Novel Measurements of Proton Structure at HERA

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On behalf of the H1 and ZEUS collaborations

Rencontres de Moriond
QCD and High Energy Interactions
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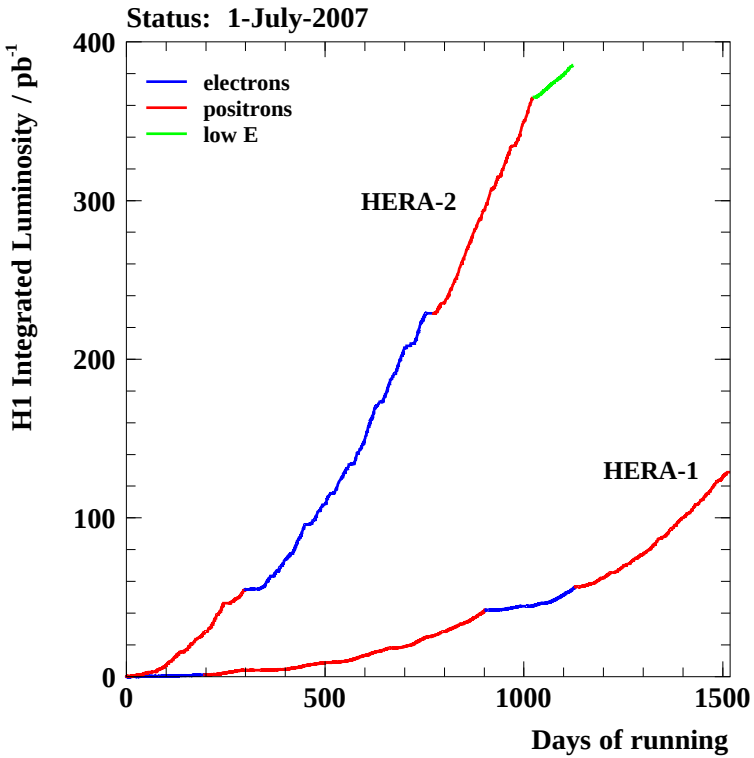
HERA, H1 and ZEUS

HERA collided protons with longitudinally polarized $e^{\pm}$

- H1 and ZEUS were multi-purpose collider detectors at HERA
- 0.5 fb^{-1} luminosity taken by each experiment



HERA Energies

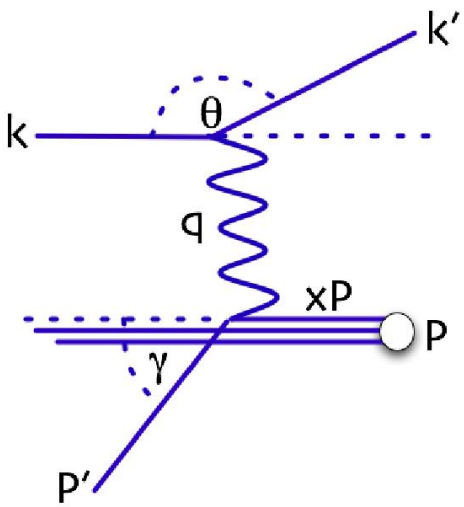
p beam: 920 GeV

$e^{\pm}$ beam: 27.5 GeV

Centre of mass energy: 318 GeV

Mean polarization: 30 - 40%

Kinematics & Deep Inelastic Scattering



Neutral current
exchange of γ or Z°
Charged current
exchange of $W^\pm$

Probing power of the lepton:

$$Q^2 = -q^2 = -(k - k')^2 = sxy$$

Bjorken scaling variable, the fraction of the proton's momentum carried by the struck quark

$$x = \frac{Q^2}{2p.q}$$

Inelasticity, the energy fraction transferred from the lepton in the proton's rest frame

$$y = \frac{p.q}{p.k}$$

Centre of mass energy squared:

$$s = (p + k)^2$$

Neutral Current Cross Sections

Unpolarised neutral current reduced cross section

$$\tilde{\sigma}_{NC}^{e^{\pm}p} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = F_2 \mp \frac{Y_-}{Y_+}xF_3 - \frac{y^2}{Y_+}F_L$$

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

Structure functions at Leading Order

F_2	$\propto \sum(q+\overline{q})$	Dominant contribution
xF_3	$\propto \sum(q-\overline{q})$	Contributes at high Q^2 (γZ interference)
F_L	$= 0$	Zero at Leading Order

Charged Current Cross Sections

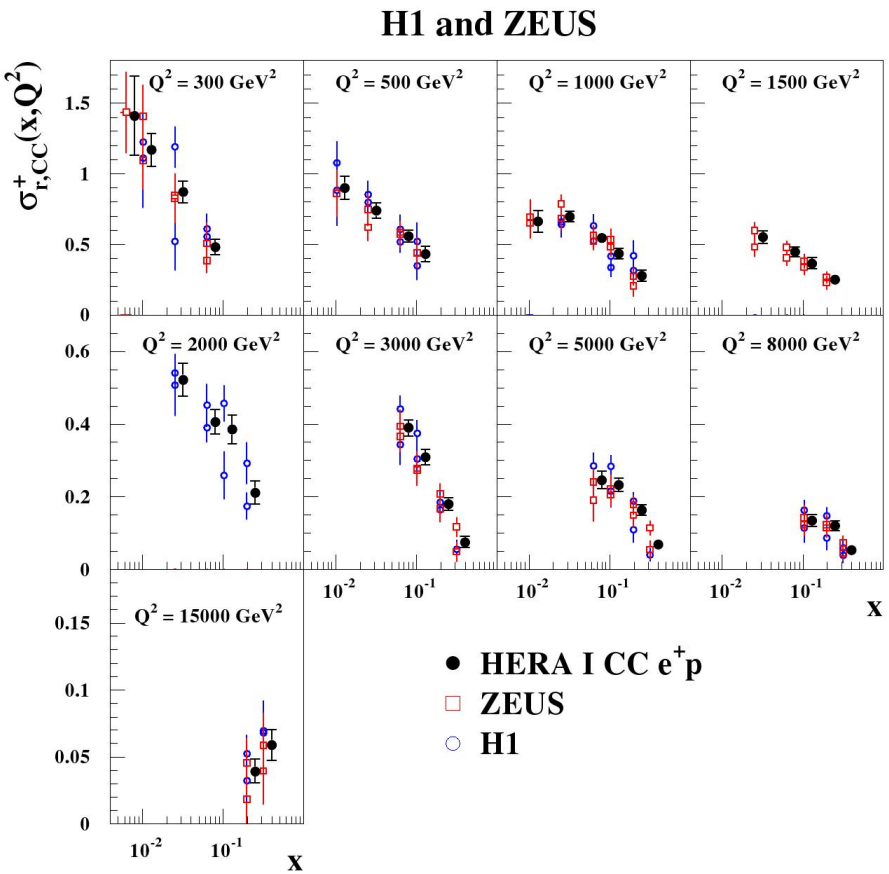
Charged current reduced cross section

$$\tilde{\sigma}(e^- p)_{CC} = (1 - P_e)\,[u + c + (1 - y)^2(\overline{d} + \overline{s})]$$
$$\tilde{\sigma}(e^+ p)_{CC} = (1 + P_e)\,[\overline{u} + \overline{c} + (1 - y)^2(d + s)]$$

- Linear polarisation dependence
- Electron (positron) data is sensitive to u (d) valence quark
- Probes flavour structure of the proton

HERA-I Inclusive Cross Section Combination

- H1 & ZEUS have combined inclusive cross sections from HERA I data ($\sim 115\ \text{pb}^{-1}$ per experiment)
- Combination procedure:
  1. Swim all points to a common $Q^2 - x$ grid
  2. Move 820 GeV data to 920 GeV p-beam energy
  3. Calculate average values and uncertainties
  4. Evaluate procedural uncertainties
- Data combination uses χ^2 minimisation method

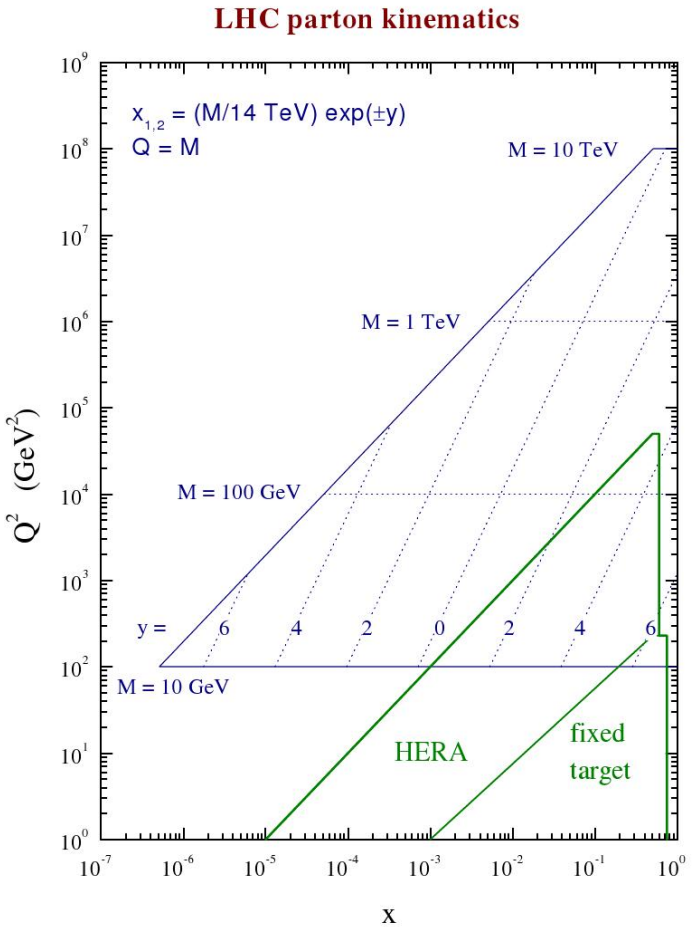


Overall precision is improved
$\chi^2/\text{NDF} = 637/656$

QCD Fits

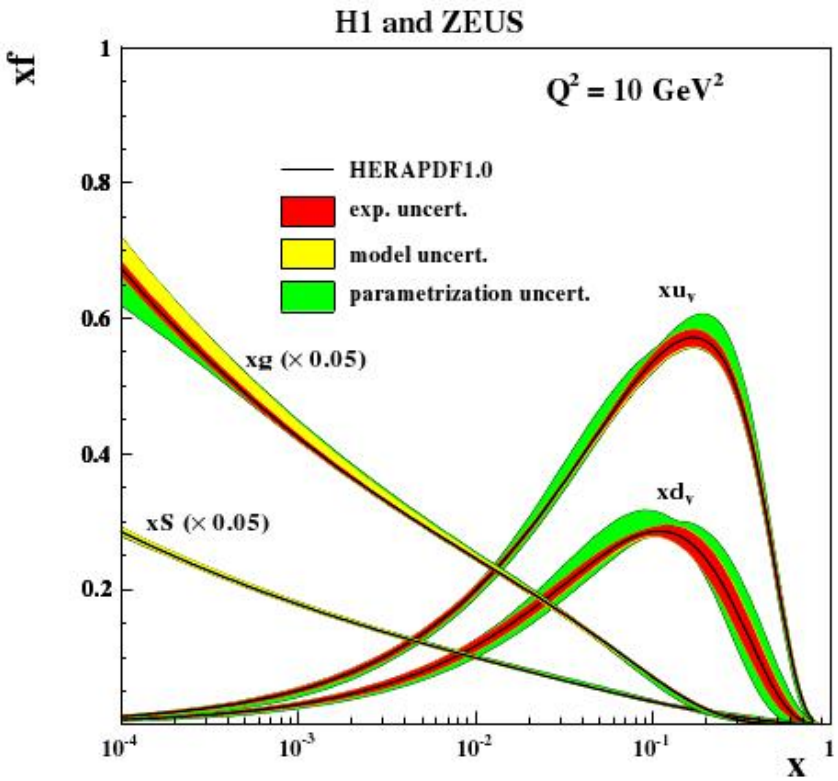
- NC and CC reduced cross sections are the main input used to determine Parton Distribution Functions (PDFs) by performing QCD Fits

