

Beyond the Desert '03

4th International Conference on Physics Beyond the Standard Model
Castle Ringberg, 11 June 2003

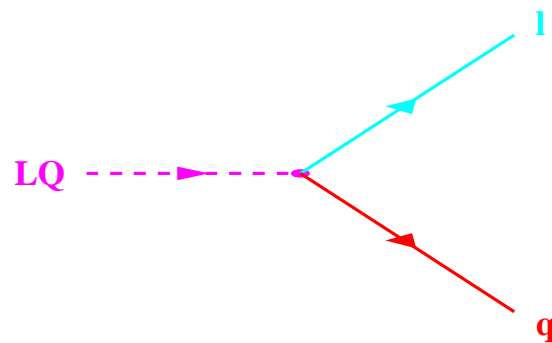
Searches for LEPTOQUARKS with the OPAL detector

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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 symmetry **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**) :
 - $l \leftrightarrow q$ 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 |
| $\tilde{S}_{1/2}$ (\tilde{d}_L, \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)

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

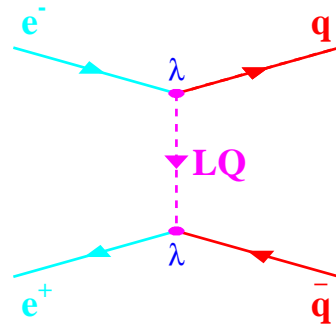
$i \equiv$ lepton generation, $j \equiv$ quark generation

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

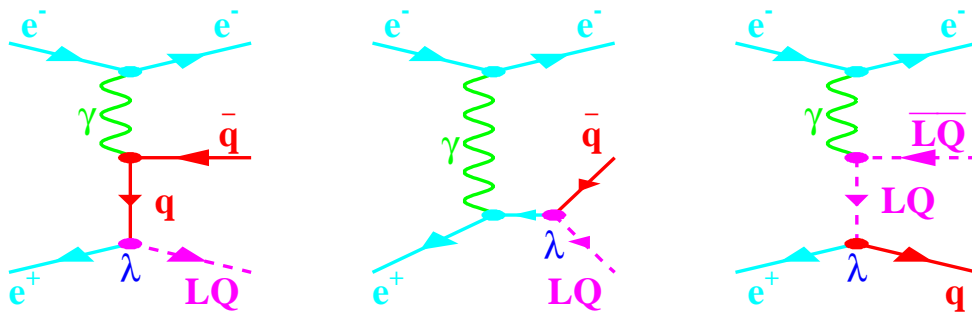
LQ in e^+e^- collisions

- Virtual effects :

