Beyond the Standard Model: Searches at HERA

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for the H1 and ZEUS collaborations

- ★ Introduction
- ★ Contact interactions
- ★ Leptoquarks
- ★ High-p_T leptons
- ★ Excited fermions
- ★ Conclusions

XXXVth Rencontres de Moriond
electroweak interactions and unified theories
11 – 18 March 2000

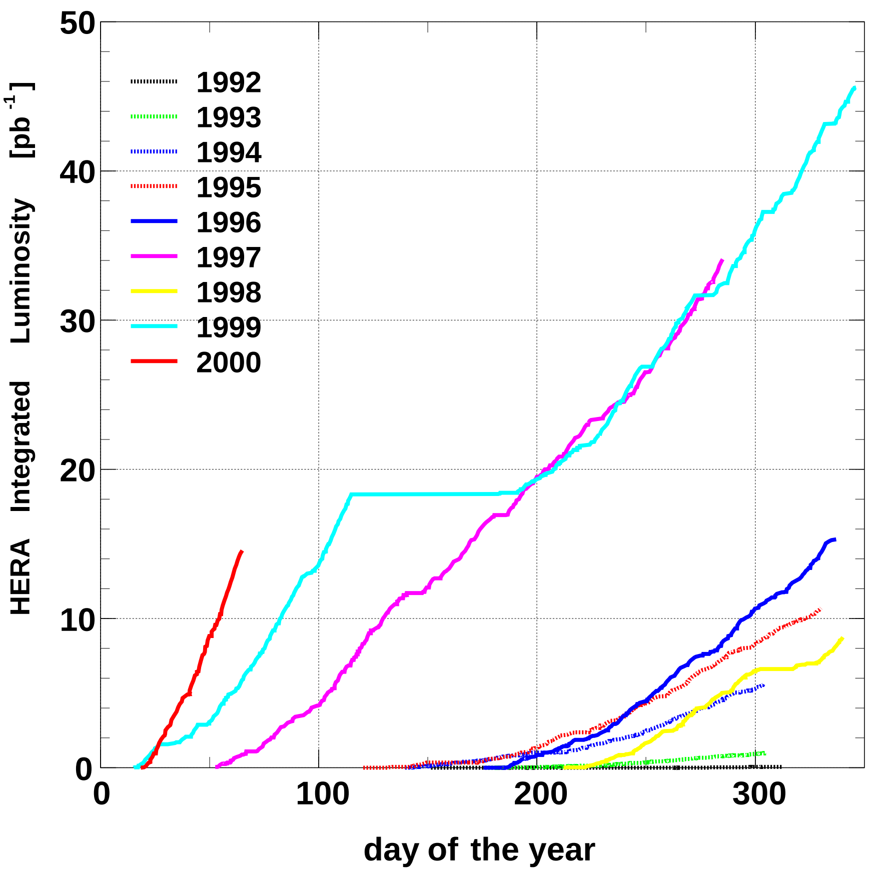
INTRODUCTION TO HERA

HERA: ep-COLLIDER, UNIQUE !

e → ← p

27.5 GeV   820/920 GeV $\Rightarrow \sqrt{s} \approx 300/320$ GeV

ANNUAL INTEGRATED LUMINOSITY:

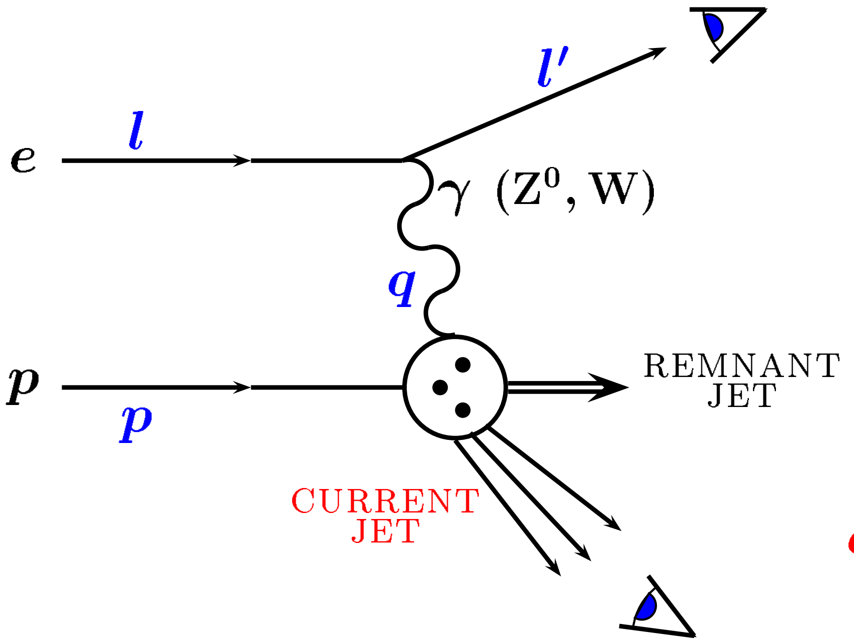


DATA SAMPLES:

YEAR	LEPTON CHARGE	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [pb^{-1}] /EXP.
92,93	e^-p	300	**0.5**
94–97	e^+p	300	**40**
98–99	e^-p	320	**15**
99	e^+p	320	**20**
$\sum$ 94–SEP 2000 (EXPECT.)			$\approx$**100**

Physics at HERA

- STUDY STRUCTURE OF THE PROTON IN DEEP INELASTIC SCATTERING:

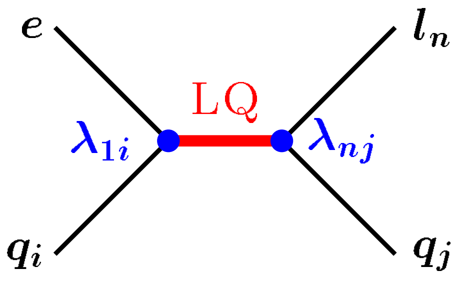


$$s = 4E_eE_p$$
$$Q^2 = -q^2 = sxy$$
$$x = \frac{Q^2}{2p\cdot q}$$
$$y = \frac{p\cdot q}{p\cdot l}$$
$$M = \sqrt{xs}$$

$$d\sigma/dy|_x \propto 1/y^2$$

- BUT HERA ALSO VERY WELL SUITED TO SEARCH FOR PHENOMENA BEYOND THE SM, E.G.:

  - DIRECT PRODUCTION OF f^*'S OR RESONANT STATE
    LEPTOQUARKS: $L, B \neq 0$
    $d\sigma/dy|_x \propto (1-y)^2$ OR CONST.

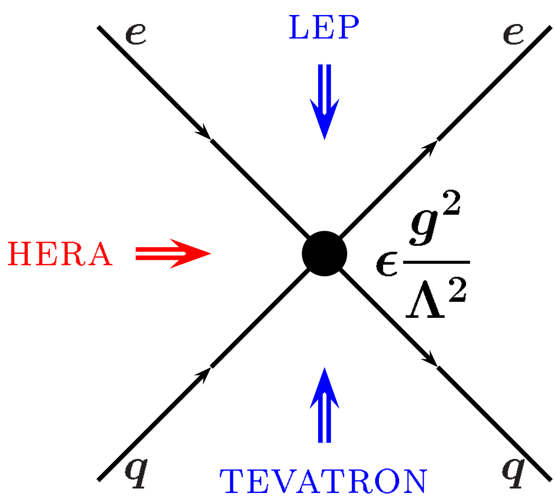


  - INDIRECT PHENOMENA AT LARGE SCALES
    $\longrightarrow$ DISTORTIONS OF SM DISTRIBUTIONS

Contact Interactions

★ at large scales ($\gg \sqrt{s}$)
new phenomena
indirectly observable
as deviations from SM
prediction

★ can be parametrised as
contact interaction (C.I.)



