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Leptoquark/Squark at HERA: Implications for e^+e^- Scattering at LEP2

DIS'97, Chicago, April 1997

Outline:

1. Classification
2. $e^+e^- \to q\bar{q}$
3. leptoquarks
4. squarks
5. sleptons

hep-ph/9703288
hep-ph/9703436

Objective:

➔ cross checking possible interpretations of HERA events at $e^+e^- \to q\bar{q}$

➔ new phenomena at e^+e^- scattering ?

Hera events ⟺ LEP 1, LEP 2

Choudhury, Raychaudhuri, hep-ph/9702392
Altarelli, Ellis, Giudice, Lola, Mangano, hep-ph/9703276
Dreiner, Morawitz, hep-ph/9703279
Donchoski, Godfrey, hep-ph/9703285
Kalinowski, Rückl, Spiesberger, Zerwas, hep-ph/9703288
Babu, Kolda, March-Russel, Wilczek, hep-ph/9703299
Barger, Cheung, Hagiwara, Zeppenfeld, hep-ph/9703311
Hewett, Rizzo, hep-ph/9703337
Gonzalez-Garcia, Novaes, hep-ph/9703346
Papadopoulos, hep-ph/9703372
Di Bartolomeo, Fabbrichesi, hep-ph/9703375
Jadach, Ward, Wąs, hep-ph/9704241
Kalinowski, Rückl, Spiesberger, Zerwas, hep-ph/9703436

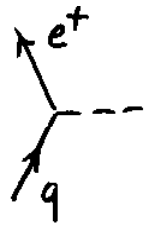
1. Classification (respecting SU(3)×SU(2)×U(1))

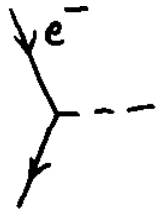
Buchmüller, Rückl, Wyler '8:

s-channel resonance in $l^{\pm}p$ scattering

e^+p $\qquad$ e^-p

$F = 0$



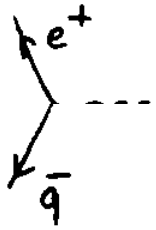


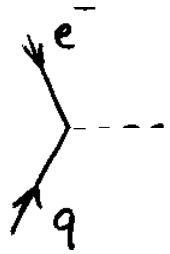
$S_{1/2}$, $\tilde{S}_{1/2}$, V_0, $\tilde{V}_0$, V_1

$\updownarrow$

$\tilde{q}_L$ in SUSY $\not{R}$

$F = \pm 2$





S_0, $\tilde{S}_0$, S_1, $V_{1/2}$, $\tilde{V}_1$

$\updownarrow$

$\tilde{d}_R$ in SUSY $\not{R}$

Constraints on masses/couplings

- B and L conserving
- flavor diagonal
- chiral L or R couplings
- rare processes, $0\nu\beta\beta$ decay, and atomic parity violation

LQ	Q	Decay Mode	BR $e^{\pm} j$	Coupling	Limits Ref.[11,12]	HERA estimates	$e_i^- e^+ \to q_k \bar{q}$ ik
$S_{1/2}$	$-2/3$	$\nu_L \bar{u}$	0	g_L	$g_L < 0.1$	–	–
		$e_R \bar{d}$	1	$-g_R$		0.052	RL
	$-5/3$	$e_L \bar{u}$	1	g_L	$g_R < 0.09$	0.026	LR
		$e_R \bar{u}$		g_R		0.026	RL
$\tilde{S}_{1/2}$ $\bar{\tilde{d}}_L$	$+1/3$	$\nu_L \bar{d}$	0	g_L	$g_L < 0.1$	–	–
$\bar{\tilde{u}}_L$	$-2/3$	$e_L \bar{d}$	1	g_L		0.052	LR
V_0	$-2/3$	$e_L \bar{d}$	$\frac{1}{2}$	g_L	$g_L < 0.05$	0.080	LL
		$\nu_L \bar{u}$		g_L			–
		$e_R \bar{d}$	1	g_R	$g_R < 0.09$	0.056	RR
$\tilde{V}_0$	$-5/3$	$e_R \bar{u}$	1	g_R	$g_R < 0.09$	0.027	RR
V_1	$+1/3$	$\nu_L \bar{d}$	0	$\sqrt{2} g_L$	$g_L < 0.04$	–	–
	$-2/3$	$e_L \bar{d}$	$\frac{1}{2}$	$-g_L$		0.080	LL
		$\nu_L \bar{u}$		g_L			–
	$-5/3$	$e_L \bar{u}$	1	$\sqrt{2} g_L$		0.019	LL
S_0 $\tilde{d}_R$	$-1/3$	$e_L u$	$\frac{1}{2}$	g_L	$g_L < 0.06$	0.40	LL
		$\nu_L d$		$-g_L$			–
		$e_R u$	1	g_R	$g_R < 0.1$	0.28	RR
$\tilde{S}_0$	$-4/3$	$e_R d$	1	g_R	$g_R < 0.1$	0.30	RR
S_1	$+2/3$	$\nu_L u$	0	$\sqrt{2} g_L$	$g_L < 0.09$	–	–
	$-1/3$	$\nu_L d$	$\frac{1}{2}$	$-g_L$		0.40	–
		$e_L u$		$-g_L$			LL
	$-4/3$	$e_L d$	1	$-\sqrt{2} g_L$		0.21	LL
$V_{1/2}$	$-1/3$	$\nu_L d$	0	g_L	$g_L < 0.09$	–	–
		$e_R u$	1	g_R		0.30	RL
	$-4/3$	$e_L d$	1	g_L	$g_R < 0.05$	0.32	LR
		$e_R d$		g_R		0.32	RL
$\tilde{V}_{1/2}$	$+2/3$	$\nu_L u$	0	g_L	$g_L < 0.09$	–	–
	$-1/3$	$e_L u$	1	g_L		0.32	LR

