Searches Beyond the Standard Model at HERA

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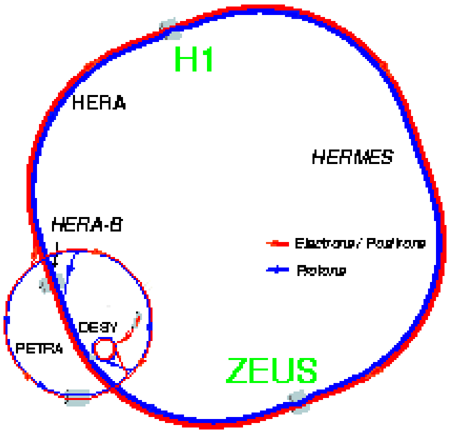
On behalf of the ZEUS & H1 Collaborations

Outline:

- Introduction to HERA
- Excited Fermions
- Leptoquarks
- Lepton Flavour Violation
- $\not{R}_p$ Supersymmetry Searches
- Contact Interactions
- Prospects for the future …

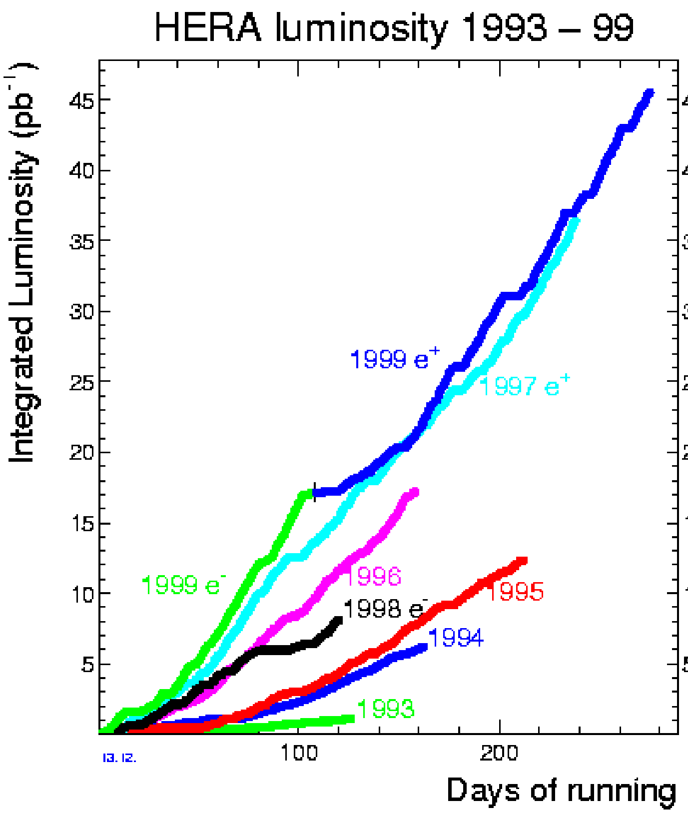
Lake Louise Winter Institute : 20-26 February 2000

HERA Physics ...

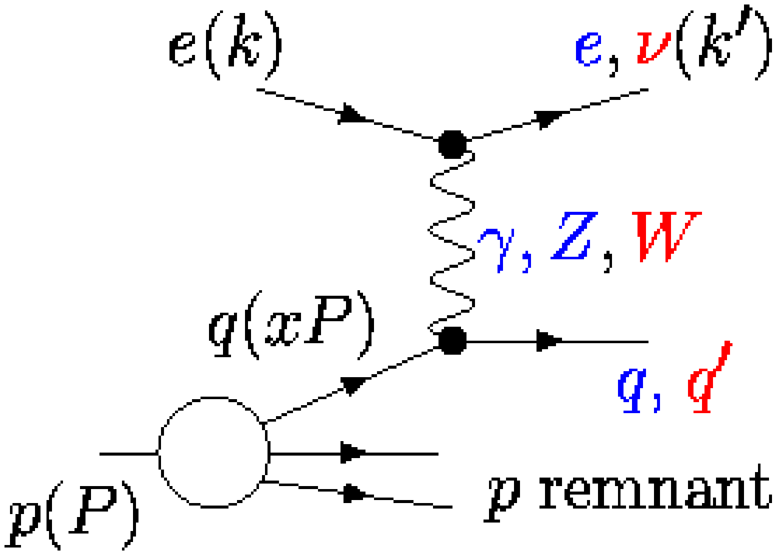


$e^{\pm}\ 27.5\ GeV$
$p\ 820-920\ GeV$
$\longrightarrow \sqrt{s} \approx 300-320\ GeV$

- *1994-1997:* $e^{+}p@820GeV$
  - $\mathcal{L} \approx 37(H1),\ 47(ZEUS)pb^{-1}$
- *1998-1999:* $e^{-}p@920GeV$
  - $\mathcal{L} \approx 16pb^{-1}$
- *July 1999-present:* $e^{+}p@920GeV$
  - $\mathcal{L} \approx 21pb^{-1}$



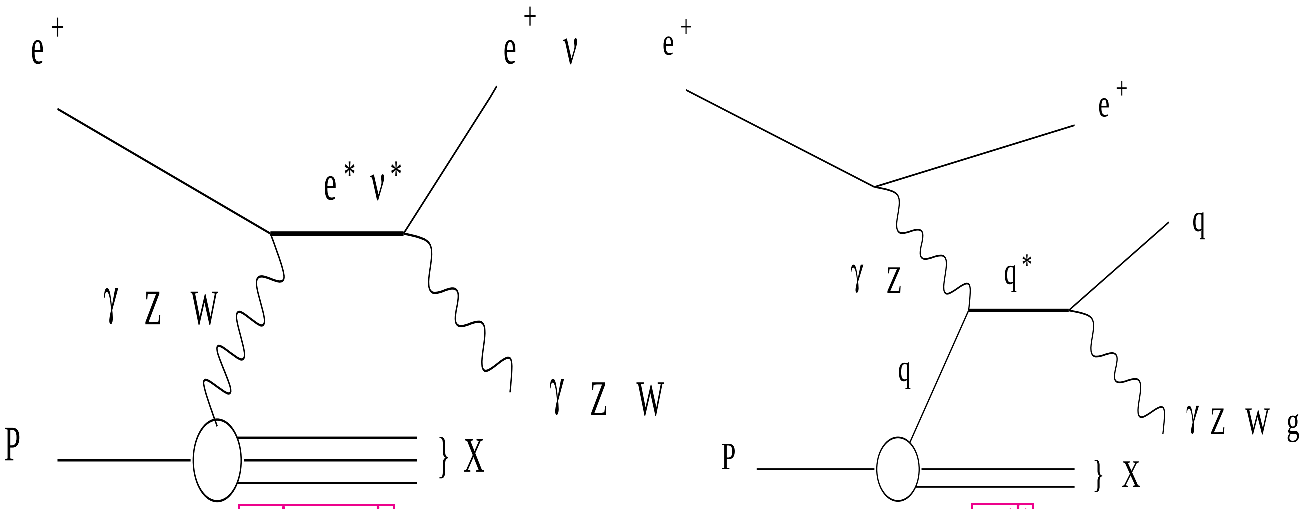
Main SM Process : *Deep Inelastic Scattering* (DIS)



$$
\begin{aligned}
Q^2 &= -(k-k')^2 = sxy \\
x &= \frac{Q^2}{2P\cdot(k-k')} \\
y &= \frac{P\cdot(k-k')}{P\cdot k}
\end{aligned}
$$

Excited Fermions

Excited fermions are signals for compositness at energies $O(\Lambda_{compositness})$.



