Electroweak Studies and Searches in Inclusive High Q^2 ep Collisions

IVIIth Rencontres de Moriond, 10.3.–17.3.2007

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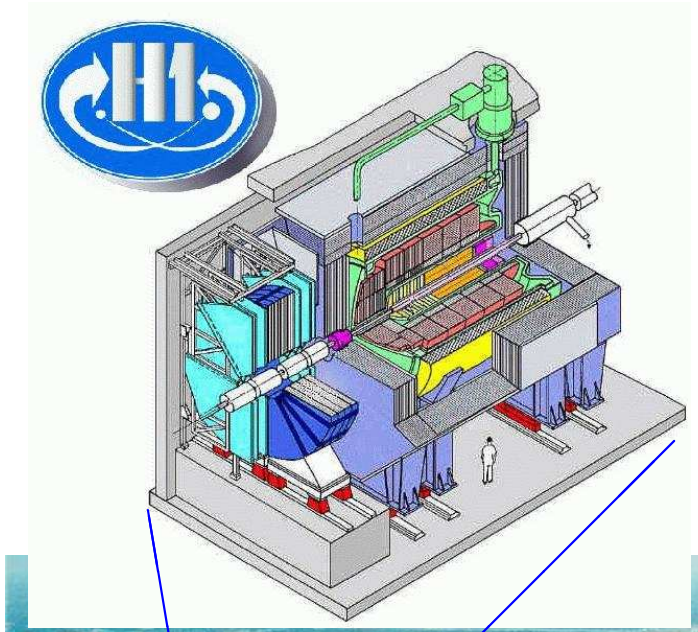
More HERA results:

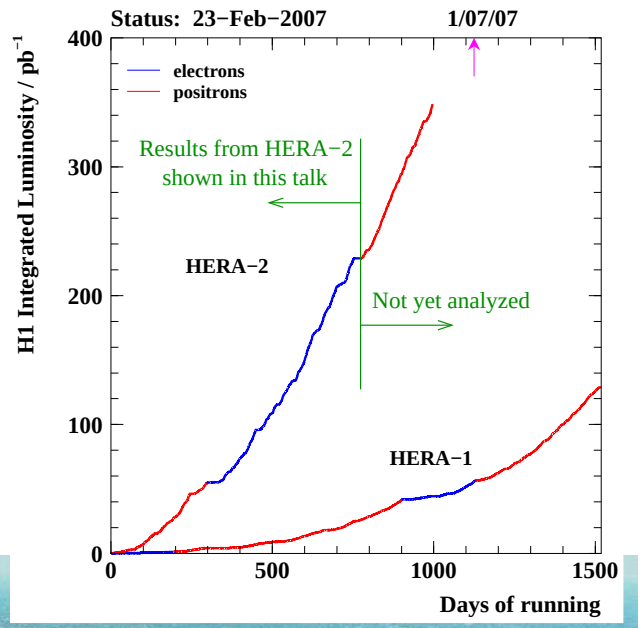
`http://www-h1.desy.de`

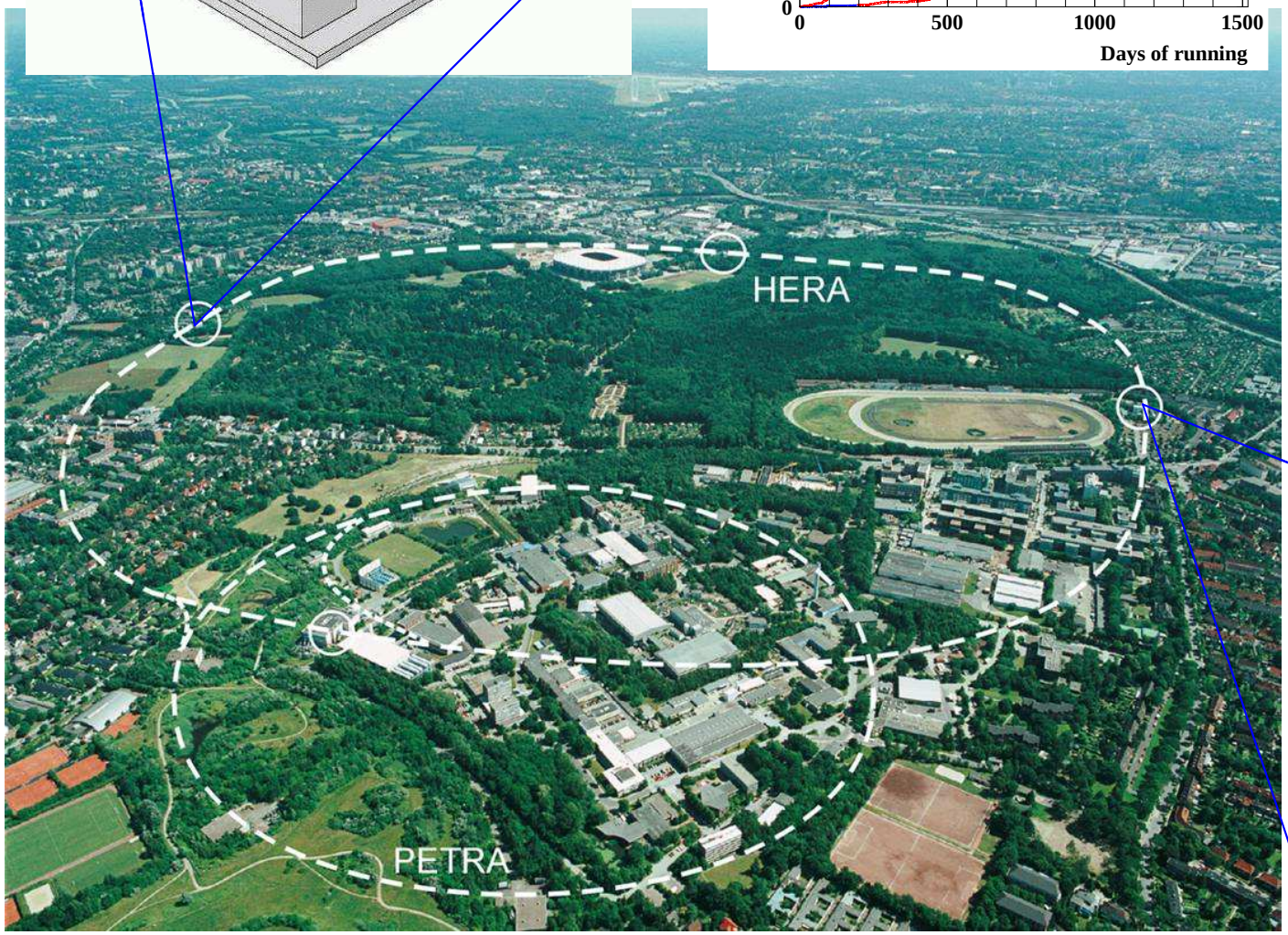
`http://www-zeus.desy.de`

- The HERA collider and the experiments ZEUS and H1
- Inclusive cross-sections
- Polarized inclusive cross-sections
- Electroweak studies
- Searches for leptoquarks and contact interactions

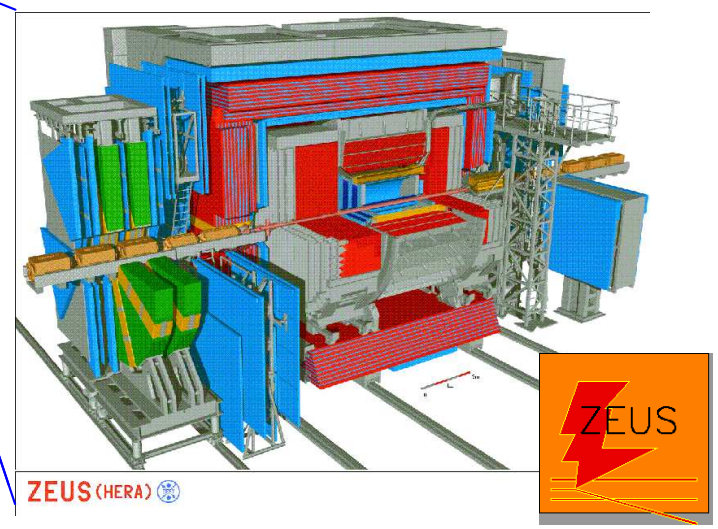
The HERA collider and the experiments H1 and ZEUS



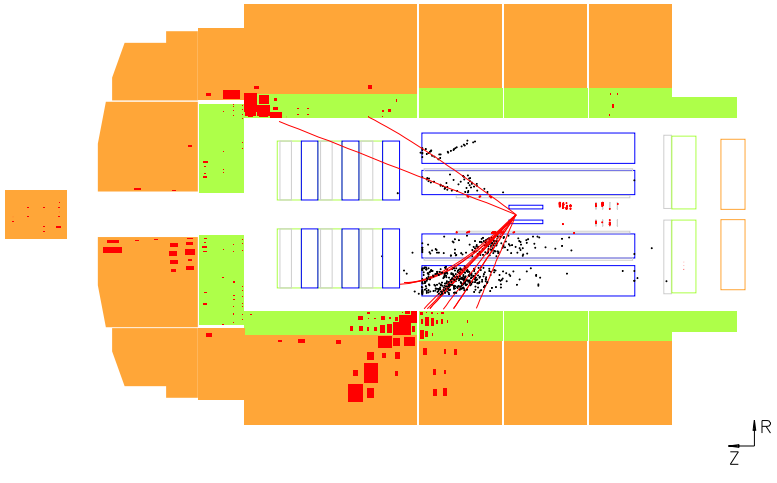




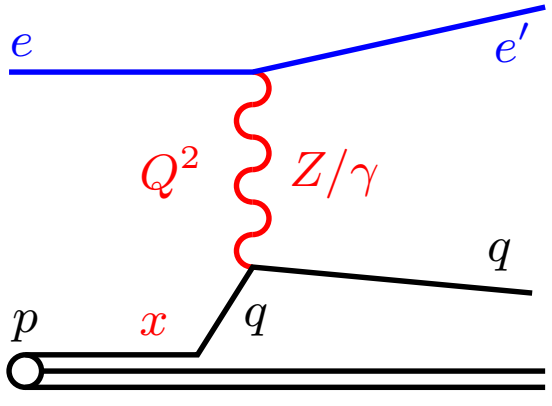
- $e^{\pm}p$ collider at DESY/Hamburg
- $E_e = 27.6\,\text{GeV}$ and $E_p = 920\,\text{GeV}$, $\sqrt{s} = 320\,\text{GeV}$
- 1994–2000: HERA I: $2 \times 120\,\text{pb}^{-1}$
- 2003–2007: HERA II: $2 \times 350\,\text{pb}^{-1}$ and longitidinally polarized $e^{\pm}$



Neutral Current cross-section



Neutral current



Event topology:

- Scattered electron in the detector

Kinematic variables:

- Momentum transfer squared Q^2
- Fraction of proton momentum x carried by struck quark
- Inelasticity $y = \frac{1-cos\theta^\star}{2} = \frac{Q^2}{sx}$

Cross-section:

$$\frac{d^2\sigma^{NC}}{dx\,dQ^2}\left(e^\pm p\right) = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\,\tilde{F}_2 \mp Y_-\,x\tilde{F}_3 - y^2\,\tilde{F}_L\right] \quad \text{Helicity functions: } Y_\pm = 1 \pm (1-y)^2$$

