Search for Lepton Flavour Violation at HERA.

Leptoquarks at HERA
Search for First Generation Leptoquarks
Search for Second and Third Generation Leptoquarks *arXiv:1103.4938*
Conclusions

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on behalf of the H1 Collaboration
XIX International Workshop on Deep Inelastic Scattering and Related Subjects
Newport News, VI, USA 11-15 April 2011

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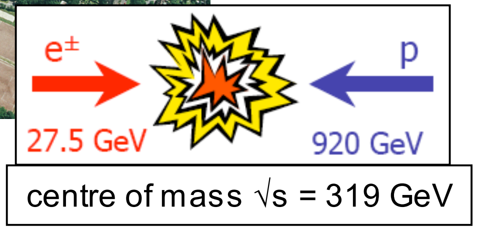
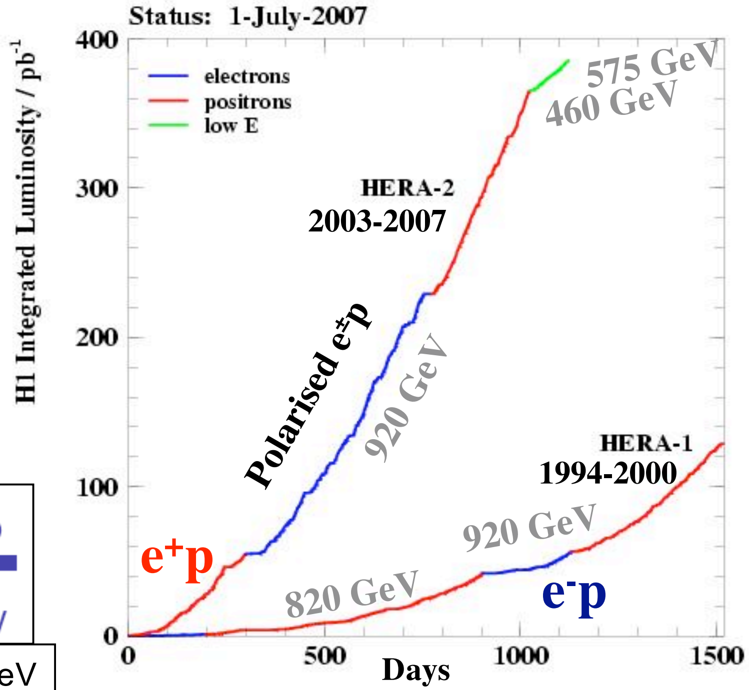
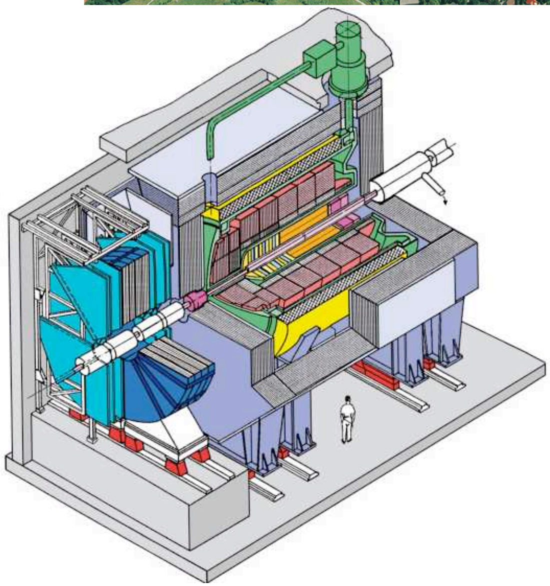
DESY

The H1 Experiment at HERA







- The world's most powerful electron microscope HERA, with counter-rotating 6.3 km long accelerators
- 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}

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 14 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)

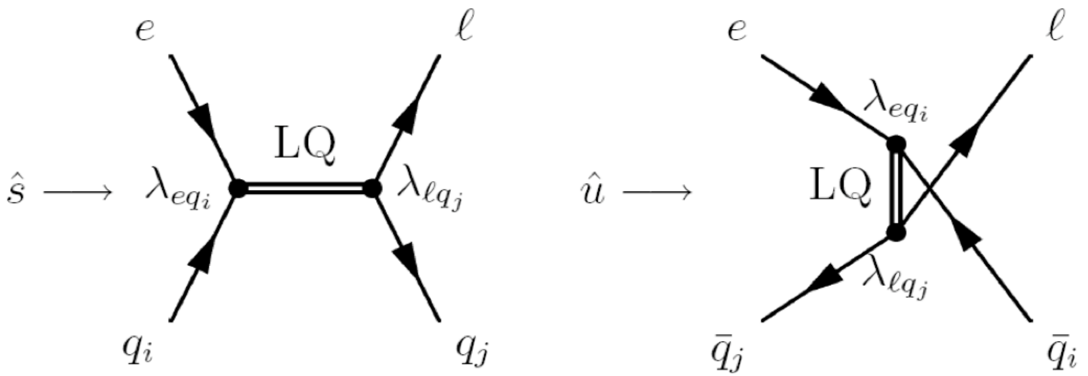
*Buchmüller, Rückl, Wyler, Phys. Lett. B191 (1987) 442

14 LQ types in the BRW Model

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

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

Leptoquarks at HERA: Production



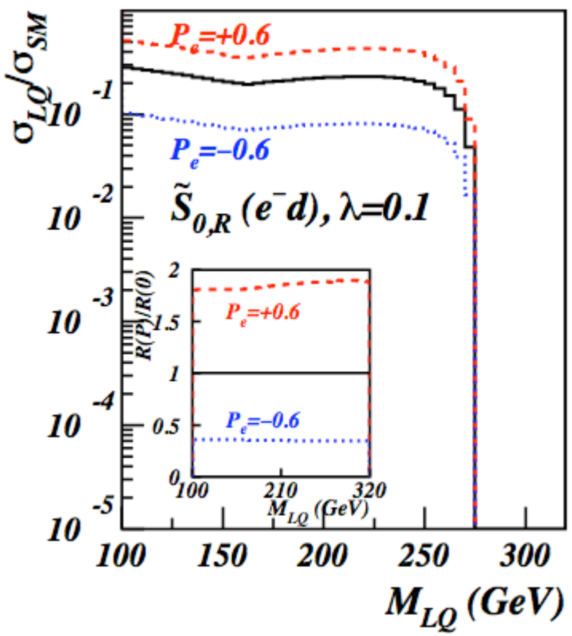
1st gen: eq → LQ → e(ν)q
2nd gen: eq → LQ → μ(ν)q
3rd gen: eq → LQ → τ(ν)q

