Beyond the Desert '03

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Searches for LEPTOQUARKS with the OPAL detector

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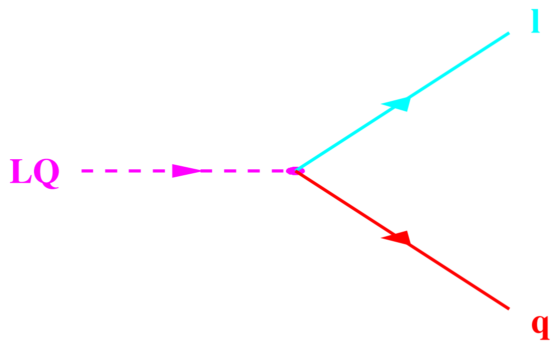
- Introduction.
- LQ in e^+e^- interactions :
  - virtual effects;
  - single production;
  - pair production.
- Searches with the OPAL detector.
- Conclusions.

- LEPTOQUARK : scalar or vector particle coupling to a lepton and a quark.



- Why LEPTOQUARKS?
  - Apparent simmetry quarks - leptons, unrelated "objects" within the Standard Model.

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

  - Beyond the Standard Model (e.g. G.U.T., Composite Models) :
    $\Longrightarrow$ l $\leftrightarrow$ q transitions mediated by fields carrying both quarks and leptons quantum numbers.

- Minimal requirements:
  - Baryon (B) and lepton (L) numbers conservation.
  - Respect of the SM simmetries $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

LQ (RPV $\tilde{q}$)	F=3B+L	Q_{em}	λ
S_0 ($\tilde{d}_R$)	2	-1/3	λ_L, λ_R
$\tilde{S}_0$	2	-4/3	λ_R
S_1	2	2/3 -1/3 -4/3	λ_L
$S_{1/2}$	0	-2/3 -5/3	λ_L, λ_R
$\tilde{S}_{1/2}$ ($\bar{\tilde{d}}_L$, $\bar{\tilde{u}}_L$)	0	1/3 -2/3	λ_L
V_0	0	-2/3	λ_L, λ_R
$\tilde{V}_0$	0	-5/3	λ_R
V_1	0	1/3 -2/3 -5/3	λ_L
$V_{1/2}$	2	-1/3 -4/3	λ_L, λ_R
$\tilde{V}_{1/2}$	2	2/3 -1/3	λ_L

W.Buchmüller, R.Rückl & D.Wyler, Phys.Lett. B191(1987)

$\lambda_{L,R} \Leftrightarrow \lambda^{i,j}_{(\mathrm{LQ})L,R}$

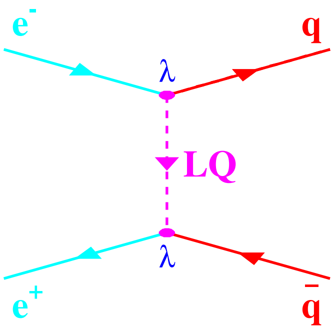
$i \equiv$ lepton generation, $j \equiv$ quark generation

- Within this model :
  - Coupling within a single fermions' generation. $\Longrightarrow$ Three LQ generations.

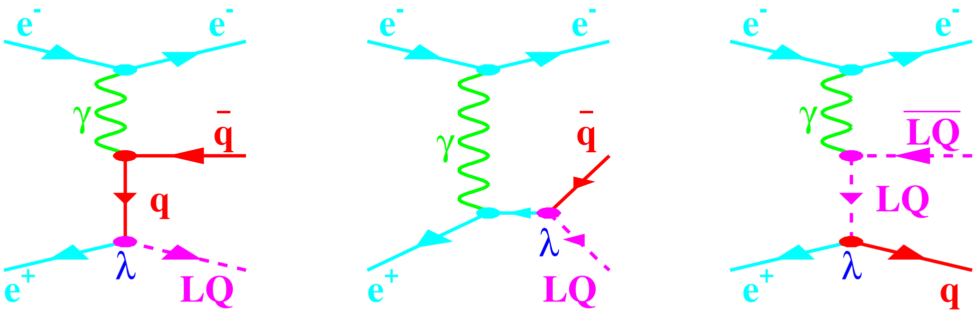
LQ in e^+e^- collisions

- Virtual effects :

