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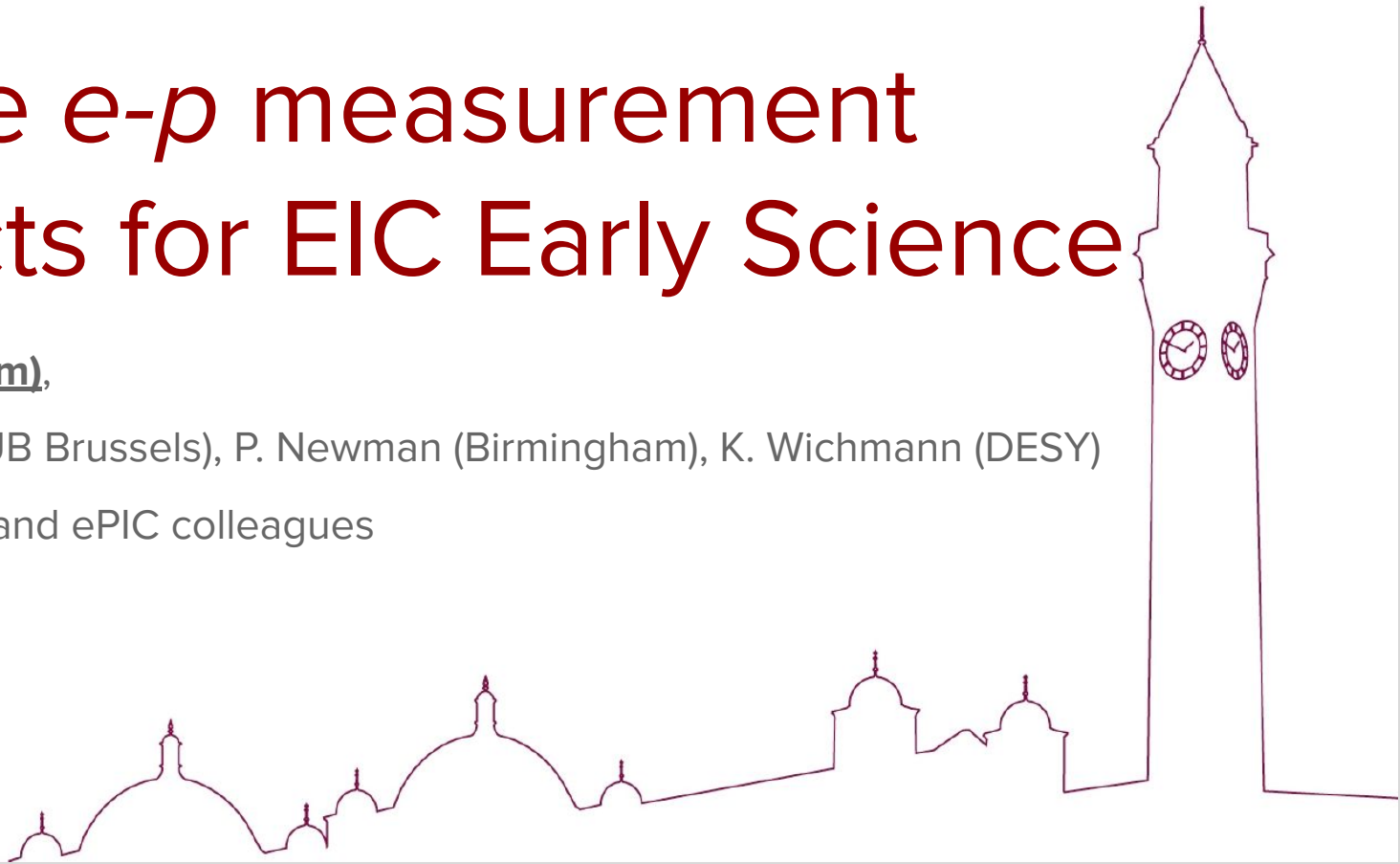
SCHOOL OF
PHYSICS AND
ASTRONOMY

Inclusive e - p measurement prospects for EIC Early Science

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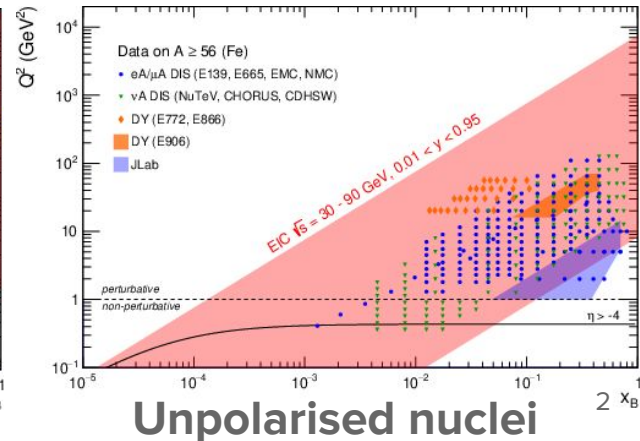
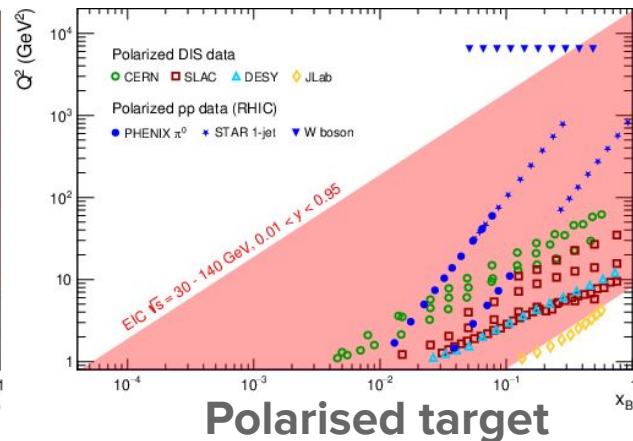
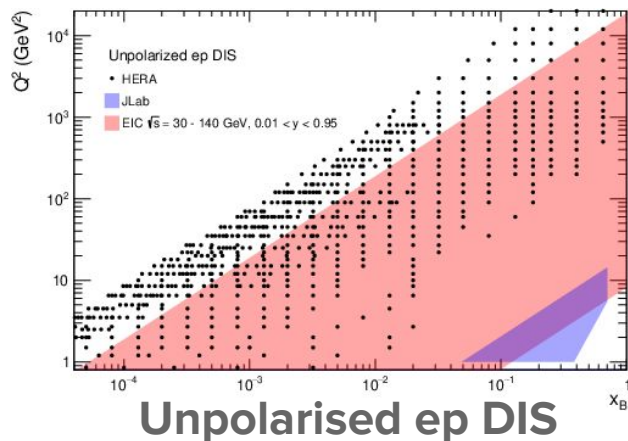
... with thanks to EIC and ePIC colleagues



Inclusive DIS 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

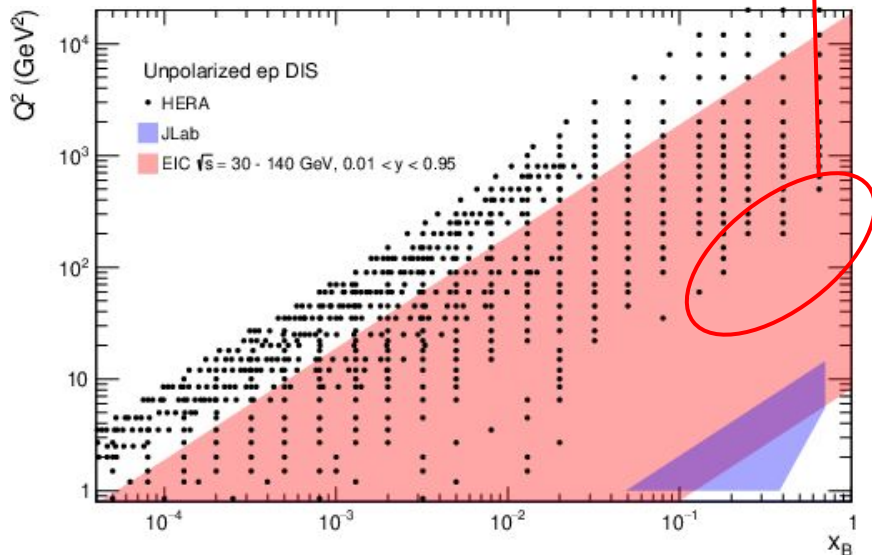
All over a wide range in x and Q^2 !