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possible sources for C.I., e.g.:

★ composite fermions

★ exchange of a new heavy particle, like leptoquark, or heavy boson

★ low scale quantum gravity effects

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effective Lagrangian:

considering only vector terms:

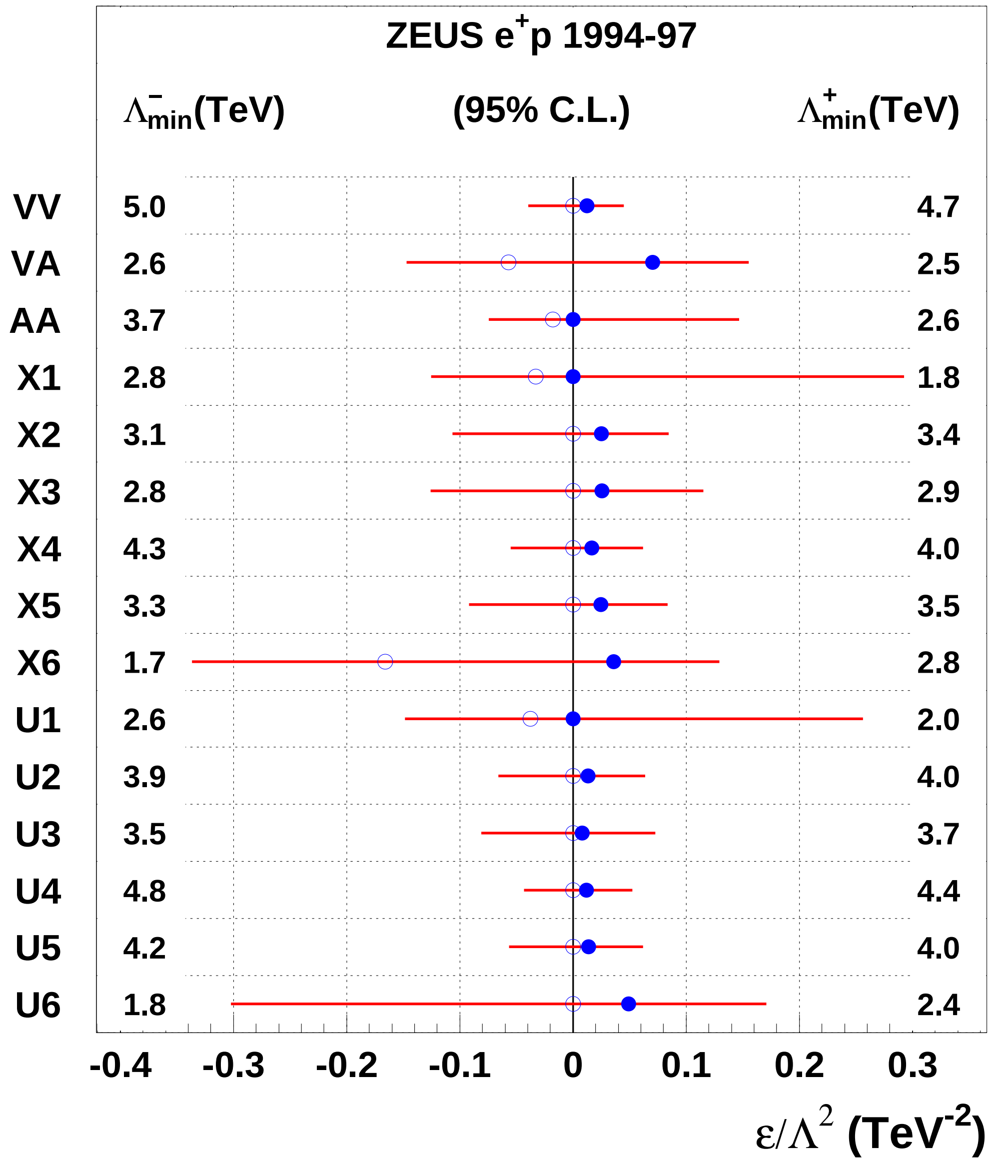
$$\mathcal{L}_V = \sum_{\substack{a,b=L,R \\ q=u,d}} \eta^q_{ab} (\bar{e}_a \gamma^\mu e_a)(\bar{q}_b \gamma_\mu q_b)$$

$\eta^q_{ab} = \epsilon (g/\Lambda^q_{ab})^2$ depend on model,
$\epsilon = \pm 1$ determines interference with SM
g coupling strength, Λ effective mass scale)

Contact Interactions - Compositeness Scales

FOR COMPOSITENESS MODELS $\eta^q_{ab} = \epsilon \frac{g^2}{\Lambda^2} = \pm \frac{4\pi}{\Lambda^2}$

RESULTS FROM ZEUS AND H1 FOR 94-97 e^+p-DATA



NO EVIDENCE FOR CI SIGNAL $\Rightarrow$ SET LIMITS

●(○) BEST FIT FOR $\eta = +(-)1$

— LIMITS AT 95% C.L.

Models considered:

VV, AA, VA:	vector/axial couplings
U_i:	parity conserving combinations
X_i:	same as U_i with $\eta^{eu}_{ab} = \eta^{ed}_{ab}$

LIMITS RANGE FROM 1.7 TEV TO 5 TEV


ALEPH
D0
OPAL
L3
H1

Contact Interactions - other models

H1 studied also other models as sources for C.I.

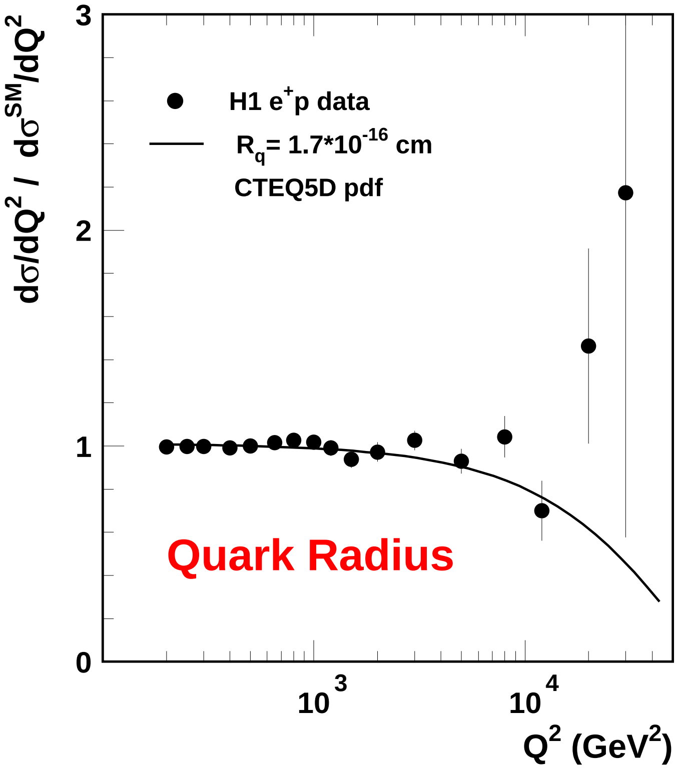
study compositeness of quarks in terms of quark radius by using form factors

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

$$f_q(Q^2) = 1 - \frac{1}{6} R_q^2 Q^2$$

$R_q < 1.7 \cdot 10^{-16}$ cm

(95% c.l.)



by exchange of a heavy LQ ($M_{LQ} \gg \sqrt{s}$) contract propagator $\Rightarrow$ four fermion interaction

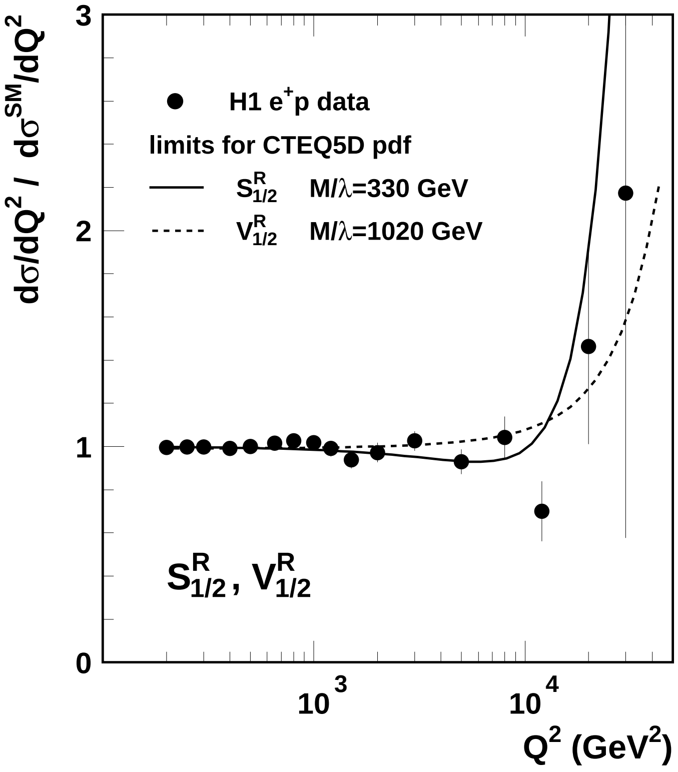
$$\eta_{ab} \propto \epsilon\left(\frac{\lambda}{M_{LQ}}\right)^2$$

a, b depend on LQ type

- best limits for vector LQ coupling to u-quark:

$$\boxed{M_{LQ}/\lambda > \mathcal{O}(1) \text{ TeV}}$$

(95% c.l.)



