Physics with eP collisions at highest Q^2 and P_T

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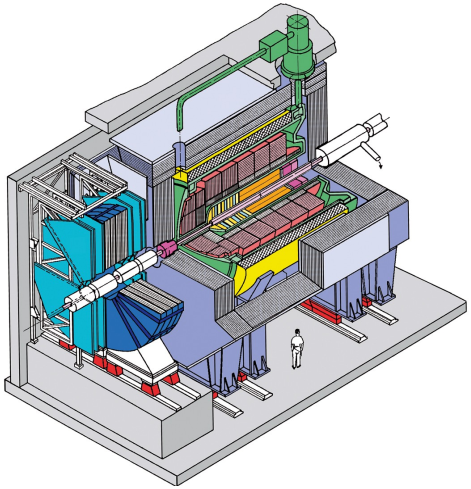
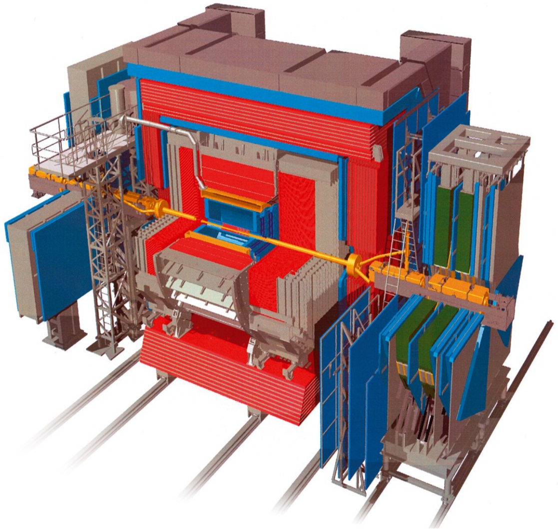
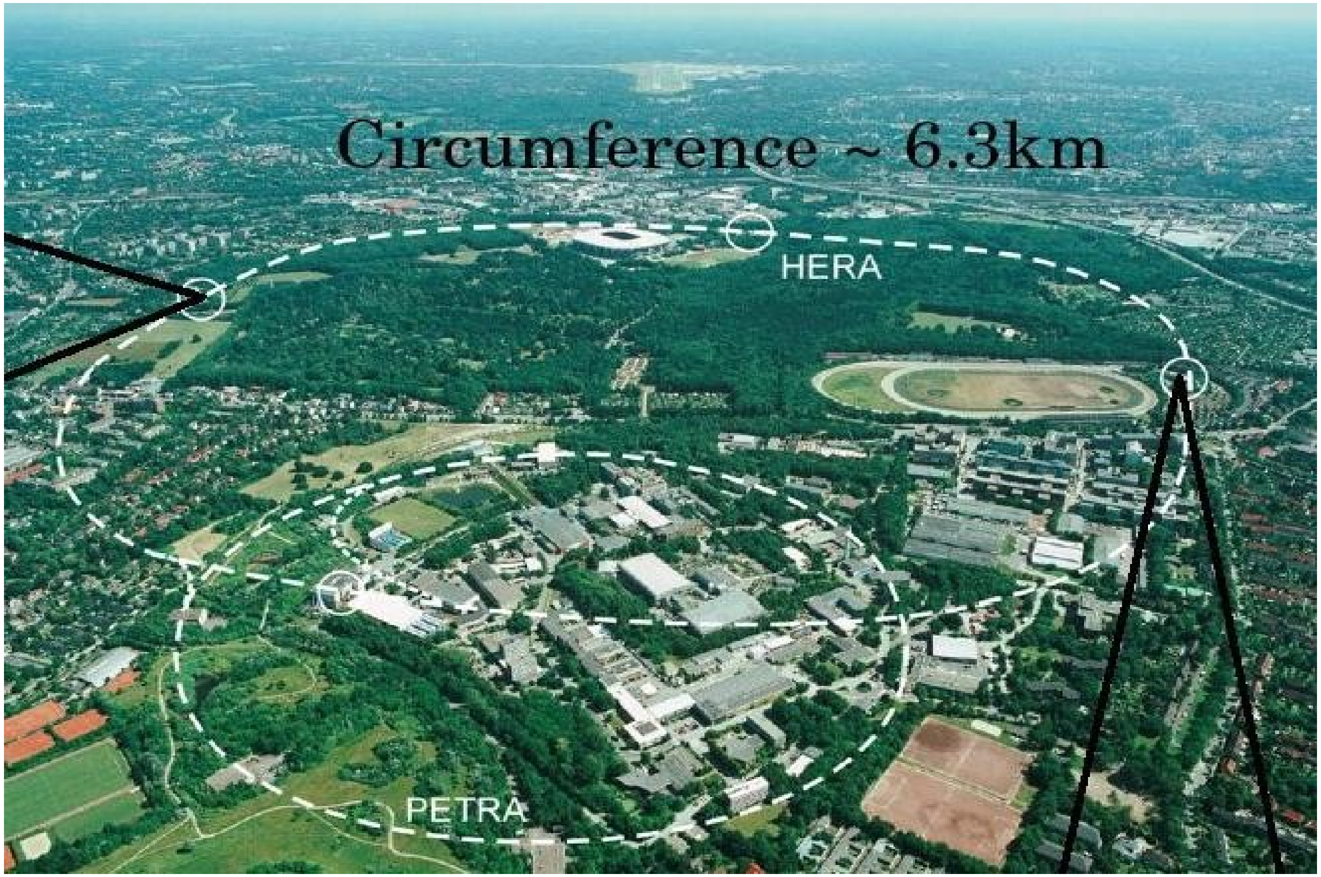
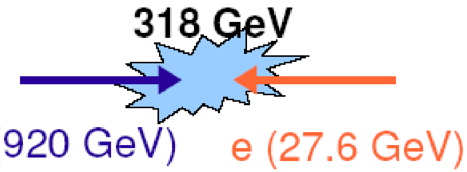


- Introduction
- HERA collider and experiments
- Polarized NC/CC cross sections
- Combined QCD/EW analysis of the data
- Searches
- Conclusions and outlook



HERA collider at DESY



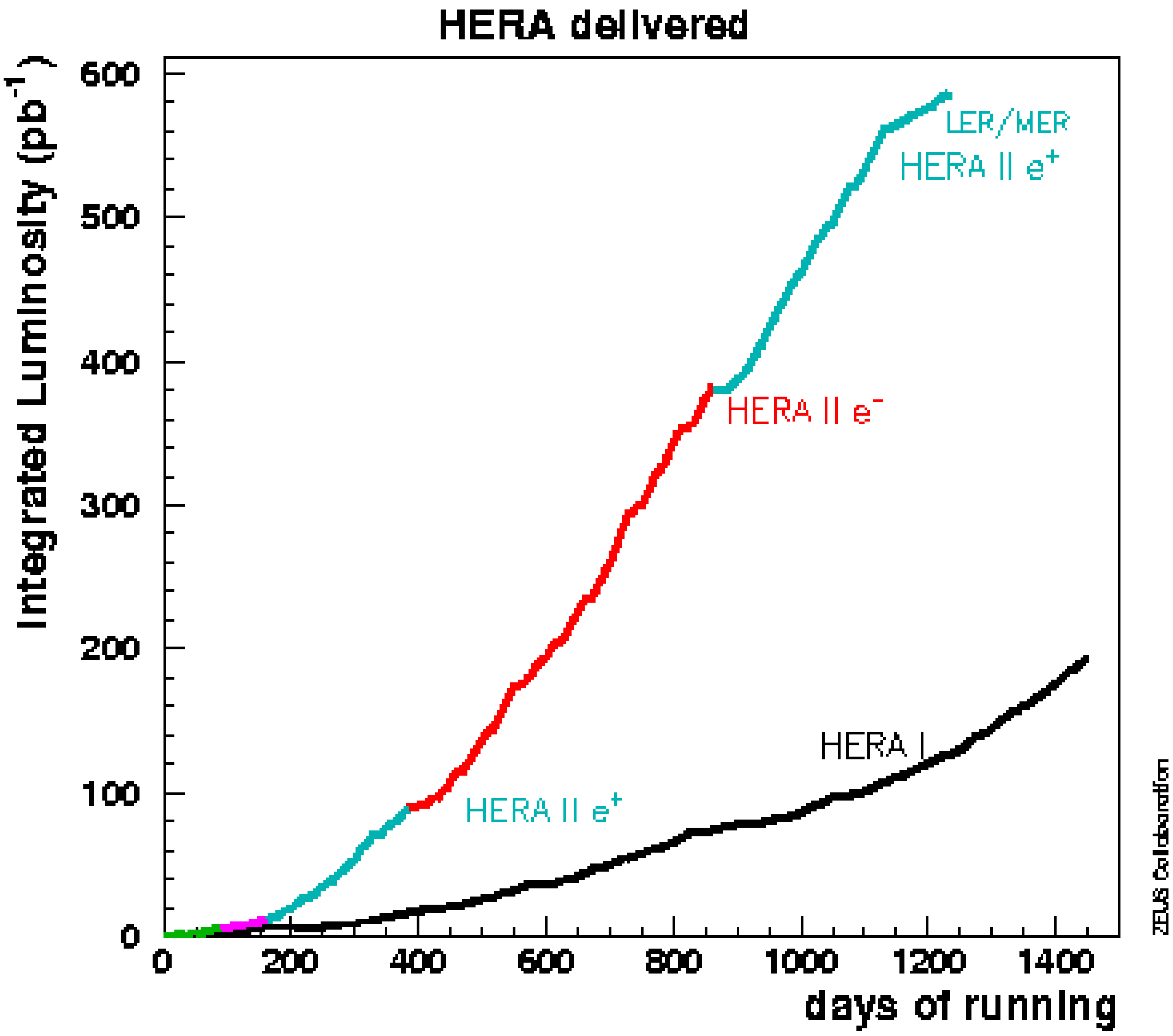


HERA:

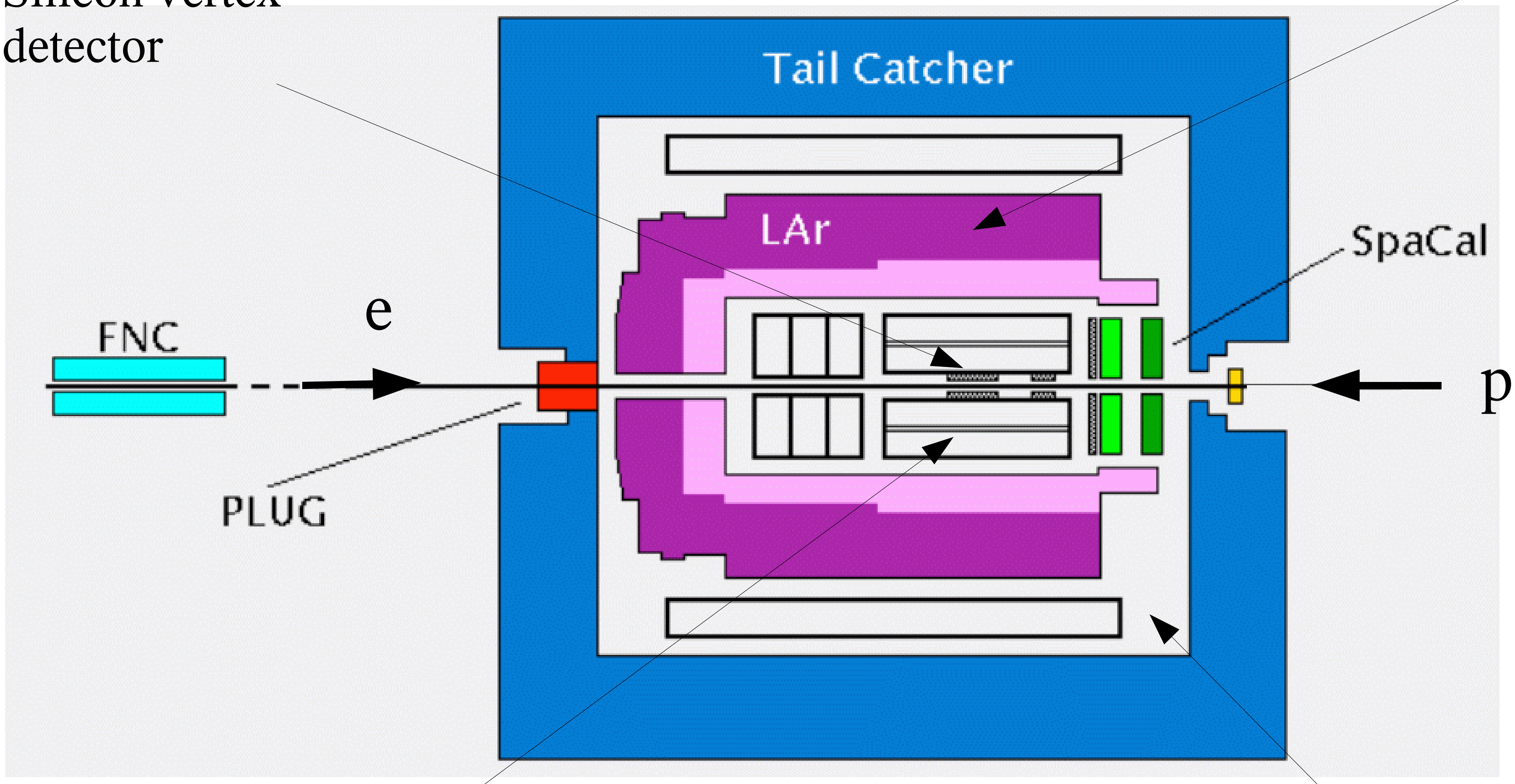
Available data sets

HERA:

- end of operation on 30th june 2007
- collected ~0.5 fb^{-1} per experiment
- equal sharing between lepton charges and polarizations



H1 detector



Liquid Argon calorimeter

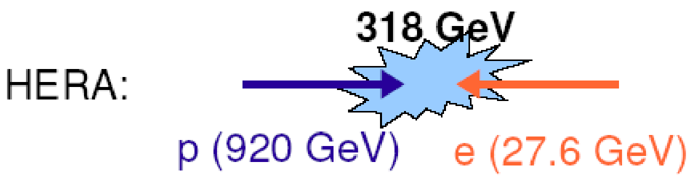
Silicon vertex detector

e

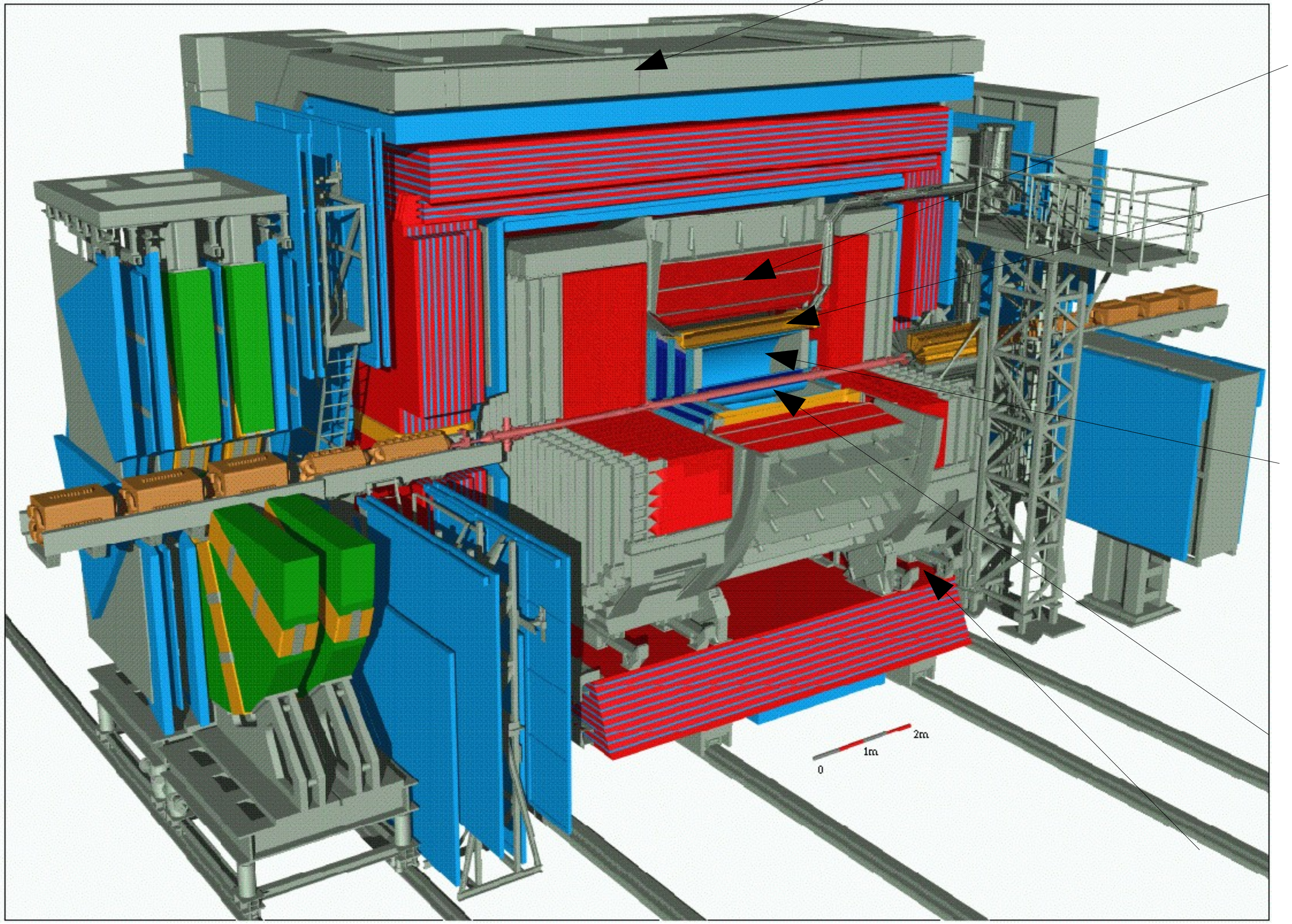
p

Tracking detector (jet chamber)

