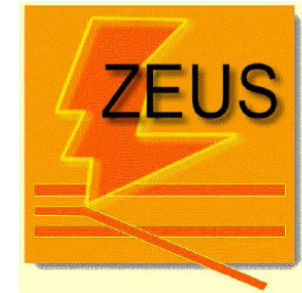




HSQCD 2008



## Search for new physics at HERA

L. Bellagamba  
INFN Bologna  
on behalf of the H1 and ZEUS collaborations

# HERA history and outline

15 years of succesful operations !!

Data taking ended last summer:

- 1992-2000 (HERA I)  $L \sim 120 \text{ pb}^{-1}$  (mostly e+p)
- 2002-2007 (HERA II)  $L \sim 360 \text{ pb}^{-1}$  (polarization  $\sim 30\text{-}40\%$ , e+/e-p balanced)

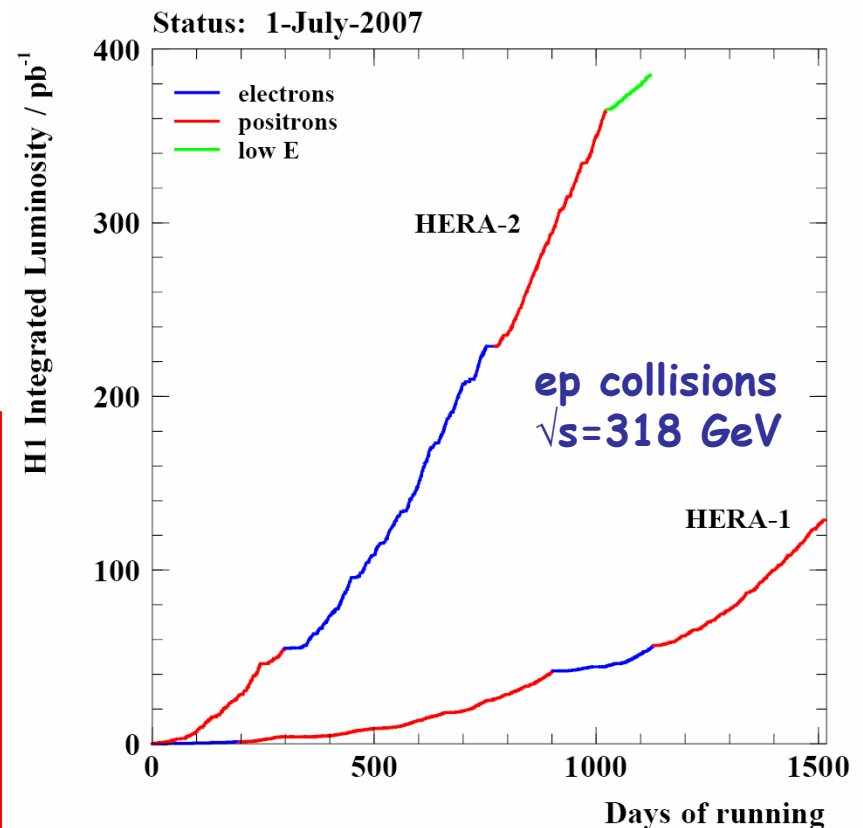
Many results produced on searches:

Leptoquarks, LFV, excited fermions, FCNC, SUSY, monopoles, contact interactions, double charged Higgs.....

→ competitive with other colliders or precise low energy experiments

I summarize recent update, using full statistics, of some of the mainstream searches at HERA:

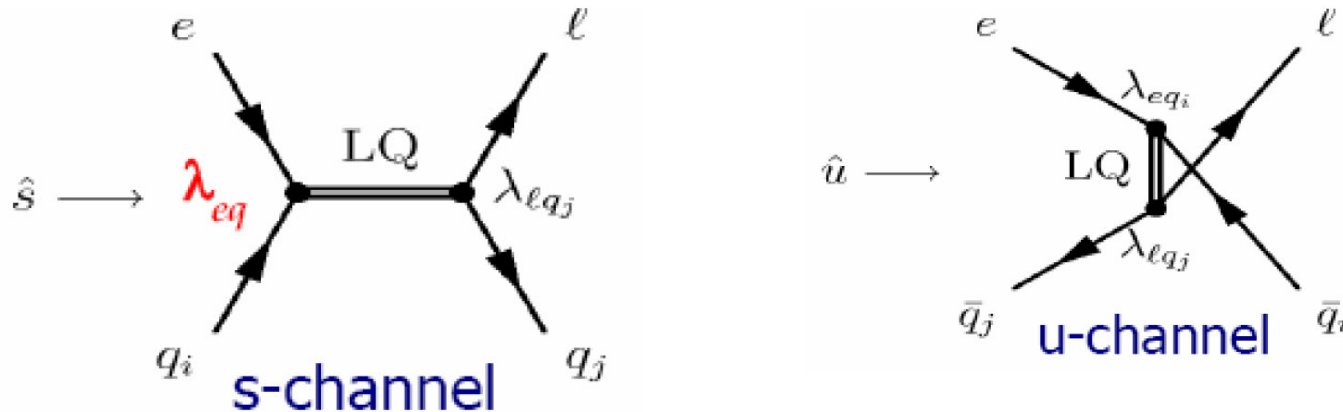
- Leptoquarks
- Contact Interactions
- High-pt leptons
- Single top



# Leptoquarks

- Hypothetical bosons connecting the quark and the lepton sectors.
- Naturally arise in unified models where quarks and leptons are arranged in common multiplets.
- Carry SU(3) colour, fractional electric charge and both lepton (L) and baryon (B) number: fermion number  $F = 3B + L = 0, 2$

At HERA can be resonantly produced in the s-channel for  $M_{LQ} < \sqrt{s}$  or exchanged in the u-channel, then can decay to  $eq$  or  $\nu q$

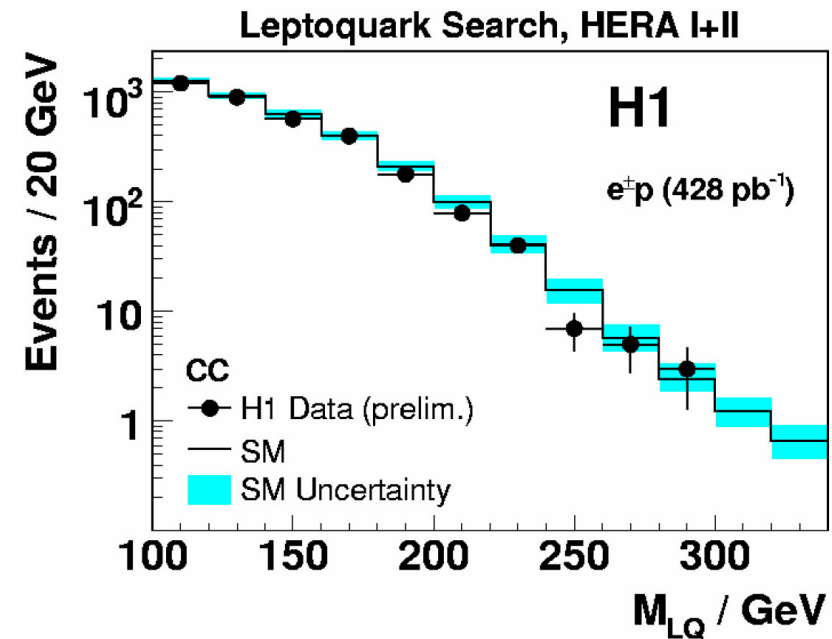
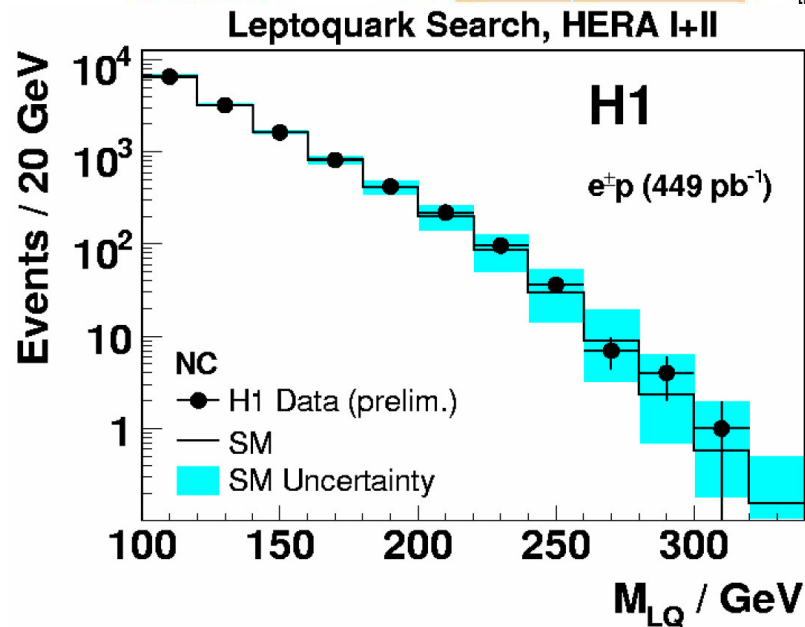
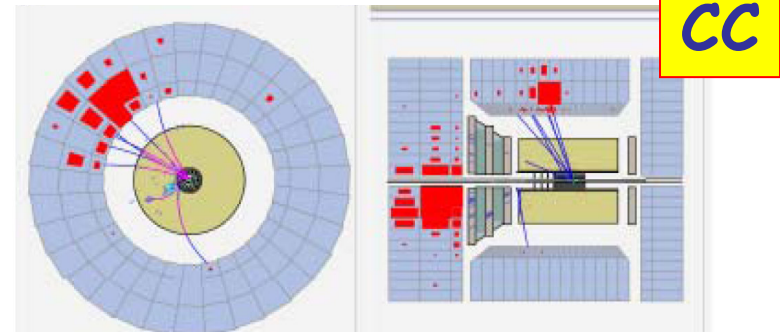
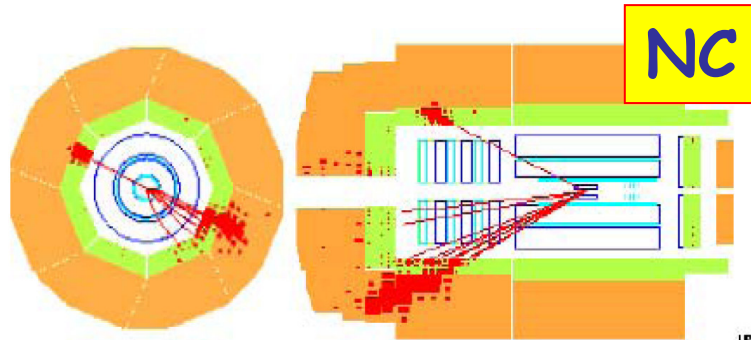


