Minireview on Leptoquarks at HERA, LEP and the Tevatron

Bruce Straub
Yale University

- Introduction
- OPAL limits from $e\gamma -> LQ + q$
- OPAL limits on LQ pair production
- HERA LQ Search
- eeqq Contact Interactions
- H1 Limits on Contact Interaction
- L3 indirect LQ limits
- LEP comb. LQ limits, 2nd+3rd gen Quarks
- Lepton Flavor Violation
- Summary
- Future

Introduction to Leptoquarks

Leptoquarks are color triplet bosons with spin zero or one and with $L \neq 0$ and $B \neq 0$.

Partial widths:
$(\lambda^2/16\pi)M_{\rm LQ}$ for spin zero
$(\lambda^2/24\pi)M_{\rm LQ}$ for spin one

Scalar LQs decay isotropically
Vector LQs decay $\sim (1+\cos\theta^*)^2$

Buchmuller, Rückl, Wyler model

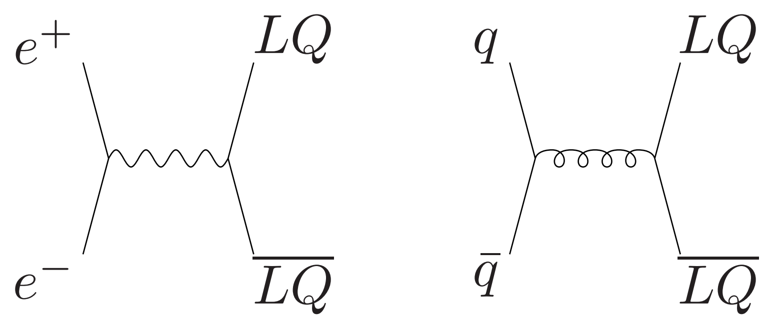
Dimensionless chiral coupling(s) λ_L, λ_R are $SU(3)\times SU(2)\times U(1)$ invariant.

10 LQ species, 4 of which *could* couple to both λ_L and λ_R, but LQ mediated rare π and K decays are not seen $\Rightarrow$ $\lambda_L\lambda_R << (M_{\rm LQ}/10$ TeV$)$ So assume either $\lambda_L = 0$ or $\lambda_R = 0$.

F	spin	species
2	0	$S_{0,L}$; $S_{0,R}$; $\tilde{S}_{0,R}$; $S_{1,L}$
2	1	$V_{1/2,L}$; $V_{1/2,R}$; $\tilde{V}_{1/2,L}$
0	0	$S_{1/2,L}$; $S_{1/2,R}$; $\tilde{S}_{1/2,L}$
0	1	$V_{0,L}$; $V_{0,R}$; $\tilde{V}_{0,R}$; $V_{1,L}$

labeled by weak isospin and lepton helicity.

Pair Production



λ not needed! (except to decay the LQ)

LQ may couple to any flavor q, ℓ

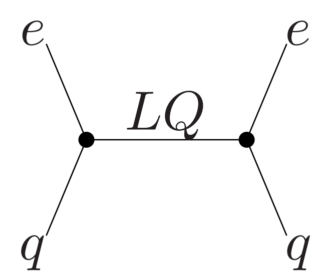
e^+e^- limits: $M_{\rm LQ} > \sqrt{s}/2$

Tevatron scalar $M_{\rm LQ}$ limits

gen	β_ℓ	signal	CDF	D0
1	1	$eeqq$	242 GeV	
1	0	$\nu\nu qq$		98 GeV
2	1	$\mu\mu qq$	202 GeV	200 GeV
2	0	$\nu\nu cc$	123 GeV	98 GeV
3	1	$\tau\tau bb$	99 GeV	
3	0	$\nu\nu bb$	148 GeV	94 GeV