} LFV

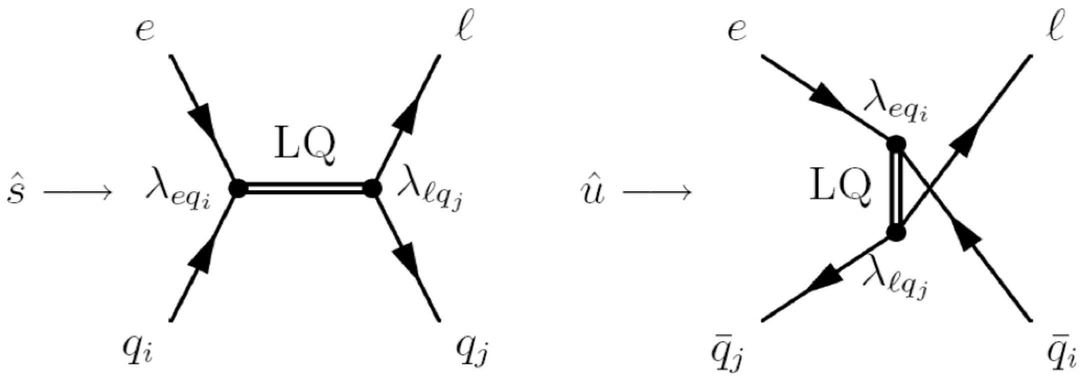
s-channel: resonant production
For $M_{LQ} \leq (sx)^{1/2}$
Cross section $\sigma \sim \lambda^2$

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



Leptoquarks at HERA: Decay



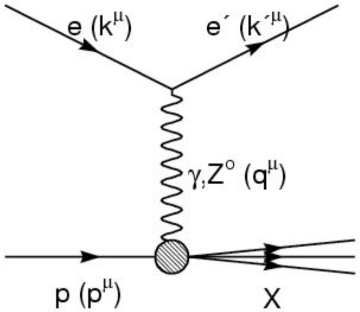
1st gen: eq → LQ → e(ν)q
2nd gen: eq → LQ → μ(ν)q
3rd gen: eq → LQ → τ(ν)q
} LFV

- 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

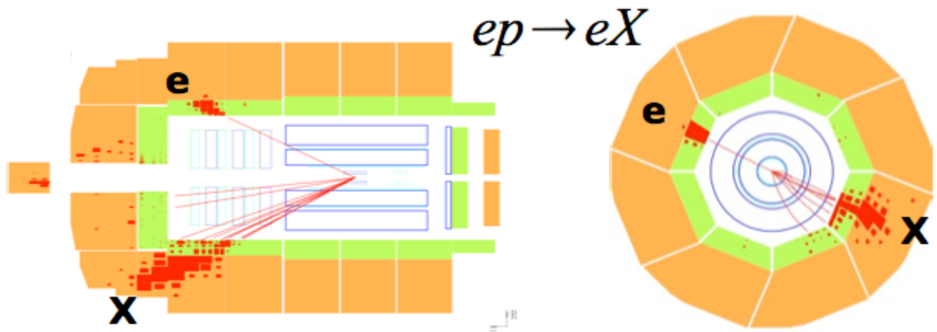
- Second and third generation searches: LQ → μq, τq
  - No CC contributions considered in the analysis, neutrino flavours indistinguishable
  - Branching ratio $\beta = \beta_\ell \times \beta_{LFV}$ with $\beta_{LFV} = \dfrac{\Gamma_{\mu(\tau)q}}{\Gamma_{\mu(\tau)q} + \Gamma_{eq}}$ and $\Gamma_{\ell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

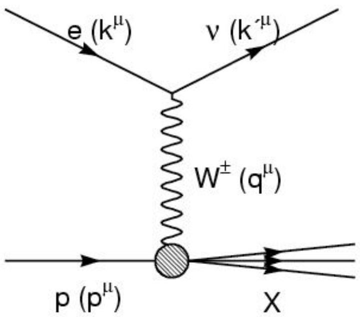
First Generation Search Background: High Q^2 NC and CC

- Final state indistinguishable from SM NC/CC DIS: jet + electron/neutrino
  - Selection based on the inclusive DIS analyses
  - Look for enhancements in mass spectra

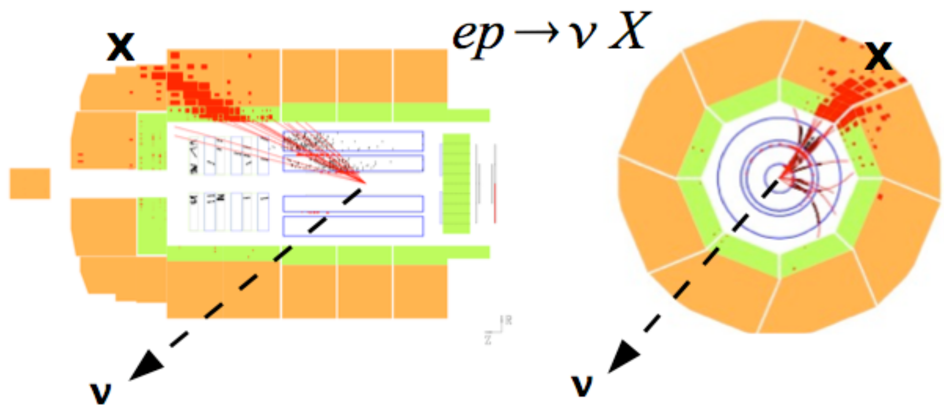


- Main NC Selection Criteria
  - Isolated electron
  - $E_e > 11$ GeV
  - $Q_e^2 > 500$ GeV^2
  - $0.1 < y_e < 0.9$

