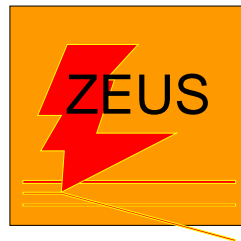


# Search for Leptoquark Production and Lepton Flavour Violation

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# Outline

- Introduction
  - Leptoquark model
- Search for leptoquark pair-production
  - DØ(#594), CDF(#490), OPAL(#731),
- Search for single leptoquark production
  - OPAL(#726), H1(#105), ZEUS(#496)
- Search for effects of virtual leptoquark exchange
  - H1(#99), L3(#192)
- Search for Lepton Flavour Violation
  - ZEUS(#498), OPAL(#724)      ⇐ contributions covered in this talk



# Introduction

**Leptoquarks:** bosons ( $J=0,1$ ) with lepton and baryon numbers

Interactions:

- strong color
- electroweak weak isospin and charge
- Yukawa  $l$ - $q$ - $LQ$  coupling  $\lambda$

## **Buchmüller-Rückl-Wyler (BRW) model**

- $SU(3)_C \times SU(2)_L \times U(1)_Y$  invariance of SM
- lepton and baryon number conservation
- either left- or right-handed couplings (bounds from rare decays)  
 $\Rightarrow$  7 scalar and 7 vector leptoquarks

fermion number  $F=0,2$ , branching ratio to  $lq$ :  $\beta_{lq} = 0, \frac{1}{2}, 1$

Two parameters for each leptoquark (LQ): mass and Yukawa coupling



# Pair-production at Tevatron

Predominantly by *gg* fusion

⇒ independent of  $\lambda$

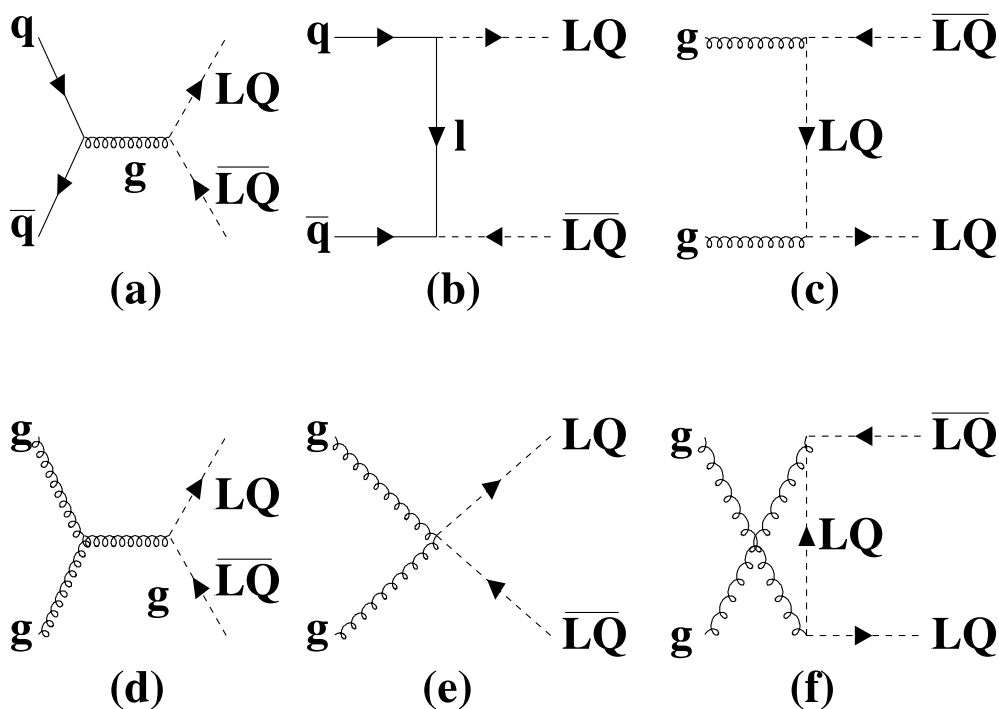
⇒ depends only on spin  
(scalar or vector) and  $\beta_{lq}$

New results from Run II:

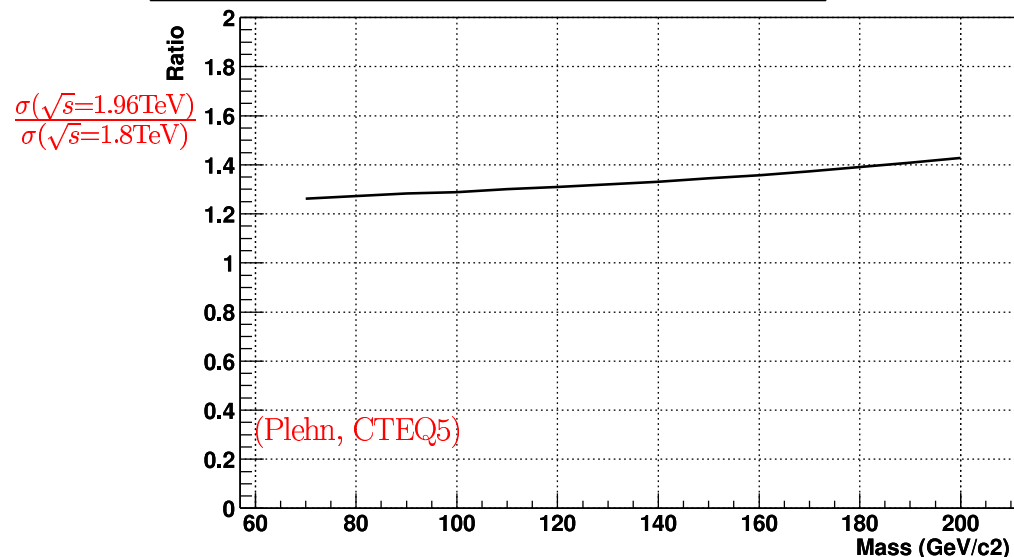
- $D\emptyset$ :  $41 \text{ pb}^{-1}$
- CDF:  $72\text{--}76 \text{ pb}^{-1}$

Cross section increase by  $\sim 30\text{--}40 \%$

$\sigma(\sqrt{s} = 1.96\text{TeV}) / \sigma(\sqrt{s} = 1.8\text{TeV})$  (w.r.t. Run I)



Ratio of NLO Scalar LQ Cross Section with sqrt(s)

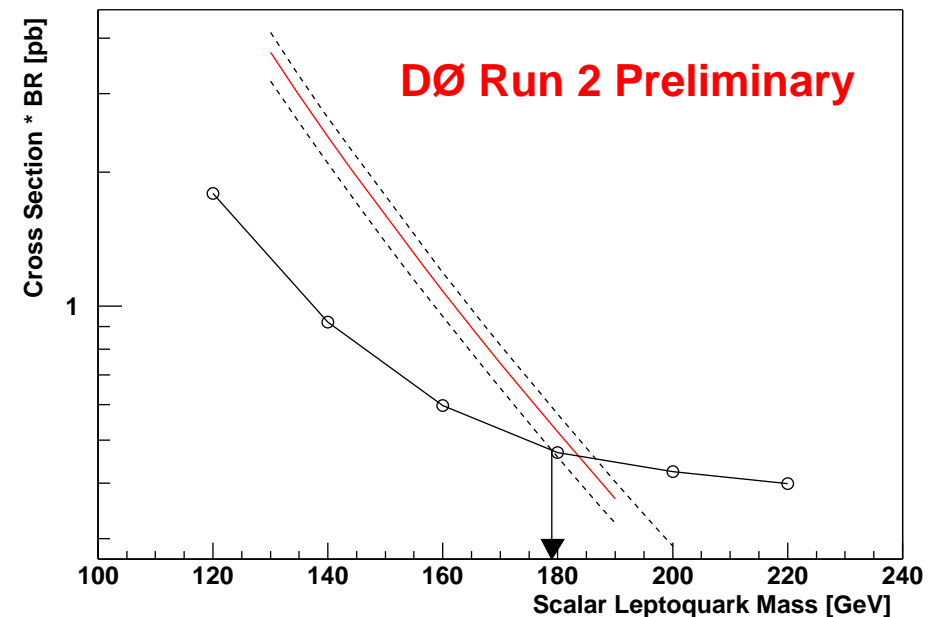
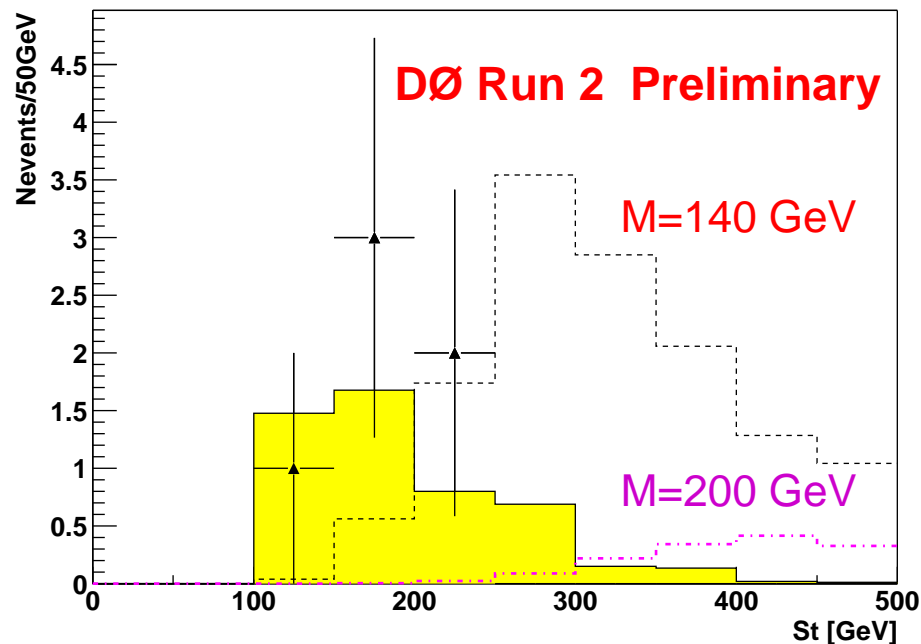


# Pair-production at Tevatron

**DØ**: search for first generation leptoquarks  $LQ \bar{L}Q \rightarrow eejj$

Total transverse energy:

Cross section limit:  $(41 \text{ pb}^{-1})$



For  $\beta_{eq} = 1$  mass limit for scalar leptoquarks is  $M > 179 \text{ GeV}$  (95%CL)

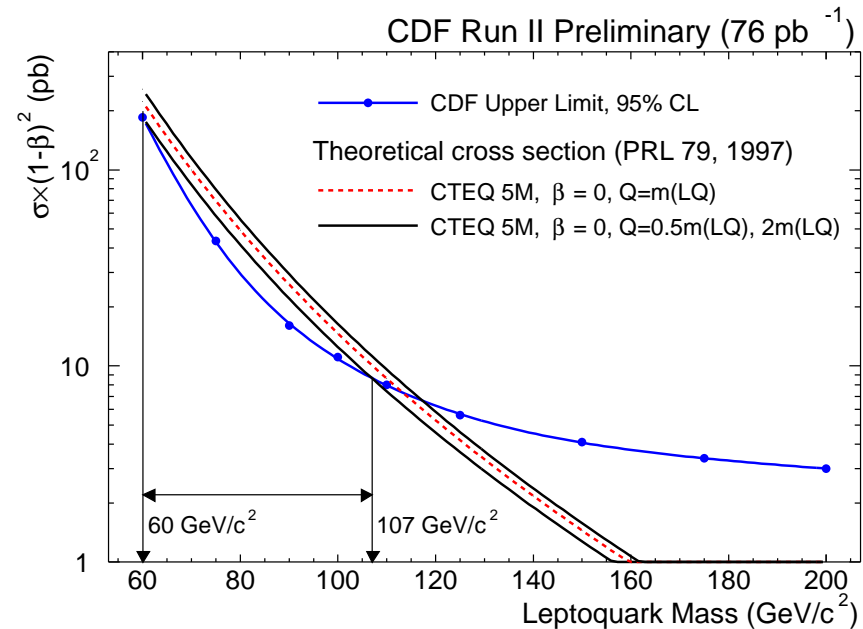
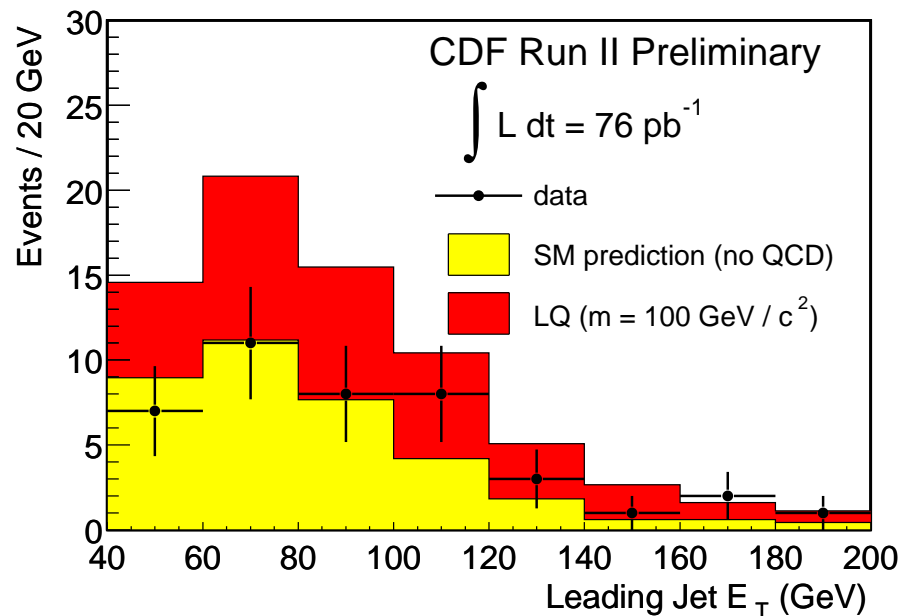
Second generation LQs ( $\mu\mu jj$  channel):  $M > 157 \text{ GeV}$  ( $\beta_{\mu q} = 1$ )

