# Search for Excited fermions

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Results of searches for excited fermion production at LEP and HERA are presented. The data were collected with the DELPHI detector at LEP at $e^+e^-$ centre-of-mass energies ranging from 189 GeV to 209 GeV, corresponding to an integrated luminosity of approximately 600 pb$^{-1}$, and with the H1 detector at HERA in $e^+p$ collisions at a centre-of-mass energy of 300 GeV and in $e^-p$ collisions at a centre-of-mass energy of 318 GeV, with integrated luminosities of 37 pb$^{-1}$ and 15 pb$^{-1}$, respectively. In searches for pair-produced excited leptons, lower mass limits were established in the range 94 – 103 GeV/$c^2$, depending on the channel and model assumptions. In searches for singly-produced excited fermions, upper limits on the parameter $f/\Lambda$ were set up to masses of the order of 250 GeV/$c^2$.

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## 1. Introduction

Excited fermions are predicted by models of composite leptons and quarks. In the phenomenological model considered [1] excited fermions are assumed to have spin and weak isospin equal to 1/2 and to have both their left-handed and right-handed components in weak isodoublets. In this model the $SU(3) \times SU(2) \times U(1)$ gauge invariant effective Lagrangian describing the magnetic transition between excited fermions and the SM fermions has the form:

$$\mathcal{L}_{ff^*} = \frac{1}{2\Lambda} \overline{F^*} \sigma^{\mu\nu} \left[ g_s f_s \frac{\lambda_a}{2} G^a_{\mu\nu} + g f \frac{\overrightarrow{\tau}}{2} \cdot \overrightarrow{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] F_L + h.c.$$

where $F^* = F^*_L + F^*_R$ and $F_L$ is the weak isodoublet with the left-handed components of the SM fermions; $\sigma^{\mu\nu}$ is the covariant bilinear tensor, $\overrightarrow{\tau}$ are the Pauli matrices, $Y$ is the weak hypercharge, $G^a_{\mu\nu}$, $\overrightarrow{W}_{\mu\nu}$ and $B_{\mu\nu}$ represent the gauge field tensors of SU(3), SU(2) and U(1) respectively, with $g_s$, $g$ and $g'$ being the corresponding SM coupling constants; the parameter $\Lambda$ sets the compositeness scale, with $f_s$, $f$ and $f'$ being weight factors associated with the three gauge groups.

At LEP excited fermions of all three generations could be pair produced through $s$-channel $\gamma$ and $Z^0$ exchange or singly produced through $s$-channel and $t$-channel. At HERA, excited electrons or quarks are accessible through the t-channel exchange of a $\gamma$ or a $Z^0$, and excited neutrinos by the t-channel exchange of a $W^{\pm}$.

Results from the search for single and pair production of excited leptons of the three generations ($\nu^*_e, \nu^*_\mu, \nu^*_\tau, e^*, \mu^*, \tau^*$) with the DELPHI detector [2] at LEP and from the search for single production of excited quarks and excited electron neutrinos with the H1 detector [3] at HERA are presented here. The decays of excited fermions to a Standard Model (SM) fermion by radiating a $\gamma$, $W^{\pm}$ or $Z^0$ boson were considered. To reduce the number of free parameters, DELPHI and H1 interpret the search results assuming $|f| = |f'|$ and $f_s = 0$. H1 derived also limits for the excited neutrinos under broader assumptions.

## 2. Experimental strategies

The results from DELPHI are based on a total integrated luminosity of 598.7 pb$^{-1}$, at centre-of-mass energies ranging from 189 GeV to 209 GeV, corresponding to an average centre-of-mass energy of $<\sqrt{s}> \simeq 198.5$ GeV. The H1 searches presented here were performed using data collected in $e^+p$ collisions at a centre-of-mass energy of 300 GeV and in $e^-p$ collisions at a centre-of-mass energy of 318 GeV, with integrated luminosities of 37 pb$^{-1}$ and 15 pb$^{-1}$, respectively.

