

# High $Q^2$ cross sections, EW and BSM at HERA

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**DESY**

on behalf of  and  collaborations



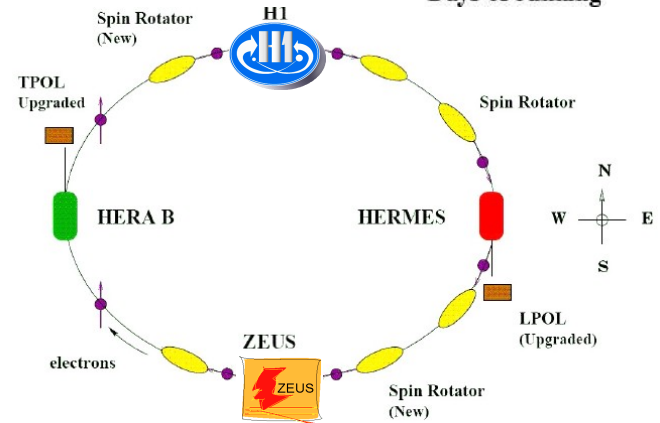
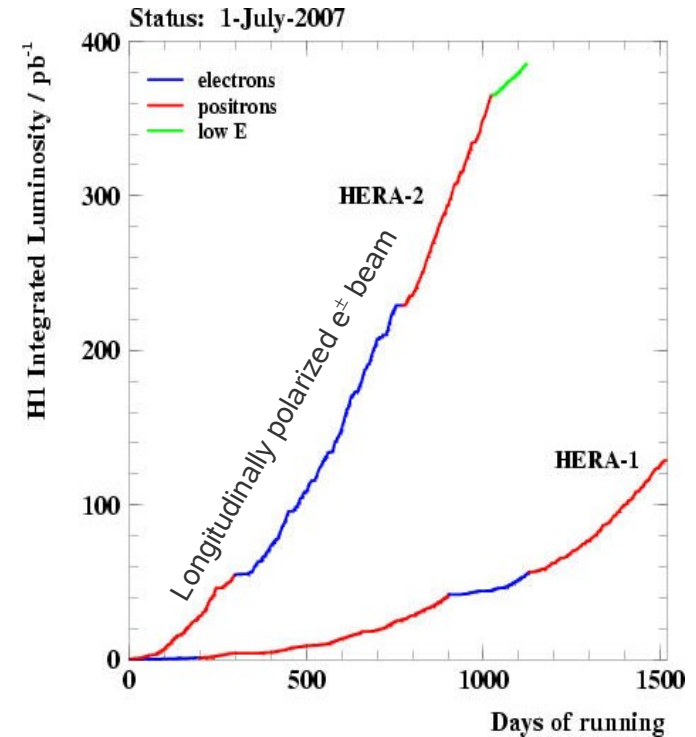
- DIS at HERA
- High  $Q^2$  cross sections and electroweak physics
- Physics beyond Standard Model
- Summary

# HERA

- $e^\pm(27.5 \text{ GeV})$ ,  $p(820/920 \text{ GeV})$ ,  
 $\sqrt{s} = 300/318 \text{ GeV}$
- Two large multipurpose detectors:  
**H1** and **ZEUS** (asymmetric design)
- 1994-2000: HERA I data  
2003-07 HERA II data with  
longitudinal  $e^\pm$  polarisation:

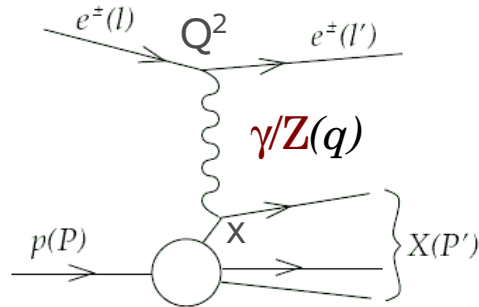
$$P_e = \frac{N_R - N_L}{N_R + N_L} \sim 30\text{-}40\% \text{ at HERA}$$

- $\sim 1 \text{ fb}^{-1}$  (H1+ZEUS) of luminosity  
delivered by HERA



# Neutral current DIS cross section

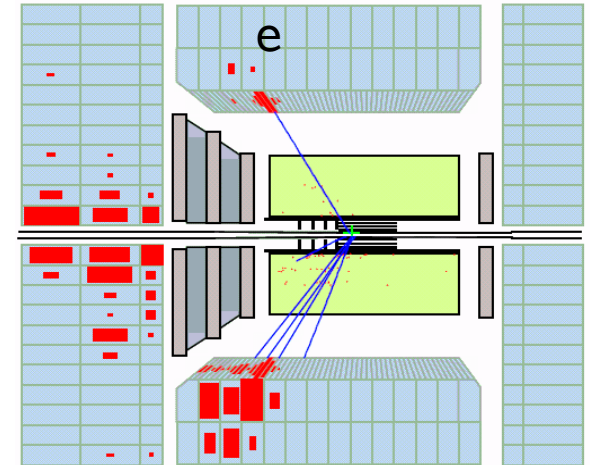
neutral current DIS cross section:



$Q^2$  - virtuality of exchange boson

$x$  - Bjorken scaling variable

$y$  - inelasticity



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

dominant contribution

important at high  $Q^2$

sizable at high  $y$

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

$$k = \frac{1}{4 \sin^2 \theta_w \cos^2 \theta_w} \frac{Q^2}{Q^2 + M_Z^2}$$

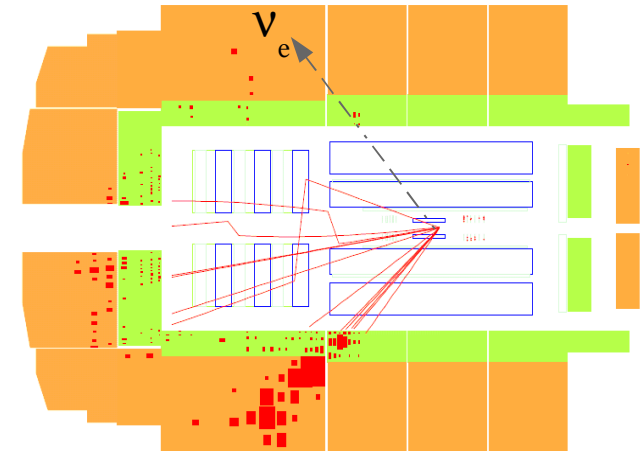
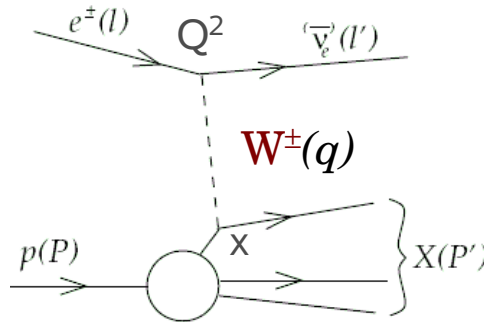
→ polarisation dependence due to  $\gamma Z$  interference and  $Z$  terms:

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

$$x \tilde{F}_3^\pm = k(-a_e \mp P_e v_e) x F_3^{\gamma Z} + k^2(2v_e a_e \pm P_e(v_e^2 + a_e^2)) x F_3^Z$$

# Charged current DIS cross section

charged current DIS cross section:



$$\frac{d^2 \sigma_{CC}^{e^{\pm}p}}{dx dQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \tilde{\sigma}_{CC}^{e^{\pm}p}$$

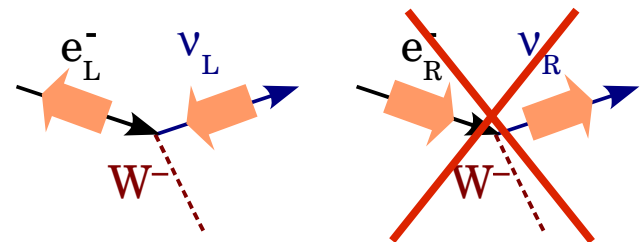
→ linear polarisation dependence

$e^+/e^-$  sensitive to different quark densities:

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

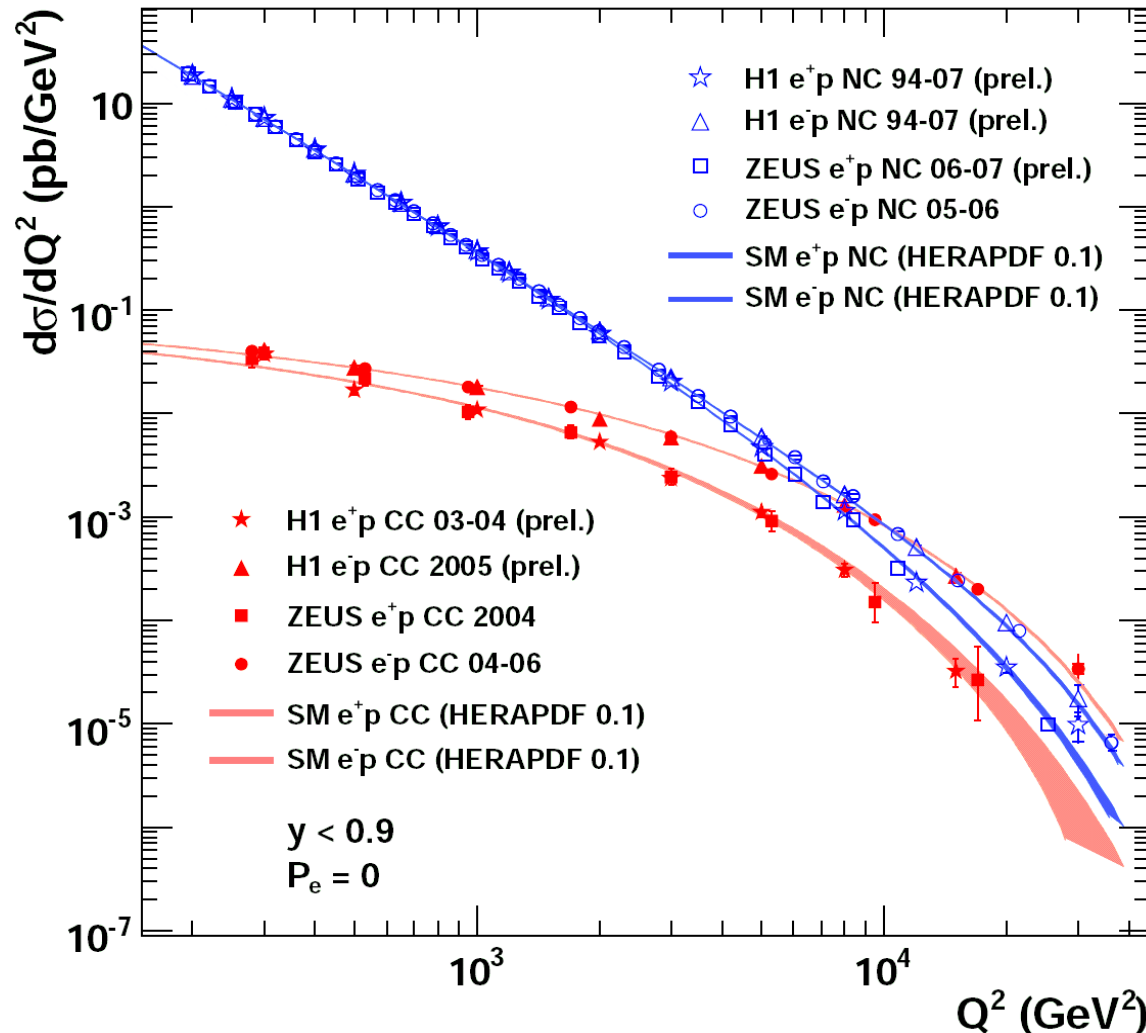
$$\tilde{\sigma}_{CC}^{e^-p} = x[\textcolor{blue}{u} + c] + (1-y)^2 x[\bar{d} + \bar{s}]$$

In SM weak interaction acts only on left-handed particles (right-handed anti-particles)



# Charged and neutral currents at HERA

HERA I & II



neutral ( $\gamma/Z$ )  
charged ( $W^\pm$ )  
currents cross sections  
at  $Q^2 \gtrsim M_{Z/W}^2$  scale  
get similar:  
EW unification

good agreement with  
SM (HERAPDF 0.1)

# Neutral currents at HERA

- the charge dependent polarisation asymmetries in neutral currents
  - direct measure of EW effects

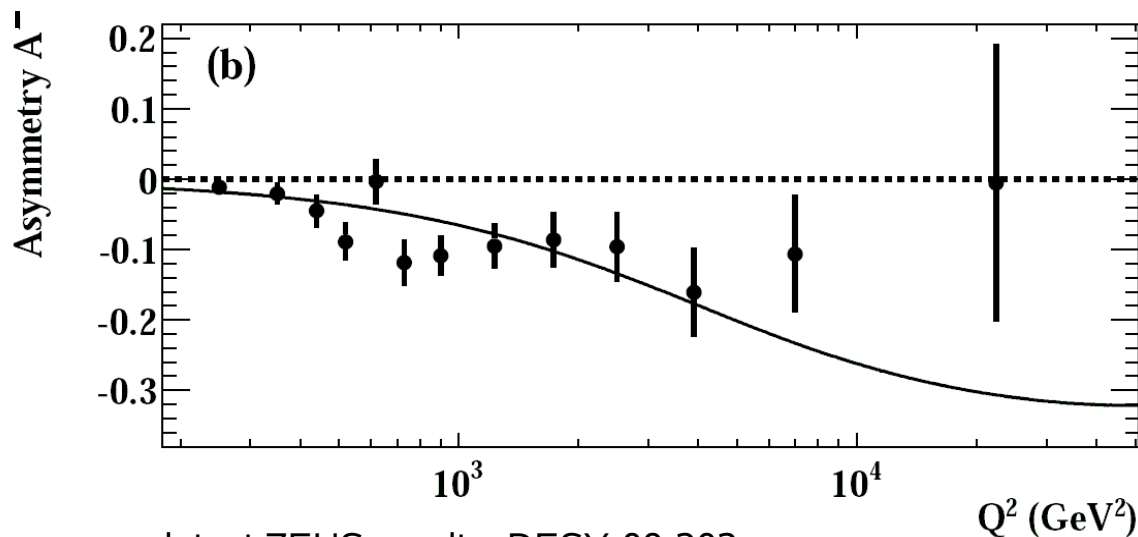
neglecting Z term generalised structure function  $F_2$  is expressed:

$$\tilde{F}_2^\pm \approx F_2 + k(-v_e \mp \textcolor{red}{P_e} a_e) F_2^{\gamma Z}$$

at LO:  $F_2^{\gamma Z} = x \sum 2e_q \textcolor{blue}{v}_q (q + \bar{q})$

**polarisation asymmetry A** is proportional to a  $v_e v_q$  combination:

$$A^\pm = \frac{2}{P_R - P_L} \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)} \simeq \mp k \textcolor{blue}{a}_e \frac{F_2^{\gamma Z}}{F_2}$$



