

# Physics at Very High Energies and Search for New Physics at HERA

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On behalf of the H1 and ZEUS  
collaborations

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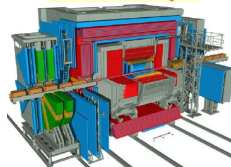
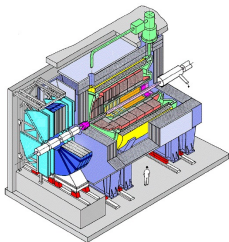
- 1 Introduction
- 2 High  $Q^2$  Cross-Sections
- 3 Contact Interactions
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- 5 Final State Searches
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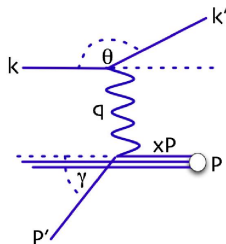
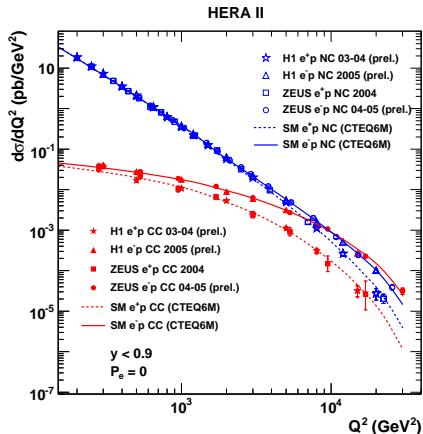


# HERA, ZEUS and H1

- H1 and ZEUS were multi-purpose detectors located on the  $ep$  collider HERA. Data taking ended on 30th June 2007
- $0.5 \text{ fb}^{-1}$  luminosity taken by each experiment



# High $Q^2$ Cross-Sections



Probing power:

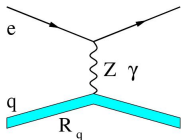
$$Q^2 = -q^2$$

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

- **Neutral current:**  $\gamma/Z^0$  exchange
- **Charged current:**  $W^\pm$  exchange

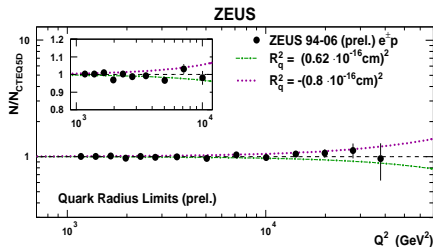
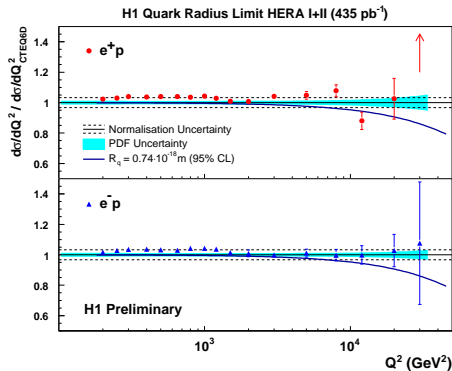
- Proton energy: 920 GeV
- Electron energy: 27.5 GeV
- $\sqrt{s} = 318$  GeV

# Quark Radius



Finite quark size  $\rightarrow$  SM cross-section modified:

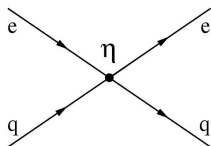
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \times \left(1 - \frac{R_q^2}{6} Q^2\right)$$



**ZEUS**  $R_q < 0.67 \times 10^{-18} \text{ m}$   
**H1**  $R_q < 0.74 \times 10^{-18} \text{ m}$

# Contact Interactions

- 4-fermion contact interactions describe effects from processes at higher scales: ( $\sqrt{s} \ll \Lambda$ ):
  - Exchange of extra gauge bosons
  - Production or exchange of leptoquarks or squarks
  - Compositeness
  - Gravitational effects from extra dimensions
- Could alter the SM distributions at high- $Q^2$



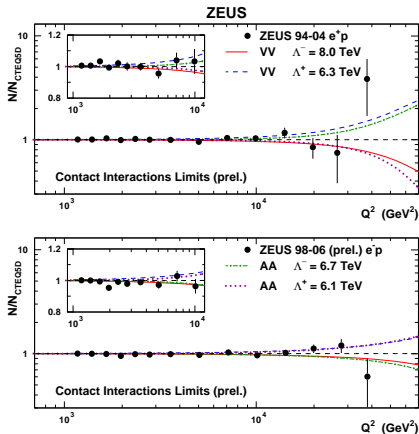
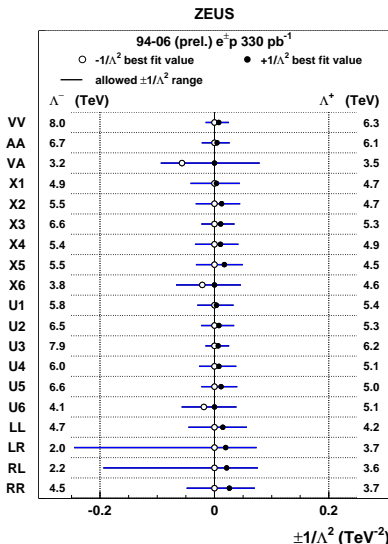
Lagrangian for vector  $eeqq$  contact interactions:

