# Search for Lepton Flavour Violation at HERA.

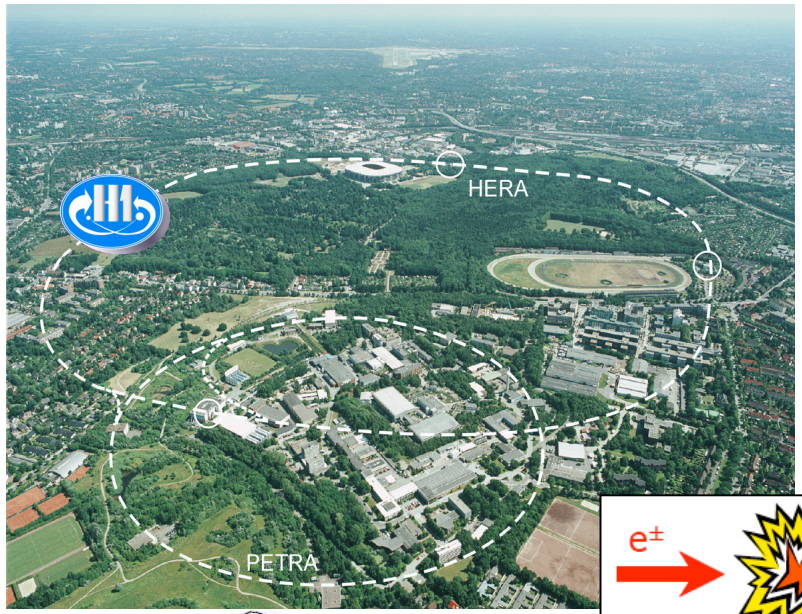
Leptoquarks at HERA
Search for First Generation Leptoquarks
Search for Second and Third Generation Leptoquarks *arXiv:1103.4938*
Conclusions

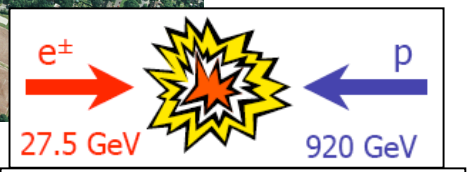
David South
on behalf of the H1 Collaboration
XIX International Workshop on Deep Inelastic Scattering and Related Subjects
Newport News, VI, USA 11-15 April 2011

HELMHOLTZ ASSOCIATION

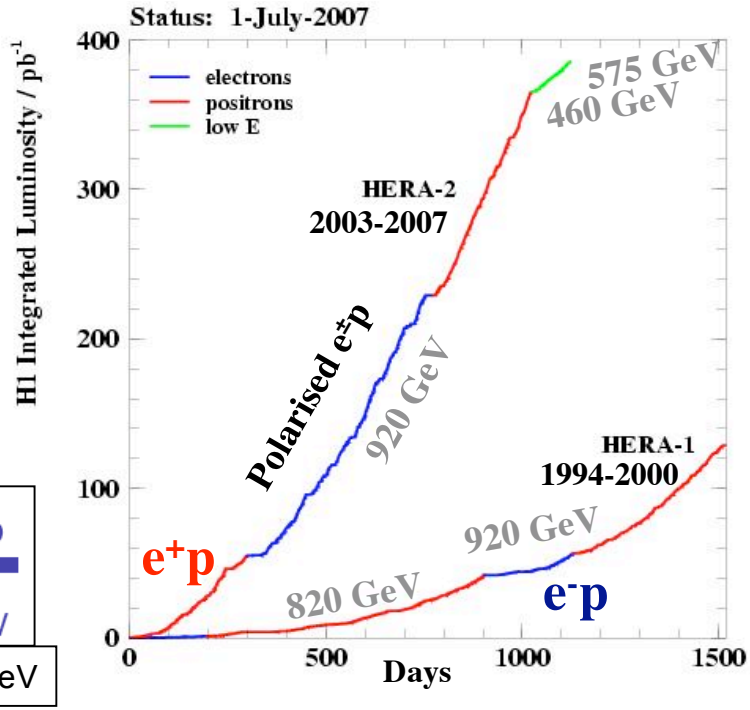
DESY

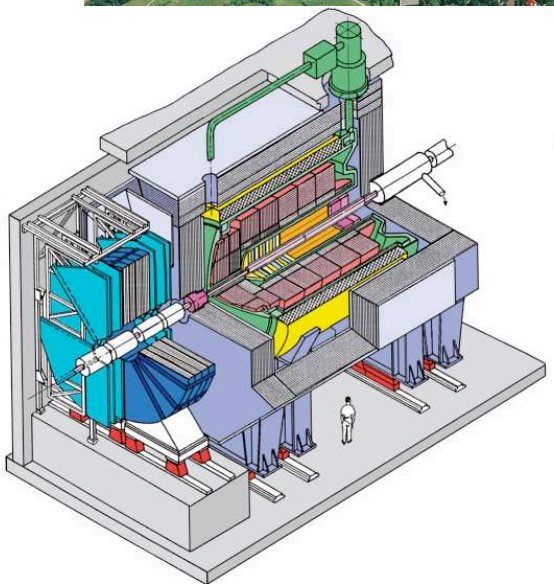
# The H1 Experiment at HERA




centre of mass √s = 319 GeV



- 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 $\lambda$ 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 $\mu$q or $\tau$q imply lepton flavour violation (LFV)

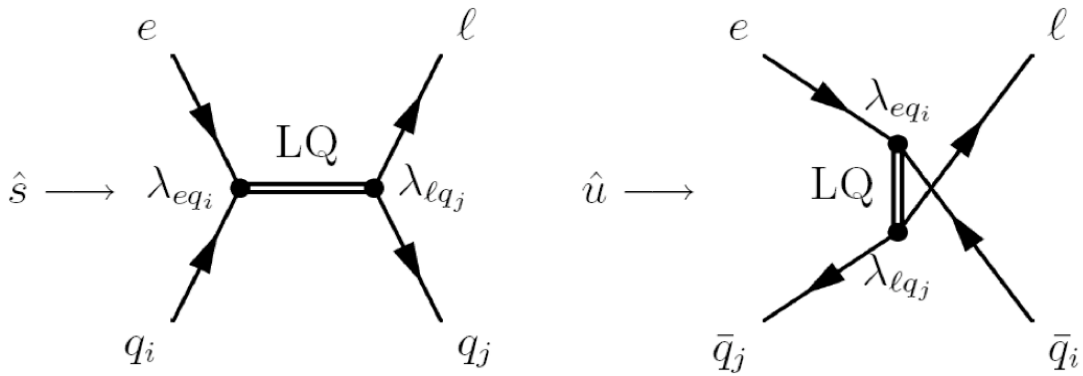
*Buchmüller, Rückl, Wyler, Phys. Lett. B191 (1987) 442

# 14 LQ types in the BRW Model

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

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

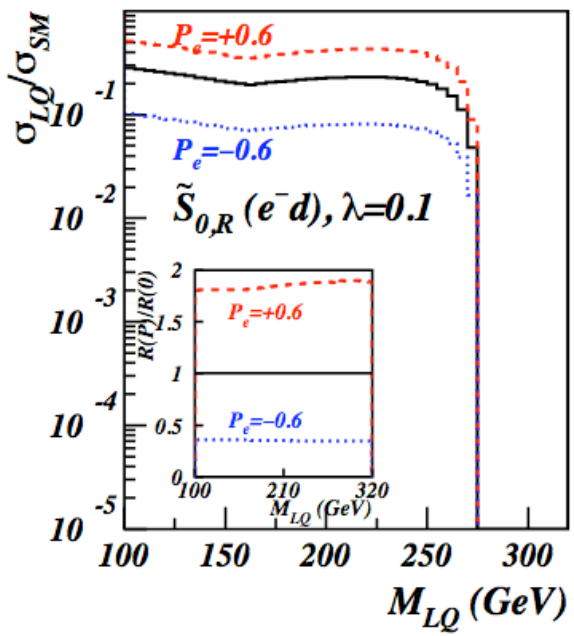
# Leptoquarks at HERA: Production




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

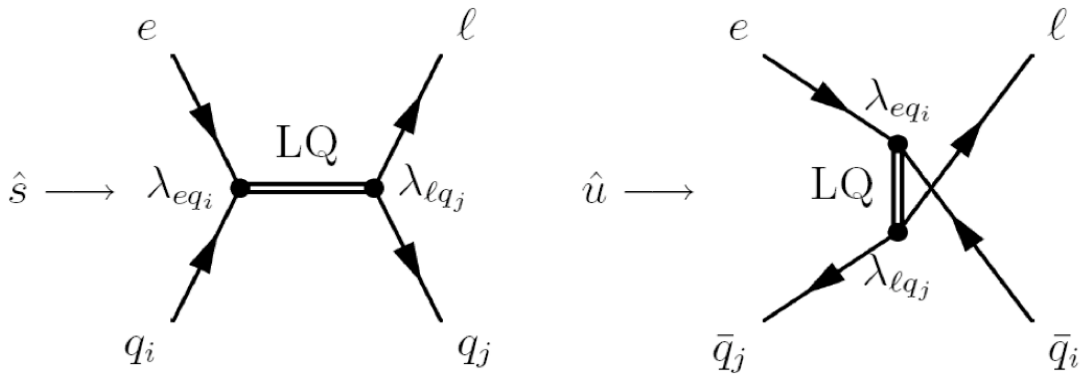
s-channel: resonant production
For $M_{LQ} \leq (sx)^{1/2}$
Cross section $\sigma \sim \lambda^2$