latest ZEUS results: DESY-08-202

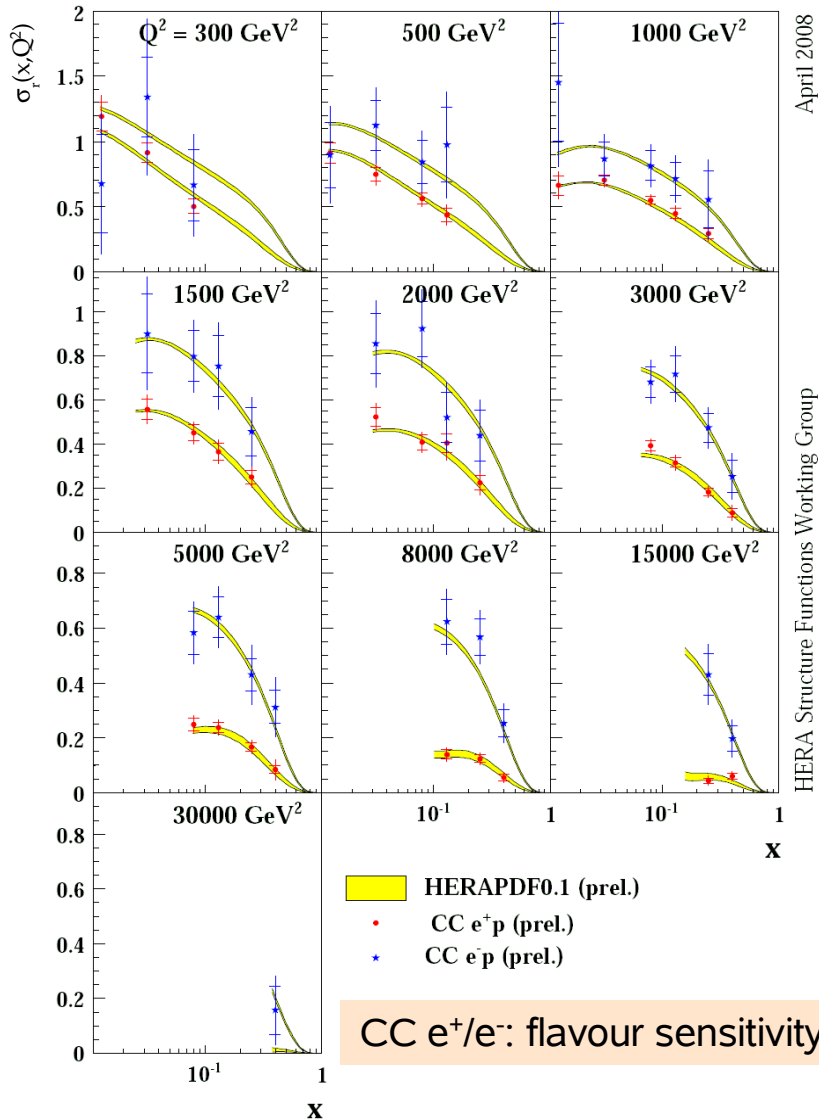
and directly measures the parity violation

→ to be updated with all HERA II data



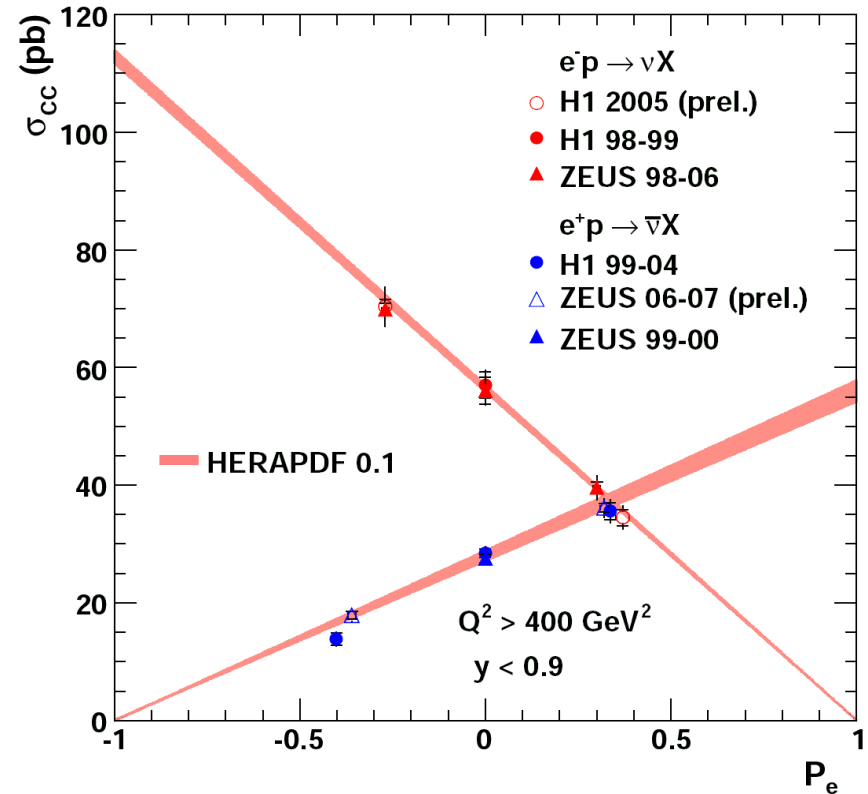
# Charged currents at HERA

H1 and ZEUS Combined PDF Fit



SM weak interactions: only left-handed particles interact (right-handed currents forbidden)

HERA Charged Current  $e^\pm p$  Scattering

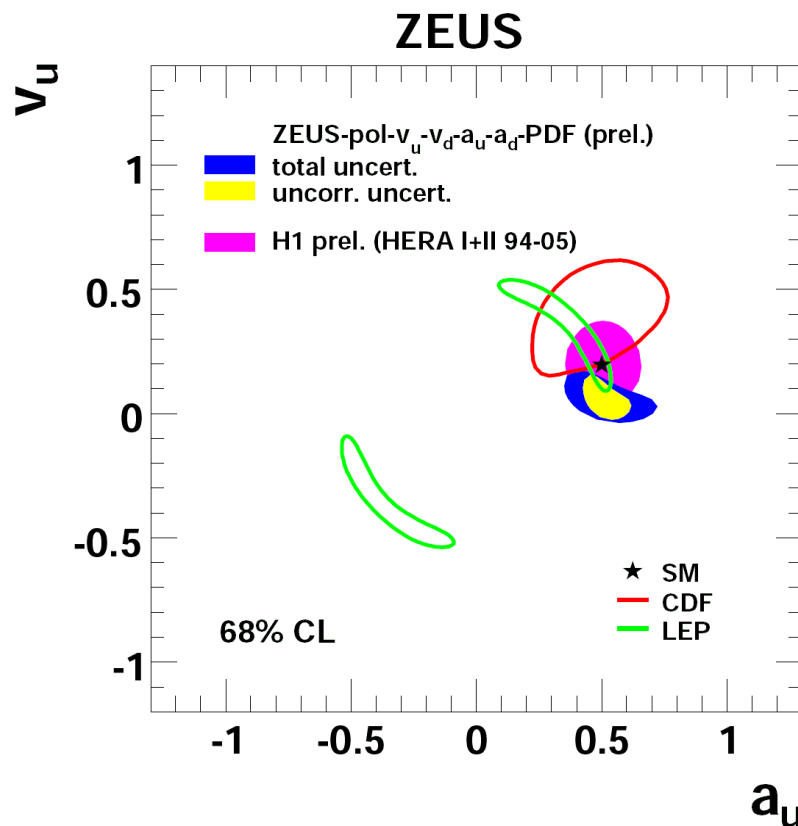


HERA results are consistent with SM

# Combined QCD & EW fit

- weak couplings  $a_u, a_d, v_u, v_d$  of light quarks to Z boson can be extracted from DIS data with combined QCD-EW fit
  - $\gamma Z$  interference and Z exchange in neutral currents
  - charged currents for u-, d-quark separation
- preliminary results with part of polarised HERA II data bring additional sensitivity, especially on  $v_q$

HERA results are competitive to LEP and Tevatron





# Searches in inclusive DIS

Model-based searches:

- quark radius
- leptoquarks
- squarks in R-parity violating SUSY
- single top
- excited fermions
- magnetic monopoles

## Search for new physics in rare excl. processes

Model-independent searches:

- isolated leptons with large missing  $P_T$
- multi leptons at high  $P_T$
- general search