Structure functions:

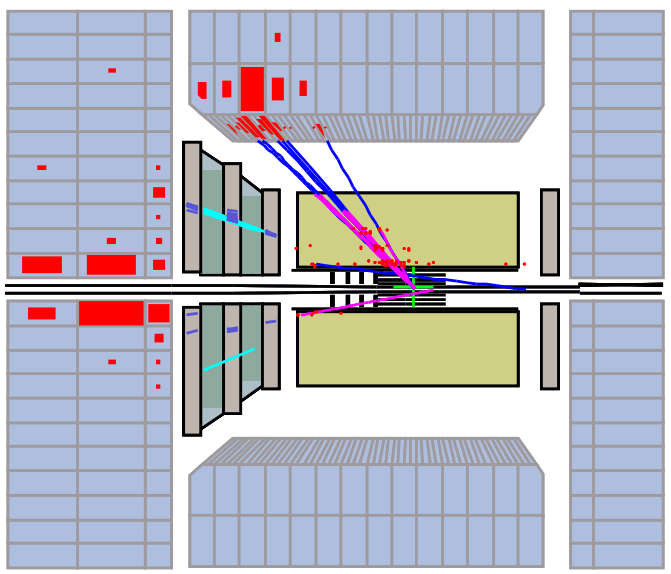
$$\begin{aligned}
\tilde{F}_2^\pm &= F_2 - (v_e \pm P_e a_e)\kappa\frac{Q^2}{Q^2+M_Z^2}F_2^{\gamma Z} + \dots \\
x\tilde{F}_3^\pm &= - (a_e \pm P_e v_e)\kappa\frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z} + \dots
\end{aligned}$$

γ exchange — $Z\gamma$ interference — Z exchange

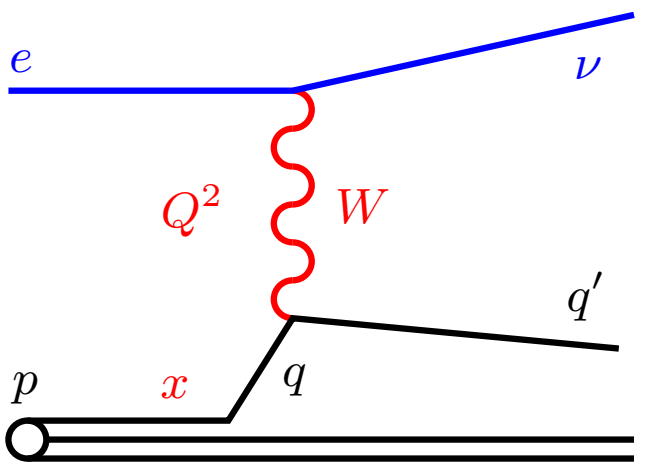
P_e: e beam polarisation
$\kappa^{-1} = \sin^2 2\theta_W$
v, a: electroweak couplings

$\tilde{F}_2$ is sensitive to sea and valence quarks: $F_2 \sim \sum_q (q + \bar{q})$
$x\tilde{F}_3$ is sensitive to valence quarks alone: $xF_3 \sim \sum_q (q - \bar{q})$

Charged Current cross-section



Charged current



Event topology:

- Neutrino escapes detection

Kinematic variables:

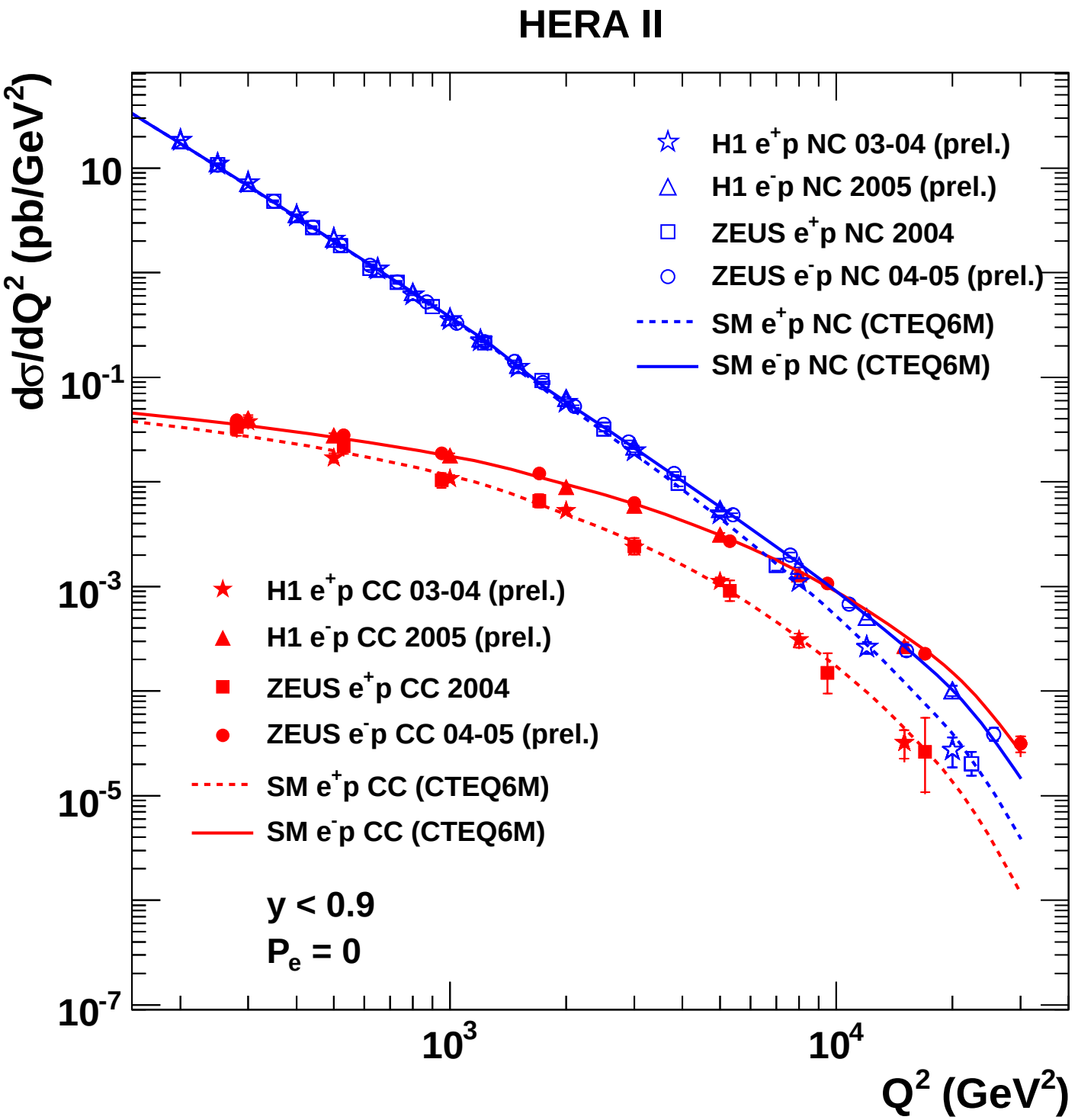
- Momentum transfer squared Q^2
- Fraction of proton momentum x carried by struck quark
- Inelasticity $y = \frac{1-cos\theta^\star}{2} = \frac{Q^2}{sx}$

$$\frac{d^2\sigma^{CC}}{dx\,dQ^2}(e^+p) = (1+P_e)\ \frac{1}{x}\ \frac{G_F^2 M_W^4}{4\pi(Q^2+M_W^2)^2}\ [(1-y)^2(xd+xs)+(x\bar{u}+x\bar{c})]$$

$$\frac{d^2\sigma^{CC}}{dx\,dQ^2}(e^-p) = (1-P_e)\ \frac{1}{x}\ \frac{G_F^2 M_W^4}{4\pi(Q^2+M_W^2)^2}\ \left[(xu+xc)+(1-y^2)(x\bar{d}+x\bar{s})\right]$$

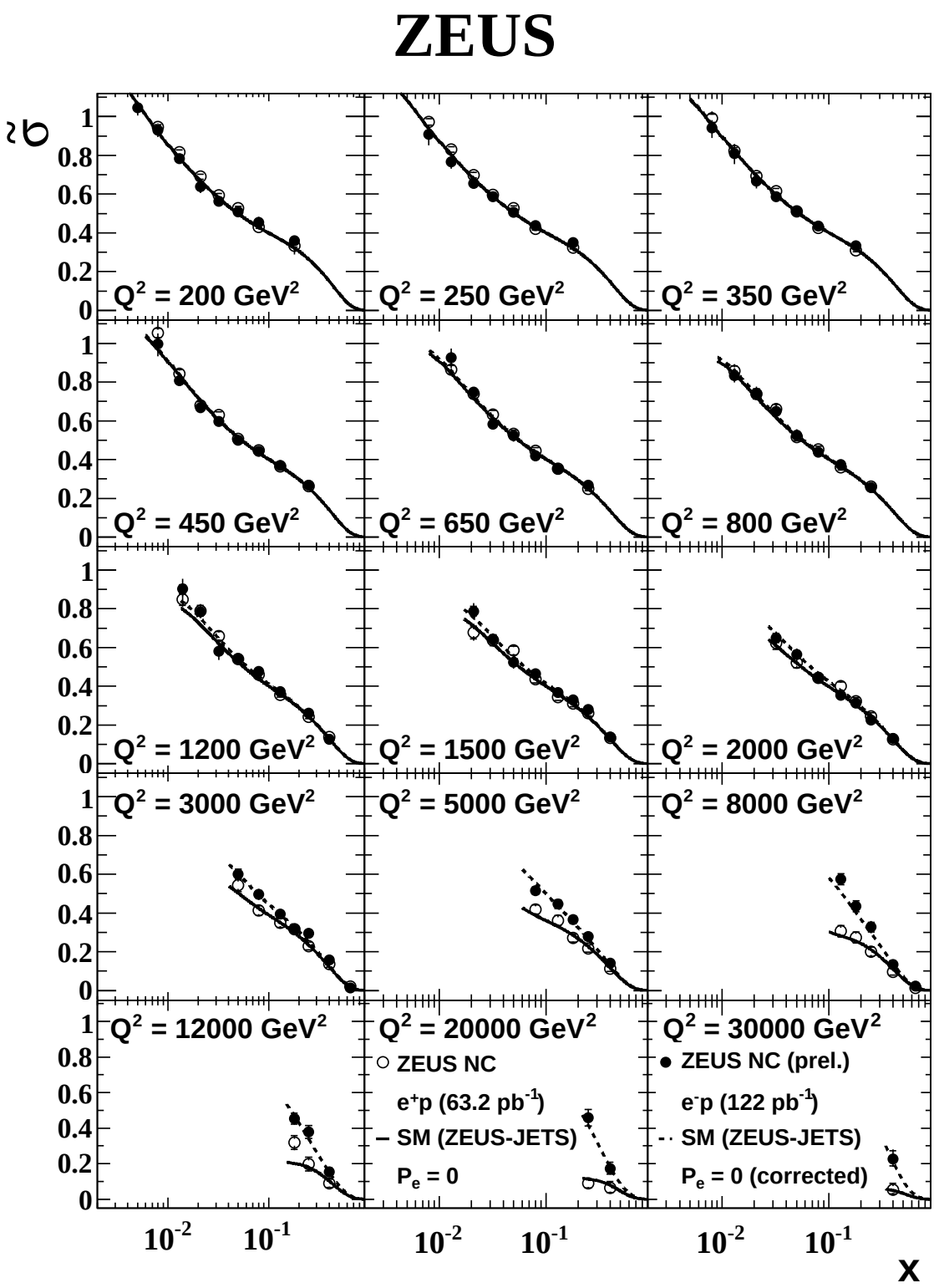
Polarisation — W exchange — Parton densities