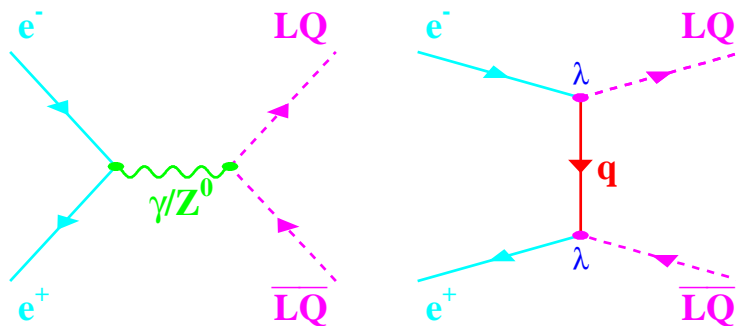
$$e^+e^- \rightarrow q\bar{q}$$



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

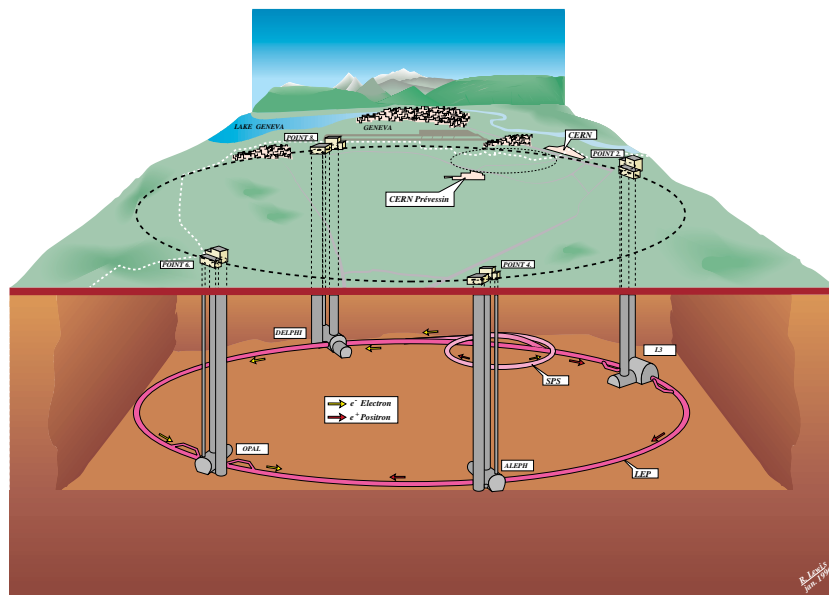


- Pair production : $e^+e^- \rightarrow LQ\bar{L}Q$

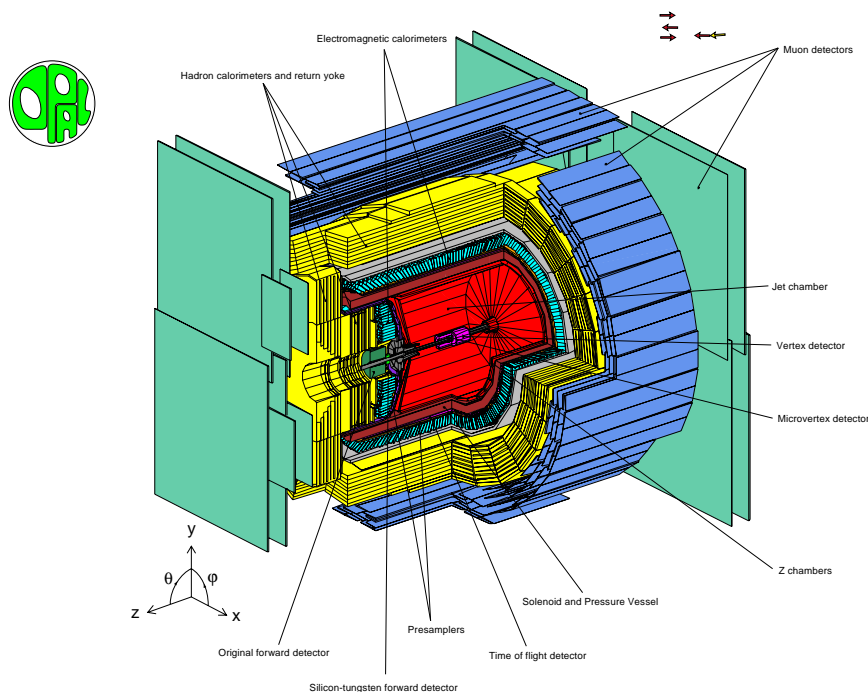


The LEP collider and the OPAL experiment

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

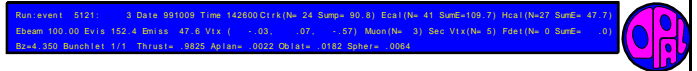


- **OPAL** : **O**mnipurpose **A**pparatus at **L**EP

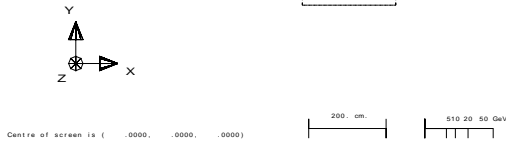
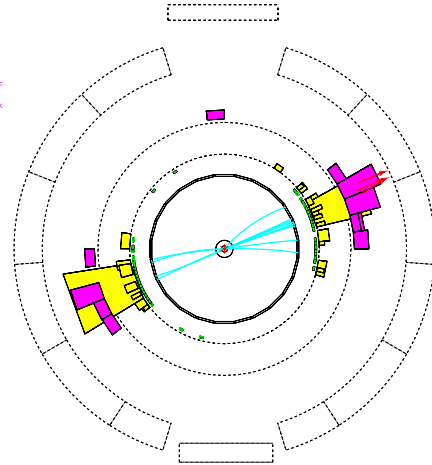
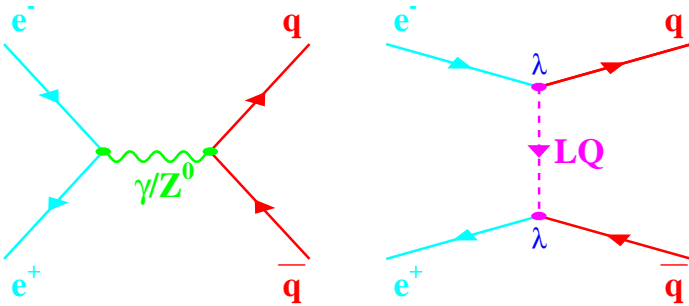


Virtual effects in $e^+e^- \rightarrow q\bar{q}$ (1)