# Pair-production at Tevatron

**CDF** : search for first generation leptoquarks  $LQ \bar{L}Q \rightarrow \nu\nu jj$

Leading jet  $E_T$ :

Cross section limit:  $(76 \text{ pb}^{-1})$



For  $\beta_{eq} = 0$  mass limit for **scalar** leptoquarks is  $M > 107 \text{ GeV}$

for  $\beta_{eq} = 0.5$  (search in  $e\nu jj$  channel):  $M > 166 \text{ GeV}$

for  $\beta_{eq} = 1$  (search in  $ee jj$  channel):  $M > 230 \text{ GeV}$

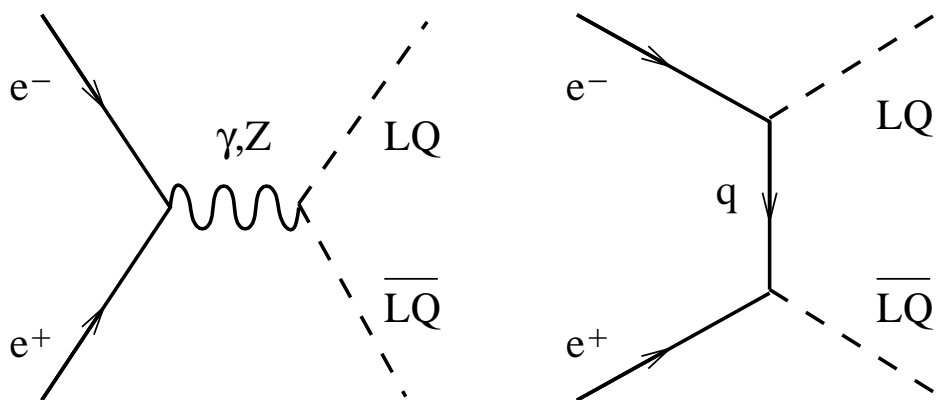


# Pair-production at LEP

New **OPAL** results

$596 \text{ pb}^{-1}$ ,  $\sqrt{s} = 189 - 209 \text{ GeV}$

Pair-production  $e^+e^- \rightarrow LQ \bar{L}Q$ :  
 $s$ -channel  $\gamma$  or  $Z^0$  exchange

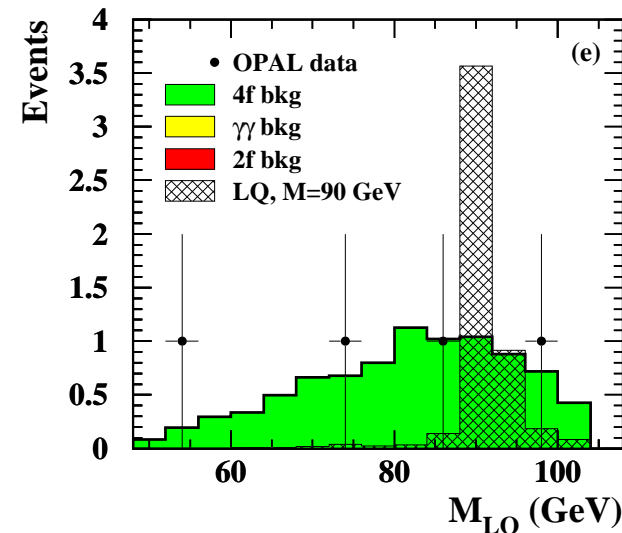
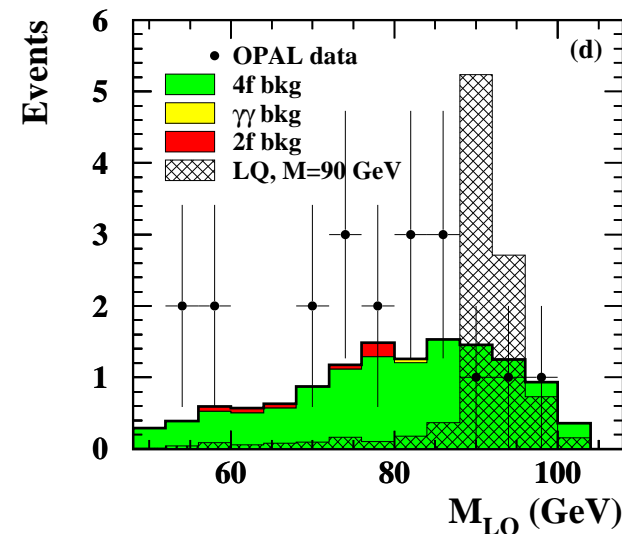


$t$ -channel  $q$  exchange (1<sup>st</sup> gen.)  
 negligible for small  $\lambda$

LQ mass  
 kinematic fit

$e^+e^- qq$   
 events  $\Rightarrow$

$\mu^+\mu^- qq$   
 events  $\Rightarrow$



# Pair-production at LEP

Search in  $l^+l^-qq$ ,  $l\nu qq$  and  $\nu\nu qq$  channels, for  $l = e, \mu, \tau$

$\Rightarrow$  for  $\beta_{lq} = 1$  mass limits between **96** and **102 GeV**,

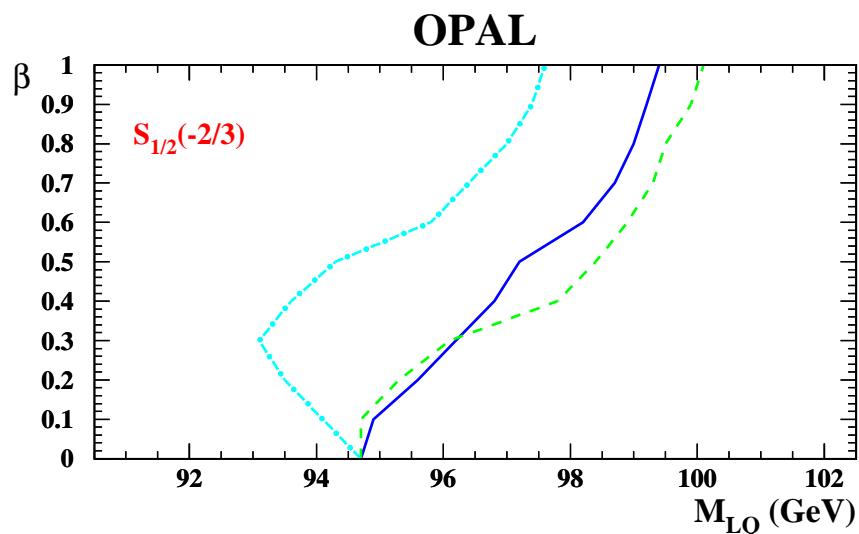
$\Rightarrow$  for  $\beta_{lq} = 0$  mass limits between **89** and **101 GeV**

depending on generation and leptoquark type

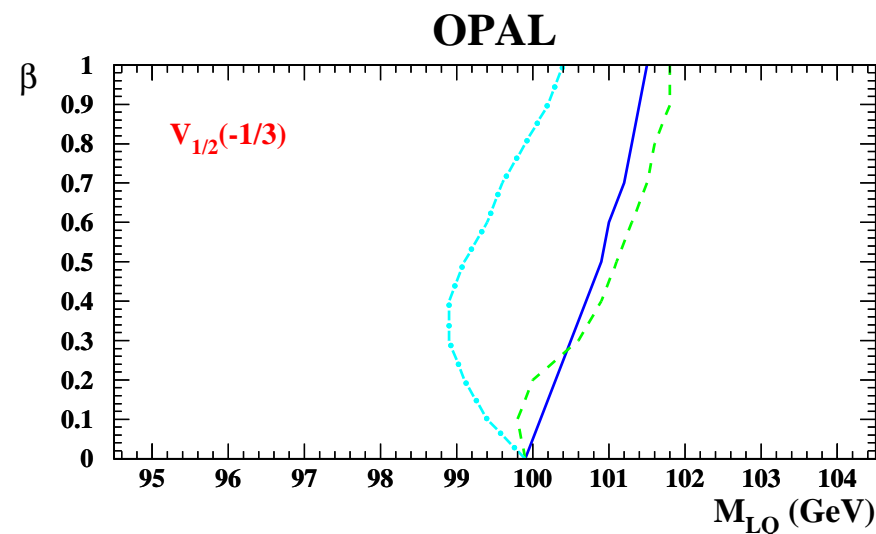
For leptoquarks with  $\beta_{lq}$  value depending on  $\lambda_L$  and  $\lambda_R$ :

$S_{1/2}$  (scalar LQ with  $Q=-2/3$ )

$V_{1/2}$  (vector LQ with  $Q=-1/3$ )



— 1<sup>st</sup> gen.    - - - 2<sup>nd</sup> gen.    ····· 3<sup>rd</sup> gen.



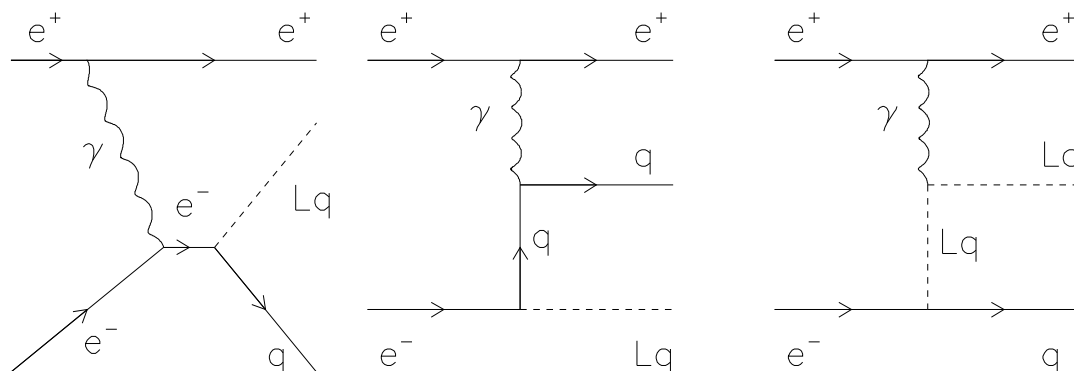
— 1<sup>st</sup> gen.    - - - 2<sup>nd</sup> gen.    ····· 3<sup>rd</sup> gen.

# Single-production at LEP

**OPAL** results for  $\sqrt{s} = 189 - 209$  GeV

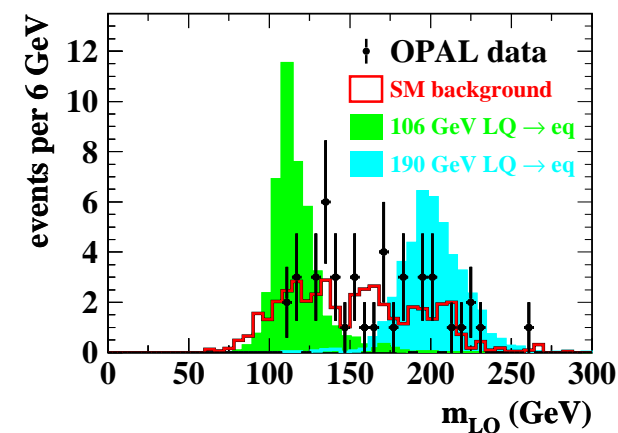
Single leptoquarks can be produced in  $e\gamma$  collisions.