Inclusive cross-sections as a function of Q^2: NC and CC



- HERA II data: better precision for e^-p data
  Integrated Luminosity $\times 10$
- Neutral current $\propto \frac{1}{Q^4}$
- Charged current $\propto \frac{1}{(Q^2+M_W^2)^2}$
- NC and CC cross-sections are similar at $Q^2 \approx M_W^2$: electroweak unification
- Difference between e^+p and e^-p:
  NC: γZ interference
  CC: (d vs u) and helicity factor

Double-differential NC cross-section, xF_3



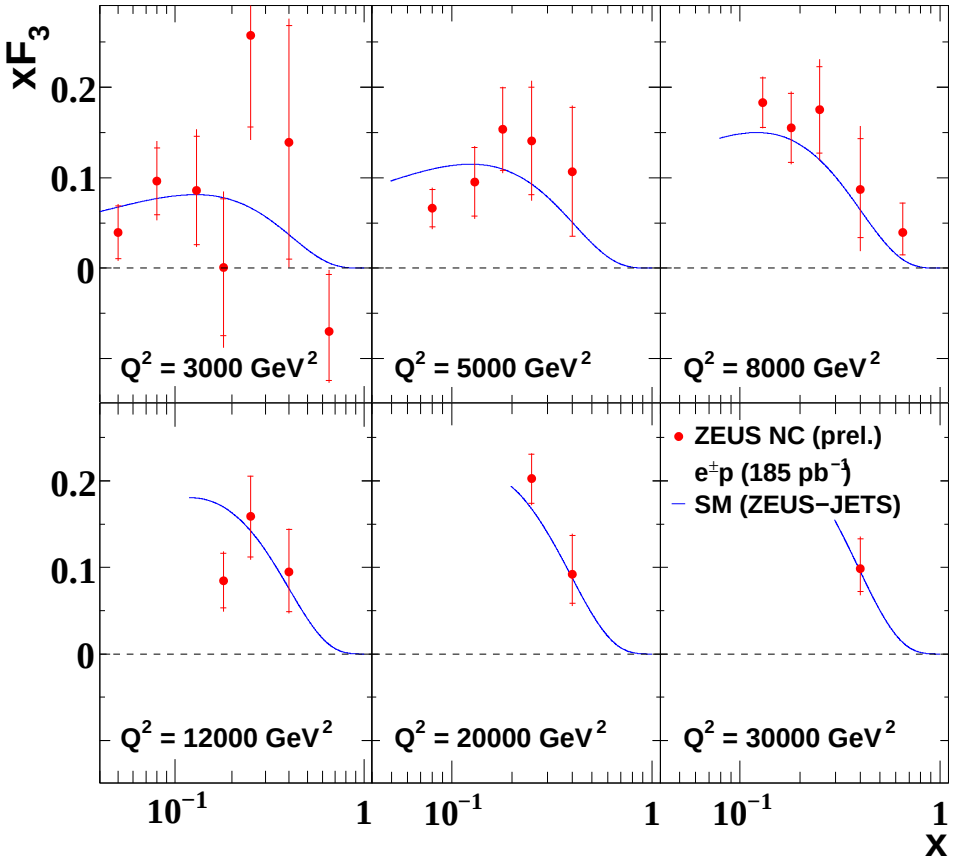
Reduced cross-section

$$\tilde{\sigma}^{\pm} = Y_+ \tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2 \tilde{F}_L$$

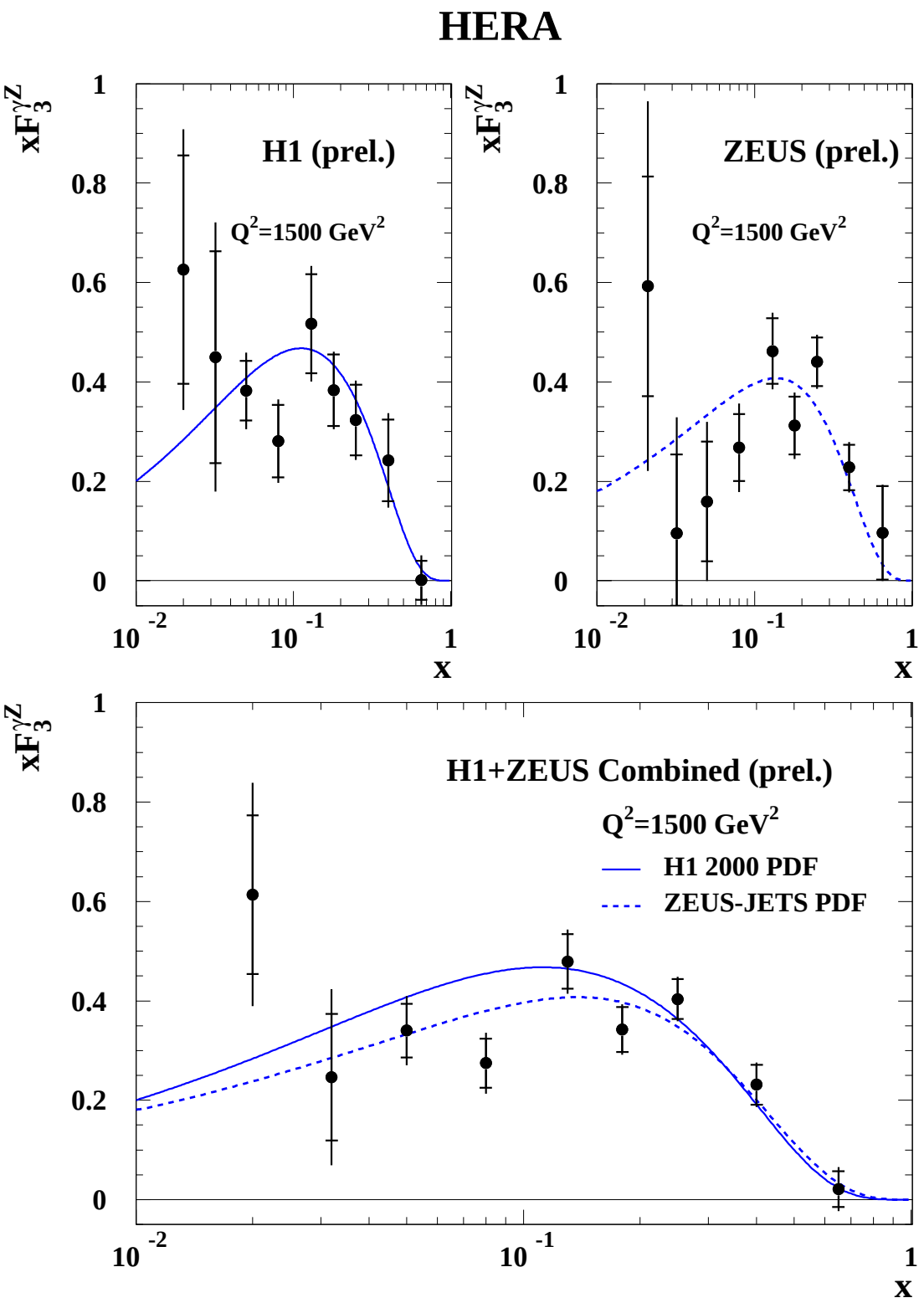
Plot: ZEUS high Q^2 data for HERA I (e^+p) and HERA II (e^-p)

Difference between e^+ and e^-: electroweak effects

$\rightarrow$ extract structure function $x\tilde{F}_3$



Extraction of $xF_3^{\gamma Z}$



$xF_3^{\gamma Z}$: $\tilde{F}_3$ with kinematical factors removed

$$xF_3^{\gamma Z} = \sum_q 2e_q a_q (xq - x\bar{q}) = \tfrac{2}{3} x u_v + \tfrac{1}{3} x d_v$$

$\rightarrow$ Valence quark content of p

$\rightarrow$ Sensitivity to a_q

Weak Q^2 dependence $\rightarrow$ transform all points to $Q^2 = 1500\,\mathrm{GeV}^2$

Sum rule:

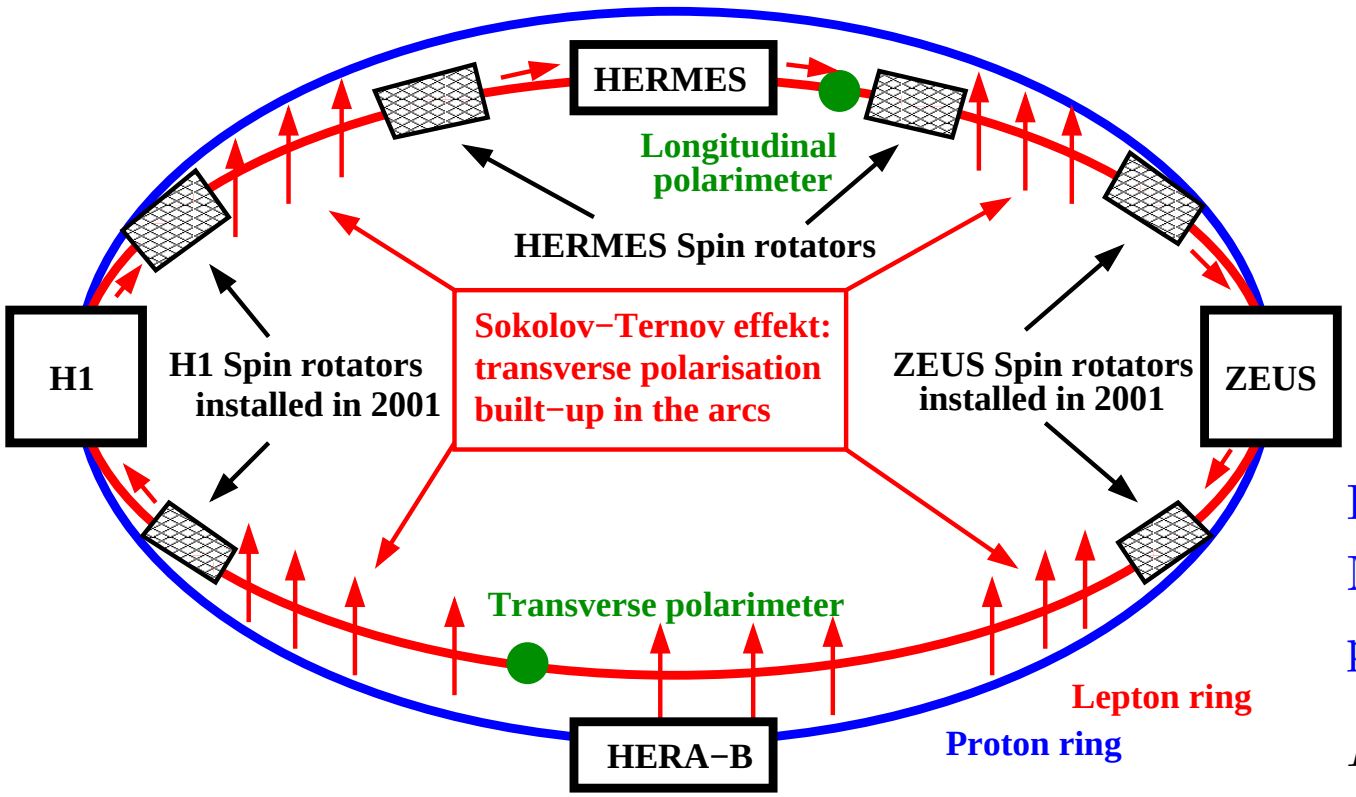
$$\int_0^1 \frac{xF_3^{\gamma Z}}{x} dx = \int_0^1 (\tfrac{2}{3} u_v + \tfrac{1}{3} d_v) dx = \tfrac{5}{3}$$

