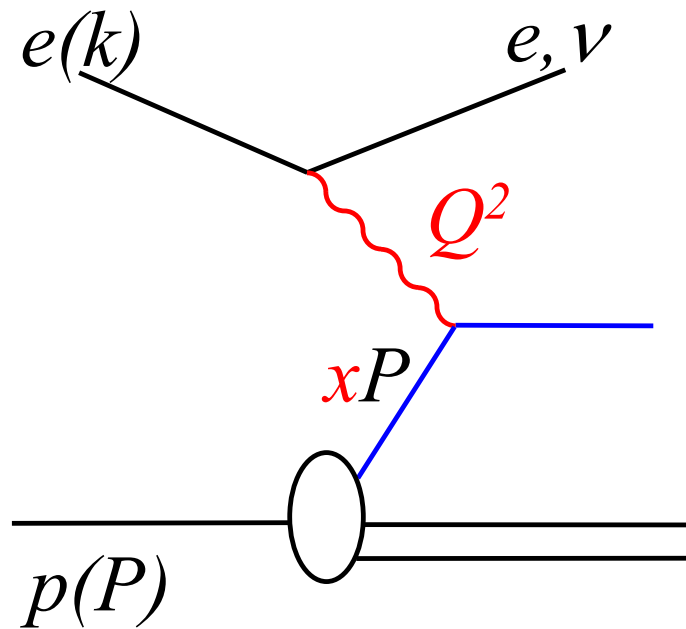


# H1 & ZEUS

High  $Q^2$  physics and the future physics program at HERA-II

LLWI 2002

- Summary of high  $Q^2$  results from HERA-I
- HERA upgrade
- H1 and ZEUS upgrades
- Physics potential
- Summary

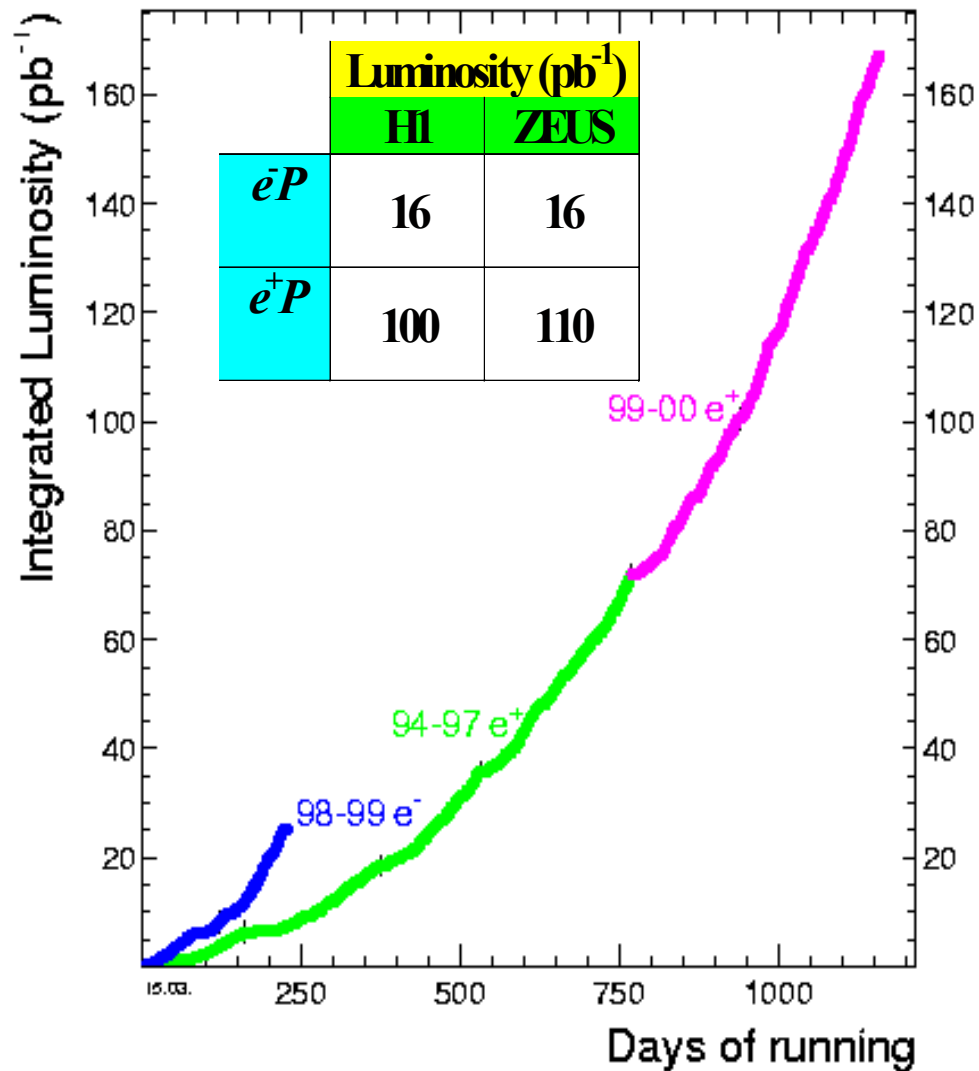


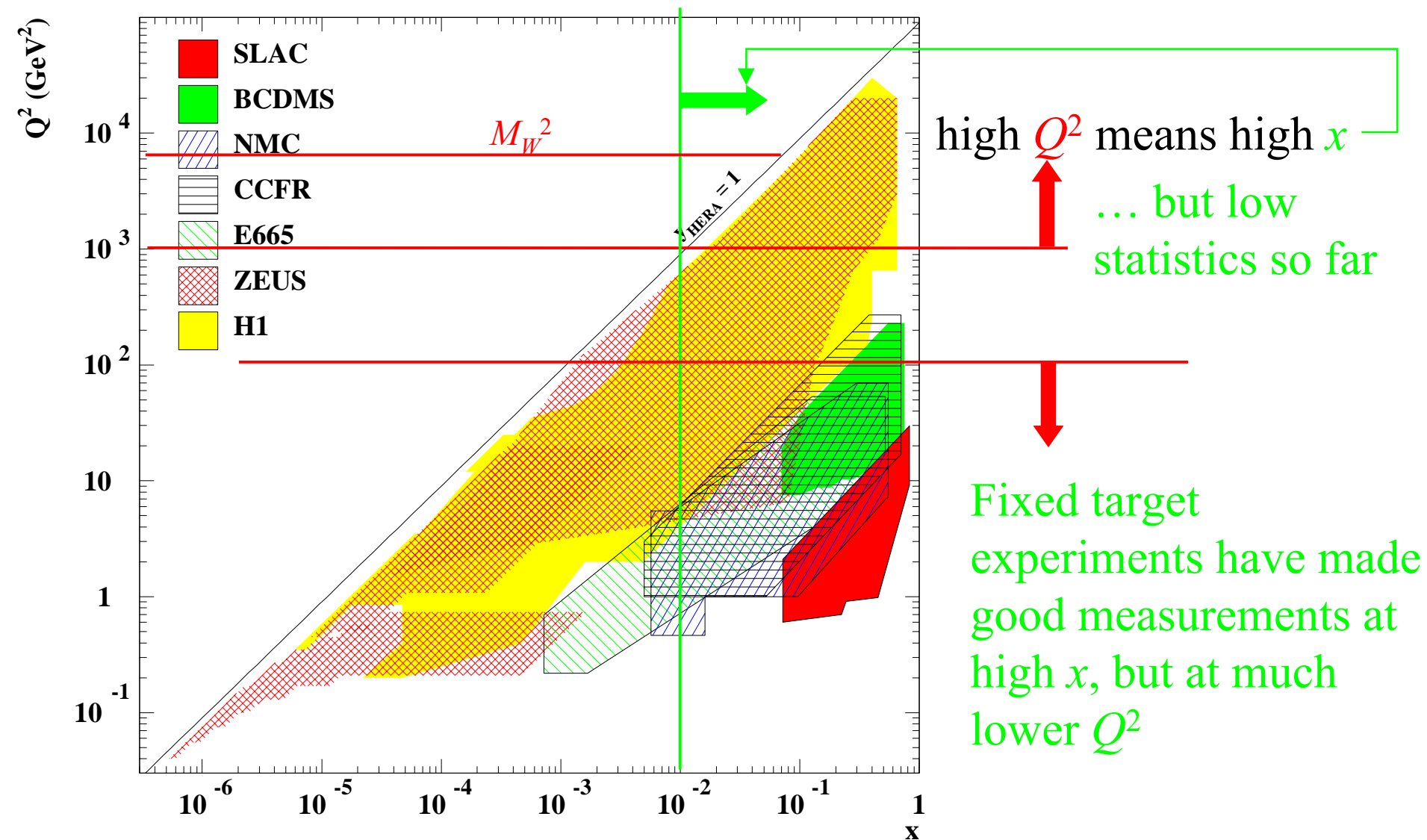
$$Q^2 = sxy$$

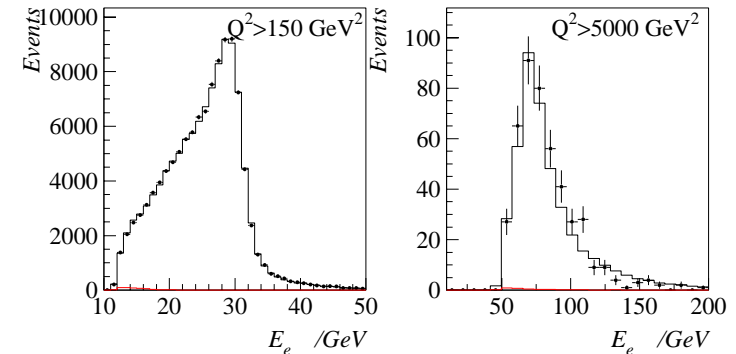
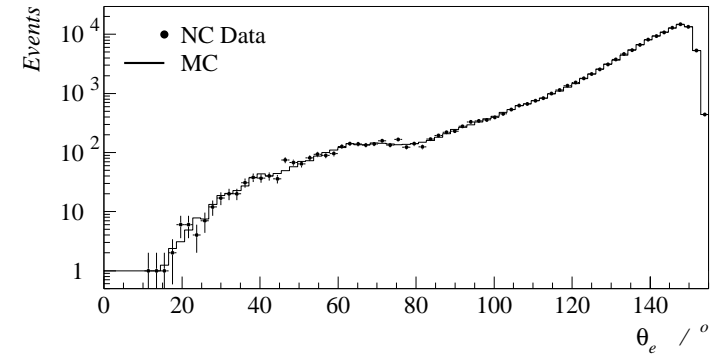
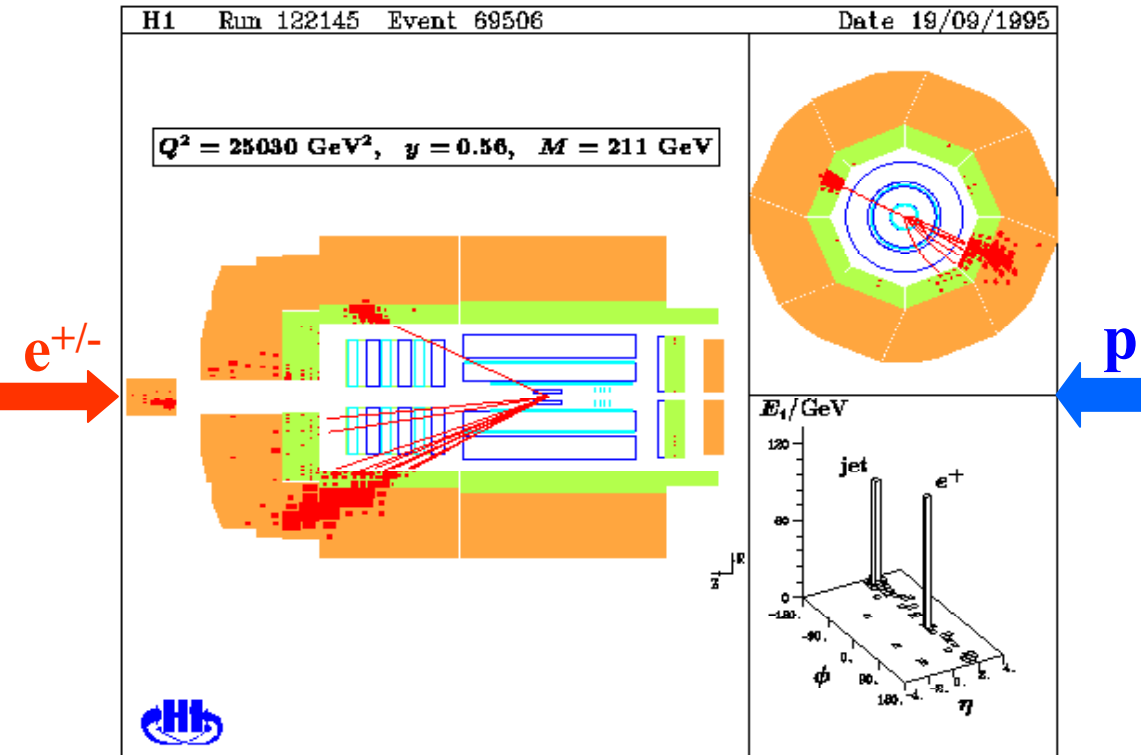
$s = 300 \text{ GeV} \text{ (94-97)}$

$= 318 \text{ GeV} \text{ (98-00)}$

HERA luminosity 1994 – 2000



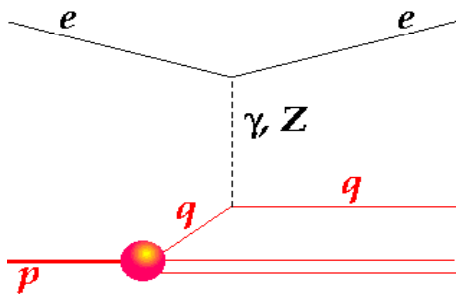




Events easy to recognize: high trigger efficiency, low background

lepton back-scattered, high energy

CC (signature is missing  $p_T$ ) more difficult at low  $y$



$$\frac{d^2 \sigma_{NC}^{e^+p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot \left[ Y_+ \cdot F_2(x, Q^2) \mp Y_- \cdot xF_3(x, Q^2) - y^2 F_L(x, Q^2) \right]$$

small at high  $Q^2$

Parity conserving

Parity violating

$$F_2^{NC} = x \sum_f A_f(Q^2) [q(x, Q^2) + \bar{q}(x, Q^2)]$$

$$xF_3^{NC} = x \sum_f B_f(Q^2) [q(x, Q^2) - \bar{q}(x, Q^2)]$$

$$A_f = e_f^2 - 2v_e v_f e_f \chi_Z + (v_e^2 + a_e^2)(v_f^2 + a_f^2) \chi_Z^2$$

$\gamma$  exch.

