HERA Searches for Leptoquarks and Excited Fermions

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Excited Fermions
Hunting for substructure

Leptoquarks
The classic resonance and beyond

R_P Violation
Squarks may be Leptoquarks!

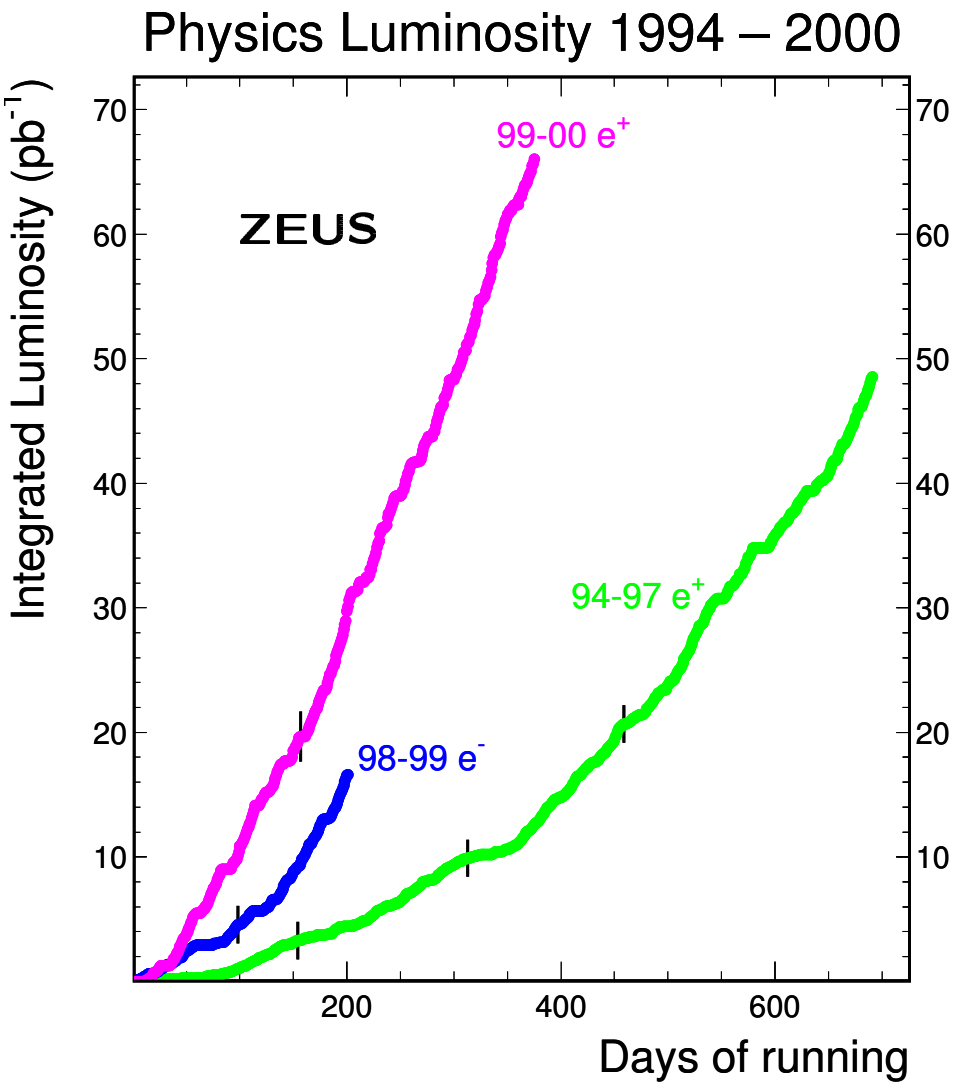
Results of the ZEUS and H1 Collaborations

Lepton Flavor Violation
induced by Leptoquarks

Summary and Outlook

Created with LaTeX on Linux

Luminosity and Data Samples



Data samples:

beam	$\sqrt{s}$ [GeV]	years	luminosity [pb^{-1}]
e^+p	300	94-97	~ 40
e^+p	318	99-00	~ 66
e^-p	318	98-99	~ 16

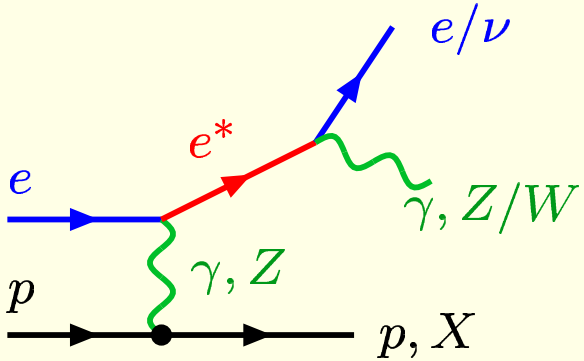
Sensitivities:

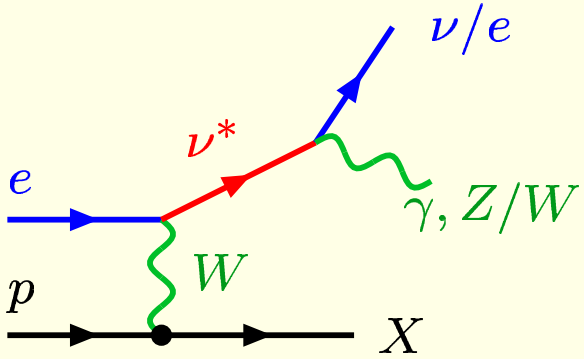
- Cross sections below 0.1 pb;
- Direct production of new particles up to ~ 300 GeV;
- High statistical precision for indirect searches (deviations from SM predictions).

Excited Fermions: Phenomenology

Production and decay:

High-mass excitations of fermions could exist and might be produced at HERA if fermions are composite:





This talk: concentrate on e^* and ν^*.

The Hagiwara model:

- f-f^*-(gauge boson) couplings described by mass scale Λ and 3 coupling parameters:

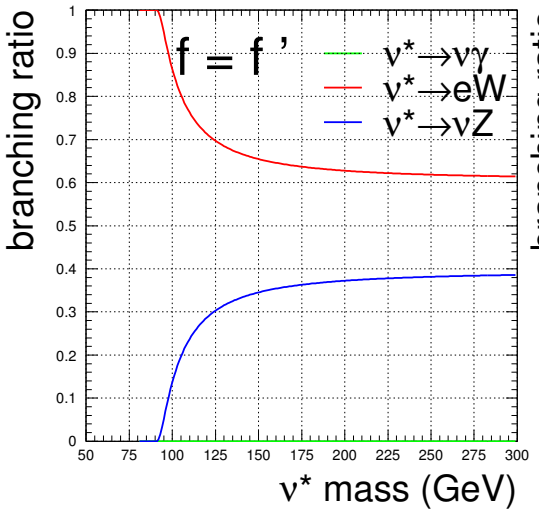
$$\mathcal{L}_{ff^*} = \frac{1}{\Lambda}\overline{f^*}\sigma^{\mu\nu}\left[f g\frac{\vec{\tau}}{2}\partial_\mu \vec{W}_\nu + f' g'\frac{Y}{2}\partial_\mu B_\nu + f_s g_s\frac{\lambda^a}{2}\partial_\mu G^a_\nu\right] f$$

