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Searches for Exotica at LEP

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EPS99, Tampere, Finland, 15-21 July 1999

OUTLINE:

- Standard Model vs LEP results
  - Precision EW tests and New Physics
  - Why beyond the Standard Model?
  - Challenges beyond the SM
- Any experimental hints?
  - Contact Interactions
  - New Generations
  - Compositeness
  - Technicolour
  - Quantum Gravity
- Conclusions

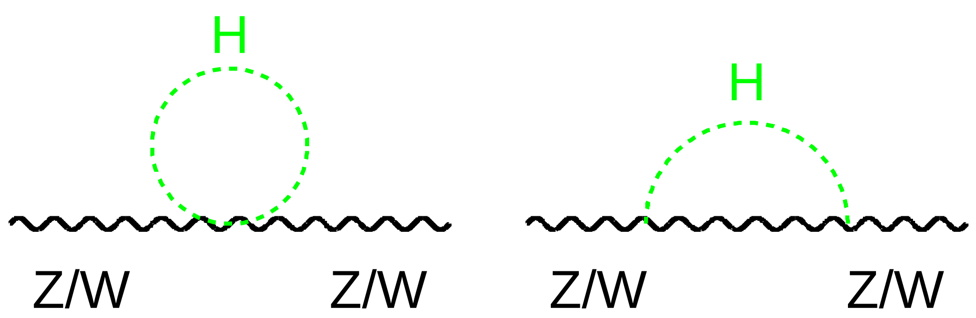
LEP results and Standard Model

Precision LEP results

- Masses of the gauge bosons
- Neutral couplings of fermions
- Self-couplings of gauge bosons

Qualitative LEP results

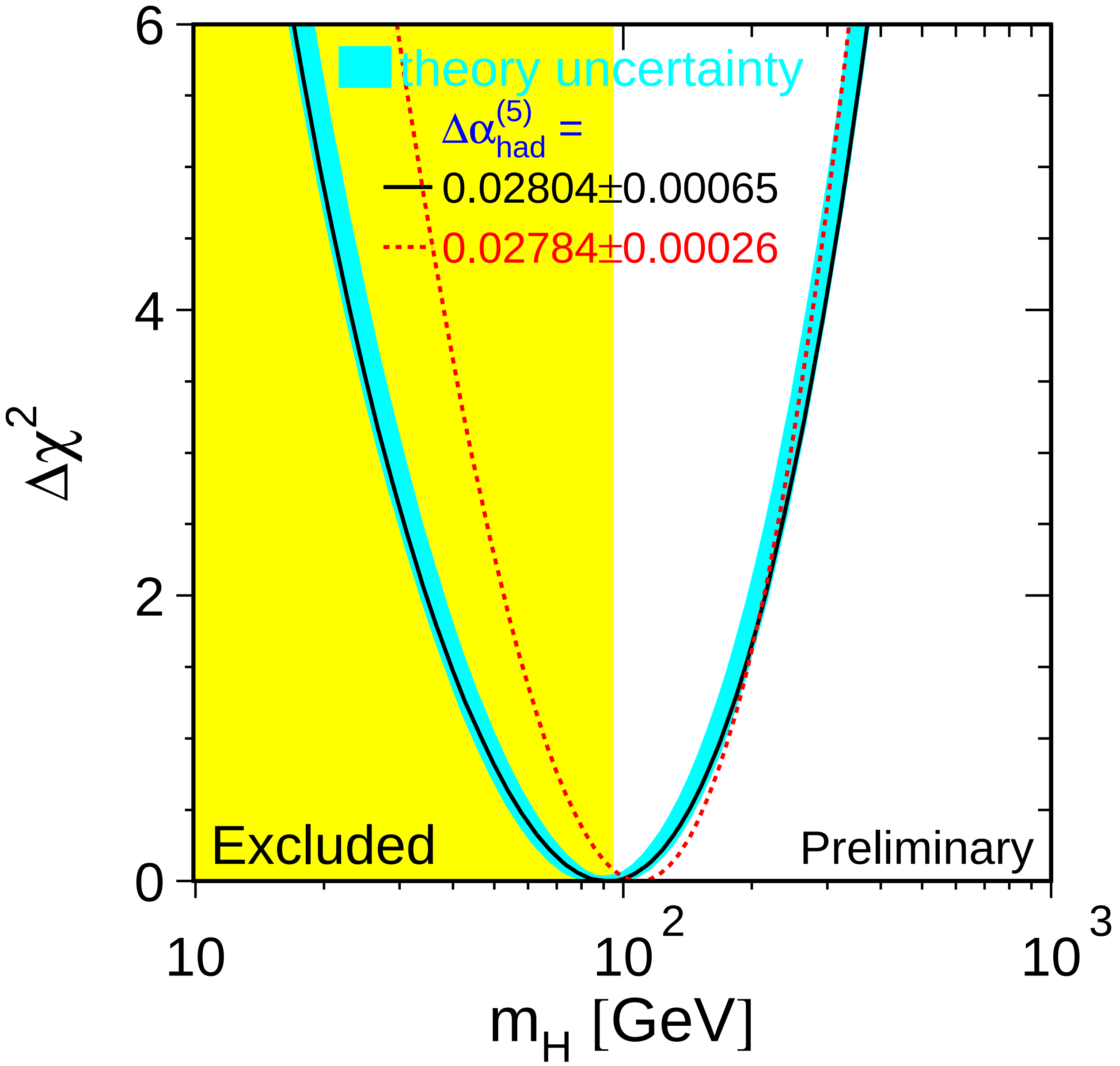
- Evolution of couplings beyond EW scale
- Sensitivity to the hidden sector of the Model
  (top quark and Higgs boson)



Precision EW tests and New Physics

LEP Electroweak Working Group,
measurements from LEP, Tevatron and SLAC:

$$M_H = 92^{+78}_{-45}\ \text{GeV}$$



$$M_H < 245\ \text{GeV at } 95\%\ \text{CL}$$

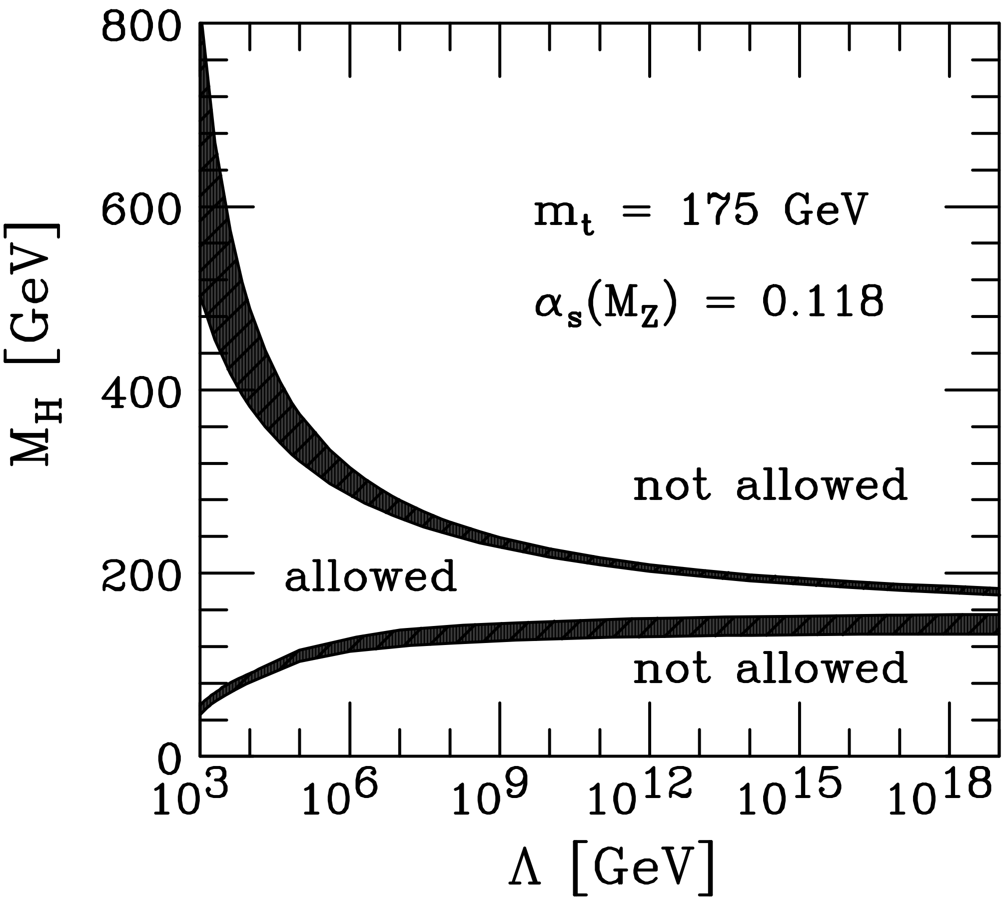
Higgs mass in the Standard Model

Higgs boson may not be too light, otherwise

- Higgs running coupling become negative
- our vacuum becomes metastable
- $m_H \geq 130$ GeV
  G.Altarelli and G.Isidori, Phys. Lett., B337 (1994) 141

Higgs boson may not be too heavy, otherwise

- unitarity limit is reached for gauge boson scattering
- quadric Higgs coupling behaves unsatisfactory
- $m_H \leq 180$ GeV
  T.Hambye and K.Riesselmann, Phys.Rev. D55 (1997) 7255



Why beyond the Standard Model ?

"Great Desert" scenario is not very attractive

Hierarchy problem

- Radiative corrections to Higgs mass are large
  $\delta \mathrm{M}_{\mathrm{H}}^2 \sim \Lambda_{\mathrm{NP}}^2 = \mathrm{M_P}^2$
- $\mathrm{M_P} >> M_W$, however $\mathrm{M_H} \sim M_W$
- Why gravity is so much detached?

Flavour dynamics

- Universal fermion couplings to gauge bosons
- However, flavour symmetry is broken
- Fermion mass values in SM are hand-made
- No hints why the pattern is so bizarre

May all that be fixed in one go?

Challenges beyond the SM

SUSY

- Solves the hierarchy problem
- Doubles the spectrum of particles
- Does not address the flavour symmetry breaking
- Does not explain $M_P >> M_W$

Technicolour

- Attempts to address flavour symmetry breaking
- Dynamic EW symmetry breaking (no Higgs!)
- Does not explain $M_P >> M_W$

Low scale quantum gravity

- Attempts to explain $M_P >> M_W$
- Attempts to include gravity into the theory
- Does not address flavour dynamics

Price to pay:

- New phenomena predicted, yet to be observed
- More free parameters, “flexibility” of predictions

LEP data

– Electron-positron collider near Geneva

– 27 km circumference

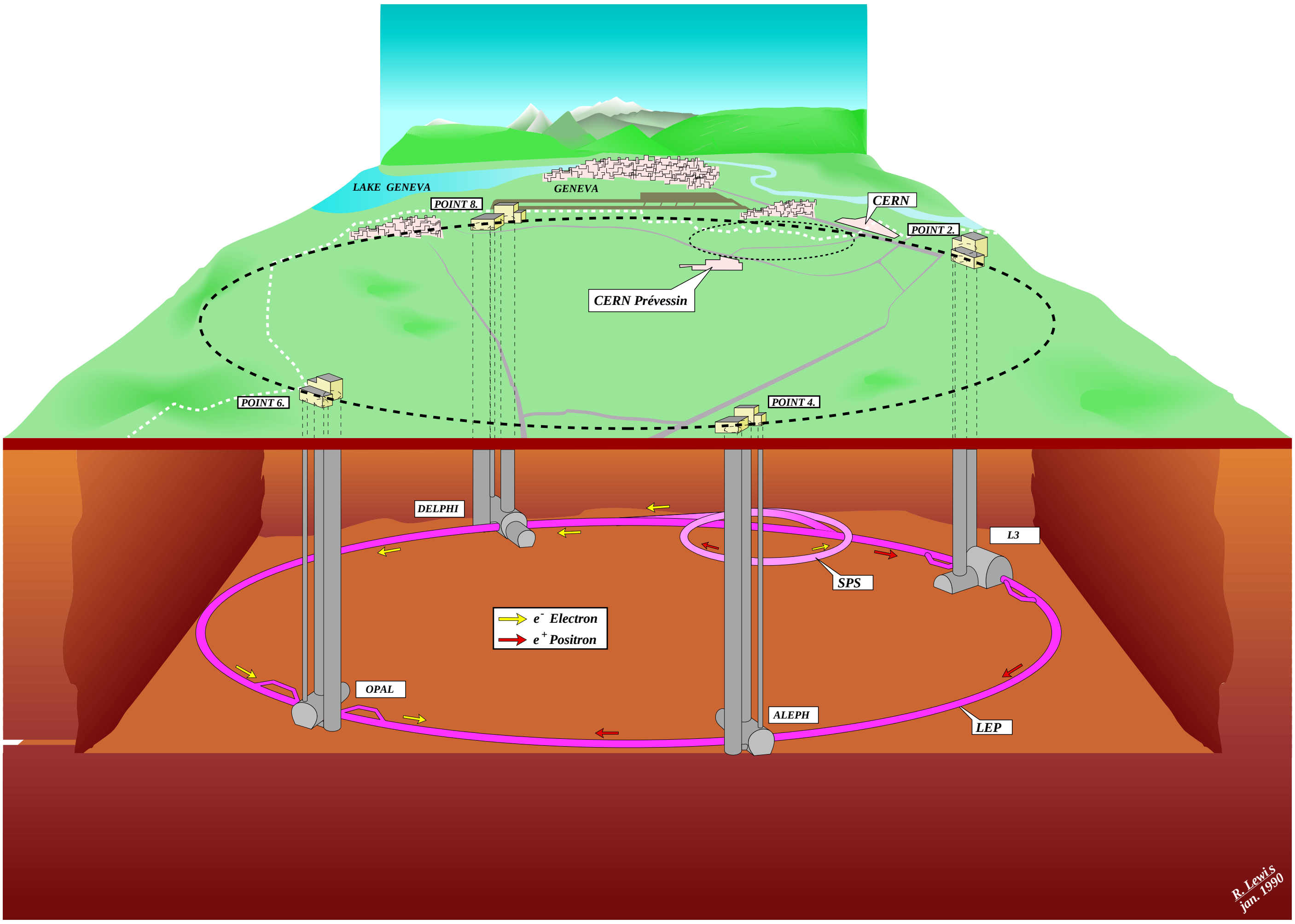
– Maximal energy $\sqrt{s} \sim 200$ GeV

