Search for Lepton Flavour Violation at HERA.

Search for Second and Third Generation Leptoquarks

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on behalf of the H1 Collaboration

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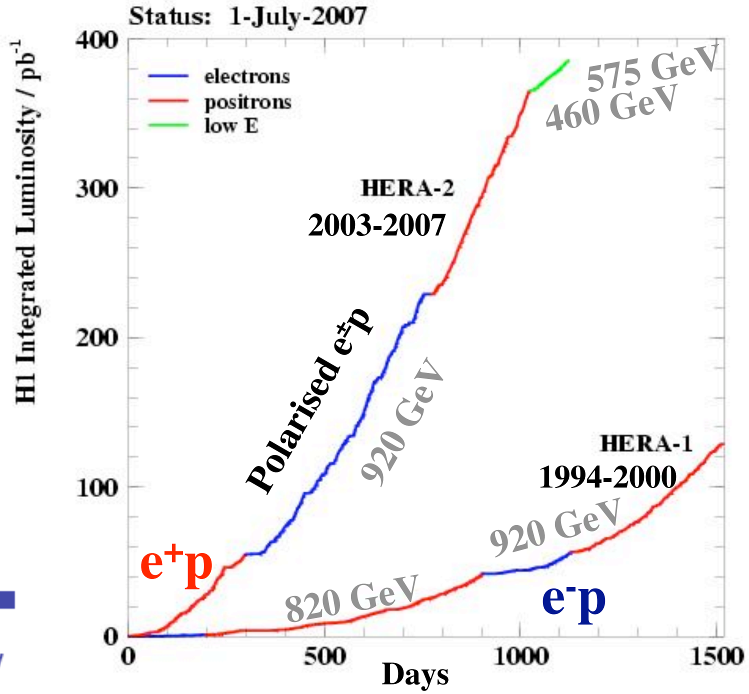
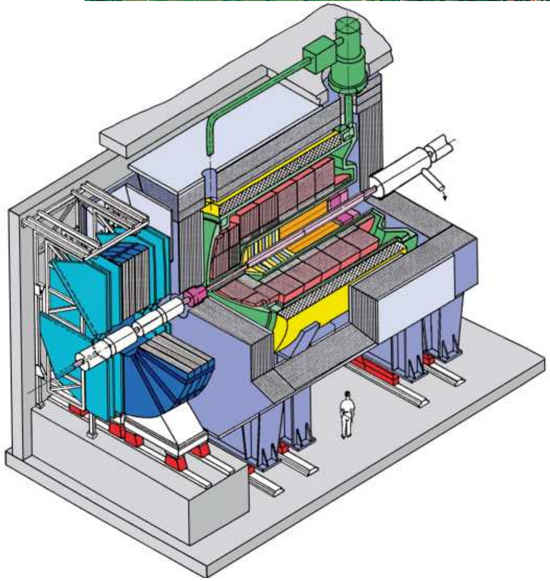
HELMHOLTZ
ASSOCIATION

DESY

The H1 experiment at HERA

Centre of mass √s = 319 GeV





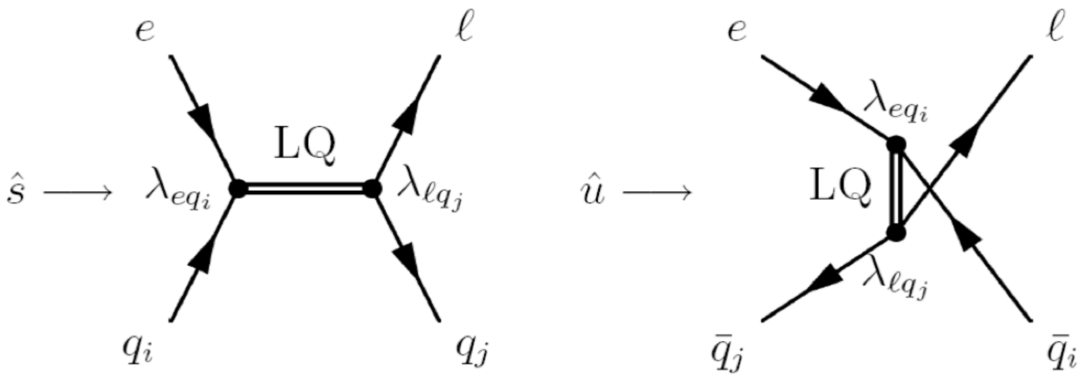
- H1 detector operated 1992-2007, asymmetric design
- HERA II phase with longitudinally polarised $e^{\pm}$ beam
- Luminosity of full H1 high energy data ~ 0.5 fb^{-1}
- Initial $e^{\pm}p$ state: Ideal machine to find Leptoquarks

Leptoquark basics

- Leptoquarks are hypothetical colour triplet bosons, with fractional charge, with both lepton and baryon number ≠ 0
- Couple to both quarks and leptons (as well as gluons)
- Parameterised in terms of mass M_{LQ}, coupling λ and quantum numbers
- The most general model with respect to the SM symmetry groups $SU(3)_c \times SU(2)_L \times U(1)_Y$ results in the 14 different LQ types*
- Classified by weak isospin, charge, spin and chirality, where the fermion number $F = | L + 3B | = 0, 2$
- LQ decays to μq or τq imply lepton flavour violation (LFV)

*** W. Buchmüller, R. Rückl, D. Wyler, "*Leptoquarks in lepton-quark collisions*", Phys. Lett. B191 (1987) 442**

Leptoquarks at HERA: Production



1st gen: eq → LQ → e(ν)q
2nd gen: eq → LQ → μ(ν)q
3rd gen: eq → LQ → τ(ν)q
} LFV

s-channel: resonant production
For $M_{LQ} \leq (sx)^{1/2}$
Cross section $\sigma \sim \lambda^2$

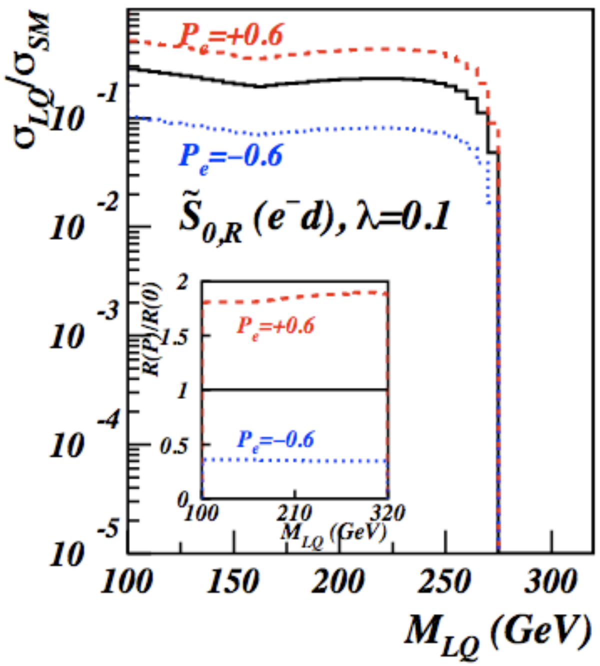
u-channel: LQ exchange
For $M_{LQ} > s^{1/2}$
Cross section $\sigma \sim \lambda^4$

> For LQ masses up to the centre of mass at HERA, resonant production in the s-channel dominates
  - Electron-proton collisions, mainly $F = | L + 3B | = 2$ LQs produced
  - Positron-proton collisions, mainly $F = | L + 3B | = 0$ LQs produced

