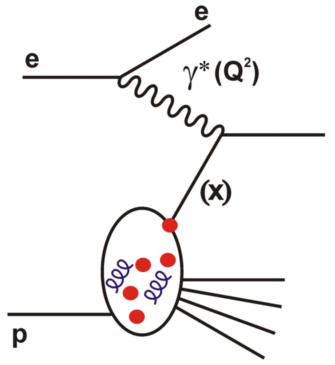
Structure Functions and Parton Densities from Inclusive EIC ep Data

EIC-UK Discussion Meeting
19 November 2024

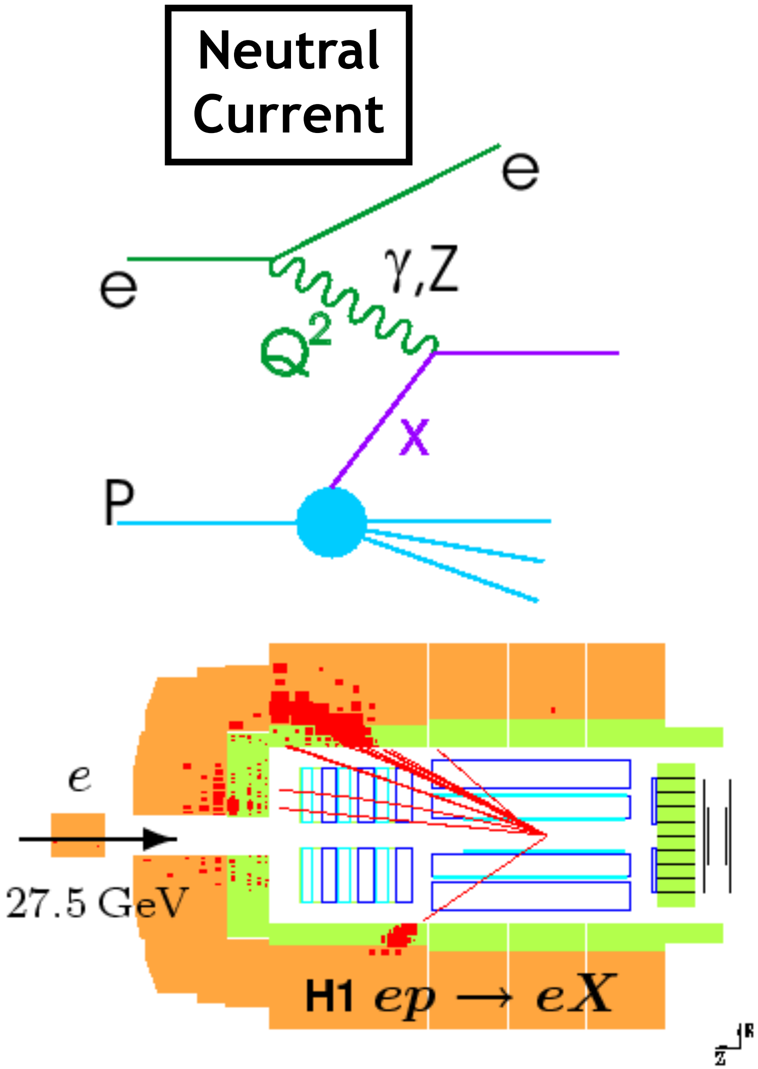


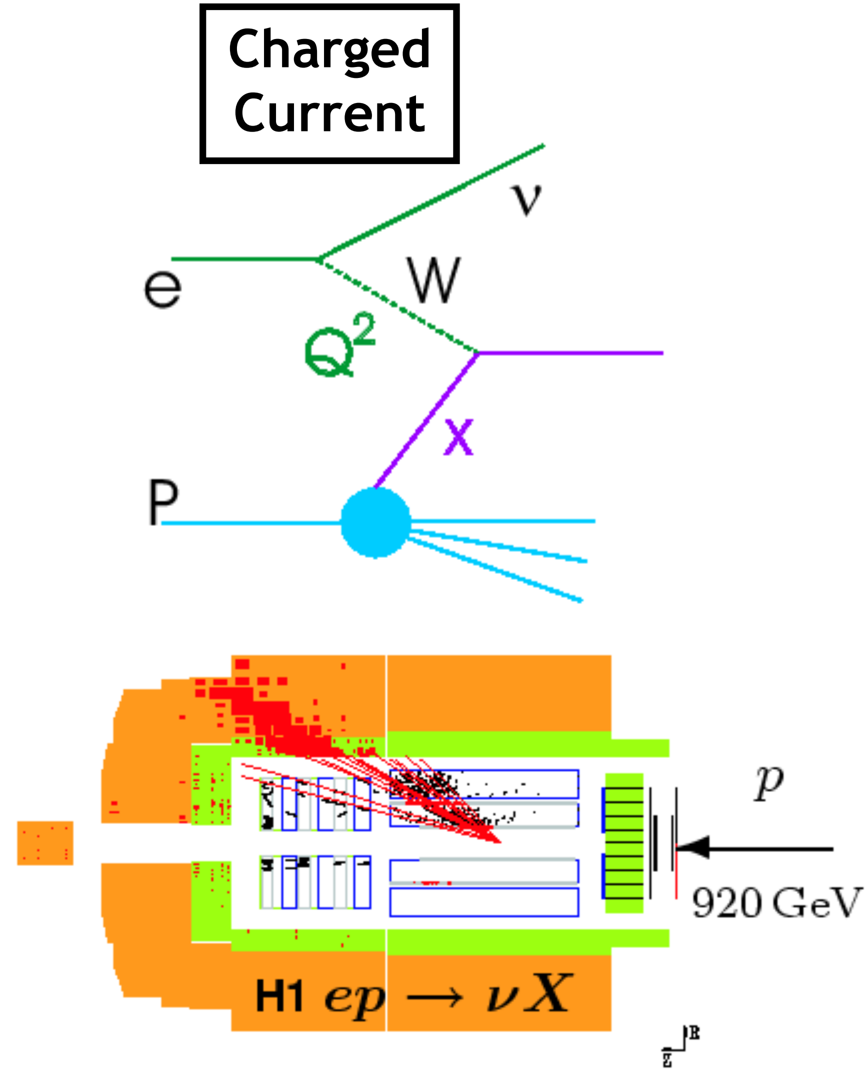
Paul Newman (Birmingham)

Work done in collaboration with many colleagues (see attributions on following slides) and All members of the ePIC and formerly ATHENA collaborations

- Introduction
- PDFs from Inclusive EIC data
- Strong Coupling
- The Longitudinal Structure Function

Basic Deep Inelastic Scattering Processes

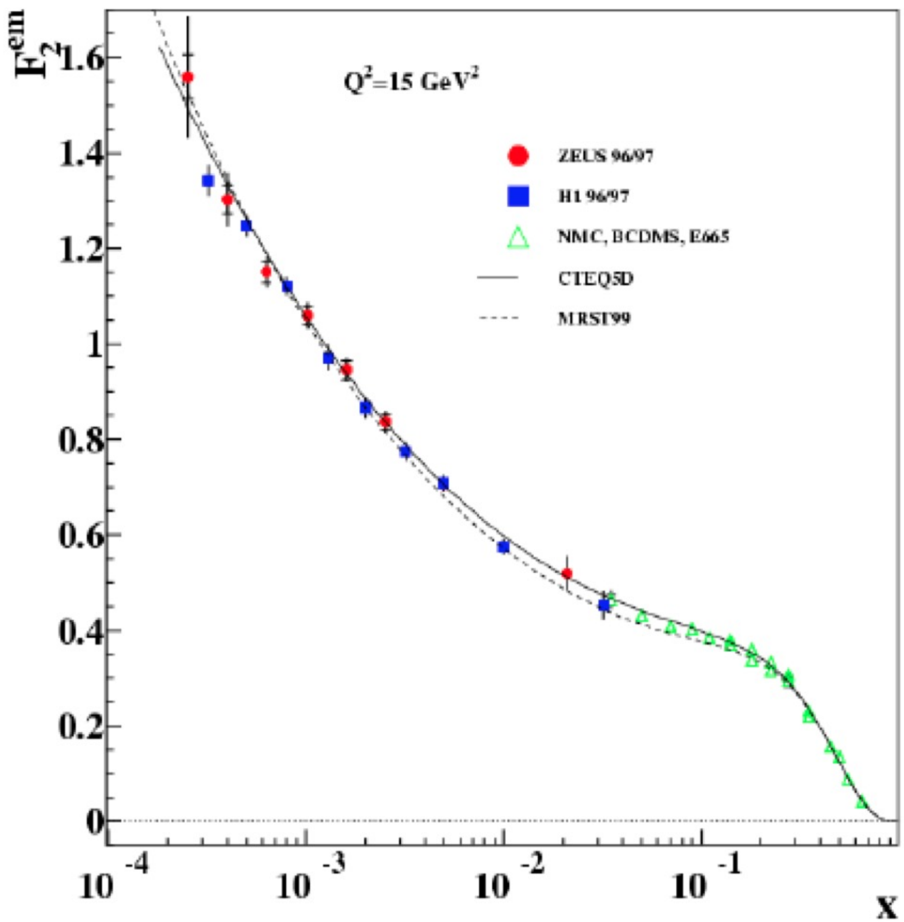


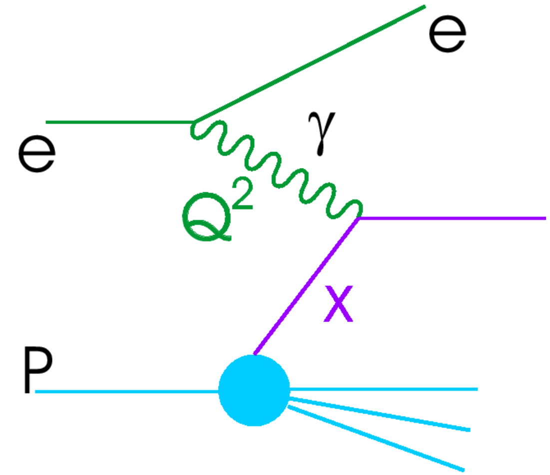


We will only be concerned with Neutral Currents here

Example Inclusive Neutral Current Data

Fixed target and (early) HERA data
at a single Q^2 value (15 GeV^2)