F= 0

F= 2

e^+

q

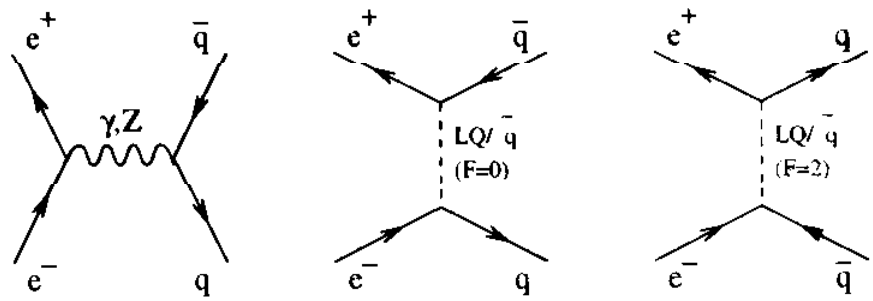
e^-

$\bar{q}$

SUSY

in both NC and CC

2. $e^+e^- \to q\bar{q}$ including $LQ/\tilde{q}$



a) b) c)

Fierz transformation: t/u-channel $\Rightarrow$ standard s-channel,
only *(lepton vector current)*$\times$*(quark vector current)*

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \to q\bar{q}) = \frac{3}{128\pi s}\left\{s^2(1+\cos\theta)^2\left(|f_{LL}|^2+|f_{RR}|^2\right) + s^2(1-\cos\theta)^2\left(|f_{LR}|^2+|f_{LR}|^2\right)\right\}$$

$$f_{LR} = \frac{Q^{eq}_{LR}}{s} + \delta_{qu}\left(\frac{g_L^2}{2(t-S_{1/2})} - \frac{g_L^2}{u-\tilde{V}_{1/2}}\right) + \delta_{qd}\left(\frac{g_L^2}{2(t-\tilde{S}_{1/2})} - \frac{g_L^2}{u-V_{1/2}}\right)$$

$\tilde{u}_L$ in SUSY

f_{RR} : $S_0,\ \tilde{S}_0,\ V_0,\ \tilde{V}_0$

f_{LL} : $\underline{S_0},\ S_1,\ V_0,\ V_1$ can contribute

f_{RL} : $S_{1/2},\ V_{1/2}$

$$Q^{eq}_{ik} = e^2 Q_e Q_q + \frac{g_i^e g_k^q}{1-m_Z^2/s}, \qquad g_L^f = \frac{e}{s_W c_W}\left[I_3^f - s_W^2 Q_f\right], \quad g_R^f = \frac{e}{s_W c_W}\left[-s_W^2 Q_f\right]$$

at LEP2: $\begin{cases} Q^{eu}_{ij} < 0 \\ Q^{ed}_{RL} < 0, \quad Q^{ed}_{LL},\ Q^{ed}_{RR},\ Q^{ed}_{LR} > 0 \end{cases}$

3. Leptoquarks

taking s-channel resonance with $M = 200$ GeV

- for $F = 0$ leptoquarks in

  e^+u : $g \sim 0.02 - 0.03$

  e^+d : $g \sim 0.04 - 0.08$

  $\Rightarrow$ weak couplings $\sim e/10$

- for $F = 2$ leptoquarks in

  $e^+\bar{u}$: $g \sim 0.3$

  $e^+\bar{d}$: $g \sim 0.3 - 0.4$

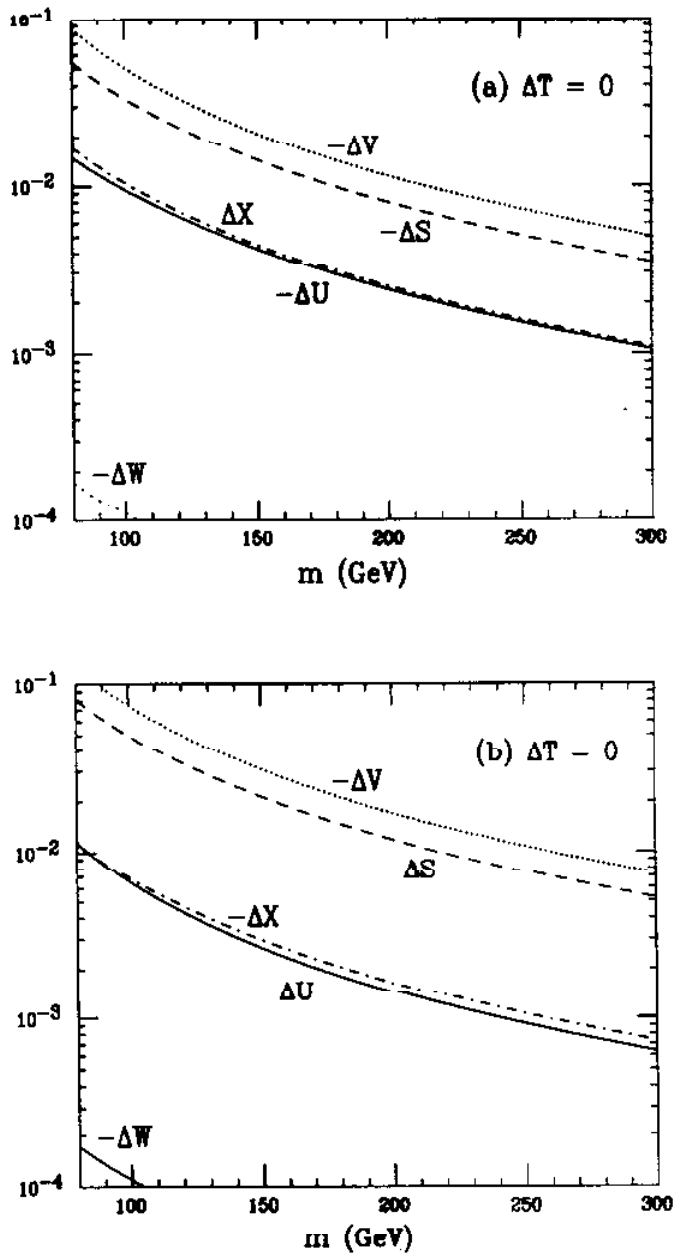
  $\Rightarrow$ excluded by e^-p and rare processes

Implications for $e^+e^- \to q\bar{q}$

- LEP1: oblique corrections small $\to F$
- LEP2: corrections to the total cross section $\to F$

  sensitivity to couplings/masses $\to F$

Hewett, Rizzo hep-ph/9303337



$\tilde{S}_{1/2}$

$S_{1/2}$

Figure 7: Shifts in the oblique parameters as functions of the leptoquark mass for the (a) $\tilde{R}_{2L}$ and (b) R_{2L} or R_{2R} cases.