Dominant contribution from  $\gamma \rightarrow q\bar{q}$

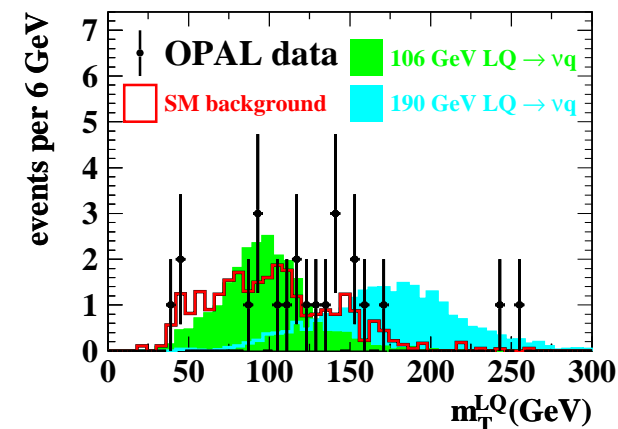


LQ candidate mass

$LQ \rightarrow eq$  search



$LQ \rightarrow \mu q$  search

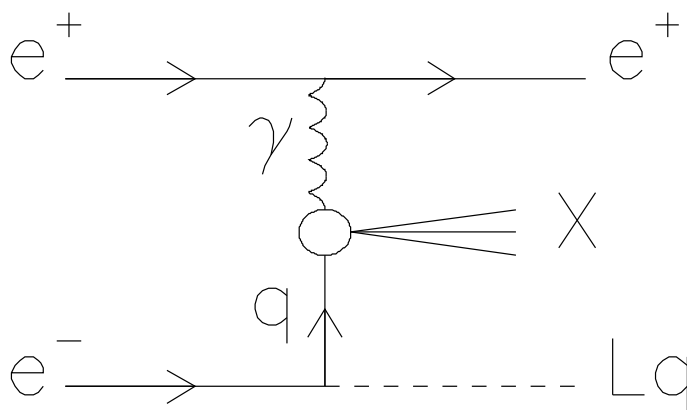


# Single-production at LEP

**OPAL** results for  $\sqrt{s} = 189 - 209$  GeV

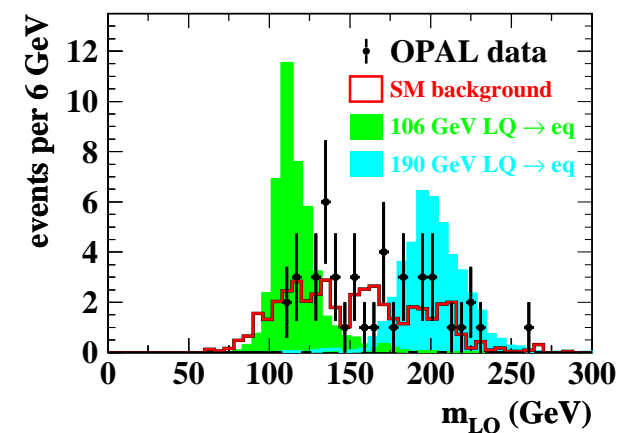
Single leptoquarks can be produced in  $e\gamma$  collisions.

Dominant contribution from  $\gamma \rightarrow q\bar{q}$  and “resolved photon” diagram:

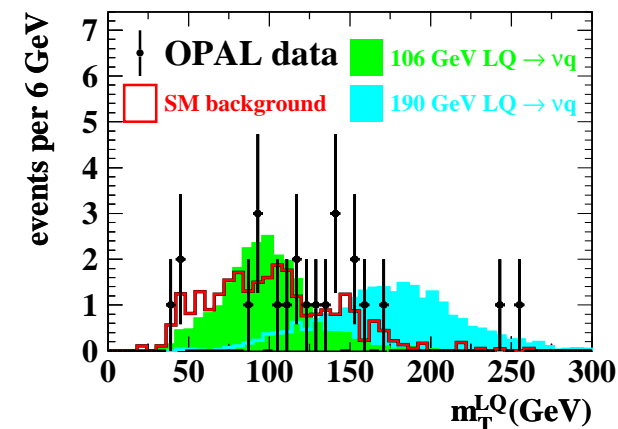


LQ candidate mass

$LQ \rightarrow eq$  search



$LQ \rightarrow \mu q$  search

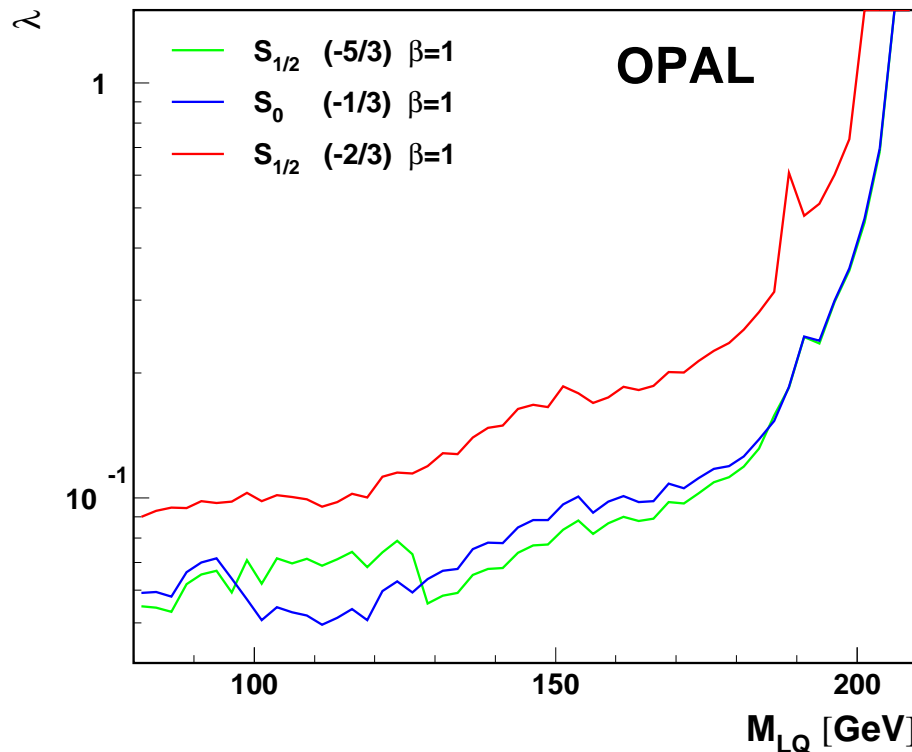


# Single-production at LEP

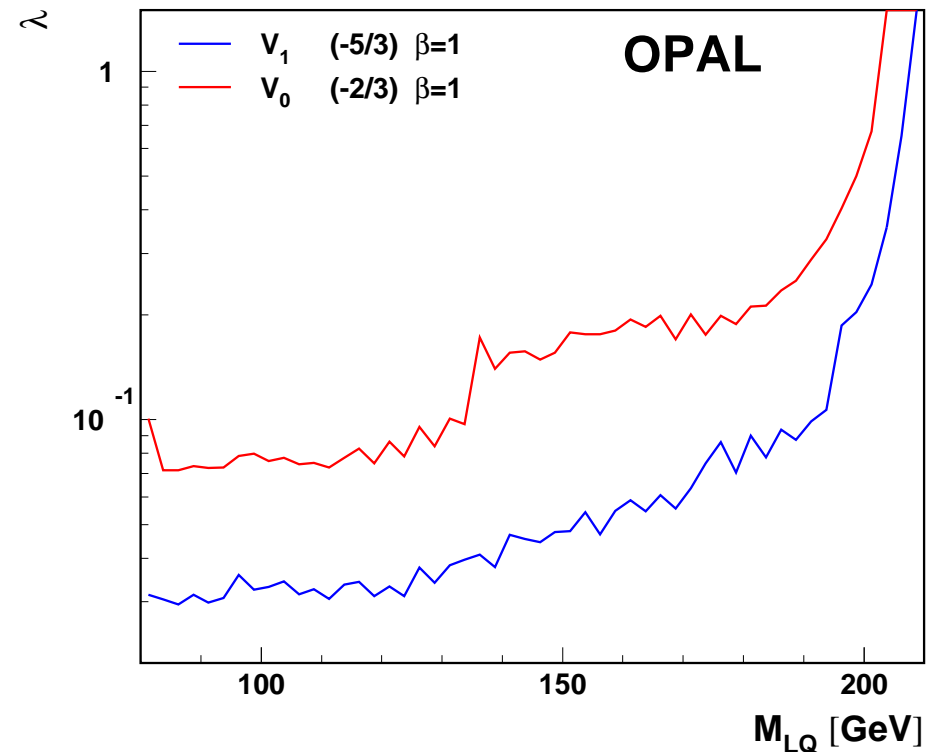
Mass dependent  $\lambda$  limits from **OPAL**

Strongest limits for  $|Q| = 1/3, 5/3$ , **weakest** limits for  $|Q| = 2/3$

Scalar



Vector



For  $\lambda = \sqrt{4\pi\alpha}$ :  $M_{LQ} > 183 - 202 \text{ GeV}$

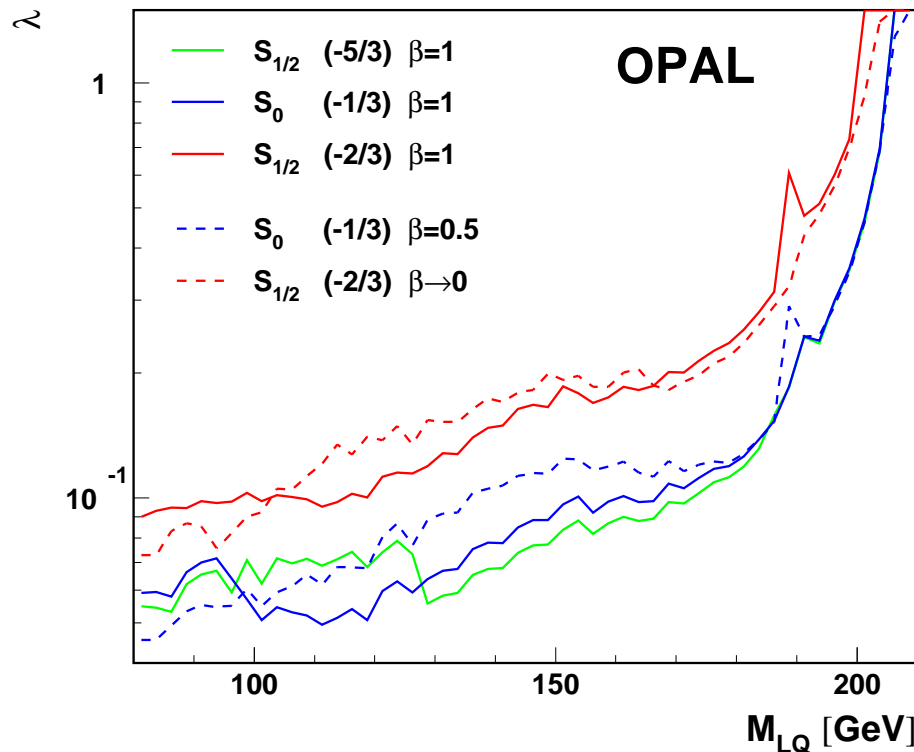


# Single-production at LEP

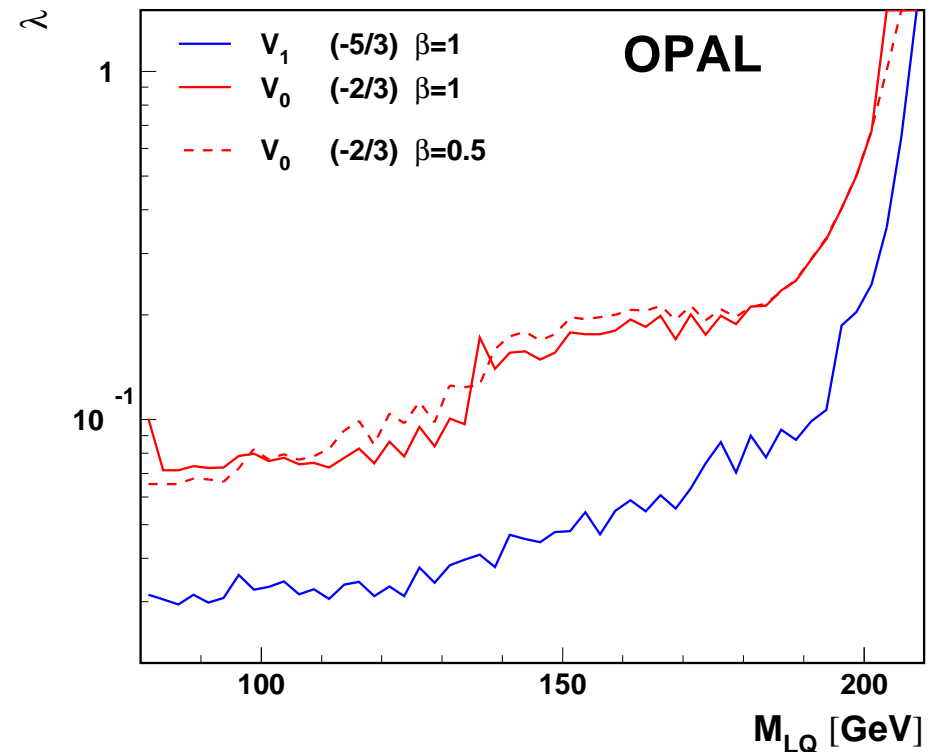
Mass dependent  $\lambda$  limits from **OPAL**

Strongest limits for  $|Q| = 1/3, 5/3$ , **weakest** limits for  $|Q| = 2/3$

Scalar



Vector

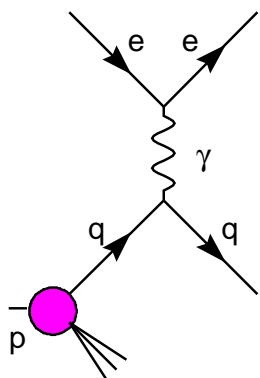


Both  $eq$  and  $\nu q$  decay channels  $\Rightarrow$  limits weakly depend on  $\beta$

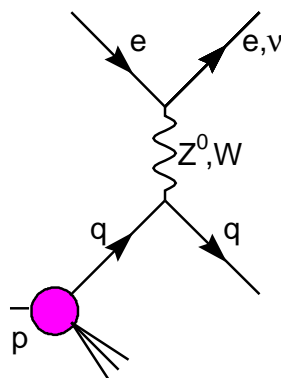


# Single-production at HERA

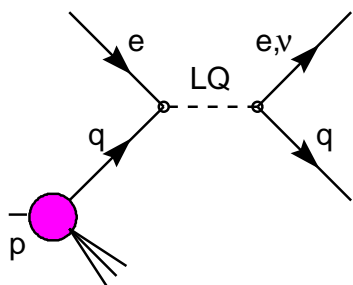
Direct  $eq$  interactions:



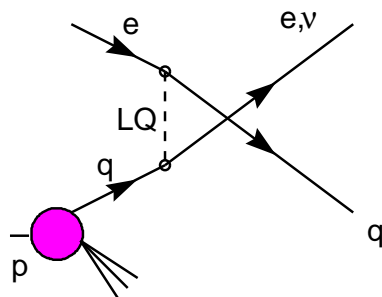
(a)



(b)



(c)



(d)

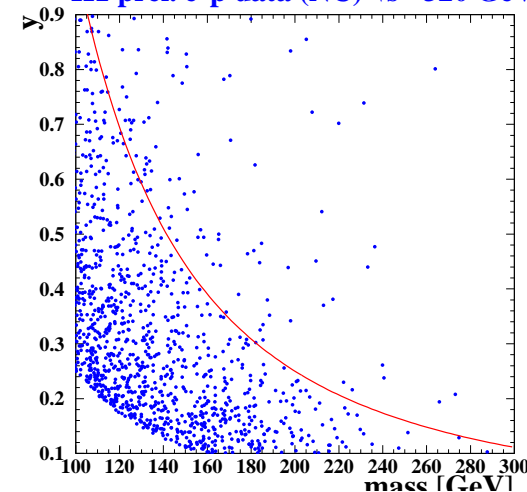
Large **SM** background from **NC** and **CC DIS**

$eq$  invariant mass vs scattering angle  $\Rightarrow$

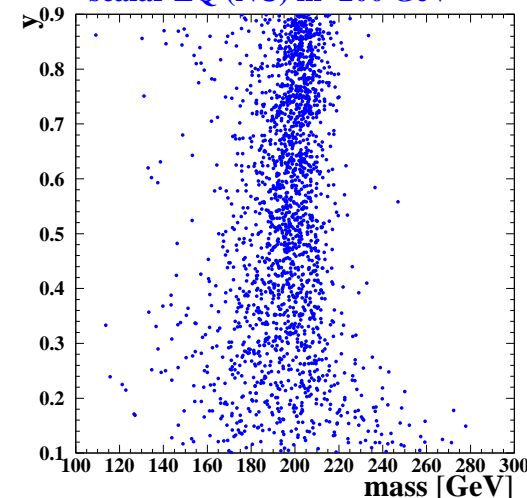
$$y = \frac{1}{2}(1 - \cos \theta^*)$$

**LQ signal** can be extracted from **2-dimensional event distribution**

H1 leptoquark search  
H1 prel.  $e^+p$  data (NC)  $\sqrt{s}=320$  GeV



H1 leptoquark search  
scalar LQ (NC)  $m=200$  GeV



# Single-production at HERA

**H1** and **ZEUS** results based on analysis of 1994-2000 HERA data

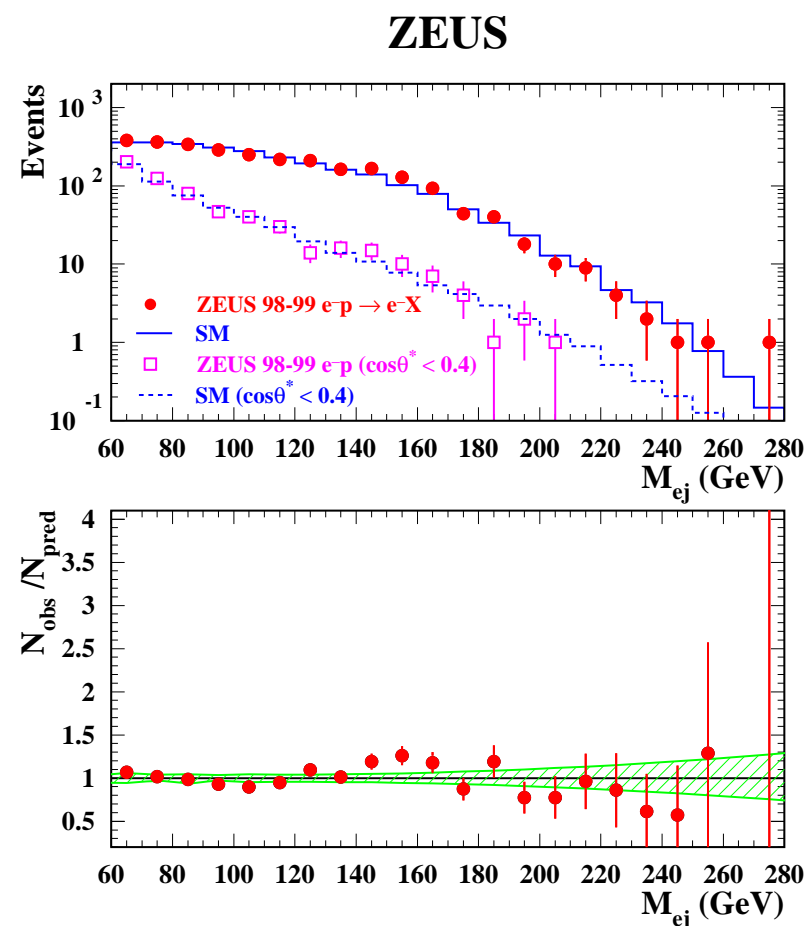
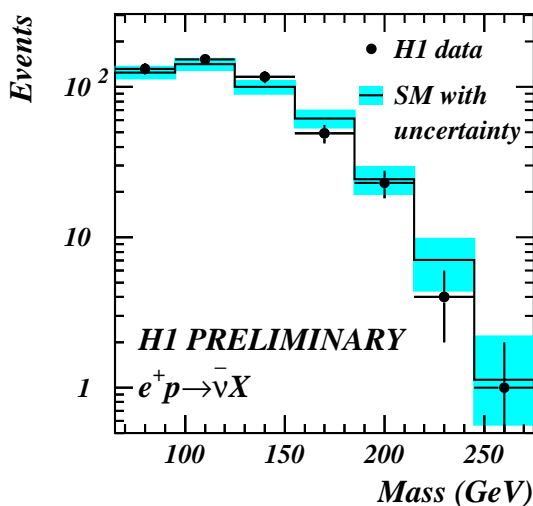
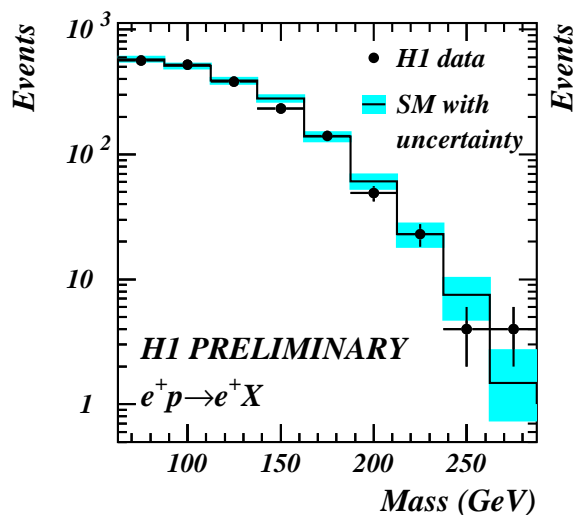
$e^+p$  and  $e^-p$  DIS at  $\sqrt{s} = 300\text{-}318$  GeV

**ZEUS:**  $e^-p \rightarrow e^-X$

Comparison of observed and expected invariant mass distributions

**H1:**  $e^+p \rightarrow e^+X$

$e^+p \rightarrow \bar{\nu}_e X$



# Single-production at HERA

Combined analysis of **NC** and **CC DIS** events

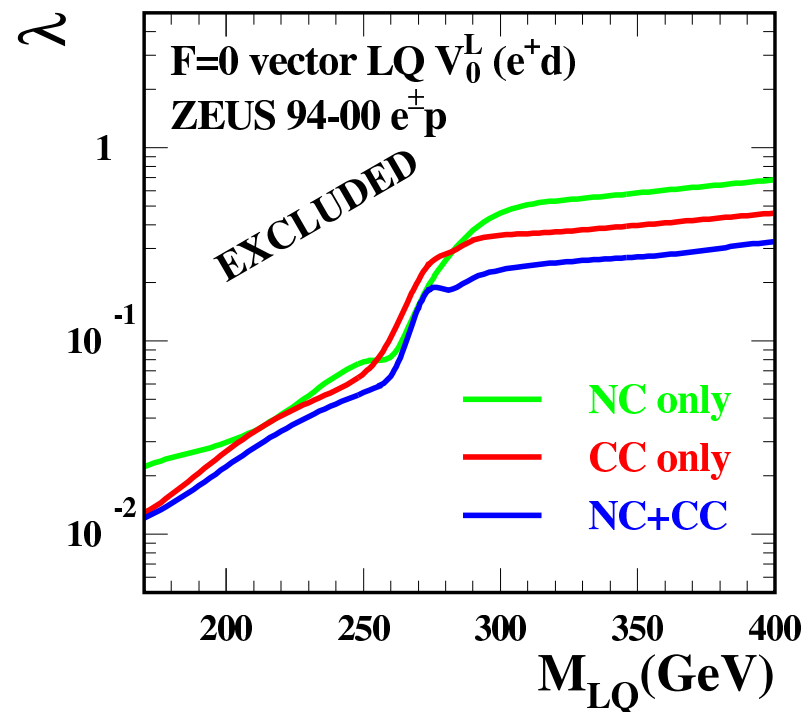
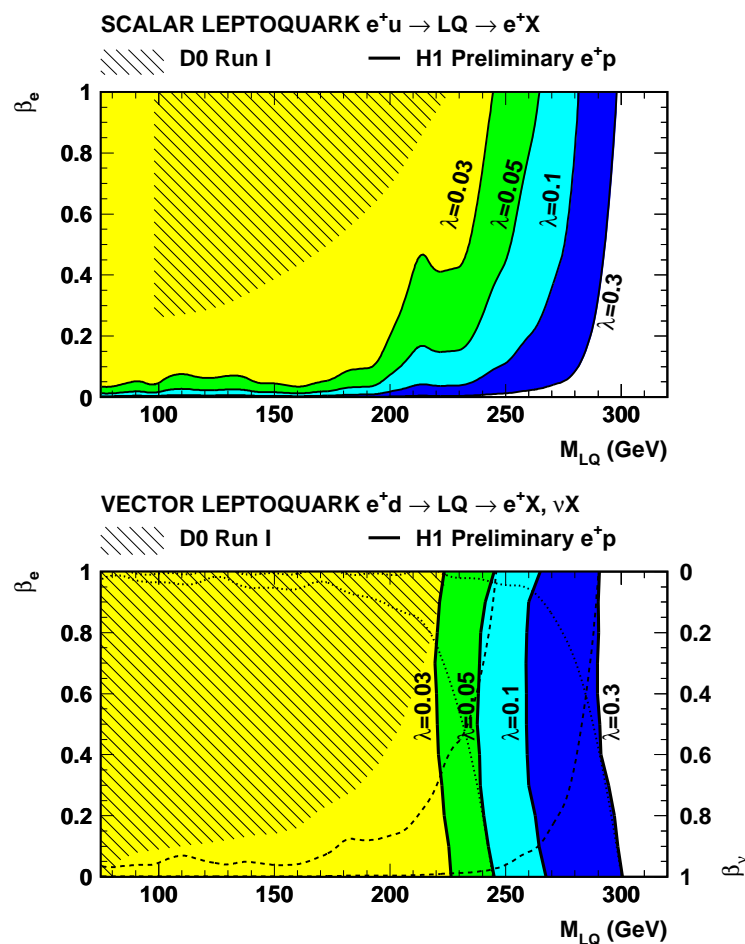
Generic model

⇒  $\beta$  vs  $M_{LQ}$  limits

BRW model

Improved limits for  $\beta = 0.5$  leptoquarks

**ZEUS**

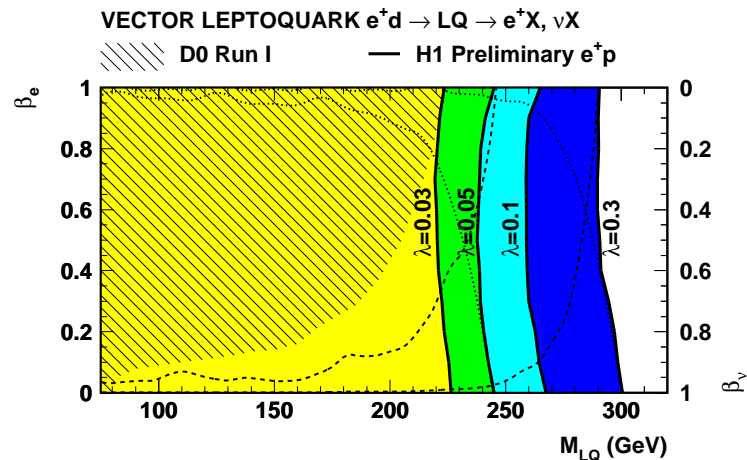
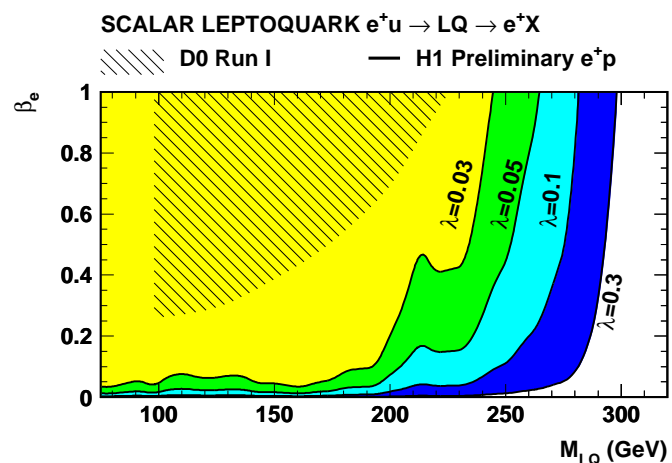


