Searches for Excited Fermions and Leptoquarks at HERA

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Beyond the Desert 99
Schloß Ringberg
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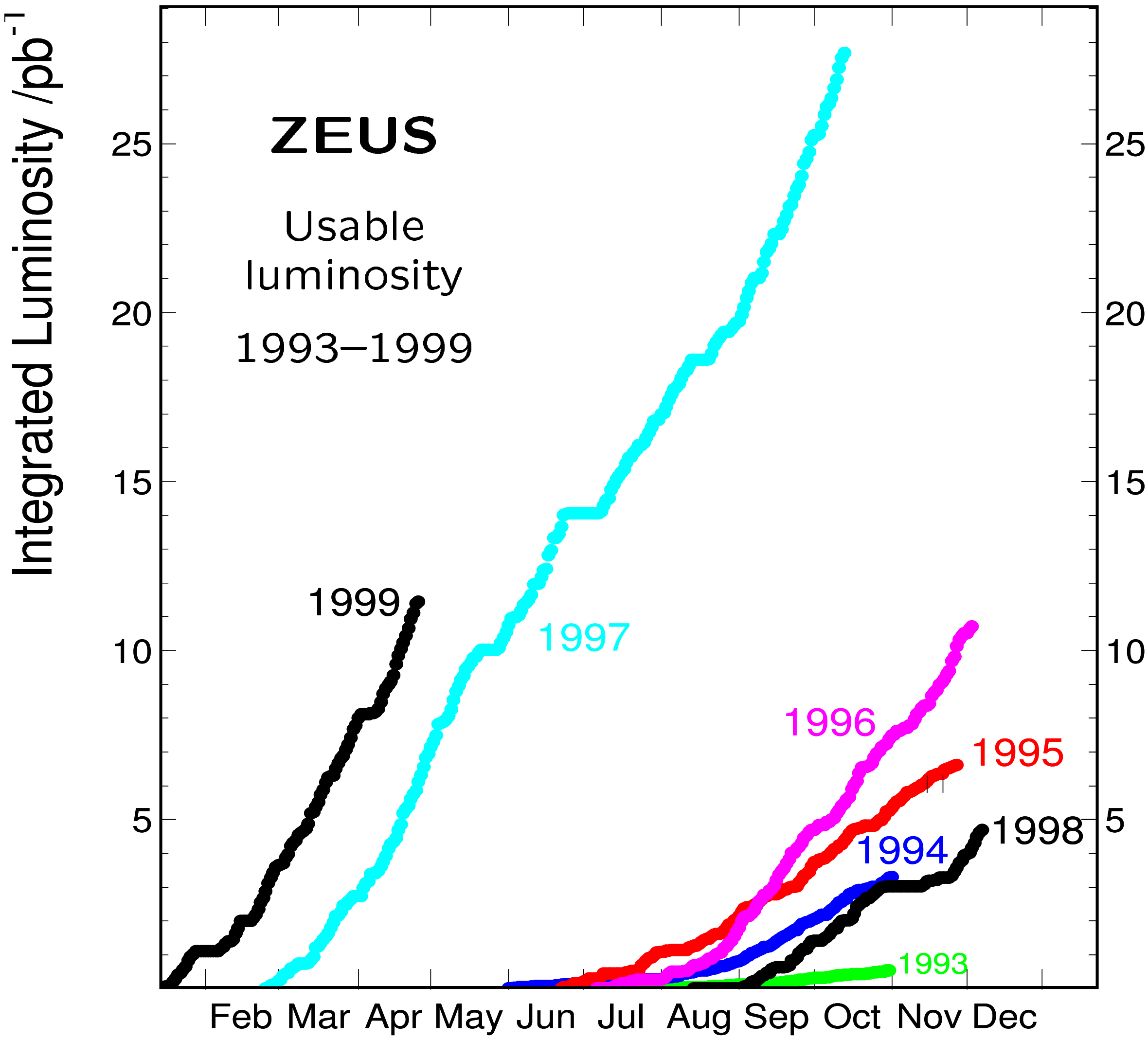
- Excited Fermions
- Leptoquarks
- Contact Interactions
- Conclusions and Outlook

Data Samples



ZEUS 1994–1997 e^+p: $\mathcal{L} = 47.7\,\mathrm{pb}^{-1}$

H1 1994–1997 e^+p: $\mathcal{L} = 37.0\,\mathrm{pb}^{-1}$

$\sim 15.0\,\mathrm{pb}^{-1}$ e^-p data each (1998–1999)

e^+p centre–of–mass energy = 300 GeV

electron–quark invariant mass up to $\sim$ 200 GeV

spatial resolution down to $\sim 10^{-16}$ cm

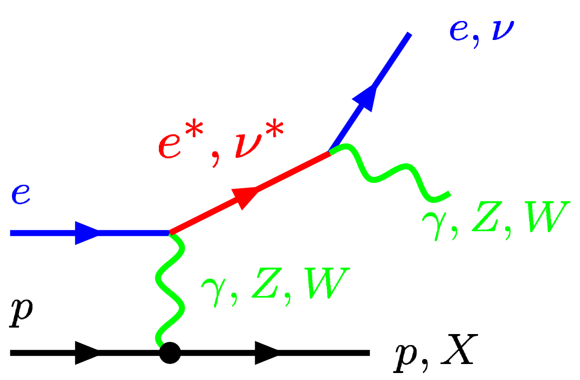
Excited Fermions

Substructure of fermions

$\Leftrightarrow$ high–mass excited fermion states f^*

coupling to ground–state fermions plus gauge bosons

e^*, ν^* production at HERA:



Model:

(Hagiwara, Komamiya, Zeppenfeld)

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

At HERA:

Assume $|f| = |f'|$ and $f_s = 0$

reaction	f^* decay	signature	studied by
$ep \to e^* X$	$e^* \to e + \gamma$	$e + \gamma$	H1, ZEUS
	$e^* \to e + Z_{\to q\bar{q}}$	$e +$ 2jets	H1
	$e^* \to e + Z_{\to e^+e^-}$	$3e$	H1
	$e^* \to e + Z_{\to \nu\bar{\nu}}$	$e + \not{P}_t$	H1
	$e^* \to \nu + W_{\to q\bar{q}'}$	$\not{P}_t +$ 2jets	H1
	$e^* \to \nu + W_{\to e\nu}$	$e + \not{P}_t$	H1
$ep \to \nu^* X$	$\nu^* \to \nu + \gamma$	$\gamma + \not{P}_t$	H1
	$\nu^* \to e + W_{\to q\bar{q}'}$	$e +$ 2jets	H1
	$\nu^* \to e + W_{\to e\nu}$	$2e + \not{P}_t$	H1
	$\nu^* \to \nu + Z_{\to q\bar{q}}$	$\not{P}_t +$ 2jets	H1
	$\nu^* \to \nu + Z_{\to e^+e^-}$	$2e + \not{P}_t$	H1
$ep \to q^* X$	$q^* \to q + \gamma$	γ+jet	H1
	$q^* \to q' + W_{\to e\nu}$	$e + \not{P}_t$+jet	H1

Search for $e^* \to e + \gamma$ (ZEUS)

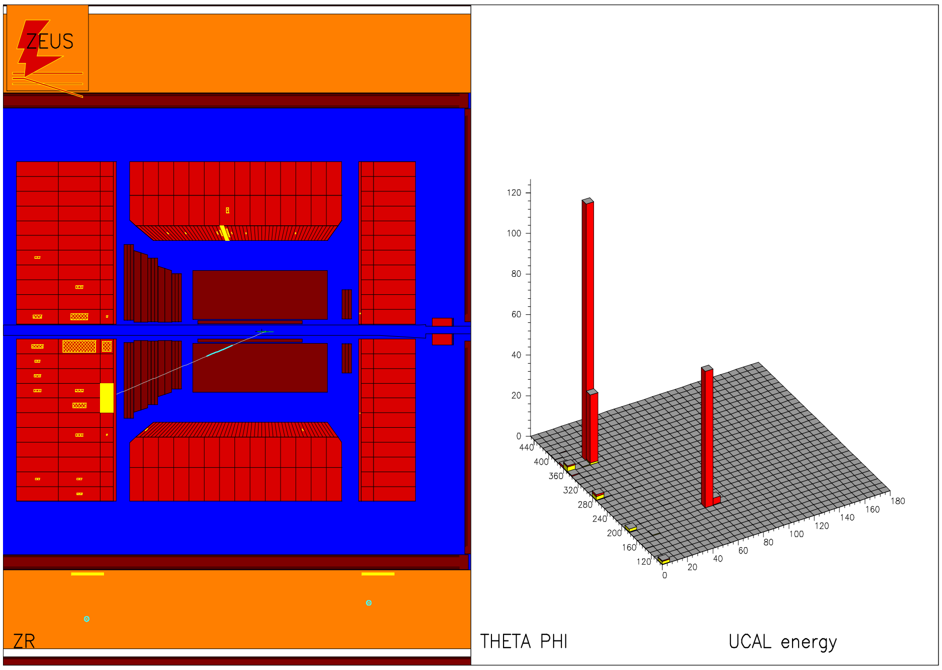
Signatures: 2 isolated elm. clusters

no or low–P_T hadronic system

no missing momentum

Highest–mass ZEUS candidate event

($M_{e\gamma}$=159 GeV)

