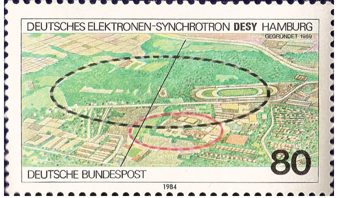
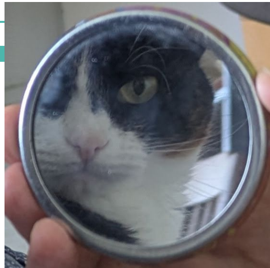


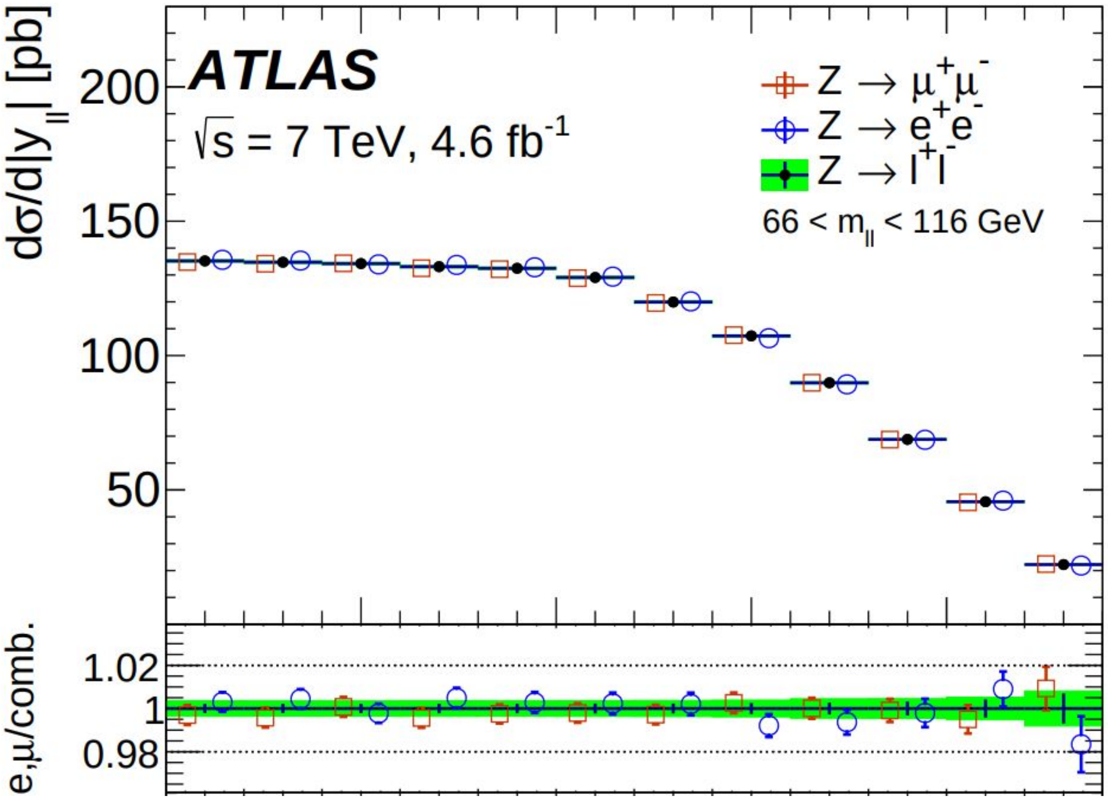
H1 and ZEUS combination

S. Glazov, 11 Dec 2025

Based on JHEP 03 (2010) 035



Example of two "detectors" measuring the same quantity

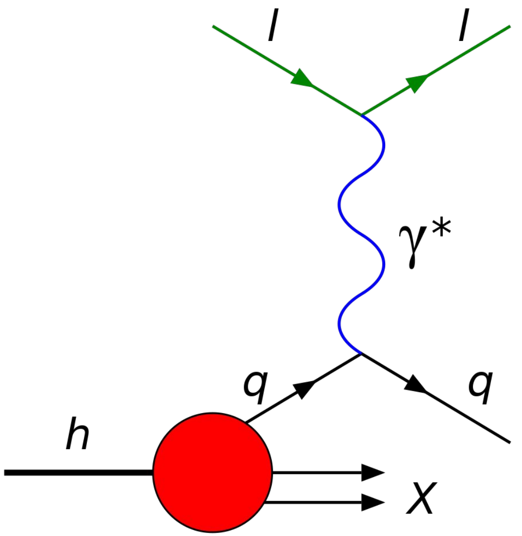


An example of detector cross-calibration: differential measurement of $Z \rightarrow ll$ at the LHC using electron and muon final state.