Kalinowski, Kullel, Spreisberger, [illegible]

hep-ph/9703288

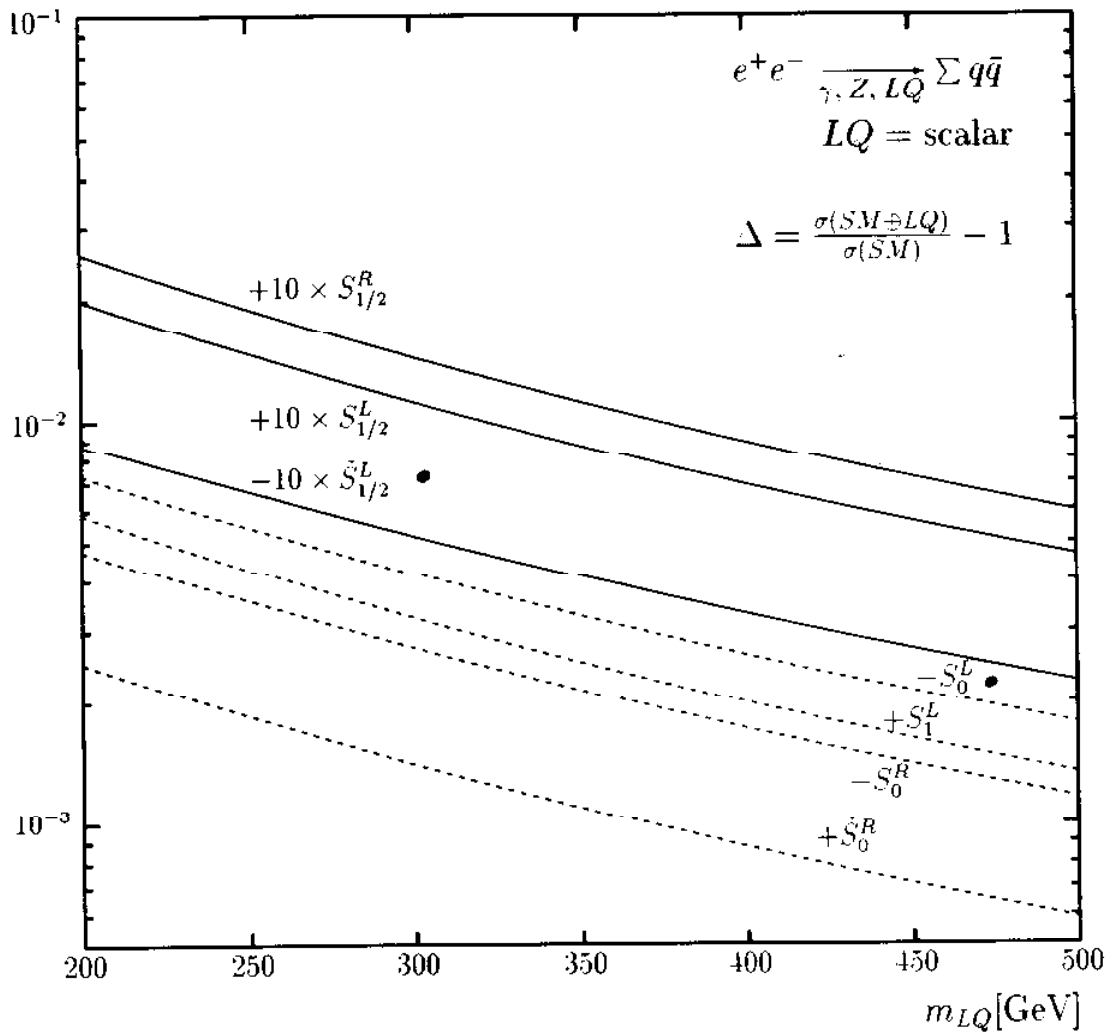


Figure 1: *Effect of t/u-channel exchange of scalar leptoquarks on the total hadronic cross section as a function of m_{LQ} for $\sqrt{s} = 192$ GeV. The couplings have been fixed arbitrarily to $(g_L, g_R) = (0.1, 0)$ or $(0, 0.1)$ indicated by $LQ^{L,R}$, respectively .*