$\gamma$ -Z interference

Z exch.

$$B_f = -2a_e a_f e_f \chi_Z + 4v_e a_e v_f a_f \chi_Z^2$$

$$\chi_Z = \frac{1}{4\sin^2 \vartheta_W \cos^2 \vartheta_W} \frac{Q^2}{Q^2 + M_Z^2}$$

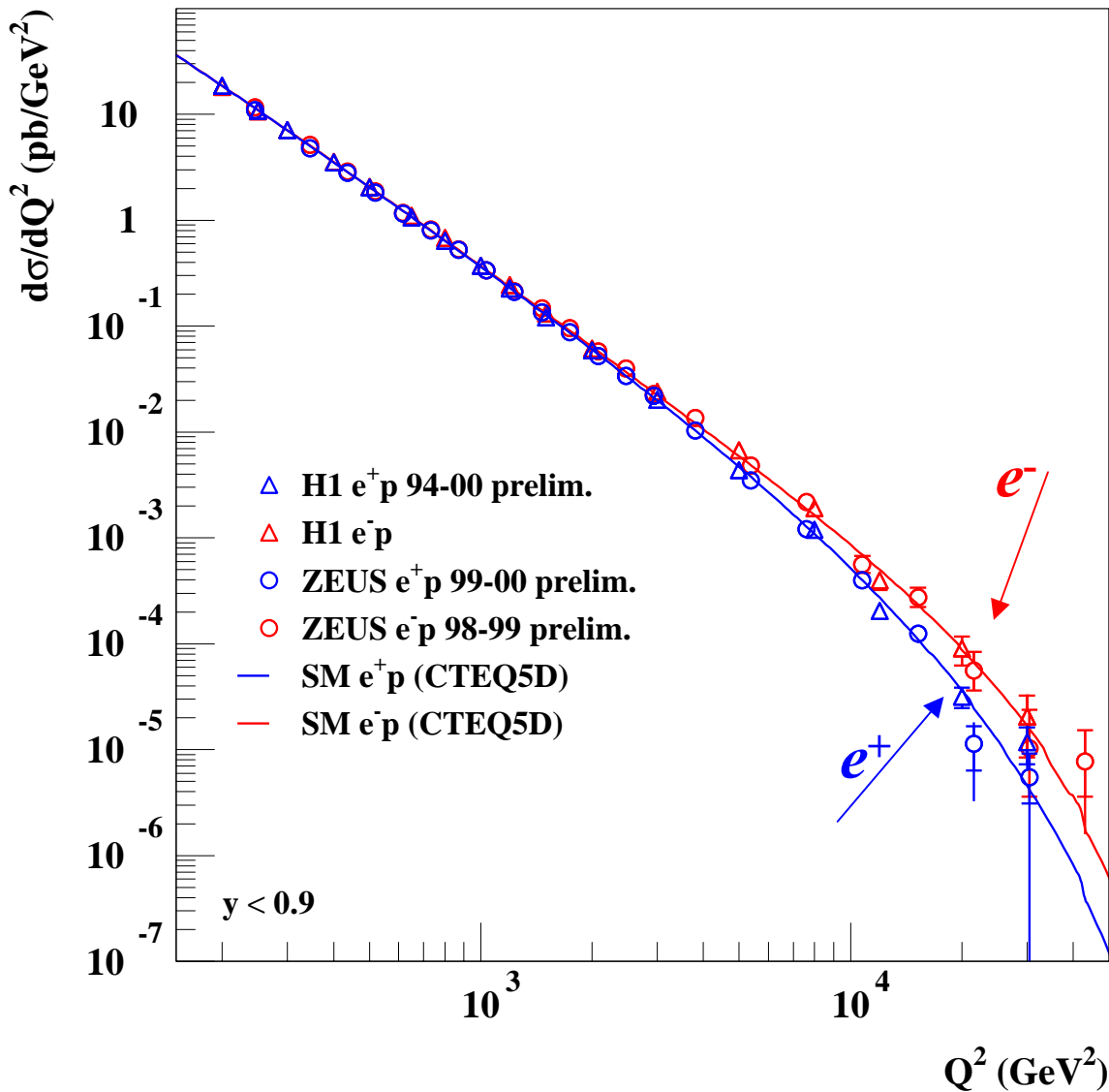
$v_e, a_e, v_f, a_f$  : weak couplings

Reduced cross section:

$$\tilde{\sigma}_{NC}^{\pm} = \frac{xQ^4}{2\pi\alpha^2} \frac{1}{Y_{\pm}} \frac{d^2 \sigma^{NC}}{dx dQ^2}$$

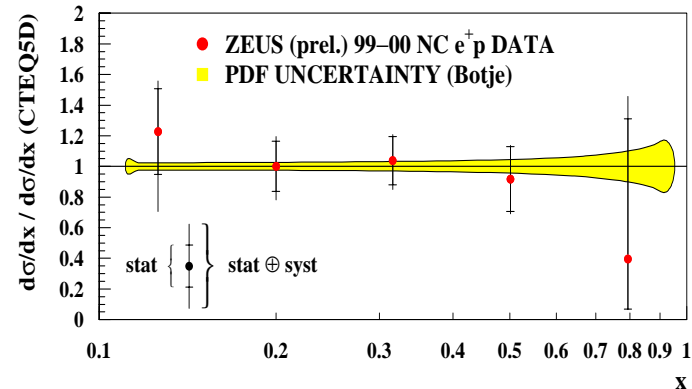
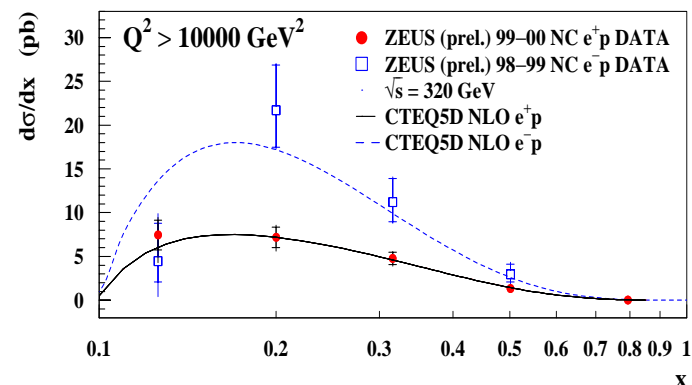
$$Y_{\pm} = 1 \pm (1-y)^2$$

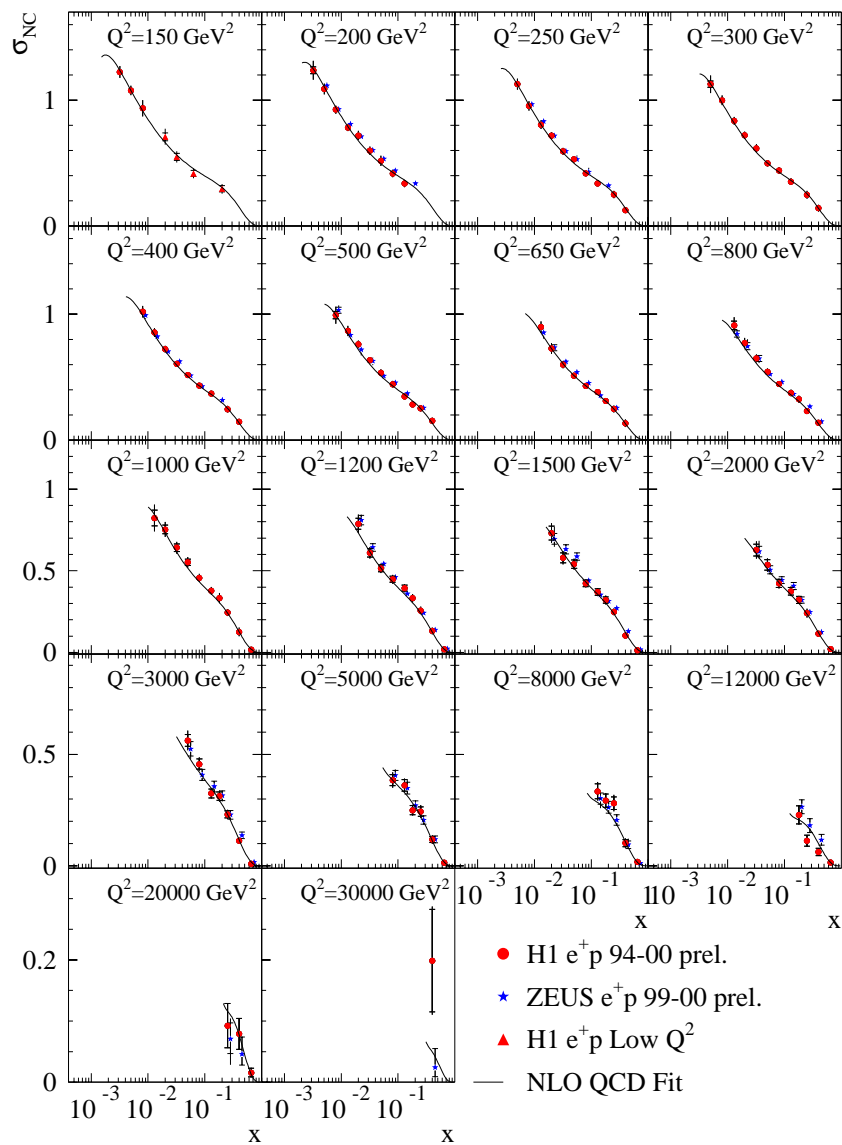
## HERA Neutral Current



- SM describes shape over  $10^6$  fall in cross section
- evidence for the effect of  $\gamma$ -Z interference at high  $Q^2$

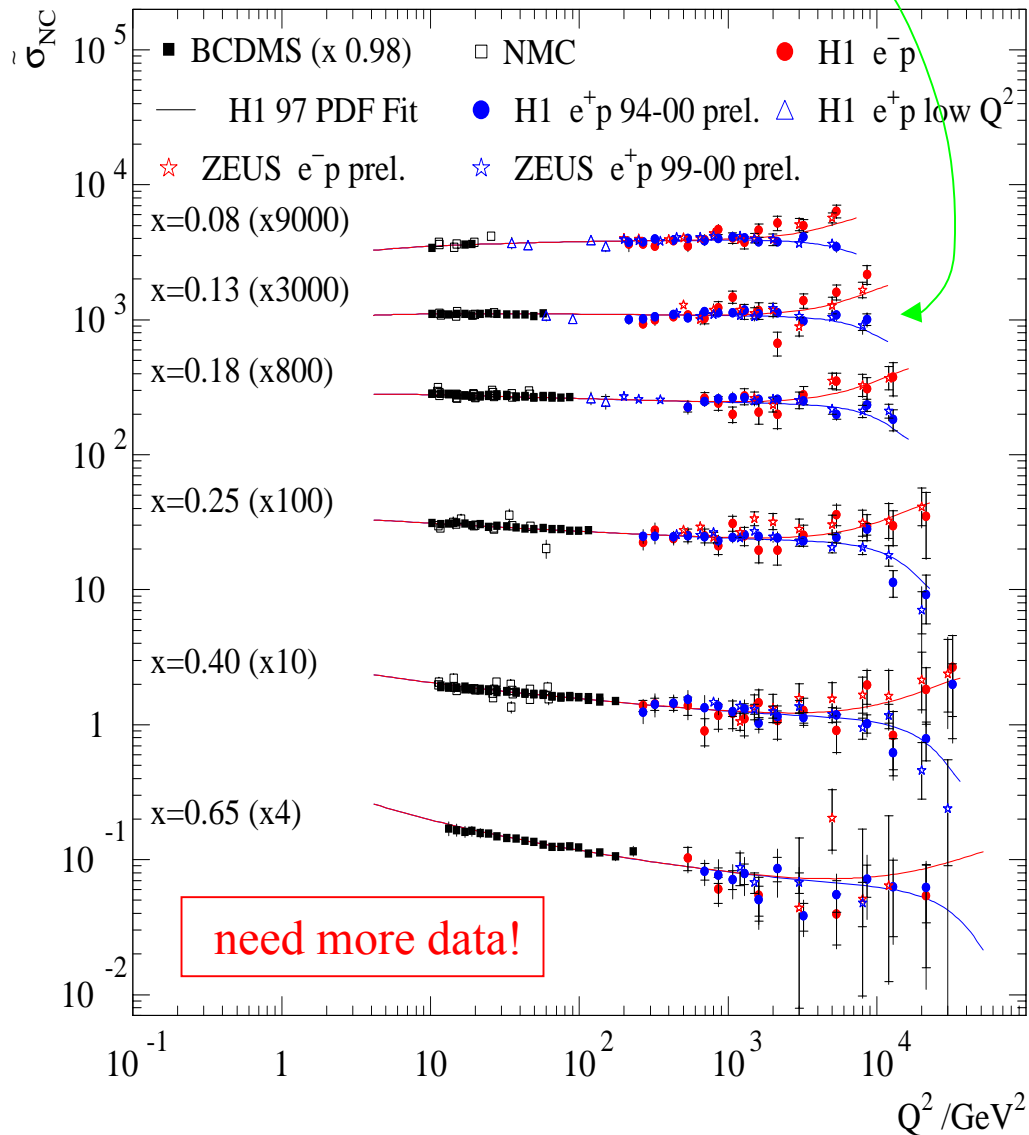
## ZEUS





good agreement H1/ZEUS/SM

effect of Z-exchange



- agrees with QCD: small changes over large range of  $Q^2$  due to QCD scaling violations
- results limited by small  $e^-$  sample
- sensitive to valence quarks:

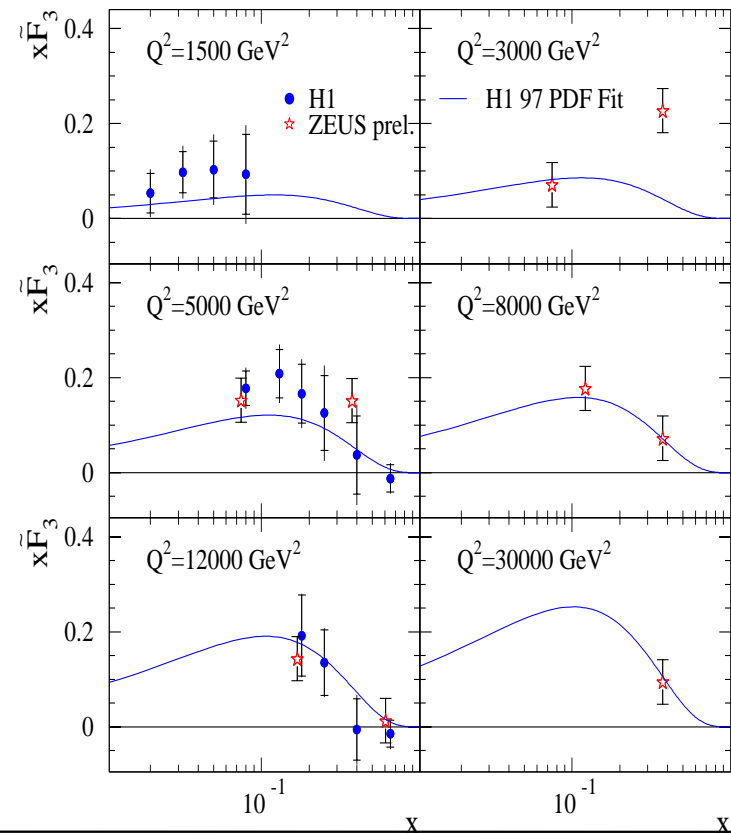
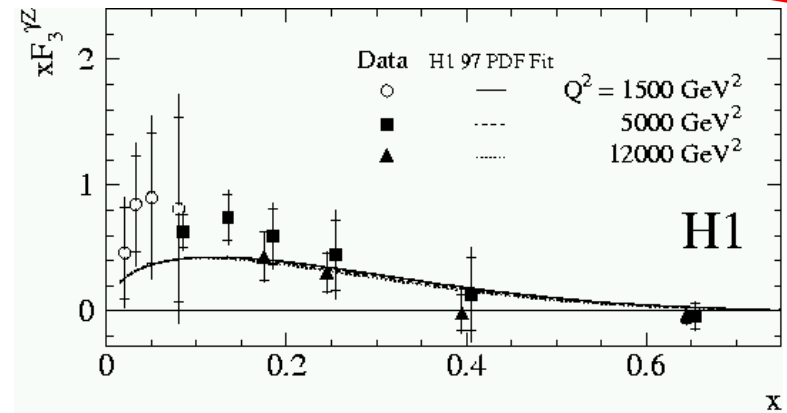
$$xF_3 \propto (q - \bar{q}) = ((q_v + q_{sea}) - \bar{q}_{sea}) \approx q_v$$