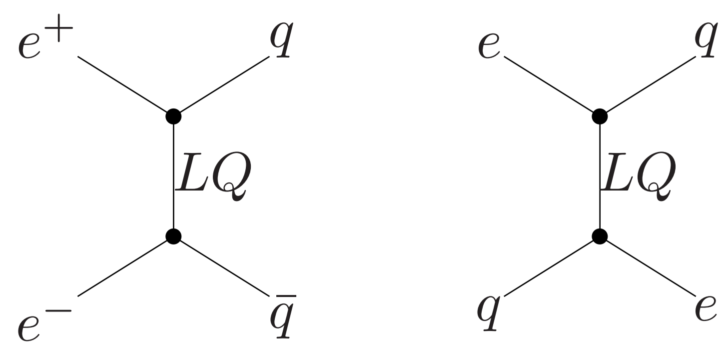
β_ℓ = BR to charged lepton

Resonant Production



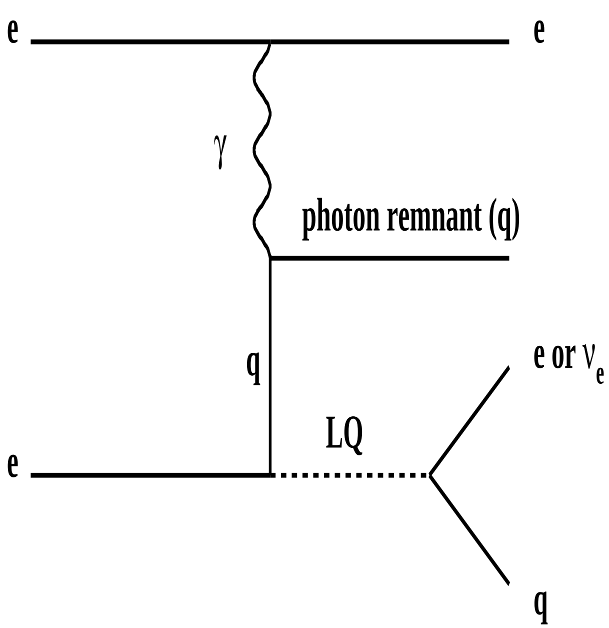
cross sect.$\sim \lambda^2$

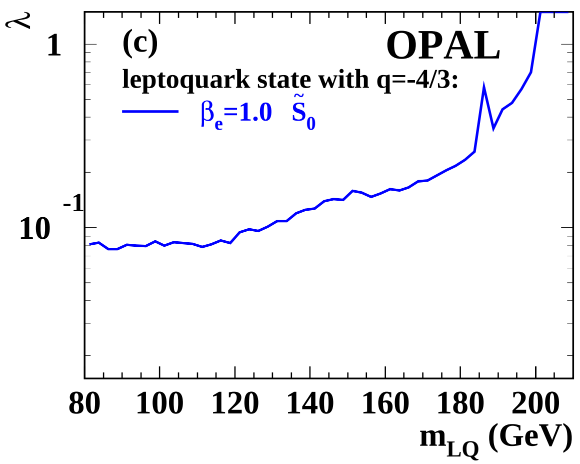
t- and u-Channel

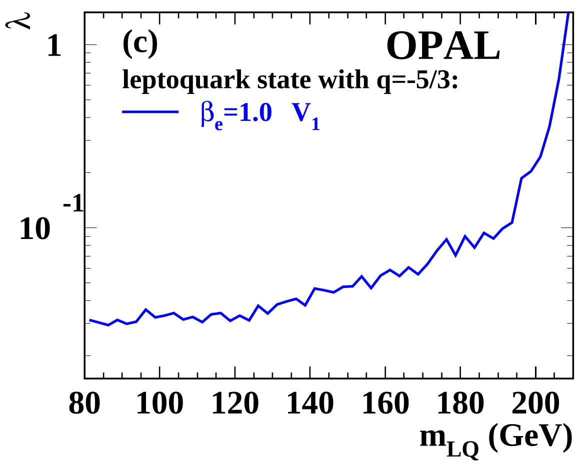


Sensitive for $M_{\rm LQ} > \sqrt{s}$

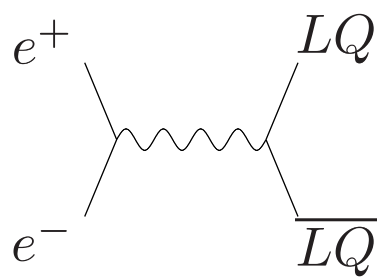
OPAL: $e\gamma \rightarrow LQ + X$ (#309)







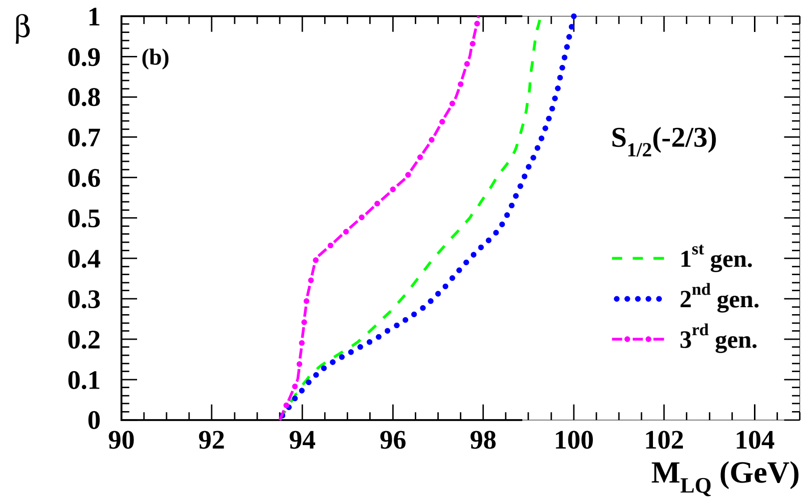
OPAL: LQ pair production (#516)

