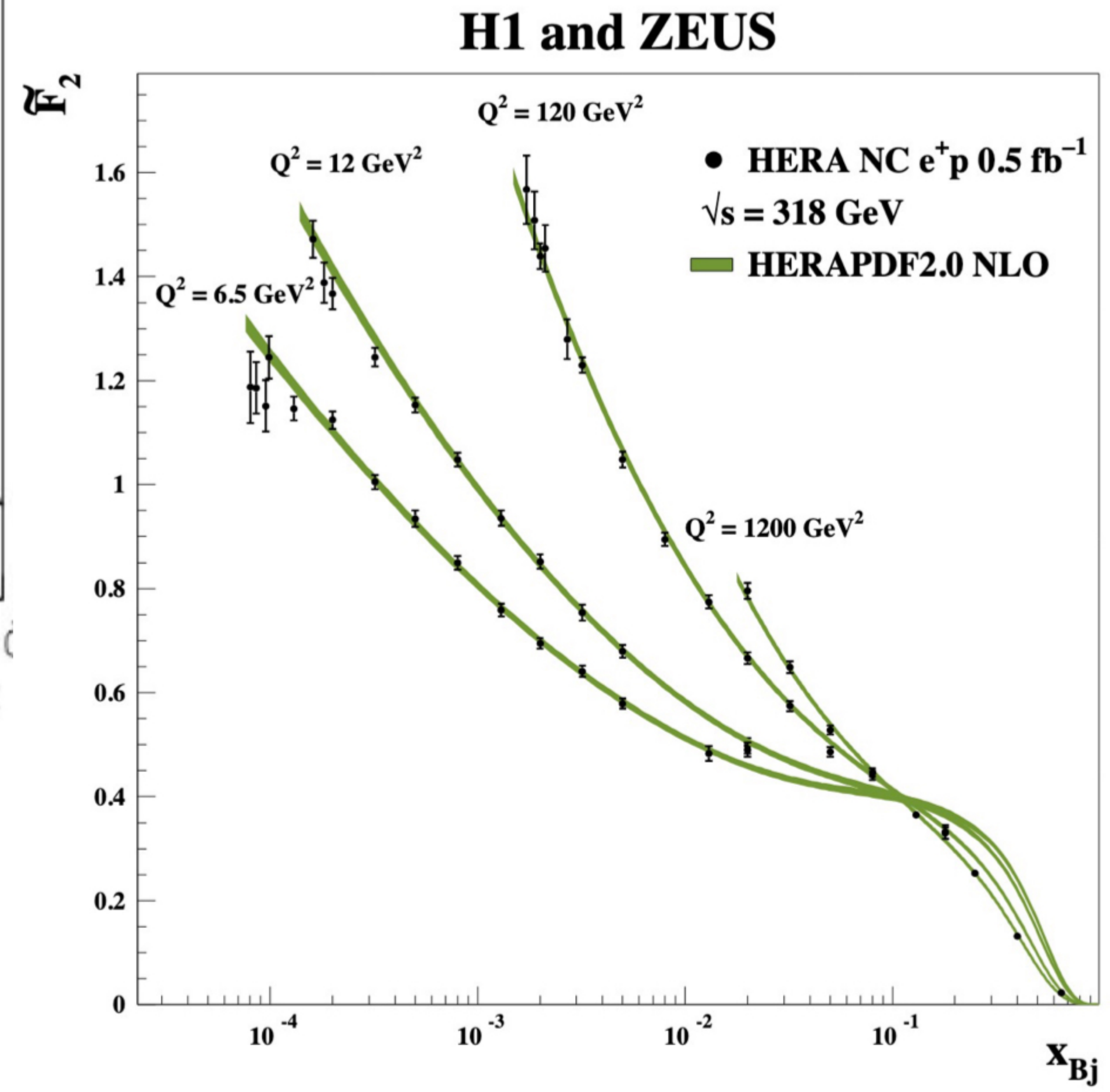
Uncertainty ratios

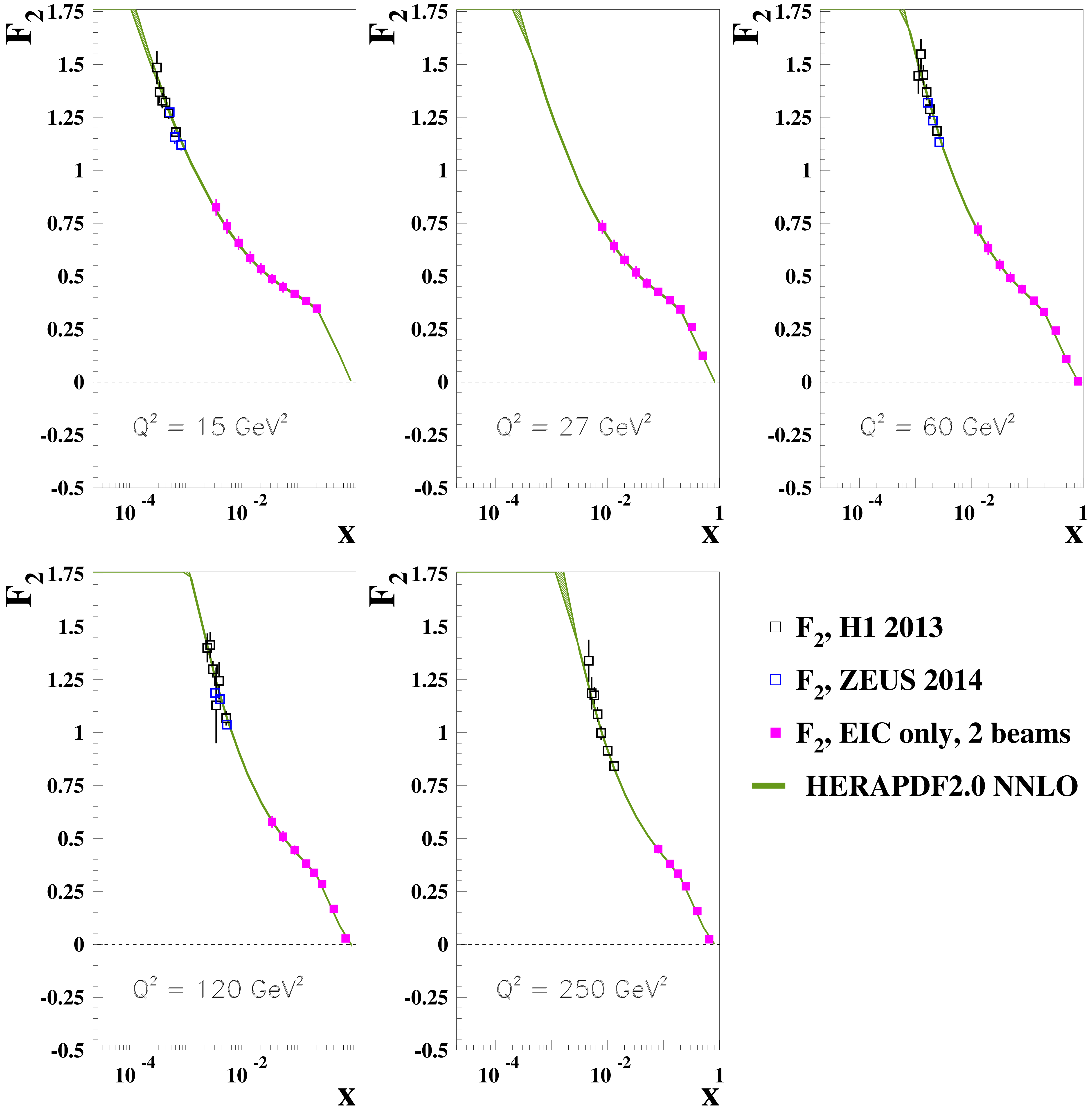


- At HERA, the uncertainties on F_2 were obtained as the relative total uncertainties of the cross sections using various models to determine the contribution of F_L
- We are presenting a completely model independent extraction of F_2 using the Rosenbluth separation technique
- There are no model uncertainties and the only uncertainties that play a role in the extraction are those on the cross sections using

Comparing F_2 among HERA and EIC







Collinear PDFs

HERAPDF parametrisation

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

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v} x^2\right)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}}(1 + D_{\overline{U}} x)$$