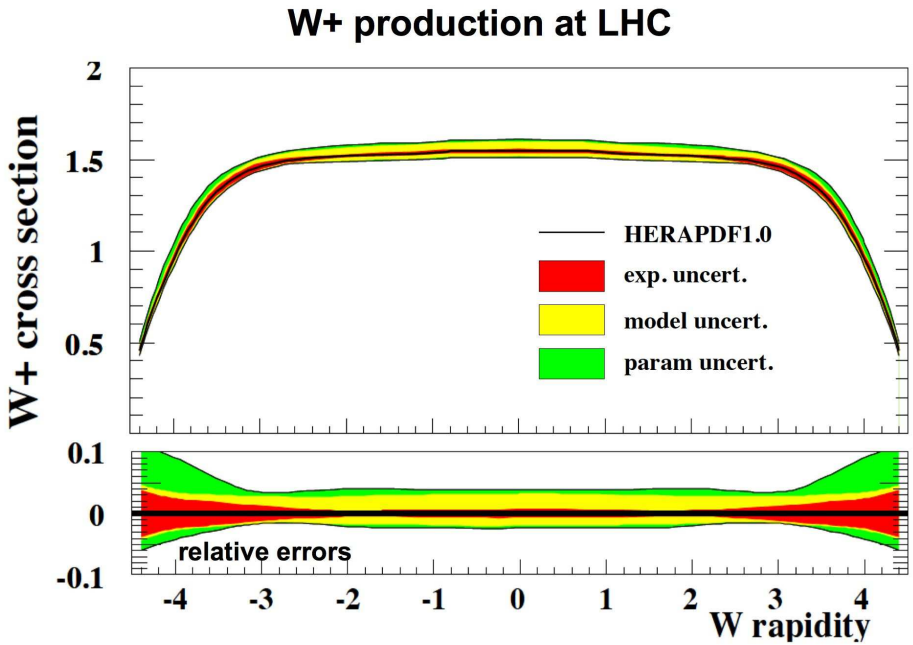
- Measure $\tilde{\sigma}$ for polarised data
- Obtain F_2, xF_3 and extract the PDFs: $q(x, Q^2)$, $\overline{q}(x, Q^2)$, $g(x, Q^2)$
- Proton PDFs are an important input for LHC physics
- Evolve PDFs to the LHC kinematic region with DGLAP equations
- Only need to evolve in Q^2 since HERA x range is comparable to that of LHC



HERAPDF1.0

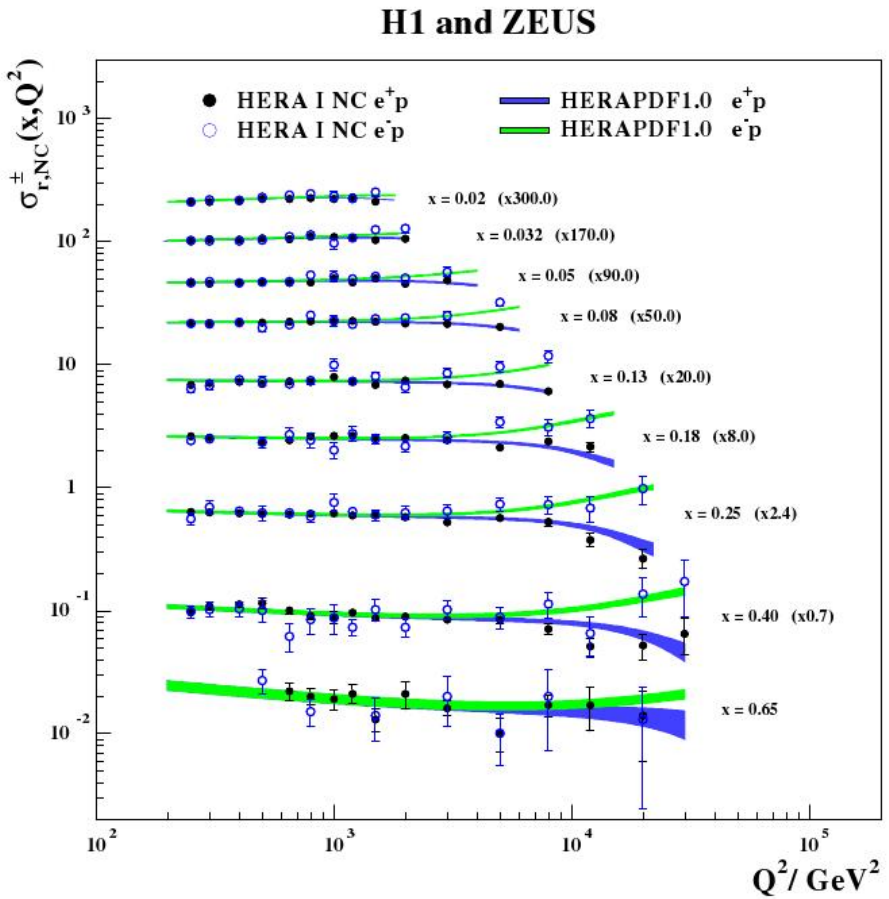
Combined HERA-I data are the sole input in determination of a new set of PDFs with small experimental uncertainties: HERAPDF1.0





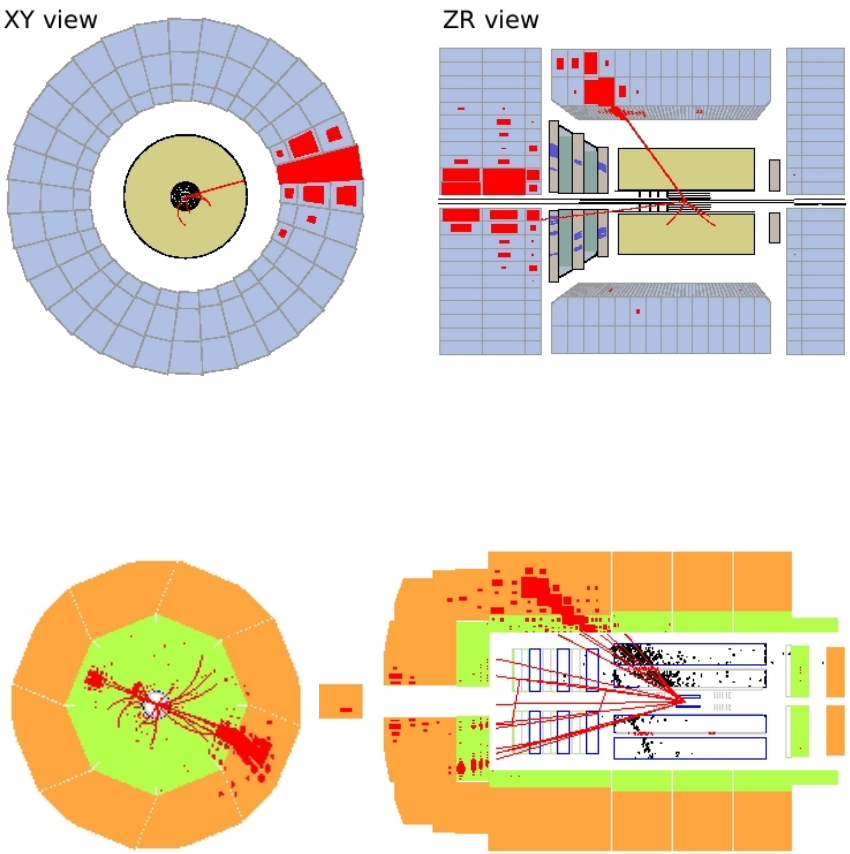
Combined Data With HERAPDF1.0

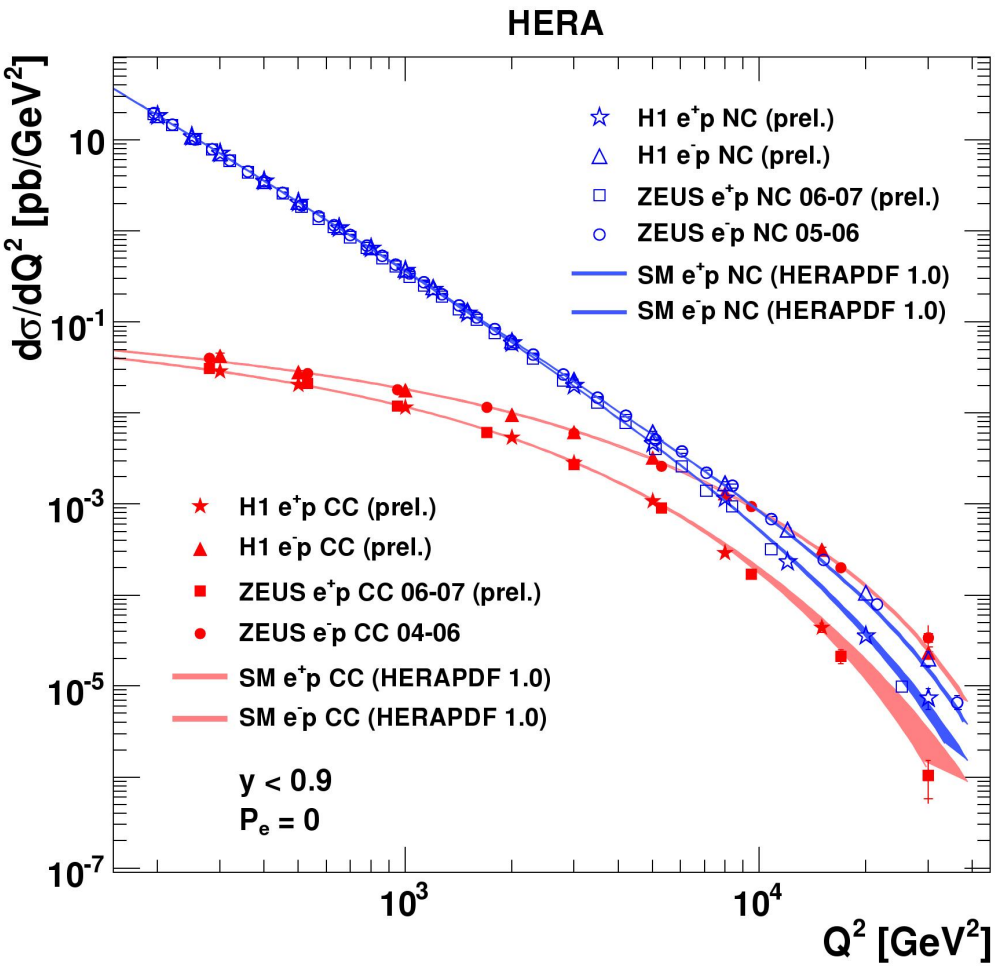
- HERA-I data:
  - Good sensitivity at low Q^2
  - BUT limited statistical precision at high Q^2
- HERA-II data not yet included: further improvement possible!