Solenoidal magnet



Zeus detector



Muon system

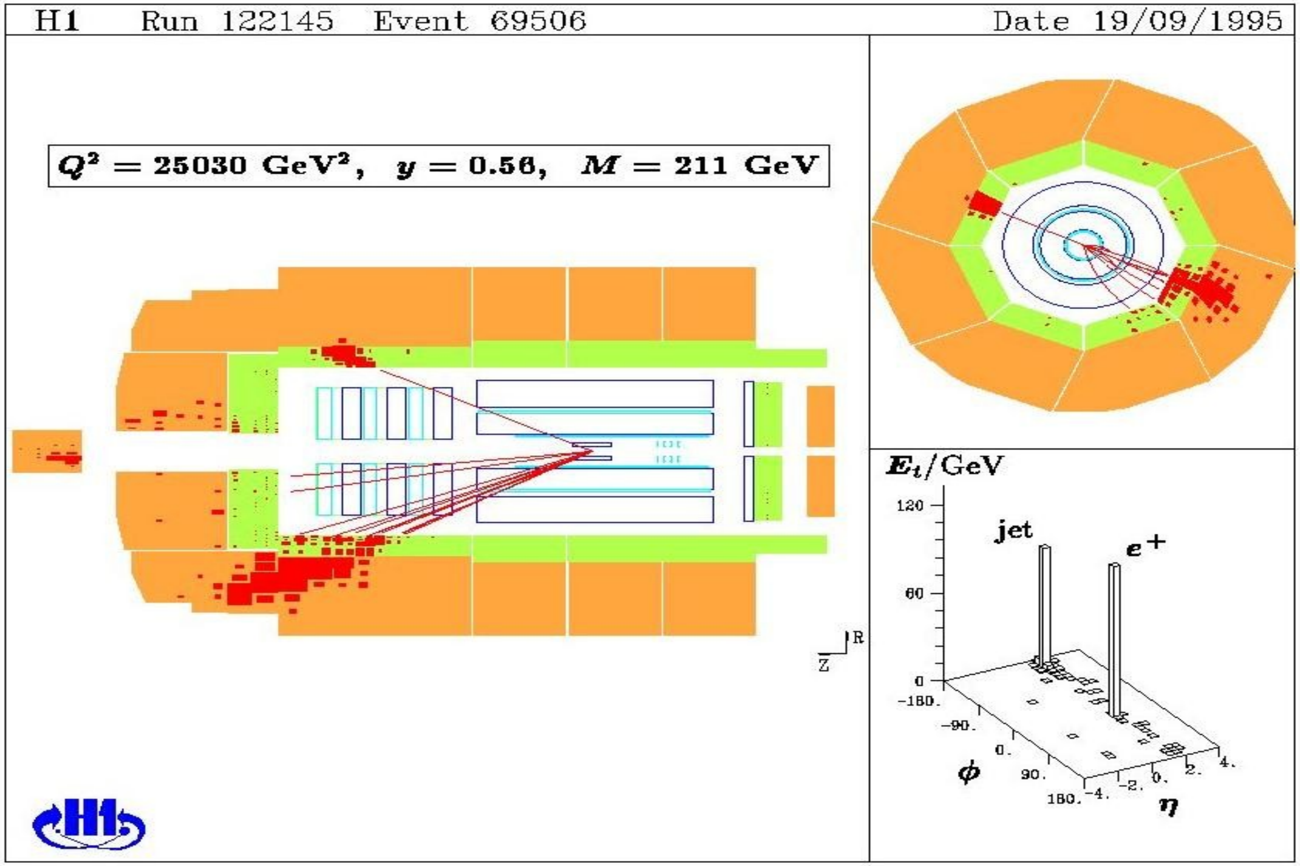
Depleted uranium calorimeter

Solenoidal magnet

Tracking detector (jet chamber)

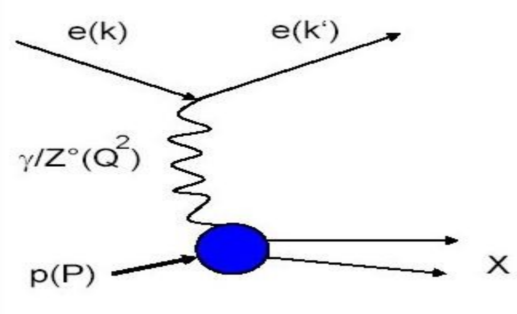
Vertex detector

Neutral current scattering

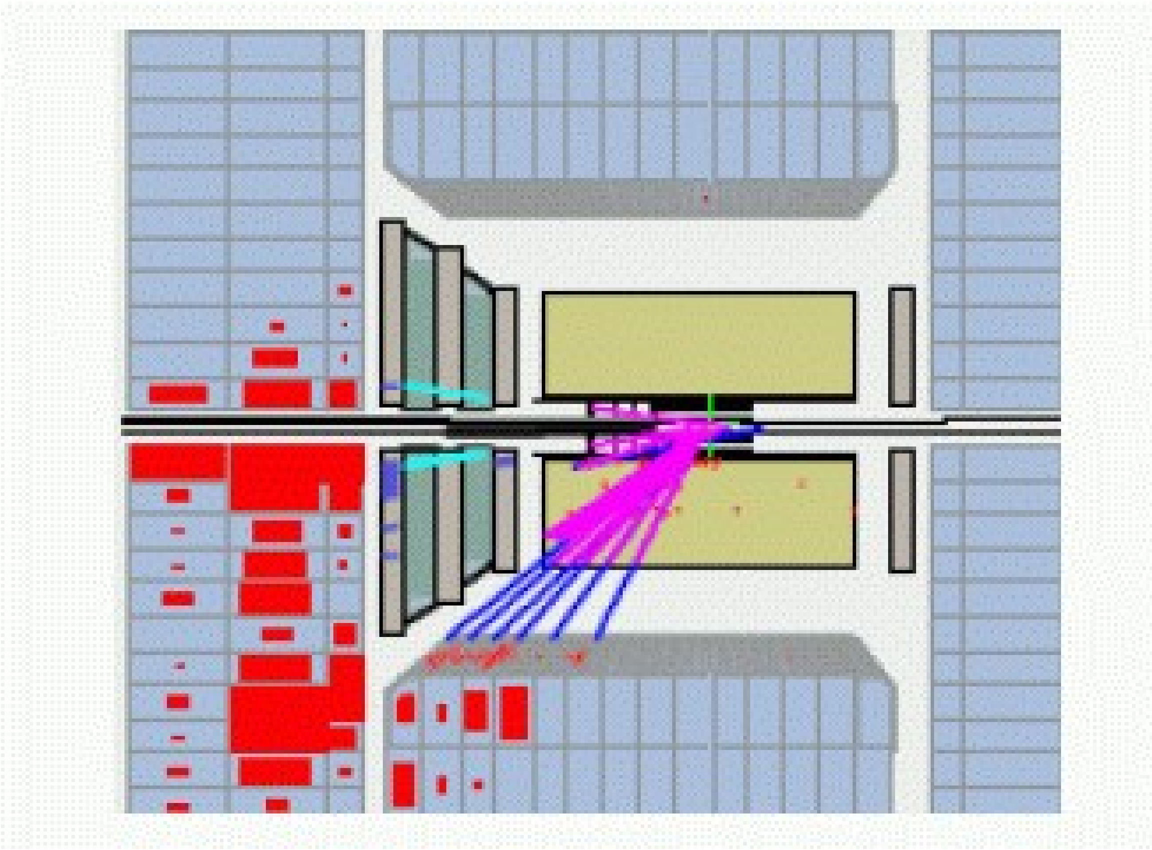


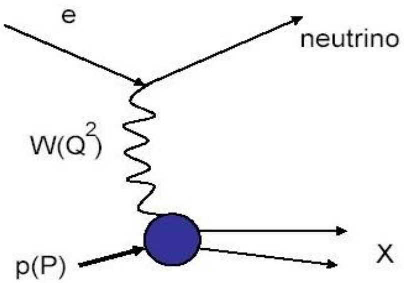
Experimental signatures:

- Scattered electron and hadron jet(s)
- Transverse momentum balance



Charged current scattering

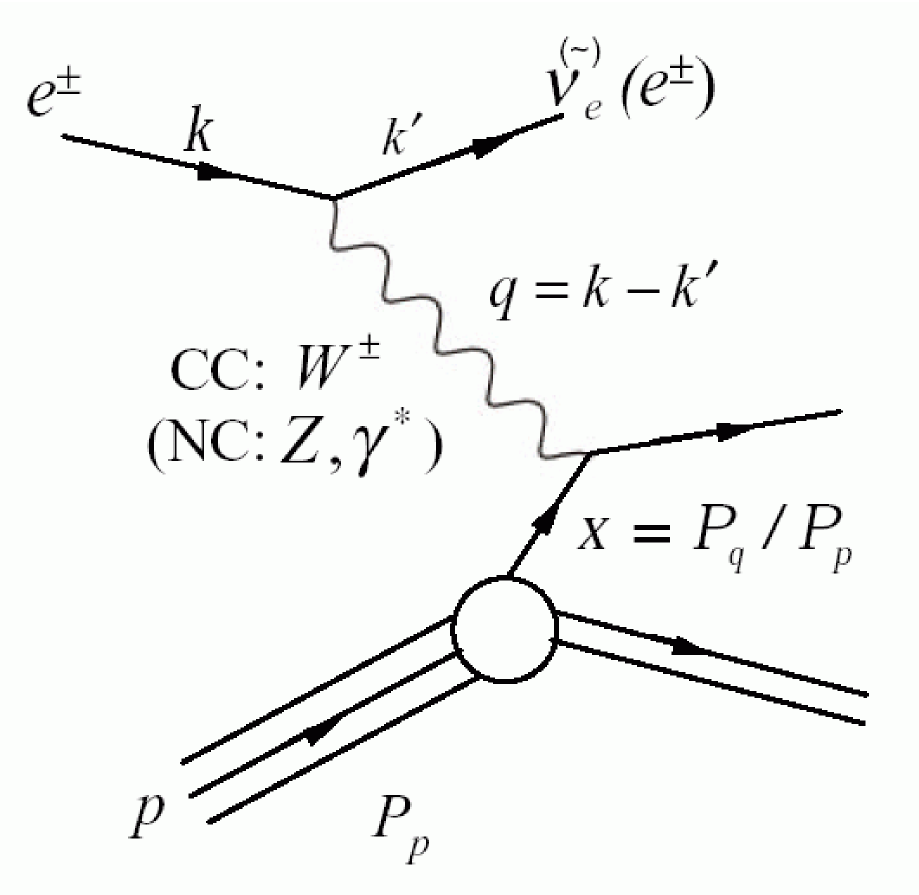




Experimental signatures:

- Hadron jet(s)
- Missing transverse momentum

Kinematics of ep interactions:



Four momentum transfer:

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

Bjorken x: (in LO the fraction of the proton momentum carried by the parton)

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

Inelasticity: (in the proton rest frame the fraction of the electron energy loss)

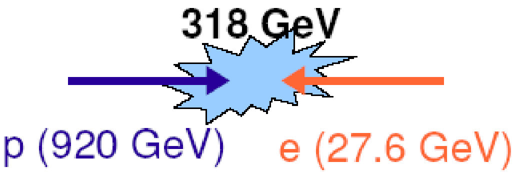
$$y = \frac{P.q}{P.k}$$

At fixed center of mass energy only two of them are independent:

$$Q^2 = sxy$$

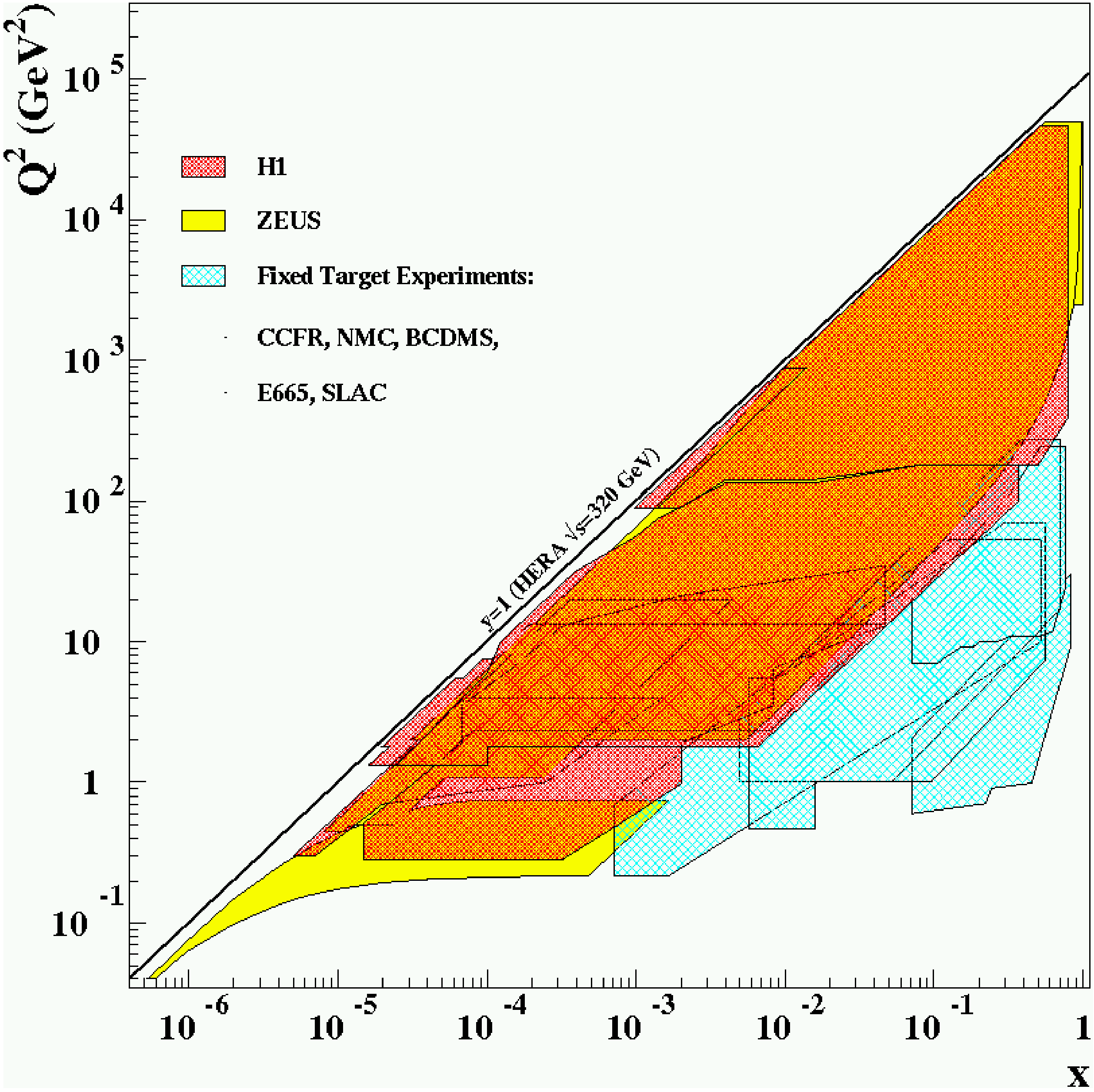
Kinematic range of HERA

HERA:



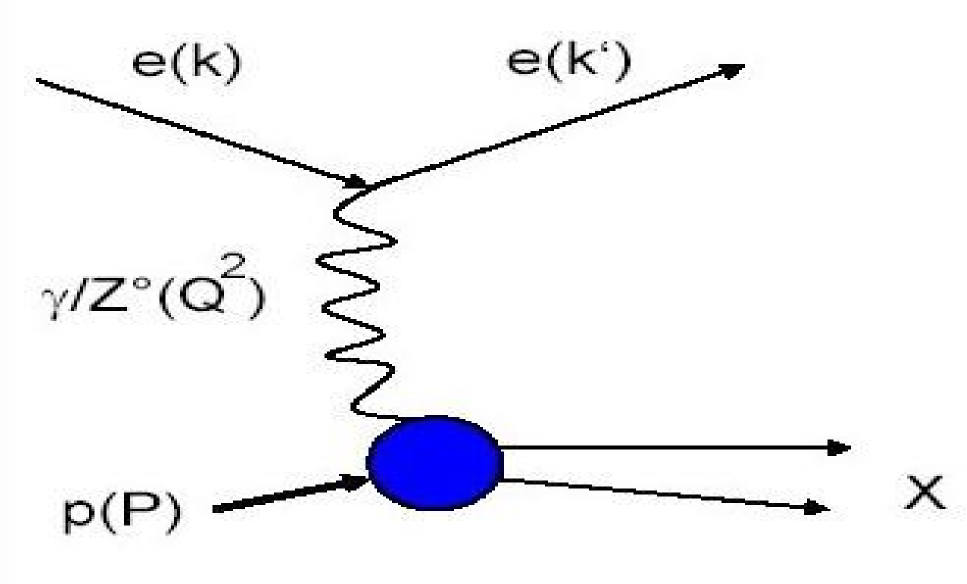
$$Q^2 = sxy$$

- kinematic range determined by available CMS energy
- sufficient to observe EW effects in both NC and CC scattering!