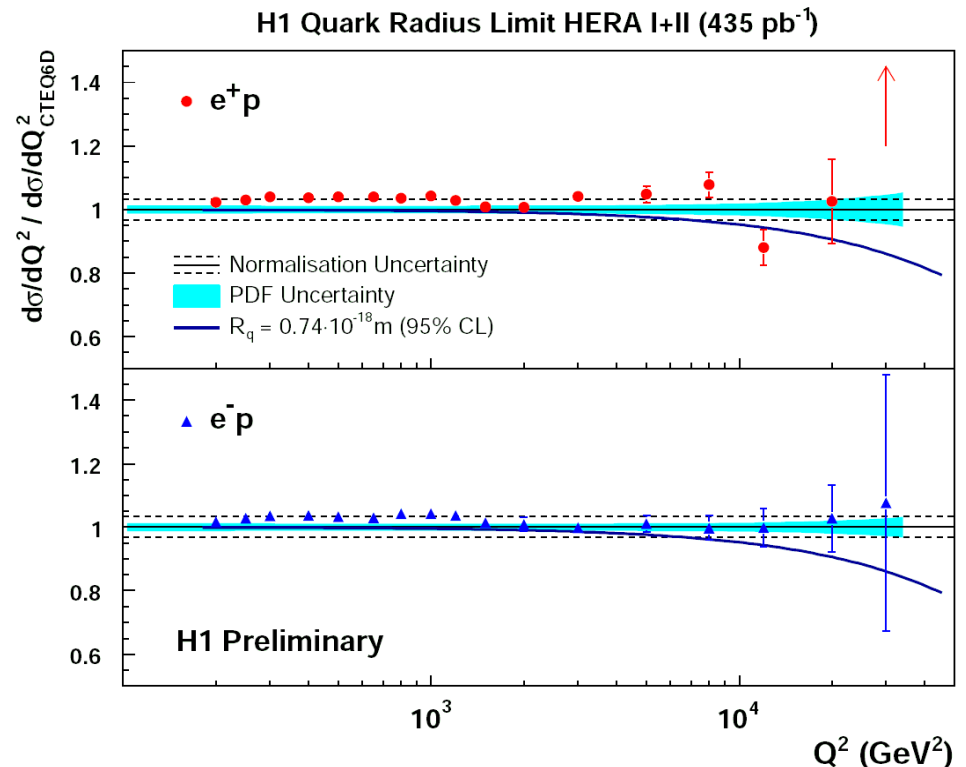
# Quark form factor

- Possible new interactions between e and q can modify DIS cross section at high  $Q^2$  via virtual effects
- **Fermion substructure** can be detected measuring the spatial distribution of charge radius:

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

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

- R is the root-mean-square radius of the electroweak charge of the e/q
- reduces SM cross section at high momentum transfer
- assuming:  
 $f_e = 1$ ,  $R_q$  can be constrained  
 $f_e = f_q$ , common limit on fermion sizes



**ZEUS** (combined 94-06):

$$R_q < 0.62 \cdot 10^{-18} \text{ m}$$

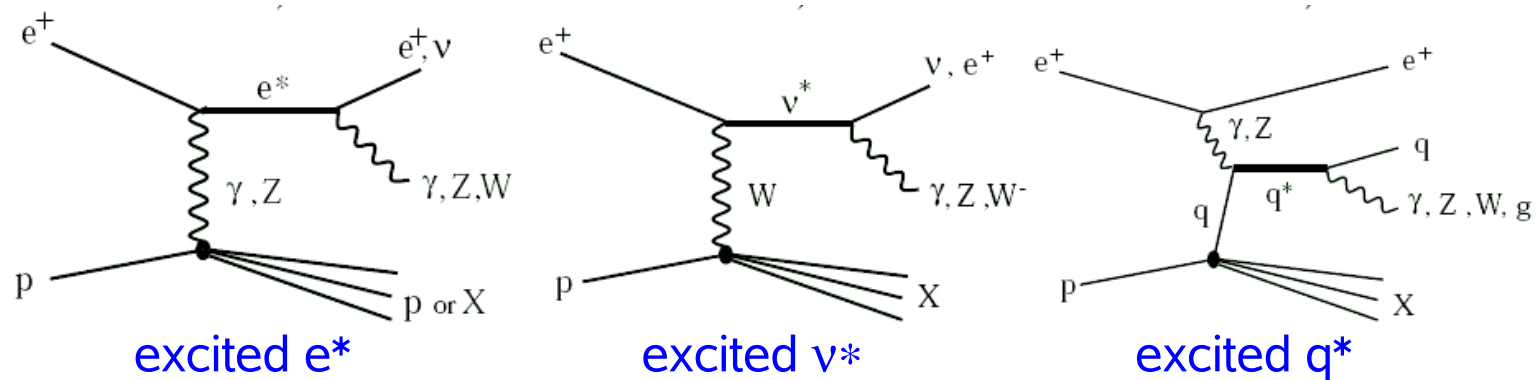
**H1** (94-07, all HERA data):

$$R_q < 0.74 \cdot 10^{-18} \text{ m}$$

# Excited states of first generation fermions

- Models with composite quarks and leptons can explain the **three-family structure and mass hierarchy of fermions**

- these models predict existence of excited states of leptons and quarks



$$\mathcal{L}_{GM} = \frac{1}{2} \bar{F}_R^* \sigma^{\mu\nu} \left[ g f \frac{\tau^a}{2} W_{\mu\nu}^a + g' f' \frac{Y}{2} B_{\mu\nu} + g_s f_s \frac{\lambda^a}{2} G_{\mu\nu}^a \right] F_L + h.c.$$

compositeness scale

couplings associated to SU(2)xU(1)xSU(3)

$e^* \rightarrow e\gamma, e^* \rightarrow eZ, e^* \rightarrow \nu W$   
 $\nu^* \rightarrow \nu\gamma, \nu^* \rightarrow \nu Z, \nu^* \rightarrow eW$   
 $q^* \rightarrow q\gamma, q^* \rightarrow qZ, q^* \rightarrow qW$

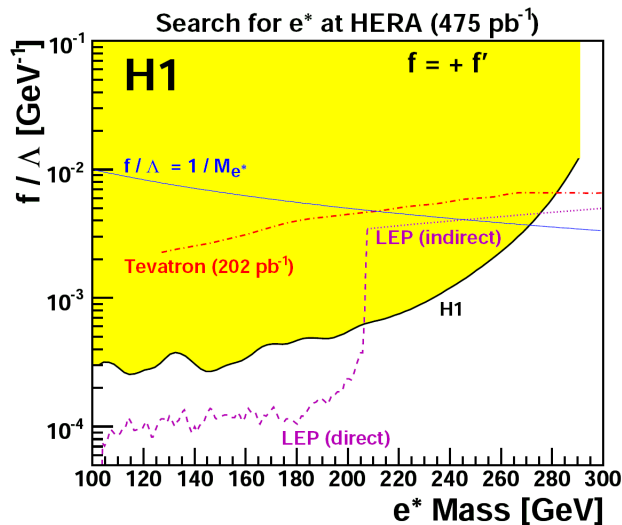
decay channels with hadronic and leptonic decays considered

→ H1: full HERA  $e^\pm p$  data ( $\sim 0.5 \text{ fb}^{-1}$ ) used for searches