$\boxed{e^*, \nu^*}$ $\boxed{q^*}$

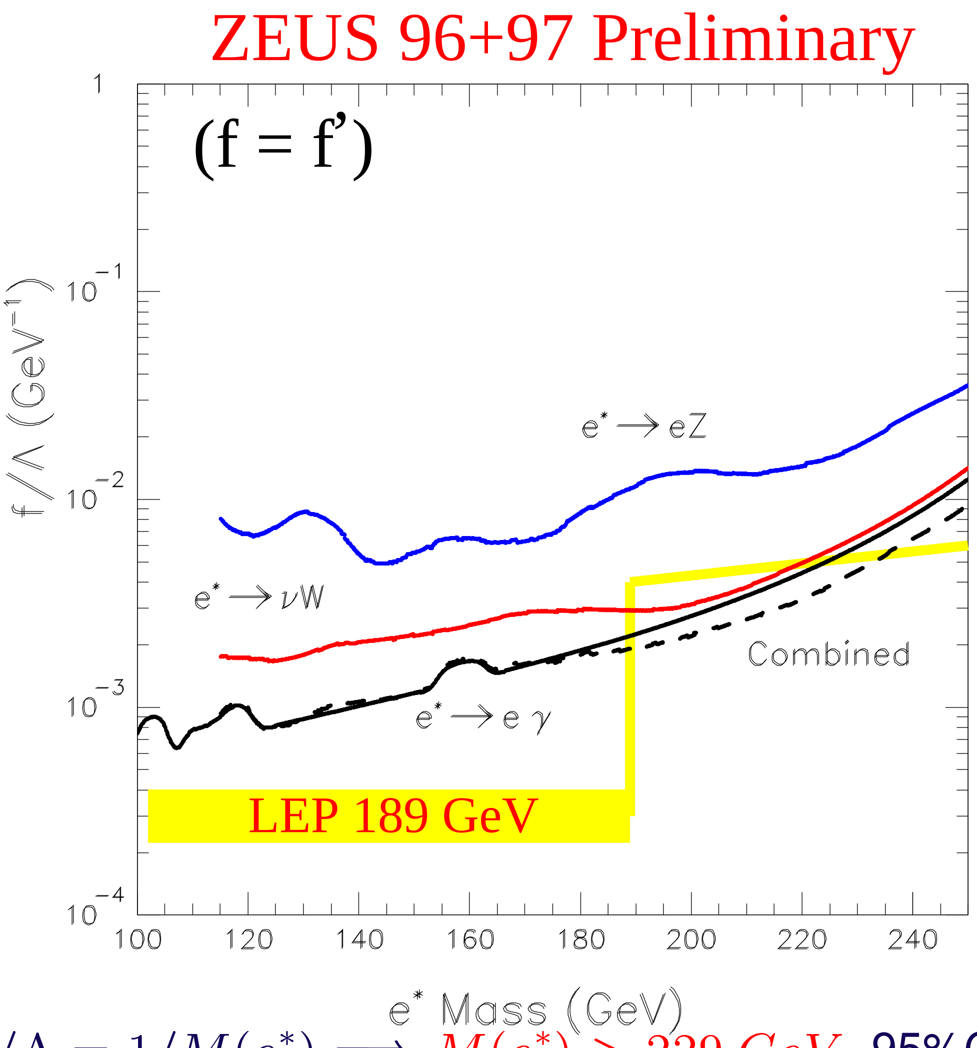
Phenomenological Model of *Hagiwara, Komamiya & Zeppenfeld :*

$$\mathcal{L}_{ff^*} = \frac{1}{\Lambda} \cdot f_R^* [f(gV)_{SU(2)_L} + f'(gV)_{U(1)_Y} + f_s(gV)_{SU(3)_c}] f_L$$

- Multiple signatures: $e+\gamma, e+jets, e+P_T^{miss}, \gamma+P_T^{miss}$
- Search for a fermion-boson resonance.

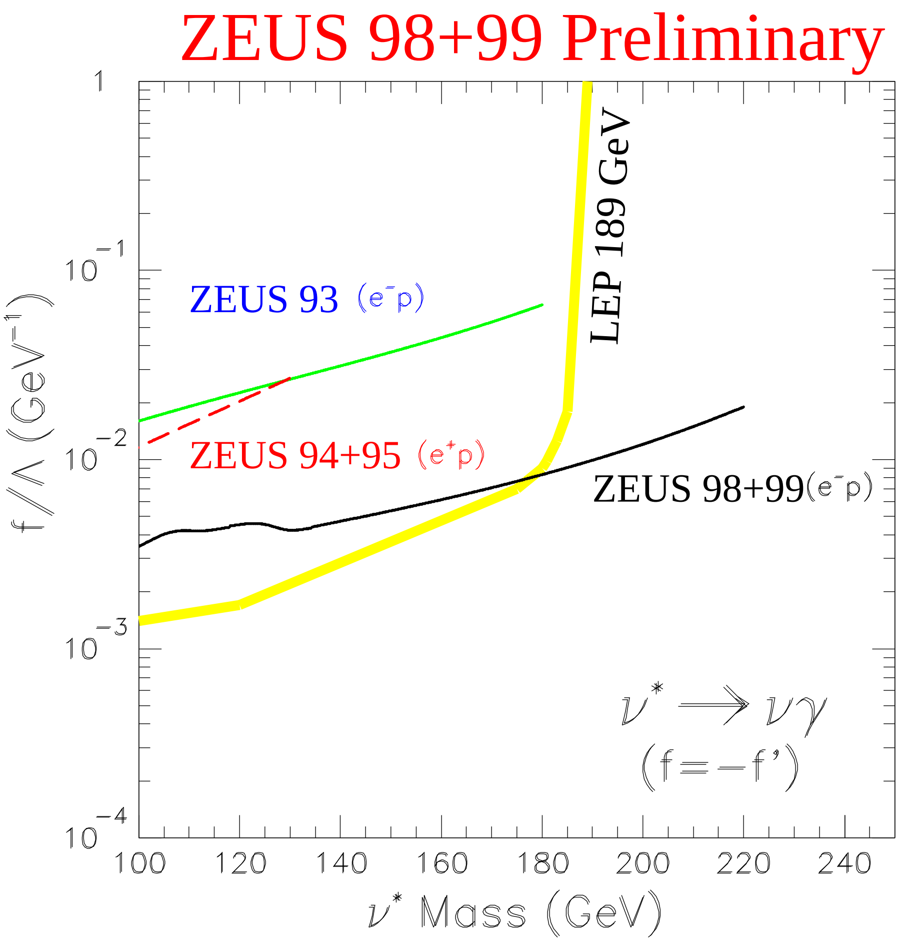
No evidence for a resonance peak was observed, hence limits are set on f/Λ where $|f| = |f'|$ & $f_s = 0$