# Single-production at HERA

Combined analysis of **NC** and **CC DIS** events

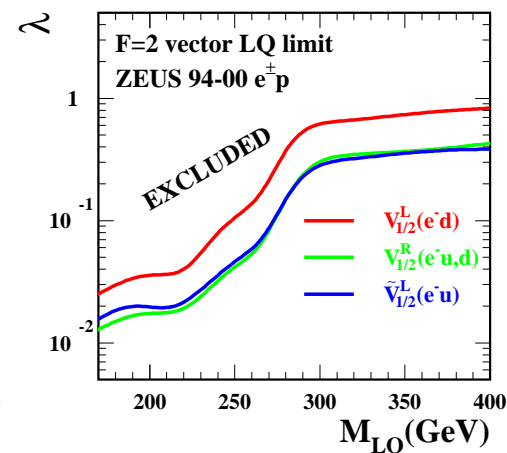
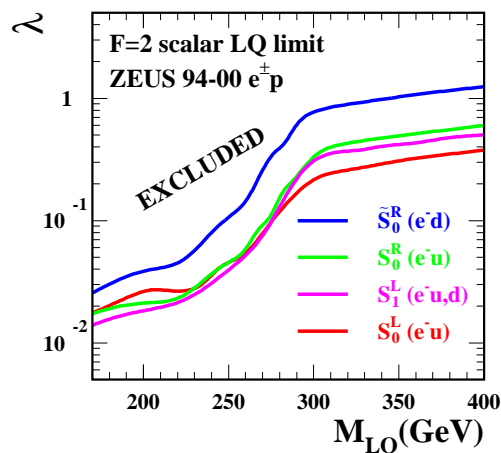
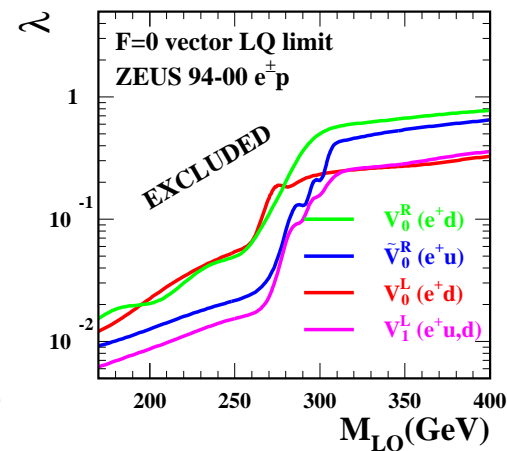
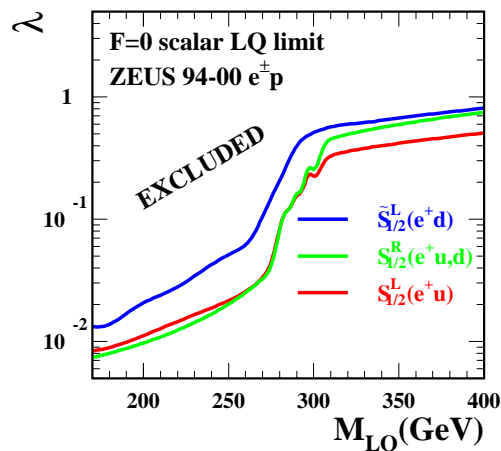
Generic model

⇒  $\beta$  vs  $M_{LQ}$  limits



BRW model

ZEUS



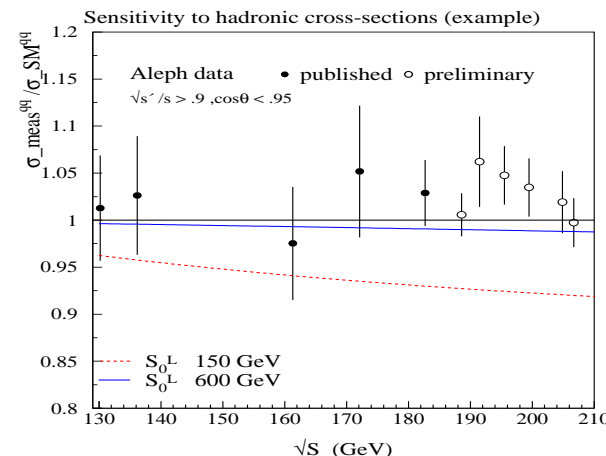
For  $\lambda = \sqrt{4\pi\alpha}$ :  $M_{LQ} > 273 - 386$  GeV



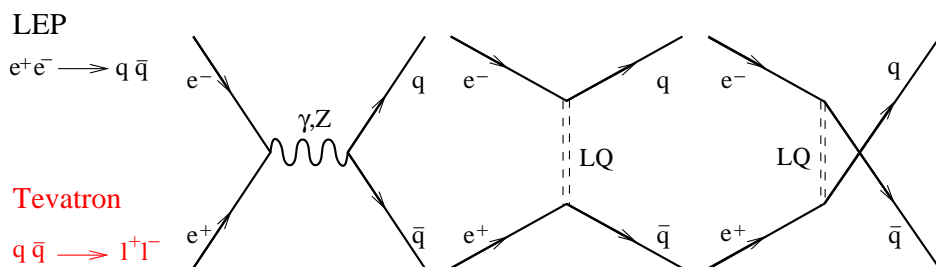
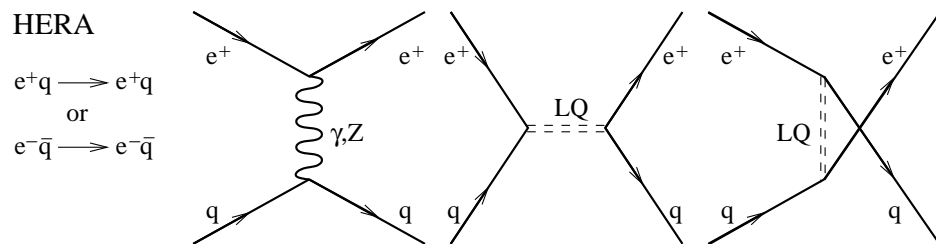
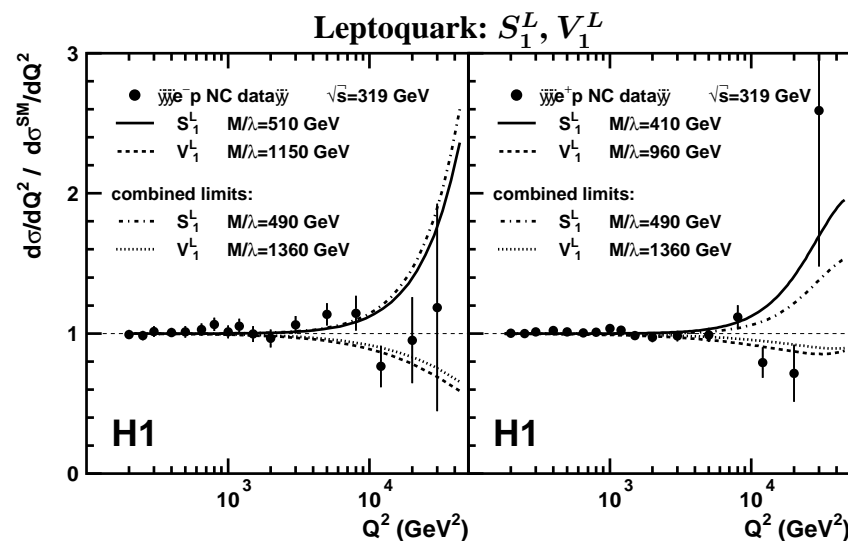
# Search for virtual effects

Virtual **LQ exchange** can affect HERA, LEP and Tevatron measurements even for  $M_{LQ} \gg \sqrt{s}$

$\sigma_{had}$  at LEP:



**NC DIS** at HERA:

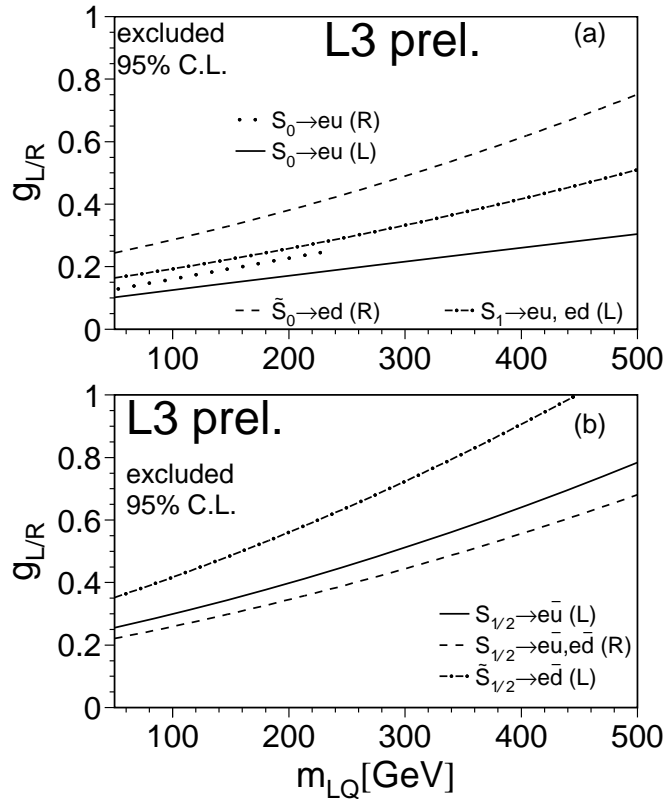


Interference with SM processes important

# Search for virtual effects

$M_{LQ}/\lambda$  limits [TeV] (1<sup>st</sup> generation)

## L3 limits on $\lambda$



For  $\lambda = \sqrt{4\pi\alpha}$ :

$M > 112 - 375$  GeV (scalar)

$M > 159 - 557$  GeV (vector)

LQ	H1	L3*	ZEUS	ALEPH*	LEP2*
$S_0^L$	0.71	1.24	0.75	2.13	2.16
$S_0^R$	0.64	0.88	0.69	0.41	1.72
$\tilde{S}_0^R$	0.33	0.40	0.31	0.57	0.67
$S_{1/2}^L$	0.85	0.37	0.91	0.53	0.59
$S_{1/2}^R$	0.37	0.52	0.69	0.61	0.77
$\tilde{S}_{1/2}^L$	0.43	-	0.50	-	-
$S_1^L$	0.49	0.89	0.55	1.48	1.19
$V_0^L$	0.73	1.84	0.69	2.59	3.03
$V_0^R$	0.58	0.53	0.58	0.49	0.55
$\tilde{V}_0^R$	0.99	1.25	1.03	1.29	1.62
$V_{1/2}^L$	0.42	0.84	0.49	0.81	1.00
$V_{1/2}^R$	0.95	0.71	1.15	0.68	0.75
$\tilde{V}_{1/2}^L$	1.02	0.55	1.26	0.55	0.58
$V_1^L$	1.36	1.73	1.42	1.98	2.18