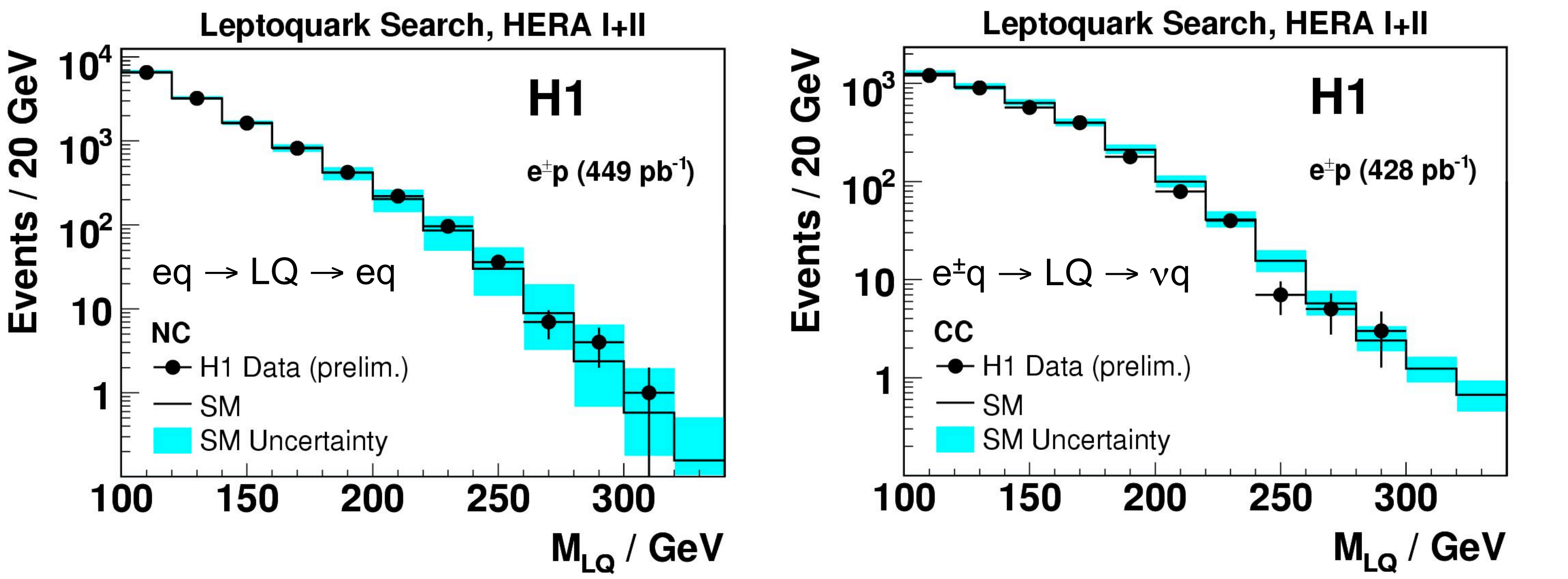




- Main CC Selection Criteria
  - $P_T^{miss} > 12$ GeV
  - $Q_h^2 > 1000$ GeV^2
  - $0.1 < y_h < 0.9$



Mass Plots in the First Generation Search



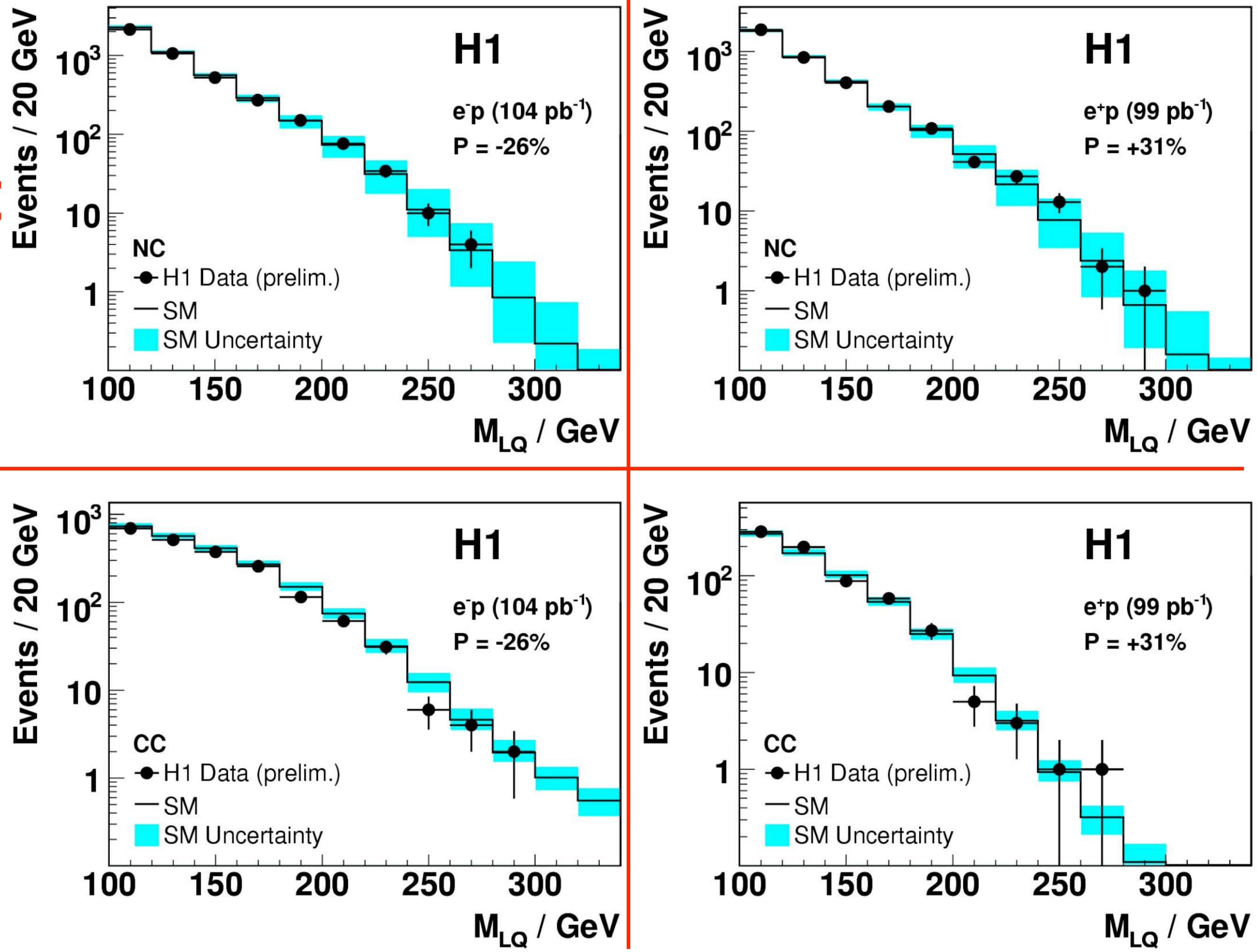
- Good description of data by the prediction no significant deviation from SM
- Analysis also performed in separate polarisation running periods
- No evidence for LQ signal: interpret in terms of exclusion limits

1st Generation LQ Search in HERA II Polarisation Periods

left handed e^-p | right handed e^+p

NC

CC



- Data analysis takes into account the different polarisation periods
- Good description of the H1 data by the SM prediction
- Similar for LH e^+p and RH e^-p