– Four major experiments: ALEPH, DELPHI, L3, OPAL

– $\sqrt{s} = M_Z$ in 1989-1995

– $130 < \sqrt{s} < 196$ GeV in 1995-1999

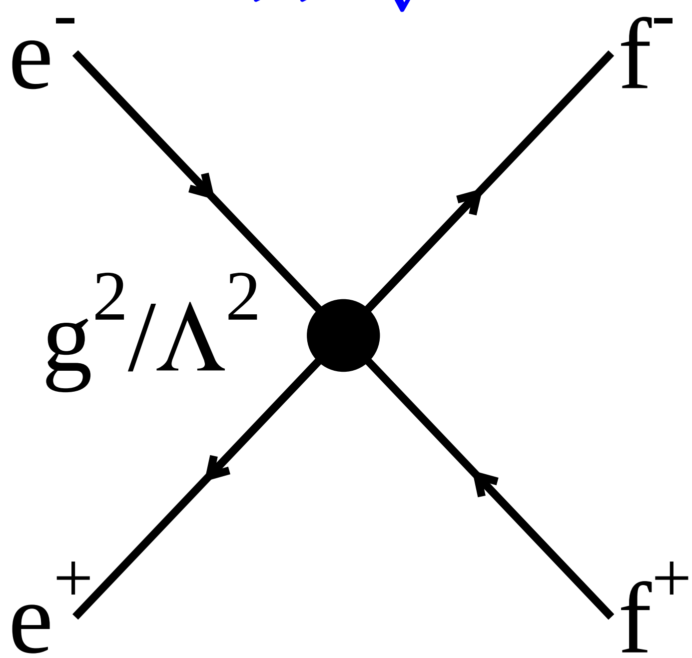
– $\sqrt{s} \sim 200$ GeV in 2000



Presented results are based on $4 \cdot 175\ pb^{-1}$ at $\sqrt{s} = 189$ GeV

Contact interactions

General framework to describe new interactions with typical energy scale $\Lambda >> \sqrt{s}$



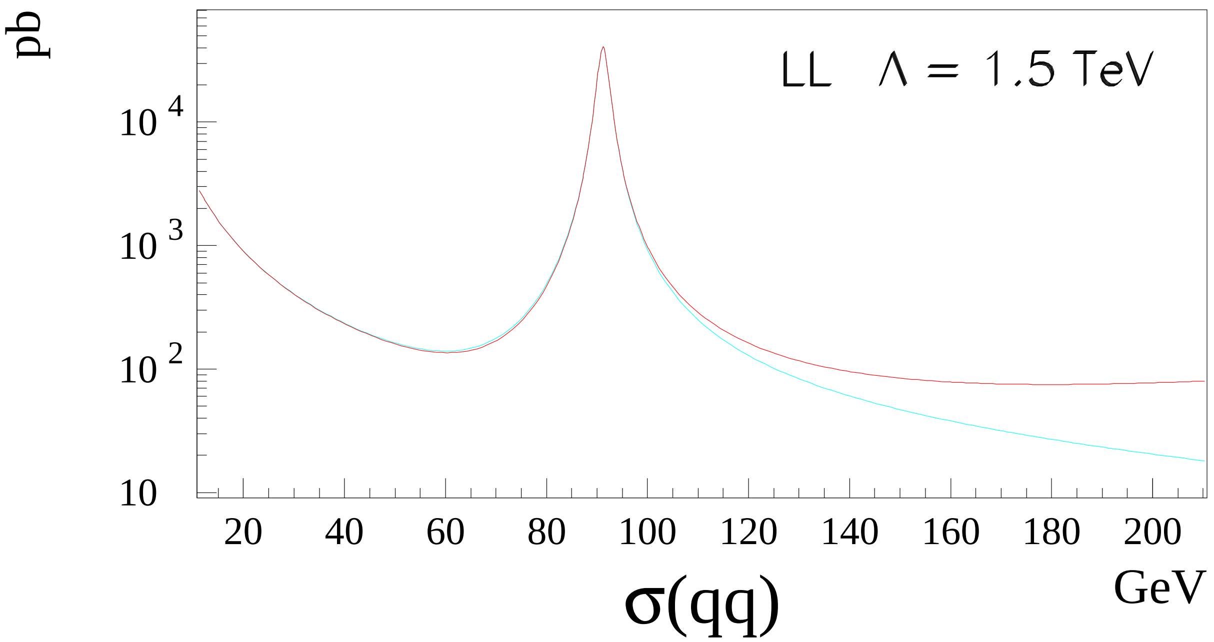
$$\mathcal{L} = \frac{1}{1+\delta} \sum_{i,j=L,R} \eta_{i,j} \frac{g^2}{\Lambda^2_{i,j}} (\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_i)(\bar{f}_j \gamma^\mu f_j)$$

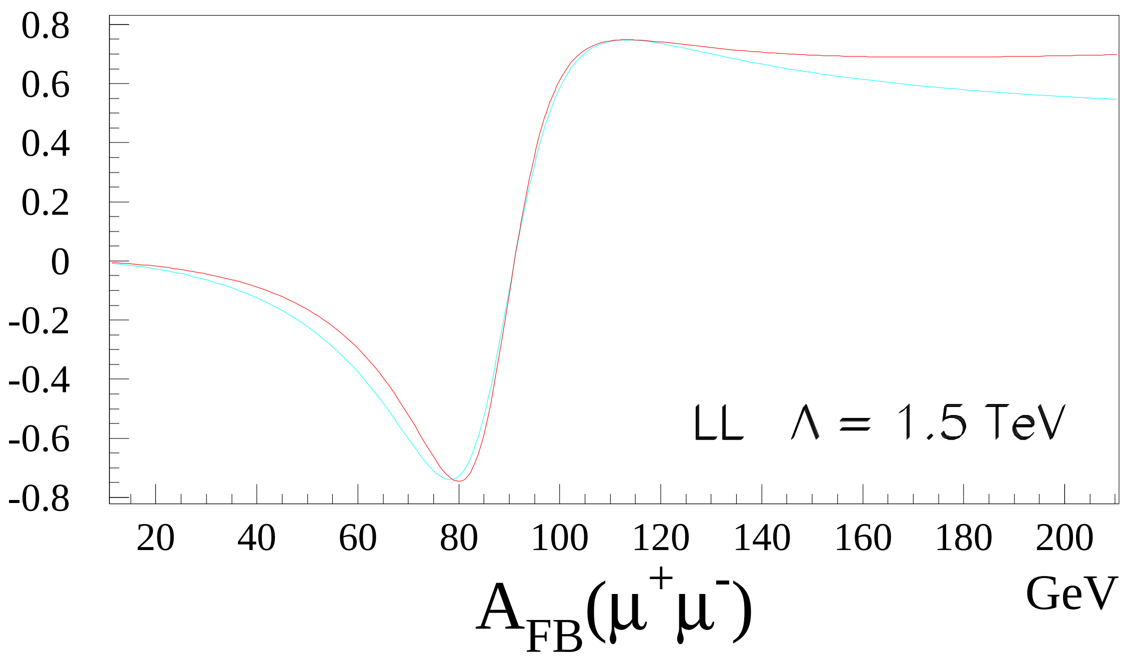
g – couplings ($g^2/4\pi = 1$ is assumed)
$\eta_{i,j}$ – helicity amplitudes: $|\eta_{i,j}| = 0, 1$
Λ – new physics scale

$$\frac{d\sigma}{d\Omega} = \mathrm{SM}(s,t) + \frac{g^2}{4\pi\Lambda^2} \cdot C_{\mathrm{int}}(s,t) + \frac{g^4}{16\pi^2\Lambda^4} \cdot C_{\mathrm{NP}}(s,t)$$