NC: parametrization of cross section

Described by γ or Z exchange (or their interference) :



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

$$\frac{d^2\sigma^{e^\pm p}_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

dominant contribution

high Q²

high y

In quark-parton model:

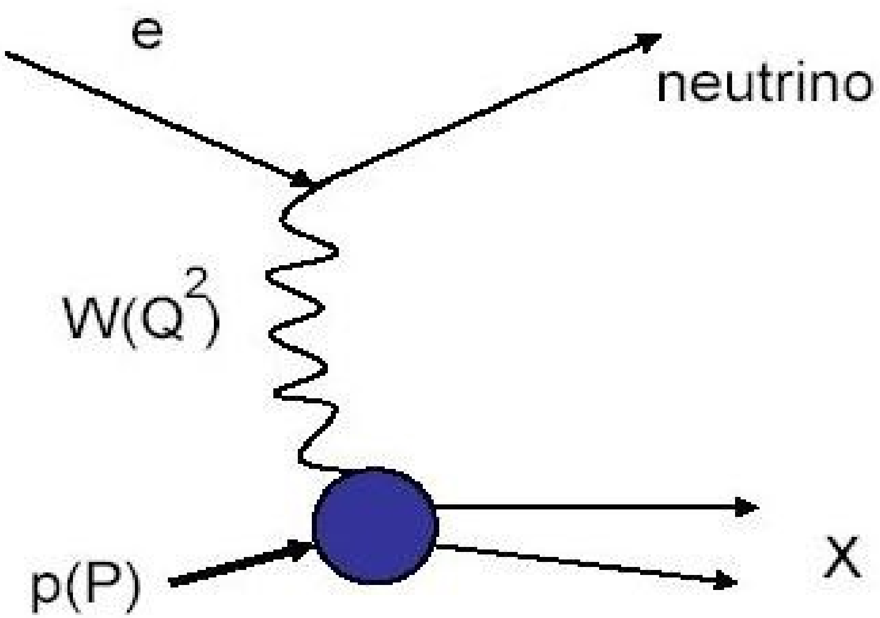
$$F_2 \sim x\sum e_q^2[q+\bar{q}]$$

$$xF_3 \sim x\sum e_q a_q[q-\bar{q}]$$

$$F_L = 0$$

CC: parametrization of cross section

Described by the exchange of $W^{\pm}$ bosons:



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

$$\frac{d^2\sigma_{CC}^{e^{\pm}p}}{dx dQ^2} = \frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 [Y_+ W_2 \mp Y_- x W_3 - y^2 W_L]$$

In quark-parton model:

$$\sigma_{CC}^{+} \sim x[(\overline{u}+\overline{c}) + (1-y)^2 (d+s)]$$

$$\sigma_{CC}^{-} \sim x[(u+c) + (1-y)^2 (\overline{d}+\overline{s})]$$

NC/CC at high Q²

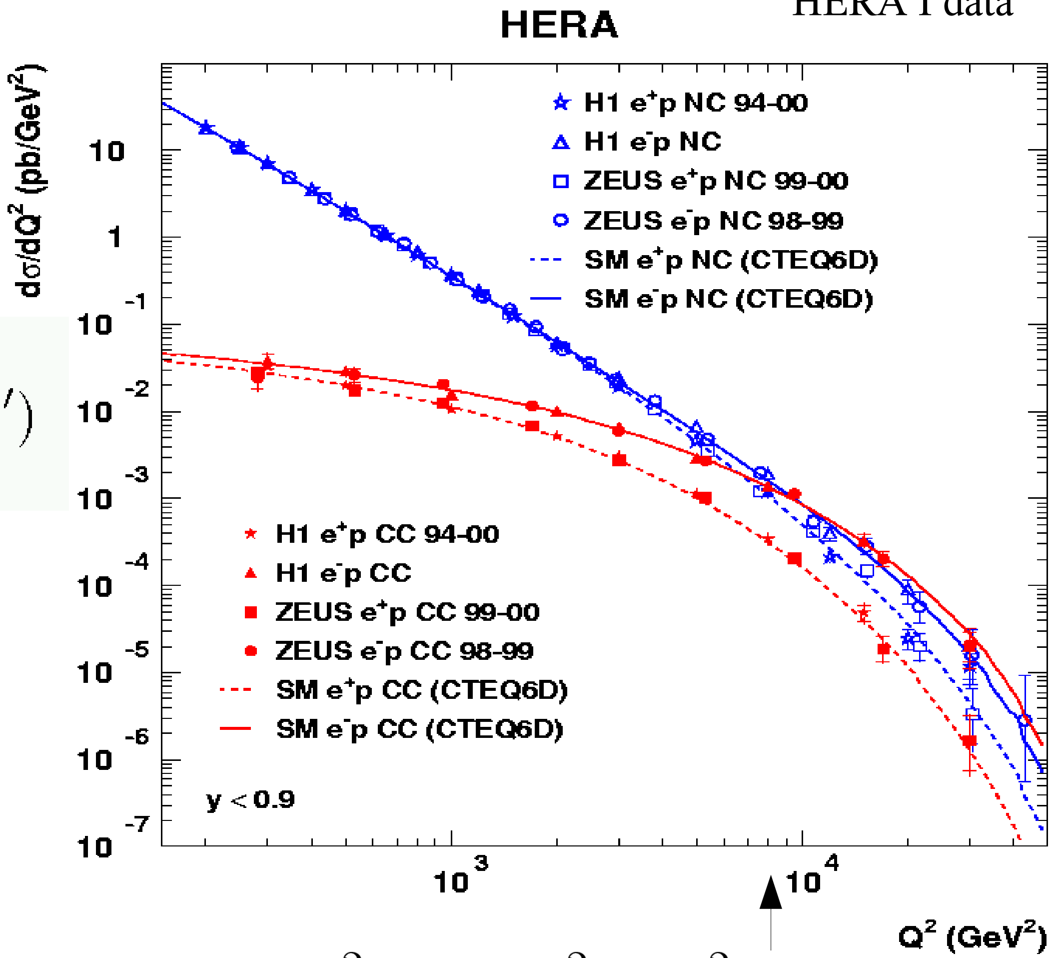
NC/CC cross sections are similar above Q² equal to W mass!

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} \sim \frac{2\pi\alpha^2}{xQ^4} f(pdf)$$

$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dxdQ^2} \sim \frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 f(pdf')$$

- Low Q2 : very different, different propagators
- High Q2: still some difference
- NC and CC are sensitive to different combinations of pdf's

HERA I data



$$M_W^2 = 80.4^2 GeV^2$$

NC and lepton charge assymetry at high Q^2

$$\frac{d^2\sigma^{e^\pm p}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[\ldots \mp Y_- x\tilde{F}_3 - \ldots]$$

$$x\tilde{F}_3 = -a_e\chi_Z xF_3^{\gamma Z} + 2v_e a_e\chi_Z^2 xF_3^Z$$

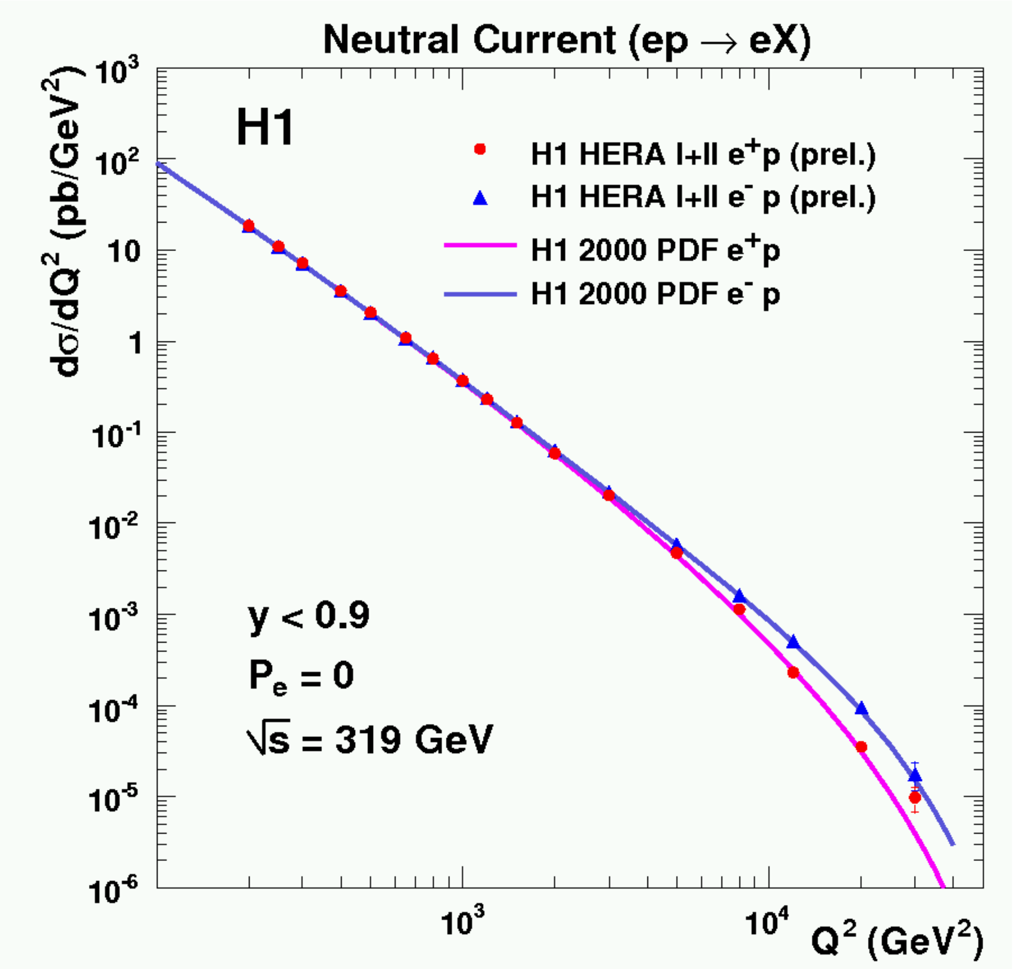
Dominant

Suppressed

$$\chi_Z = \frac{1}{sin^2 2\theta_W}\frac{Q^2}{M_Z^2+Q^2}$$

$$xF_3 \sim 2x\sum[q-\bar{q}]$$

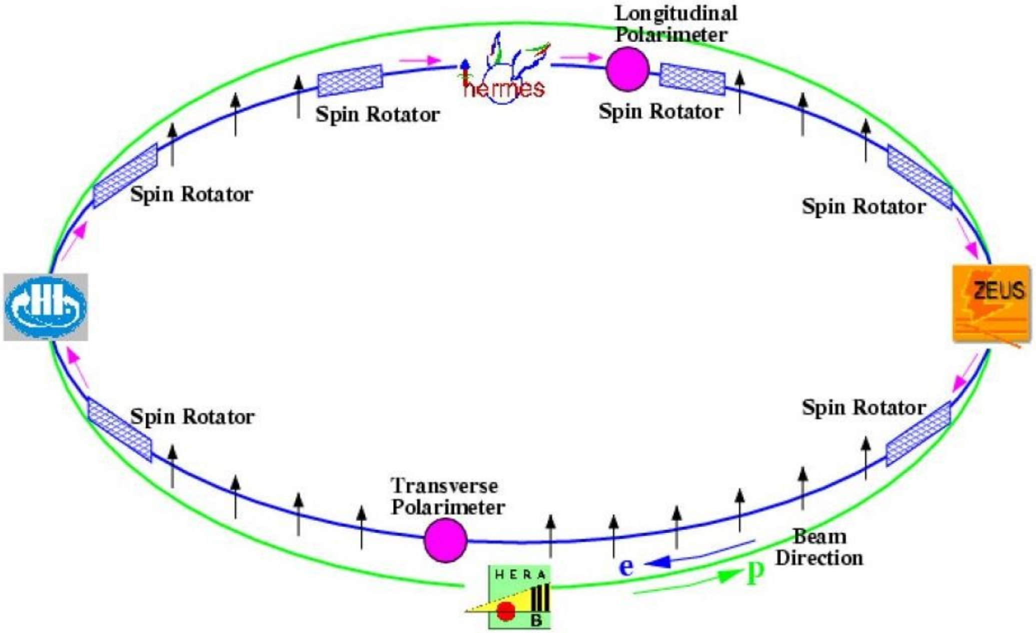
Lepton charge asymmetry due to γ-Z interference term is clearly visible !



Longitudinal polarization at HERA

Longitudinal polarization of lepton beam: new at HERA II.

- The transverse polarization builds up naturally (Sokolov-Ternov effect)
- Typical build-up time ~40 min
- Spin rotators flip the polarization to longitudinal just before the interaction regions
- Typical level of polarization – 30 – 40 %



Level of polarization P is defined as:

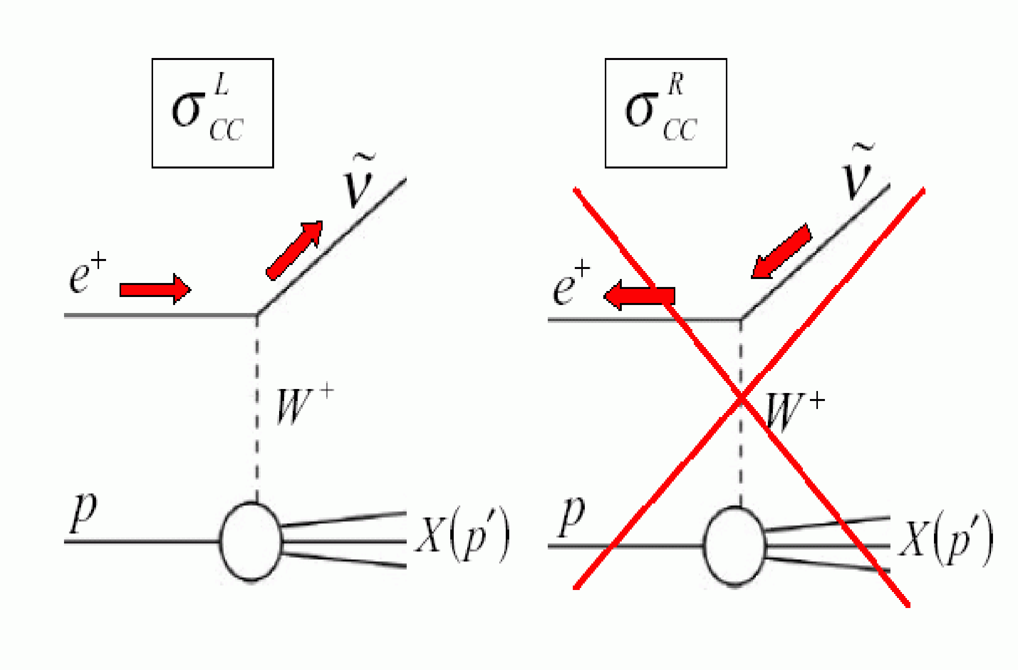
$$P = \frac{N_R - N_L}{N_R + N_L}$$

N_R, N_L - number of lh (rh) leptons in beam

Polarized CC cross section I.