Signature identical to NC or CC DIS

Analysis look for possible deviations in e-jet or  $\nu$ -jet invariant mass

# Leptoquarks results

Complete H1 data set both  $e^+p$  and  $e^-p$   $L \sim 0.5 \text{ fb}^{-1}$



Good agreement between data and SM predictions

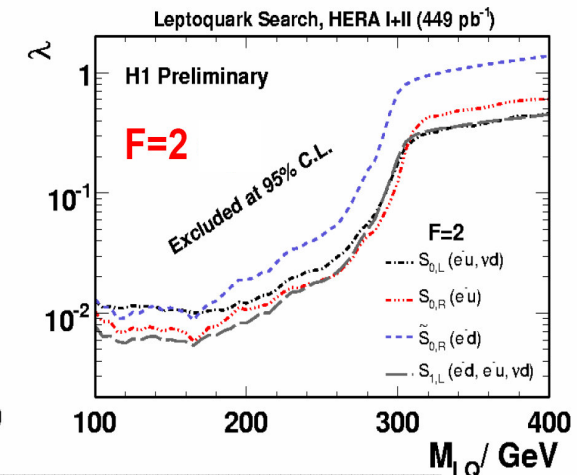
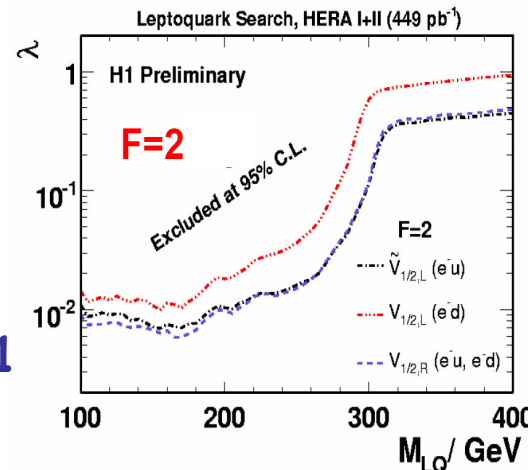
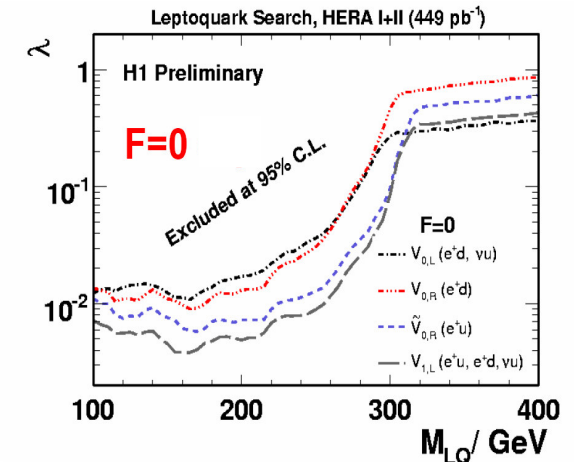
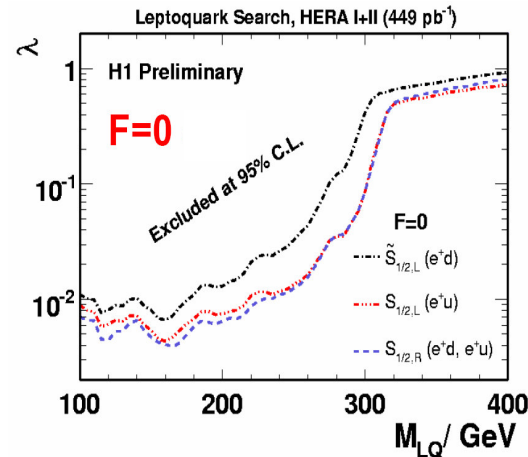
# Leptoquarks results

Phenomenological model of Buchmuller-Ruckl-Wyler used in limit setting:

- $U(1)_Y \times SU(2)_L \times SU(3)_c$  invariance
- lepton and baryon number conservation
- either left- or right-handed coupling to lepton but not both (bounds from rare decays)



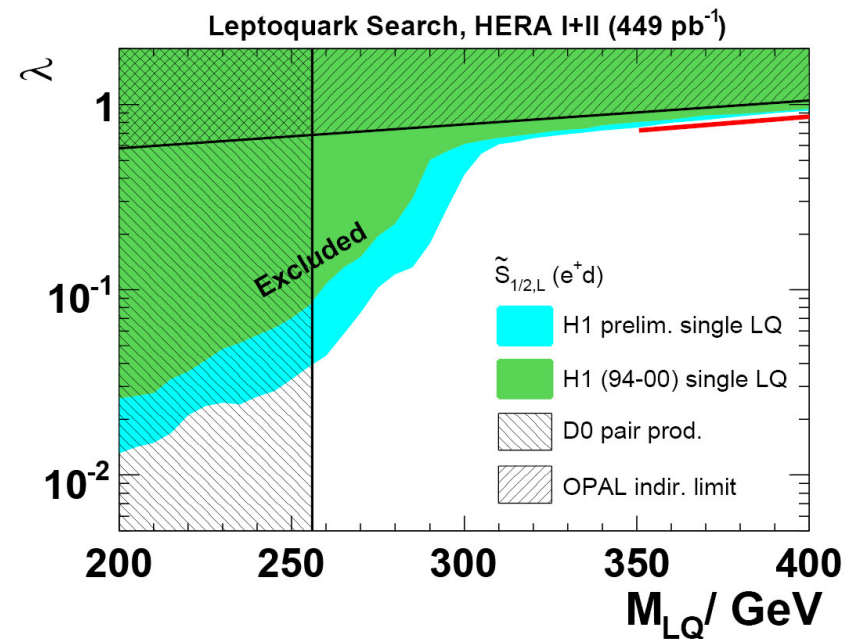
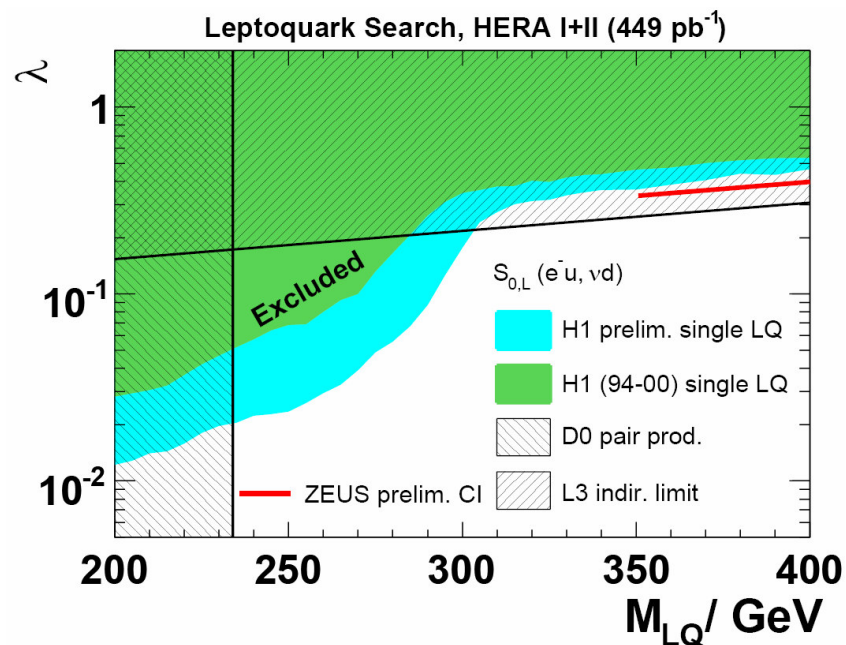
- 7 scalar + 7 vector states
- decay to  $eq$  or  $vq$  with  $\beta=0, \frac{1}{2}, 1$