\* - calculated from  $M_{LQ}$  limits for  $\lambda = \sqrt{4\pi\alpha(0)}$



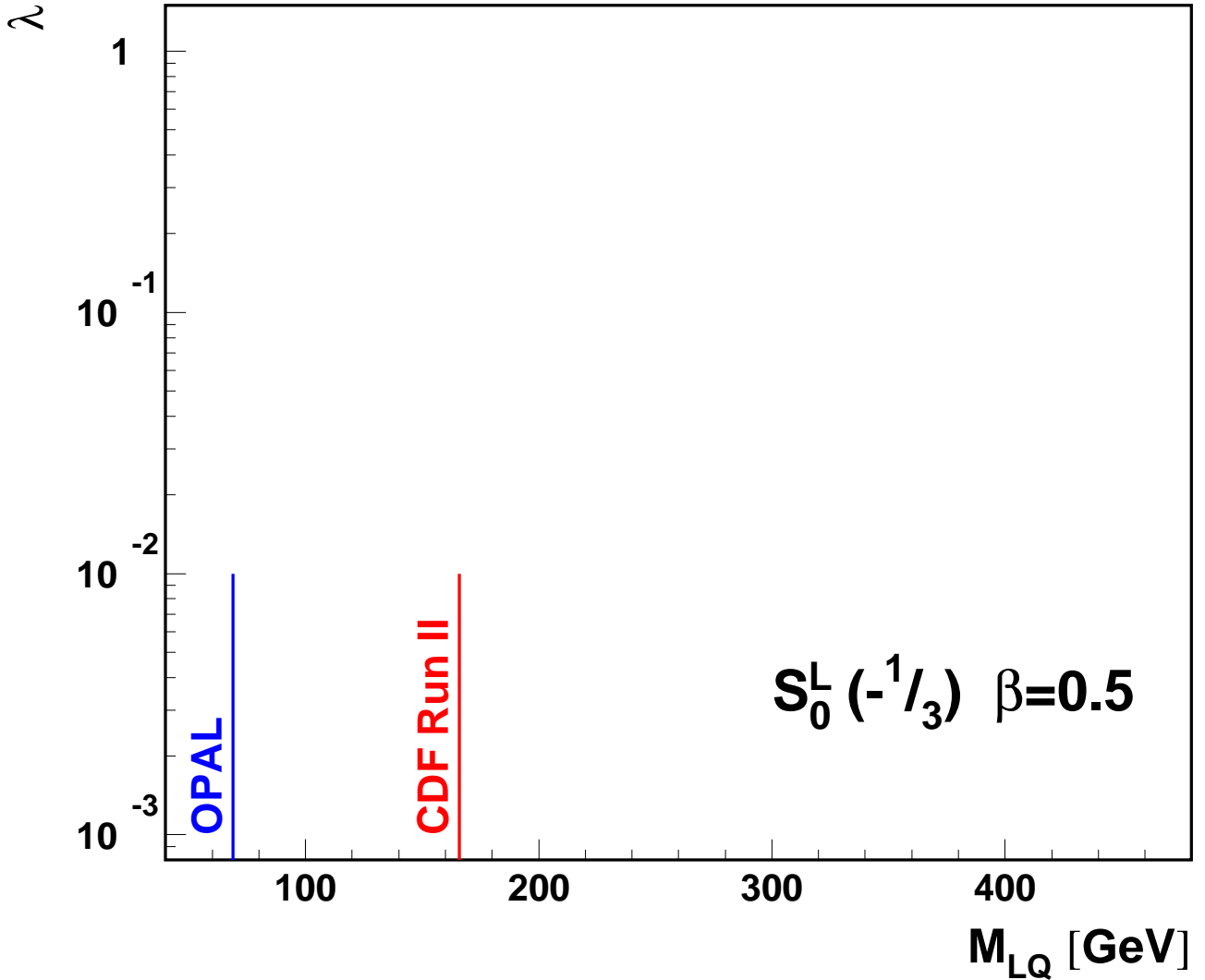


# Comparison of leptoquark limits

Limits on  $S_0^L$  (1<sup>st</sup> gen.)

Best constraints:

pair prod.  $\Rightarrow$  Tevatron



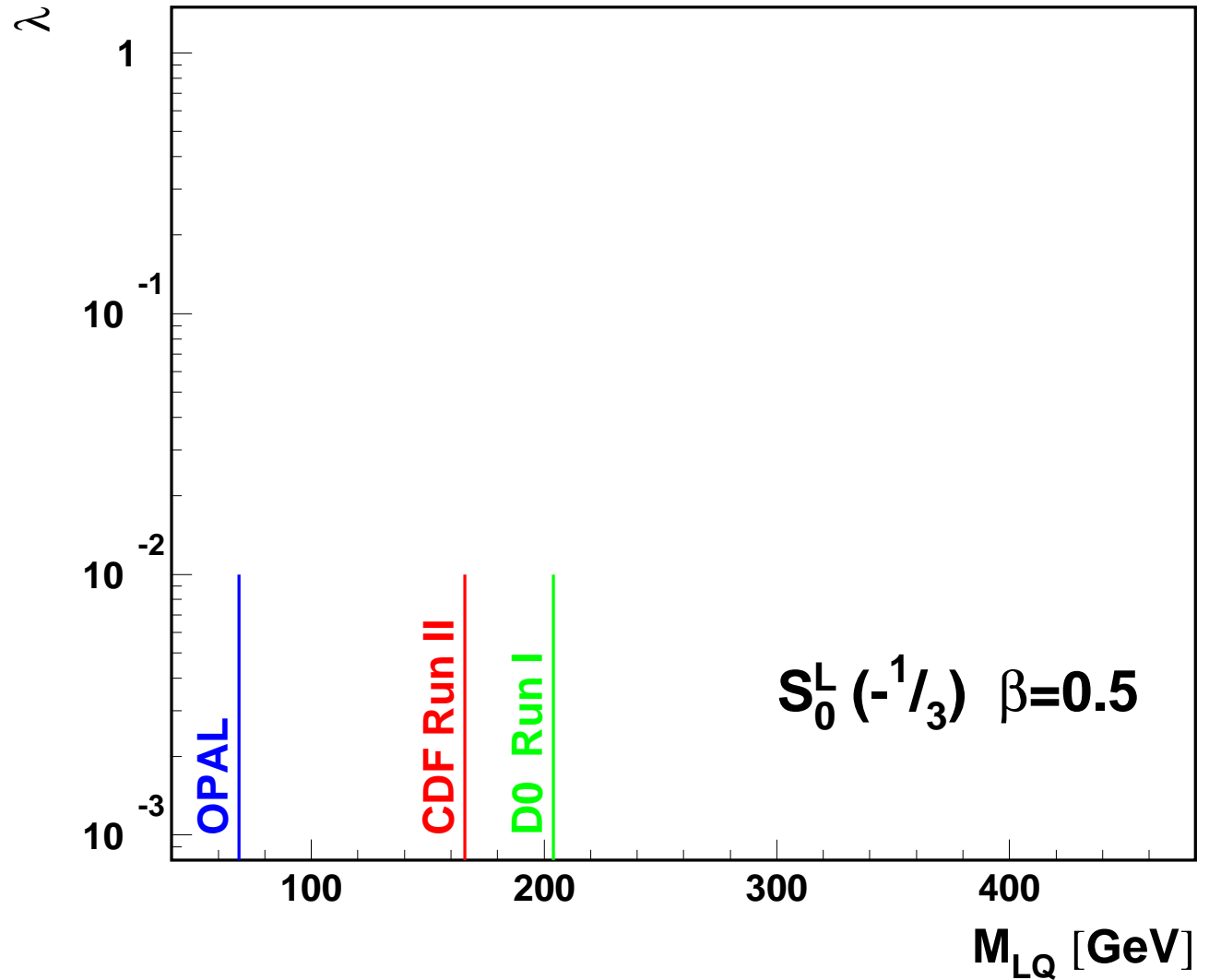


# Comparison of leptoquark limits

Limits on  $S_0^L$  (1<sup>st</sup> gen.)

Best constraints:

pair prod.  $\Rightarrow$  Tevatron  
Run I





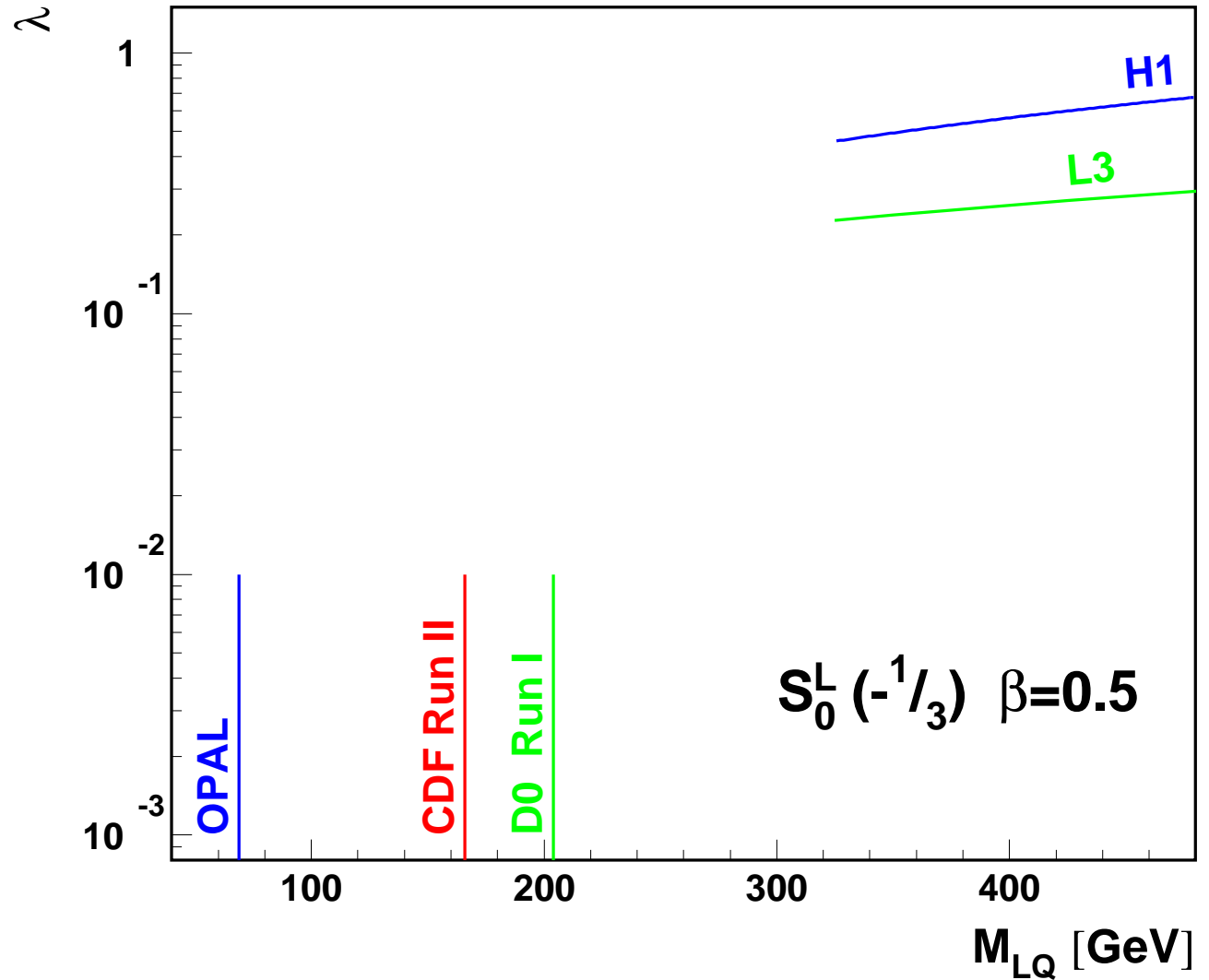
# Comparison of leptoquark limits

Limits on  $S_0^L$  (1<sup>st</sup> gen.)

Best constraints:

pair prod.  $\Rightarrow$  Tevatron  
Run I

virtual effects  $\Rightarrow$  LEP





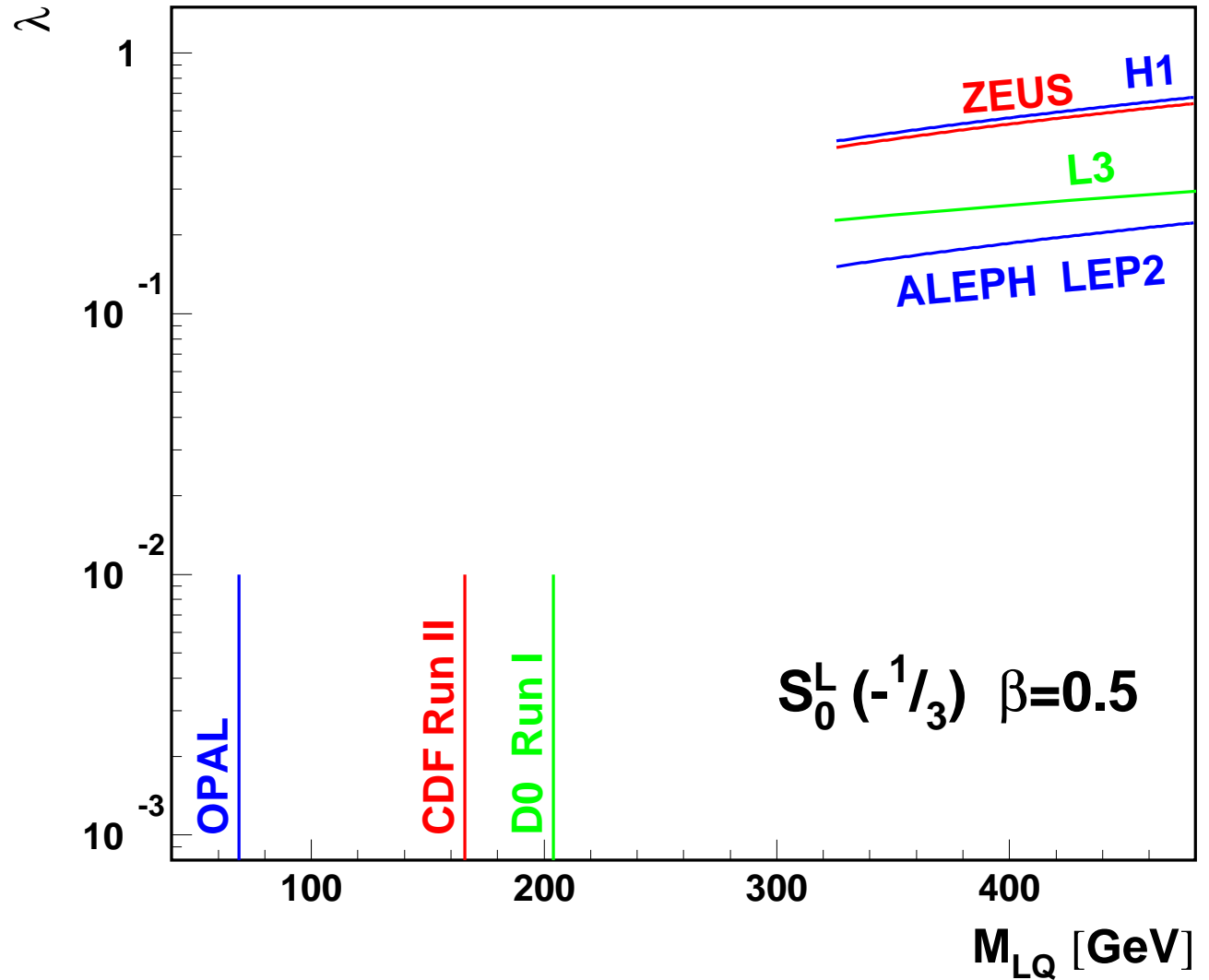
# Comparison of leptoquark limits

Limits on  $S_0^L$  (1<sup>st</sup> gen.)