Contact Interactions - large extra dimensions

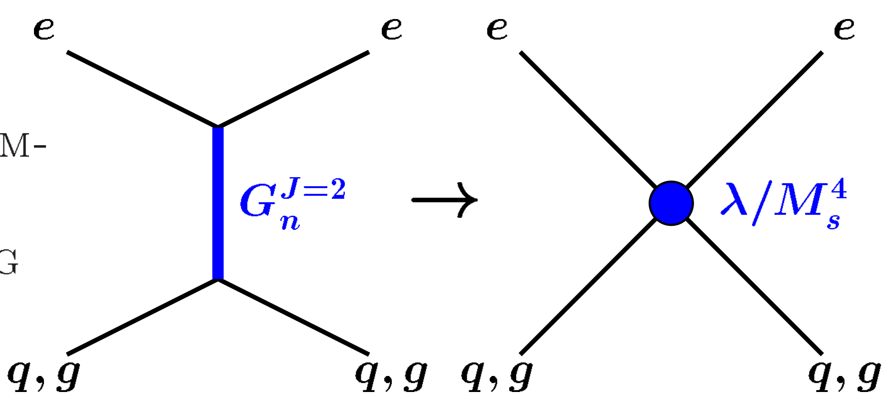
N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B429 (1998):

- consider n very large extra dimensions of radius R
$\rightarrow$ gravity is characterized in $4+n$ dimensions by $M_{Pl}^2 \sim R^n M_S^{n+2}$, where $M_S \sim \mathcal{O}$(TeV)

- possible modification of gravitational law for $r < R$; no experimental test in sub-millimeter range!

- graviton propagates in extra dimensions,
in 4 dim. $\rightarrow$ series of "KK excitations"

- large density of KK states compensates the $\sim 1/M_{Pl}$ coupling

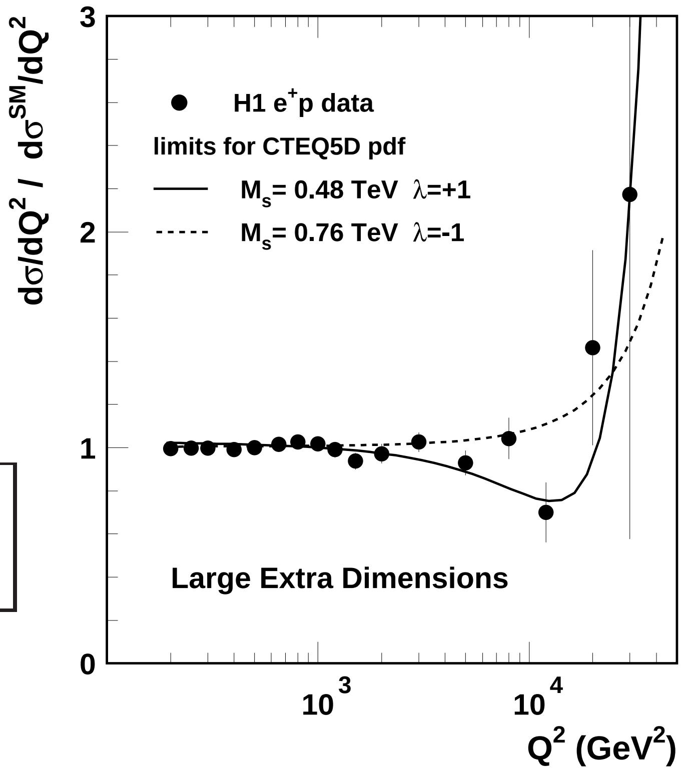


$\rightarrow$ effective CI coupling $\eta_G = \frac{\lambda}{M_s^4}$

H1 C.I. results interpreted in this frame:

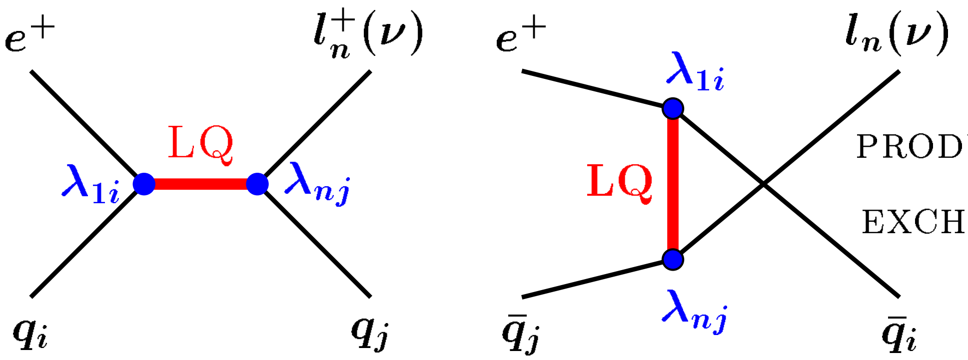
$$\boxed{\begin{aligned} M_S > \quad & 0.48 \text{ TeV} \ldots \lambda = +1 \\ & 0.72 \text{ TeV} \ldots \lambda = -1 \end{aligned}}$$

(95% C.L.)



LeptoQuarks

- Appear in many extensions to SM
- Scalar or Vector colour triplet bosons
- carry $B, L \neq 0$ and couple to quarks and leptons



in ep collisions:
produced in s-channel
exchanged in u-channel

- $F = 0$ $(e^+ + q \rightarrow LQ)$; $|F| = 2$ $(e^+ + \bar{q} \rightarrow LQ)$

★ First generation LQ's couple to 1st generation fermions only ⇒ DIS like final state, but different angular (y) distributions:

- DIS: $\sim 1/y^2$
- LQ: flat or $(1-y)^2$ depending on type & channel

→ search for narrow mass peak in high y events!

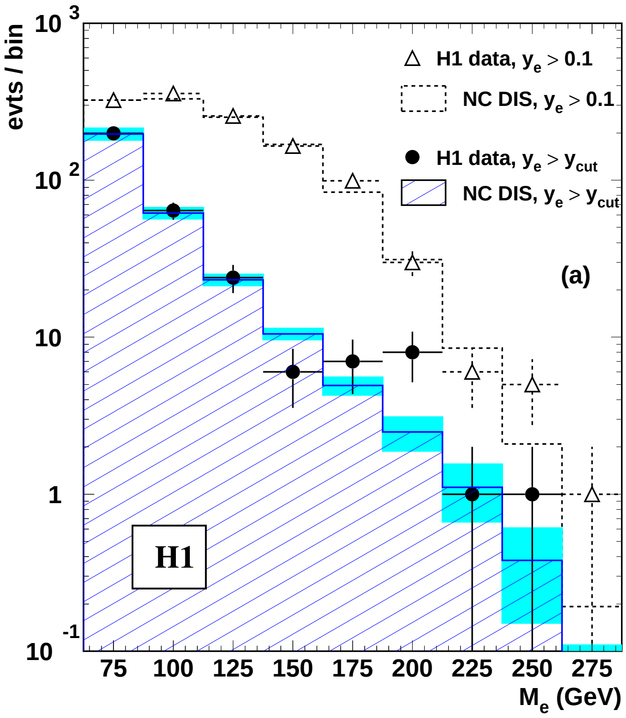
★ Buchmüller, Rückl, Wyler (BRW) model

- classifies LQ's depending on quantum numbers $S^J_{L,R}$ and $V^J_{L,R}$ (S, V.. scalar/vector LQ; L, R...couples to left/right-handed fermions; J...weak isospin)
- branching ratios fixed: $\beta_e = \beta(LQ \rightarrow eq) = 0.5$ or 1