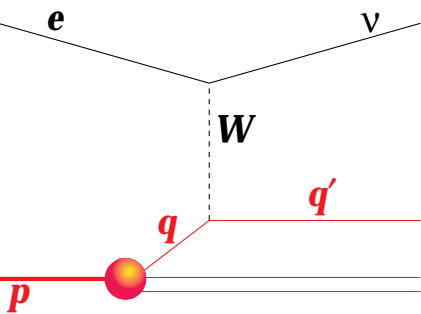
- sum rule test:

$$\text{recall: } xF_3^{\gamma-Z} = x \sum_q 2e_q a_q (q - \bar{q})$$

$$\text{then: } \int_0^1 F_3^{\gamma-Z} dx \approx 2e_u a_u N_u + 2e_d a_d N_d = 5/3$$

$$\text{H1: } \int_{0.02}^{0.65} F_3^{\gamma-Z} dx = 1.88 \pm 0.35(\text{stat.}) \pm 0.27(\text{syst.})$$





$$\frac{d^2 \sigma_{CC}^{e^+p}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ Y_+ \cdot F_2^{CC}(x, Q^2) \mp Y_- \cdot x F_3^{CC}(x, Q^2) - y^2 F_L^{CC}(x, Q^2) \right]$$

small

$$e^- p \rightarrow \nu X \left\{ \begin{array}{l} F_2^{CC} = x(q + \bar{q}) = x(u + c + \bar{d} + \bar{s}) \\ xF_3^{CC} = x(q - \bar{q}) = x(u + c - \bar{d} - \bar{s}) \end{array} \right.$$

$$\tilde{\sigma}_{CC}^{e^- p} = u + c + (1-y)^2 (\bar{d} + \bar{s})$$

Probe u valence

$$e^+ p \rightarrow \bar{\nu} X \left\{ \begin{array}{l} \text{similarly ...} \end{array} \right.$$

$$\tilde{\sigma}_{CC}^{e^+ p} = \bar{u} + \bar{c} + (1-y)^2 (d + s)$$

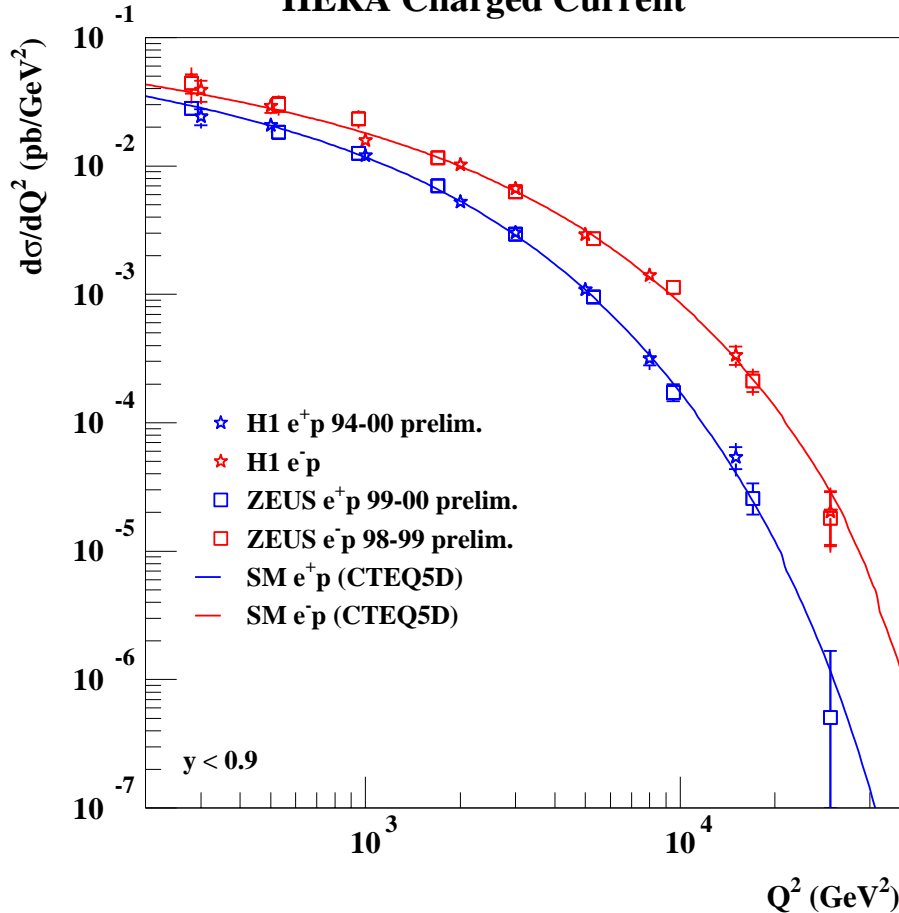
Probe d valence

- extract individual quark densities
- measure  $M_W$  from propagator dependance

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

$$\tilde{\sigma}_{CC} = \frac{2\pi x}{G_F^2} \left[ \frac{Q^2 + M_W^2}{M_W^2} \right]^2 \frac{d^2 \sigma_{CC}}{dx dQ^2}$$

HERA Charged Current



- SM describes shape well:
  - below  $M_W^2$ , slow fall with  $Q^2$  due to reduced  $x$  phase space
  - above  $M_W^2$ , rapid fall due to  $W$  propagator
- difference  $e^-$  vs  $e^+$ :
  - low  $Q^2$ , sea important,  $\sigma \sim$  same
  - high  $Q^2$ , valence dominates:

$$\tilde{\sigma}_{CC}^{e^-p} \approx u$$

$$\tilde{\sigma}_{CC}^{e^+p} \approx (1-y)^2 d$$

so rough expectation:

proton has  $2u, 1d$ ;  $\int (1-y)^2 dy = 1/3$

$$\Rightarrow \sigma^{e^-p} / \sigma^{e^+p} \approx 6$$

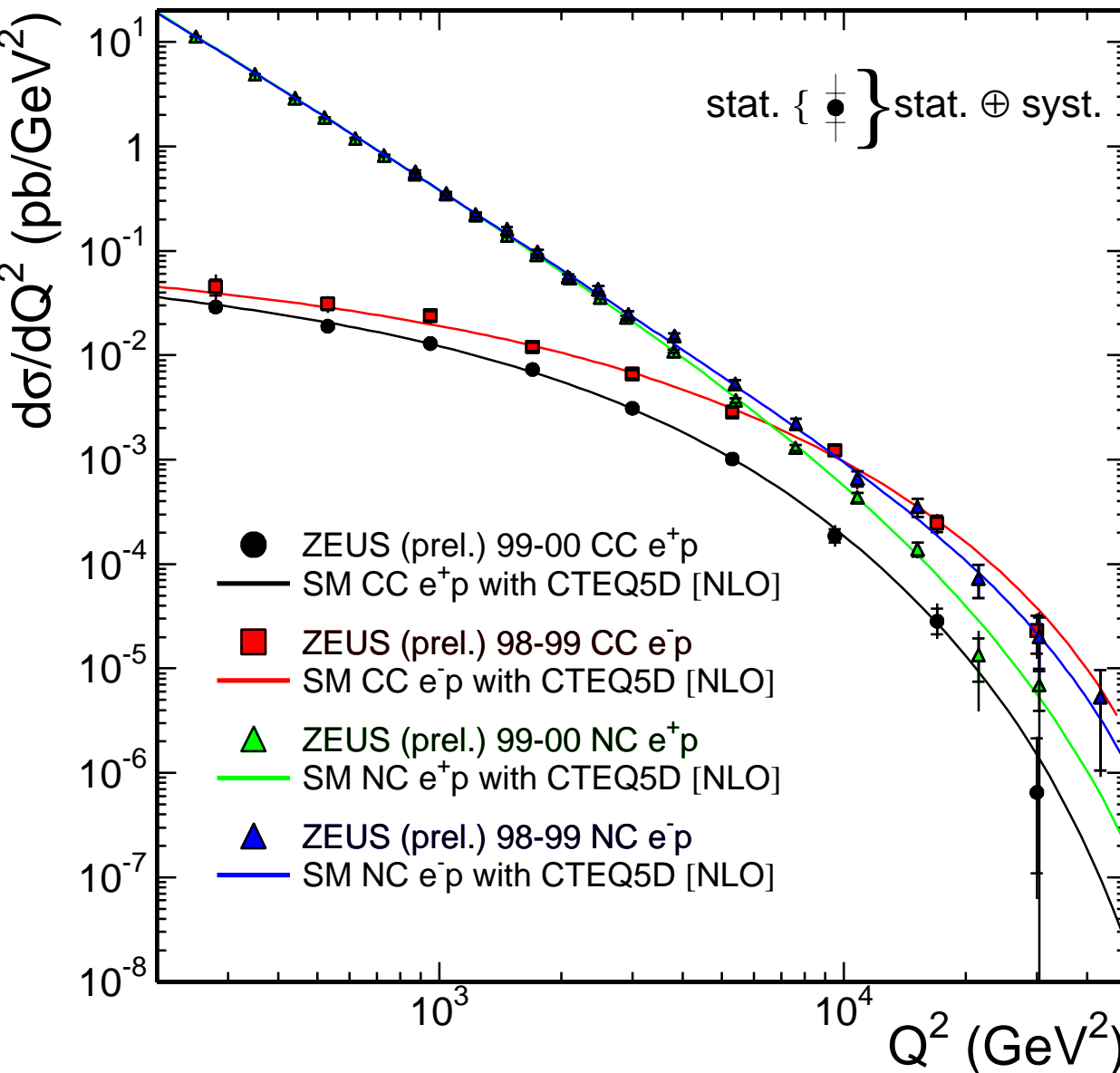
Space-like  $M_W$  measurement:

H1:  $M_W = 80.9 \pm 3.3 \pm 1.7 \pm 3.7 \text{ GeV}$

ZEUS:  $M_W = 81.4 \pm 2.7 \pm 2.0 \pm 3.3 \text{ GeV}$

- d/u critical measurement

## ZEUS

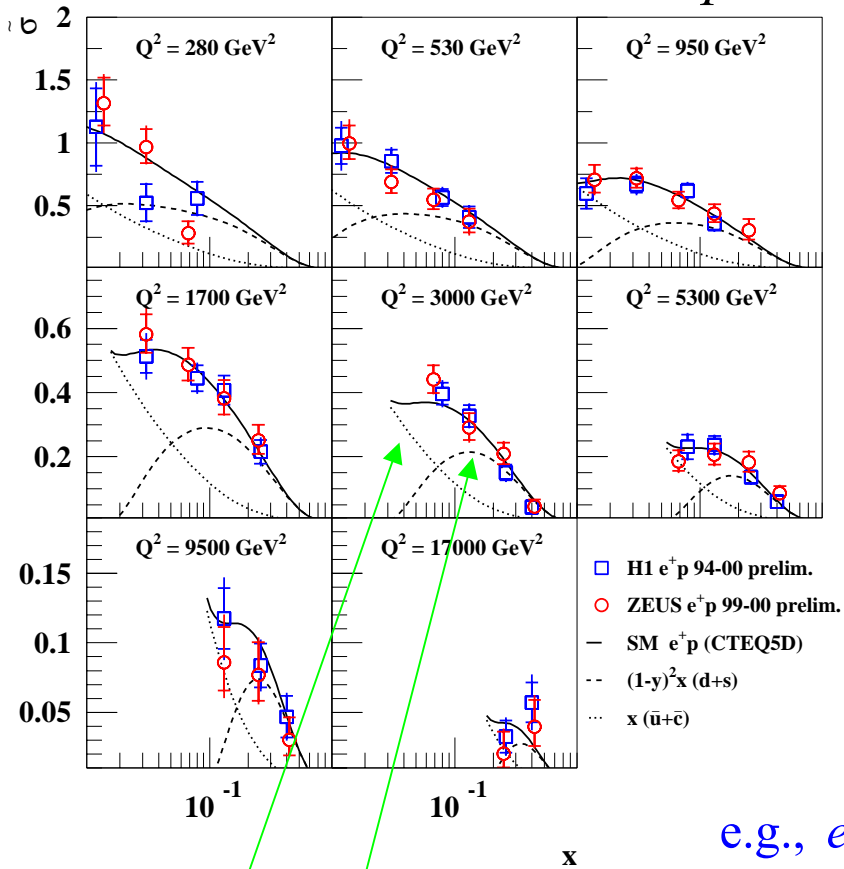


$$\sigma_{CC} \approx \sigma_{NC}$$

for

$$Q^2 > M_W^2, M_Z^2$$

## HERA Charged Current $e^+ p$

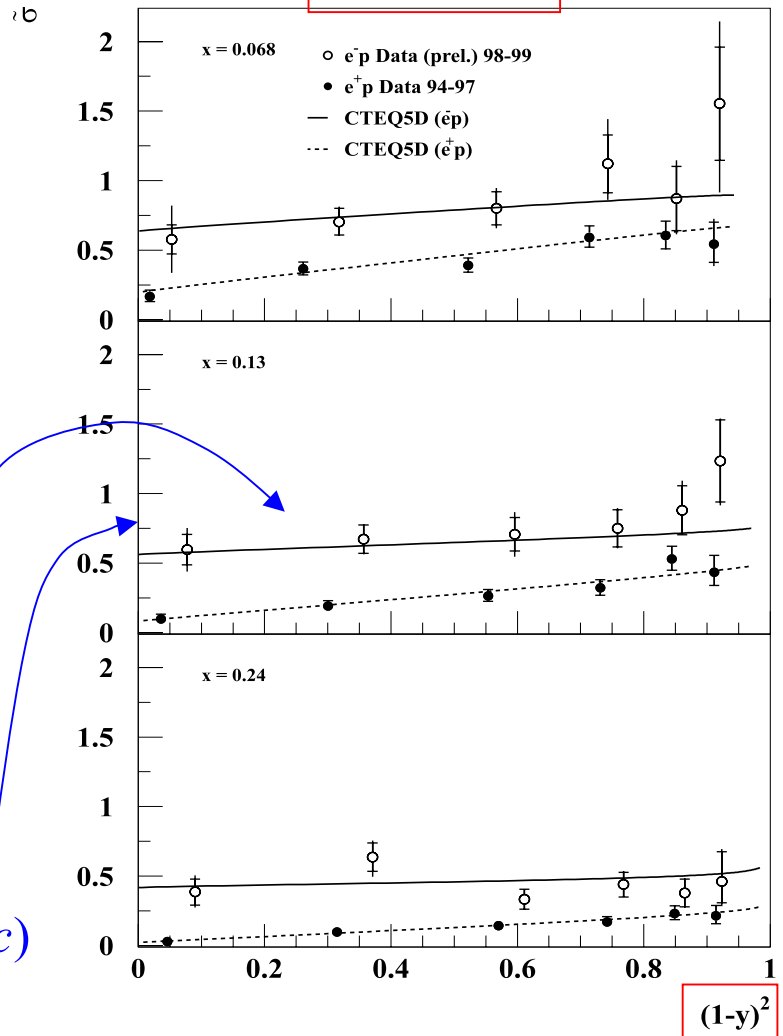


$$x(\bar{u} + \bar{c})$$

$$(1-y)^2 x(d+s)$$

e.g.,  $e^- p$ :  
 slope =  $(\bar{d} + \bar{s})$   
 intercept =  $(u + c)$

## ZEUS



$$(1-y)^2$$

- NLO QCD fit to H1 data (yellow)