# Excited states of first generation fermions

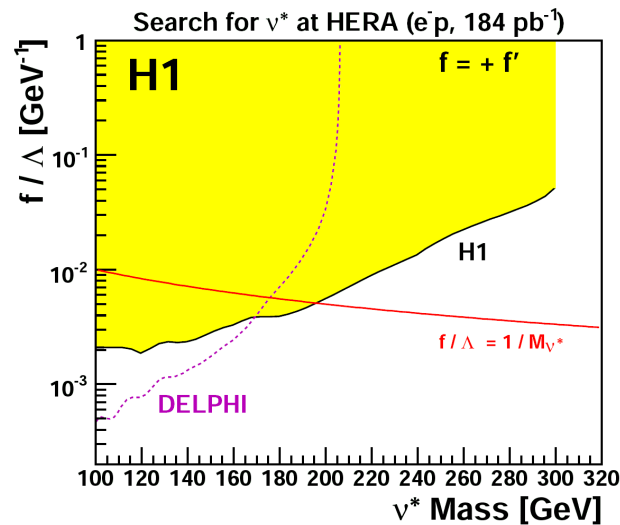
- no indication of signal found, mass exclusion limits on  $f/\Lambda$  derived
- shown for  $f=+f'$  ( $f=-f'$  also derived for  $\nu^*$ )

excited  $e^*$



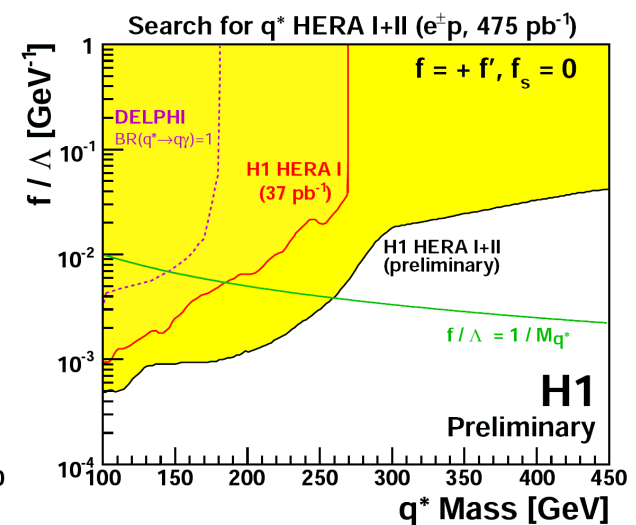
for  $f=+f'$  and  $f/\Lambda = 1/M_{e^*}$   
 $M_{e^*} < 272$  GeV excluded

excited  $\nu^*$



for  $f=+f'$  and  $f/\Lambda = 1/M_{\nu^*}$   
 $M_{\nu^*} < 196$  GeV excluded

excited  $q^*$

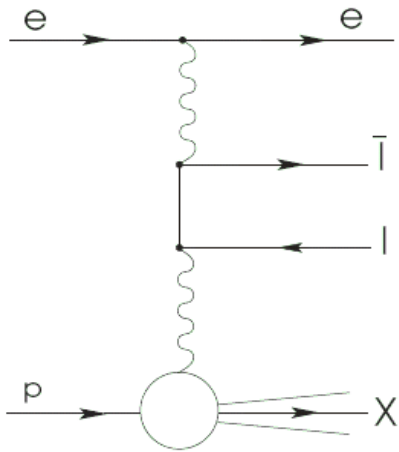


for  $f=+f', f_s = 0, f/\Lambda = 1/M_{q^*}$   
 $M_{q^*} < 259$  GeV excluded

→  $e^*, \nu^*$  results are complementary to LEP and Tevatron,  
 $q^*$  results has better sensibility (at low  $M_{q^*}$ )

# Events with multi leptons and high $P_T$

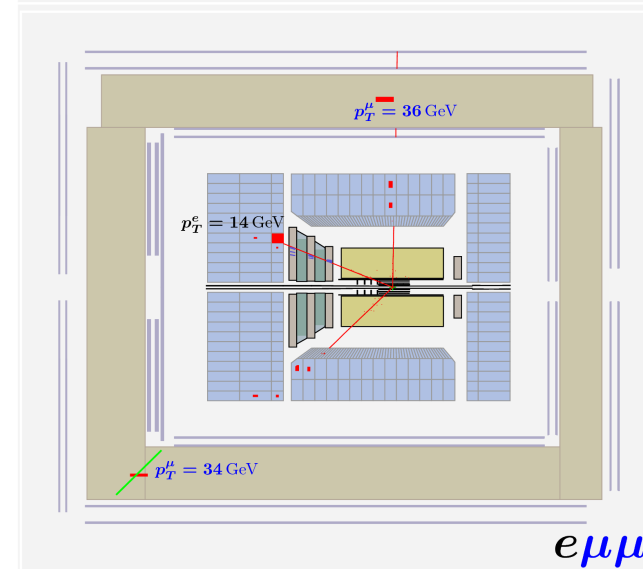
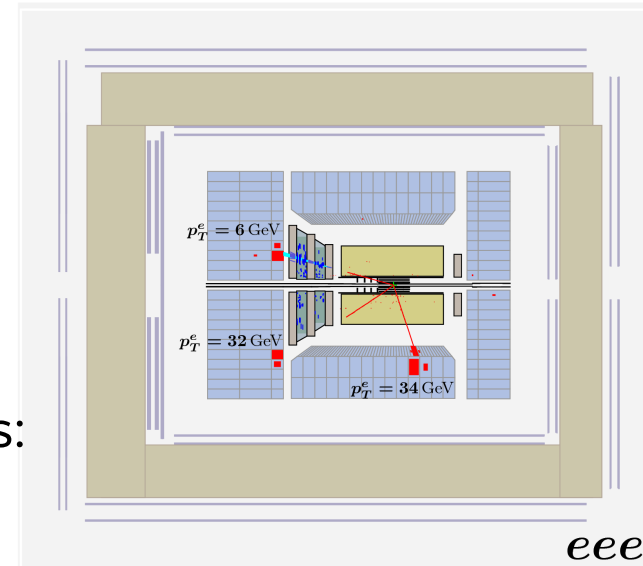
- in Standard Model events with multi leptons are produced in photon-photon interactions ( $\gamma\gamma \rightarrow l^+l^-$ )
  - at large invariant masses deviations from SM may indicate new physics



- considered final state topologies:  $ee, eee, e\mu, \mu\mu, e\mu\mu$

- full HERA data ( $\sim 1 \text{ fb}^{-1}$ ) considered by H1 and ZEUS

- the combination of H1 and ZEUS multi-electron analyses is ongoing (next slide)



# Events with multi leptons and high $P_T$

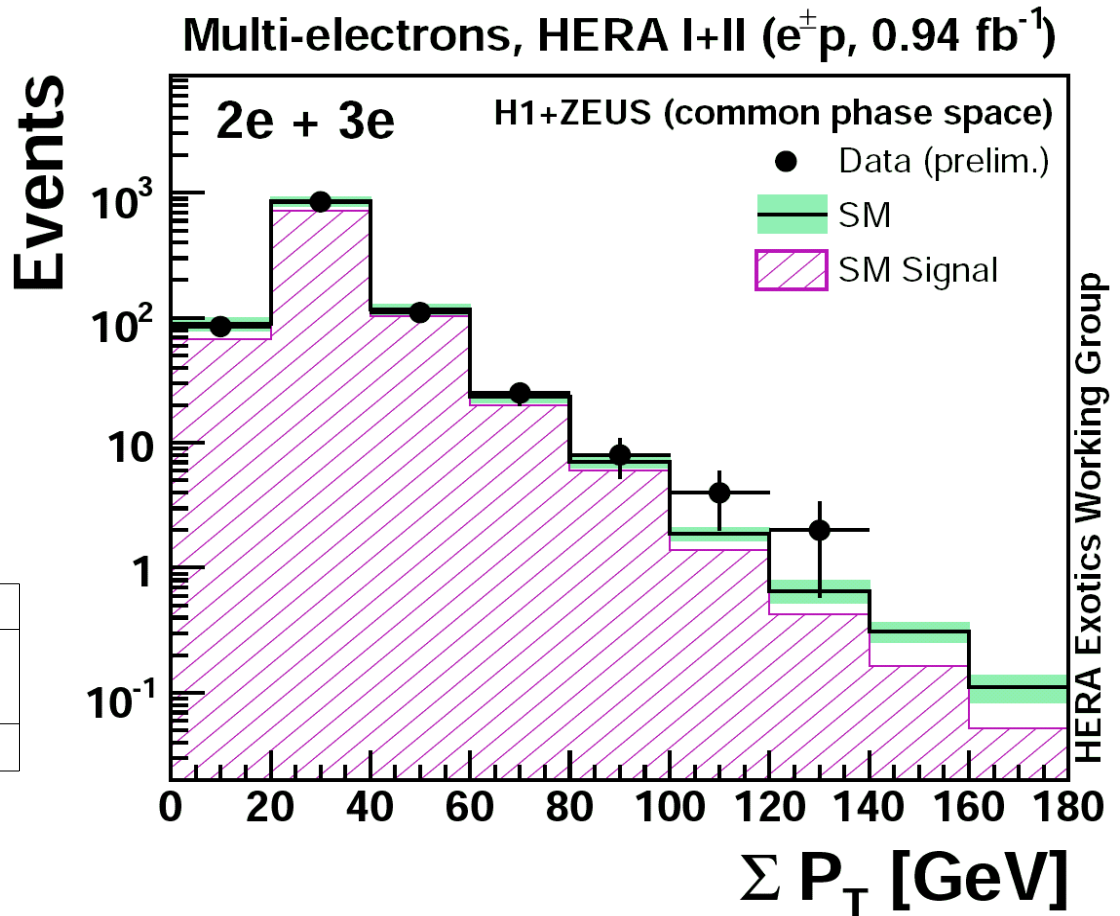
→ H1 and ZEUS combined results in the common phase space ( $\sim 0.94 \text{ fb}^{-1}$ )  
sensitivity to new physics – 'hardness' scale ( $\Sigma P_T$ )