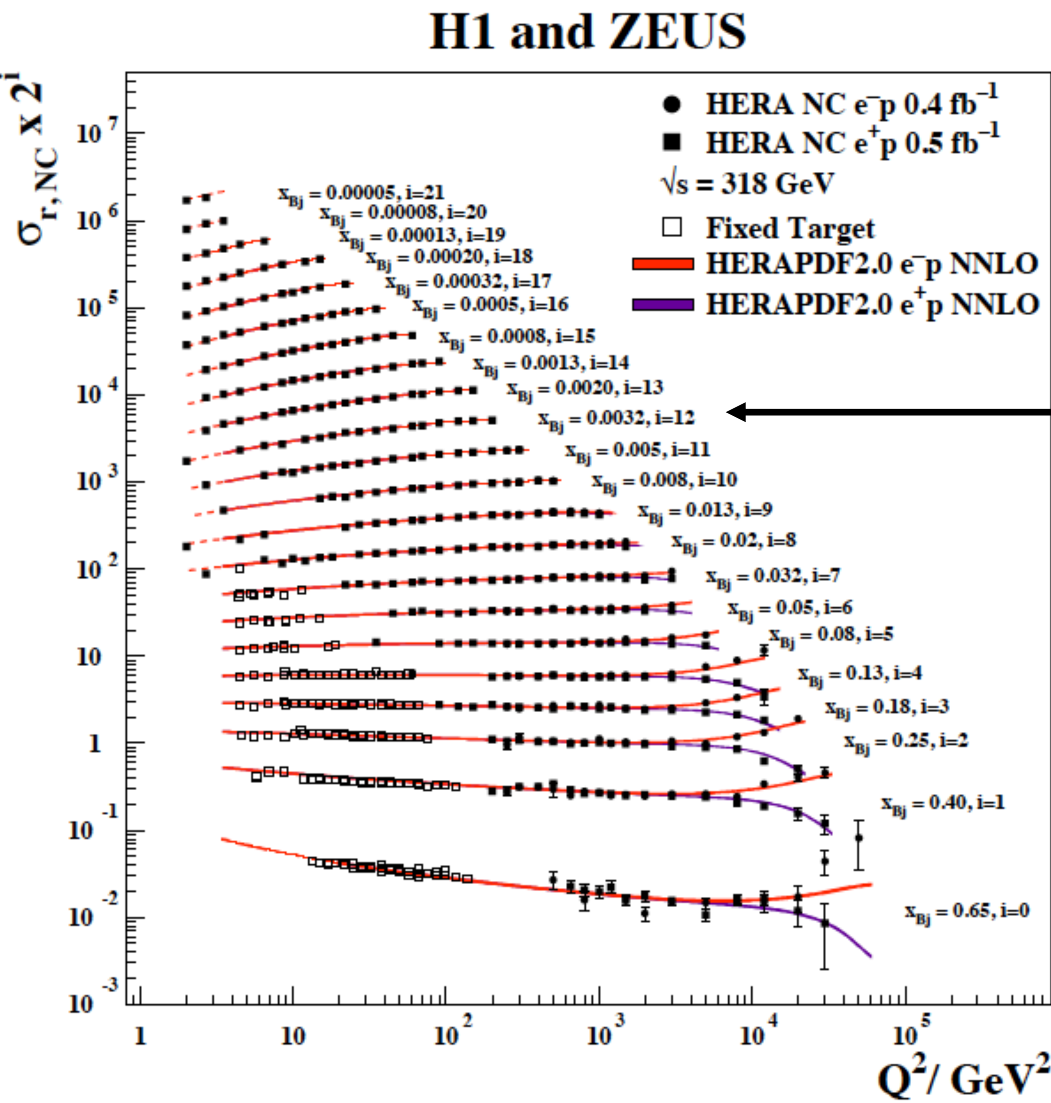
- Photon-exchange component of NC data measures

$$\frac{d\sigma}{dx\,dQ^2} \sim F_2 = \sum_q e_q^2\, x\,(q+\bar{q})$$

- Due to e_q^2 photon coupling, this mainly constrains **u & ubar**

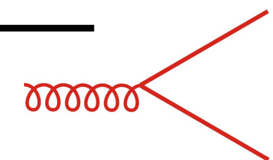
… shape of quark densities already qualitatively apparent

QCD Evolution and the Gluon Density



- Q^2 dependence sensitive to gluon density via splitting function …

$$g \to q\bar{q}$$

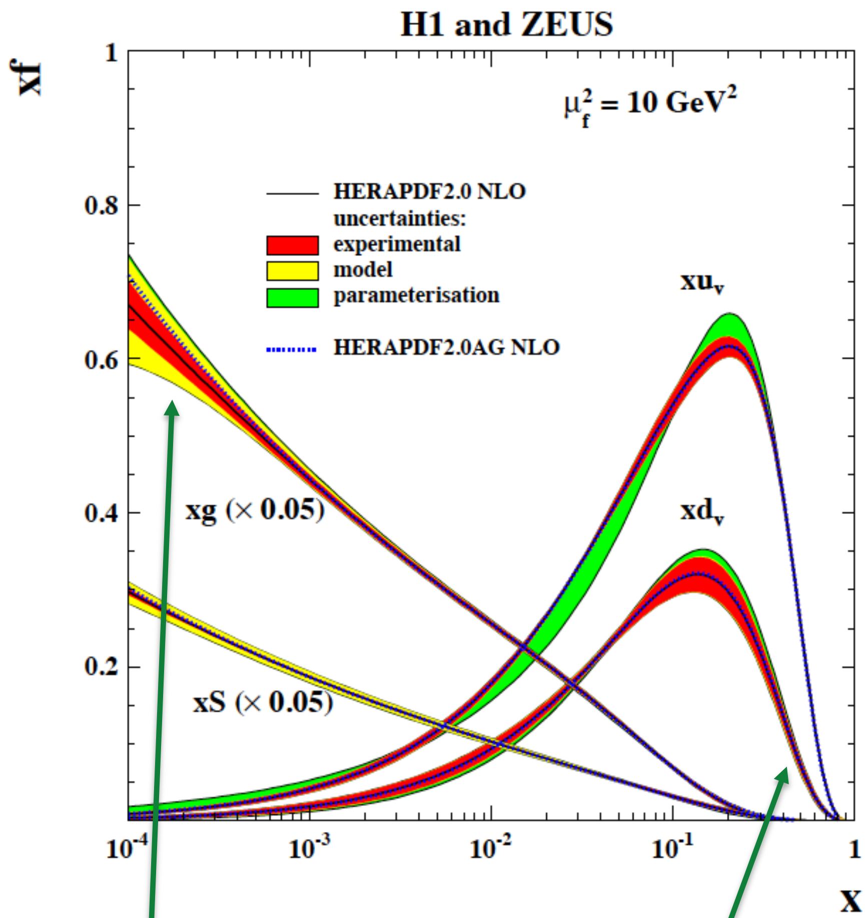


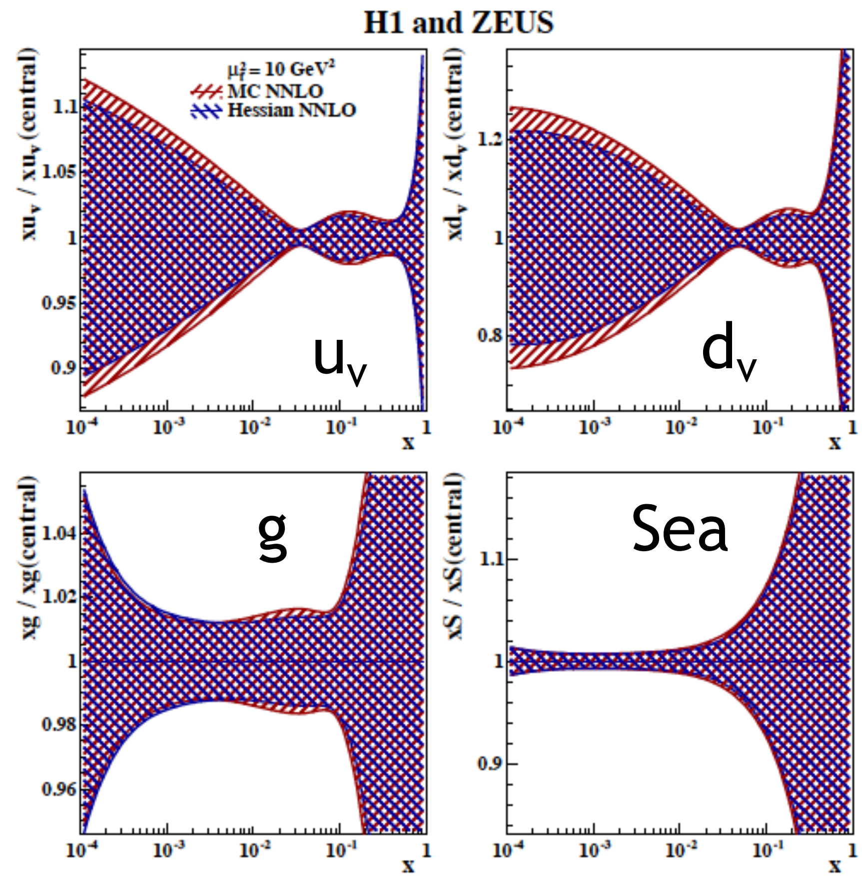
- DGLAP equations describe QCD evolution (to NNLO and approximate N^3LO accuracy)

- EW effects give different quark sensitivities (Z-exchange separates e^+p v e^-p, W-exchange gives charged current ($ep \rightarrow \nu X$)

→ Fits to data to extract proton parton densities

Proton PDFs from HERA only (HERAPDF2.0)