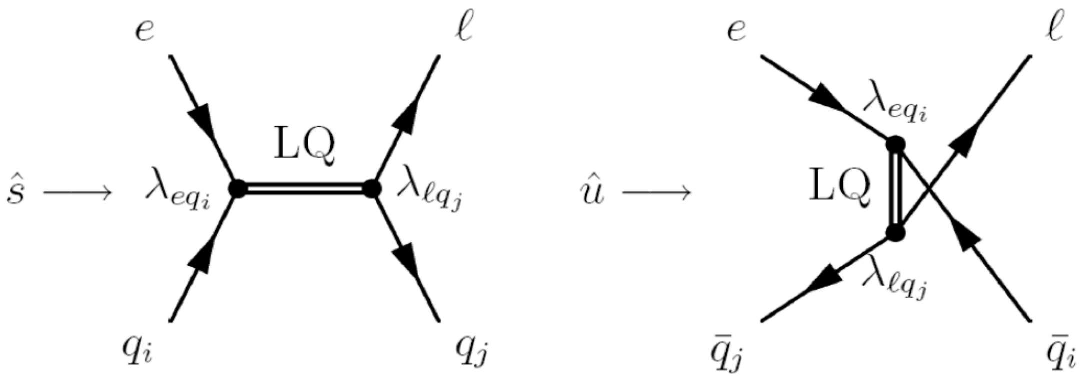
> For LQ masses well above 319 GeV, the u-channel also contributes: e^-p and e^+p similar sensitivity to $F = 0,2$ LQs

> LQ are chiral particles, gain in sensitivity at HERA II due to polarised lepton beam

Polarisation dependence



Leptoquarks at HERA: Decay



1st gen: eq → LQ → e(ν)q
2nd gen: eq → LQ → μ(ν)q
3rd gen: eq → LQ → τ(ν)q

} LFV

- First generation search: LQ → e(ν)q
  - Some LQs decay to neutrino-quark as well as electron-quark: search in NC/CC DIS
  - Gauge invariance leads to a branching fraction $\beta_\ell = \Gamma_{\ell q}/(\Gamma_{\ell q} + \Gamma_{\nu_\ell q}) = 0.5$
  - Interference with SM NC/CC (identical final state) included in the model

- Second and third generation searches: LQ → μq, τq
  - No CC contributions considered in the analysis, neutrino flavours indistinguishable
  - Branching ratio $\beta = \beta_\ell \times \beta_{LFV}$ with $\beta_{LFV} = \frac{\Gamma_{\mu(\tau)q}}{\Gamma_{\mu(\tau)q} + \Gamma_{eq}}$ and $\Gamma_{\ell q} = m_{\mathrm{LQ}} \lambda_{\ell q}^2 \times \begin{cases} \frac{1}{16\pi} & \text{scalar} \\ \frac{1}{24\pi} & \text{vector} \end{cases}$
  - Assuming lepton universality, and that only one LFV transition is possible, $\beta_{LFV} = 0.5$
  - No LFV transition: first generation only

14 LQ types in the BRW model

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \rightarrow \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$	λ_L $-\lambda_L$	$1/2$ $1/2$
S_0^R	0	2	$-1/3$	$e_R^- u_R \rightarrow \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \rightarrow \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$ $-4/3$	$e_L^- u_L \rightarrow \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$ $e_L^- d_L \rightarrow \ell^- d$	$-\lambda_L$ $-\lambda_L$ $-\sqrt{2}\lambda_L$	$1/2$ $1/2$ 1
$V_{1/2}^L$	1	2	$-4/3$	$e_L^- d_R \rightarrow \ell^- d$	λ_L	1
$V_{1/2}^R$	1	2	$-1/3$ $-4/3$	$e_R^- u_L \rightarrow \ell^- u$ $e_R^- d_L \rightarrow \ell^- d$	λ_R λ_R	1 1
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e_L^- u_R \rightarrow \ell^- u$	λ_L	1

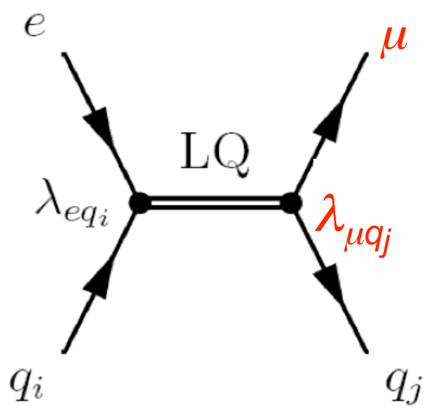
Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
V_0^L	1	0	$+2/3$	$e_R^+ d_L \rightarrow \begin{cases} \ell^+ d \\ \bar{\nu}_\ell u \end{cases}$	λ_L λ_L	$1/2$ $1/2$
V_0^R	1	0	$+2/3$	$e_L^+ d_R \rightarrow \ell^+ d$	λ_R	1
$\tilde{V}_0^R$	1	0	$+5/3$	$e_L^+ u_R \rightarrow \ell^+ u$	λ_R	1
V_1^L	1	0	$+2/3$ $+5/3$	$e_R^+ d_L \rightarrow \begin{cases} \ell^+ d \\ \bar{\nu}_\ell u \end{cases}$ $e_R^+ u_L \rightarrow \ell^+ u$	$-\lambda_L$ λ_L $\sqrt{2}\lambda_L$	$1/2$ $1/2$ 1
$S_{1/2}^L$	0	0	$+5/3$	$e_R^+ u_R \rightarrow \ell^+ u$	λ_L	1
$S_{1/2}^R$	0	0	$+2/3$ $+5/3$	$e_L^+ d_L \rightarrow \ell^+ d$ $e_L^+ u_L \rightarrow \ell^+ u$	$-\lambda_R$ λ_R	1 1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \rightarrow \ell^+ d$	λ_L	1

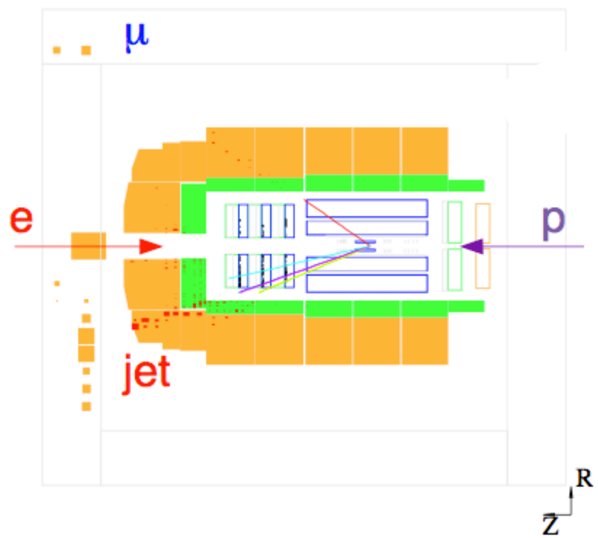
For ease of comparison to hadron collider limits:

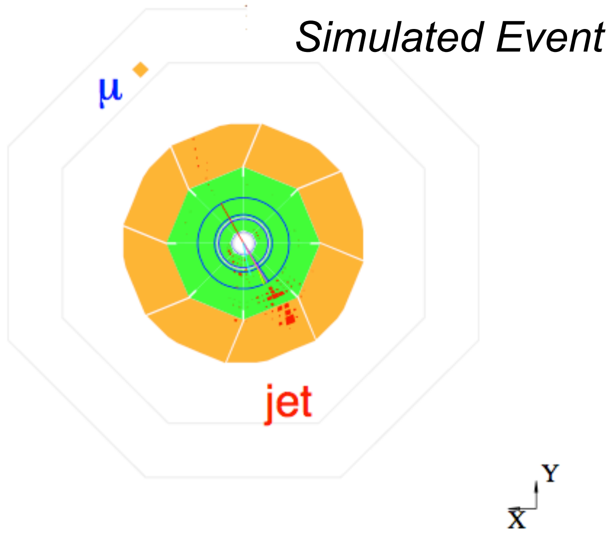
$$\beta = \beta_\ell \times \beta_{LFV} = 0.5 \text{ LQs}: S_0^R\ \tilde{S}_0^R\ V_{1/2}^L\ V_{1/2}^R\ \tilde{V}_{1/2}^L\ V_0^R\ \tilde{V}_0^R\ S_{1/2}^L\ S_{1/2}^R\ \tilde{S}_{1/2}^L$$

↗ 1.0 (β_ℓ)   ↖ 0.5 (β_{LFV})

Search for LFV: Second generation leptoquarks

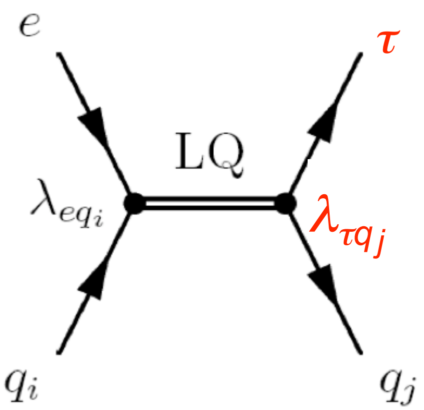


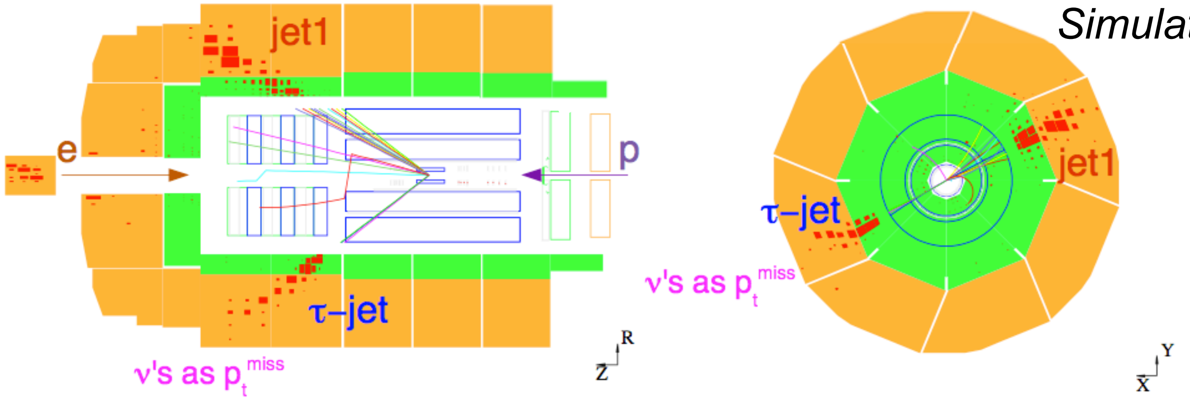




- High P_T muon back-to-back with a high P_T jet
- Clean experimental signature, essentially free from SM background
- Main selection criteria:
  - One well measured, isolated muon with P_T > 8 GeV in the central region of the detector
  - Large missing transverse momentum in the calorimeter P_T^{calo} > 25 GeV
  - Azimuthal balance of the muon and hadronic system, $\Delta\phi_{\mu\text{-}X} > 170^o$
- After all selection cuts: 1 event observed / 2.0 ± 0.4 from background processes
  - Remaining SM dominated by muon-pair events $\gamma\gamma \rightarrow \mu\mu$, where one muon is not seen

Search for LFV: Third generation leptoquarks



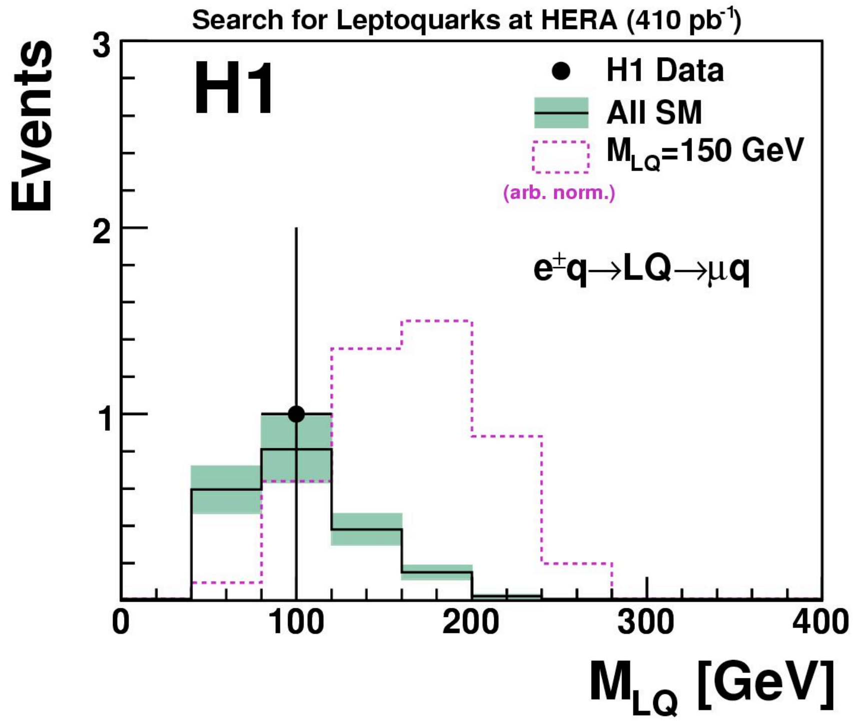


Simulated Event

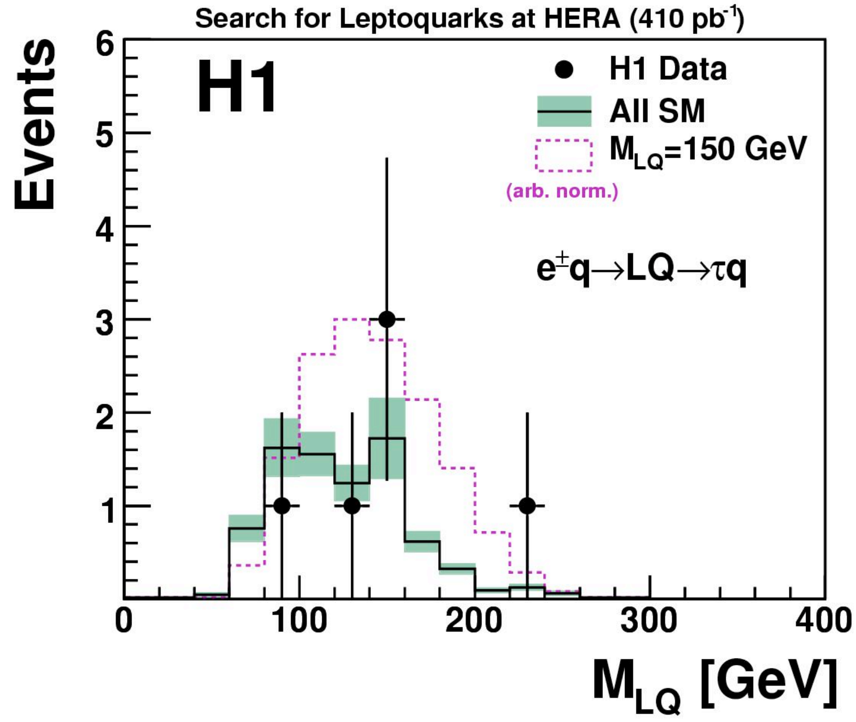
- Tau lepton with hadronic decay: search covers 1 prong decays, BR about 50%
- Narrow, pencil-like jet with one track back-to-back with a hadronic jet
- Main selection criteria:
  - Di-jet selection, P_T^{jet1} > 20 GeV, P_T^{jet2} > 15 GeV
  - Narrow tau-jet with R_{jet} < 0.12, isolated from other jets, tracks
  - Azimuthal balance of the tau-jet and hadronic system, $\Delta\phi_{\tau\text{-}X} > 160^o$
- After all selection cuts: 6 events observed / 8.2 ± 1.1 from background processes
  - Remaining SM dominated by remaining NC DIS di-jet events