$M < 300$  GeV resonant production  $\rightarrow$  stronger limits  
 For a coupling of EM strength  $\lambda=0.3$ ,  $M < 291-300$  GeV @ 95%CL

# Leptoquarks results

## Comparison with other colliders:



LEP (OPAL, L3): indirect constraints from  $ee \rightarrow qq$

TEVATRON (D0): pair production via  $qq$  annihilation or  $gg$  fusion

→ limit independent of  $\lambda$

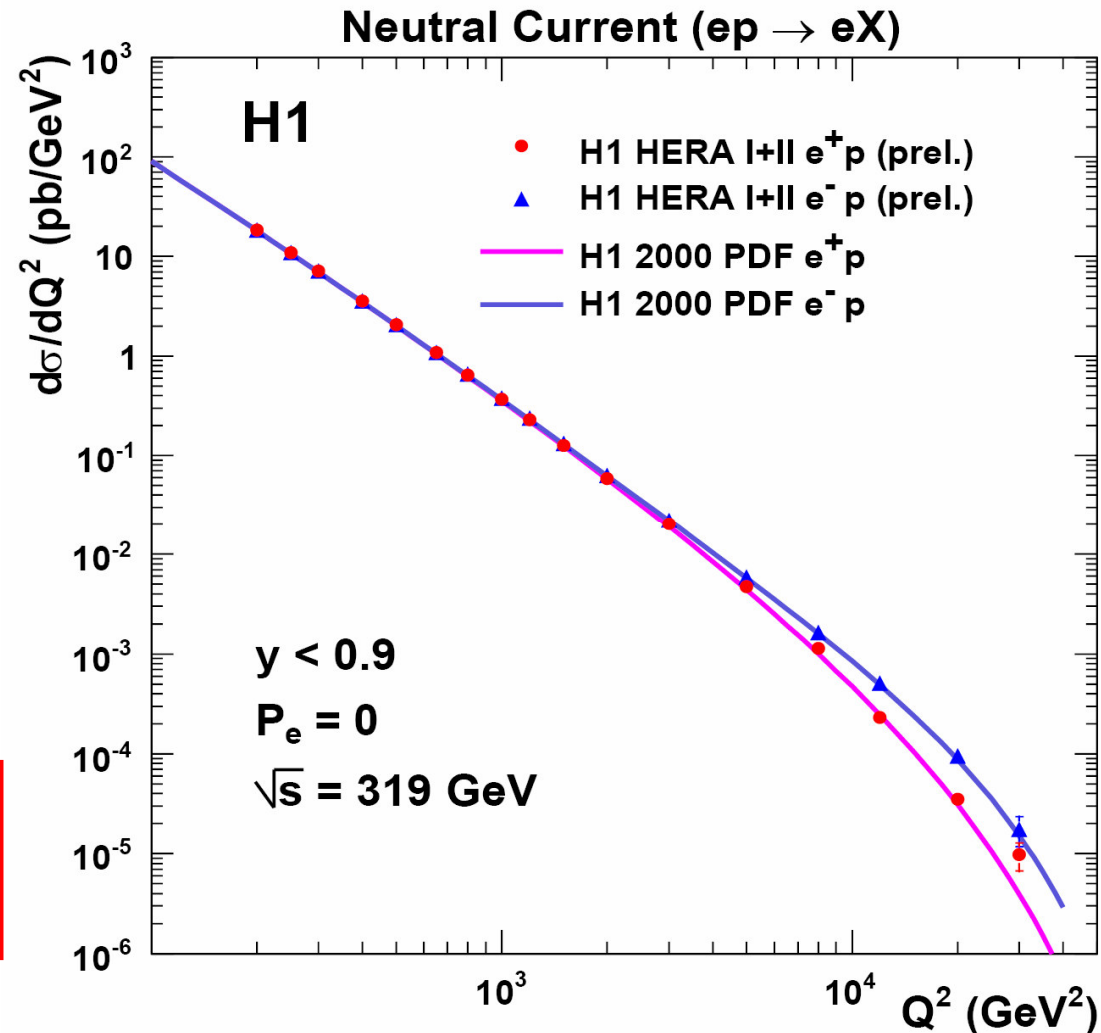
**HERA extends the excluded domain for masses beyond the TEVATRON limit**



# Contact interactions

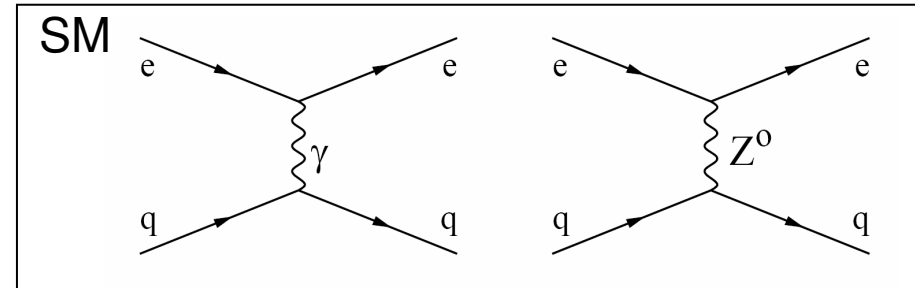
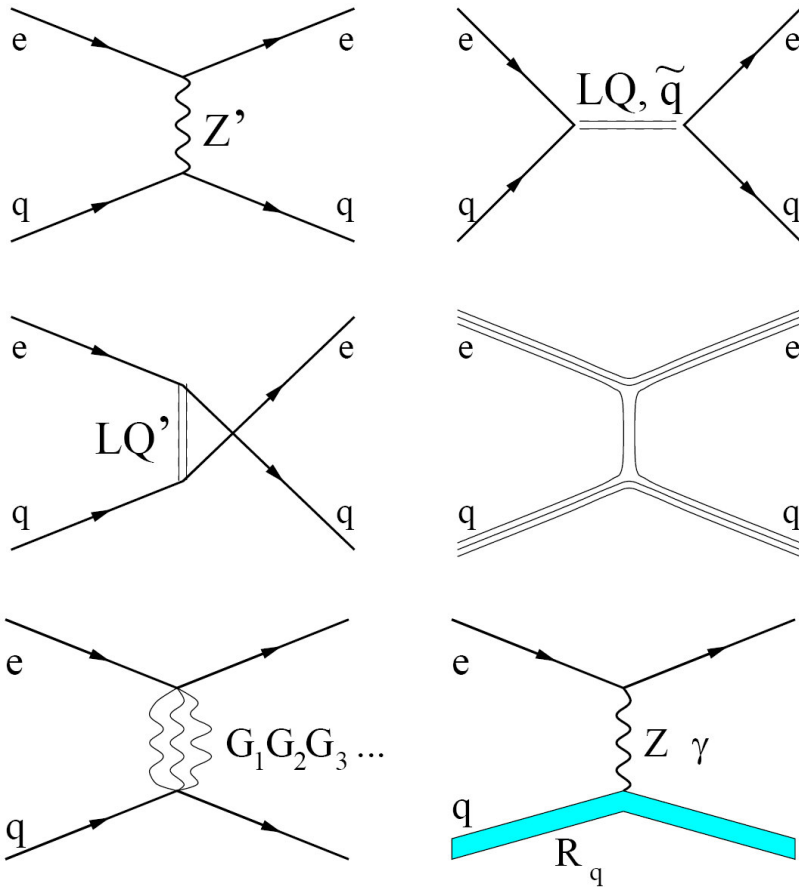
- Neutral current DIS data: excellent agreement between data and predictions over many orders of magnitude.
- Precise test for SM and QCD looking at possible deviations at high  $Q^2$  due to CI induced by virtual effects of new physics at much higher scale.

$Q^2$  up to 40000  $\text{GeV}^2$   
Resolution =  $1/Q \sim 10^{-16}$  cm  
1/1000 of proton radius

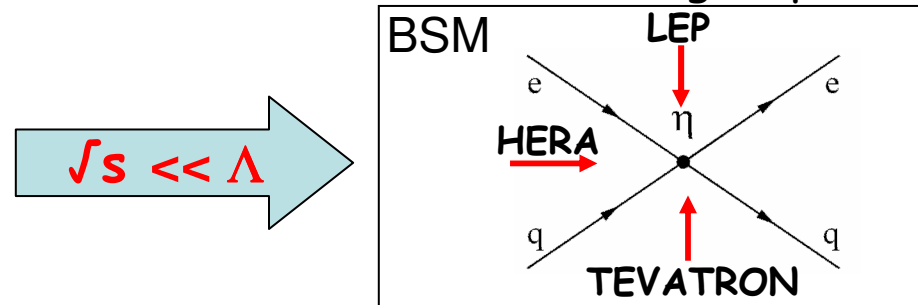


# Contact interactions

Possible scenarios:



CI modifies  $eq \rightarrow eq$  tree level scattering amplitude



Effective lagrangian for vector  $eeqq$  coupling (scalar and tensor couplings constrained beyond HERA sensitivity)

$$\mathcal{L}_{CI} = \sum_{\alpha, \beta=L, R} \eta_{\alpha\beta}^{eq} \cdot (\bar{e}_{\alpha} \gamma^{\mu} e_{\alpha})(\bar{q}_{\beta} \gamma_{\mu} q_{\beta})$$