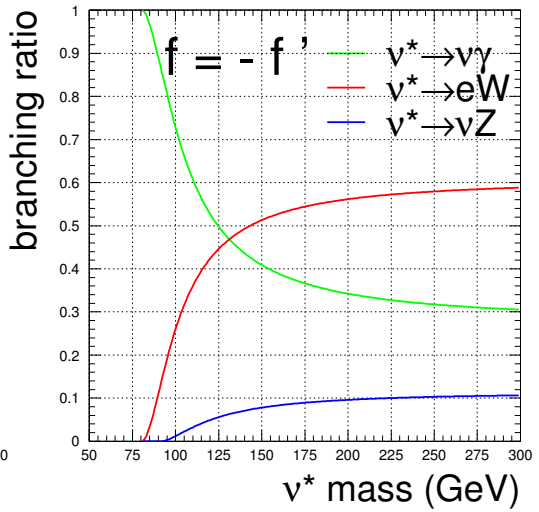
(Hagiwara, Komamiya, Zeppenfeld, 1985)

- Assumptions for HERA searches:

$$|f'| = |f| \text{ or } f'/f \in [-5;5] \qquad f_s = 0$$

($\Rightarrow$ cross sections and branching ratios).



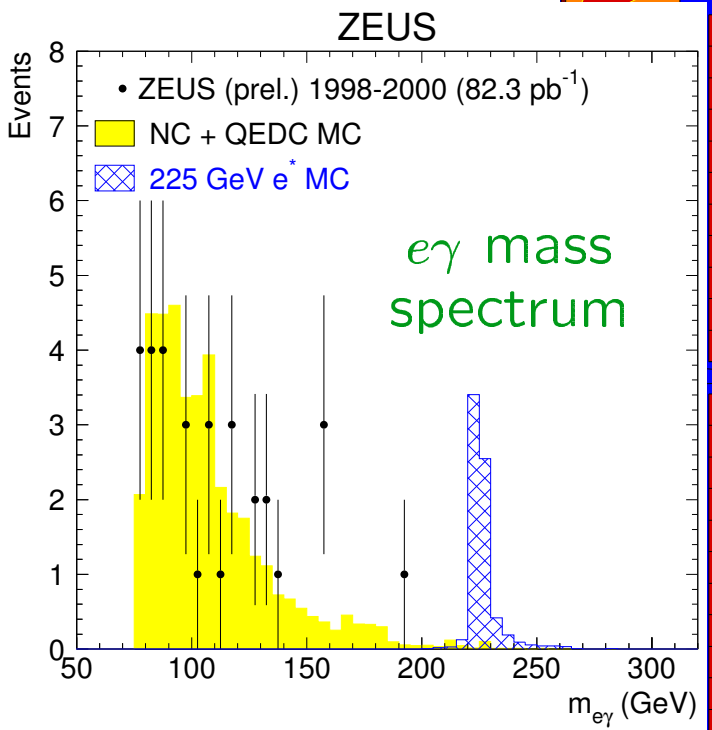


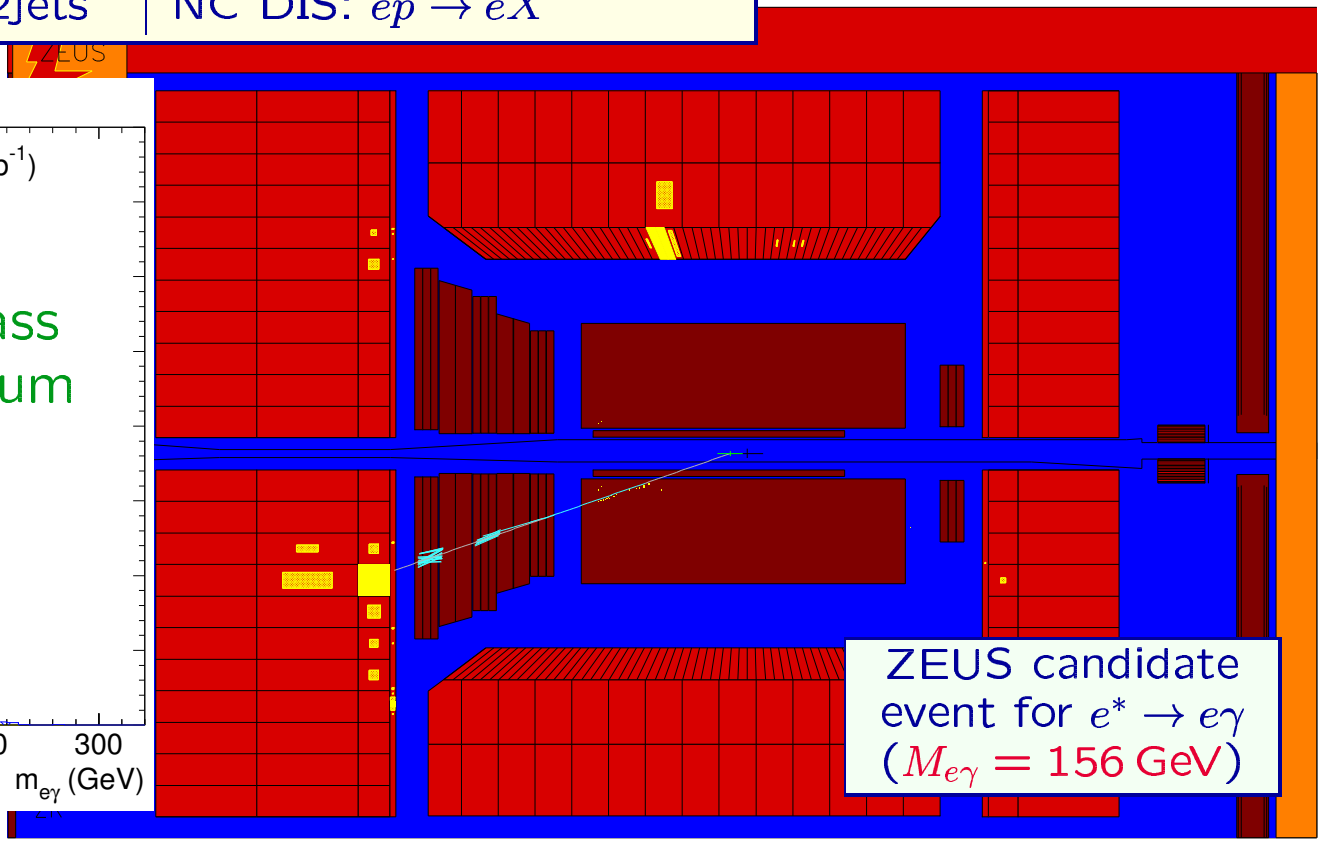
Excited Fermion Searches at HERA

Channels studied at HERA:

f^* decay	signature	SM background
$e^* \to e\gamma$	$e + \gamma$	QED-Compton
$e^* \to eZ \to eq\bar{q}$	$e +$ 2jets	NC DIS: $ep \to eX$
$e^* \to \nu W \to \nu q\bar{q}'$	$\not{P}_t +$ 2jets	CC DIS: $ep \to \nu X$; PHP
$\nu^* \to \nu\gamma$	$\not{P}_t + \gamma$	CC DIS: $ep \to \nu X$
$\nu^* \to \nu Z \to \nu q\bar{q}$	$\not{P}_t +$ 2jets	CC DIS: $ep \to \nu X$; PHP
$\nu^* \to eW \to eq\bar{q}'$	$e +$ 2jets	NC DIS: $ep \to eX$

No evidence for f^* production found so far.