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

$\eta \propto \pm \frac{1}{\Lambda^2}$  where  $\Lambda$  is effective scale

## Contact Interactions II

### ■ Fit to NC data yields limits on $\Lambda$

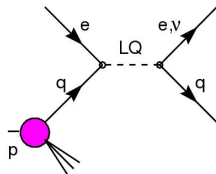


ZEUS (94-06)  $\Lambda = 2.0-8.0$  TeV

H1 (HERA-I)  $\Lambda = 1.6-5.5$  TeV

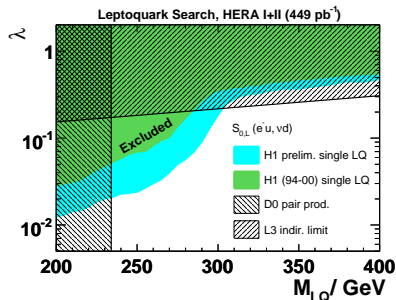
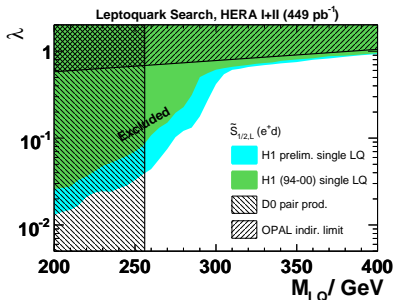
# Leptoquarks

- Leptoquarks are scalar or vector colour triplet bosons
- They carry both lepton and baryon number and have fermion number  $F = 3B + L$



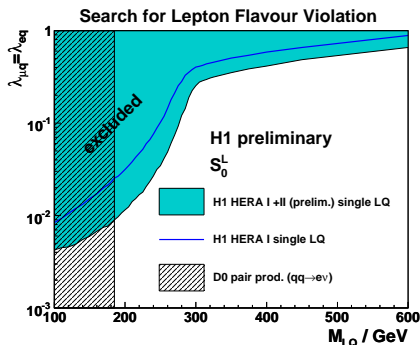
- $M_{LQ} < \sqrt{s}$ : s channel dominates
- Resonant production of single leptoquark
- Sensitivity to leptoquark coupling and mass
- Two searches have been performed:
  - First generation leptoquarks, no lepton flavour violation
  - First and second generation leptoquarks, allowing lepton flavour violation

# Leptoquarks: No Flavour Violation Limits



- $\tilde{S}_{1/2}^L$  and  $S_0^L$  can be interpreted as squarks ( $\tilde{u}_{j,L}$  and  $\tilde{d}_{k,R}$  respectively) produced via a R-parity violating coupling
- For couplings of electromagnetic strength the production of  $\tilde{S}_{1/2}^L$  and  $S_0^L$  is excluded for masses up to 295 GeV and 310 GeV, respectively

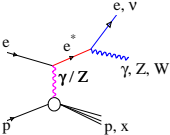
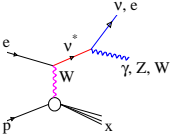
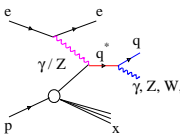
# Leptoquarks: With Lepton Flavour Violation



- Search for F=2 leptoquarks coupling to 1st and 2nd generation fermions in  $e^-p$  HERA-II data
- For coupling of electromagnetic strength, leptoquark masses below 291-433 GeV are ruled out

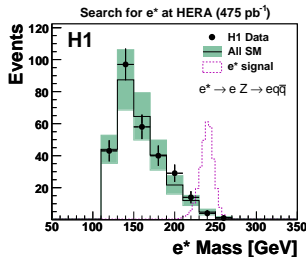
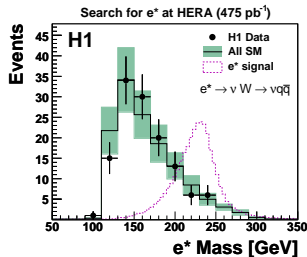
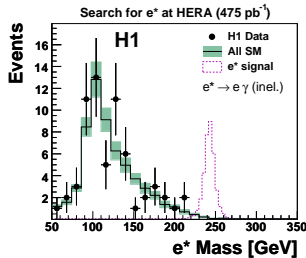
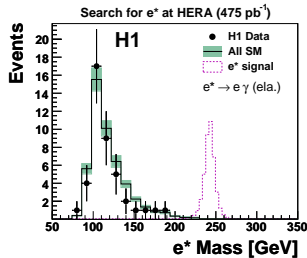
# H1 Excited Leptons & Quarks

- Compositeness models allow excited states of electrons, neutrinos and quarks

	Electrons	Neutrinos	Quarks
Lumi ( $pb^{-1}$ )	475	184	475
Decays	$e^* \rightarrow e\gamma$ $e^* \rightarrow eZ^0$ $e^* \rightarrow \nu W^\pm$	$\nu^* \rightarrow \nu\gamma$ $\nu^* \rightarrow \nu Z^0$ $\nu^* \rightarrow eW^\pm$	$q^* \rightarrow q\gamma$ $q^* \rightarrow qZ^0$ $q^* \rightarrow qW^\pm$
Diagrams			

- Hadronic or leptonic decays of the  $W^\pm$  and  $Z^0$  considered.