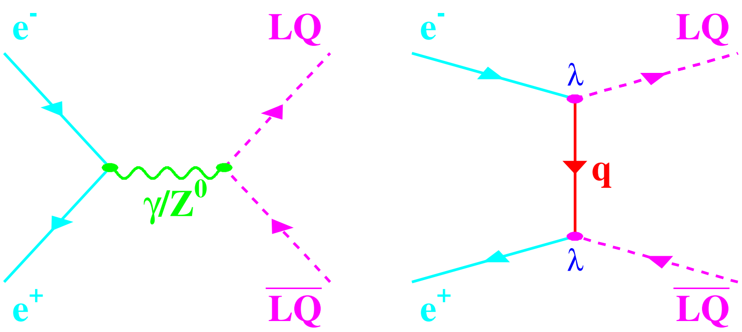
  $e^+e^- \rightarrow q\bar{q}$



- Single production : $e^+e^- \rightarrow LQeq$

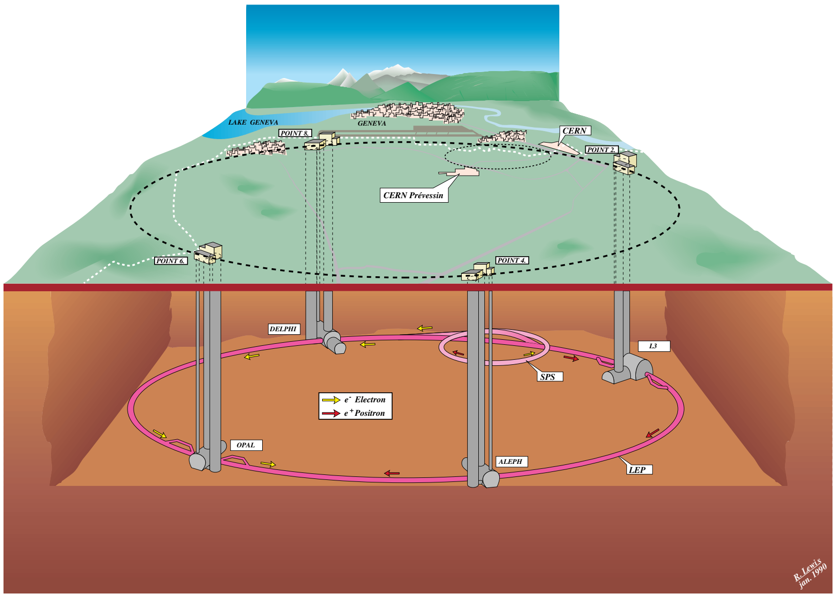


- Pair production : $e^+e^- \rightarrow LQ\overline{LQ}$

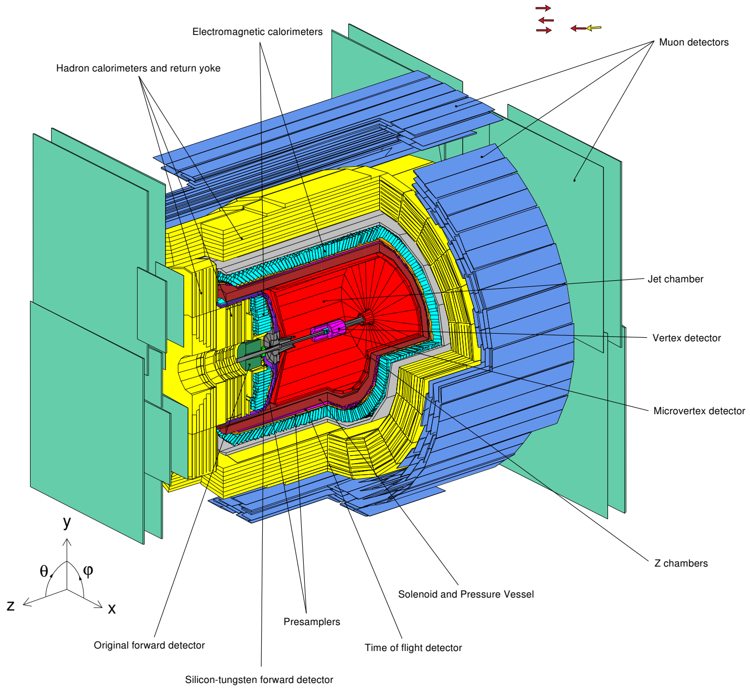


The LEP collider and the OPAL experiment

- **LEP** : **L**arge **E**lectron **P**ositron collider

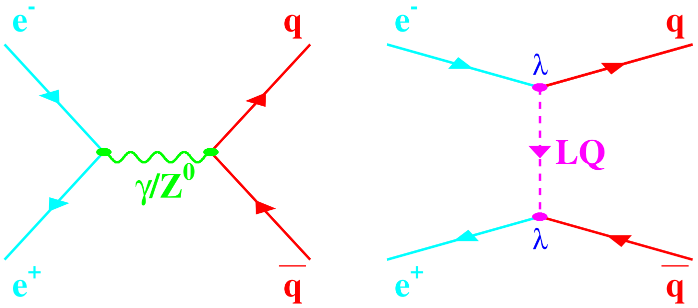


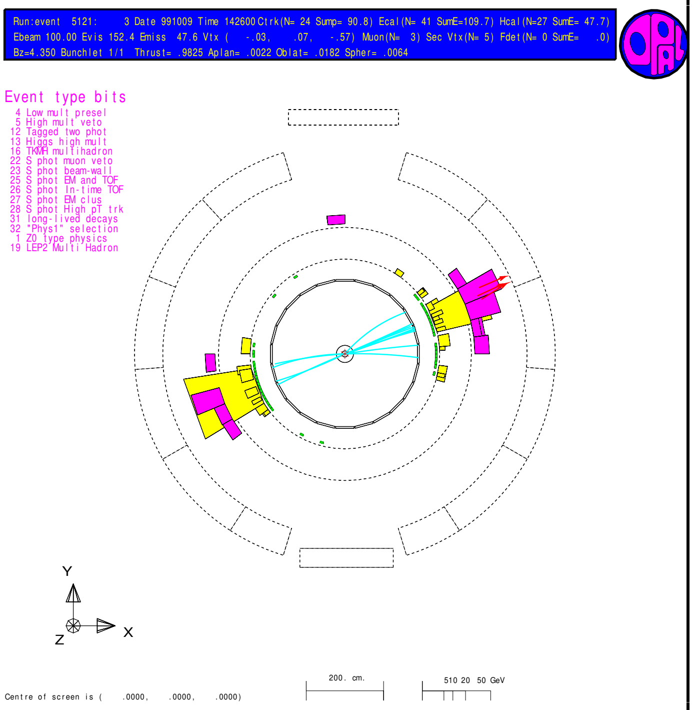
- **OPAL** : **O**mni **P**urpose **A**pparatus at **L**EP



