# Searches for Heavy and Excited Fermions at $\sqrt{s}$ =183–189 GeV at LEP2

Richard Teuscher

CERN EP

Representing the

LEP Collaborations

- **NEW RESULTS** from $\sqrt{s} = 183 - 189$ GeV
- Search for Heavy Leptons

  Unstable Heavy Leptons

  Long-Lived/Stable Heavy Leptons
- Search for Excited Fermions
- Summary

References: Contributed Papers 102, 215, 277, 283, 497, 498.

All results are preliminary and limits are at the 95% CL.

# Physics Beyond the Standard Model

## (A) Unification

- SUSY, strings, GUT models ($E_6, SO(10)$)
- SM particles are pointlike
- New Fermions: Heavy Charged Leptons $\mathrm{L}^{\pm}$
- Heavy Neutral Leptons N (Dirac, Majorana)

  See-Saw Mechanism: $m_{N_\ell} = m_\ell^2 / m_{\nu_\ell}$

  If $\mathrm{m}_{\nu_\mathrm{e}} \sim (3, 1.5)$ eV $\rightarrow m_{N_e} \approx (87, 170)$ GeV

## (B) Compositeness

- SM particles are composite at scale $\Lambda \geq 1$ TeV
- Excited Fermions (vector, with left and right doublets)

$$\begin{pmatrix} \nu_\ell^* \\ \ell^* \end{pmatrix}_{\mathrm{L}} ; \begin{pmatrix} \nu_\ell^* \\ \ell^* \end{pmatrix}_{\mathrm{R}}$$

Either pair-produced or singly via (left-handed) coupling to ordinary leptons.

# (A) Searches for Heavy Neutral Leptons

- Production: $e^+e^- \longrightarrow N\,\bar{N}$
- Decay (assuming 100% CC) via mixing to $\ell = e, \mu, \tau$.

  Mixing angle: $\mathcal{O}(10^{-12}) < \zeta^2 < 0.005$

  Limits: decay radius $< \mathcal{O}$(1 cm), fits to EW data.

  (For smaller $\zeta^2$, special searches for long-lived N).

Dirac N:

$$e^+e^- \longrightarrow \mathrm{N}\,\bar{\mathrm{N}}$$
$$\hookrightarrow \ell^+ \mathrm{W}^{-*} \hookrightarrow q_i \bar{q}_j\ ,\ \ell^- \bar{\nu}_\ell$$
$$\hookrightarrow \ell^- \mathrm{W}^{+*} \hookrightarrow q_k \bar{q}_\ell\ ,\ \ell^+ \nu_\ell$$

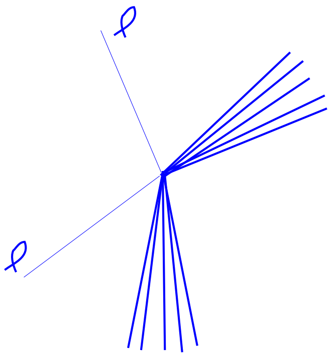
Majorana N:

$$e^+e^- \longrightarrow \mathrm{N}\,\bar{\mathrm{N}}$$
$$\hookrightarrow \ell^\pm \mathrm{W}^{\mp*} \hookrightarrow q_i \bar{q}_j\ ,\ \ell^\mp \overset{(-)}{\nu}_\ell$$
$$\hookrightarrow \ell^\pm \mathrm{W}^{\mp*} \hookrightarrow q_k \bar{q}_\ell\ ,\ \ell^\mp \overset{(-)}{\nu}_\ell$$

same-sign $\ell$ possible

Typical topology :

two isolated leptons + jets



# Results of Search for $\mathrm{NN} \rightarrow \ell\ell\mathrm{WW}$

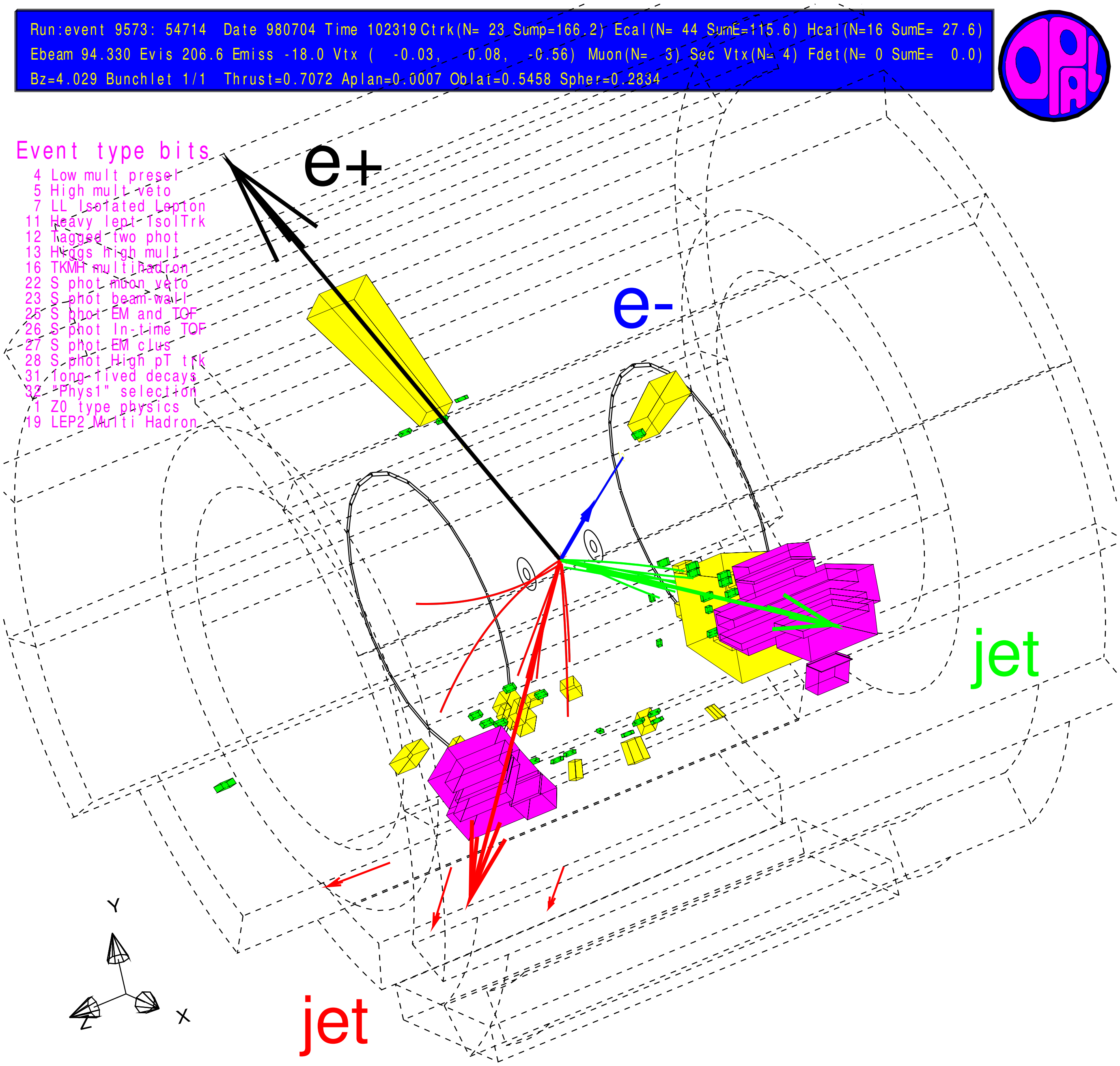
Combined searches $\sqrt{s} = 183 - 189$ GeV,
(all 1997-1998 data, $\approx$ 57+37 pb$^{-1}$)
$\mathcal{L}_{\mathrm{tot}} \approx$ 94 pb$^{-1}$

| Topology | Data | Total Bkd | $M_{\mathrm{N}}$ =80 GeV | | |
|---|---|---|---|---|---|
| | | | Expected Signal | | |
| | | | Dirac | Majorana | Efficiency |
| $\mathrm{e^+e^-WW}$ | 8 | 8.9 | 21.1 | 6.0 | 48% |
| $\mu^+\mu^-\mathrm{WW}$ | 6 | 5.8 | 20.2 | 5.9 | 48% |
| $\tau^+\tau^-\mathrm{WW}$ | 66 | 80.4 | 15.2 | 4.0 | 32% |

OPAL Preliminary

- Main SM backgrounds are $\ell\ell\mathrm{qq}$ and qqqq production.
- No excess observed. $\rightarrow$ Mass limits
- Efficiencies and expected signal are calculated using EXOTIC Monte Carlo (R. Tafirout, G. Azuelos, submitted to Comp. Phys. Comm.)
- Similar analysis by L3 gives no excess in 189 GeV data.