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



Event type bits
 4 Low mult preset
 5 High mult veto
 12 Tagged two phot
 13 Higgs high mult
 15 TDR multihadron
 22 S phot muon veto
 23 S phot beam-wall
 25 S phot EM and TCF
 26 S phot In-time TCF
 27 S phot EM class
 28 S phot High pt trk
 31 long-lived decays
 32 "Phys1" selection
 15 LEPC Mult Hadron



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

- Only 1st gen. LQ coupling to electrons

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

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

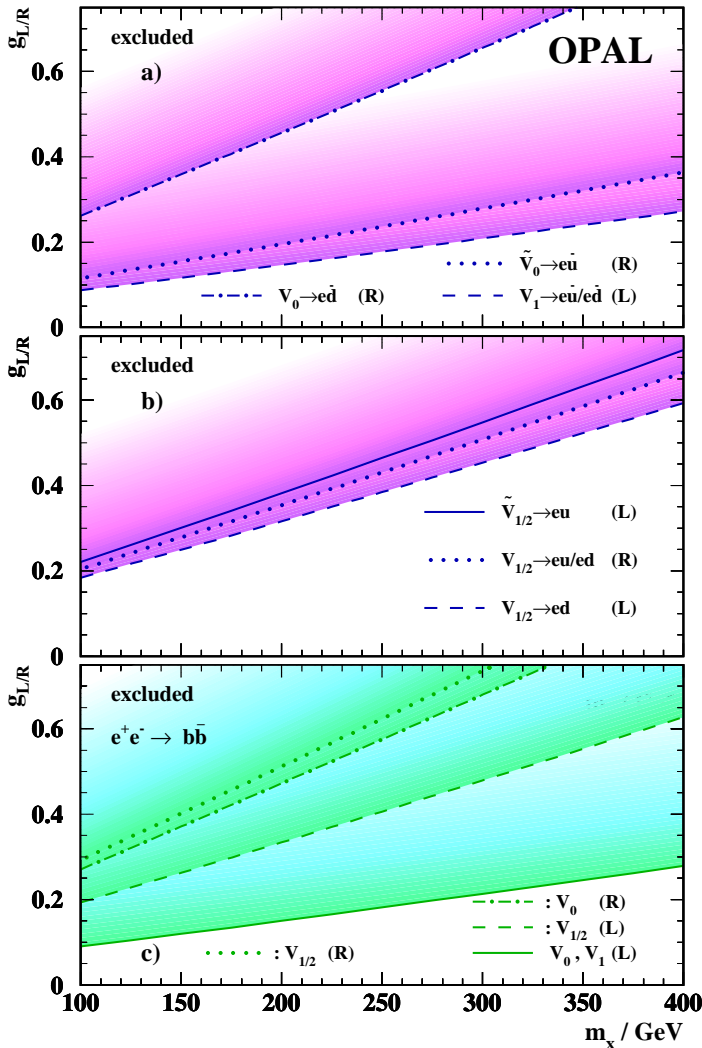
LEP combined : CERN-EP-2002-091
 December 2002.

