

Search for Leptoquarks

Siena 2001

Seventh Topical Seminar on
“The legacy of LEP and SLC”

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- Introduction
- Direct Searches at Tevatron, LEP and HERA
- Limits from Contact Interaction
- Future Leptoquark Searches (LHC, Tesla)

Leptons and Quarks

- “Mat(t)erialistic view” of the SM:

	quarks		leptons	
Q	-1/3	2/3	-1	0
3. family	b	t	τ	ν_τ
2. family	s	c	μ	ν_μ
1. family	d	u	e	ν_e

link?

Several links between leptons and quarks:

- electric charges are multiples of $1/3$
- same number of generations: $n_q = n_\ell$
(SM renormalizable)
- mixing between generations (SuperK)

- Compositeness - why should (unstable) SM particles be fundamental?
 - Several Models: Rishons, Haplons, Preons, etc.
 - Problem: underlying dynamics unknown
- Leptoquarks
 - carry multiple charges of $Q = 1/3$
 - carry lepton number, baryon number, $SU(3)_c$ color

Motivation

Theory:

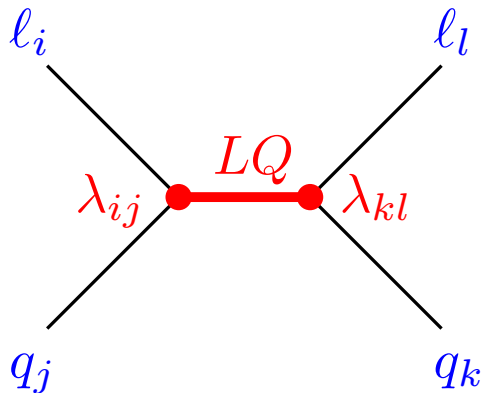
- many GUT models predict new bosons carrying Lepton and Baryon number
 - Models with light Leptoquarks $m_{LQ} \ll m_{GUT} = 10^{15}$ GeV:
 - "Fourth Color" model (Pati, Salam)
 - E6, SO(10) (if couplings are non-SU(5) symmetric)
 - Supersymmetry, Technicolor, Superstrings
- ⇒ Leptoquark masses might be of electroweak scale 100 – 1000 GeV

Experimental Hints?

- slight APV in Cesium of 2.3σ (Bennett, Wieman)
 - ⇒ interpretation as 1.1 – 1.3 TeV Leptoquark (Barger, Kingman Cheung)
- Muon anomalous magnetic moment $\Delta a_\mu = (42.6 \pm 16.5) \times 10^{-10}$ (E821)
 - ⇒ 2.6σ deviation interpreted as 0.7 – 2.2 TeV Leptoquark (Kingman Cheung)
- Excess of high Q^2 events observed at early HERA in 1997 by H1 and ZEUS? ⇒ update

Leptoquark Couplings

- Yukawa Couplings:



Leptoquarks are **color triplets** and carry $B, L \neq 0$:

$\lambda_{ij}, \lambda_{kl} =$ Yukawa (fermion) couplings

\Rightarrow FCNC, Lepton Flavour Violation

fermion number $F = L + 3B = 0$ and $F = \pm 2$

scalar (favoured by GUT models) and **vector** LQs

decay width: $\Gamma_{S(V)} = \frac{1}{16(24)\pi^2} \lambda_{L,R}^2 M \ll 1 \text{ GeV}$

- Buchmüller-Rückl-Wyler (BRW) model:

couplings respect $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ symmetry \Rightarrow

- Leptoquark classified: $Q J_I^{L,R}$

by spin $J = S, V$, chiral coupling L, R , weak isospin I and electric charge Q

- in total 12 different states (5 multiplets) of scalar and vector Leptoquark

- fixed decay branching ratios **100, 50, 0%** into ℓq and/or νq

Leptoquark Constraints

- Limits from **low energy experiments**:

- proton decay
- (Leptonic) pion decay
- rare decays (K , τ , μ , $\beta\beta$)
- Quark-lepton universality
- Atomic Parity Violation
- Limits from FCNC

\Rightarrow no diquark couplings

$\Rightarrow \frac{m_{LQ}}{\lambda} \gtrsim 1 \text{ TeV}$

\Rightarrow chiral LQs: $\lambda_L \lambda_R \approx 0$

$\Rightarrow \frac{m_{LQ}}{\lambda_{ij}} \gtrsim 1 - 100 \text{ TeV} \quad \text{for } i \neq j$

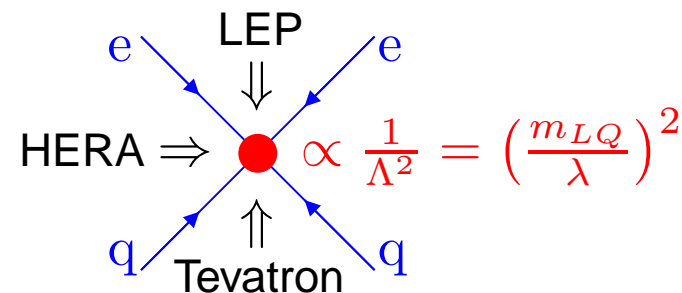
- Limits from **collider experiments** (high energies): **this talk!**

- direct searches for LQ resonances:

\Rightarrow limits on m_{LQ}

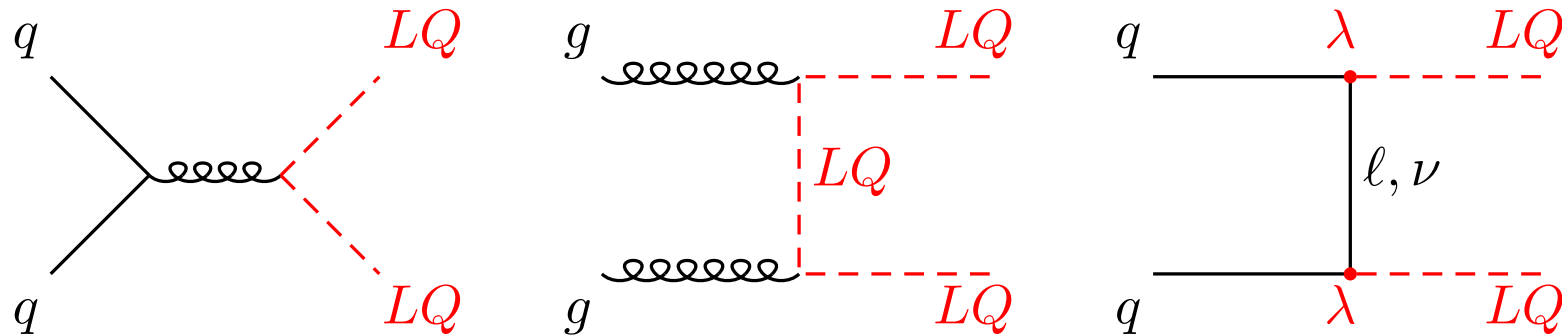
- four-fermion contact interactions:

\Rightarrow limits on $\frac{m_{LQ}}{\lambda}$



A. Direct Production of Leptoquarks at Colliders

Pair production of LQs in $pp(\bar{p})$ collisions:



- **LQ generations:** all produced
- **QCD uncertainties:** factorisation/renormalisation scale
- **LQ types:** almost independent = not sensitive
- **Yukawa couplings:** contribution highly suppressed (\rightarrow see third diagram)

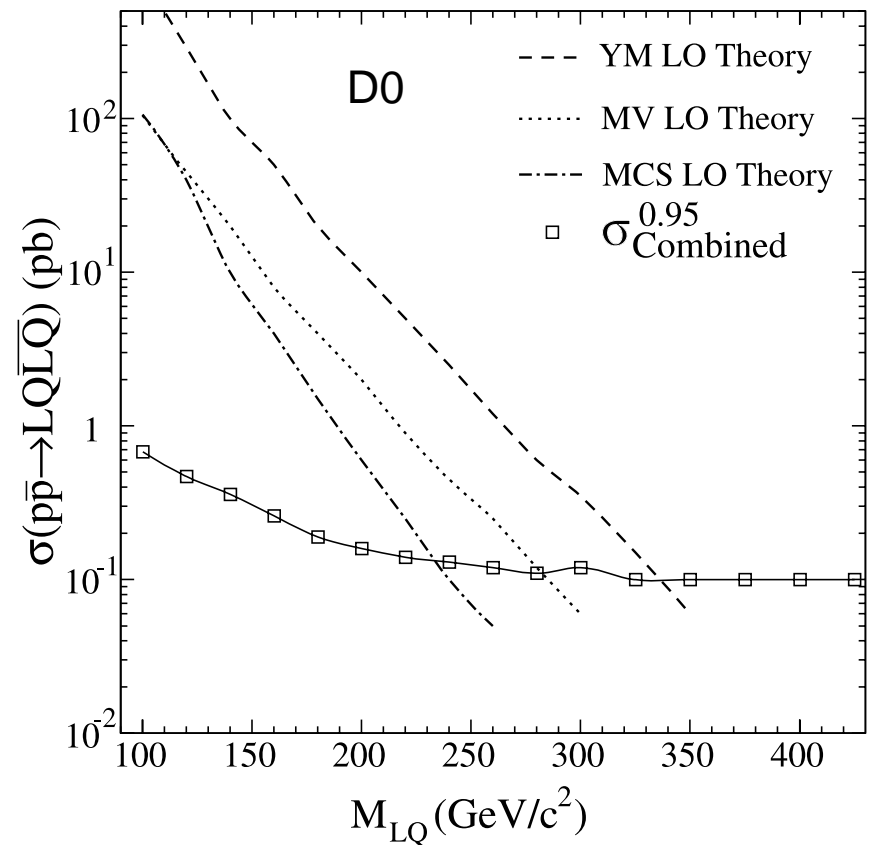
Single production of LQs in $pp(\bar{p})$ collisions:

- **High background:** \Rightarrow no sensitivity

Search for Leptoquarks at Tevatron I

First generation Vector Leptoquarks:

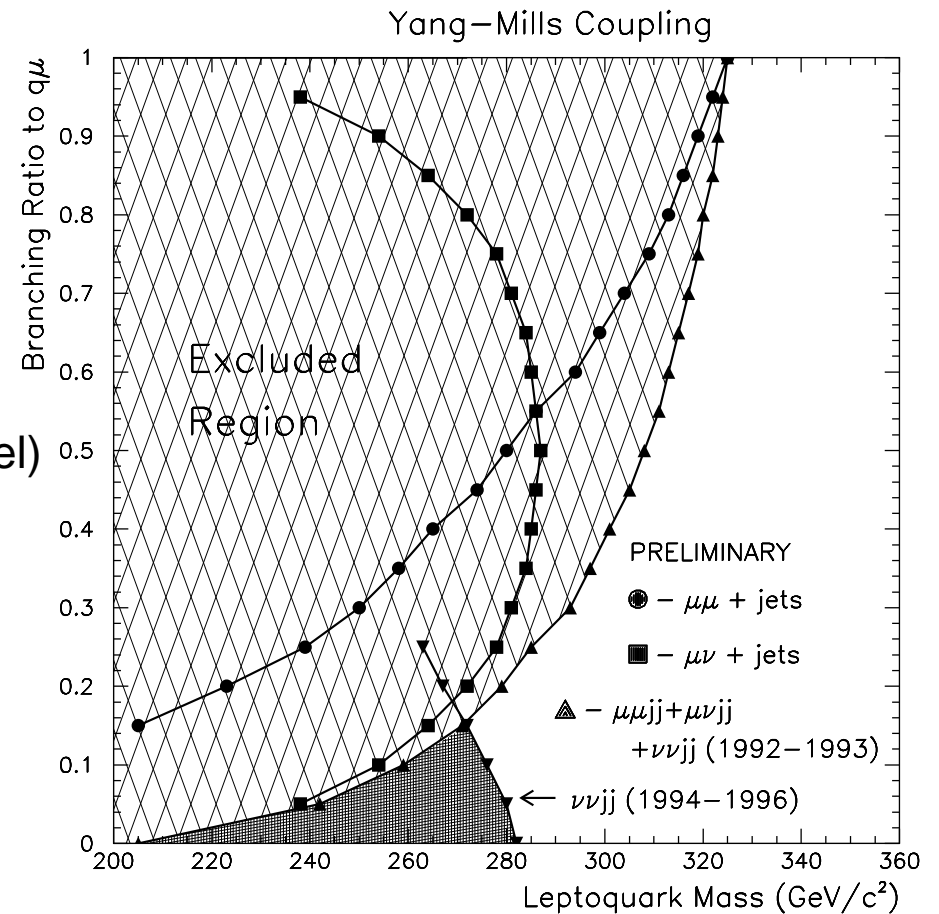
- Consider LQ with $\text{BR}(LQ \rightarrow eq) = 1/2$
i.e. $-2/3 V_0^L$, $-2/3 V_1^L$ (BRW model):
- combination of $eejj$, $e\nu jj$ and $\nu\nu jj$ channels
- expected cross section shown for:
 - minimal cross section
 - minimal vector couplings ($\kappa_G = 1$, $\lambda_G = 0$)
 - Yang Mills couplings ($\kappa_G = \lambda_G = 0$)
- exclusion limits $\gtrsim 230$ GeV depending on vector couplings



Search for Leptoquarks at Tevatron II

Second generation Vector Leptoquarks:

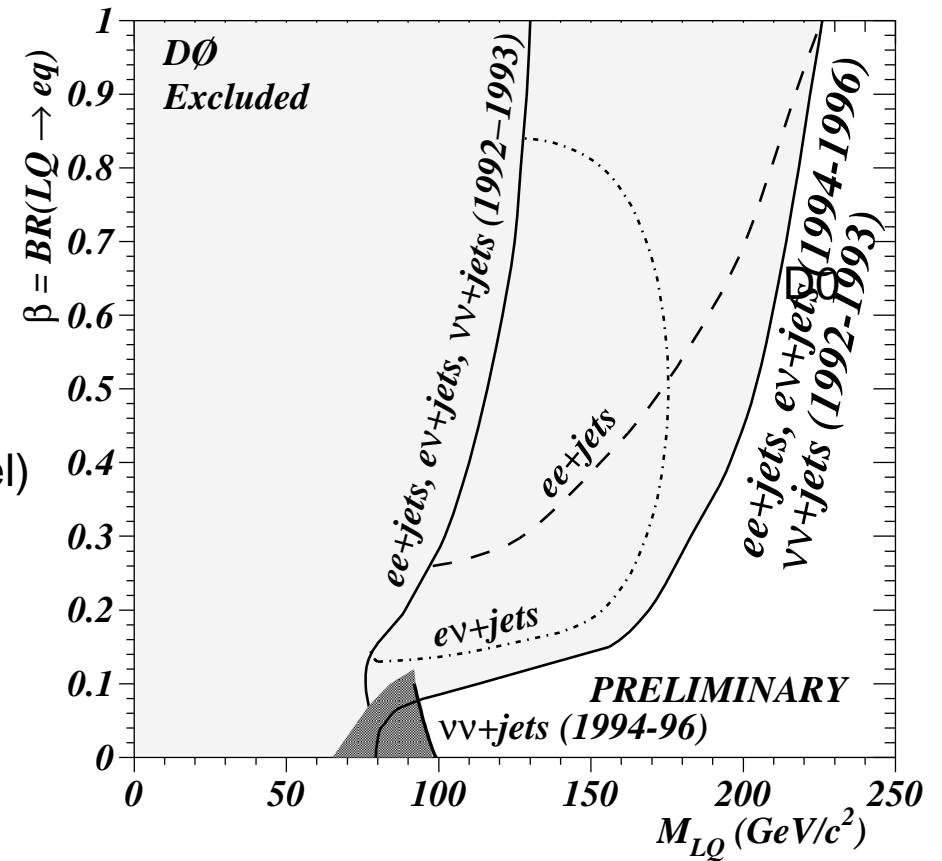
- Allow for arbitrary branching ratios:
 $BR(LQ \rightarrow \mu q, \nu q) = 0 - 1$ (general model)
- search for $\mu\mu jj$, $\mu\nu jj$ and $\nu\nu jj$
- combined limits for $BR(\mu q) + BR(\nu q) = 1$
- exclusion limits $\approx 270 - 320$ GeV for
 Y.M. couplings depending on branching ratio



Search for Leptoquarks at Tevatron III

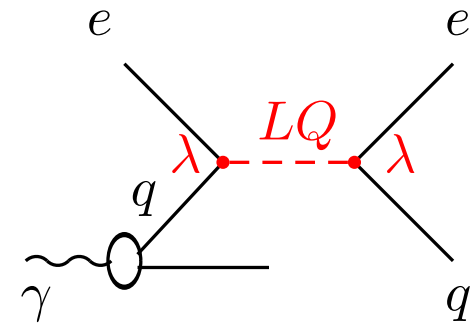
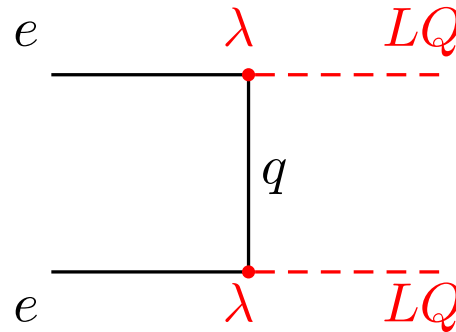
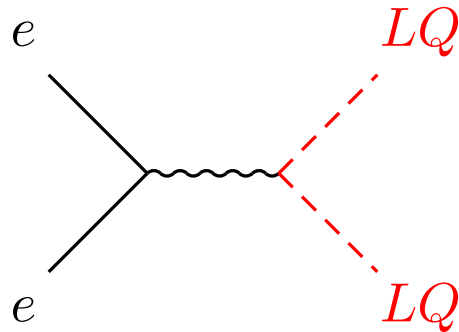
First generation Scalar Leptoquarks:

- Allow for arbitrary branching ratios:
 $\text{BR}(LQ \rightarrow eq, \nu q) = 0 - 1$ (general model)
- search for $eejj$, $evjj$ and $\nu\nu jj$
- combined limits for $\text{BR}(eq) + \text{BR}(\nu q) = 1$
- exclusion limits $\approx 90 - 220$ GeV
 depending on branching ratio



B. Direct Production of Leptoquarks at Colliders

Production of LQs in e^+e^- collisions:



Pair production:

- **LQ types:** test specific electroweak couplings
- **Yukawa couplings:** contribution negligible
- **sensitivity:** $m_{LQ} < \sqrt{s}/2$ (handicap for LEP)

Single production:

- **Process:** photoproduction testing **first generation** LQs up to $m_{LQ} \lesssim \sqrt{s}$
- **Yukawa couplings:** dependent

Search for Leptoquarks at LEP

LEP I:

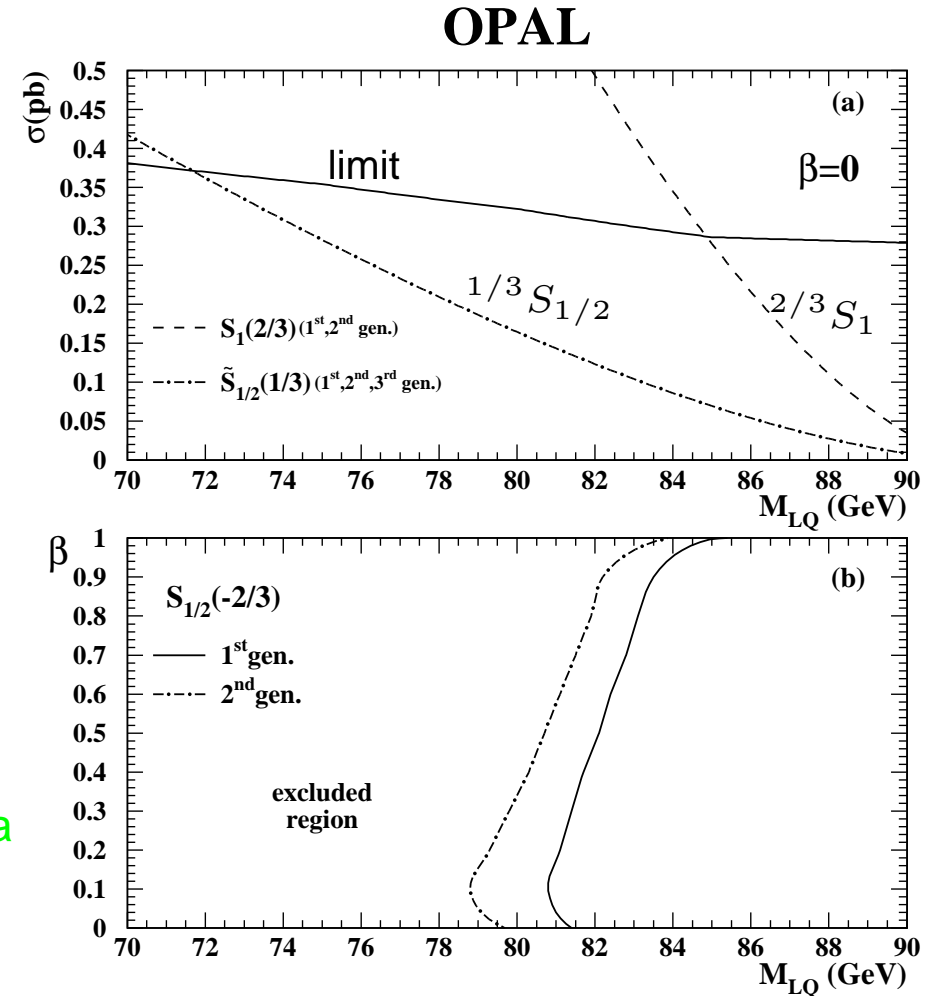
- Leptoquarks (all generations) excluded up to 45 GeV