e^* limits



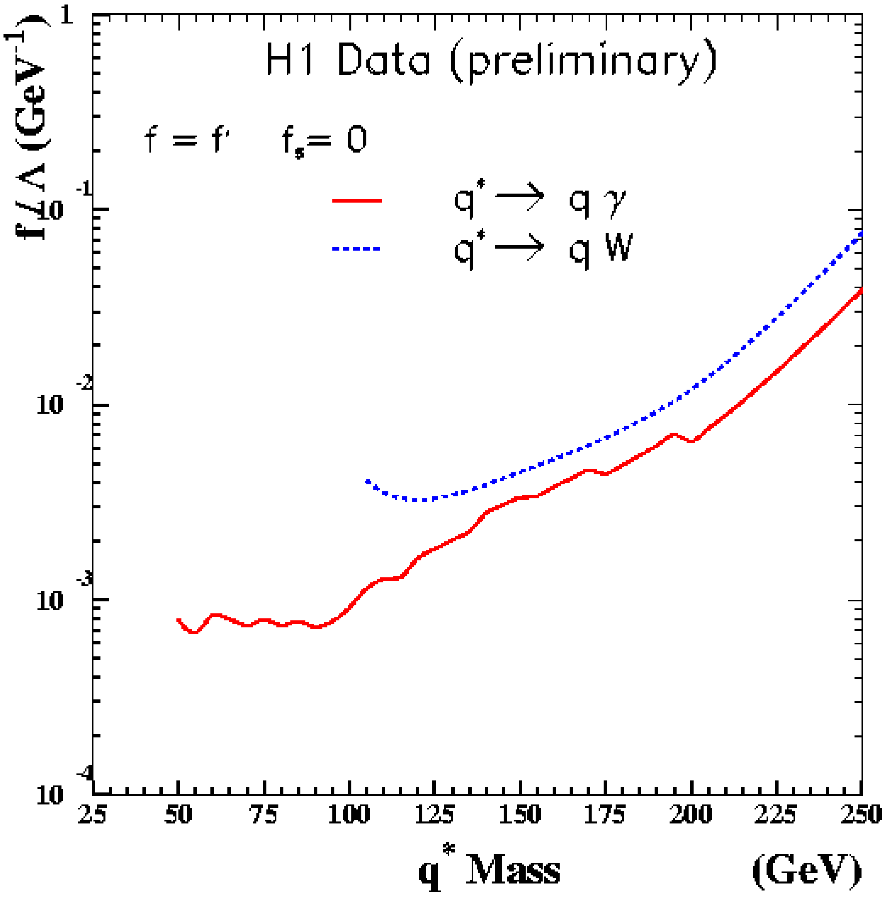
- $f/\Lambda = 1/M(e^*) \Longrightarrow M(e^*) > 229\ GeV$ 95%CL
- HERA is setting exclusion limits for $M_{e^*} > \sqrt{s_{LEP}}$ $\Longrightarrow$ Competitive

ν^* limits



- $\sigma(e^- p \to \nu^* X) \sim 100\sigma(e^+ p \to \nu^* X)$ at high mass $\Longrightarrow e^- p$ data more sensitive to ν^*
- $\nu^* \to \nu\gamma$ assumes $f = -f'$
- $f/\Lambda = 1/M(\nu^*) \Longrightarrow M(\nu^*) > 161\ GeV$ 95%CL
- Again limits extend beyond LEP kinematical limits

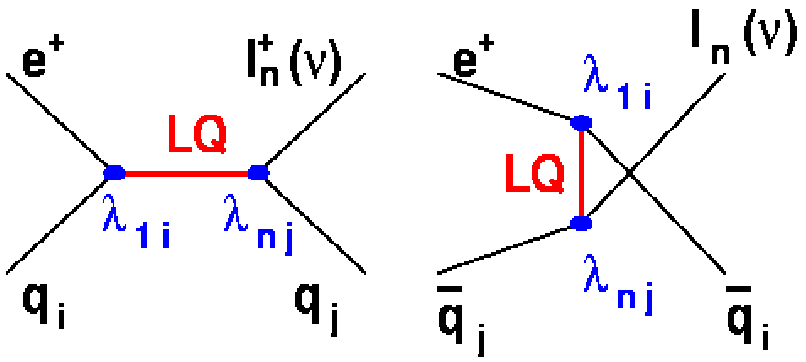
q^* limits



- $f/\Lambda = 1/M(q^*)$ ($f = f'$, $f_s = 0$)
  $\Longrightarrow M(q^*) > 250\ GeV$
- Tevatron excludes $M(q^*) = 80 - 300\ GeV$
  for $\Lambda = M(q^*)$ & $f = f' = f_s > 0.2$
  Production at Tevatron requires $f_s \neq 0$, while HERA limits are valid for $f_s = 0 \Longrightarrow$ Complementary

Leptoquarks

Leptoquarks are particles which couple to both quarks & leptons.



Buchmüller,Rückl,Wyler (BRW) Model:

- The different species of LQs are classified by their quantum numbers $S^J_{L,R}$ & $V^J_{L,R}$
- $\beta = BR(LQ \to eq) = 0.5, or 1$
- e^+p collisions : *s*-channel $F = 0$ & *u*-channel $F = |2|$ The opposite for e^-p collisions.

Signal:

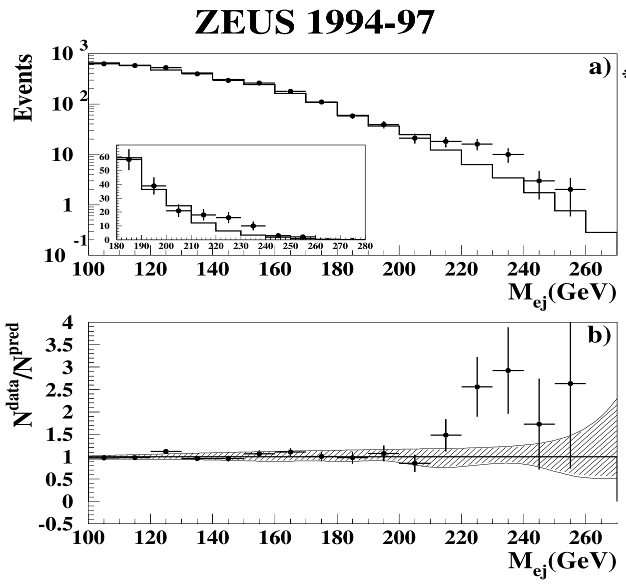
- Narrow resonance in $M_{eq} = \sqrt{x \cdot s}$
- y distribution:
  $\to$ scalar LQ: ~ 1
  $\to$ vector LQ: $\sim (1 - y)^2$