Contact interactions

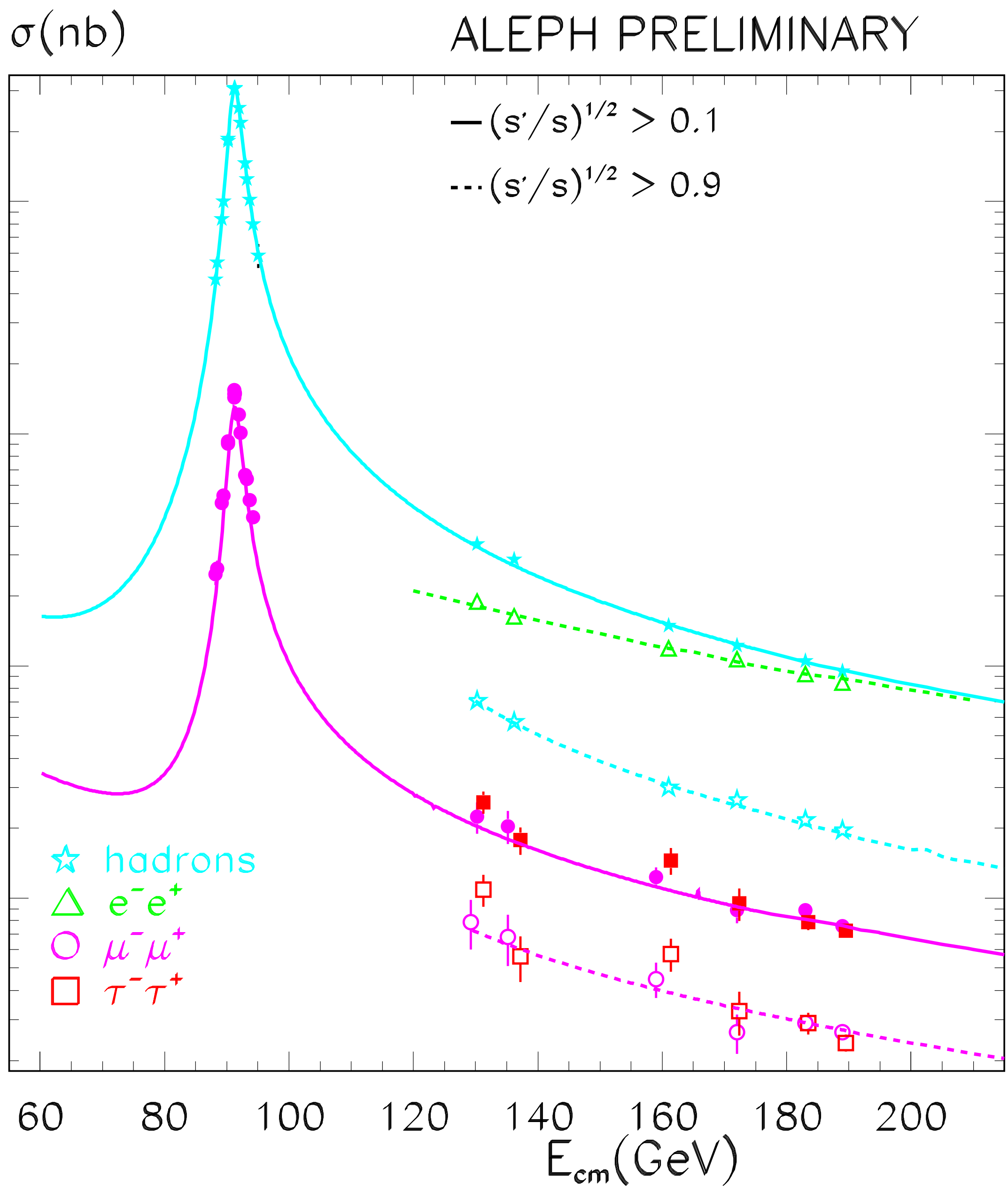
Significant effects in the cross section and charge asymmetry of fermion pairs