1^{ST} GENERATION LQ'S: 1994-97 e^+

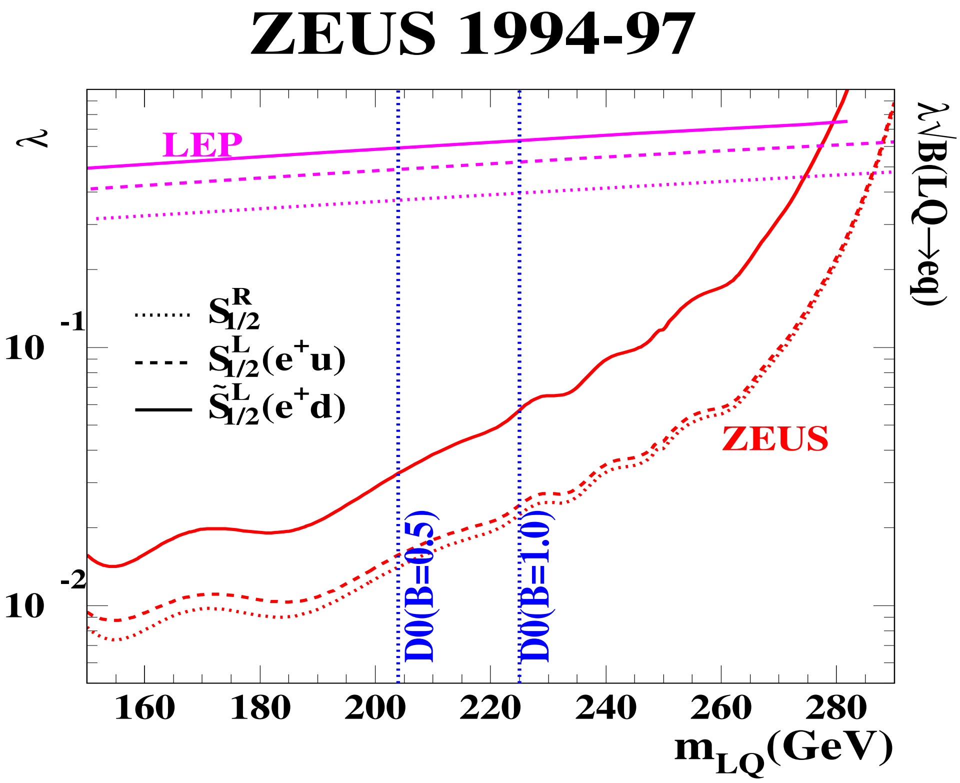
- SELECT HIGH Q^2 DIS
- INCREASE SIGNAL/BG RATIO BY OPTIMISING y OR $\cos\theta^* = 1-2y$ CUT

EXAMPLE ⇒



★ NO SIGNIFICANT DEVIATION FROM SM
→ LIMITS

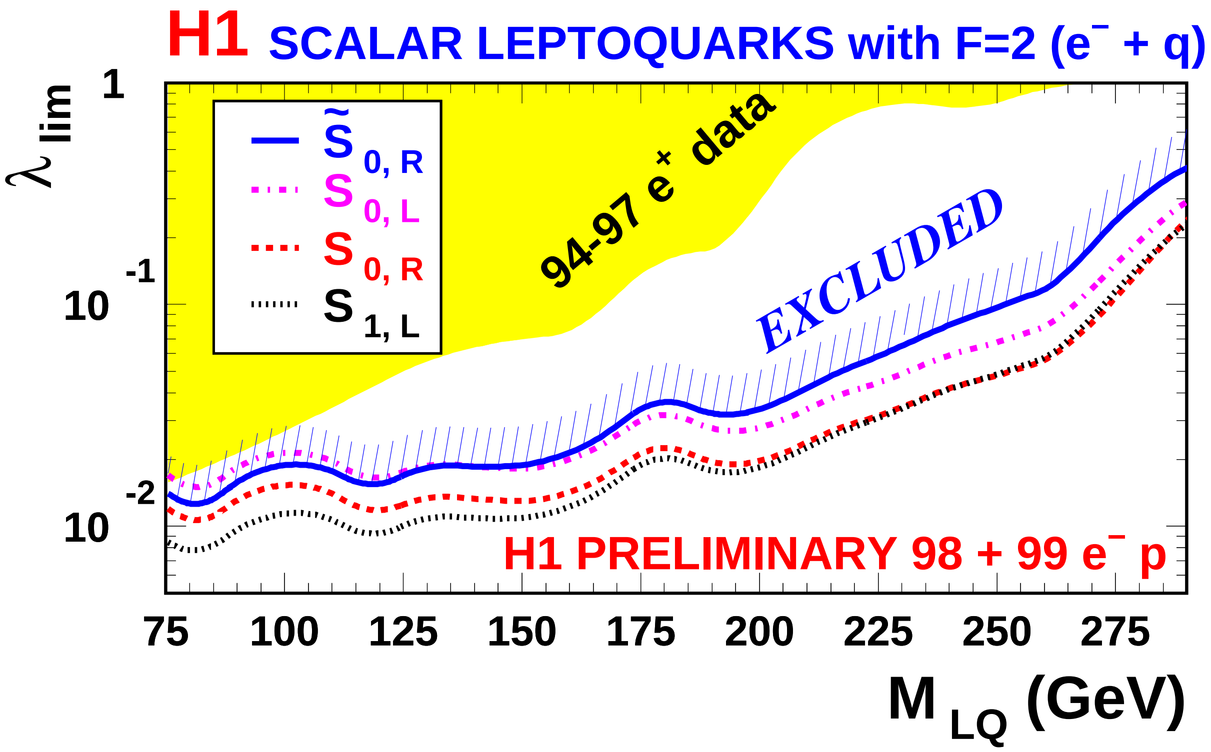
FOR e^+p: HIGHEST SENSITIVITY FOR $F = 0$ LQ'S



IN BRW MODEL, FOR $\lambda = \sqrt{4\pi\alpha_{em}} = 0.3$ SCALAR (VECTOR) LQ'S EXCLUDED AT 95% C.L. UP TO 275 (285) GEV

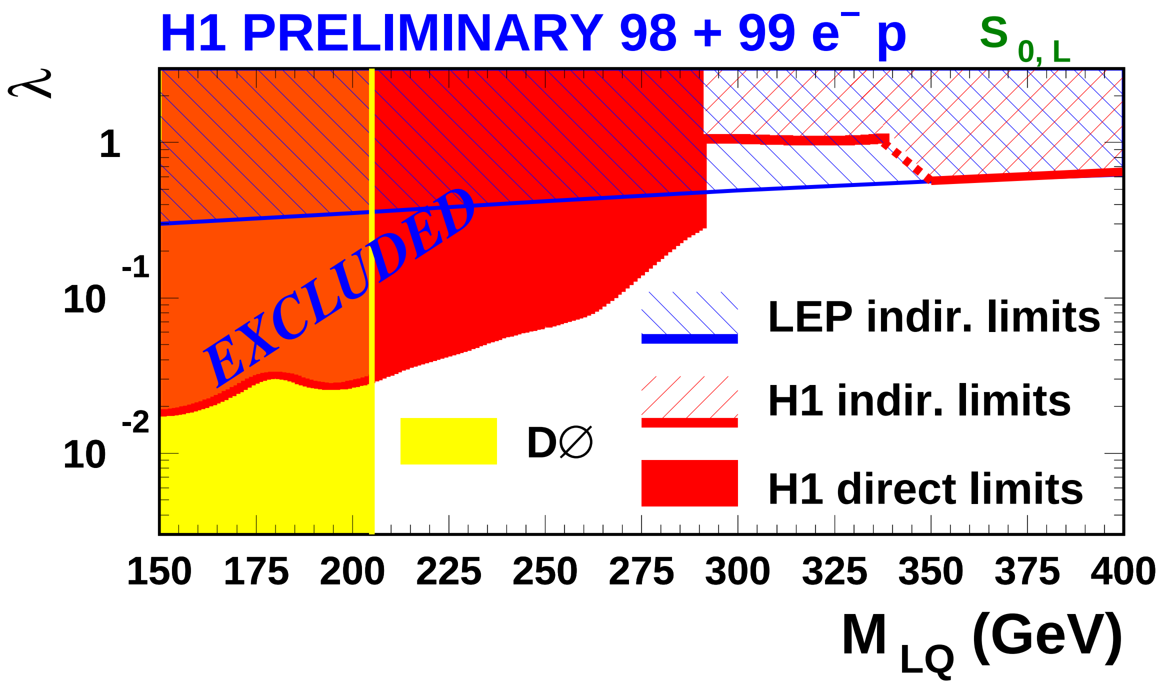
1^{st} GENERATION LQ's: 1998/99 e^-

- ★ PRELIMINARY RESULTS FROM H1 AND ZEUS FROM 1998/99 e^-p-DATA
- ★ e^- IN INITIAL STATE $\rightarrow$ HIGHER SENSITIVITY TO $|F| = 2$ LQ's
- ★ BOTH EXPERIMENTS:
  M SPECTRA COMPATIBLE WITH NC DIS
- ★ $\Rightarrow$ DERIVE LIMITS