LEP II:

- pair production limits with charged lepton final states do not compete with Tevatron:

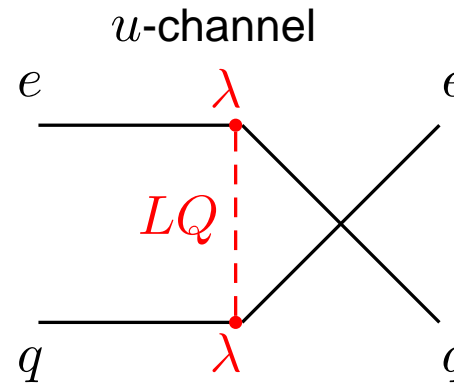
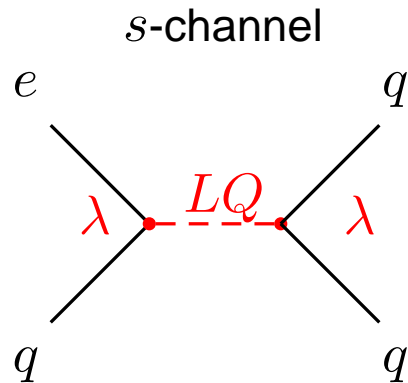
$$m_{LQ}(\text{limits}) > \sqrt{s_{LEP}}/2$$
- however, $\nu\nu jj$ channels of scalar LQs only excluded up to $\approx 90 - 100$ GeV by D0
- pair production studied at $\sqrt{s} = 183$ GeV
- limits on $LQ \rightarrow \nu q$ set by OPAL for all generations up to 85 GeV (for $^{2/3}S_1$)

⇒ potential for improving limits → 206 GeV data



C. Direct Production of Leptoquarks at Colliders

Production of LQs in $e^\pm p$ collisions:



Pair production:

- negligible: direct or resolved process

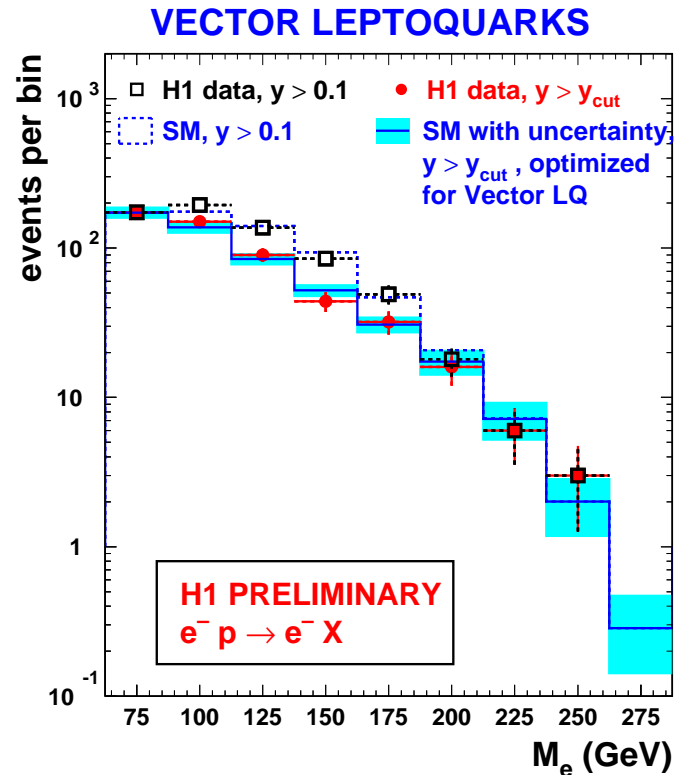
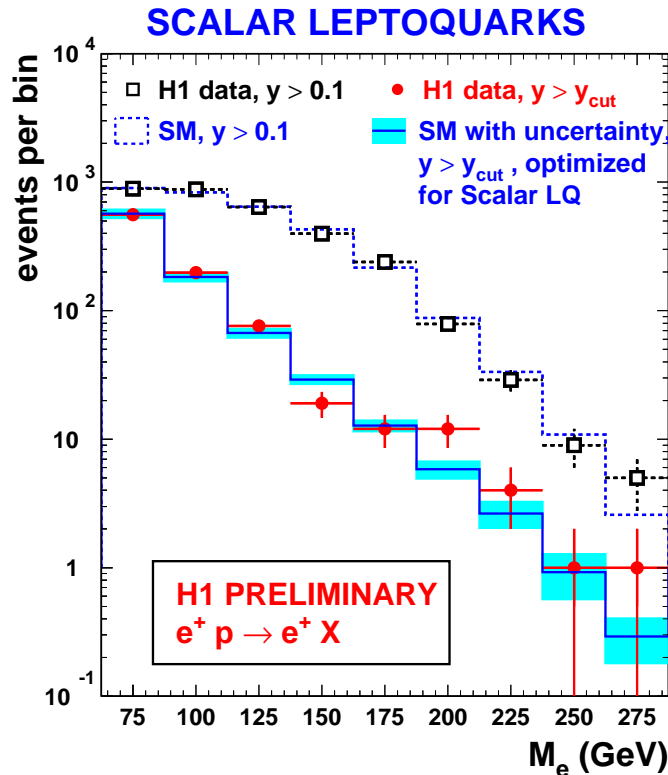
Single production:

- Yukawa couplings: directly testing eq fermion coupling \rightarrow high sensitivity on λ
- LQ types: couplings tested by exploiting
 - beam charge e^\pm
 - longitudinal polarisation (HERA II)
 - angular distributions

Leptoquark Search at HERA I

Search for eq resonances:

- full data set of HERA I analysed $\mathcal{L} \approx 15 \text{ pb}^{-1}$ of e^-p and $\approx 115 \text{ pb}^{-1}$ of e^+p scattering