in agreement with  
SM expectations

for  $\Sigma P_T > 100 \text{ GeV}$ :

	# Data	# SM
$e^+p \ 0.56 \text{ fb}^{-1}$	5	$1.82 \pm 0.21$
$e^-p \ 0.38 \text{ fb}^{-1}$	1	$1.19 \pm 0.14$
$e^\pm p \ 0.94 \text{ fb}^{-1}$	6	$3.00 \pm 0.34$

more events observed in  $e^+p$





# General Search

→ Model independent search for deviations from Standard Model predictions

→ full HERA  $e^\pm p$  data ( $\sim 0.5 \text{ fb}^{-1}$ ): final result by H1

27 different final states

final state configurations considered

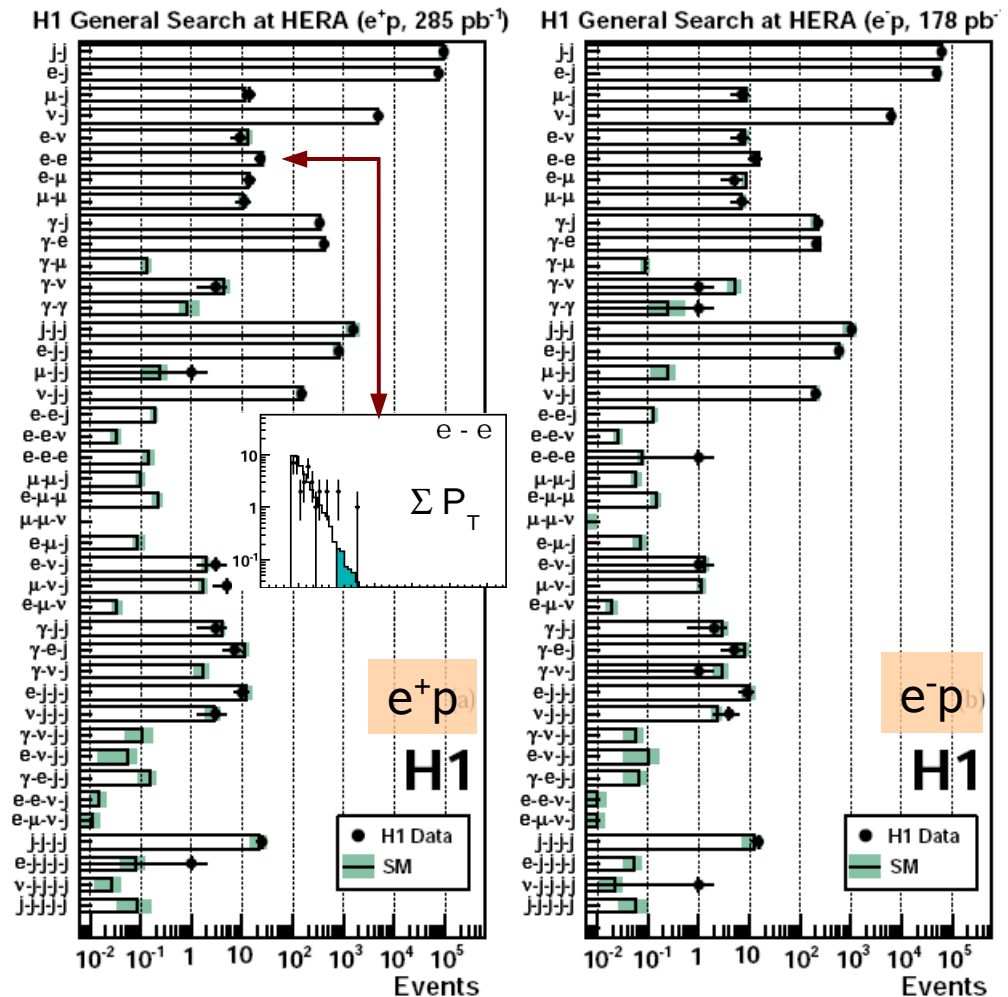
$e, \mu, \text{jets (j)}, \gamma, \nu$

– at least 2 particles with  $P_T > 20 \text{ GeV}$

→ deviations searched in  $\Sigma P_T, M_{\text{all}}$   
with dedicated algorithm

good agreement with SM

high  $P_T$  phenomena well  
understood at HERA



# Summary

→ a result of successful HERA operation

~1 fb<sup>-1</sup> of collected data by H1 and ZEUS experiments together

shown latest results of:

→ high precision measurements:

high Q<sup>2</sup> NC/CC cross sections, QCD+EW fits

→ physics beyond SM:

- quark charge radius, excited fermions, multi-leptons at high P<sub>T</sub>  
and general search