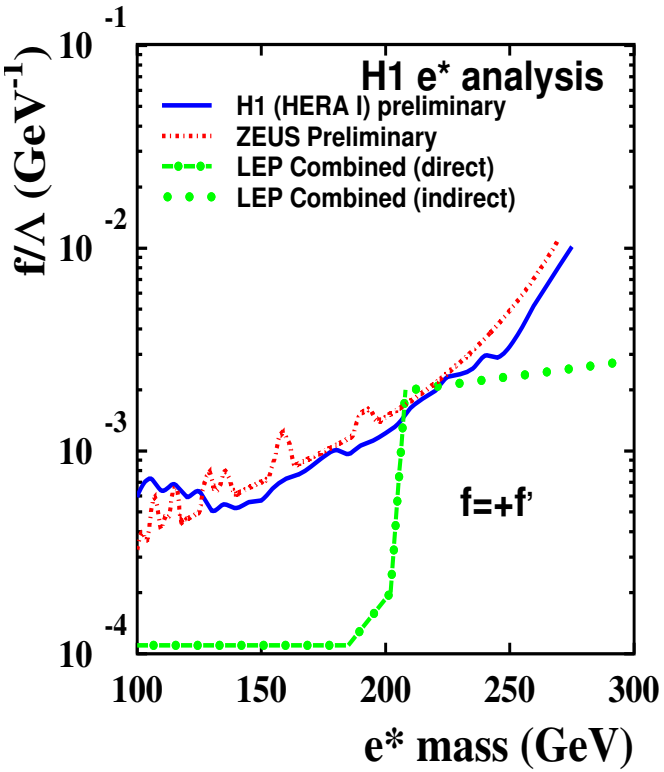


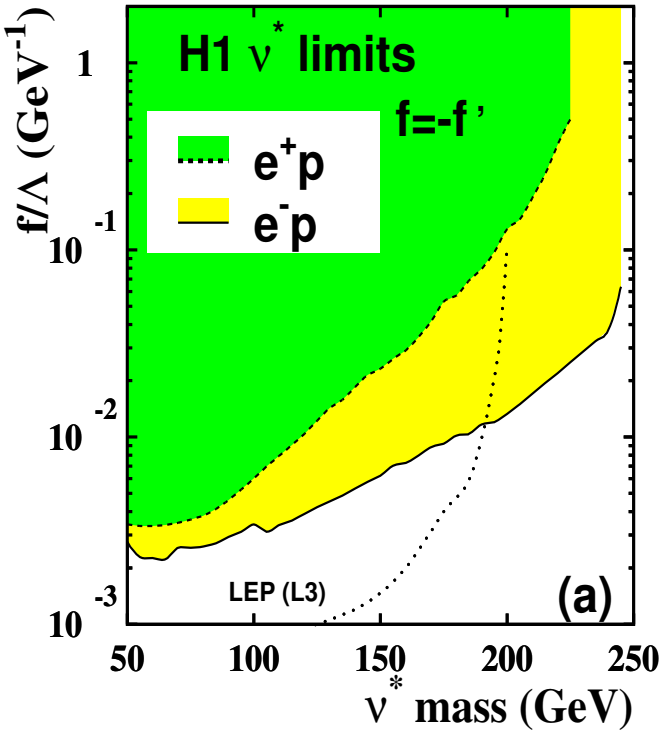
Excited Fermions: Exclusion Limits

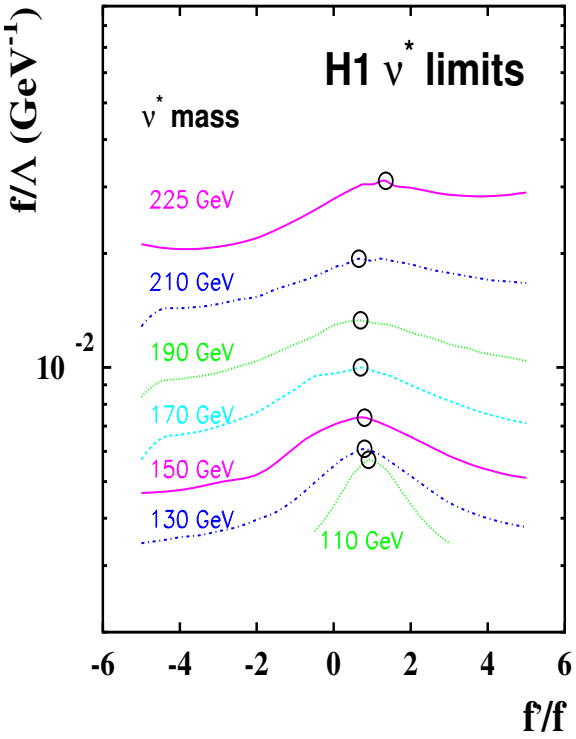
Upper limits on f/Λ:

- Excluded at 95% C.L. are the regions above the limit curves.
- ν^* production cross section larger in e^-p reactions.
- Limits from e^+e^- reactions at LEP:

$$e^+e^- \to f^*\overline{f^*} \quad M_{f^*} < \sqrt{s}/2$$
$$e^+e^- \to f^*\overline{f} \quad M_{f^*} < \sqrt{s}$$
$$e^+e^- \to \gamma\gamma \quad M_{f^*} \gtrsim \sqrt{s}$$





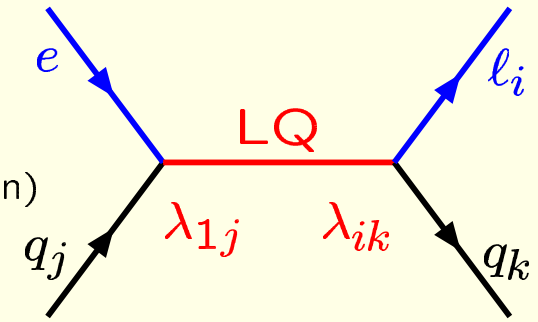


Leptoquarks (LQs)

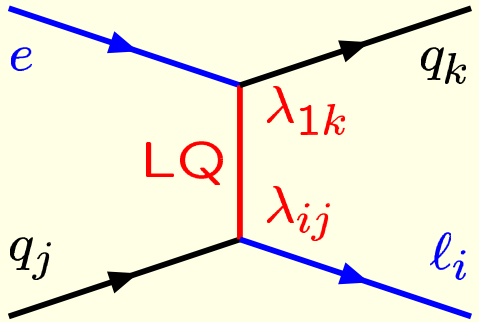
LQs in eq reactions:

Leptoquarks couple to leptons and quarks and contribute to the eq cross section:

s-channel
(resonant LQ production)



u-channel
(virtual LQ exchange)



- Same final state as in DIS → interference.
- For an e^-q (e^+q) initial state, the s-channel LQ has $|F| = 2$ (0) and the u-channel LQ has $|F| = 0$ (2).