Mass distributions

Muon Channel

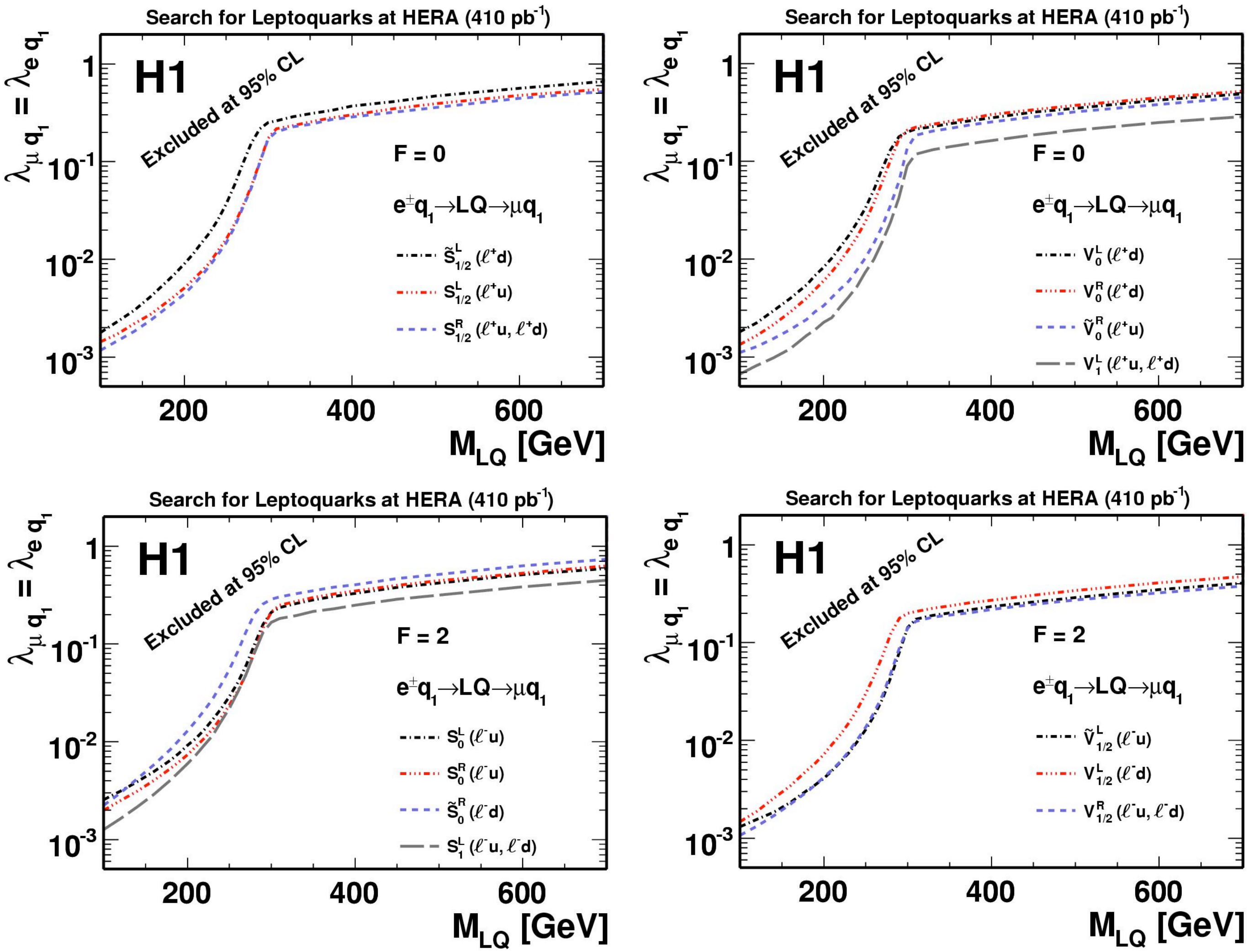


Tau Channel with 1-p hadronic decay



- No evidence for LQ signal: interpret results in terms of exclusion limits
- Third generation search also includes second generation search result in limits
  - Muonic tau decays $\tau \rightarrow \mu\nu_\mu\nu_\tau$ result in similar final state to LQ $\rightarrow \mu q$ channel
  - Electronic tau decays not included due to high SM background

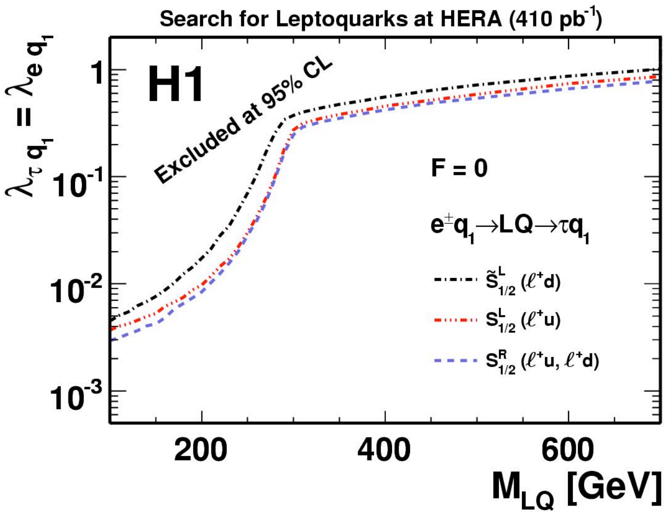
Leptoquark limits in the second generation search