From JHEP 12 (2017) 059

Can something similar be done for DIS experiments?

Inclusive DIS cross section

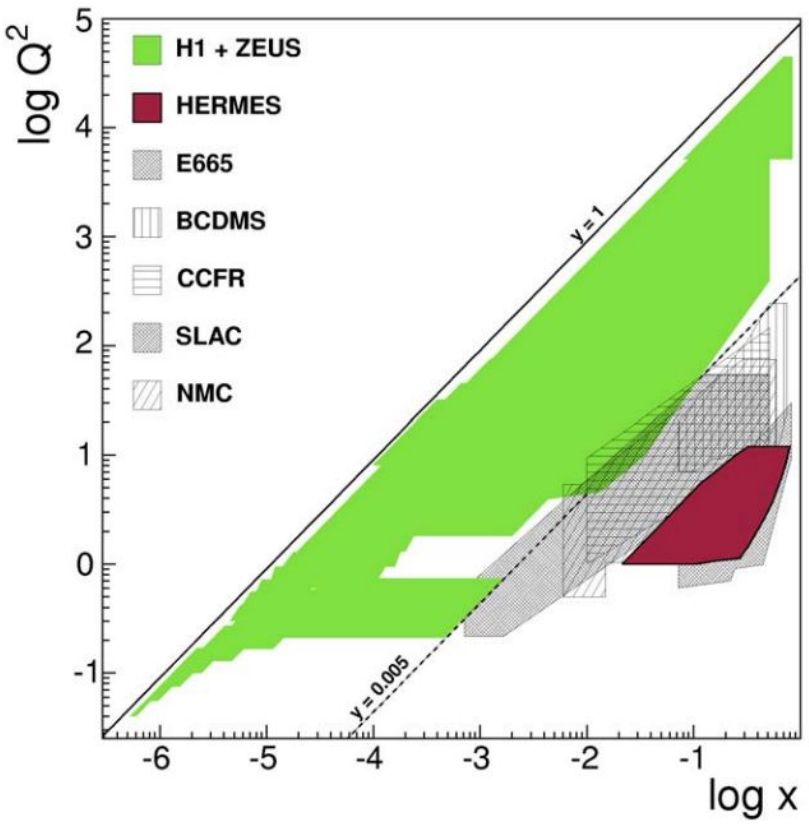


$$\frac{d^2\sigma^{NC}_{e^{\mp}p}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L \pm \frac{Y_-}{Y_+}xF_3\right)$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

- Inclusive neutral and charged current differential cross sections defined by Bjorken x, momentum transfer Q^2 and inelasticity y
- The kinematic variables can be reconstructed using scattered lepton and hadronic final state

Kinematic coverage at HERA



- Experimental results cover 1<y<0.002 and 0.1< Q^2<10^5 GeV^2 kinematic range with the most precise measurements between 0.5<y<0.02
- Results are based on several sub-detectors and different kinematic reconstruction methods

Kinematic reconstruction: electron method

$$\Sigma_e = E'_e(1 - \cos\theta_e),$$

(+Z is along p-beam)

$$y_e = 1 - \frac{\Sigma_e}{2E_e}, \qquad Q_e^2 = \frac{P_{T,e}^2}{1 - y_e}, \qquad x_e = \frac{Q_e^2}{s y_e}.$$

- Reconstruct event kinematics using beam energy and scattered electron kinematics
- Best resolution for y approaching 1, degrades as *1/y* for low *y*.
- Best Q^2 resolution
- Strong impact of QED ISR
- Measurement at low Q^2 and moderate *y* requires instrumentation at small scattering angles.