Many final state topologies arise from the production and decay of excited fermions. They involve isolated leptons, isolated photons, particle jets from quark fragmentation, missing energy and missing momentum. The final states considered in the DELPHI analyses are summarized in table 1. In the H1 search for excited quarks and neutrinos, the final states arising from the excited fermion decays to $\gamma$, $W^{\pm}$ or $Z^0$ were considered. For the decays of the heavy gauge bosons only the hadronic mode was taken into account in the $\nu^*$ search, while in the $q^*$ search the decays into hadrons, electrons or muons were examined. Final states consisting of combinations of two jets, one electromagnetic cluster and missing transverse energy were thus considered in the H1 searches. In the search for excited quarks the final states containing one jet and one or two muons and three

| Channel | Final State Topologies | |
| --- | --- | --- |
| | Single production | Pair production |
| $\ell^* \to \ell\gamma$ | $\ell\ell\gamma,\, (\ell)\ell\gamma$ | $\ell\ell\gamma\gamma$ |
| $\ell^* \to \nu W$ | $jj\ell\,\not\!E,\, jj(\ell)\,\not\!E$ | $jj\ell\,\not\!E,\, jjjj\,\not\!E$ |
| $\ell^* \to \ell Z$ | $jj\ell\ell,\, jj\ell(\ell)$ | - |
| $\nu^* \to \nu\gamma$ | $\gamma\,\not\!E$ | $\gamma\gamma\,\not\!E$ |
| $\nu^* \to \ell W$ | $jj\ell\,\not\!E$ | $jj\ell\ell\ell,\, jj\ell\ell(\ell),\, jjjj\ell\ell$ |
| $\nu^* \to \nu Z$ | $jj\,\not\!E$ | - |

**Table 1:** Final-state topologies, corresponding to the different production and decay modes of excited leptons, covered by the DELPHI searches. The spectator or final state SM lepton remaining undetected is indicated by $(\ell)$.

jet final states were also addressed. Analyses based on sequential event selection cuts were used in the various search channels. However, in the DELPHI search for pair production of charged excited leptons decaying as $\ell^*\ell^* \to \nu W \nu W$, a discriminant analysis was used. In this analysis a likelihood ratio variable is constructed from the probability density functions of relevant kinematic.

## 3. Results

In all search channels the number of observed and expected events are in good agreement. From the single production searches upper limits at 95% confidence level on the coupling $f/\Lambda$ as a function of the excited fermion mass were thus derived. Figure 1 shows the limits from the DELPHI searches for charged and neutral excited leptons, obtained assuming $f = f'$; limits for the $f = -f'$ scenario were also derived by DELPHI. From the pair production searches at DELPHI lower limits on the excited lepton masses between 94 GeV/$c^2$ and 103 GeV/$c^2$, depending on the scenario considered and the lepton flavour, were obtained. In figure 2 are shown the limits from the H1 searches for excited quarks assuming $f = f'$ and $f_s = 0$ and excited neutrinos assuming $f = -f'$. H1 derived also limits for the symmetric $f, f'$ assignment and exclusion limits for the excited neutrinos valid for $f/f'$ values in the interval $[-5, 5]$.

## 4. Summary

No evidence for excited fermion production has been found in $e^+e^-$ and $ep$ collisions. The pair production searches allowed to set lower mass limits of the order of 100 GeV/$c^2$ for all excited lepton flavours. Upper limits on the coupling $f/\Lambda$, as low as about 0.1 TeV$^{-1}$, were obtained from the single production searches. These limits, although dependent on the excited fermion mass, were derived up to masses of the order of 250 GeV/$c^2$.