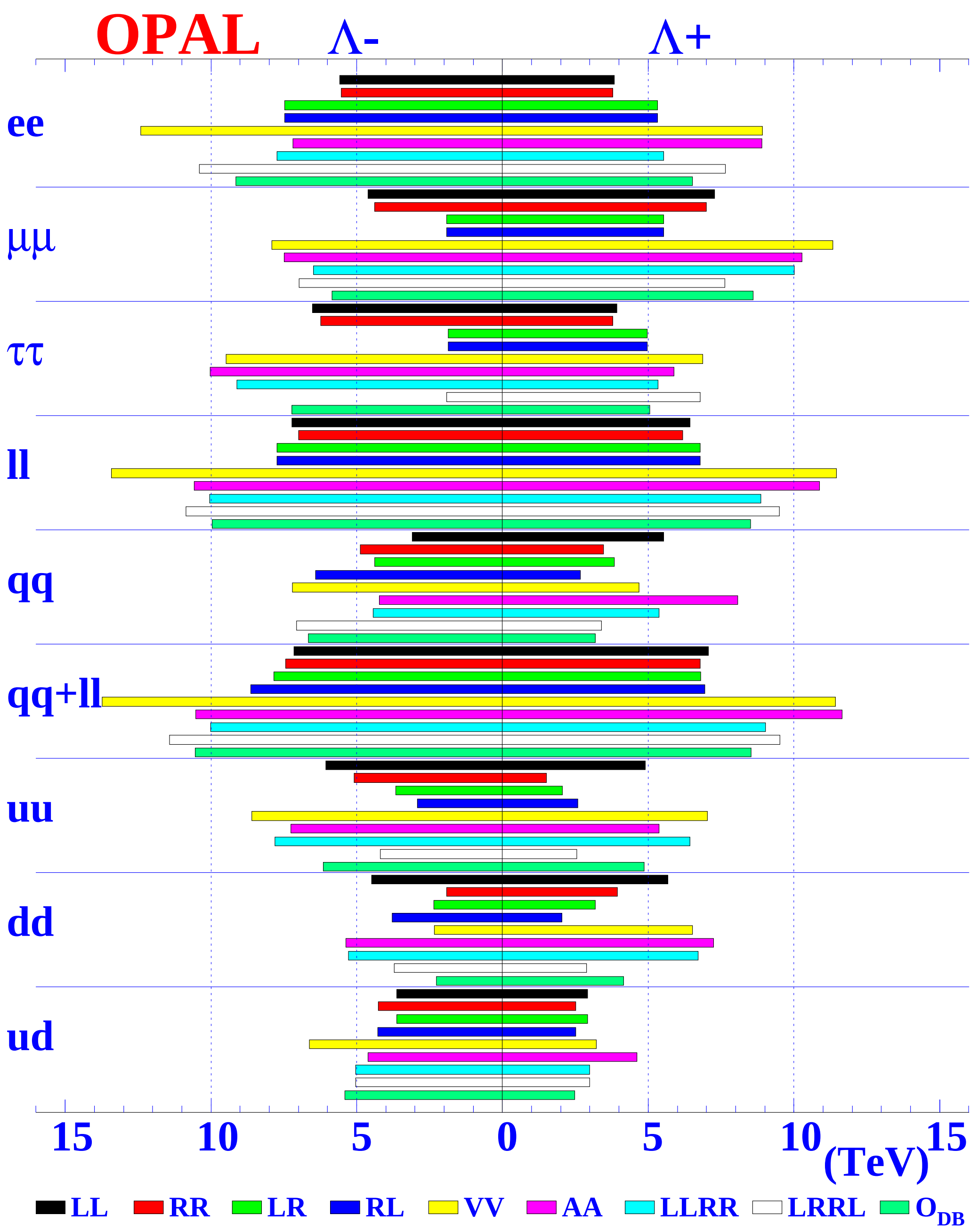
Contact interactions

Example of cross section measurements



Contact interactions

Limits on contact interactions



Similar limits from other LEP groups

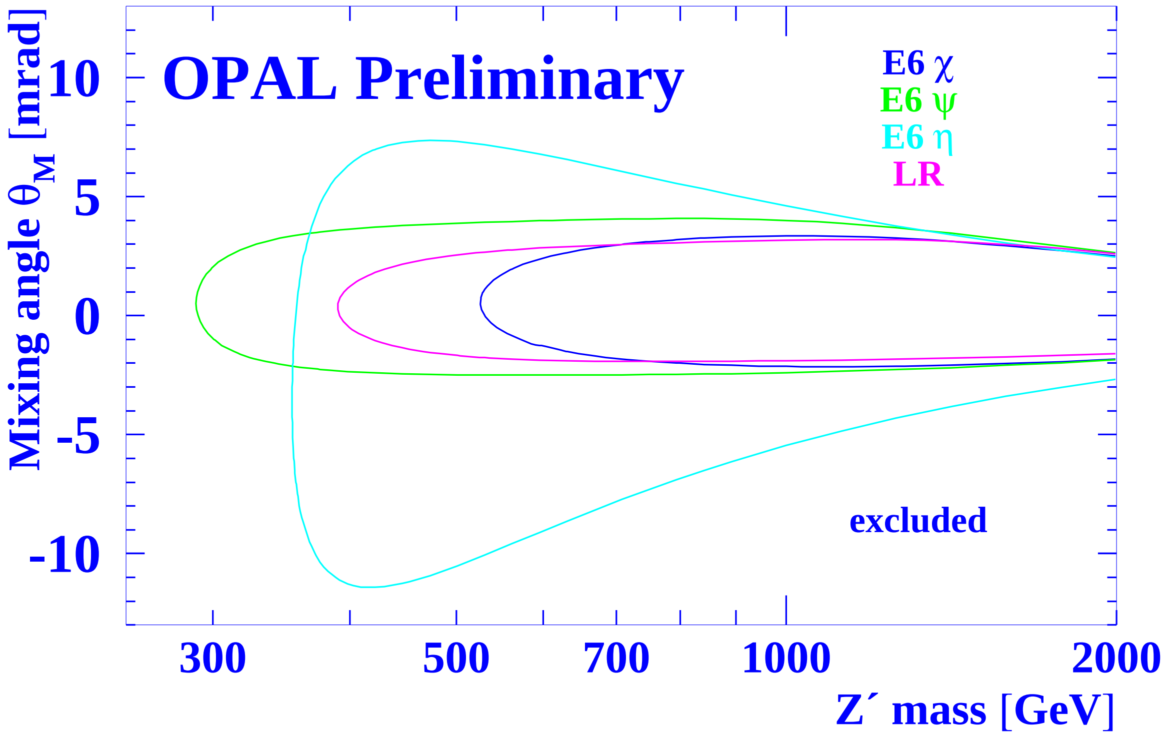
New Vector Bosons

PARAMETERS

- Mass, $M_{Z'}$
- Mixing with Z, θ_M
- Couplings to fermions, model dependent

SENSITIVITY

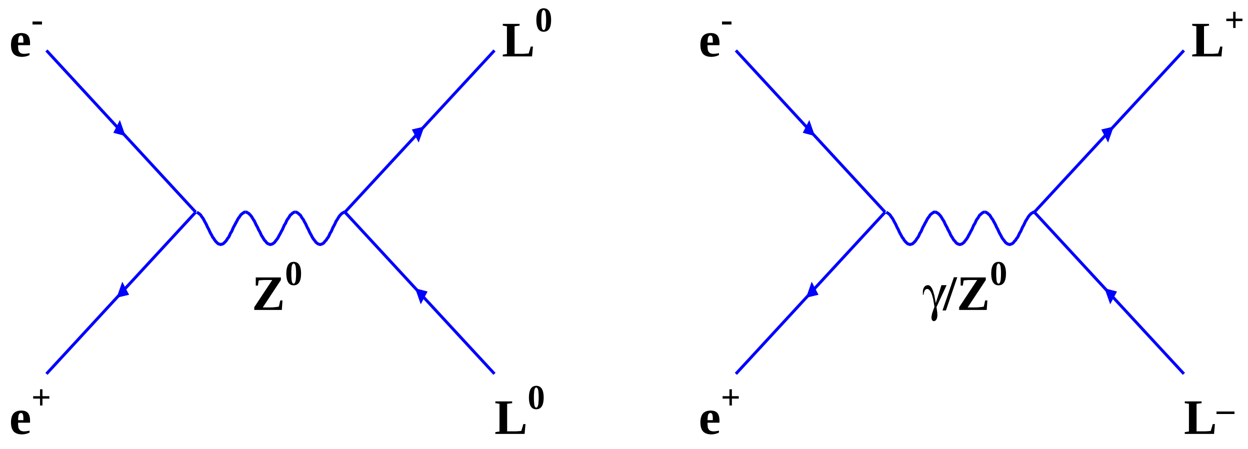
- LEP1: limits on the mixing angle
- LEP2: limits on mass and couplings



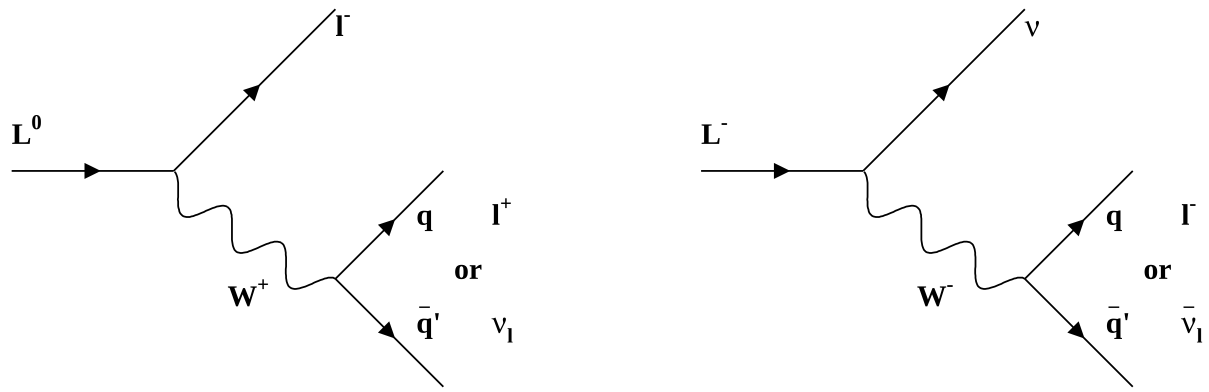
Similar exclusions reported by ALEPH, DELPHI and L3