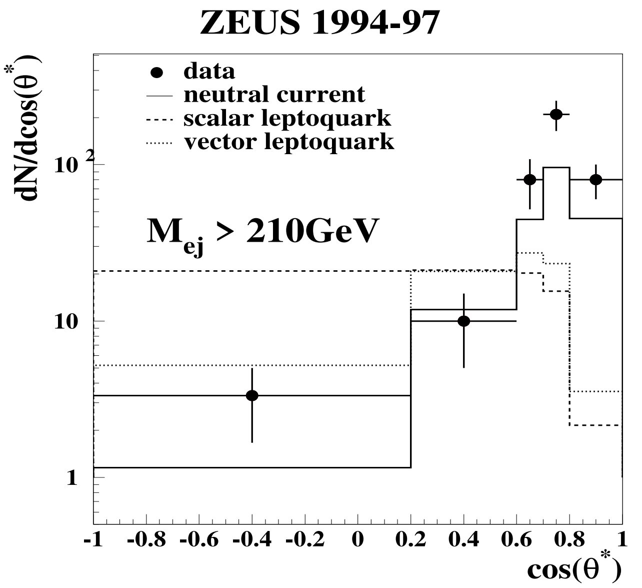
Background:

- Same event topology as NC & CC DIS
- NC DIS:$\sim 1/y^2$

1st Generation Letoquarks (BRW):

Search for an electron-jet invariant mass resonance in the High Q^2 NC DIS data.





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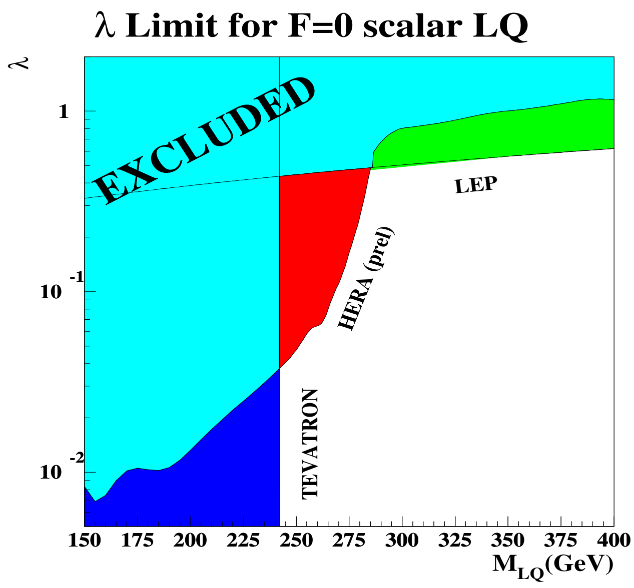
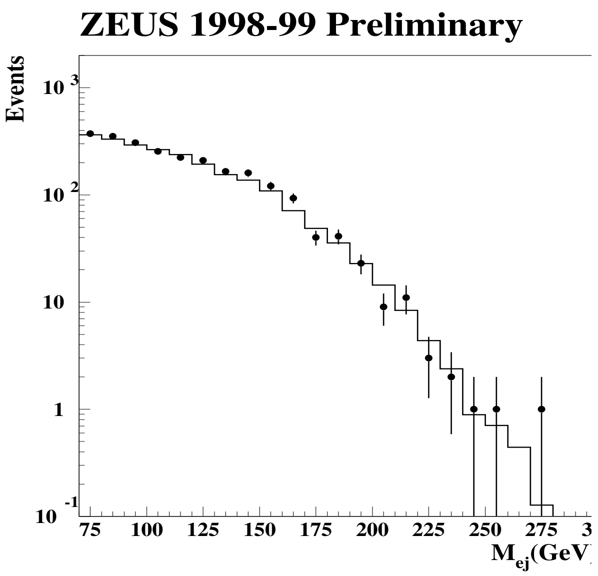
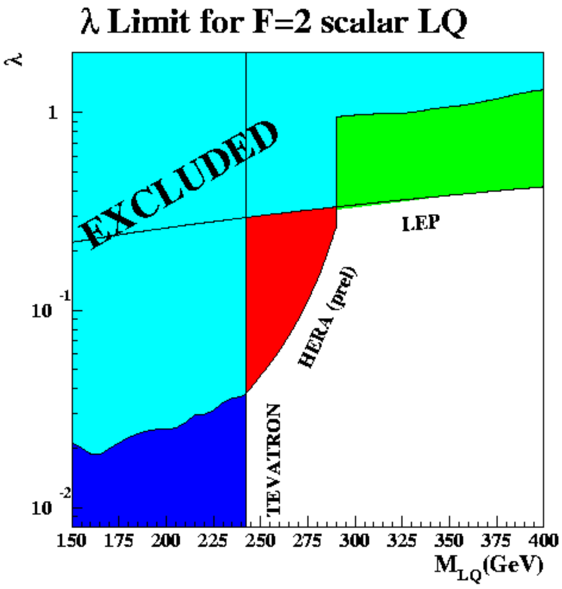


- Small *excess* not consistent with BRW assumption.
  (excess at large $cos\theta^* = 1 - 2y$ or low y)
- e^+p data more sensitive to $F = 0$ LQs
- $F = 0$ LQs for $\lambda = 0.3$ Scalar (Vector) LQs can be excluded at 95% CL up to $275(285)\ GeV$

- 1998-1999 HERA e^-p with higher $\sqrt{s} \approx 320\ GeV$
- e^-p data more sensitive to $F = |2|$ LQs ($e^-q \rightarrow LQ$ instead of $e^+\bar{q} \rightarrow LQ$)
- Same selection as 1994-1997 e^+p analysis. No signal



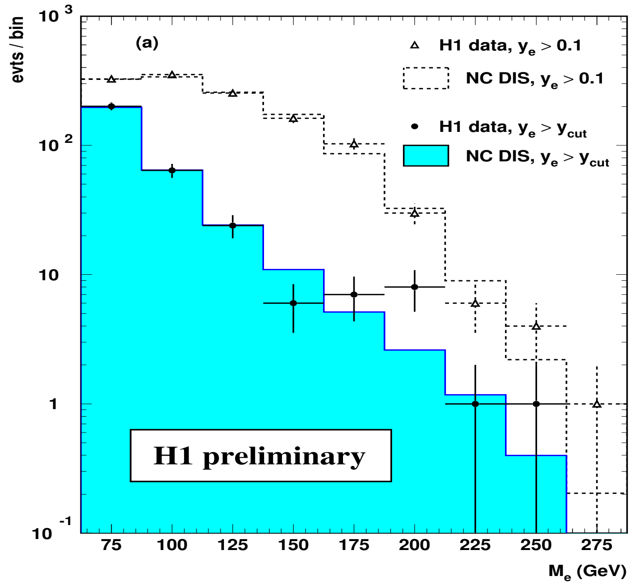


- M_{ejet} & $cos\theta^*$ distributions compatible with NC DIS.
- $F = |2|$ LQs for $\lambda = 0.3$ Scalar (Vector) LQs can be excluded at 95% CL up to $290(275)\ GeV$