$\alpha, \beta$  give the helicity structure of new interactions (4 for each  $q$  flavor)

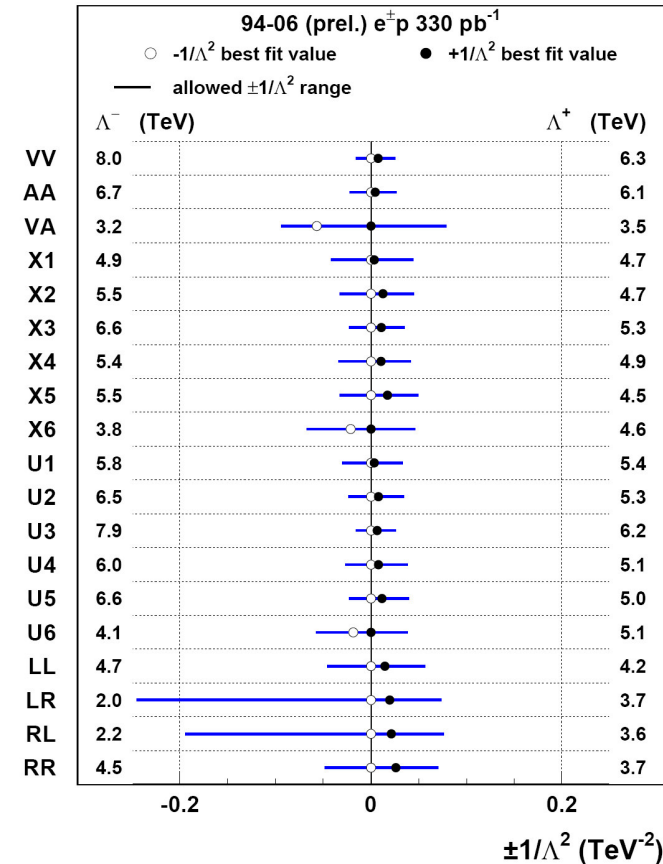
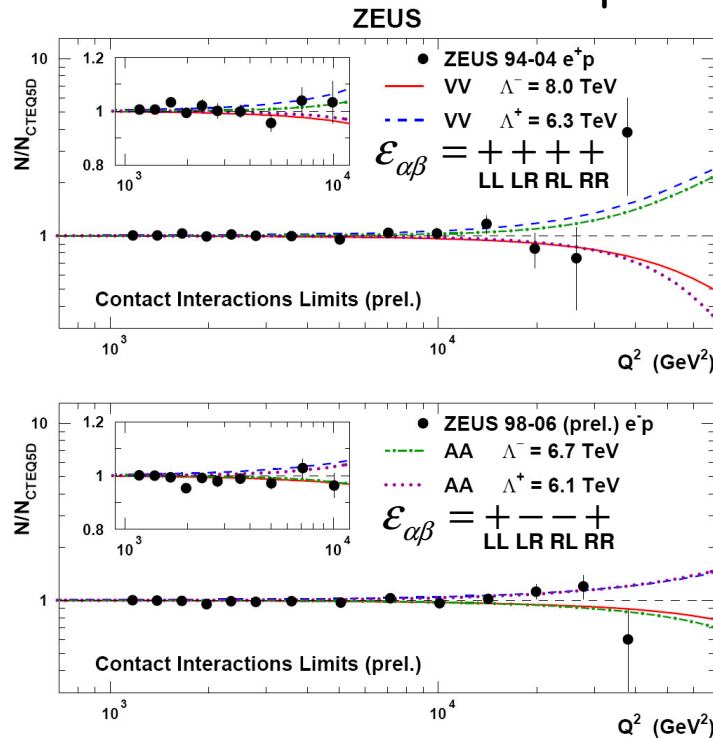


# Contact interactions results

## General models:

Couplings related to the mass scale of new physics  $\Lambda$  by  $\eta_{\alpha\beta} = \varepsilon_{\alpha\beta} 4\pi / \Lambda^2$   $\varepsilon_{\alpha\beta} = 0, \pm 1$

## Zeus data 1994-2006 / SM predictions



ZEUS 95%CL limits:  $\Lambda > 2.0 - 8.0$  TeV

H1 95% CL limits:  $\Lambda > 1.6 - 5.5$  TeV (HERA I Phys. Lett. B568(2003)35-47)

# Contact interactions results

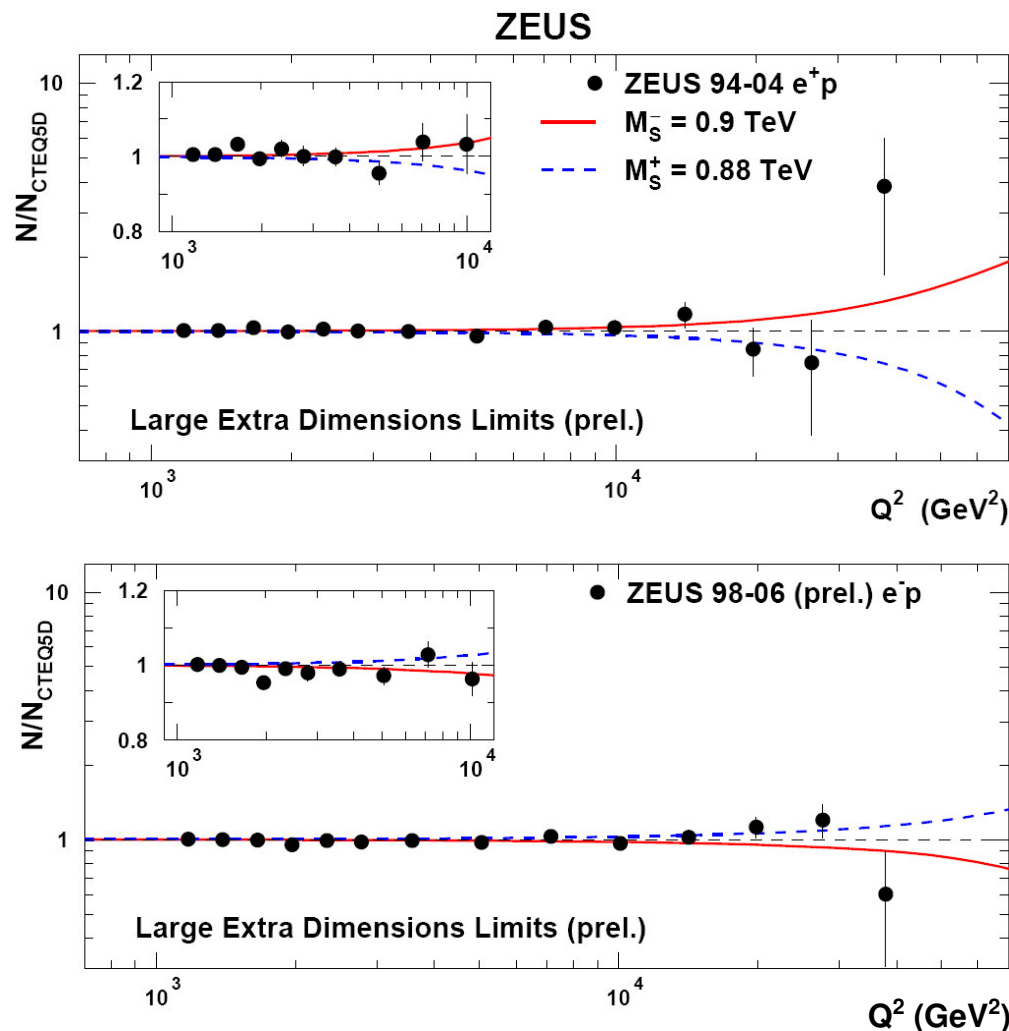
## Large extra dimensions (Arkani-Ahmed-Dimopoulos-Dvali)

If gravity propagates in  $4+\delta$  dim.,  
effective gravity mass scale  $M_S$   
can be as low as 1 TeV comparable  
to EW interactions

Contribution of gravity exchange  
to ep NC DIS via the effective  
CI coupling:

$$\eta_G = \frac{\lambda}{M_S^4}$$

Where  $\lambda$  is the coupling (positive  
or negative) and  $M_S$  the effective  
gravity scale



ZEUS 95% CL limits:  $M_S^- > 0.90$  TeV,  $M_S^+ > 0.88$  TeV  
H1 (HERA I):  $M_S^- > 0.78$  TeV,  $M_S^+ > 0.82$  TeV