Inclusive unpolarised ep DIS at the EIC

- Inclusive ep DIS at the EIC bridges gap between fixed-target + HERA kinematics
- Want high precision measurements of inclusive reduced cross section σ_r over a wide range in x and Q^2
- **From σ_r we can determine the proton structure functions, F_2 and F_L**
$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$
- **Measurements of σ_r used in fits to constrain collinear PDFs**

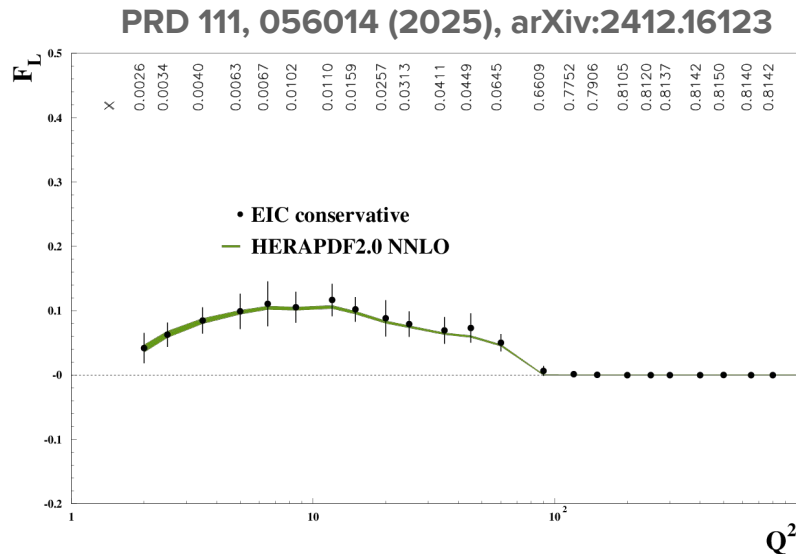
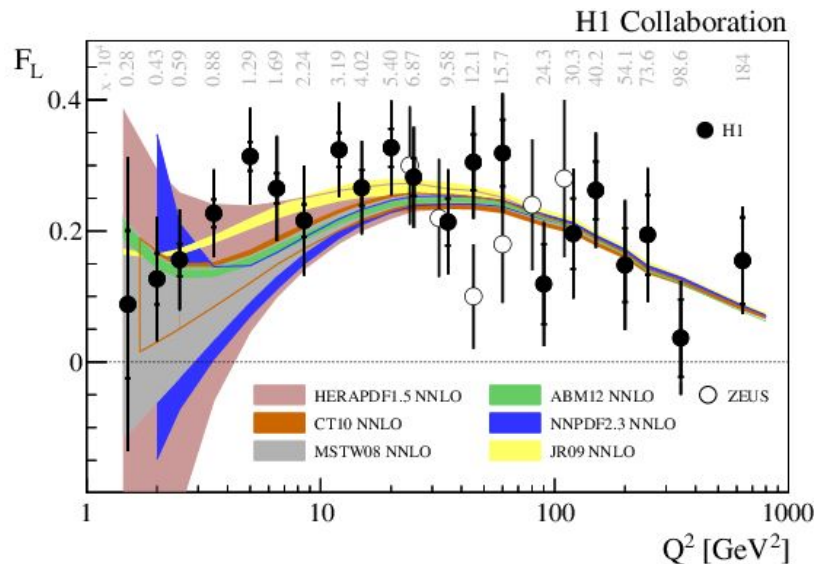
Limited high- x sensitivity for HERA data due to $1/Q^4$ factor in cross section



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 $\sqrt{s}$ over wide range offers a unique opportunity to constrain F_L



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 according to integrated luminosity

- For each pseudo-data point:

- Smearing of pseudo-data performed 1000 times
- Mean and variance calculated for N = 1000

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

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

Structure Functions

Rosenbluth separation method

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

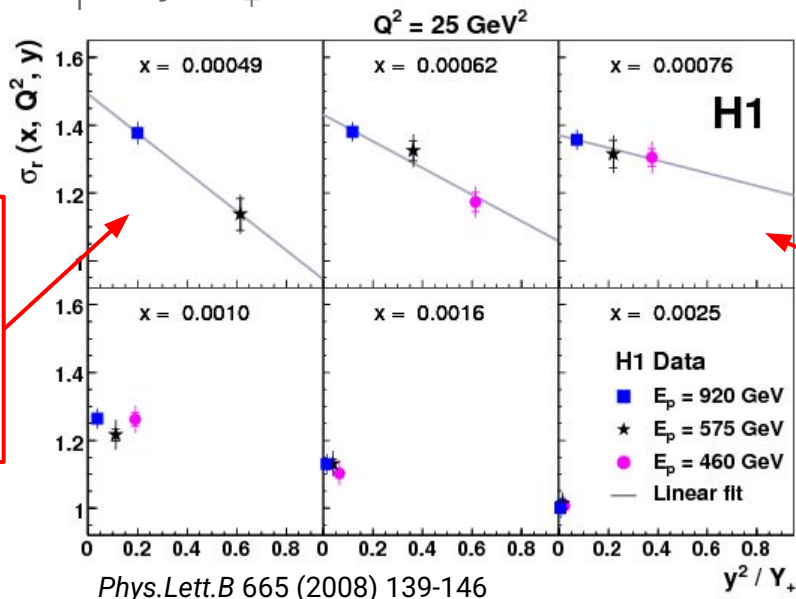
- Linear relation between DIS cross section and structure functions $\rightarrow$ plot σ_r vs y^2/Y_+ !

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

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

y^2/Y_+ changes with $\sqrt{s}$!

2 points needed to calculate slope and intercept



3 points needed for a fit

Options for early science measurements

If we optimise binning scheme to overlap

HERA DIS measurements...

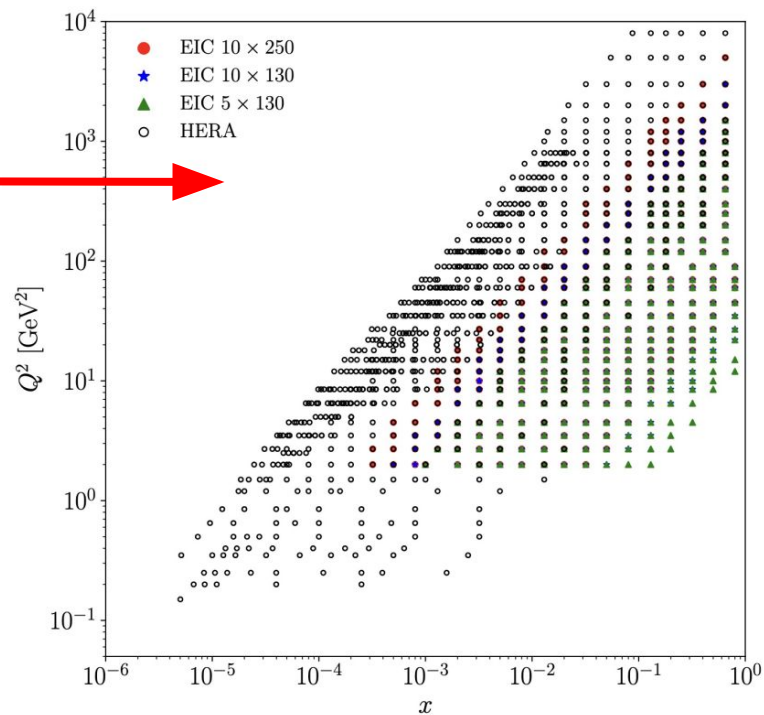
(Combined data: $\sqrt{s} = 320, 300, 251, 225$ GeV)