# $\mathrm{N_e\bar{N}_e}$ Candidate at $\sqrt{s} = 189$ GeV, July 1998




Candidate for $\mathrm{e^+e^- \to N\bar{N}, N \to eW}$.

Consistent with SM 4-fermion $\ell\ell\mathrm{qq}$ background:

$\mathrm{m_{ee}} = 34$ GeV, $\mathrm{m_{jj}} = 95$ GeV ($\gamma^*$Z)

# Search for Unstable Charged Heavy Leptons

$$e^+e^- \longrightarrow L^+ L^-$$
$$L^- \hookrightarrow \nu_\ell W^{-*} \hookrightarrow q_i\bar{q}_j \;,\; \ell^-\bar{\nu}_\ell$$
$$L^+ \hookrightarrow \bar{\nu}_\ell W^{+*} \hookrightarrow q_k\bar{q}_\ell \;,\; \ell^+\nu_\ell$$

Topologies : 4 jets and $p_T^{miss}$ or 2 jets, one lepton, and $p_T^{miss}$

Backgrounds are $\mathrm{WW} \to \mathrm{qqqq}$ and $\mathrm{WW} \to \ell\nu\mathrm{qq}$

Results for $\sqrt{s} = 181 - 189$ GeV, $\mathcal{L} \approx 94$ pb$^{-1}$:

| Topology | Data | Total Bkd | Mass $L^\pm$ 80 GeV | Mass $L^\pm$ 90 GeV |
|---|---|---|---|---|
| $\nu_\ell\nu_\ell\mathrm{jjjj}$ | 96 | 107.3 | 39.2 (22%) | 12.3(20%) |
| $\nu_\ell\nu_\ell\nu_{\ell'}\ell'\mathrm{jj}$ | 359 | 372 | 41.8 (24%) | 16.6 (27%) |

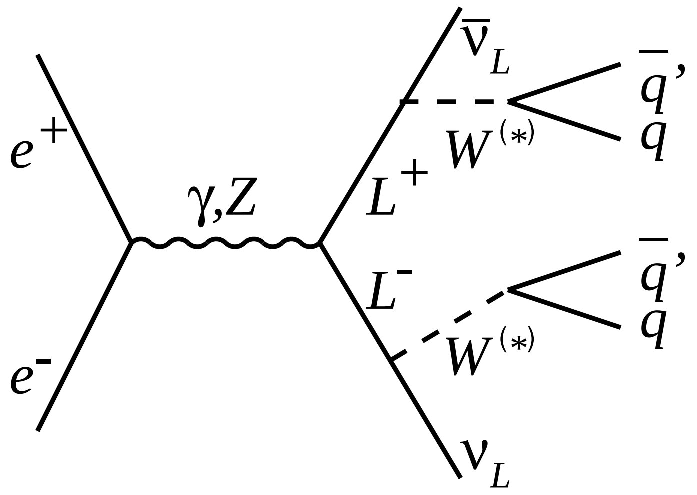
OPAL Preliminary

- No evidence for any excess
- Both channels combined for the 95% CL result:

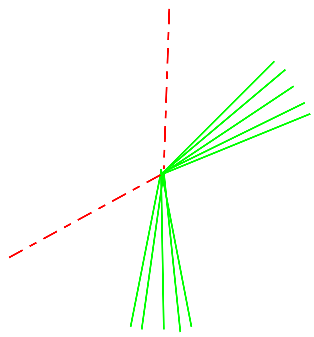
$$M_L > 91.3 \text{ GeV}$$

# Search for Stable/Long-Lived Neutral Heavy Leptons

## Final state is two virtual W*'s and missing energy.



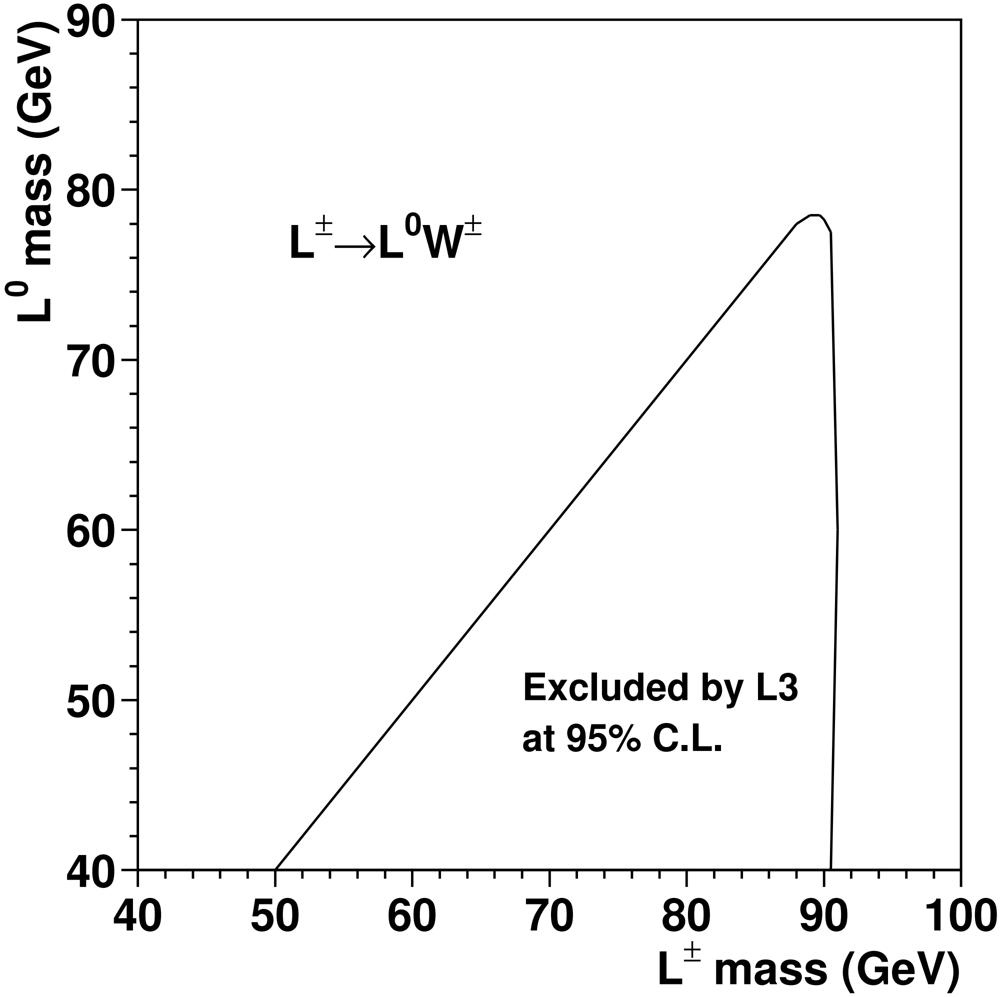

where $\nu_{\rm L}$ does not decay inside the detector

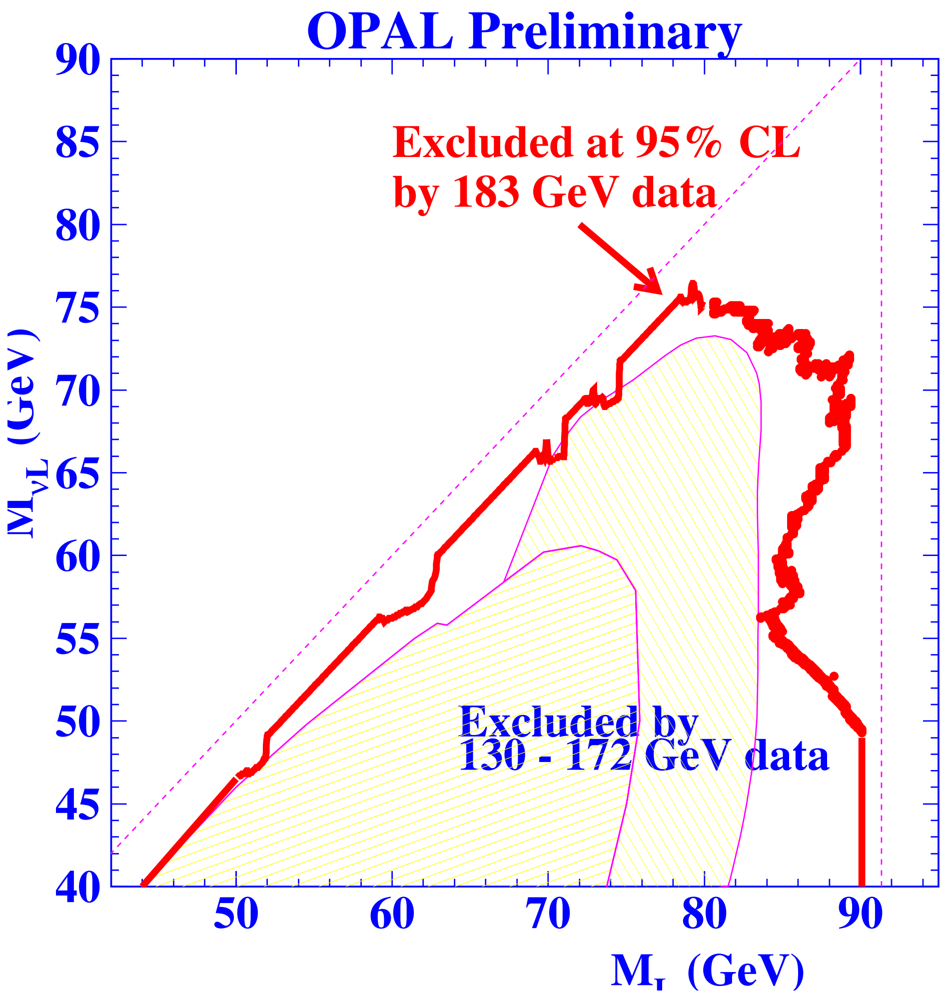


- Topology: 2 acoplanar jets/particles
- Visible energy can be small, depending on $\Delta M \equiv M_{\rm L^\pm} - M_{\nu_{\rm L}}$
- Analysis is sensitive down to $\Delta M = 3$ GeV.
- Results from $\sqrt{s} = 183$ GeV data, $\approx 57\mathrm{pb}^{-1}$.
  $\rightarrow$ Exclusion region in $(M_{\rm L^\pm}, M_{\nu_{\rm L}})$ plane

# Exclusion Region for Long-Lived Heavy Neutral Leptons

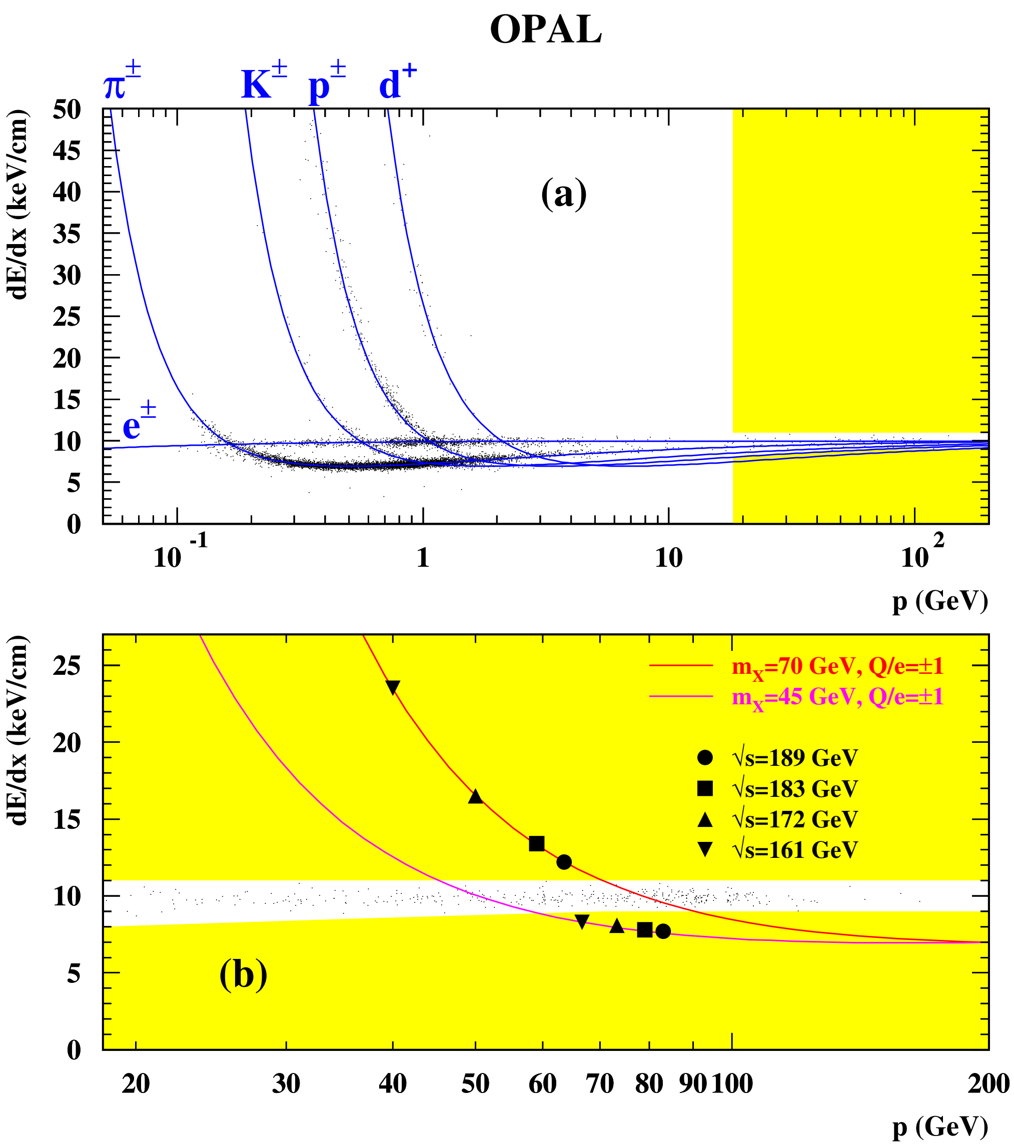
(c.f. LEP 1 limits: $M_{\nu_L} > 40$ GeV.)



# Search for Stable/Long-lived $L^+ L^-$

- Topology: two back-to-back charged tracks, without associated electromagnetic/hadronic showers (massive particles, not strongly interacting).
- Both tracks must have $dE/dx$ outside SM range
- Two particles with low $\beta = p/E_{beam}$ (kinematics)




No candidates in 183-189 GeV data.

$M_L > 92.6$ GeV.