# Contact interactions results

## High mass Leptoquarks

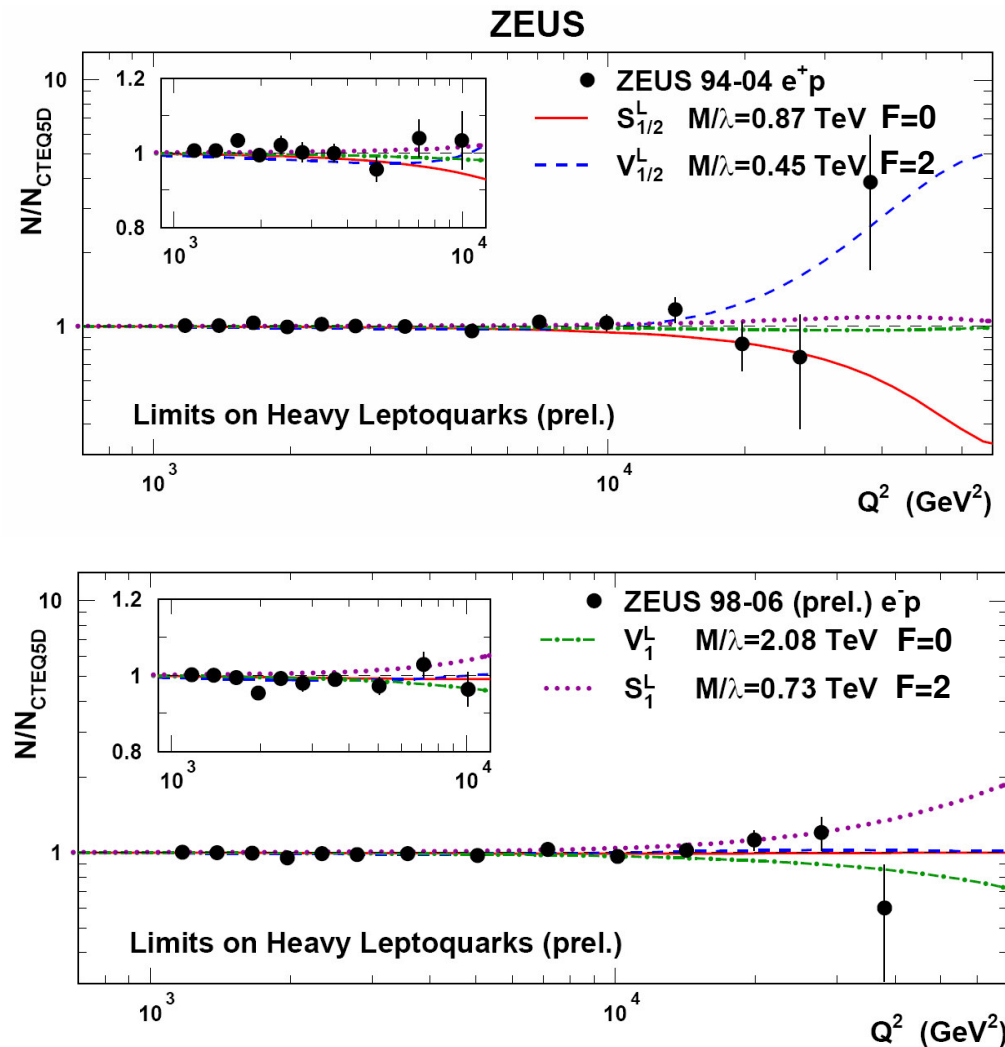
$$M_{LQ} \gg \sqrt{s}$$

Virtual production/exchange of such state results in an effective CI coupling

$$\eta_{CI} \sim \left( \frac{\lambda}{M_{LQ}} \right)^2$$

$\lambda$  LQ Yukawa coupling

Both s- and u- channel important



**ZEUS 95% CL limits:  $M_{LQ}/\lambda_{LQ} > 0.29-2.08$  TeV**

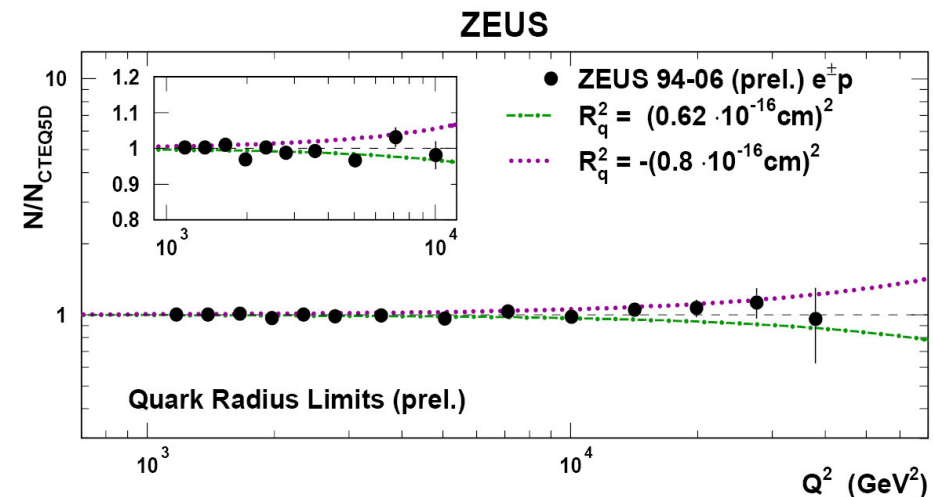
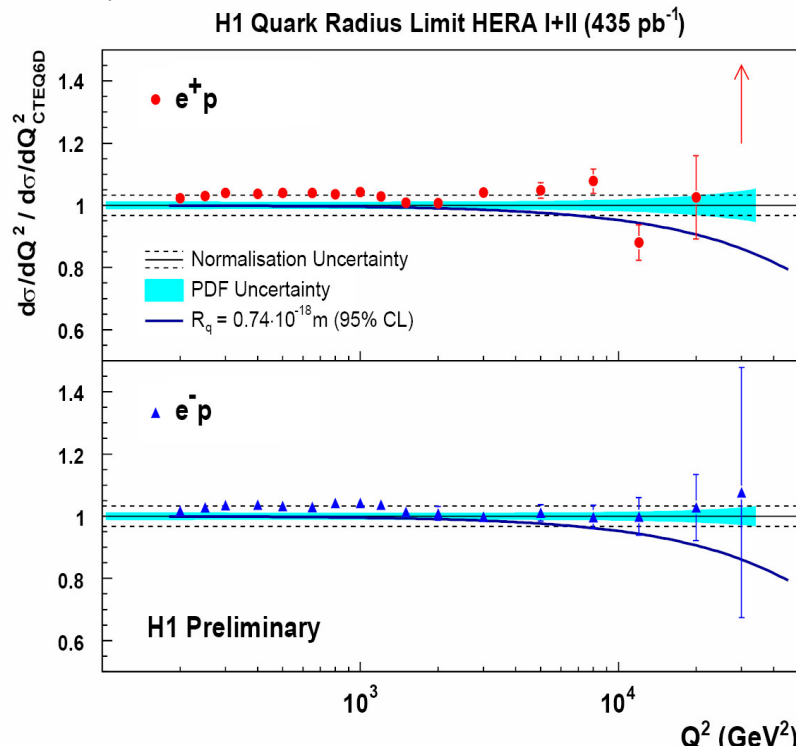
# Contact interactions results

## Quark form factor

If the colliding particles have finite size the SM cross-section is expected to decrease at large momentum transfer:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left[ 1 - \frac{R_q^2}{6} Q^2 \right]^2 \cdot \left[ 1 - \frac{R_e^2}{6} Q^2 \right]^2 \quad \leftarrow \text{Electron term not considered}$$

$R_q$  is the root mean-square radius of the EW charge distribution of the quark

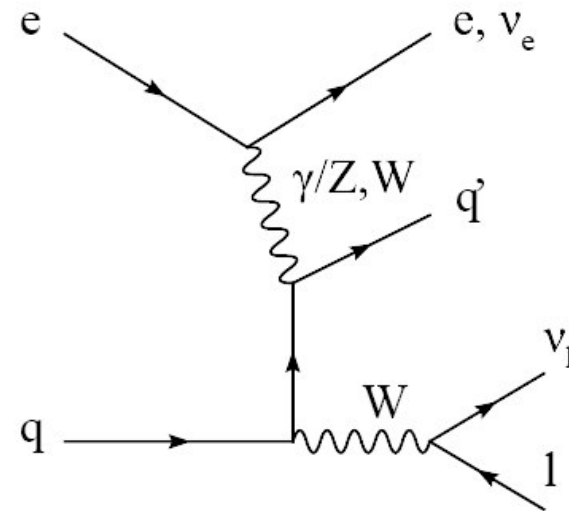
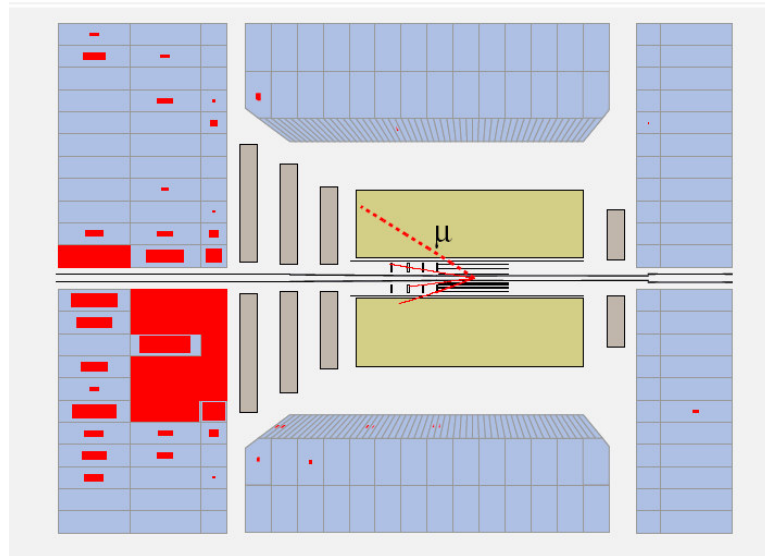