- **With only 2 energies: 10x130 and 10x250 GeV²**

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 GeV²**

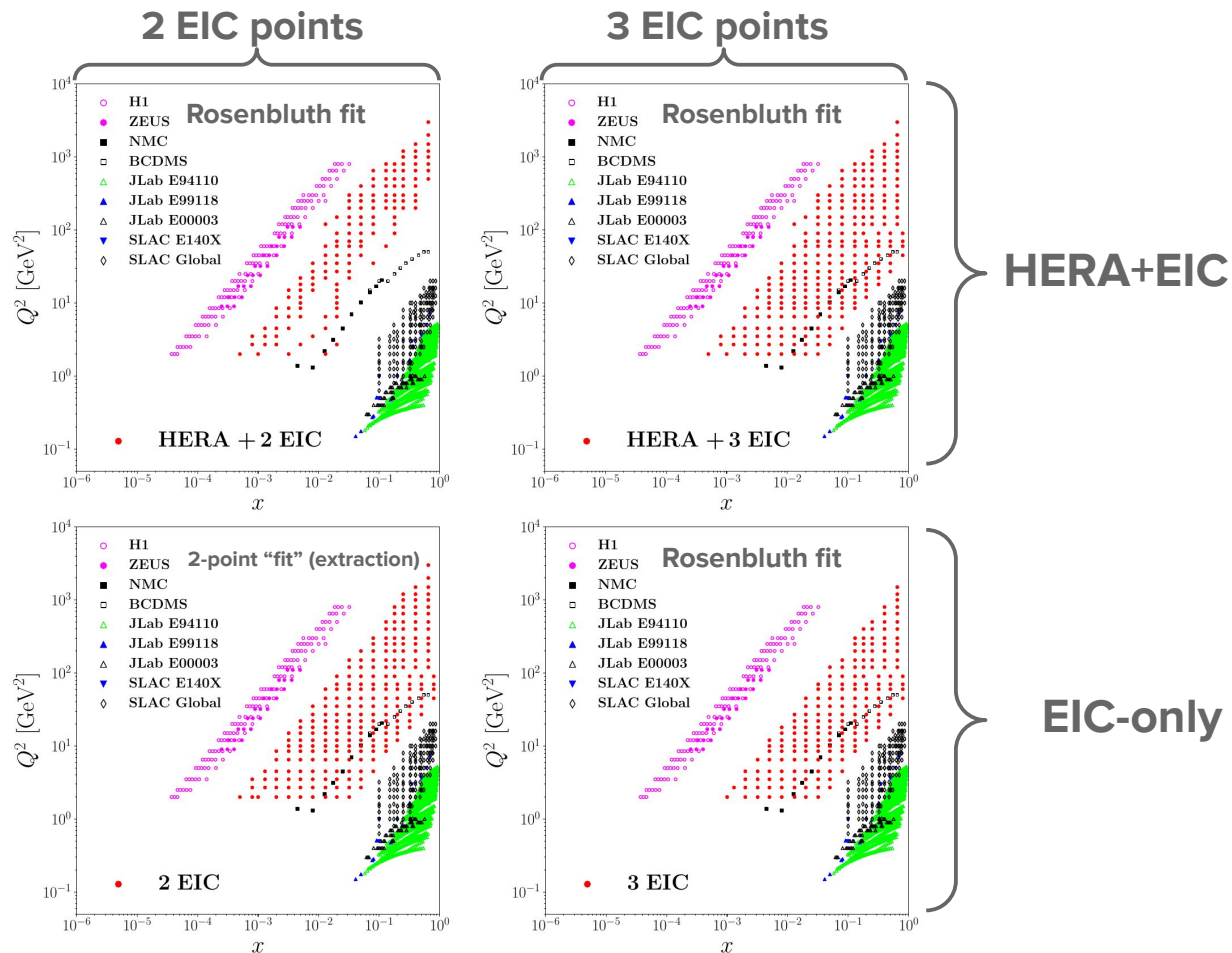
1. Fit 3 EIC + HERA
2. EIC-only fit



~5 bins per decade in x and Q^2

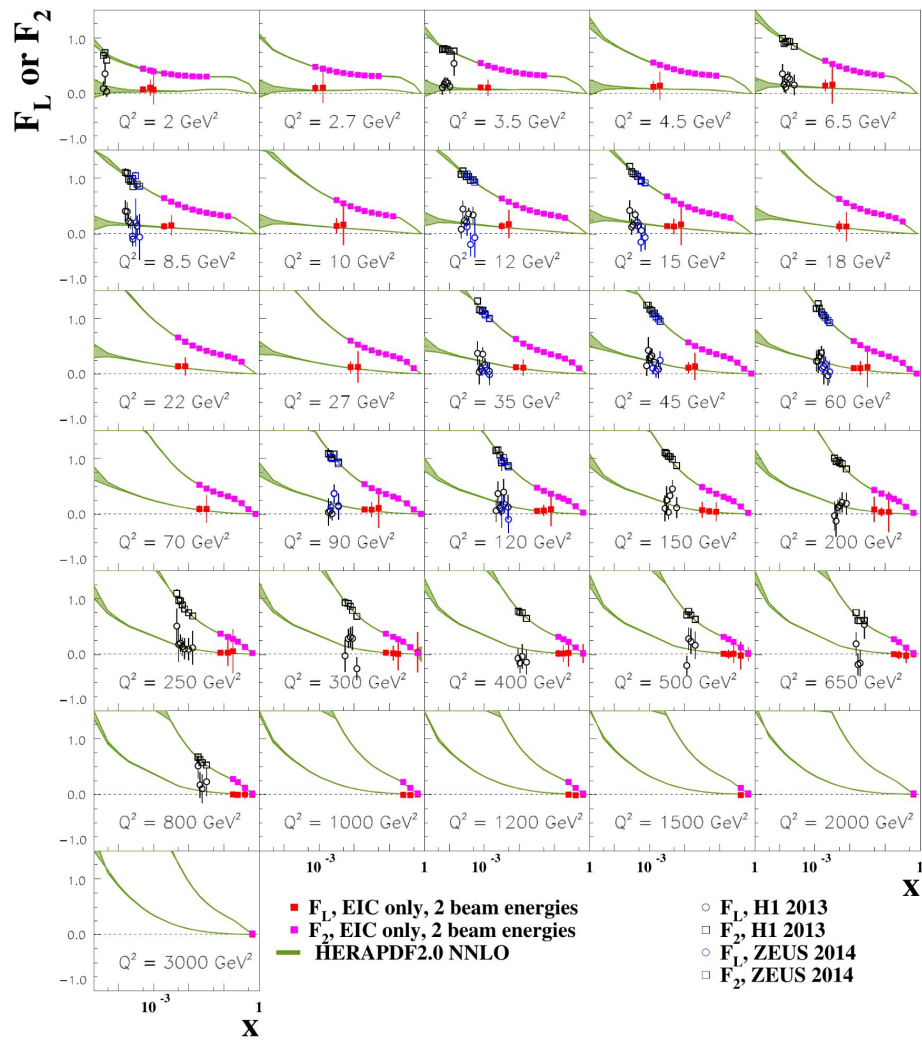
Phase space for the different scenarios

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



Structure Functions 2 EIC

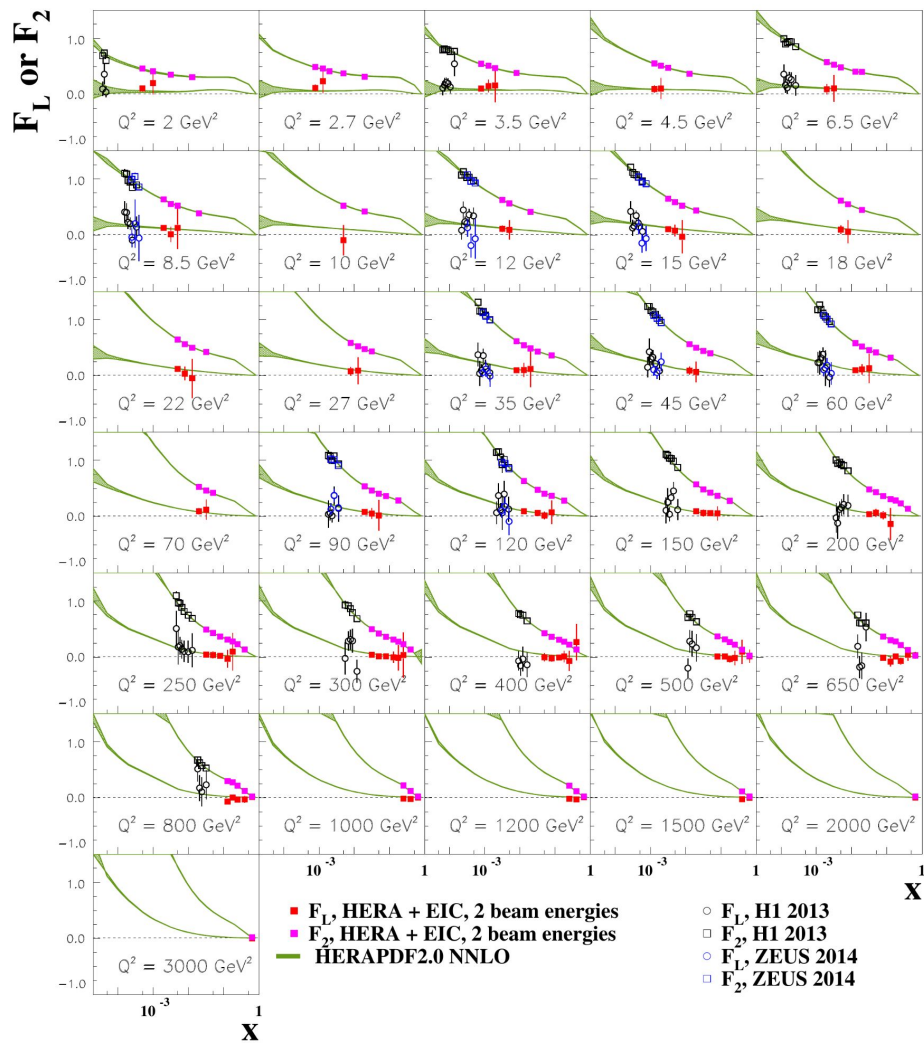
- Only draw F_L points with <0.5 uncertainty
- EIC F_L points obtained at larger x , complementing HERA points
- High precision model-independent F_2 extractions over a large range in x and Q^2



Structure Functions 2 EIC + HERA