JHEP01 (2010) 109

Charged Current & Neutral Current at HERA-II



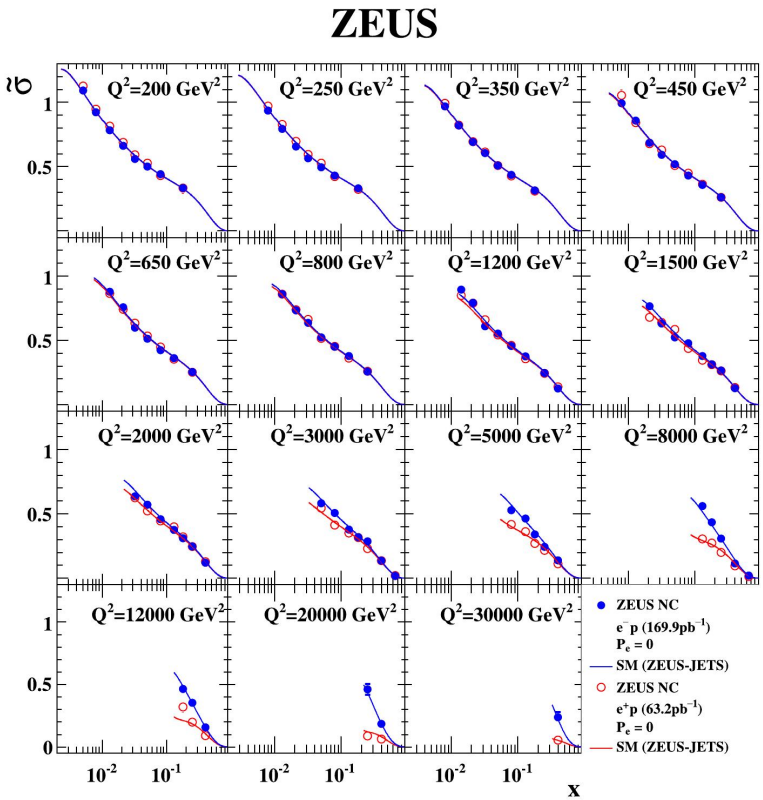


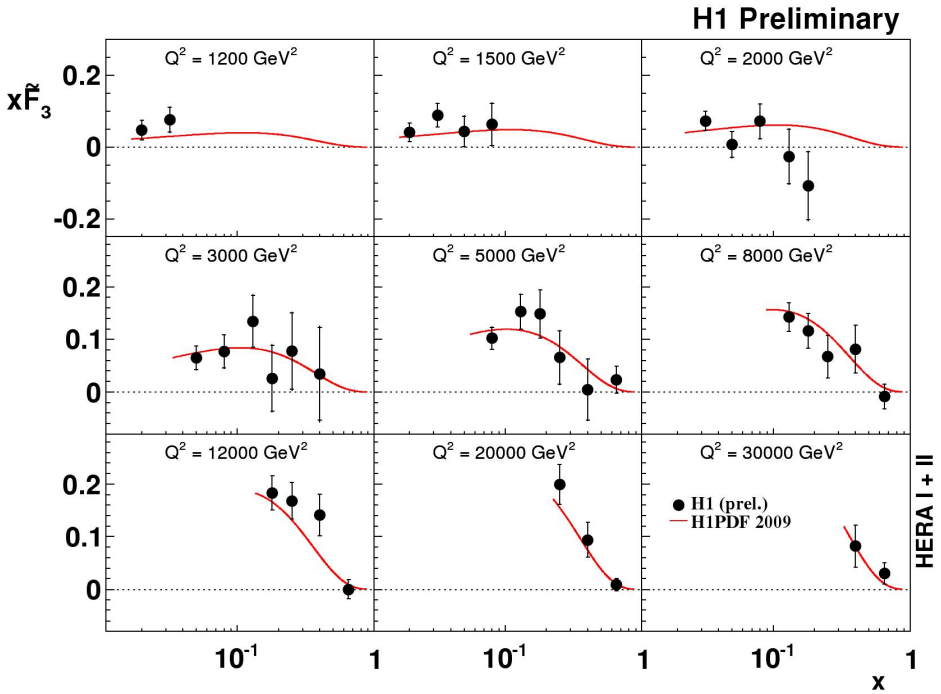
Higher statistics $\Rightarrow$ improved precision

High Q^2 NC Cross Sections I

Eur. Phys. J. C 62 (2009) 625-658

H1prelim-09-042

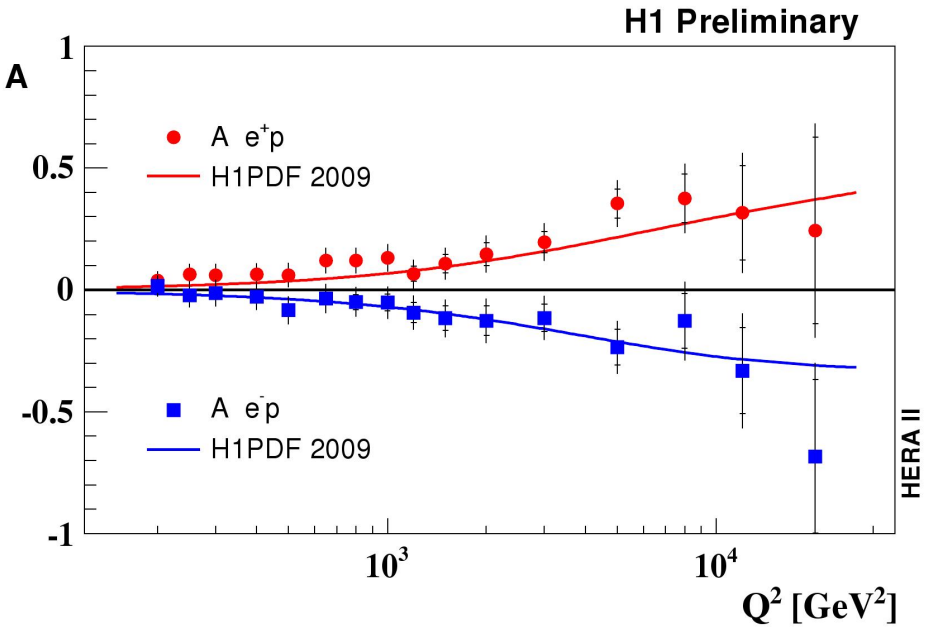




$$\tilde{\sigma}^{e^\pm p}_{NC} \approx F_2 \mp \frac{Y_-}{Y_+} xF_3 \quad \text{and} \quad x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left(\tilde{\sigma}^{e^- p} - \tilde{\sigma}^{e^+ p}\right) \approx \frac{x}{3}\left(2u_v + d_v\right)$$

High Q^2 NC Cross Sections II

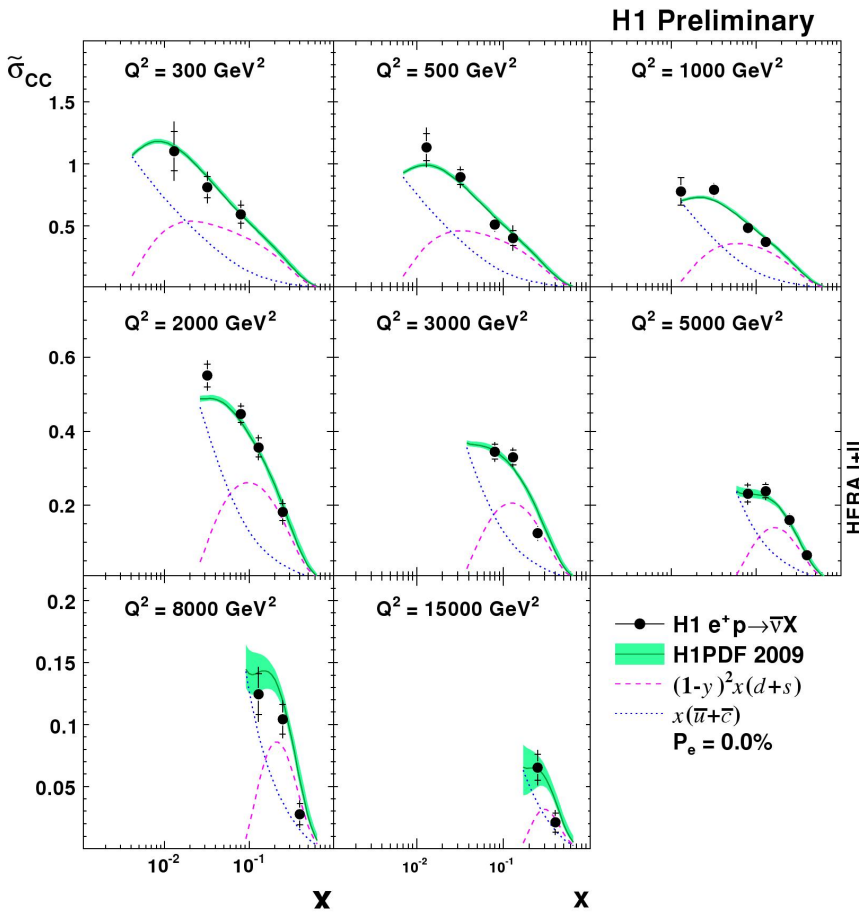
Polarization asymmetry provides a direct measure of EW effects: NC parity violation observed at EW scale



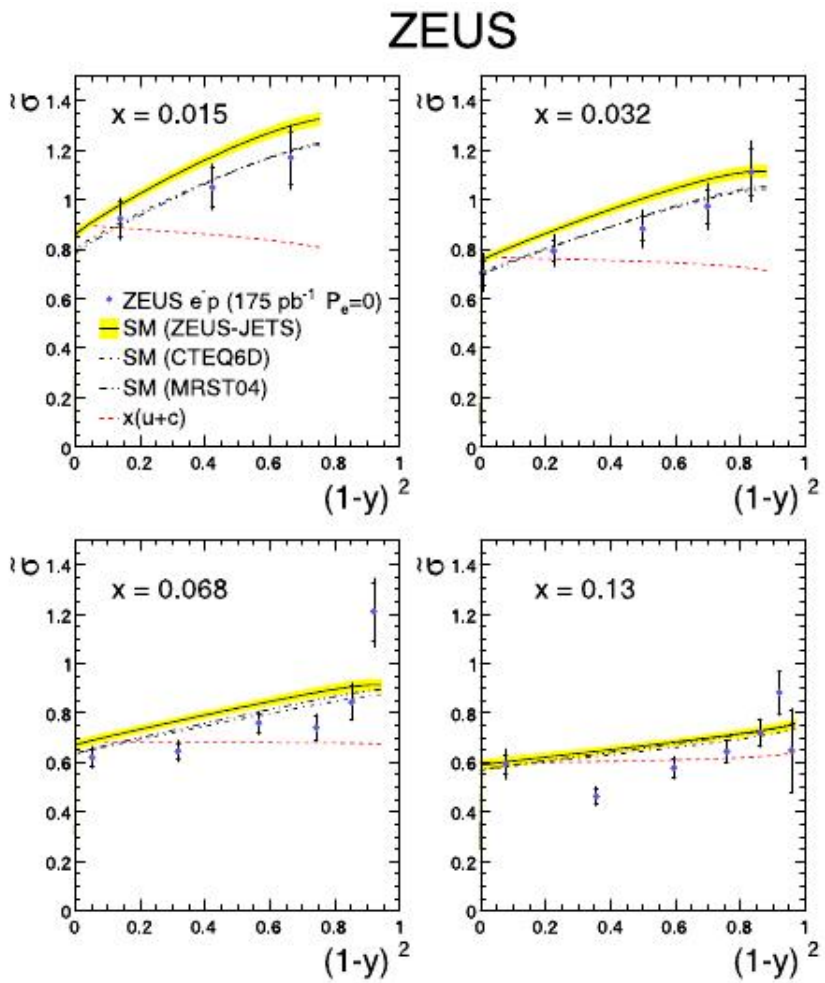
$$A^{\pm} = \frac{2}{P_e^+ - P_e^-} \left(\frac{\sigma^{\pm}(P_e^+) - \sigma^{\pm}(P_e^-)}{\sigma^{\pm}(P_e^+) + \sigma^{\pm}(P_e^-)} \right)$$