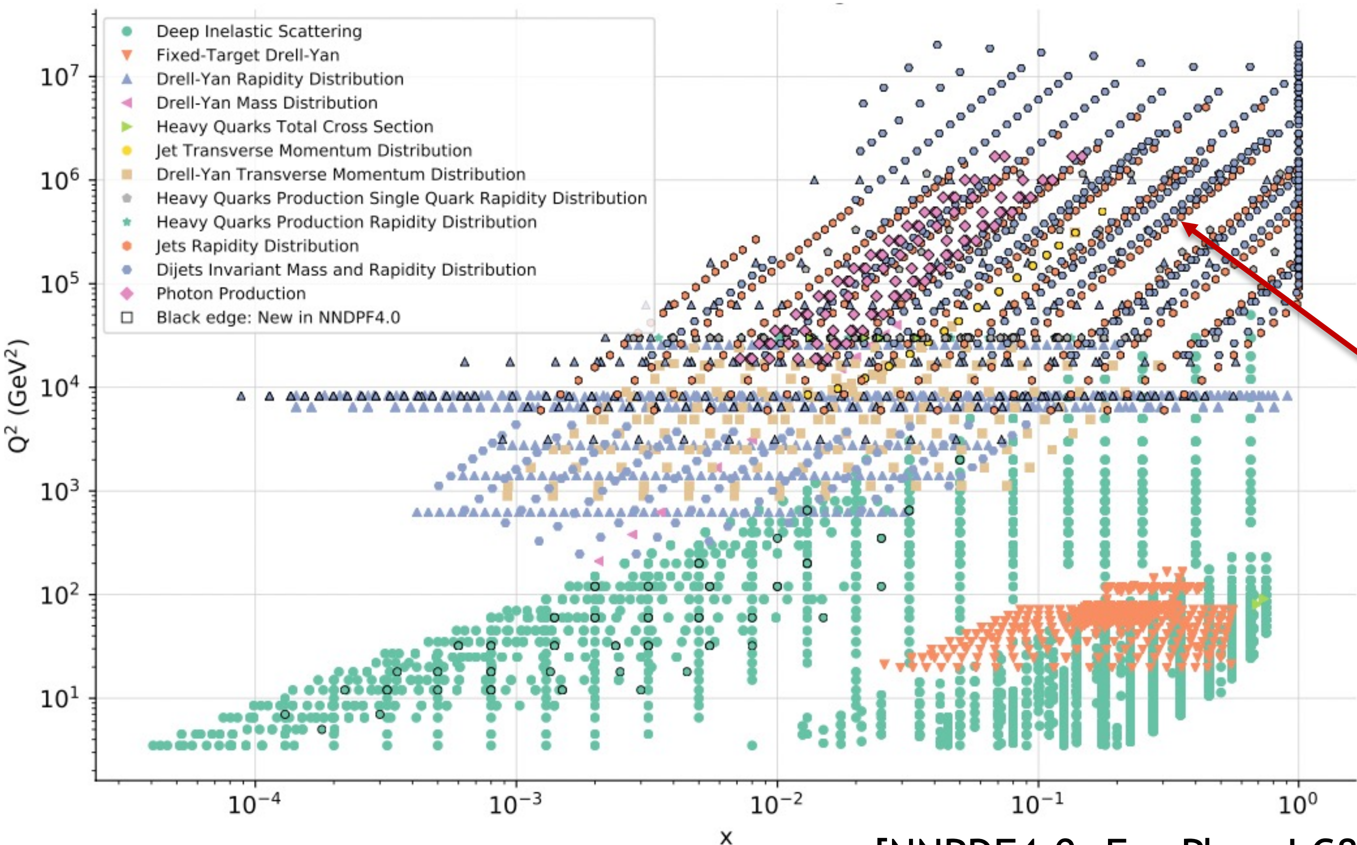


Strong interaction dragons?

Input to energy frontier discovery?

- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=10^{-3} (kinematic limit)
  - above x=10^{-1} (limited lumi)

Adding more data: Global PDF fits



Lots of PDF-sensitive observables at LHC with sensitivity to high x partons

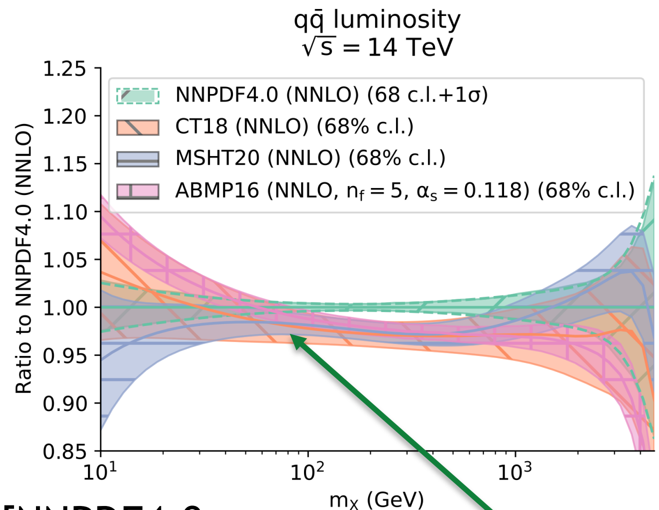
[NNPDF4.0, Eur Phys J C82 (2022) 428]

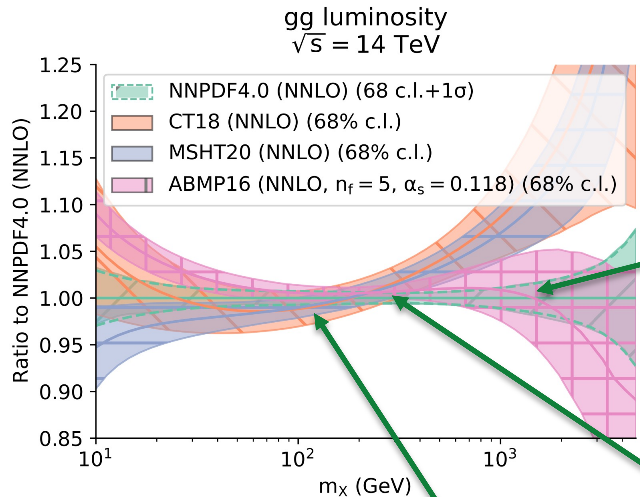
Including LHC data brings:
Advantages: improve precision at mid and high x, exploit all available inputs

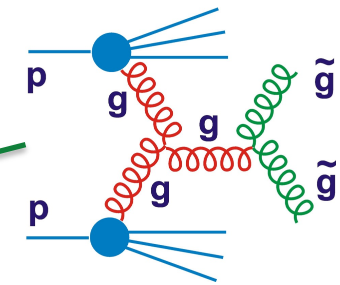
Caveats: use of data that may contain BSM effects, theoretical complexity (eg non-perturbative input), some incompatibilities between data sets

Global Fits and LHC Parton Luminosities

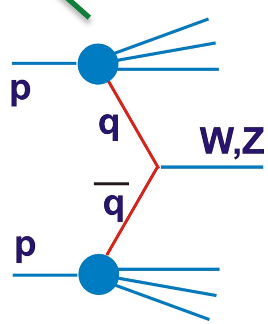
e.g. Comparisons between current global fits on LHC $q\bar{q}$ and gg luminosities

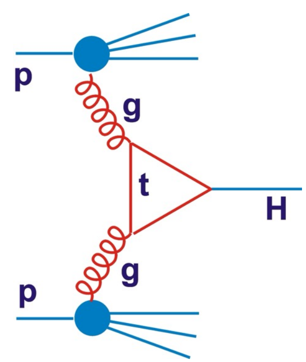


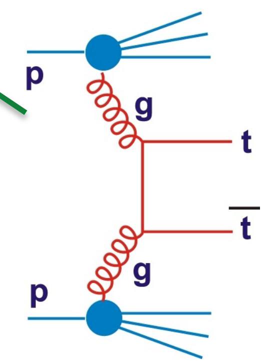




[NNPDF4.0 ,
Eur Phys J C82 (2022) 428]

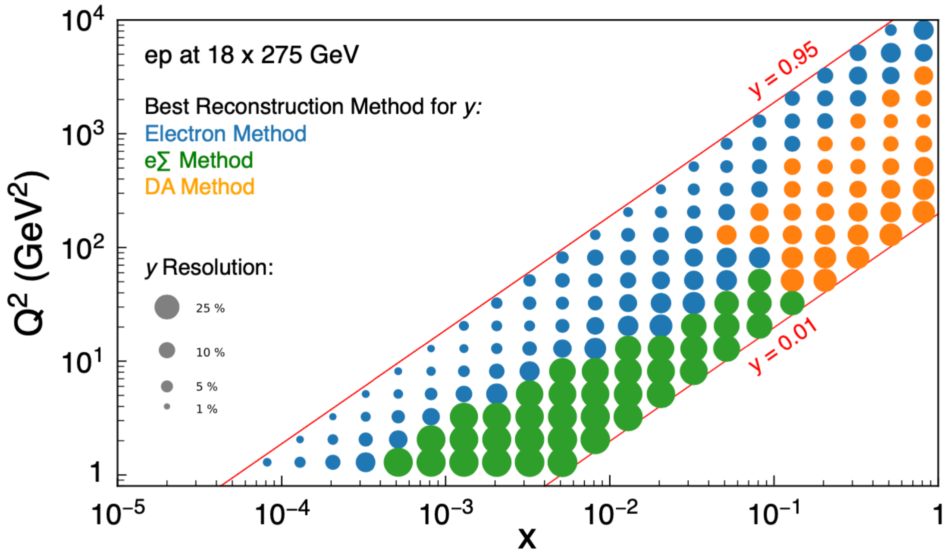






Immense recent progress, but still large uncertainties and some tensions between data sets and fitting methodologies

EIC Measurement Strategy



[S. Maple / ATHENA proposal]

- Choose reconstruction methods exploiting the hadronic final state as well as the electron to optimise (x, Q^2) resolutions throughout phase-space

- Exploit overlaps between data at different $\sqrt{s}$ to avoid 'extreme' phase space regions

e-beam E	p-beam E	$\sqrt{s}$ (GeV)	inte. Lumi. (fb^{-1})
18	275	140	15.4
10	275	105	100.0
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

- Systematic precision estimated from experience at HERA, expected EIC detector performance, and guesswork