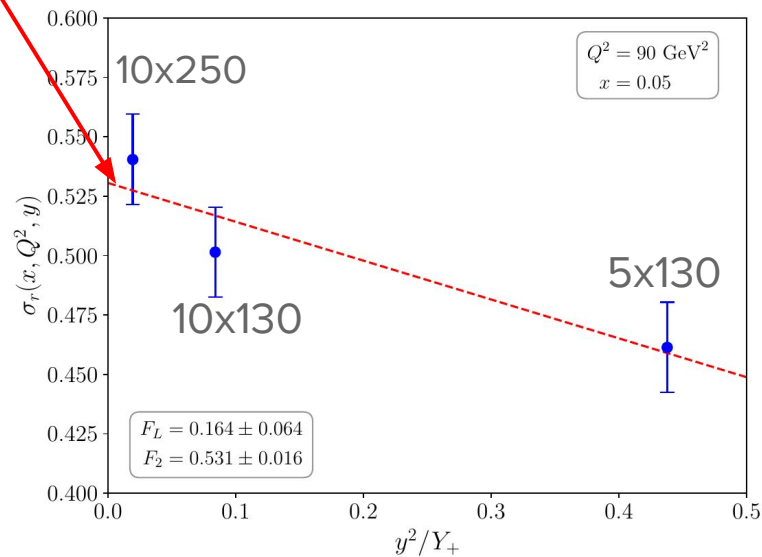
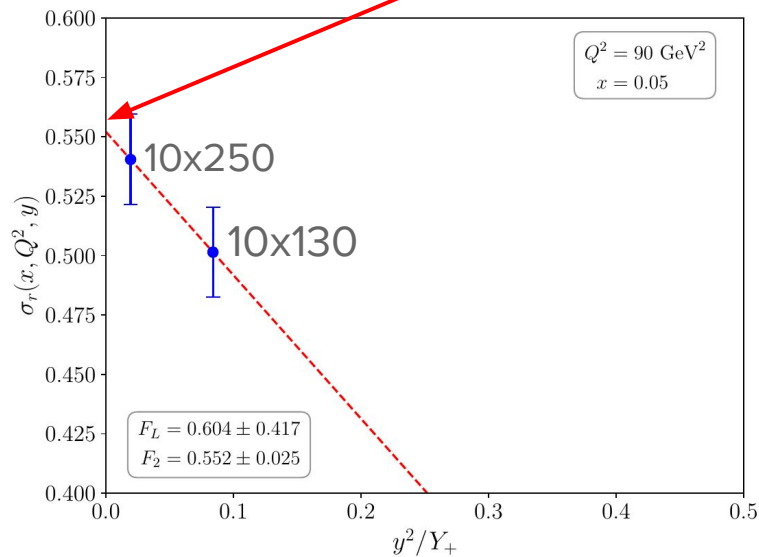
- Adding HERA data has two effects
 - Fewer bins for extraction $\rightarrow$ we require 3 points for the Rosenbluth fit: at least 1 point must come from HERA
 - Improved precision $\rightarrow$ more F_L points with <0.5 uncertainty, particularly at moderate to high Q^2

... but can we do better?

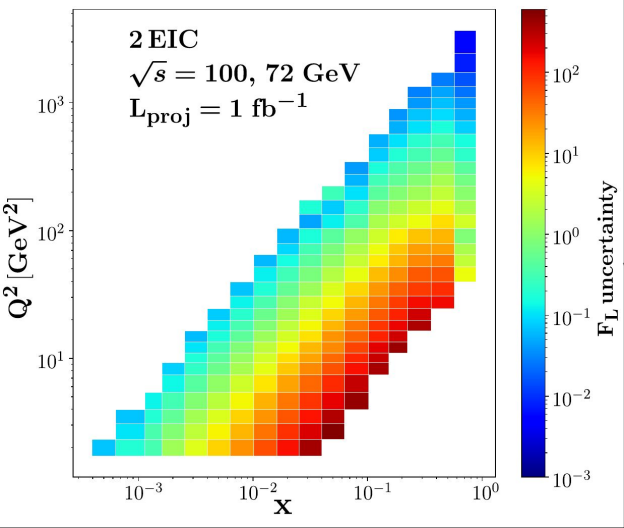


Improving F_L uncertainties

HERA points down here

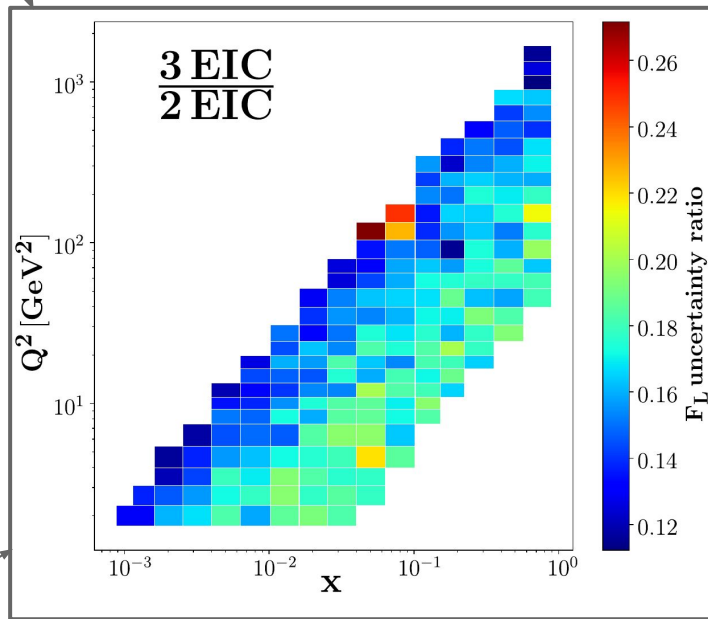
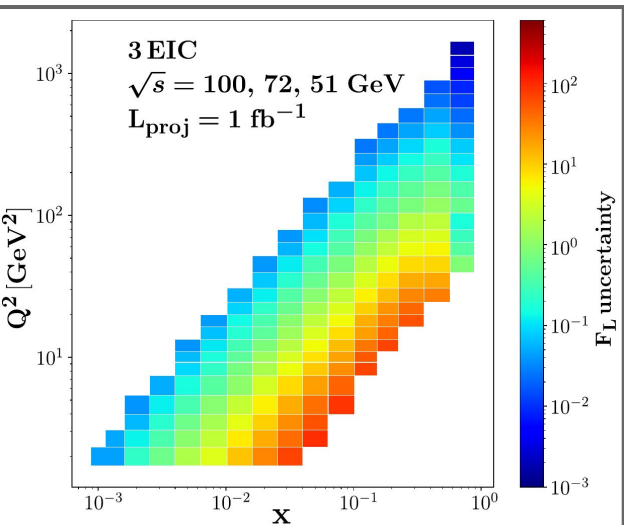


The precision on F_L benefits from high y (and therefore high y^2/Y_+) points $\rightarrow$ lower c.o.m. energy!