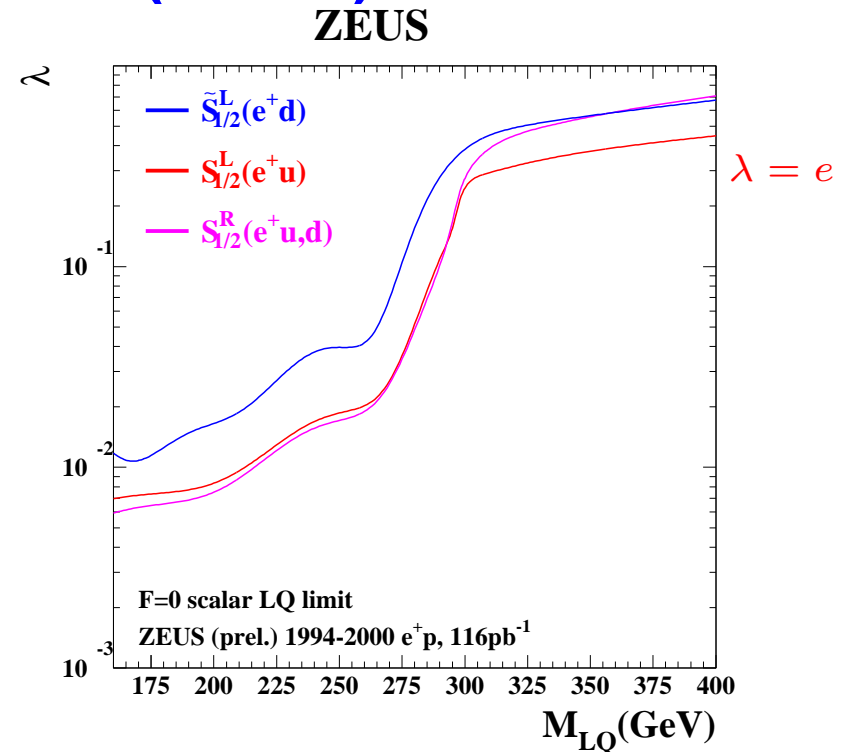
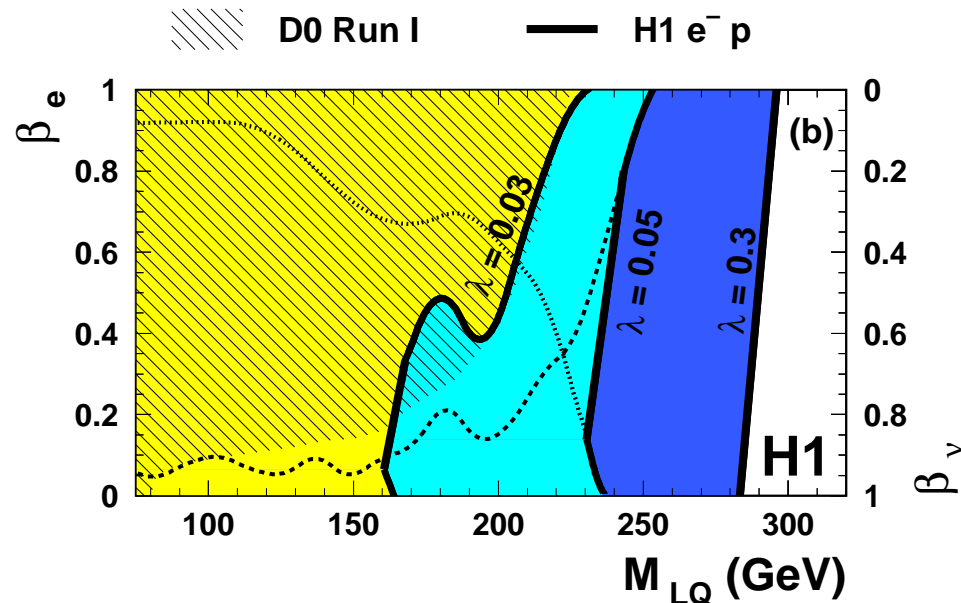
- excess of events at $m \approx 200 \text{ GeV}$ not confirmed by H1
- similar results were obtained by ZEUS

Leptoquark Search at HERA I (cont'd)

Single Production of Scalar Leptoquarks:

- set limits on Yukawa coupling as function of mass
- u -channel sensitive to LQs above collider energy:
 $\sqrt{s} \approx 314 \text{ GeV}$
- for $\lambda = e$ LQs excluded up to HERAs cms energy

SCALAR LEPTOQUARK $e^- u \rightarrow \text{LQ} \rightarrow e^- X, \nu X$



- search for eq and νq final states
- combined limits set on $\text{BR}(LQ \rightarrow eq)$
assuming $\text{BR}(eq) + \text{BR}(\nu q) = 1$
- so obtained limit almost independent

Contact Interactions

- Effective Lagrangian

(considering only vector-type terms)

$$L_V = \sum_{a, b = L, R} \eta_{ab}^q (\bar{e}_a \gamma^\mu e_a) (\bar{q}_b \gamma_\mu q_b)$$

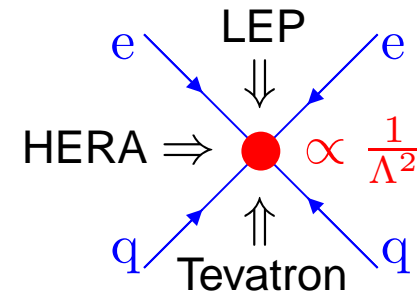
model: $\eta_{ab}^q = \epsilon \left(\frac{g}{\Lambda_{ab}^q} \right)^2$

$\epsilon = \pm 1$ interference with SM:

Λ effective mass scale

g coupling strength

often set: $g = \sqrt{4\pi} \approx 3.5 \approx 11e$



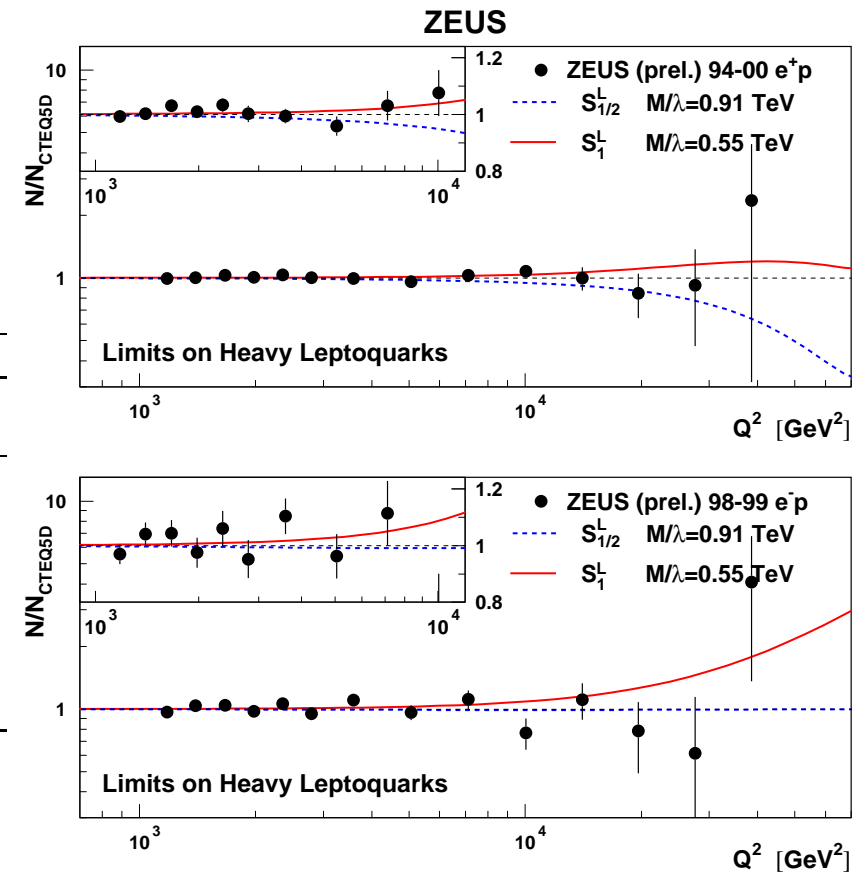
\Rightarrow testing new physics above the collider energy
at high scales, for example Q^2