Best constraints:

pair prod.  $\Rightarrow$  Tevatron  
Run I

virtual effects  $\Rightarrow$  LEP





# Comparison of leptoquark limits

Limits on  $S_0^L$  (1<sup>st</sup> gen.)

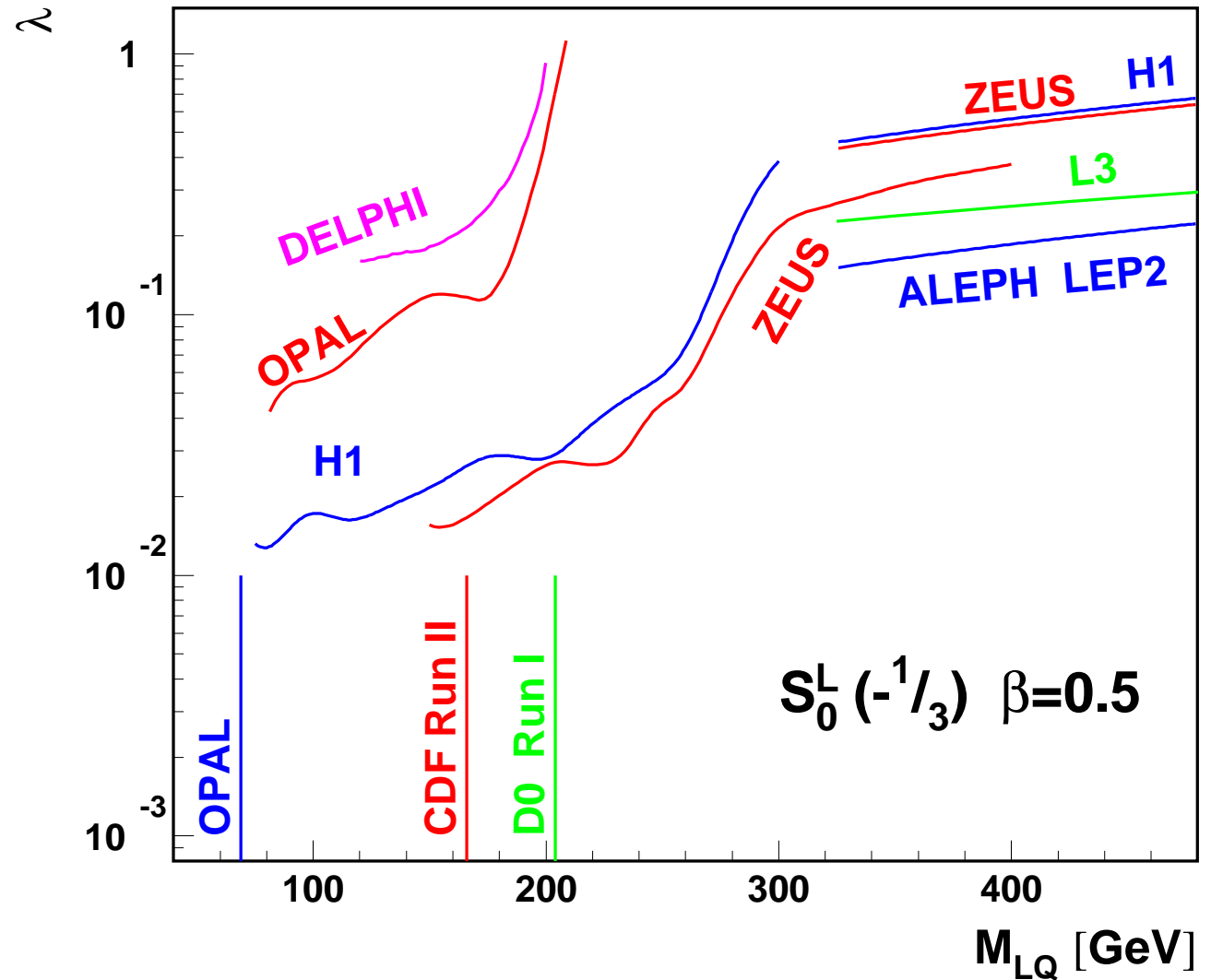
Best constraints:

pair prod.  $\Rightarrow$  Tevatron  
Run I

virtual effects  $\Rightarrow$  LEP

single prod.  $\Rightarrow$  HERA

Complementary constraints from different machines



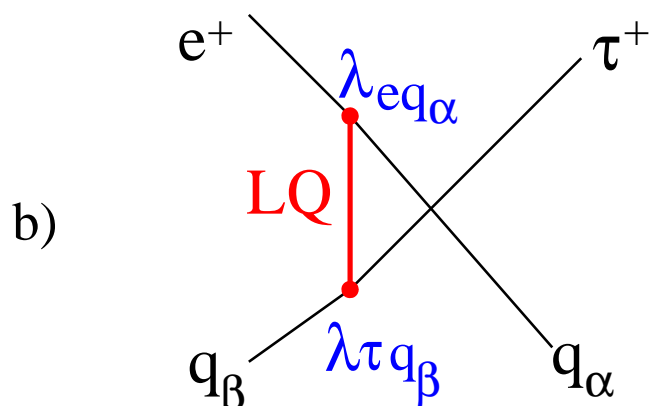
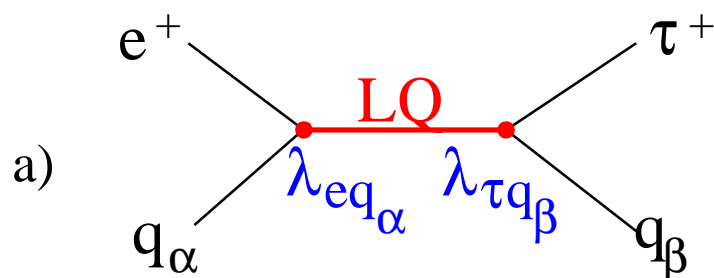
# LFV at HERA

Leptoquarks could also mediate lepton flavour violation:

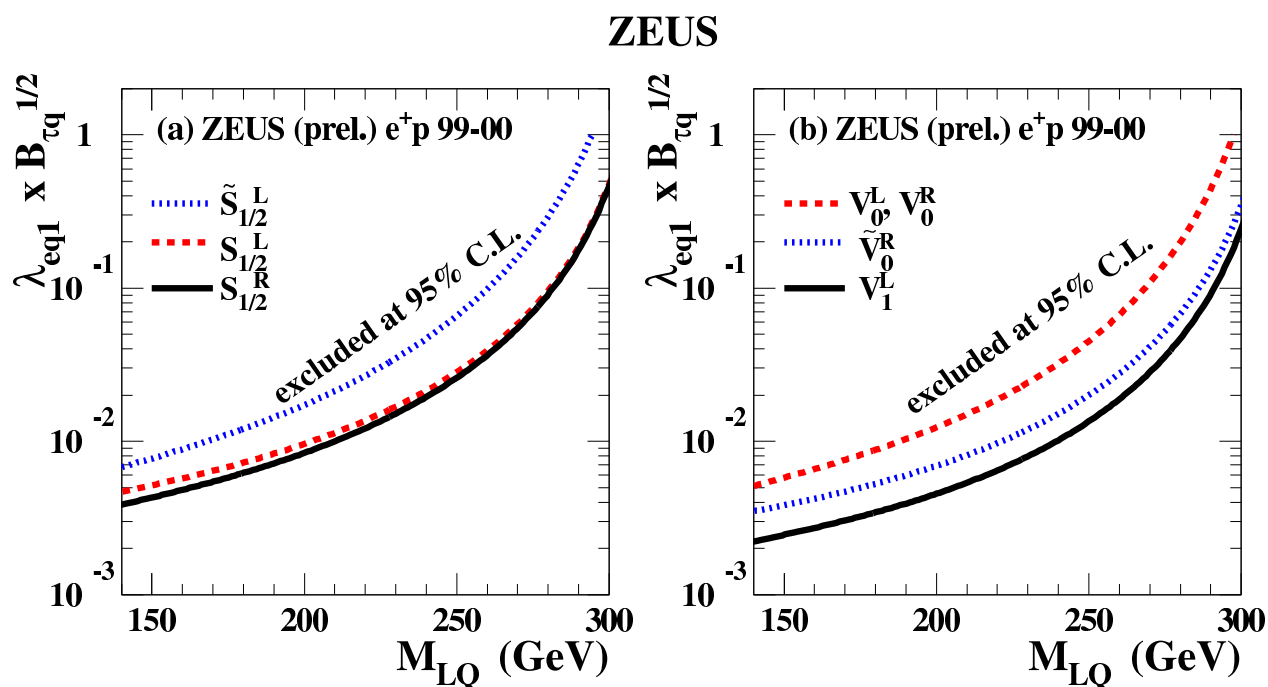
**ZEUS** search for  $e^+p \rightarrow \tau X$   
 66  $pb^{-1}$  of  $e^+p$  data 1999-2000

No events found

$\Rightarrow$  limits on  $\lambda_{eq_1} \times \sqrt{BR(LQ \rightarrow \tau q)}$



assuming  $\lambda_{eq_\alpha} \times \lambda_{\tau q_\beta} \neq 0$

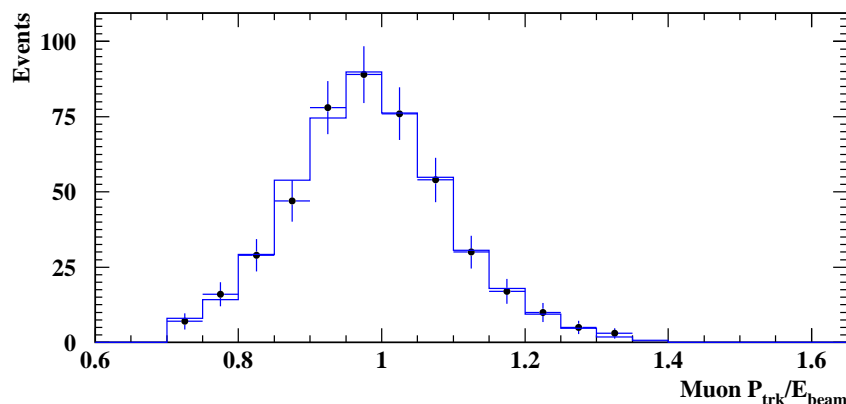
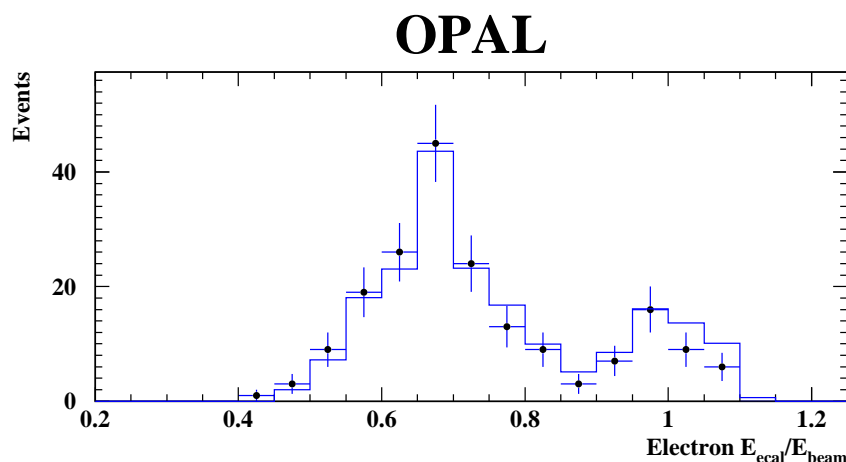


# LFV at LEP

**OPAL** analysis of LEP2 data (189-209 GeV)

Electron and muon candidates

Search for lepton flavour violating processes:



	SM exp.	Observed
$e^+e^- \rightarrow e\mu$	0.019	1
$e^+e^- \rightarrow e\tau$	5.01	5
$e^+e^- \rightarrow \mu\tau$	14.3	11

Upper cross section limits:

- 22 to  $58 fb$  for  $e\mu$
- 78 to  $144 fb$  for  $e\tau$
- 64 to  $166 fb$  for  $\mu\tau$