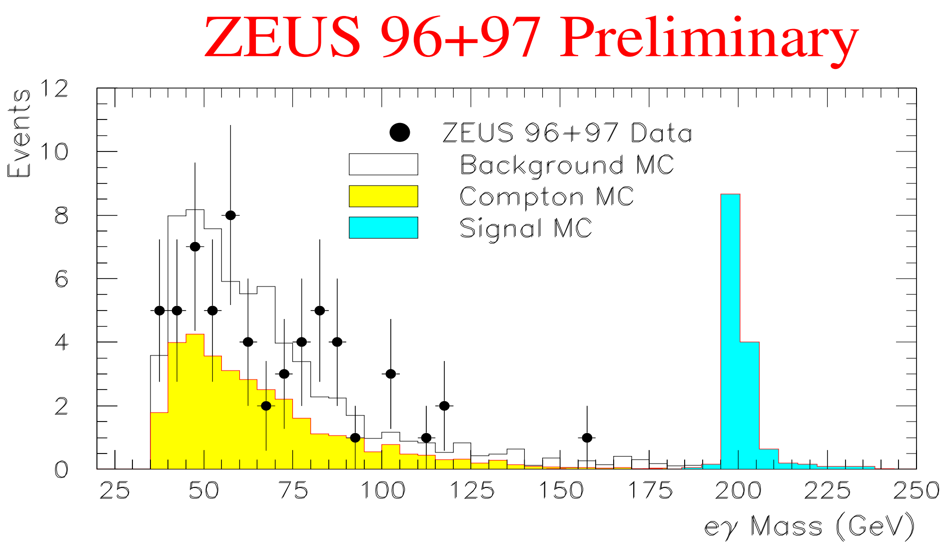


$M_{e\gamma}$ spectrum

Background:

(quasi)elastic QED–Compton

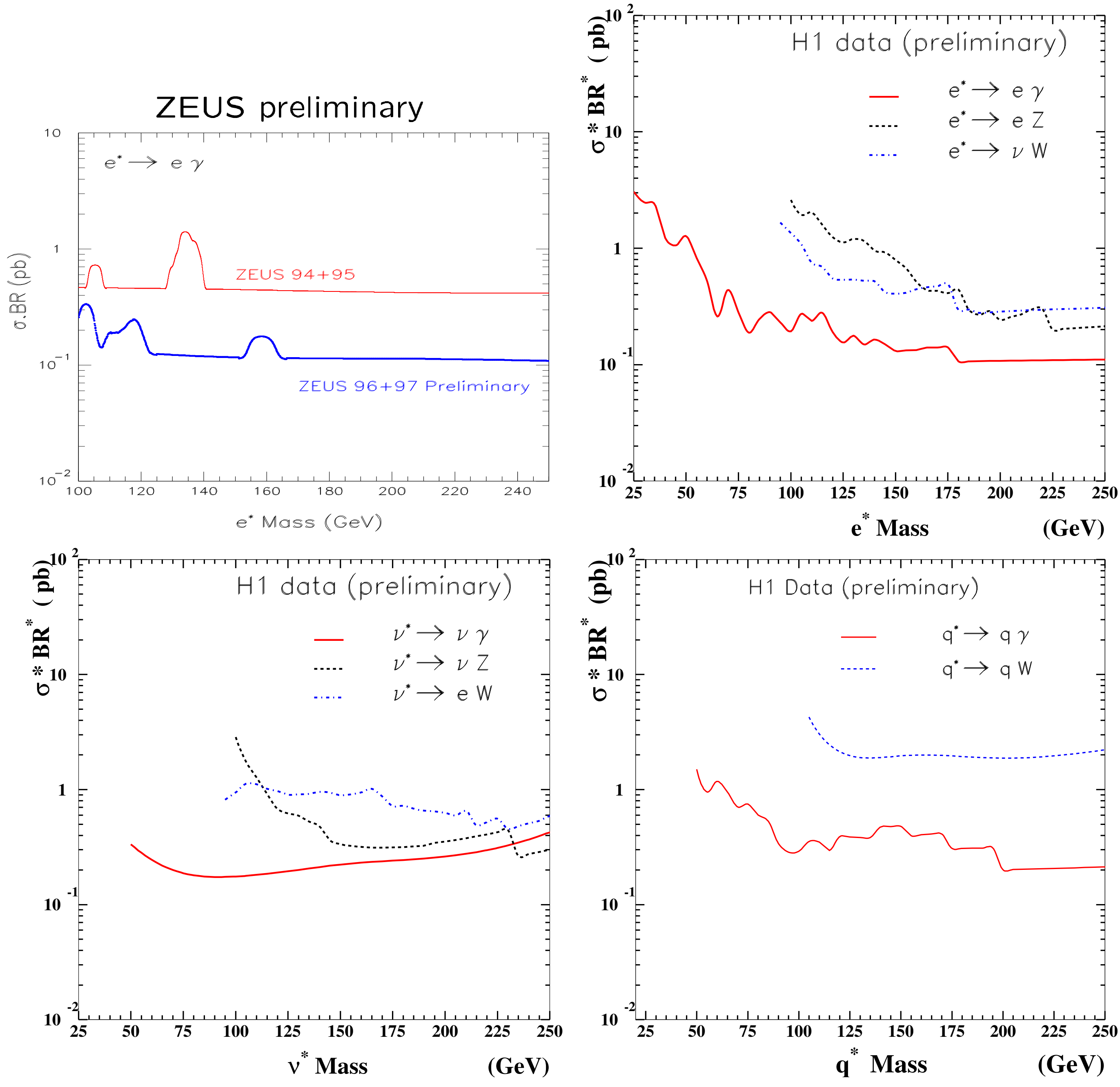
NC DIS



f^* Cross Section Limits

No evidence for f^* production

$\Rightarrow$ 95% C.L. limits on (cross section)·(branching ratio)



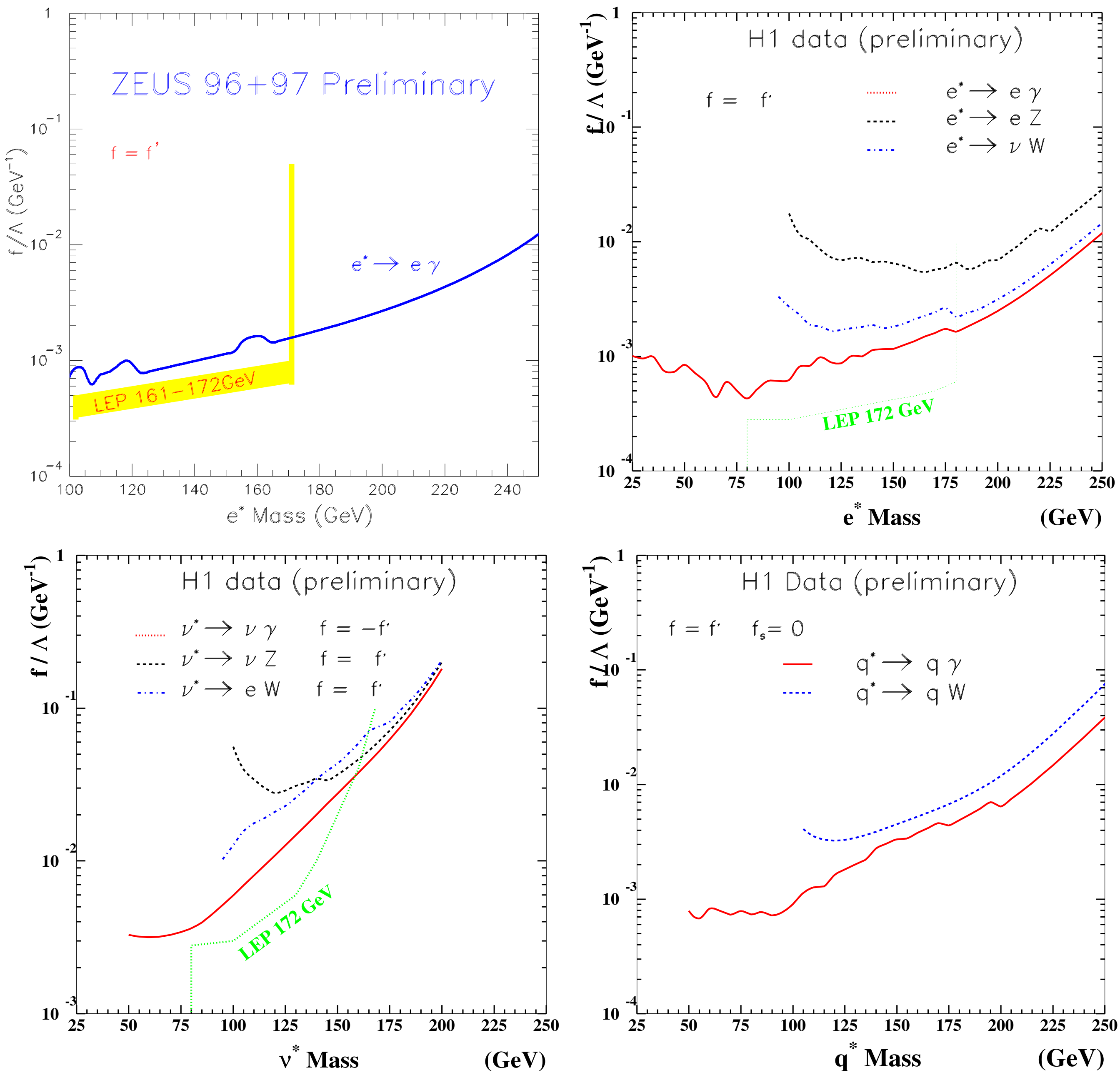
Limits are close to 3/luminosity for $M_{f^*} \gtrsim 100$ GeV