- no large deviations from SM observed

→ not all HERA results covered in this presentation

→ combinations of H1 and ZEUS results are ongoing

# Backup slides

# Common QCD fit on HERA combined data

- HERA data alone can be used for PDF fit **HERAPDF 0.1**

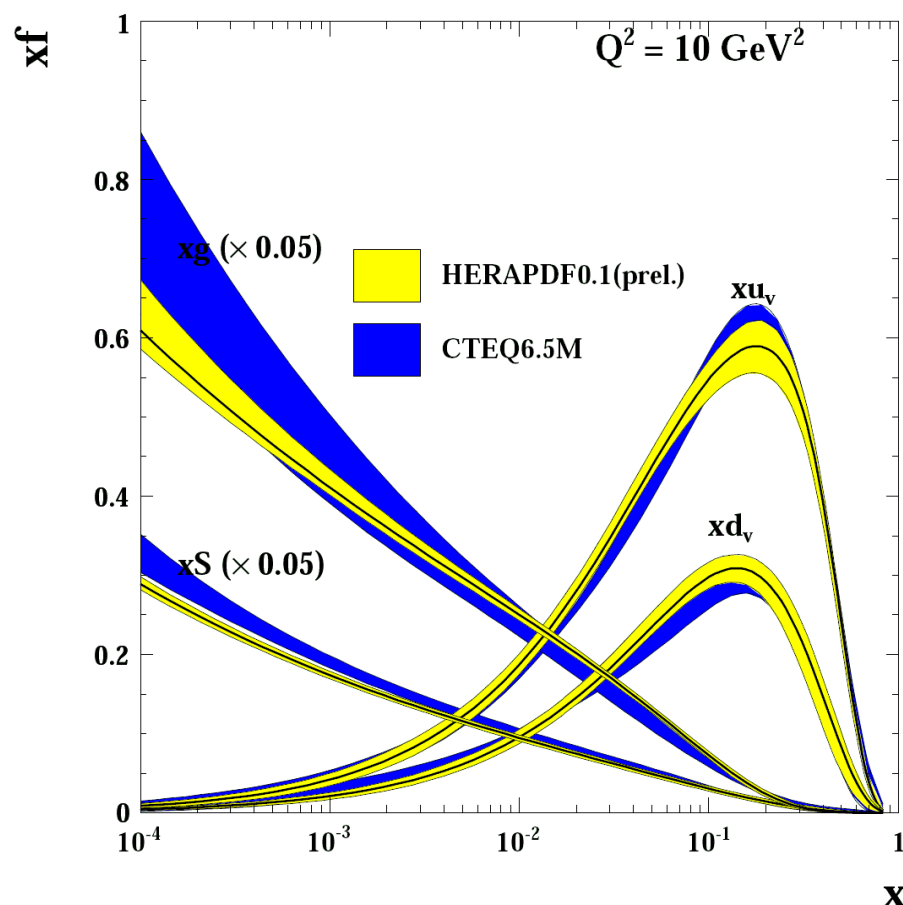
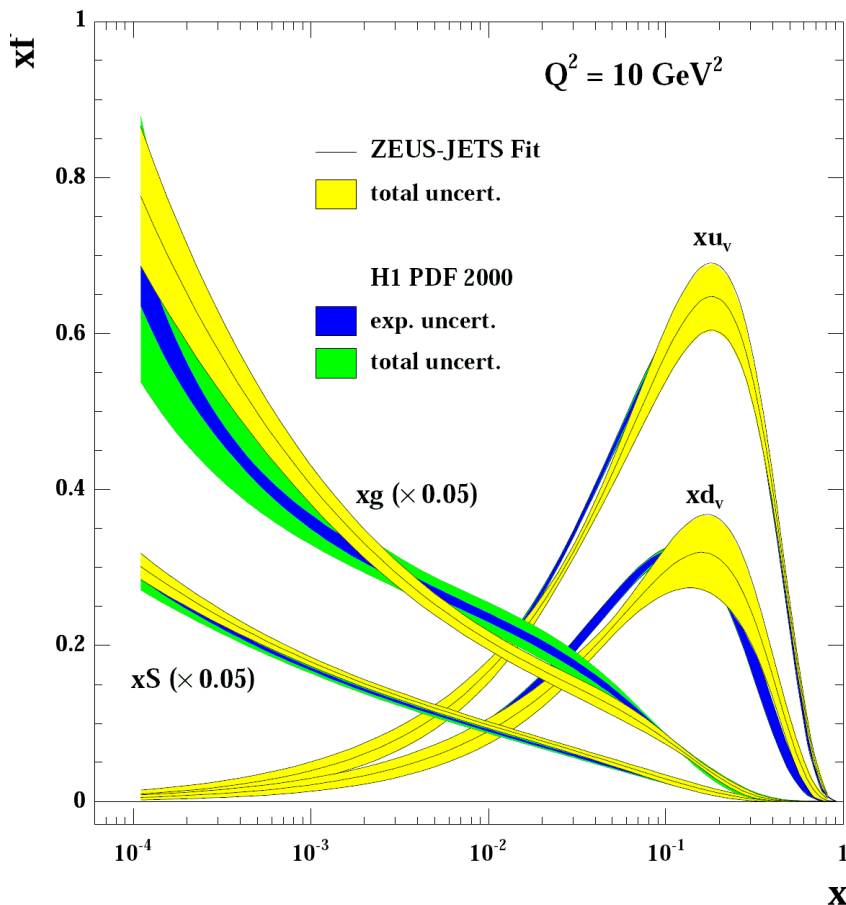
H1 prelim-08-045  
ZEUS prelim-08-003

low  $x \rightarrow$  sea and gluon PDF

high  $Q^2 \rightarrow$  valence PDF

$\rightarrow$  impressive precision achieved

$\rightarrow$  important input for LHC



# General contact interactions (CI)

- Possible new interactions between e and q can modify DIS cross section at high  $Q^2$  via virtual effects

- **Four fermion eeqq contact interactions**

→ convenient method to investigate these interferences

- Effective Lagrangian for neutral current **vector** like contact interactions:

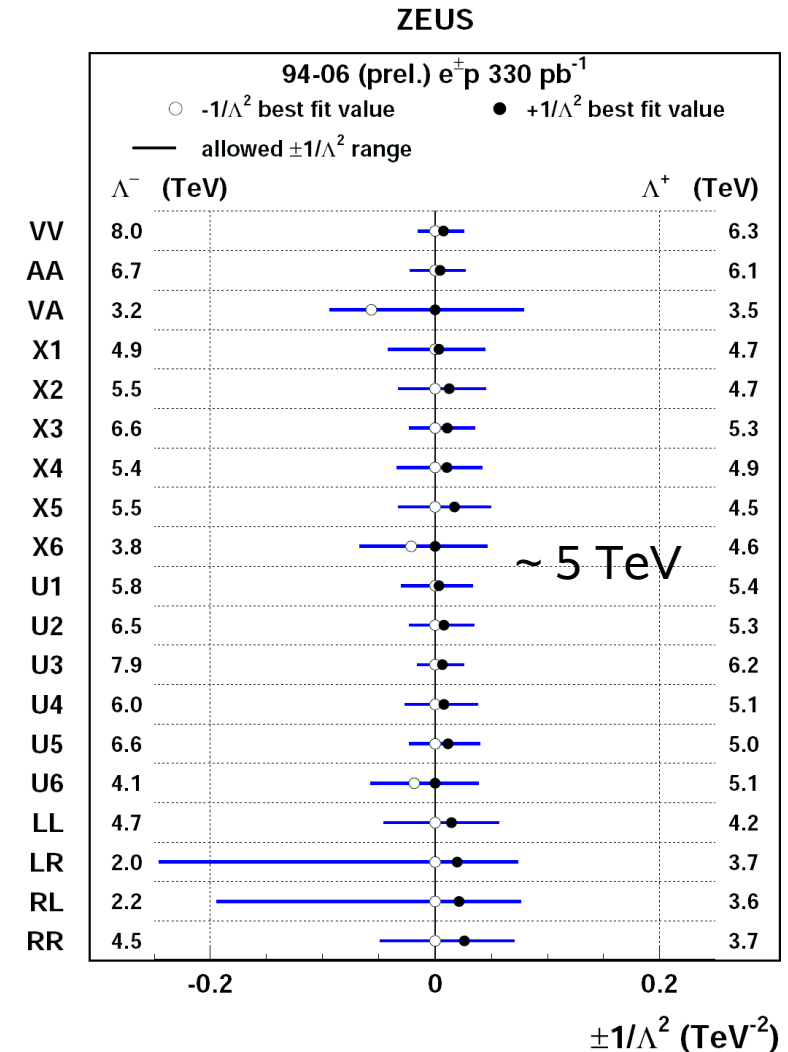
(scalar and tensor CI are constrained beyond HERA sensitivity)

$$\mathcal{L}_{CI} = \sum_{\substack{i,j=L,R \\ q=u,d,s,c,b}} \eta_{ij}^{eq} (\bar{e}_i \gamma^\mu e_i) (\bar{q}_j \gamma_\mu q_j)$$

$$\text{couplings: } \eta_{ij}^{eq} = \epsilon_{ij}^{eq} \frac{4\pi}{\Lambda^2}$$

$\Lambda$  – compositeness scale

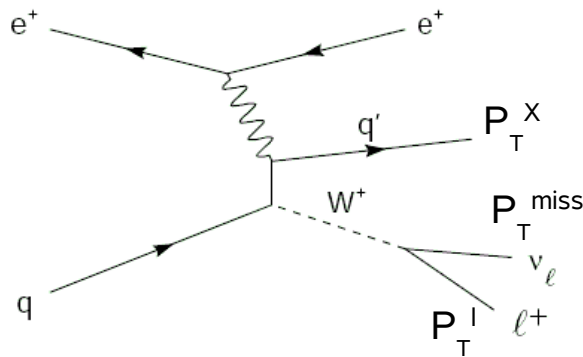
- Limits comparable with those derived at **LEP** and **TEVATRON**