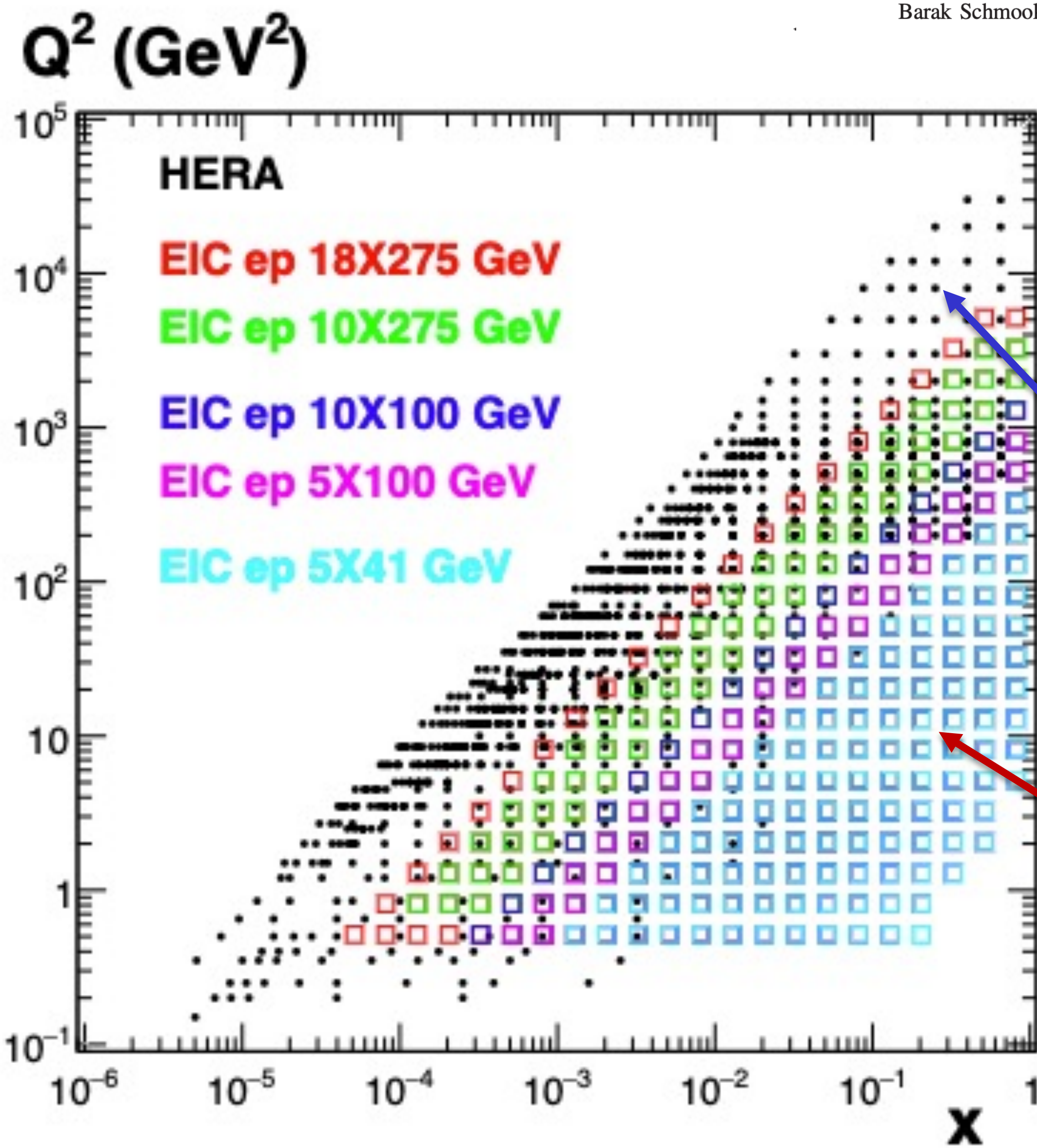
Simulations based on precision:
- 1 year of data at each beam config
- 1.5-2.5% point-to-point uncorrelated
- 2.5% normalisation

EIC PseudoData

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]

[arXiv:2309.11269]



HERA data have limited high x sensitivity due to $1/Q^4$ factor in cross section and kinematic x / Q^2 correlation

EIC data fills in large x, modest Q^2 region with high precision

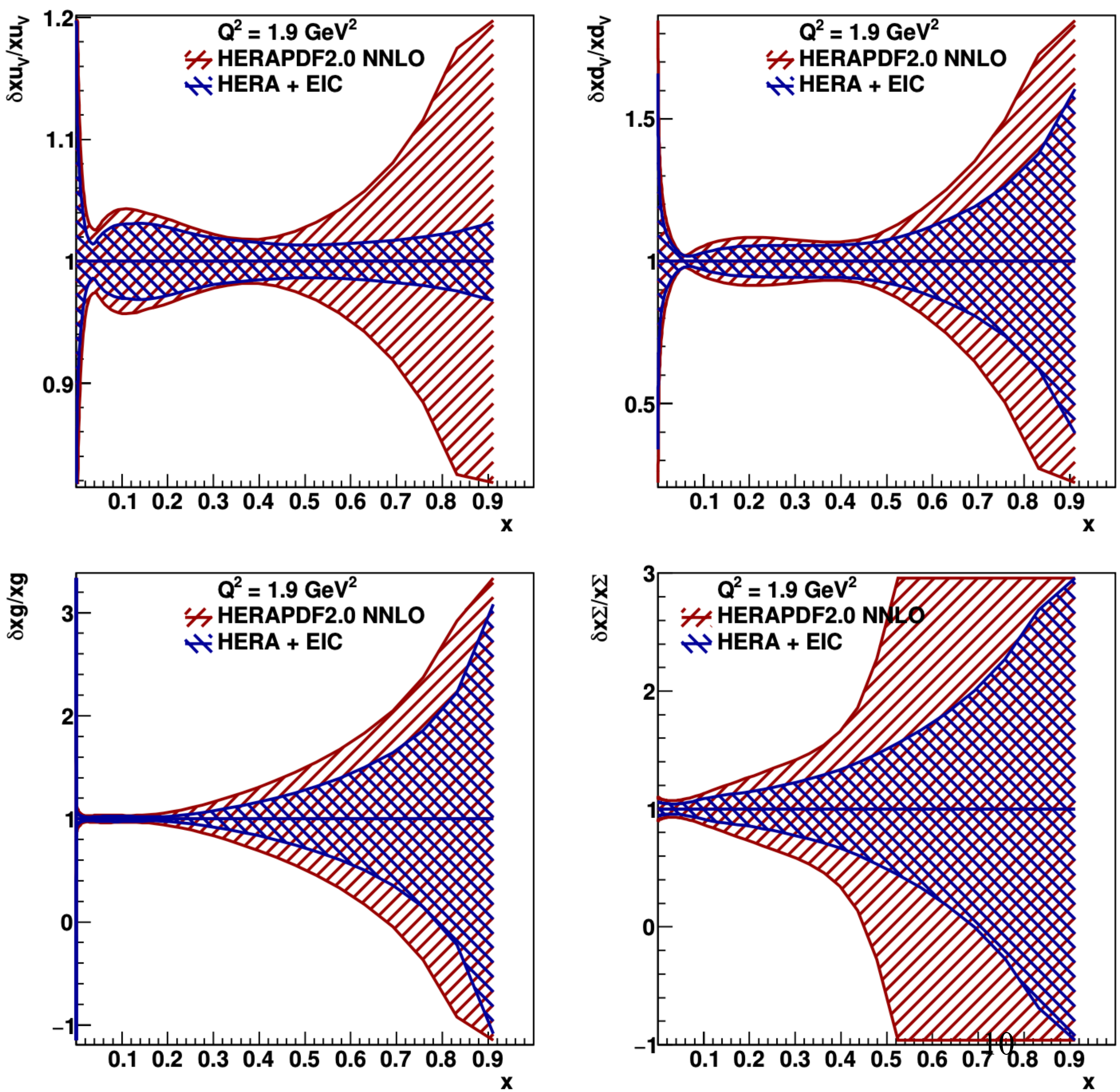
Impact of EIC/ATHENA on HERAPDF2.0

Fractional total uncertainties in DIS-only fit scenario with / without simulated EIC data

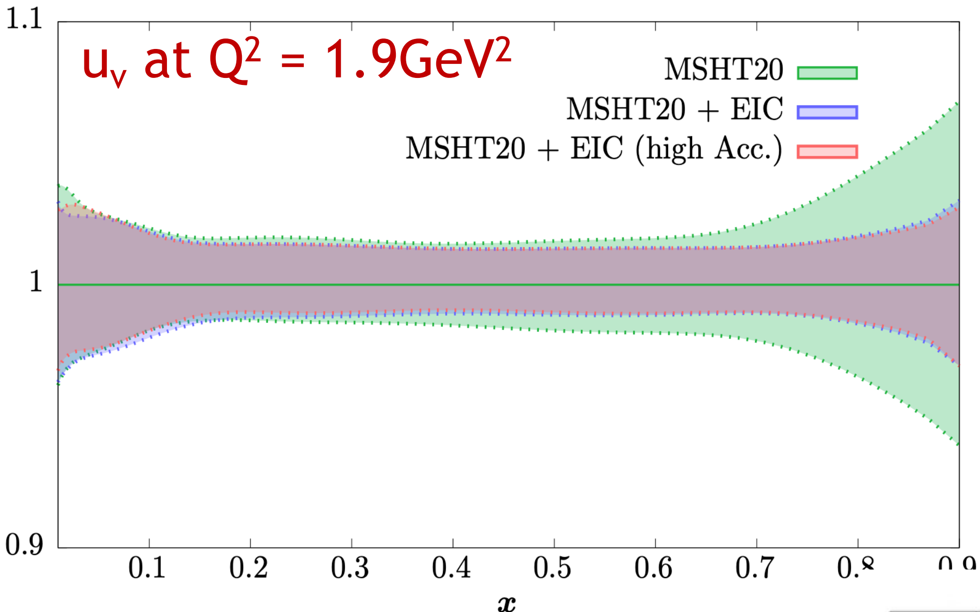
(linear x scale)

… EIC will bring significant reduction in uncertainties for all parton species at large x

… most notable improvements for up quarks (charge-squared weighting)



EIC Impact relative to MSHT20 NNLO (as an example global fit)