f^* Coupling Limits

Assume model by Hagiwara et al. ($f = \pm f'$, $f_s = 0$)

$\Rightarrow$ derive limits on f/Λ

Compare to LEP results ($e^+e^- \to e^*\overline{e^*}$, $e^+e^- \to e^*e$)

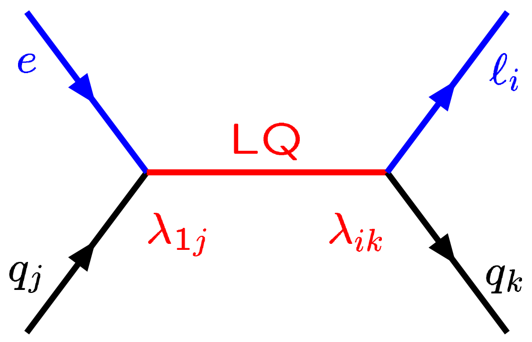


HERA has discovery potential at high M_{f^*}

Leptoquarks (LQ's)

LQ's = particles coupling to both leptons and quarks

LQ production at HERA:



Signal:

- narrow resonance in $M_{\ell q} = \sqrt{x \cdot s}$
- y distribution:
  $\rightarrow$ scalar LQ: ~ 1
  $\rightarrow$ vector LQ: $\sim (1-y)^2$

Background:

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

Models and assumptions:

- Buchmüller, Rückl, Wyler (BRW):

  LQ's only couple to leptons, quarks, gauge bosons
  LQ's preserve $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmmetry

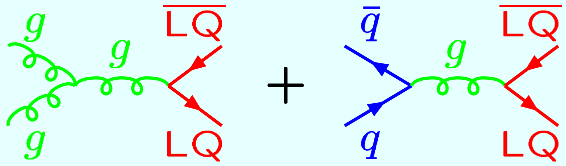
  $\Rightarrow$ For each combination of ℓ and q generations:
  14 different LQ species characterized by

  fermion number: $F = 0, \pm 2$
  spin: $S = 0$ (scalar) or $S = 1$ (vector)
  weak isospin, hypercharge, chirality of couplings
  $\beta =$BR(LQ$\rightarrow eq$)$= 0$, $1/2$ or 1

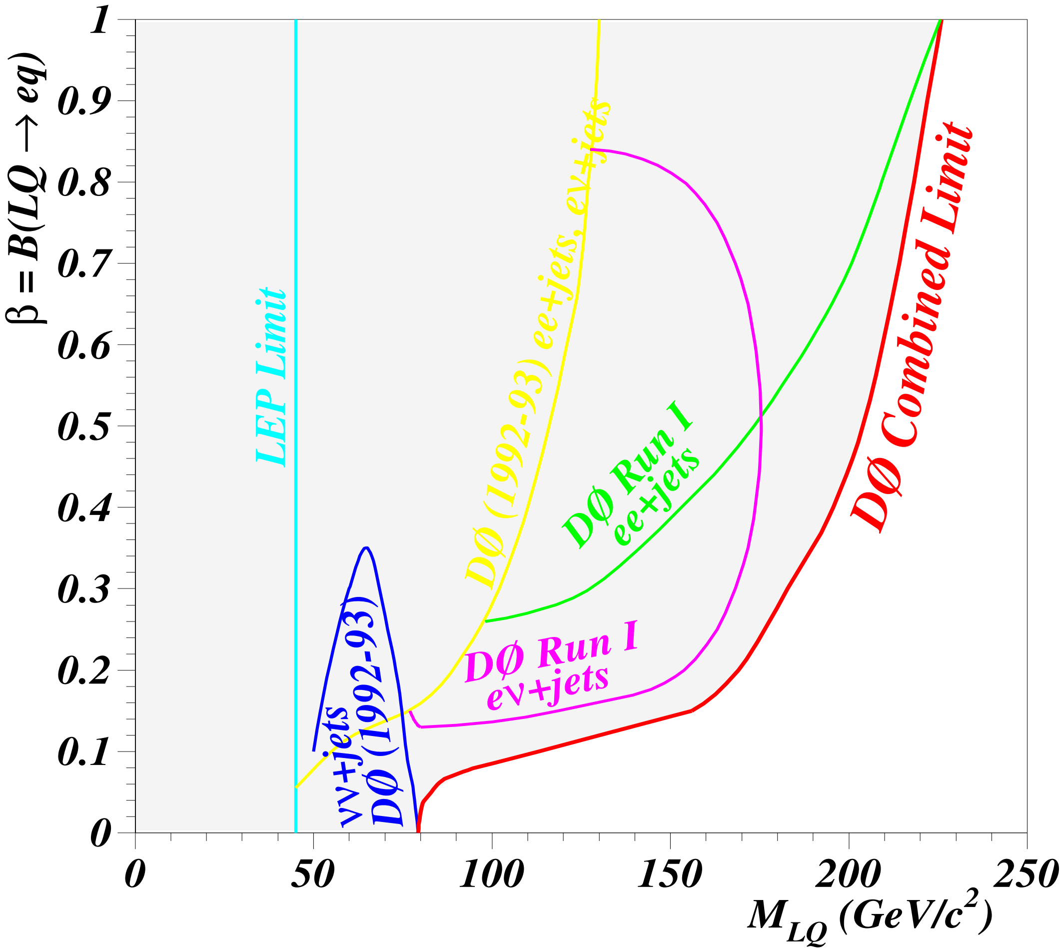
- R_P–violating squarks (talk by V. Lemaitre)
- Generalized assumptions:
  Use LQ species of BRW but leave β free

Exclusion Limits from Tevatron

$$\sigma(p\bar{p} \to \mathrm{LQ}\overline{\mathrm{LQ}}X) \propto \left| \quad + \quad + \ldots \right|^2$$



σ independent of λ_{ij}, $\sigma(p\bar{p} \to \mathrm{LQ}\overline{\mathrm{LQ}} + X \to eeqq + X) \propto \beta^2$