High Q^2 CC Cross Sections I

H1prelim-09-043

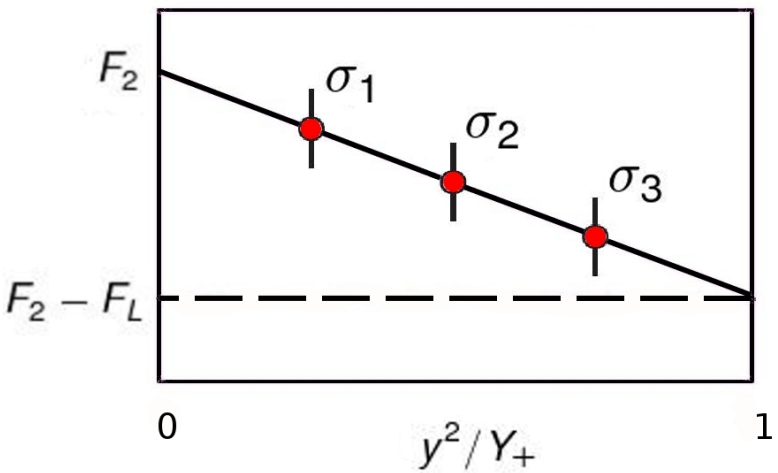


Eur. Phys. J. C 61 (2009) 223-235



F_L I

- At NLO, $F_L \propto \alpha_s xg(x, Q^2)$. F_L contributes at high y, low Q^2
- F_L has not previously been measured directly: gluon density was derived from scaling violations in F_2
- Direct F_L measurement requires measurement of the reduced cross sections at same x and Q^2 but different y
- $Q^2 = sxy \Rightarrow$ different $y \leftrightarrow$ different $s \leftrightarrow$ different beam energies



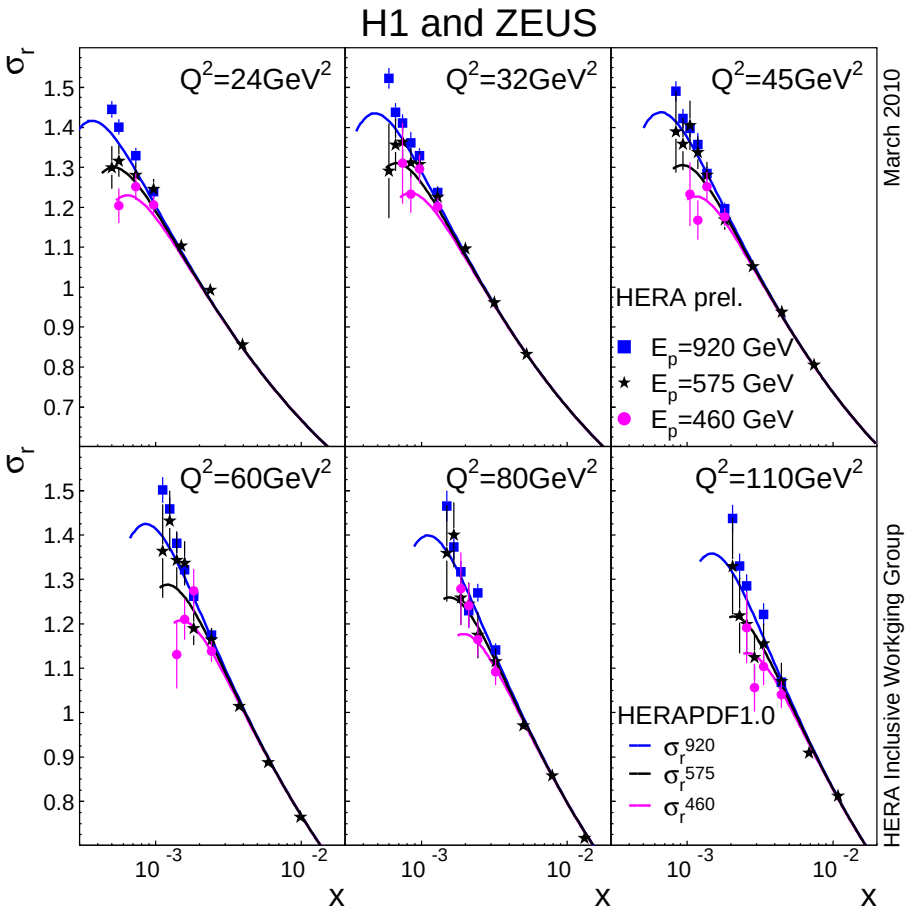
Low Q^2 NC reduced cross section

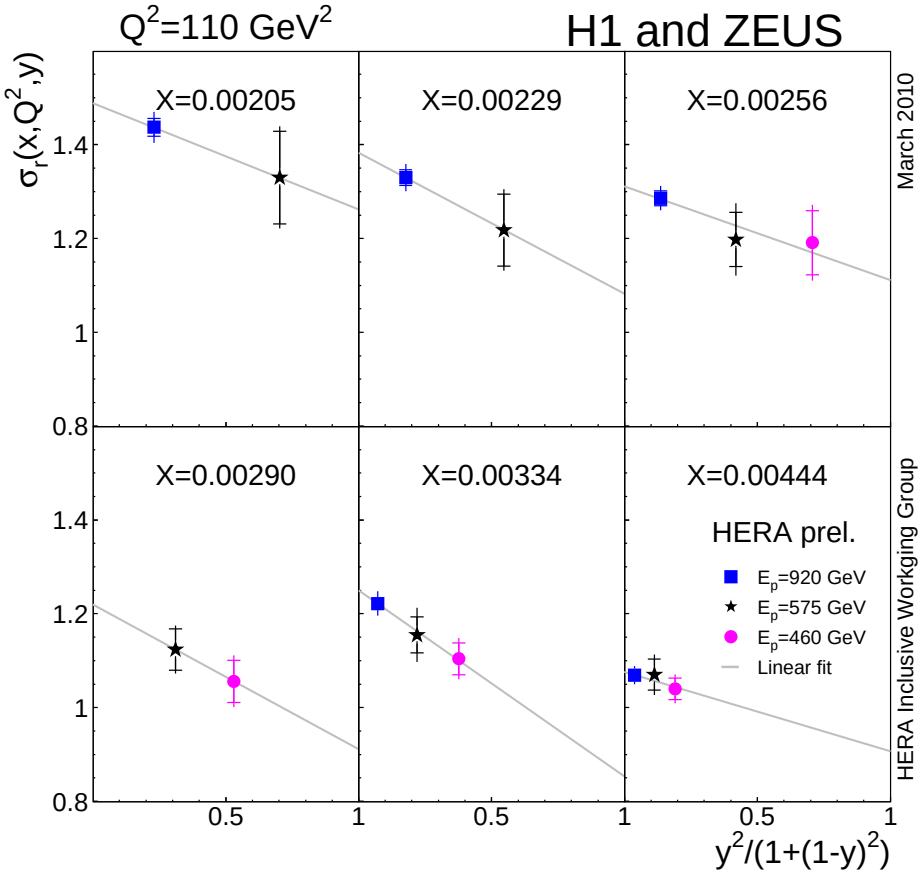
$$\tilde{\sigma}_{NC}^{e^\pm p} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

At given x and Q^2: F_2 is the intercept at y-axis, F_L is the negative slope

F_L II

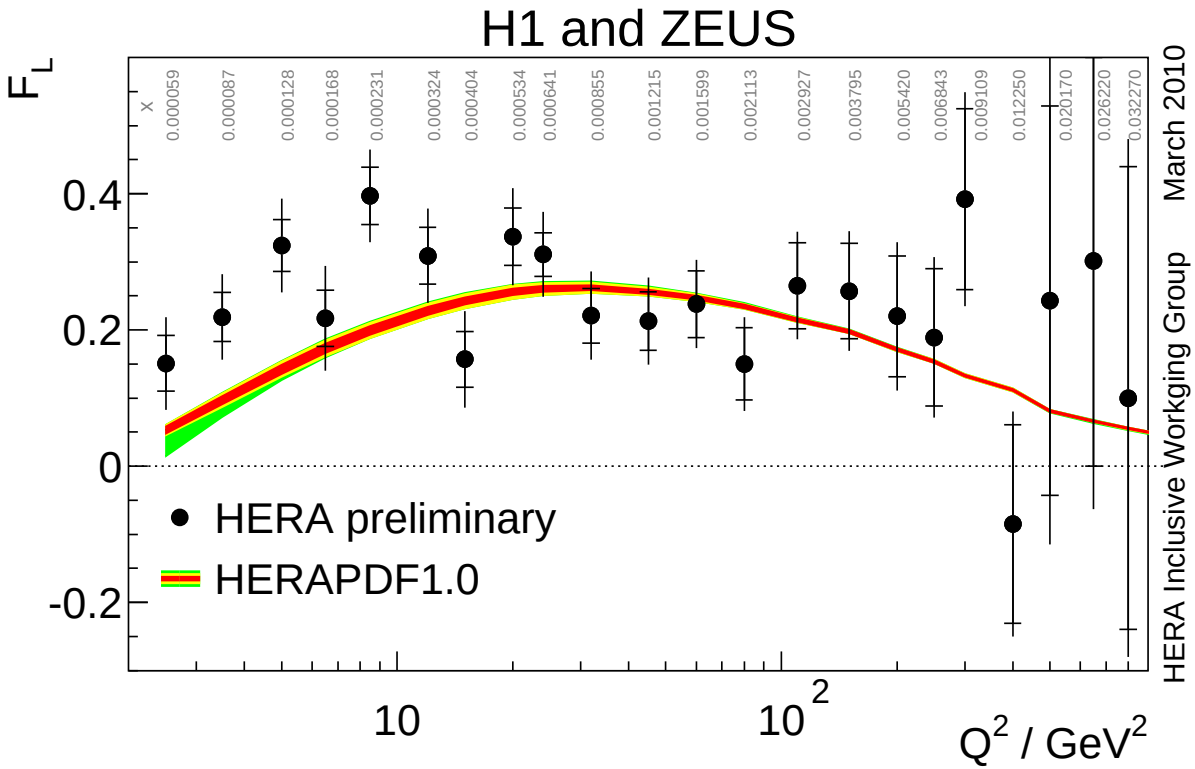
NEW: ZEUS and H1 combination





E_p (GeV)	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})
920	318	21.6
575	251	6.2
460	225	12.4

F_L III



- F_L is extracted in region: $2.5 < Q^2 < 800$ GeV^2
- A new and important input to QCD