- determine  $xu \sim 6-10\%$ ,  $xd \sim 20\%$
- at  $x=0.65$ ,  $xu$  is lower by  $\sim 17\%$  than in MRST, CTEQ5, H197

- data points “extracted”:

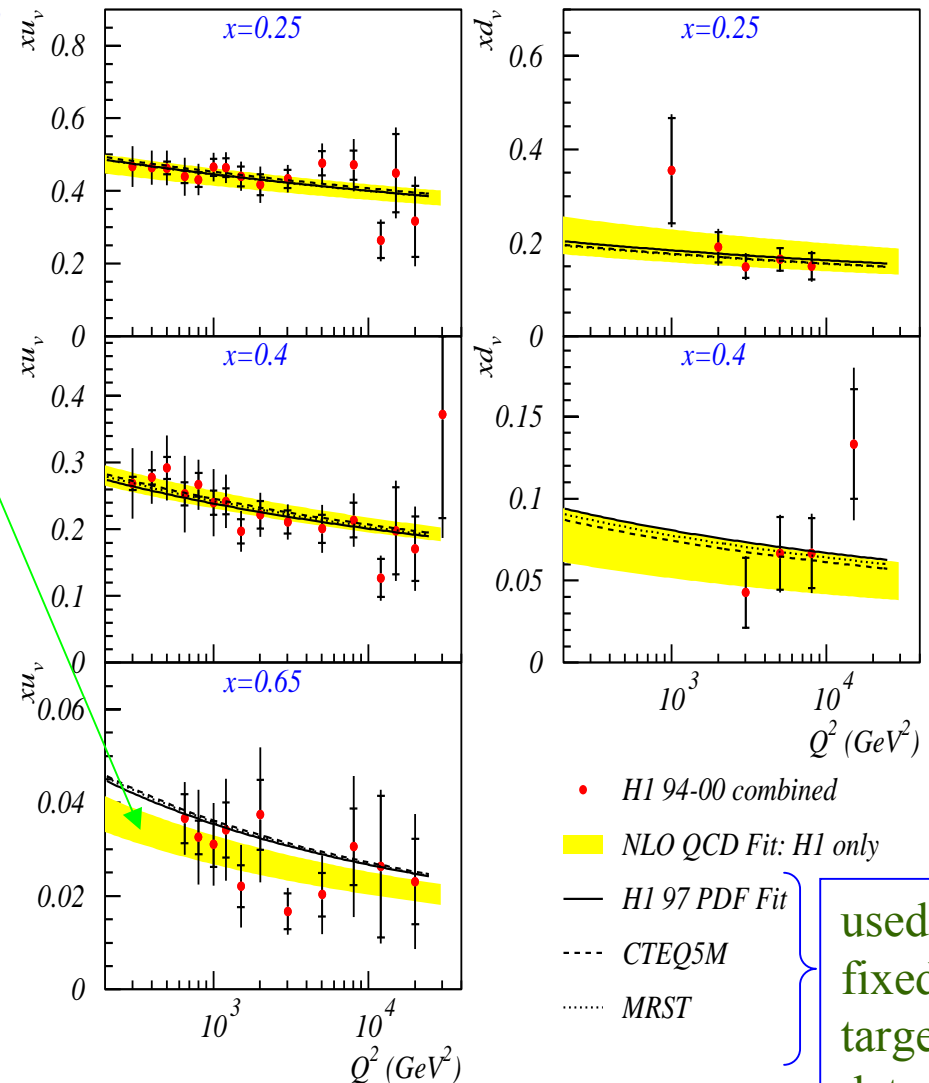
$$xq_v(x, Q^2) = \sigma_{\text{meas}}(x, Q^2) \left( \frac{xq_v(x, Q^2)}{\sigma(x, Q^2)} \right)_{\text{fit}}$$

points extracted only for  $\left( \frac{xq_v}{\sigma} \right) > 0.7$

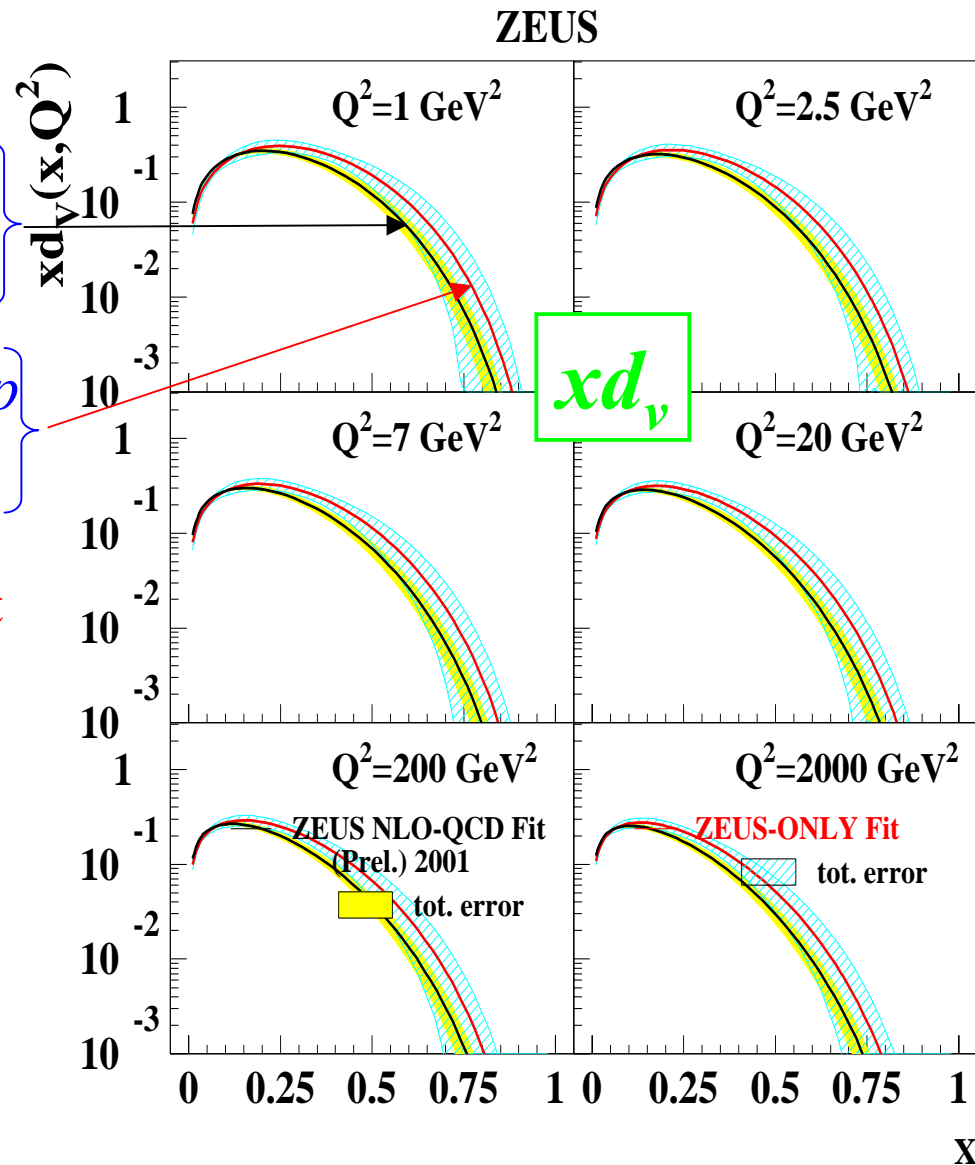
⇒ approx. model independent

- extracted points in good agreement with QCD fits

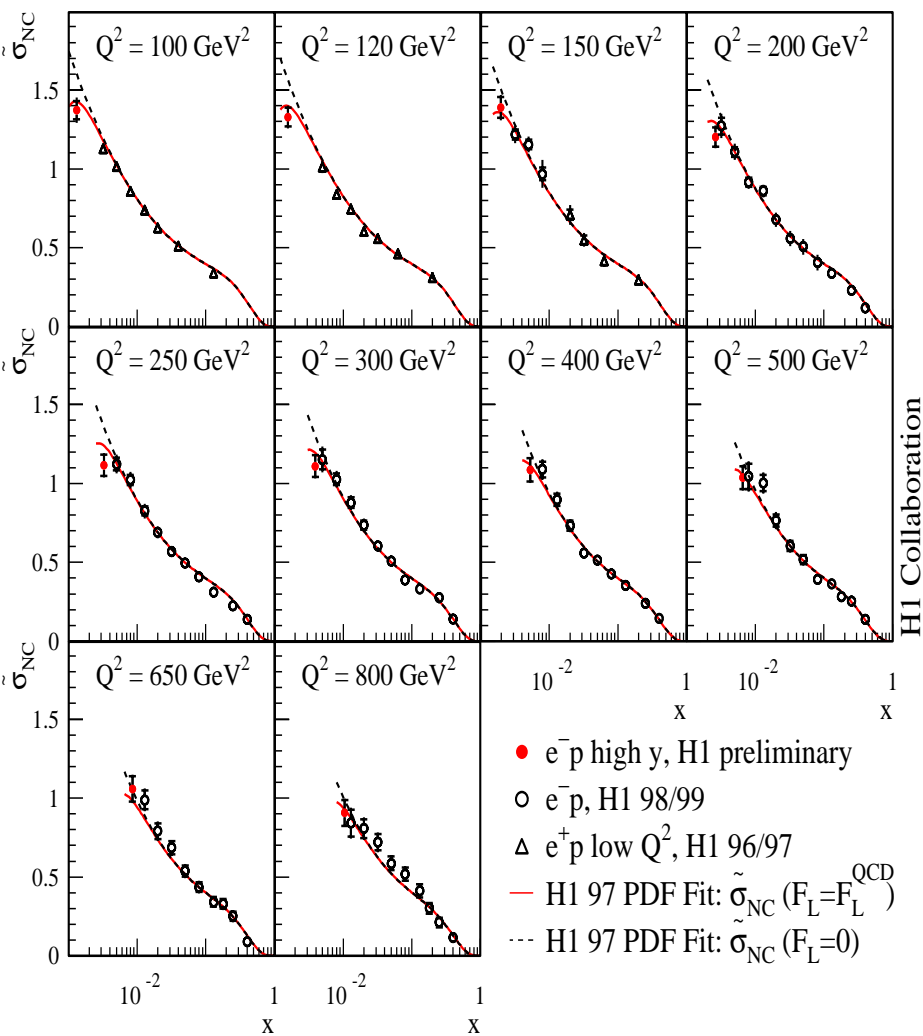
H1 Preliminary



- Uses ZEUS 96-97  $e^+p$  NC data and fixed target data
- **ZEUS-ONLY** fit uses 96-97  $e^+p$  NC/CC, 98-99  $e-p$  NC/CC
  - prefers higher  $xd_\nu$  than standard fit
- more HERA data needed: free from heavy target, higher twist, etc. corrections

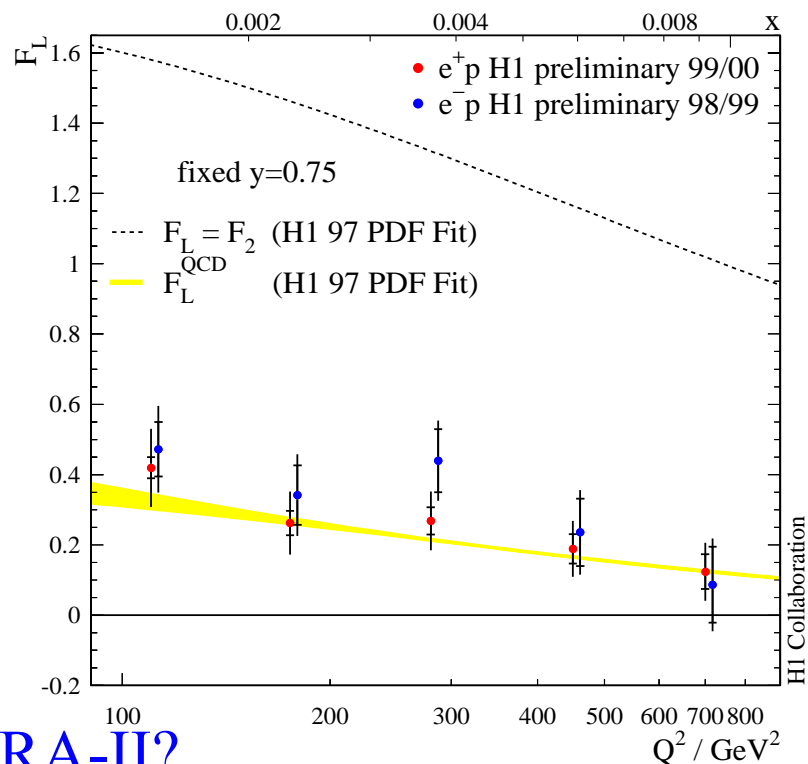


- Extend data at high  $y$  by lowering cut on scattered  $e$  from 11 to 6 GeV

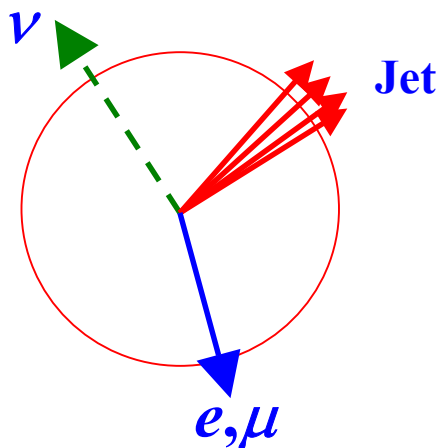


$$F_L = \frac{Y_+}{y^2} (F_2^{\text{fit}} - \tilde{\sigma})$$

from H1 97 fit  
normalized to data  $y < 0.4$



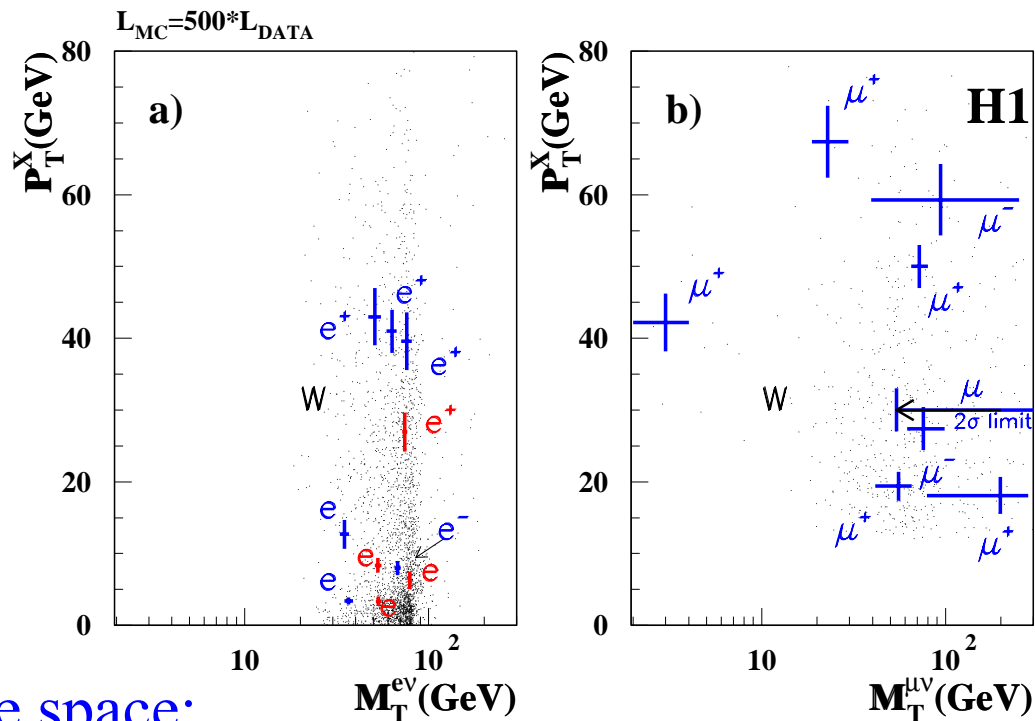
- measurement needed at lower  $E_p$  : HERA-II?