# Mass Limits for Heavy Leptons

# LEP 2 Summary

| Channel | | Mass Limit (GeV) | | | |
|---|---|---|---|---|---|
| | | OPAL 183+189 | OPAL 183 | L3 183 | DELPHI 183 |
| $\mathrm{N} \to \mathrm{eW}$ | Dirac | 89.5 | 87.3 | 86.3 | 76.5 |
| | Majorana | 77.7 | 75.7 | 72.5 | - |
| $\mathrm{N} \to \mu\mathrm{W}$ | Dirac | 89.9 | 86.4 | 87.7 | 79.5 |
| | Majorana | 78.3 | 74.0 | 74.9 | - |
| $\mathrm{N} \to \tau\mathrm{W}$ | Dirac | 80.1 | 77.0 | 75.4 | 60.5 |
| | Majorana | 62.6 | 58.1 | 63.6 | - |
| $\mathrm{L}^{\pm} \to \nu_{\ell}\mathrm{W}^{\pm}$ | | 91.3 | 84.0 | 85.0 | 78.3 |
| $\mathrm{L}^{\pm}$ stable/long-lived | | 92.6 | 89.5 | 93.5* | - |

* L3 $\mathrm{L}^{\pm}$ Limit from $\sqrt{s} = 189$ GeV

All results are preliminary and at the 95 % CL .

Improvement over 1996 PDG limits (typically 45 GeV)

($\approx 10$ GeV higher than 1998 PDG limits).

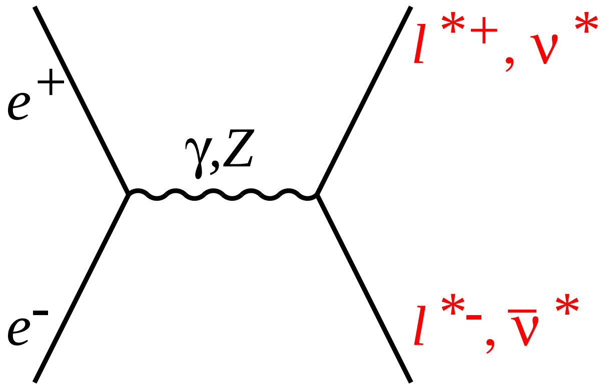
# (B) Search for Compositeness

Excited states at scale $\Lambda$, coupling to ordinary fermions:

$$\mathcal{L}_{\ell^*\ell} = \sum_{V=\gamma,\mathrm{Z}^0,\mathrm{W}^\pm} \frac{e}{2\Lambda}\overline{\ell^*}\sigma^{\mu\nu}\left(c_{V\ell^*\ell} - d_{V\ell^*\ell}\gamma_5\right)\ell_{\mathrm{L}}\partial_\mu V_\nu$$

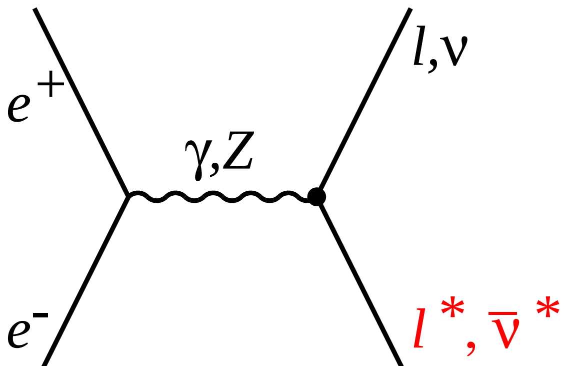
$c_{V\ell^*\ell}$, $d_{V\ell^*\ell}$ compatible with constraints from ($g-2$, EDM).

Excited fermions produced in pairs:

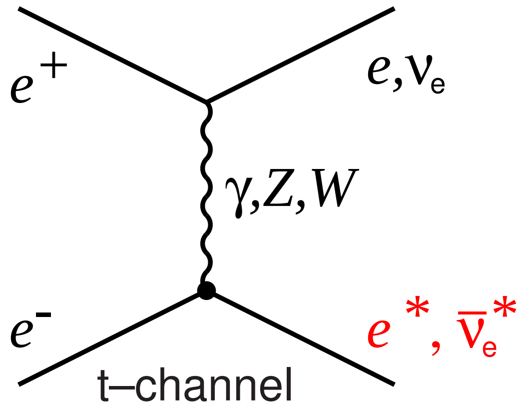



$\rightarrow$ Discovery up to $\sqrt{s}/2$

Excited fermions singly-produced:




s–channel



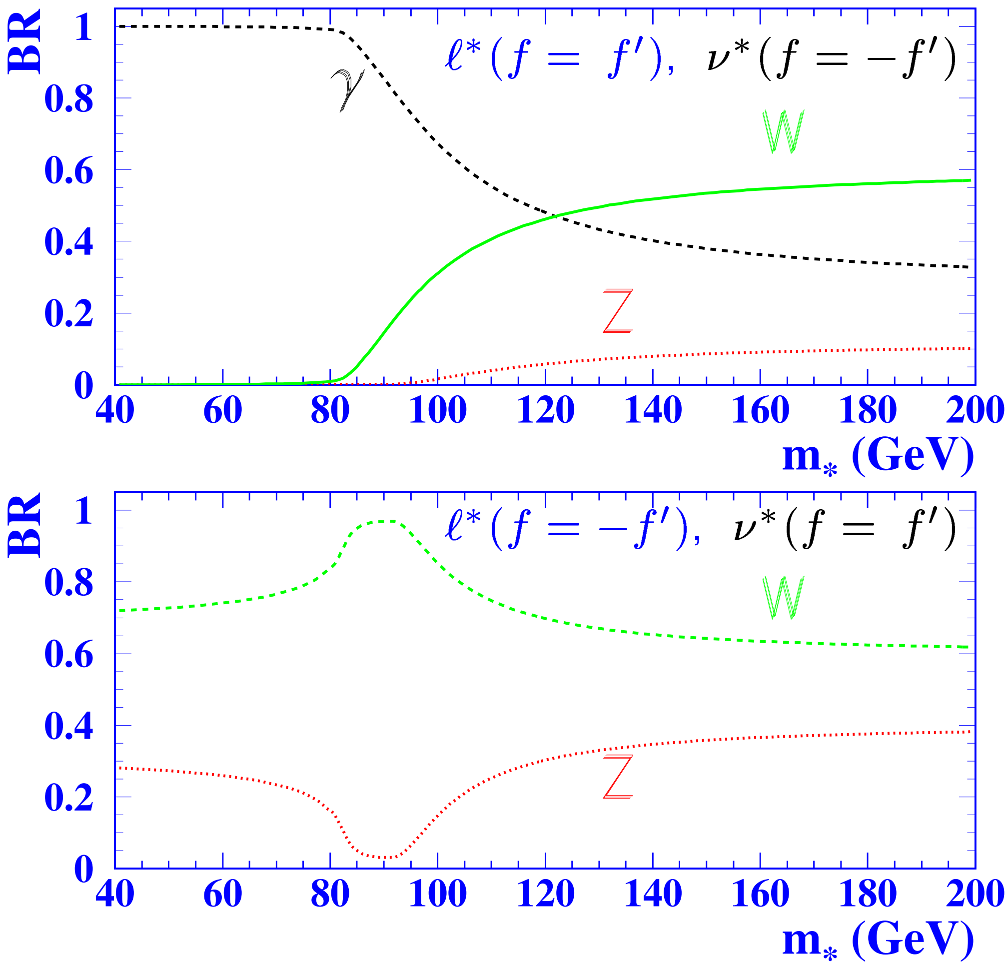

t–channel

$\rightarrow$ Discovery up to $\sqrt{s}$

# Decays of Excited Leptons

Coupling to SM fermions via effective Lagrangian:

$$\mathcal{L}_{\ell^*\ell} = \frac{1}{2\Lambda}\overline{\ell^*}\sigma^{\mu\nu}\left[g f \frac{\tau}{2}\mathrm{W}_{\mu\nu} + g' f' \frac{Y}{2}B_{\mu\nu} + g_s f_s \frac{\lambda}{2}G_{\mu\nu}\right]\ell_{\mathrm{L}}$$




Banching Ratios, final-state topologies, efficiencies depend on gauge group weights $f$, $f'$.