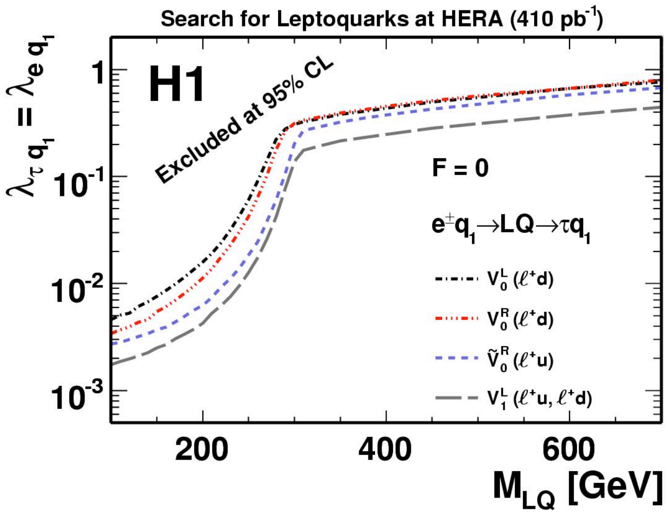


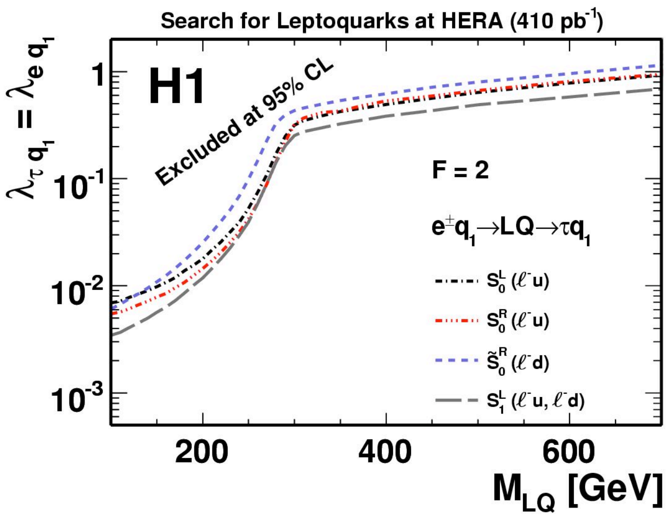
For $\lambda_{eq} = \lambda_{\mu q}$ and $\lambda_{\tau q} = 0$

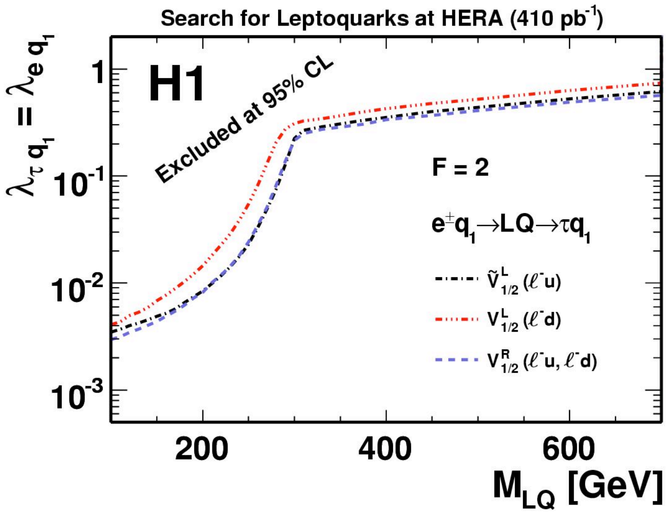
$\beta_{LFV} = 0.5$

Leptoquark limits in the third generation search





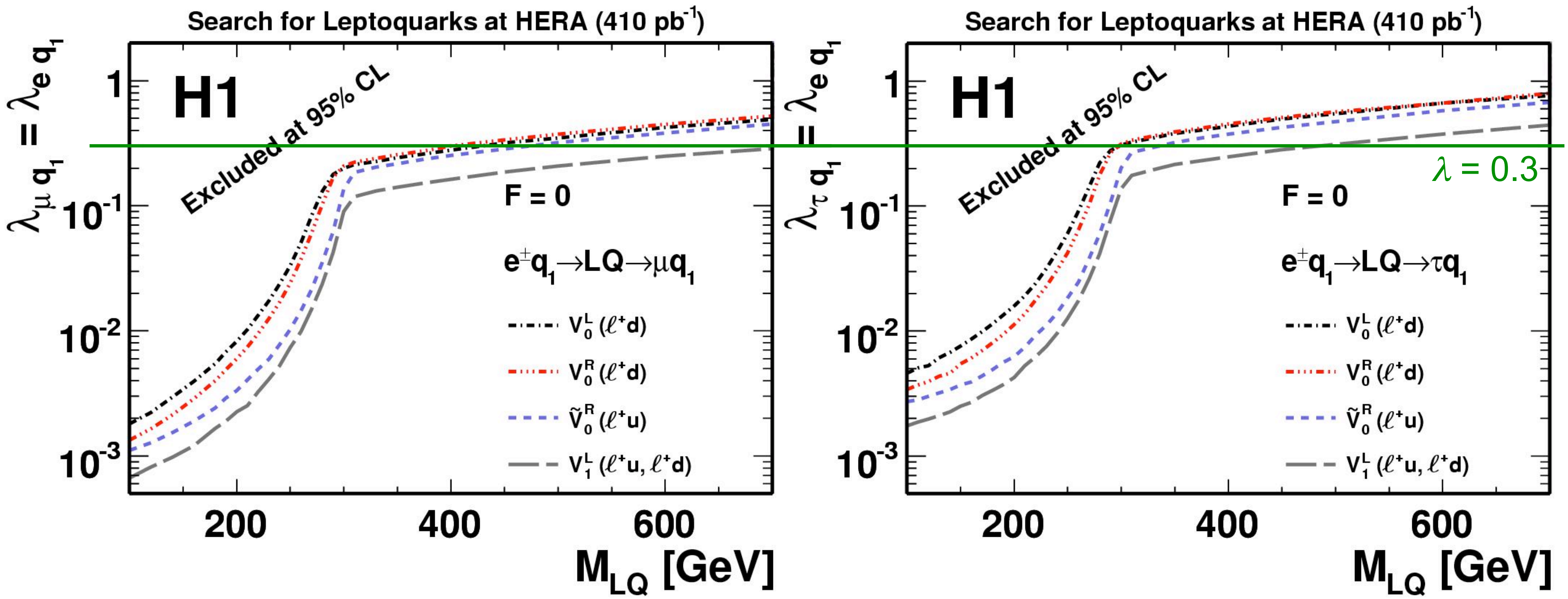




For $\lambda_{eq} = \lambda_{\tau q}$ and $\lambda_{\mu q} = 0$

$\beta_{LFV} = 0.5$

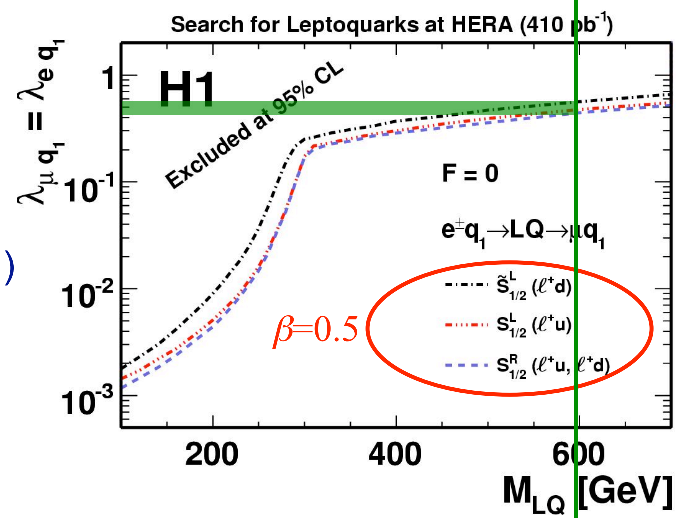
Most stringent H1 limits

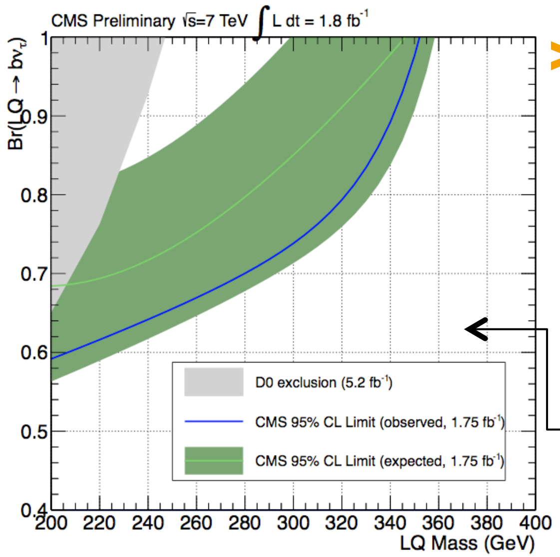


- In both cases V_1^L LQ has most stringent limits, sensitivity to both u and d quarks
- For a coupling of electromagnetic strength $\lambda = 0.3$ LQs mediating LFV via:
  - eq → LQ → μq are ruled out up to 712 GeV
  - eq → LQ → τq are ruled out up to 479 GeV