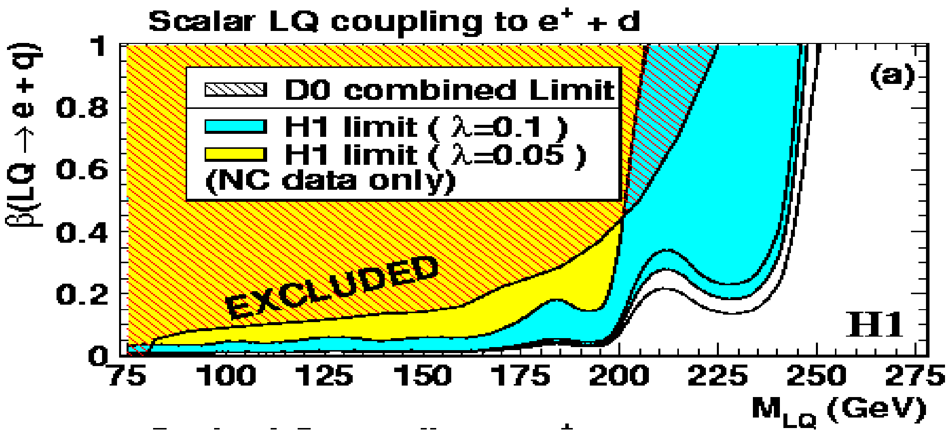
Relaxing the BRW Assumptions

- In BRW: $\beta = BR(LQ \to eq, \nu q)$ are fixed.
  Take $BR(LQ \to lq)$ as a free parameter.

HERA's Sensitivity in a more *generic* model



- Discovery potential for small β_e high β_ν

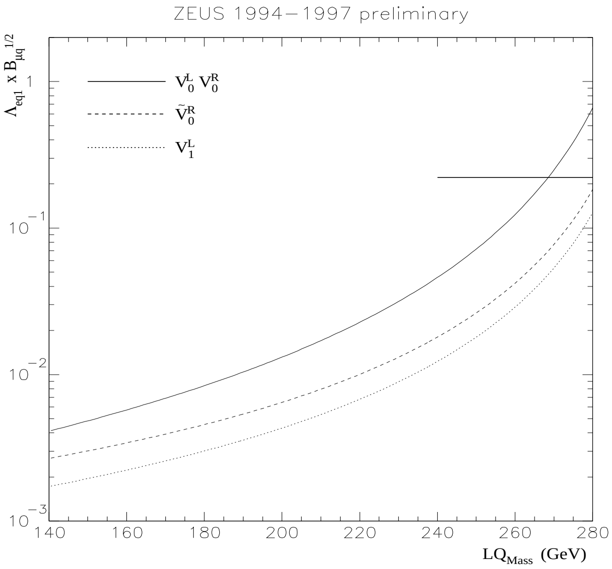


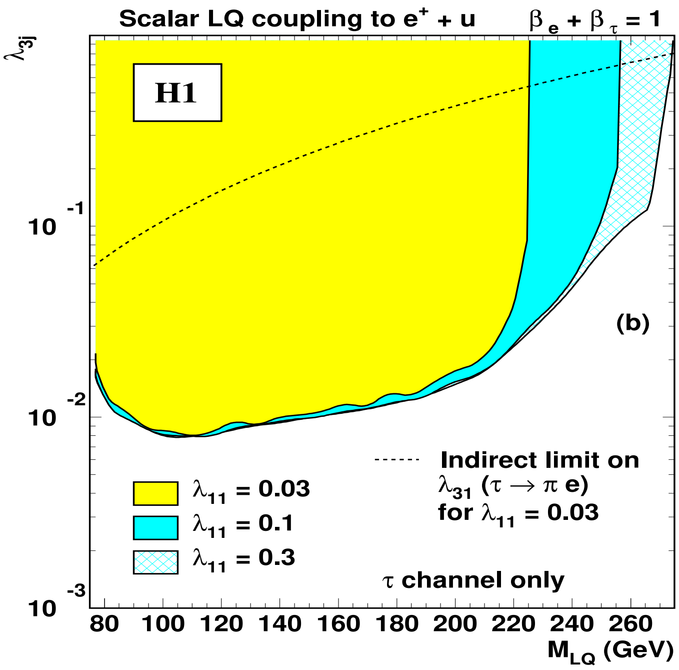
Lepton Flavour Violation (LFV)

LFV can be manifested by LQs coupling to both eq & $\mu q(\tau q)$

- Both H1 & ZEUS performed a search for $LQ \rightarrow \mu q$ topologies.
- H1 observed 4 events, None compatible with LQ kinematics.
- ZEUS had no candidate constraints on $\lambda \times \sqrt{\beta\mu}$

ZEUS Preliminary 94-97 e^+p data





- $e+p \rightarrow \tau + X$ ($\tau \rightarrow hadrons$) studied by H1
- No $\tau + jet$ candidate found
- Exclusion limits at 95% CL on λ_{3j} for fixed λ_{11}

LFV $e + p \to \tau + X$ F=0 Leptoquarks

e ⟷ τ							F = 0
BEST EXCLUSION UPPER LIMITS ON $\frac{\lambda_{1i}\lambda_{3j}}{M^2_{LQ}}$ (in 10^{-4} GeV^{-2}) FOR LEPTON FLAVOUR VIOLATING LEPTOQUARKS							
$q_i\ q_j$	$S_{1/2,L}$	$S_{1/2,R}$	$\tilde{S}_{1/2,L}$	$V_{0,L}$	$V_{0,R}$	$\tilde{V}_{0,R}$	$V_{1,L}$
1 1	$\tau \to \pi e$ 0.0032 H1: 0.046	$\tau \to \pi e$ 0.0016 H1: 0.037	$\tau \to \pi e$ 0.0032 H1: 0.062	G_F 0.002 H1: 0.049	$\tau \to \pi e$ 0.0016 H1: 0.049	$\tau \to \pi e$ 0.0016 H1: 0.041	G_F 0.002 H1: 0.019
1 2	ZEUS: 0.12 H1: 0.047	$\tau \to K e$ 0.05 H1: 0.038	$\tau \to K e$ 0.05 H1: 0.063	$\tau \to K e$ 0.03 H1: 0.053	$\tau \to K e$ 0.03 H1: 0.053	ZEUS: 0.10 H1: 0.045	$K \to \pi \nu \bar{\nu}$ 2.5 x 10^{-6} H1: 0.021
1 3	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.065	$B \to \tau \bar{e} X$ 0.08 H1: 0.065	$B \to l \nu X$ 0.02 H1: 0.062	$B \to \tau \bar{e} X$ 0.04 H1: 0.062	*	$B \to l \nu X$ 0.02 H1: 0.062
2 1	ZEUS: 0.34 H1: 0.15	$\tau \to K e$ 0.05 H1: 0.095	$\tau \to K e$ 0.05 H1: 0.12	$\tau \to K e$ 0.03 H1: 0.064	$\tau \to K e$ 0.03 H1: 0.064	ZEUS: 0.10 H1: 0.073	$K \to \pi \nu \bar{\nu}$ 2.5 x 10^{-6} H1: 0.032
2 2	$\tau \to e \gamma$ 0.03 H1: 0.18	$\tau \to e \gamma$ 0.02 H1: 0.10	ZEUS: 0.48 H1: 0.13	ZEUS: 0.25 H1: 0.076	ZEUS: 0.25 H1: 0.076	ZEUS: 0.31 H1: 0.107	ZEUS: 0.13 H1: 0.044
2 3	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.14	$B \to \tau \bar{e} X$ 0.08 H1: 0.14	$B \to l \nu X$ 0.02 H1: 0.112	$B \to \tau \bar{e} X$ 0.04 H1: 0.112	*	$B \to l \nu X$ 0.02 H1: 0.112
3 1	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.16	$B \to \tau \bar{e} X$ 0.08 H1: 0.16	V_{ub} 0.002 H1: 0.068	$B \to \tau \bar{e} X$ 0.04 H1: 0.068	*	V_{ub} 0.002 H1: 0.068
3 2	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.19	$B \to \tau \bar{e} X$ 0.08 H1: 0.19	$B \to l \nu X$ 0.02 H1: 0.083	$B \to \tau \bar{e} X$ 0.04 H1: 0.083	*	$B \to l \nu X$ 0.02 H1: 0.083
3 3	*	ZEUS: 0.72 H1: 0.23	ZEUS: 0.72 H1: 0.23	$\tau \to e \gamma$ 0.51 Z H1: 0.14	$\tau \to e \gamma$ 0.51 Z H1: 0.14	*	ZEUS: 0.38 H1: 0.14