Common settings: $f = f'$

$f = -f'$ ($\nu^* \rightarrow \gamma\nu$ possible)

$f = 0$ (no $t$-channel $\nu^*\nu^{(*)}$)

# Pair Production of Excited Leptons

| | | | |
|---|---|---|---|
| (a) CC Decays: | $\nu^* \nu^* \to \ell\, \ell\, W W$ | $(f = f')$ | Heavy Lepton |
| | $\ell^* \ell^* \to \nu \nu W W$ | $(f = -f')$ | CC Analysis |
| (b) $\gamma$ Decays: | $\ell^* \ell^* \to \ell \ell \gamma\gamma$ | $(f = f')$ | |
| | $\nu^* \nu^* \to \nu_\ell\, \nu_\ell\, \gamma\gamma$ | $(f = -f')$ | |

Combined data at 183-189 GeV

| Pair | Data | Total Bkd | Efficiency $M_* = 90$ GeV |
|---|---|---|---|
| $ee\gamma\gamma$ | 3 | 5.5 | 55.3% |
| $\mu\mu\gamma\gamma$ | 1 | 1.8 | 59.9% |
| $\tau\tau\gamma\gamma$ | 1 | 1.4 | 42.5% |
| $\nu\nu\gamma\gamma$ | 8 | 7.4 | 73.8% |

OPAL Preliminary

No excess observed. Mass limits from pair production $\rightarrow$

# Mass Limits for Excited Leptons

# LEP 2 Summary

Results are preliminary and at 95% CL

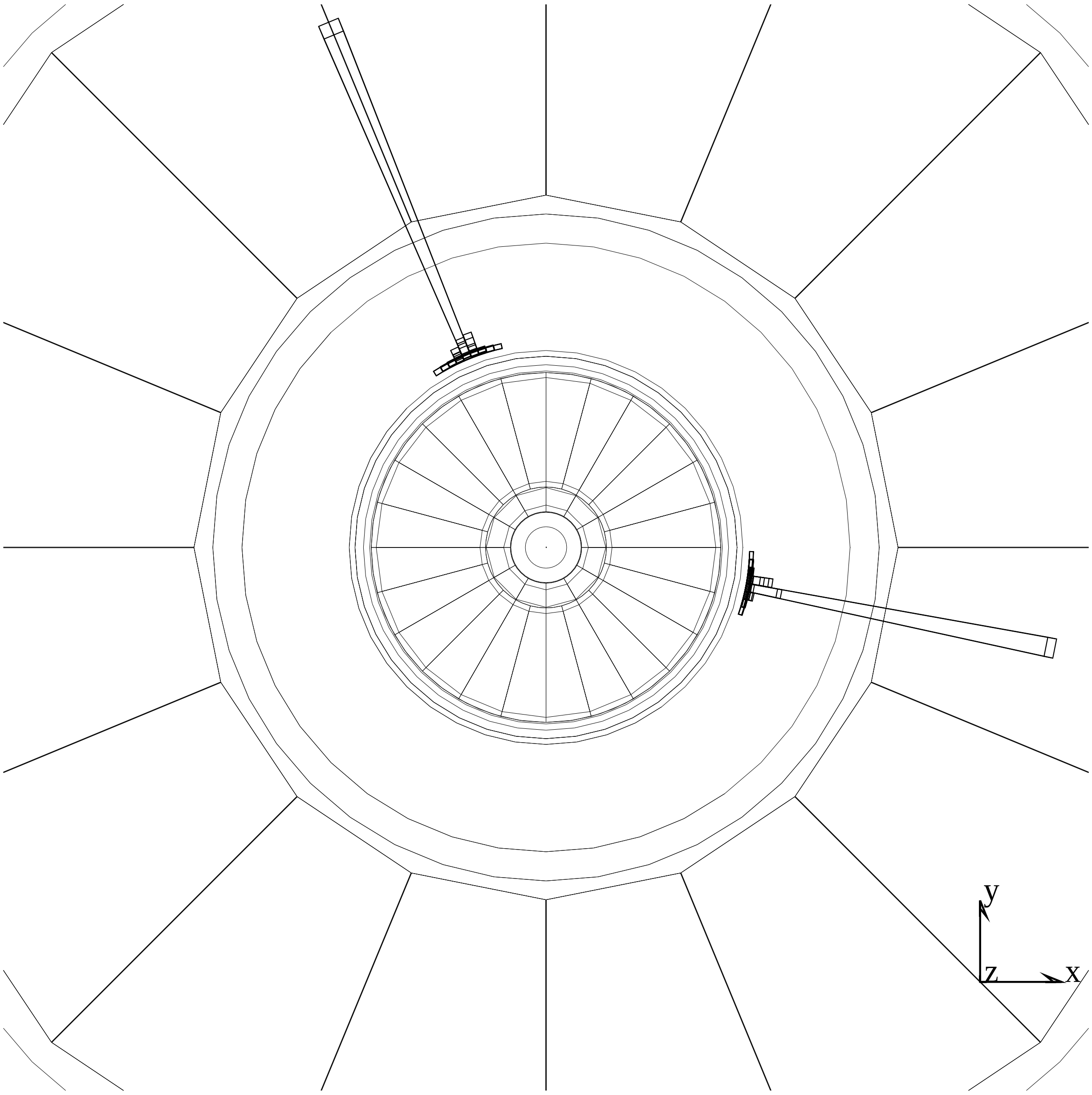
| Type | Coupling | Primary Decay | Mass Limit (GeV) OPAL 183+189 | OPAL 183 | L3 189 | DELPHI 183 |
|---|---|---|---|---|---|---|
| $\mathrm{e}^*$ | $f = f'$ | Photonic | 94.1 | 91.4 | 93.7 | 90.7 |
| $\mu^*$ | $f = f'$ | Photonic | 94.1 | 91.4 | 93.7 | 90.7 |
| $\tau^*$ | $f = f'$ | Photonic | 94.0 | 91.3 | 93.6 | 89.7 |
| $\mathrm{e}^*$ | $f = -f'$ | Charged | 91.3 | 86.0 | - | 81.3 |
| $\mu^*$ | $f = -f'$ | Charged | 91.3 | 86.0 | - | 81.3 |
| $\tau^*$ | $f = -f'$ | Charged | 91.3 | 86.0 | - | 81.3 |
| $\nu_\mathrm{e}^*$ | $f = f'$ | Charged | 92.8 | 91.1 | - | 87.3 |
| $\nu_\mu^*$ | $f = f'$ | Charged | 93.6 | 90.9 | - | 88.0 |
| $\nu_\tau^*$ | $f = f'$ | Charged | 90.5 | 87.0 | - | 81.0 |
| $\nu_\mathrm{e}^*$ | $f = -f'$ | Photonic | 93.2 | 91.0 | 85.3* | 90.0 |
| $\nu_\mu^*$ | $f = -f'$ | Photonic | 93.2 | 91.0 | 85.3* | 90.0 |
| $\nu_\tau^*$ | $f = -f'$ | Photonic | 93.2 | 91.0 | 85.3* | 90.0 |

* L3 Limit worse due to candidate in $\sqrt{s} = 189$ GeV data.