Polarization affects CC cross section in particularly clean way:

- In SM only left handed particles (right handed antiparticles) interact via CC

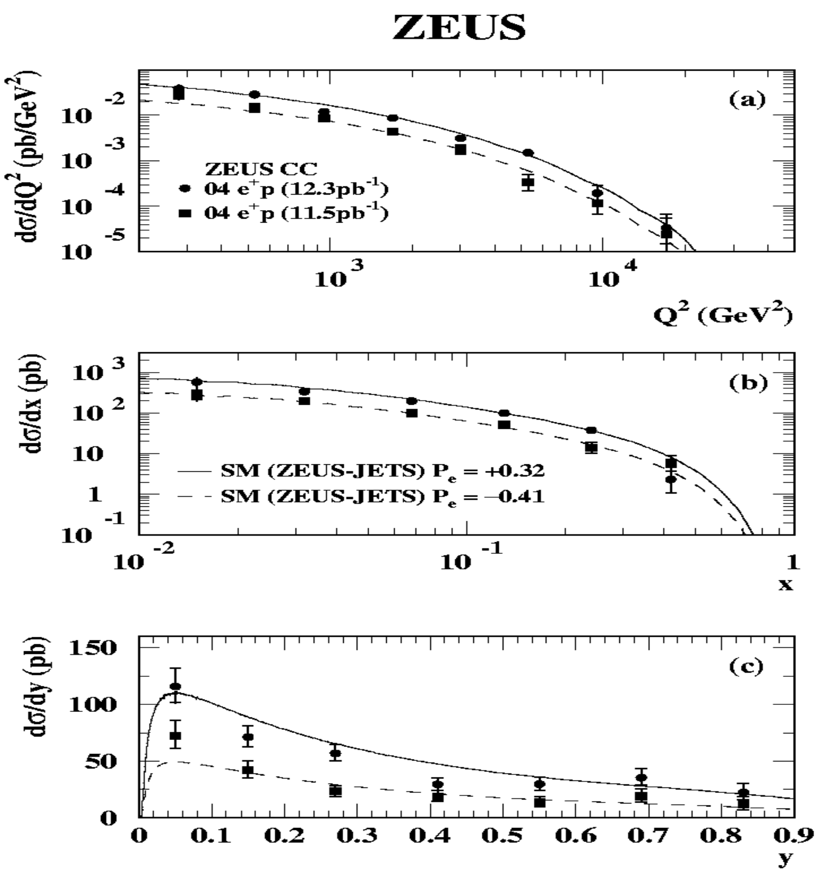


$$\frac{d^2\sigma^{e^\pm p}_{CC}}{dx dQ^2} = [1 \pm P] \frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2 + Q^2}\right]^2 [Y_+ W_2 \mp Y_- x W_3 - y^2 W_L]$$

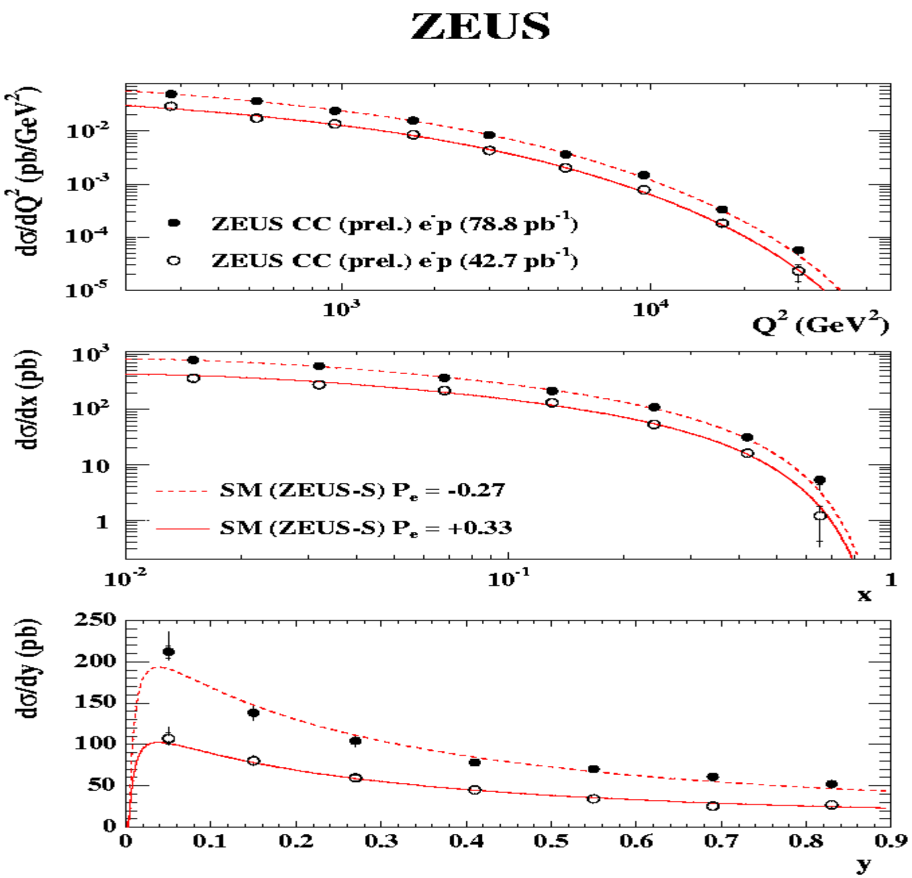
Expect linear dependence of CC cross section on P!

Polarized CC cross section II.

$e^+ p$



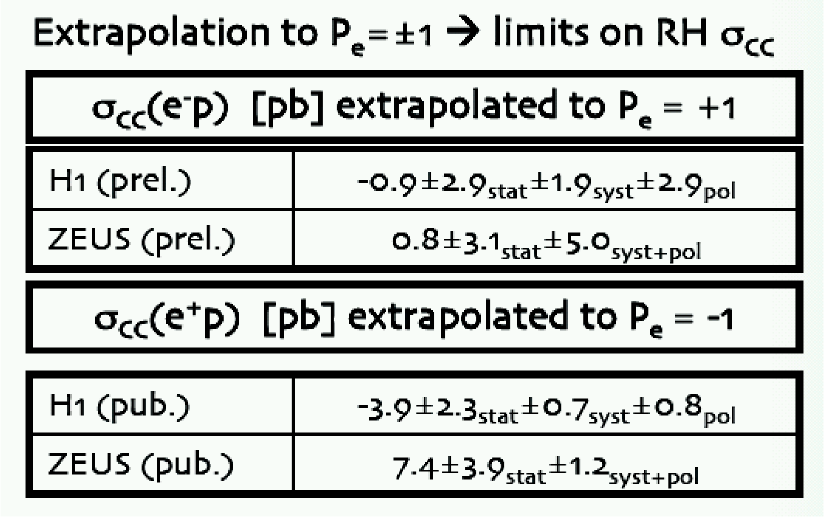
$e^- p$



Differential cross sections with different polarizations have the same shape, the normalization is different

Polarized CC cross section III.

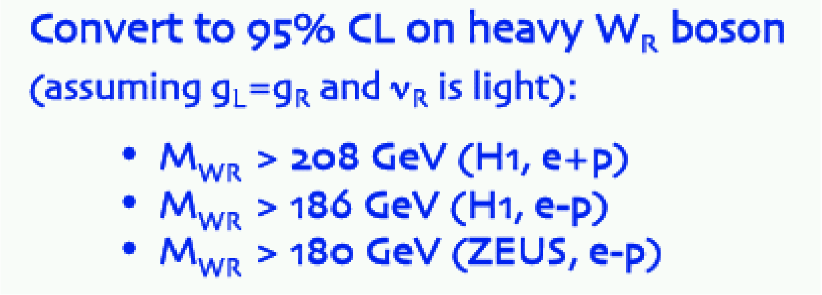
- Data are in good agreement with SM prediction
- Fit by straight line



Extrapolation to $P_e = \pm 1$ → limits on RH σ_{CC}

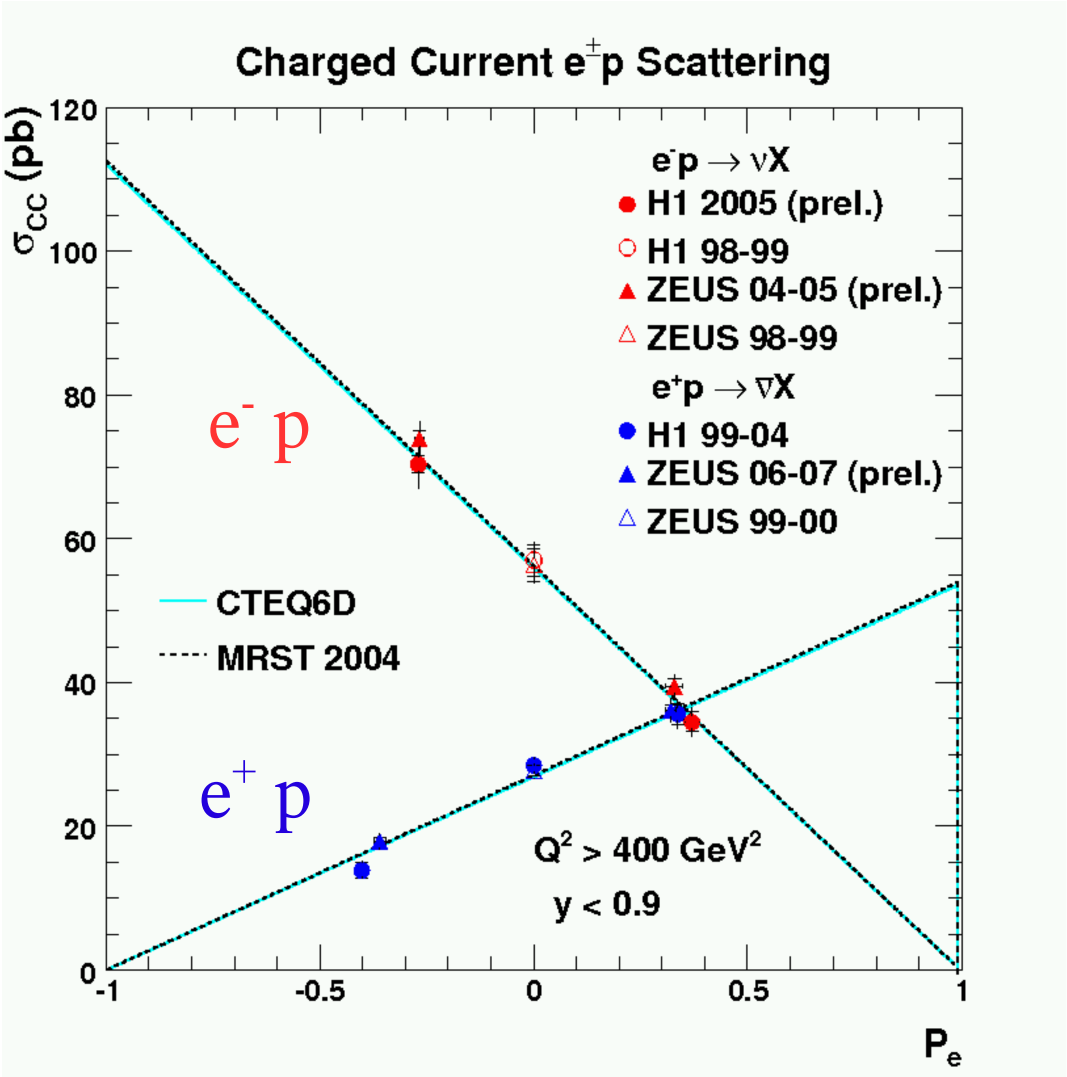
$\sigma_{CC}(e^-p)$ [pb] extrapolated to $P_e = +1$	
H1 (prel.)	$-0.9 \pm 2.9_{stat} \pm 1.9_{syst} \pm 2.9_{pol}$
ZEUS (prel.)	$0.8 \pm 3.1_{stat} \pm 5.0_{syst+pol}$

$\sigma_{CC}(e^+p)$ [pb] extrapolated to $P_e = -1$	
H1 (pub.)	$-3.9 \pm 2.3_{stat} \pm 0.7_{syst} \pm 0.8_{pol}$
ZEUS (pub.)	$7.4 \pm 3.9_{stat} \pm 1.2_{syst+pol}$



Convert to 95% CL on heavy W_R boson (assuming $g_L = g_R$ and ν_R is light):

- M_{WR} > 208 GeV (H1, e+p)
- M_{WR} > 186 GeV (H1, e-p)
- M_{WR} > 180 GeV (ZEUS, e-p)



Data are in good agreement with SM!

Polarized NC cross section I.

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L]$$

Generalized structure functions depend on polarization:

$$x\tilde{F}_3 = -(a_e \pm P_e v_e)\chi_Z xF_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_Z^2 xF_3^Z$$

$$x\tilde{F}_3 \sim -a_e\chi_Z xF_3^{\gamma Z}$$

To first order does not depend on P, allows to measure unpolarized xF3

$$\tilde{F}_2 = F_2 - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2 F_2^Z$$

$$\tilde{F}_2 \sim F_2 \pm P_e a_e \chi_Z F_2^{\gamma Z}$$

To first order the same magnitude and opposite sign for two lepton beam charges

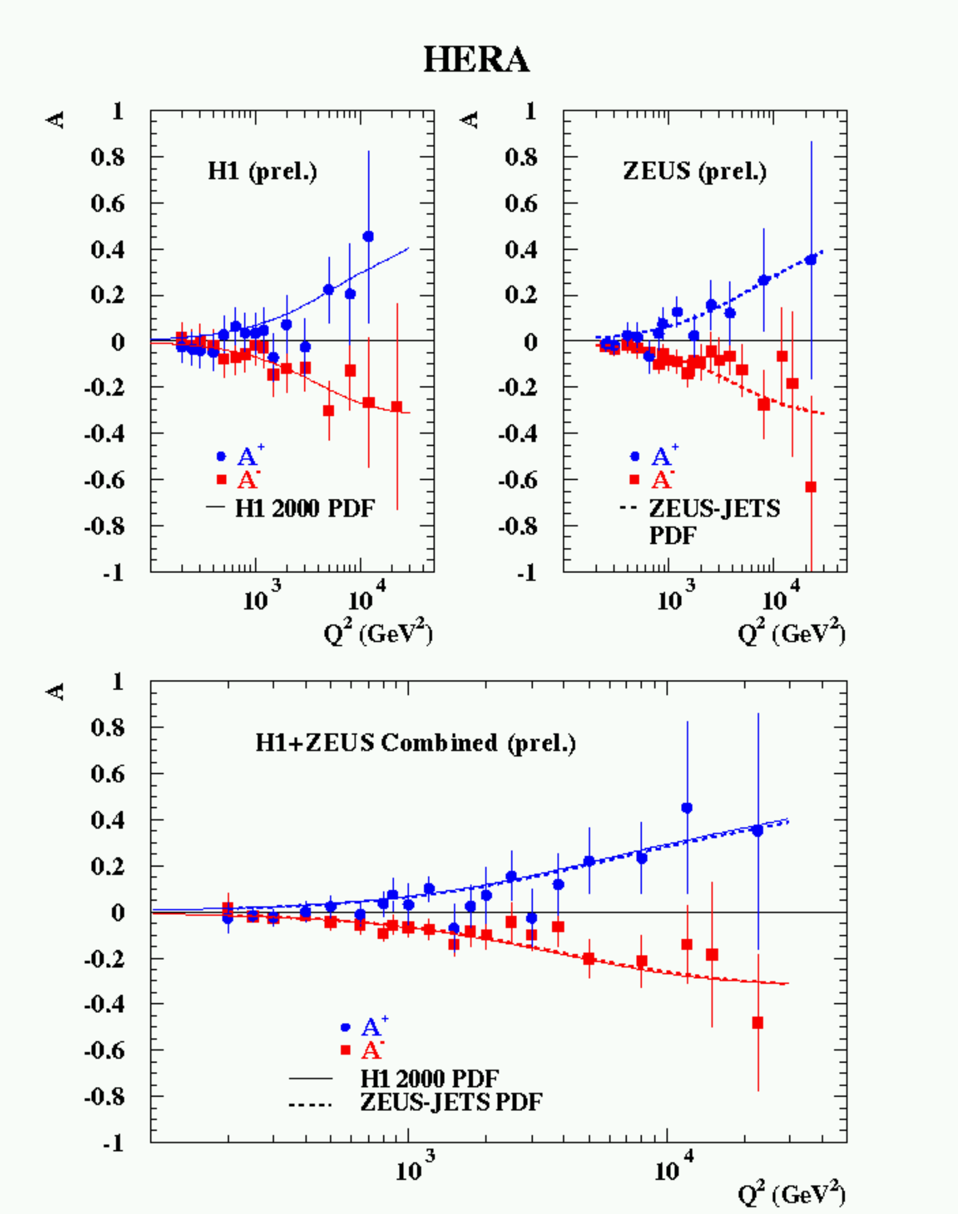
$$a_e = -0.5$$
$$v_e \approx -0.04$$

Polarized NC cross section II.