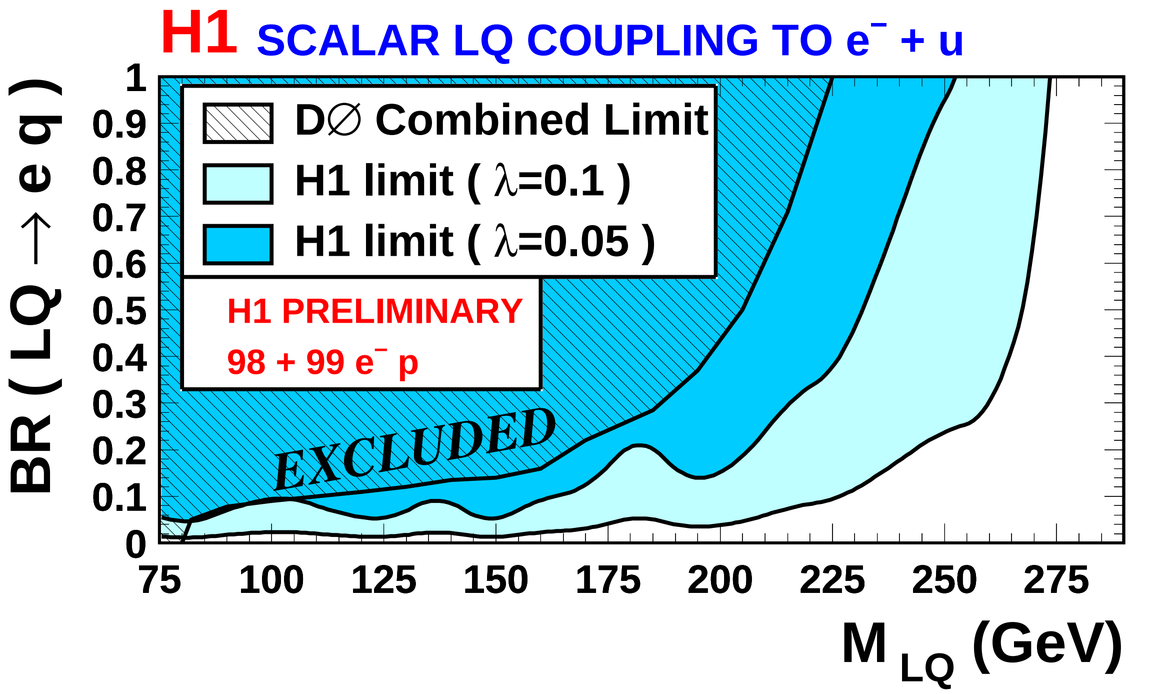


LIMITS COMPLEMENTARY TO THOSE FROM e^+p-DATA
$\mathcal{L} = 14.4\text{pb}^{-1}$, FOR $|F|=2$ LQs SENSITIVITY ALREADY BETTER THAN WITH 1994-97 e^+ SAMPLE

FOR $\lambda = 0.3$: $F = 2$ LQ's EXCLUDED UP TO 290 GeV



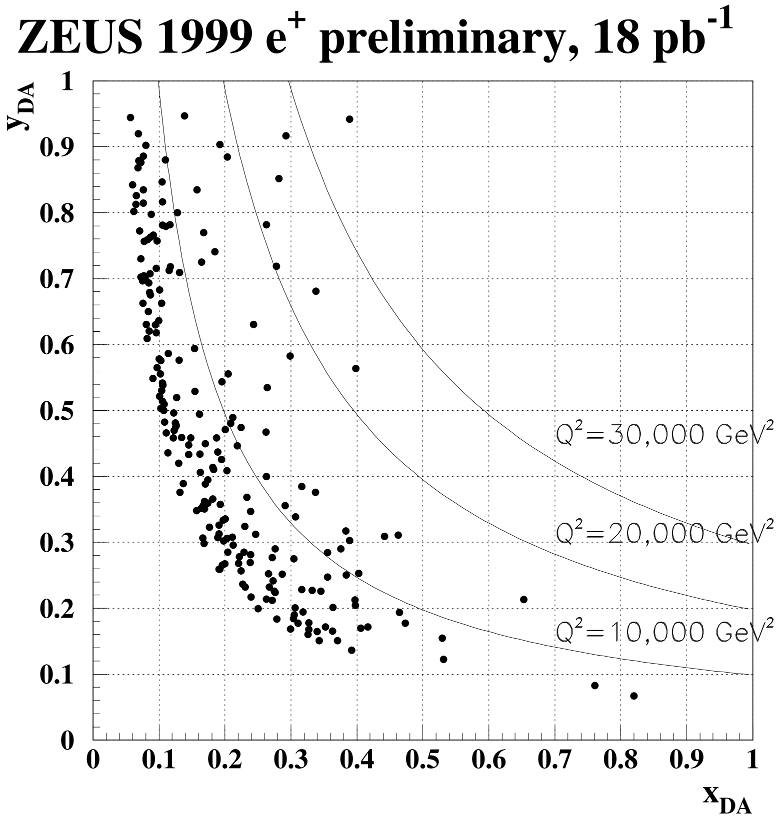
- Relax BRW model: β_e free parameter



- H1 limits extend into new $\beta_e - M$ range
- discovery potential for small β_e with $\nearrow \mathcal{L}$

FIRST LOOK AT 99 e^+ DATA

ZEUS HAD A FIRST LOOK AT **18** PB^{-1} OF e^+-DATA TAKEN IN 1999 AT $\sqrt{s} = 320$ GEV

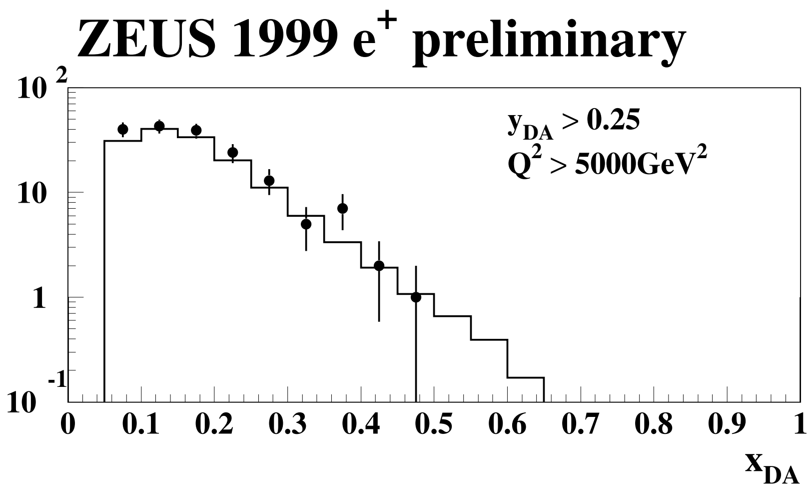


KINEMATICS (x_{DA}, y_{DA}) RECONSTRUCTED WITH "DOUBLE ANGLE" METHOD (USE MEASURED SCATTERING ANGLES OF ELECTRON AND JET)

$$M = \sqrt{xs}$$

COMPARE DATA TO SM MC:

- ● DATA
- — NC DIS MC



$Q^2 >$	99 e^+ data	NC MC
5,000	216	190
10,000	37	33.0
20,000	7	3.3
30,000	1	0.52

MORE DATA COMING IN 2000 (ALREADY $\approx$ 10 PB^{-1}/EXP.)

LEPTON FLAVOUR VIOLATING LQ'S

- LFV CAN BE MEDIATED BY LQ'S COUPLING TO eq AND μq OR τq PAIRS, SEARCH IN 94-97 e^+p SAMPLE

★ τ +JET FINAL STATES, WHERE $\tau \rightarrow$ HADRONS STUDIED BY H1

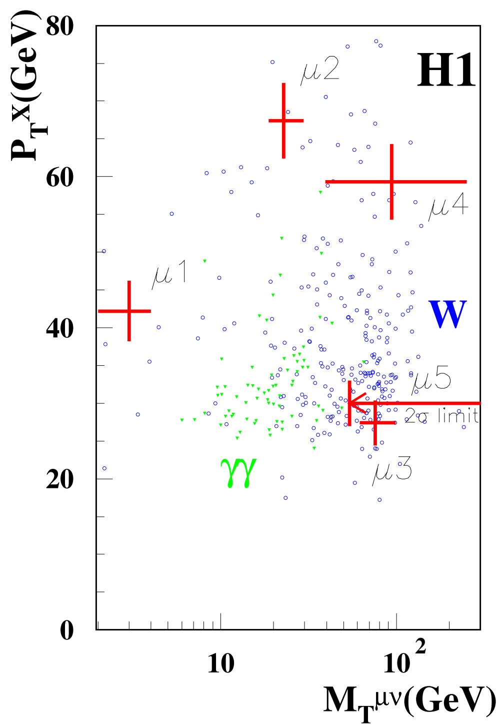
NO τ +JET CANDIDATE COMPATIBLE WITH LQ $\rightarrow$ LIMITS