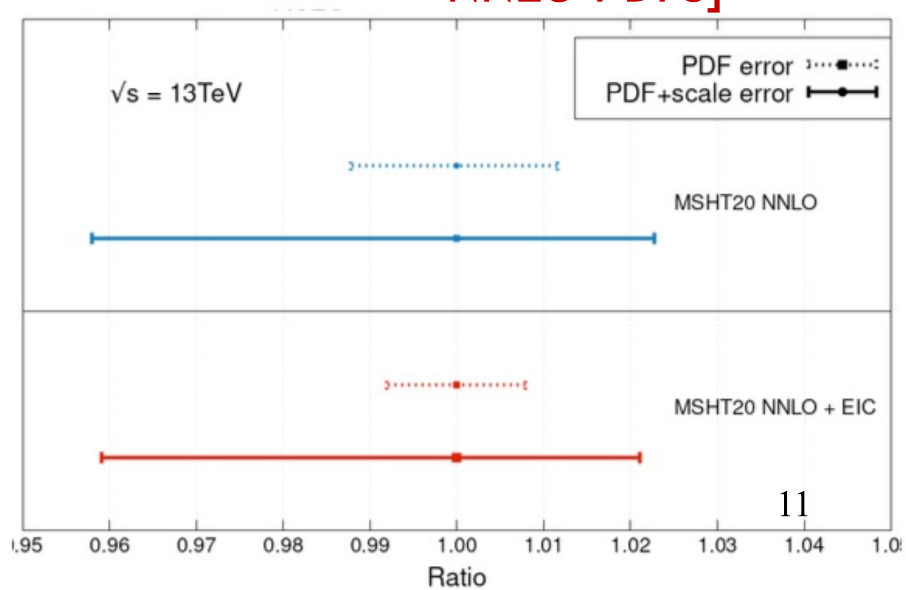


Significant impact of EIC simulated data in up quark precision as x→1

... small, but valuable improvements in all parton species at all x, Q^2

... e.g. gluon improvement feeds through parton-parton luminosities to significant improvement in PDF uncertainty on gg→H at LHC

σ(gg→H) uncertainties @ LHC [N^{3}LO matrix elements with NNLO PDFs]

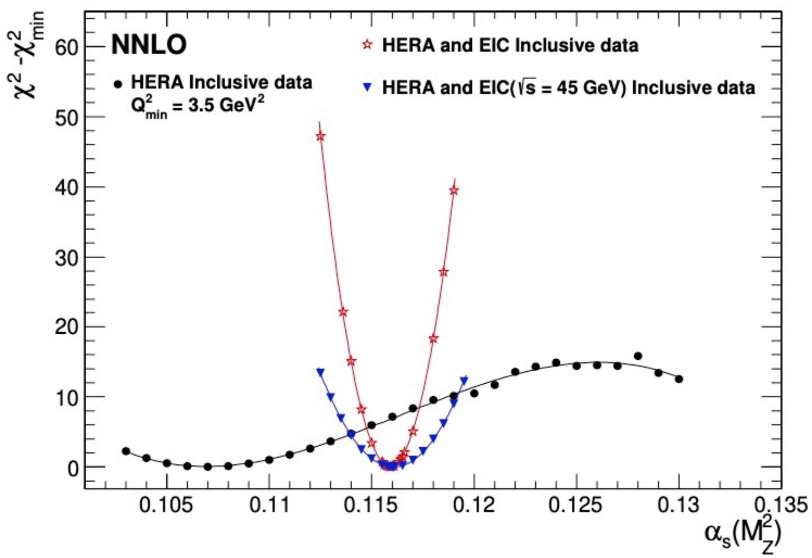


Taking α_s as an additional free parameter

Extraction of the strong coupling with HERA and EIC inclusive data

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

arXiv:2307.01183

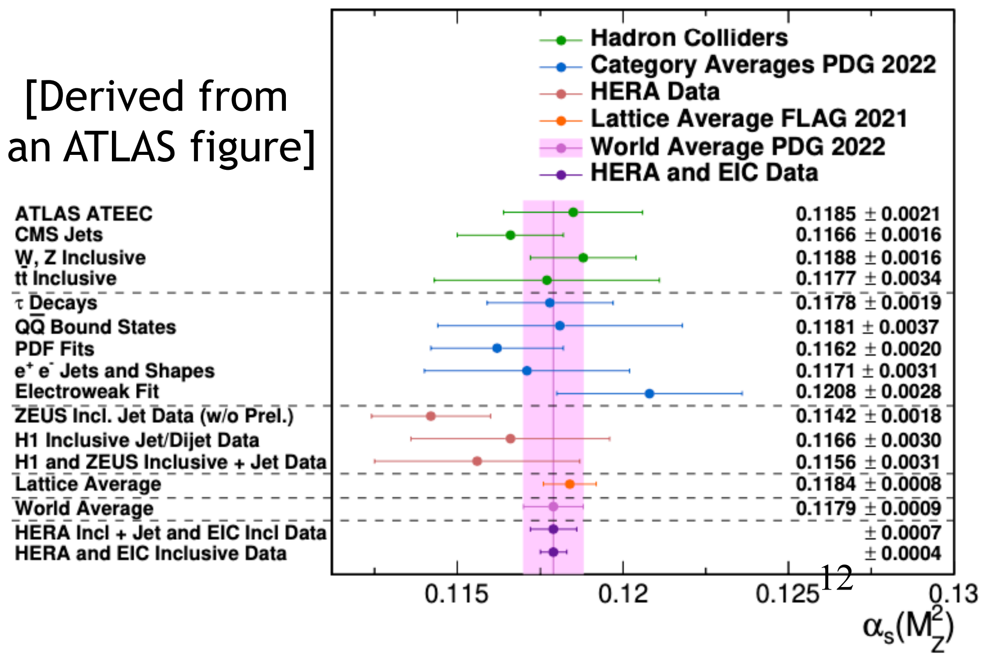


- HERA data alone (HERAPDF2.0) shows only limited sensitivity when fitting inclusive data only.

- Adding EIC simulated data has a remarkable impact

$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004 \text{ (exp)}$$
$$^{+0.0002}_{-0.0001} \text{ (model + parameterisation)}$$

[Derived from an ATLAS figure]



Precision high x EIC data leads to α_s precision a factor ~2 better than current world experimental average, and lattice QCD average

Scale uncertainties remain to be understood (ongoing work)

Another Approach to the Gluon Density: Longitudinal Structure Function

Prospects for Measurements of the longitudinal proton structure function F_L at the EIC

Javier Jiménez-López[1], Paul R. Newman[2], and Katarzyna Wichmann[3]

[Work in progress]

$$\frac{d^2\sigma^{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right] = \frac{2\pi\alpha^2 Y_+}{xQ^4}\sigma_r(x,Q^2,y)$$

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

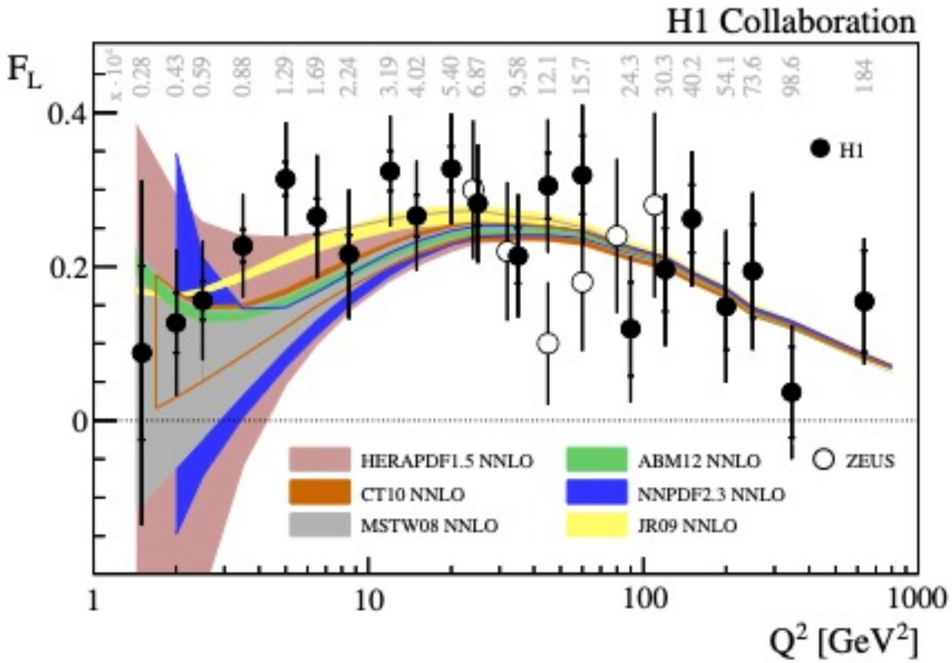
- F_L is closely related to the gluon density: ~ α_s g(x,Q^2) … so enthusiastically used in theory and PDF determinations

- Experimentally difficult, as only contributes strongly as y→1 and measured in combination with F2

- Standard experimental method is via 'Rosenbluth Decomposition' by measuring at multiple centre of mass energies, so fixed x and Q^2 correspond to varying y: Linear fit of cross section versus y^2/Y_+

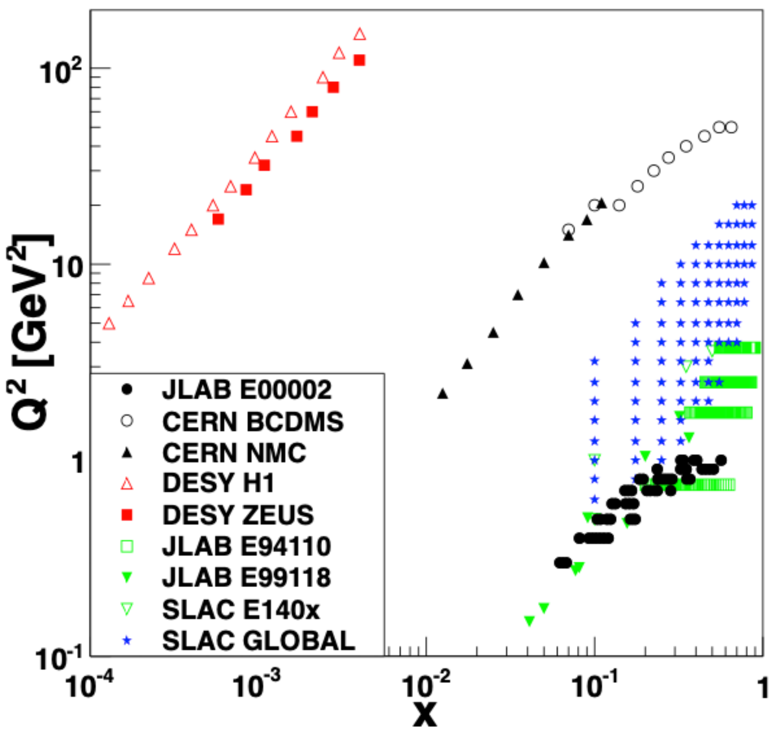
$$\sigma_r(x,Q^2,y) = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)$$