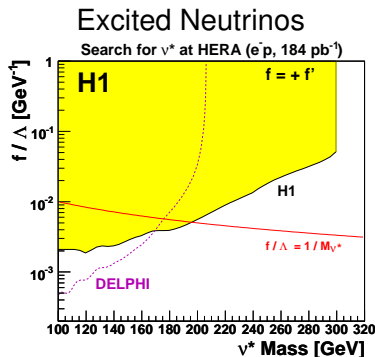
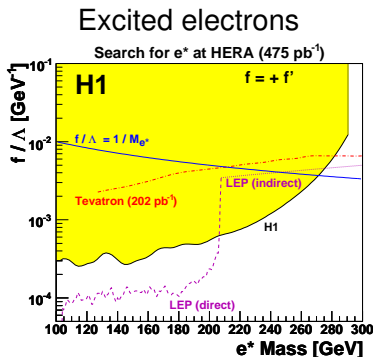
# H1 Excited Electrons



$e^*$  signal histogram:  
 reconstructed mass  
 distribution of  $e^*$  events  
 with  $M_{e^*} = 240$  GeV  
 (normalisation is  
 arbitrary)

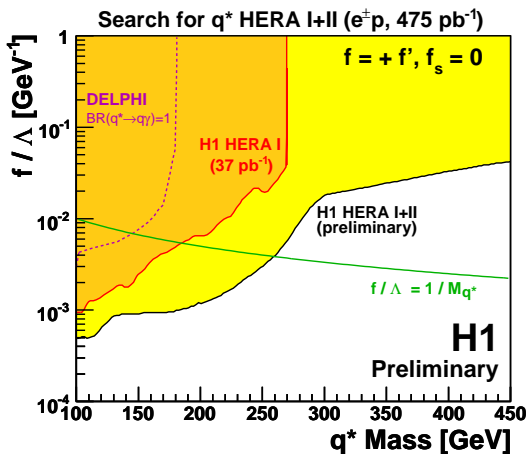
# H1 Excited Leptons

- Derive mass-dependent limits on the ratio of the coupling to the compositeness scale ( $f/\Lambda$ )



- No evidence for excited lepton production is found

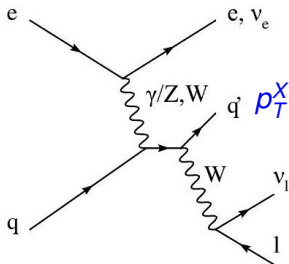
# H1 Excited Quarks



■ No evidence for  $q^*$  states.

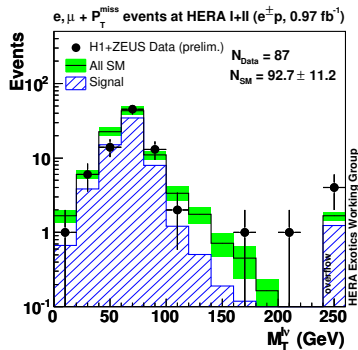
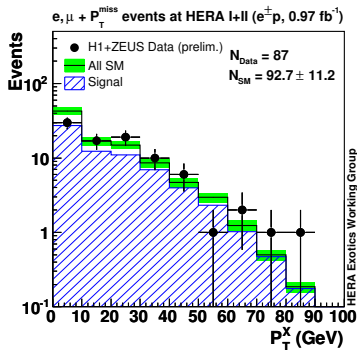
# Isolated Leptons And $W^\pm$ Production I

- Main SM source of isolated leptons with missing transverse momentum at HERA is single  $W^\pm$  production ( $\sigma \approx 1.3\text{pb}$ )
- H1 saw excess in HERA-I data over the SM for both isolated  $e$  and isolated  $\mu$  searches



- Excess at high hadronic transverse momentum ( $p_T^X$ )  $\rightarrow$  new physics?
- HERA I+II data from both experiments have now been combined

# Isolated Leptons And $W^\pm$ Production II

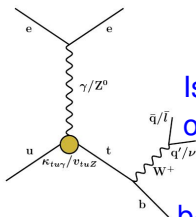


$W^\pm$  production cross-section:

SM	$1.31 \pm 0.20$ (theory syst.) pb
ZEUS	$0.89^{+0.25}_{-0.22}$ (stat.) $\pm 0.10$ (syst.) pb
H1	$1.23 \pm 0.25$ (stat.) $\pm 0.22$ (syst.) pb