for vector leptoquarks × 2

Hewett, R. 220 hep-ph/9703

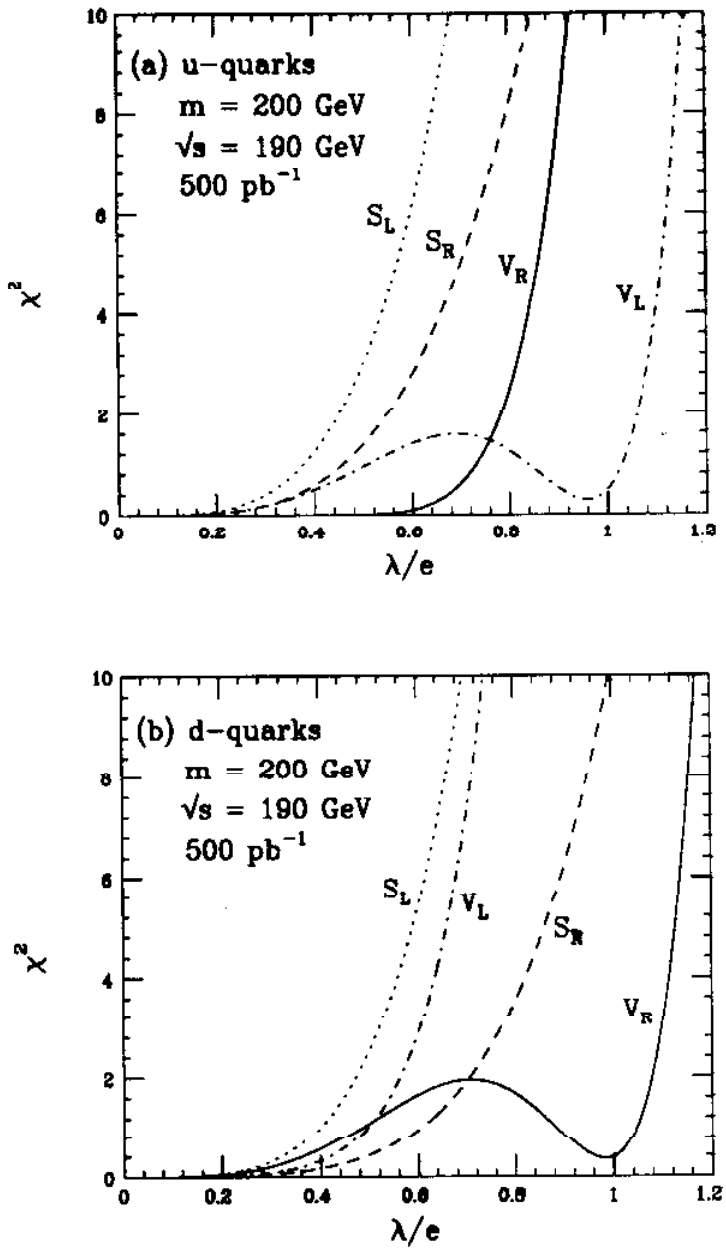


Figure 9: χ^2 fits to the SM angular distribution for $e^+e^- \to q\bar{q}$ at 190 GeV including the effects of a 200 GeV leptoquark coupling to (a) u- or (b) d-quarks. In both cases the dotted(dashed) curve corresponds to a scalar leptoquark with a left(right)-handed coupling while the dash-dotted(solid) curve corresponds to the vector leptoquark case with left(right)-handed couplings. The 95% CL limits are obtained when $\chi^2 = 3.842$.

Contact Interaction Interpretation

→ see Zeppenfeld

if $m_{LQ} \gg s$([redacted]t, u), the results can be interpreted as due to lepton-quark contact terms described by the effective Lagrangian

$$\begin{aligned} \mathcal{L}_{eff} &= \sum_{i,k=L,R} \frac{g_i^2}{m_{LQ}^2} \alpha^{ik} \left(\bar{e}_i \gamma^\mu e_i\right) \left(\bar{q}_k \gamma_\mu q_k\right) \\ &:= \sum_{i,k=L,R} \eta_{ik} \frac{4\pi}{\Lambda_{ik}^2} \left(\bar{e}_i \gamma^\mu e_i\right) \left(\bar{q}_k \gamma_\mu q_k\right) \end{aligned} \tag{1}$$

with $\eta_{ik} = sgn(\alpha_{ik})$ and $\Lambda_{ik}^2 = 4\pi m_{LQ}^2 / g_i^2 |\alpha^{ik}|$

	$u\bar{u}$ final state				$d\bar{d}$ final state			
α^{ik}	RR	LL	RL	LR	RR	LL	RL	LR
S_0	$\frac{1}{2}$	$\frac{1}{2}$						
$\tilde{S}_0$					$\frac{1}{2}$			
S_1		$\frac{1}{2}$				1		
$V_{1/2}$			1				1	1
$\tilde{V}_{1/2}$				1				
$S_{1/2}$			$-\frac{1}{2}$	$-\frac{1}{2}$			$-\frac{1}{2}$	
$S_{1/2}$								$-\frac{1}{2}$
V_0					-1	-1		
$\tilde{V}_0$	-1							
V_1		-2				-1		

for leptoquarks: $m \sim 200$ GeV, $g \sim 0.1$

$\Rightarrow \Lambda \sim 8 - 15$ TeV

if too heavy for HERA $\Rightarrow \Lambda \sim 2-3$ TeV required

Adopting pure phenomenological approach

$$\Rightarrow \Delta = \sigma(SM \oplus LQ)/\sigma(SM) - 1 \text{ at } \sqrt{s} = 192 \text{ GeV}$$

$\frac{\sigma - \sigma_{SM}}{\sigma}$:

ik	$u\bar{u}$ final state			$d\bar{d}$ final state		
$\Lambda[TeV]$	1.5	2.5	3.5	1.5	2.5	3.5
	$\eta = +1$					
LL	−0.11	−0.14	−0.09	0.92	0.23	0.10
RR	0.08	−0.07	−0.05	0.63	0.12	0.05
LR	0.30	0.01	−0.01	0.52	0.08	0.003
RL	0.41	0.05	0.01	0.30	0.004	−0.001
	$\eta = -1$					
LL	0.99	0.26	0.12	−0.03	−0.11	−0.07
RR	0.81	0.19	0.08	0.26	−0.008	−0.02
LR	0.59	0.11	0.04	0.37	0.03	0.002
RL	0.48	0.07	0.02	0.59	0.11	0.04

to compare with recent Opal results for Λ (Opal note PN 280 1997)

q	$u\bar{u}$		$d\bar{d}$	
η	+	−	+	−
LL	1.1	2.4	2.4	1.0
RR	1.4	1.7	2.1	1.2
LR	1.5	1.6	1.7	1.4
RL	1.7	1.4	1.6	1.5

in TeV

also strong constraints from APV and $\Gamma(Z \to e^+e^-)$

4. Squarks in R-parity Breaking SUSY

→ see Lol.

operator that couples squarks to quarks and leptons

$$W_{\not R} = \lambda'_{ijk} L^i_L Q^j_L \bar{D}^k_R$$

$$\text{violates} \quad R = (-1)^{3B+L+2S} = \begin{cases} +1 & : \text{ SM particles} \\ -1 & : \text{ superpartners} \end{cases}$$

the interaction Lagrangian

$$\mathcal{L}_{\not R} = \lambda'_{ijk} \left[\tilde{u}^j_L \bar{d}^k_R e^i_L + (\tilde{d}^k_R)^* (\bar{e}^i_L)^c u^j_L + \ldots \right] + h.c.$$

in $\underline{e^+ p}$ collisions $i = 1$, so $\lambda'_{1jk} \neq 0 \Rightarrow$

$$e^+ + d^k_R \to \tilde{u}^j_L \qquad\qquad e^+ + \bar{u}^j_L \to (\tilde{d}^k_R)^*$$
$$\tilde{u}^j = \tilde{u}, \tilde{c}, \tilde{t} \qquad\qquad \tilde{d}^k = \tilde{d}, \tilde{s}, \tilde{b}$$