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

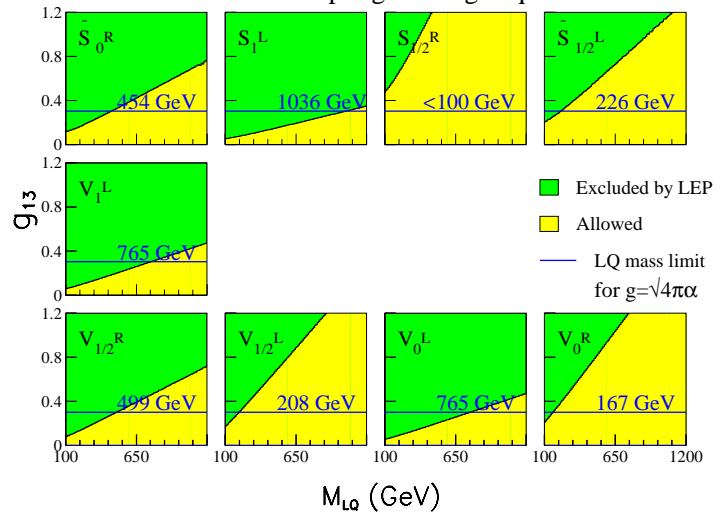
Virtual effects in $e^+e^- \rightarrow q\bar{q}$ (2)

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

Limits on the coupling for Vector Leptoquarks



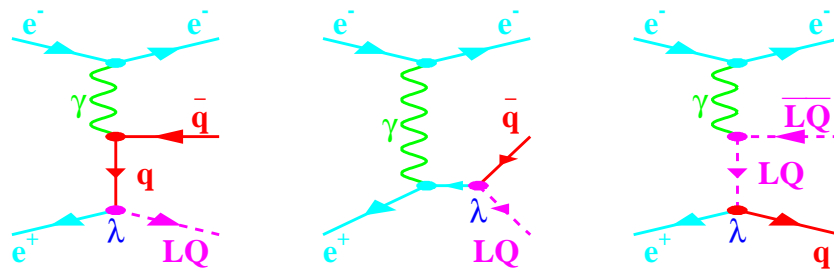
LEP Prelim - Coupling to 3rd gen quarks



- 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: $LQ \rightarrow lq$ ($l = e, \nu$)

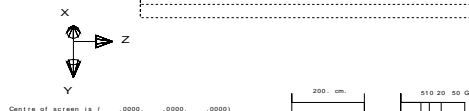
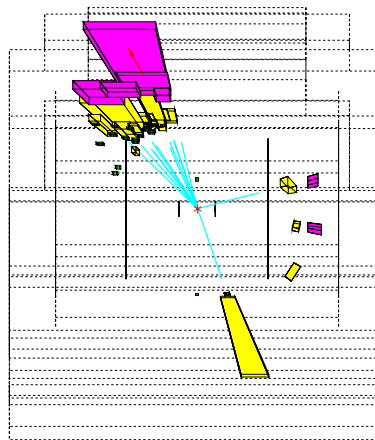
\Rightarrow Energetic, isolated and high p_t lepton balanced by a hadronic jet.

Run event: 7211, 43 Data 88207 Time 190098 Dirk(Hr 22 Super=25.6) Ecal(Hr 20 Super=131.2) Hcal(Hr16 Super= 73.4) Ebeam 91.50 Evls 212.7 Emss -29.7 Vtx [-03, -10, 1.51] Muon(Nr 1) Sec Vtx(Nr 0) Fst(Nr 1) SumE -1.61 Bwd 300 BunchId 111 Thrust= 0.952 Aplan= 0.146 Oplan= 0.768 Sph= 0.734



Event type bits

4 Low mult preseal
5 High mult veto
7 LL Isolated Lepton
11 Heavy Ion Isotrk
12 Tagged low phot
13 High mult veto
16 TMM multihadron
22 S phot mult veto
25 S phot EM and TOF
26 S phot In-time TOF
27 S phot EM clus
28 S phot High pT trk
30 S phot no HEM veto
31 long-lived decays
32 Phys* selection
1 Z0 type physics
2 Lumi type physics
18 LEP2 Muon Hadron



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

Single production (2)

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

- Data sample :

$$\sqrt{s} = 189 - 209 \text{ GeV}; \quad \int \mathcal{L} dt \simeq 612 \text{ pb}^{-1}$$

- Chiral couplings are assumed $\Leftrightarrow \lambda_L \cdot \lambda_R = 0$
 $\Rightarrow \beta \equiv \text{B.R.}(\text{LQ} \rightarrow \text{l}^- \text{q}) = 0, 0.5, 1$
 (LQ with $\beta = 0$ not allowed).