LQ classification:

(Buchmüller, Rückl, Wyler, 1987)

- Assumptions:
  - → LQs conserve $SU(2)_L \times U(1)_Y$.
  - → LQs only couple to leptons, quarks and SM gauge bosons.
- Classify LQs by
  - → Fermion number $F = 0, \pm 2$;
  - → Spin $J = 0$ (S) or $J = 1$ (V);
  - → Charge.
- 14 LQ species for each combination of ℓ and q generations.
- LQs decay to $\ell^\pm q$ or $\nu_\ell q'$ with branching ratios $\beta_\ell, \beta_\nu = 0, 1/2, 1$.

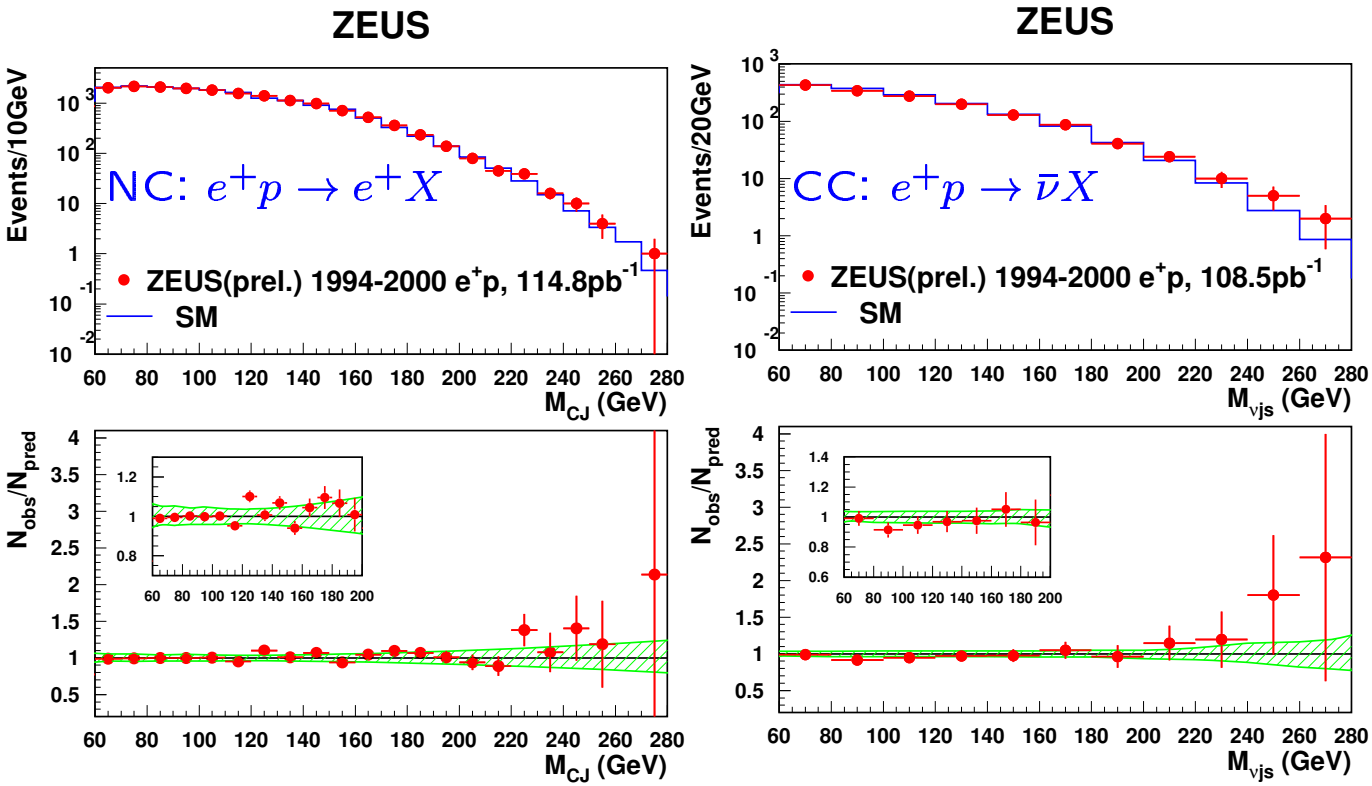
LQ signal:

- Resonant production ($M_{LQ} \lesssim \sqrt{s}$):
  - → Spike in $M_{LQ} = \sqrt{xs}$.
  - → Large $\sphericalangle(e_{in}, e_{out})$ ($\Rightarrow$ large y).
- DIS cross section modification (yields sensitivity for $M_{LQ} > \sqrt{s}$).

Search for Resonant Leptoquark Production

Experimental evidence:

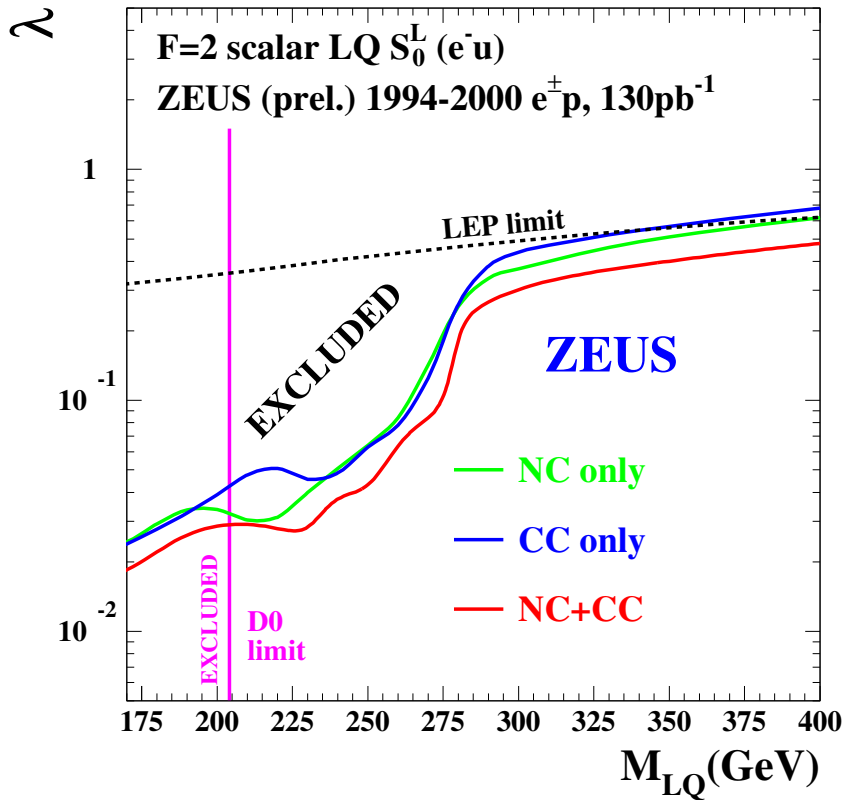
- Distributions of reconstructed e + jet(s) and $\bar{\nu}$ + jet(s) masses in good agreement with SM prediction.
- Similar results for $e^- p$ reactions and from H1.
- Mismatch at highest $\bar{\nu}$ + jet mass may be a PDF effect.
- No evidence for LQ signal, previous "high-Q^2 anomaly" not confirmed.