$R\!\!\!/_p$ Supersymmetry

- General Superpotential contains:

$$W_{R\!\!\!/_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

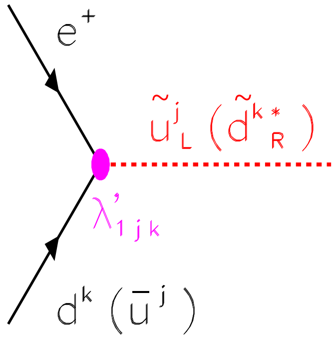
- $R_p = (-1)^{3B+L+2S}$ is +1 for SM & -1 for SUSY

<u>If R-parity is not conserved</u>

- Resonant production of SUSY particles at HERA up to the kinematical limit.
- Lightest Supersymmetric Particle (LSP) is not necessarily stable.

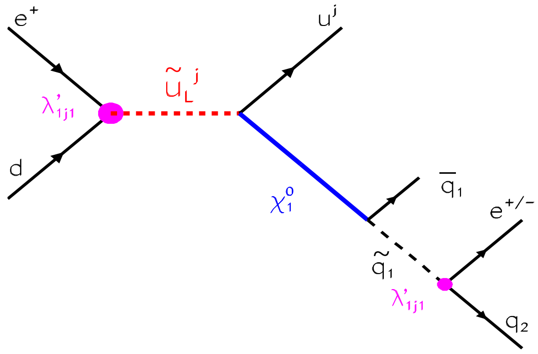
$\lambda'_{ijk} L_i Q_j \bar{D}_k \Longrightarrow$

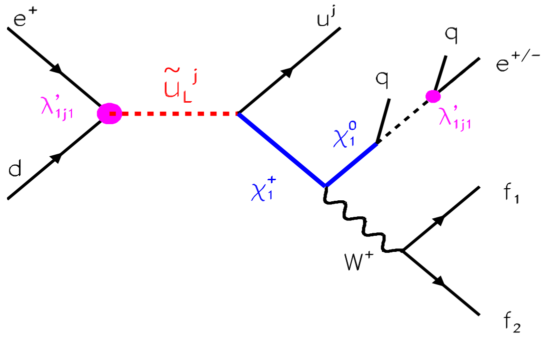
(Relevant for HERA)



$\Longrightarrow e^+ q, \nu q$

(*LQ-like*)

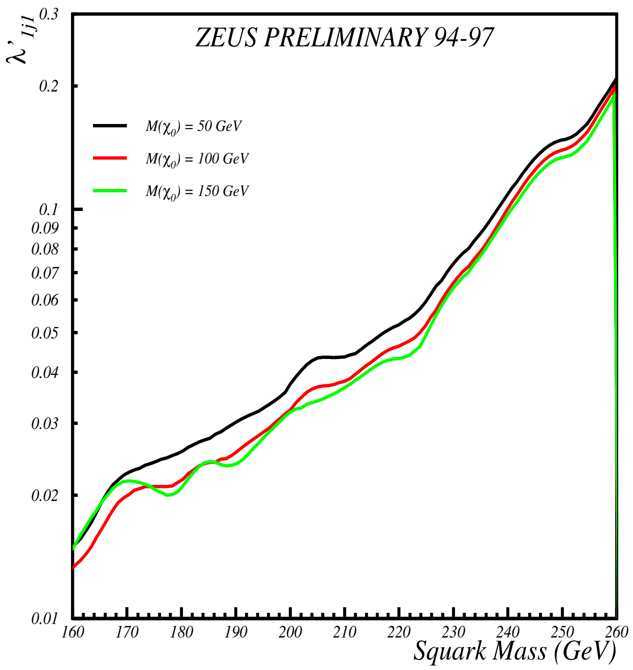


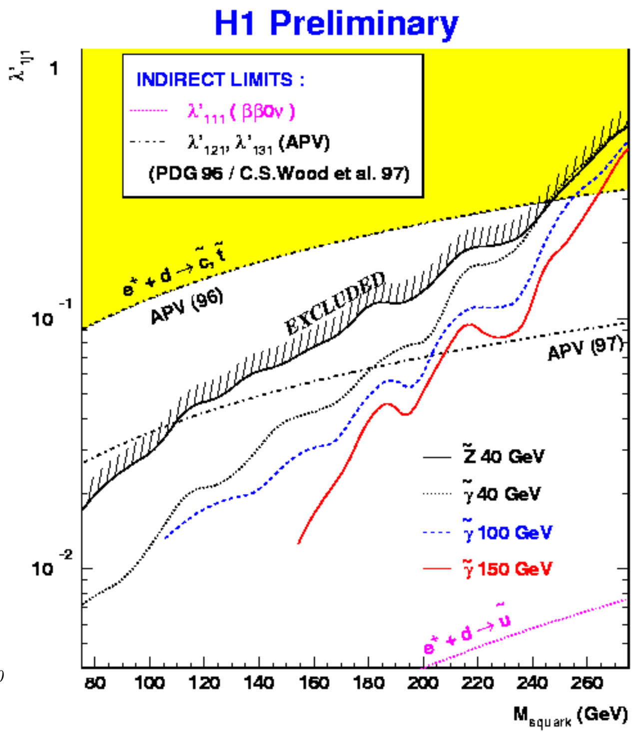


$\Longrightarrow$ *wrong sign lepton* signature (background free)

$\not{R}_p$ Squark λ'_{1j1} limits

- H1 & ZEUS perform search combining $eq, e^+ + jets, e^- + jets$ topologies
- Both experiments see no deviation from SM.
- The Rejection limits depend on masses & mixtures of the $\chi_i^0, \chi_j^+ \longrightarrow$ MSSM parameters