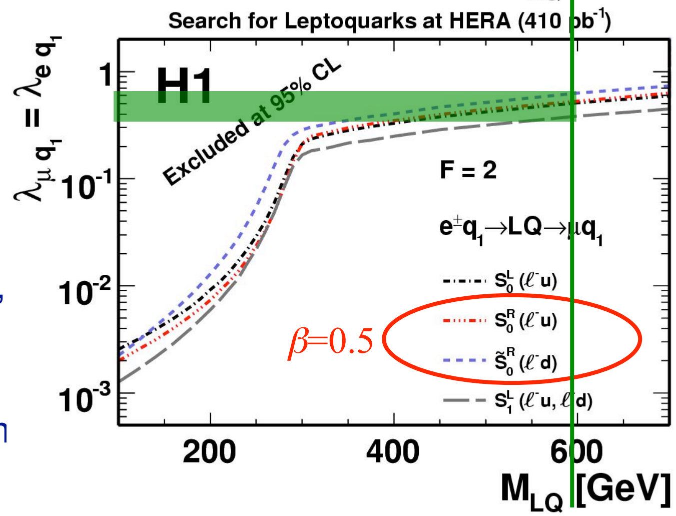
Comparison of H1 LFV limits with those from hadron colliders

- Leptoquark produced in pairs at the Tevatron or the LHC
  - No sensitivity from such decays to the coupling λ
- Highest excluded mass in a 3rd generation search
  - 350 GeV for β=1 from 2012 CMS scalar LQ search
  - 317 GeV for β=1 from 2007 CDF vector LQ search (YM coupling)
- Highest excluded mass in a 2nd generation search
  - 685 GeV for β=1 from 2012 ATLAS scalar LQ search





- Most appropriate value to compare to HERA is β=0.5
  - Second generation limit from ATLAS is 595 GeV
  - For this mass, and for such LQs, H1 excludes couplings in the range λ=0.35-0.7
  - Best third generation limit is from CMS, still below 200 GeV for β=0.5



Comparison with low energy experiments

- For LQ masses well above the kinematic limit, the cross-section depends only on $(\lambda_{eqi}\lambda_{lqj} / M^2_{LQ})^2$

- LFV limits derived at HERA from searches for high mass leptoquarks can be compared to those from low energy experiments
  - Transform the limit on $\lambda_{eq} = \lambda_{\mu(\tau)q}$ into a limit on the value $\lambda_{eq}\lambda_{\mu(\tau)q} / M^2_{LQ}$

- Dependence of the signal selection efficiency on the quark flavour is determined for each $eq_i \rightarrow \mu(\tau)q_j$ process individually
  - Sensitivity to quark flavours via the PDF

$ep \rightarrow \tau X$				**H1**			$F = 0$
Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/m^2_{\mathrm{LQ}}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL							
$q_i q_j$	$S^L_{1/2}$ $\ell^-\bar{U}$ ℓ^+U	$S^R_{1/2}$ $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D	$\tilde{S}^L_{1/2}$ $\ell^-\bar{D}$ ℓ^+D	V^L_0 $\ell^-\bar{D}$ ℓ^+D	V^R_0 $\ell^-\bar{D}$ ℓ^+D	$\tilde{V}^R_0$ $\ell^-\bar{U}$ ℓ^+U	V^L_1 $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D
1 1	$\tau \rightarrow \pi e$ 0.06 **1.4**	$\tau \rightarrow \pi e$ 0.03 **1.2**	$\tau \rightarrow \pi e$ 0.06 **2.2**	$\tau \rightarrow \pi e$ 0.03 **1.2**	$\tau \rightarrow \pi e$ 0.03 **1.3**	$\tau \rightarrow \pi e$ 0.03 **0.9**	$\tau \rightarrow \pi e$ 0.005 **0.4**
1 2	**1.5**	$\tau \rightarrow Ke$ 0.04 **1.2**	$K \rightarrow \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.2**	$\tau \rightarrow Ke$ 0.02 **1.5**	$\tau \rightarrow Ke$ 0.02 **1.6**	**1.2**	$K \rightarrow \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.5**
1 3	*	$B \rightarrow \tau\bar{e}$ 0.07 **2.2**	$B \rightarrow \tau\bar{e}$ 0.07 **2.2**	$B \rightarrow \tau\bar{e}$ 0.03 **1.8**	$B \rightarrow \tau\bar{e}$ 0.03 **1.8**	*	$B \rightarrow \tau\bar{e}$ 0.03 **1.8**
2 1	**3.4**	$\tau \rightarrow Ke$ 0.04 **2.8**	$K \rightarrow \pi\nu\bar{\nu}$ 5.8×10^{-4} **3.9**	$\tau \rightarrow Ke$ 0.02 **1.5**	$\tau \rightarrow Ke$ 0.02 **1.6**	**1.2**	$K \rightarrow \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.5**
2 2	$\tau \rightarrow 3e$ 0.6 **6.4**	$\tau \rightarrow 3e$ 0.9 **4.2**	$\tau \rightarrow 3e$ 1.8 **5.0**	$\tau \rightarrow 3e$ 0.9 **2.7**	$\tau \rightarrow 3e$ 0.9 **2.8**	$\tau \rightarrow 3e$ 0.3 **3.5**	$\tau \rightarrow 3e$ 0.2 **1.4**
2 3	*	$B \rightarrow \tau\bar{e}X$ 14.0 **5.8**	$B \rightarrow \tau\bar{e}X$ 14.0 **5.6**	$B \rightarrow \tau\bar{e}X$ 7.2 **3.6**	$B \rightarrow \tau\bar{e}X$ 7.2 **4.0**	*	$B \rightarrow \tau\bar{e}X$ 7.2 **3.6**
3 1	*	$B \rightarrow \tau\bar{e}$ 0.07 **5.3**	$B \rightarrow \tau\bar{e}$ 0.07 **4.8**	V_{ub} 0.14 **1.5**	$B \rightarrow \tau\bar{e}$ 0.03 **1.7**	*	V_{ub} 0.14 **1.5**
3 2	*	$B \rightarrow \tau\bar{e}X$ 14.0 **7.9**	$B \rightarrow \tau\bar{e}X$ 14.0 **7.6**	$B \rightarrow \tau\bar{e}X$ 7.2 **2.9**	$B \rightarrow \tau\bar{e}X$ 7.2 **3.1**	*	$B \rightarrow \tau\bar{e}X$ 7.2 **2.9**
3 3	*	$\tau \rightarrow 3e$ 0.9 **10.1**	$\tau \rightarrow 3e$ 1.8 **9.1**	$\tau \rightarrow 3e$ 0.9 **4.7**	$\tau \rightarrow 3e$ 0.9 **4.9**	*	$\tau \rightarrow 3e$ 0.2 **4.7**

Summary and conclusions

- The ep collisions at the HERA collider are the ideal environment to search for leptoquarks
  - Searches for LQs of all generations have been performed by the H1 experiment using the complete high energy data taken at $\sqrt{s}$ = 319 GeV
- No significant deviation from the SM observed and limits are set on the production of such particles
  - For large values of the coupling λ, HERA limits in CI region are still beyond current limits from hadron colliders
  - Search for LFV via LQ exchange: limits competitive with low energy experiments in a number of channels and LQ masses up to 712 GeV are ruled out @ 95% CL for λ = 0.3

Final H1 search papers:

"Search for Lepton Flavour Violation at HERA", Phys. Lett. B701 (2011) 20 [arXiv:1103.4938].
"Search for First Generation Leptoquarks at HERA", Phys. Lett B704 (2011) 388 [arXiv:1107.3716].
"Search for Contact Interactions in ep Collisions at HERA", Phys. Lett. B705 (2011) 52 [arXiv:1107.2478].