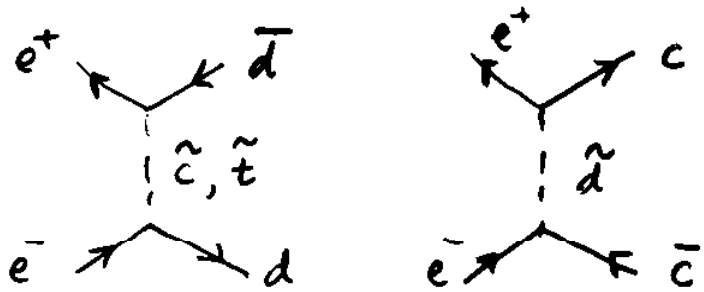
$$0\nu\beta\beta \text{ data} \Rightarrow |\lambda'_{111}| \lesssim 10^{-3}$$

note: $\lambda'_{1jk} \neq 0$ for Aleph 4-jet events

possibilities consistent with low-energy constraints

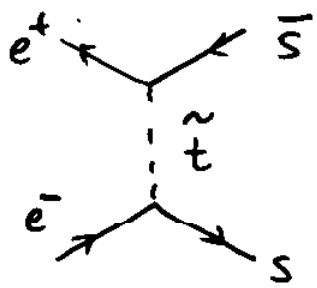
(a) $\lambda'_{1j1} \gtrsim 0.04$, $j = 2, 3$, *i.e.* $e^+d \to \tilde{c}$ or $\tilde{t}$

➡ in $e^+e^- \to q\bar{q}$



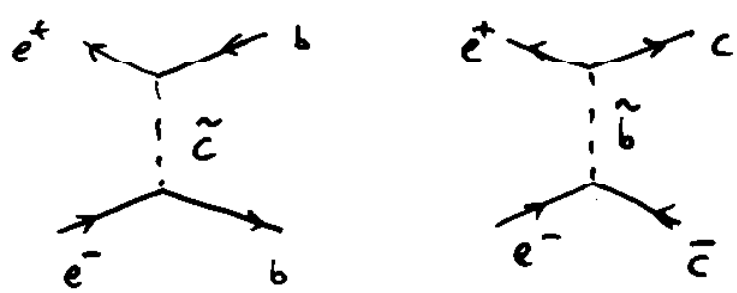
(b) $\lambda'_{132} \gtrsim 0.3$, *i.e.* $e^+s \to \tilde{t}$

➡ in $e^+e^- \to q\bar{q}$



(c) $\lambda'_{123} \gtrsim 0.4$, *i.e.* $e^+b \to \tilde{c}$ or $e^+\bar{c} \to (\tilde{b})^*$ or both