★ μ +JET FINAL STATES WITH p_t^{miss} IN CALORIMETER STUDIED BY H1 AND ZEUS

NO μ +JET CANDIDATE COMPATIBLE WITH LQ $\rightarrow$ LIMITS

HOWEVER, H1 FOUND 5 EVENTS (0.8 EXP.) WITH:

- ISOLATED μ WITH HIGH p_t
- LARGE MISSING p_t
- HIGH p_t HADRONIC JET



POSSIBLE EXPLANATIONS INSIDE SM:

- W PRODUCTION
- INELASTIC $\gamma\gamma$ INTERACTIONS

$\rightarrow$ OBSERVED EVENTS SHOW OUTSTANDING KINEMATICS

$\leftarrow$ STATISTICS OF SM MC 500 $\times$ DATA

$P_T^X = \sum p_t$ OF ALL PARTICLES EXCEPT THE μ

LEPTON FLAVOUR VIOLATION: HIGH M LQ'S

$$M_{LQ} \gg \sqrt{s_{ep}} \Rightarrow \sigma \propto (\lambda_{1i}\lambda_{3j}/M_{LQ}^2)^2$$

$e \longleftrightarrow \tau$ **F = 0**

BEST EXCLUSION UPPER LIMITS ON $\dfrac{\lambda_{1i}\ \lambda_{3j}}{M^2_{LQ}}$ (in 10^{-4} GeV^{-2})

FOR LEPTON FLAVOUR VIOLATING LEPTOQUARKS

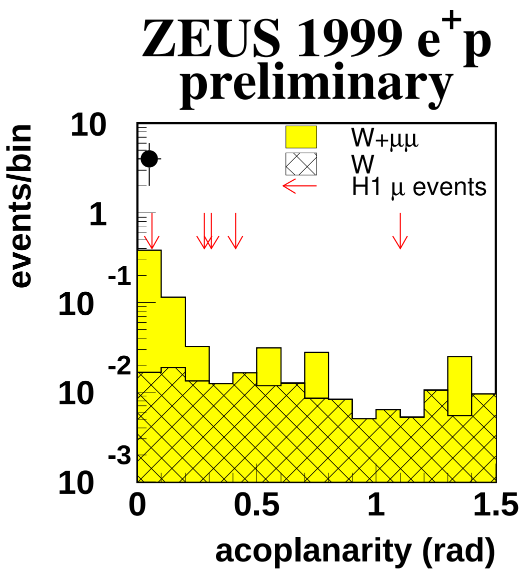
$q_i\ q_j$	$S_{1/2,L}$	$S_{1/2,R}$	$\tilde{S}_{1/2,L}$	$V_{0,L}$	$V_{0,R}$	$\tilde{V}_{0,R}$	$V_{1,L}$
1 1	$\tau \to \pi e$ 0.0032 H1: 0.046	$\tau \to \pi e$ 0.0016 H1: 0.037	$\tau \to \pi e$ 0.0032 H1: 0.062	G_F 0.002 H1: 0.049	$\tau \to \pi e$ 0.0016 H1: 0.049	$\tau \to \pi e$ 0.0016 H1: 0.041	G_F 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	$K \to \pi \nu \bar{\nu}$ 2.5×10^{-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	$K \to \pi \nu \bar{\nu}$ 2.5×10^{-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

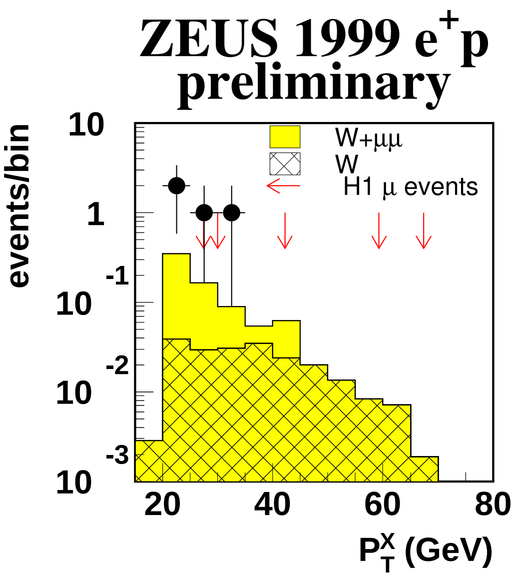
SEVERAL INDIRECT BOUNDS CONSIDERABLY IMPROVED

ISOLATED LEPTONS

HERA MODE YEAR	e^+p (300 GEV) 94-97	e^-p (320 GEV) 98/99	e^+p (320 GEV) 99
H1 LUMI	**37**PB^{-1}	**14**PB^{-1}	
EVENTS	OBSERVED (EXPECTED)	OBSERVED (EXPECTED)	
H1 e	**1** ($\mathbf{2.4 \pm 0.5}$)	**0** ($\mathbf{0.37 \pm 0.07}$)	
H1 μ	**5** ($\mathbf{0.8 \pm 02}$)	**0** ($\mathbf{0.14 \pm 0.04}$)	
ZEUS LUMI	**48**PB^{-1}	**16**PB^{-1}	**18**PB^{-1}
EVENTS	OBSERVED (EXPECTED)	OBSERVED (EXPECTED)	OBSERVED (EXPECTED)
ZEUS e	**3** ($\mathbf{3.5 \pm 0.7}$)	**2** ($\mathbf{0.8 \pm 0.4}$)	**2** ($\mathbf{1.8 \pm 0.4}$)
ZEUS μ	**0** ($\mathbf{2.0 \pm 0.4}$)	**0** ($\mathbf{0.8 \pm 0.1}$)	**4** ($\mathbf{0.9 \pm 0.1}$)

H1, ZEUS PRELIMINARY





IN TOTAL ZEUS OBSERVES (PRELIMINARY):

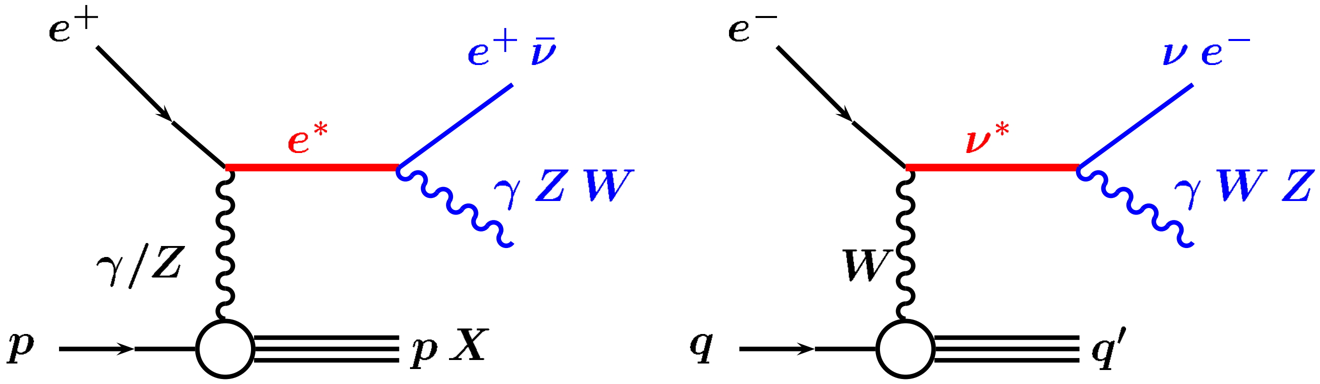
e: 7 (EXP. $\mathbf{6.1 \pm 0.9}$) μ: 4 (EXP. $\mathbf{3.7 \pm 0.4}$)

RATE AGREES WITH SM, μ-KINEMATICS STILL UNDER STUDY

EXCITED FERMIONS

EXCITED FERMIONS ARE SIGNALS FOR COMPOSITENESS AT ENERGIES $\mathcal{O}(\Lambda)$, (Λ = COMPOSITENESS SCALE)

AT HERA: SINGLE PRODUCTION OF e^*, ν^*, q^* POSSIBLE, FOLLOWED BY $f^* \to f(f') + V$



PHENOMENOLOGICAL MODEL OF HAGIWARA, KOMAMIYA & ZEPPENFELD:

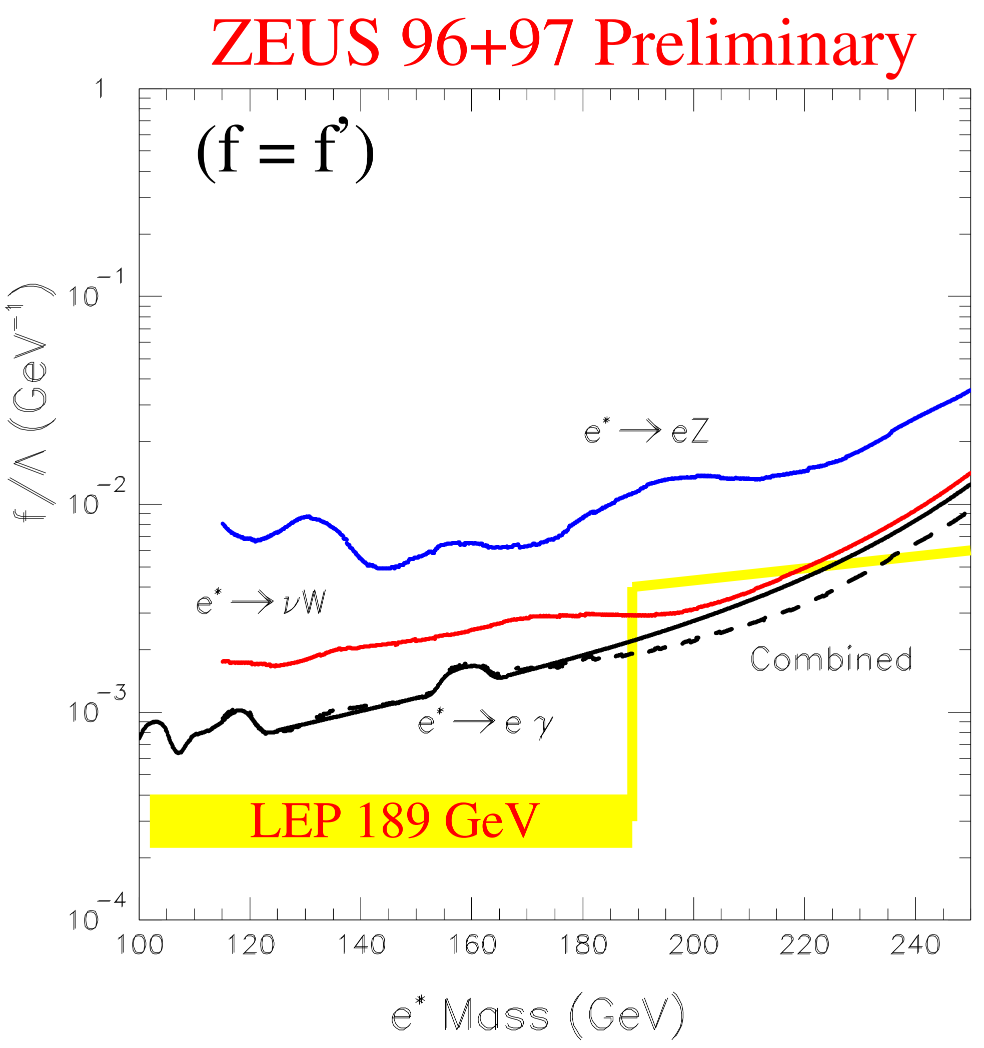
$$\mathcal{L}_{ff^*} = \frac{1}{\Lambda} \cdot f_R^* [f\, SU(2)_L + f' U(1)_Y + f_S SU(3)_c] f_L$$

WITH: (f_R^*, f_L^*) DOUBLETS OF $SU(2)_L$
f', f, f_S COUPLINGS TO $U(1)$, $SU(2)$, $SU(3)$ BOSONS

SEARCH FOR FERMION-BOSON RESONANCE
SIGNATURES: $e + \gamma, e + jets, e + p_t^{miss}, \gamma + p_t^{miss}$

LIMITS ON e^*

NO EVIDENCE FOR A RESONANCE PEAK OBSERVED
LIMITS ARE SET ON f/Λ, ASSUMING $|f| = |f'|$

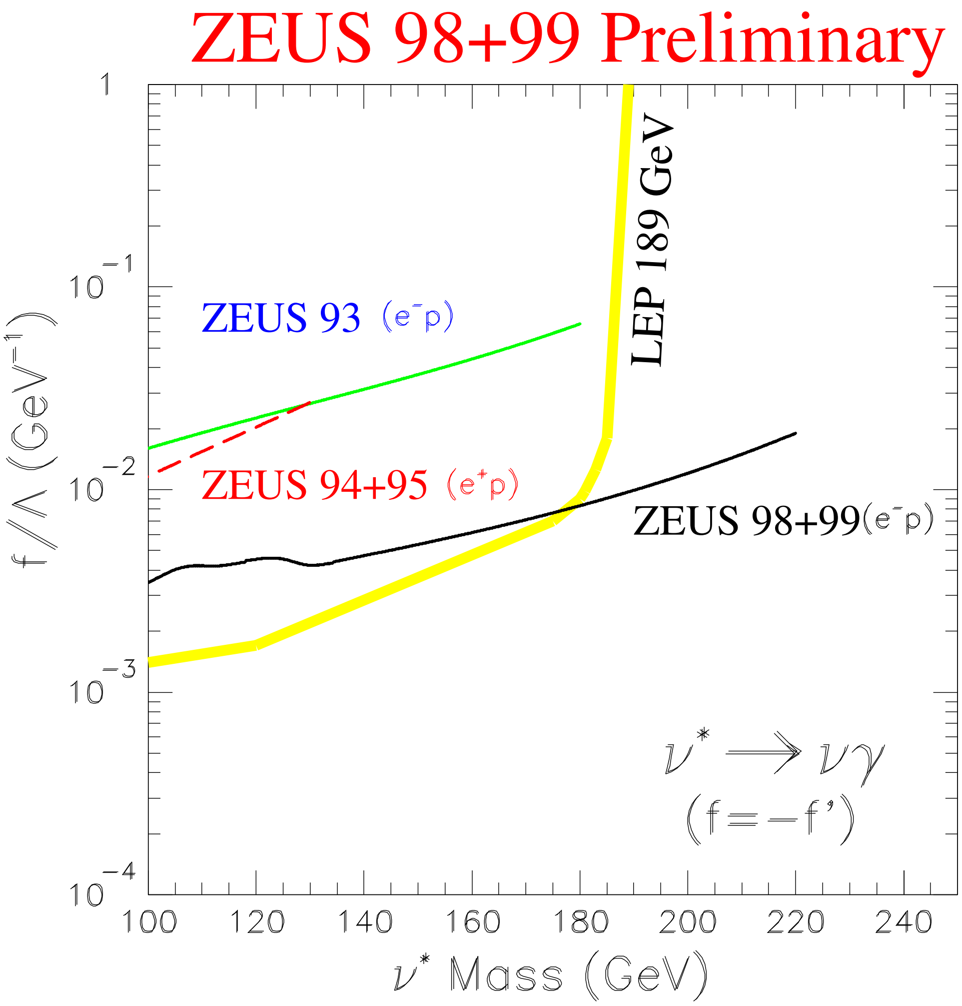


★ $f/\Lambda = 1/M(e^*) > 229\mathrm{GeV}$ AT 95% CL

★ HERA LIMITS: $M(e^*) > \sqrt{s_{LEP}}$

$\Rightarrow$ COMPETITIVE

LIMITS ON ν^*



- ★ $\sigma(e^-p \rightarrow \nu^* X) \approx 100\ \sigma(e^+p \rightarrow \nu^* X)$
  $\Rightarrow$ BETTER SENSITIVITY FOR ν^* WITH 16 pb^{-1} e^-p-DATA, THAN FOR FULL e^+p SAMPLE!
- ★ $\nu^* \rightarrow \nu\gamma$ ASSUMES $f = -f'$
- ★ $f/\Lambda = 1/M(\nu^*) \rightarrow M(\nu^*) > 161\text{GeV}$, 95% CL
- ★ LIMITS EXTEND BEYOND LEP KINEMATICAL LIMITS