Published:
H1: Phys. Lett. B665 (2008) 139-146
ZEUS: Phys. Lett. B682 (2009) 8-22

Combined:
H1prelim-10-043
ZEUS-prel-10-001

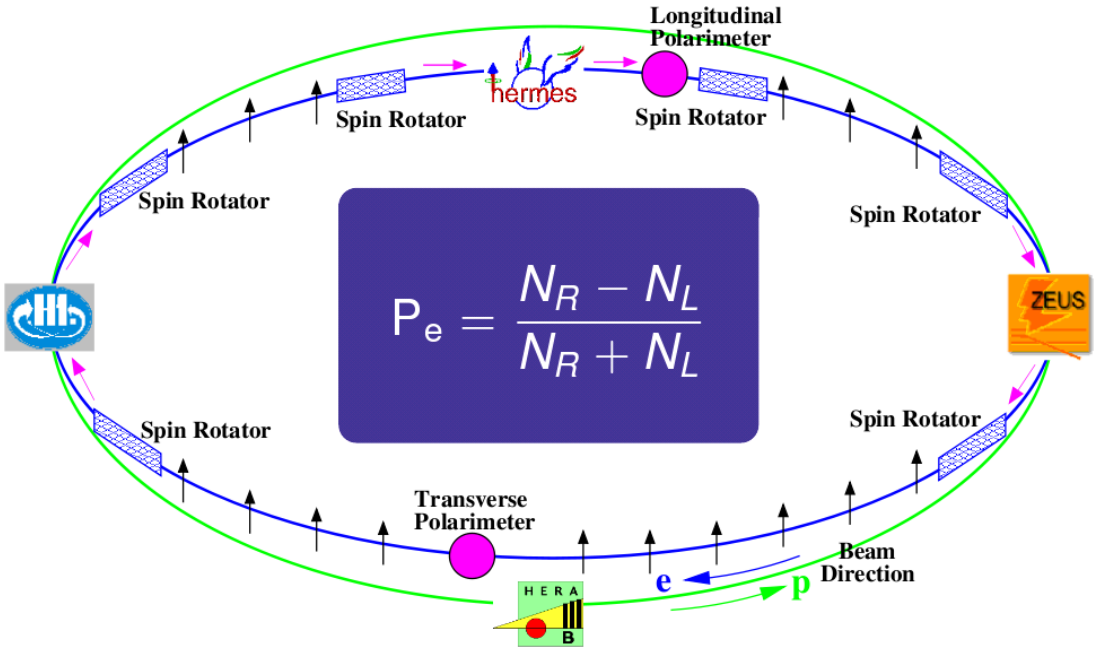
Summary

- A lasting legacy of HERA is a far greater understanding of the structure of the proton
- H1 and ZEUS will continue to combine data to achieve greater precision
- HERA data is necessary for precise predictions at the LHC

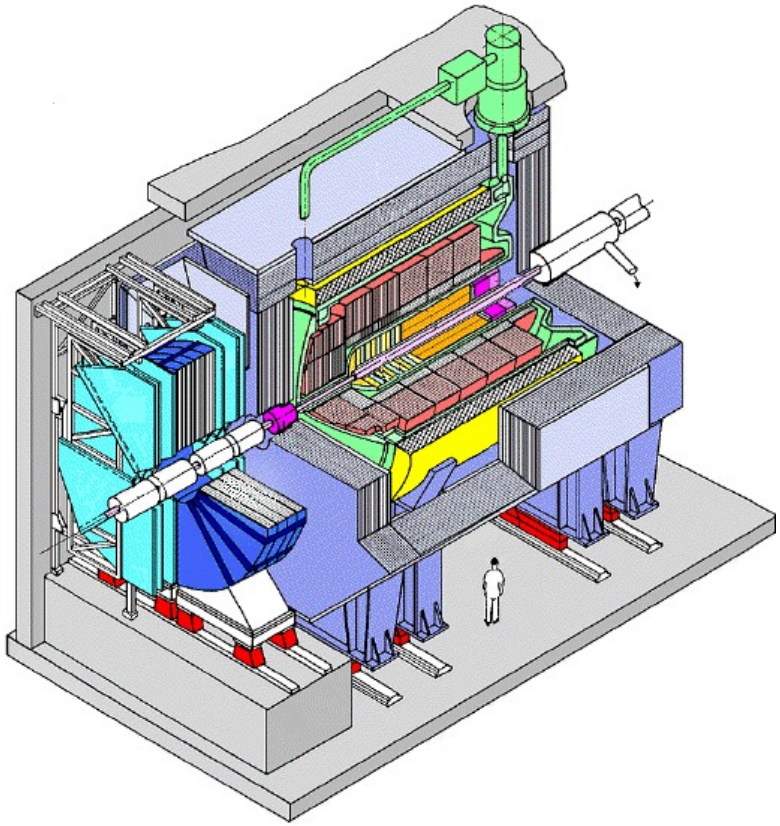
Back-Up Slides

HERA: Polarised Lepton Beam

- e beam becomes transversely polarized through emission of synchrotron radiation
- Spin rotators were installed during the HERA upgrade to obtain longitudinal polarization at both IPs
- Mean (lumi weighted) polarization achieved: 30 - 40%



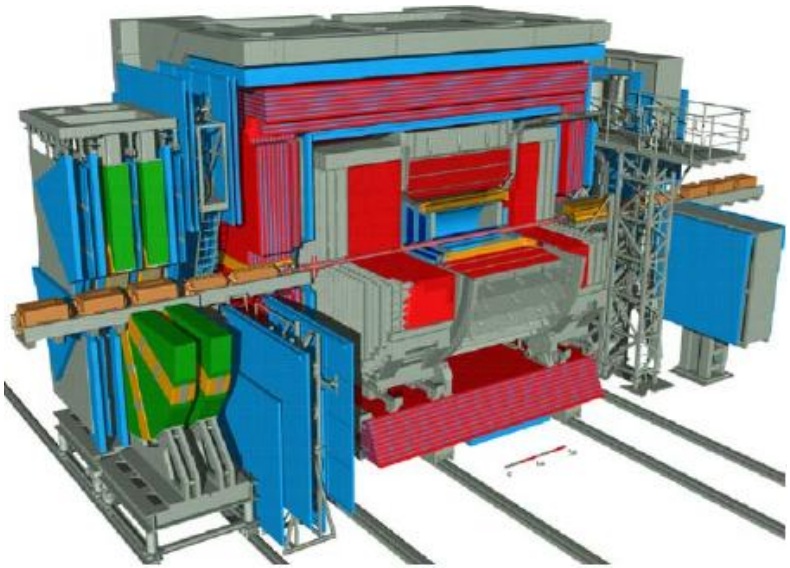
H1



- Hermetic - 4π detector
- Tracking:
  - Central drift chamber
  - Silicon Microvertex detector
- Liquid-argon calorimeter (LAr)
- Rear lead-scinitillator (SPACAL)
- μ chambers