Previous Data



HERA – by varying E_p for short periods at very end of operations

World data (most recently from JLAb experiments)



Pseudodata

- EIC simulation based on 1 year's data in 5 different ep beam configurations

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

- Following previous studies for inclusive physics and PDFs, take 5 bins per decade in x, Q^2 at each beam energy

- Rosenbluth fits are very sensitive to uncertainties that are uncorrelated between different beam energies …

Consider 2 uncertainty scenarios (truth likely to be somewhere in between)

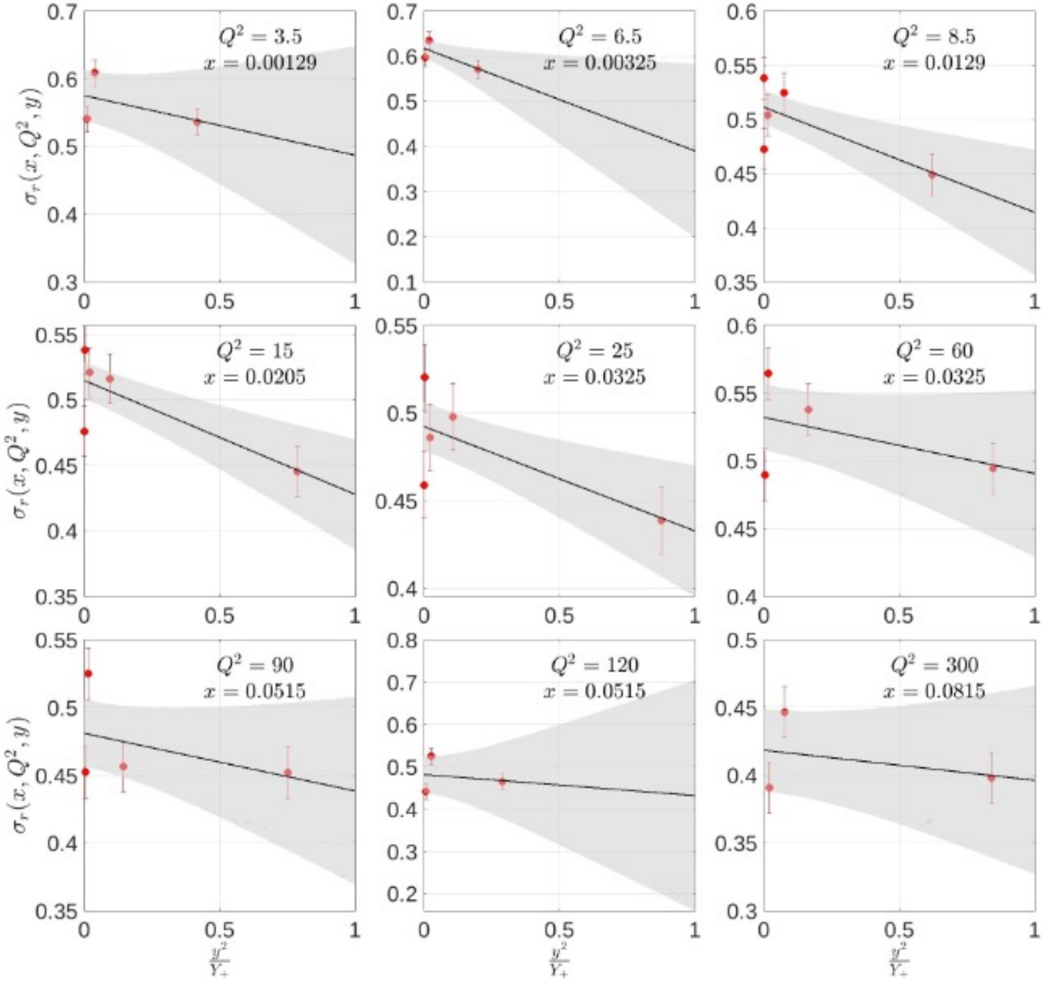
1) 'Conservative': 3.9% (assumed in ATHENA PDF fits, worse than HERA)

2) `Optimistic': 1% (assumed in corresponding diffractive studies)

… randomly smear data points accordingly before performing fits

Rosenbluth Fits
(Example Bins in Conservative Scenario)

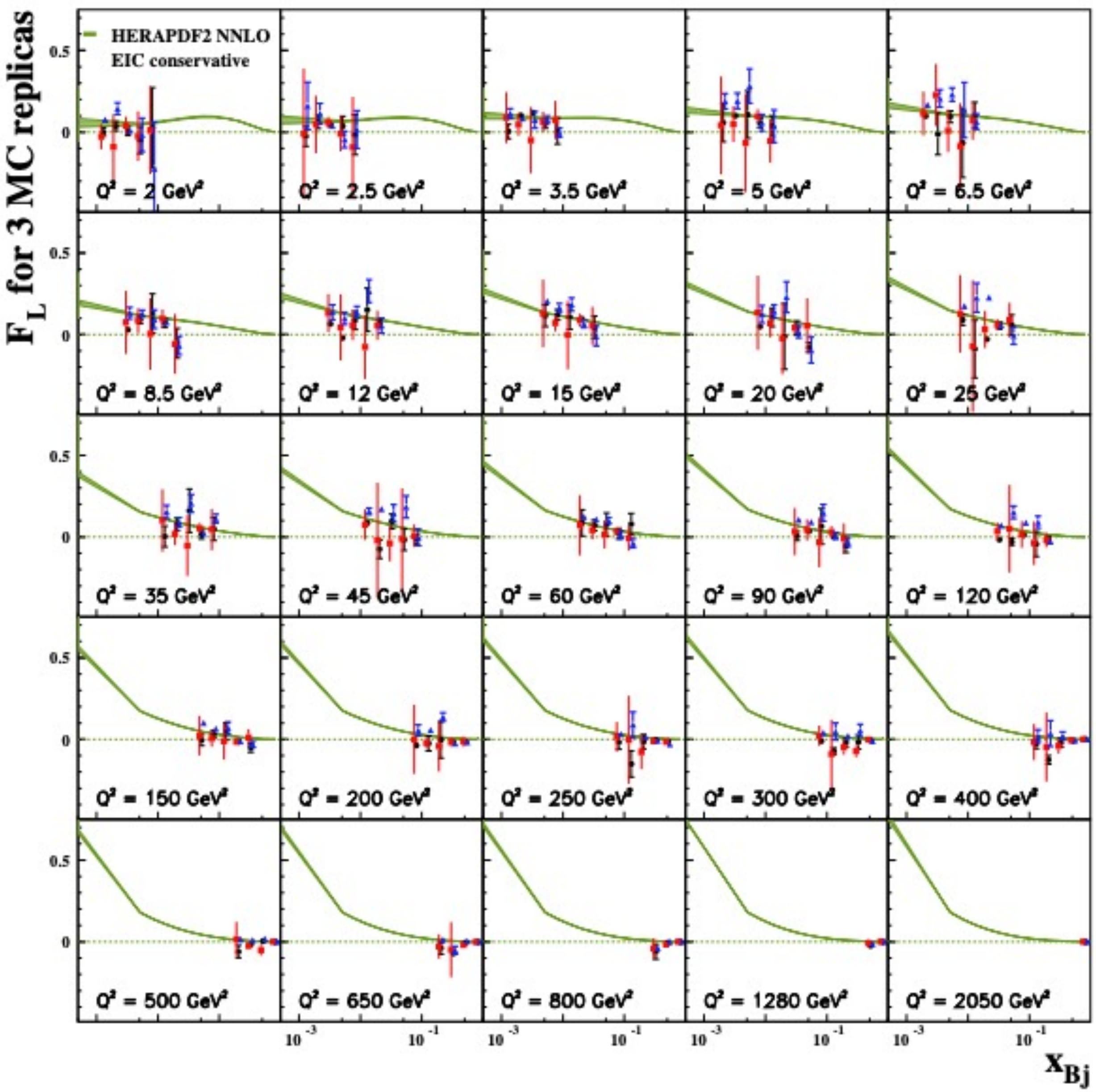
$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$