New generations

Production of Heavy Sequential Leptons



Their Decay Modes



Experimental signatures

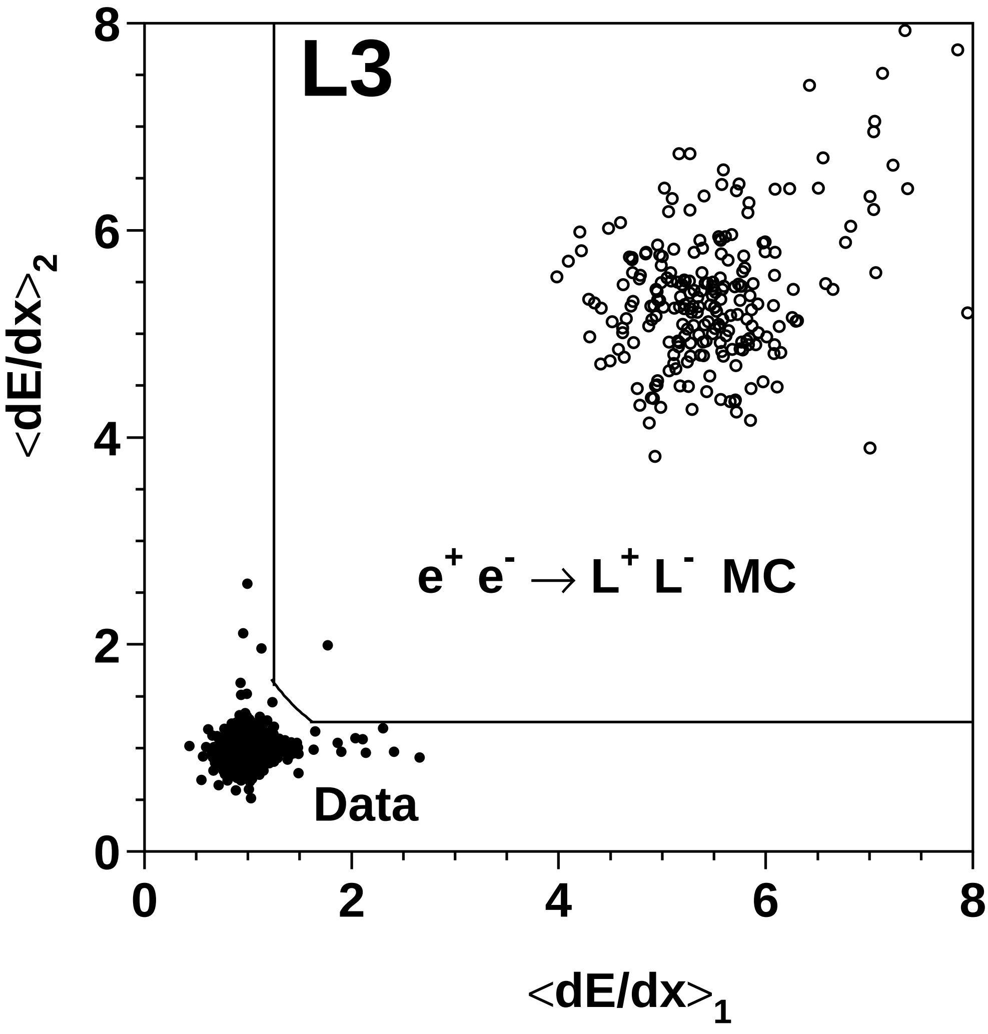
- Two isolated leptons
- Hadronic activity

- Missing momentum
- Hadronic activity
- Isolated leptons
- Highly ionising tracks

New Sequential Leptons

L3 Sequential Lepton search summary

Channel	Data	Background	Efficiency
$L^0 \longrightarrow eW$	6	7.2	$\sim 34\%$
$L^0 \longrightarrow \mu W$	1	1.2	$\sim 32\%$
$L^0 \longrightarrow \tau W$	33	32.3	$\sim 20\%$
$L^\pm \longrightarrow \nu_\ell W^{\pm *}$	51	53.3	$\sim 20\%$



New Sequential Leptons

Limits from L3

Channel	95% CL Mass Limit GeV	
L^0	Dirac	Majorana
$L^0 \longrightarrow eW$	92.4	81.8
$L^0 \longrightarrow \mu W$	93.3	84.1
$L^0 \longrightarrow \tau W$	83.3	73.5
$L^{\pm} \longrightarrow \nu_{\ell} W^{\pm *}$	92.4	
Stable $L^{\pm}$	93.5	

Limits from OPAL

Channel	95% CL Mass Limit GeV	
L^0	Dirac	Majorana
$L^0 \longrightarrow eW$	93.4	84.9
$L^0 \longrightarrow \mu W$	92.9	83.4
$L^0 \longrightarrow \tau W$	80.1	62.6
$L^{\pm} \longrightarrow \nu_{\ell} W^{\pm *}$	91.3	
Stable $L^{\pm}$	92.6	

Similar limits on $L^{\pm}$ from ALEPH and DELPHI

Isosinglet Heavy Neutrino

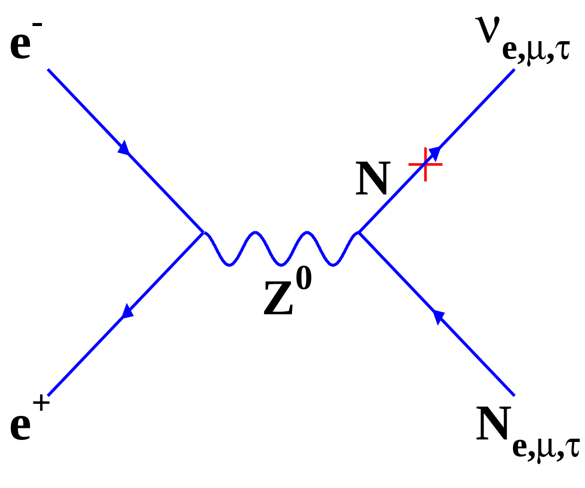
SM $\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$ isodoublets

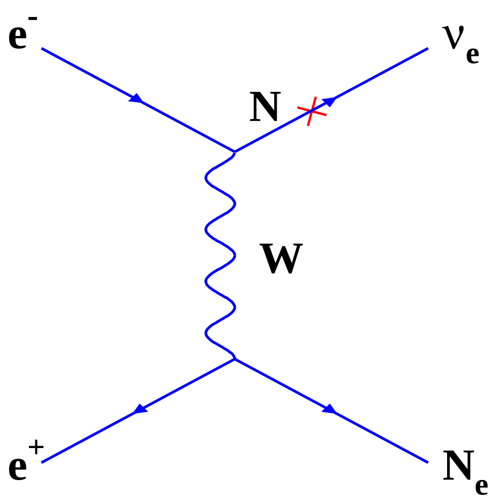
$e_R \quad \mu_R \quad \tau_R$ isosinglets

? $N_e \quad N_\mu \quad N_\tau$ New isosinglet

Pair production is suppressed ($\sim |U_\ell|^4$), compared to single production ($\sim |U_e|^2$)

t-channel dominates (factor ~ 50)!