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



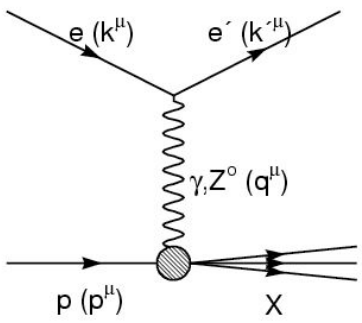

1st gen: eq → LQ → e(ν)q
2nd gen: eq → LQ → μ(ν)q
3rd gen: eq → LQ → τ(ν)q
} LFV

- 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

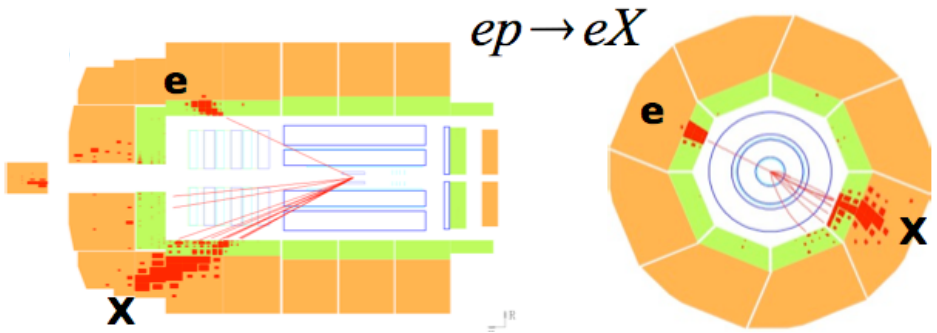
- Second and third generation searches: LQ → μq, τq
  - No CC contributions considered in the analysis, neutrino flavours indistinguishable
  - Branching ratio $\beta = \beta_\ell \times \beta_{LFV}$ with $\beta_{LFV} = \dfrac{\Gamma_{\mu(\tau)q}}{\Gamma_{\mu(\tau)q} + \Gamma_{eq}}$ and $\Gamma_{\ell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

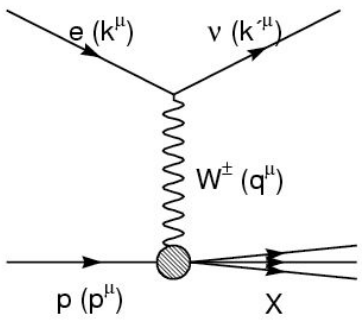
# First Generation Search Background: High $Q^2$ NC and CC

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

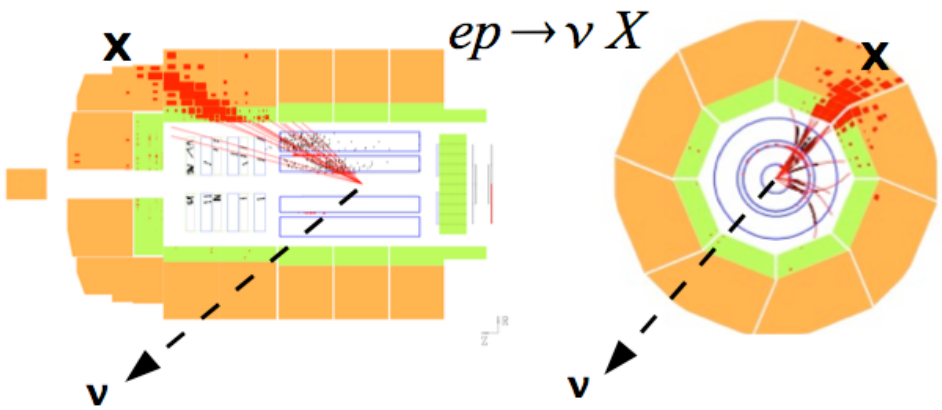



- Main NC Selection Criteria
  - Isolated electron
  - $E_e > 11$ GeV
  - $Q_e^2 > 500$ GeV$^2$
  - $0.1 < y_e < 0.9$

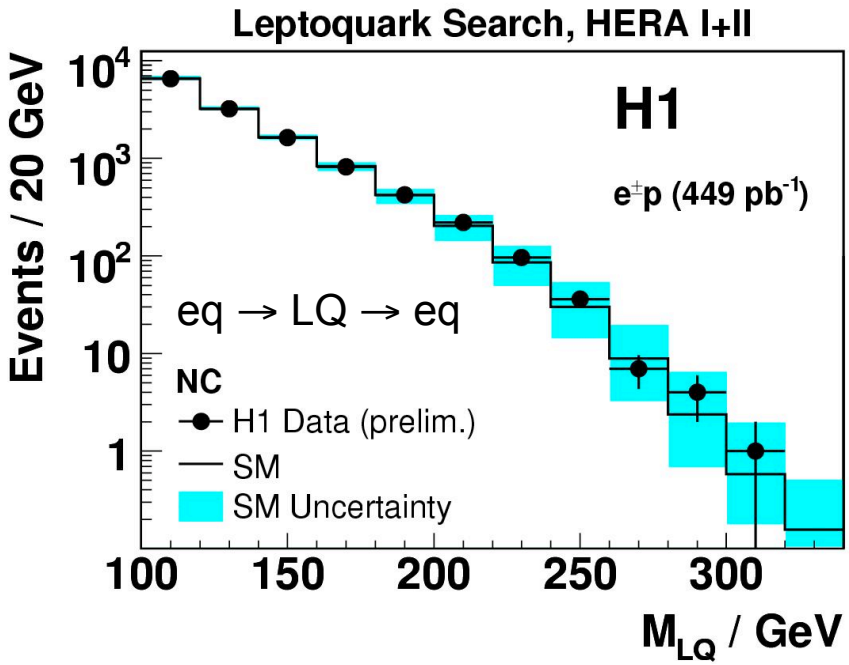


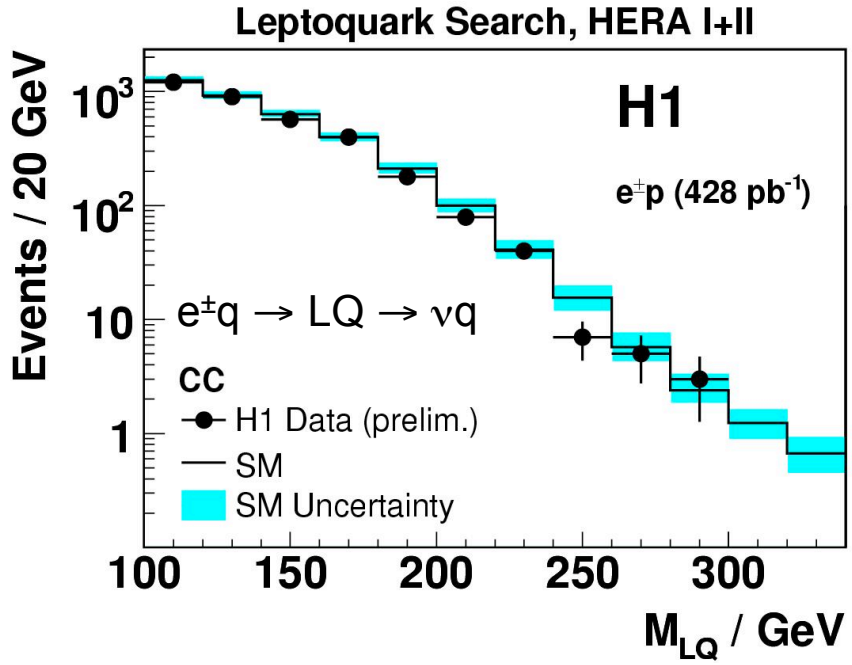




- Main CC Selection Criteria
  - $P_T^{miss} > 12$ GeV
  - $Q_h^2 > 1000$ GeV$^2$
  - $0.1 < y_h < 0.9$