➡ in $e^+e^- \to q\bar{q}$



limits from OPAL →

Kalinowski, Rückl, Spira, Zerwas
hep-ph/9703288

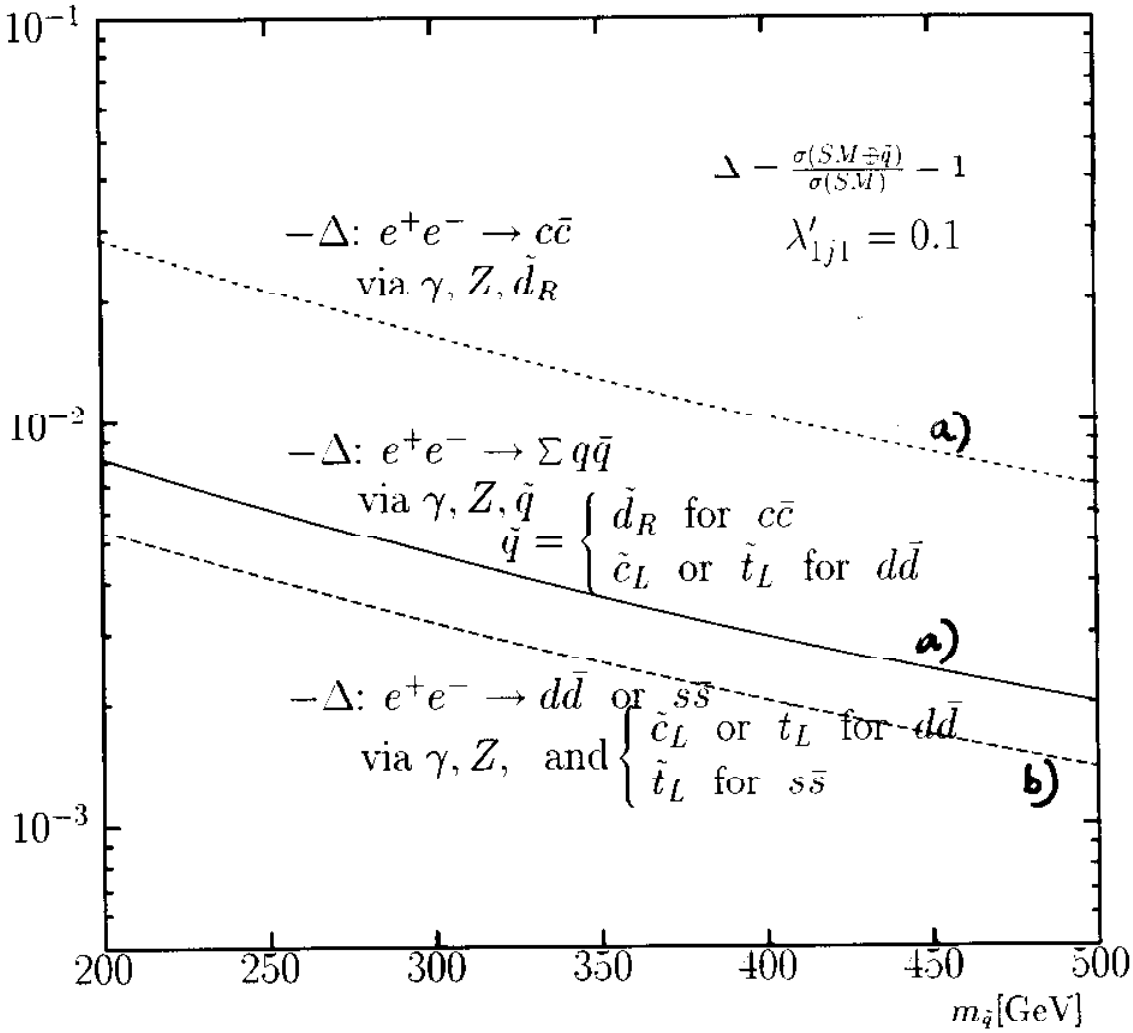
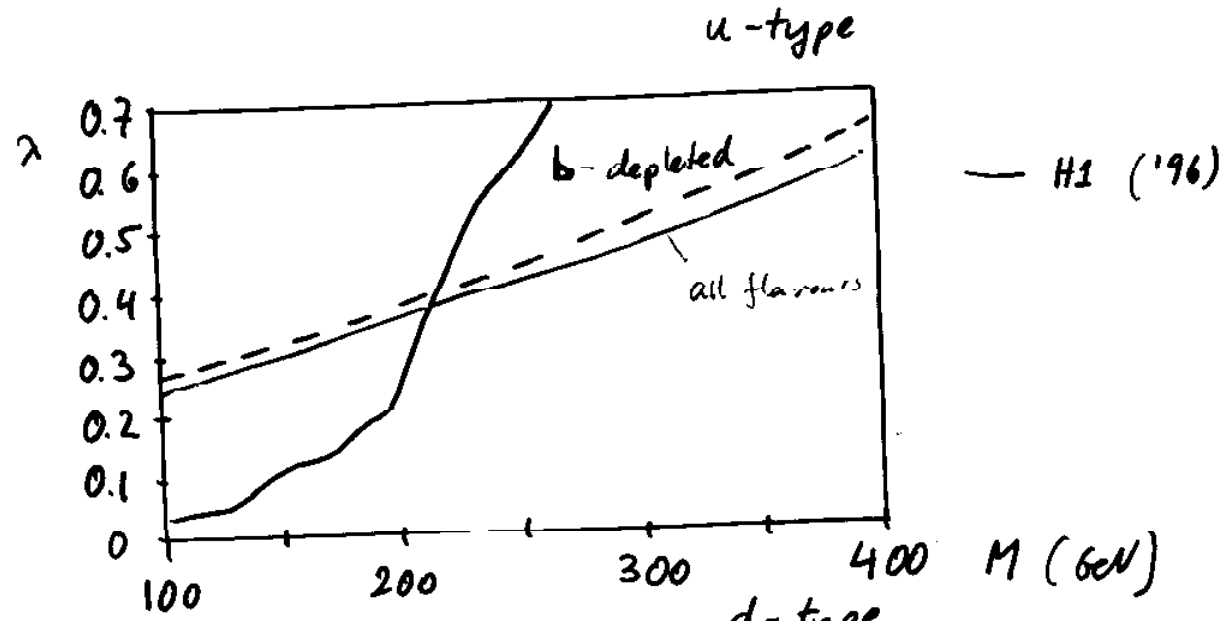
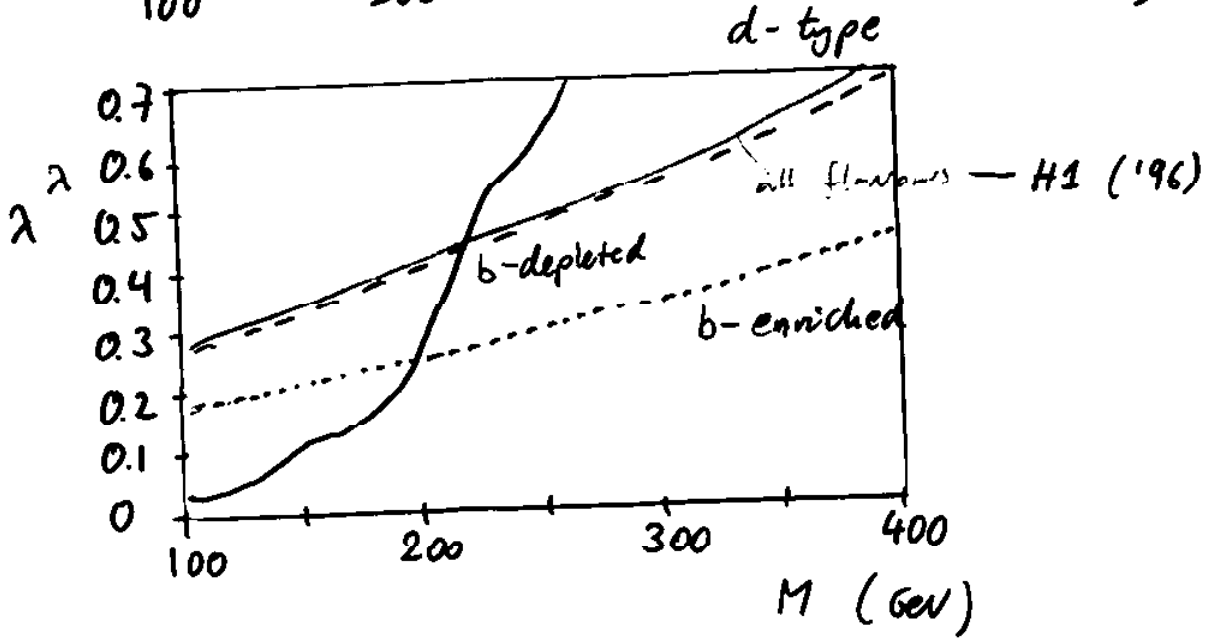