Kinematic reconstruction: sigma method

$$2E_e = E - P_z = E'_e(1 - \cos\theta_e) + \sum_i (E_i - p_{z,i}) = \Sigma_e + \Sigma_h,$$

$$y_h = \frac{\Sigma_h}{2E_e}, \qquad y_\Sigma = \frac{\Sigma_h}{E - P_z}, \qquad Q^2_\Sigma = \frac{P^2_{T,e}}{1 - y_\Sigma}, \qquad x_\Sigma = \frac{Q^2_\Sigma}{s y_\Sigma}$$

- Use energy-momentum conservation to define hadron reconstruction methods
  - Little sensitivity to losses in the forwarded region
  - Good resolution for $0.01 < y < 0.1$
- "Sigma method": reconstruction of y is not sensitive to **QED ISR**
  - Several modifications of the method:
    - E-sigma method: keep Q^2 from electron method (better resolution)
    - x can be computed using modified s too.

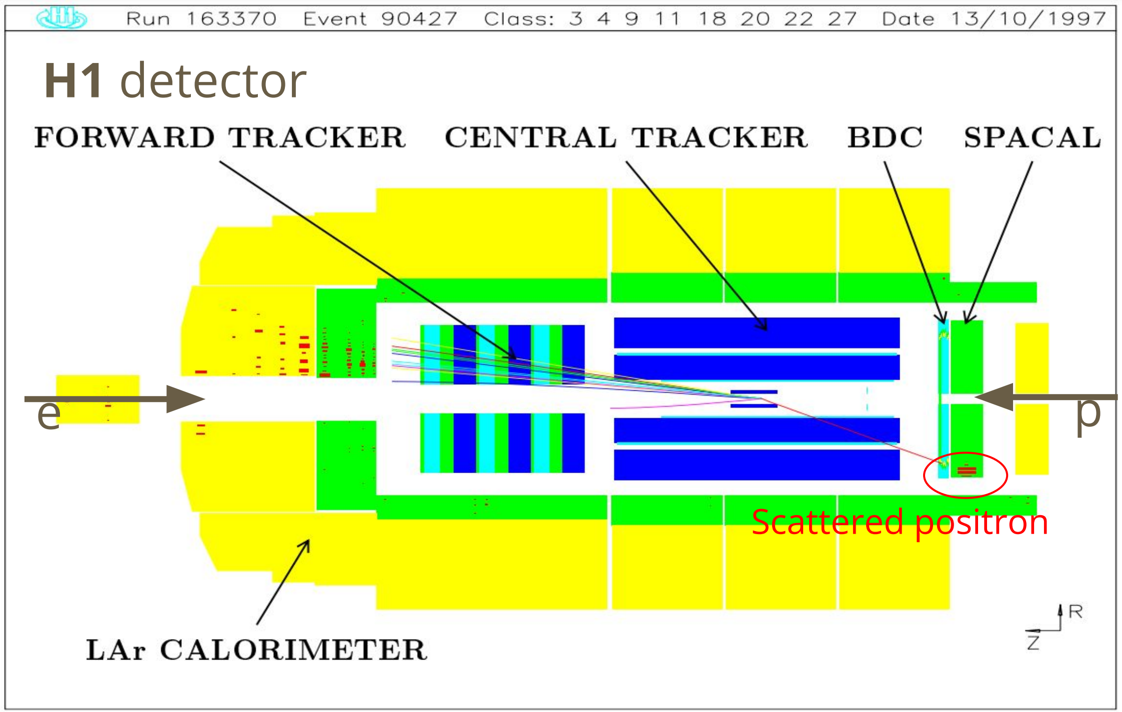
Kinematic reconstruction: double angle method

$$y_{DA} = \frac{\tan(\theta_h/2)}{\tan(\theta_e/2) + \tan(\theta_h/2)}, \qquad Q^2_{DA} = 4E_e^2 \cdot \frac{\cot(\theta_e/2)}{\tan(\theta_e/2) + \tan(\theta_h/2)}, \qquad x_{DA} = \frac{Q^2_{DA}}{s y_{DA}}$$