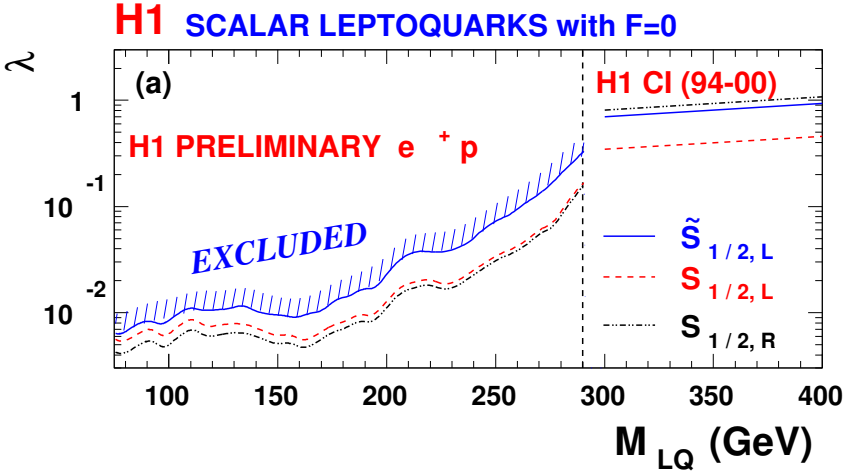


Search strategy:

- Use 2-dimensional event distribution in M_{LQ}, y;
- Compare to SM prediction using likelihood method;
- Consider s-channel, u-channel, SM-LQ interference;
- Determine cross section limits;
- Derive coupling limits using BRW model.

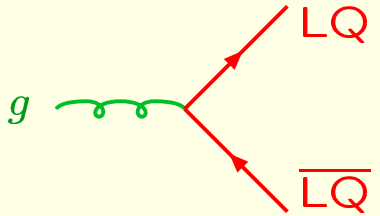
Leptoquarks: Exclusion Limits (I)





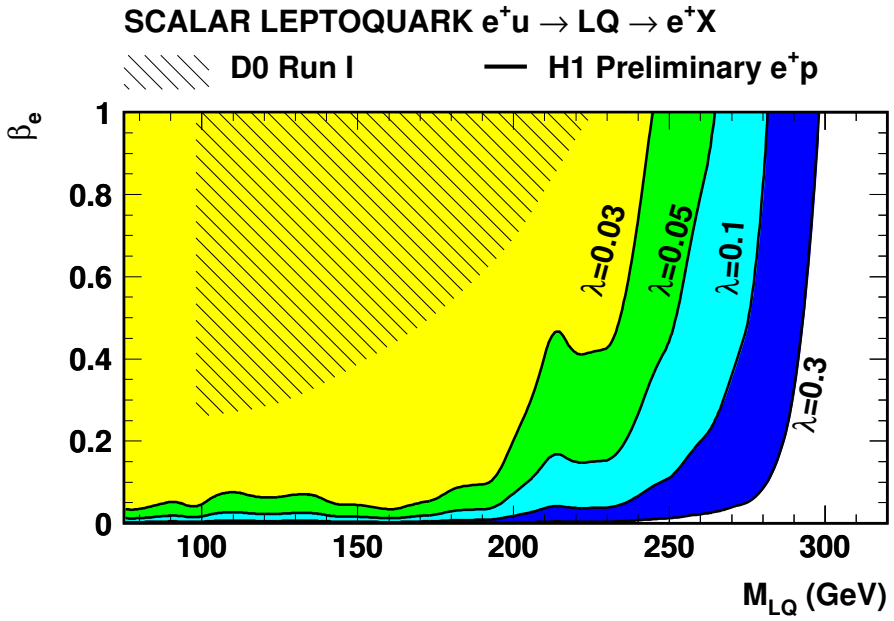
Coupling limits (95 % C.L.):

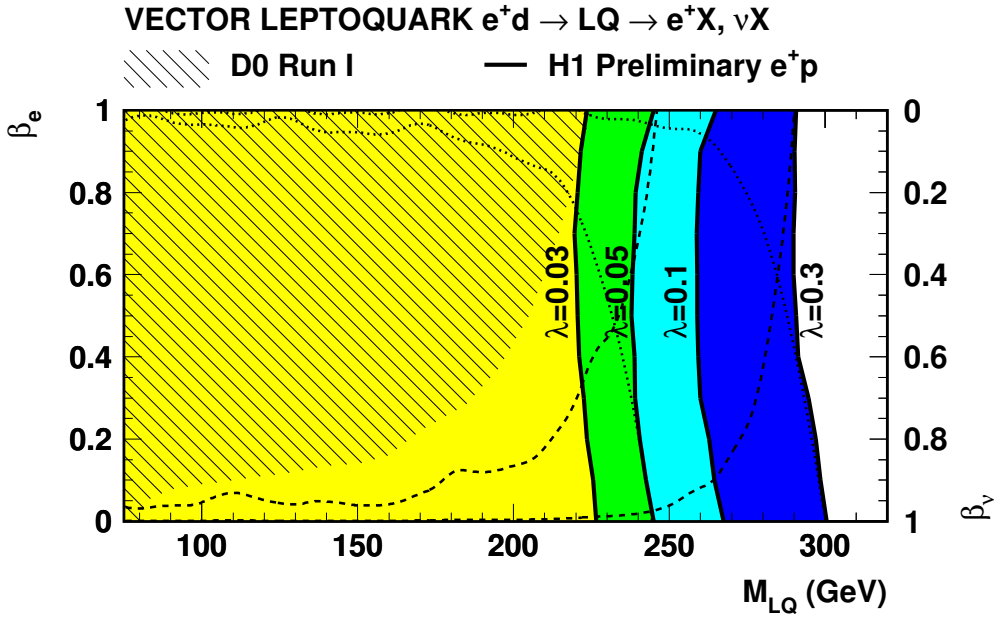
- Shown: two examples for LQ species with $|F| = 2$ (top) and $F = 0$ (bottom).
- Note:
  e^-p data sensitive to $F = 2$ (e^-q)
  e^+p data sensitive to $F = 0$ (e^+q).
- Combination of NC and CC information increases sensitivity.
- Limit from TeVatron:
  LQ pair production in $p\bar{p}$ reactions via SM $SU(3)_c$ gauge coupling.



  Search for $p\bar{p} \to \ell\ell + 2\,\text{jets}$,
  exclusion limit independent of coupling λ.
- Limit from LEP:
  LQ-induced virtual effects in $e^+e^- \to q\bar{q}$
  (contact interaction analysis).