Decay Modes

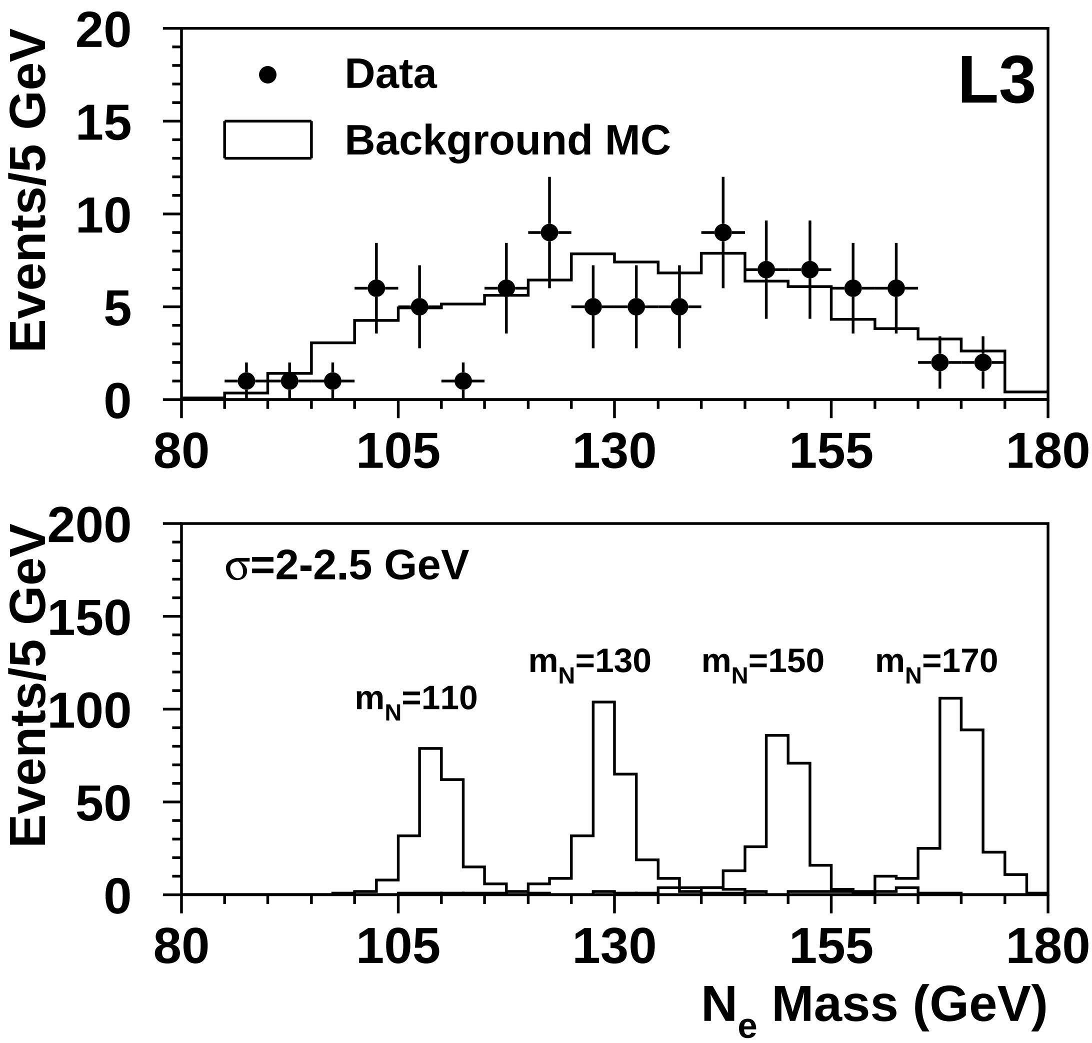
$N_e \longrightarrow e + W$ (Br=67%)

$N_e \longrightarrow \nu_e + Z$ (Br=33%)

Isosinglet Heavy Neutrino

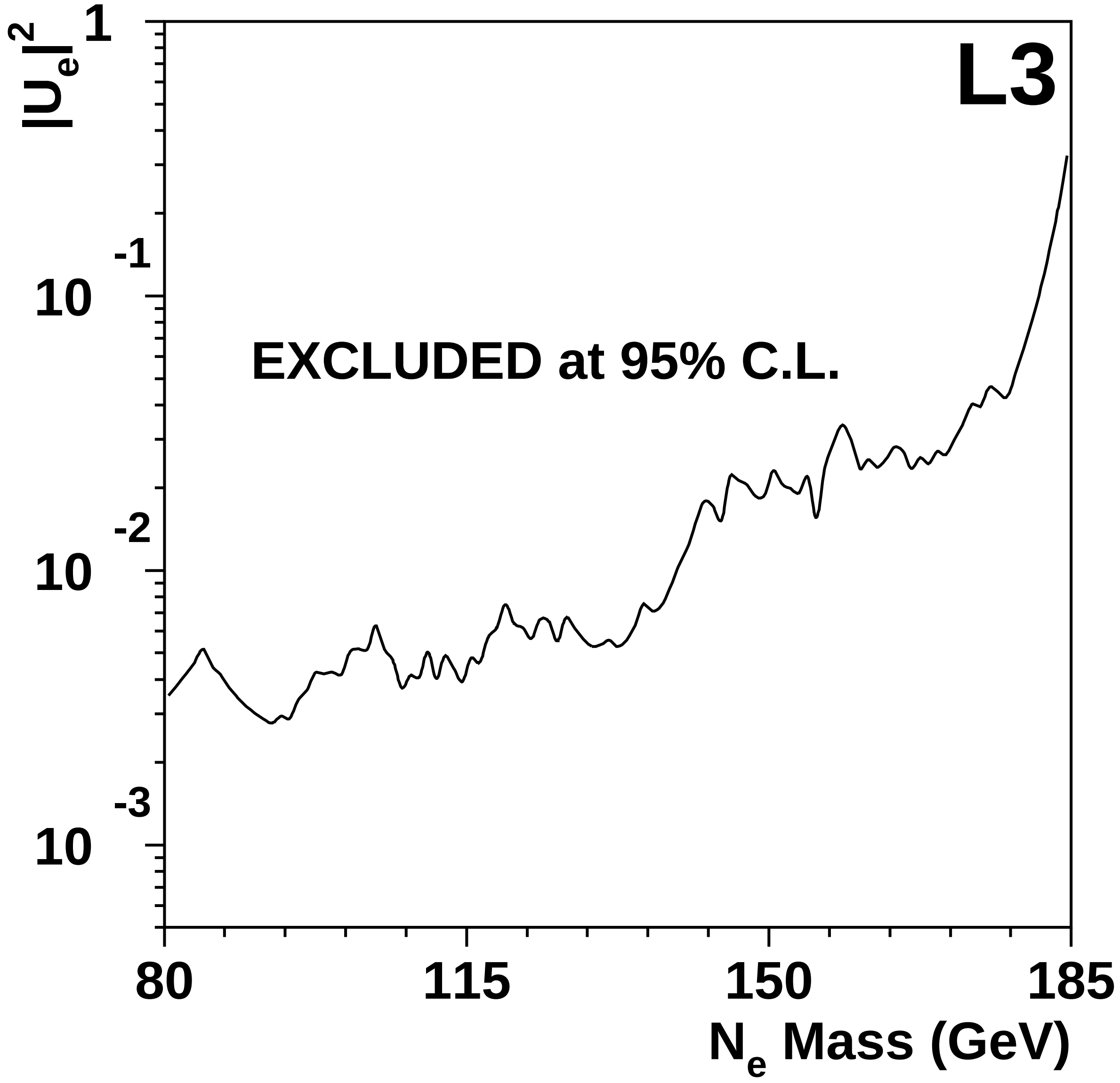
Search technique

- $N_e \longrightarrow$ e + W $\longrightarrow$ e + 2jets
- Signature: isolated electron, missing momentum, hadronic activity
- Invariant mass reconstruction using energy-momentum conservation