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

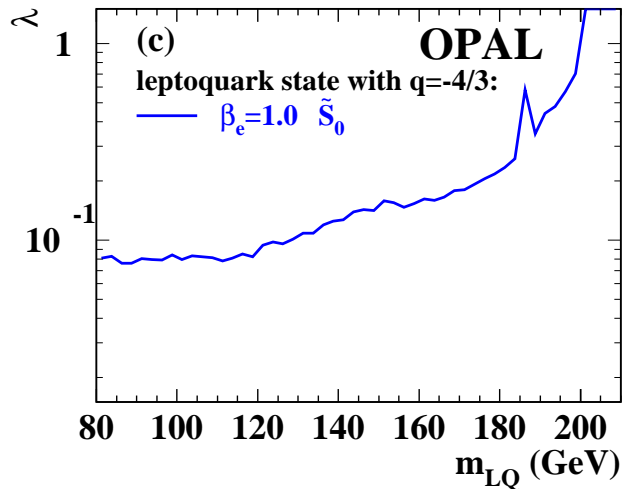
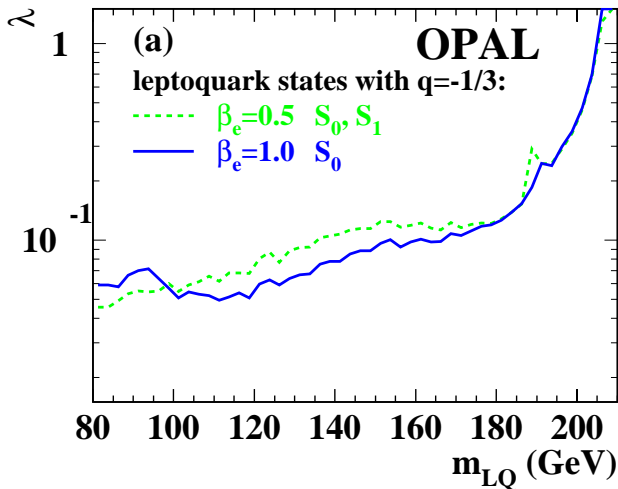
- No excess is observed in the data
w.r.t. the expected bkg.

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

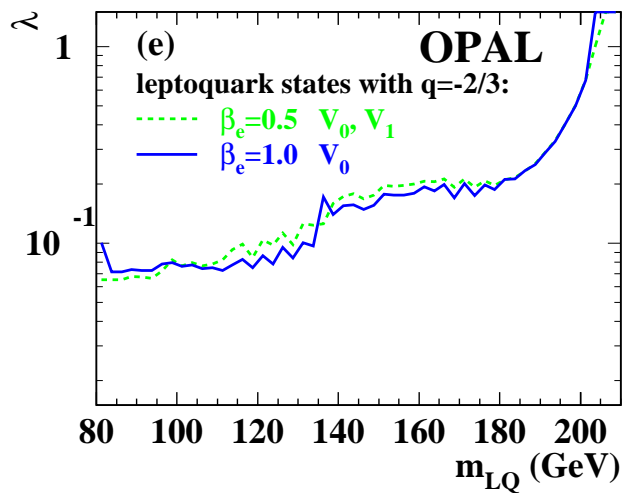
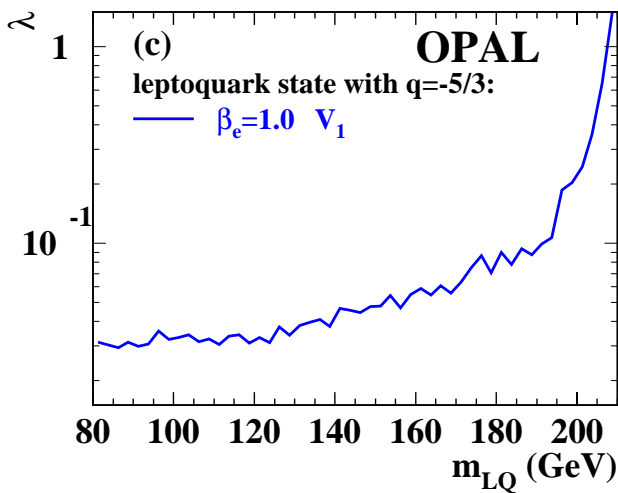
Single production (3)