ZEUS 95% CL limit:  $R_q < 0.62 \cdot 10^{-16} \text{cm}$   
H1 95% CL limit:  $R_q < 0.74 \cdot 10^{-16} \text{cm}$   
(H1 preliminary 07-141 for LP2007)

# Isolated leptons

## High-pt leptons + missing Pt

low Background environment, well suited to look for new physics effect



At HERA main SM source of isolated high-pt leptons and missing transverse momentum is W production via  $\gamma p$  interactions with  $\sigma \approx 1 \text{ pb}$

Cross section evaluated at NLO, theoretical uncertainty  $\sim 15\%$

W predominantly produced at low transverse momentum

→ low transverse momentum of the hadronic system ( $P_T^X$ )

# Isolated leptons: HERA I results

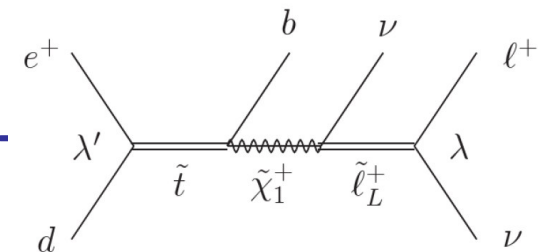
Excess over the SM predictions observed by H1 in both electron and muon channel not confirmed by ZEUS

1994-2000 $e^\pm p$		Electron obs./exp. ( $W^\pm$ contribution)	Muon obs./exp. ( $W^\pm$ contribution)
H1 118.4 pb <sup>-1</sup>	Full sample	11 / 11.54 $\pm$ 1.50 (71%)	8 / 2.94 $\pm$ 0.50 (86%)
	$p_T^X > 25\text{GeV}$	5 / 1.76 $\pm$ 0.30 (82%)	6 / 1.68 $\pm$ 0.30 (88%)
	$p_T^X > 40\text{GeV}$	3 / 0.66 $\pm$ 0.13 (80%)	3 / 0.64 $\pm$ 0.14 (92%)

In the  $\tau$  channel ZEUS observed  $2/0.2 \pm 0.05$  (45%) at  $P_T^X > 25\text{ GeV}$

A lot of interest triggered by these results in the HEP community

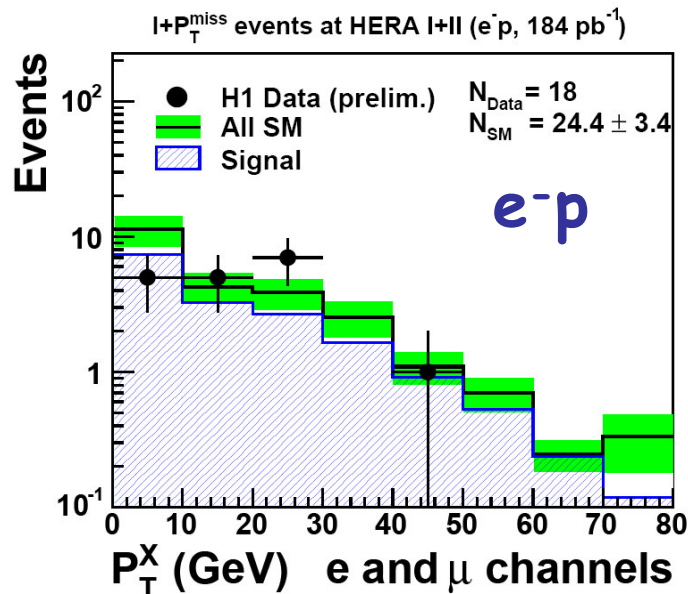
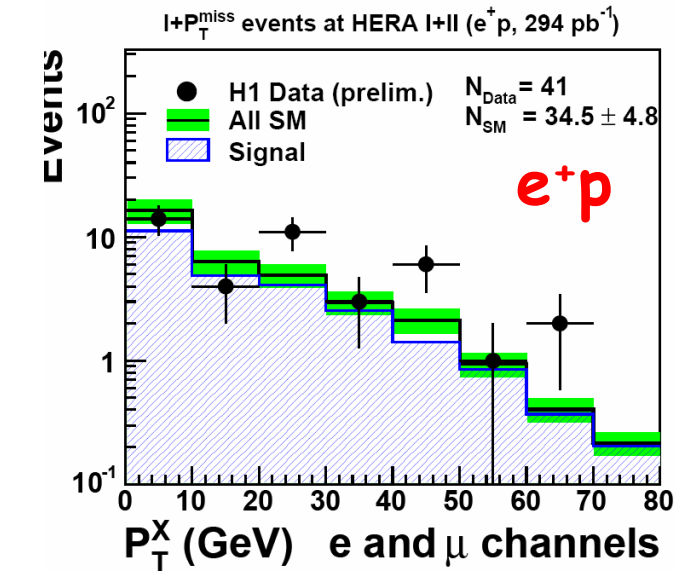
Attempts to explain the possible excess in term of R-parity violating SUSY models (Eur. Phys. J C51 543 (2007))



➡ A joint group was created to ensure the compatibility of the analysis and to produce combined results for HERA II data



# Isolated leptons: H1 HERA I+II results



$P_t^l > 10 \text{ GeV}$  + well isolated from other jets and tracks

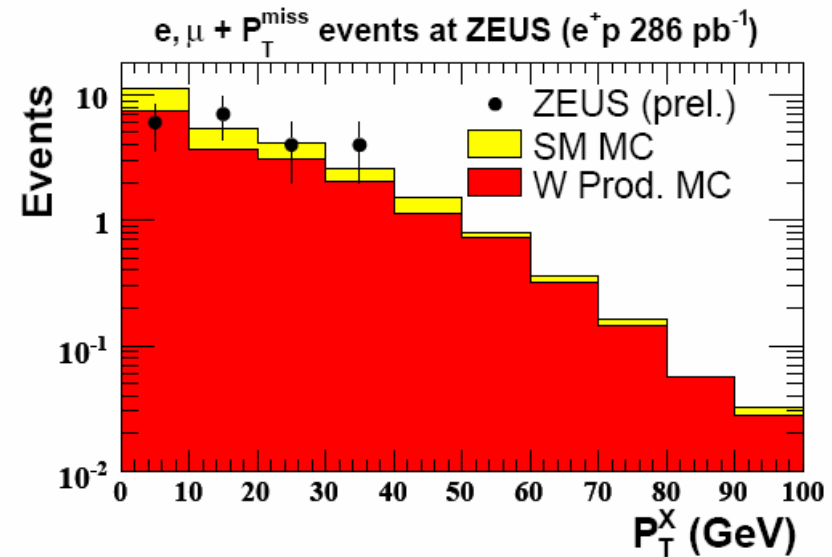
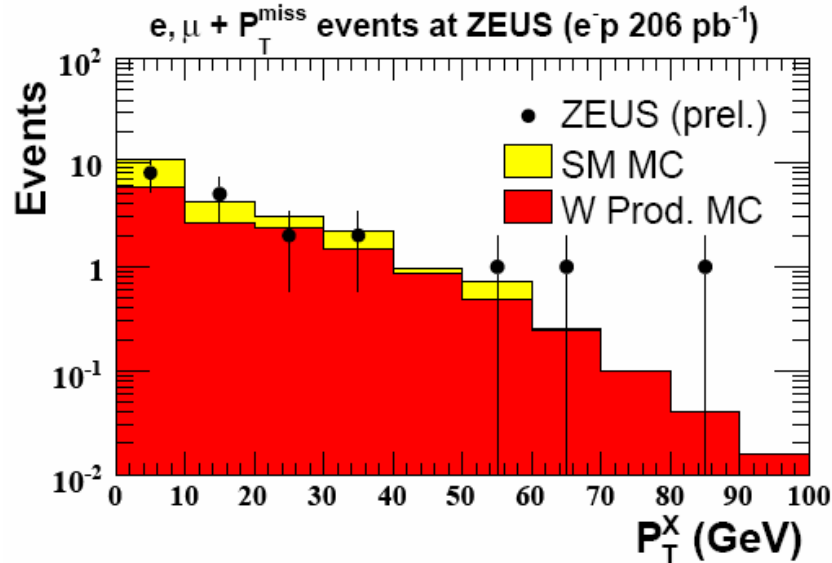
$5^\circ < \vartheta_\ell < 140^\circ$   $P_t^{\text{miss}} > 12 \text{ GeV}$