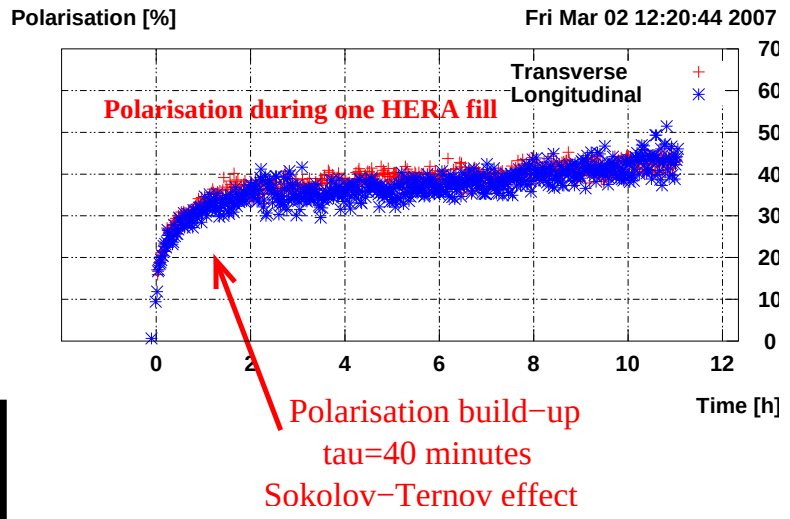
Combined result from ZEUS, H1:

$$\int_{0.02}^{0.65} \frac{xF_3^{\gamma Z}}{x} dx = 1.21 \pm 0.09\ (\mathrm{stat}) \pm 0.08\ (\mathrm{sys})$$

Compatible with Sum rule if integral is extrapolated to $[0, 1]$

Lepton polarisation at HERA II





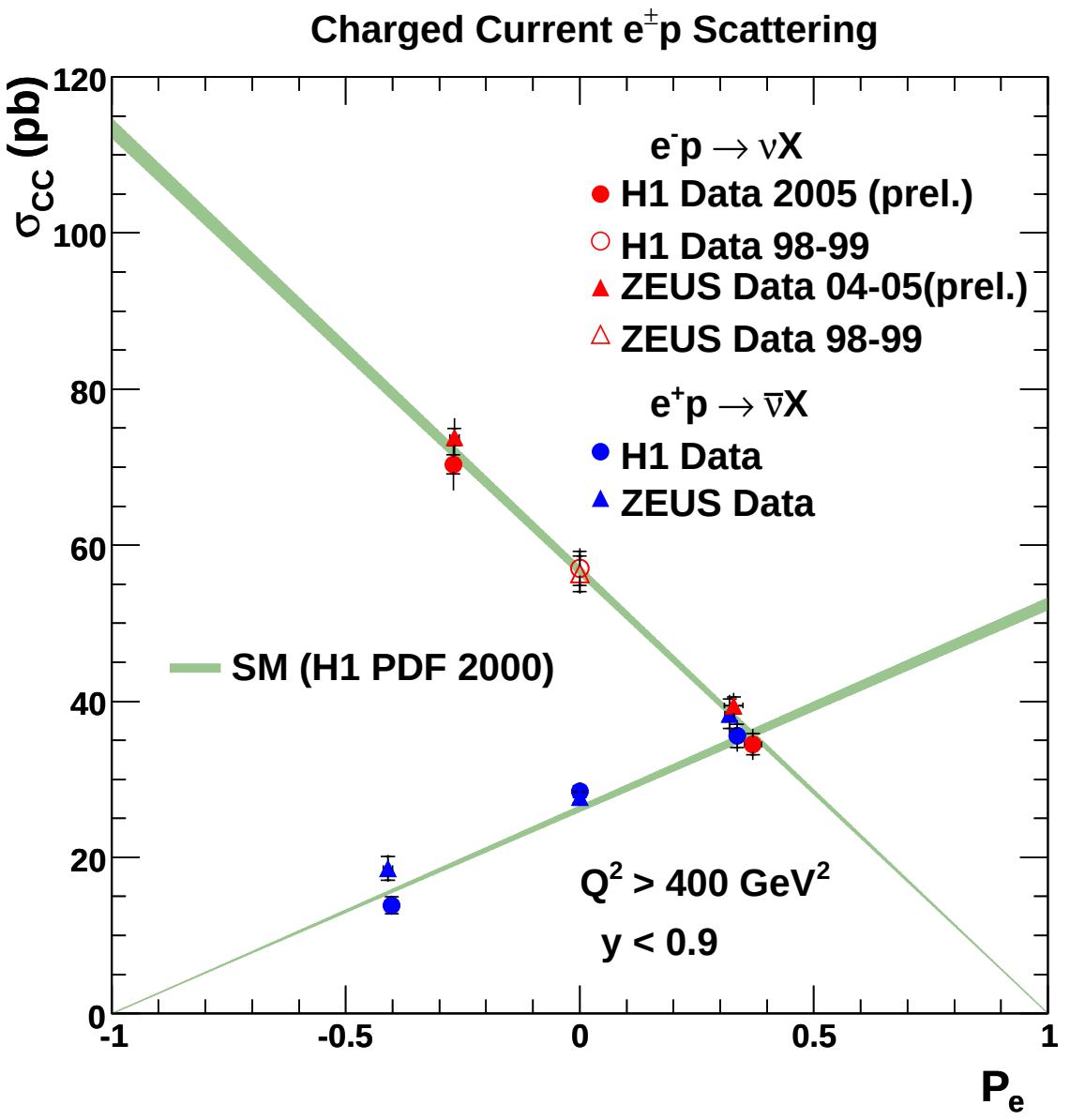
Polarisation is changing during the fill
Monitored by two independent Compton polarimeters

$P_e = 30 \ldots 45\%$ achieved regularly

HERA I+II:
Transverse polarisation for H1+ZEUS
Not useful for physics

HERA II:
Luminosity upgrade for H1+ZEUS
Longitudinal polarisation for H1+ZEUS
→ new electroweak results

Polarised Charged current cross-section



$$\sigma^{CC}(e^{\pm}p) = (1 \pm P_e) \times \sigma^{CC}_{P_e=0}(e^{\pm}p)$$

Linear dependence of σ^{CC} on P_e confirmed.

Extrapolation to $P_e = \pm 1$

$\sigma^{CC}(e^-p)$ [pb] extrapolated to $P_e = 1$	
H1 (prel.)	$-0.9 \pm 2.9_{\text{stat}} \pm 1.9_{\text{sys}} \pm 2.9_{\text{pol}}$
ZEUS (prel.)	$0.8 \pm 3.1_{\text{stat}} \pm 5.0_{\text{sys+pol}}$
$\sigma^{CC}(e^+p)$ [pb] extrapolated to $P_e = -1$	
H1	$-3.9 \pm 2.3_{\text{stat}} \pm 0.7_{\text{sys}} \pm 0.8_{\text{pol}}$

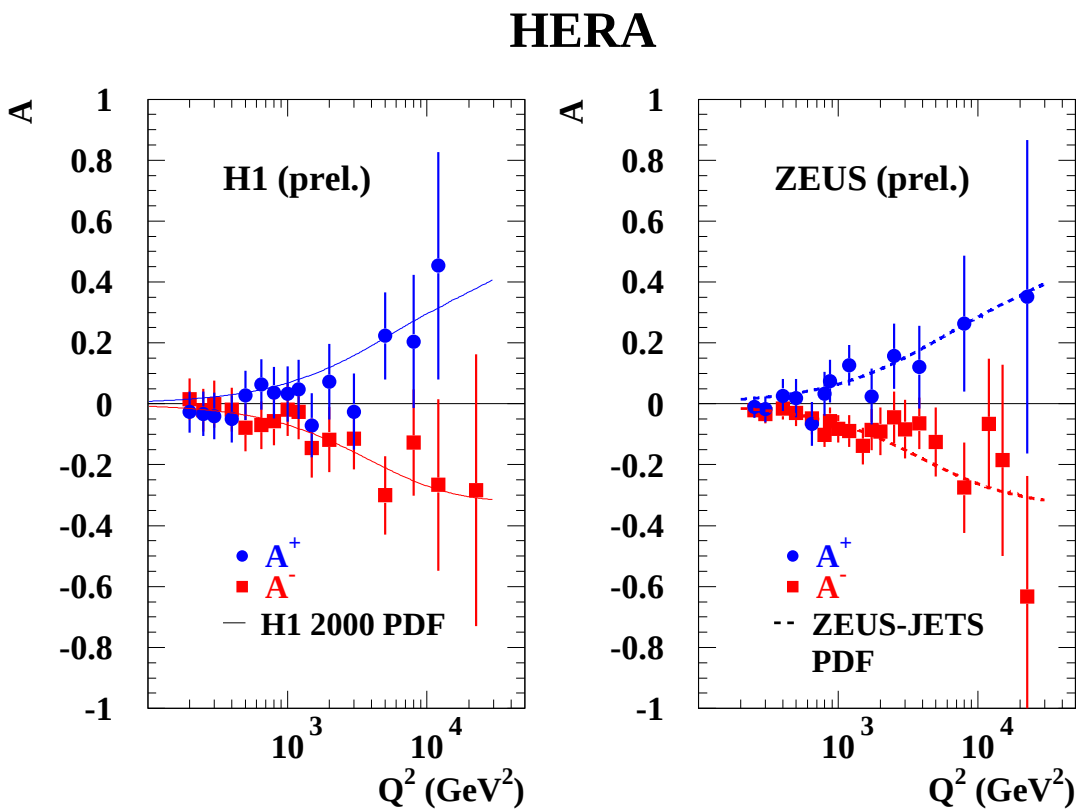
No sign of right-handed charged currents!