- considering proper LQ couplings

\Rightarrow access to Leptoquarks

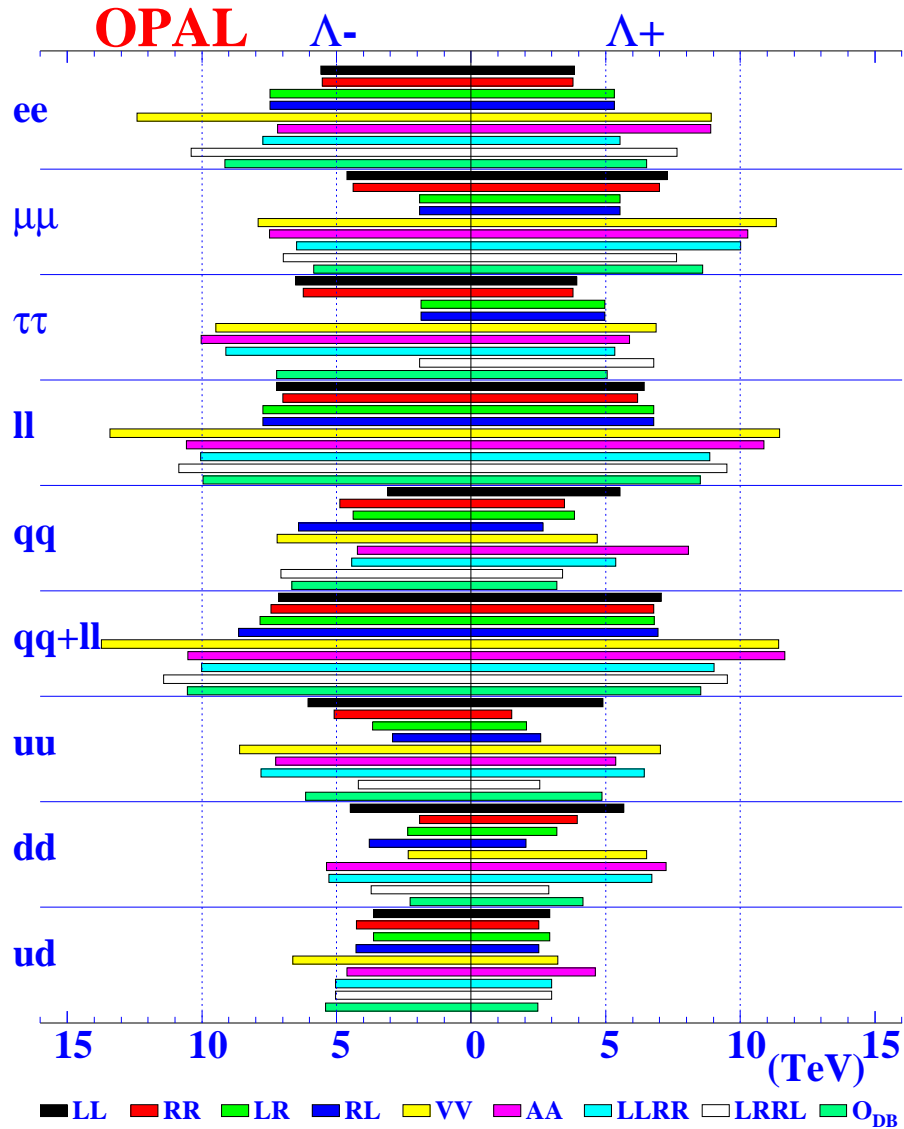
Contact Interactions at HERA

- measure Q^2 distribution of NC events and fit LQ hypothesis
- limits set on the ratio M/λ ($= \Lambda/g$)
- LQ exclusion limits up to **0.3-1.4 TeV** set



ZEUS (prel.) 1994-2000 $e^\pm p$									
Model	Coupling structure								95% CL [TeV] M_{LQ}/λ_{LQ}
	a_{LL}^{ed}	a_{LR}^{ed}	a_{RL}^{ed}	a_{RR}^{ed}	a_{LL}^{eu}	a_{LR}^{eu}	a_{RL}^{eu}	a_{RR}^{eu}	
S_0^L					$+\frac{1}{2}$				0.75
S_0^R								$+\frac{1}{2}$	0.69
\tilde{S}_0^R				$+\frac{1}{2}$					0.31
$S_{1/2}^L$						$-\frac{1}{2}$			0.91
$S_{1/2}^R$			$-\frac{1}{2}$				$-\frac{1}{2}$		0.69
$\tilde{S}_{1/2}^L$		$-\frac{1}{2}$							0.50
S_1^L	$+1$				$+\frac{1}{2}$				0.55
V_0^L	-1								0.69
V_0^R				-1					0.58
\tilde{V}_0^R								-1	1.03
$V_{1/2}^L$		$+1$							0.49
$V_{1/2}^R$			$+1$				$+1$		1.15
$\tilde{V}_{1/2}^L$						$+1$			1.26
V_1^L	-1				-2				1.42