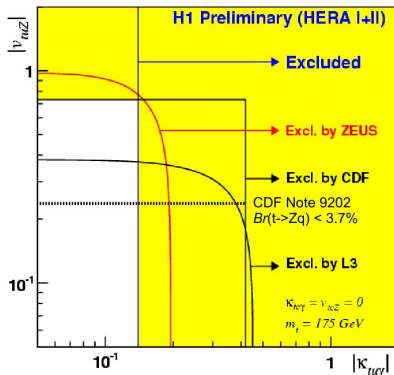
# Anomalous Top Production

- Flavour changing neutral current process
- SM single top production at HERA  $< 1\text{fb}$
- $\kappa_{t\bar{u}\gamma}$ : coupling of  $t$ ,  $u$  and photon
- $\nu_{tuZ}$ : vector coupling of  $t$ ,  $u$  and  $Z^0$  (assumed = 0 by H1)



Isolated lepton +  $p_T^{\text{miss}}$   
or 2 light jets

b-jet



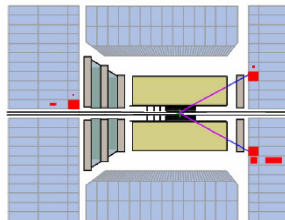
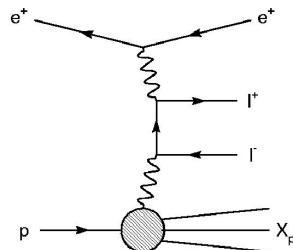
H1 limits:

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

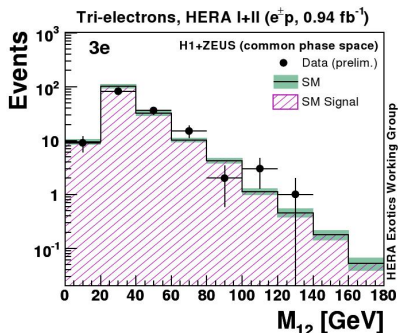
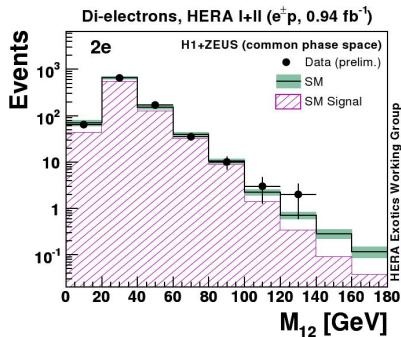
$$\kappa_{t\bar{u}\gamma} < 0.14$$

# Multi-Electrons I

- Main production mechanism: Bethe-Heitler.  $\gamma\gamma \rightarrow e^+ e^-$
- QED process  $\rightarrow$  precisely calculable
- SM prediction falls steeply with  $p_T$
- Deviation from SM could be new physics
- H1 and ZEUS have combined results for the multi-electron analysis
- Multi-muon analyses not yet combined

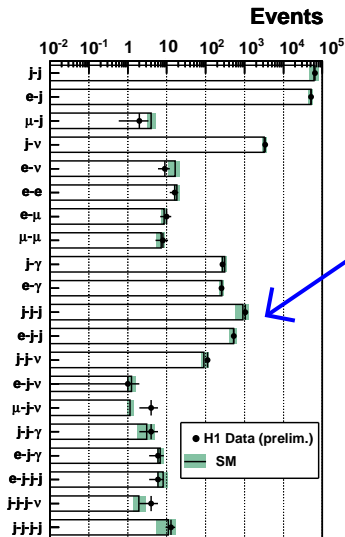


# Multi-Electrons II

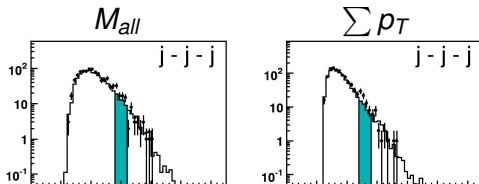


■  $M_{12}$  is the invariant mass of the two highest  $p_T$  electrons

# H1 General Search I



H1 General Search, HERA II  $e^+p$  (178 pb<sup>-1</sup>)



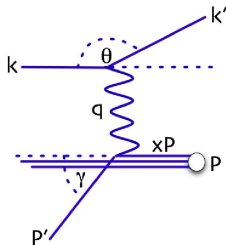
- Look for final states with high  $p_T$  objects,  $p_T > 20\text{GeV}$
- For each topology, examine  $\sum p_T$  and  $M_{all}$  distributions to look for deviation from SM
- Determine the significance of deviations