# Events with isolated leptons and missing $P_T$

- Rare topology events with high energy isolated lepton **and** missing transverse momentum may be a sign for new physics
  - in SM: real W production  $ep \rightarrow eW^\pm X$  with leptonic decay  $W^\pm \rightarrow l \nu_l$

example of W production:



→ previously an excess in **e** and **μ** has been reported by H1 collaboration (not observed by ZEUS)

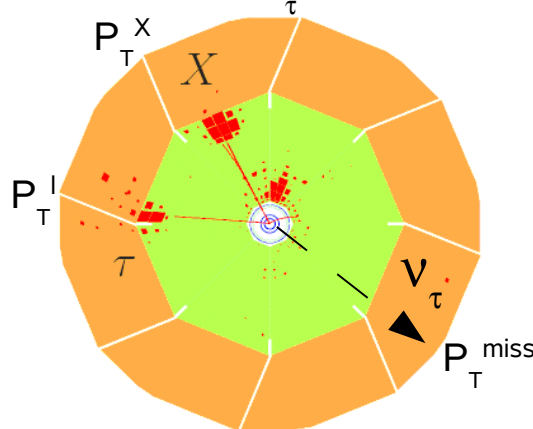
$P_T^X$  (hadronic transverse momentum) > 25 GeV

→ now full HERA statistics are exploited by both experiments (2 x 0.5 fb<sup>-1</sup>)

**consistent with SM**

event with  $W \rightarrow \nu_\tau$  observed in H1:

→ the production cross section of W boson measured



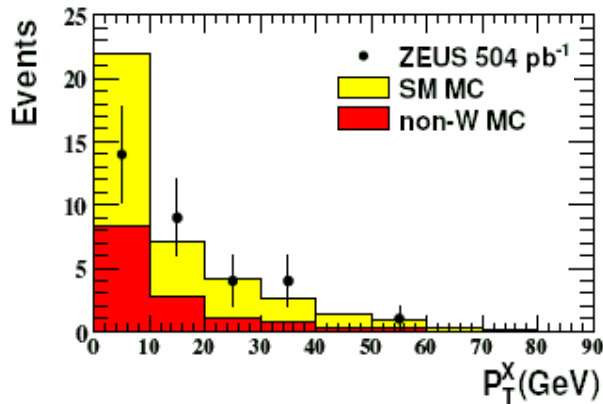
DESY-08-170  
DESY-08-089

SM:	$1.27 \pm 0.19$ pb
H1:	$1.14 \pm 0.25_{\text{stat}} \pm 0.14_{\text{syst}}$ pb
ZEUS:	$0.89 \pm 0.25_{\text{stat}} \pm 0.10_{\text{syst}}$ pb

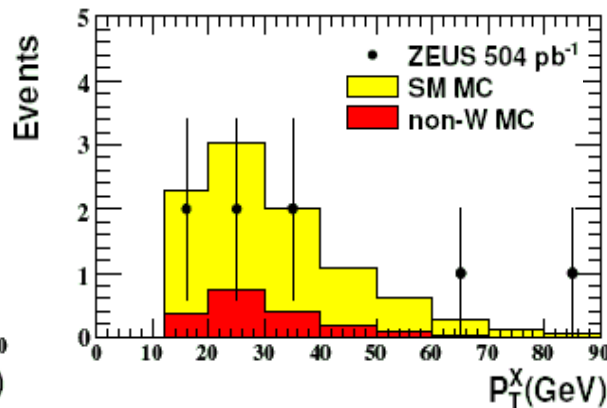


# Events with isolated leptons and missing $P_T$

e channel



$\mu$  channel

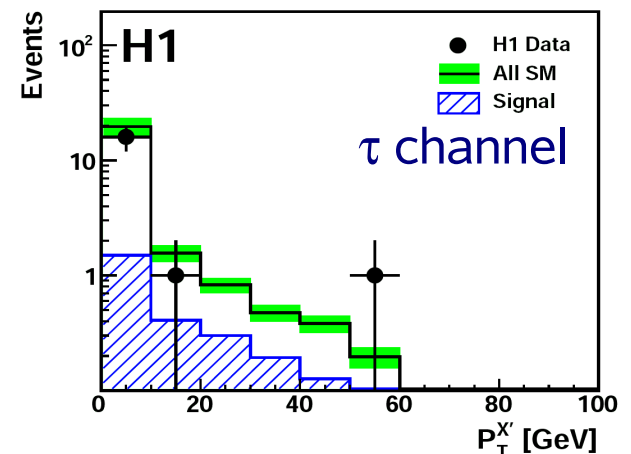


DESY-08-170  
ZEUS pub-08-005

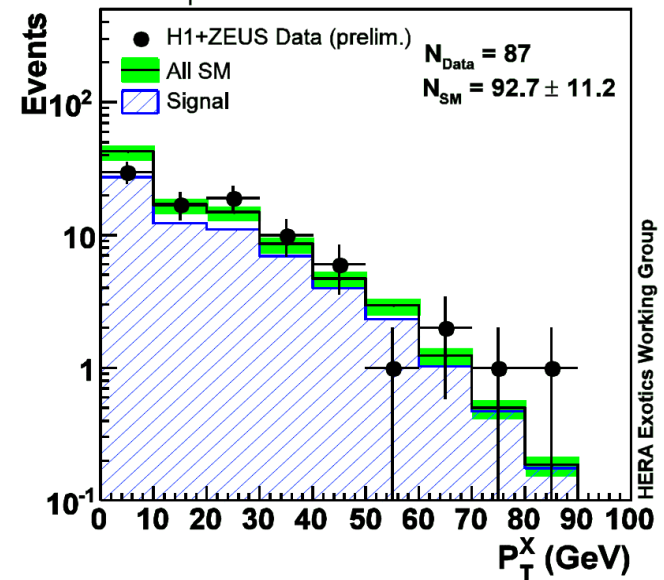
H1  $e, \mu + P_T^{\text{miss}}$ : **2.4 $\sigma$  excess** of events in  $e^+p$   
not confirmed by ZEUS

combinations of H1 and ZEUS  
results are ongoing

$\tau + P_T^{\text{miss}}$  events at HERA ( $e^\pm p$ , 474  $\text{pb}^{-1}$ )



$e, \mu + P_T^{\text{miss}}$  events at HERA I+II ( $e^\pm p$ , 0.97  $\text{fb}^{-1}$ )



HERA Exotics Working Group

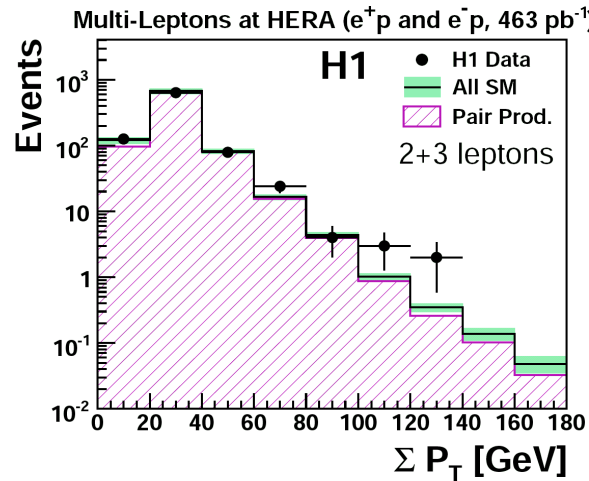
# Events with multi leptons and high $P_T$

sensitivity to new physics – 'hardness' scale ( $\Sigma P_T$ )

in agreement with  
SM expectations

for  $\Sigma P_T > 100$  GeV ( $0.94 \text{ fb}^{-1}$ ):

data = 6 (5 in  $e^+p$ )  
SM =  $3.00 \pm 0.34$  (1.82 in  $e^+p$ )



latest ZEUS (HERAII) results