$$\tan\frac{\theta_h}{2} = \frac{\Sigma_h}{P_{T,h}}$$

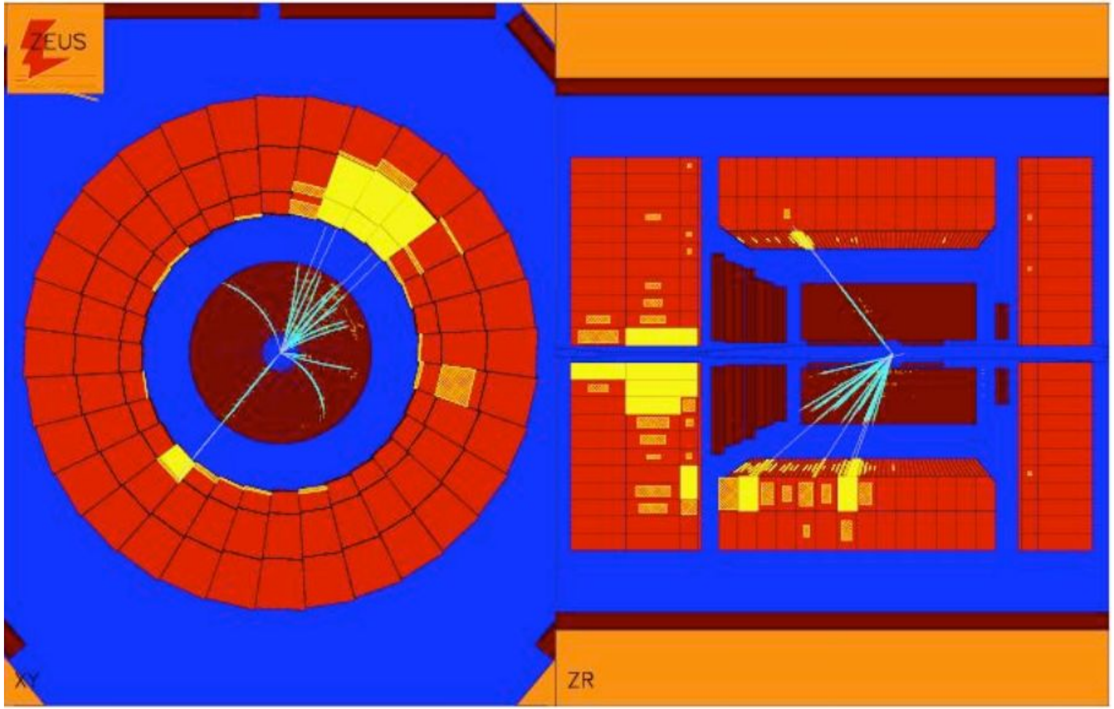
- Double angle method is to first order not sensitive to the measured energies
- Good resolution for $0.02<y<0.5$
- Modifications of the method to use electron $P_{t,e}$ instead of $P_{T,h}$ to compute hadron angle ("PT" method)

H1 detector



- Good electromagnetic calorimeters (EM SpaCal and LAr)
- Good central and backward tracking – standalone electron reconstruction
- Relatively poor backward hadronic calorimeter, poorly performing forward tracking
- Prefered reconstruction methods: electron, sigma and e-sigma.
- Largely independent measurements with the electron reconstructed in SPACAL vs LAr

ZEUS detector



- Compensating hadronic calorimeter with excellent energy resolution
- Very good central tracker
- Main reconstruction method: (modified) double angle. Electron method used in some cases
- Additional detectors to measure in low Q^2 domain (BPC, BPT)

Summary of the measurements

Data Set		x Range		Q^2 Range GeV^2		$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	x,Q^2 Reconstruction Method Equation
H1 svx-mb	95-00	5×10^{-6}	0.02	0.2	12	2.1	e^+p	301-319	10,14,16
H1 low Q^2	96-00	2×10^{-4}	0.1	12	150	22	e^+p	301-319	10,14,16
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301	15
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301	11
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319	15
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319	11
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319	10
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319	15
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319	11
ZEUS BPC	95	2×10^{-6}	6×10^{-5}	0.11	0.65	1.65	e^+p	301	10
ZEUS BPT	97	6×10^{-7}	0.001	0.045	0.65	3.9	e^+p	301	10, 15
ZEUS SVX	95	1.2×10^{-5}	0.0019	0.6	17	0.2	e^+p	301	10
ZEUS NC	96-97	6×10^{-5}	0.65	2.7	30000	30.0	e^+p	301	18
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	301	11
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	319	17
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	319	11
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	319	17
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	319	11

