Search for Leptoquarks

Siena 2001

Seventh Topical Seminar on

“The legacy of LEP and SLC”

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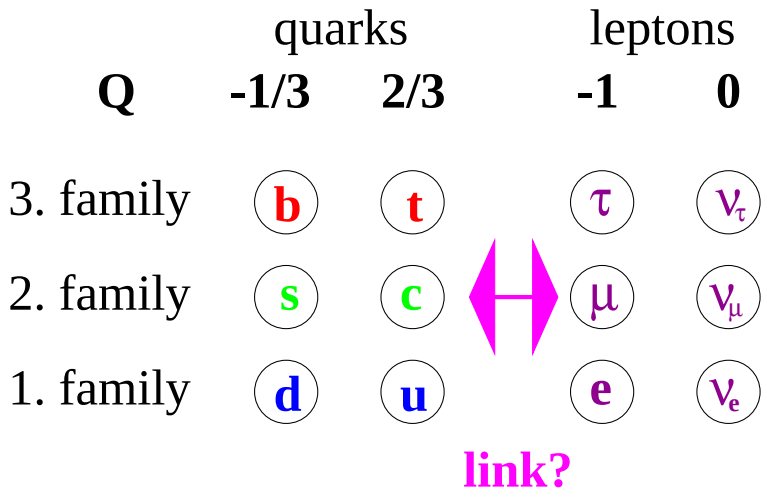
- Introduction
- Direct Searches at Tevatron, LEP and HERA
- Limits from Contact Interaction
- Future Leptoquark Searches (LHC, Tesla)

Leptons and Quarks

- "Mat(t)erialistic view" of the SM:



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)

$\longrightarrow$ Compositeness - why should (unstable) SM particles be fundamental?

- Several Models: Rishons, Haplons, Preons, etc.
- Problem: underlying dynamics unknown

$\longrightarrow$ 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

  $\Rightarrow$ Leptoquark masses might be of electroweak scale $100 - 1000$ GeV

Experimental Hints?

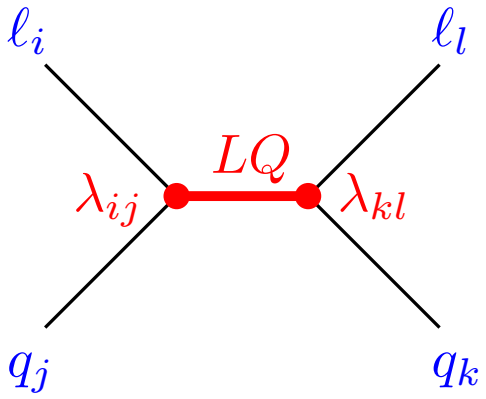
- slight APV in Cesium of $2.3\ \sigma$ (Bennett, Wieman)

  $\Rightarrow$ 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)

  $\Rightarrow$ $2.6\ \sigma$ deviation interpretated 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? $\Rightarrow$ 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: $\Gamma_{S(V)} = \frac{1}{16(24)\pi^2} \lambda^2_{L,R} M \ll 1$ GeV

- Buchm¨uller-R¨uckl-Wyler (BRW) model:

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

- Leptoquark classified: ${}^{Q}J^{L,R}_{I}$

  by spin $J = S, V$, chiral coupling L, R, weak isospin I and electic 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, $\beta\beta$)

  $\Rightarrow$ no diquark couplings

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

  - Quark-lepton universality
  - Atomic Parity Violation
  - Limits from FCNC

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

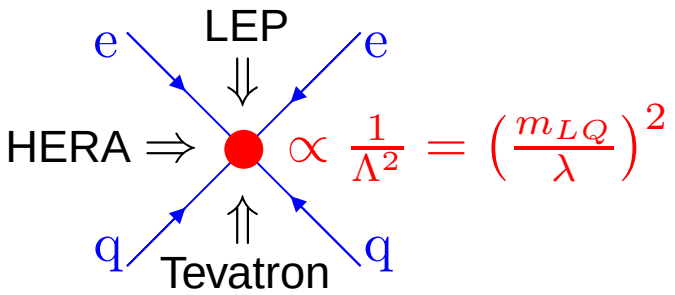
  $\Rightarrow \frac{m_{LQ}}{\lambda_{ij}} \gtrsim 1 - 100$ TeV for $i \neq j$

- Limits from collider experiments (high energies): this talk!
  - direct searches for LQ resonances:

    $\Rightarrow$ limits on m_{LQ}

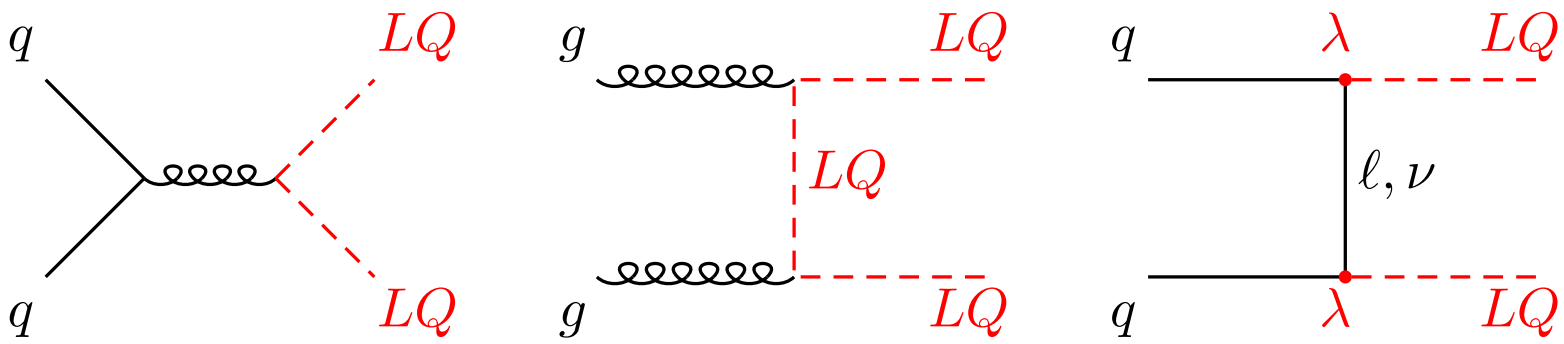
  - four-fermion contact interactions:

    $\Rightarrow$ 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 ($\longrightarrow$ see third diagram)