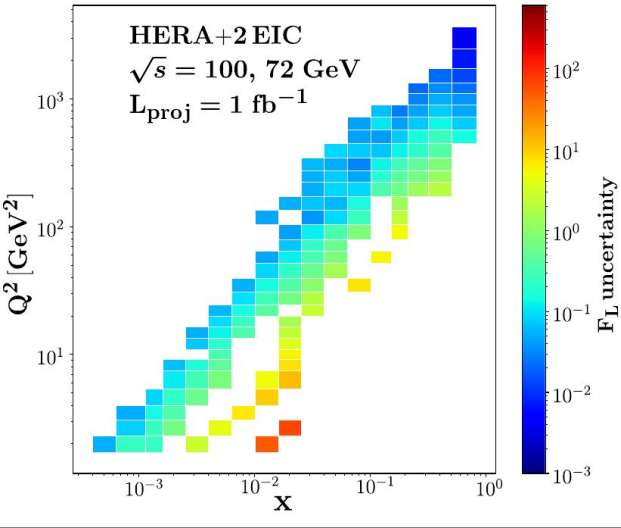
Uncertainties on F_L (EIC-only)

- Difference in number of data points and y^2/Y_+ lever arm $\rightarrow$ significant improvement in uncertainties between 2- and 3-beam F_L results



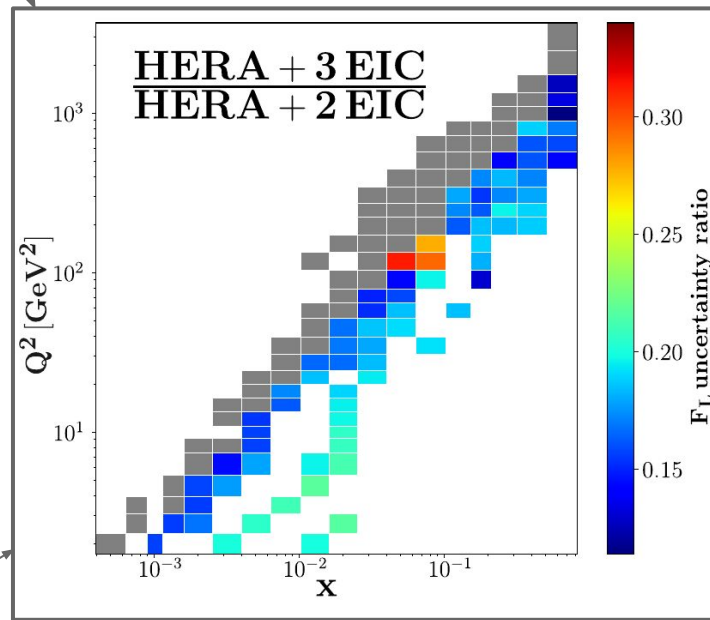
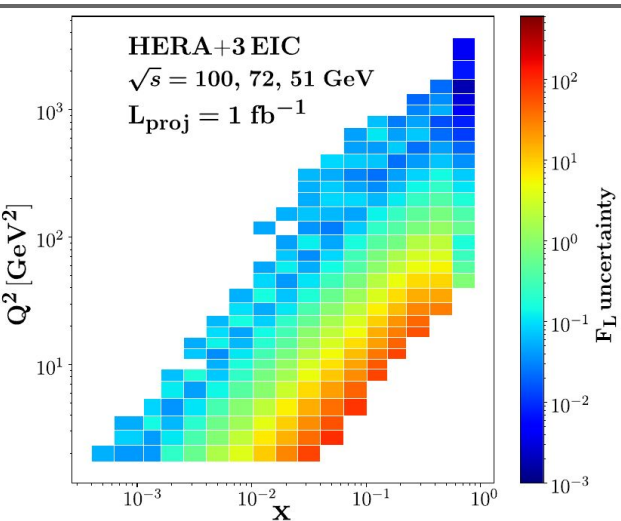
**Ratio of uncertainties for
3- to 2-beam F_L results in
common phase-space**

5-7x improvement!



Uncertainties on F_L (HERA+EIC)

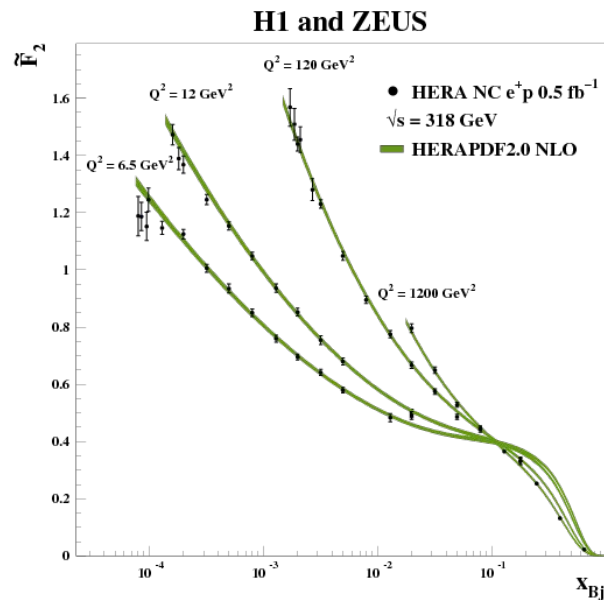
- Adding in HERA reduced cross sections... same story!
- **Getting 3 ep c.o.m. energies as soon as possible during EIC science operations will be key to making high precision F_L measurements at moderate x !**



Grey = same EIC
 points $\rightarrow$ 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 $\rightarrow$ 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



Model-independent F_2 extraction

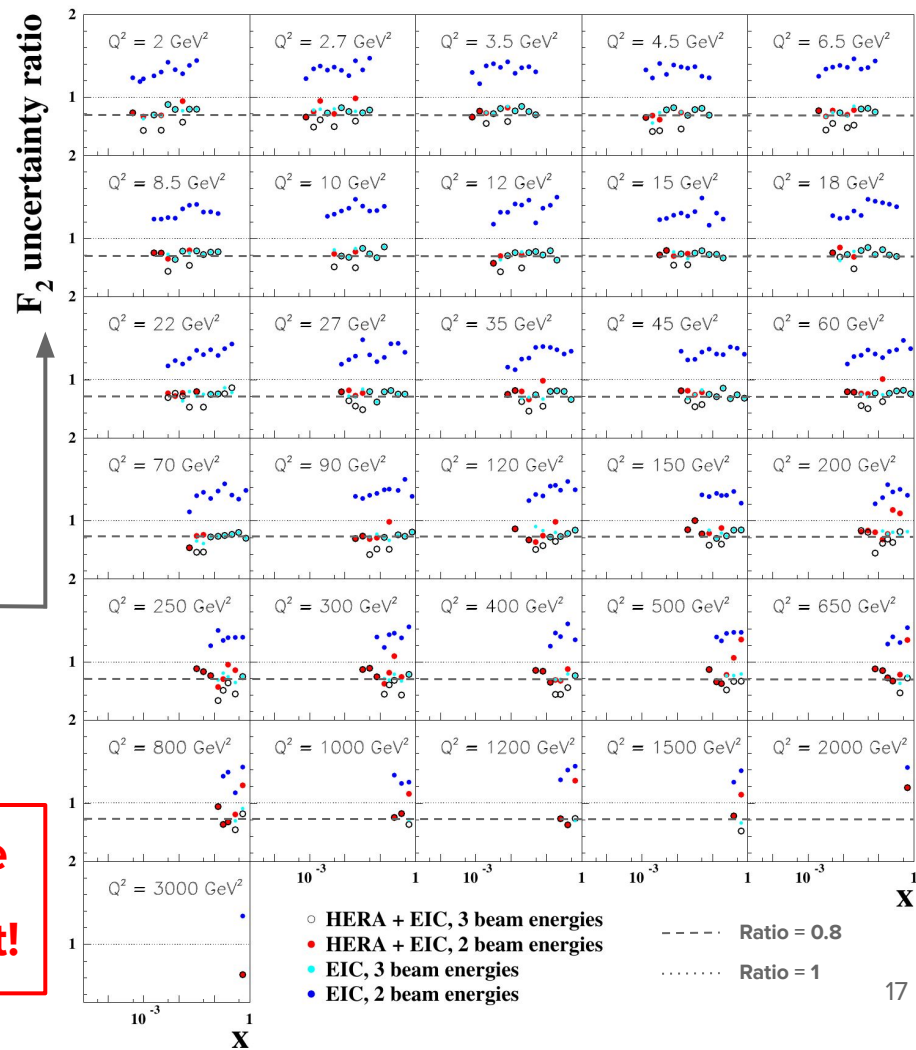
Model-dependent F_2 : Take σ_r and apply correction for F_L contribution from model
 $\rightarrow \delta F_2$ from relative uncertainty on σ_r