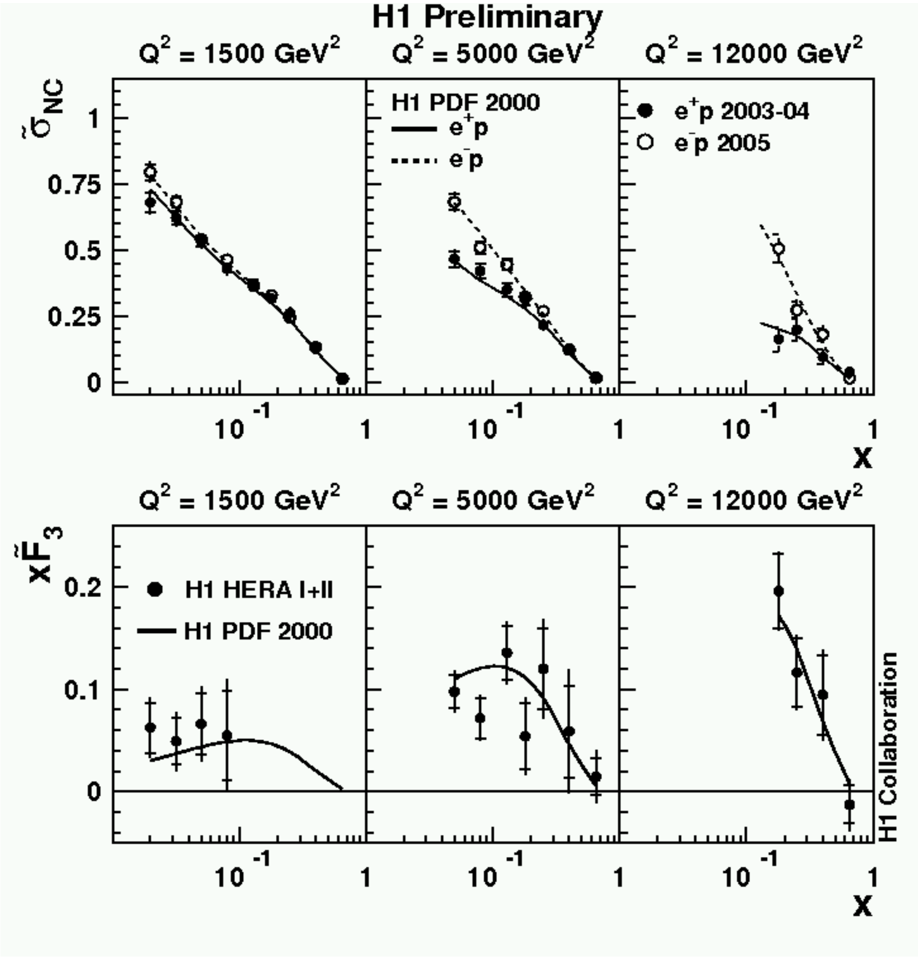
plotting charge dependent polarisation asymmetry A:

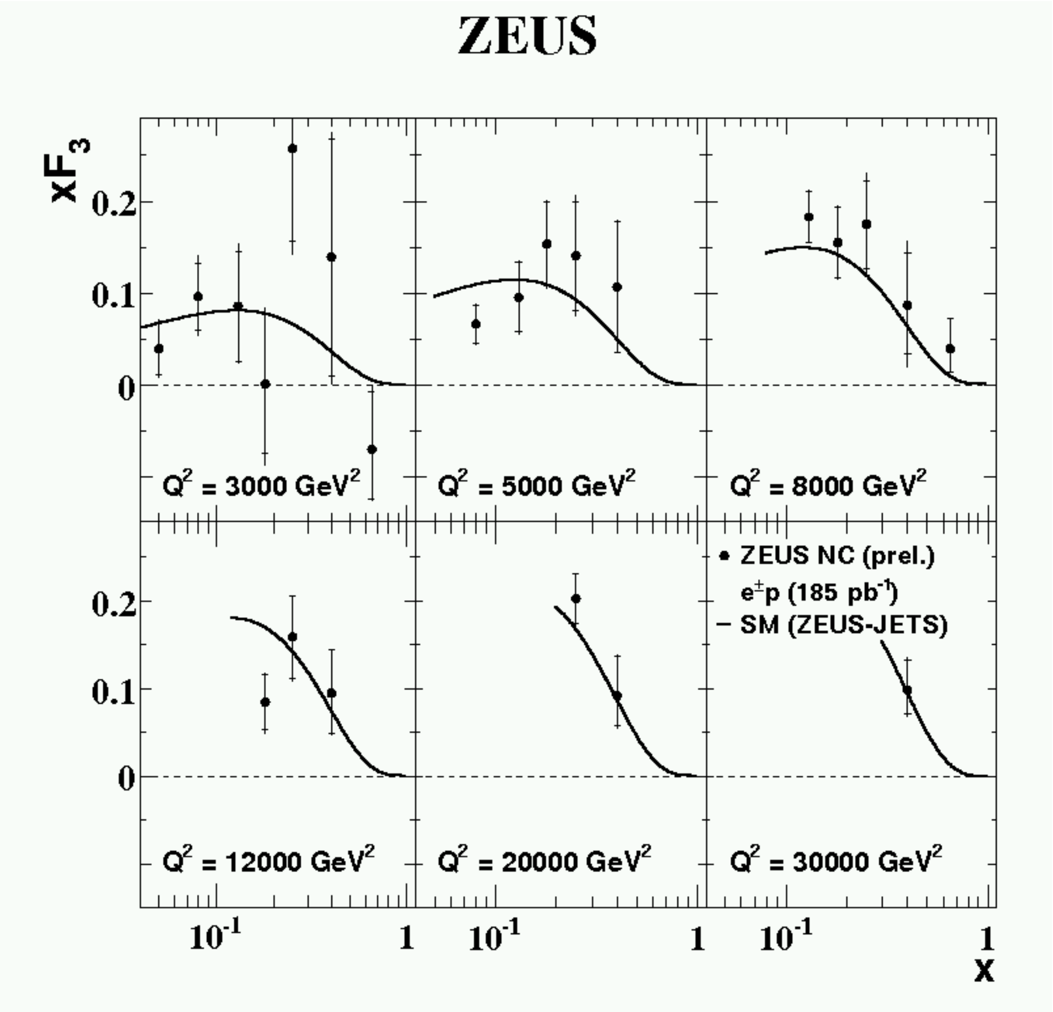
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}$$

- asymmetries well described by SM predictions (using H1 and ZEUS pdf's)
- observation of parity violation at distances down to 10^{-18} m



xF_3 from NC cross section I.





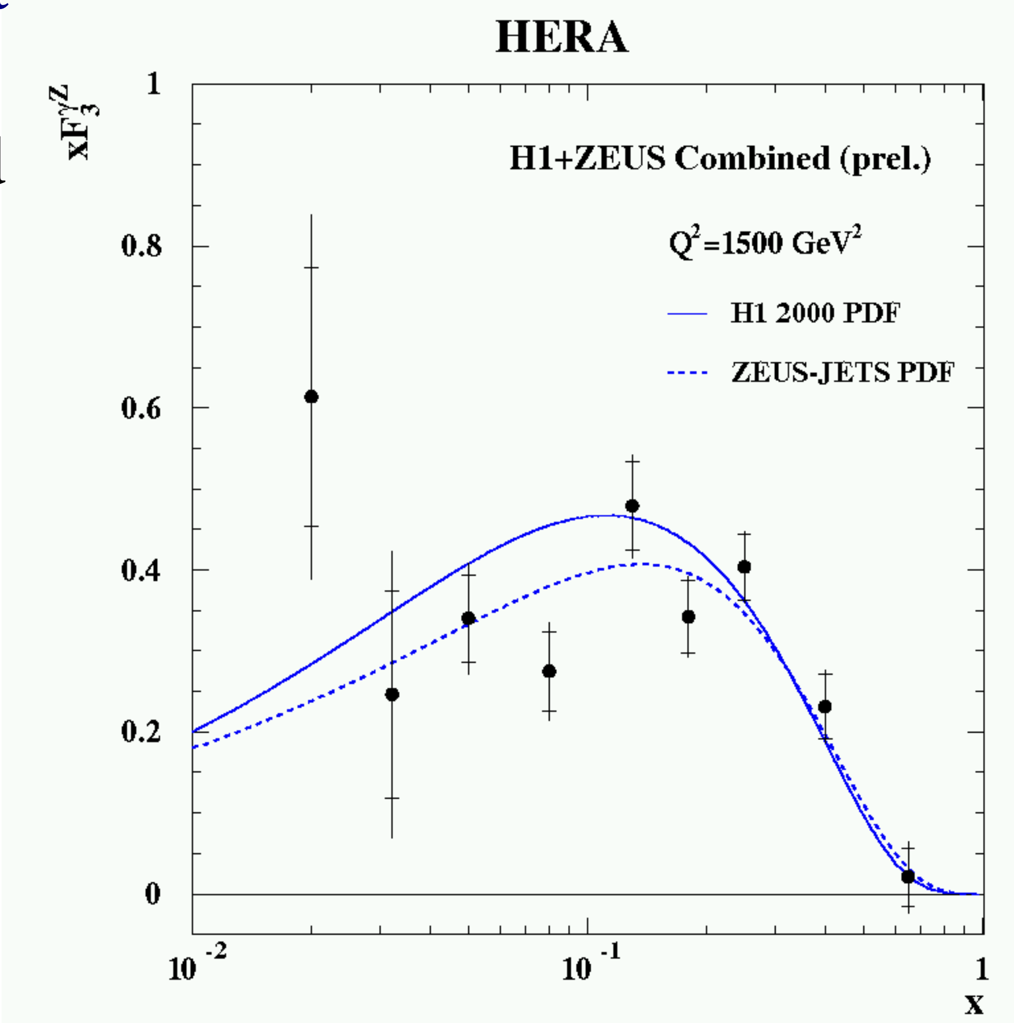
data corrected for (small) polarization effects, difference in $e^+ p$ and $e^- p$ cross sections gives xF_3

xF_3 from NC cross section II.

measured xF_3 is used to extract γ-Z interference term:

- H1 and ZEUS data adjusted to common Q^2=1500 GeV^2
- take out kinematic terms
- common result obtained as weighted average of H1 and ZEUS result

direct measurement of valence quark distributions down to (rather) low x



The EW/QCD analysis of NC/CC data

Precise data sets allow combined EW+QCD analysis:

- Use several data sets (NC, CC, jets in p (ZEUS))
- Fit QCD parameters (pdf)
- EW parameters at the same time

Recent EW+QCD fits:

- H1 HERA I (Phys.Lett.B632(2006)35) (94-00)
- H1 HERA I+II (preliminary) (94-05)
- ZEUS HERA I+II (preliminary) (94-06)

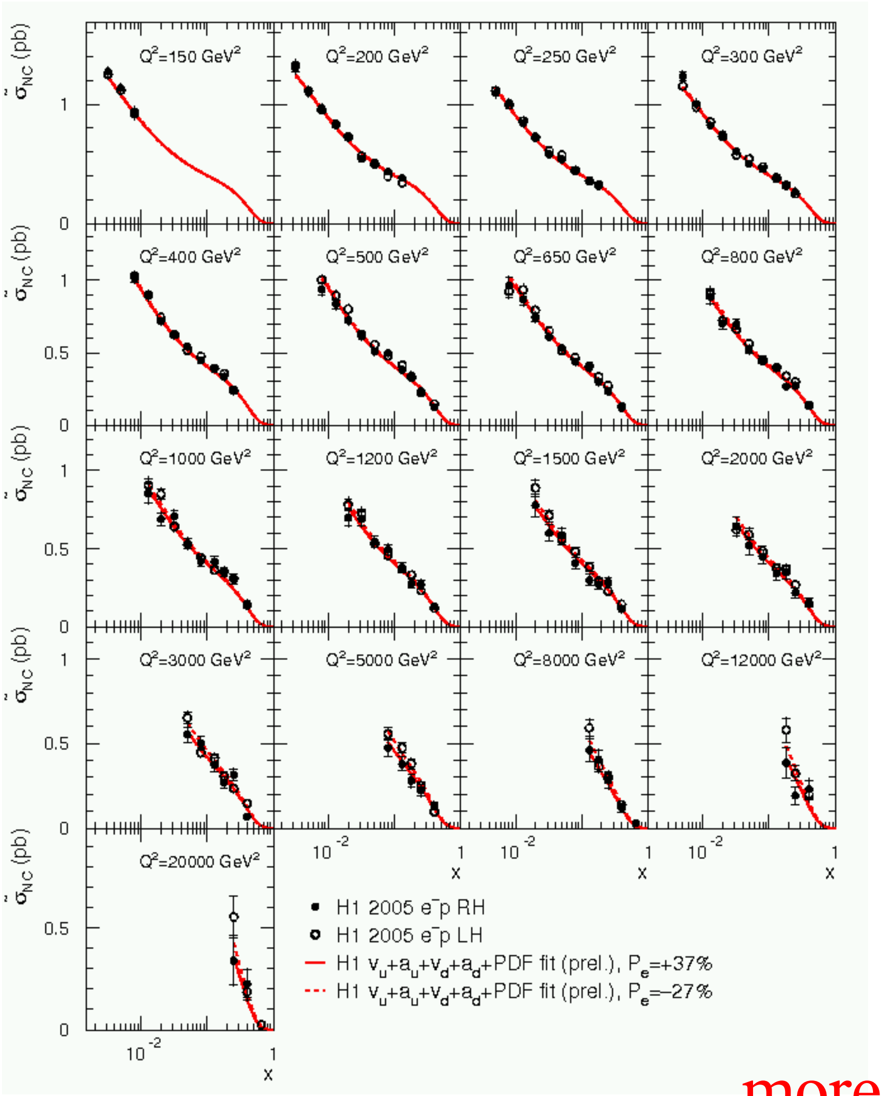
CC is sensitive to M_W:

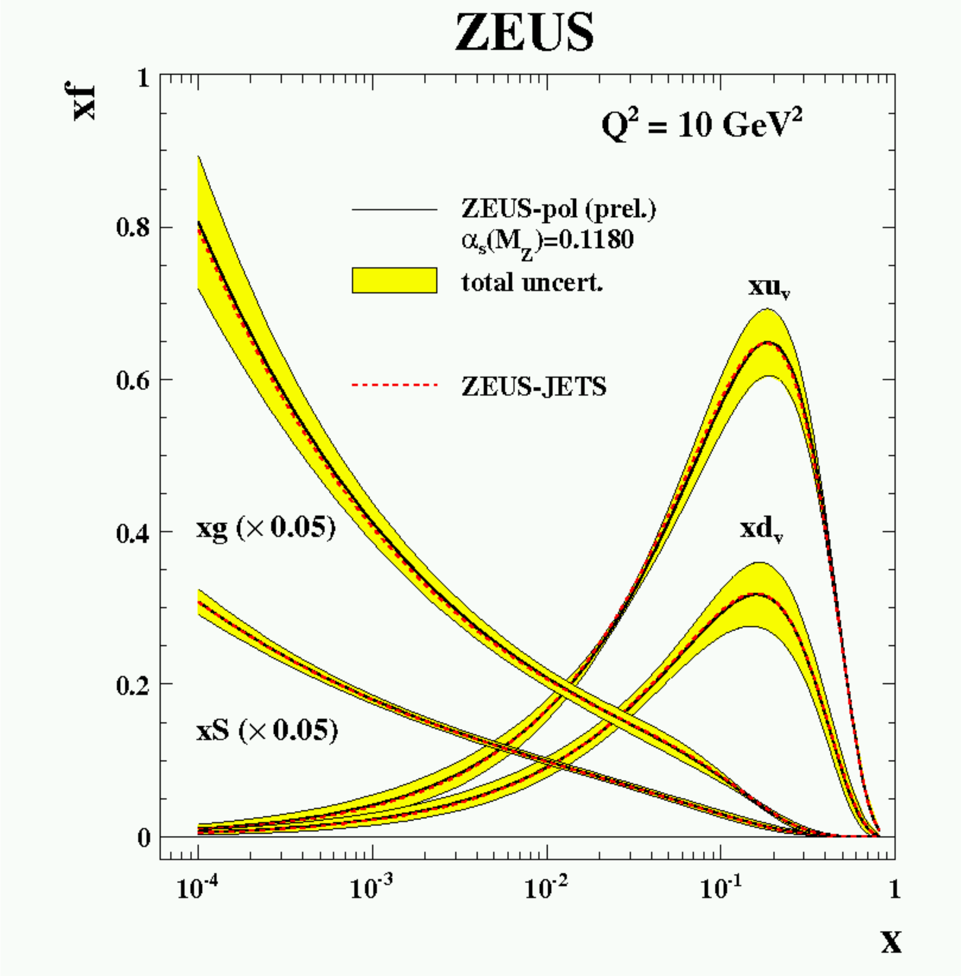
$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx\,dQ^2} = \frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 \left[Y_+ W_2 \mp Y_- x W_3 - y^2 W_L\right]$$

NC is sensitive to quark axial and vector couplings to Z:

$$\tilde{F}_2 = F_2 - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z}(a_i, v_i) + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2 F_2^Z(a_i, v_i)$$

The EW/QCD analysis: pdf's

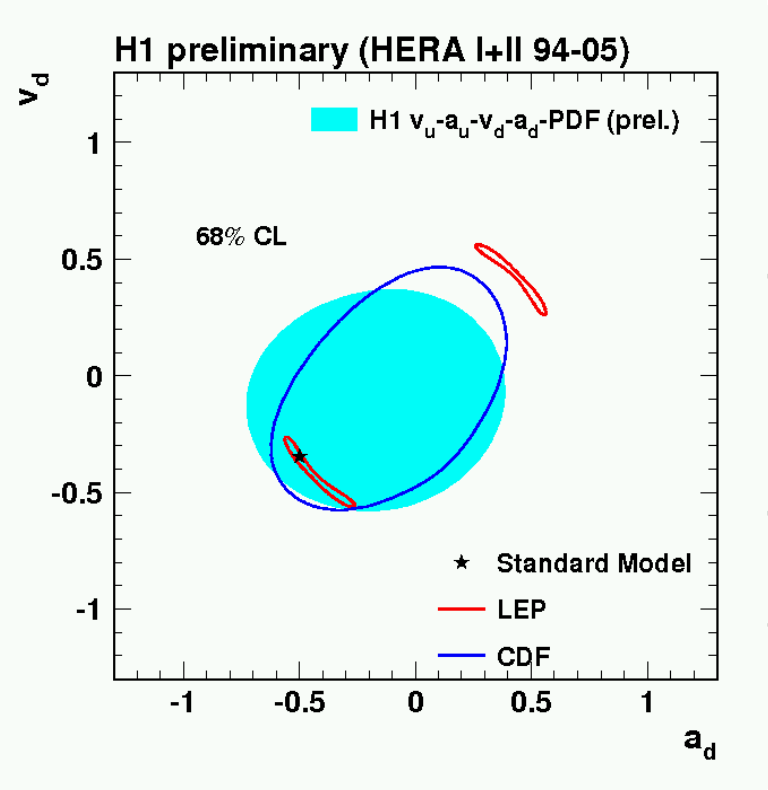


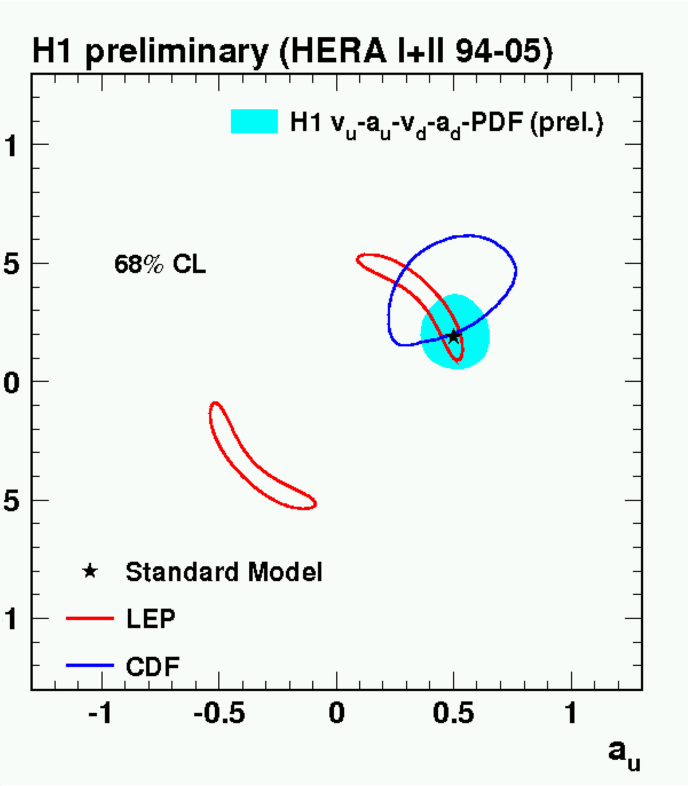


more details in talk of A. Cooper-Sarkar!