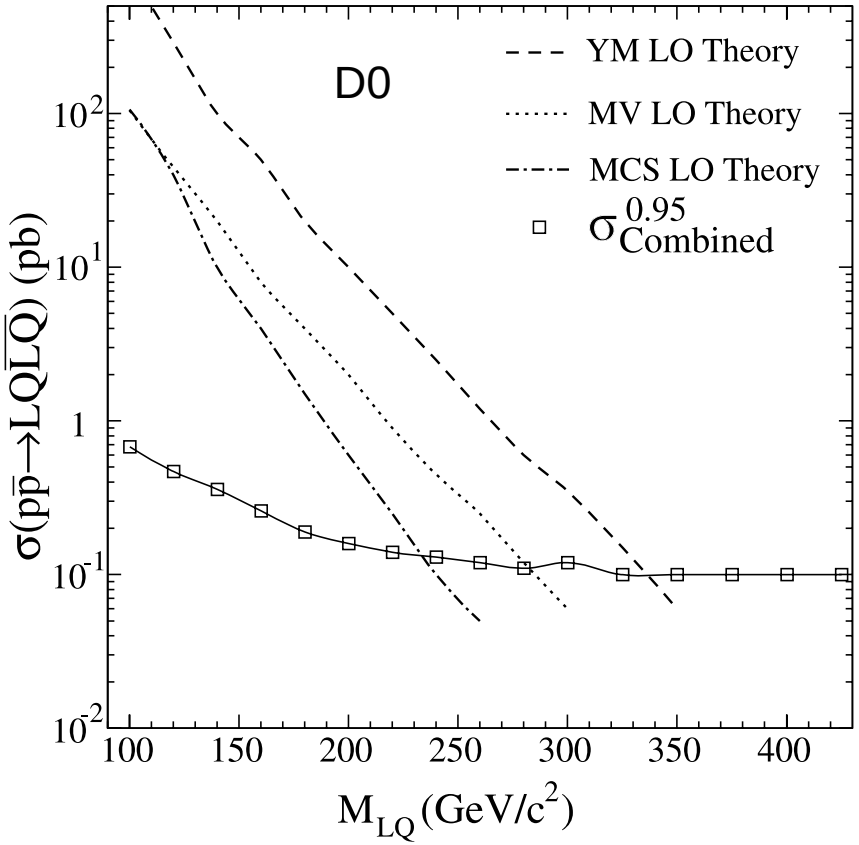
Single production of LQs in $pp(\bar{p})$ collisions:

- High background: $\Rightarrow$ no sensitivity

Search for Leptoquarks at Tevatron I

First generation Vector Leptoquarks:

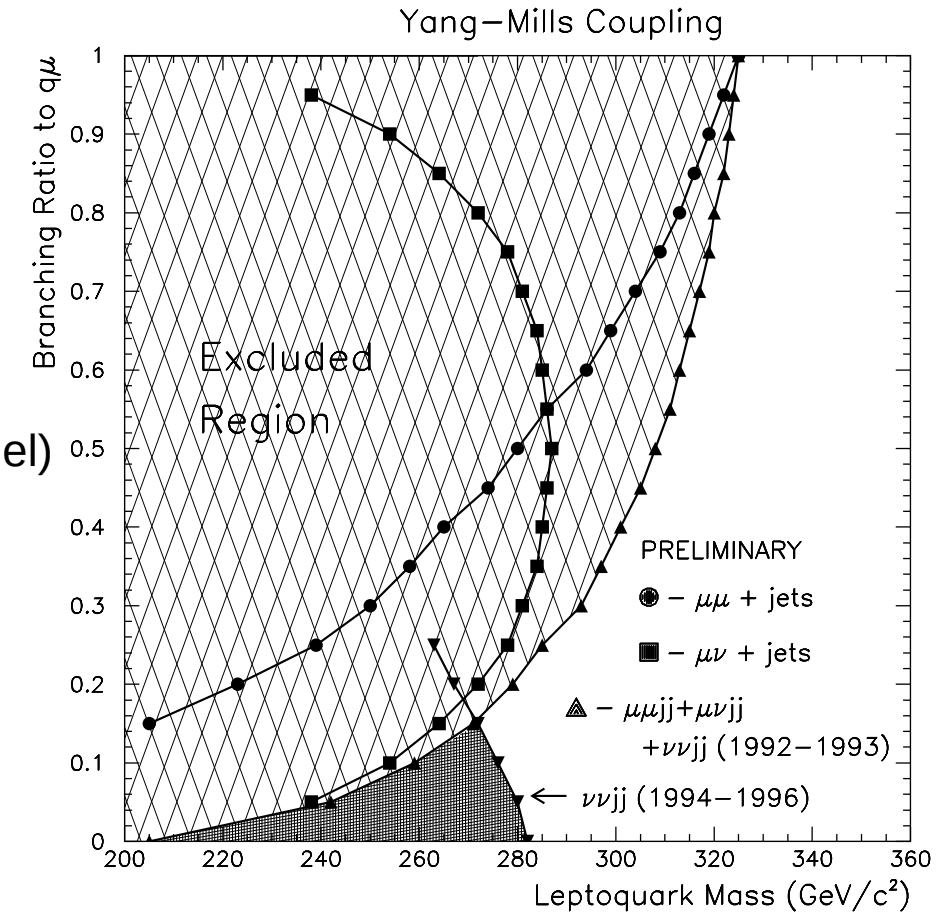
- Consider LQ with BR$(LQ \rightarrow eq)$=1/2
  i.e. $^{-2/3}V_0^L$, $^{-2/3}V_1^L$ (BRW model):
- combination of $eejj$, $e\nu jj$ and $\nu\nu jj$ channels
- expected cross section shown for:
  - minimal cross section
  - minimal vector couplings ($\kappa_G = 1, \lambda_G = 0$)
  - Yang Mills couplings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



Search for Leptoquarks at Tevatron II

Second generation Vector Leptoquarks:

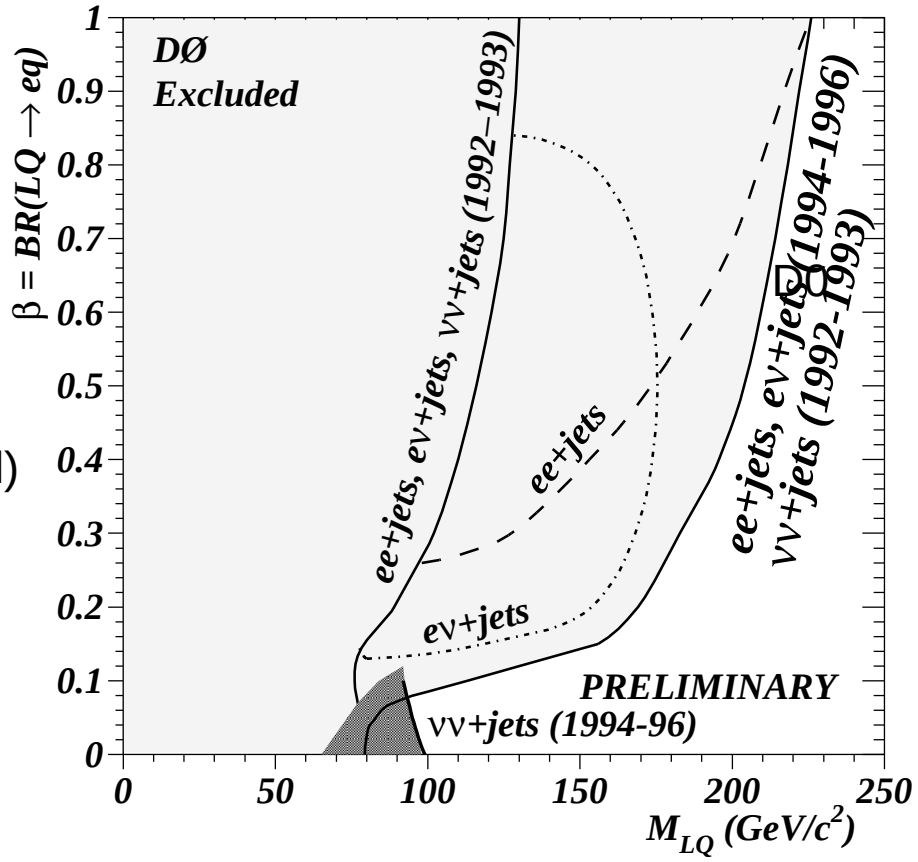
- Allow for arbitrary branching ratios:
  $\mathrm{BR}(LQ \to \mu q,\ \nu q) = 0 - 1$ (general model)
- search for $\mu\mu jj$, $\mu\nu jj$ and $\nu\nu jj$
- combined limits for $\mathrm{BR}(\mu q) + \mathrm{BR}(\nu q) = 1$
- exclusion limits $\approx 270 - 320$ GeV for
  Y.M. couplings depending on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



Search for Leptoquarks at Tevatron III

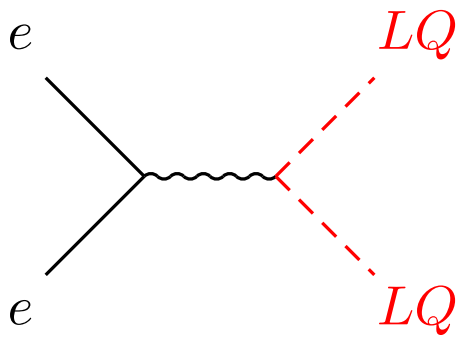
First generation Scalar Leptoquarks:

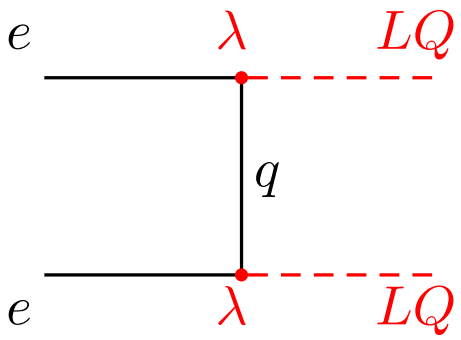
- Allow for arbitrary branching ratios:
  $\mathrm{BR}(LQ \to eq,\ \nu q) = 0 - 1$ (general model)
- search for $eejj$, $e\nu jj$ and $\nu\nu jj$
- combined limits for $\mathrm{BR}(eq) + \mathrm{BR}(\nu q) = 1$
- exclusion limits $\approx 90 - 220$ GeV
  depending on branching ratio

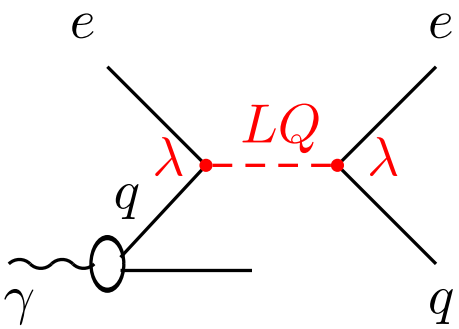


B. Direct Production of Leptoquarks at Colliders

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







Pair production:

- LQ types: test specific electroweak coulings
- 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

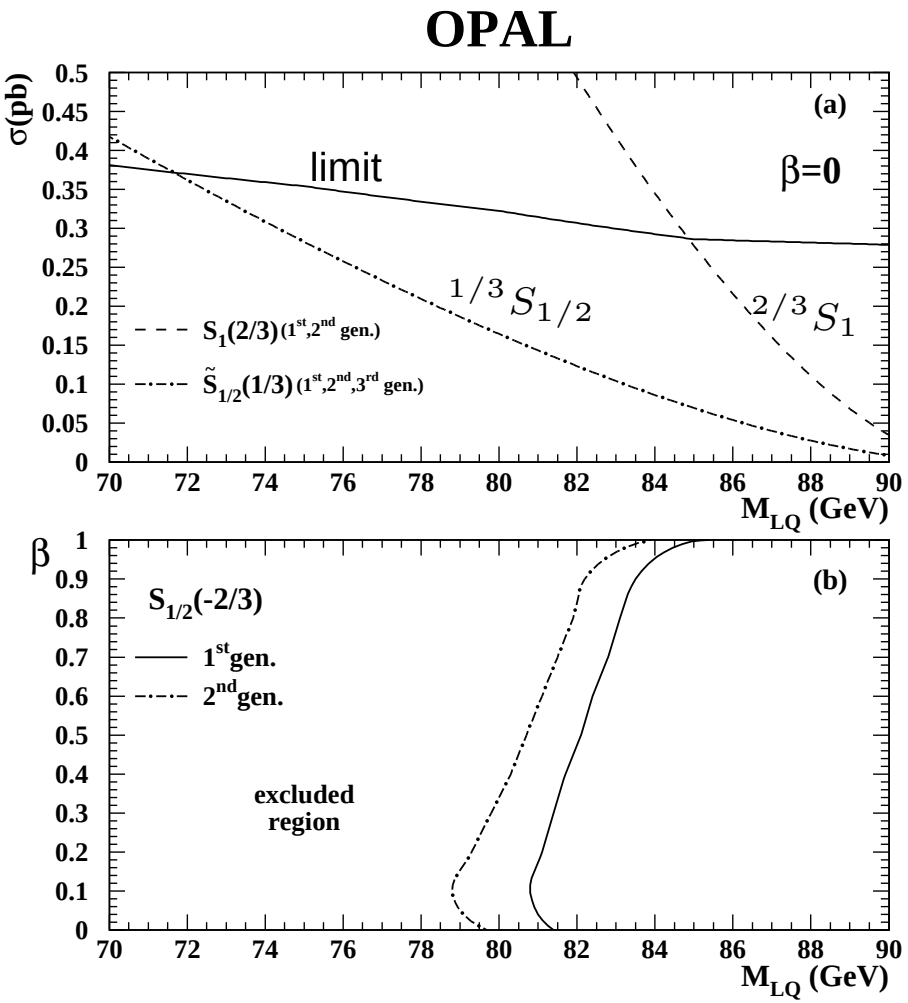
LEP I:

- 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}(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 $LQ \to \nu q$ set by OPAL for all generations up to 85 GeV (for $^{2/3}S_1$)

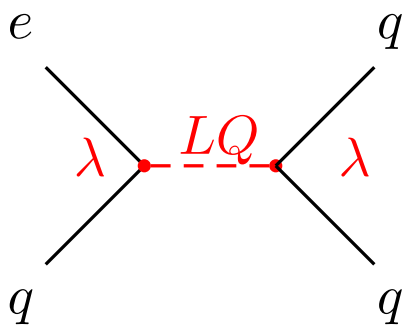
$\Rightarrow$ potential for improving limits $\to$ 206 GeV data



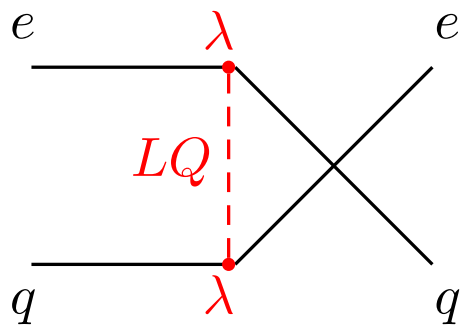
C. Direct Production of Leptoquarks at Colliders

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

s-channel



u-channel



Pair production:

- negligible: direct or resolved process

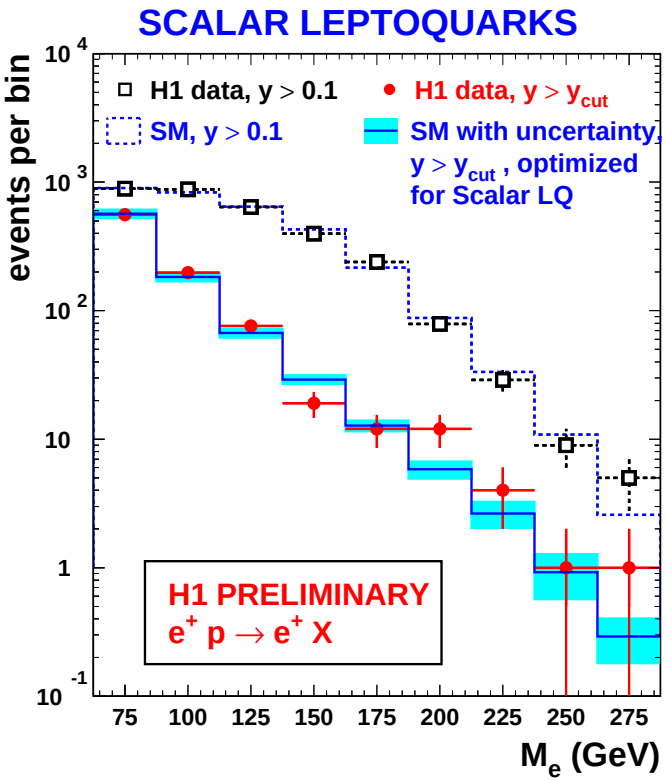
Single production:

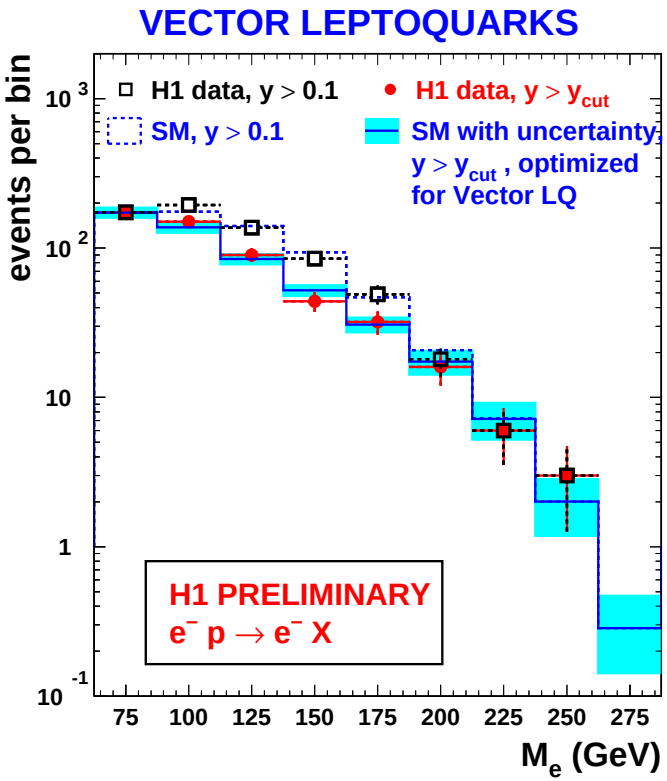
- Yukawa couplings: directly testing eq fermion coupling $\longrightarrow$ high sensitivity on λ
- LQ types: couplings tested by exploiting
  - beam charge $e^{\pm}$
  - longitudinal polarisation (HERA II)
  - angular distributions

Leptoquark Search at HERA I

Search for eq resonances:

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



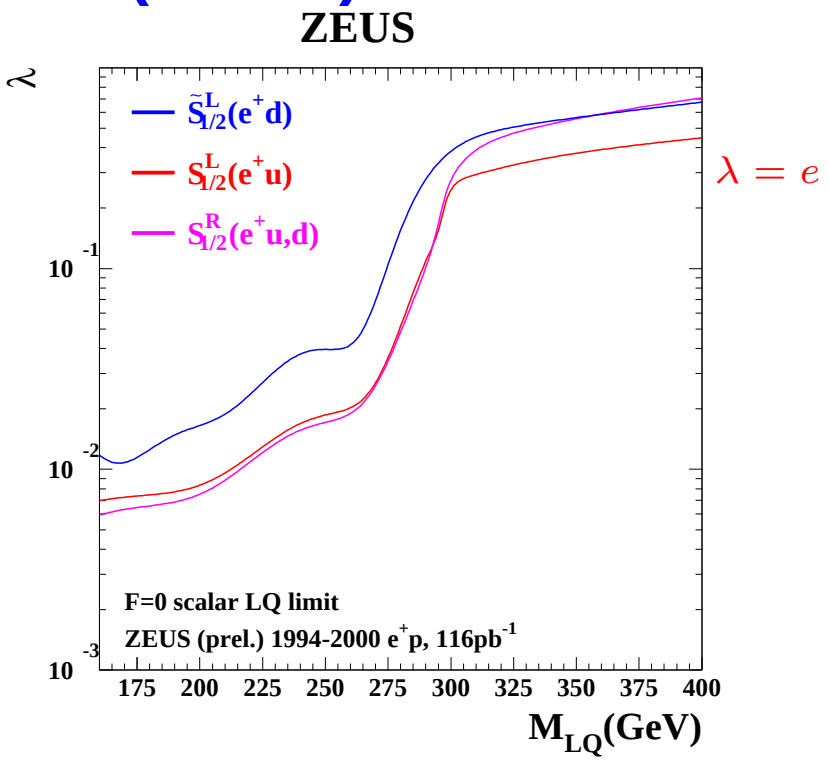


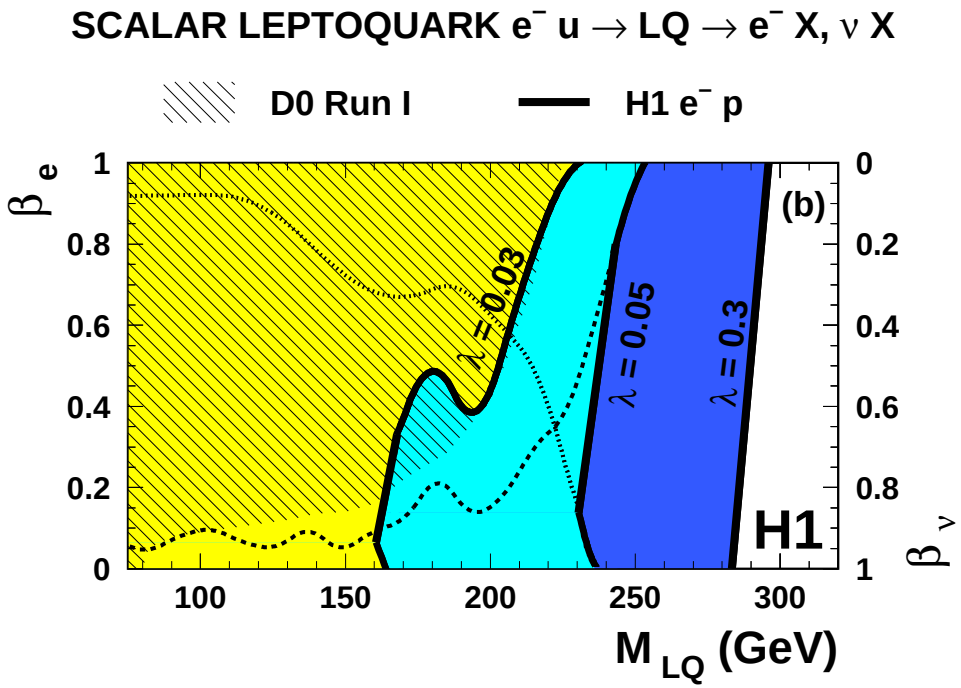
- excess of events at $m \approx 200$ GeV not confirmed by H1
- similar results were obtained by ZEUS

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:
  $\sqrt{s} \approx 314$ GeV
- for $\lambda = e$ LQs excluded up to HERAs cms energy





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

Contact Interactions

- Effective Lagrangian

  (considering only vector-type terms)

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

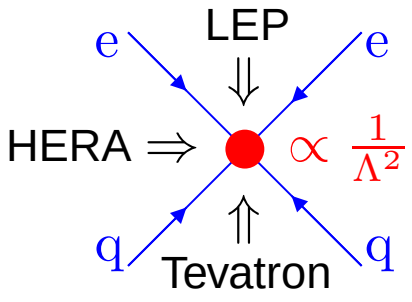
model: $\eta^q_{ab} = \epsilon (\frac{g}{\Lambda^q_{ab}})^2$