H1 Preliminary $l+P_T^{\text{miss}}$ events at HERA I+II		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
$e^+p$	Full Sample	26 / $27.3 \pm 3.8$ (71%)	15 / $7.2 \pm 1.1$ (85%)	41 / $34.5 \pm 4.8$ (74%)
294 $\text{pb}^{-1}$	$P_T^X > 25 \text{ GeV}$	11 / $4.7 \pm 0.9$ (75%)	10 / $4.2 \pm 0.7$ (85%)	21 / $8.9 \pm 1.5$ (80%)
$e^-p$	Full Sample	16 / $19.4 \pm 2.7$ (65%)	2 / $5.1 \pm 0.7$ (78%)	18 / $24.4 \pm 3.4$ (68%)
184 $\text{pb}^{-1}$	$P_T^X > 25 \text{ GeV}$	3 / $3.8 \pm 0.6$ (61%)	0 / $3.1 \pm 0.5$ (74%)	3 / $6.9 \pm 1.0$ (67%)
$e^\pm p$	Full Sample	42 / $46.7 \pm 6.5$ (69%)	17 / $12.2 \pm 1.8$ (82%)	59 / $58.9 \pm 8.2$ (72%)
478 $\text{pb}^{-1}$	$P_T^X > 25 \text{ GeV}$	14 / $8.5 \pm 1.5$ (68%)	10 / $7.3 \pm 1.2$ (79%)	24 / $15.8 \pm 2.5$ (73%)

H1 excess observed in HERA I data  
 confirmed in HERA II  $e^+p$  data:  
 $e^+p$  excess  $\sim 3\sigma$   
 $e^-p$  agreement with SM

# Isolated leptons: ZEUS HERA I+II results

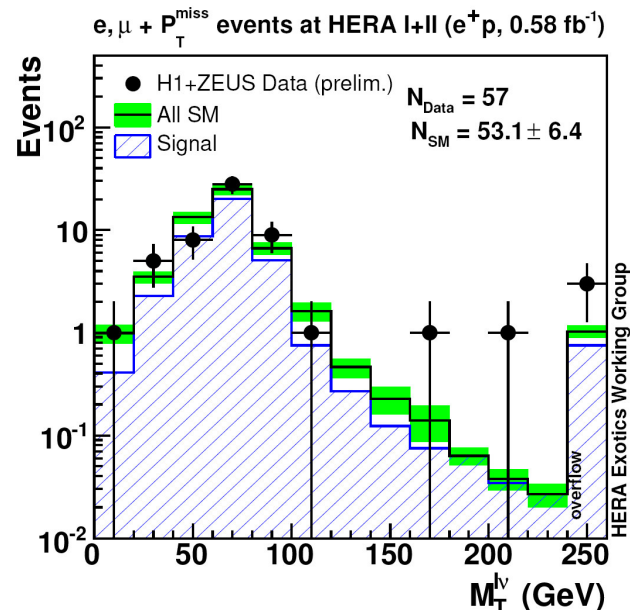
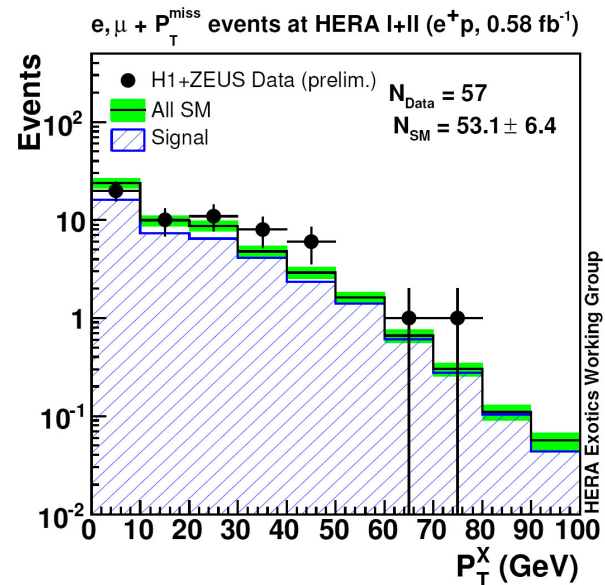
Selection very similar to H1 except reduced angular acceptance for leptons:  $15^\circ < \vartheta_\ell < 120^\circ$  (Combined analysis use this range)



Isolated Lepton Candidates	$P_T^X < 12$ GeV	$12 < P_T^X < 25$ GeV	$P_T^X > 25$ GeV
$e^-p$ 208 $\text{pb}^{-1}$	9/11.3 $\pm$ 1.5 (54%)	6/5.1 $\pm$ 0.7 (67%)	5/5.5 $\pm$ 0.8 (75%)
$e^+p$ 296 $\text{pb}^{-1}$	7/12.6 $\pm$ 1.7 (68%)	7/6.2 $\pm$ 0.9 (75%)	6/7.4 $\pm$ 1.0 (79%)
$e^\pm p$ 504 $\text{pb}^{-1}$	16/23.9 $\pm$ 3.1 (61%)	13/11.2 $\pm$ 1.5 (71%)	11/12.9 $\pm$ 1.7 (77%)

**ZEUS results:**  
 agreement with SM both for  $e^+p$  and  $e^-p$

# Isolated leptons: comb. HERA I+II results



Both analysis restricted to a common phase space region

H1+ZEUS Preliminary $l + P_T^{\text{miss}}$ events at HERA I+II		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
1994-2007 $e^+p$ $0.58 \text{ fb}^{-1}$	Full Sample	39 / $41.3 \pm 5.0$ (70%)	18 / $11.8 \pm 1.6$ (85%)	57 / $53.1 \pm 6.4$ (73%)
	$P_T^X > 25 \text{ GeV}$	12 / $7.4 \pm 1.0$ (78%)	11 / $7.2 \pm 1.0$ (85%)	23 / $14.6 \pm 1.9$ (81%)
1998-2006 $e^-p$ $0.39 \text{ fb}^{-1}$	Full Sample	25 / $31.6 \pm 4.1$ (63%)	5 / $8.0 \pm 1.1$ (86%)	30 / $39.6 \pm 5.0$ (68%)
	$P_T^X > 25 \text{ GeV}$	4 / $6.0 \pm 0.8$ (67%)	2 / $4.8 \pm 0.7$ (87%)	6 / $10.6 \pm 1.4$ (76%)
1994-2007 $e^\pm p$ $0.97 \text{ fb}^{-1}$	Full Sample	64 / $72.9 \pm 8.9$ (67%)	23 / $19.9 \pm 2.6$ (85%)	87 / $92.7 \pm 11.2$ (71%)
	$P_T^X > 25 \text{ GeV}$	16 / $13.3 \pm 1.7$ (73%)	13 / $12.0 \pm 1.6$ (86%)	29 / $25.3 \pm 3.2$ (79%)

$e^+p$  excess

H1 only

$3\sigma$

H1 comm. ph. sp.

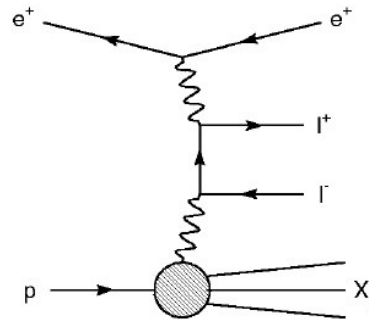
$2.9\sigma$

H1+ZEUS comb.

$2\sigma$

# Multi-electrons: comb. HERA I+II results

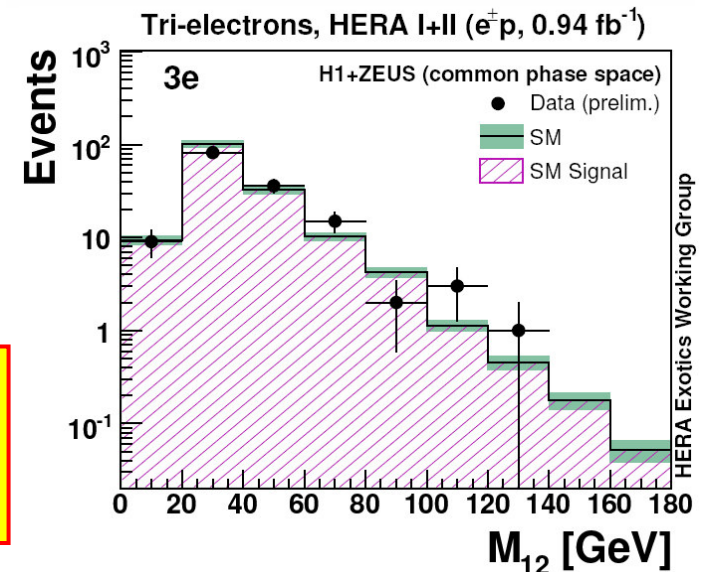
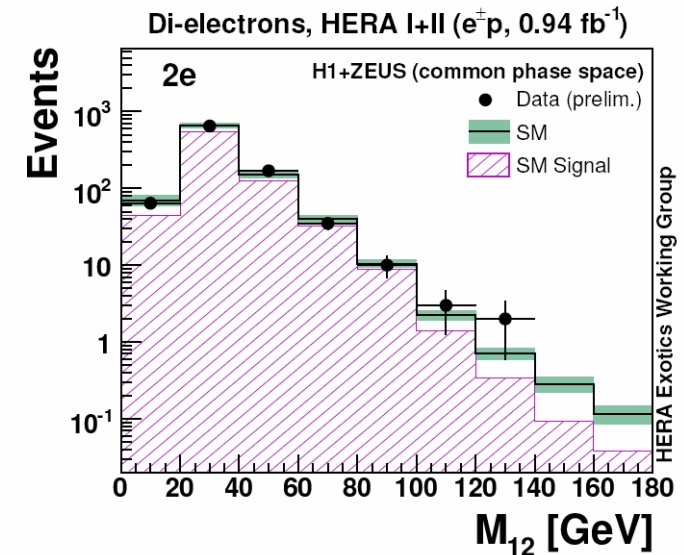
- Main SM production  $\gamma\gamma \rightarrow ee$
- QED process theoretically very well known
- Production falls steeply with the lepton  $p_T$