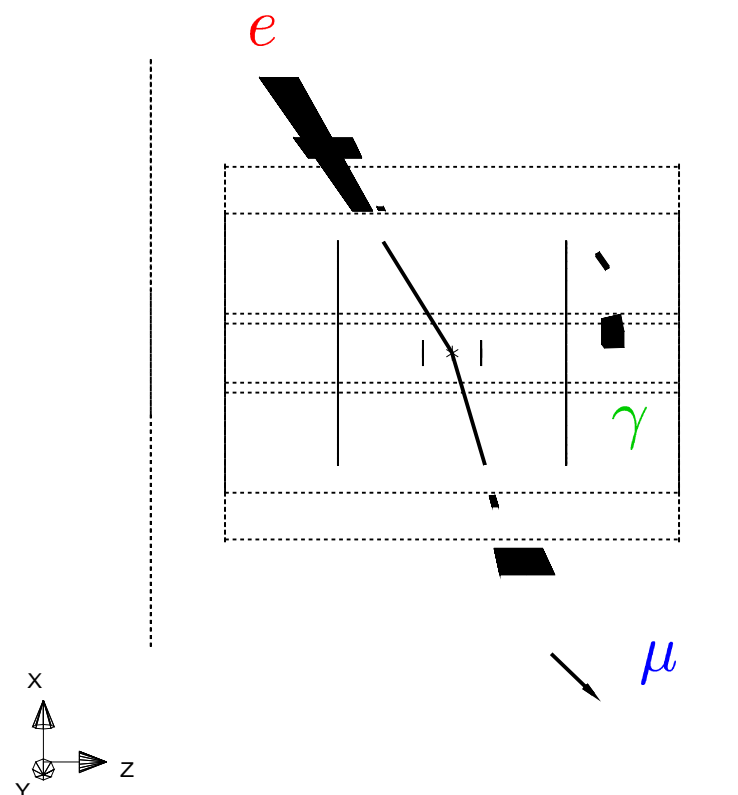
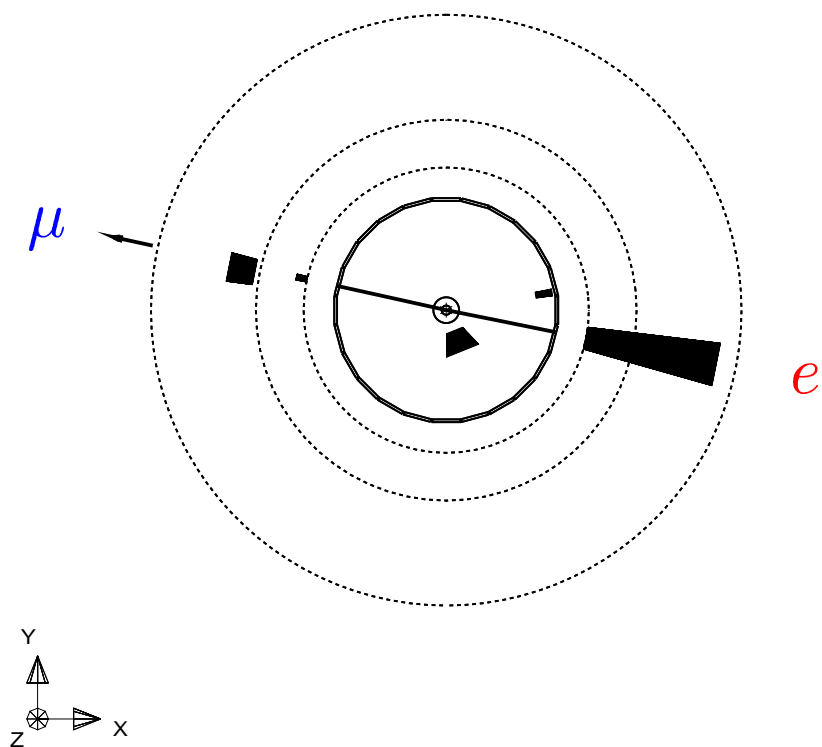
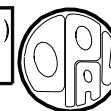


# Lepton Flavour Violation

## OPAL $e^+e^- \rightarrow e\mu$ event

Run:event 9298:115615 Ctrk(N= 2 Sump=168.4) Ecal(N= 4 SumE= 84.9)  
 Ebeam 94.32 Vtx ( -.04, .08, .44) Hcal(N= 4 SumE= 5.1) Muon(N= 1)

Run:event 9298:115615 Ctrk(N= 2 Sump=168.4) Ecal(N= 4 SumE= 84.9)  
 Ebeam 94.32 Vtx ( -.04, .08, .44) Hcal(N= 4 SumE= 5.1) Muon(N= 1)





# Summary

New results from **leptoquark searches** at LEP, HERA and Tevatron

No signal of LQ production observed

**Complementary limits** from different processes and experiments

No signal of **lepton flavour violation** for charged leptons

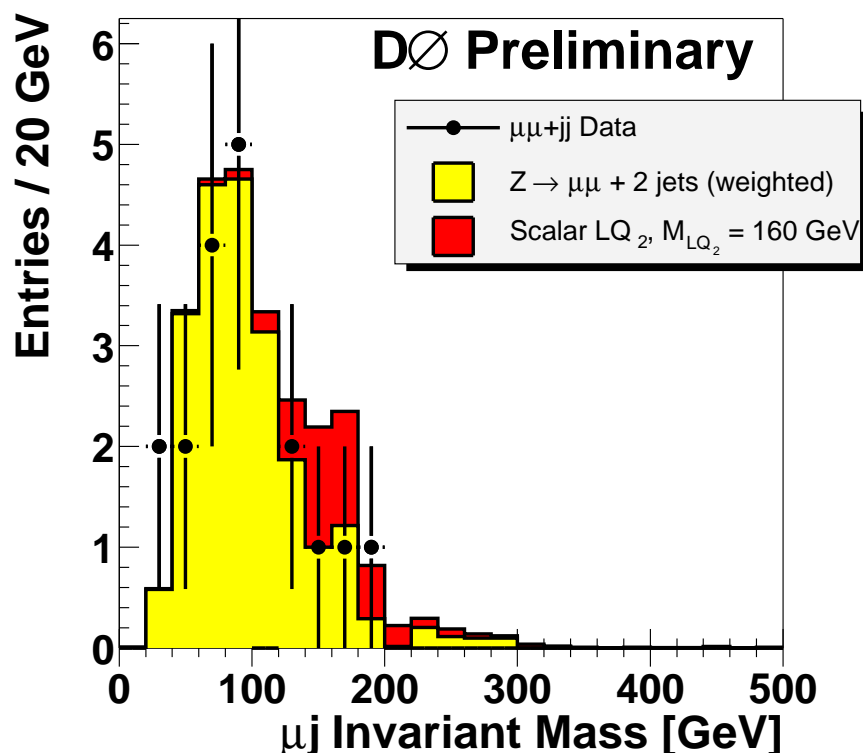
Single  $e^+e^- \rightarrow e\mu$  event from OPAL:  
interesting, but not a discovery yet...



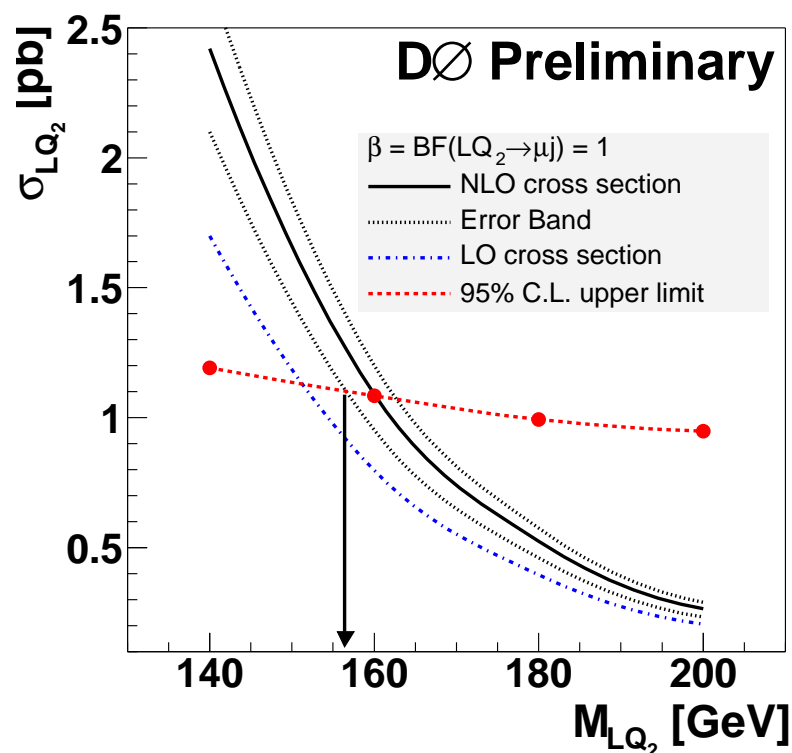
# Pair-production at Tevatron

**DØ**: search for second generation leptoquarks  $LQ \bar{L}Q \rightarrow \mu\mu jj$

Reconstructed mass:



Cross section limit:  $(41 \text{ pb}^{-1})$



For  $\beta_{\mu q} = 1$  limit for scalar leptoquarks is  $M > 157 \text{ GeV}$  (95% CL)

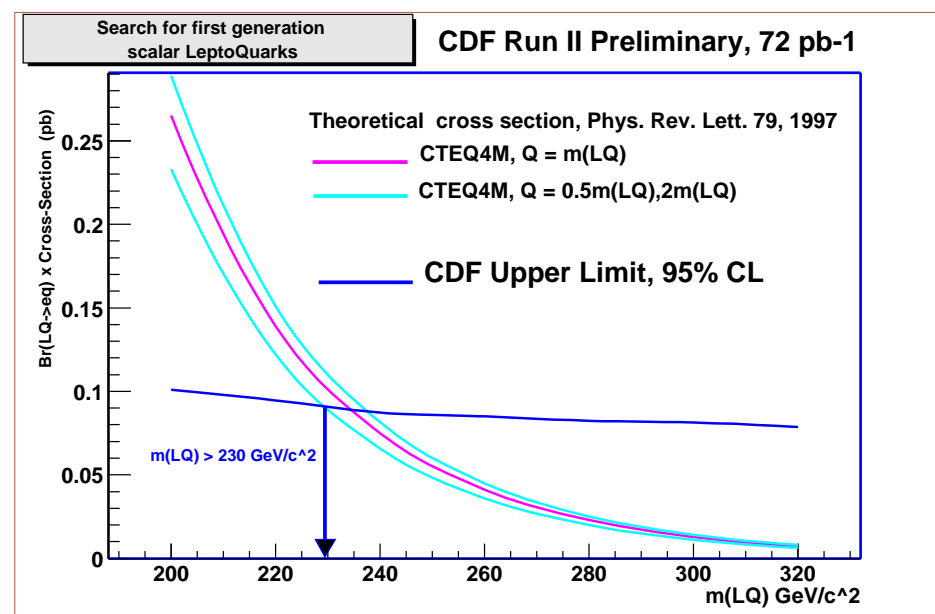
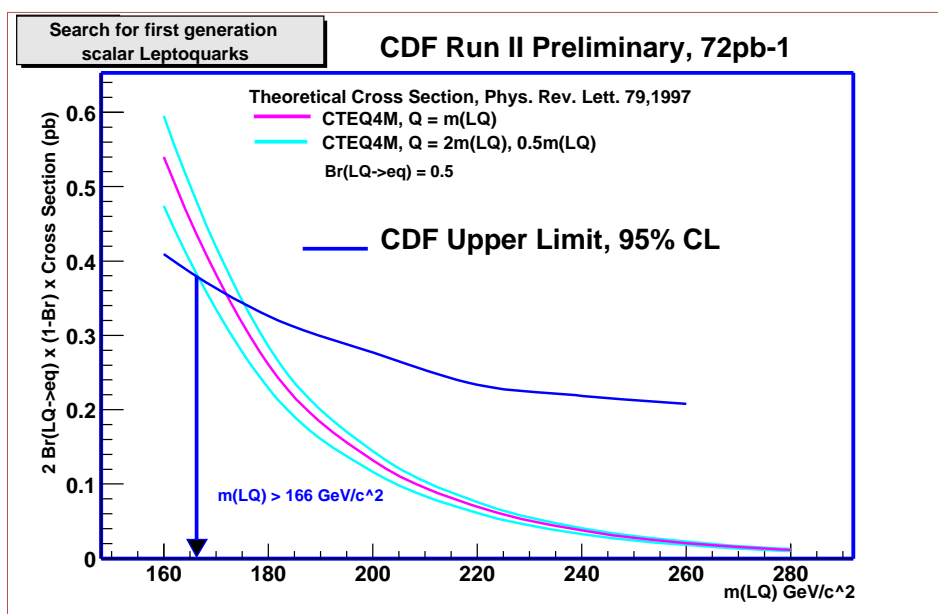


# Pair-production at Tevatron

**CDF** : search for first generation leptoquarks

$LQ \bar{L}Q \rightarrow evjj$

$LQ \bar{L}Q \rightarrow eejj$



$$\beta_{eq} = 0.5 \Rightarrow M > 166 \text{ GeV}$$

$$\beta_{eq} = 1 \Rightarrow M > 230 \text{ GeV}$$



# Comparison of leptoquark limits

Limits on  $S_{1/2}^L$  (1<sup>st</sup> gen.)  $\lambda$