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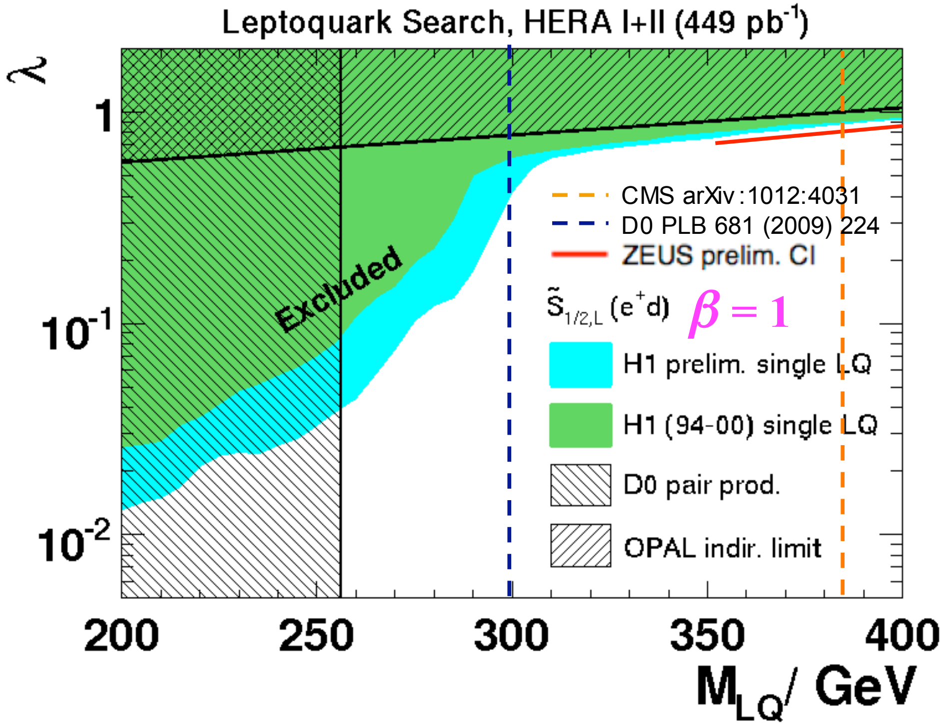
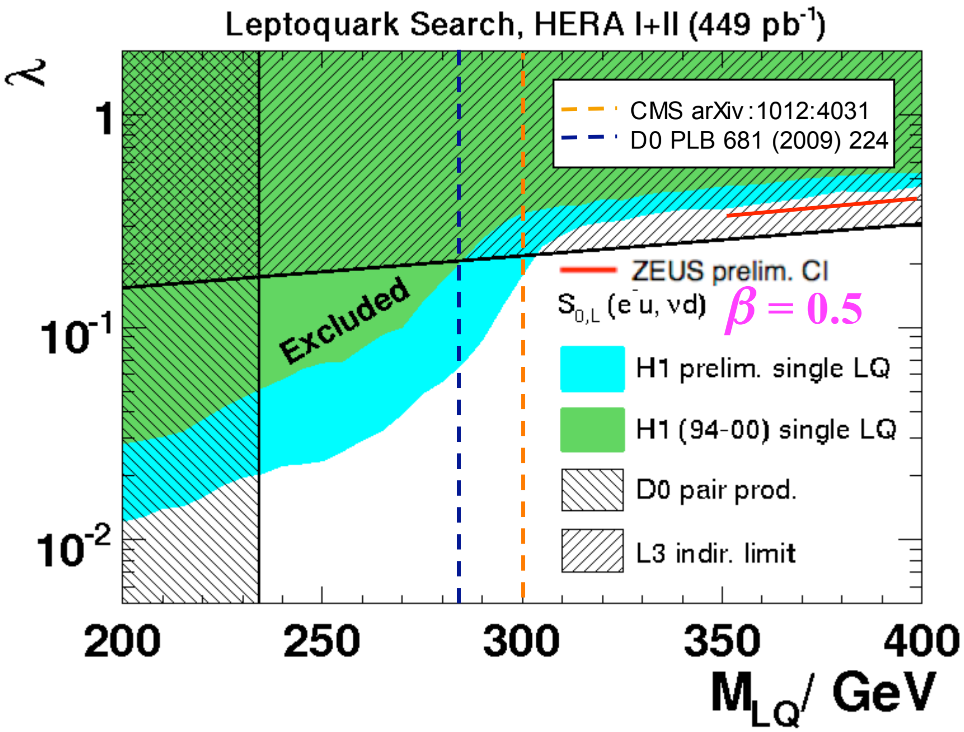
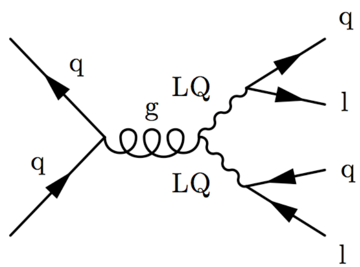
First Generation Leptoquark Search: Example Limits





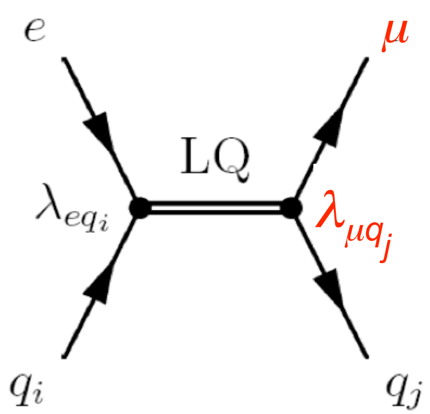
> For a coupling of electromagnetic strength $\lambda = 0.3$, LQ masses in the range 291-330 GeV ruled out @ 95% C.L.

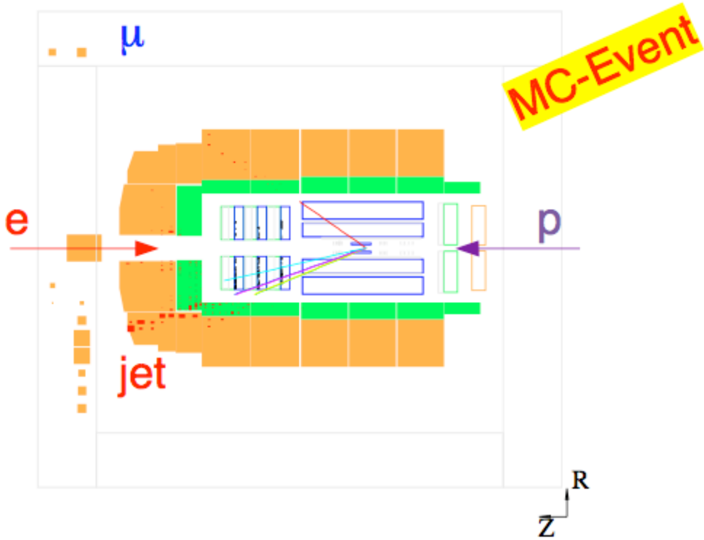
- H1 limits in the resonant LQ production region now superseded by those from the Tevatron and LHC (pair production, independent of λ)

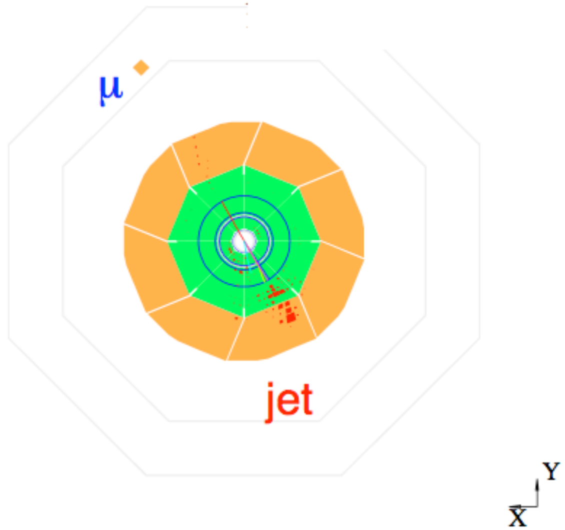


> Still some H1 sensitivity in the CI region, for large values of λ

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°
- 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