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

If Ratio < 1 then Rosenbluth fit gives better F_2 precision

We see $R \approx 0.8$ except for 2 EIC!

Uncertainties from Rosenbluth method are almost always better + model-independent!



DIS-only Collinear Proton PDFs and α_s **(...in HERAPDF style)**

Collinear PDFs (full EIC running)

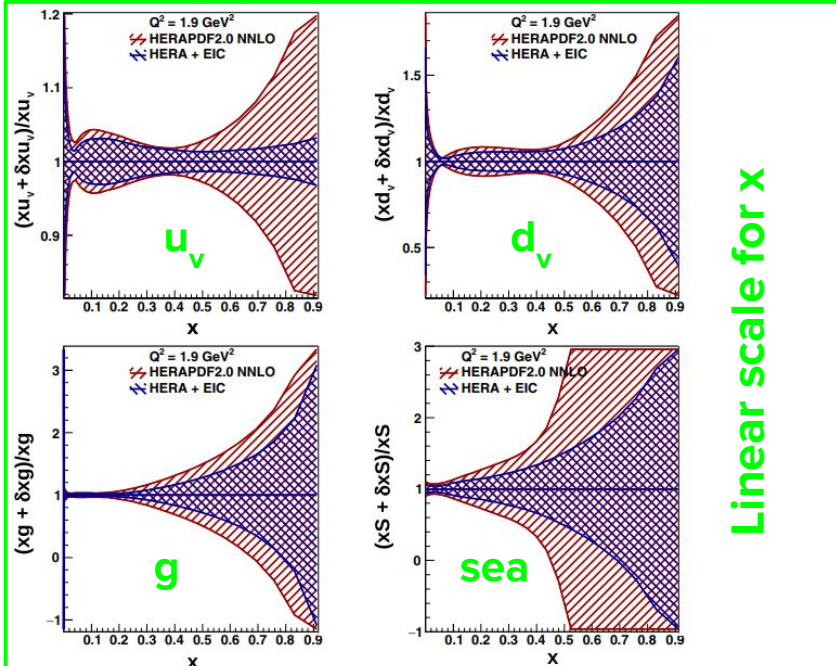
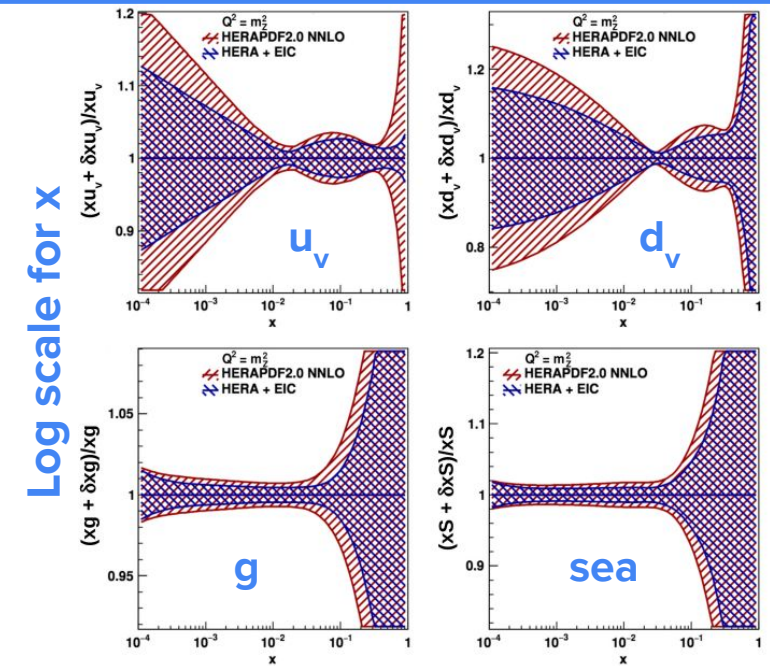
E_p (GeV)	E_e (GeV)	$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})
275	18	141	15.4
275	10	105	100
100	10	63	79.0
100	5	45	61.0
41	5	29	4.4

HERA DIS data form backbone of global fits → aim to combine EIC+HERA for consistent DIS dataset spanning wide range

Fit EIC inclusive pseudo-data ($W^2 > 10$) alongside HERA data in

HERAPDF parametrisation using xFitter

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



Relative experimental uncertainties (no parametrisation/theory):

Phys.Rev.D 109 (2024), arXiv:2309.11269

Collinear PDFs (Early Science)

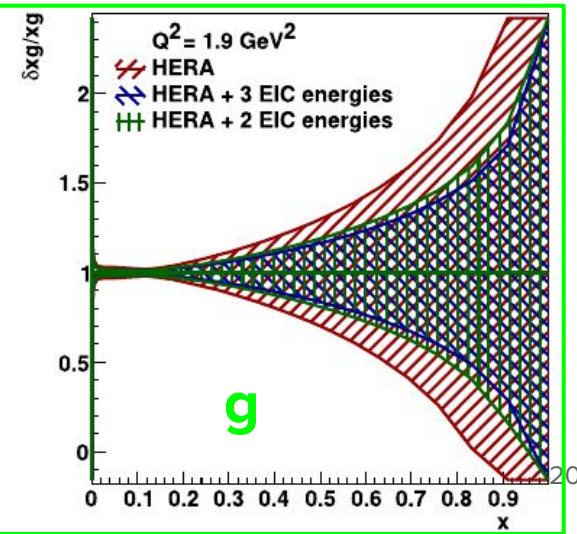
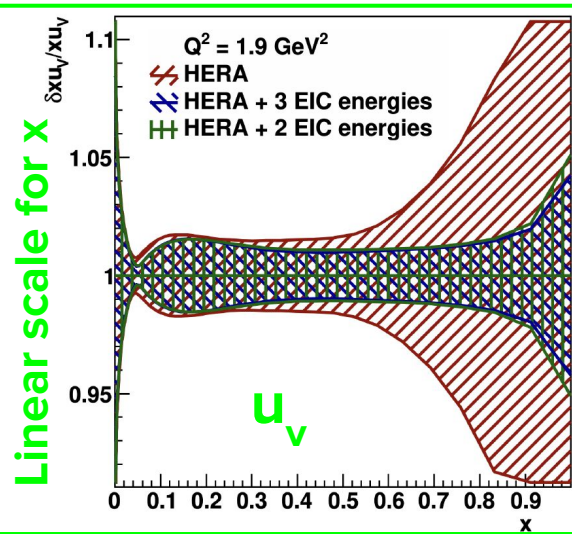
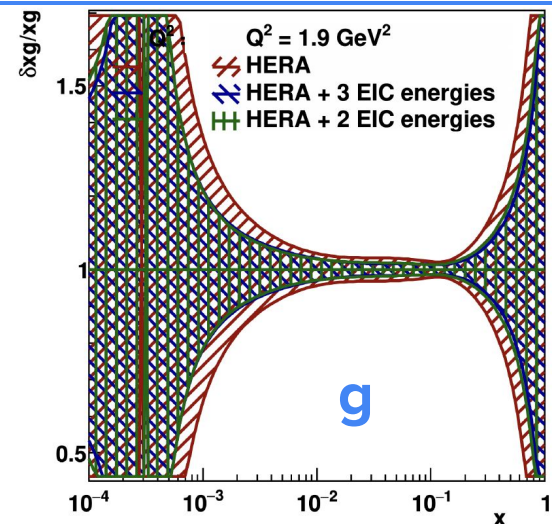
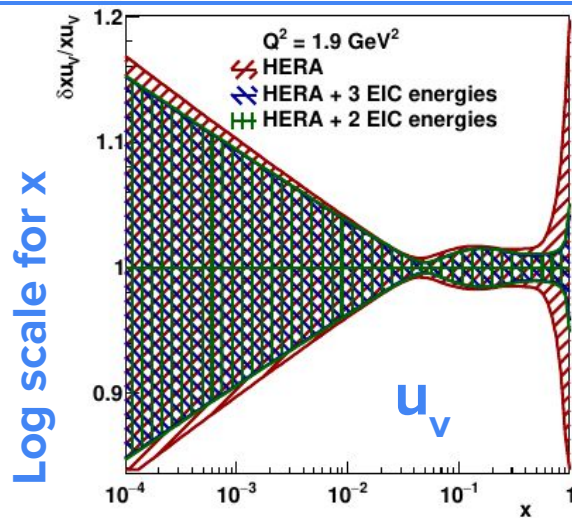
Relative experimental uncertainties for u_v and g (no parametrisation//theory):