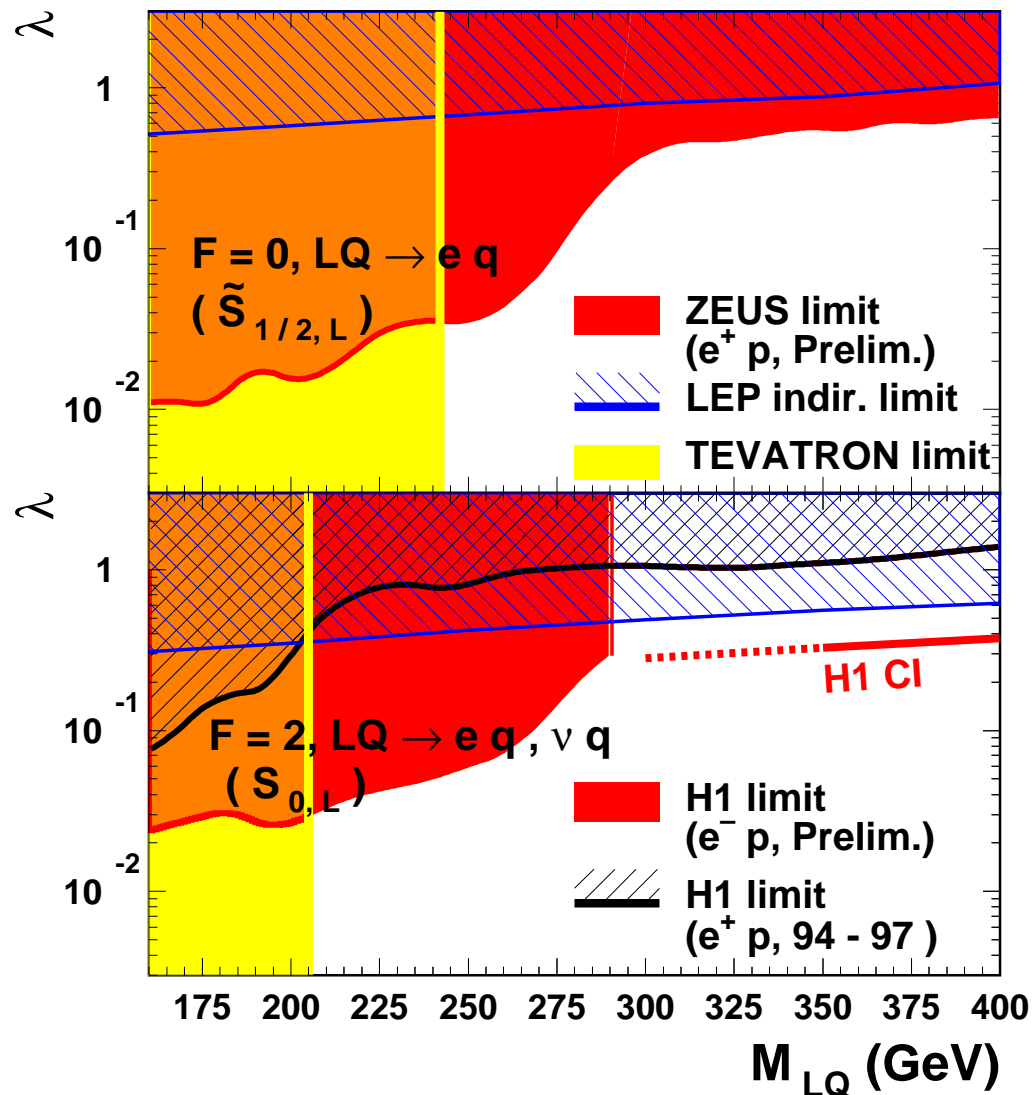
Contact Interactions at LEP



- Limits on effective compositeness scales from 2-fermion final states
- LQ interpretation can be derived for qq final states
- $g = \sqrt{4\pi}$ fixed
- results comparable with those from HERA

Leptoquark Constraints from Direct Searches

Constraints on Scalar Leptoquarks

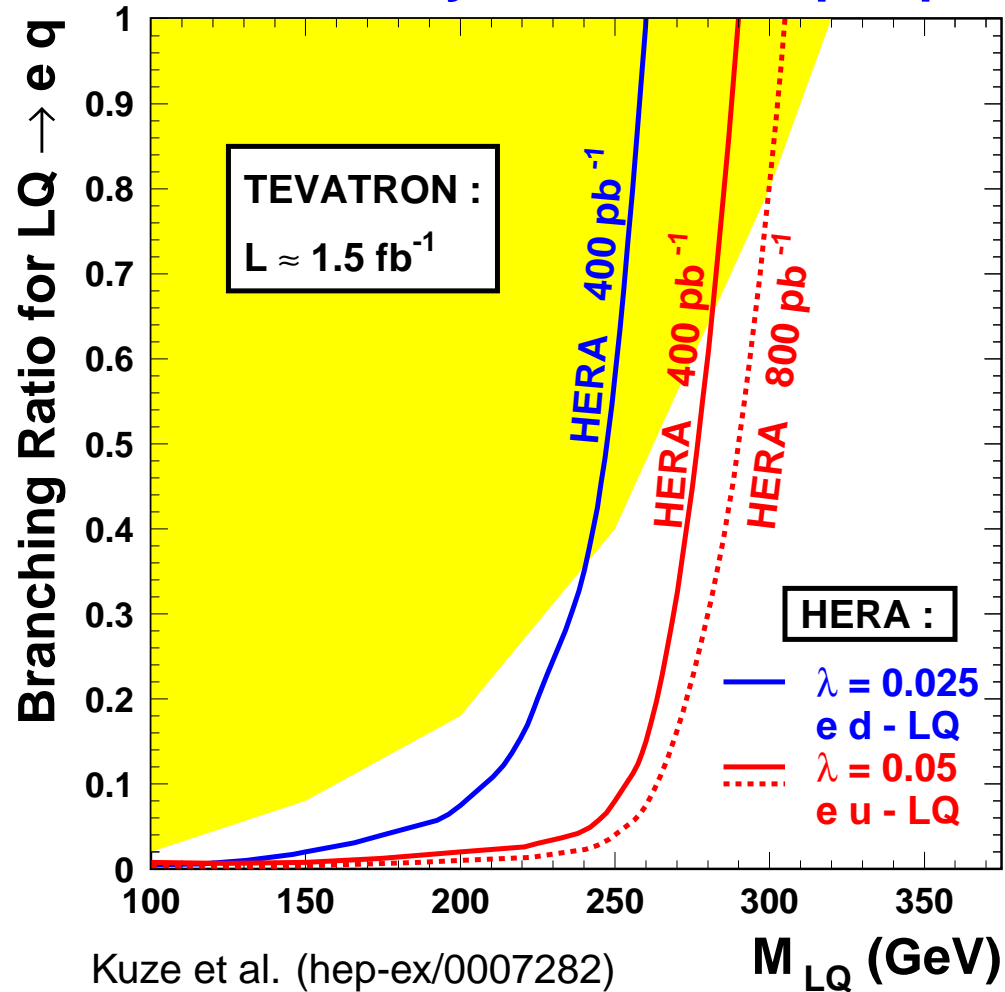


Experimental Summary

- Tevatron limits independent of λ
- HERA testing LQ fermion couplings in the range $0.01-0.1 \alpha_{em}$
- constraints for $m \gtrsim 300$ GeV from contact interactions (LEP, HERA)

Prospects in Leptoquark Searches at HERA

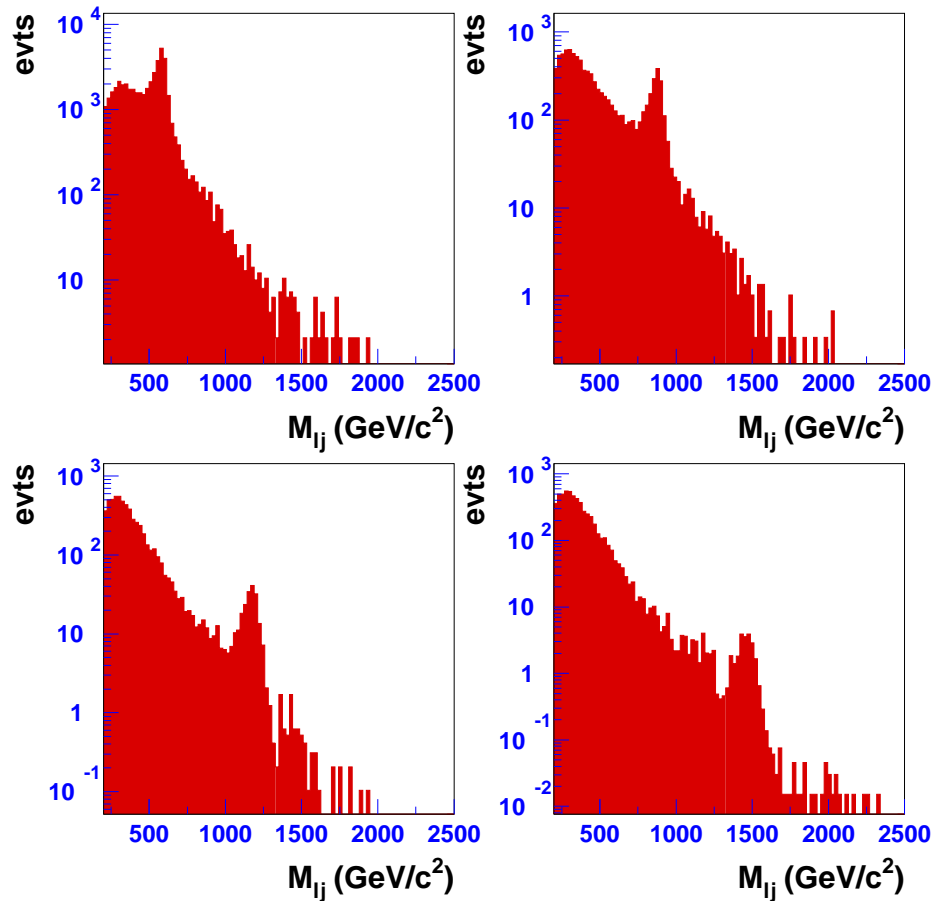
Future Sensitivity on Scalar Leptoquarks