Virtual effects in $e^+e^- \to q\bar{q}$ (1)

- Process
  $e^+e^- \to q\bar{q}$





- $\sigma_{tot} = \sigma_{SM} + \sigma(\lambda, \mathrm{M_{LQ}})$

- Only 1^{st} gen. LQ coupling to electrons

- Fit of the predicted σ_{tot} to the data $\Longrightarrow$ Exclusion curves (95% C.L.) in the $(\lambda, \mathrm{M_{LQ}})$ plane.

- OPAL : Eur. Phys. J. **C6** (1999) 1.
  (1997 data, $\sqrt{s}$ = 183 GeV).

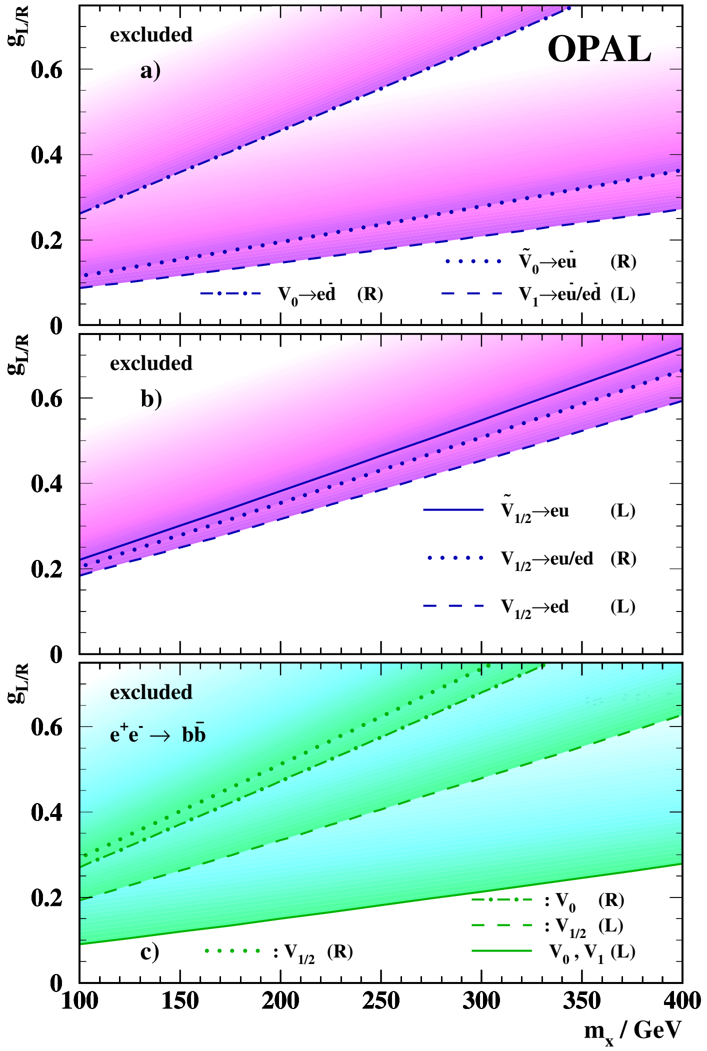
  LEP combined : CERN-EP-2002-091
  December 2002.