Start from fit of HERA data → add in early science pseudo-data ($W^2 > 10$) instead

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

Modest improvement for low-to-mid x ,
large improvement for $x > 0.1$ for gluons
 and u_v

- d_v and total sea only show minor improvement)
- **Only small difference between two- and three- beams scenarios**



Determining α_s from DIS-only (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

The possibility to extract α_s from **only HERA+EIC**

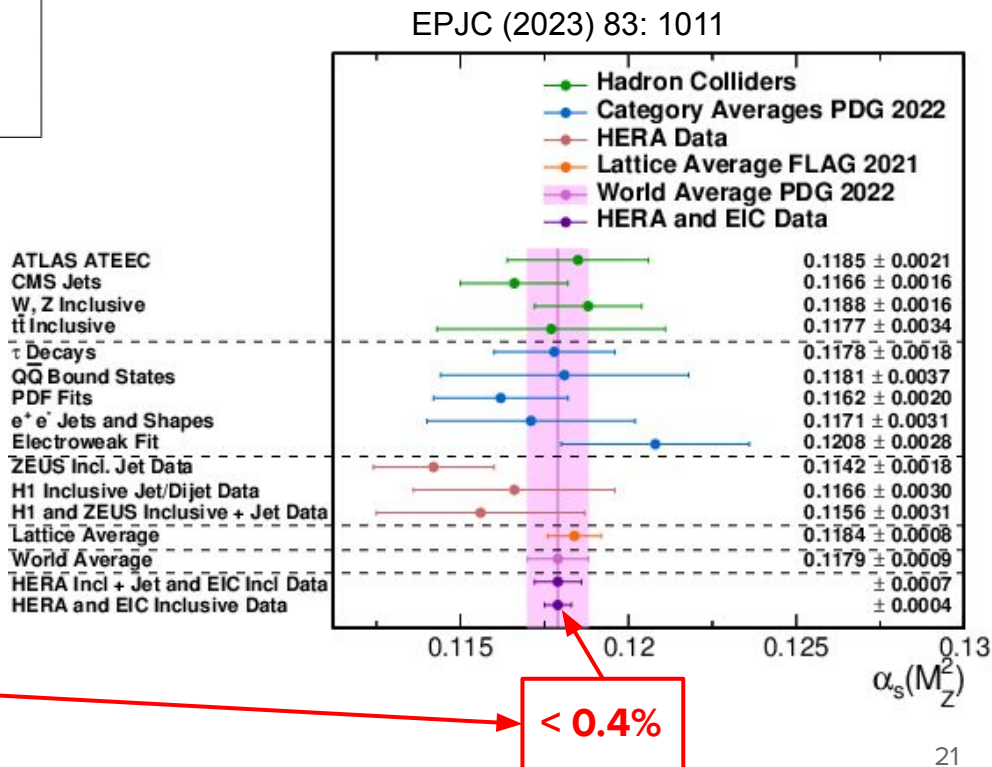
DIS data was shown in [EPJC \(2023\) 83: 1011](#)

- 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



Early Science prospects for strong coupling

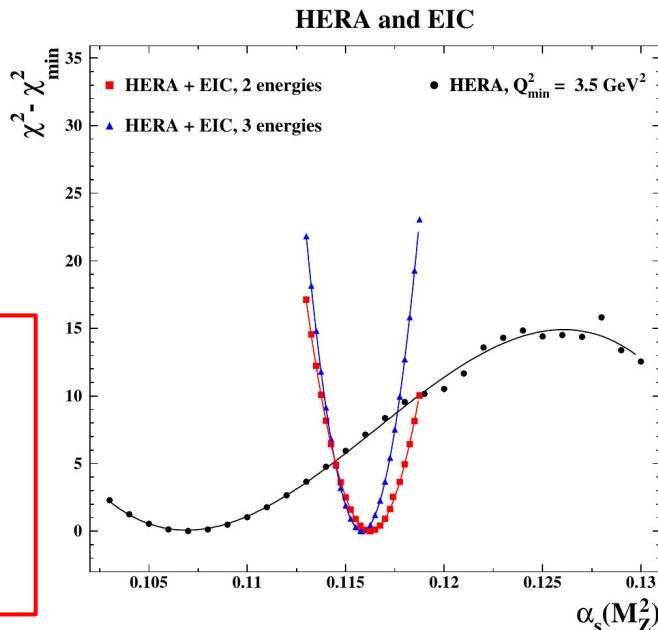
- For 2 EIC beam energies $\alpha_s(M_Z^2) = 0.1162 \pm 0.0008$ (exp)

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

- Experimental precision already very precise with 2 EIC Early Science beam configurations

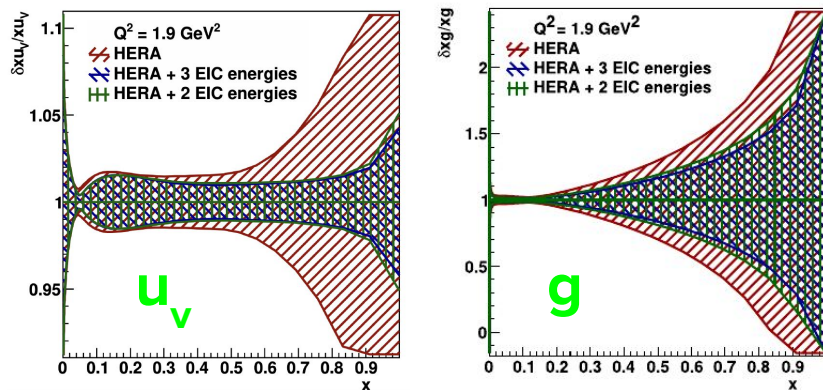
- Comparable to lattice QCD determinations and present world average

- Question about theoretical uncertainties of such DIS-only determinations remains open
[EPJC 86 \(2026\) 3, 216](#)
- **Proper treatment of theory uncertainties and QCD at higher orders will be key to realising best possible precision**