Leptoquarks: Exclusion Limits (II)





Generalized analysis:

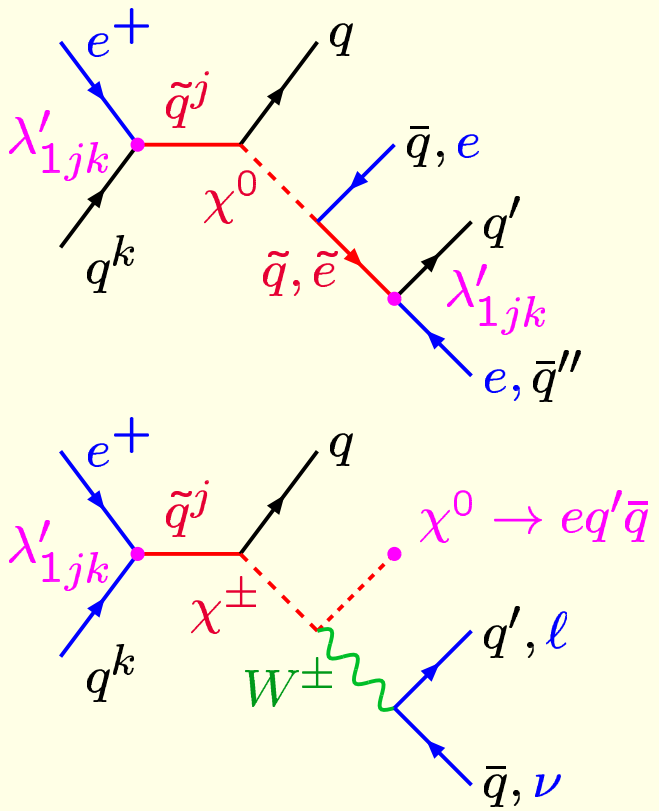
- Leave $\beta_e = \mathrm{BR}(\mathrm{LQ} \to eq)$ free but assume $\beta_e + \beta_\nu = 1$.
- Derive exclusion limits in $(M_{\mathrm{LQ}}, \beta_e)$-plane for fixed λ values.
- Sensitivity almost to the kinematic limit, also for small values of β_e.
- Complementary to TeVatron (small efficiency in $2\nu + 2\,\mathrm{jets}$ channel).

Squarks in R_P-Violating SUSY

Squarks in eq reactions:

If R_P is not conserved, squarks can interact like LQs: $\tilde{q}^j \xrightarrow{\lambda'_{1jk}} eq^k$.

In addition, they have various SUSY cascade decays like these (i.e. $\beta_e < 1$):



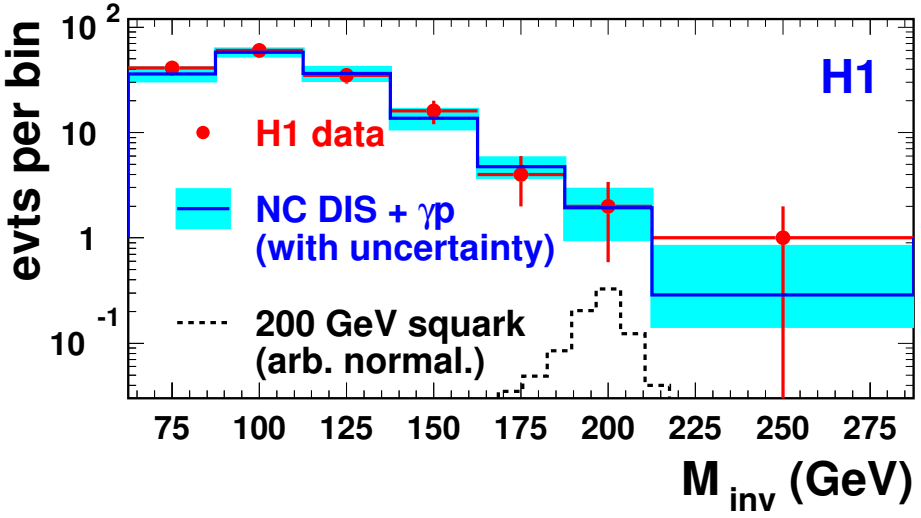
Search strategy:

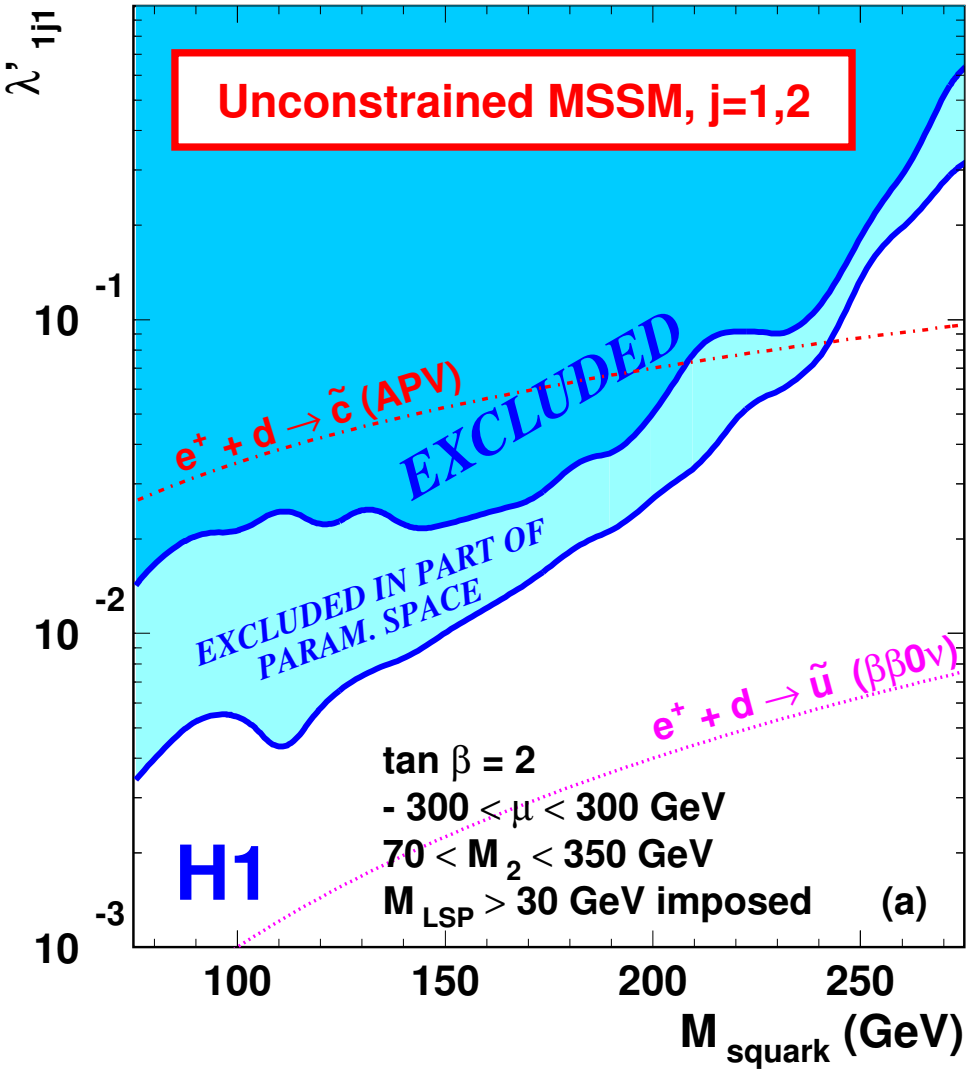
- Combine LQ search in eq channel with search for cascade decays.
- Very striking signatures:
  - $\rightarrow$ e + several jets;
  - $\rightarrow$ wrong-sign electron in some channels;
  - $\rightarrow$ "spherical" events.
- Scan SUSY parameter space, calculate branching ratios etc. for each parameter set, evaluate cross section limit.
- Derive best/worst exclusion limits in $(\lambda', M_{\tilde{q}})$-plane.