Excited leptons excluded below $\sim \mathrm{M_Z}$

# L3 Excited Neutrino Candidate in 189 GeV Data

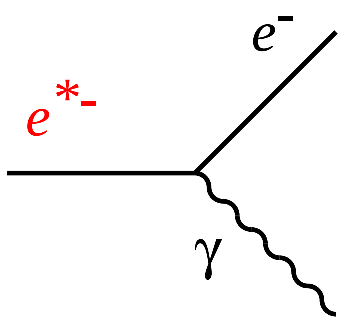
**Run #** **703702** **Event #** **4493** Total Energy : 76.38 GeV




| | | | |
|---|---|---|---|
| **Transverse Imbalance :** .3904 | | **Longitudinal Imbalance :** -.5698 | |
| **Thrust :** .7334 | **Major :** .6699 | **Minor :** .0000 | |
| **Event DAQ Time :** | *980708 84005* | | |

Candidate for $\nu^*\nu^*\rightarrow\nu_\ell\,\nu_\ell\,\gamma\gamma$

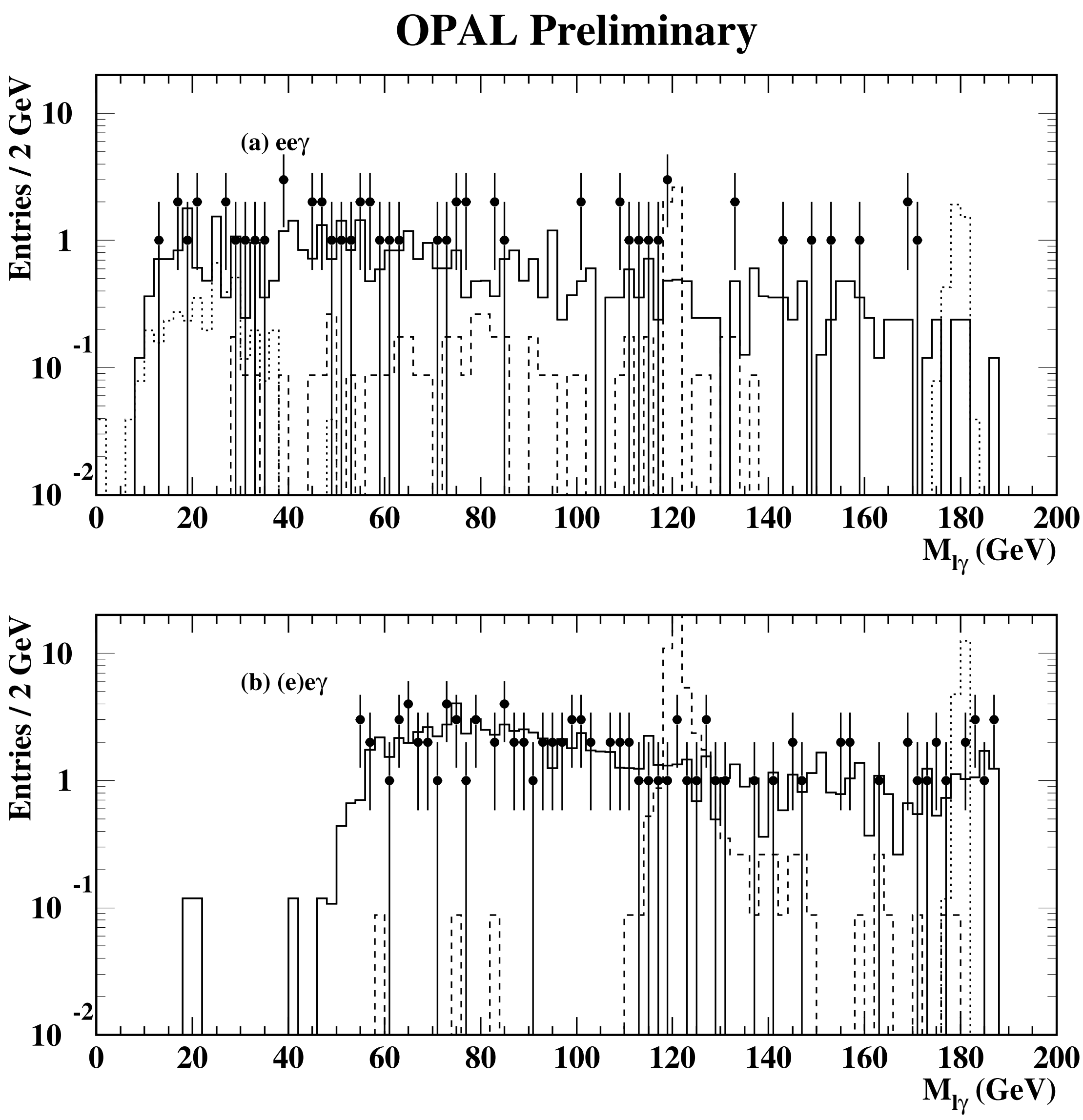
# Single Production of Excited Electrons




(a) $e^*e \rightarrow ee\,\gamma$

(b) $e^*e \rightarrow e(e)\ \ \gamma$

Look for excess in $m_{e\gamma}$




No peaks in mass distributions, $\sqrt{s} = 189$ GeV .

# Single Production of Excited Leptons

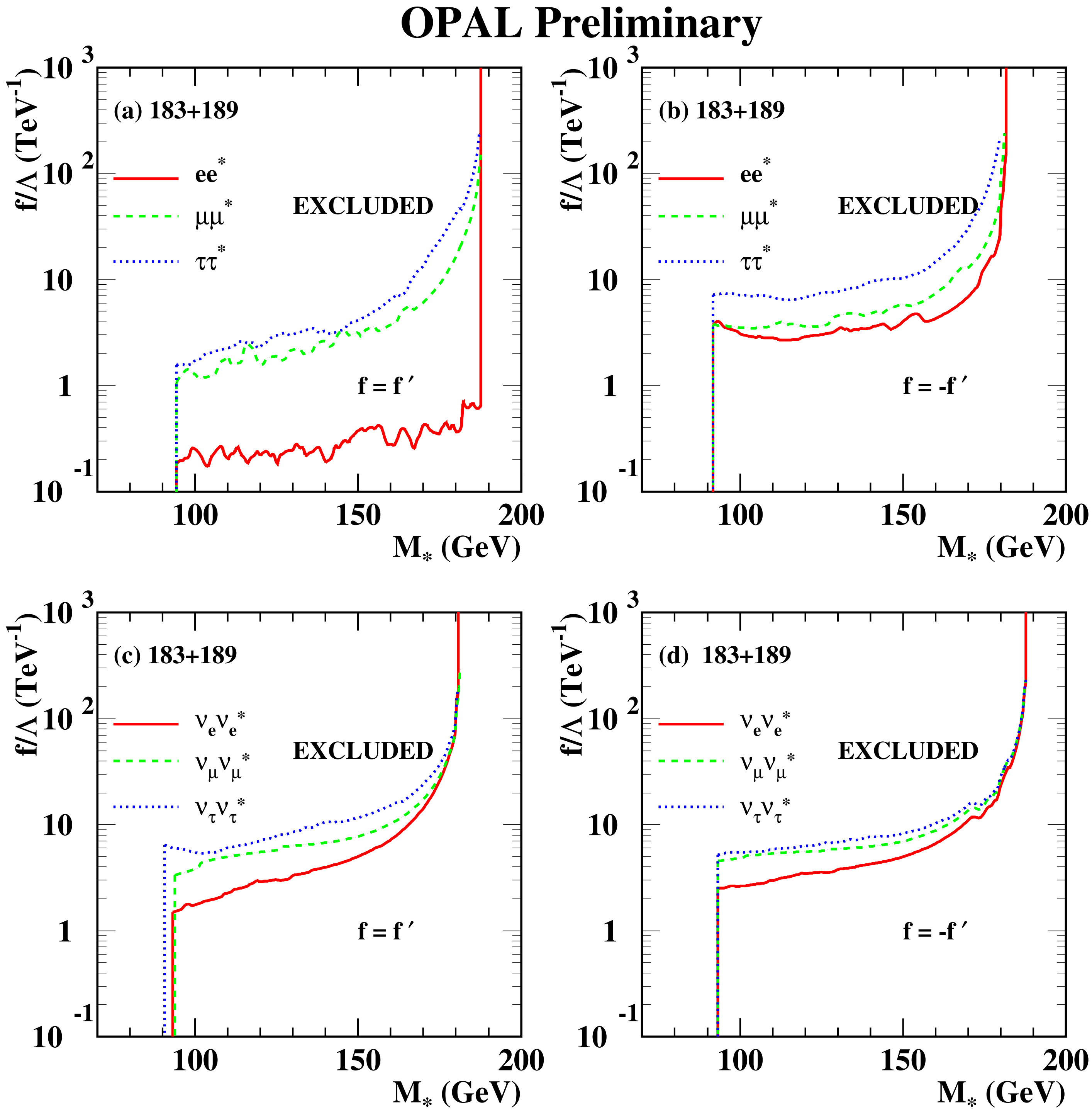
| Mode | Topology | Data | Total Bkd |
|---|---|---|---|
| $\ell^*\ell \to \nu\ell\mathrm{W}$ | $\mathrm{e}^*\mathrm{e} \to \nu_\mathrm{e}\mathrm{e}\,\mathrm{q}\bar{\mathrm{q}}$ | 11 | 17.2 |
| | $\mu^*\mu \to \nu_\mu\mu\mathrm{q}\bar{\mathrm{q}}$ | 2 | 5.3 |
| | $\tau^*\tau \to \nu_\tau\tau\mathrm{q}\bar{\mathrm{q}}$ | 34 | 39.4 |
| $\nu^*\nu \to \nu\ell\mathrm{W}$ | $\nu_\mathrm{e}^*\nu_\mathrm{e} \to \nu_\mathrm{e}\mathrm{e}\,\mathrm{q}\bar{\mathrm{q}}$ | 11 | 17.2 |
| | $\nu_\mu^*\nu_\mu \to \nu_\mu\mu\mathrm{q}\bar{\mathrm{q}}$ | 2 | 5.3 |
| | $\nu_\tau^*\nu_\tau \to \nu_\tau\tau\mathrm{q}\bar{\mathrm{q}}$ | 27 | 35.0 |
| $\ell^*\ell \to \ell\ell\mathrm{Z}$ | $\mathrm{e}^*\mathrm{e} \to \mathrm{ee}\,\mathrm{q}\bar{\mathrm{q}}$ | 2 | 3.7 |
| | $\mathrm{e}^*\mathrm{e} \to \mathrm{e(e)}\,\mathrm{q}\bar{\mathrm{q}}$ | 45 | 45 |
| | $\mu^*\mu \to \mu\mu\,\mathrm{q}\bar{\mathrm{q}}$ | 3 | 1.9 |
| | $\tau^*\tau \to \tau\tau\,\mathrm{q}\bar{\mathrm{q}}$ | 16 | 15 |
| $\nu^*\nu \to \nu\nu\mathrm{Z}$ | $\nu^*\nu \to \nu\nu\,\mathrm{q}\bar{\mathrm{q}}$ | 21 | 22 |
| $\ell^*\ell \to \ell\ell\gamma$ | $\mathrm{e}^*\mathrm{e} \to \mathrm{ee}\,\gamma$ | 54 | 63.6 |
| | $\mathrm{e}^*\mathrm{e} \to \mathrm{e(e)}\,\gamma$ | 324 | 340.2 |
| | $\mu^*\mu \to \mu\mu\,\gamma$ | 25 | 27.0 |
| | $\tau^*\tau \to \tau\tau\,\gamma$ | 34 | 39.5 |
| $\nu^*\nu \to \nu\nu\gamma$ | $\nu^*\nu \to \nu\nu\,\gamma$ | 7 | 3.5 |