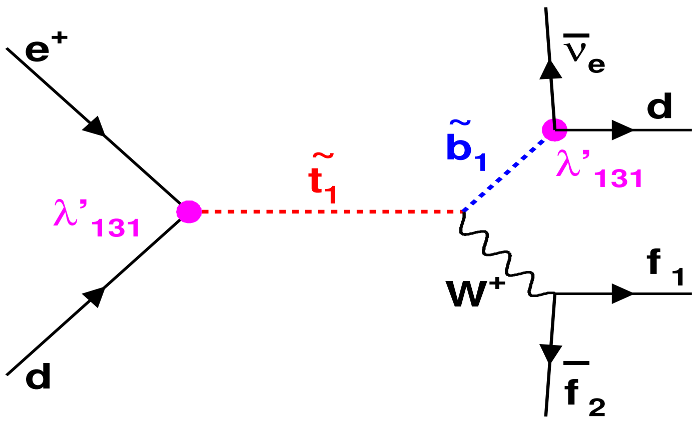
- ZEUS:
  - LSP is pure photino $\chi_1^0 = \tilde{\gamma}$
  - $\beta_{eq} + \beta_{\tilde{\gamma}q} = 1$
- H1:
  - LSP dominated by $\tilde{\gamma}, \tilde{Z}$

- for $\lambda' = 0.3 \Longrightarrow M_{\tilde{q}} > 270\ GeV$
- comparable/better $\lambda'_{121}, \lambda'_{131}$ sensitivity than indirect limits (APV)

$\not{R}_p$ SUSY : $\nu + jets$ Signatures

- H1 has also studied the channel $\tilde{q} \to q\chi$ followed by $\chi \to \nu qq$
- No signal observed
- As a *by-product* of this analysis H1 looked at the following topology:

  (Assumptions: $\tilde{b}_1$ is the LSP with $M_{\tilde{b}_1} < M_{\tilde{t}_1} < M_{\chi_1^+}$)

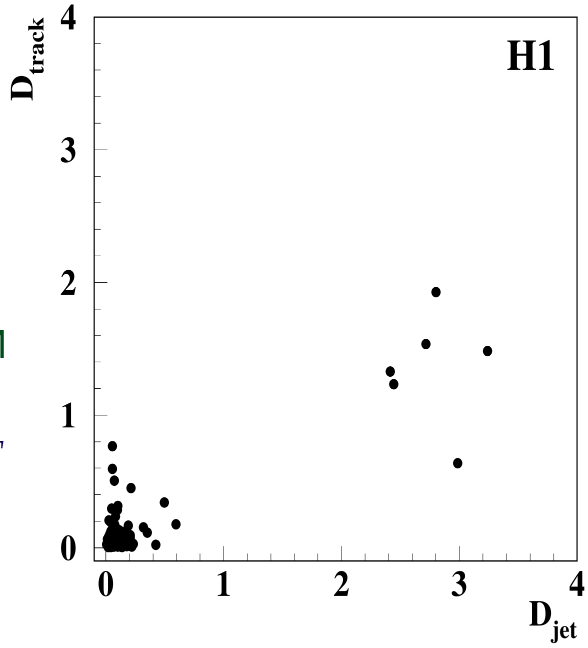


- H1 reported an *excess* of isolated High P_T muons : 5 observed 0.8 expected from SM processes. ZEUS observed no such excess.
- Kinematics of the *H1 μ events* not incompatible with $M(\tilde{t}_1) \sim 200\ GeV,\ M(\tilde{b}_1) \sim 100\ GeV$
- No signal seen by H1 in the $W \to hadrons$ channel

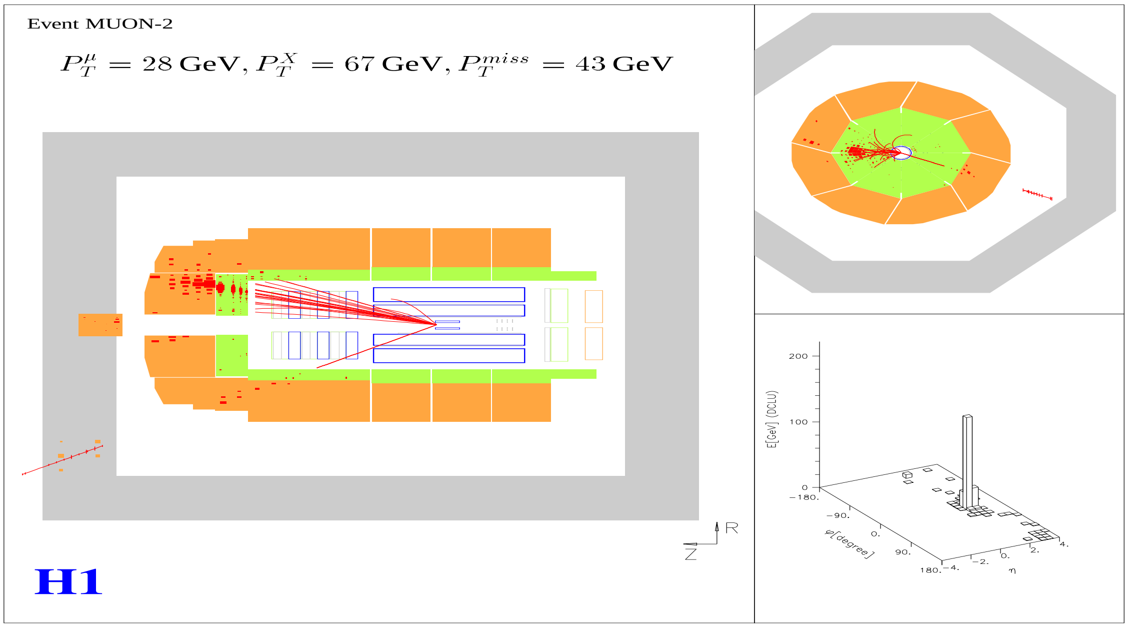
$\Longrightarrow$ μ events unlikely to come from this process for the assumed $\tilde{t}$ & $\tilde{b}$ masses.

H1 High P_T μ events

- Main Cuts
  $P_T^{CAL} > 25\ GeV$
  & $P_T^{trk} > 10 GeV$
  $\Longrightarrow$ Large reduction of SM Background.
- Look at Isolated High P_T tracks