Extra Slides

Comparison of H1 LFV Limits to Low Energy Expt's, F = 0 LQs

$ep \to \mu X$ **H1** $F = 0$

Upper exclusion limits on $\lambda_{eq_i}\lambda_{\mu q_j}/m^2_{LQ}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL

$q_i q_j$	$S^L_{1/2}$ $\ell^-\bar{U}$ ℓ^+U	$S^R_{1/2}$ $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D	$\tilde{S}^L_{1/2}$ $\ell^-\bar{D}$ ℓ^+D	V^L_0 $\ell^-\bar{D}$ ℓ^+D	V^R_0 $\ell^-\bar{D}$ ℓ^+D	$\tilde{V}^R_0$ $\ell^-\bar{U}$ ℓ^+U	V^L_1 $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D
1 1	$\mu N \to eN$ 5.2×10^{-5} **0.6**	$\mu N \to eN$ 2.6×10^{-5} **0.6**	$\mu N \to eN$ 5.2×10^{-5} **0.9**	$\mu N \to eN$ 2.6×10^{-5} **0.5**	$\mu N \to eN$ 2.6×10^{-5} **0.6**	$\mu N \to eN$ 2.6×10^{-5} **0.4**	$\mu N \to eN$ 0.8×10^{-5} **0.2**
1 2	$D \to \mu\bar{e}$ 0.8 **0.7**	$K \to \mu\bar{e}$ 2×10^{-5} **0.5**	$K \to \mu\bar{e}$ 2×10^{-5} **0.9**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.7**	$D \to \mu\bar{e}$ 0.4 **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.2**
1 3	*	$B \to \mu\bar{e}$ 0.08 **1.0**	$B \to \mu\bar{e}$ 0.08 **0.9**	$B \to \mu\bar{e}$ 0.04 **0.7**	$B \to \mu\bar{e}$ 0.04 **0.8**	*	$B \to \mu\bar{e}$ 0.04 **0.7**
2 1	$D \to \mu\bar{e}$ 0.8 **1.4**	$K \to \mu\bar{e}$ 2×10^{-5} **1.2**	$K \to \mu\bar{e}$ 2×10^{-5} **1.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.7**	$D \to \mu\bar{e}$ 0.4 **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.2**
2 2	$\mu N \to eN$ 9.2×10^{-4} **2.4**	$\mu N \to eN$ 1.3×10^{-3} **1.7**	$\mu N \to eN$ 3×10^{-3} **1.9**	$\mu N \to eN$ 1.5×10^{-3} **1.0**	$\mu N \to eN$ 1.5×10^{-3} **1.1**	$\mu N \to eN$ 4.6×10^{-4} **1.4**	$\mu N \to eN$ 2.7×10^{-4} **0.5**
2 3	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.3**	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.5**	*	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**
3 1	*	$B \to \mu\bar{e}$ 0.08 **2.1**	$B \to \mu\bar{e}$ 0.08 **1.9**	V_{ub} 0.14 **0.6**	$B \to \mu\bar{e}$ 0.04 **0.7**	*	V_{ub} 0.14 **0.6**
3 2	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **3.2**	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.8**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.2**	*	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**
3 3	*	$\mu N \to eN$ 1.3×10^{-3} **3.8**	$\mu N \to eN$ 3×10^{-3} **3.4**	$\mu N \to eN$ 1.5×10^{-3} **1.7**	$\mu N \to eN$ 1.5×10^{-3} **1.9**	*	$\mu N \to eN$ 2.7×10^{-4} **1.7**

$ep \to \tau X$ **H1** $F = 0$

Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/m^2_{LQ}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL

$q_i q_j$	$S^L_{1/2}$ $\ell^-\bar{U}$ ℓ^+U	$S^R_{1/2}$ $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D	$\tilde{S}^L_{1/2}$ $\ell^-\bar{D}$ ℓ^+D	V^L_0 $\ell^-\bar{D}$ ℓ^+D	V^R_0 $\ell^-\bar{D}$ ℓ^+D	$\tilde{V}^R_0$ $\ell^-\bar{U}$ ℓ^+U	V^L_1 $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D
1 1	$\tau \to \pi e$ 0.06 **1.4**	$\tau \to \pi e$ 0.03 **1.2**	$\tau \to \pi e$ 0.06 **2.2**	$\tau \to \pi e$ 0.03 **1.2**	$\tau \to \pi e$ 0.03 **1.3**	$\tau \to \pi e$ 0.03 **0.9**	$\tau \to \pi e$ 0.005 **0.4**
1 2	**1.5**	$\tau \to Ke$ 0.04 **1.2**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.2**	$\tau \to Ke$ 0.02 **1.5**	$\tau \to Ke$ 0.02 **1.6**	**1.2**	$K \to \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.5**
1 3	*	$B \to \tau\bar{e}$ 0.07 **2.2**	$B \to \tau\bar{e}$ 0.07 **2.2**	$B \to \tau\bar{e}$ 0.03 **1.8**	$B \to \tau\bar{e}$ 0.03 **1.8**	*	$B \to \tau\bar{e}$ 0.03 **1.8**
2 1	**3.4**	$\tau \to Ke$ 0.04 **2.8**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **3.9**	$\tau \to Ke$ 0.02 **1.5**	$\tau \to Ke$ 0.02 **1.6**	**1.2**	$K \to \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.5**
2 2	$\tau \to 3e$ 0.6 **6.4**	$\tau \to 3e$ 0.9 **4.2**	$\tau \to 3e$ 1.8 **5.0**	$\tau \to 3e$ 0.9 **2.7**	$\tau \to 3e$ 0.9 **2.8**	$\tau \to 3e$ 0.3 **3.5**	$\tau \to 3e$ 0.2 **1.4**
2 3	*	$B \to \tau\bar{e}X$ 14.0 **5.8**	$B \to \tau\bar{e}X$ 14.0 **5.6**	$B \to \tau\bar{e}X$ 7.2 **3.6**	$B \to \tau\bar{e}X$ 7.2 **4.0**	*	$B \to \tau\bar{e}X$ 7.2 **3.6**
3 1	*	$B \to \tau\bar{e}$ 0.07 **5.3**	$B \to \tau\bar{e}$ 0.07 **4.8**	V_{ub} 0.14 **1.5**	$B \to \tau\bar{e}$ 0.03 **1.7**	*	V_{ub} 0.14 **1.5**
3 2	*	$B \to \tau\bar{e}X$ 14.0 **7.9**	$B \to \tau\bar{e}X$ 14.0 **7.6**	$B \to \tau\bar{e}X$ 7.2 **2.9**	$B \to \tau\bar{e}X$ 7.2 **3.1**	*	$B \to \tau\bar{e}X$ 7.2 **2.9**
3 3	*	$\tau \to 3e$ 0.9 **10.1**	$\tau \to 3e$ 1.8 **9.1**	$\tau \to 3e$ 0.9 **4.7**	$\tau \to 3e$ 0.9 **4.9**	*	$\tau \to 3e$ 0.2 **4.7**