10: electron,

14,16: sigma

11: hadron

15: e-sigma

18: PT

17: double angle

Most important systematic uncertainties

- Global normalizations: luminosity measured with Bethe-Heitler scattering ($ep \to ep\gamma$): common 0.5% from theory, otherwise 1-2%
- EM energy scale (0.5%): dominant for e-method at low y
- HAD energy scale (1%): important for low y
- Calorimeter noise: dominant for the lowest $y < 0.01$
- Photoproduction background: largest for $y>0.5$
- Selection efficiencies (2%): one of the main sources for bin-to-bin un-correlated systematics

Combination procedure

$$\chi^2_{\exp}(\boldsymbol{m}, \boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,\mathrm{stat}}\, \mu^i \left(m^i - \sum_j \gamma^i_j m^i b_j\right) + \left(\delta_{i,\mathrm{uncor}}\, m^i\right)^2} + \sum_j b^2_j\,.$$

- Data provided in bins of *(Q^2,x)*, corrected to bin centers, as reduced cross section: correct to a common grid, keep data at different CME and high y>0.35 uncombined
- Statistical uncertainties provided as uncorrelated together with MC stats and some of the systematic sources while most of systematic sources are correlated.
- Assume “improved χ^2” statistics: multiplicative corrections for systematics, poisson-like treatment for statistics, correlated systematic uncertainties propagated using nuisance parameters b

Correlation model

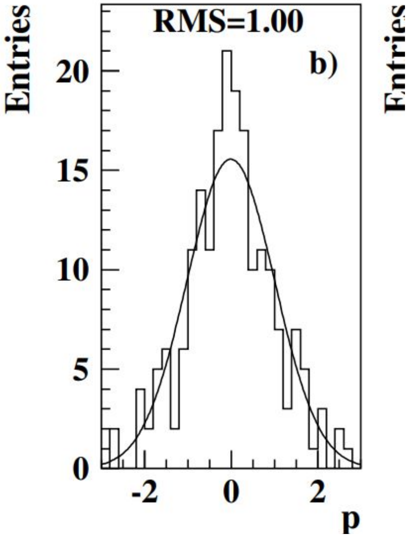
Source	Data Samples
H1 E'_e	δ_1 H1 NC[4] — δ_1 H1 NC HY[5] — δ_1 H1 NC[3] — δ_1 H1 NC[5]
H1 E_h	δ_2 H1 CC[3] — δ_2 H1 CC[5] — δ_2 H1 CC[4] — δ_3 H1 NC[4] — δ_3 H1 NC HY[5] — δ_3 H1 NC[3] — δ_3 H1 NC[5]
H1 γp asymmetry	δ_6 H1 NC HY[5] — δ_6 H1 NC[5]
H1 γp background	δ_4 H1 CC[3] — δ_4 H1 CC[5] — δ_4 H1 CC[4] — δ_5 H1 NC[4] — δ_5 H1 NC HY[5] — δ_5 H1 NC[3] — δ_5 H1 NC[5]
H1 θ_e	δ_2 H1 NC[4] — δ_2 H1 NC HY[5] — δ_2 H1 NC[5]
H1 CC cuts	δ_1 H1 CC[5] — δ_1 H1 CC[4]
H1 LAr Noise	δ_3 H1 CC[3] — δ_3 H1 CC[5] — δ_3 H1 CC[4] — δ_4 H1 NC[4] — δ_4 H1 NC HY[5] — δ_4 H1 NC[3] — δ_4 H1 NC[5]
H1 Lumi 94 – 97	δ_5 H1 CC[3] — δ_6 H1 NC[3]
H1 Lumi 98 – 99	δ_5 H1 CC[4] — δ_6 H1 NC[4] — δ_7 H1 NC HY[5]
H1 Lumi 99 – 00	δ_5 H1 CC[5] — δ_7 H1 NC[5]
ZEUS E'_e	δ_1 ZEUS NC[11] — δ_1 ZEUS NC[13]
ZEUS E_h a	δ_1 ZEUS CC[12] — δ_1 ZEUS CC[14]
ZEUS E_h b	δ_2 ZEUS CC[12] — δ_2 ZEUS CC[14]
ZEUS E_h in BCAL	δ_2 ZEUS CC[10] — δ_6 ZEUS NC[9]
ZEUS E_h in FCAL	δ_1 ZEUS CC[10] — δ_5 ZEUS NC[9]
ZEUS δ cut	δ_8 ZEUS BPC[6] — δ_1 ZEUS BPT[7]
ZEUS γp background	δ_2 ZEUS NC[11] — δ_2 ZEUS NC[13]
ZEUS γp background	δ_9 ZEUS BPC[6] — δ_{14} ZEUS BPT[7] — δ_8 ZEUS SVX[8]
ZEUS y_h cut	δ_3 ZEUS BPC[6] — δ_2 ZEUS BPT[7]
ZEUS BPC linearity	δ_5 ZEUS BPC[6] — δ_9 ZEUS BPT[7]
ZEUS BPC shower	δ_4 ZEUS BPC[6] — δ_3 ZEUS BPT[7]
ZEUS CAL energy	δ_2 ZEUS BPC[6] — δ_{12} ZEUS BPT[7] — δ_9 ZEUS SVX[8]
ZEUS Cuts_1	δ_3 ZEUS NC[11] — δ_3 ZEUS NC[13]
ZEUS Cuts_2	δ_4 ZEUS NC[11] — δ_4 ZEUS NC[13]
ZEUS HFS model	δ_3 ZEUS CC[10] — δ_3 ZEUS CC[12] — δ_6 ZEUS NC[11] — δ_6 ZEUS NC[13] — δ_3 ZEUS CC[14]
ZEUS Lumi 94 – 97	δ_4 ZEUS CC[10] — δ_{11} ZEUS NC[9]
ZEUS Lumi 98 – 99	δ_4 ZEUS CC[12] — δ_7 ZEUS NC[11]
ZEUS Lumi 99 – 00	δ_9 ZEUS NC[13] — δ_4 ZEUS CC[14]