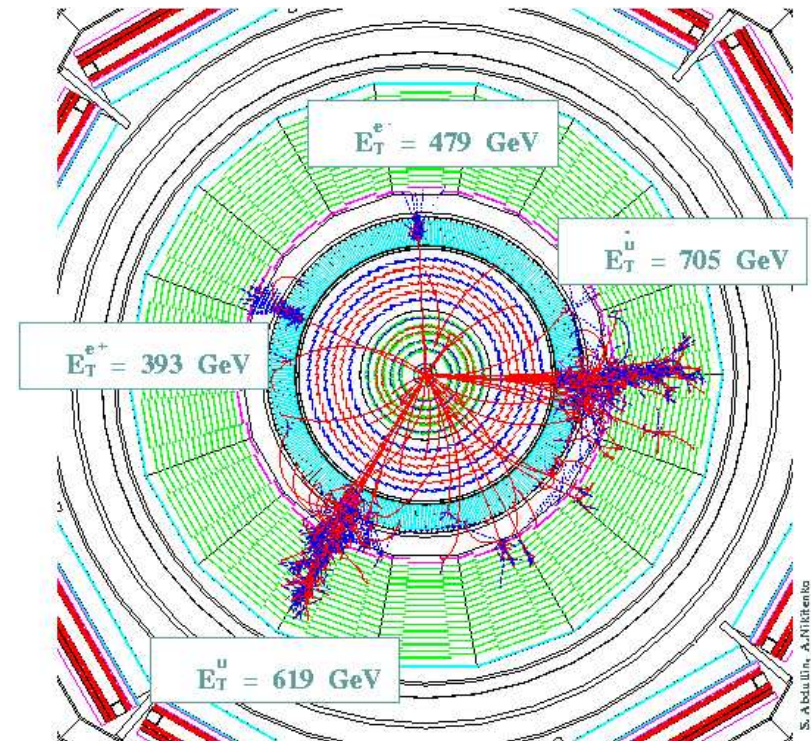
- Anticipate 2 years (400 pb^{-1}) or 4 years (800 pb^{-1}) of HERA II.
- For not too small couplings λ and branching ratios into $eq < 100\%$ HERA has a large potential to discover Leptoquarks

Prospects in Leptoquark Searches at LHC

Simulation study performed for CMS



S.Abdullin, F.Charles (hep-ex/9905396)

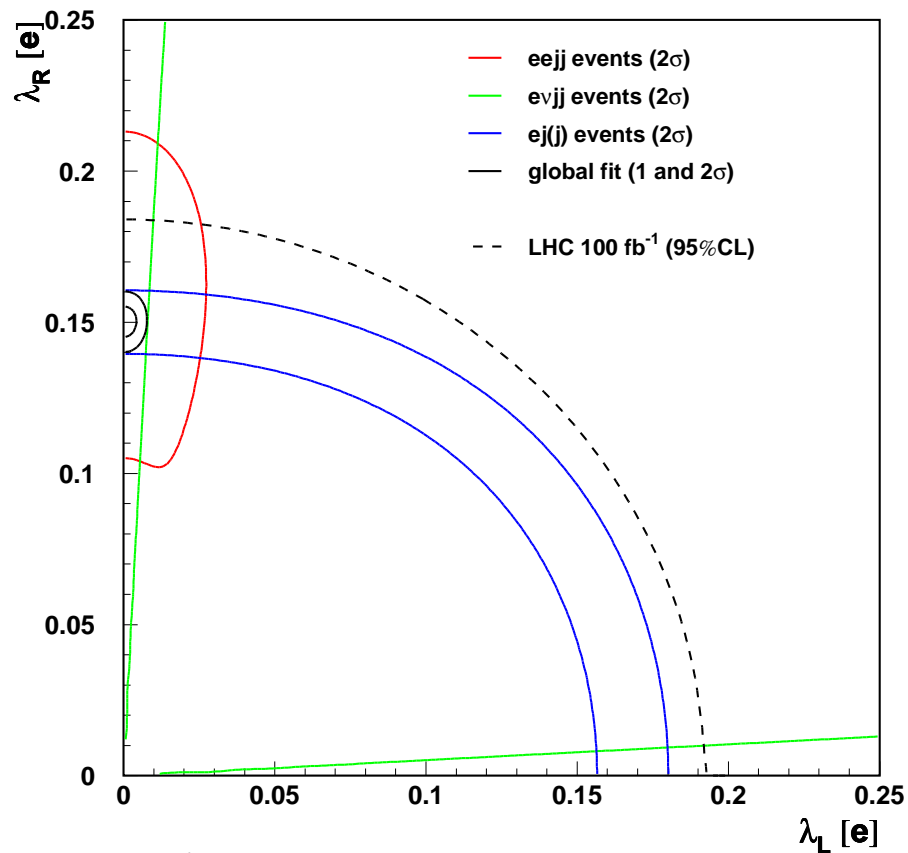


- discovery potential up to 1.5 TeV
- (experimental) mass resolution 30-40 GeV
- not high discriminative power

Prospects in Leptoquark Searches at Tesla

Leptoquark analysis exploiting differential distributions

Example:



F.Żarnecki (hep-ex/0102043)

- generated $S_{1/2}^R$ Leptoquark
- $M_{LQ} = 350 \text{ GeV}$
- $\lambda_R = 0.15e, \lambda_L = 0$
- determination of LQ chiralities using likelihood fits
 - ⇒ couplings measurable on a few percent level
- narrow mass peaks
 - ⇒ different LQ types can be disentangled

Summary

- Leptoquark searches at $pp(\bar{p})$, e^+e^- and ep colliders are complementary – in the **past** and in the (near) **future**
 - ⇒ Tevatron and LHC have highest mass reach
 - ⇒ HERA and e^+e^- colliders able to resolve states and couplings
- However, no real sign for common lepton-quark states
 - ⇒ One of the key questions of the SM on the “nature” of quarks and leptons still puzzling