The extraction of quark couplings to Z I.

- No sign ambiguity (interference terms)
- Sensitive both to v and a, different Q^2 dependence
- Polarization helps with v





In QPM:

$$F_2^{\gamma Z} = 2x \sum e_i v_i [q_i + \overline{q_i}]$$

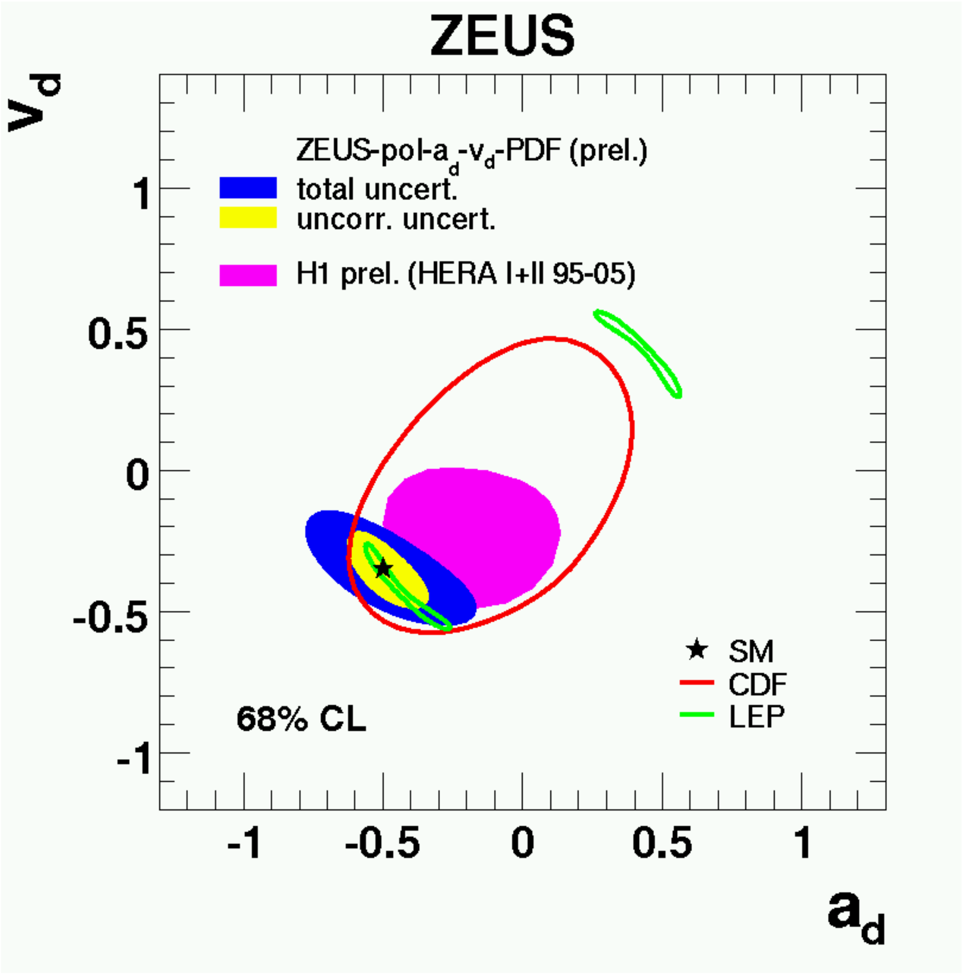
$$xF_3^{\gamma Z} = 2x \sum e_i a_i [q_i - \overline{q_i}]$$

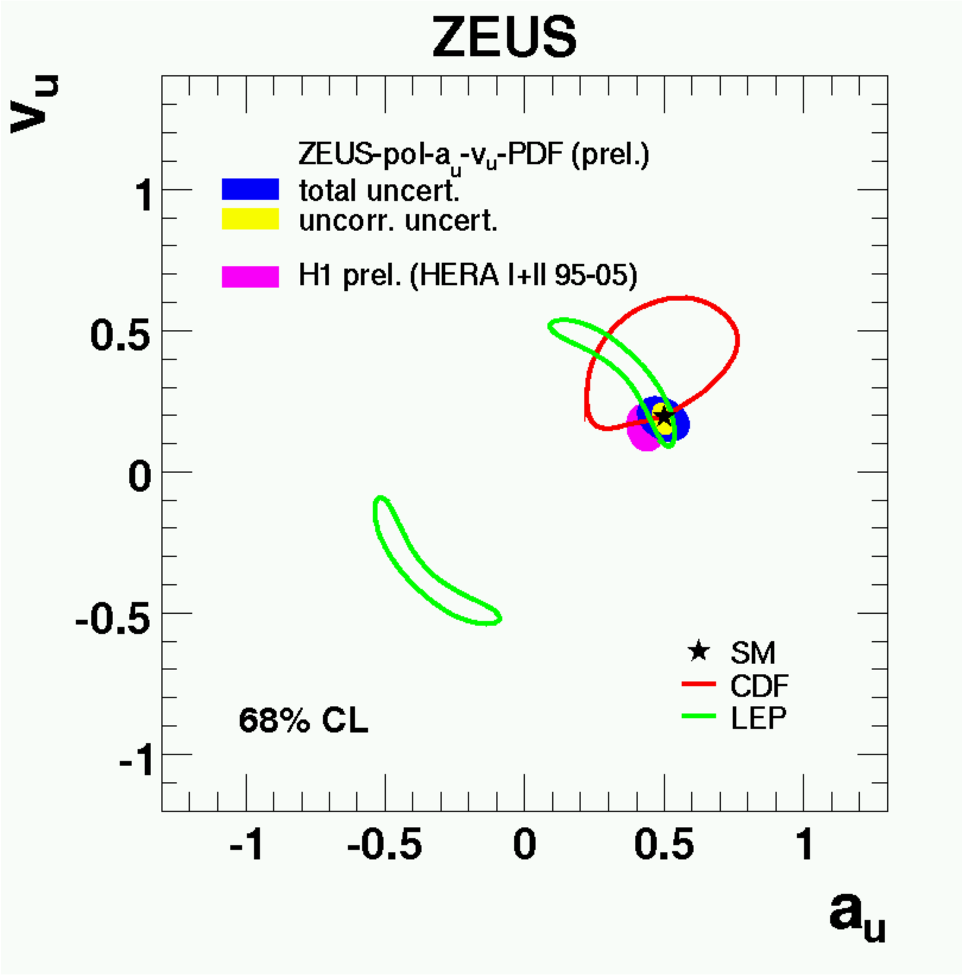
$$F_2^{Z} = x \sum (v_i^2 + a_i^2) [q_i + \overline{q_i}]$$

$$xF_3^{Z} = 2x \sum v_i a_i [q_i - \overline{q_i}]$$

The extraction of quark couplings to Z II.

Fit results with either u or d quark couplings fixed to SM values:





for u quarks best available measurement!

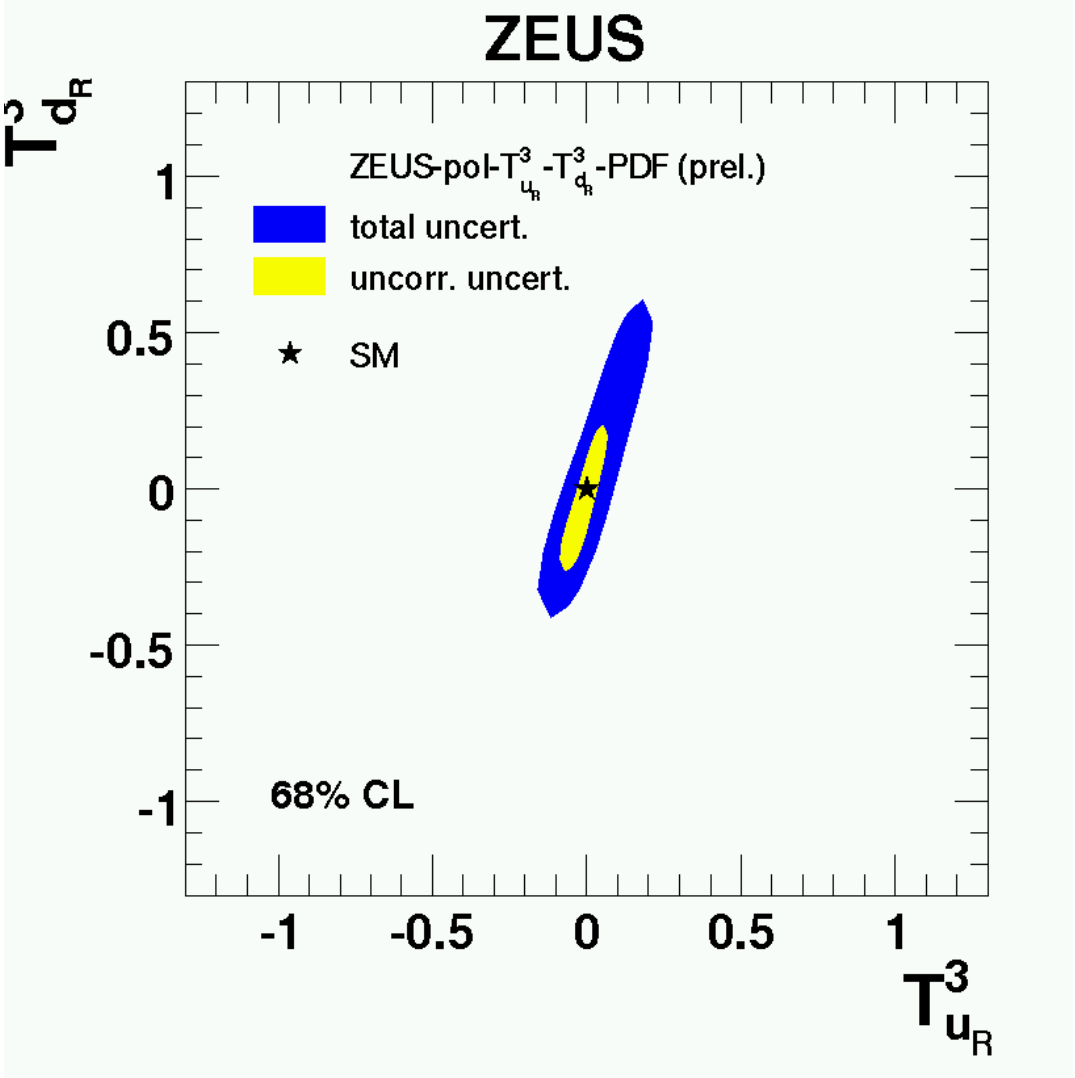
EW/QCD analysis: Right handed isospin

Introduce right handed isospin, should be zero in SM:

$$a_q = T^3_{q,L} + T^3_{q,R}$$

$$v_q = T^3_{q,L} - T^3_{q,R} - 2e_q sin^2\theta_W$$

$T^3_{q,L}, sin^2\theta_W$ fixed to SM values



In agreement with SM

EW/QCD analysis: propagator mass

The mass of the propagator can be determined from the Q^2 dependence of the CC cross section:

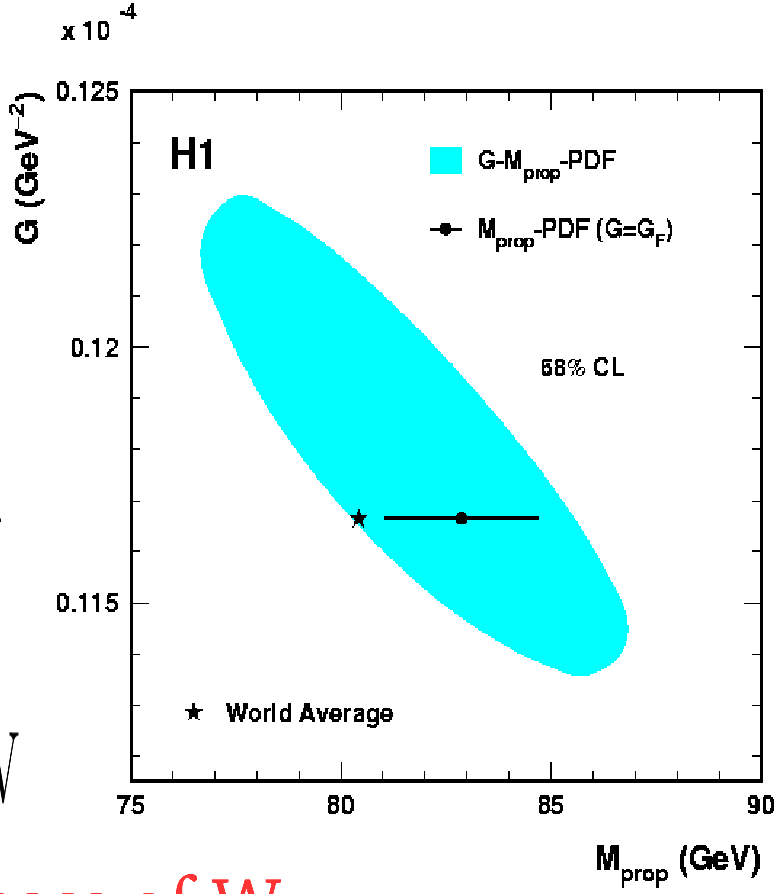
$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dxdQ^2} = \frac{G_F^2}{4\pi x}\left[\frac{M_{prop}^2}{M_{prop}^2 + Q^2}\right]^2 [\ldots]$$

G fixed to world average:

$$\mathrm{H1}: M_{prop} = 82.87 \pm 1.82(\mathrm{exp})^{+0.32}_{-0.18}(\mathrm{model})\ \mathrm{GeV}$$

$$\mathrm{ZEUS}: M_{prop} = 79.1 \pm 0.77(\mathrm{st}+\mathrm{uncor}) \pm 0.99(\mathrm{cor.syst.})\ \mathrm{GeV}$$

Fit simultaneously G and M_{prop}:



In good agreement with on-shell mass of W

Physics Beyond Standard Model: Introduction

HERA is one of energy frontier machines:

- energy (318 GeV) between LEP (up to about 200 GeV) and TEVATRON(up to about 2 TeV)
- “cleanliness” of ep also between ee and $p\bar{p}$

Two possible ways of searches:

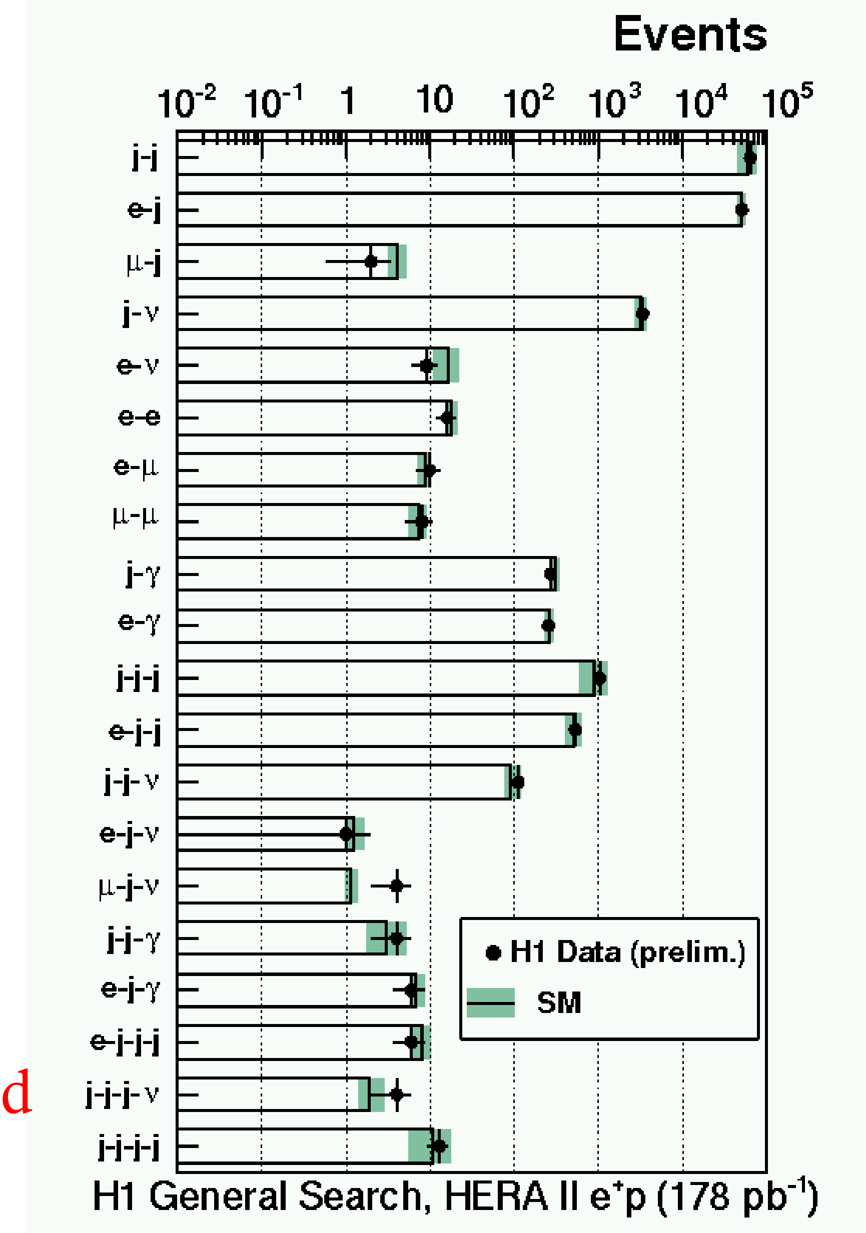
- Look for deviations from the SM in tails of distributions
  - investigate all possible high P_T topologies
    - great generality, minimize probability to miss something
- Look for predicted signatures of BSM models
  - adapt an analysis for each exotic prediction
    - Larger sensitivity