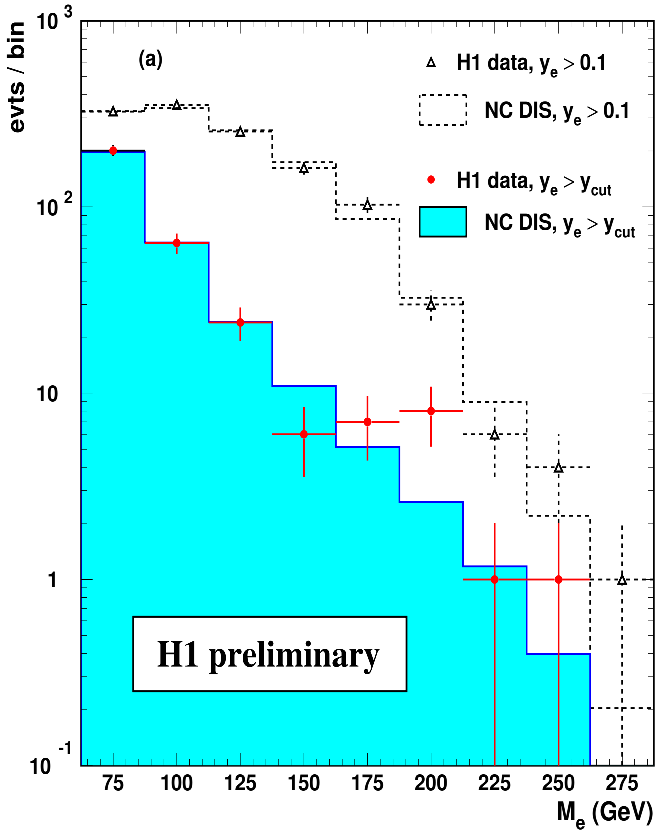


Tevatron 95% C.L. lower LQ mass limits (GeV)			
LQ type	$\beta = 1$ DØ	$\beta = 1$ CDF+DØ	$\beta = 1/2$ DØ
$S = 0$ (scalar)	225	242	204
$S = 1$ (vector)	298	—	270

H1 and ZEUS e+Jet Mass Spectra

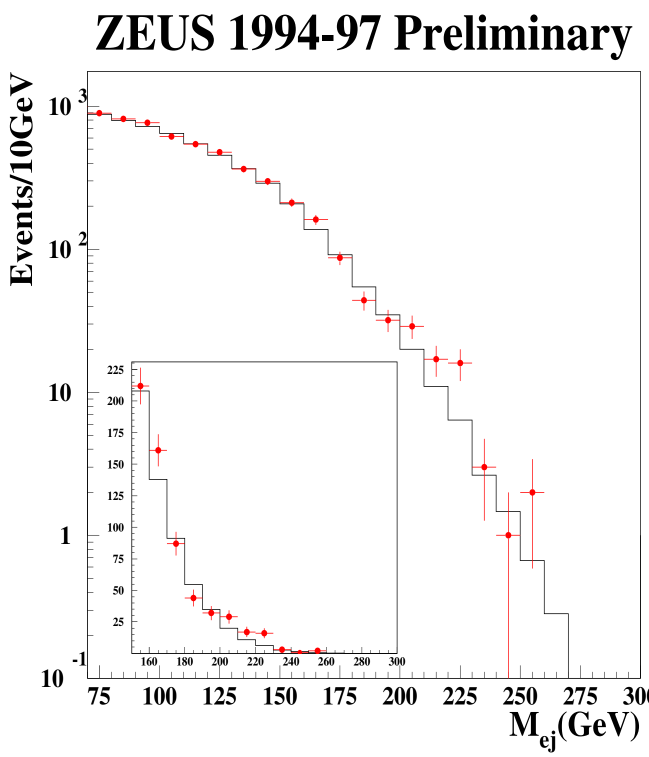
H1:

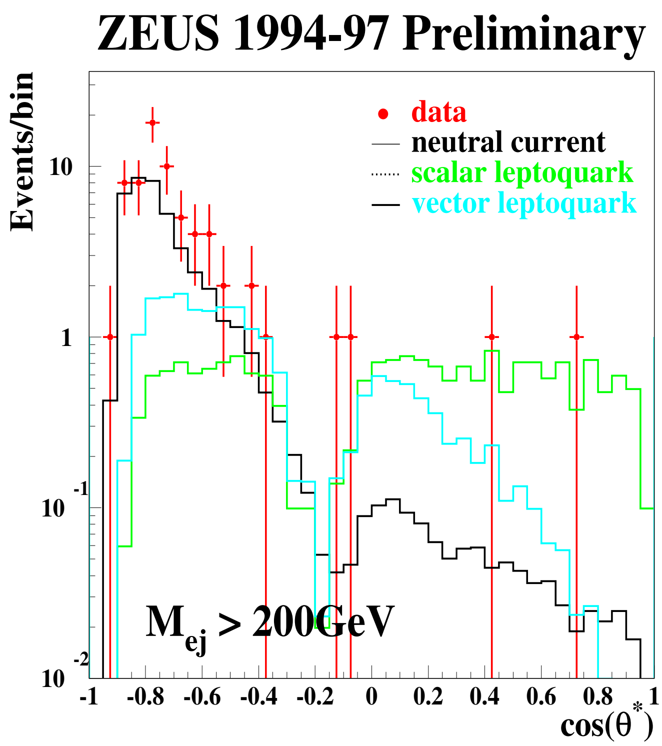
- spectrum of $M_e = \sqrt{x_e s}$ for $y > y_{\text{cut}}$
- y_{cut} optimized for scalar LQ search



ZEUS:

- M_{ej} without y cut
- study y distribution for $M_{ej} > 200$ GeV





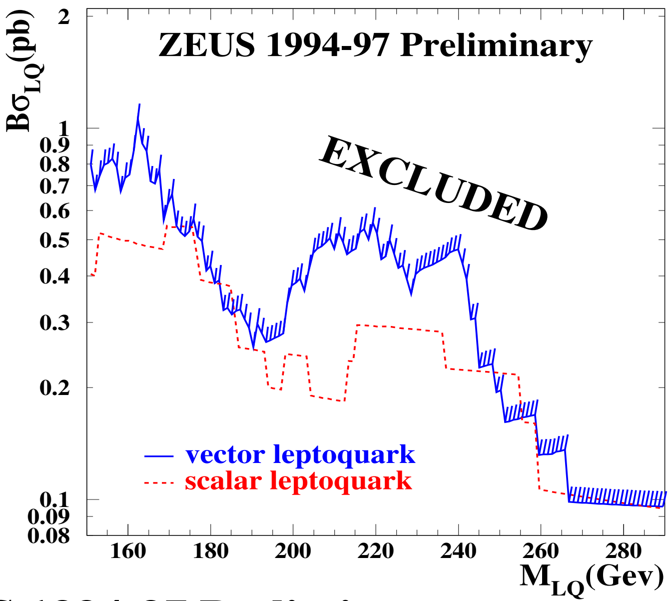
ZEUS LQ Limits (1^{st} Generation)

right:

- 95% C.L. limits on $\sigma \cdot \beta$ for $e^+p \to \mathrm{LQ} + X$
  $\to e^+q + X$

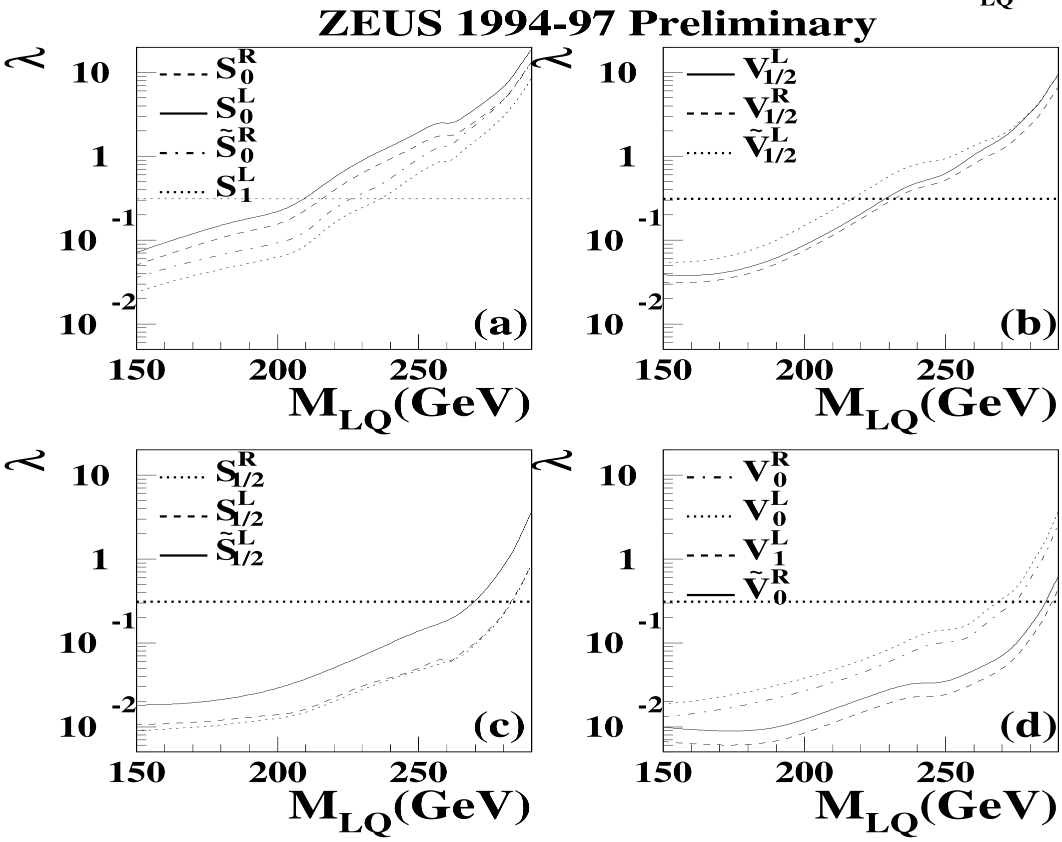
below:

- 95% C.L. limits on $\lambda = \lambda_{1j}$ for different BRW LQ's



$F = 2$
$(e^+\bar{q})$

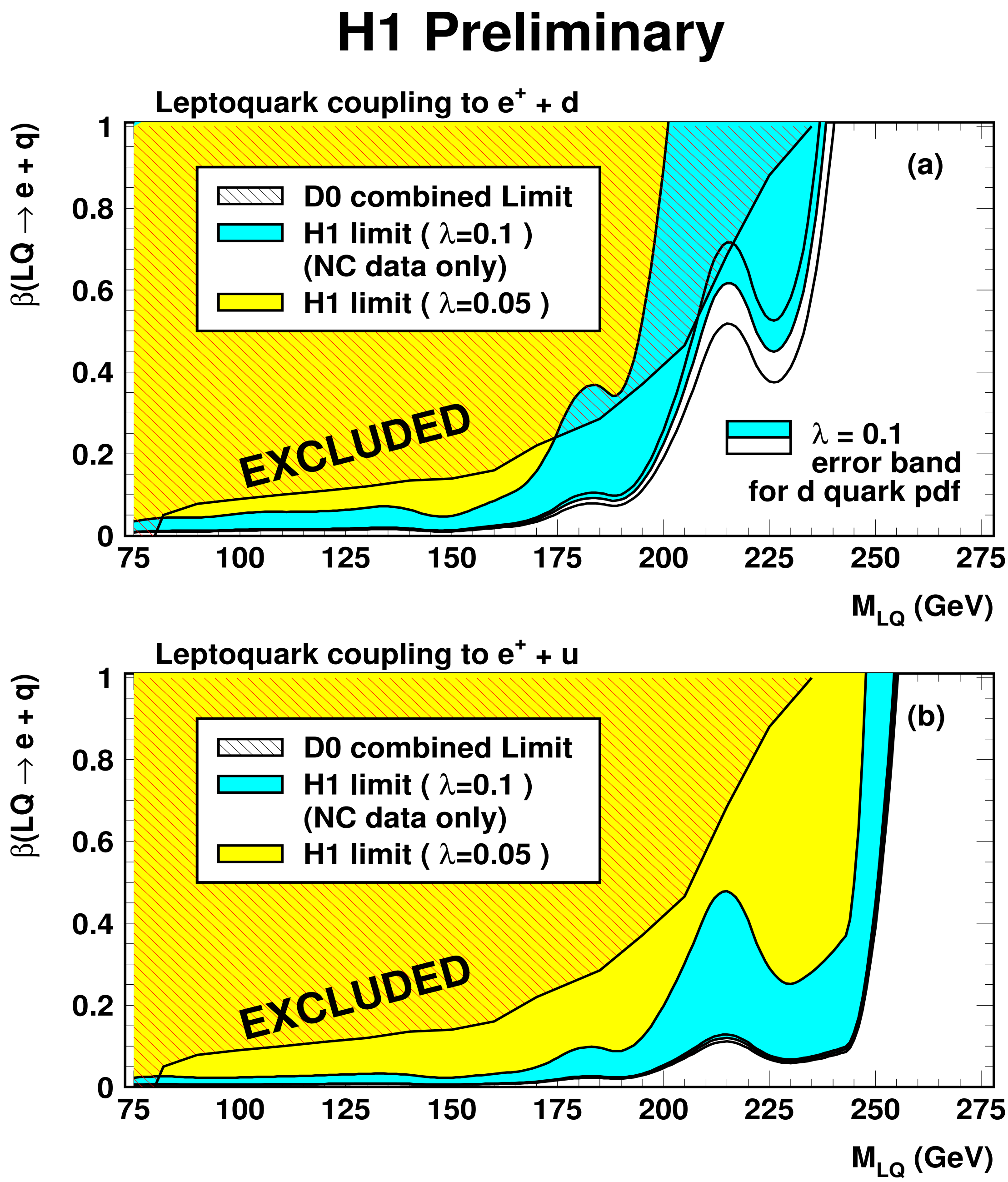
$F = 0$
(e^+q)



Very similar limits from H1
Sensitivity higher for F=0 (e^+q) than for F=2 $(e^+\bar{q})$
LQ's with elm. coupling excluded for $M_{LQ} \lesssim 270$ GeV (F=0)

H1 LQ Limits (1^{st} Generation)

95% C.L. limits on β =BR(LQ$\rightarrow eq$) for fixed λ_{1j} (F=0)

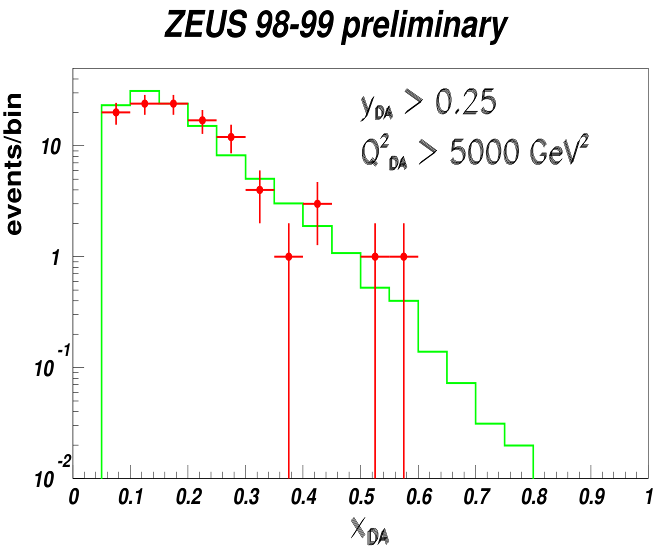


Discovery potential at small β, high M_{LQ}

Sensitivity highest for F=0 LQ's coupling to (e^+u)

A First Look at the New e^-p Data

e^-p data provide sensitivity to LQ's with F=2

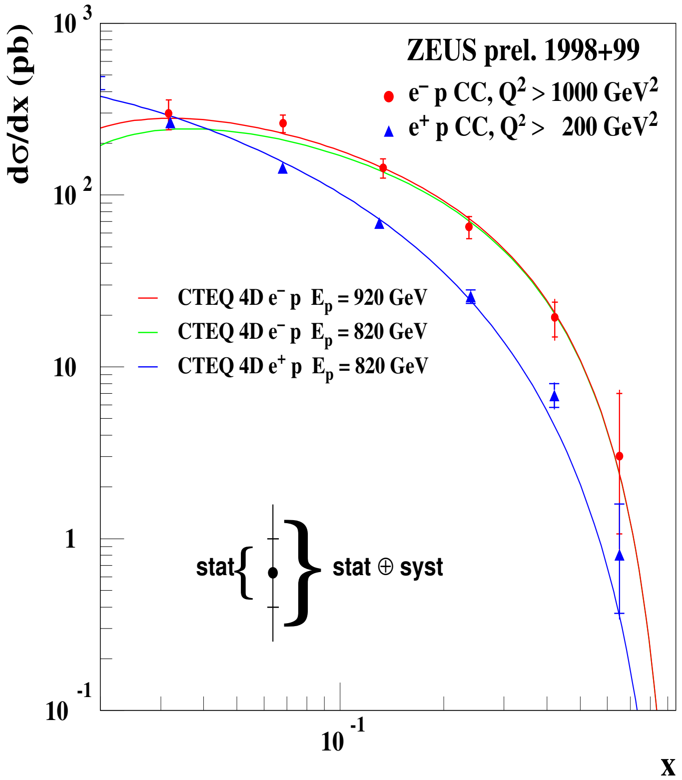


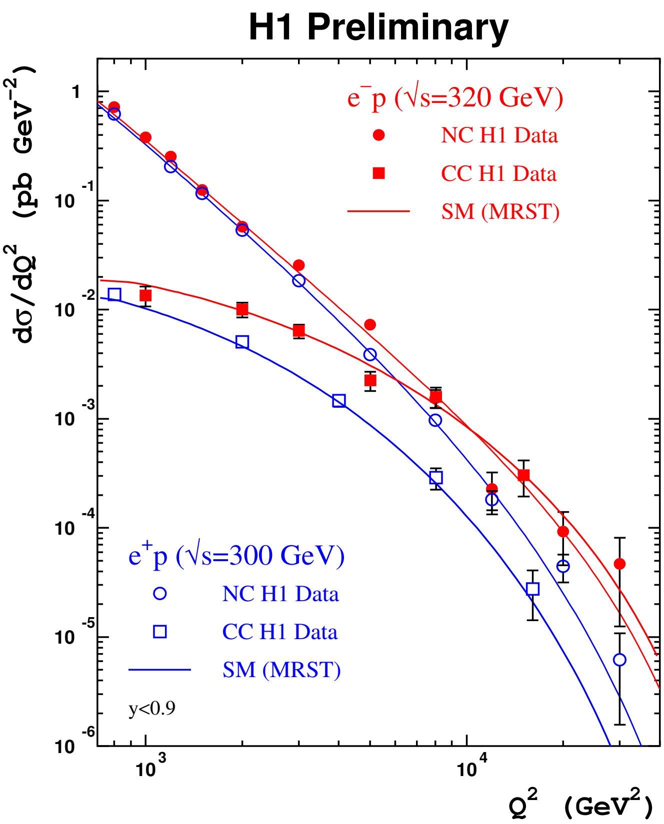
ZEUS:

- x distribution in NC data (top left)
- $d\sigma/dx$ in CC data (bottom left)

H1:

- $d\sigma/dQ^2$ in NC and CC data (bottom right)





Good agreement with Standard Model predictions

$\Rightarrow$ no evidence for surprises in the e^-p data

Lepton Flavor Violation Search (H1)

Search for LQ's coupling both to eq and $\tau q'$

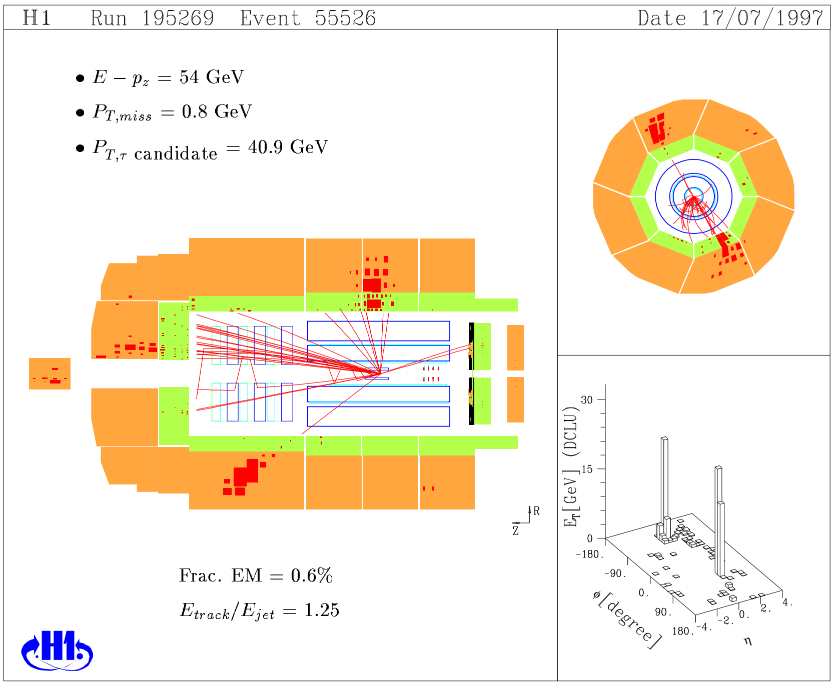
$$e^+p \to \mathrm{LQ} + X \to \tau^+ q + X$$

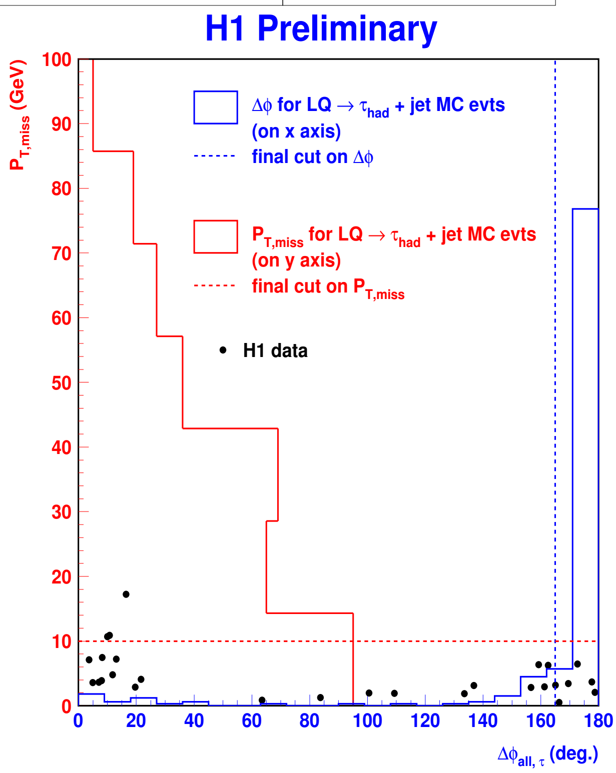
H1 candidate event surviving preselection

After preselection:

$N_{\mathrm{obs}}=28$

$N_{\mathrm{exp}}=23.7 \pm 5.7$





Event selection:

- isolated $\tau \to$hadron candidate
- $\not{P}_t > 10$ GeV in τ direction

Efficiency:

- $\sim 10\% \ \ldots \ 25\%$, rising with M_{LQ}

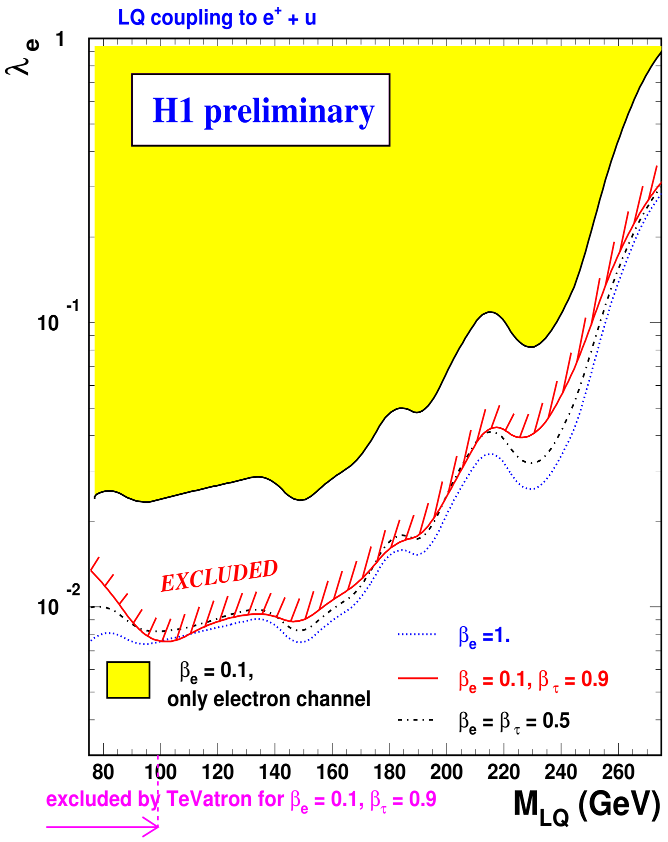
Yield:

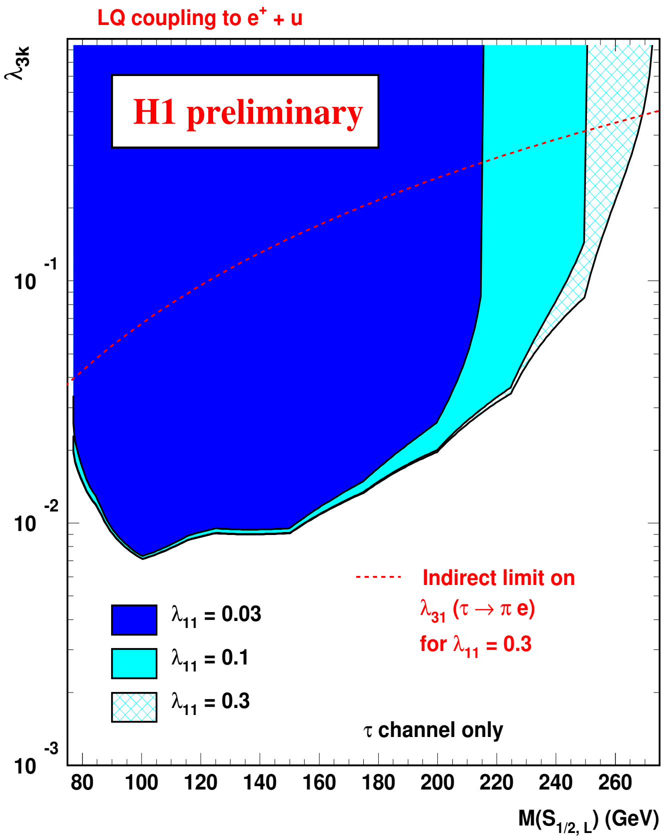
- no event survives selection

H1 LQ Limits (3^{rd} Generation)