Preliminary OPAL results for 183 GeV (NC,CC decays), 183-189 GeV $\gamma$ (decays).

Limits on $f/\Lambda \to$

# Limits for Excited Leptons

## 183-189 GeV Data



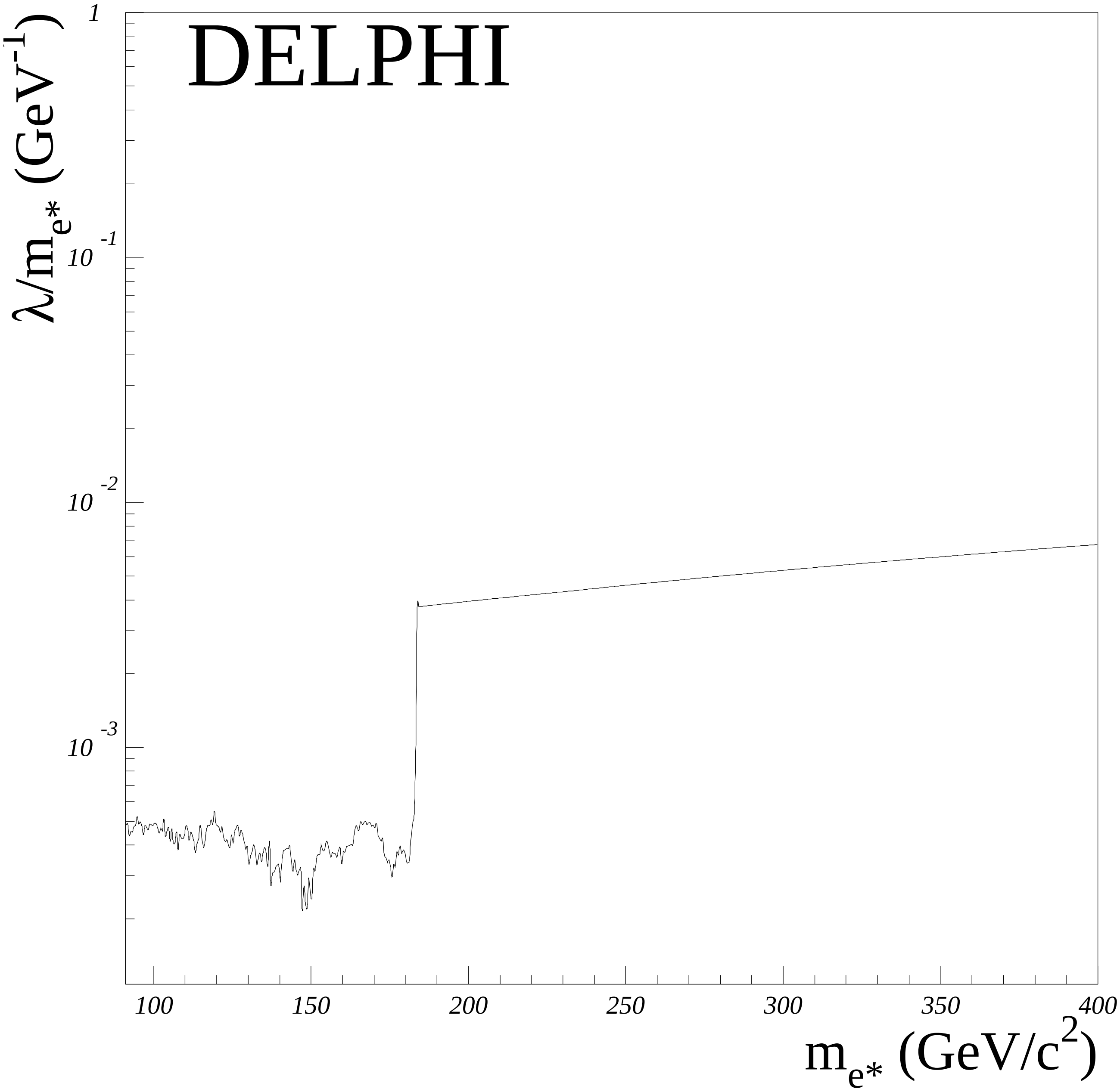

Upper limits on $f/\Lambda$ versus mass of excited fermion.