- SM background mostly  $W$
- Compare expts in same phase space:

$P_T^x > 25$ GeV	$e$ Obs (exp)	$\mu$ Obs (exp)	$e+\mu$ Obs (exp)
H1	4 (1.3)	6 (1.5)	10 (2.8 $\pm$ 0.7)
ZEUS	1 (1.1)	1 (1.3)	2 (2.4 $\pm$ 0.2)


H1 PRELIMINARY 101.6pb<sup>-1</sup> e<sup>+</sup>p data 94-00



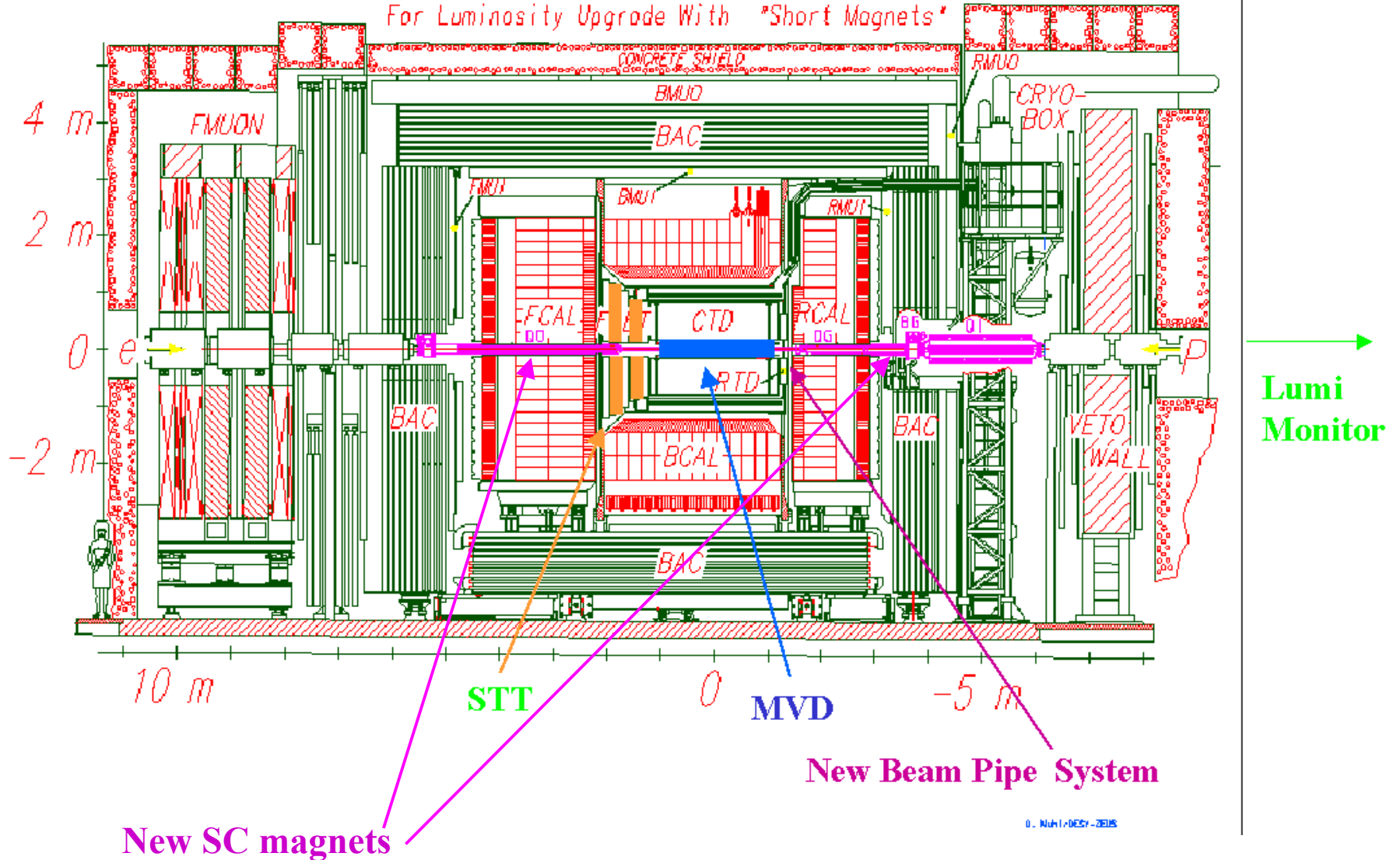
H1 sees them, ZEUS doesn't

?? puzzle ??

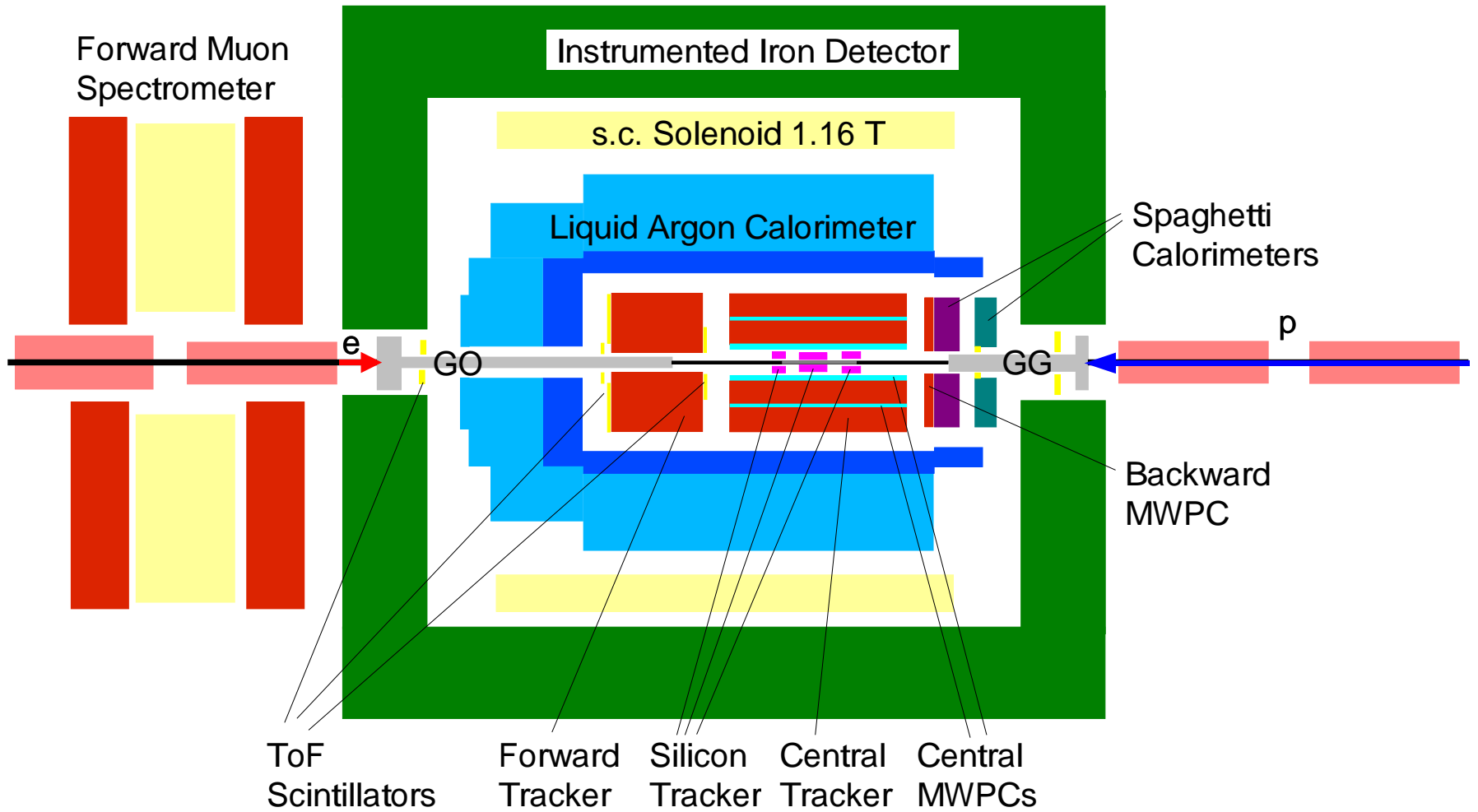
need more data to resolve

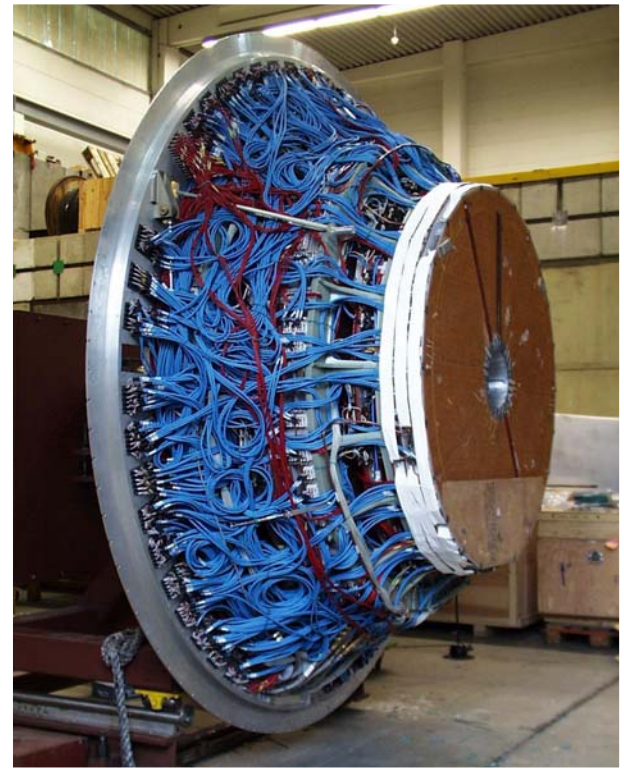
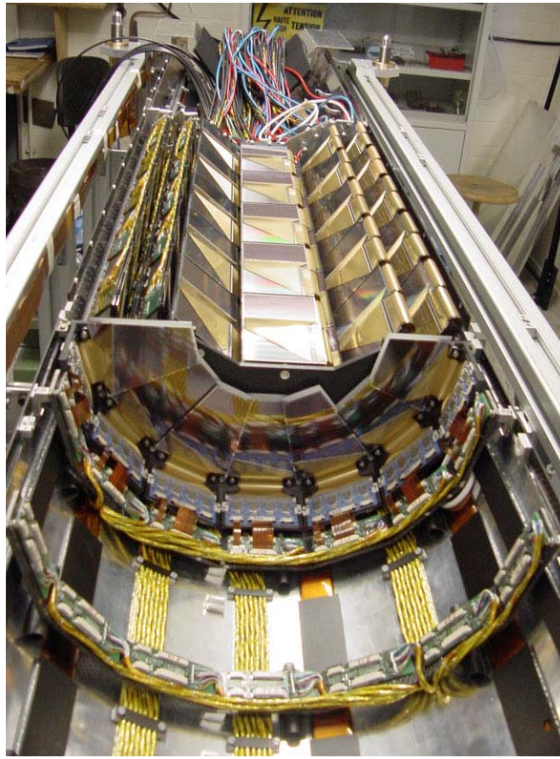
- Luminosity upgrade 5x increase  150-200 pb<sup>-1</sup>/yr
  - strong focusing inside experiments: SC magnets
  - new magnet arrangement +/- 100 m from experiments
- Longitudinal polarization for H1/ZEUS
  - >50% (70% design goal)
- experiment upgrades:
  - forward tracking, Si vtx detector (new for ZEUS, new fwd. planes for H1)
    - needed for forward jets, high energy scattered electron, heavy quarks
  - online triggers
    - short decays for  $b, c$  ;  $D^*$  reconstruction
  - lumi and pol measurement detectors
- HERA-II run until 2006 : goal 1000 pb<sup>-1</sup>/experiment 10x current data set
  - divided ~ equally  $e_R^+, e_L^+, e_R^-, e_L^-$

Overview Of The ZEUS Detector  
( Longitudinal Cut )  
For Luminosity Upgrade With "Short Magnets"