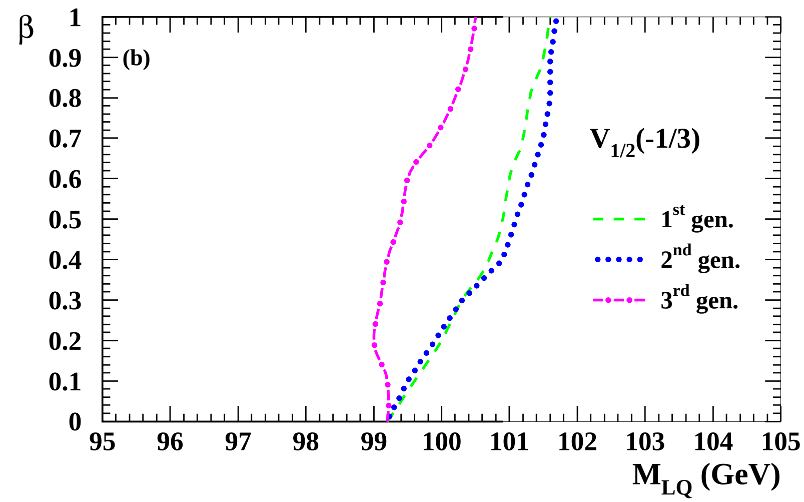


$\sqrt{s}$ between 189 and 209 GeV
$\mathcal{L} = 596\,\mathrm{pb}^{-1}$

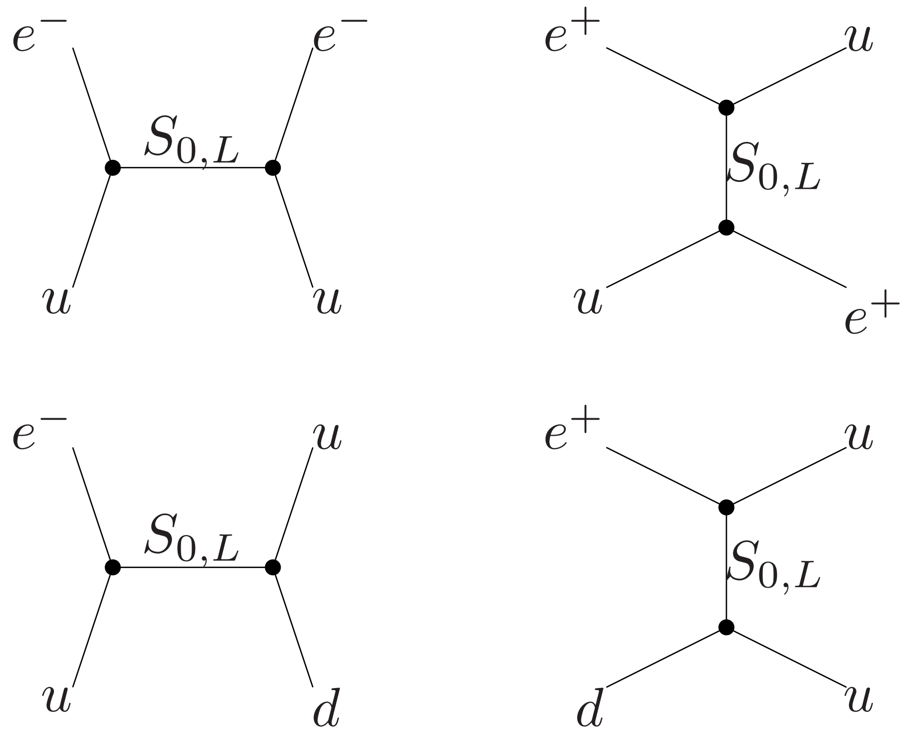
consider $q\bar{q}\nu\bar{\nu}$, $q\bar{q}\ell\bar{\nu}$, $q\bar{q}\ell^+\ell^-$
$\ell = e$ or μ or τ
$q = u, d, c, s, b$

$\beta = BR(LQ \rightarrow \ell q)$
sensitive to LQs which couple only to νq





LQ Search at HERA ep Collider



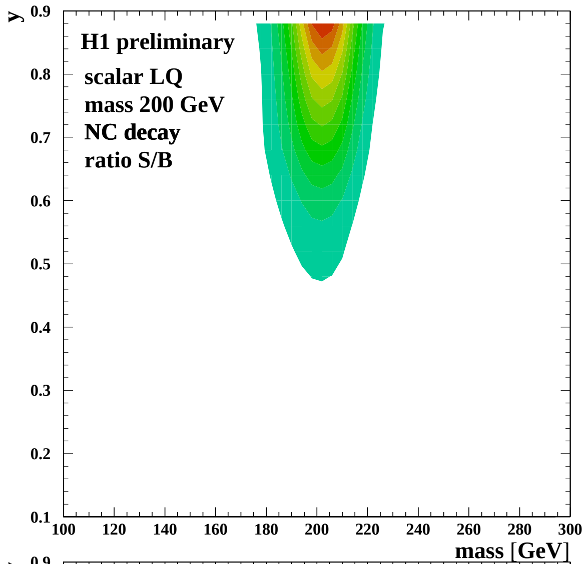
Sensitive in up to 4 channels
u-channel helps for $M_{\mathrm{LQ}} \gtrsim \sqrt{s}$

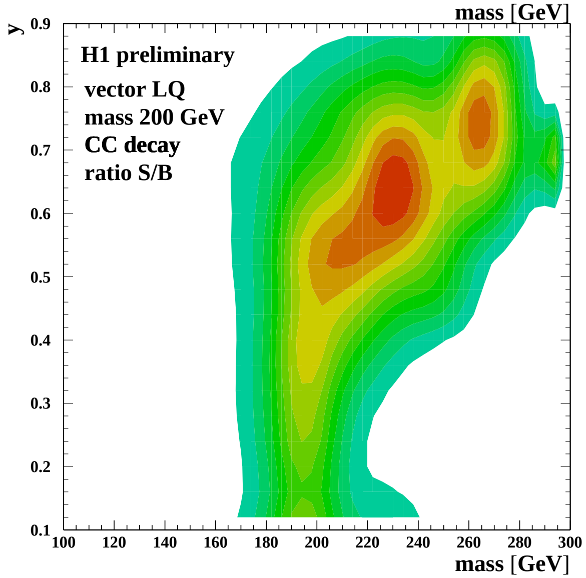
Use both NC (eq) and CC (νq) data for LQ search.

$\sqrt{s}$ = 300 and 318 GeV

e^+p	e^-p	
$115\,\mathrm{pb}^{-1}$	$17\,\mathrm{pb}^{-1}$	ZEUS
$102\,\mathrm{pb}^{-1}$	$15\,\mathrm{pb}^{-1}$	H1

H1 and ZEUS LQ Search





Search over 2-dimensional distribution

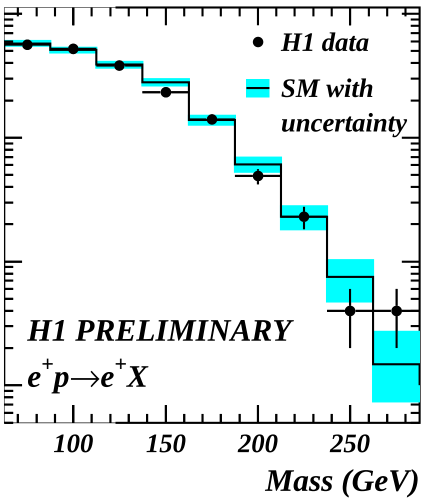
H1: (mass, y)