H1+ZEUS Multi-electron analysis HERA I+II (preliminary)

$M_{12} > 100 \text{ GeV}$				
Selection	Data	SM	Pair Production	NC-DIS + Compton
$e^+p$ collisions ( $0.56 \text{ fb}^{-1}$ )				
2e	4	$1.97 \pm 0.22$	$1.10 \pm 0.21$	$0.87 \pm 0.18$
3e	4	$1.10 \pm 0.12$	$1.10 \pm 0.12$	—
$e^-p$ collisions ( $0.38 \text{ fb}^{-1}$ )				
2e	1	$1.44 \pm 0.15$	$0.77 \pm 0.10$	$0.67 \pm 0.12$
3e	0	$0.75 \pm 0.08$	$0.75 \pm 0.08$	—
$e^\pm$ collisions ( $0.94 \text{ fb}^{-1}$ )				
2e	5	$3.41 \pm 0.37$	$1.87 \pm 0.25$	$1.54 \pm 0.29$
3e	4	$1.85 \pm 0.24$	$1.85 \pm 0.24$	—

Few events at large mass in  $e+p$  collisions  
Overall acceptable agreement with SM predictions

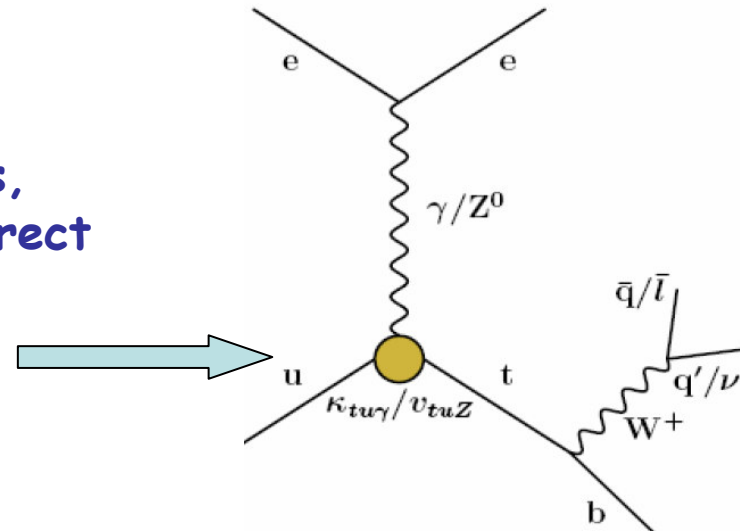


# Single top

SM cross section at HERA  $< 1\text{fb}$

Topology: high pt leptons, high-ptmiss, large hadronic Pt (differently from direct W production)

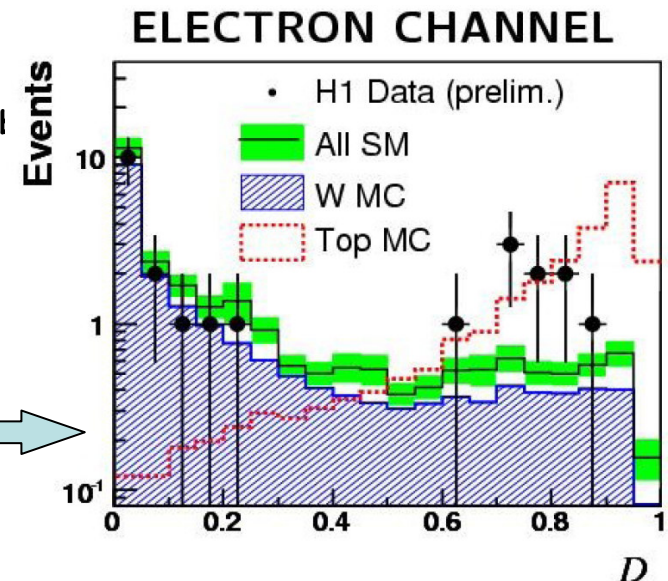
Possible anomalous production due to FCNC couplings  $\kappa_{tu\gamma}/\nu_{tuZ}$



Selection:

- Standard high-pt lepton selection + good lepton charge and top mass reconstruction  $M_{lv}$
- Multivariate discriminant based on  $M_{lvb}$ ,  $\theta(W)$ ,  $P_t^X$

Few events compatible with top, no large significance





# Single top results

New H1 result (HERA I+II  $L \sim 0.5 \text{ fb}^{-1}$ )

Charm contribution neglected

Vector coupling to  $Z^0$  neglected

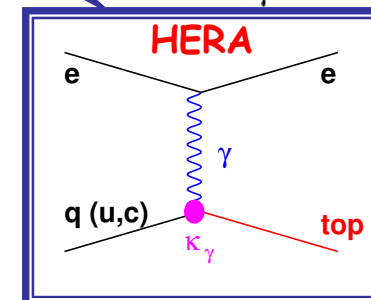
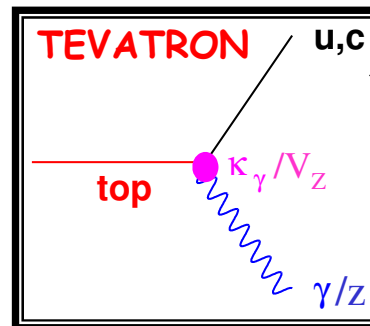
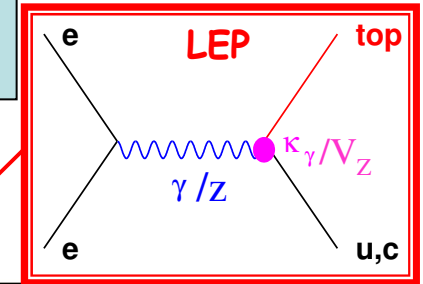
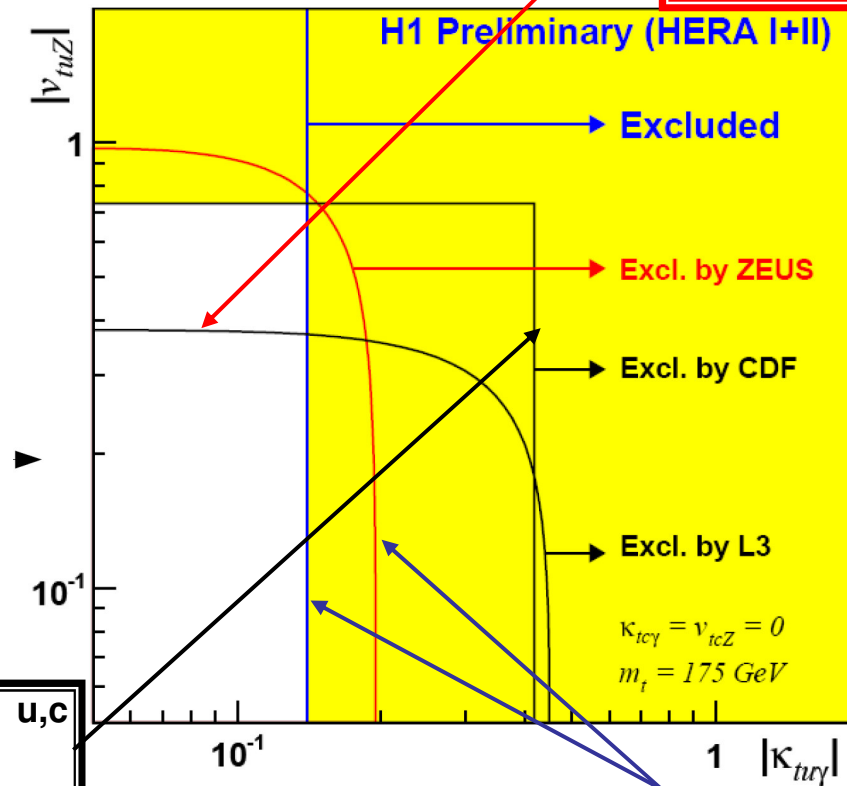
upper bound on cross section  
at 95%CL:

$$\sigma_{ep \rightarrow etX} < 0.16 \text{ pb}$$

upper bound on the anomalous  
coupling:

$$K_{t\gamma} < 0.14$$

HERA limits for  
 $K_{t\gamma}$  more stringent  
than TEVATRON  
and LEP





# Conclusions

HERA ceased data taking after 15 years of honoured activity  
Each experiment collected  $\sim 0.5 \text{ fb}^{-1}$  of ep data

## HERA valuable legacy:

- A deeper understanding of the proton structure
  - Indispensable input to LHC physics
- Study of short distance eq interactions, unique opportunity to search for BSM particles and interactions
  - Lot of results spread over the whole spectrum of interests of the HEP community
  - Many constraints competitive or complementary with other colliders

## Activity is ongoing

- Further searches are going to be updated using the whole HERA data
- H1+ZEUS WG is working to produce further combined results