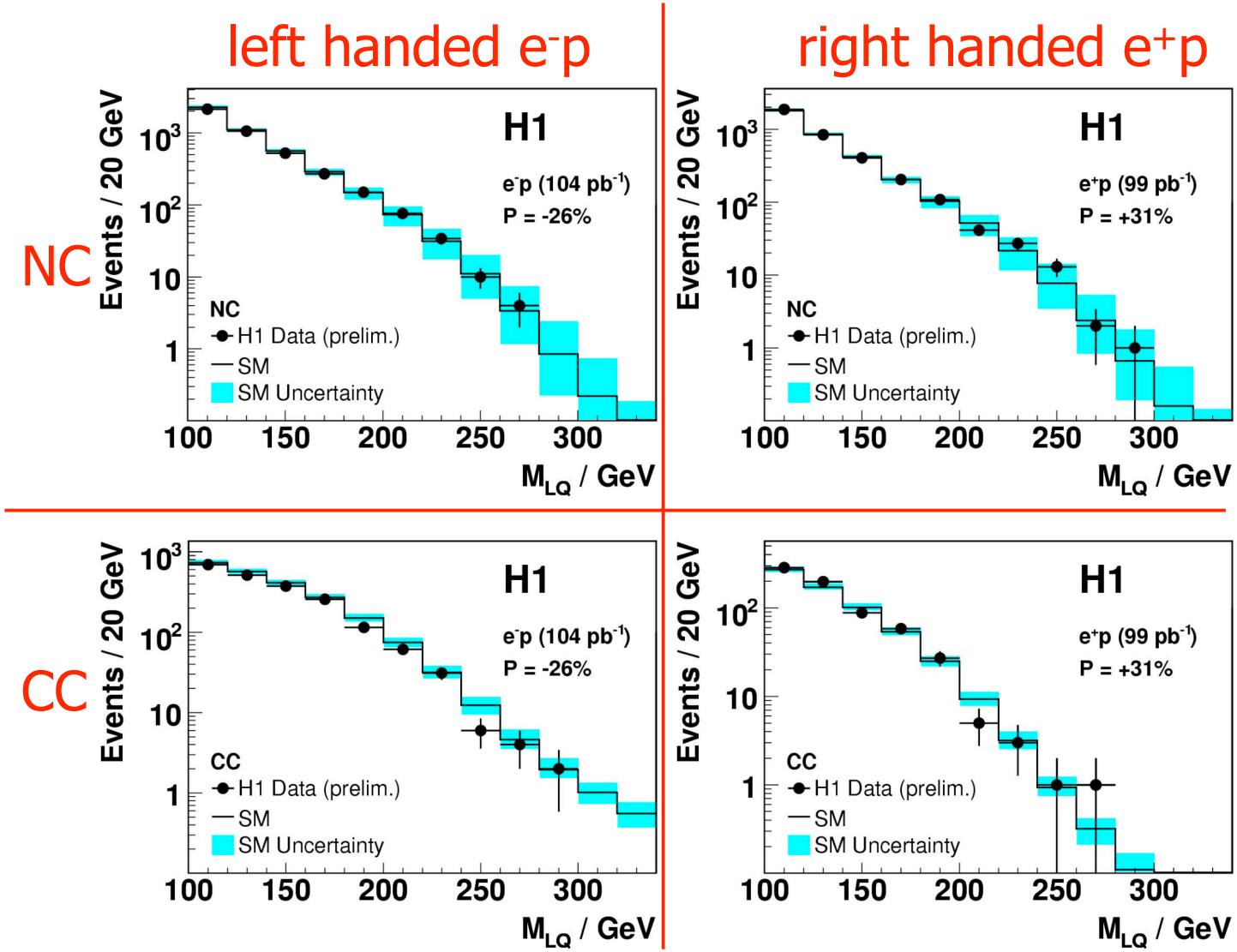
# Mass Plots in the First Generation Search



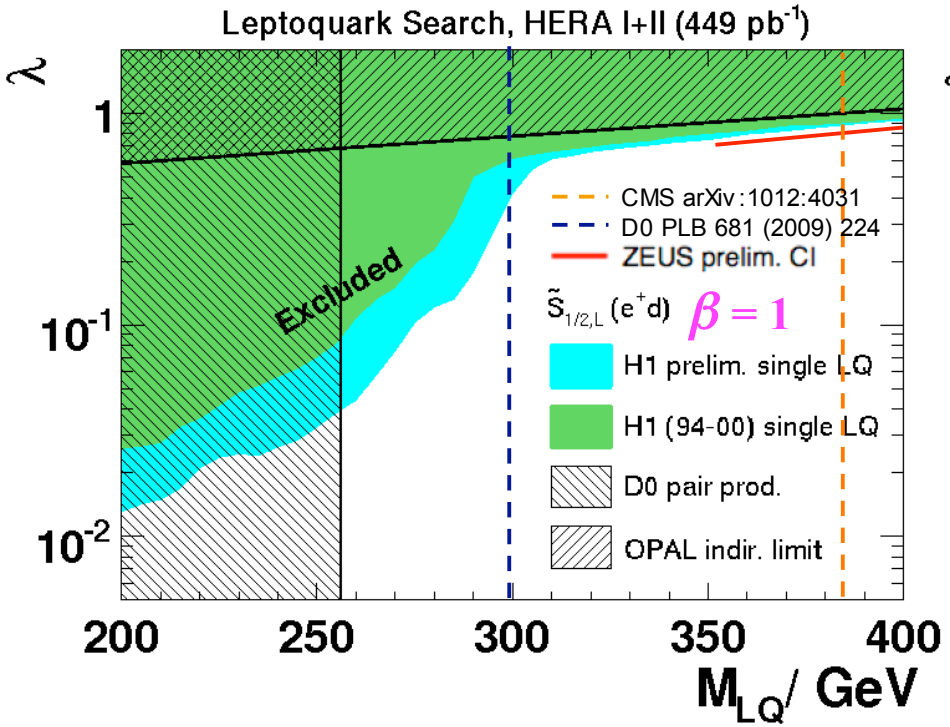

- Good description of data by the prediction no significant deviation from SM
- Analysis also performed in separate polarisation running periods
- No evidence for LQ signal: interpret in terms of exclusion limits

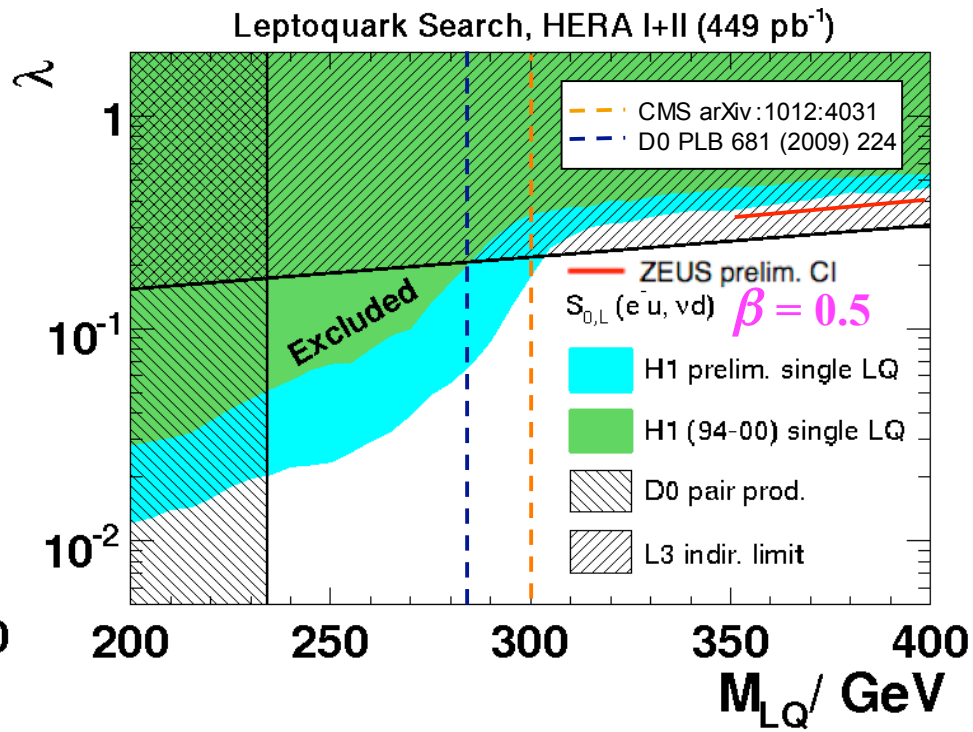
# 1st Generation LQ Search in HERA II Polarisation Periods