Overall, compatible with SM



# Back-up Slides

# Energy, Kinematics & Deep Inelastic Scattering



$$Q^2 = -q^2$$

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

Probing power

$$x = \frac{Q^2}{2p \cdot q}$$

Bjorken scaling variable

$$y = \frac{p \cdot q}{p \cdot k}$$

Inelasticity

$$s = (p + k)^2$$

Centre of mass energy

$$Q^2 = sxy$$

Neutral current

exchange of  $\gamma$  or  $Z^0$

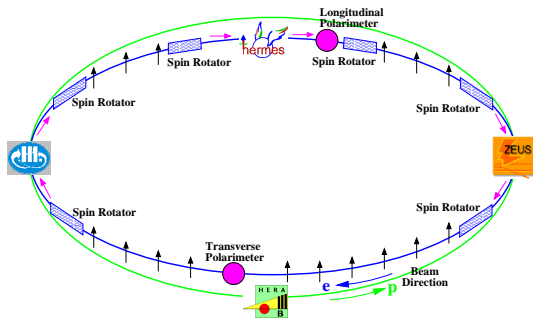
Charged current

exchange of  $W^\pm$

- Proton energy: 920 GeV
- Electron energy: 27.5 GeV
- $\sqrt{s} = 318 \text{ GeV}$

# HERA: Polarised Lepton Beam

- e beam becomes transversely polarized through emission of synchrotron radiation
- Spin rotators were installed during the HERA upgrade to obtain longitudinal polarization at both IPs
- Polarization measured by polarimeters
- Mean (lumi weighted) polarization achieved: 30 - 40%



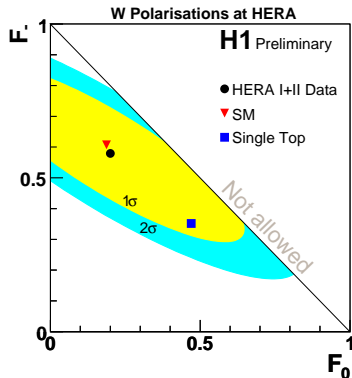
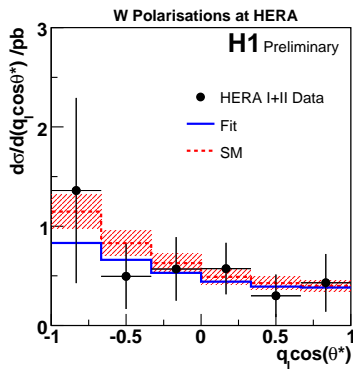
## $W^\pm$ Polarisation I

- Longitudinal polarisation fraction:  $F_0$
- Left handed polarisation fraction:  $F_-$
- Right handed polarisation fraction:  $F_+ = 1 - F_- - F_0$
- $\theta^*$  is the angle between the  $W^\pm$  momentum in the lab frame and the charged decay lepton in the  $W^\pm$  rest frame

$$\begin{aligned}\frac{dN_{W^+}}{d\cos\theta^*} &\propto (1 - F_- - F_0) \times \frac{3}{8}(1 + \cos\theta^*)^2 \\ &+ F_0 \times \frac{3}{4}(1 - \cos^2\theta^*) \\ &+ F_- \times \frac{3}{8}(1 - \cos\theta^*)^2\end{aligned}$$

- Fit data to  $\cos\theta^*$  distribution. Extract best values of  $F_-$  &  $F_0$

# $W^\pm$ Polarisation II



$$F_- = 0.58 \pm 0.15 \text{ (stat)} \pm 0.12 \text{ (sys)}$$

$$F_0 = 0.15 \pm 0.21 \text{ (stat)} \pm 0.09 \text{ (sys)}$$

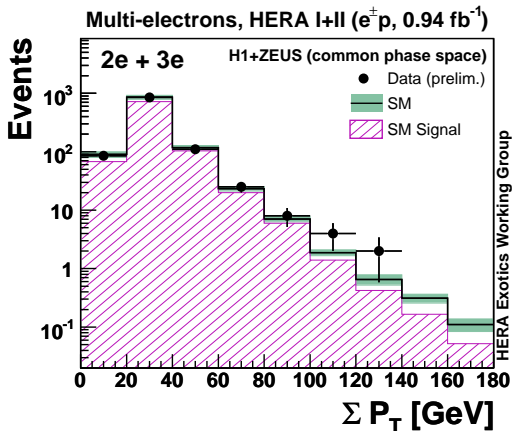
$$\text{SM: } 0.61 \pm 0.01 \text{ (stat)}$$

$$\text{SM: } 0.19 \pm 0.01 \text{ (stat)}$$

# Isolated Leptons: Table

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%)

# Multi-Electrons: 2e and 3e Samples Combined



# Multi-Leptons: Tables I

H1+ZEUS Multi-electron analysis HERA I+II ( $0.94 \text{ fb}^{-1}$ , preliminary)

Selection	Data	SM	Pair Production	NC-DIS + Compton
2e	937	$937 \pm 67$	$756 \pm 48$	$181 \pm 39$
3e	148	$161 \pm 10$	$160 \pm 10$	$0.4 \pm 0.01$
All	1085	$1098 \pm 75$	$916 \pm 58$	$182 \pm 39$

H1+ZEUS Multi-electron analysis HERA I+II ( $0.94 \text{ fb}^{-1}$ , preliminary)