Figure 3: *Effect of t/u-channel exchange of squarks in the supersymmetry scenario (a) on the total hadronic cross section, $\Delta = \sigma(SM \oplus \tilde{q})/\sigma(SM) - 1$, as a function of $m_{\tilde{q}}$ for $\lambda'_{1j1} = 0.1$, $j = 2$ or 3 (or $\lambda'_{132} = 0.1$ for $s\bar{s}$) and $\sqrt{s} = 192$ GeV.*

Opal note PN 280
(27.02.97)

95% CL limits
$\sqrt{s}$ = 133, 161, 172 GeV





5. Sleptons in R-parity Breaking SUSY

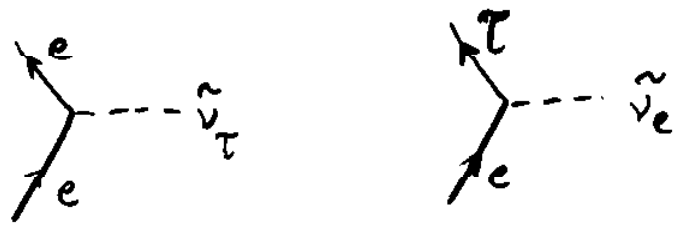
lepton-number violating operators

$$W_{\not R} = \lambda_{ijk} L^i_L L^j_L \bar{E}^k_R + \lambda'_{ijk} L^i_L Q^j_L \bar{D}^k_R$$

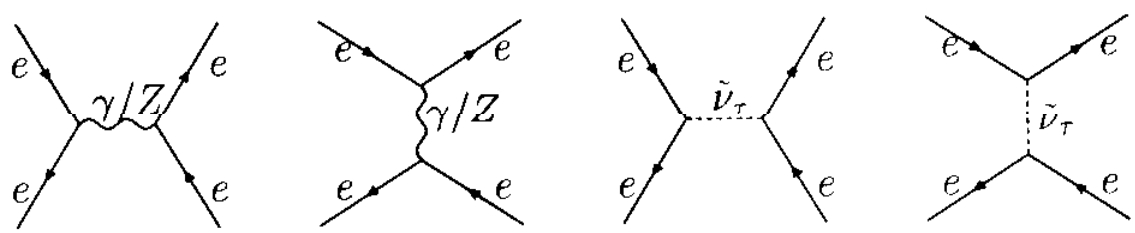
the interaction lagrangian in pure leptonic sector

$$\begin{aligned}\mathcal{L}^l_{\not R} &= \lambda_{ijk}\Big[\tilde{\nu}^j_L \bar{e}^k_R e^i_L + (\tilde{e}^k_R)^*(\bar{e}^i_L)^c \nu^j_L + \tilde{e}^i_L \bar{e}^k_R \nu^j_L \\ &\qquad -\tilde{\nu}^i_L \bar{e}^k_R e^j_L - (\tilde{e}^k_R)^*(e^j_L)^c \nu^i_L - \tilde{e}^j_L \bar{e}^k_R \nu^i_L\Big] + h.c.\end{aligned}$$

for example, if $\lambda_{131} \neq 0$



for Bhabha scattering



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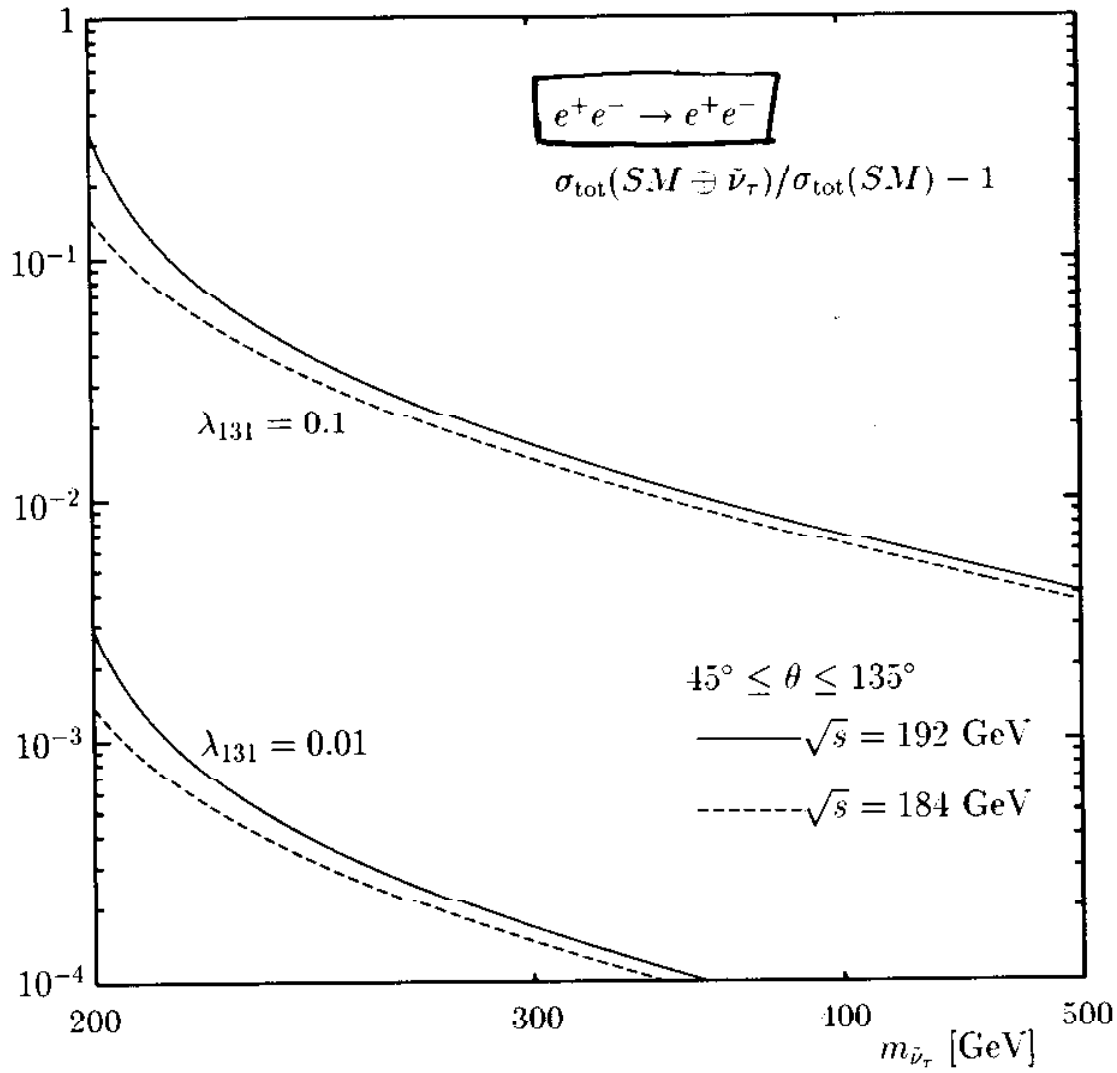