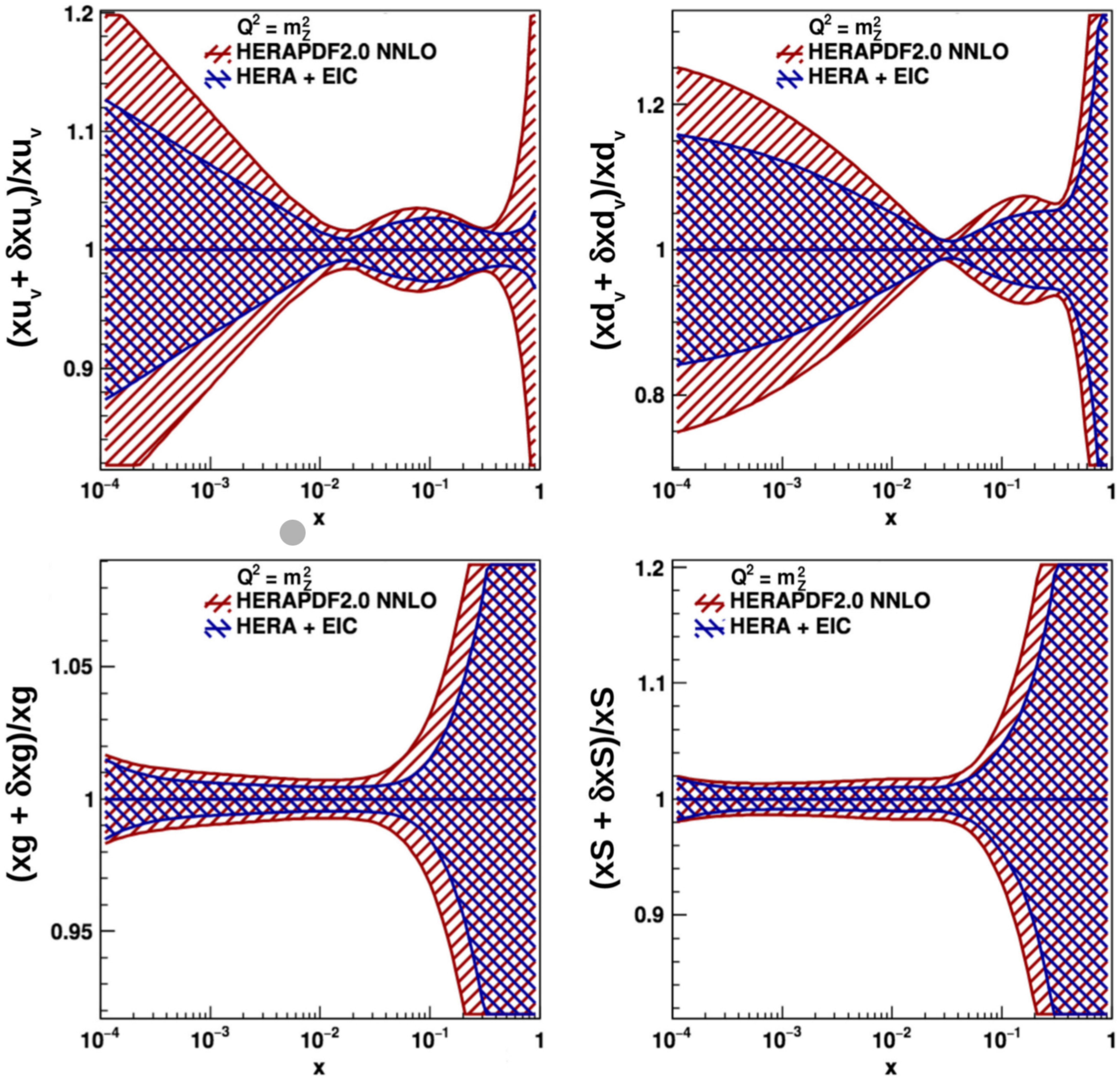
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}$$

Additional constraints:

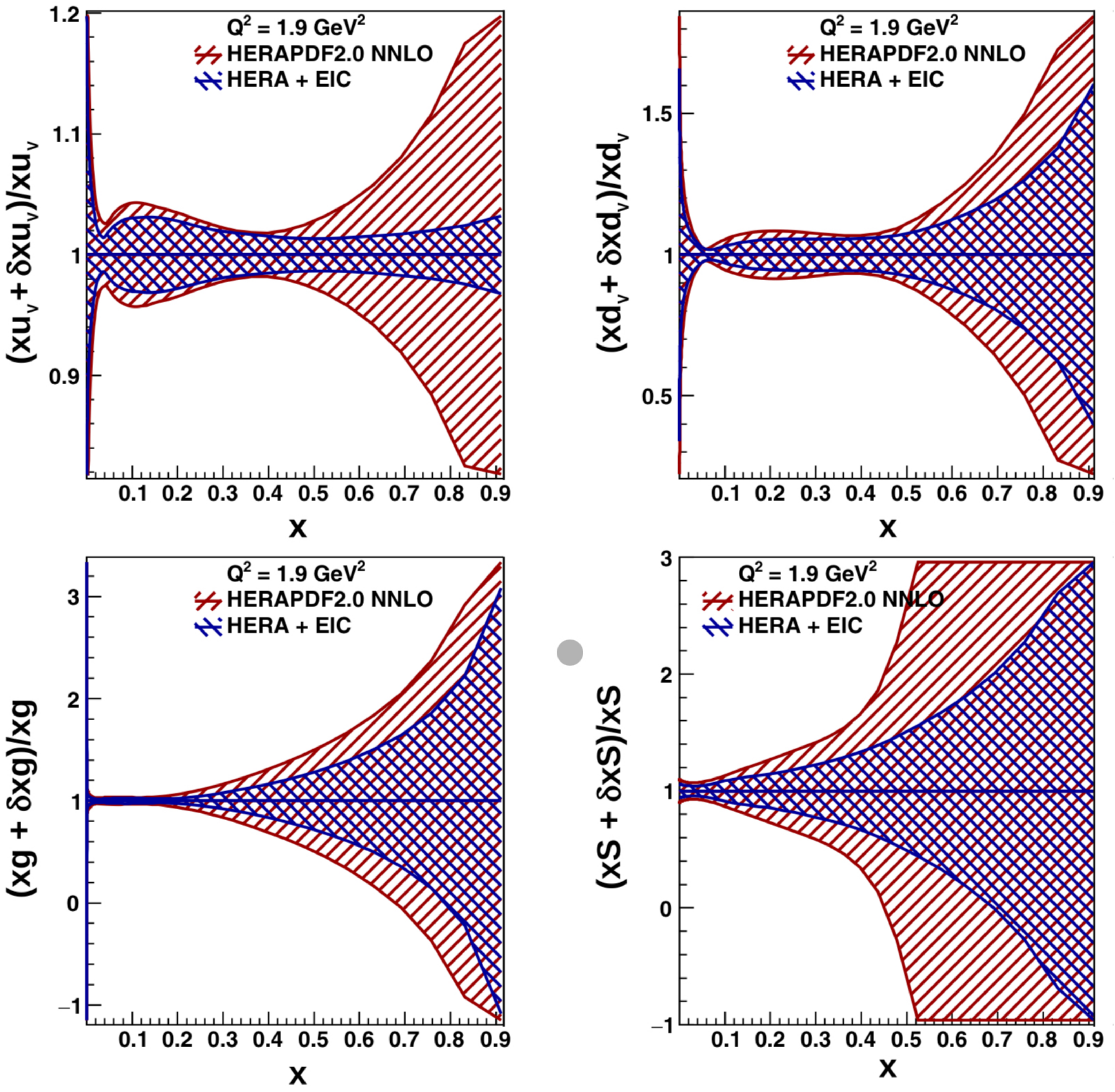
- A_{u_v}, A_{d_v} and A_g are constrained by the quark-number sum rules and momentum sum rule
- $B_{\overline{U}} = B_{\overline{D}}$
- $x\bar{s} = f_s x\overline{D}$, at initial scale $f_s = 0.4$
- Charm and beauty masses from HERA HF data