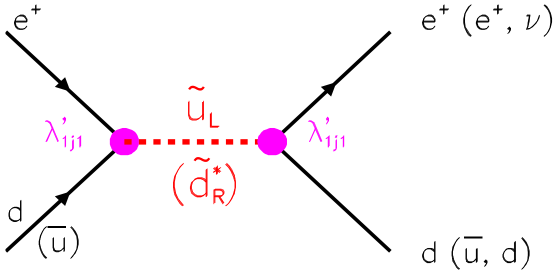
R-PARITY VIOLATING SUSY

- RESONANT $\tilde{q}$ PRODUCTION IN $\not{R}_p$ SUSY

$\not{R}_p$ PART OF SUPERPOTENTIAL:

$$\boxed{W_{\not{R}_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}$$

$\Rightarrow$ SINGLE PRODUCTION OF SFERMIONS



e^+ PROBES MAINLY λ'_{1j1}

COUPLINGS:

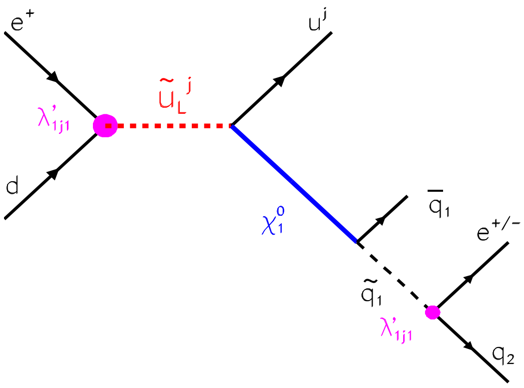
$$e^+ d \rightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$$

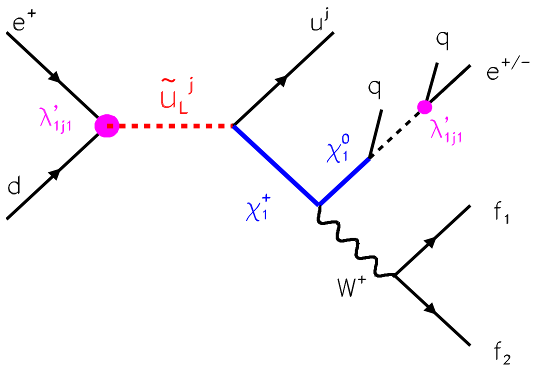
$$\sigma(ep \rightarrow \tilde{u}^j_L) \propto {\lambda'_{1j1}}^2$$

- $\not{R}_p$ DECAYS: $\Rightarrow$ CF LEPTOQUARKS

FINAL STATE: HIGH-p_t $e(\nu)+$ JET, WITH $d\sigma/dy|_x \propto$ CONST.

- GAUGE DECAYS:



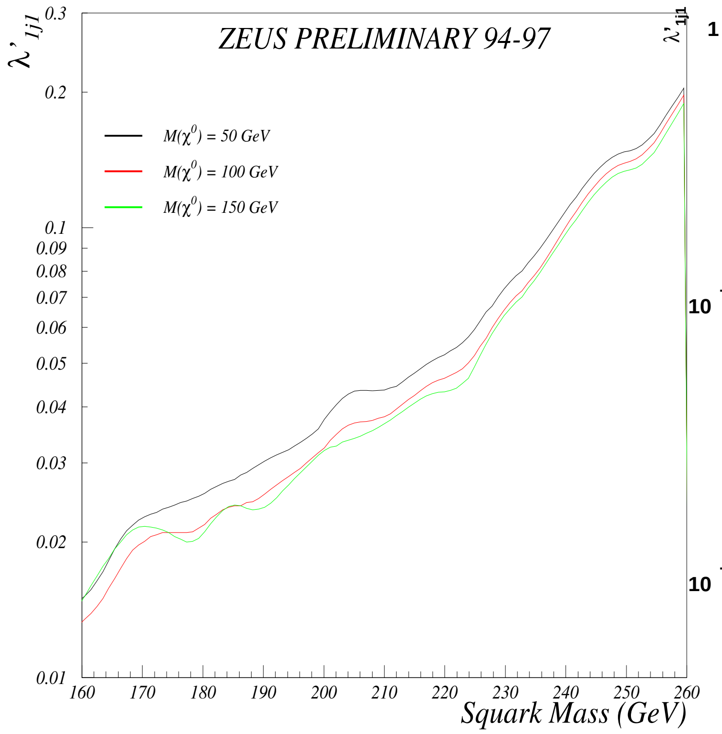


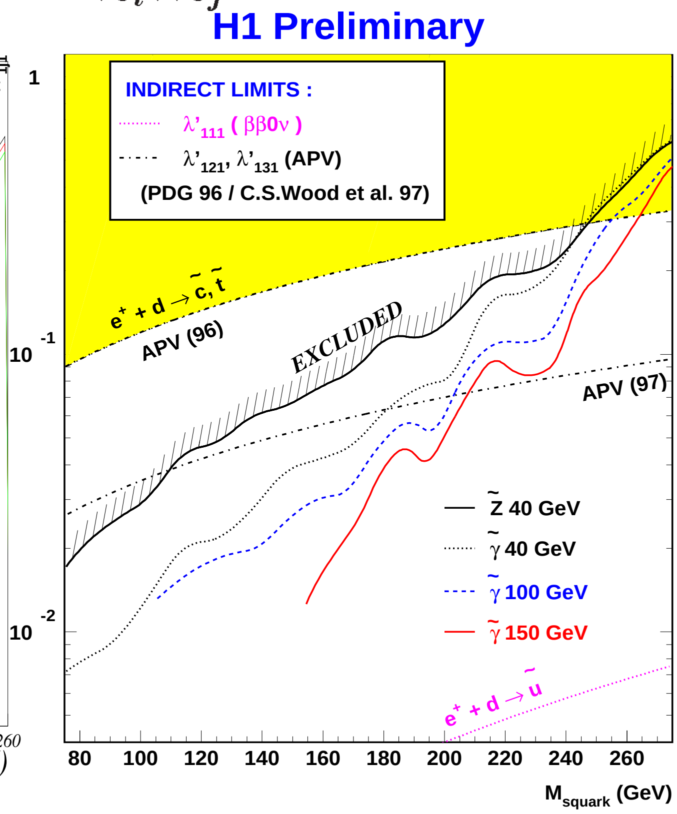
$\not{R}_p \Rightarrow$ LSP (χ^0_1) UNSTABLE, ASSUME $m_{\tilde{q}} < m_{\tilde{g}}$ $(\tilde{q} \nrightarrow q + \tilde{g})$

LIMITS ON λ'_{1j1} FOR $R\!\!\!/_p$ SQUARKS

- H1 & ZEUS SEARCH FOR eq, $e^{\pm} + jets$ TOPOLOGIES

- NO DEVIATION FROM SM FOUND $\Rightarrow$ CHANNELS COMBINED FOR REJECTION LIMITS, WHICH DEPEND ON MSSM PARAMETERS VIA MASSES AND MIXTURES OF χ_i^0, χ_j^+





- ZEUS: LSP IS PURE $\tilde{\gamma}$ – $\beta_{eq} + \beta_{\tilde{\gamma}q} = 1$
- H1: LSP DOMINATED BY $\tilde{\gamma}, \tilde{Z}$

- FOR GIVEN $M_{\chi_1^0}$ BETTER SENSITIVITY IF $\chi_1^0 \simeq \tilde{\gamma}$
- LIMITS IMPROVE WITH LARGER $M_{\chi_1^0}$ (BETTER ϵ)
- $M_{\tilde{q}}(\lambda' \simeq 0.3) > 260$ GEV; $M_{\tilde{q}}(\lambda' = 0.03) > 175$ GEV
- COMPARABLE/BETTER $\lambda'_{121}, \lambda'_{131}$ SENSITIVITY THAN INDIRECT LIMITS (APV)

Conclusions and Outlook

- ★ no evidence for new physics was observed in $\approx 2 \times 40$ pb^{-1} of e^+p-data in the searches for excited fermions, leptoquarks, and contact interactions (and $\not{R}_p$ susy)
- ★ preliminary analysis of ≈ 15 pb^{-1} of e^-p data showed no evidence for LQ signal
- ★ models of LQ, f^*, C.I. have been constrained & compared to other experiments:
  - ☆ new limits on LQ's are competitive with LEP and TeVatron results
  - ☆ still discovery potential, e.g. for 1st generation LQ's with low $\beta(lq \to eq)$, LFV LQ's, contact interactions and f^* with $M_{f^*} > \sqrt{s_{LEP}}$
- ★ ZEUS had first look at 18 pb^{-1} of $\sqrt{s}$=320 GeV positron data;
  30 pb^{-1}/exp. will be taken in 2000
- ★ Septembre 2000 - summer 2001 shutdown for lumi upgrade
  - ☆ after summer 2001: 170 pb^{-1}/year $\Rightarrow$ 1 fb^{-1} until 2005
  - ☆ polarised e-beam