Richard.Teuscher@cern.ch ICHEP 98 Vancouver July 24, 1998

# Single Production of Excited Electrons

From direct searches at 183 GeV

and indirect searches $e^+e^- \to \gamma\gamma,\ f = f'$

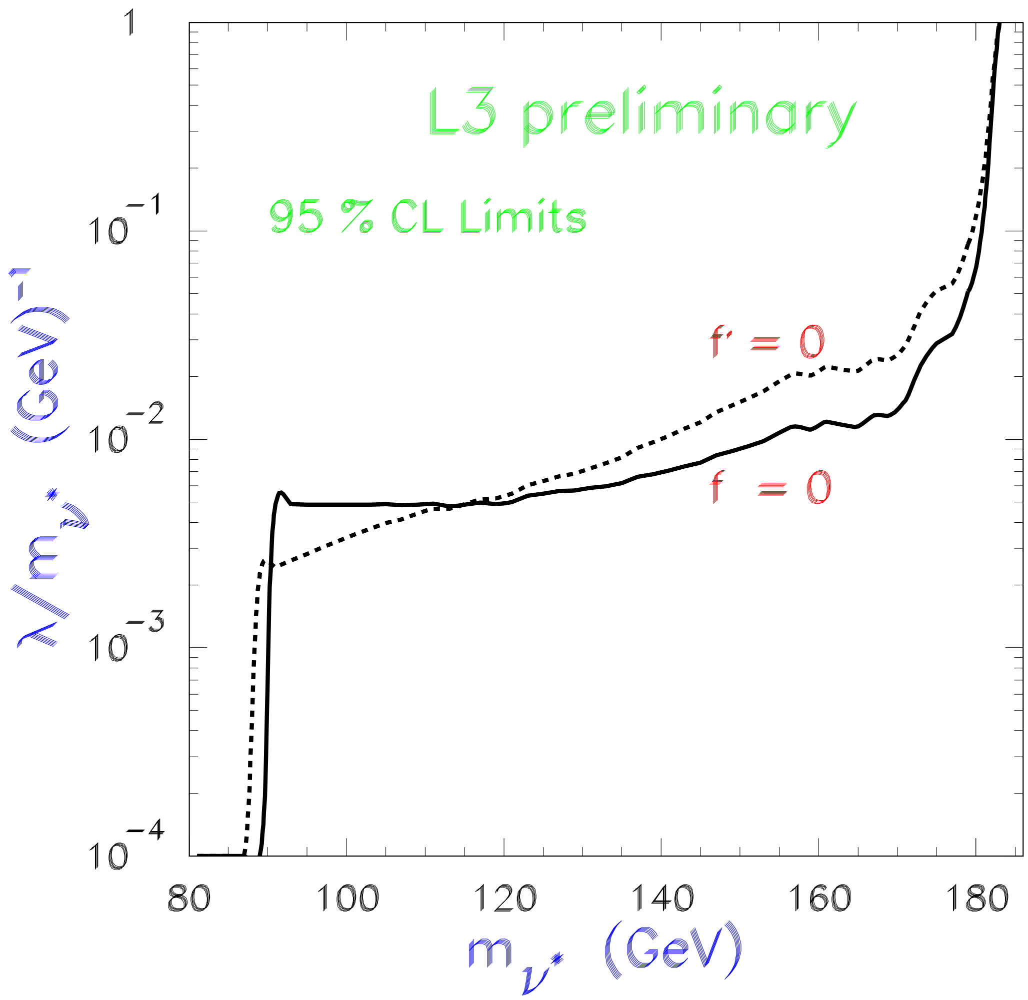



Limits for coupling $\lambda/\mathrm{m}_{q^*} = f/(\sqrt{2}\Lambda)$

# Limits for Excited Neutrinos: $f = 0, f' = 0$

If $f = 0$: no $t$-channel $\nu^*\nu^{(*)}$ production

| Channel | 183 GeV Data | Total Bkd. | Efficiency |
|---|---|---|---|
| $\nu^*\nu^* \rightarrow \nu\nu\gamma\gamma$ | 0 | 0.5 | 53% |
| $\nu^*\nu \rightarrow \nu\nu\gamma$ | 73 | 73 | 72% |

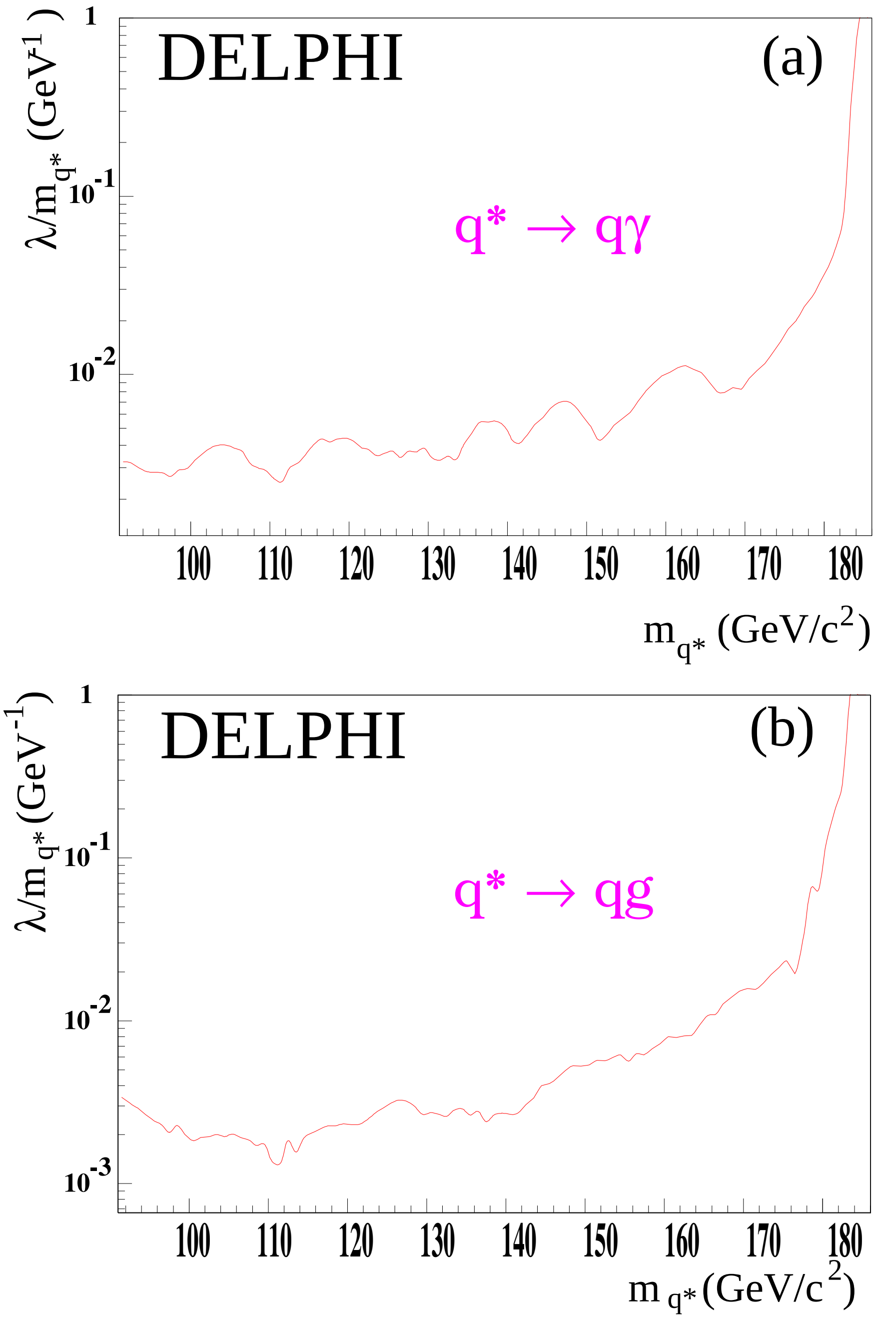



Limits for coupling $\lambda/\mathrm{m}_{\nu^*} = f/(\sqrt{2}\Lambda)$

# Single Production of Excited Quarks

| Channel | 161-183 GeV Data | Total Bkd | Efficiency $M_{q^*} = 170$ GeV |
|---|---|---|---|
| $q^* \to q\gamma$ | 196 | 191 | 31% |
| $q^* \to qg$ | 140 | 152 | 19% |

Assuming up-type excited quarks.



# Summary

- No discovery yet.
- LEP 2 Searches from DELPHI, L3, OPAL for

    Heavy Neutral Leptons,

    Heavy Charged Leptons,

    Long-Lived Heavy Leptons,

    Excited Leptons

    Excited Quarks

- From May 25, 1998 data-taking at $\sqrt{s}$ =189 GeV, LEP 2 Results with 37pb$^{-1}$ at already higher than 1998 PDG Limits by $\sim 10$ GeV
- Expect full $\sqrt{s}$ =183-189 GeV data 57+150 pb$^{-1}$ Chance for discovery?