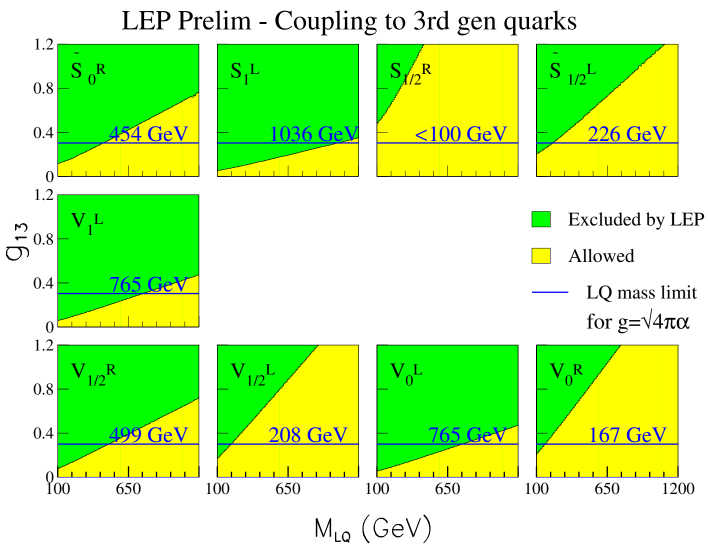
  (chiral couplings are assumed i.e. $\lambda_L \cdot \lambda_R = 0$)

Virtual effects in $e^+e^- \rightarrow q\bar{q}$ (2)

- OPAL: $\sqrt{s} = 183$ GeV.

Limits on the coupling for Vector Leptoquarks

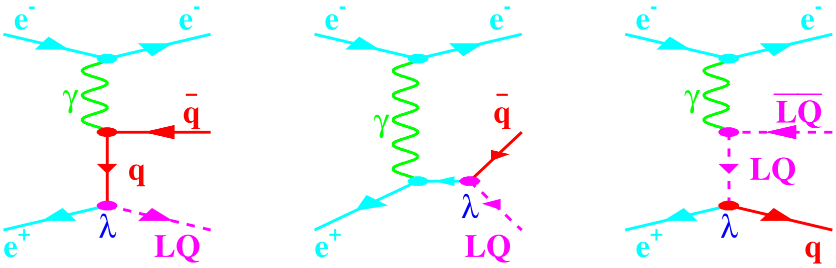




- LEP: $\sqrt{s}$ up to 209 GeV

Single production (1)