## References

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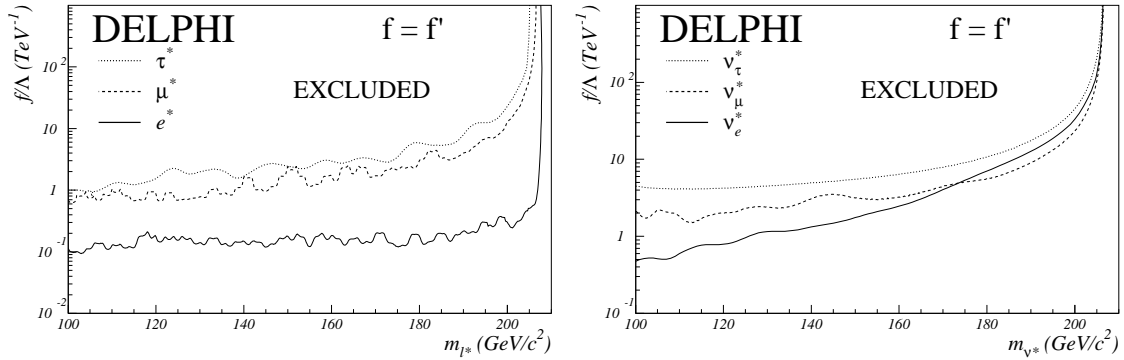[5] L3 Coll., M. Acciarri et al., Phys. Lett. **B 502** (2001) 37.

**Figure 1:** Results from the DELPHI direct search for single production of excited charged (left plot) and neutral (right plot) leptons. The lines show the upper limits at 95% confidence level on $f/\Lambda$ as a function of the excited lepton mass, assuming $f = f'$.
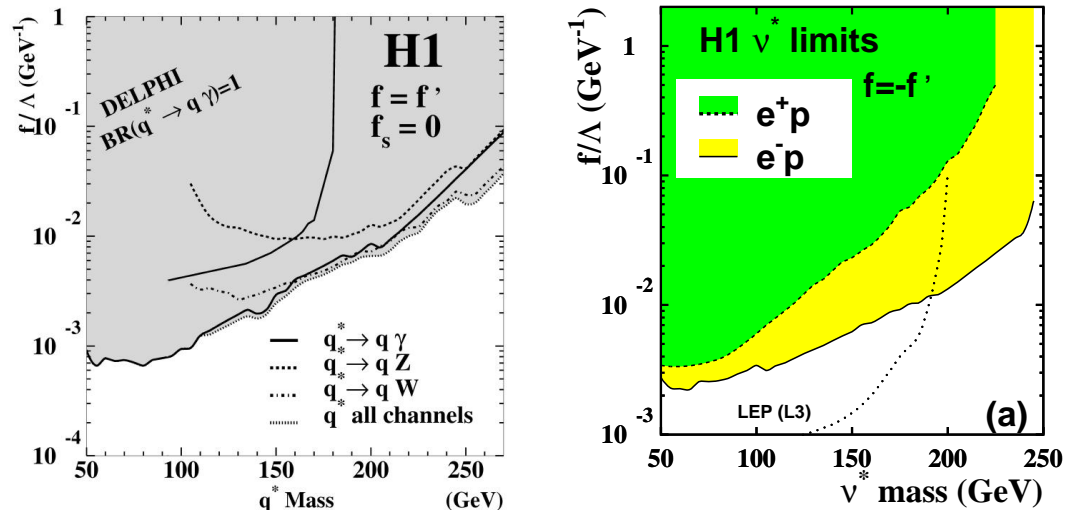


**Figure 2:** Results from the H1 search for single production of excited quarks (left plot) and excited electron neutrinos (right plot). The lines show the upper limits on the coupling $f/\Lambda$ at 95% confidence level as a function of the mass, for the scenario $f = f', f_s = 0$ in the case of $q^*$ and $f = -f'$ for $\nu^*$. Excited quark limits are shown for each decay channel separately and for all decays combined (dotted line); the curve going up at a $q^*$ mass of the order of 180 GeV/$c^2$ is the upper limit obtained previously by DELPHI [4] assuming that the branching ratio for $q^* \to q\gamma$ is equal to 1. Excited neutrino exclusion limits are given for $e^- p$ data (full line) with an integrated luminosity of 15 pb$^{-1}$ and $e^+ p$ data (dashed line) with an integrated luminosity of 37 pb$^{-1}$ and for L3 [5] (dotted line)