- Exclusion curves (examples)

Scalar LQ

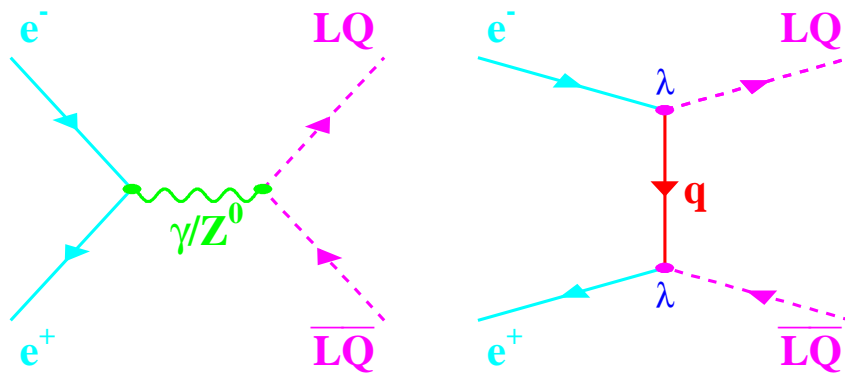


Vector LQ



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}
($\sqrt{s}/2 \Leftrightarrow \sim 100 \text{ GeV}$ @LEP2).

Pair production (2)

- $LQ \rightarrow lq, \overline{LQ} \rightarrow \overline{l}q'$



Three possible final states
for each generation

$$\begin{aligned} & \left. \begin{aligned} - l^+ l^- q \bar{q} \\ - l^\pm \nu_l q \bar{q} \\ - \nu_l \nu_l q \bar{q} \end{aligned} \right\} l = e, \mu, \tau \end{aligned} \iff$$

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

- Signal events:

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

- Main bkg: $W^+W^-, We\nu$ ($l^\pm \nu_l q \bar{q}$)
 Z^0Z^0 ($l^+l^- q \bar{q}, \nu_l \nu_l q \bar{q}$)

Pair production (3)

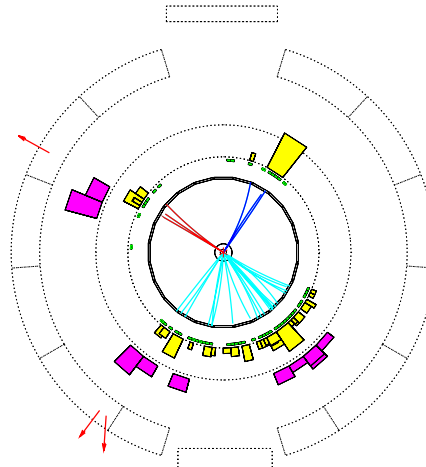
- $\tau^+ \tau^- q \bar{q}$
 $M_{LQ} = 90 \text{ GeV}$
 $\sqrt{s} = 189 \text{ GeV}$

```
Run/event: 8352, 9500 Date: 981022 Time: 085515 Cirr(N: 39 Sump: 81.7) Ecal(N: 69 SumE: 66.6) Hcal(N:19 SumE: 31.6)
Ebeam: 94.50 Evls: 145.4 Emiss: 43.6 Vtx ( .04, .10, 1.15) Muon(N: 3) Sec Vtx(N: 1) Fdet(N: 0 SumE: 0)
Bz=4.350 Bunchlet: 1/1 Thrust: .7371 Aplan= .0759 Oblate: 4009 Spher= 6708
```