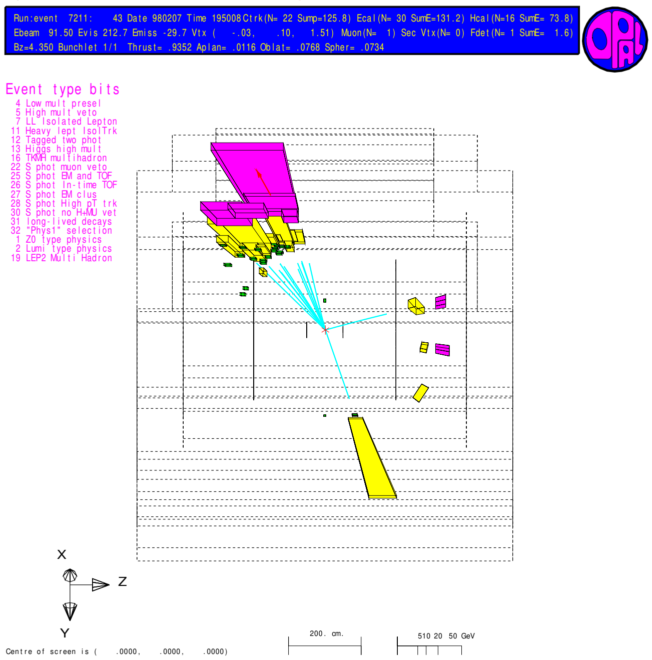
- $e^+e^- \rightarrow$ LQ e q



- The production x-section depends on the λ couplings (but *not* on the chirality).
- Only 1st gen. LQ coupling to e can be produced.
- LQ with $|Q_{em}| = 1/3,\ 5/3$ (eu couplings) favoured w.r.t. LQ with $|Q_{em}| = 2/3,\ 4/3$ (ed couplings).
- After the production: LQ $\rightarrow$ lq $\quad$ ($l = e, \nu$)

$\Longrightarrow$ Energetic, isolated and high p_t lepton balanced by a hadronic jet.

- LQ $\rightarrow$ e q
  $M_{LQ} = 160$ GeV
  $\sqrt{s} = 183$ GeV



Single production (2)

- Search for single production events :
  (Phys. Lett. **B526** (2002) 233).

  - Data sample :
    $\sqrt{s} = 189 - 209$ GeV; $\int \mathcal{L}\mathrm{dt} \simeq 612\ pb^{-1}$
  - Chiral couplings are assumed $\Leftrightarrow \quad \lambda_L \cdot \lambda_R = 0$
    $\Longrightarrow \beta \equiv \mathrm{B.R.}(\mathrm{LQ} \rightarrow \mathrm{l}^- \mathrm{q}) = 0,\ 0.5,\ 1$
    (LQ with $\beta = 0$ not allowed).

channel	ε (%) ($\mathrm{M_{LQ}} = 80 \div 200$ GeV)	Exp. Bkg. (MC)	data
eq	10÷50	44.7 ± 14.0	43
νq	30÷60	26.7 ± 8.6	25

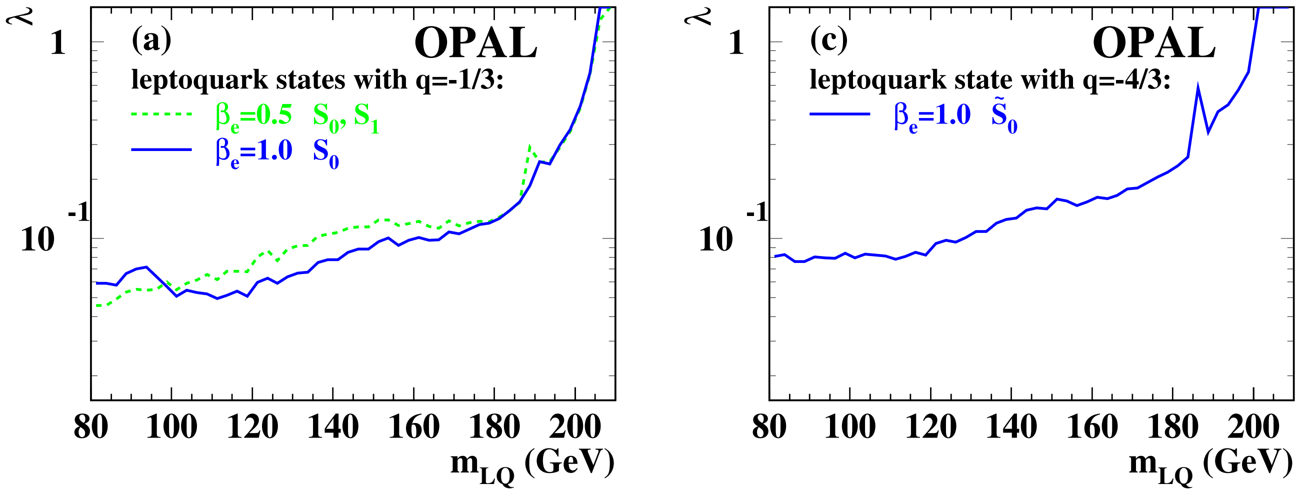
  - No excess is observed in the data w.r.t. the expected bkg.