$\Sigma P_T > 100 \text{ GeV}$				
Data sample	Data	SM	Pair Production	NC-DIS + Compton
$e^+p$ ( $0.56 \text{ fb}^{-1}$ )	5	$1.82 \pm 0.21$	$1.28 \pm 0.16$	$0.54 \pm 0.10$
$e^-p$ ( $0.38 \text{ fb}^{-1}$ )	1	$1.19 \pm 0.14$	$0.79 \pm 0.09$	$0.40 \pm 0.08$
$e^\pm p$ ( $0.94 \text{ fb}^{-1}$ )	6	$3.00 \pm 0.34$	$2.07 \pm 0.24$	$0.94 \pm 0.16$

# Multi-Leptons: Tables II

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	$1.85 \pm 0.24$	$1.85 \pm 0.24$	—

# Electron Radius

- Classical radius:  $2.82 \times 10^{-15}\text{m}$
- Bhabha scattering at LEP:  $2.8 \times 10^{-19}\text{m}$
- Drell-Yan at TeVatron:  $5.6 \times 10^{-19}\text{m}$
- Single electron in a Penning Trap:  $< 10^{-22}\text{m}$

## Contact Interactions II

- Effective Lagrangian for **vector**  $eeqq$  contact interactions:

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

- Different models assume different helicity structure of new interactions, given by set of couplings  $\eta_{\alpha\beta}^{eq}$
- 4 couplings for every flavour  $q$

### Models conserving parity:

Model	$\eta_{LL}^{ed}$	$\eta_{LR}^{ed}$	$\eta_{RL}^{ed}$	$\eta_{RR}^{ed}$	$\eta_{LL}^{eu}$	$\eta_{LR}^{eu}$	$\eta_{RL}^{eu}$	$\eta_{RR}^{eu}$
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$
X1	$+\eta$	$-\eta$			$+\eta$	$-\eta$		
X2	$+\eta$		$+\eta$		$+\eta$		$+\eta$	
X3	$+\eta$			$+\eta$	$+\eta$			$+\eta$
X4		$+\eta$	$+\eta$			$+\eta$	$+\eta$	
X5		$+\eta$		$+\eta$		$+\eta$		$+\eta$
X6			$+\eta$	$-\eta$			$+\eta$	$-\eta$
U1					$+\eta$	$-\eta$		
U2					$+\eta$		$+\eta$	
U3					$+\eta$			$+\eta$
U4						$+\eta$	$+\eta$	
U5						$+\eta$		$+\eta$
U6							$+\eta$	$-\eta$

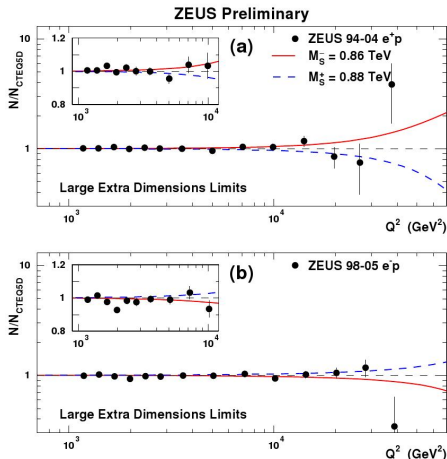
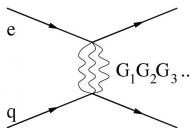
### Models violating parity:

LL	$+\eta$				$+\eta$			
LR		$+\eta$				$+\eta$		
RL			$+\eta$				$+\eta$	
RR				$+\eta$				$+\eta$

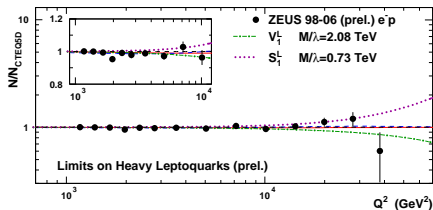
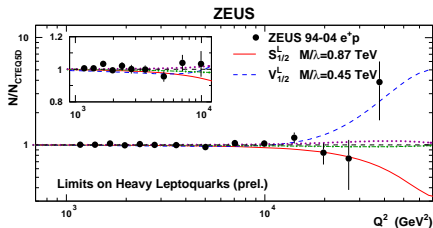
# Extra Dimensions

- Extra dimensions have size  $R \approx 1 \text{ mm}$  in the Arkani- Hamed- Dimopoulos- Dvali model (4+n dimension string theory)

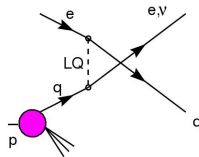
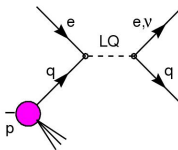
- Gravity is comparable in strength to EW f effective mass scale  $M_S \approx 1 \text{ TeV}$
- Contributions from graviton exchange to NC DIS cross-section.
- Contact interaction parameterization:  $\eta^G = \frac{\lambda}{M_S^4}$