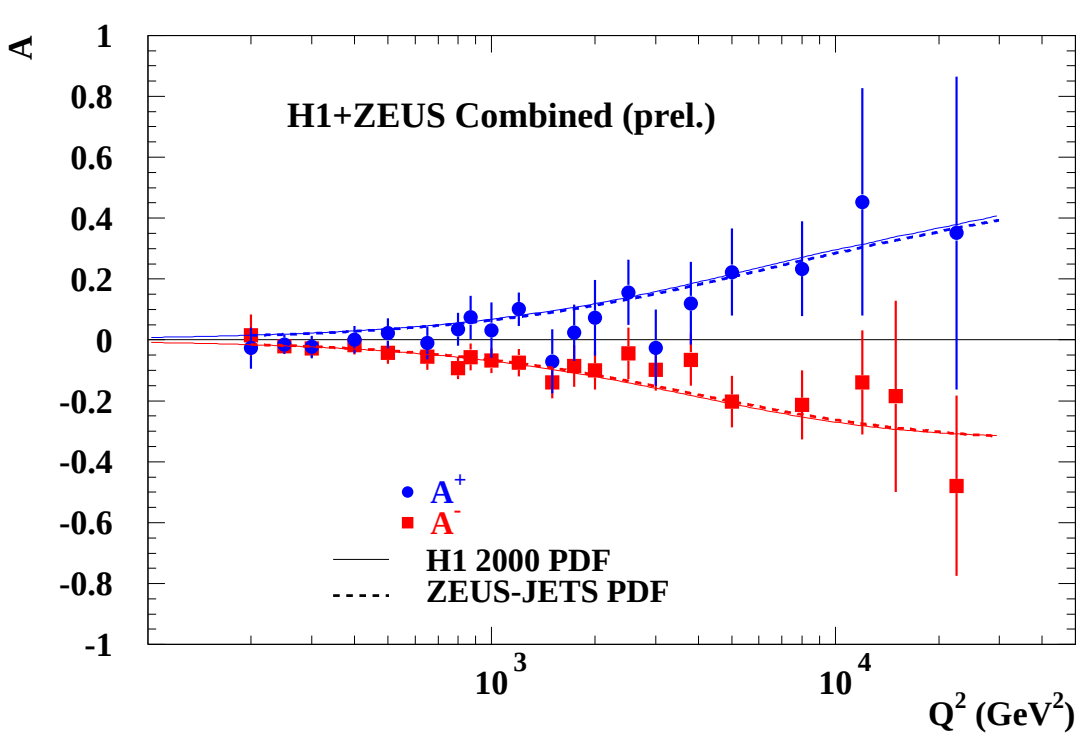
Convert to 95% limit on heavy W_R boson:

$M_{W,R} > 208\,\text{GeV}$ (H1, e^+p)

Complementary to direct searches at Tevatron.

New results from HERA II: Polarised Neutral current cross-section





Asymmetry of the two polarisation states

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

$A \neq 0$ at highest Q^2:

Evidence for parity violation in neutral currents at small distances $10^{-18}\,m$

Expect $A^+ \approx -A^-$ within the standard model.

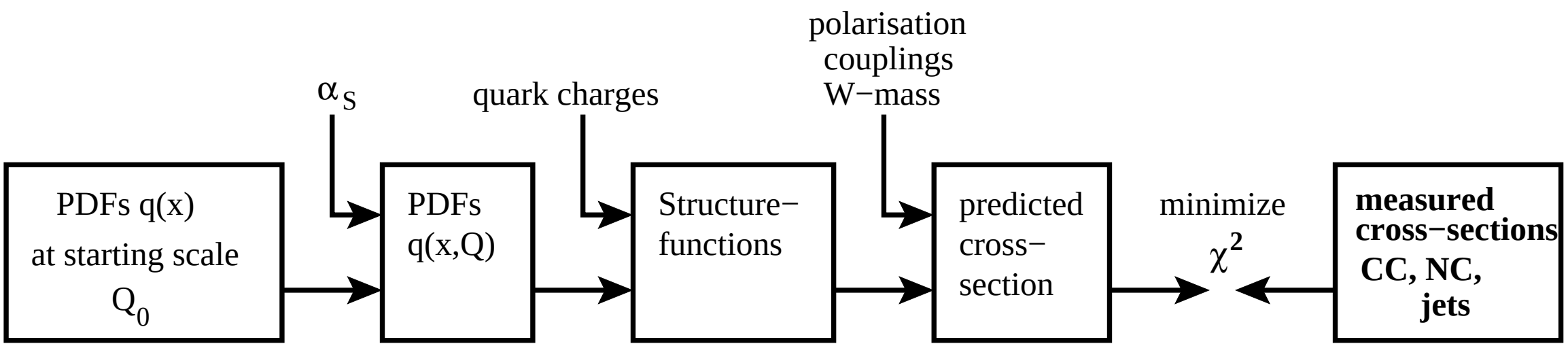
$$A \sim \frac{\sum_q e_q v_q (q + \bar{q})}{\sum_q e_q^2 (q + \bar{q})}$$

Sensitivity to the quark vector couplings v_q.

Electroweak fits at HERA

Charged current: sensitivity to G_F, M_W

Neutral current: sensitivity to light quark axial and vector couplings $v_{u,d}$, $a_{u,d}$



HERA fits: mainly about precise determination of α_S and PDFs

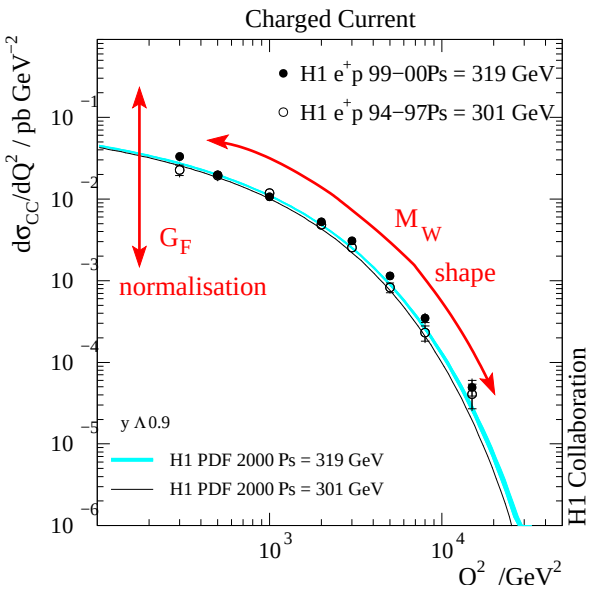
Results presented here: recent papers about HERA fits of electroweak parameters.

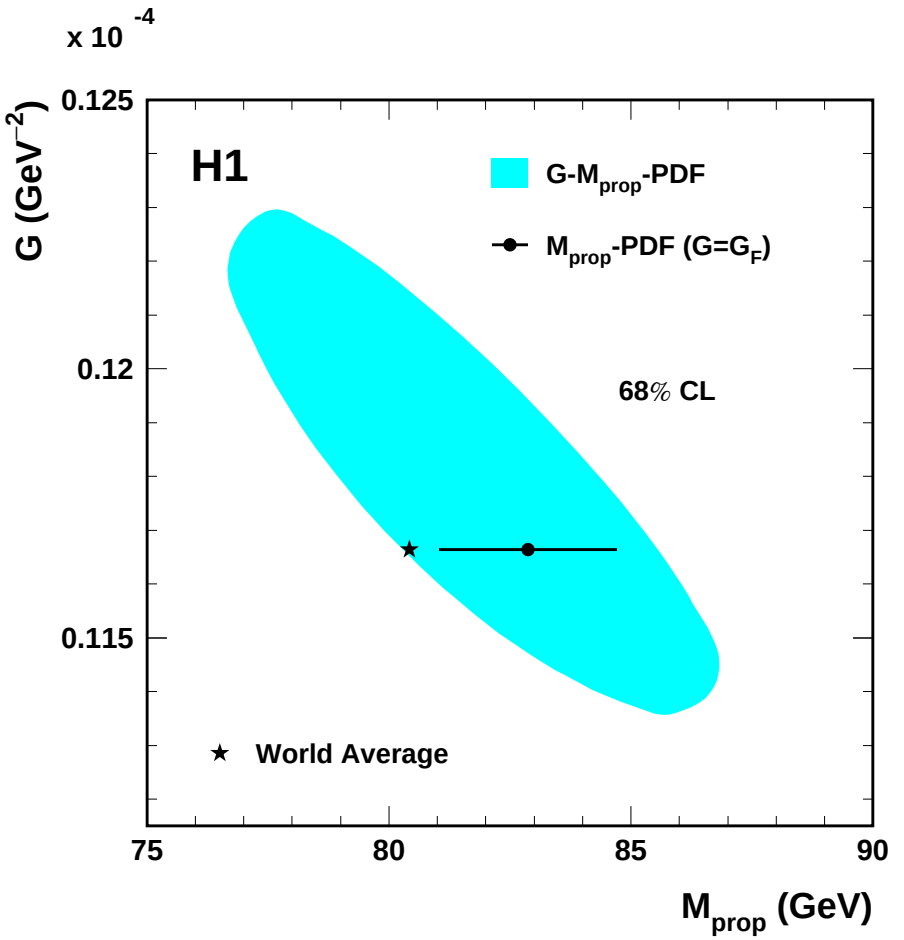
W mass determination

Charged Current: sensitive to G_F and M_W

Fit I: fixed G_F, determine M_W

FIT II: simultaneous fit of G_F and M_W





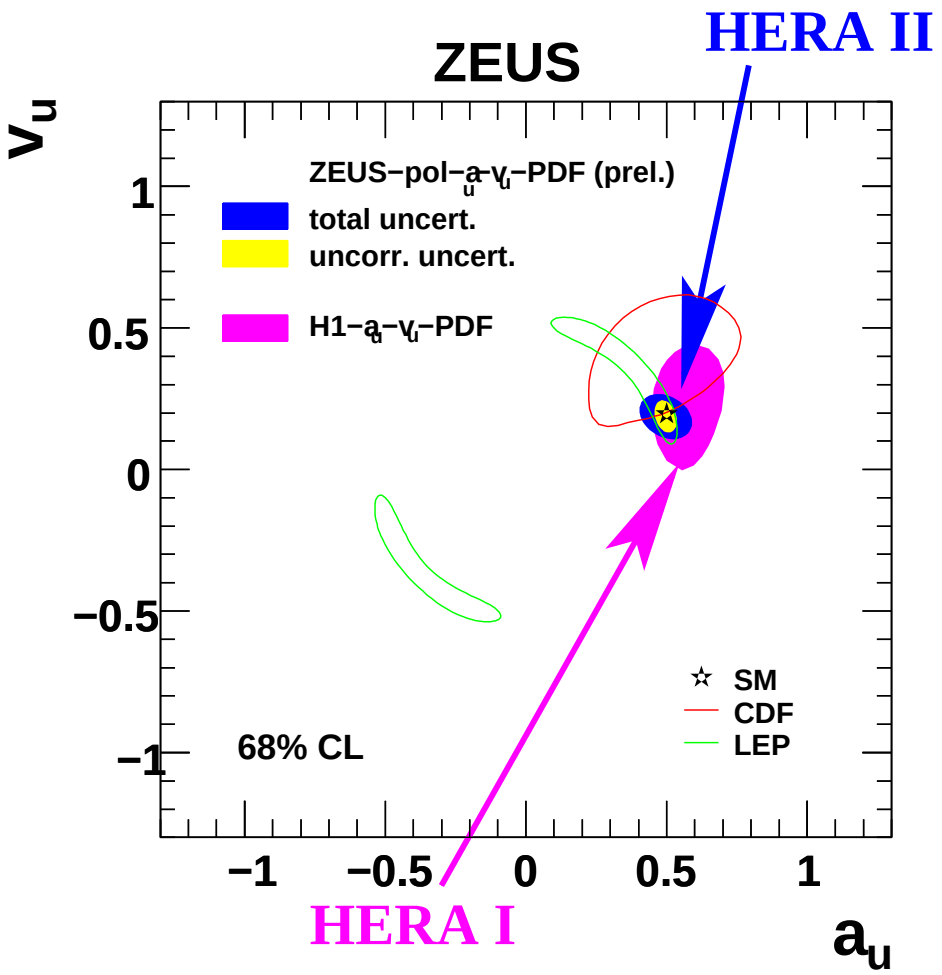
G_F fixed	M_W [GeV]	
H1 (HERA I)	$82.87 \pm 1.82_{\text{exp}}\,^{+0.30}_{-0.16}\,\vert_{\text{model}}$	
ZEUS (HERA I+II)	$79.10 \pm 0.77_{\text{stat}} \pm 0.99_{\text{sys}}$	
G_F free	M_W [GeV]	G_F [10^{-5}GeV^{-2}]
ZEUS (HERA I+II)	$82.8 \pm 1.5_{\text{stat}} \pm 1.3_{\text{sys}}$	$1.127 \pm 0.013_{\text{stat}} \pm 0.014_{\text{sys}}$