EPJC (2015) 75, 580

Results for full luminosity and 5 energies

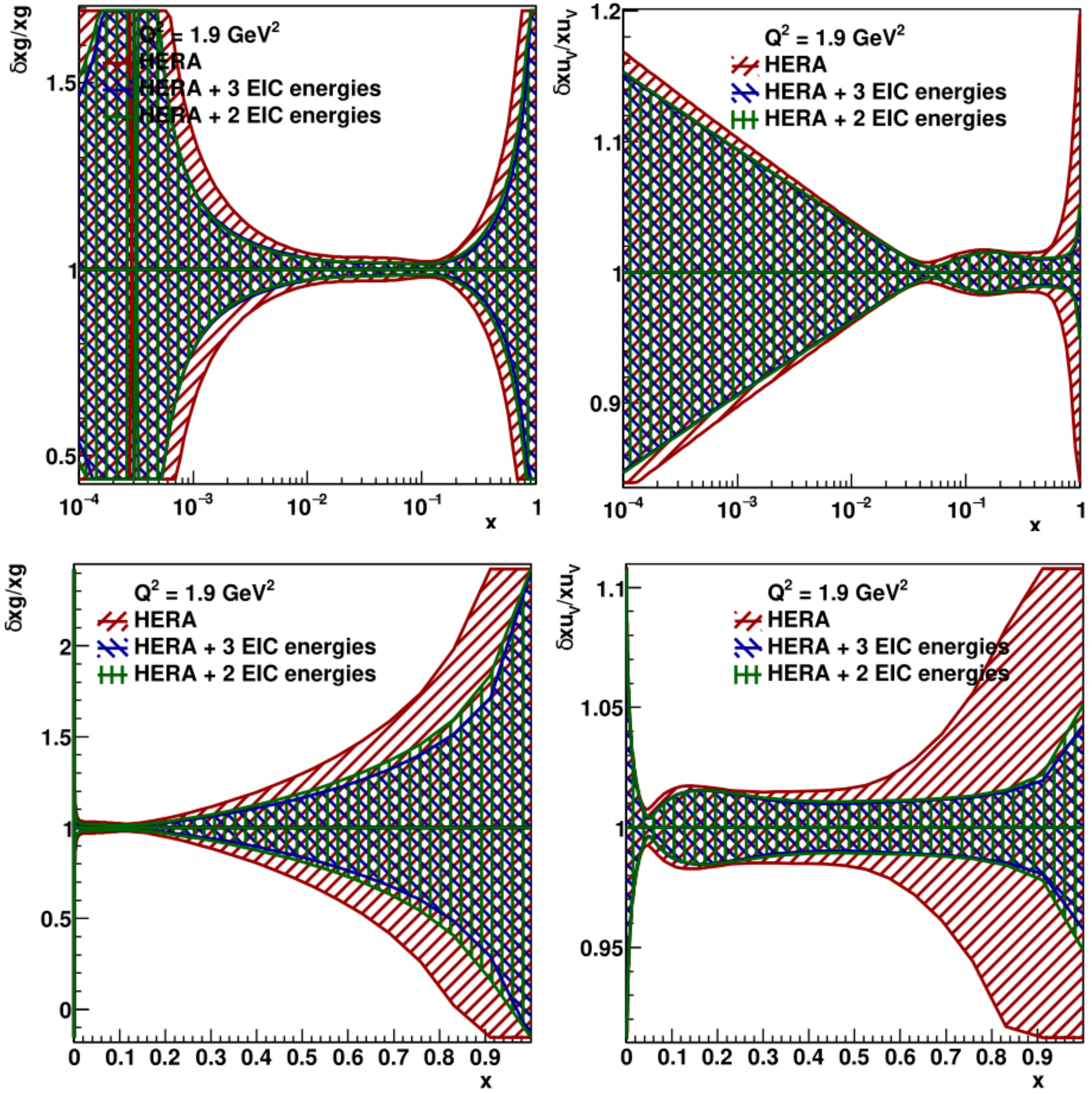


PRD 109 (2024) 5, 054019, arXiv: 2309.11269



PRD 109 (2024) 5, 054019, arXiv: 2309.11269

Prospects for the early running

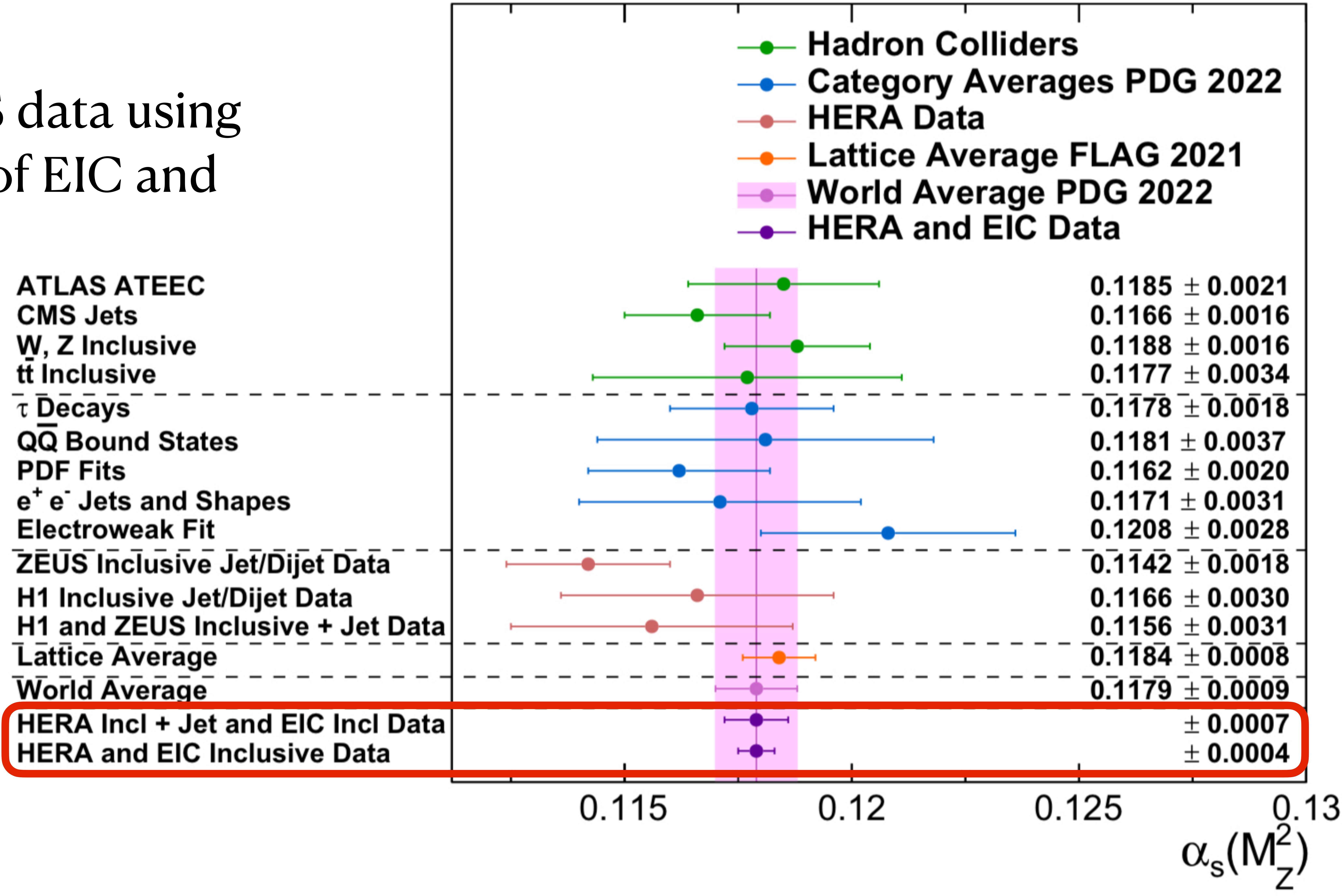


- $W > 10\,\mathrm{GeV}$
- Large improvement for $x > 0.1$ for gluons and up-valence quark
- Modest improvement for low-to-mid x for the up-valence quark and gluons
- Minor improvement for the middle x values for total sea
- No significant improvement for the down-valence quark
- There is a very small difference between the results with 2 and 3 beams