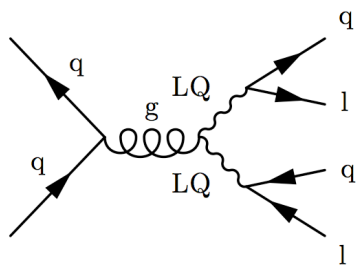

- Data analysis takes into account the different polarisation periods
- Good description of the H1 data by the SM prediction
- Similar for LH $e^+p$ and RH $e^-p$

# First Generation Leptoquark Search: Example Limits



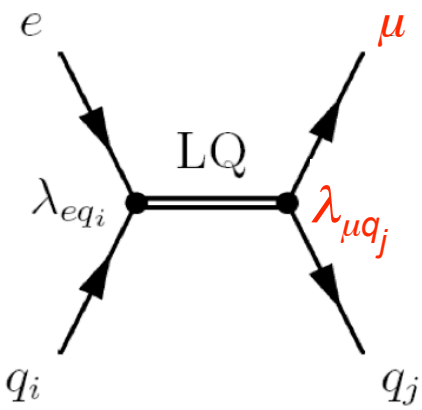



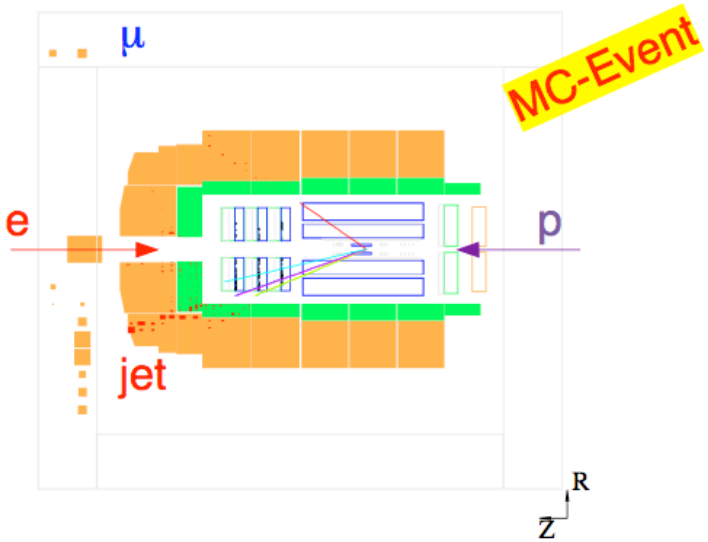

- For a coupling of electromagnetic strength $\lambda = 0.3$, LQ masses in the range 291-330 GeV ruled out @ 95% C.L.
  - H1 limits in the resonant LQ production region now superseded by those from the Tevatron and LHC (pair production, independent of $\lambda$)

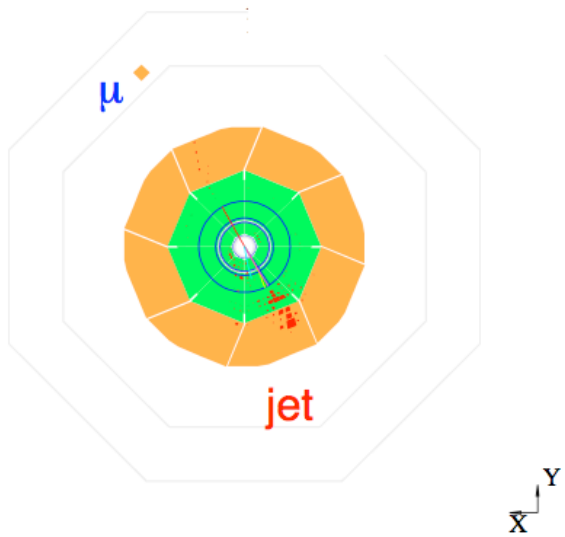



- Still some H1 sensitivity in the CI region, for large values of $\lambda$

# Search for LFV: Second Generation Leptoquarks

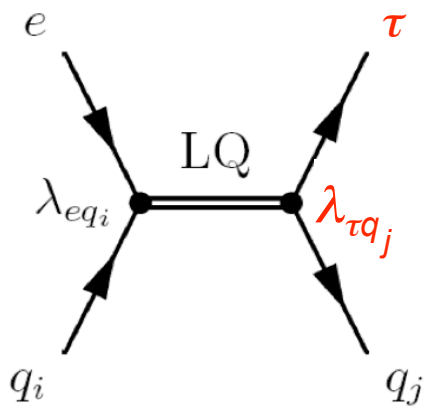


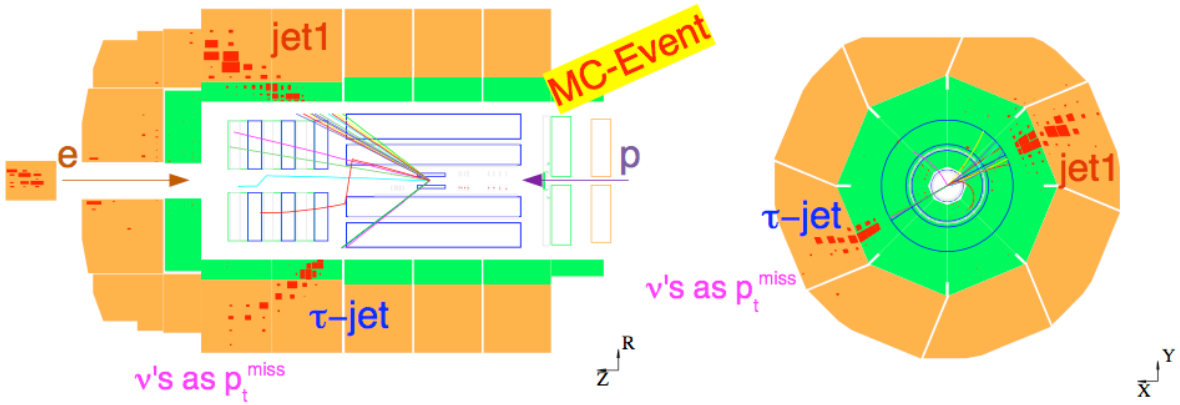




- High $P_T$ muon back-to-back with a high $P_T$ jet
- Clean experimental signature, essentially free from SM background
- Main selection criteria:
  - One well measured, isolated muon with $P_T$ > 8 GeV in the central region of the detector
  - Large missing transverse momentum in the calorimeter $P_T^{calo}$ > 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