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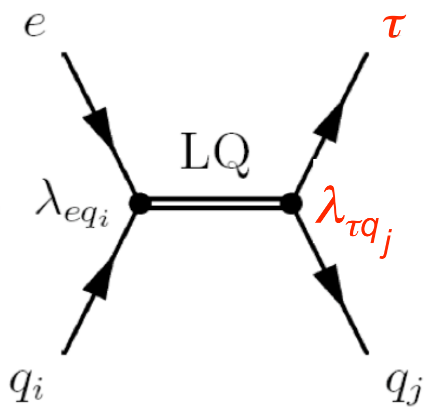
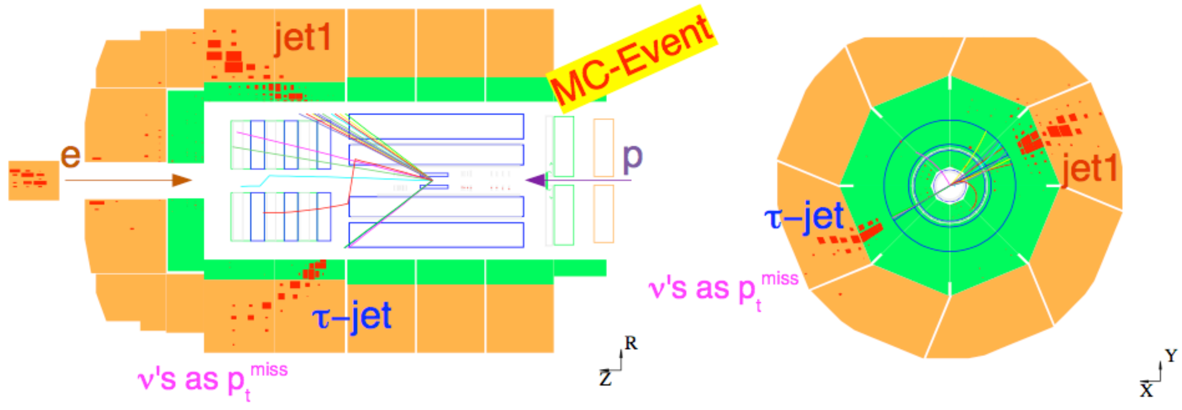
Search for LFV: Third Generation Leptoquarks

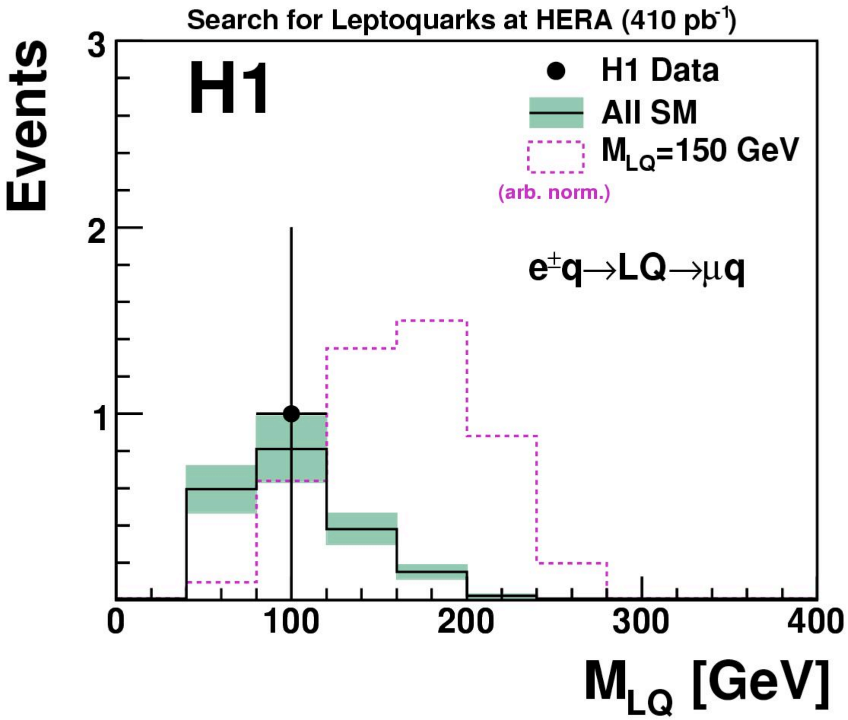




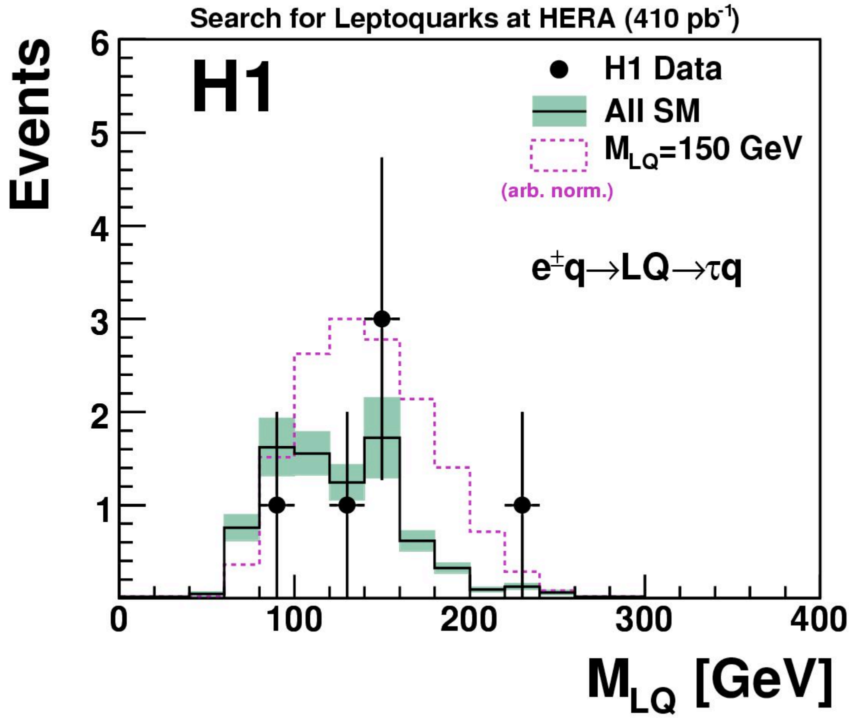
- Tau lepton with hadronic decay: search covers 1 prong decays, BR about 50%
- Narrow, pencil-like jet with one track back-to-back with a hadronic jet
- Main selection criteria:
  - Di-jet selection, P_T^{jet1} > 20 GeV, P_T^{jet2} > 15 GeV
  - Narrow tau-jet with R_{jet} < 0.12, isolated from other 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 Plots in the Second and Third Generation Searches