Strong coupling

Extraction of the strong coupling with HERA + EIC

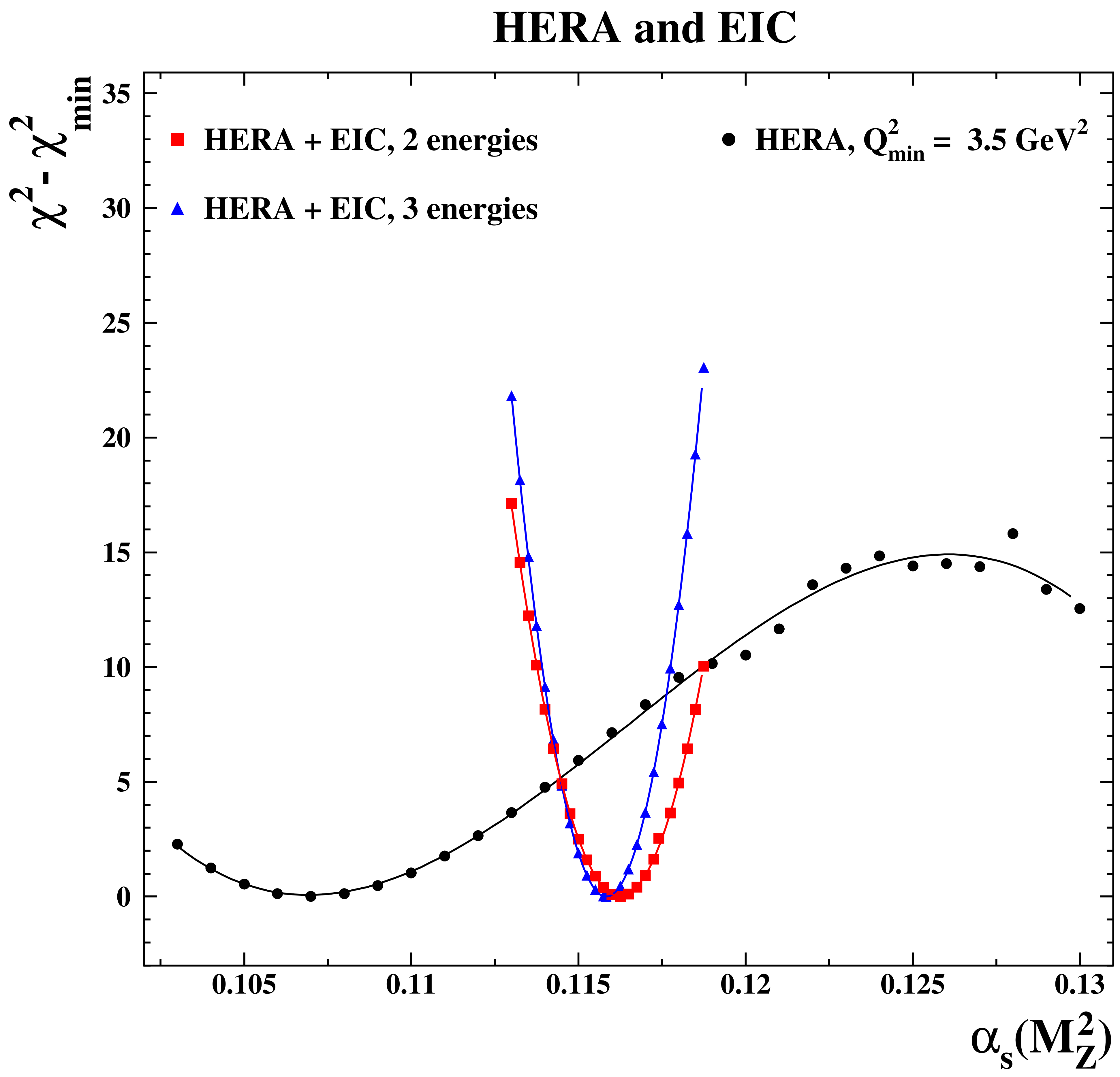
Results with only inclusive DIS data using the 5 nominal configurations of EIC and full luminosity



EPJC (2023) 83: 1011, arXiv: 2307.01183

Early running prospects for the strong coupling

- 2 beam energies: $\alpha_s(M_Z^2) = 0.1162 \pm 0.0008\,(\mathrm{exp})$
- 3 beam energies: $\alpha_s(M_Z^2) = 0.1158 \pm 0.0006\,(\mathrm{exp})$



- Parametrisation and model uncertainties are expected to be very small
- The method for the theoretical uncertainties remains uncertain
- The result with 2 energies is already very precise and consistent with the present α_s determinations, further improved by adding the third energy

Conclusions and final remarks

- EIC has great potential to measure the proton structure functions F_L and F_2 and the strong coupling with unprecedented precision already in the early-running phase
- This precision can be further improved by adding one additional beam configuration to the two that have been planned
- We still have to see if the luminosity that can be achieved during the early running is higher than 1 fb^{-1}. If so, our results could be further improved
- Systematics might be lower than what we have considered, but again, this is yet to be confirmed once the experiment is running, and could benefit our current calculations

Backup

Given two points $(x_1, y_1 + \sigma_1)$ and $(x_2, y_2 + \sigma_2)$, the slope of the line that passes through them is:

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

and the intercept, written in terms of the original coordinates, is given by:

$$b = \frac{y_1 x_2 - y_2 x_1}{x_2 - x_1}$$

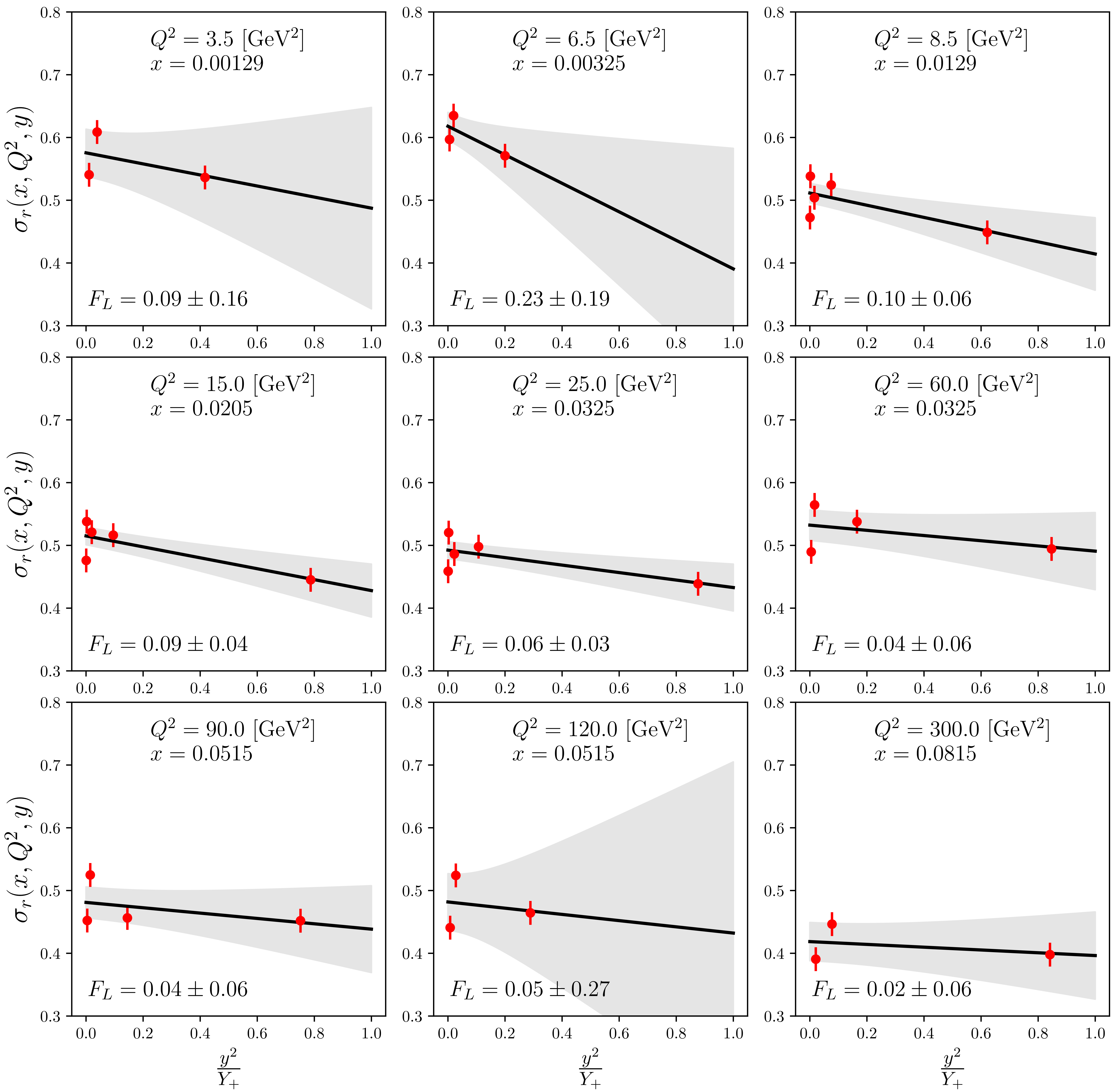
The uncertainties in both can be calculated using the following formula:

$$\delta f(a, b) = \sqrt{\left(\frac{\partial f}{\partial a}\right)^2 (\delta a)^2 + \left(\frac{\partial f}{\partial b}\right)^2 (\delta b)^2}$$

which then allows the calculation fo the uncertainty on m and b as:

$$\delta m = \frac{\sqrt{\sigma_1^2 + \sigma_2^2}}{|x_2 - x_1|} \qquad \delta b = \frac{\sqrt{x_2^2 \sigma_1^2 + x_1^2 \sigma_2^2}}{|x_2 - x_1|}$$

Example fits



- Each point comes from a different c.o.m. energy.
- At least 3 points per (x, Q^2) bin are quivered to attempt the extraction of F_L.
- The point with the highest y^2/Y_+ comes from the lowest c.o.m. energy.