    $\Longrightarrow$ Lower limits (95% C.L.) on $\mathrm{M_{LQ}}$ as functions of the λ couplings (exclusion curves in the $(\lambda,\ \mathrm{M_{LQ}})$ plane).

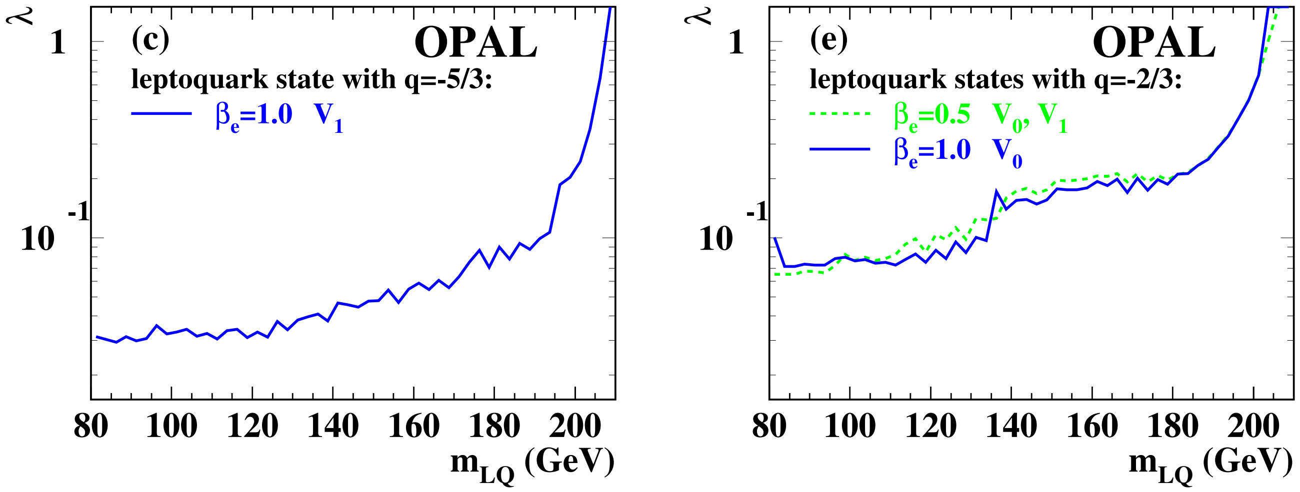
Single production (3)

- Exclusion curves (examples)

Scalar LQ

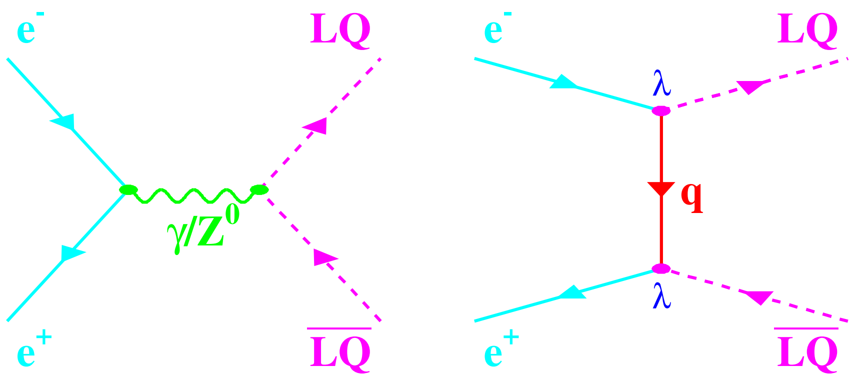


Vector LQ



Pair production (1)

- $e^+e^- \rightarrow LQ\overline{LQ}$



- $\sigma = \sigma(M_{LQ}, Q_{em}, I_3, \lambda)$.
  The *t*/*u*-channel contribution (λ dependent) exists only for LQ coupling to electrons.

- Advantages (w.r.t. single production) :
  - $\sigma \geq \mathcal{O}(1\text{pb})$ @LEP2 even for small values of the λ couplings to fermions ($< 10^{-1}$).
  - Any LQ in the model could be produced.

- Drawback :
  - Lower kinematic limit for M_{LQ} ($\sqrt{s}/2 \quad \Leftrightarrow \quad \sim 100$ GeV @LEP2).