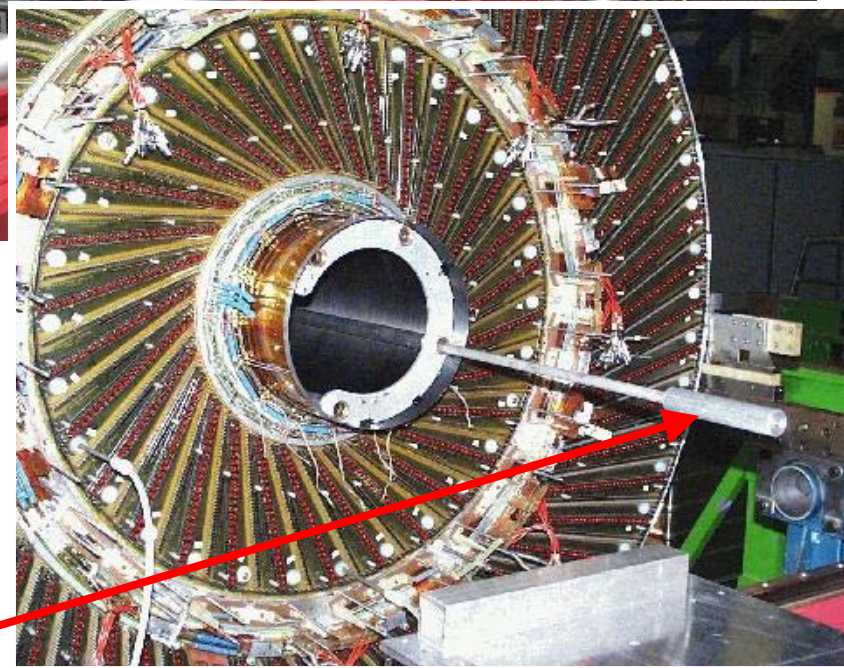
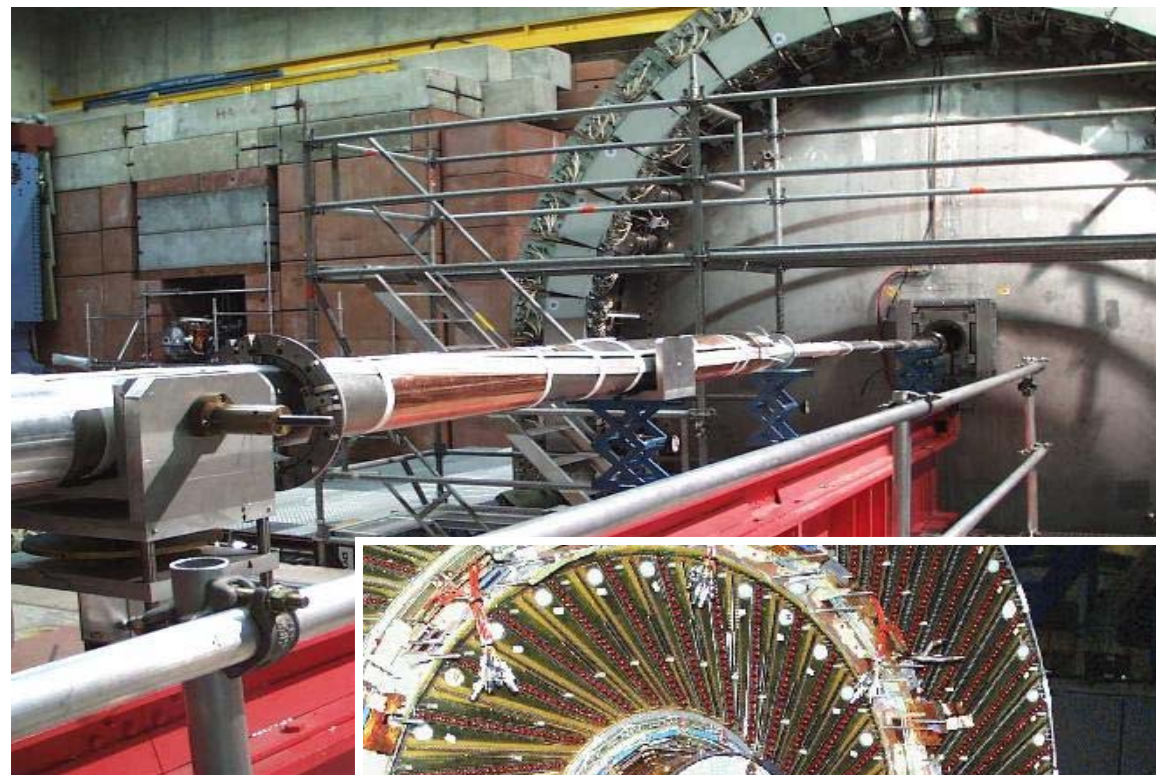
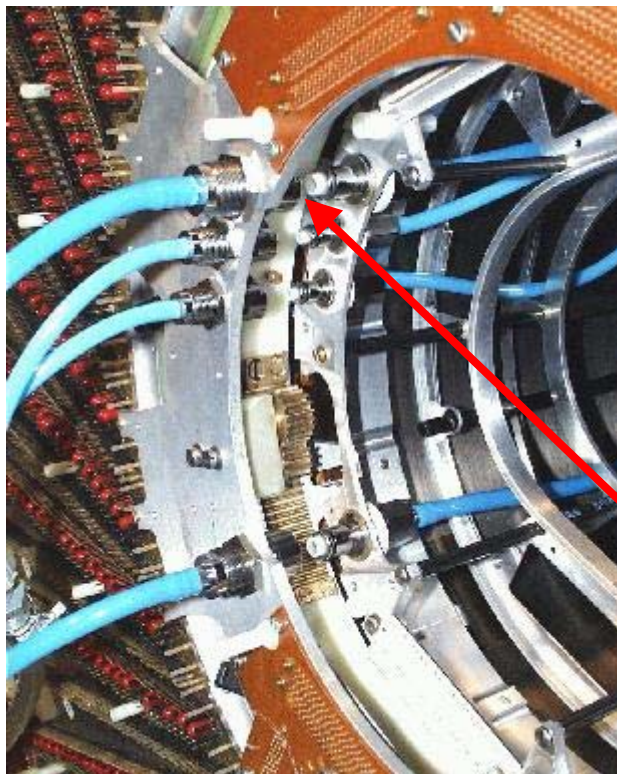
©. H1/DESY-ZEUS





# H1 installation of central components H1 & ZEUS

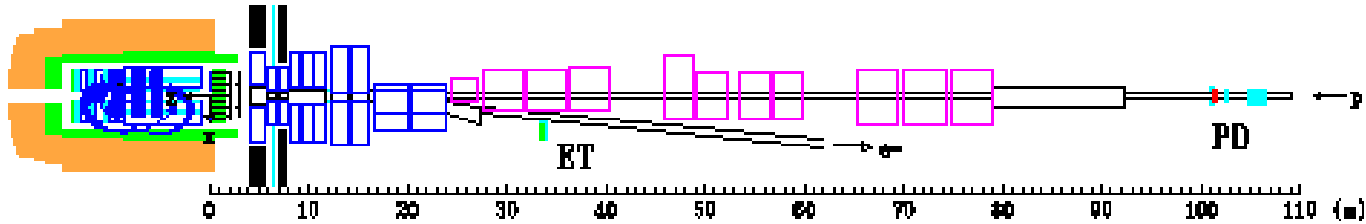
- Very tricky operation ... had to be done blind from one end!!



Connectors had to mate inside!

Remote tool

- H1: crystal cerenkov detectors to detect  $e$  and  $\gamma$  in  $ep \rightarrow ep\gamma$

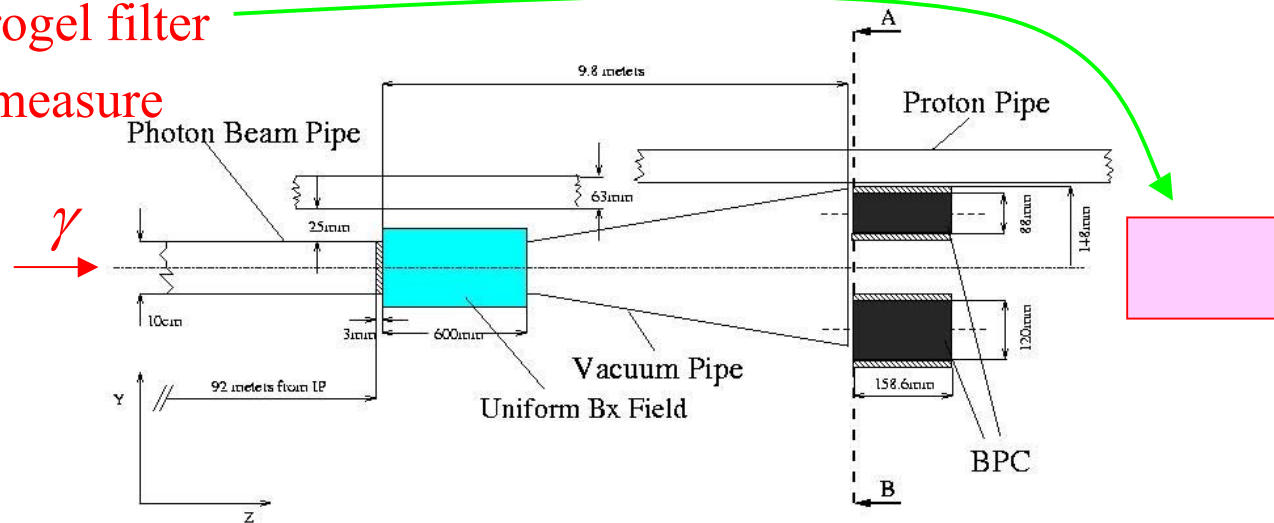


- ZEUS: 2 methods (different systematics) to detect  $\gamma$

- calorimeter + active aerogel filter

- dipole spectrometer to measure  $e^+e^-$  conversions

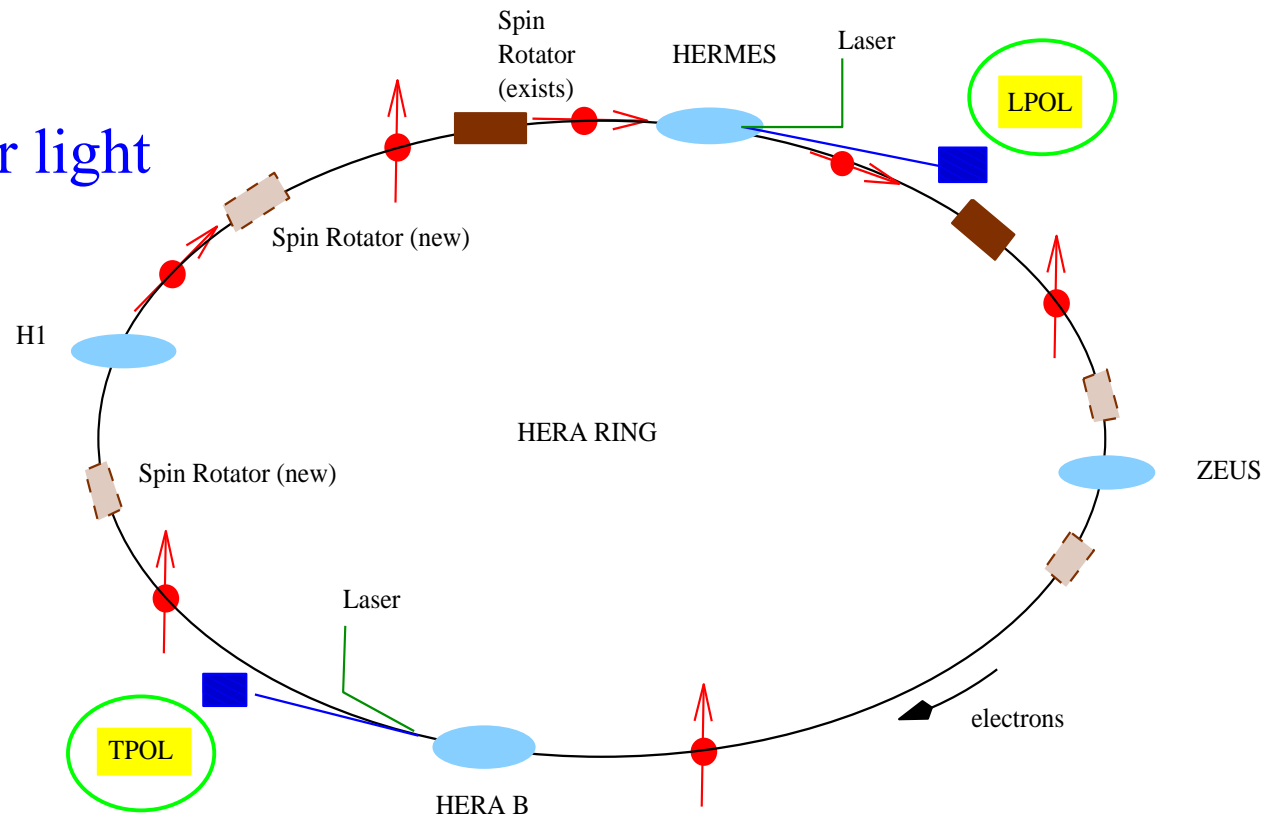
- scattered electron measured in W/fibre calorimeter at 6 m



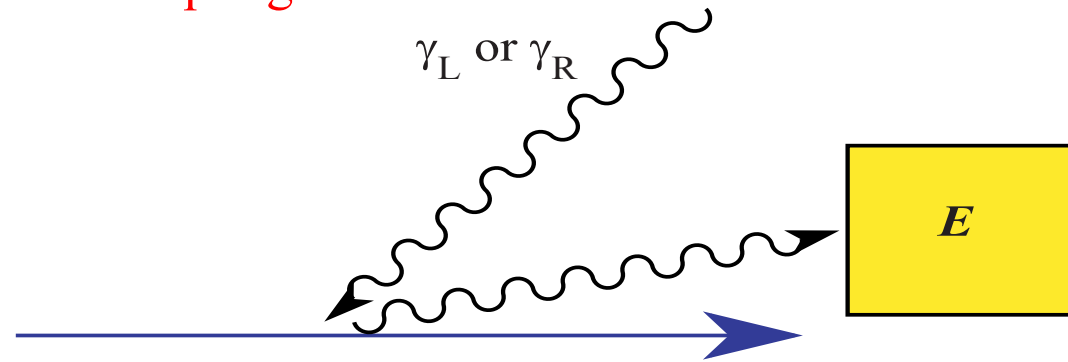
- goal: 1%

- face increased synchrotron background, multiple overlapping  $\gamma$ + physics

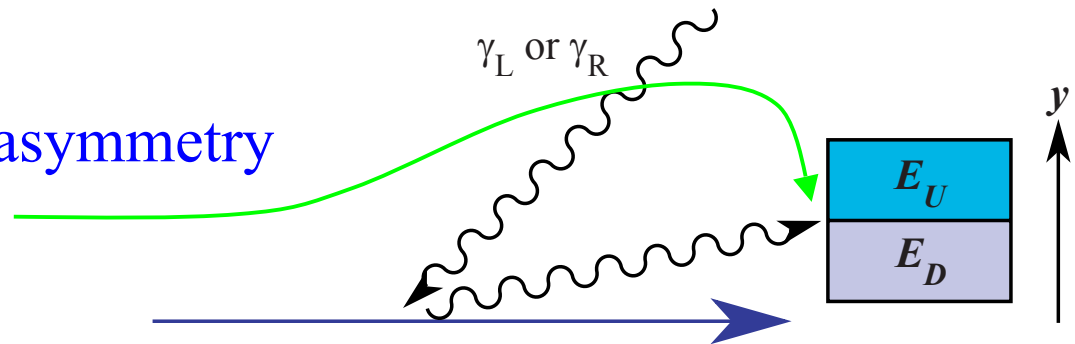
- cross-check with accurate measurement of both transverse (TPO) and longitudinal (LPOL) polarization plus machine lattice simulation
- need short time-scale measurement, ideally bunch-by-bunch
  - challenge in high synchrotron radiation environment
- use back-scattered laser light and precision detectors and DAQ
- goal: 1%
  - was 5% at HERA-I for HERMES



- Laser beam switched between R and L circular polarization
- LPOL: measure  $E$  asymmetry of back-scattered Compton photons
  - new Fabry-Perot cavity + laser, new sampling calorimeter
  - high rate 1  $\gamma$  per bunch
  - calibration on Compton edge