FL corresponds to the slope

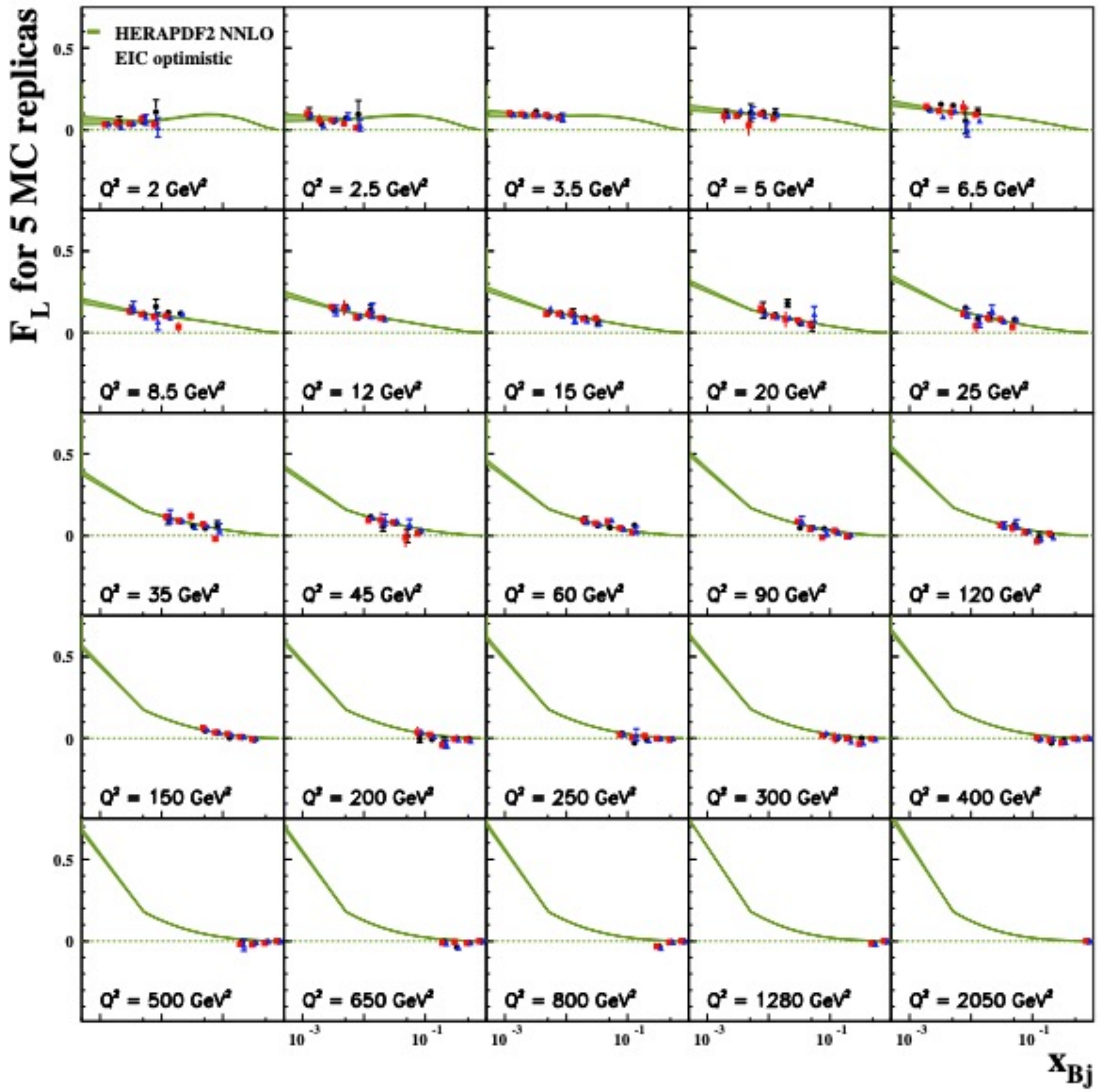
Grey bands are 1σ confidence bands from fits

Results in Conservative Scenario



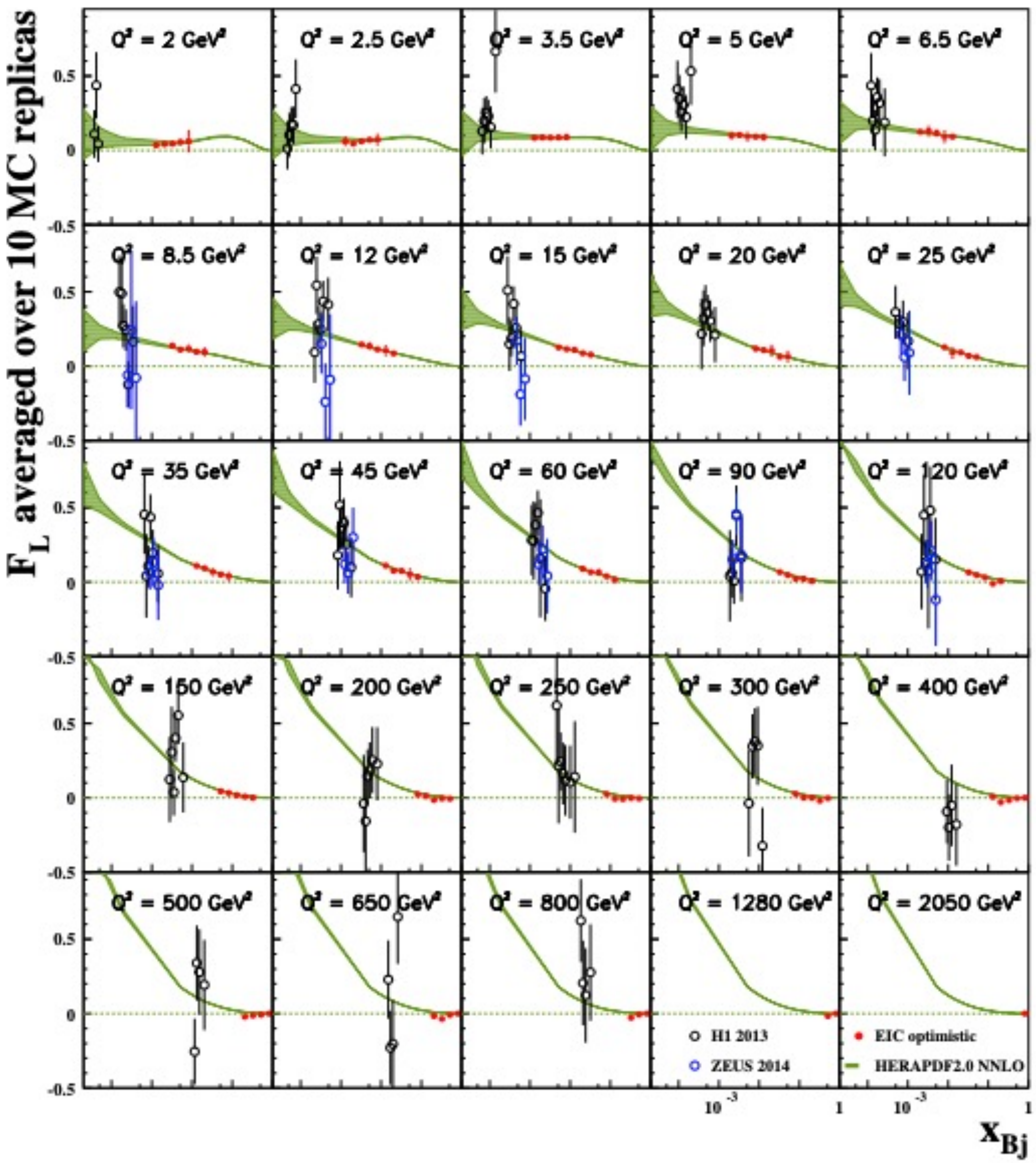
… shown for 3 different 'replicas' with different smearing of individual data Points

Results in Optimistic Scenario



… shown for
3 different
'replicas' with
different
smearing of
individual data
Points

Optimistic Scenario Compared with HERA



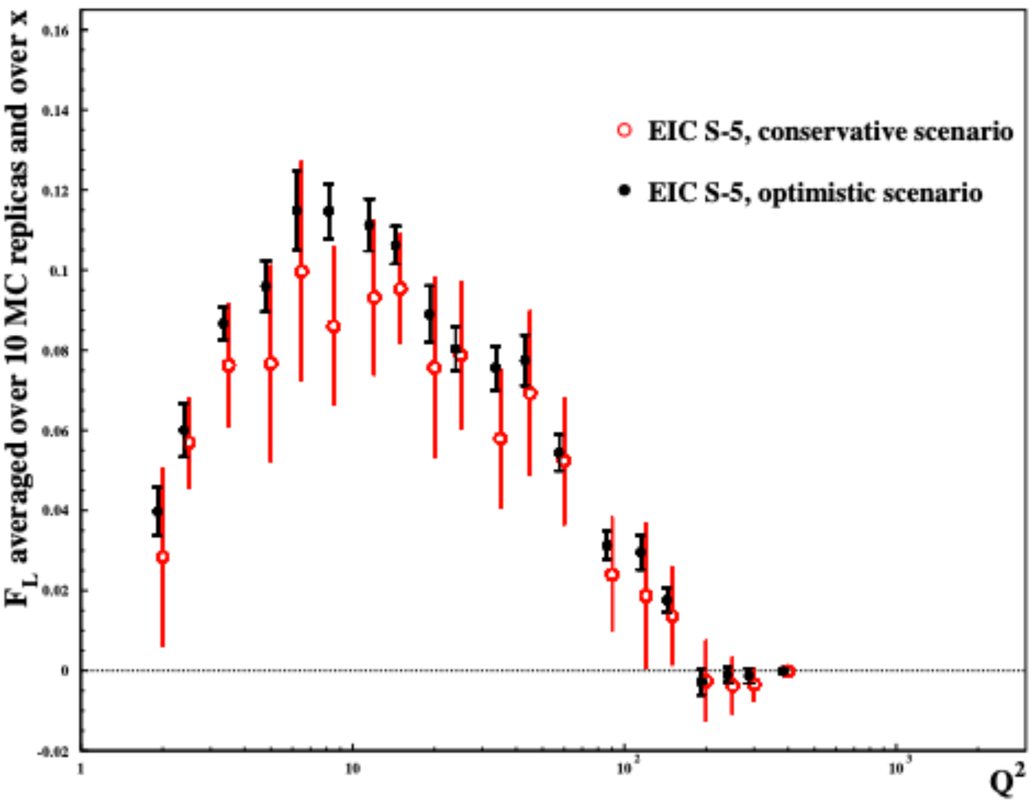
Averaged over many different scenarios

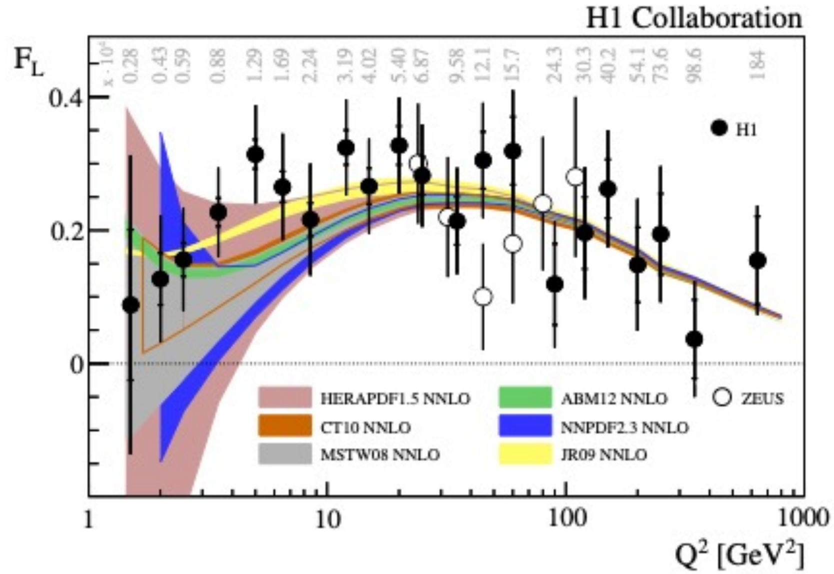
$$\overline{F_L} = \frac{\sum_{i=1}^{N} \omega_i F_L^{(i)}}{\sum_{i=1}^{N} \omega_i}, \qquad \omega_i = \frac{1}{\left[\Delta F_L^{(i)}\right]^2}.$$