Muon Channel

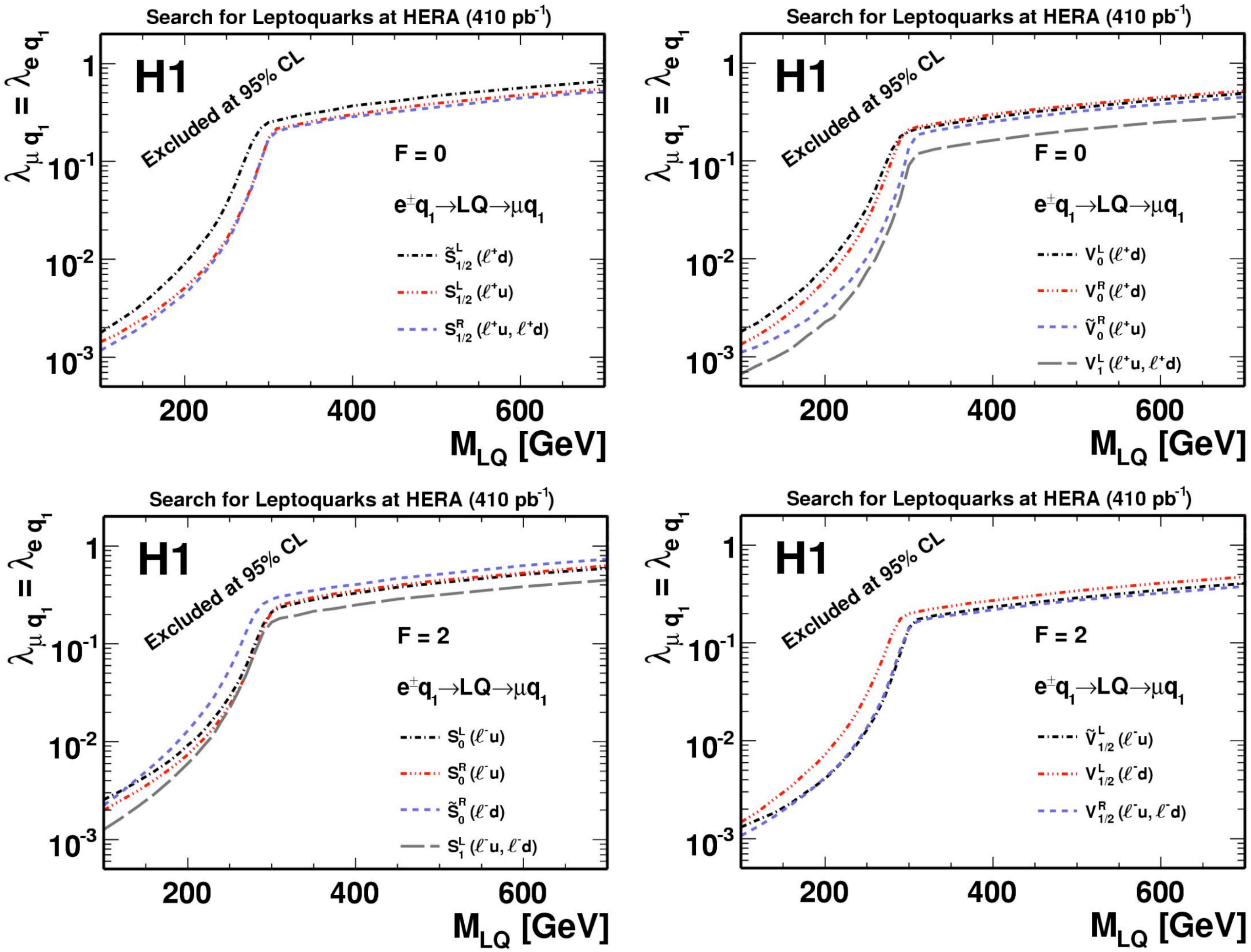


Tau Channel with 1-p hadronic decay



- 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

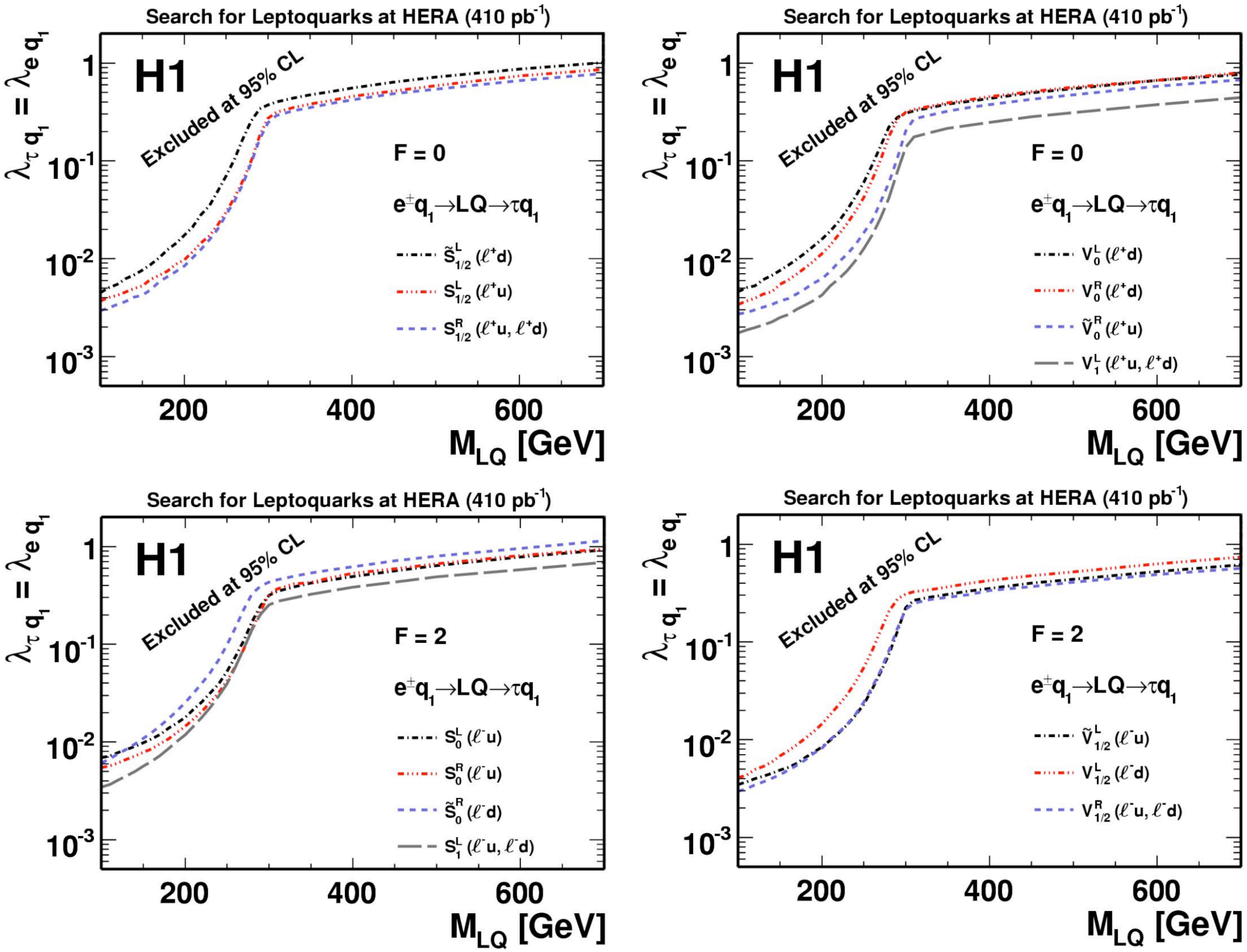
LQ Limits in the Second Generation Search