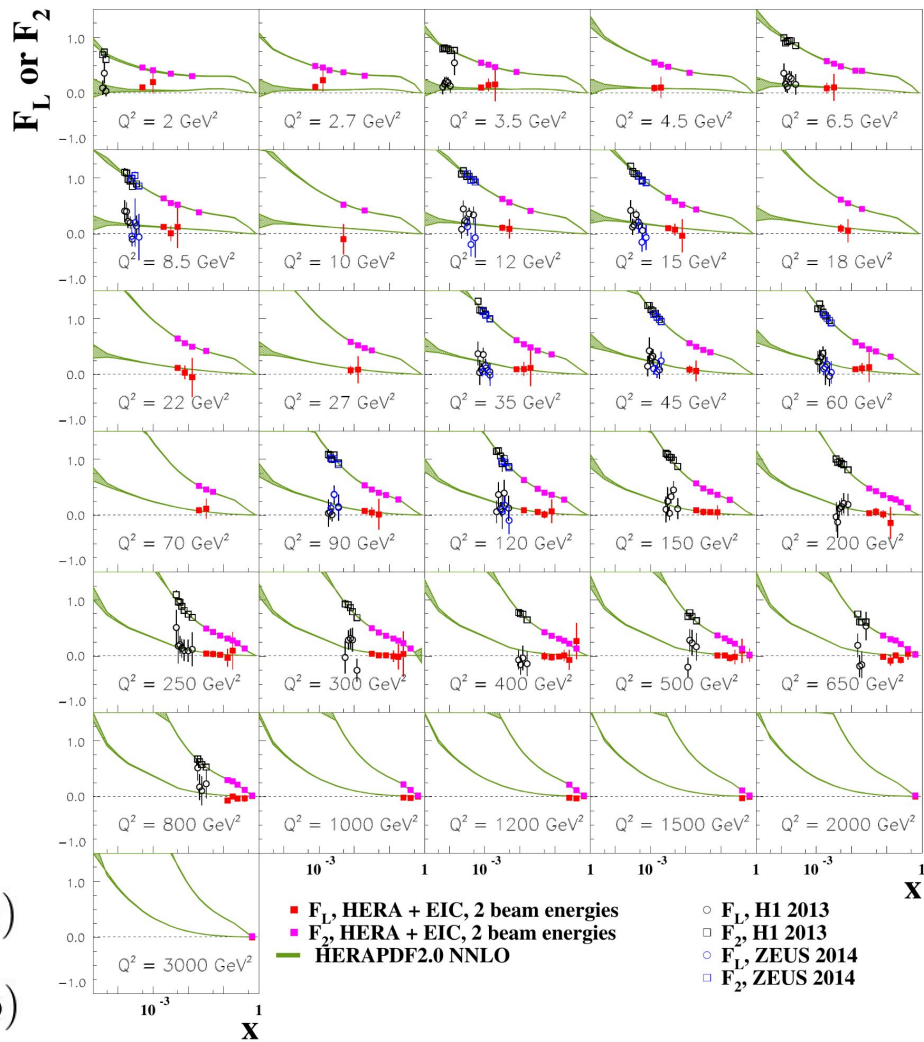
Takeaway message

- EIC offers opportunity to extract F_L and F_2 in complementary phase-space to HERA during early science
- Early science inclusive DIS data improves impact of DIS data at high- x in PDF fits for u_v and g
- DIS-only α_s extraction with world-leading experimental precision $\rightarrow$ theory uncertainties become very important



2 EIC: $\alpha_s(M_Z^2) = 0.1162 \pm 0.0008 \text{ (exp)}$

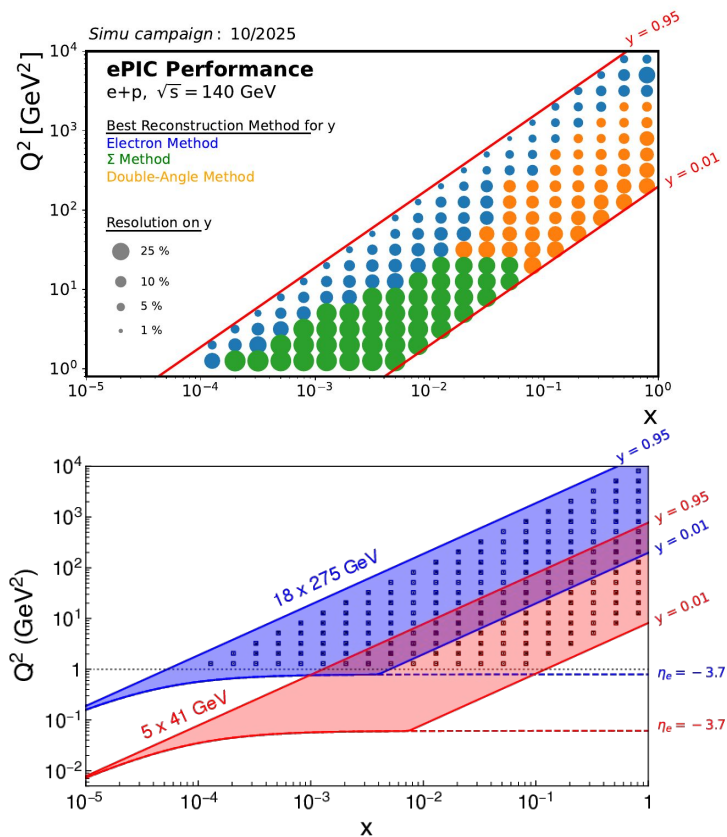
3 EIC: $\alpha_s(M_Z^2) = 0.1158 \pm 0.0006 \text{ (exp)}$



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 $\rightarrow$ “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



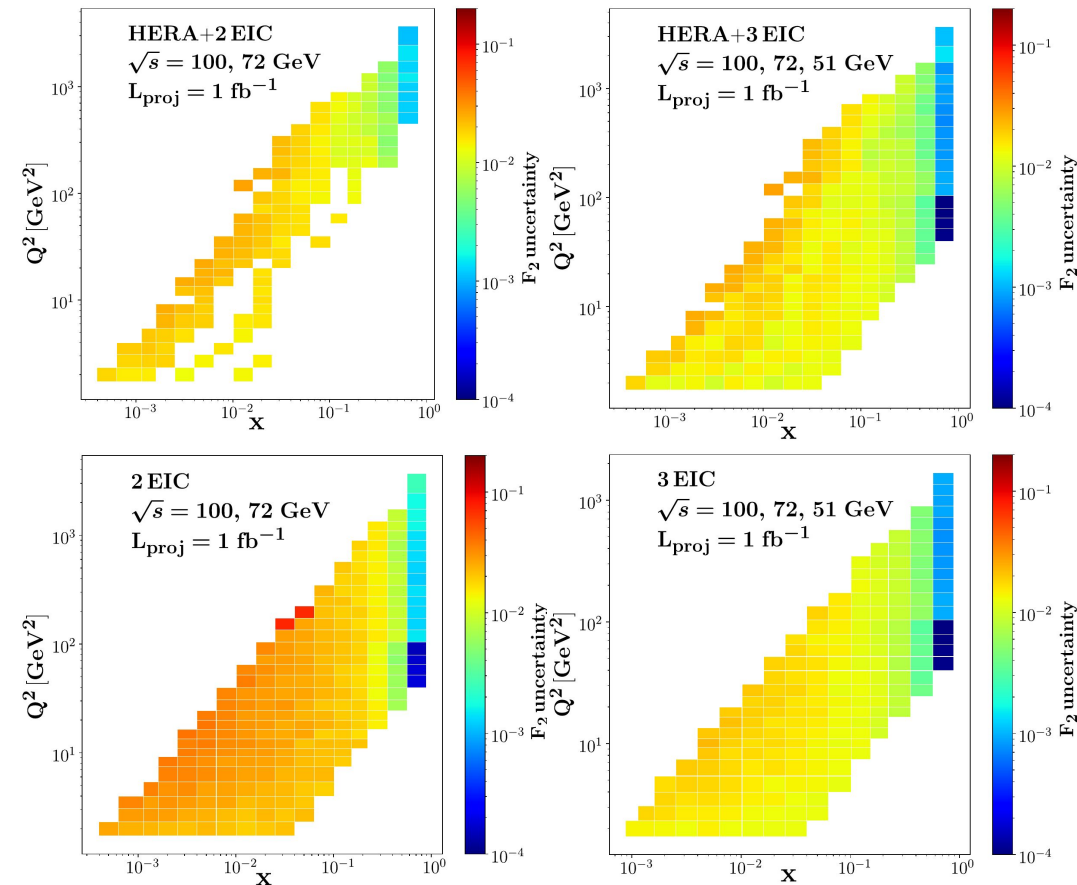
MC replica method

- 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 $N = 1000$

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

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

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

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

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x),$$

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

- Additional Constraints:

- A_{u_v}, A_{d_v}, 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