Event type bits

```
4 Low mult presel
5 High mult veto
7 LL Isolated Lepton
13 Higgs high mult
16 TMM multihadron
22 S phot muon veto
23 S phot beam veto
25 S phot EM and TOP
26 S phot In-time TOP
27 S phot EM plus
28 S phot High pT trk
31 long-lived decays
32 "Phys1" selection
1 Z0 type physics
10 Chirno Gen ADSP
13 GP Chargino
19 LEP2 Multi Hadron
```



Centre of screen is (.0000, .0000, .0000) 200. um 510 20 50 GeV

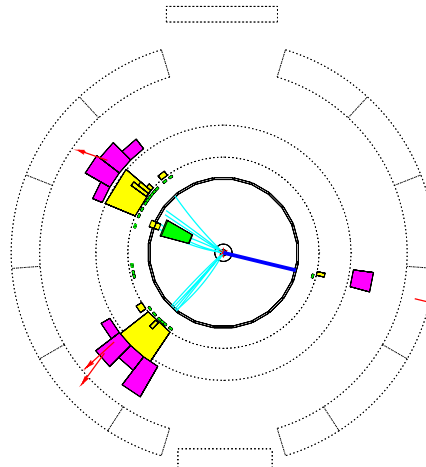
- $\mu\nu q \bar{q}$
 $M_{LQ} = 90 \text{ GeV}$
 $\sqrt{s} = 189 \text{ GeV}$

```
Run/event: 8352, 12014 Date: 981025 Time: 152929 Cirr(N: 17 Sump:133.9) Ecal(N: 25 SumE: 40.5) Hcal(N:22 SumE: 48.6)
Ebeam: 94.50 Evls: 150.2 Emiss: 1.3 Vtx ( -.03, -.11, 1.24) Muon(N: 4) Sec Vtx(N: 3) Fdet(N: 0 SumE: 0)
Bz=4.350 Bunchlet: 1/1 Thrust: .8535 Aplan= .0914 Oblate: 4503 Spher= 2423
```



Event type bits

```
4 Low mult presel
5 High mult veto
7 LL Isolated Lepton
11 Heavy lept isolITK
13 Higgs high mult
16 TMM multihadron
22 S phot muon veto
25 S phot EM and TOP
26 S phot In-time TOP
27 S phot EM plus
28 S phot High pT trk
30 S phot no H+MJ vet
31 long-lived decays
32 "Phys1" selection
1 Z0 type physics
10 Chirno Gen ADSP
13 GP Chargino
17 Unagged GC Incl.
19 LEP2 Multi Hadron
```



Centre of screen is (.0000, .0000, .0000) 200. um 510 20 50 GeV

Pair production (4)

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

- Assumption : t/u -channel contribution is negligible ($\lambda < \mathcal{O}(10^{-2})$ for 1st gen. LQ).

- Data sample :

$$\sqrt{s} = 189 - 209 \text{ GeV}; \quad \int \mathcal{L} dt \simeq 596 \text{ pb}^{-1}.$$

| channel | ε (%) ($M_{LQ} = 50 \div 102 \text{ GeV}$) | 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 |
| $e^\pm \nu q\bar{q}'$ | 9÷36 | $13.7^{+6.3}_{-5.9}$ | 13 |
| $\mu^\pm \nu q\bar{q}'$ | 11÷43 | $24.5^{+5.4}_{-5.0}$ | 26 |
| $\tau^\pm \nu q\bar{q}'$ | 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**.

\implies Lower limits (95% C.L.) on M_{LQ}
 as functions of $\beta \equiv \text{B.R.}(LQ \rightarrow l^- q)$
 (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 $\forall \beta \equiv \text{B.R.}(LQ \rightarrow l^- q)$

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.



– Direct search for single production and measurements of the **hadronic** x-sections.



Exclusion curves in the (λ, M_{LQ}) plane for 1st generation **LQ**.

– Search for pair production



Lower limits on M_{LQ} or exclusion curves in the (β, M_{LQ}) plane.

- The results improve existing lower limits on M_{LQ} in the region of small β and enlarge exclusion regions in the (λ, M_{LQ}) plane.