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

Λ effective mass scale

g coupling strength

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



⇒ testing new physics above the collider energy

at high scales, for example Q^2

- considering proper LQ couplings

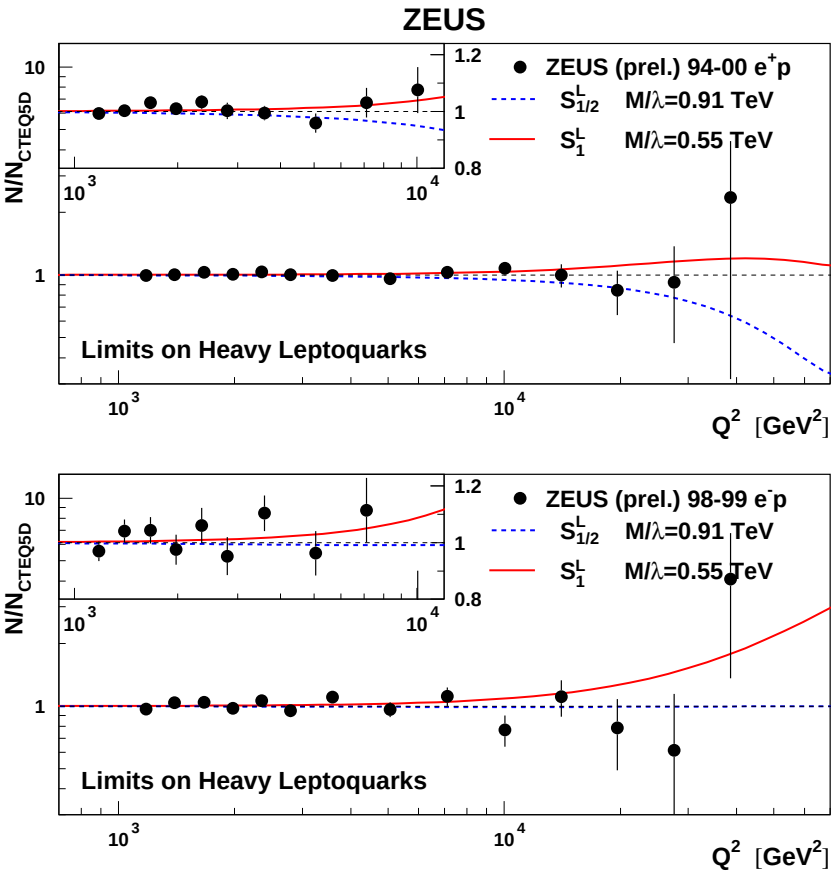
  ⇒ access to Leptoquarks

Contact Interactions at HERA

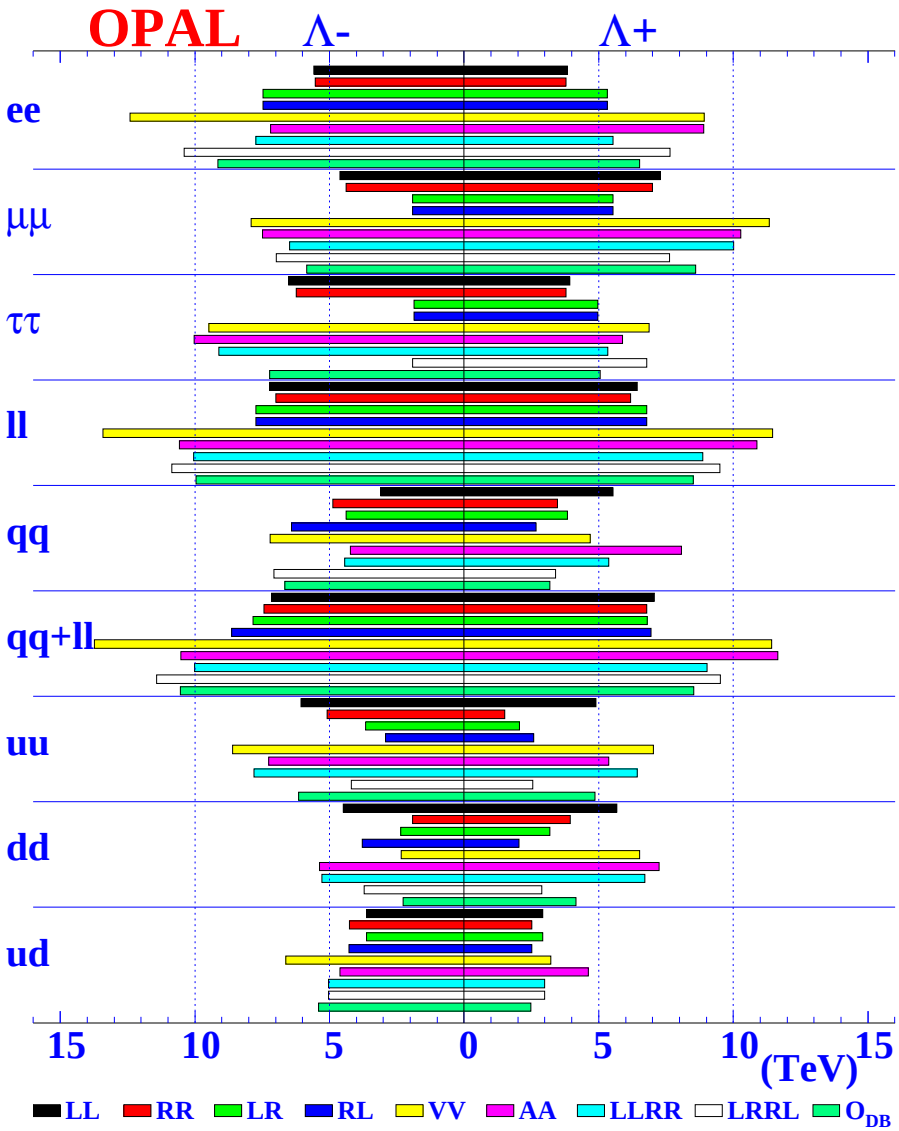
- measure Q^2 distribution of NC events and fit LQ hypothesis
- limits set on the ratio $M/\lambda \quad (= \Lambda/g)$
- LQ exclusion limits up to 0.3-1.4 TeV set

ZEUS (prel.) 1994-2000 $e^{\pm}p$

Model	Coupling structure a^{ed}_{LL}	a^{ed}_{LR}	a^{ed}_{RL}	a^{ed}_{RR}	a^{eu}_{LL}	a^{eu}_{LR}	a^{eu}_{RL}	a^{eu}_{RR}	95% CL [TeV] M_{LQ}/λ_{LQ}
S^L_0					$+\frac{1}{2}$				0.75
S^R_0								$+\frac{1}{2}$	0.69
$\tilde{S}^R_0$				$+\frac{1}{2}$					0.31
$S^L_{1/2}$						$-\frac{1}{2}$			0.91
$S^R_{1/2}$			$-\frac{1}{2}$				$-\frac{1}{2}$		0.69
$\tilde{S}^L_{1/2}$		$-\frac{1}{2}$							0.50
S^L_1	$+1$				$+\frac{1}{2}$				0.55
V^L_0	-1								0.69
V^R_0				-1					0.58
$\tilde{V}^R_0$								-1	1.03
$V^L_{1/2}$		$+1$							0.49
$V^R_{1/2}$			$+1$				$+1$		1.15
$\tilde{V}^L_{1/2}$						$+1$			1.26
V^L_1	-1				-2				1.42