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

$\beta_{LFV} = 0.5$

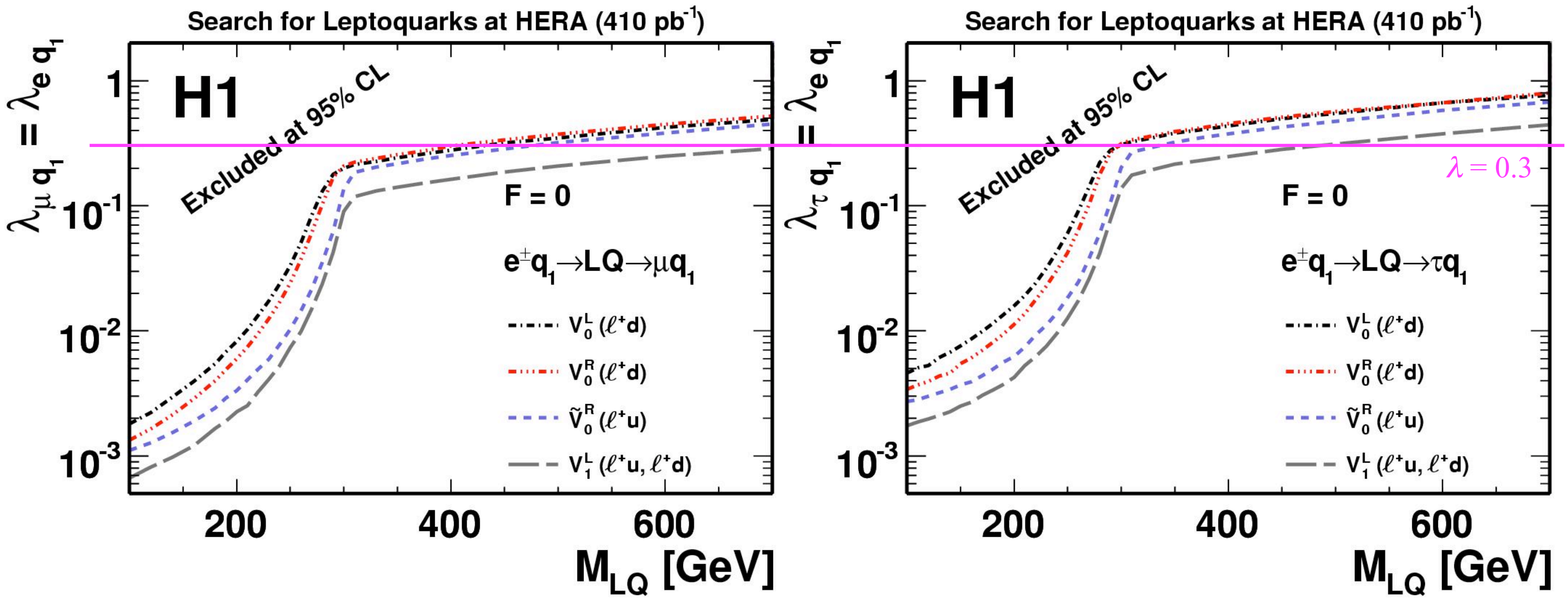
LQ Limits in the Third Generation Search



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

$\beta_{LFV} = 0.5$

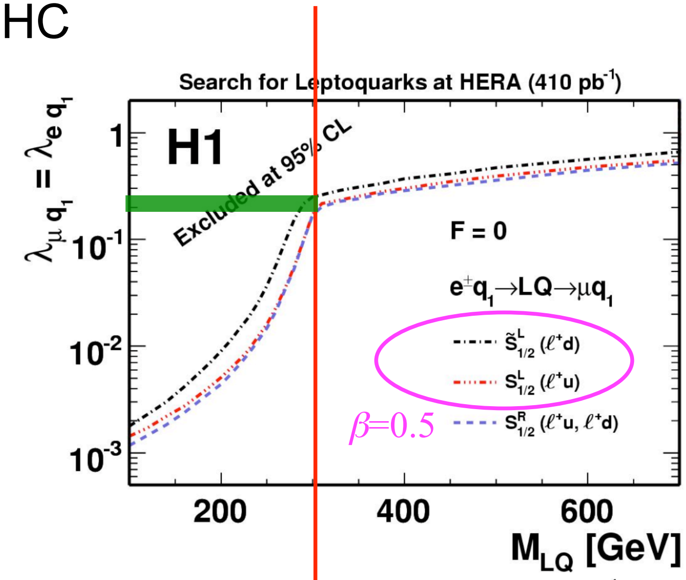
Most Stringent H1 Limits



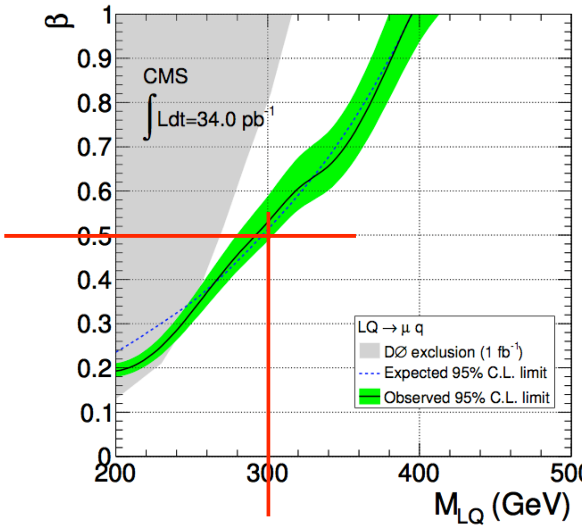
- In both cases V_1^L LQ has most stringent limits, sensitivity to both u and d quarks
- For a coupling of electromagnetic strength $\lambda = 0.3$ LQs mediating LFV via:
  - eq → LQ → μq are ruled out up to 712 GeV
  - eq → LQ → τq are ruled out up to 479 GeV

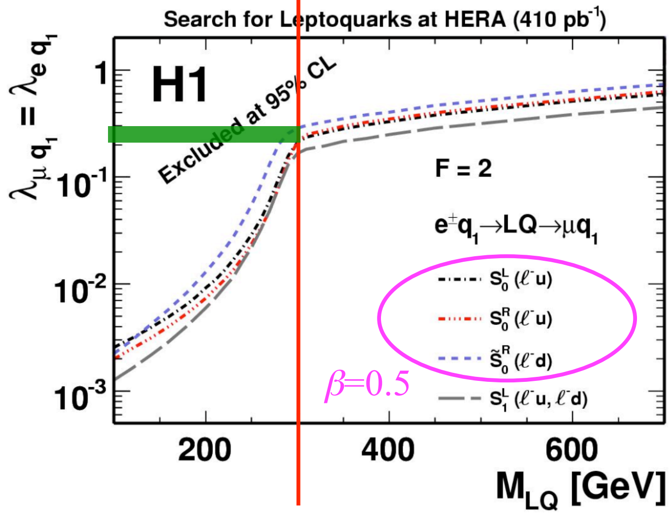
Comparison of H1 LFV Limits with those from Hadron Colliders