Optimised for precision measurement of the scattered electron

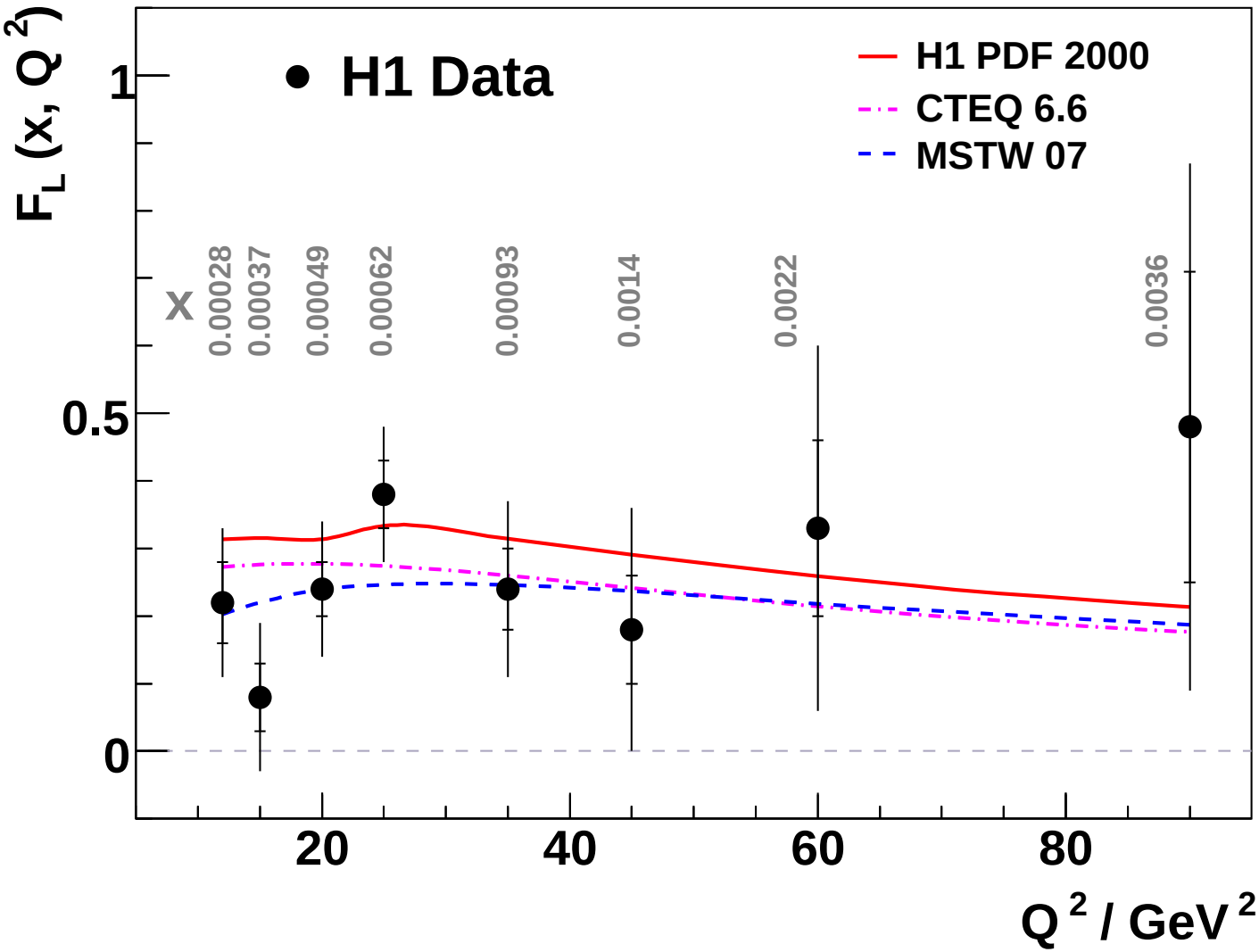
ZEUS



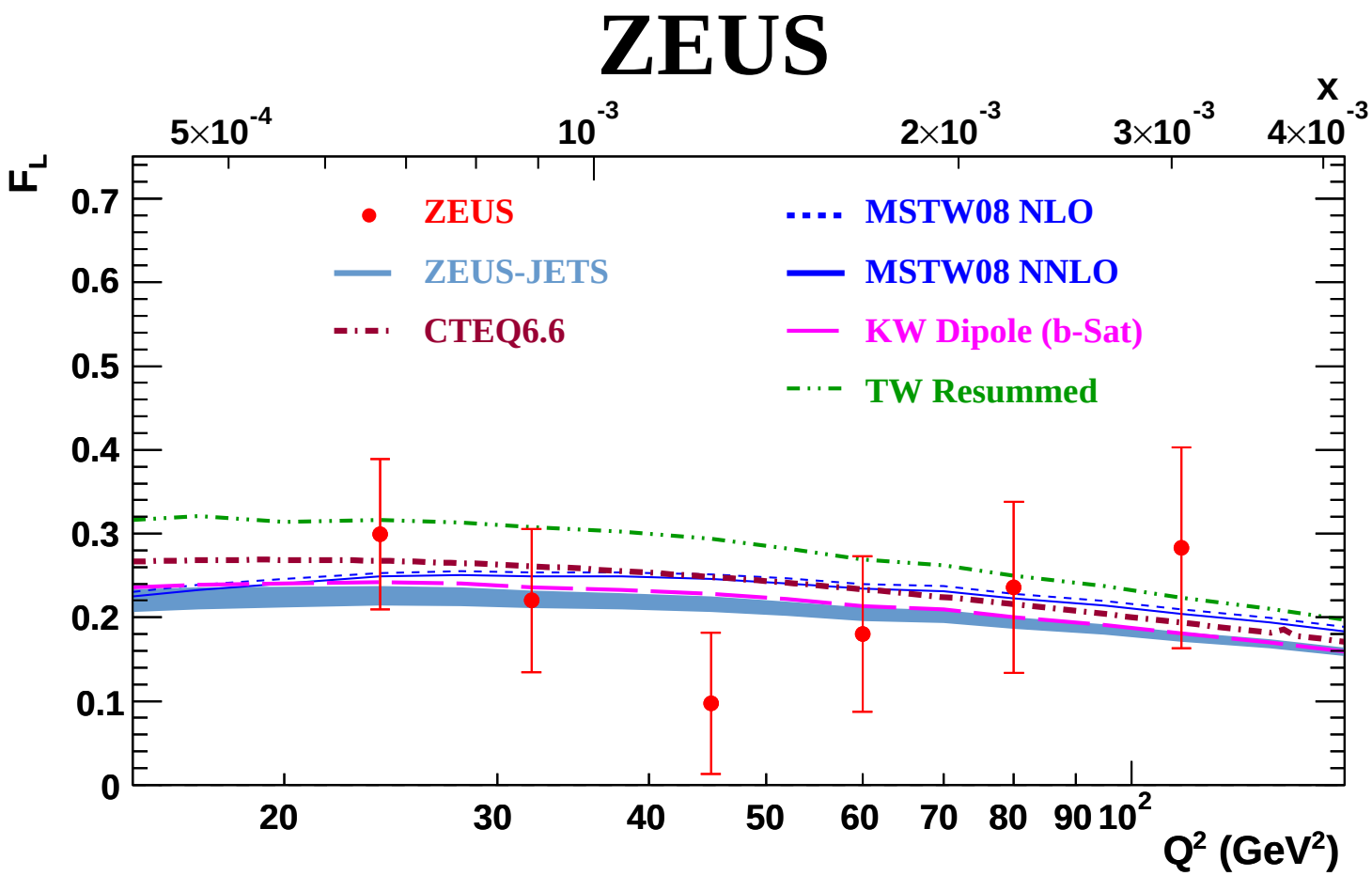
- Hermetic - 4π detector
- Tracking:
  - Central Tracking Detector (CTD), a cylindrical drift chamber
  - Silicon Microvertex detector (MVD) (HERA-II)
- Compensating uranium scintillator calorimeter (UCAL)
- μ chambers

Optimised for precision measurement of the hadronic final state

F_L: H1 Comparison To Theory Curves



F_L: ZEUS Comparison To Theory Curves



F_L: Indirect Measurement

Low Q^2 reduced cross section $\tilde{\sigma}^{NC}$

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

- Derivative method:

$$\frac{d\tilde{\sigma}}{d\ln y}|_{Q^2} \approx \frac{dF_2}{d\ln y}|_{Q^2} - \frac{2y^2(2-y)}{Y_+^2} F_L$$

  - Derivative dominated by F_L term at high y

- Shape method:

$$\tilde{\sigma}_{fit} = cx^{-\lambda} - \frac{y^2}{Y_+} F_L$$

  - Shape driven by kinematic factor rather than F_L

F_2 & F_3

Consider the total cross-section: $\sigma^0 + P\sigma^P$:
The unpolarised cross-section is given by $\sigma^0 = Y_+ F_2^0 + Y_- x F_3^0$:

- $F_2^0 = \sum_i A_i^0(Q^2)[xq_i(x,Q^2) + x\bar{q}_i(x,Q^2)]$
- $xF_3^0 = \sum_i B_i^0(Q^2)[xq_i(x,Q^2) - x\bar{q}_i(x,Q^2)]$
- $A_i^0(Q^2) = e_i^2 - 2e_i v_i v_e P_Z + (v_e^2 + a_e^2)(v_i^2 + a_i^2)P_Z^2$
- $B_i^0(Q^2) = -2e_i a_i a_e P_Z + 4a_i a_e v_i v_e P_Z^2$

The polarised cross-section is given by $\sigma^P = Y_+ F_2^P + Y_- x F_3^P$:

- $F_2^P = \sum_i A_i^P(Q^2)[xq_i(x,Q^2) + x\bar{q}_i(x,Q^2)]$
- $xF_3^P = \sum_i B_i^P(Q^2)[xq_i(x,Q^2) - x\bar{q}_i(x,Q^2)]$
- $A_i^P(Q^2) = 2e_i v_i a_e P_Z - 2v_e a_e (v_i^2 + a_i^2)P_Z^2$
- $B_i^P(Q^2) = 2e_i a_i v_e P_Z - 2a_i v_i (v_e^2 + a_e^2)P_Z^2$

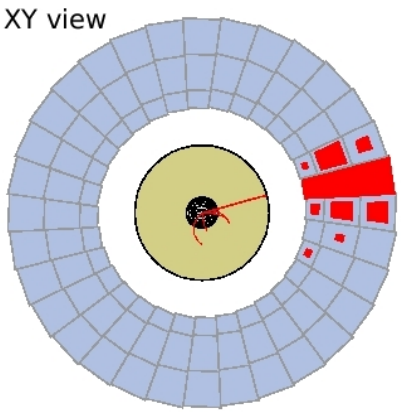
$$P_Z = \frac{Q^2}{(M_Z^2+Q^2)\sin^2(2\theta_W)}$$

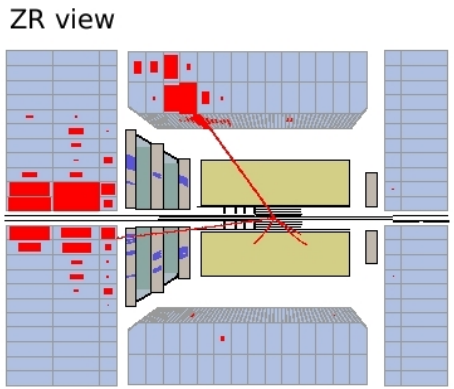
$P_Z \gg P_z^2$ (γZ interference dominant)
v_e very small (~ 0.04)
so:
Unpolarised $xF_3 \rightarrow a_i$
Polarised $F_2 \rightarrow v_i$

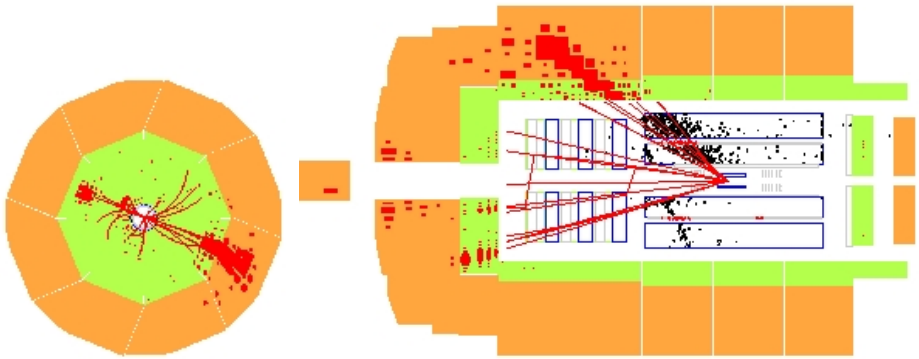
Charged Current & Neutral Current Events

CC Event: Large missing transverse momentum (p_T) due to neutrino

NC Event: High p_T isolated scattered electron/positron and balanced total p_T





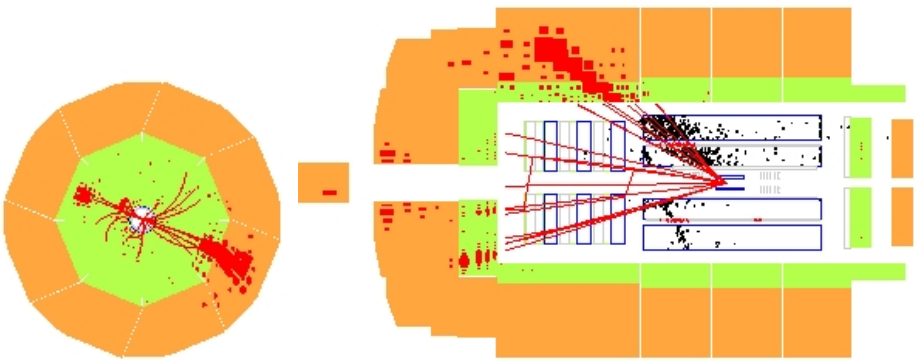


Final selection: $\sim 10^3$ events per sample

Final selection: $\sim 10^5$ events per sample

Neutral Current Event Selection

High p_T isolated scattered electron/positron and balanced total p_T



- Suppress photoproduction background: conserve longitudinal energy-momentum: $\delta = E - p_z \approx 2E_e$
- Final selection: $\sim 10^5$ events per sample