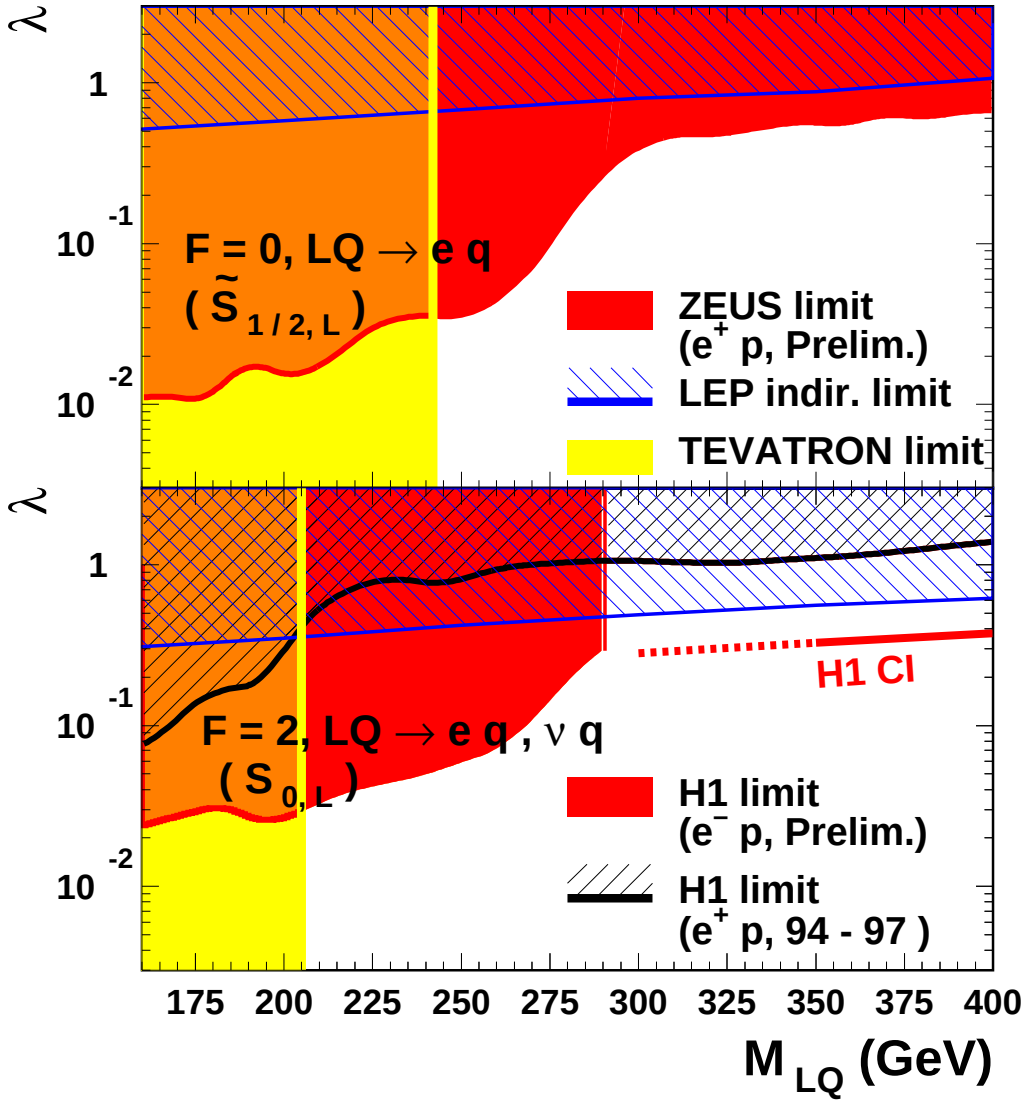
Contact Interactions at LEP



- 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

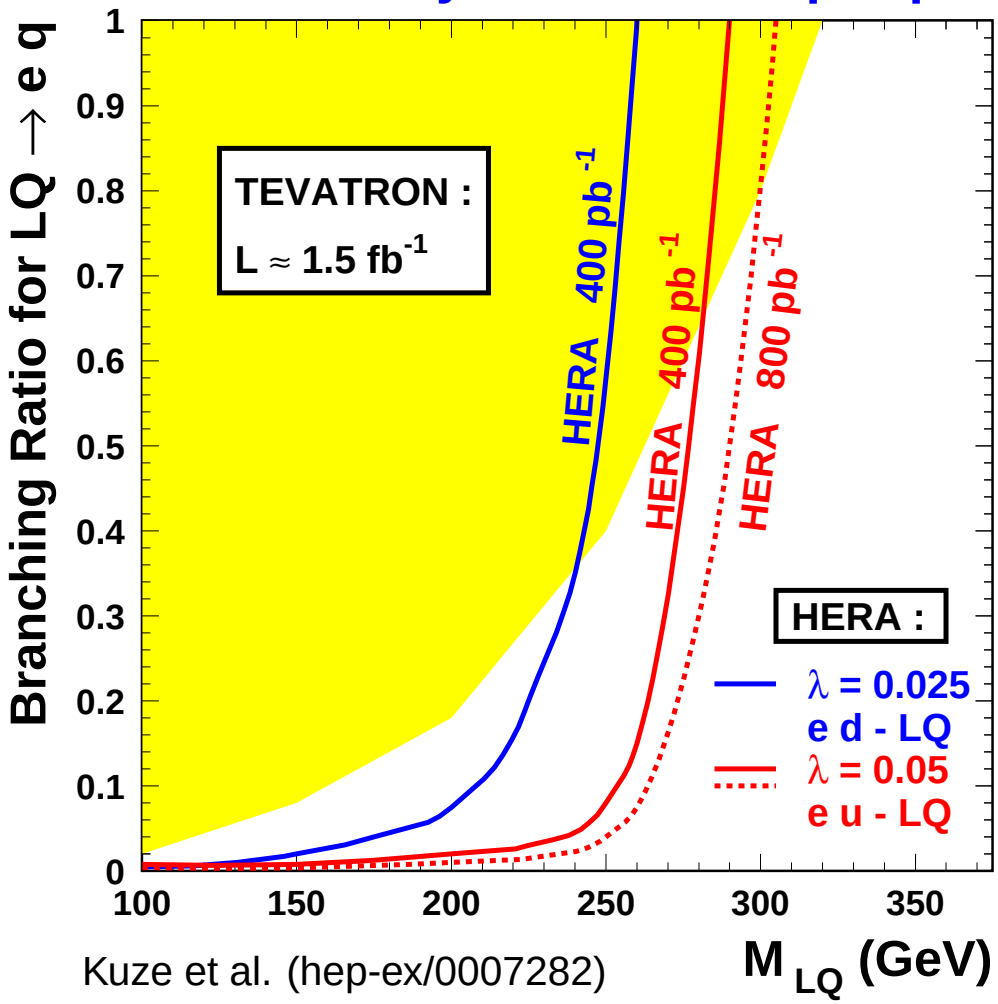


Experimental Summary

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

Prospects in Leptoquark Searches at HERA

Future Sensitivity on Scalar Leptoquarks

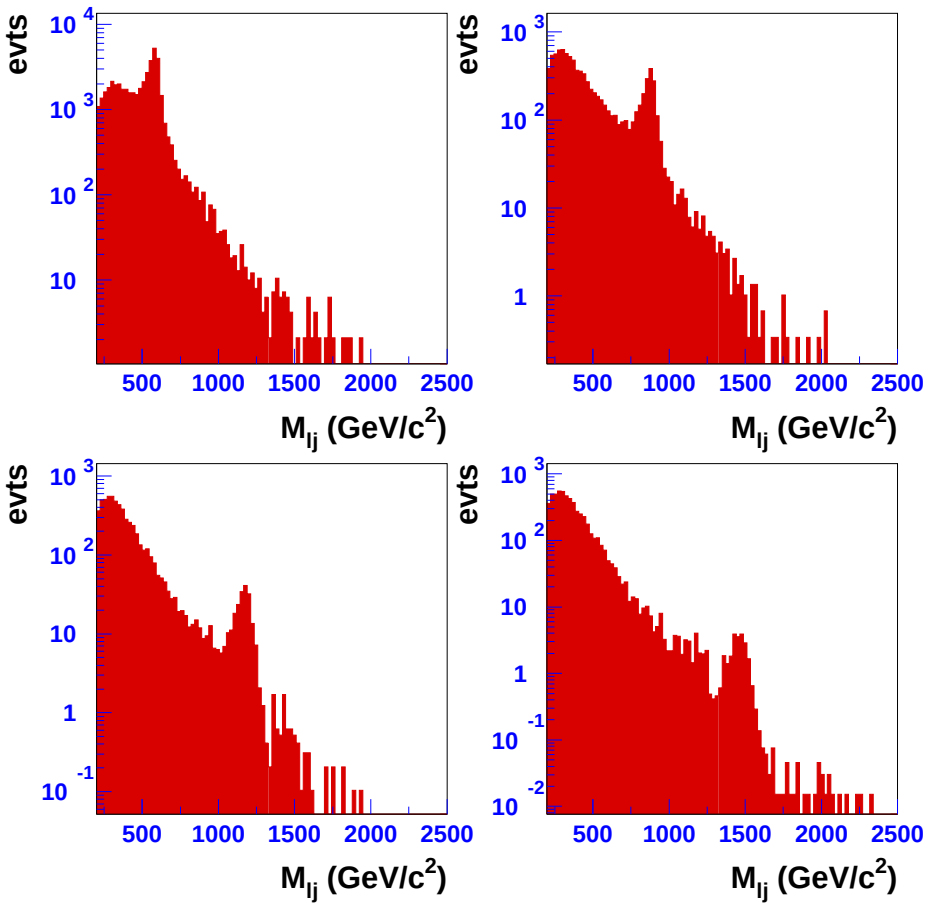


Kuze et al. (hep-ex/0007282)