Several systematic sources are considered correlated across publications

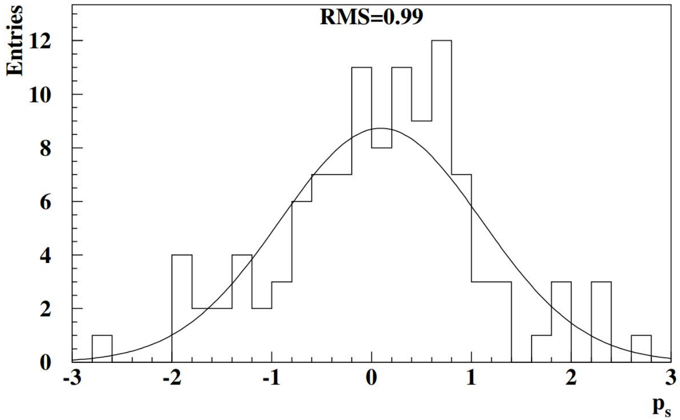
Common 0.5% for all data samples due to theoretical uncertainty on Bethe-Heitler process

Uncertainties are predominantly uncorrelated between H1 and ZEUS (other assumptions tested, included as “procedural uncertainty”)

Combined result: pulls



$$p^{i,e} = \frac{\mu^{i,e} - \mu^{i,\mathrm{ave}}\left(1 - \sum_j \gamma_j^{i,e} b_{j,\mathrm{ave}}\right)}{\sqrt{\Delta_{i,e}^2 - \Delta_{i,\mathrm{ave}}^2}}$$