Pair production (2)

- $\mathrm{LQ} \to \mathrm{l q}, \quad \overline{\mathrm{LQ}} \to \overline{\mathrm{l'}}\mathrm{q'}$

$$\Downarrow$$

Three possibile final states for each generation $\Longleftrightarrow$

- $\mathrm{l^+ l^- q\bar{q}}$
- $\mathrm{l^\pm \nu_l q\bar{q}}$
- $\mathrm{\nu_l \nu_l q\bar{q}}$

$\Big\}\ \mathrm{l} = \mathrm{e},\ \mu,\ \tau$

- For a given LQ the fraction of events falling in each final state depends on $\beta \equiv \mathrm{B.R.}(\mathrm{LQ} \to \mathrm{l}^- + \mathrm{q})$ $(\Rightarrow 1 - \beta \equiv \mathrm{B.R.}(\mathrm{LQ} \to \nu + \mathrm{q}'))$

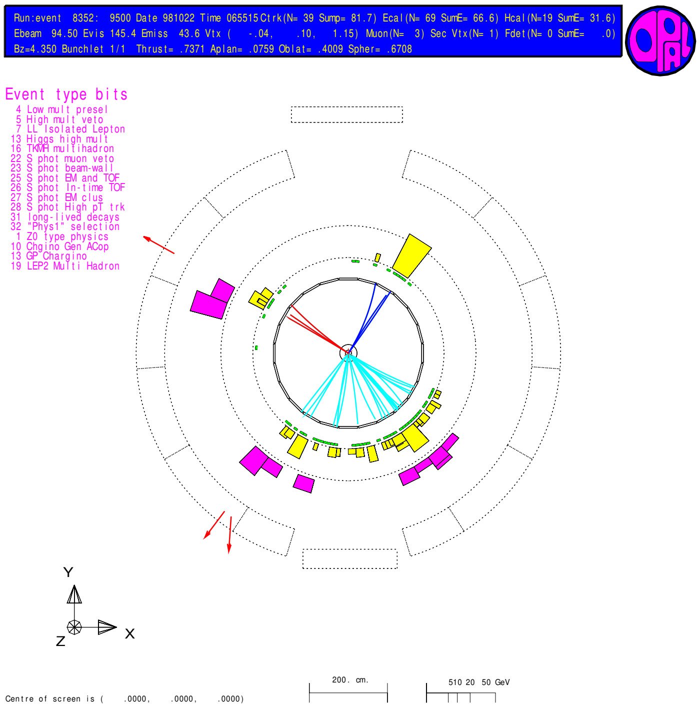
- Signal events:
  - High multiplicity (hadronic jets).
  - High fraction of visible energy.
  - Energetic and isolated leptons.

- Main bkg: $\mathrm{W^+W^-}, \mathrm{We\nu} \quad (\mathrm{l^\pm \nu_l q\bar{q}})$

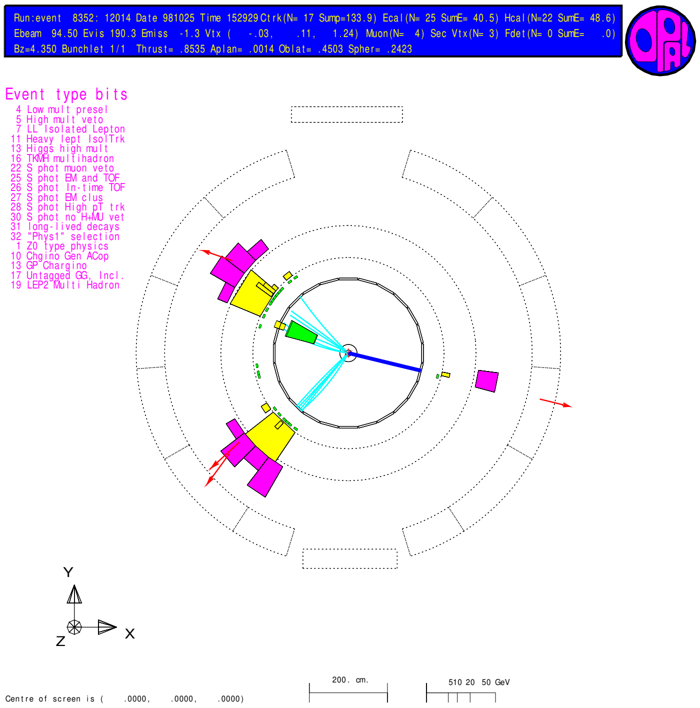
  $\mathrm{Z^0Z^0} \quad (\mathrm{l^+l^- q\bar{q}}, \mathrm{\nu_l\nu_l q\bar{q}})$