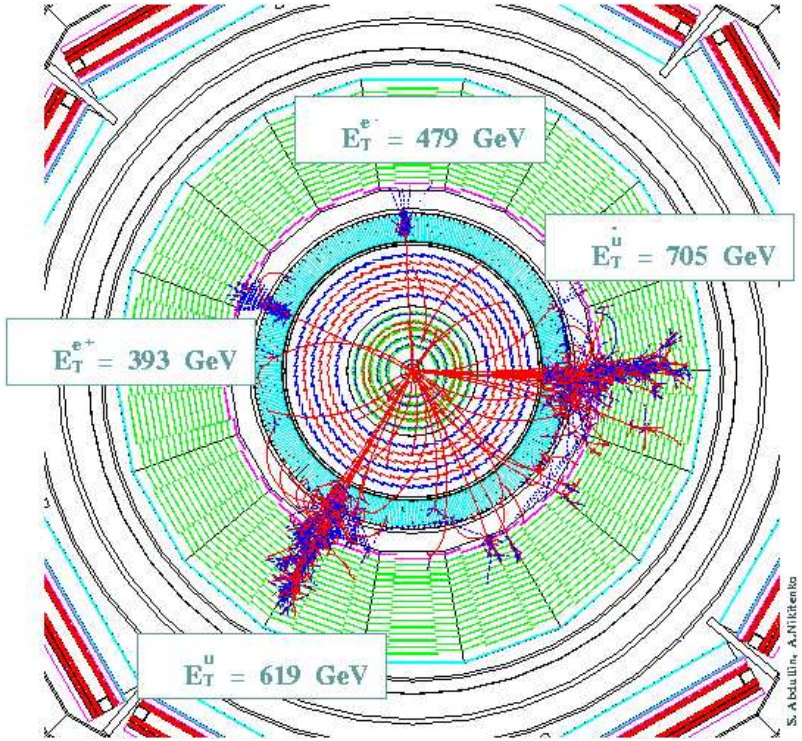
- Anticipate 2 years (400pb^{-1}) or 4 years (800 pb^{-1}) of HERA II.
- For not too small couplings λ and branching ratios into $eq < 100\%$ HERA has a large potential to discover Leptoquarks

Prospects in Leptoquark Searches at LHC

Simulation study performed for CMS



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

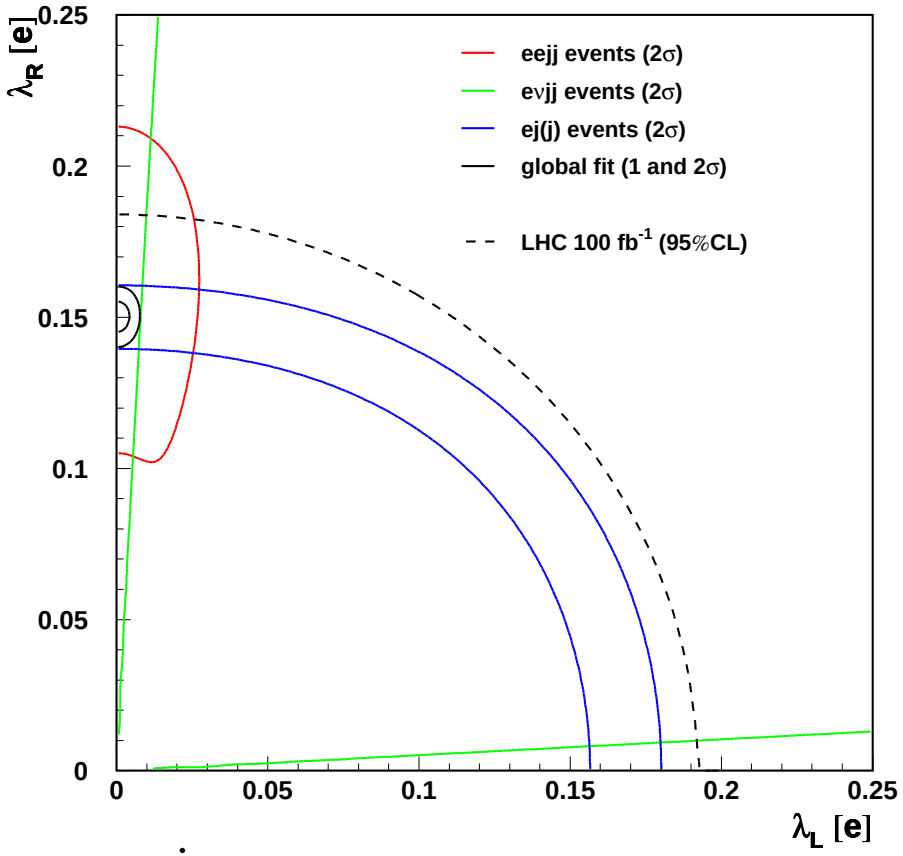


- discovery potential up to 1.5 TeV
- (experimental) mass resolution 30-40 GeV
- not high discriminative power

Prospects in Leptoquark Searches at Tesla

Leptoquark analysis exploiting differential distributions

Example:



F.Żarnecki (hep-ex/0102043)

- generated $S^R_{1/2}$ Leptoquark
- $M_{LQ} = 350$ GeV
- $\lambda_R = 0.15e$, $\lambda_L = 0$

- determination of LQ chiralities using likelihood fits

$\Rightarrow$ couplings measurable on a few percent level

- narrow mass peaks

$\Rightarrow$ 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

  $\Rightarrow$ Tevatron and LHC have highest mass reach

  $\Rightarrow$ HERA and e^+e^- colliders able to resolve states and couplings

- However, no real sign for common lepton-quark states

  $\Rightarrow$ One of the key questions of the SM on the "nature" of quarks and leptons still puzzling