# Search for LFV: Third Generation Leptoquarks

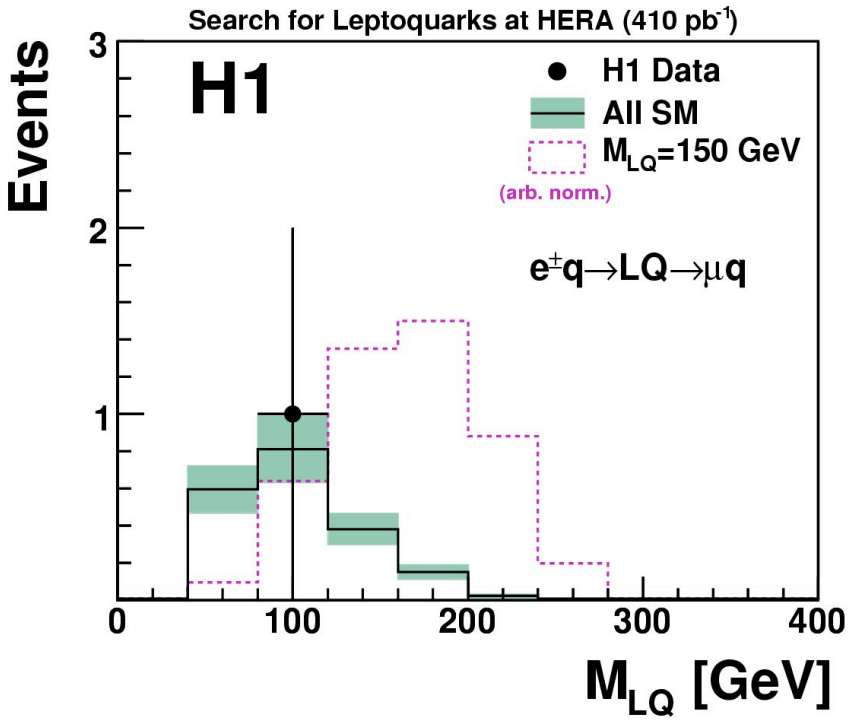


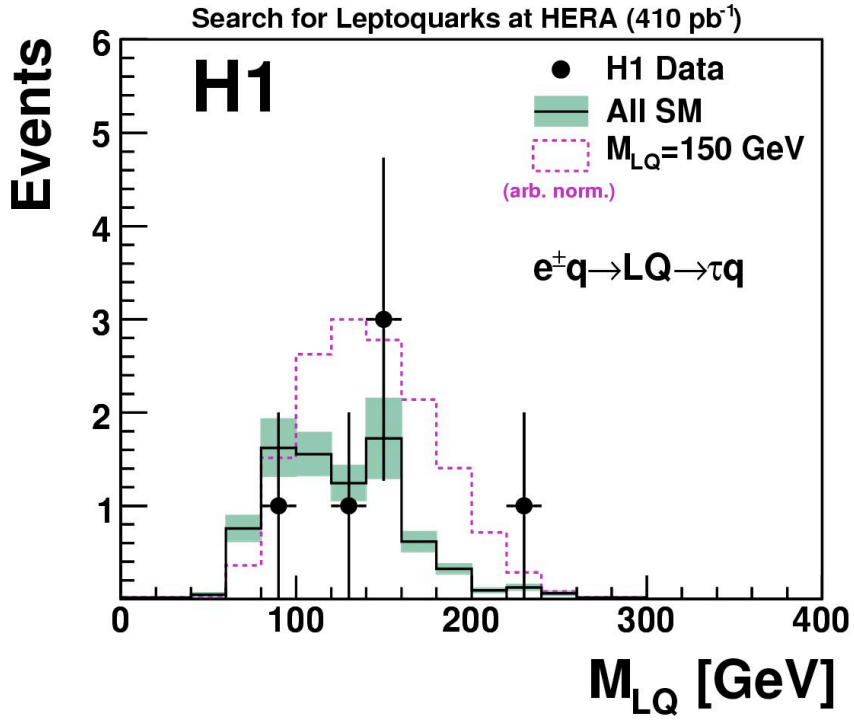

- Tau lepton with hadronic decay: search covers 1 prong decays, BR about 50%
- Narrow, pencil-like jet with one track back-to-back with a hadronic jet
- Main selection criteria:
  - Di-jet selection, $P_T^{jet1} > 20$ GeV, $P_T^{jet2} > 15$ GeV
  - Narrow tau-jet with $R_{jet} < 0.12$, isolated from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

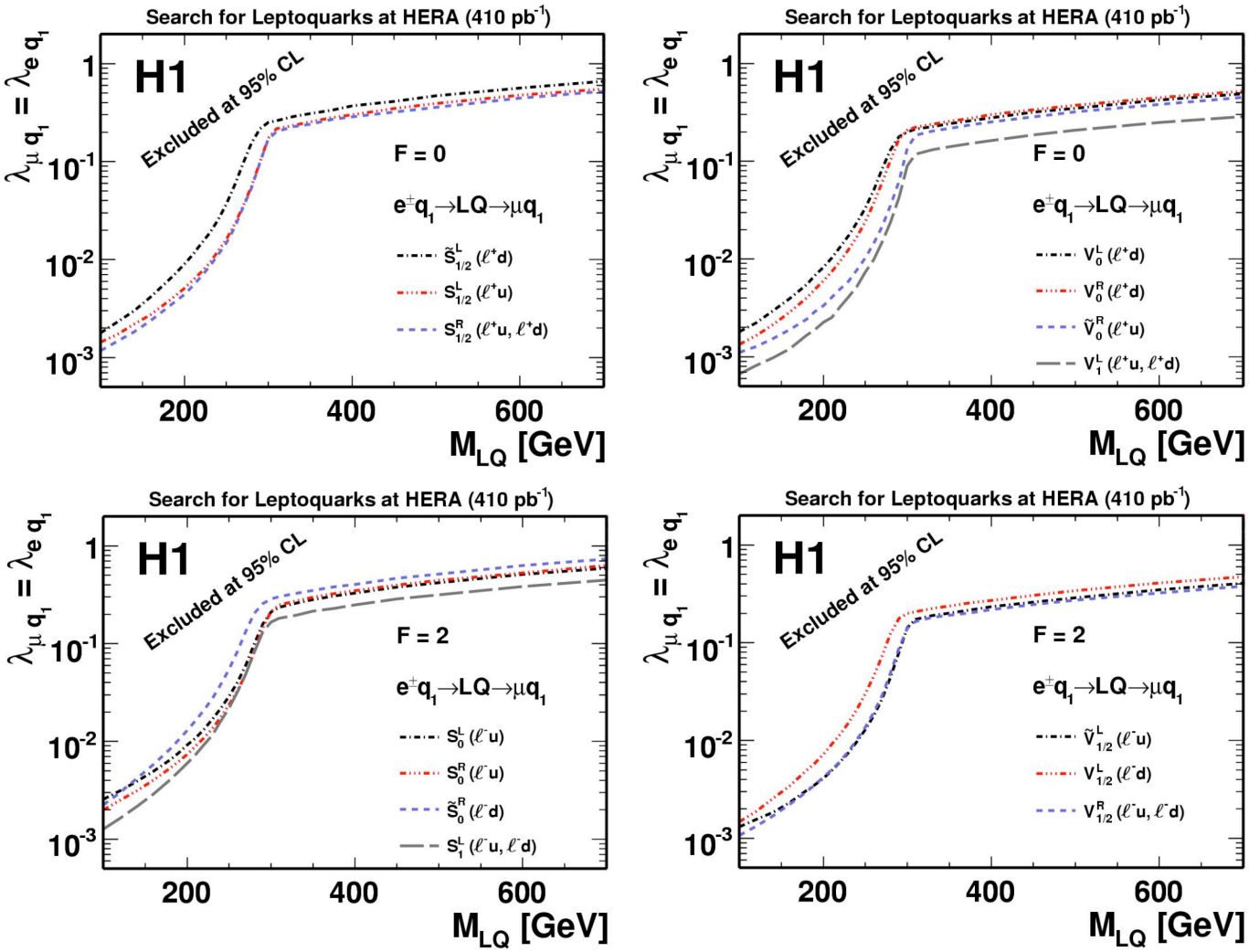



**Tau Channel with 1-p hadronic decay**




- 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

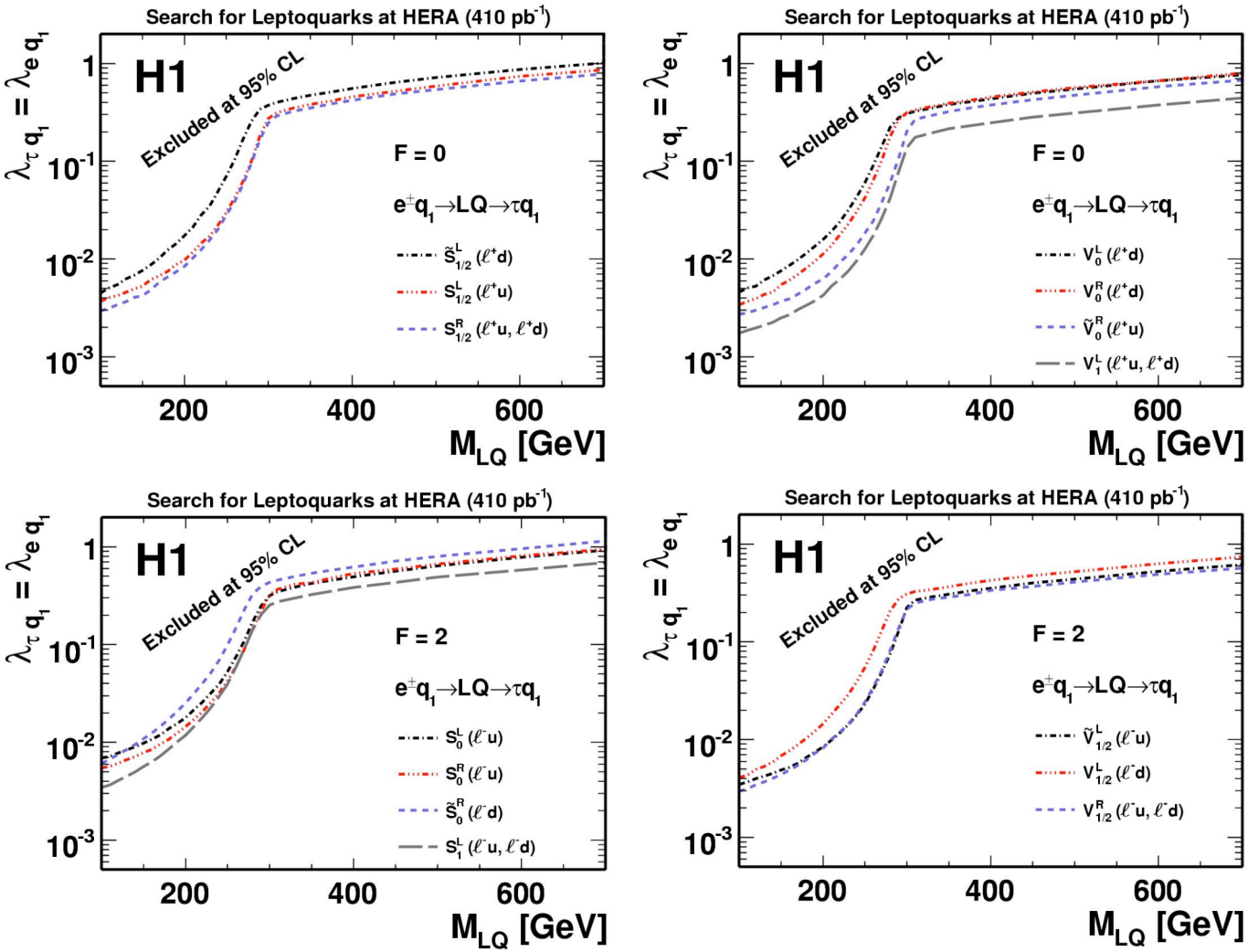
# LQ Limits in the Second Generation Search