Electroweak u and d quark couplings

NC cross-section: measure u, d quark axial and vector couplings:

- $F_2^{\gamma Z}$ is sensitive to v_q: $F_2^{\gamma Z} = 2\sum_q e_q v_q (xq + x\bar{q})$
- $F_3^{\gamma Z}$ is sensitive to a_q: $F_3^{\gamma Z} = 2\sum_q e_q a_q (xq + x\bar{q})$

HERA I analyses: reduced sensitivity to v_q (no polarisation)



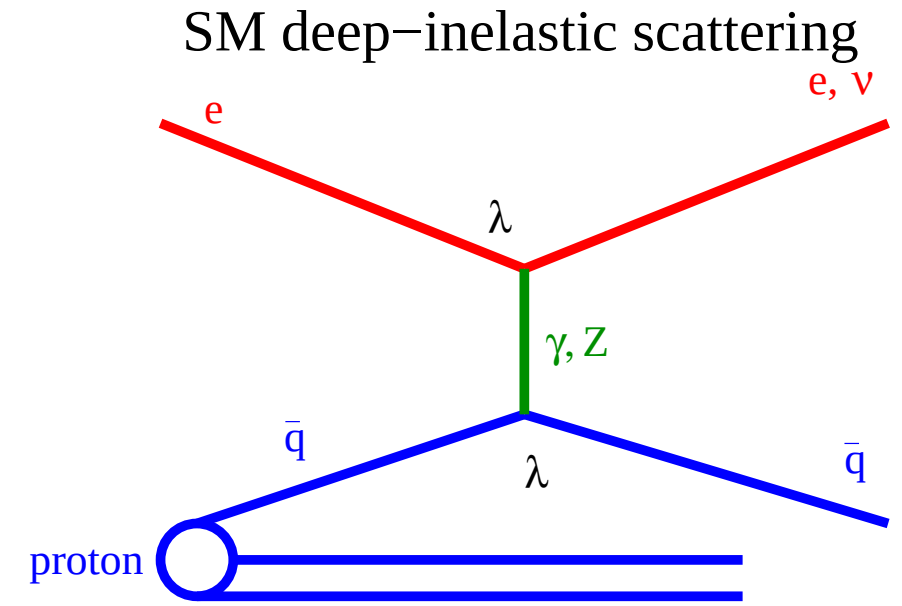
(a_u, v_u) Fit	a_u	v_u
H1 (HERA I)	0.57 ± 0.08	0.27 ± 0.13
ZEUS (HERA II)	0.50 ± 0.10	0.19 ± 0.08
SM value	0.5	0.196

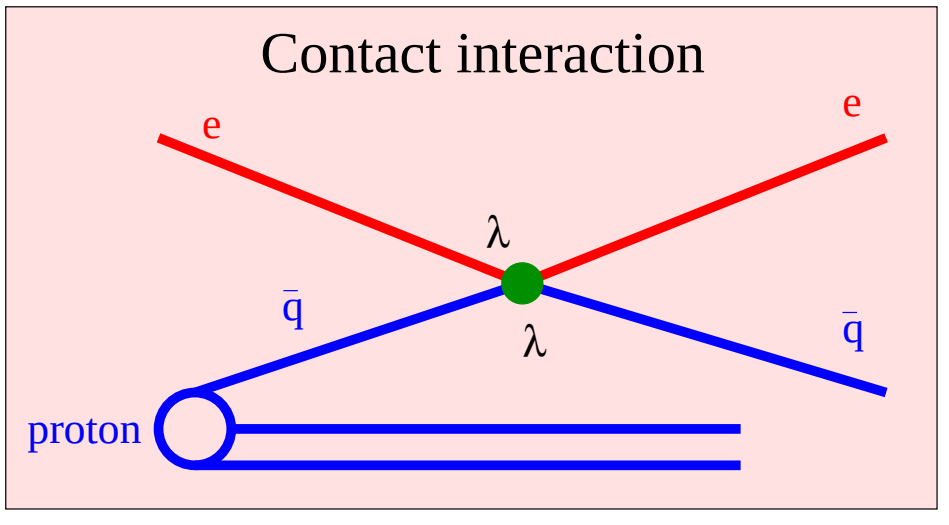
(a_d, v_d) Fit	a_d	v_d
H1 (HERA I)	-0.80 ± 0.24	-0.33 ± 0.33
ZEUS (HERA II)	-0.49 ± 0.30	-0.37 ± 0.22
SM value	-0.5	-0.346

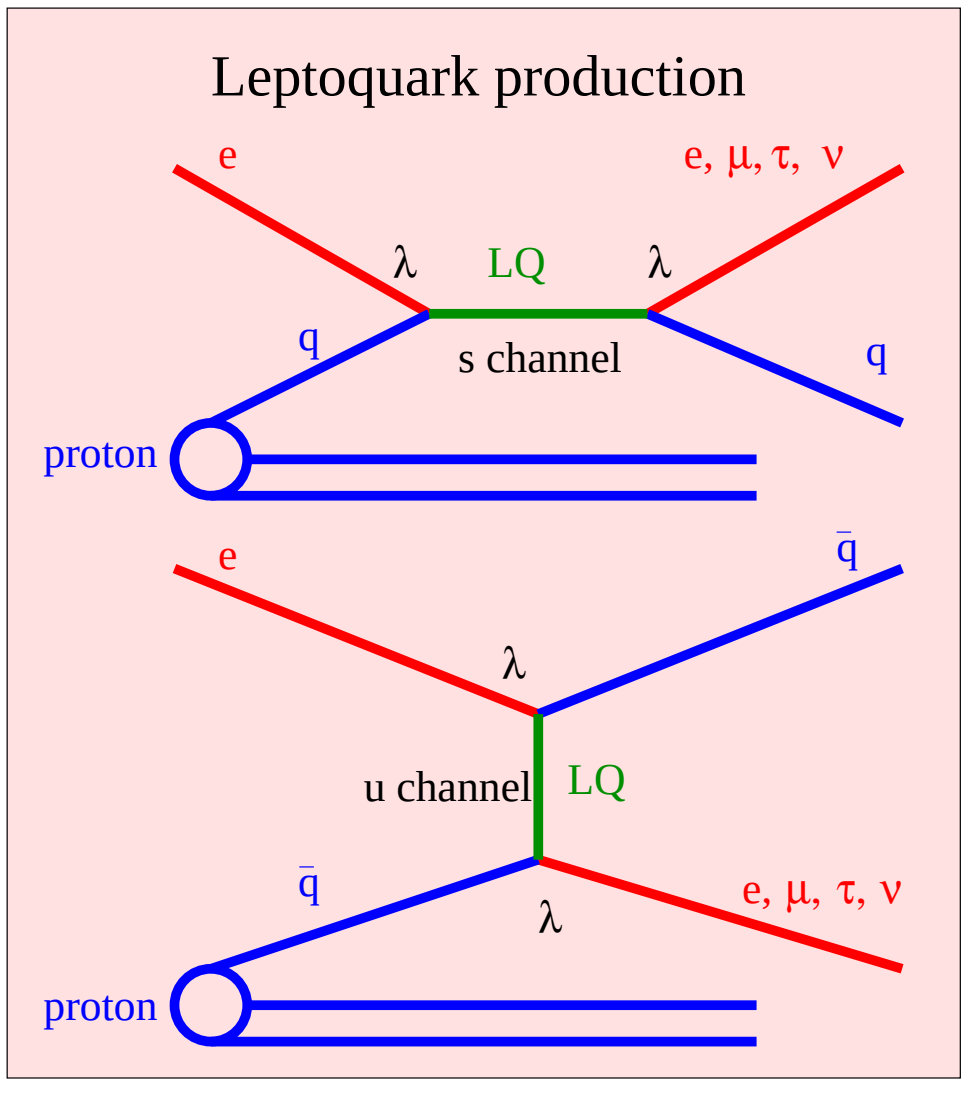
Searches for new physics in inclusive ep data

Topics presented in this talk: searches for leptoquarks, contact interactions

See talk by **James Ferrando** for other searches at HERA.