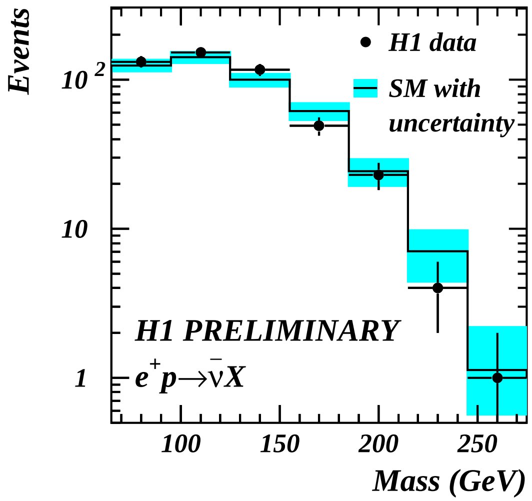
ZEUS: $(\mathrm{mass}, \cos\theta^*)$

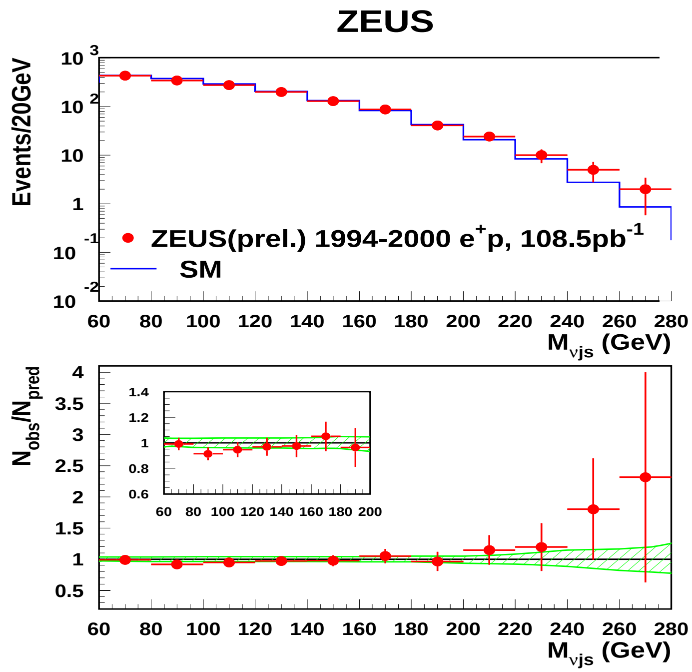
$\theta^* = e$ scattering angle

$y = (1 - \cos\theta^*)/2$

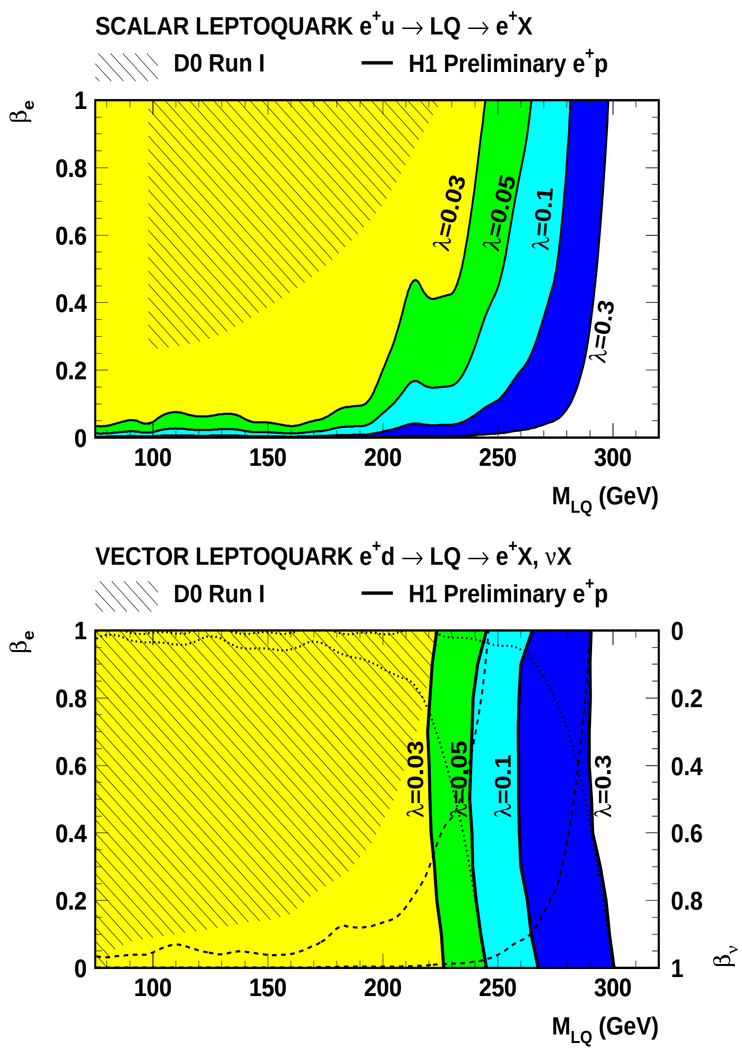
H1 and ZEUS Mass Spectra

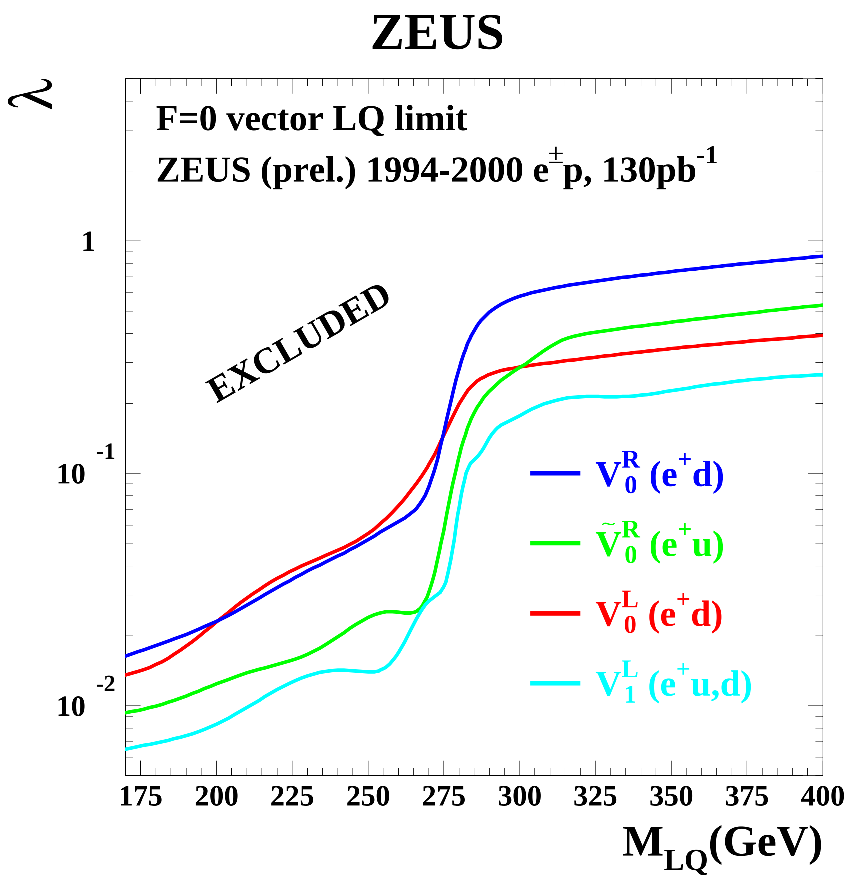




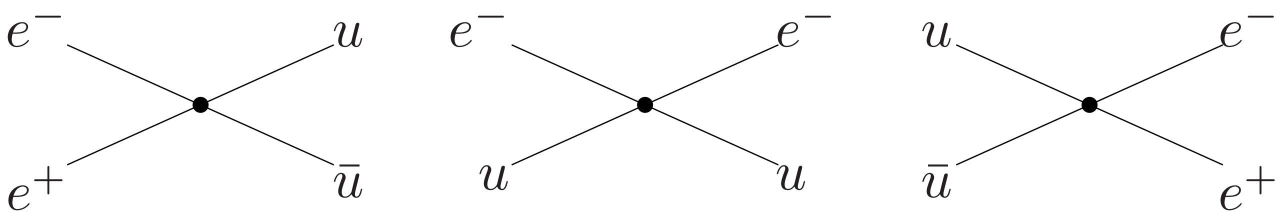


H1, D0 Limits in (M, β_e) for several λ's