BSM: Generic search I

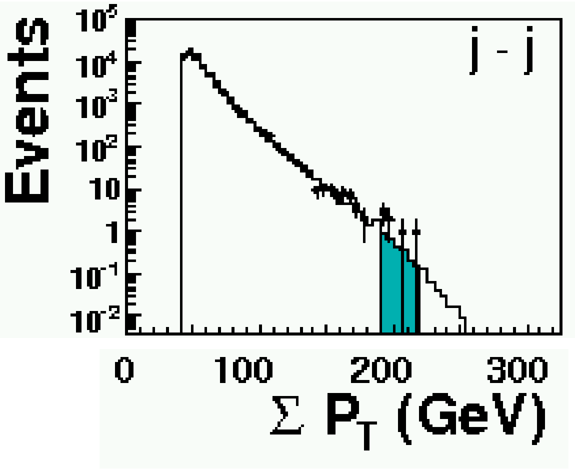
General, model independent search for deviations from SM:

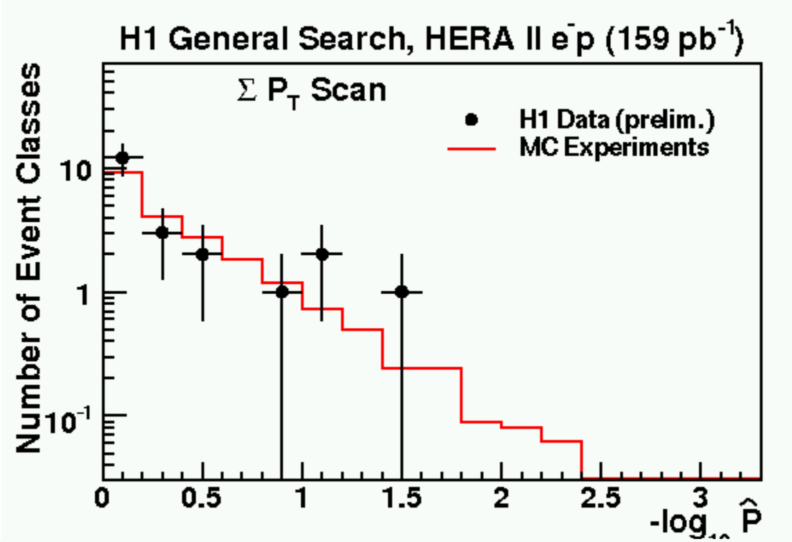
- find isolated high P_T particles: e, γ, μ, jet, ν,...
- common phase space:
  - P_T>20 GeV
  - $10^o < \theta < 140^o$
  - isolation: $\Delta\eta^2 + \Delta\phi^2 > 1$
- classify events into exclusive channels (>= 2 particles), for example e-jet, jet-jet, jet-ν, ...

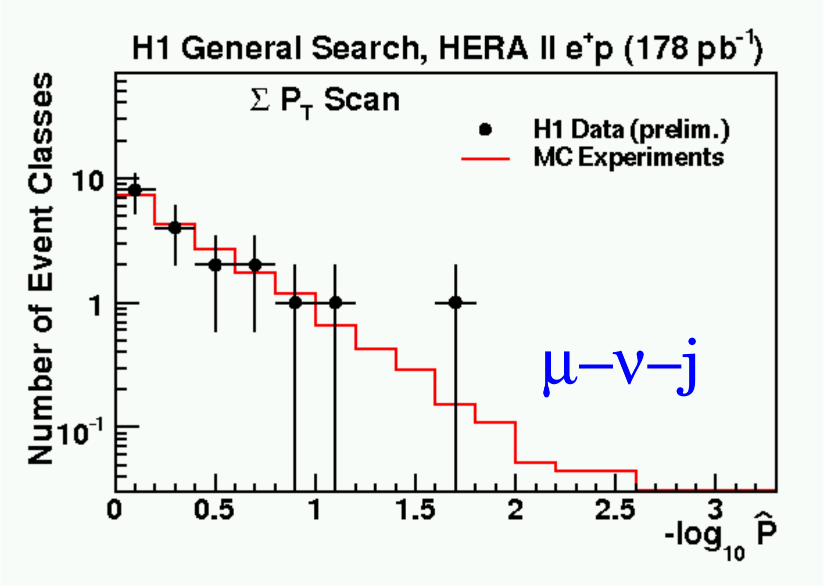
number of events in each channel in good agreement with SM prediction



BSM: Generic search II





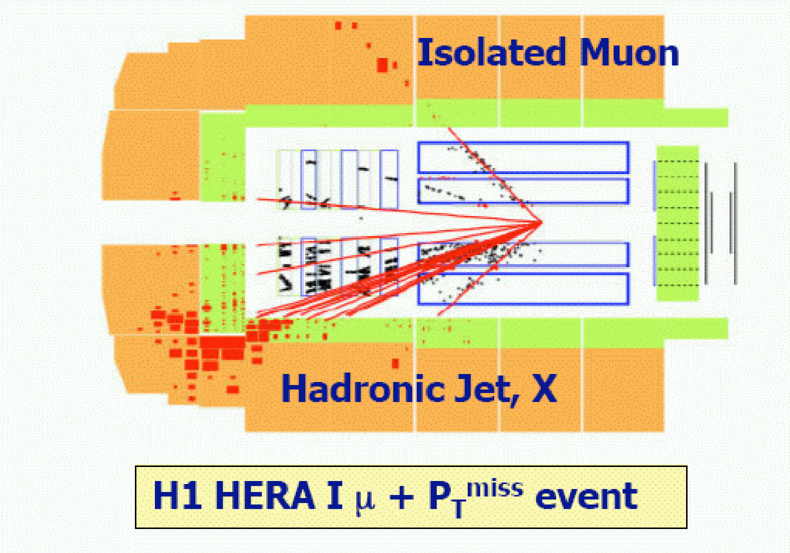


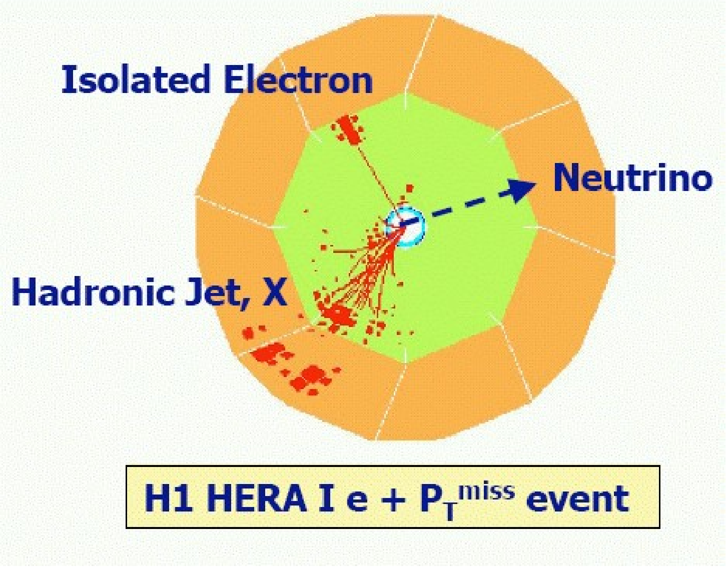
Look for deviations in spectra:

- find regions of spectrum with largest deviation from SM
- use many generated SM MC samples to determine what deviations we expect from statistical fluctuations

No very significant deviation found, most deviating channel is μ–ν–j in e+p data

BSM: Isolated leptons I.

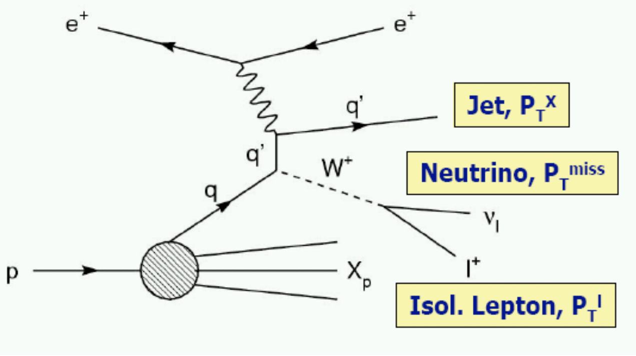




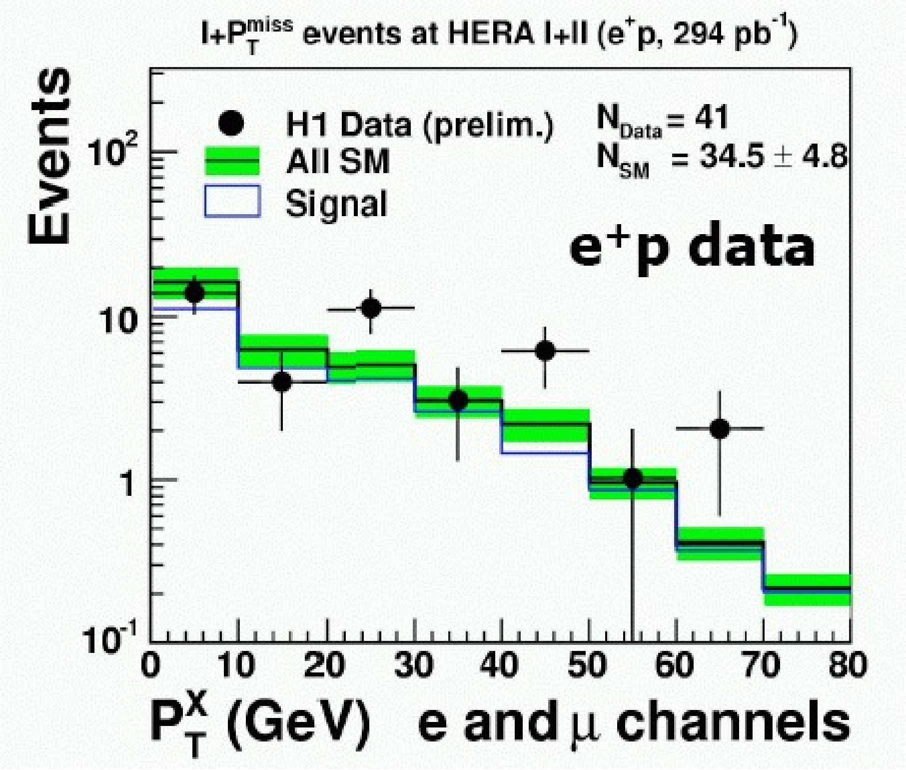
Events (DIS or γp) with:

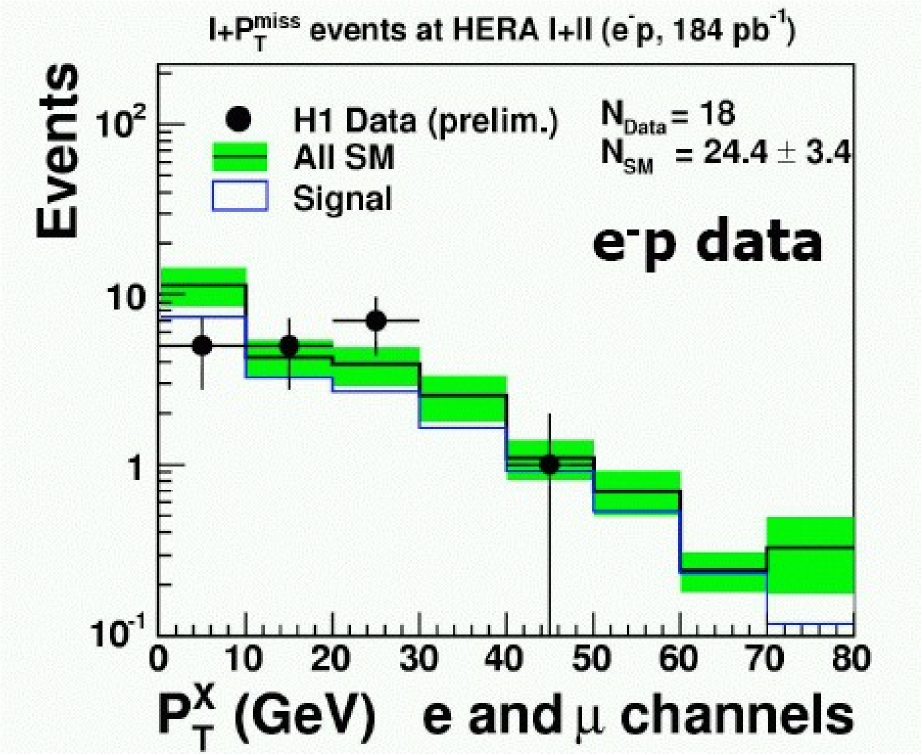
- high $P_{T\ miss}$
- isolated high P_T lepton (e or μ)
- hadronic final state P_T^X

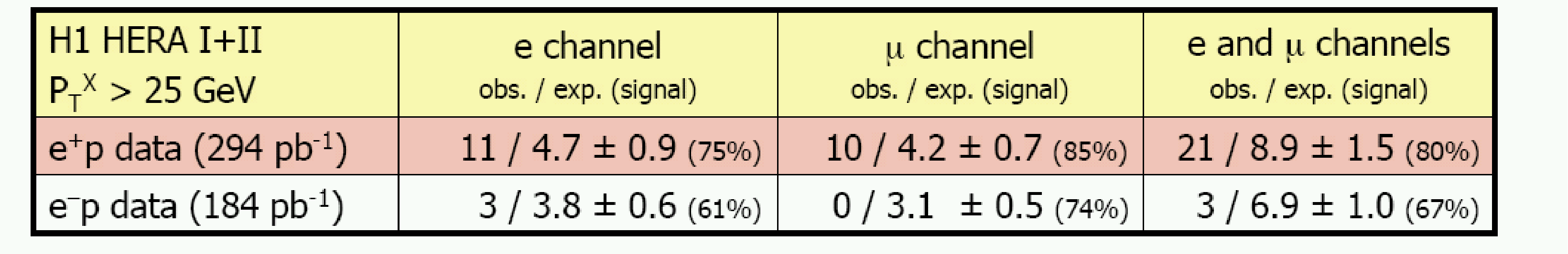
Main SM process: photoproduction of W (low P_T^X)



BSM: Isolated leptons II.