- TPOL: measure position asymmetry
  - pre-radiator + Si detector

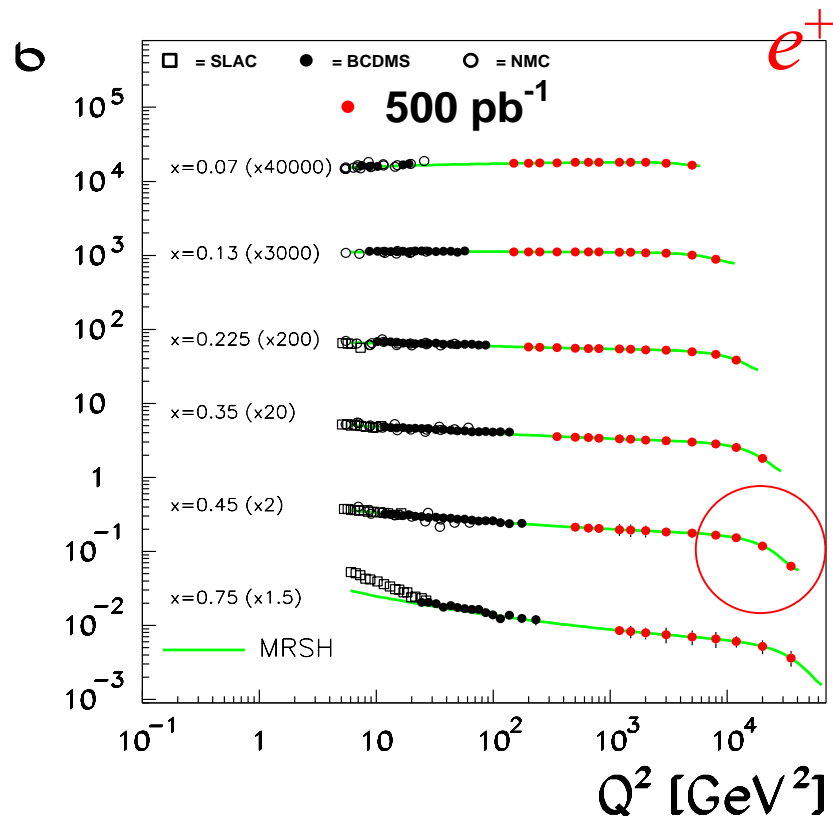
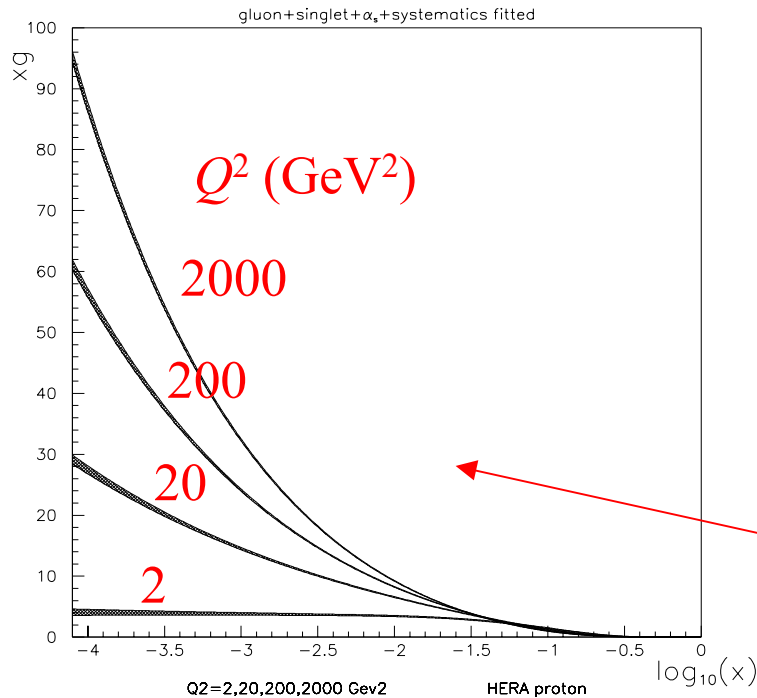


$$P = (\langle y \rangle_L - \langle y \rangle_R) K_\eta$$

- High precision (3%) over unprecedented range:

$$2 \cdot 10^{-5} < x < 0.7$$

$$Q^2 < 5 \cdot 10^4 \text{ GeV}^2$$



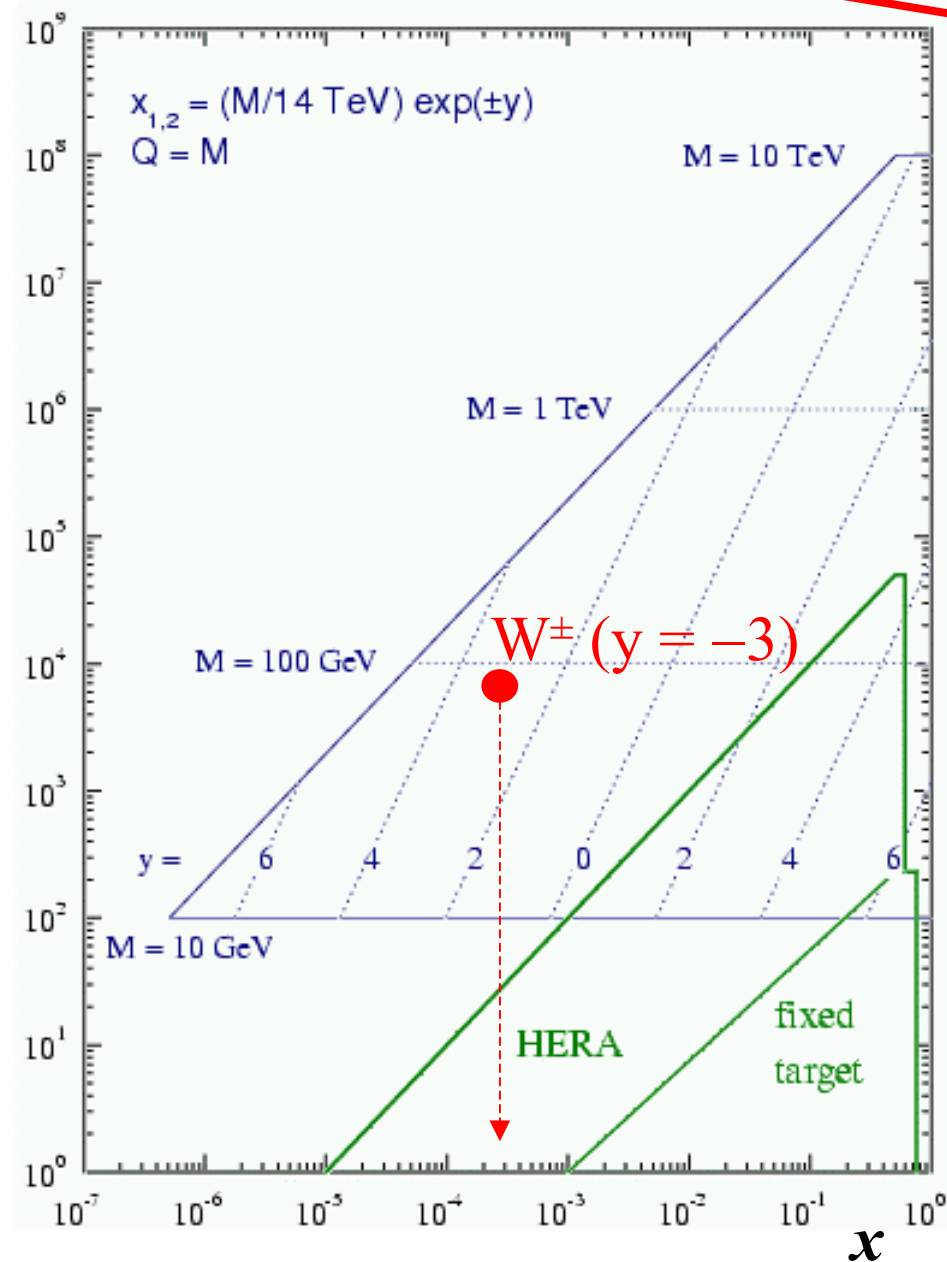
- beyond NLO fit will give:

- gluon to 3% (important for Higgs)

-  $\alpha_s$  to 0.001

## LHC parton kinematics (LO)

- e.g.,  $W$  production at high  $y$ 
  - low  $x = 0.0003$
- can the extrapolation to high  $Q^2$  be done reliably??
  - an area of active theoretical research: NNLO, resummation of  $\ln 1/x$  terms, etc.
  - e.g., for  $F_L$ , LO  $\rightarrow$  NLO  $\rightarrow$  NNLO converges only for  $Q^2 > 5 \text{ GeV}^2$



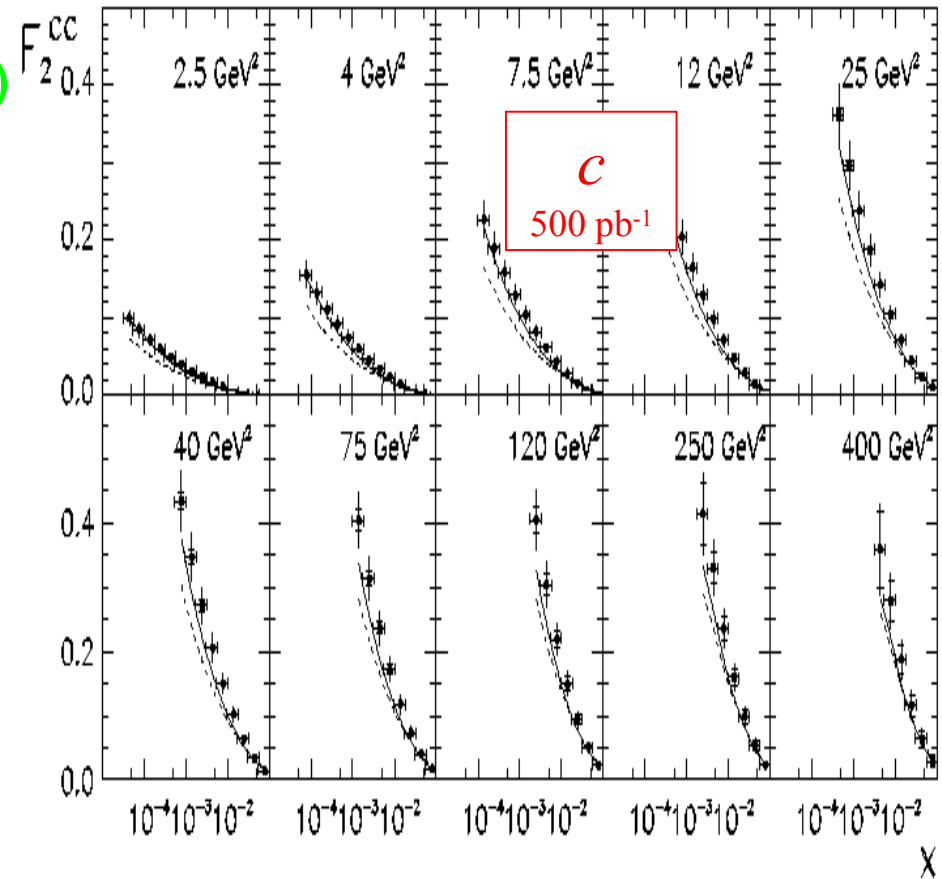
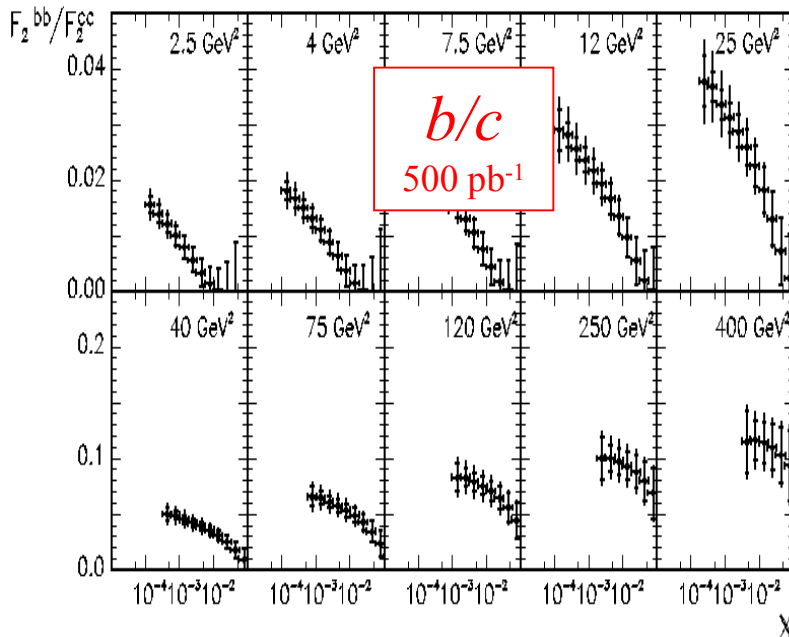
High  $\mathcal{L}$  + short decay tagging  
gives  $c$  and  $b$  ( $> \times 20$  increase)

CC  $e^+$  and  $e^-$  gives

$u, d, s$  (from  $Ws \rightarrow c$ )

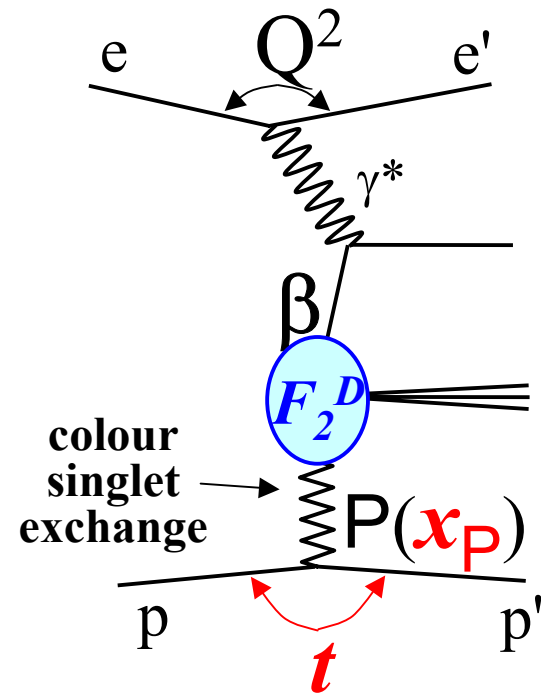
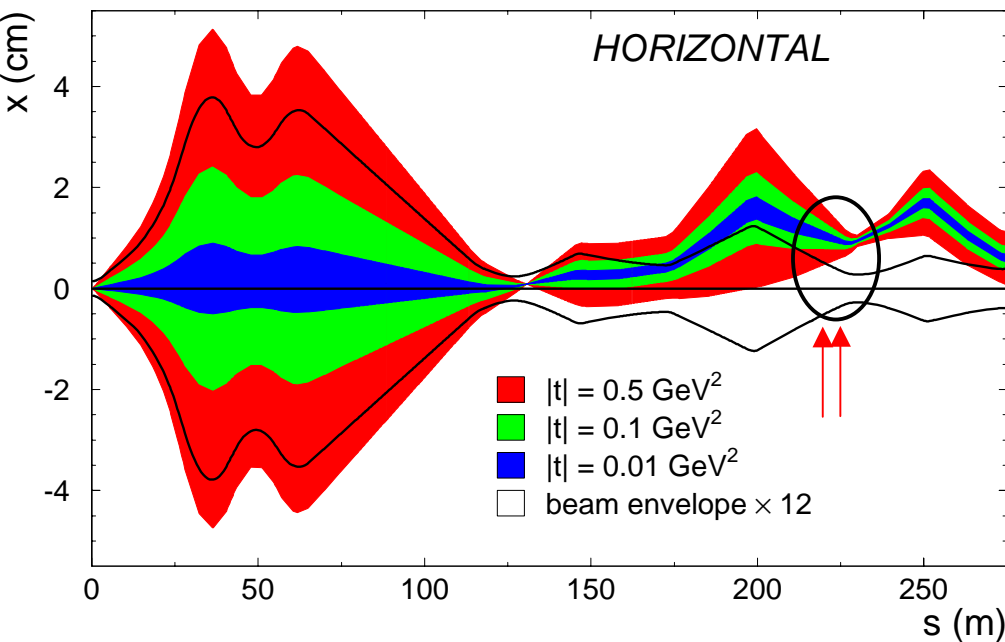
$$\tilde{\sigma}^+ = x \left[ \bar{u} + \bar{c} + (1-y)^2 (d + s) \right]$$

$$\tilde{\sigma}^- = x \left[ u + c + (1-y)^2 (\bar{d} + \bar{s}) \right]$$



$\Rightarrow$  complete survey of  
parton content of the proton!