4-Fermion Contact Interactions

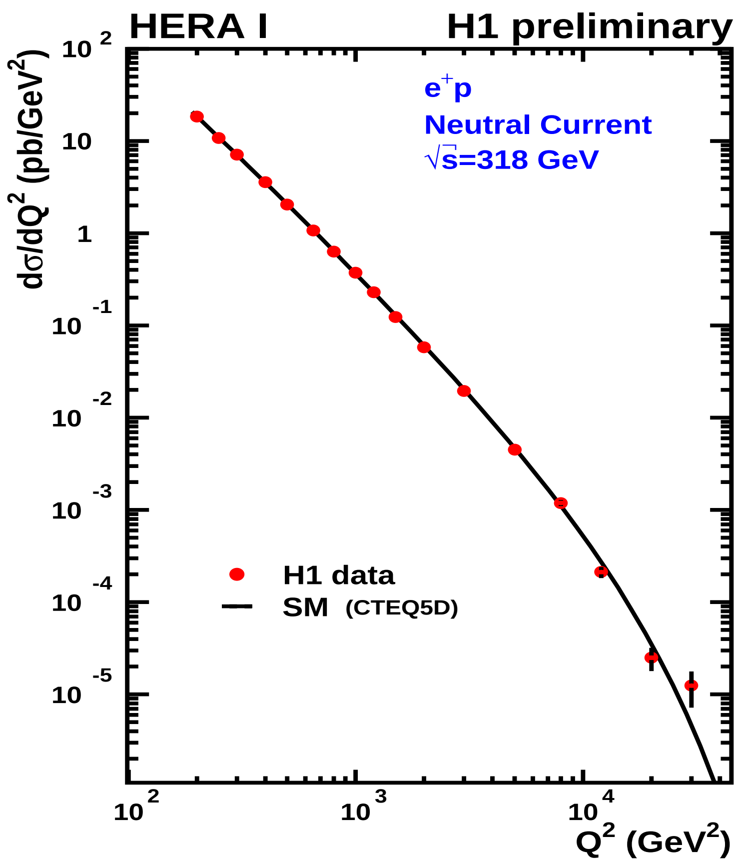


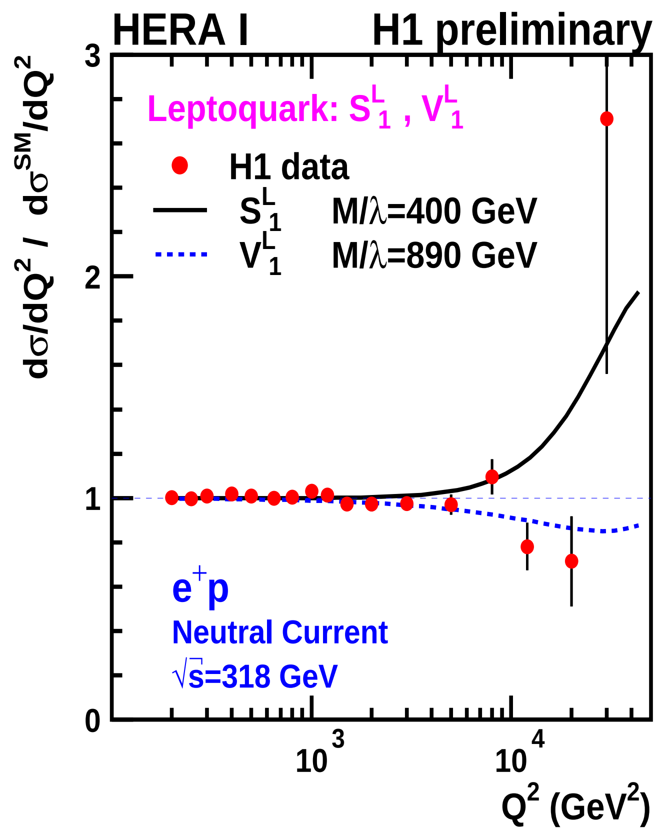
$$\mathcal{L} = \frac{4\pi}{\Lambda^2} \sum_{q=u,d} \sum_{\alpha=L,R} \sum_{\beta=L,R} \eta^{eq}_{\alpha\beta} (\overline{e}_\alpha \gamma^\mu e_\alpha)(\overline{q}_\beta \gamma_\mu q_\beta)$$

The $\eta^{eq}_{\alpha\beta}$ define a contact int. Some combinations represent leptoquarks.