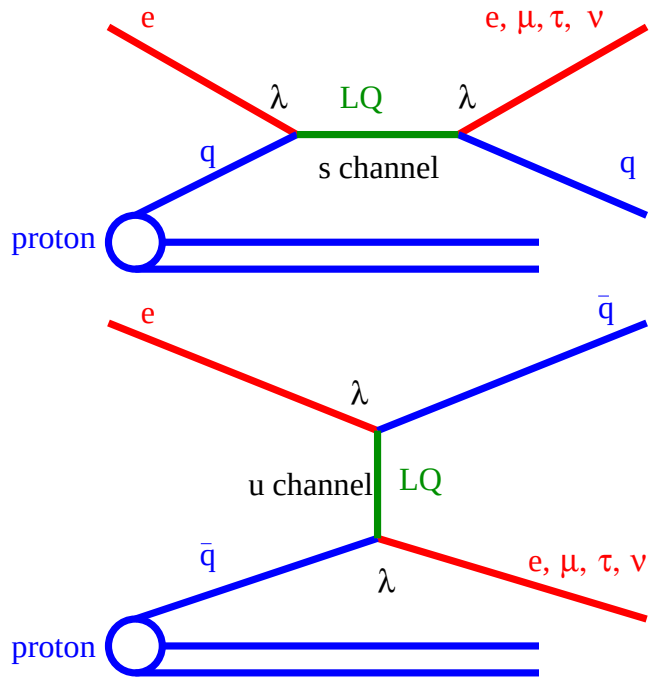


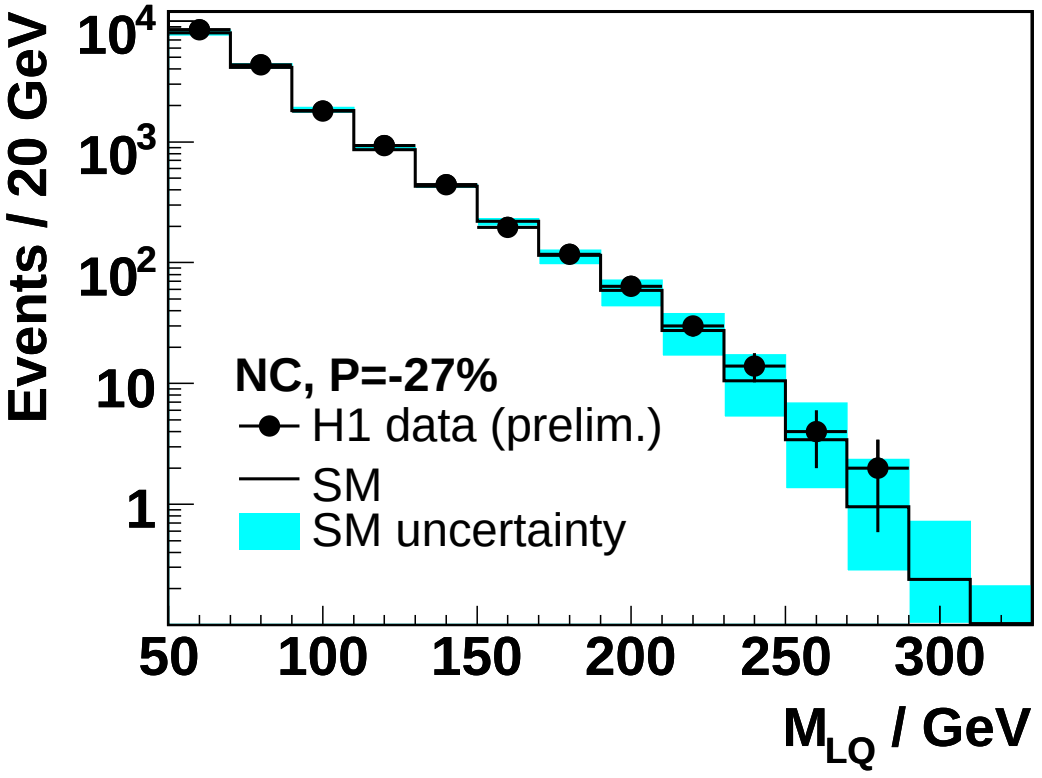


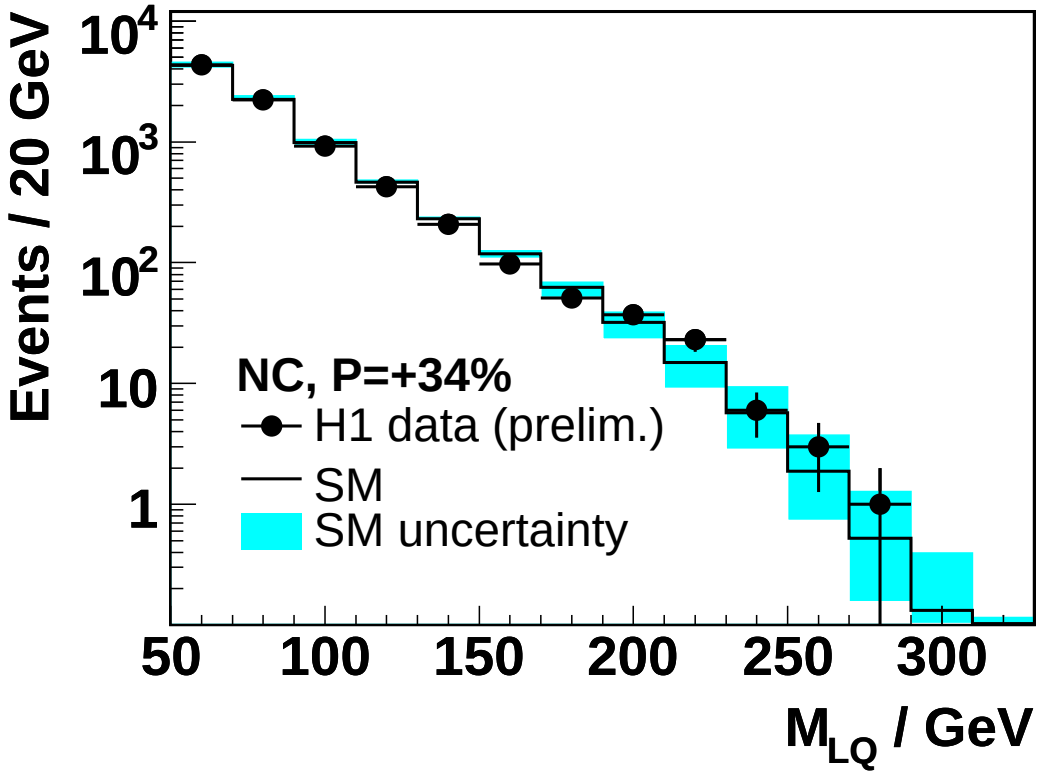


Leptoquark searches at HERA

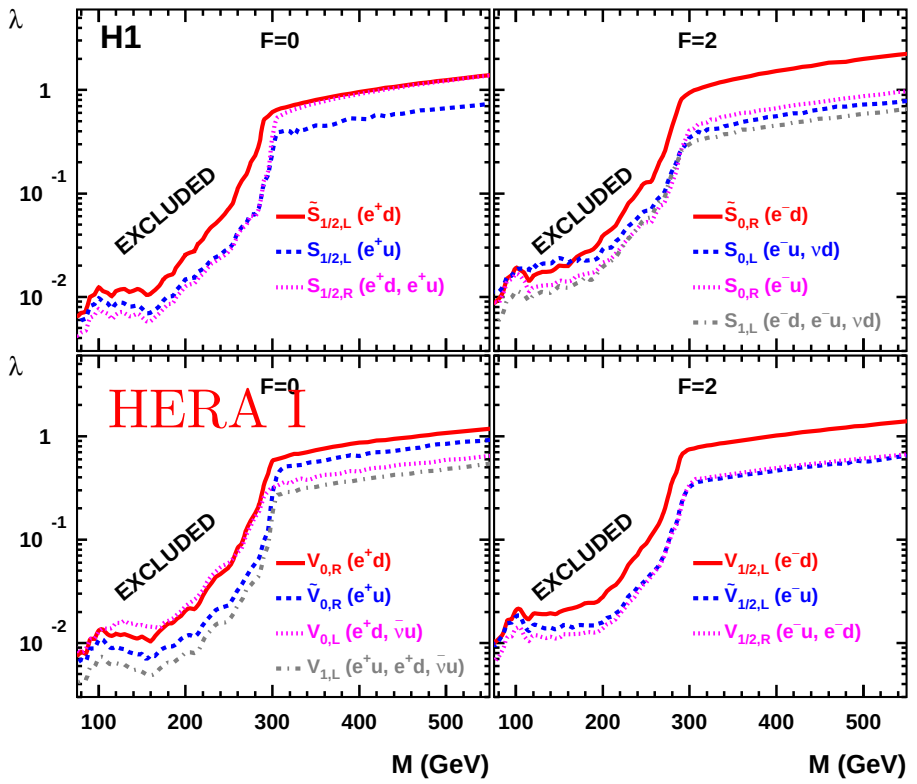
- Leptoquark (LQ): boson with baryonic and leptonic quantum numbers, fermion number $F = 3B + L$
- Example: Squark in R_p violating SUSY
- LQ at HERA: single production
  - $M_{LQ} < 300$ GeV: resonant production $M_{LQ} = \sqrt{sx}$ (F=0 in e^+p and F=2 in e^-p)
  - $M_{LQ} \gg 300$ GeV: contact interaction
- Decay: Neutral current or charged current

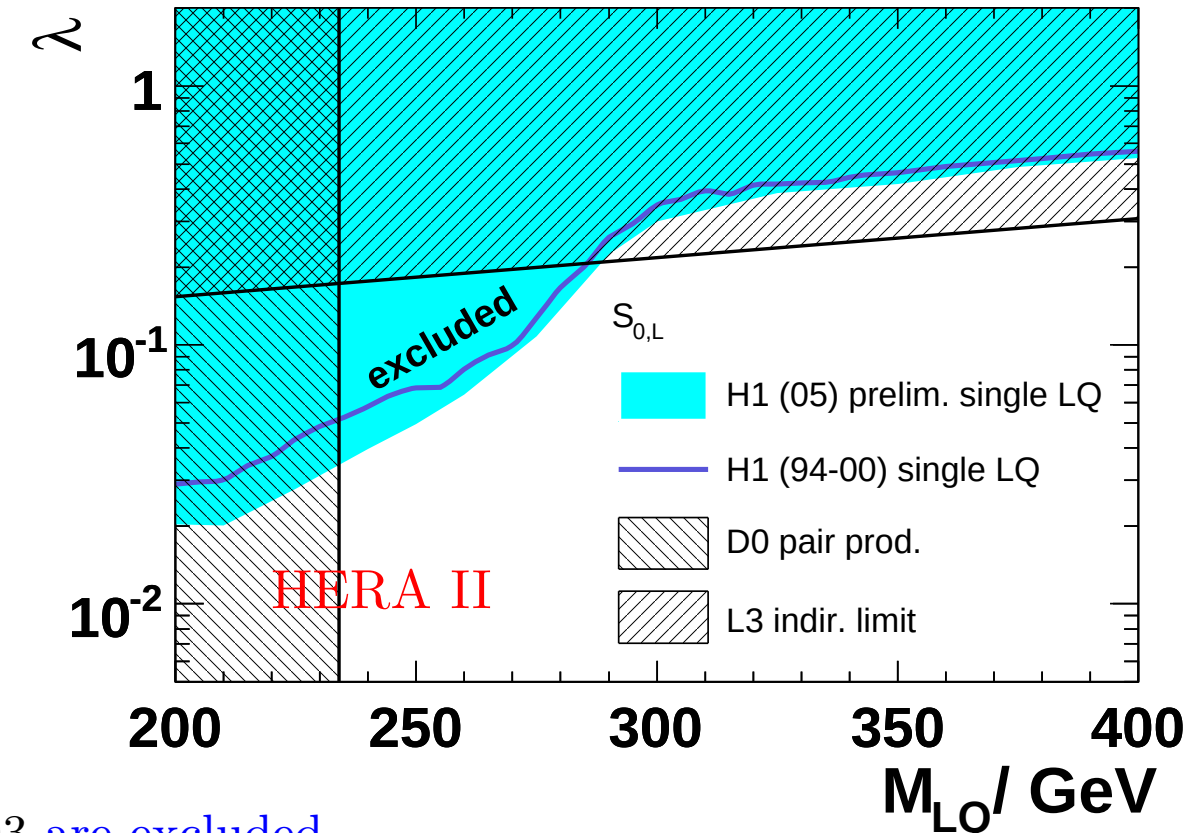






Leptoquark limits





For $M_{LQ} = 200$ GeV: couplings of order $\lambda \gtrsim 0.03$ are excluded.

For $\lambda = 0.3$ (el. magn. strength) LQ masses of order $M_{LQ} \lesssim 300$ GeV are excluded.