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

$\beta_{LFV} = 0.5$

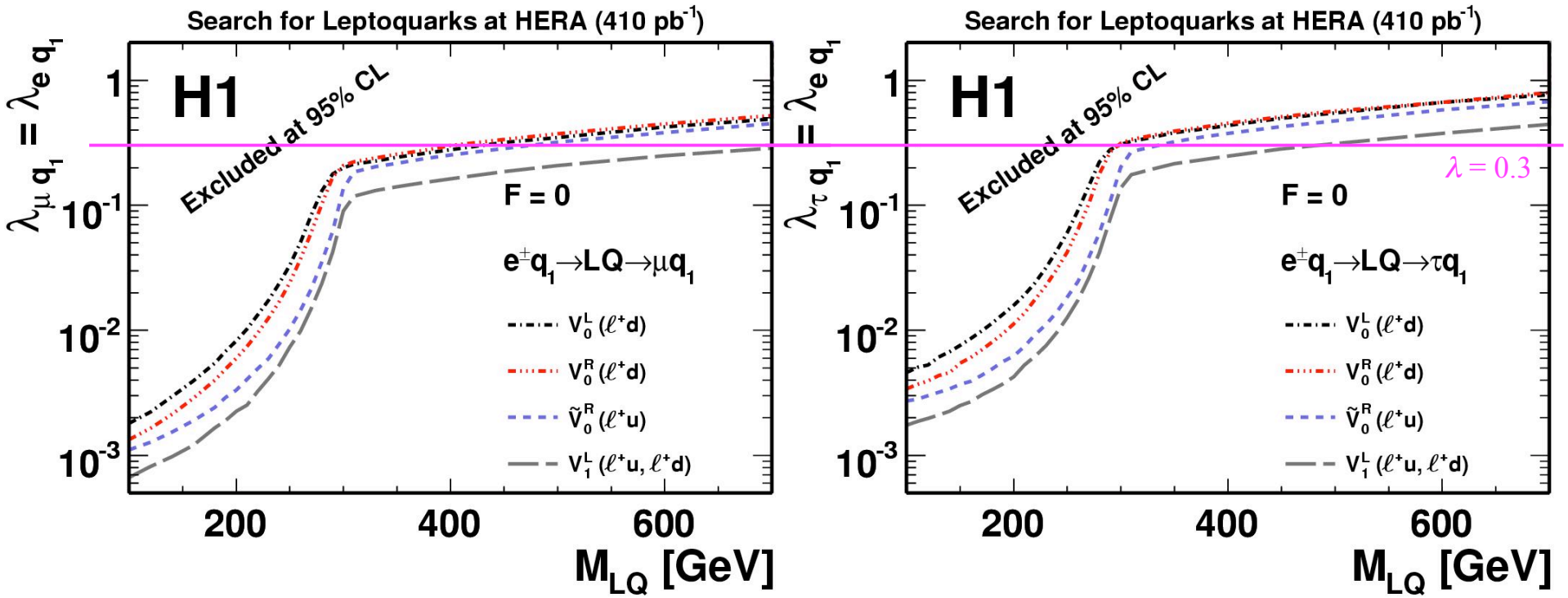
# LQ Limits in the Third Generation Search