LQ	η^{ed}_{LL}	η^{ed}_{LR}	η^{ed}_{RL}	η^{ed}_{RR}	η^{eu}_{LL}	η^{eu}_{LR}	η^{eu}_{RL}	η^{eu}_{RR}
S^L_0					$+\frac{1}{2}$			
S^R_0								$+\frac{1}{2}$
$\tilde{S}^R_0$				$+\frac{1}{2}$				
$S^L_{1/2}$						$-\frac{1}{2}$		
$S^R_{1/2}$			$-\frac{1}{2}$				$-\frac{1}{2}$	
$\tilde{S}^L_{1/2}$		$-\frac{1}{2}$						
S^L_1	$+1$				$+\frac{1}{2}$			

H1 Contact Interaction Limits

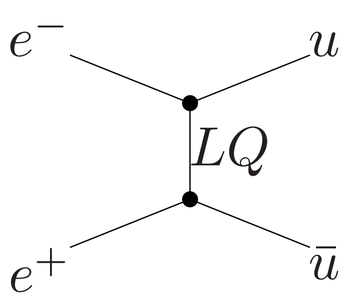




Curves show models ruled out at 95% CL

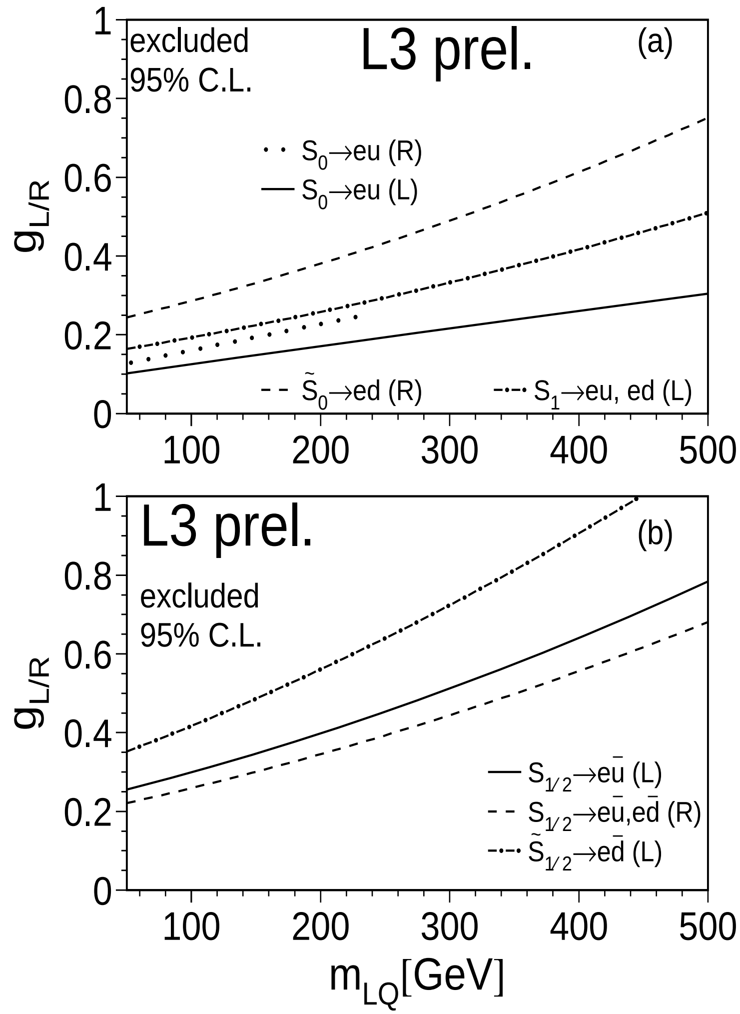
Contact Interactions are flat in $\frac{d\sigma}{dQ^2}$ (Interference with SM$\sim \frac{1}{Q^2}$)

L3 indirect LQ limits (#462)