Squark Searches and Limits

Experimental results:

- H1, ZEUS: no evidence for signal in $e+$jets channels.
- Example (H1): e and ≥ 2 jets with high p_t.
- No events with wrong-sign electron plus jets.
- Exclusion limits for λ'_{1j1} (i.e. for initial-state u or d quark).
- Sensitivity exceeds low-energy constraints for $\tilde{c}$ and $\tilde{t}$ squarks.

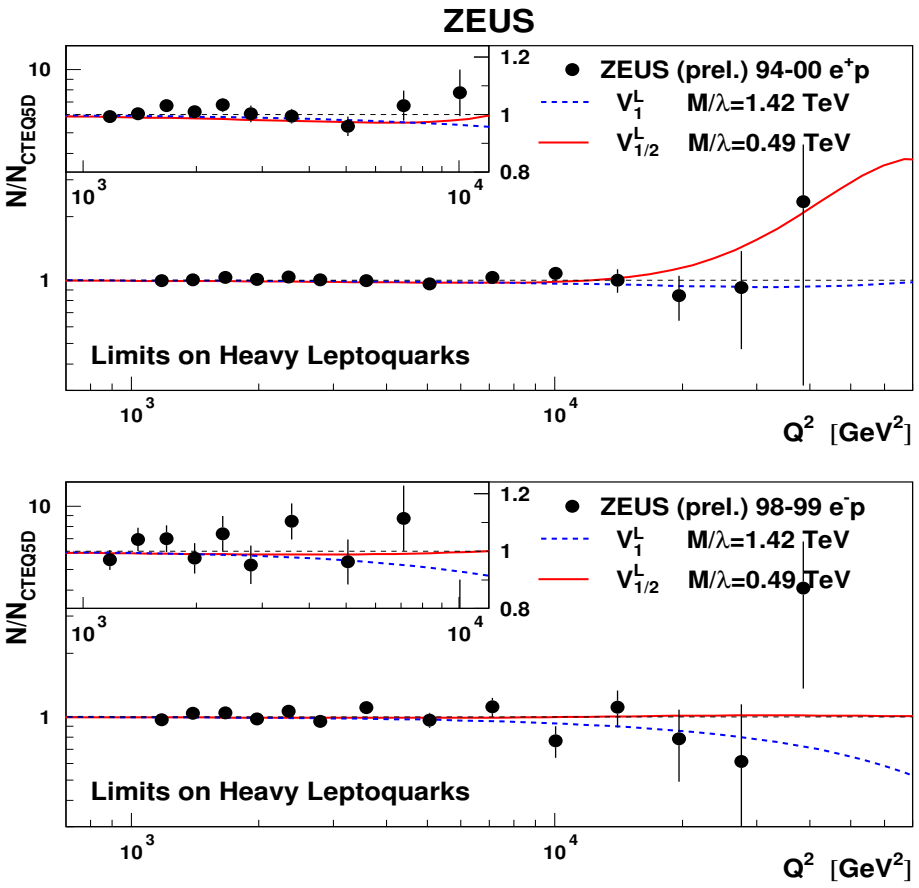




Indirect Leptoquark and Squark Searches

Contact interaction analysis:

- High-mass LQs modify the DIS cross section $d\sigma/dQ^2$.
- Absence of the corresponding signal yields lower limits on M_{LQ}/λ.
- Also applicable for squarks ($M_{\tilde{q}^j}/\lambda'_{1j1}$).



Limits (95 % C.L.):

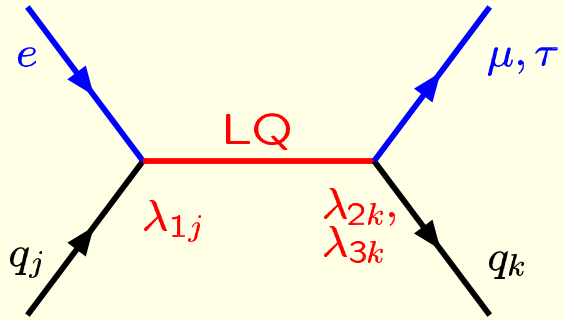
LQ or $\tilde{q}$	F	M_{LQ}/λ [GeV] ZEUS	H1
S_0^L or $\tilde{d}$	2	750	720
S_0^R	2	690	670
$\tilde{S}_0^R$	2	310	330
S_1^L	2	550	480
$S_{1/2}^L$	0	910	870
$S_{1/2}^R$	0	690	370
$\tilde{S}_{1/2}^L$ or $\tilde{u}$	0	500	430
V_0^L	0	690	770
V_0^R	0	580	640
$\tilde{V}_0^R$	0	1030	1000
V_1^L	0	1420	1380
$V_{1/2}^L$	2	490	420
$V_{1/2}^R$	2	1150	940
$\tilde{V}_{1/2}^L$	2	1260	1020

Attention: Limits only applicable for LQs/squarks mith mass $\gg \sqrt{s_{HERA}}$.

Lepton-Flavor Violating Leptoquarks

LQ-induced lepton flavor violation:

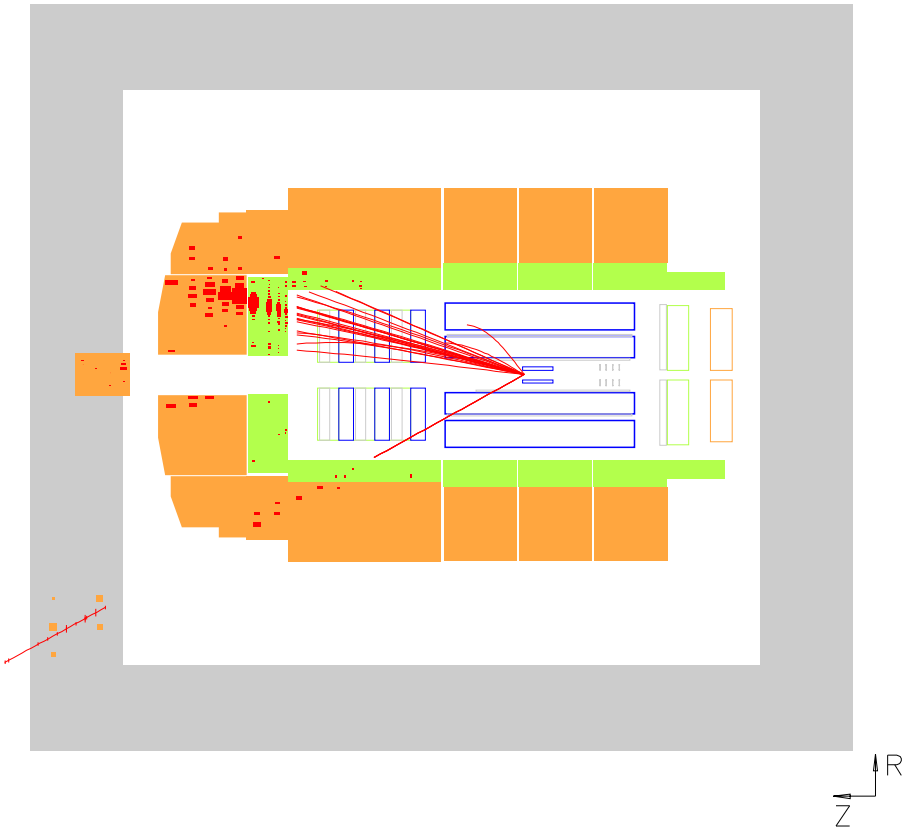
- LQs with couplings to more than one lepton generation could induce lepton flavor violation (LFV):



- Signature:
  DIS-like reaction with a μ or τ replacing the final-state electron.
- Similar signal for low-mass ($M^2_{LQ} \lesssim s$) and high-mass ($M^2_{LQ} \gg s$) LQs.
- Search sensitive to any LFV reaction, but results quantified in terms of LQ masses and couplings.