Use both e+jet and τ+jet samples to constrain coupling of 3rd generation LQ's

Assume LQ only couples to e^+u and τ^+q





Limits on λ_{11}

- fix β_e =BR(LQ$\to eu$), use $\beta_\tau = 1 - \beta_e$
- derive limits on $\lambda_e = \lambda_{11}$

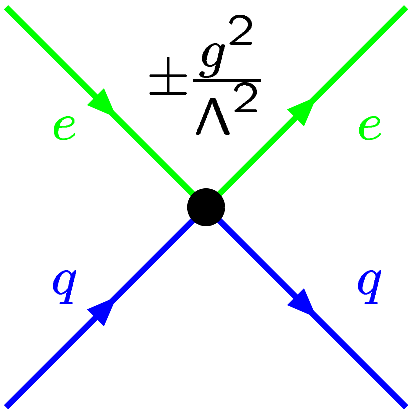
Limits on λ_{3k}

- fix λ_{11}
- derive limits on λ_{3k}

HERA has unique sensitivity to lepton flavor violation in the $e \to \tau$ channel

Contact Interactions (CI)

eq CI at HERA:



CI can represent:

- Heavy boson exchange
- Leptoquark (s or u channel)
- Interaction of composite electron and quark
- ...

Historical equivalent:
4–fermion interaction

Effective Lagrangian:

$$\mathcal{L} = \frac{g^2}{\Lambda^2} \cdot \sum_{\substack{a,b=L,R \\ q=u,d}} \eta^q_{ab} (\bar{e}_a \gamma^\mu e_a)(\bar{q}_b \gamma_\mu q_b)$$

- $\eta^q_{ab} = \pm 1, 0$ and $g^2 = 4\pi$ by convention
- Only chiral vector couplings considered
  (avoids e.g. severe constraints from π decays)
- Interference with SM constructive or destructive
- BRW LQ species correspond to specific η^q_{ab}

CI Scenarios

CI	η^u_{LL}	η^u_{LR}	η^u_{RL}	η^u_{RR}	η^d_{LL}	η^d_{LR}	η^d_{RL}	η^d_{RR}	studied by
LL	+	0	0	0	+	0	0	0	H1
LR	0	+	0	0	0	+	0	0	
RL	0	0	+	0	0	0	+	0	
RR	0	0	0	+	0	0	0	+	
VV	+	+	+	+	+	+	+	+	ZEUS,H1
AA	+	−	−	+	+	−	−	+	
VA	+	−	+	−	+	−	+	−	
X1	+	−	0	0	+	−	0	0	ZEUS
X2	+	0	+	0	+	0	+	0	ZEUS
X3	+	0	0	+	+	0	0	+	ZEUS,H1
X4	0	+	+	0	0	+	+	0	ZEUS,H1
X5	0	+	0	+	0	+	0	+	ZEUS
X6	0	0	+	−	0	0	+	−	ZEUS
U1	+	−	0	0	0	0	0	0	ZEUS
U2	+	0	+	0	0	0	0	0	
U3	+	0	0	+	0	0	0	0	
U4	0	+	+	0	0	0	0	0	
U5	0	+	0	+	0	0	0	0	
U6	0	0	+	−	0	0	0	0	

- Marginal effect if including s, c, b, t
- Severe limits from Atomic Parity Violation if

$$\eta_{LL} + \eta_{LR} - \eta_{RL} - \eta_{RR} \neq 0$$

(in particular for pure LL,LR,RL,LL scenarios)

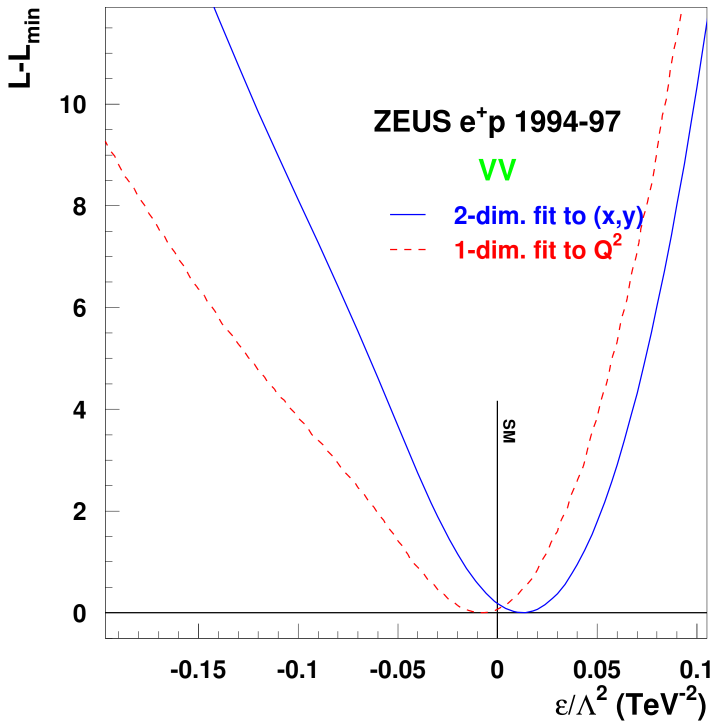
Contact Interaction Analyses

ZEUS analysis:

- Input: raw distributions without acceptance or migration corrections
- Simulate CI's by reweighting MC events
- Determine log–likelihood: $LL(\pm 1/\Lambda^2)$
- Limit setting:
  One–sided 95% C.L. limits from MC experiments

Two approaches:

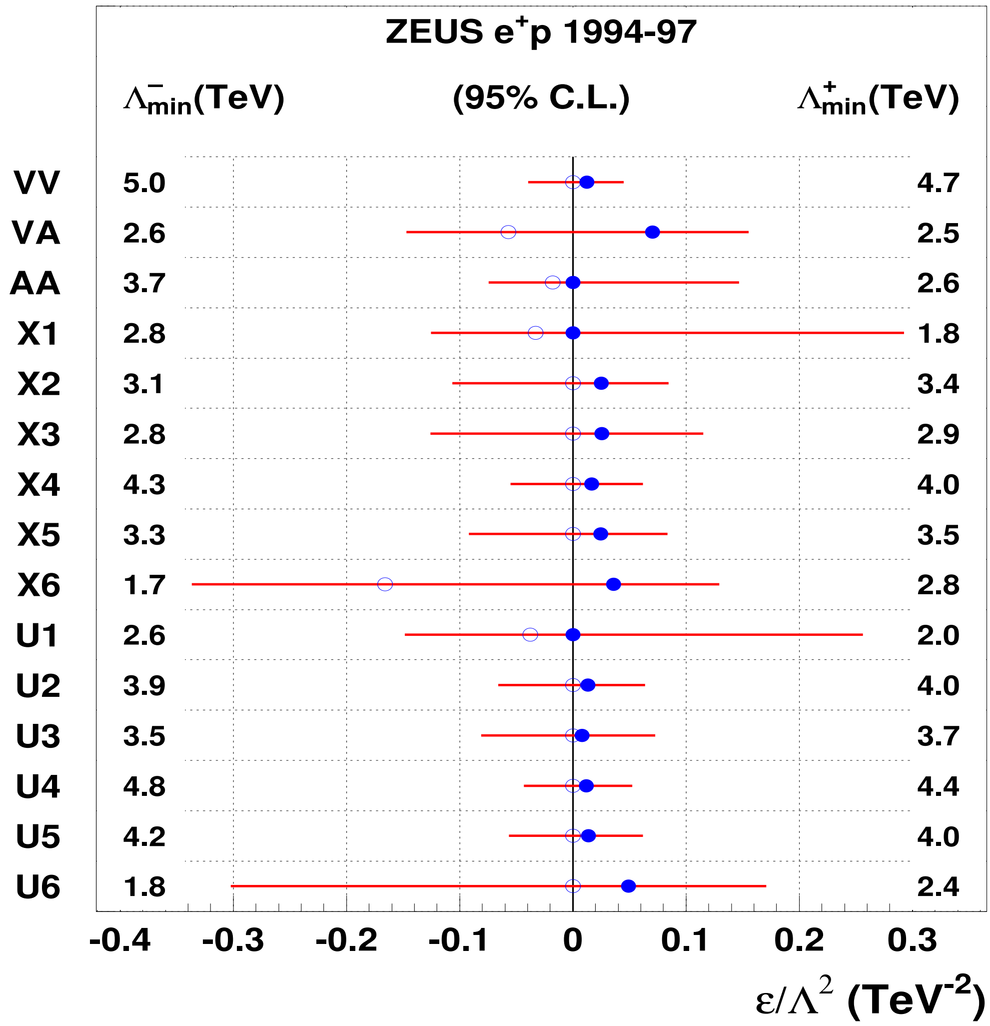
- Binned LL in Q^2
- Unbinned LL in (x, y)
- Very similar results