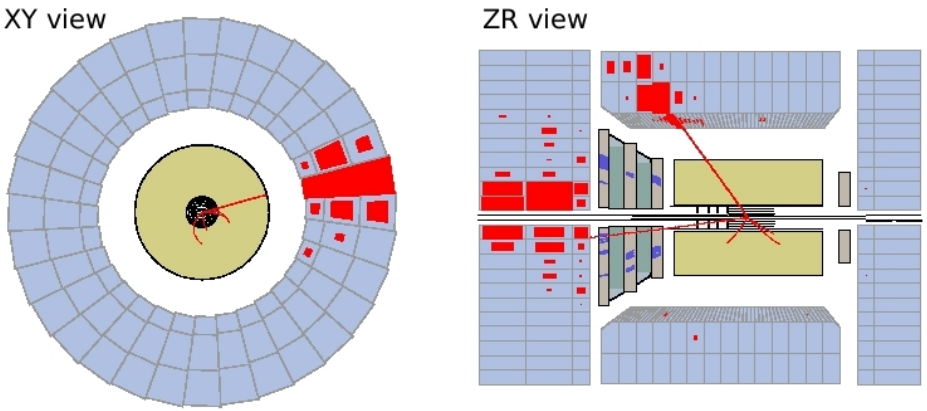
Kinematic reconstruction: angle and energy of scattered electron

$$Q^2_{el} = 2E_e E'_e(1+\cos\theta_e) \qquad x_{el} = \frac{E_e}{E_p}\frac{E'_e(1+\cos\theta_e)}{2E_e - E'_e(1-\cos\theta_e)}$$

$$y_{el} = 1 - \frac{E'_e}{2E_e}(1-\cos\theta_e)$$

Charged Current Event Selection

Large missing transverse momentum (p_T) due to neutrino



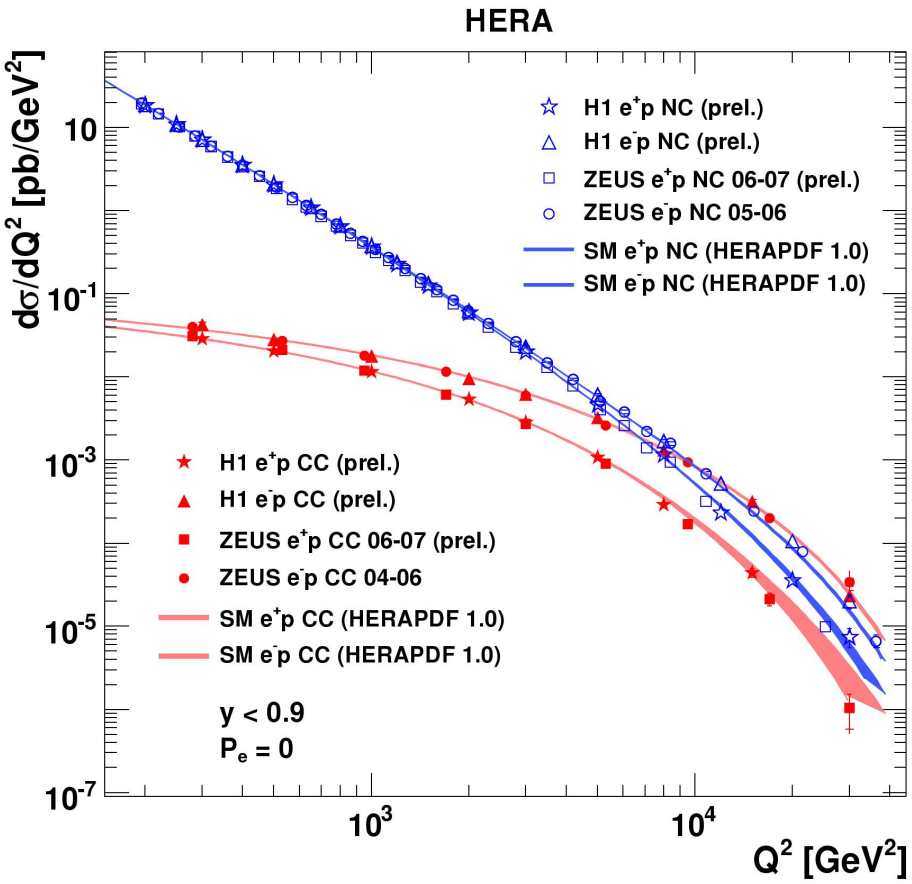
- Suppress dominant background (photoproduction)
- Topological finders to remove cosmic muons
- Final selection: $\sim 10^3$ events per sample

Kinematic reconstruction from hadrons (Jacquet-Blondel)

$$\delta = \sum_i \left(E^i - p_z^i\right) \qquad p_T^2 = \left(\sum_i p_x^i\right)^2 + \left(\sum_i p_y^i\right)^2$$

$$y_{JB} = \frac{\delta}{2E_e} \qquad x_{JB} = \frac{p_T^2}{s y_{JB}(1-y_{JB})} \qquad Q^2_{JB} = s x_{JB} y_{JB}$$

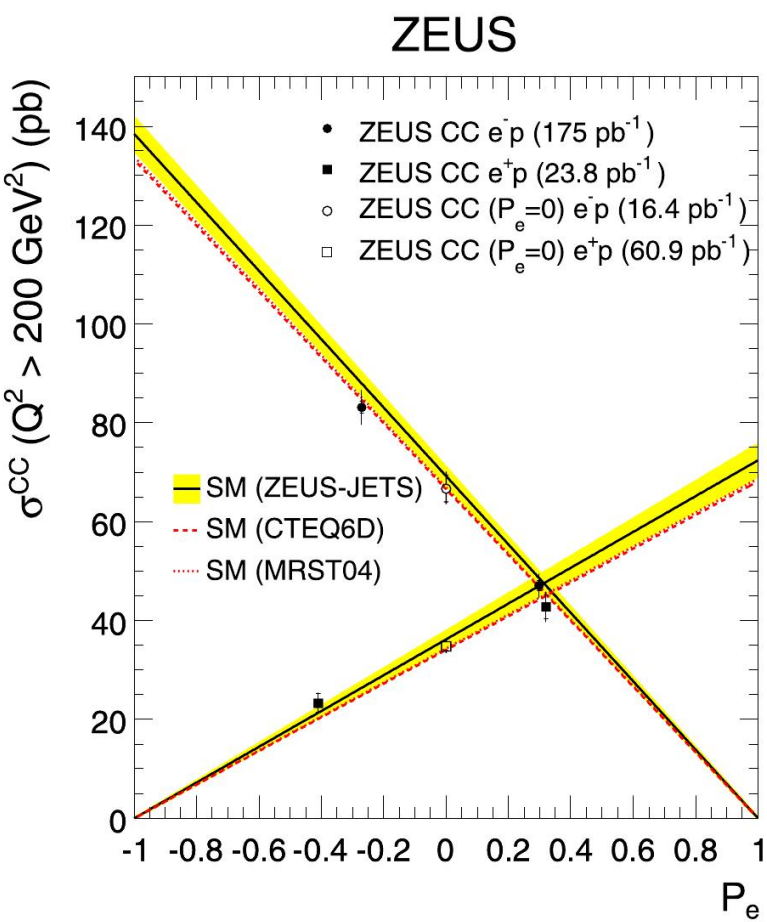
High Q^2 NC and CC Cross Sections



- NC and CC high Q^2 cross sections are measured very precisely over many orders of magnitude in Q^2

High Q^2 CC Cross Sections II

$$\sigma_{CC}^{e^{\pm}p}(P_e) = (1 \pm P_e)\sigma_{CC}^{e^{\pm}p}(P_e = 0)$$



- Tests chiral nature of the SM
- Do not constrain linear fit to zero at P_e = +1 (P_e = -1) for electrons (positrons)
- Assume non-zero cross section due to a right-handed W boson (W_R)
- Derive lower limit on mass of W_R assuming:
  - $g_L = g_R$
  - Light ν_R

	Electron	Positron
H1	186 GeV	208 GeV
ZEUS	180 GeV	

ZEUS & H1 Combination Method

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

Combination Method: χ^2

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

$$\chi^2_{\rm tot}(\boldsymbol{m},\boldsymbol{b}') = \chi^2_{\rm min} + \sum_{i=1}^{N_M} \frac{\left[m^i - \sum_j \gamma^{i,\rm ave}_j m^i b'_j - \mu^{i,\rm ave}\right]^2}{\delta^2_{i,\rm ave,stat}\,\mu^{i,\rm ave}\left(m^i - \sum_j \gamma^{i,\rm ave}_j m^i b'_j\right) + \left(\delta_{i,\rm ave,uncor}\, m^i\right)^2} + \sum_j (b'_j)^2.$$

μ^i	Measured value at point i
γ^i_j	Relative correlated systematic
$\delta_{i,\,\rm stat}$	Relative statistical uncertainty
$\delta_{i,\,\rm uncor}$	Relative uncorrelated systematic uncertainty
m^i	Prediction for measurement
b_j	Shifts of correlated error sources

Combination Method: Procedural Uncertainties

- Additive vs multiplicative nature of the error sources
  - typically below 0.5%
- A study of the possible correlated systematic uncertainties between H1 and ZEUS was performed:
  - Identified 12 possible uncertainties of common origin
  - Compared 212 averages taking all pairs as correlated/uncorrelared in turn
  - Mostly negligible except for:
    1. Correlated systematic uncertainty for the photoproduction background (few % at high-y)
    2. Correlated systematic uncertainty for the hadronic energy scale (at the per mille level)

Combination Method: Uncertainties

- 1402 points are combined to 741 unique cross section measurements
- χ^2/NDF = 637/656
- 110 systematic errors from the experimental considerations
- 3 procedural systematic errors
- Overall precision:
  - $3 < Q^2 < 500$ GeV: 2% precision
  - $20 < Q^2 < 100$ GeV: 1% precision

Combination Method: Cross-Calibration

- Several correlated systematic uncertainties are reduced considerably for the averaged result:
  - Uncertainty on H1 calorimeter energy scale reduced by 55%
  - Uncertainty on ZEUS γP background reduced by 65%
- Different reconstruction methods $\Rightarrow$ similar systematic sources influence cross sections differently as a function of Q^2 and x
  - Requiring agreement at all Q^2 and x constrains systematics
- In some regions, one experiment has better precision
  - The less precise measurement is fitted to the more precise one
  - Reduction in correlated systematic uncertainty

PDF Details

Scheme:	Thorne-Roberts VFNS
Evolution:	QCDNUM
Order:	NLO
Q_0^2	1.9 GeV^2
f_s	0.31
Renormalisation scale:	Q^2
Factorisation scale:	Q^2
Q^2_{min}	3.5 GeV^2
$\alpha_S(M_W)$	0.1176
M_c	1.4 GeV
M_b	4.75 GeV

PDF Experimental Uncertainties

- Uncorrelated uncertainties:
  - Statistical errors
  - Point-to-point uncorrelated uncertainties:
    - e.g statistical errors due to MC simulations
    - Are added in quadrature to the statistical errors
- Correlated uncertainties:
  - Point-to-point correlated uncertainties:
    - e.g. electromagnetic and hadronic energy scale calibration
    - often common for CC and NC for a given experiment and run period
- Overall normalisation uncertainty:
  - Correlated for all data points for a given experiment and run period
- Correlations between H1 and ZEUS:
  - H1 and ZEUS use similar analyses methods
  - Largest from γP background and hadronic energy scales

PDF Model Uncertainties

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	1.35[a]	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.5[b]	2.5[c,d]

[a] $Q^2_0 = 1.8$
[b] $f_s = 0.29$
[c] $m_c = 1.6$
[d] $f_s = 0.34$

- Numerical values used for the central fit are varied
- Difference between the nominal fit and fits corresponding to model variations are added in quadrature
  $\Rightarrow$ Total model uncertainty

PDF Parametrisation Uncertainties

1. Variation in Q_0^2 (starting scale)
2. Negative gluon contribution at low-x is allowed
3. $B_{u_v} \neq B_{d_v}$ for u_v and d_v parametrisations:

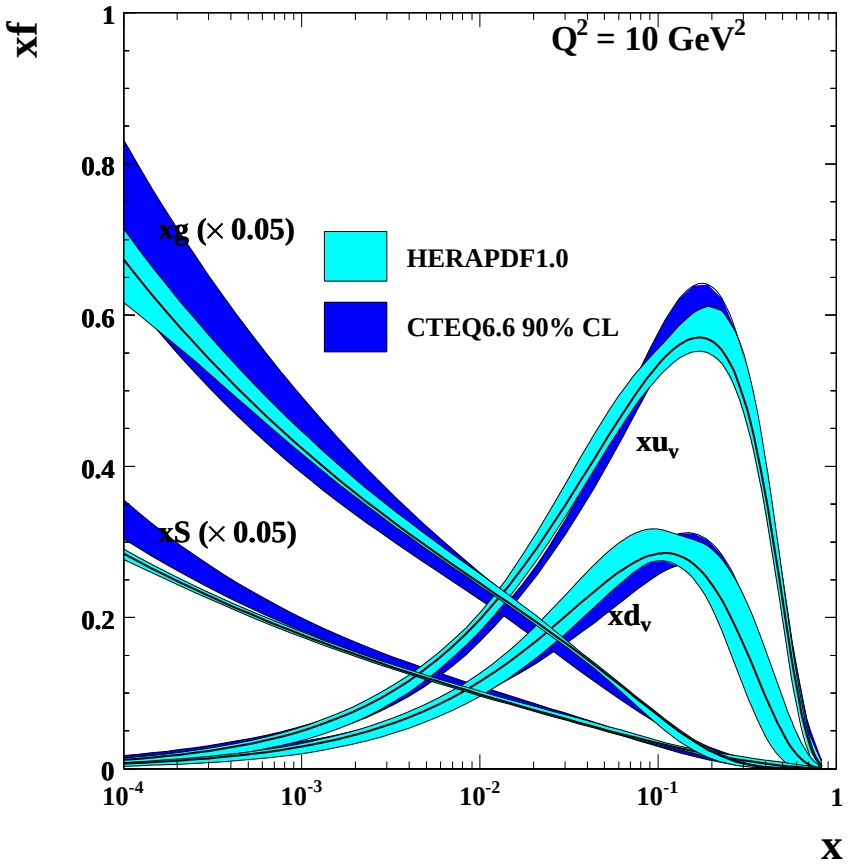
$$\begin{aligned} xu_v(x) &= A_{u_v} x^{B_{uv}} (1-x)^{C_{uv}} (1 + E_{u_v} x^2) \\ xd_v(x) &= A_{d_v} x^{B_{dv}} (1-x)^{C_{dv}} \end{aligned}$$

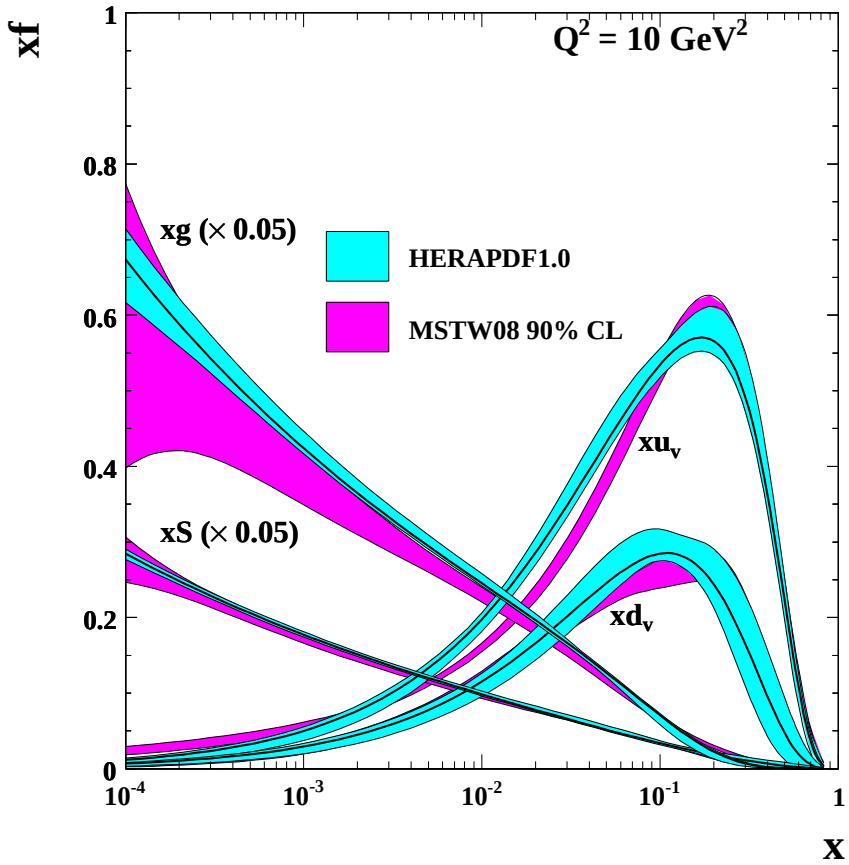
4. Variation in number of terms in the polynomial:

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

Envelope representing the maximum deviation at each x value is constructed to represent the parametrisation uncertainty

HERAPDF1.0: Comparison to Other PDFs

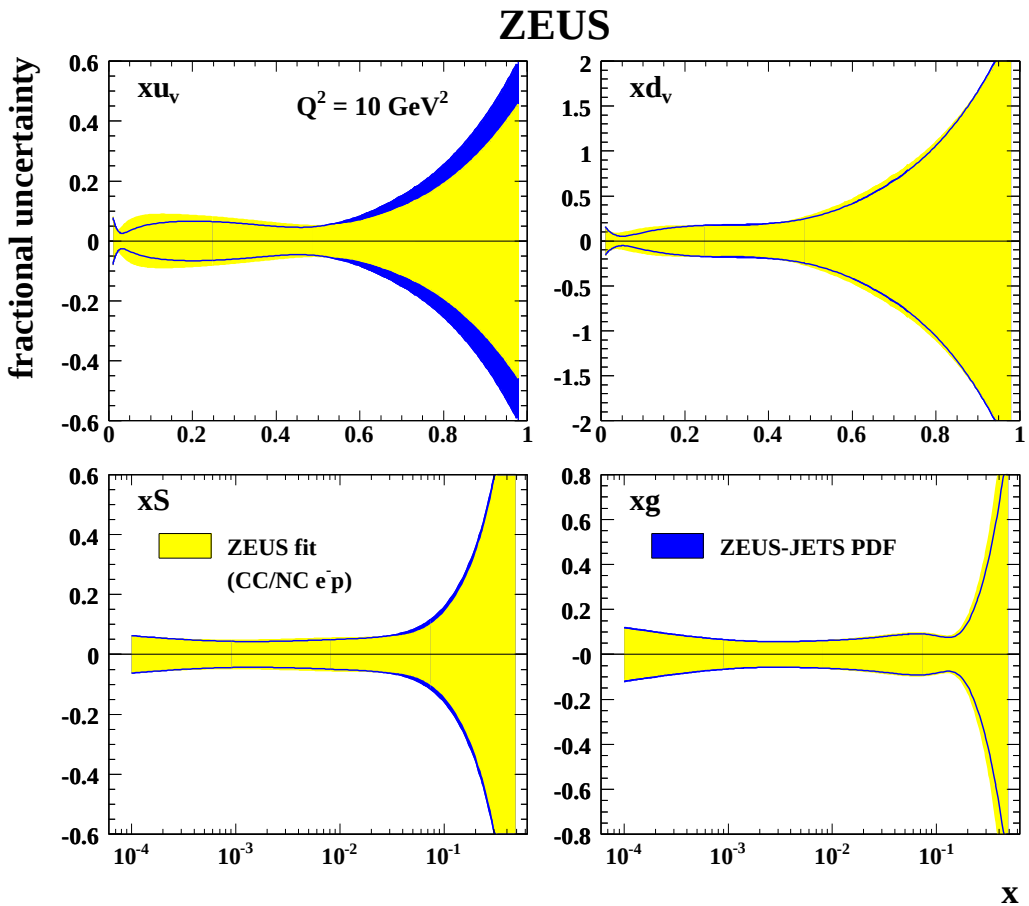




ZEUSfit09: Adding High Q^2 NC and CC Polarised $e^- p$ Data

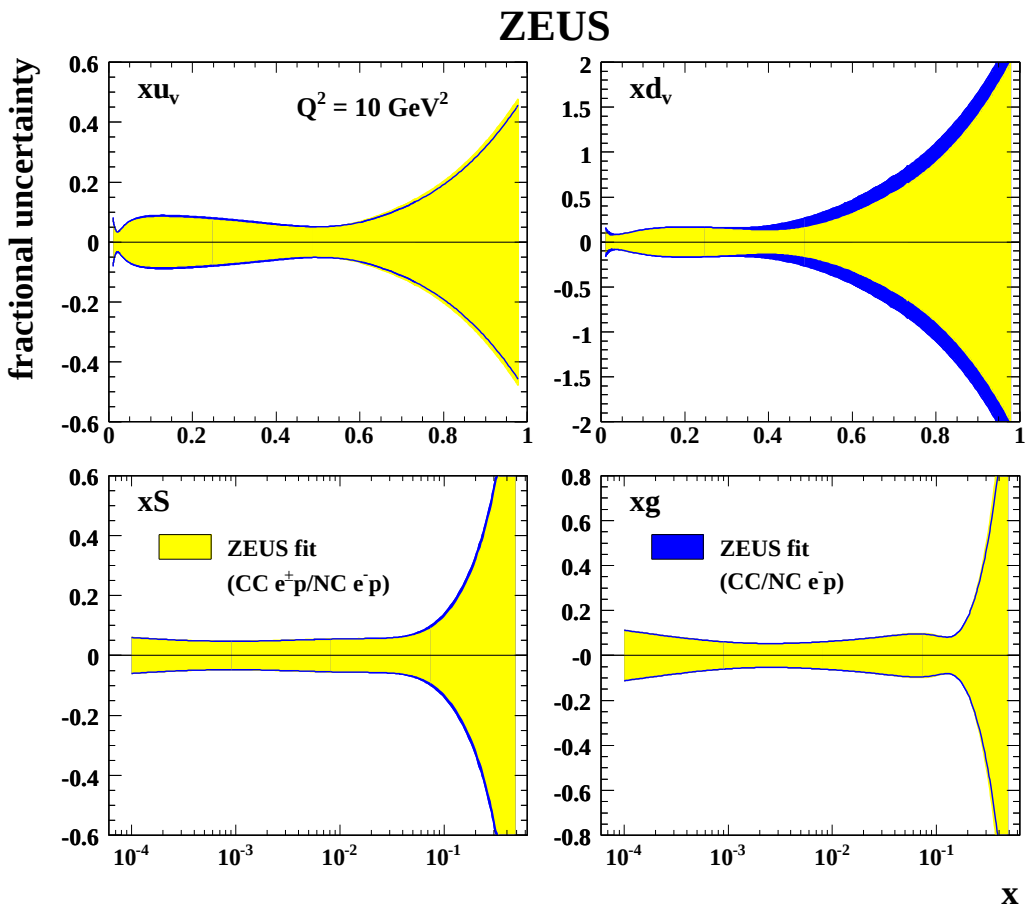
The ZEUS-JETS PDF was modified by incorporating:

1. high-Q^2 NC polarised $e^- p$ data: Eur. Phys. Journal C 62 (2009) 625-658)
2. high-Q^2 CC polarised $e^- p$ data: Eur. Phys. Journal C 61 (2009) 223-235)



ZEUSfit09: Adding High Q^2 CC Polarised e^+p Data

In addition, high-Q^2 CC polarised e^+p data was added (ZEUS-prel-09-002)



ZEUSfit09: Adding High Q^2 NC and CC Polarised $e^- p$ and High Q^2 CC Polarised $e^+ p$ Data

The ZEUS-JETS PDF was modified by incorporating:

1. high-Q^2 NC polarised $e^- p$ data: Eur. Phys. Journal C 62 (2009) 625-658
2. high-Q^2 CC polarised $e^- p$ data: Eur. Phys. Journal C 61 (2009) 223-235
3. high-Q^2 CC polarised $e^+ p$ data: ZEUS-prel-09-002