$$\delta_{\text{avg}} = \sqrt{\frac{1}{\sum_{i=1}^{N} \omega_i}}.$$

and compared with HERA data

Averaging over x



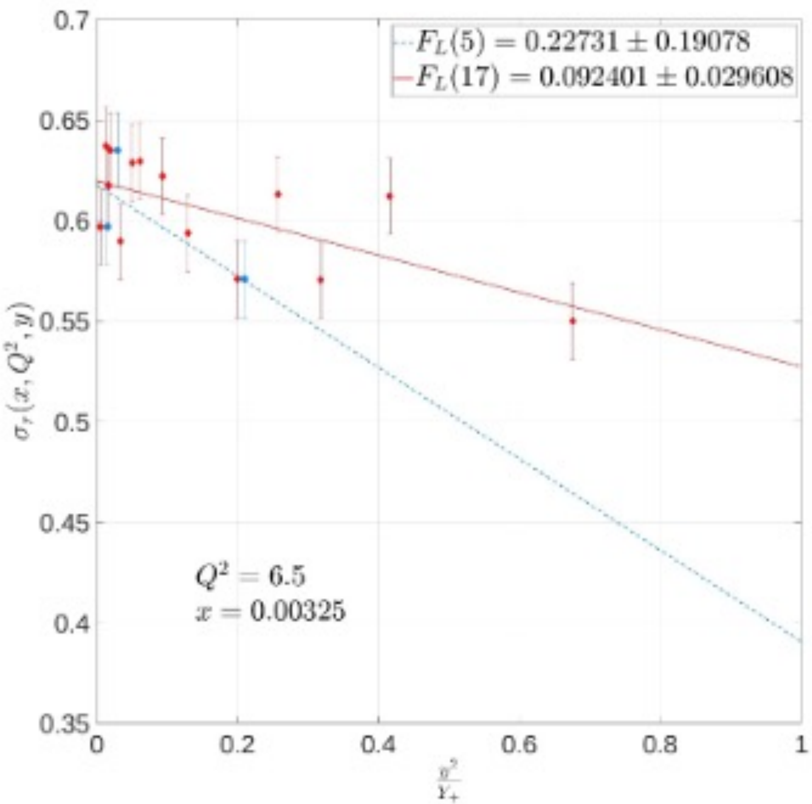


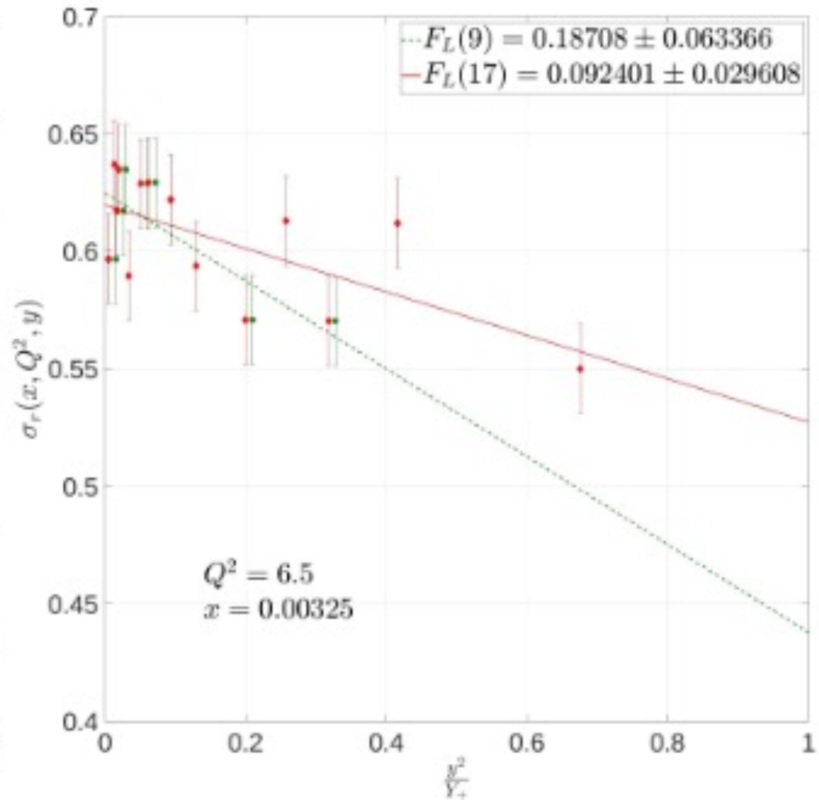
Adding more Beam Energy Configurations

		E_p [GeV]					
		41	100	120	165	180	275
E_e [GeV]	5	**29**	**45**	49	**57**	60	74
	10	40	**63**	69	**81**	85	**105**
	18	54	**85**	93	**109**	114	**141**

$F_L(9)$ adds the green-coded combinations

$F_L(17)$ adds all except (10 GeV, 180GeV)





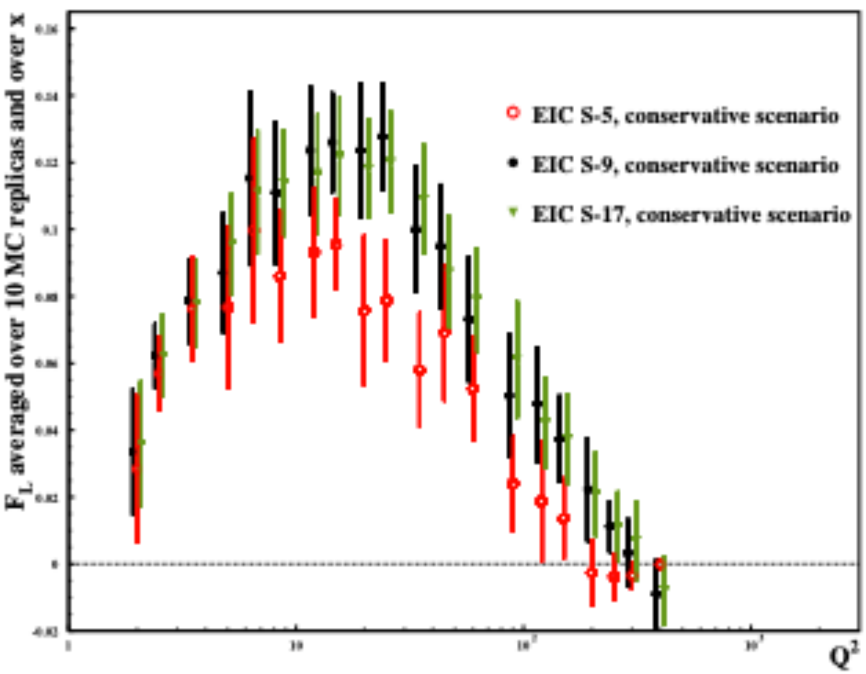
[Rosenbluth fits in example bin]

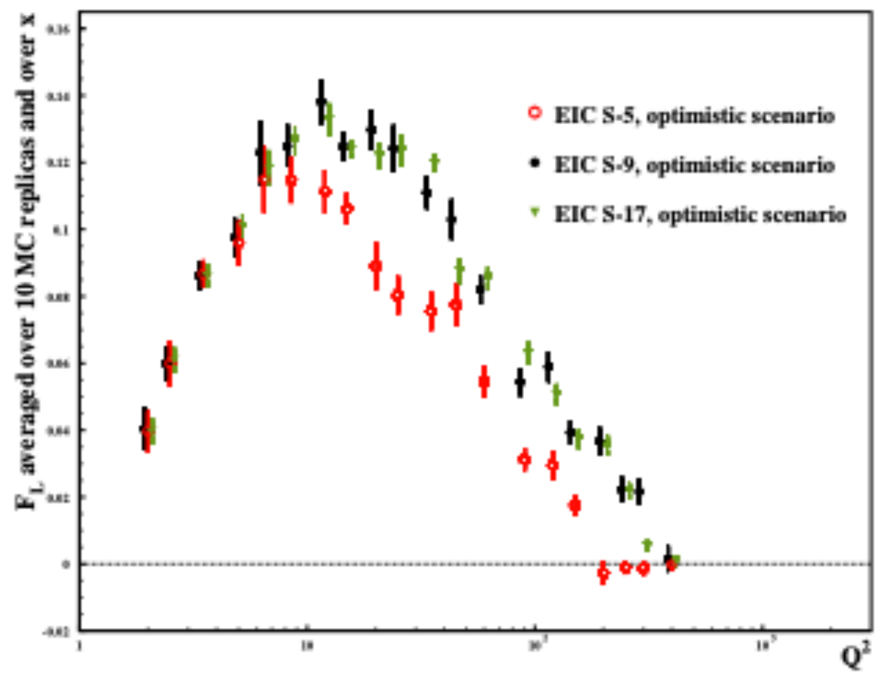
Adding more Beam Energy Configurations

E_e [GeV]		E_p [GeV]					
		41	100	120	165	180	275
	5	**29**	**45**	49	**57**	60	74
	10	40	**63**	69	**81**	85	**105**
	18	54	**85**	93	**109**	114	**141**

$F_L(9)$ adds the green-coded combinations

$F_L(17)$ adds all except (10 GeV, 180GeV)





The F_L world in 2045? (5 configs only)