# Heavy Leptoquarks



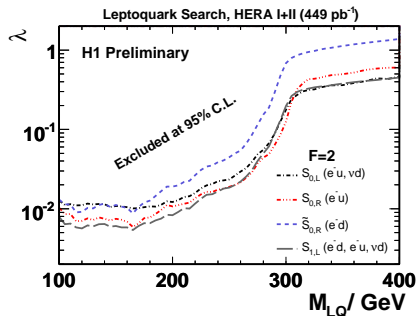
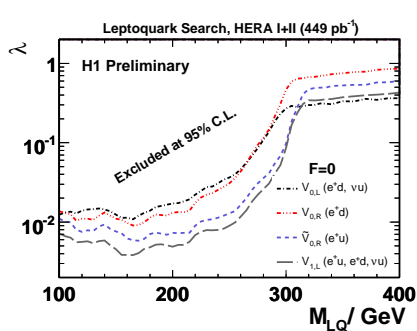
- Leptoquarks are scalar or vector colour triplet bosons
- They carry both lepton and baryon number
- Fermion number  $F = 3B + L$
- Model: RPV SUSY for example



# Leptoquarks: The Buchmüller-Rückl-Wyler model

- Standard model symmetries are conserved (lepton and baryon number conserved)
- Leptoquark couplings are flavor diagonal ( $\rightarrow$  no FCNC)
- Couple either to left-handed or to right-handed leptons
- 7 scalar and 7 vector leptoquarks
- All 14 LQs couple to  $eq$ , 2 scalar and 2 vector LQs also to  $\nu q$
- For  $e^-p$ ,  $F=2$  is preferred (produced from valence quarks), LQs with  $F=0$  produced from antiquarks (sea quarks)
- For  $e^+p$ ,  $F=0$  is preferred (produced from valence quarks), LQs with  $F=2$  produced from antiquarks (sea quarks)

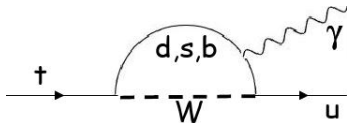
# Leptoquarks: No Lepton Flavour Violation



## FCNC: SM & BSM

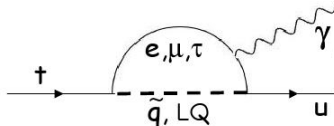
### Standard Model

- FCNC one-loop process mediated by W-boson.
- Strongly suppressed by GIM mechanism

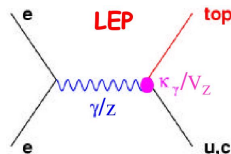
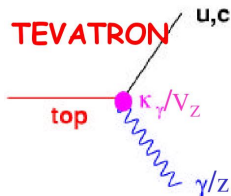
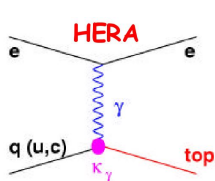


### Beyond Standard Model

- Leptoquarks or squarks enter the loop
- Enhance FCNC beyond the SM expectation



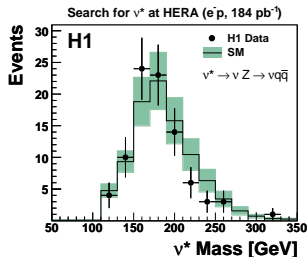
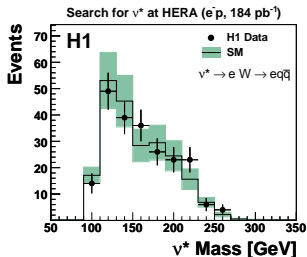
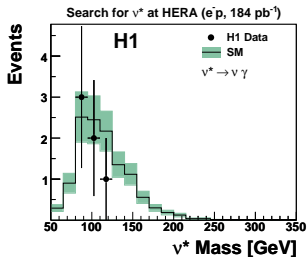
# FCNC: HERA, TeVatron & LEP



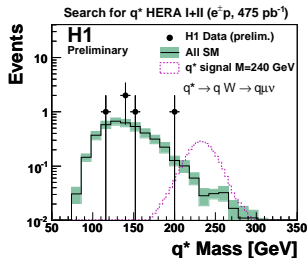
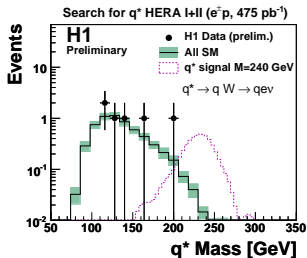
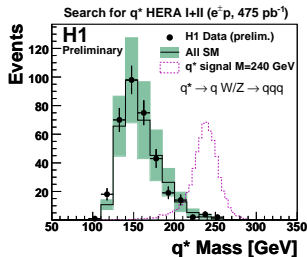
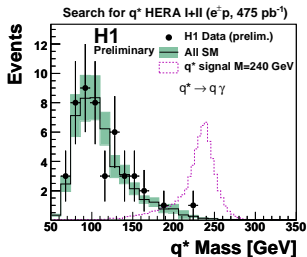
- LEP and TeVatron have sensitivity to  $\kappa_{tc\gamma}$
- HERA has low sensitivity to  $\nu_{tuZ}$