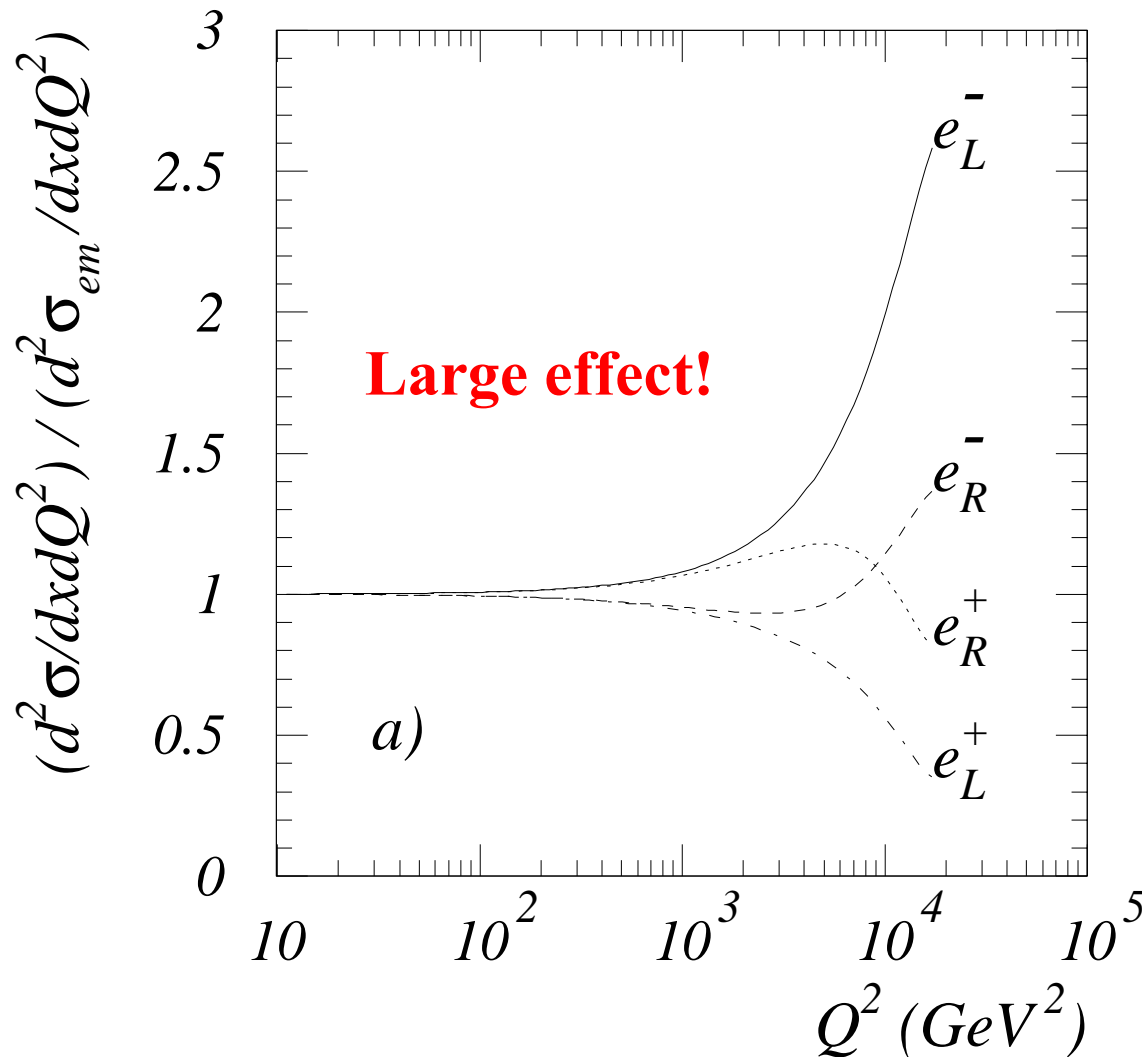
- QCD understanding of colour singlet exchange still intense field of study
- need more data with jets, VM, charm, with tagged leading  $p$



- H1: new spectrometer at 220 m
- measure  $-t < 0.5 \text{ GeV}^2$ , resolution  $\sim 0.2 \text{ GeV}^2$

at  $Q^2 = 10,000 \text{ GeV}^2$ ,  $x = 0.2$ ,

$$\frac{\sigma(e_L^-)}{\sigma(e_R^-)} \approx 1.7 \pm 0.06(\text{Stat.})$$

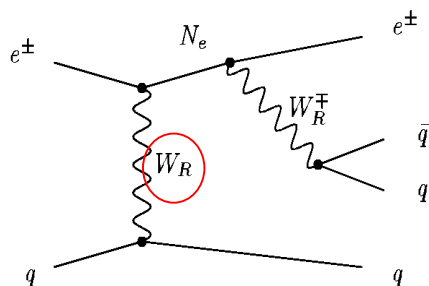


$$\sigma_{CC}^{e^\pm p} \propto (1 \pm P)$$

- CC interactions with or  $e^+_L$  or  $e^-_R$

$\Rightarrow W_R$  sensitive to  $\sim 500-700$  GeV

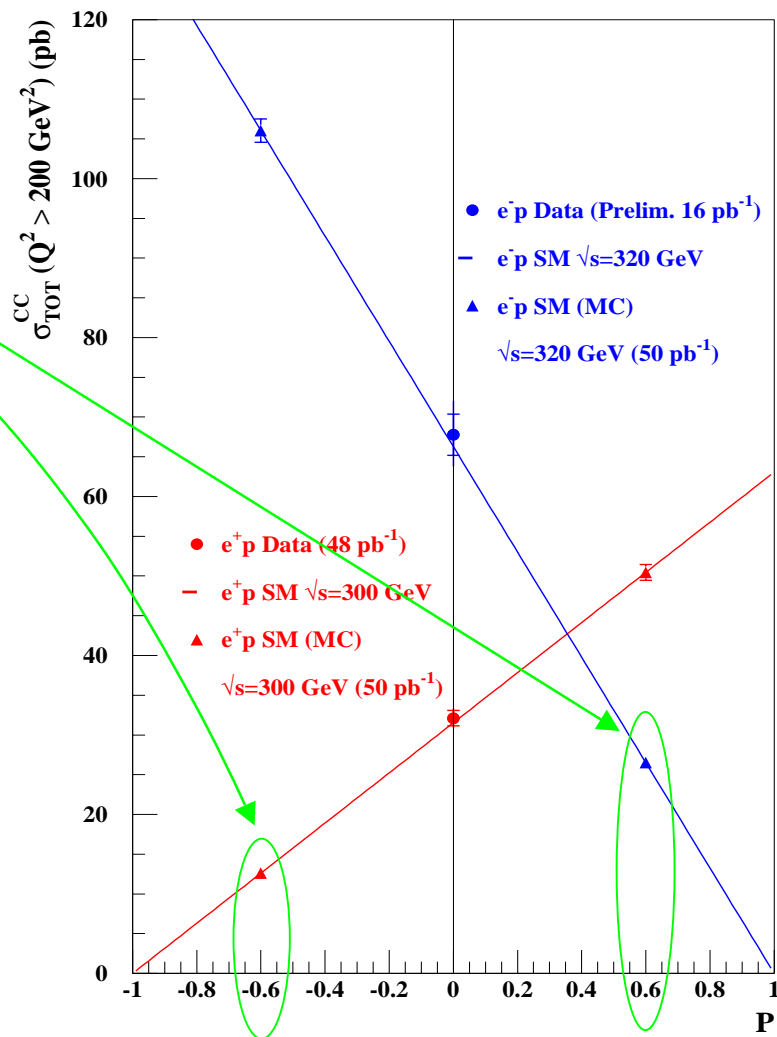
sensitive to  $M_N \sim 150$  GeV



- in general, vary polarization to reduce SM backgrounds

$\Rightarrow$  enhance S/B for new physics with different couplings

### ZEUS CC Cross Sections

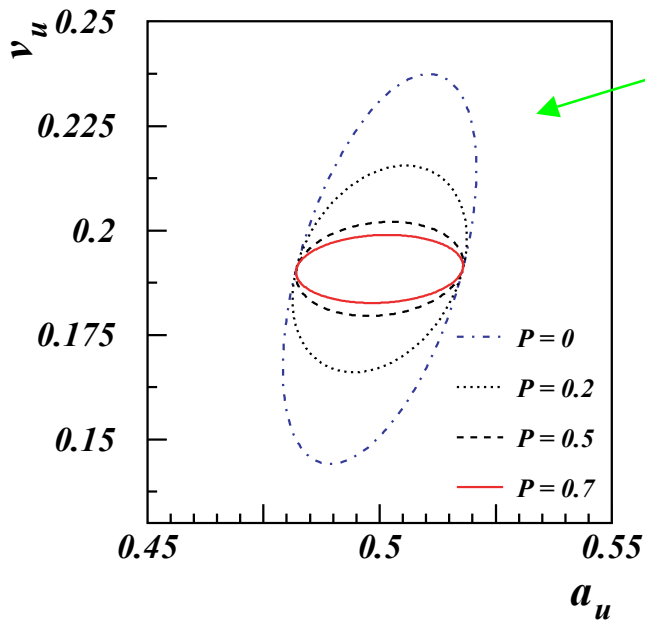
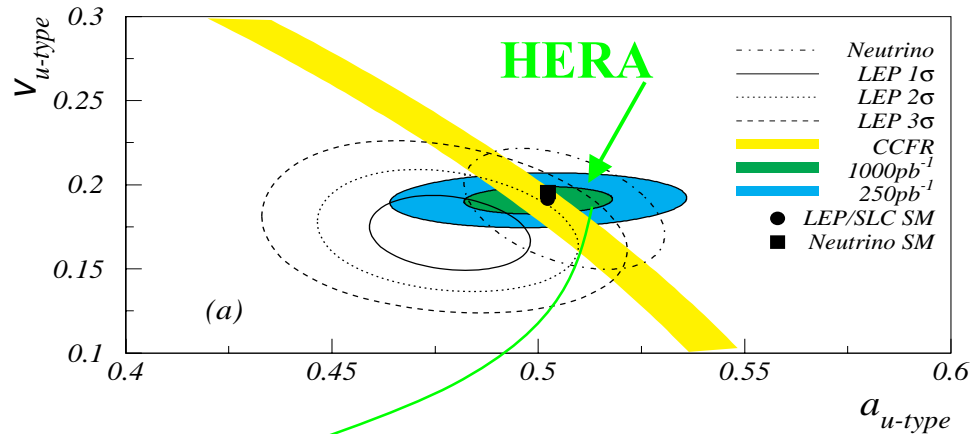


Measure:

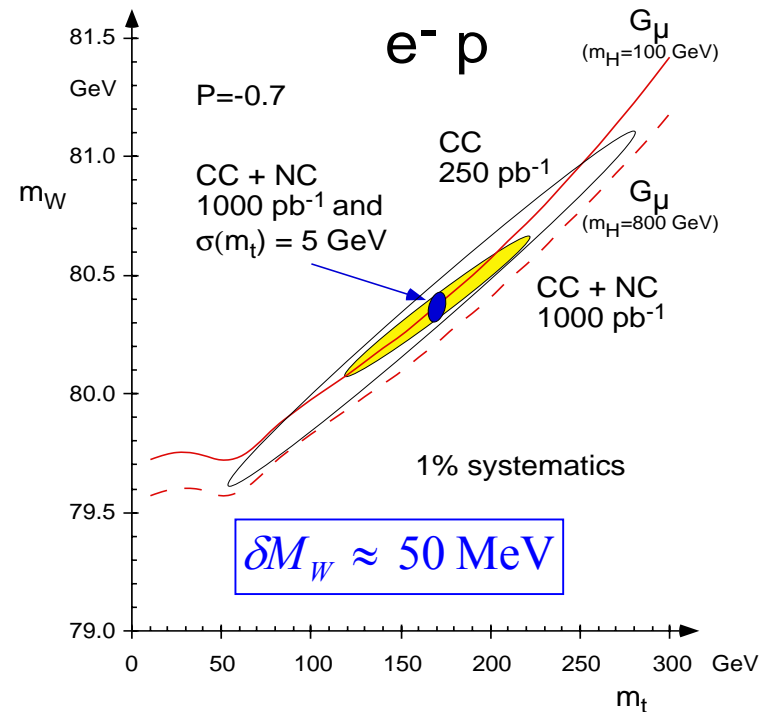
$v_u$  to  $\sim 13\%$

$a_u$  to  $\sim 7\%$

(cf. LEP c and b)



Sensitivity to beam polarization



- Rp violating SUSY
- lepton flavour violation
- excited fermions
- contact interactions

In many regions of “search phase space” HERA already sets the best limits (see [Corradi](#)). Large luminosity increase will further enhance the sensitivity.

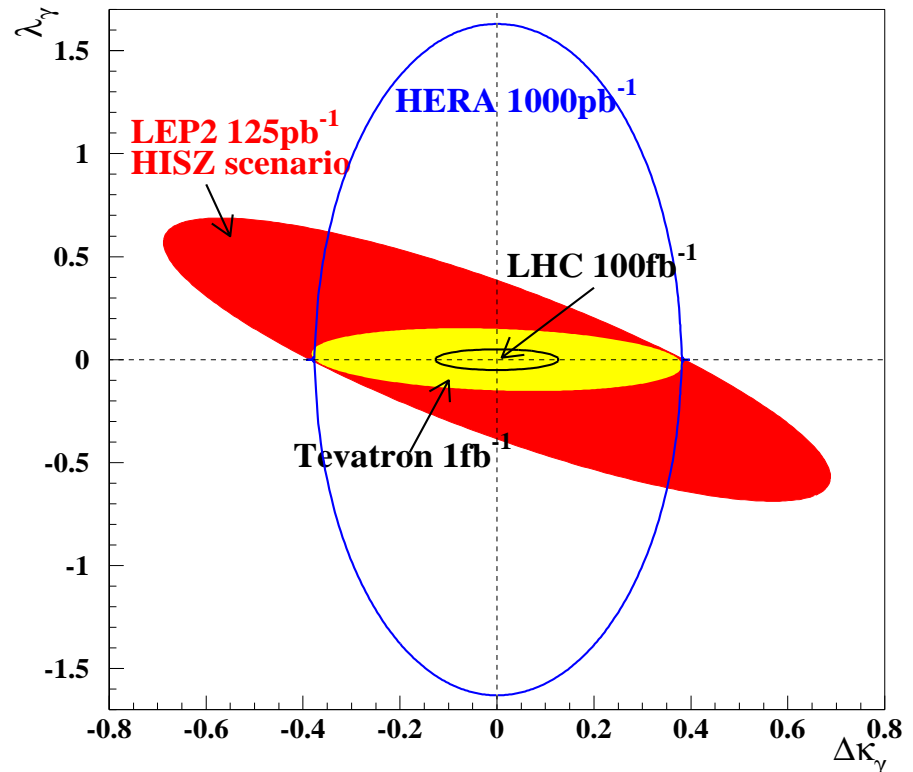
e-polarization: improve S/B

Sensitivity to  $WW\gamma$  vertex:

anomalous couplings

$\Delta\kappa_\gamma$ ,  $\lambda_\gamma$  parameterize

deviation from SM



- No time for a summary!
- HERA-II about to begin:
  - first test lumi run in December
  - problems with
    - proton ring aperture now fixed
    - synch. radiation way too high new collimators being built  
install early March
- first lumi run begins Mar 17
  - experiments are ready
  - start with  $e^+$ , switch to  $e^-$  in June
- we look forward to exciting physics with high luminosity