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

$\beta_{LFV} = 0.5$

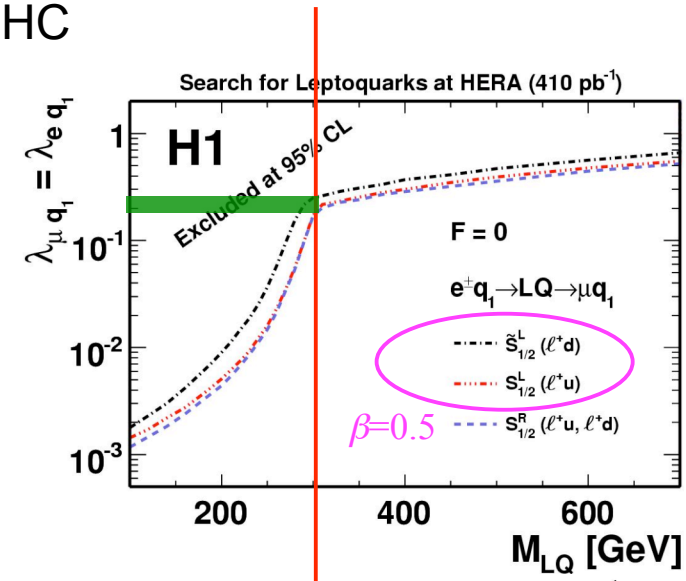
# Most Stringent H1 Limits

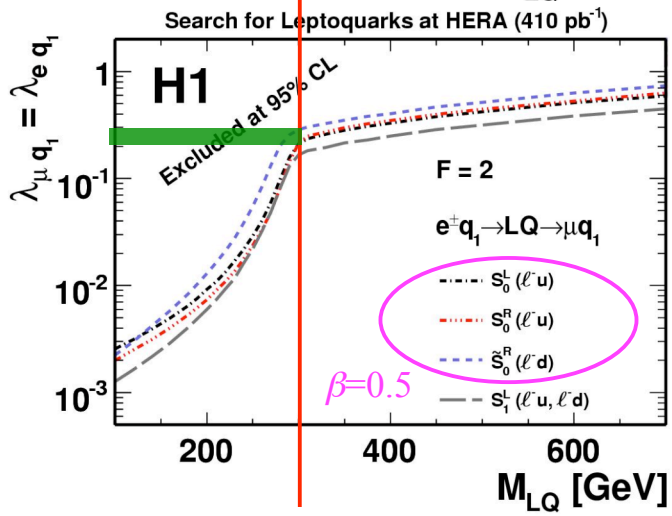


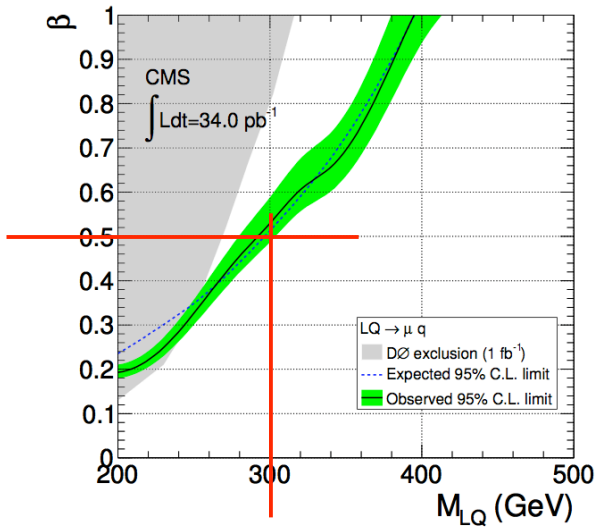

- In both cases $V_1^L$ LQ has most stringent limits, sensitivity to both u and d quarks
- For a coupling of electromagnetic strength $\lambda = 0.3$ LQs mediating LFV via:
  - $eq \rightarrow LQ \rightarrow \mu q$ are ruled out up to 712 GeV
  - $eq \rightarrow LQ \rightarrow \tau q$ are ruled out up 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 $\lambda$
- Highest excluded mass in a 3rd generation search
  - 247 GeV for $\beta$=1 from D0 scalar LQ search
  - 317 GeV for $\beta$=1 from CDF vector LQ search (YM coupling)
- Highest excluded mass in a 2nd generation search
  - 394 GeV for $\beta$=1 from CMS scalar LQ search
- More appropriate value to compare to HERA is $\beta$=0.5
  - For $\beta$=0.5 the CMS limit is ~ 300 GeV
  - For this mass, and for such LQs, H1 excludes couplings in the range $\lambda$=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 $\lambda_{eq_i}\lambda_{\tau q_j}/m^2_{\mathrm{LQ}}$ ($\mathrm{TeV}^{-2}$) for lepton flavour violating leptoquarks at 95% CL | | | | | | | |
| $q_iq_j$ | $S^L_{1/2}$ $\ell^-\bar{U}$ $\ell^+U$ | $S^R_{1/2}$ $\ell^-\bar{U}, \ell^-\bar{D}$ $\ell^+U, \ell^+D$ | $\tilde{S}^L_{1/2}$ $\ell^-\bar{D}$ $\ell^+D$ | $V^L_0$ $\ell^-\bar{D}$ $\ell^+D$ | $V^R_0$ $\ell^-\bar{D}$ $\ell^+D$ | $\tilde{V}^R_0$ $\ell^-\bar{U}$ $\ell^+U$ | $V^L_1$ $\ell^-\bar{U}, \ell^-\bar{D}$ $\ell^+U, \ell^+D$ |
| 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** | $K \rightarrow \pi\nu\bar{\nu}$ $5.8 \times 10^{-4}$ **2.2** | $\tau \rightarrow Ke$ 0.02 **1.5** | $\tau \rightarrow Ke$ 0.02 **1.6** | **1.2** | $K \rightarrow \pi\nu\bar{\nu}$ $1.5 \times 10^{-4}$ **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** | $K \rightarrow \pi\nu\bar{\nu}$ $5.8 \times 10^{-4}$ **3.9** | $\tau \rightarrow Ke$ 0.02 **1.5** | $\tau \rightarrow Ke$ 0.02 **1.6** | **1.2** | $K \rightarrow \pi\nu\bar{\nu}$ $1.5 \times 10^{-4}$ **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

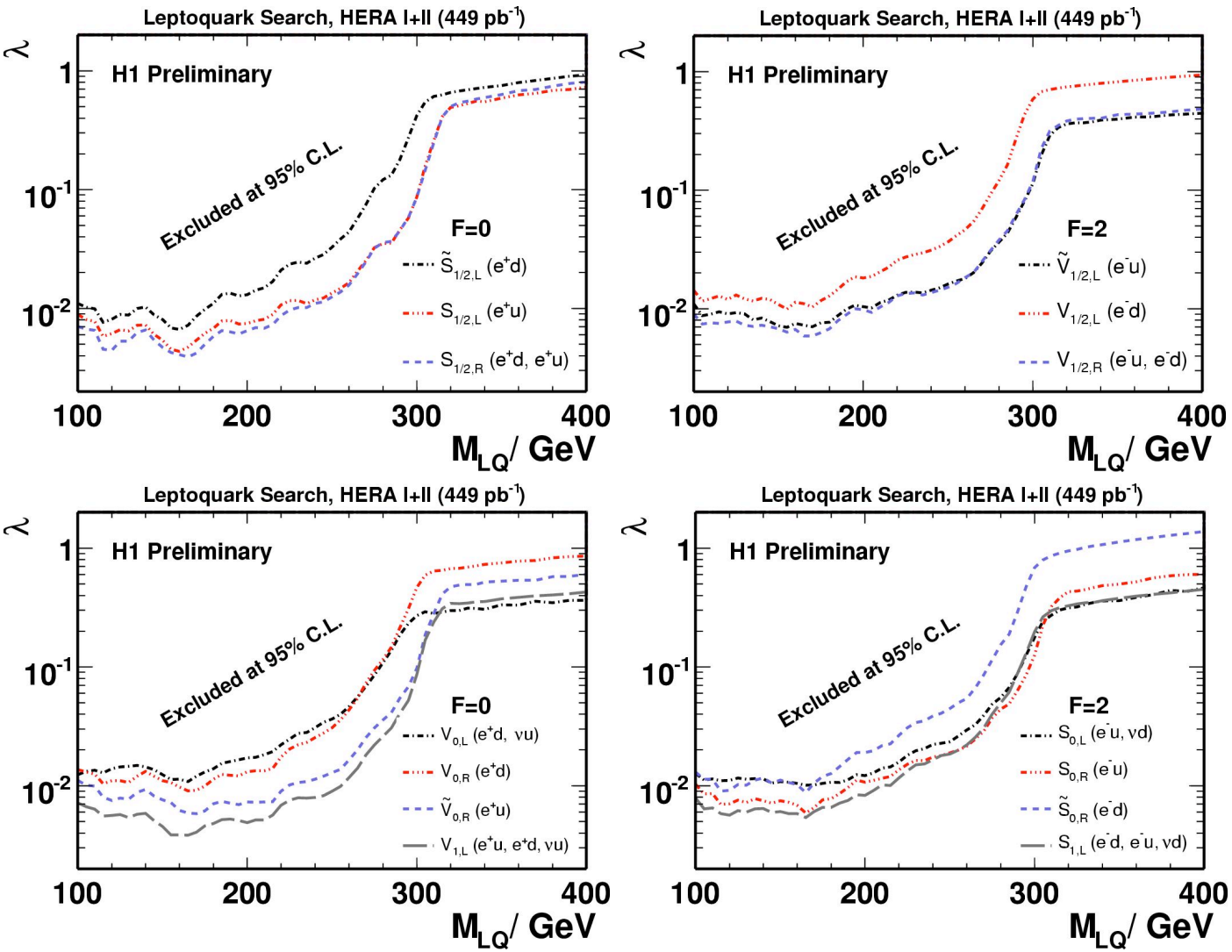
- Searches for LQs of all generations have been performed by the H1 experiment using the complete high energy data taken at $\sqrt{s}$ = 319 GeV

- No significant deviation from the SM observed and limits are set on the production of such particles
  - For large values of the coupling $\lambda$, 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 $\lambda$=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 $\lambda_{eq_i}\lambda_{\mu q_j}/m^2_{\mathrm{LQ}}$ (TeV$^{-2}$) for lepton flavour violating leptoquarks at 95% CL | | | | | | | |
| $q_i q_j$ | $S^L_{1/2}$ $\ell^-\bar{U}$ $\ell^+U$ | $S^R_{1/2}$ $\ell^-\bar{U}, \ell^-\bar{D}$ $\ell^+U, \ell^+D$ | $\tilde{S}^L_{1/2}$ $\ell^-\bar{D}$ $\ell^+D$ | $V^L_0$ $\ell^-\bar{D}$ $\ell^+D$ | $V^R_0$ $\ell^-\bar{D}$ $\ell^+D$ | $\tilde{V}^R_0$ $\ell^-\bar{U}$ $\ell^+U$ | $V^L_1$ $\ell^-\bar{U}, \ell^-\bar{D}$ $\ell^+U, \ell^+D$ |
| 1 1 | $\mu N \to eN$ $5.2 \times 10^{-5}$ **0.6** | $\mu N \to eN$ $2.6 \times 10^{-5}$ **0.6** | $\mu N \to eN$ $5.2 \times 10^{-5}$ **0.9** | $\mu N \to eN$ $2.6 \times 10^{-5}$ **0.5** | $\mu N \to eN$ $2.6 \times 10^{-5}$ **0.6** | $\mu N \to eN$ $2.6 \times 10^{-5}$ **0.4** | $\mu N \to eN$ $0.8 \times 10^{-5}$ **0.2** |
| 1 2 | $D \to \mu\bar{e}$ 0.8 **0.7** | $K \to \mu\bar{e}$ $2 \times 10^{-5}$ **0.5** | $K \to \mu\bar{e}$ $2 \times 10^{-5}$ **0.9** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.6** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.7** | $D \to \mu\bar{e}$ 0.4 **0.5** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **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** | $K \to \mu\bar{e}$ $2 \times 10^{-5}$ **1.2** | $K \to \mu\bar{e}$ $2 \times 10^{-5}$ **1.5** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.6** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.7** | $D \to \mu\bar{e}$ 0.4 **0.5** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.2** |
| 2 2 | $\mu N \to eN$ $9.2 \times 10^{-4}$ **2.4** | $\mu N \to eN$ $1.3 \times 10^{-3}$ **1.7** | $\mu N \to eN$ $3 \times 10^{-3}$ **1.9** | $\mu N \to eN$ $1.5 \times 10^{-3}$ **1.0** | $\mu N \to eN$ $1.5 \times 10^{-3}$ **1.1** | $\mu N \to eN$ $4.6 \times 10^{-4}$ **1.4** | $\mu N \to eN$ $2.7 \times 10^{-4}$ **0.5** |
| 2 3 | * | $B \to \bar{\mu}eK$ $2.0 \times 10^{-3}$ **2.3** | $B \to \bar{\mu}eK$ $2.0 \times 10^{-3}$ **2.1** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.4** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.5** | * | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **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 | * | $B \to \bar{\mu}eK$ $2.0 \times 10^{-3}$ **3.2** | $B \to \bar{\mu}eK$ $2.0 \times 10^{-3}$ **2.8** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.1** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.2** | * | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.1** |
| 3 3 | * | $\mu N \to eN$ $1.3 \times 10^{-3}$ **3.8** | $\mu N \to eN$ $3 \times 10^{-3}$ **3.4** | $\mu N \to eN$ $1.5 \times 10^{-3}$ **1.7** | $\mu N \to eN$ $1.5 \times 10^{-3}$ **1.9** | * | $\mu N \to eN$ $2.7 \times 10^{-4}$ **1.7** |