# H1 Excited Neutrinos

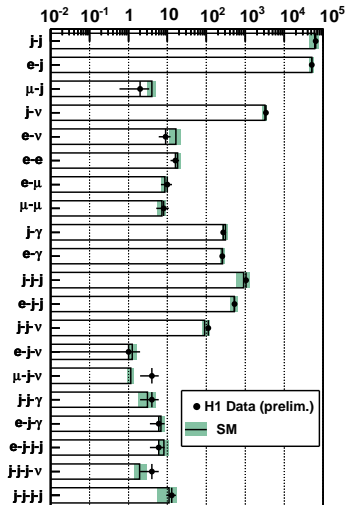


# H1 Excited Quarks



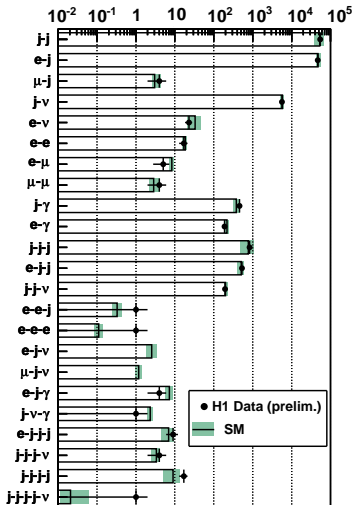
# H1 General Search I

Events



H1 General Search, HERA II  $e^+p$  (178  $\text{pb}^{-1}$ )

Events



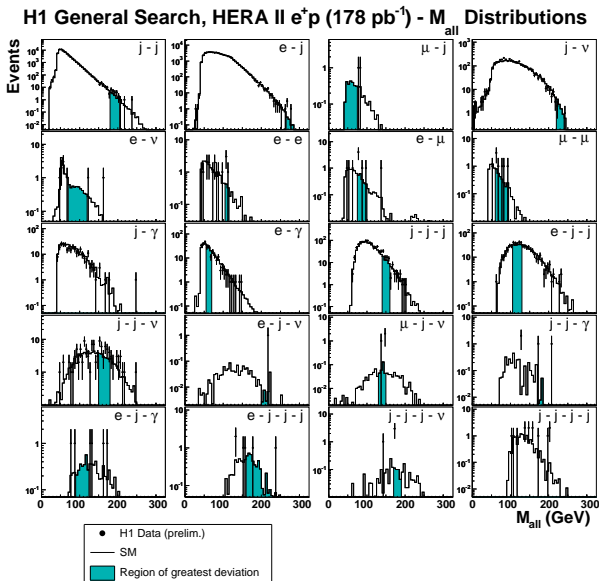
H1 General Search, HERA II  $e^-p$  (159  $\text{pb}^{-1}$ )

- Final states with high  $p_T$  objects,  $p_T > 20\text{GeV}$
- Overall good agreement with SM

# H1 General Search II

- Look at invariant mass and  $\sum p_T$  distributions for each channel
- Select window with largest deviation from SM using statistical estimator,  $p$ . The region of greatest interest (largest deviation) has the smallest  $p$  value,  $p_{min}^{data}$
- Determine the significance of this fluctuation:
  - Randomly fill many hypothetical data histograms from the probability density function of the SM prediction
  - Find the region of greatest deviation and  $p_{min}^{SM}$  for each hypothetical SM histogram
  - $\hat{P}$  is the fraction of data histograms with  $p_{min}^{SM} < p_{min}$

# H1 General Search: Region of Greatest Deviation



# H1 General Search: Statistical Estimator $p$

$$p = A \int_0^\infty db G(b; N_{SM}, \delta N_{SM}) \sum_{i=N_{obs}}^{\infty} \frac{e^{-b} b^i}{i!} \quad \text{if } N_{obs} > N_{SM}$$

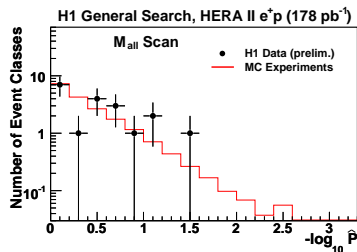
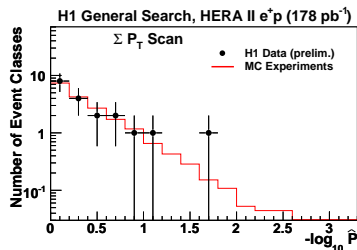
$$p = A \int_0^\infty db G(b; N_{SM}, \delta N_{SM}) \sum_{i=0}^{i=N_{obs}} \frac{e^{-b} b^i}{i!} \quad \text{if } N_{obs} < N_{SM}$$

$$A = \left( \int_0^\infty db G(b; N_{SM}, \delta N_{SM}) \sum_{i=0}^{\infty} \frac{e^{-b} b^i}{i!} \right)^{-1} \quad (\text{normalise to 1})$$

Convolution of:

- Poisson probability density function to account for statistical errors
- Gaussian probability density function to account for non-negligible systematic uncertainties

# H1 General Search: $\hat{P}$



- $\hat{P}$ : a measure of the statistical significance of the deviation observed in the data
- A  $p_{\text{min}}$  value of  $5.7 \times 10^{-7}$  (a  $5\sigma$  effect) corresponds to  $-\log_{10} \hat{P}$  between 5 and 6