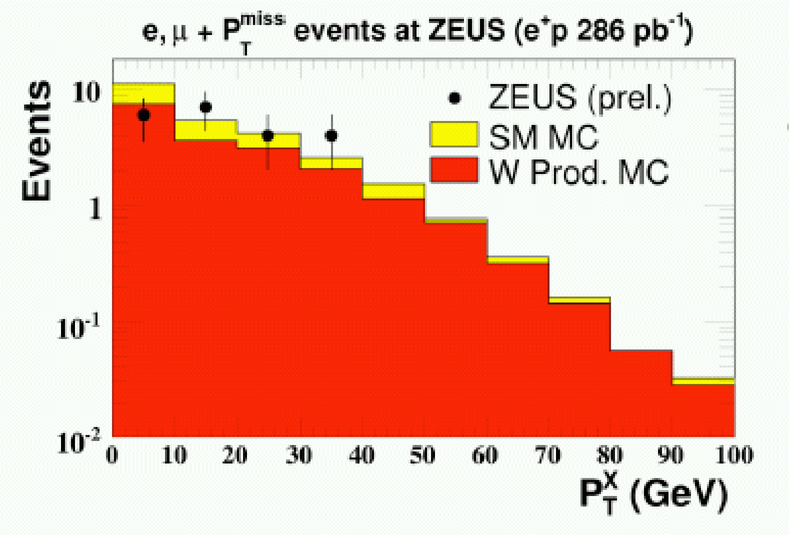


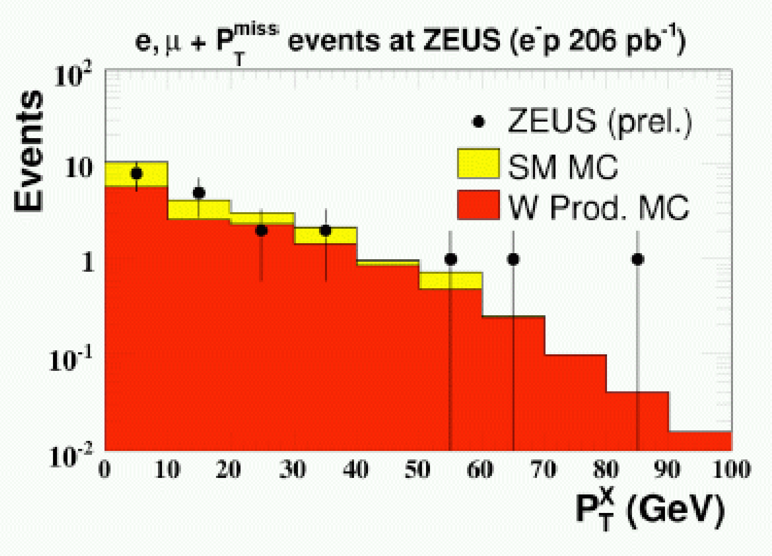
H1 HERA I+II P_T^X > 25 GeV	e channel obs. / exp. (signal)	μ channel obs. / exp. (signal)	e and μ channels obs. / exp. (signal)
e^+p data (294 pb^{-1})	11 / 4.7 ± 0.9 (75%)	10 / 4.2 ± 0.7 (85%)	21 / 8.9 ± 1.5 (80%)
e^-p data (184 pb^{-1})	3 / 3.8 ± 0.6 (61%)	0 / 3.1 ± 0.5 (74%)	3 / 6.9 ± 1.0 (67%)

Excess of events at high P_T^X for e+p observed (~3 σ)

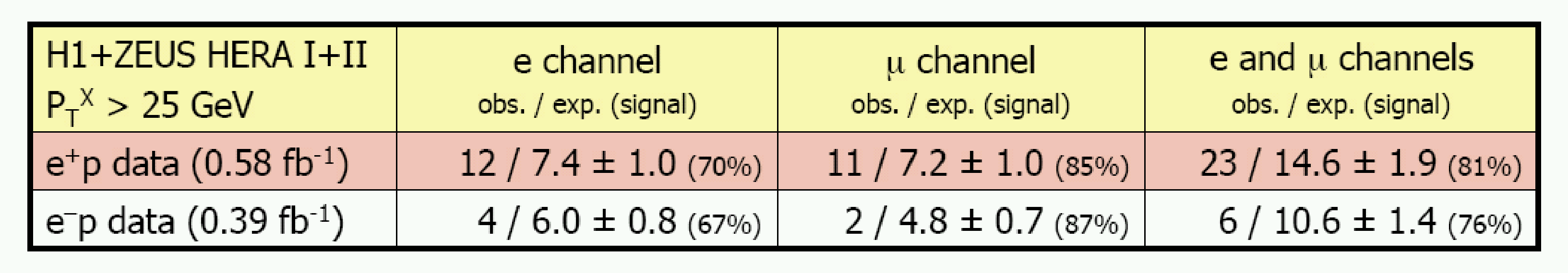
BSM: Isolated leptons III.

ZEUS in agreement with SM:





Combined (H1+ZEUS) analysis:



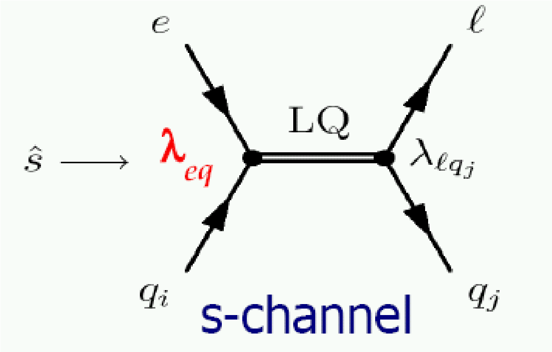
H1+ZEUS HERA I+II P_T^X > 25 GeV	e channel obs. / exp. (signal)	μ channel obs. / exp. (signal)	e and μ channels obs. / exp. (signal)
e$^+$p data (0.58 fb^{-1})	12 / 7.4 ± 1.0 (70%)	11 / 7.2 ± 1.0 (85%)	23 / 14.6 ± 1.9 (81%)
e$^-$p data (0.39 fb^{-1})	4 / 6.0 ± 0.8 (67%)	2 / 4.8 ± 0.7 (87%)	6 / 10.6 ± 1.4 (76%)

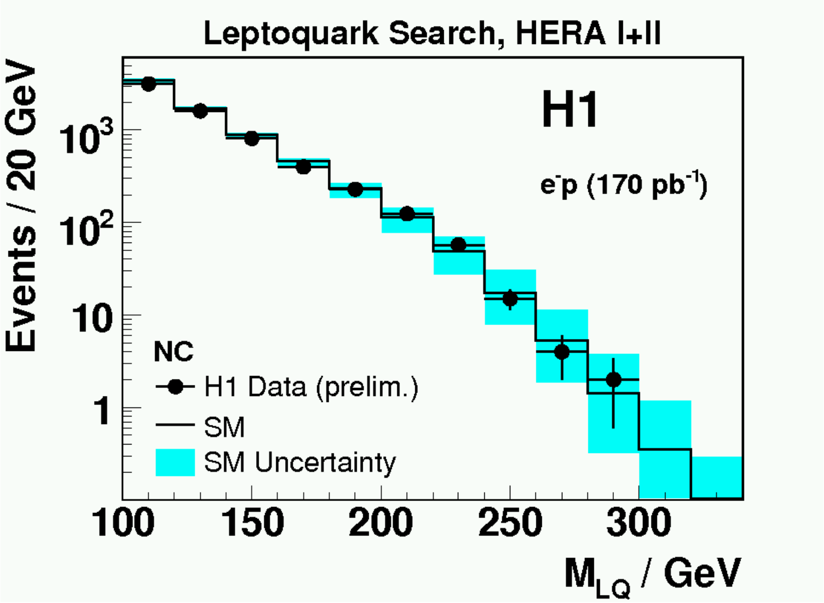
For combined analysis excess drops (~2 σ)

BSM: Leptoquarks I.

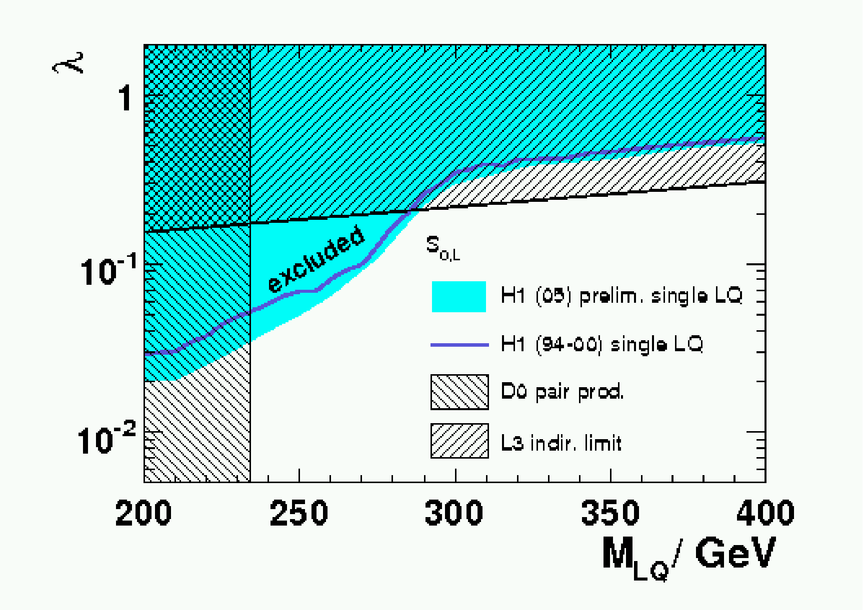
Leptoquarks:

- bosons coupling to lepton-quark pairs
- naturally appear in various unifying theories BSM

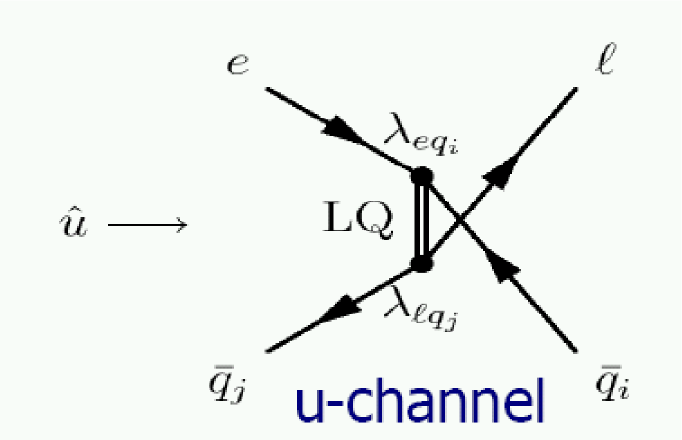


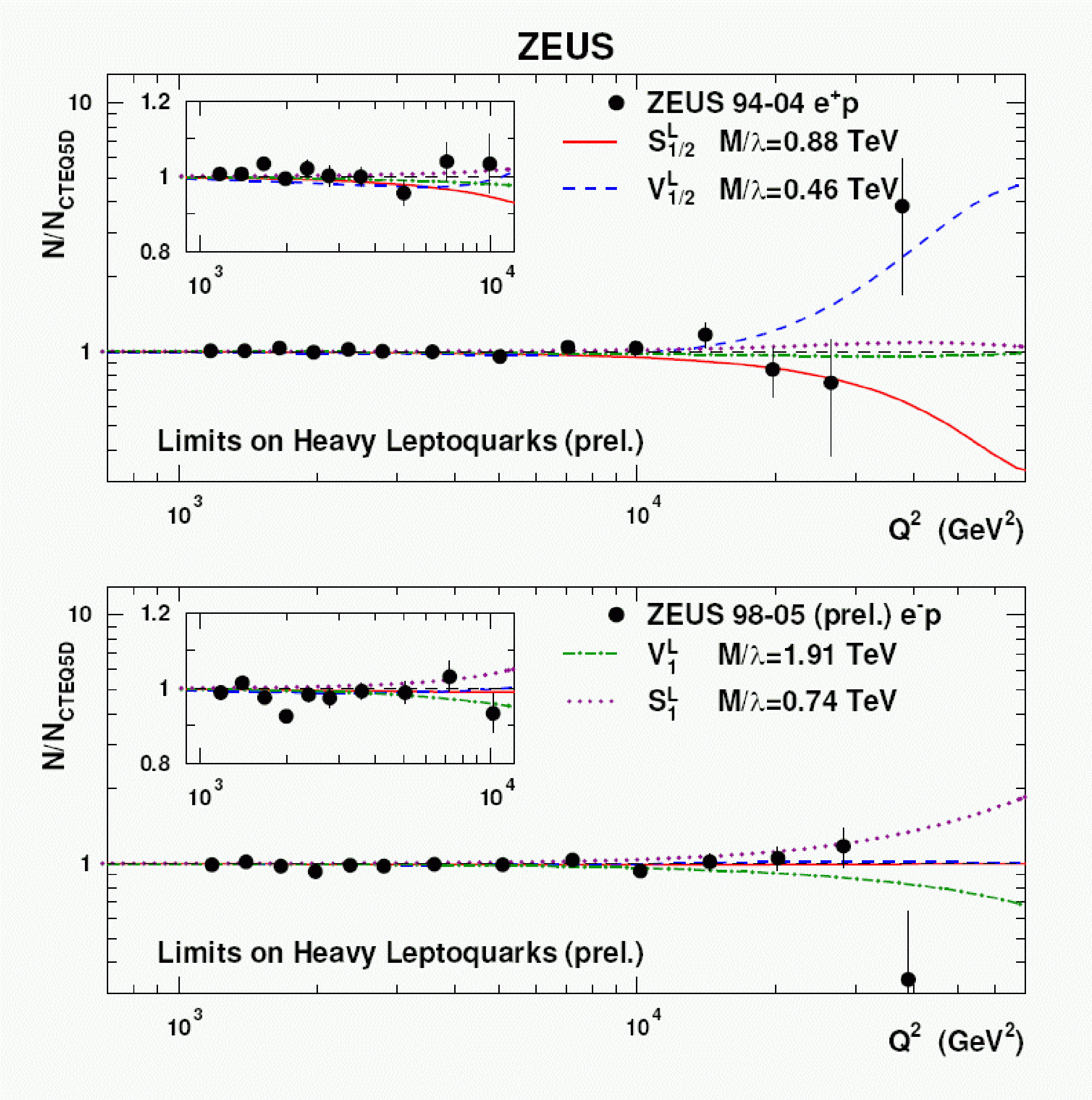


- Low mass LQ: look for peak in M_{LQ} distribution
- confidence limits on M_{LQ} and Yukava coupling λ



BSM: Leptoquarks II.





- High mass LQ: search for deviation of cross section from SM at high Q^2 (contact term)
- determine limits on M$_{LQ}$/λ

BSM: Quark (and lepton) radius

Search for non-pointlike structure of quarks (leptons):

- at high Q^2 should modify SM cross section:

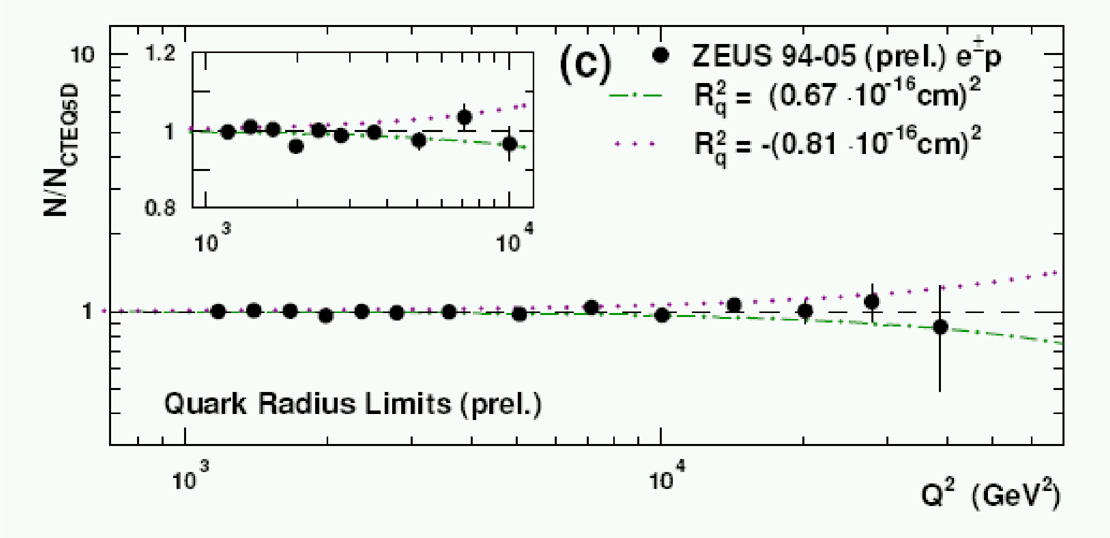
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} f_e^2(Q^2)\, f_q^2(Q^2)$$

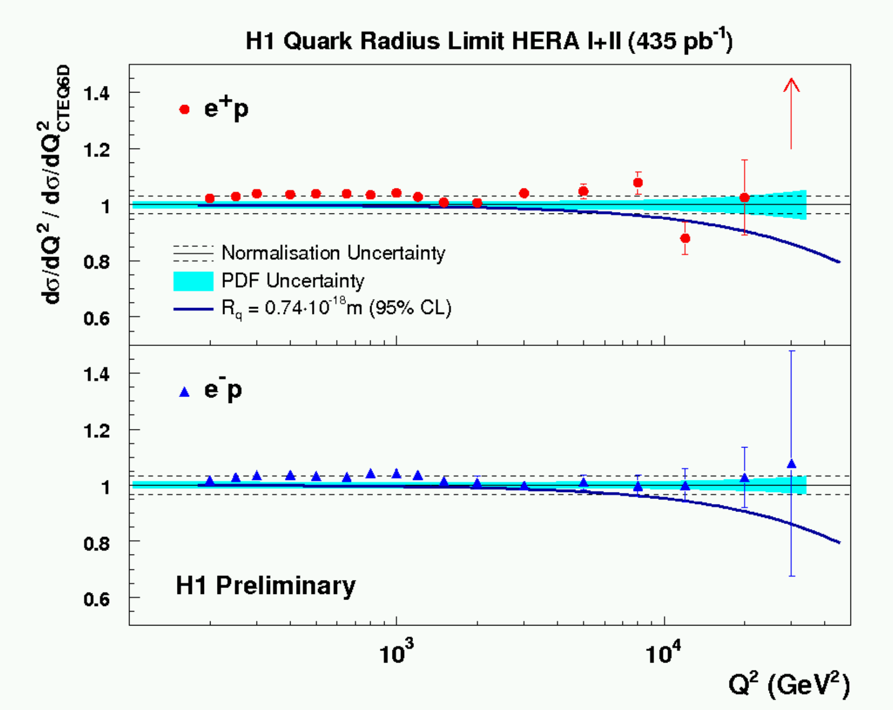
where $f(Q^2) = 1 - \frac{\langle r^2 \rangle}{6} Q^2$

- no deviation from SM prediction seen, allows to set confidence limits:

$$r_q < 0.74 \,.\, 10^{-18} \text{ m (H1)}$$

$$r_q < 0.67 \,.\, 10^{-18} \text{ m (ZEUS)}$$





Conclusions and Outlook

- HERA experiments collected large data sets with lepton polarization for both lepton beam charges
- Rich electroweak physics at high Q^2 and P_T
- Measurement of EW parameters from combined EW+QCD fits
- competitive limits on BSM physics

more of precision results from full HERA I+II data set still to come!