| $ep \to \tau X$ | **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 | | | | | | | |
| $q_i q_j$ | $S^L_{1/2}$ $\ell^-\bar{U}$ $\ell^+U$ | $S^R_{1/2}$ $\ell^-\bar{U}, \ell^-\bar{D}$ $\ell^+U, \ell^+D$ | $\tilde{S}^L_{1/2}$ $\ell^-\bar{D}$ $\ell^+D$ | $V^L_0$ $\ell^-\bar{D}$ $\ell^+D$ | $V^R_0$ $\ell^-\bar{D}$ $\ell^+D$ | $\tilde{V}^R_0$ $\ell^-\bar{U}$ $\ell^+U$ | $V^L_1$ $\ell^-\bar{U}, \ell^-\bar{D}$ $\ell^+U, \ell^+D$ |
| 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** | $K \to \pi\nu\bar{\nu}$ $5.8 \times 10^{-4}$ **2.2** | $\tau \to Ke$ 0.02 **1.5** | $\tau \to Ke$ 0.02 **1.6** | **1.2** | $K \to \pi\nu\bar{\nu}$ $1.5 \times 10^{-4}$ **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** | $K \to \pi\nu\bar{\nu}$ $5.8 \times 10^{-4}$ **3.9** | $\tau \to Ke$ 0.02 **1.5** | $\tau \to Ke$ 0.02 **1.6** | **1.2** | $K \to \pi\nu\bar{\nu}$ $1.5 \times 10^{-4}$ **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 $\lambda_{eq_i}\lambda_{\mu q_j}/m^2_{\rm LQ}$ (TeV$^{-2}$) for lepton flavour violating leptoquarks at 95% CL | | | | | | | |
| $q_iq_j$ | $S_0^L$ $\ell^-U$ $\ell^+\bar{U}$ | $S_0^R$ $\ell^-U$ $\ell^+\bar{U}$ | $\tilde{S}_0^R$ $\ell^-D$ $\ell^+\bar{D}$ | $S_1^L$ $\ell^-U, \ell^-D$ $\ell^+\bar{U}, \ell^+\bar{D}$ | $V_{1/2}^L$ $\ell^-D$ $\ell^+\bar{D}$ | $V_{1/2}^R$ $\ell^-U, \ell^-D$ $\ell^+\bar{U}, \ell^+\bar{D}$ | $\tilde{V}_{1/2}^L$ $\ell^-U$ $\ell^+\bar{U}$ |
| 1 1 | $\mu N \to eN$ $5.2 \times 10^{-5}$ **0.7** | $\mu N \to eN$ $5.2 \times 10^{-5}$ **0.8** | $\mu N \to eN$ $5.2 \times 10^{-5}$ **1.1** | $\mu N \to eN$ $1.7 \times 10^{-5}$ **0.4** | $\mu N \to eN$ $2.6 \times 10^{-5}$ **0.5** | $\mu N \to eN$ $1.3 \times 10^{-5}$ **0.3** | $\mu N \to eN$ $2.6 \times 10^{-5}$ **0.3** |
| 1 2 | $K \to \pi\nu\bar{\nu}$ $1 \times 10^{-3}$ **0.8** | $D \to \mu\bar{e}$ 0.8 **0.9** | $K \to \mu\bar{e}$ $2 \times 10^{-5}$ **1.2** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.4** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.8** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **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 | $K \to \pi\nu\bar{\nu}$ $1 \times 10^{-3}$ **1.2** | $D \to \mu\bar{e}$ 0.8 **1.2** | $K \to \mu\bar{e}$ $2 \times 10^{-5}$ **1.5** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.6** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.5** | $K \to \mu\bar{e}$ $1 \times 10^{-5}$ **0.3** | $D \to \mu\bar{e}$ 0.4 **0.4** |
| 2 2 | $\mu N \to eN$ $9.2 \times 10^{-4}$ **2.4** | $\mu N \to eN$ $9.2 \times 10^{-3}$ **2.7** | $\mu N \to eN$ $3 \times 10^{-3}$ **2.1** | $\mu N \to eN$ $2.5 \times 10^{-3}$ **0.9** | $\mu N \to eN$ $1.5 \times 10^{-3}$ **1.0** | $\mu N \to eN$ $6.7 \times 10^{-4}$ **0.9** | $\mu N \to eN$ $4.6 \times 10^{-4}$ **1.2** |
| 2 3 | * | * | $B \to \bar{\mu}eK$ $2.0 \times 10^{-3}$ **2.3** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.0** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.4** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **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 | * | * | $B \to \bar{\mu}eK$ $2.0 \times 10^{-3}$ **3.2** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.4** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.1** | $B \to \bar{\mu}eK$ $1.0 \times 10^{-3}$ **1.2** | * |
| 3 3 | * | * | $\mu N \to eN$ $3 \times 10^{-3}$ **3.8** | $\mu N \to eN$ $2.5 \times 10^{-3}$ **1.7** | $\mu N \to eN$ $1.5 \times 10^{-3}$ **1.7** | $\mu N \to eN$ $6.7 \times 10^{-4}$ **1.9** | * |

| $ep \to \tau X$ | H1 | | | | | | $F = 2$ |
|---|---|---|---|---|---|---|---|
| Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/m^2_{\rm LQ}$ (TeV$^{-2}$) for lepton flavour violating leptoquarks at 95% CL | | | | | | | |
| $q_iq_j$ | $S_0^L$ $\ell^-U$ $\ell^+\bar{U}$ | $S_0^R$ $\ell^-U$ $\ell^+\bar{U}$ | $\tilde{S}_0^R$ $\ell^-D$ $\ell^+\bar{D}$ | $S_1^L$ $\ell^-U, \ell^-D$ $\ell^+\bar{U}, \ell^+\bar{D}$ | $V_{1/2}^L$ $\ell^-D$ $\ell^+\bar{D}$ | $V_{1/2}^R$ $\ell^-U, \ell^-D$ $\ell^+\bar{U}, \ell^+\bar{D}$ | $\tilde{V}_{1/2}^L$ $\ell^-U$ $\ell^+\bar{U}$ |
| 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 | $K \to \pi\nu\bar{\nu}$ $5.8 \times 10^{-4}$ **1.9** | **2.1** | $\tau \to Ke$ 0.04 **2.9** | $K \to \pi\nu\bar{\nu}$ $2.9 \times 10^{-4}$ **1.1** | $K \to \pi\nu\bar{\nu}$ $2.9 \times 10^{-4}$ **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 | $K \to \pi\nu\bar{\nu}$ $5.8 \times 10^{-4}$ **2.7** | **2.7** | $\tau \to Ke$ 0.04 **3.5** | $K \to \pi\nu\bar{\nu}$ $2.9 \times 10^{-4}$ **1.4** | $K \to \pi\nu\bar{\nu}$ $2.9 \times 10^{-4}$ **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** | * |