$\sqrt{s}$ from 130 to 209 GeV
$\mathcal{L} = 705\,\mathrm{pb}^{-1}$

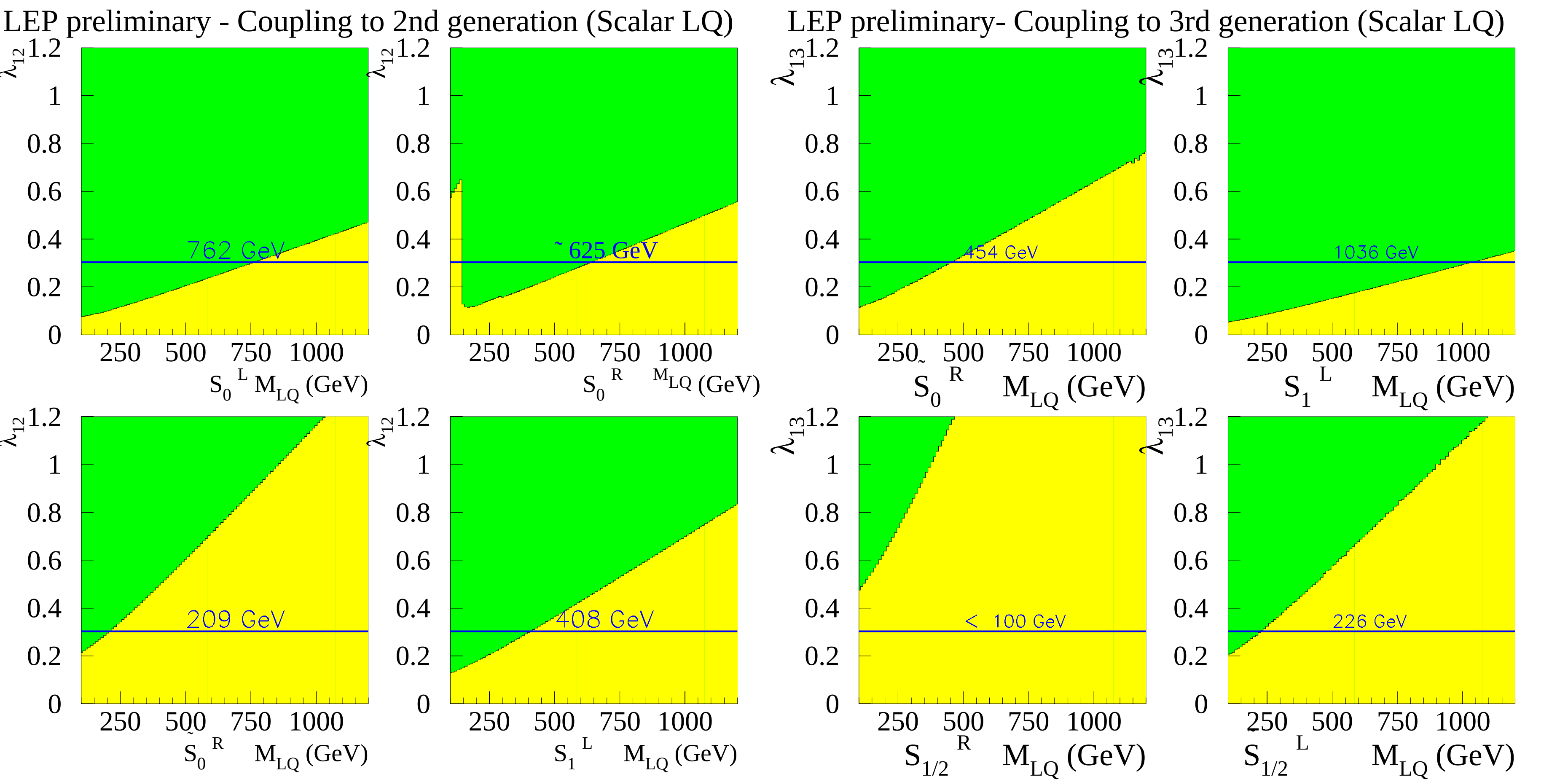
$g = \lambda$



$\leftarrow F = 2$

$\leftarrow F = 0$

LEP Combined indirect LQ limits. 2nd and 3rd Generation Quarks



Uses R_c, A^c_{FB}, qq cross section. b content fixed to SM.

Uses R_b and A^b_{FB}. c content fixed to SM.

Limits also exist for vector leptoquarks

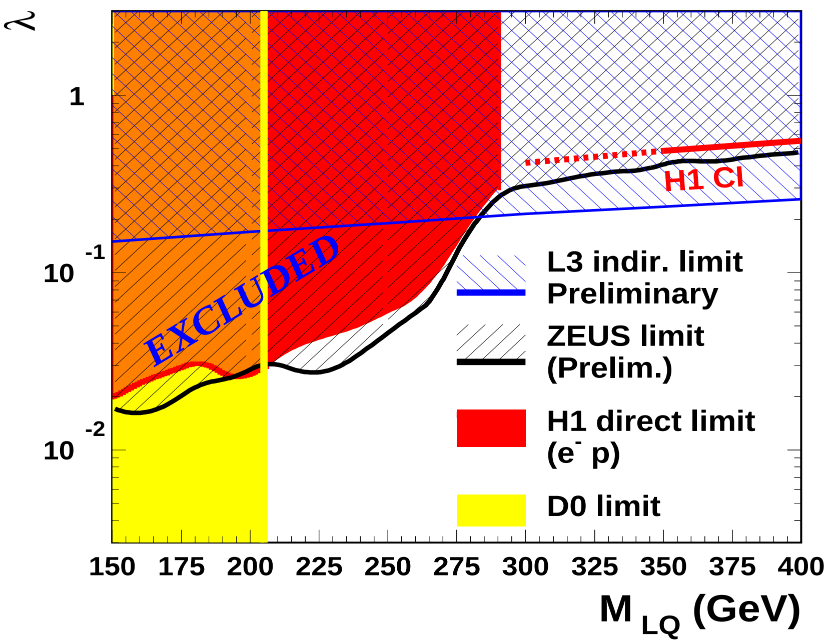
Lower Limits on $M_{\rm LQ}/\lambda$ (TeV^{-1})

species	LEP	L3	H1	ZEUS
S_0^L	2.09	1.20	0.72	0.75
S_0^R	1.66	0.85	0.67	0.69
$\tilde{S}_0^R$	0.64	0.39	0.33	0.31
$S_{1/2}^L$	0.57	0.36	0.87	0.91
$S_{1/2}^R$	0.74	0.50	0.37	0.69
$\tilde{S}_{1/2}^L$	-	-	0.43	0.50
S_1^L	1.15	0.86	0.48	0.55
V_0^L	2.93	1.78	0.77	0.69
V_0^R	0.53	0.51	0.64	0.58
$\tilde{V}_0^R$	1.56	1.21	1.00	1.03
$V_{1/2}^L$	0.97	0.81	0.42	0.49
$V_{1/2}^R$	0.72	0.69	0.94	1.15
$\tilde{V}_{1/2}^L$	0.56	0.53	1.02	1.26
V_1^L	2.10	1.67	1.38	1.42

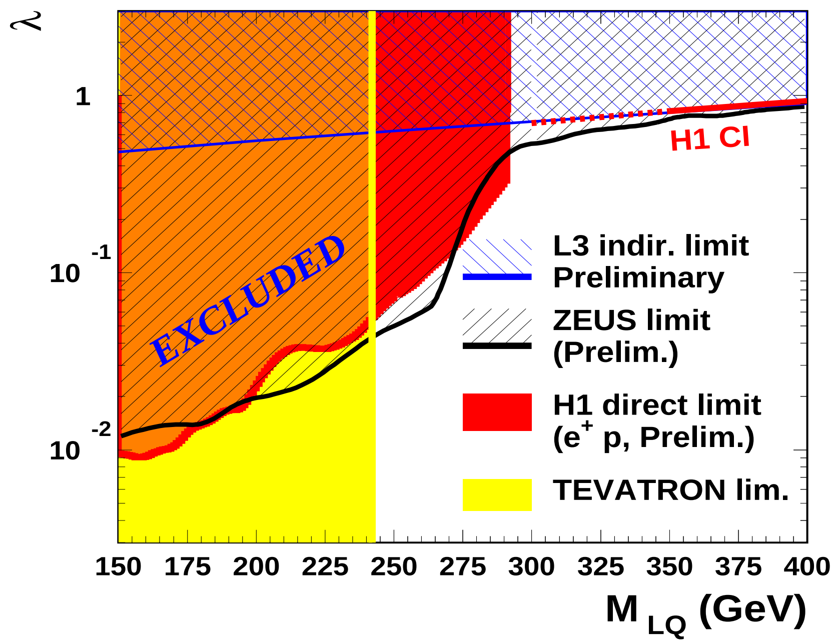
LEP combined and L3 limits were converted from lower limits on $M_{\rm LQ}$ for $\lambda = \sqrt{4\pi\alpha}$.