Figure 4: *Effect of sneutrino $\tilde{\nu}_\tau$ exchange on the cross section for Bhabha scattering for $45° \leq \theta \leq 135°$ at $\sqrt{s} = 192$ GeV (full lines) and $\sqrt{s} = 184$ GeV (dashed lines).*

Kalinowski, Rückl, Spira-Berger, Zerwas
hep-ph/9703436

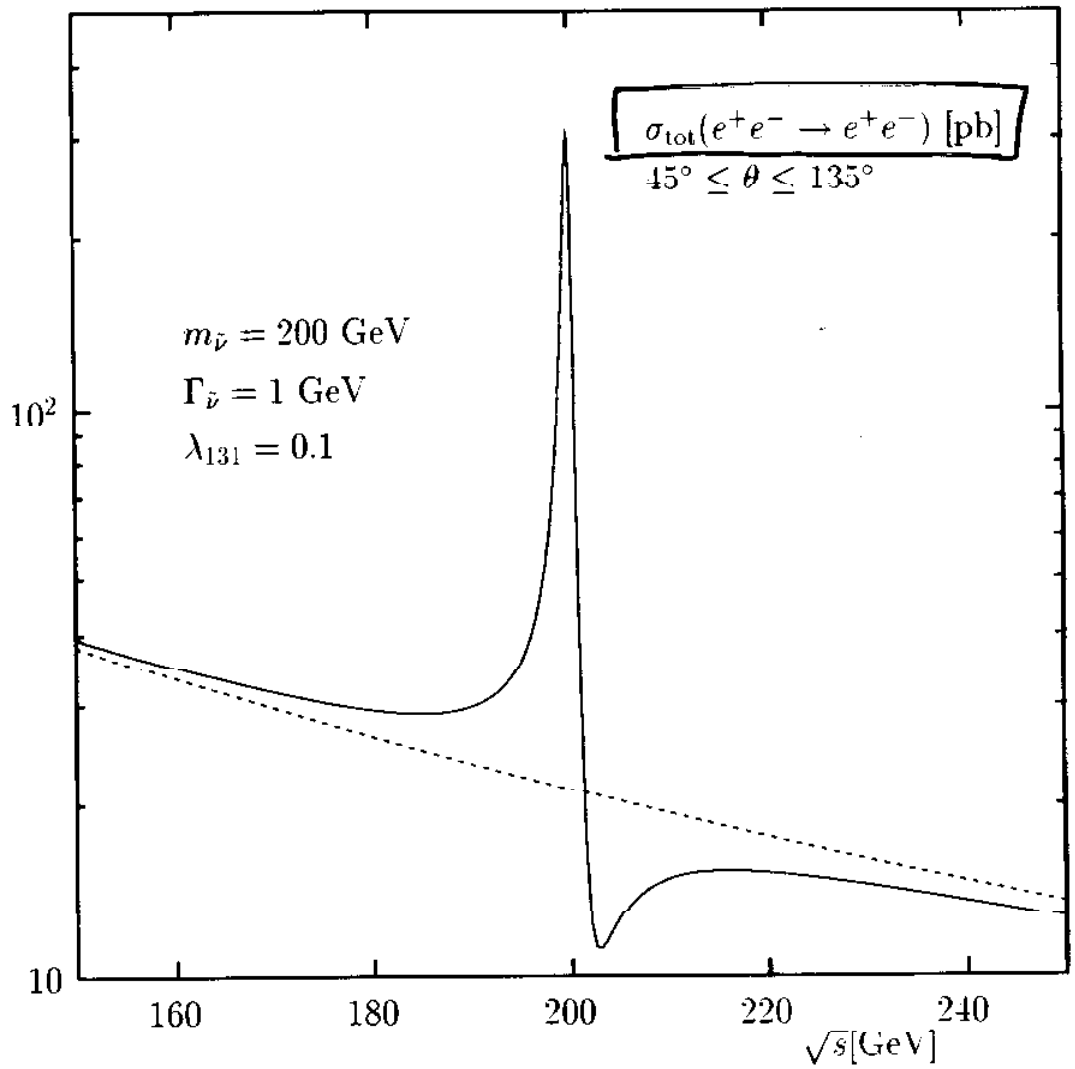

Figure 6: *Cross section for Bhabha scattering including $\tilde{\nu}_\tau, \bar{\tilde{\nu}}_\tau$ sneutrino resonance formation for $45° < \theta \leq 135°$ as a function of the e^+e^- center-of-mass energy. Parameters: $m_{\tilde{\nu}} = 200$ GeV, $\Gamma_{\tilde{\nu}} = 1$ GeV, and $\lambda_{131} = 0.1$.*

Summary

- only indirect tests of leptoquark/squark at present in $e^+e^- \to q\bar{q}$
- s-resonance interpretation of HERA events
  - ➡ consistent with LEP1
  - ➡ small effects in $e^+e^- \to q\bar{q}$ at LEP2
    with $\lambda'_{121} > 0.04$ consistent with Aleph 4-jet
- contact term interpretation can be tested at LEP2
  - ➡ current limits from Opal: $\Lambda \gtrsim 1.5 - 2.5$ TeV
  - ➡ by the end of 1997, $\Lambda \gtrsim 4 - 6.5$ TeV expected
- if also sleptons light, interesting effects in leptonic processes
  - ➡ for $\lambda_{131} \neq 0$, Bhabha scattering via $\tilde{\nu}_\tau$
  - ➡ if light enough, resonance in s-channel