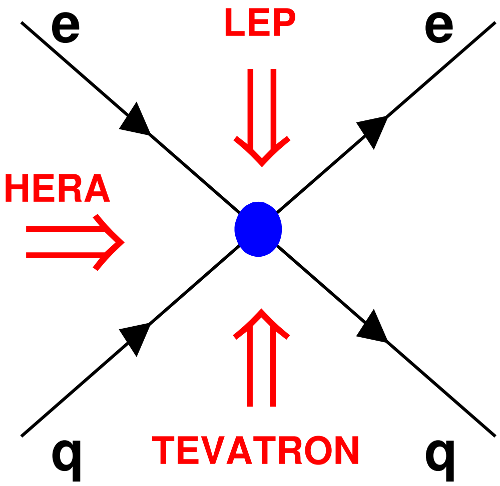


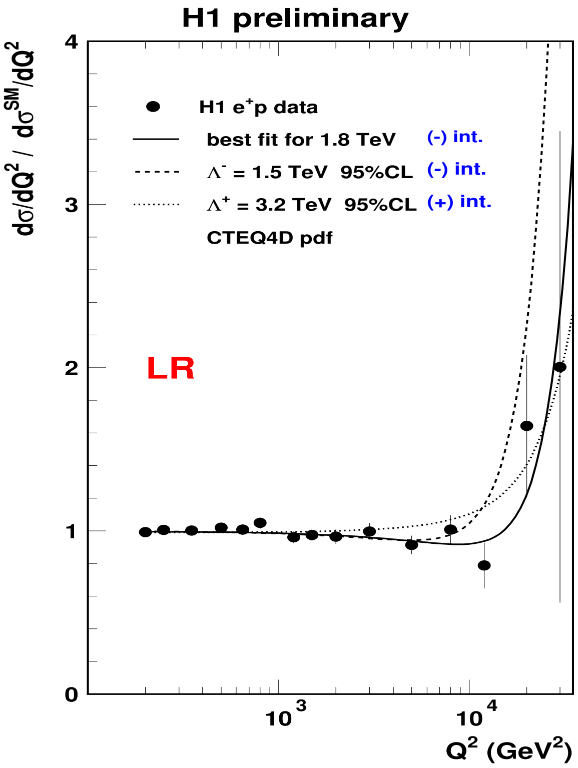
$$e^+ p \rightarrow \mu^+ X$$



Contact Interactions

- At HERA, new phenomena at mass scales above the kinematical limit can be approximated in their low energy limit by $eeqq$ CI.





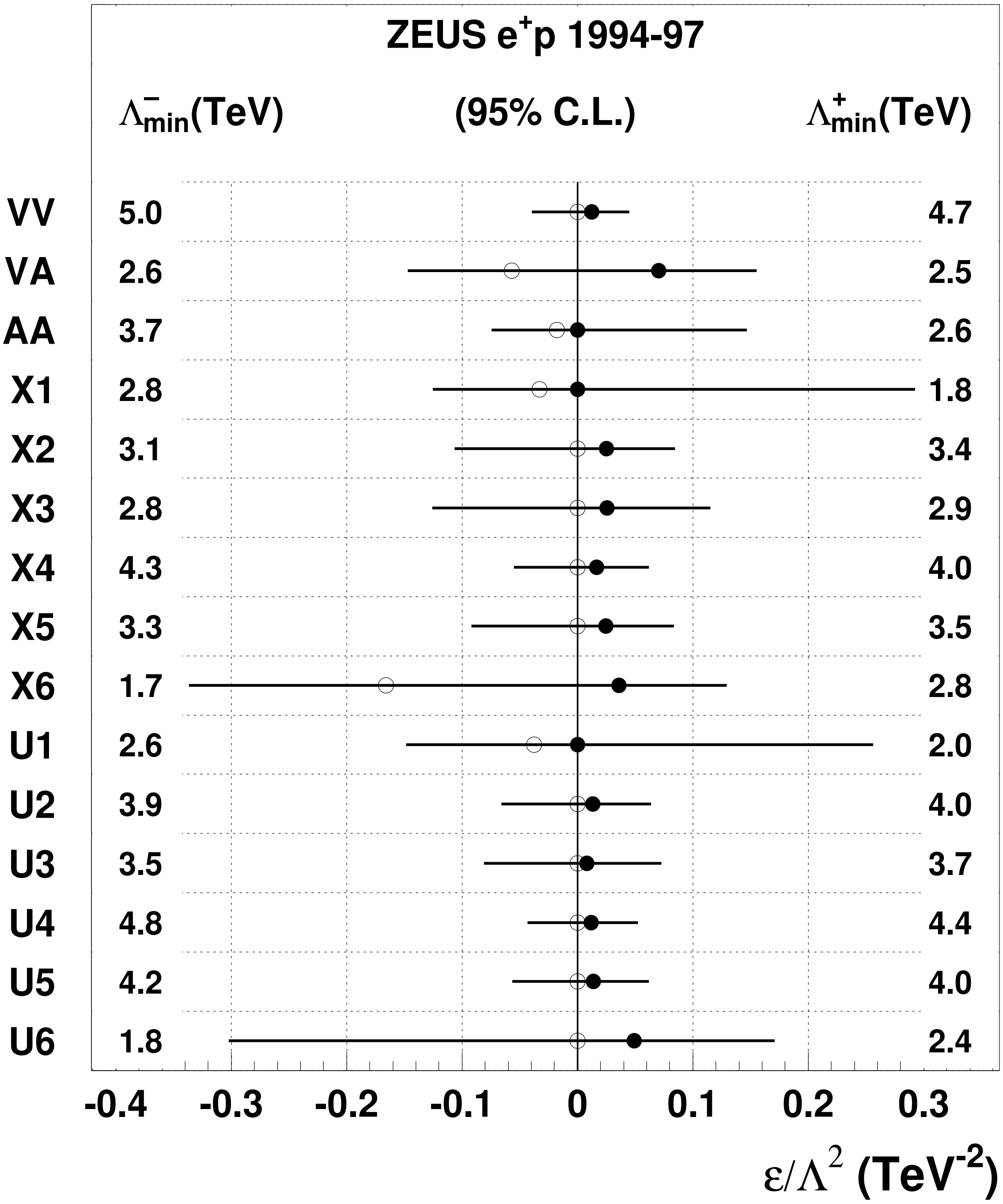
- Only Vector terms are considered since strong limits beyond HERA's sensitivity have been placed on the scalar & tensor terms.

$$\mathcal{L}_{CI} = \Sigma\eta_{ij}^{eq}(\bar{e}_i\gamma^{\mu}e_i)(\bar{q}_j\gamma_{\mu}q_j)$$

$$(i, j = L, R)$$

- Search for distortions in Q^2 spectrum, set limits on Λ where $\eta = \pm 4\pi/\Lambda^2$

The data did not indicate any significant amplitudes for any of the CI scenarios considered $\Longrightarrow$ limits set.



Conclusions & Future Prospects

- The 1994-1997 e^+p ZEUS+H1 data has been analyzed to search for a new high mass resonance.
- No Evidence was observed for new physics in the search for Excited Fermions,Leptoquarks,LFV,Contact Interactions or $\not{R}_p$ Supersymmetry in the aforementioned data set.
- Preliminary analyses on the 1998-1999 e^-p also has so far revealed no signal.
- Models of LQ, f^*, CI & $\not{R}_p$ SUSY have been constrained & compared to other experiments:
  - New limits on Leptoquark couplings are competitive with LEP & Tevatron results
  - still a discovery potential for 1st generation LQs with low $BR(LQ \to eq)$, LFV LQs, Contact Interactions
  - HERA has potential for discovery for $M_{f^*} > \sqrt{s_{LEP}}$
  - limits on some $\not{R}_p$ couplings are comparable or better then APV limits.

2000-2001 HERA Luminosity upgrade & e polarization promise continued exciting SEARCHES in $\sim 1 fb^{-1}$ 2001-2006 HERA running.

THE SEARCH CONTINUES....