H1 analysis:

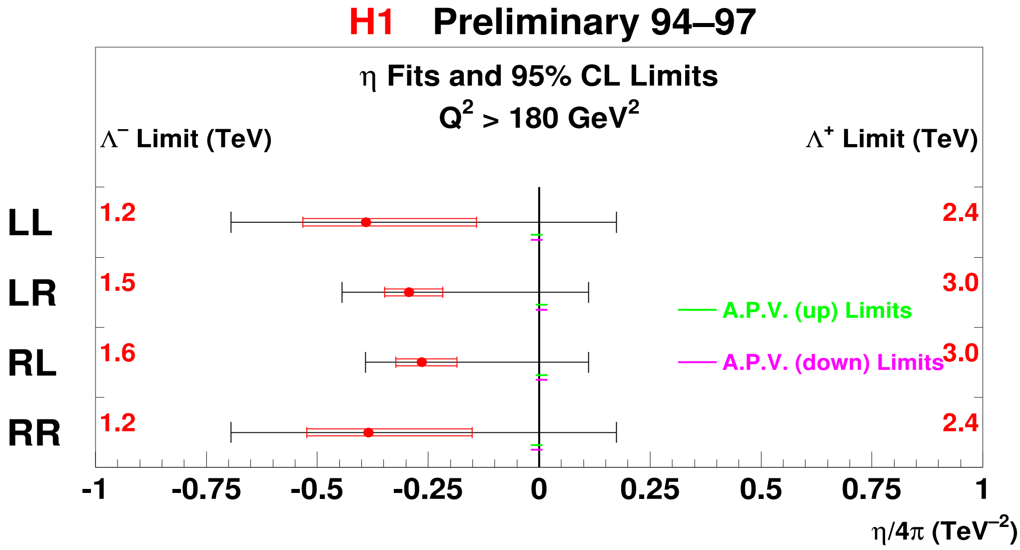
- χ^2–fit to $d\sigma/dQ^2$
- Two–sided 68% and 95% C.L. intervals from χ^2 contour

HERA CI Exclusion Limits



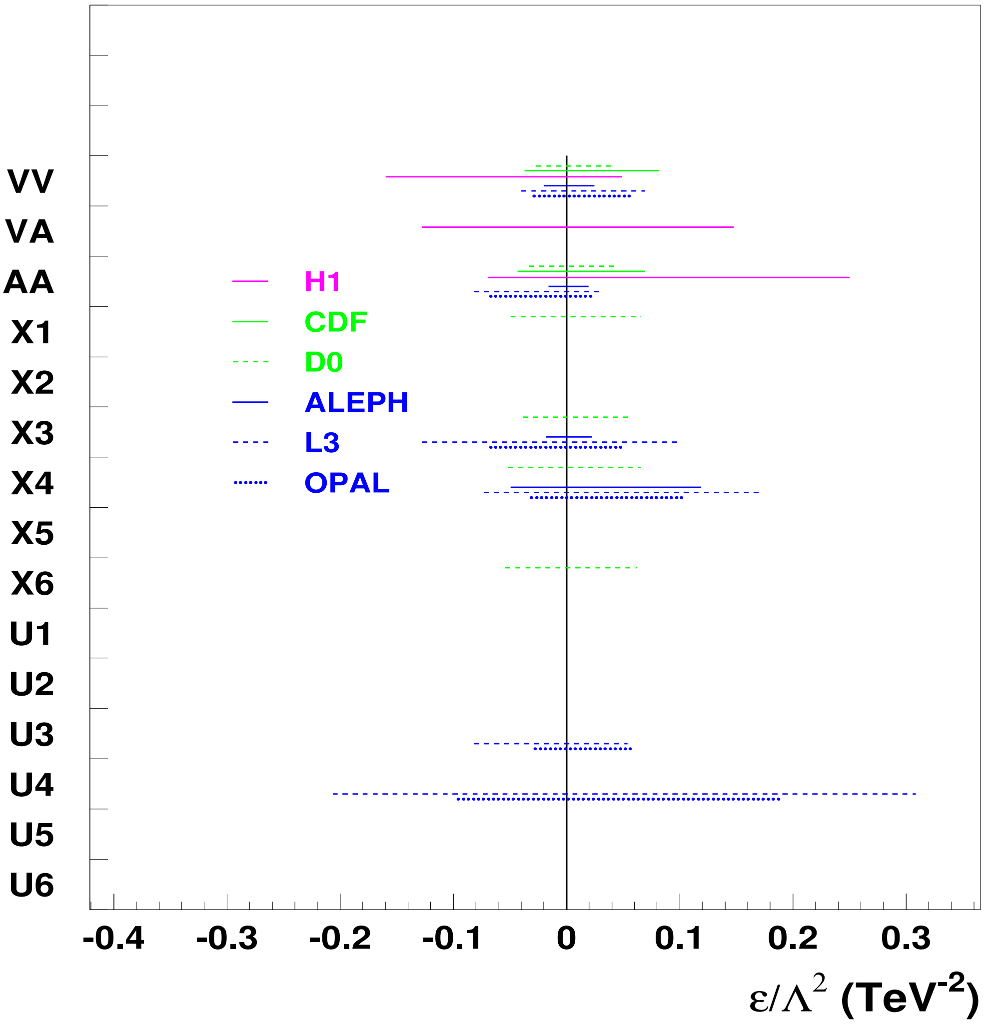
No evidence for CI signal ⇒ set limits

● best fit
— limits at 95% C.L.



● best fit
— limits at 95% C.L.
= 1σ limits

CI Limits from Other Experiments



LQ Limits from CI Studies (H1)

Transform CI limits for the LL,LR,RL,RR scenarios into limits on LQ mass/coupling (M_{LQ}/λ)

Needed: CI limits for u and d quarks singly

$$(\eta_{ab})_{\text{lim}} = \pm\frac{4\pi}{\Lambda^2_{\text{lim}}} = a \cdot \left(\frac{M_{\text{LQ}}}{\lambda}\right)_{\text{lim}}$$

LQ	F	coupling to u	coupling to d	$(M_{LQ}/\lambda)_{\text{lim}}$ (GeV)
S_0^L	2	$a_{LL} = +1/2$	—	598
S_0^R	2	$a_{RR} = +1/2$	—	554
$\tilde{S}_0^R$	2	—	$a_{RR} = +1/2$	202
$S_{1/2}^L$	0	$a_{LR} = -1/2$	—	294
$S_{1/2}^R$	0	$a_{RL} = -1/2$	$a_{RL} = -1/2$	308
$\tilde{S}_{1/2}^L$	0	—	$a_{LR} = -1/2$	416
S_1^L	2	$a_{LL} = +1/2$	$a_{LL} = +1$	385
V_0^L	0	—	$a_{LL} = -1$	655
V_0^R	0	—	$a_{RR} = -1$	547
$\tilde{V}_0^R$	0	$a_{RR} = -1$	—	299
$V_{1/2}^L$	2	—	$a_{LR} = +1$	345
$V_{1/2}^R$	2	$a_{RL} = +1$	$a_{RL} = +1$	859
$\tilde{V}_{1/2}^L$	2	$a_{LR} = +1$	—	952
V_1^L	0	$a_{LL} = -2$	$a_{LL} = -1$	400

These limits are not applicable for $M_{LQ} \lesssim \sqrt{s}$
and are questionable for $\lambda \gg 1$
Strong(er) limits can be determined from APV

Conclusions and Outlook

HERA opens new kinematic domains for the search for new particles and phenomena.

No hint of "new physics" in the search for excited fermions, lepton–quark resonances and contact interactions.
Observed deviations from the expectations are not consistent with these hypotheses.

Exclusion limits based on about $\sim 40\,\mathrm{pb}^{-1}$ of e^+p data per experiment have been reported.
They exhibit similar or better sensitivity as searches by other experiments.

We have $\sim 15\,\mathrm{pb}^{-1}$ of e^-p data and expect $\sim 40\,\mathrm{pb}^{-1}$ of new data until 2000 (mainly e^+p).
After 2000, HERA will deliver increased luminosity and e polarization.
We are looking forward to an exciting future of exotic physics at HERA