HERA II limits: sizeable improvements wrt. HERA I limits (luminosity, polarisation)

Limits at high masses $M_{LQ} \gg 300GeV$:

$F=0:$ $\frac{M_{LQ}}{\lambda}$ [TeV]	$S^L_{1/2}$	$S^R_{1/2}$	$\tilde{S}^L_{1/2}$	V^0_L	V^R_0	$\tilde{V}^R_0$	V^L_1
ZEUS HERA I+II	0.88	0.46	0.44	0.80	0.62	1.33	1.91
H1 HERA I	0.85	0.37	0.43	0.73	0.58	0.99	1.36

$F=2:$ $\frac{M_{LQ}}{\lambda}$ [TeV]	S^L_0	S^R_0	$\tilde{S}^R_0$	S^1_L	$V^L_{1/2}$	$V^R_{1/2}$	$\tilde{V}^L_{1/2}$
ZEUS HERA I+II	0.96	0.82	0.32	0.88	0.46	1.00	1.10
H1 HERA I	0.71	0.64	0.33	0.49	0.42	0.95	1.02

Searches for Contact interactions at HERA

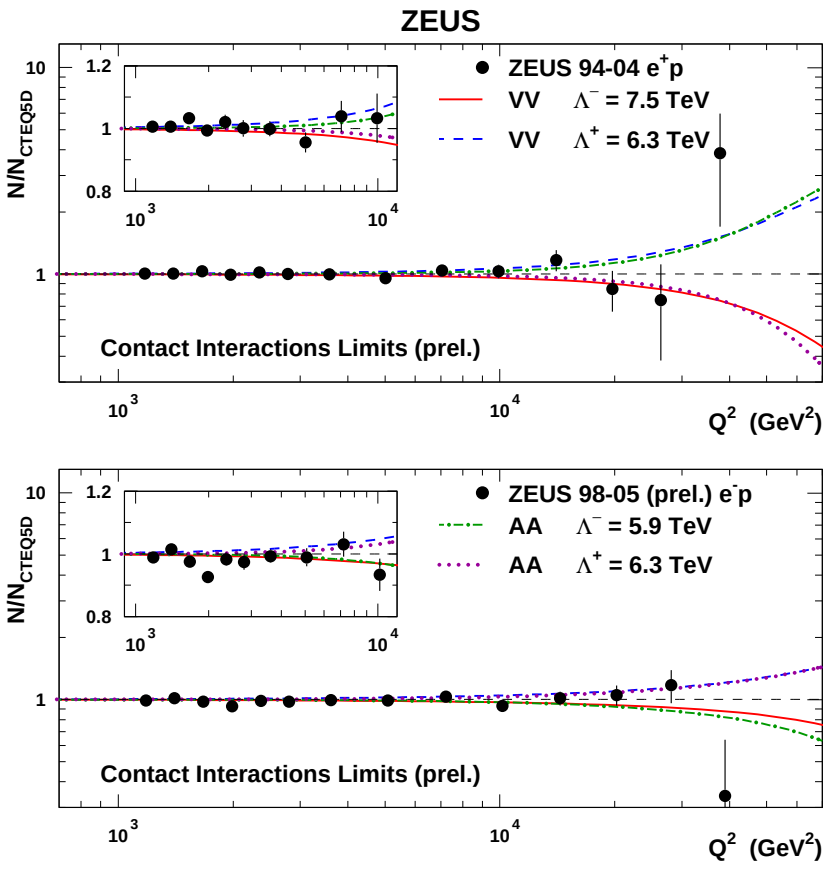
$$\mathcal{L} = \sum_{q=u,d} \eta^q_{LL}(\bar{e_L}\gamma^\mu e_L)(\bar{q_L}\gamma^\mu q_L) + \eta^q_{RL}(\bar{e_R}\gamma^\mu e_R)(\bar{q_L}\gamma^\mu q_L) +$$
$$\eta^q_{LR}(\bar{e_L}\gamma^\mu e_L)(\bar{q_R}\gamma^\mu q_R) + \eta^q_{RR}(\bar{e_R}\gamma^\mu e_R)(\bar{q_R}\gamma^\mu q_R)$$

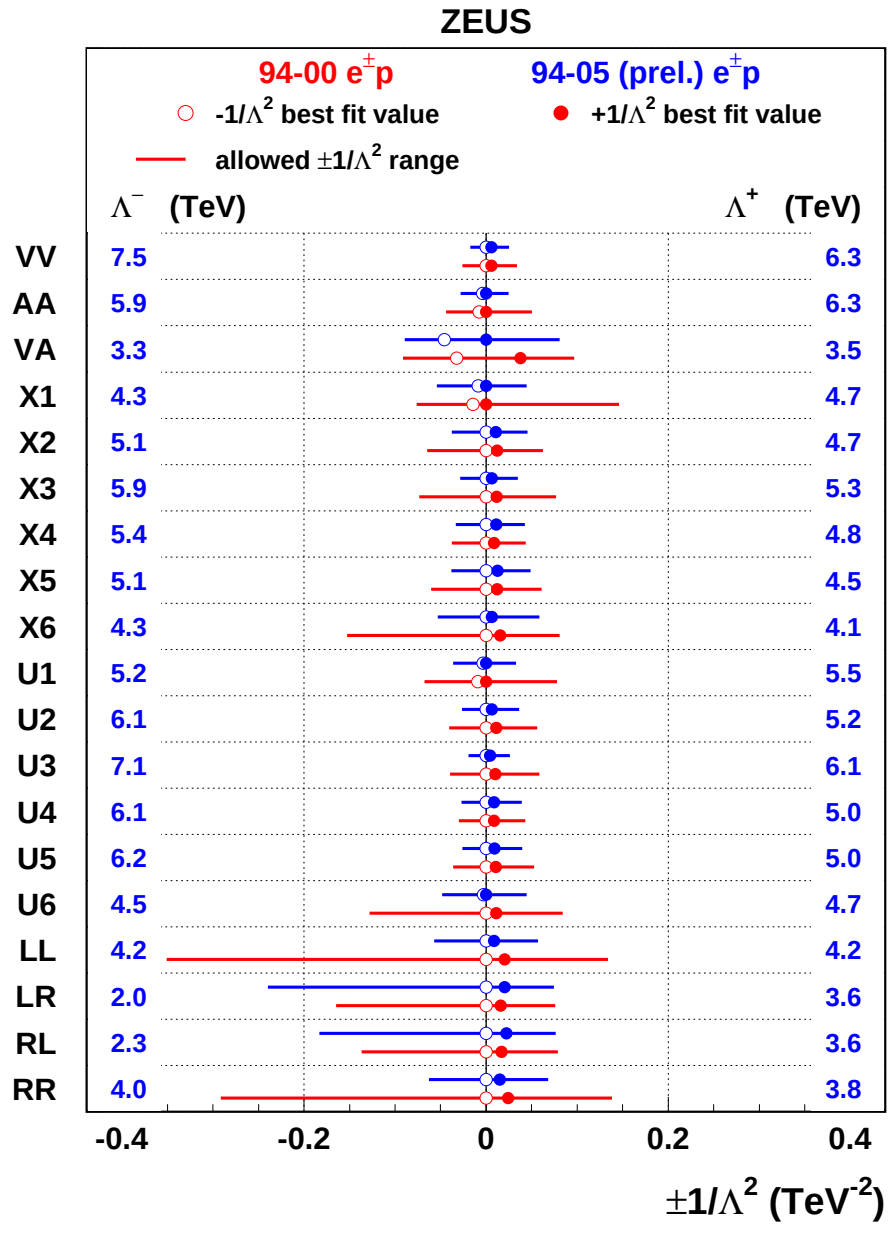
Effective Lagrangian with coupling constants $\eta^q_{ab} = \frac{\epsilon^q_{ab}}{\Lambda^2}$ and $\epsilon^q_{ab} = \begin{cases} 0 \\ \pm 1 \end{cases}$.

Cross-section shape is altered at high Q^2 in the presence of CI

New ZEUS results with full HERA I+II statistics

→ Sensitivity on Λ up to 7.5 TeV





Summary

- New results from HERA II: high luminosity and polarisation
- Probing electroweak physics in deep-inelastic scattering:

  Charged current: W mass, polarisation dependence

  Neutral current: xF_3, polarisation dependence, axial and vector couplings of u and d
- Searches for new phenomena in inclusive data:

  Leptoquarks and Contact interactions: sensitivity to the TeV scale
- Data from 2006 and 2007 still being analysed

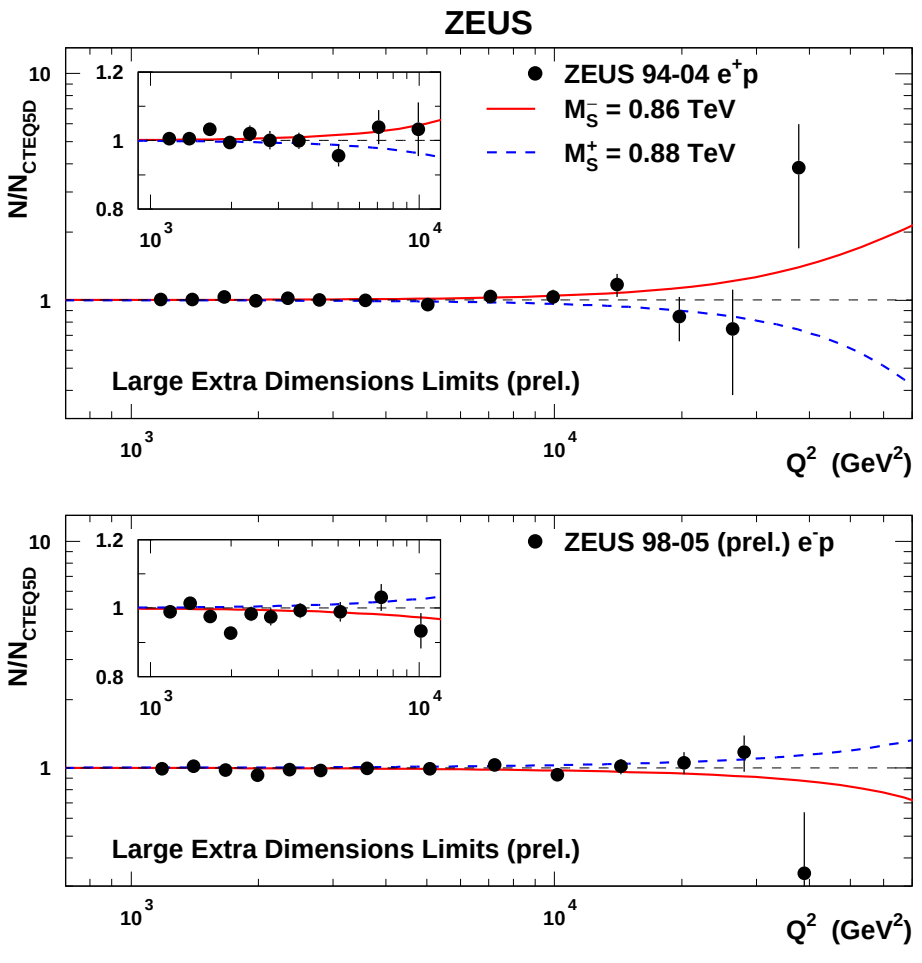
  expect new results this summer.
- Summer 2007: end of HERA operation, with integrated luminosity H1+ZEUS$\approx 1\,\mathrm{fb}^{-1}$

Backup: Large extra dimensions

Consider space time with 4+n dimensions, where the compactified extra dimensions are of size R.

Fundamental Planck scale $M_D = \mathcal{O}(\text{TeV})$ in $D = 4 + n$ dimensions
$\rightarrow$ generates Planck scale M_P in 4 dimensions, $M_P^2 \approx M_D^{2+n} R^n$.

Gravitational excitations in the extra dimensions are visible as contact interactions with effective coupling strength $\eta_G = \frac{g}{M_S^4}$ $(g = \pm 1)$, where $M_S \approx M_D$



Lower limit on M_S [TeV]		
	$g = +1$	$g = -1$
ZEUS prel (1994-2005)	0.88	0.86
ZEUS (1994-2000)	0.78	0.79
H1 (1994-2000)	0.82	0.78

Limits on M_S close to 0.9 TeV, independent of the number of extra dimensions n.

HERA II: ZEUS-prel-06-018 (ICHEP 2006)
HERA I: Phys Lett B 568 (2003) 35-47
and Phys Lett B 591 (2004) 23-41