Pair production (3)

- $\tau^+\tau^- q\bar{q}$
  $M_{LQ} = 90$ GeV
  $\sqrt{s} = 189$ GeV



- $\mu\nu q\bar{q}$
  $M_{LQ} = 90$ GeV
  $\sqrt{s} = 189$ GeV



Pair production (4)

- Search for pair-production events :
  (CERN-EP/2003-021 30^{th} April 2003, submitted to Eur. Phys. J. **C**)

  - Assumption : $t/u-$channel contribution is negligible ($\lambda < \mathcal{O}(10^{-2})$ for 1^{st} gen. LQ).
  - Data sample :
    $\sqrt{s} = 189 - 209$ GeV; $\int \mathcal{L}dt \simeq 596\ pb^{-1}$.

channel	ε (%) ($M_{LQ} = 50 \div 102$ GeV)	Exp. Bkg. (MC)	data
$e^+e^-q\bar{q}$	26÷56	$12.8^{+5.2}_{-4.8}$	20
$\mu^+\mu^-q\bar{q}$	31÷68	$8.7^{+3.5}_{-2.8}$	4
$\tau^+\tau^-q\bar{q}$	17÷35	$38.0^{+7.4}_{-7.0}$	37
$e^\pm\nu q\overline{q'}$	9÷36	$13.7^{+6.3}_{-5.9}$	13
$\mu^\pm\nu q\overline{q'}$	11÷43	$24.5^{+5.4}_{-5.0}$	26
$\tau^\pm\nu q\overline{q'}$	2÷25	$36.0^{+8.5}_{-8.3}$	35
$\nu\nu q\bar{q}$	9÷38	$22.8^{+4.4}_{-3.7}$	28

  - No significant excess is observed in the data w.r.t. the bkg expected from the Standard Model.

$\Longrightarrow$ Lower limits (95% C.L.) on M_{LQ} as functions of $\beta \equiv$ B.R.($LQ \to l^- q$)
(Likelihood Ratio method,
Experimental errors included following
Nucl. Instr. and Meth. **A434** (1999) 435) .

Pair production (5)

- Lower limits on M_{LQ} (GeV) : summary

LQ	$Q_{e.m.}$	β	1^{st} gen.	2^{nd} gen.	3^{rd} gen.
S_0	$-1/3$	[0.5,1]	69(**)	79(**)	45(*)
$\tilde{S}_0$	$-4/3$	1	99	100	98
S_1	$+2/3$	0	97	97	97
	$-1/3$	0.5	69	79	45(*)
	$-4/3$	1	100	101	99
$S_{1/2}$	$-2/3$	[0,1]	94(**)	94(**)	93(**)
	$-5/3$	1	100	100	98
$\tilde{S}_{1/2}$	$+1/3$	0	89	89	89
	$-2/3$	1	97	99	96
V_0	$-2/3$	[0.5,1]	99(**)	99(**)	97(**)
$\tilde{V}_0$	$-5/3$	1	102	102	101
V_1	$+1/3$	0	101	101	101
	$-2/3$	0.5	99	99	97
	$-5/3$	1	102	102	101
$V_{1/2}$	$-1/3$	[0,1]	99(**)	99(**)	98(**)
	$-4/3$	1	102	102	101
$\tilde{V}_{1/2}$	$+2/3$	0	99	99	99
	$-1/3$	1	101	101	99

(*): LEP1, (**): Minimum value $\forall$ $\beta \equiv$ B.R.(LQ $\rightarrow l^- q$)

Conclusions

- Leptoquarks could be directly produced or virtually exchanged in e^+e^- collisions.
- Searches for deviations from the Standard Model expectations due to LQ have been performed using the data collected by the OPAL experiment at the highest centre-of-mass energies reached by the LEP collider.
- No significant evidence for any deviation has been found.

$$\Downarrow$$

- Direct search for single production and measurements of the hadronic x-sections. $\Rightarrow$ Exclusion curves in the $(\lambda, \mathrm{M}_{\mathrm{LQ}})$ plane for 1^{st} generation LQ.
- Search for pair production $\Rightarrow$ Lower limits on M_{LQ} or exclusion curves in the $(\beta, \mathrm{M}_{\mathrm{LQ}})$ plane.

- The results improve existing lower limits on M_{LQ} in the region of small β and enlarge exclusion regions in the $(\lambda, \mathrm{M}_{\mathrm{LQ}})$ plane.