H1, ZEUS, L3, D0 Limits in (M, λ)

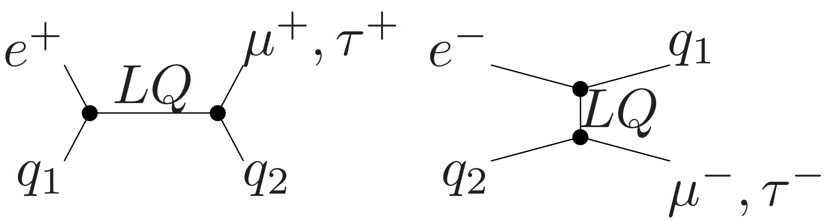
SCALAR LEPTOQUARKS WITH F=2 ($S_{0,L}$)

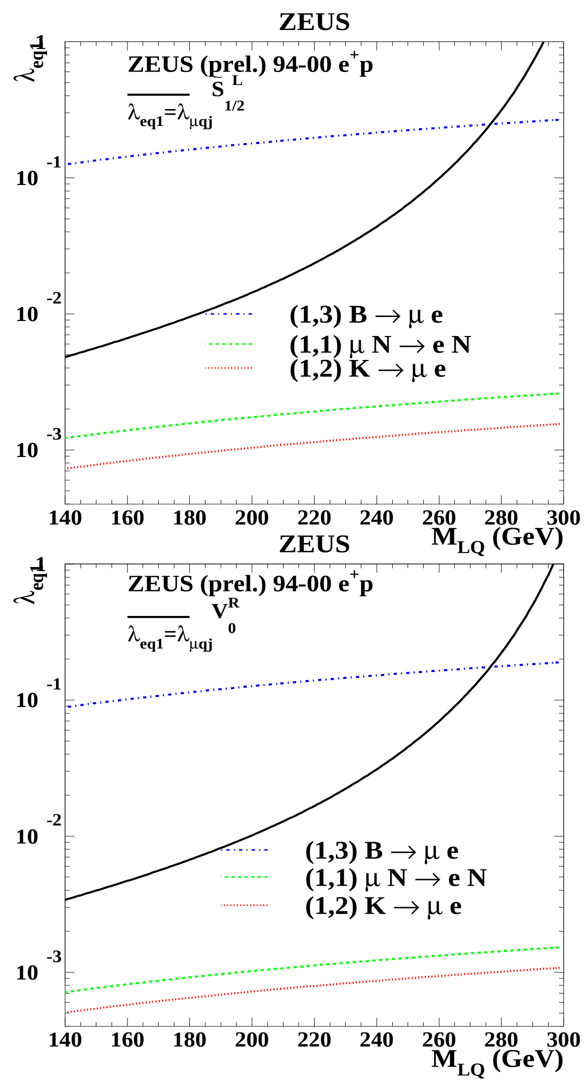


SCALAR LEPTOQUARKS WITH F=0 ($\tilde{S}_{1/2,L}$)



LQ Mediated Lepton Flavor Violation





Summary

- direct LQ searches at the Tevatron exclude

	scalar		vector	
gen	$\beta_\ell = 0$	$\beta_\ell = 1$	$\beta_\ell = 0$	$\beta_\ell = 1$
1	98 GeV	242 GeV	238 GeV	292 GeV
2	123 GeV	202 GeV	238 GeV	275 GeV
3	148 GeV	99 GeV	199 GeV	170 GeV

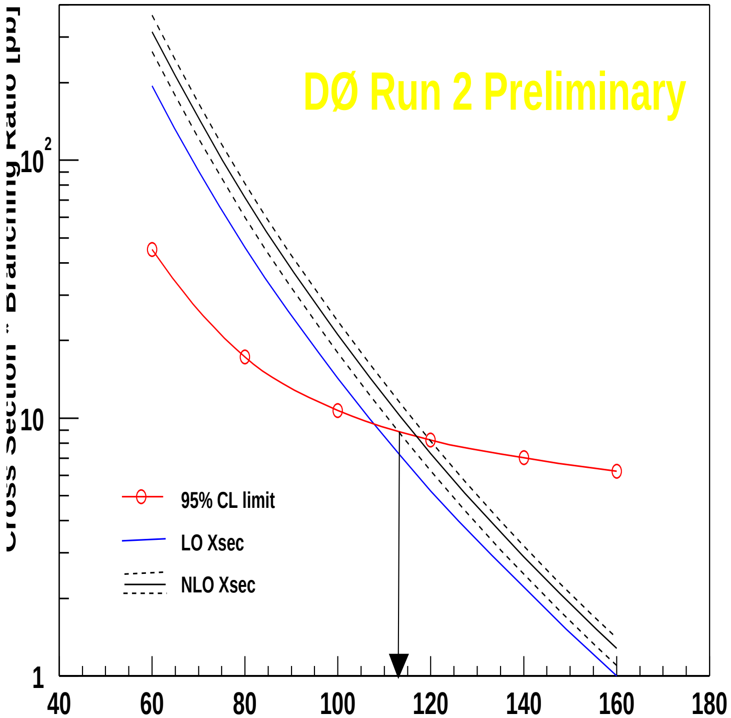
Results tabulated by M.Kuze and Y.Sirois

- Indirect Limits from LEP and HERA exclude scalars with $M_{\rm LQ}/\lambda < 0.5 \ldots 2.1$ TeV and vectors with $M_{\rm LQ}/\lambda < 1.0 \ldots 2.9$ TeV.

- HERA direct searches provide a factor of $1 - 10$ reduction in the λ limit for $200 < M_{\rm LQ} < 300$ GeV.

- LEP indirect search rules out LQs coupling to e and 2nd or 3rd generation quarks for $M_{\rm LQ}$ up to 1.0 TeV for $\lambda = \sqrt{4\pi\alpha}$.

Future



Using $8\,\mathrm{pb}^{-1}$ of data, D0 rules out scalar LQs with $M_{\mathrm{LQ}} > 113\,\mathrm{GeV}$