Comparison of H1 LFV Limits to Low Energy Expt's, F = 2 LQs

$ep \to \mu X$ — H1 — $F = 2$

Upper exclusion limits on $\lambda_{eq_i}\lambda_{\mu q_j}/m^2_{LQ}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL

$q_i q_j$	S_0^L $\ell^- U$ $\ell^+ \bar{U}$	S_0^R $\ell^- U$ $\ell^+ \bar{U}$	$\tilde{S}_0^R$ $\ell^- D$ $\ell^+ \bar{D}$	S_1^L $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$V_{1/2}^L$ $\ell^- D$ $\ell^+ \bar{D}$	$V_{1/2}^R$ $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$\tilde{V}_{1/2}^L$ $\ell^- U$ $\ell^+ \bar{U}$
1 1	$\mu N \to eN$ 5.2×10^{-5} **0.7**	$\mu N \to eN$ 5.2×10^{-5} **0.8**	$\mu N \to eN$ 5.2×10^{-5} **1.1**	$\mu N \to eN$ 1.7×10^{-5} **0.4**	$\mu N \to eN$ 2.6×10^{-5} **0.5**	$\mu N \to eN$ 1.3×10^{-5} **0.3**	$\mu N \to eN$ 2.6×10^{-5} **0.3**
1 2	$K \to \pi\nu\bar{\nu}$ 1×10^{-3} **0.8**	$D \to \mu\bar{e}$ 0.8 **0.9**	$K \to \mu\bar{e}$ 2×10^{-5} **1.2**	$K \to \mu\bar{e}$ 1×10^{-5} **0.4**	$K \to \mu\bar{e}$ 1×10^{-5} **0.8**	$K \to \mu\bar{e}$ 1×10^{-5} **0.5**	$D \to \mu\bar{e}$ 0.4 **0.6**
1 3	*	*	$B \to \mu\bar{e}$ 0.08 **1.3**	V_{ub} 0.3 **0.6**	$B \to \mu\bar{e}$ 0.04 **0.9**	$B \to \mu\bar{e}$ 0.04 **1.0**	*
2 1	$K \to \pi\nu\bar{\nu}$ 1×10^{-3} **1.2**	$D \to \mu\bar{e}$ 0.8 **1.2**	$K \to \mu\bar{e}$ 2×10^{-5} **1.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.3**	$D \to \mu\bar{e}$ 0.4 **0.4**
2 2	$\mu N \to eN$ 9.2×10^{-4} **2.4**	$\mu N \to eN$ 9.2×10^{-3} **2.7**	$\mu N \to eN$ 3×10^{-3} **2.1**	$\mu N \to eN$ 2.5×10^{-3} **0.9**	$\mu N \to eN$ 1.5×10^{-3} **1.0**	$\mu N \to eN$ 6.7×10^{-4} **0.9**	$\mu N \to eN$ 4.6×10^{-4} **1.2**
2 3	*	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.3**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.0**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.5**	*
3 1	*	*	$B \to \mu\bar{e}$ 0.08 **1.8**	$B \to \mu\bar{e}$ 0.08 **0.8**	$B \to \mu\bar{e}$ 0.04 **0.5**	$B \to \mu\bar{e}$ 0.04 **0.5**	*
3 2	*	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **3.2**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.2**	*
3 3	*	*	$\mu N \to eN$ 3×10^{-3} **3.8**	$\mu N \to eN$ 2.5×10^{-3} **1.7**	$\mu N \to eN$ 1.5×10^{-3} **1.7**	$\mu N \to eN$ 6.7×10^{-4} **1.9**	*

$ep \to \tau X$ — H1 — $F = 2$

Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/m^2_{LQ}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL

$q_i q_j$	S_0^L $\ell^- U$ $\ell^+ \bar{U}$	S_0^R $\ell^- U$ $\ell^+ \bar{U}$	$\tilde{S}_0^R$ $\ell^- D$ $\ell^+ \bar{D}$	S_1^L $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$V_{1/2}^L$ $\ell^- D$ $\ell^+ \bar{D}$	$V_{1/2}^R$ $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$\tilde{V}_{1/2}^L$ $\ell^- U$ $\ell^+ \bar{U}$
1 1	G_F 0.3 **1.6**	$\tau \to \pi e$ 0.06 **1.8**	$\tau \to \pi e$ 0.06 **2.6**	$\tau \to \pi e$ 0.01 **1.0**	$\tau \to \pi e$ 0.03 **1.1**	$\tau \to \pi e$ 0.01 **0.7**	$\tau \to \pi e$ 0.03 **0.8**
1 2	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **1.9**	**2.1**	$\tau \to Ke$ 0.04 **2.9**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.1**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.9**	$\tau \to Ke$ 0.02 **1.3**	**1.5**
1 3	*	*	$B \to \tau\bar{e}$ 0.07 **3.0**	V_{ub} 0.3 **1.3**	$B \to \tau\bar{e}$ 0.03 **2.2**	$B \to \tau\bar{e}$ 0.03 **2.4**	*
2 1	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.7**	**2.7**	$\tau \to Ke$ 0.04 **3.5**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.4**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.2**	$\tau \to Ke$ 0.02 **0.7**	**0.9**
2 2	$\tau \to 3e$ 0.6 **6.3**	$\tau \to 3e$ 0.6 **6.8**	$\tau \to 3e$ 1.8 **5.4**	$\tau \to 3e$ 1.5 **2.3**	$\tau \to 3e$ 0.9 **2.7**	$\tau \to 3e$ 0.5 **2.2**	$\tau \to 3e$ 0.3 **3.4**
2 3	*	*	$B \to \bar{\tau}eX$ 14.0 **5.8**	$B \to \bar{\tau}eX$ 7.2 **2.7**	$B \to \bar{\tau}eX$ 7.2 **3.6**	$B \to \bar{\tau}eX$ 7.2 **4.0**	*
3 1	*	*	$B \to \tau\bar{e}$ 0.07 **4.0**	$B \to \tau\bar{e}$ 0.03 **2.0**	$B \to \tau\bar{e}$ 0.03 **1.2**	$B \to \tau\bar{e}$ 0.03 **1.3**	*
3 2	*	*	$B \to \bar{\tau}eX$ 14.0 **7.9**	$B \to \bar{\tau}eX$ 7.2 **3.7**	$B \to \bar{\tau}eX$ 7.2 **2.9**	$B \to \bar{\tau}eX$ 7.2 **3.1**	*
3 3	*	*	$\tau \to 3e$ 1.8 **10.1**	$\tau \to 3e$ 1.5 **4.6**	$\tau \to 3e$ 0.9 **4.7**	$\tau \to 3e$ 0.5 **4.9**	*

Table of Scalar LQ mass limits from hadron colliders

Scalar LQs	1st Gen		2nd Gen		3rd Gen	
β	1.0	0.5	1.0	0.5	1.0	0.5
ATLAS	660[1]	607[1]	685[2]	594[2]	-	-
CMS	384[3]	340[4]	632[5]	523[5]	350[6]	-
DØ	299[7]	326[8]	316[9]	270[9]	247[10]	-
CDF	236[11]	205[11]	226[12]	208[12]	-	-

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