- 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
  - 247 GeV for β=1 from D0 scalar LQ search
  - 317 GeV for β=1 from CDF vector LQ search (YM coupling)
- Highest excluded mass in a 2nd generation search
  - 394 GeV for β=1 from CMS scalar LQ search



- More appropriate value to compare to HERA is β=0.5
  - For β=0.5 the CMS limit is ~ 300 GeV
  - For this mass, and for such LQs, H1 excludes couplings in the range λ=0.2-0.3





Comparison with Low Energy Experiments

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

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

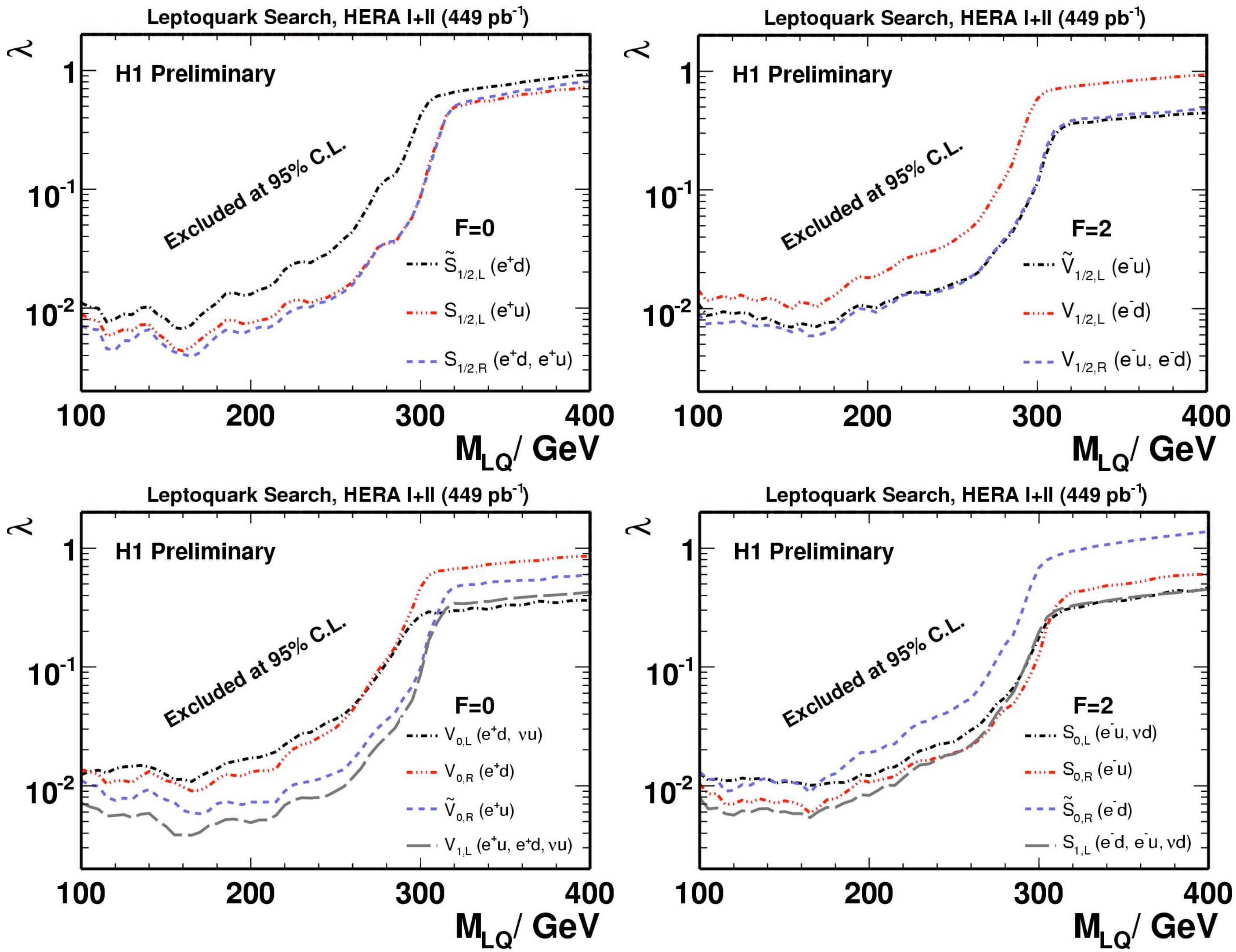
q_iq_j	$S^L_{1/2}$ ($\ell^-\bar{U}$, ℓ^+U)	$S^R_{1/2}$ ($\ell^-\bar{U},\ell^-\bar{D}$, ℓ^+U,ℓ^+D)	$\tilde{S}^L_{1/2}$ ($\ell^-\bar{D}$, ℓ^+D)	V^L_0 ($\ell^-\bar{D}$, ℓ^+D)	V^R_0 ($\ell^-\bar{D}$, ℓ^+D)	$\tilde{V}^R_0$ ($\ell^-\bar{U}$, ℓ^+U)	V^L_1 ($\ell^-\bar{U},\ell^-\bar{D}$, ℓ^+U,ℓ^+D)
1 1	$\tau\to\pi e$ 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**

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 $\lambda = 0.3$
- Further improvement possible by combining H1 and ZEUS to include the full HERA data set, before the LHC takes over

Extras Slides

H1 1st Generation Limits for all 14 Leptoquark Types



> For λ=0.3 leptoquark masses in the range 291-330 GeV are ruled out @ 95% CL

Comparison of H1 Limits to Low Energy Experiments, 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 Limits to Low Energy Experiments, F=2 LQs

$ep \to \mu X$			H1			$F=2$	
Upper exclusion limits on $\lambda_{eq_i}\lambda_{\mu q_j}/m_{\mathrm{LQ}}^2$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL							
q_iq_j	S_0^L ℓ^-U $\ell^+\bar{U}$	S_0^R ℓ^-U $\ell^+\bar{U}$	$\tilde{S}_0^R$ ℓ^-D $\ell^+\bar{D}$	S_1^L ℓ^-U,ℓ^-D $\ell^+\bar{U},\ell^+\bar{D}$	$V_{1/2}^L$ ℓ^-D $\ell^+\bar{D}$	$V_{1/2}^R$ ℓ^-U,ℓ^-D $\ell^+\bar{U},\ell^+\bar{D}$	$\tilde{V}_{1/2}^L$ ℓ^-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 $\lambda_{eq_i}\lambda_{\tau q_j}/m_{\mathrm{LQ}}^2$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL							
q_iq_j	S_0^L ℓ^-U $\ell^+\bar{U}$	S_0^R ℓ^-U $\ell^+\bar{U}$	$\tilde{S}_0^R$ ℓ^-D $\ell^+\bar{D}$	S_1^L ℓ^-U,ℓ^-D $\ell^+\bar{U},\ell^+\bar{D}$	$V_{1/2}^L$ ℓ^-D $\ell^+\bar{D}$	$V_{1/2}^R$ ℓ^-U,ℓ^-D $\ell^+\bar{U},\ell^+\bar{D}$	$\tilde{V}_{1/2}^L$ ℓ^-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**	*