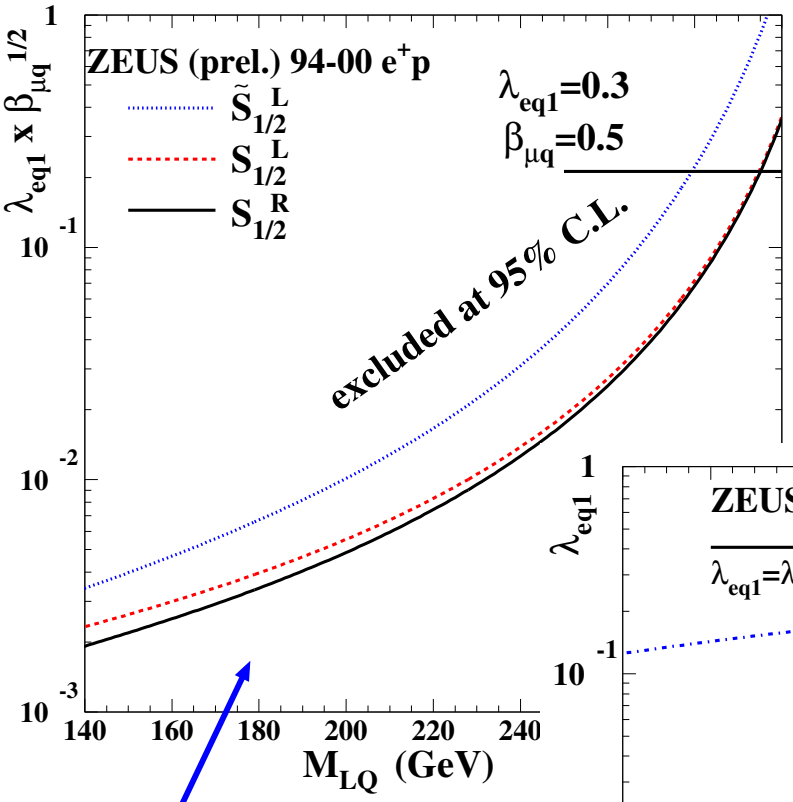
Event MUON-2

$P_T^\mu = 28\,\text{GeV}, P_T^X = 67\,\text{GeV}, P_T^{miss} = 43\,\text{GeV}$



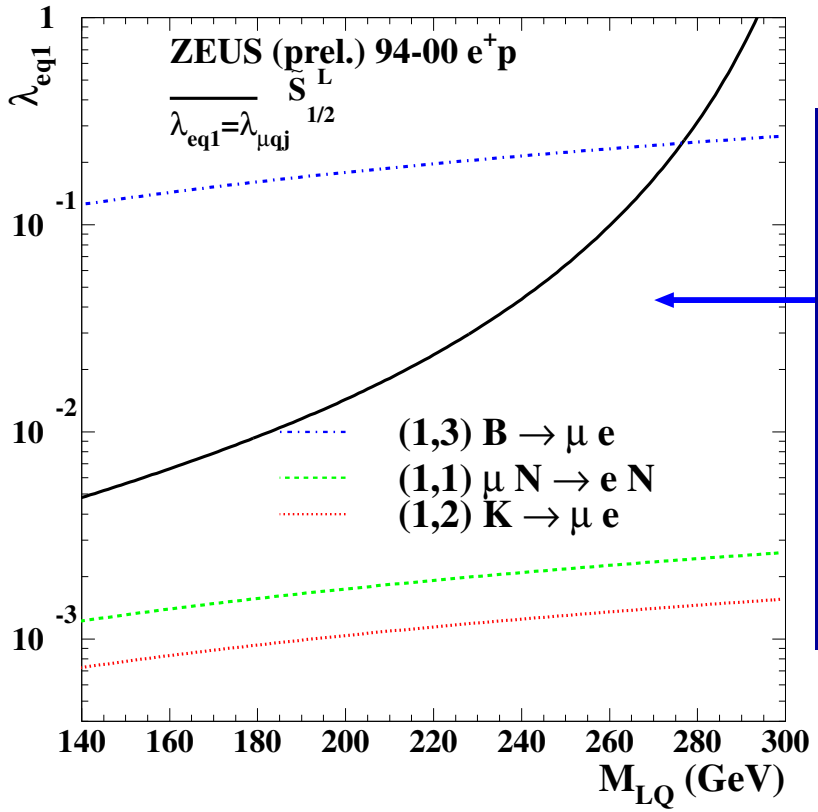
H1

Limits on Lepton-Flavor Violation



HERA results:

- No evidence for LFV found at HERA.
- HERA discovery potential in low-mass LQ regime involving 3rd-generation quarks.
- High-mass limits on $\frac{\lambda_{1j}\lambda_{xk}}{M^2_{LQ}}$ $(x = 2, 3)$ are strongest/only limits for several flavor combinations (j, k), in particular for τ leptons.



Search for $e \to \mu$ LQs ($M^2_{LQ} \lesssim s$):

Exclusion limits on

$\lambda_{11} \cdot \sqrt{\text{BR}(\text{LQ} \to \mu q)}$

for LQs with $J = 0$, $F = 0$.

Comparison to low-energy results:

Assume $\lambda_{11} = \lambda_{2k}$, i.e.

$\text{BR}(\text{LQ} \to \mu q) = 0.5$

and compare exclusion limit for $\tilde{S}^L_{1/2}$ LQ with limits from rare decays and $\mu \to e$ conversion in atoms.

Conclusions and Outlook

Summary:

- No evidence for excited fermions or leptoquarks in $\sim 240\,\mathrm{pb}^{-1}$ $e^{\pm}p$ data collected in 1994–2000 (HERA I).
- High sensitivity in various channels, complementary to other collider experiments and to low-energy measurements.
- Typical mass limits $250-300\,\mathrm{GeV}$, depending on species and coupling.

Outlook:

- HERA has resumed operation after major upgrade (HERA II).
- Detector improvements and upgrades.
- We expect
  - $\sim 1\,\mathrm{fb}^{-1}$ ep data per experiment;
  - longitudinal e polarization.
- The new data will significantly boost the HERA discovery potential for physics beyond the SM.