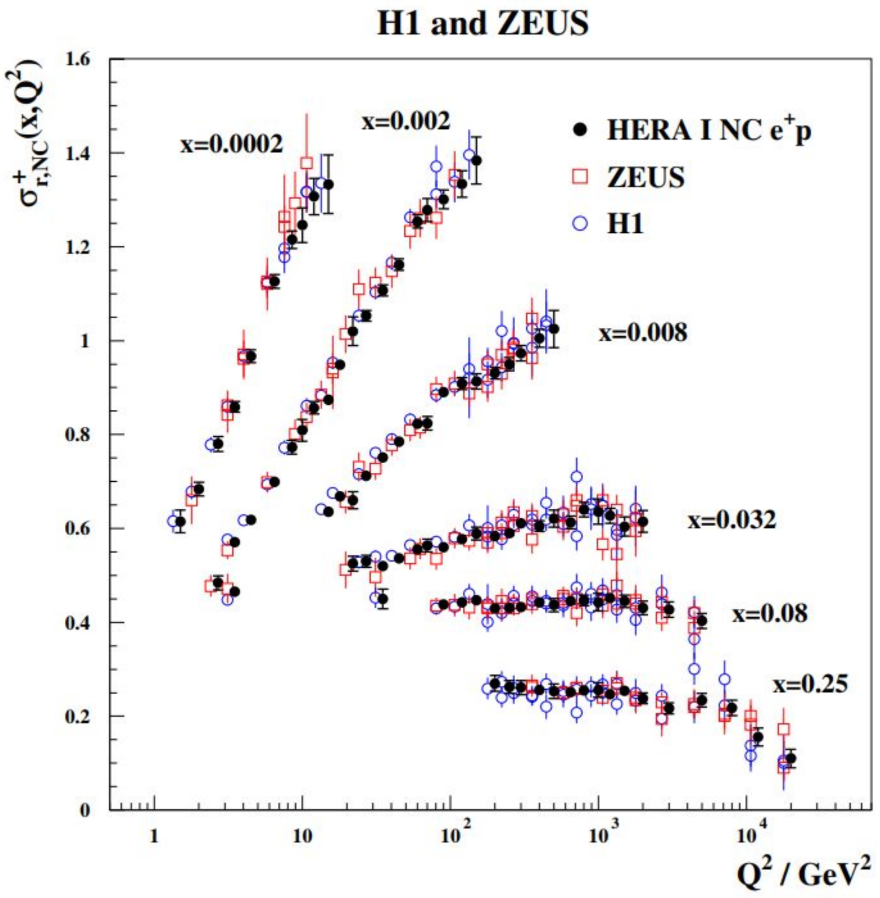
$$p_s = b_{j,\mathrm{ave}} / (1 - \Delta^2_{b_j,\mathrm{ave}})^{1/2}$$

Data set	Shift b	($b\gamma_{\mathrm{norm}}$)
H1 svx-mb [1]	−0.24	(−0.2%)
H1 low Q^2 [2]	−0.45	(−0.4%)
H1 94 – 97 [3]	−0.65	(−0.9%)
H1 98 – 99 [4,5]	−0.05	(−0.1%)
H1 99 – 00 [5]	−0.19	(−0.3%)
ZEUS BPC [6]	0.23	(0.3%)
ZEUS BPT [7]	−0.03	(−0.1%)
ZEUS SVX [8]	0.78	(1.2%)
ZEUS 94 – 97 [9,10]	0.44	(0.8%)
ZEUS 96 – 97 low Q^2 [9]	−1.10	(−1.1%)
ZEUS 98 – 99 [11,12]	0.05	(0.1%)
ZEUS 99 – 00 [13,14]	−0.18	(−0.4%)

Global Norm. shifts

- Good overall agreement of the data: 636.5/656
- Good pull distributions for data points and systematic sources

Combined result: cross sections



→Similar uncertainties of individual measurements

→Significant reduction of uncertainties for the combined measurement

Combined results: effects on systematic

- Examples of sources with significant reduction:
  - H1 LAr calorimenter scale reduced by 55%
  - ZEUS photoproduction background uncertainty reduced by 65%
- In some cases, systematics is reduced since it would generate “kinks” in the reduced cross sections (e.g. due transition from electron to sigma method) which were not allowed by measurement using different method
- In other cases, precision of one of the two detectors was superior

For discussion

- H1 and ZEUS decided on significantly different technologies for DIS event reconstruction
- This resulted in naturally preferred kinematic reconstruction methods, with different pattern of systematic uncertainties
- In addition, detectors excel in complementary kinematic regions

➔ Significant constraints on systematics, reduction of total uncertainties for the combined results

Can one replicate this at EIC?

- Kinematic coverage of the detectors should be similar for a large portion of phase space, while “gaps” (e.g. central vs endcaps) should be at different locations
- Best if one detector is excellent for the scattered electron while the other – for the hadrons
- Accuracy of the two experiments should be roughly comparable for the bulk of the phase space
- An early agreement on a more or less common binning, unfolding scheme