Isosinglet Heavy Neutrino

Upper limits on the mixing amplitude $|U_e|^2$

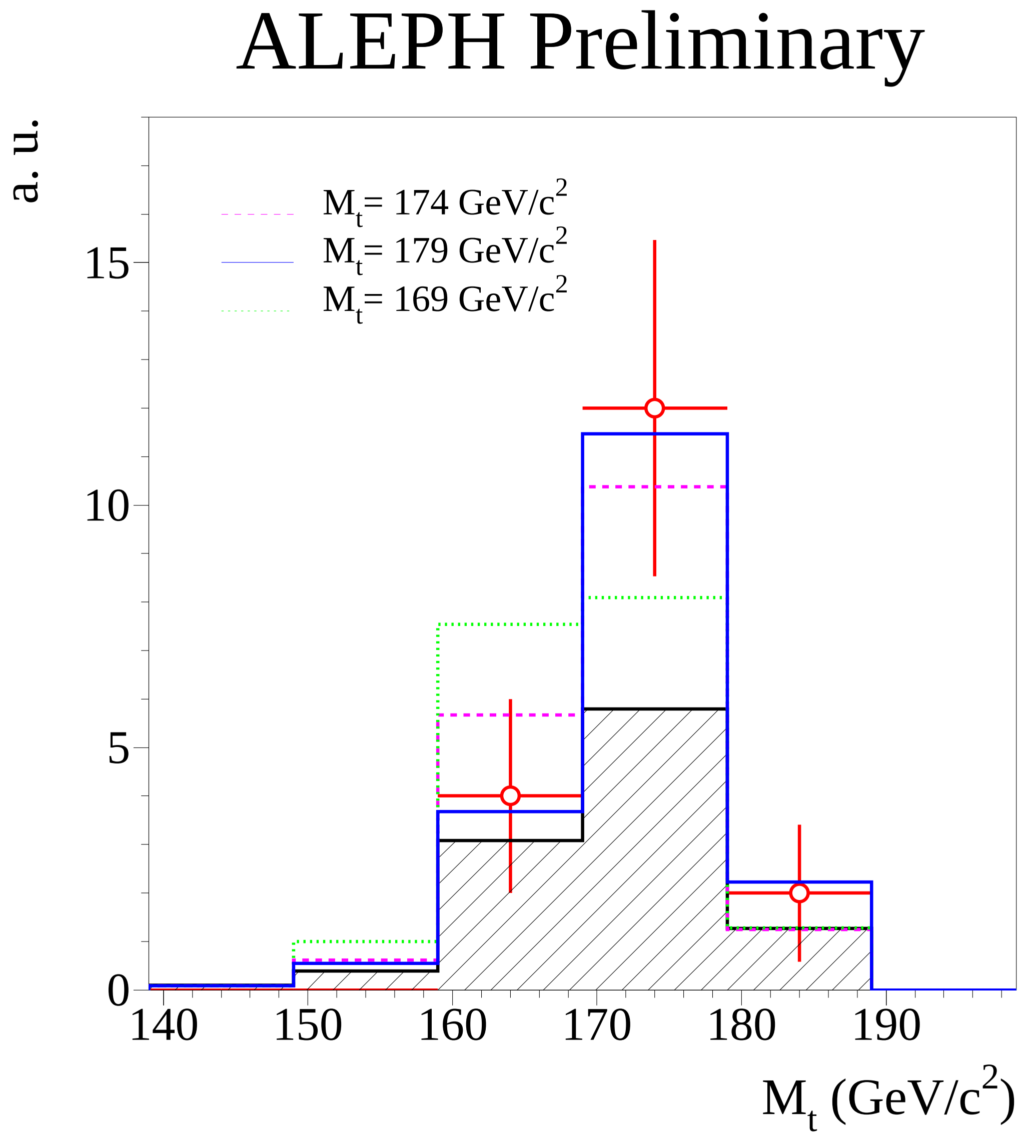


These are the only results for $M_{N_e} > 80$ GeV

Top quark production at LEP

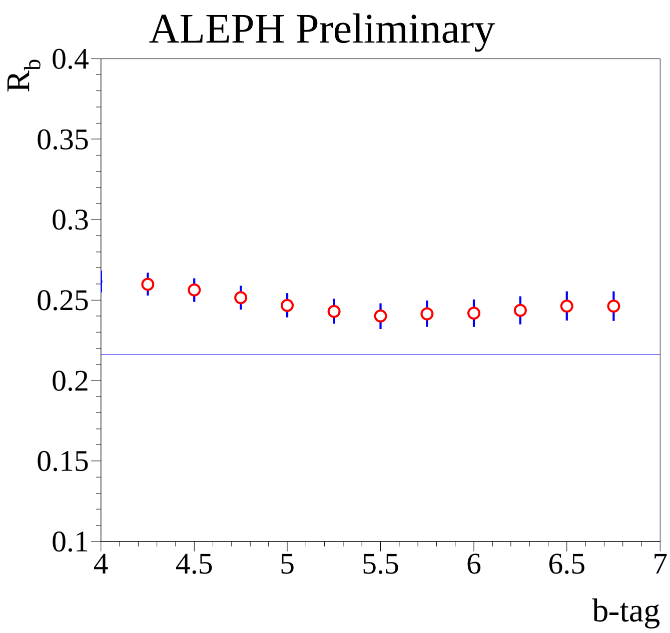
$e^+e^- \longrightarrow tc(u)$,
$t \longrightarrow bW$

- Soft c-jet $\Longrightarrow$ M_t reconstruction
- One b-jet $\Longrightarrow$ discriminate WW
- Kinematic constraints



Observation of 18 data events with
10.5 background events expected and
17.6% signal efficiency

Top quark production at LEP



- Severe b-tagging systematics
- Ad-hoc corrections applied
- Probability is 4.6%

ALEPH: $\sigma(e^+e^- \to tc(u)) < 0.6$ pb at 95% CL

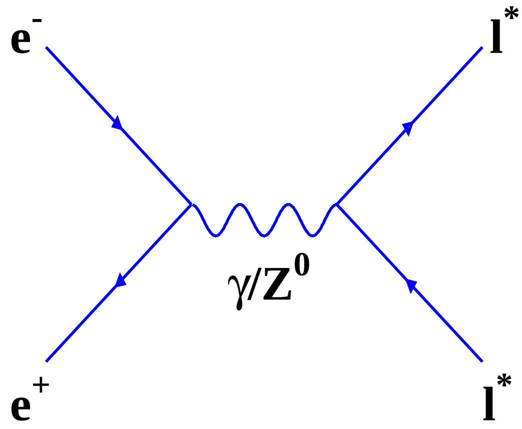
DELPHI performed a similar analysis, with tighter b-tag requirements

DELPHI: 0 (2) data events with 1.0 (4.7) background events expected and 6.6% (5.0%) signal efficiency for $W \to \ell\nu$ (qq′)

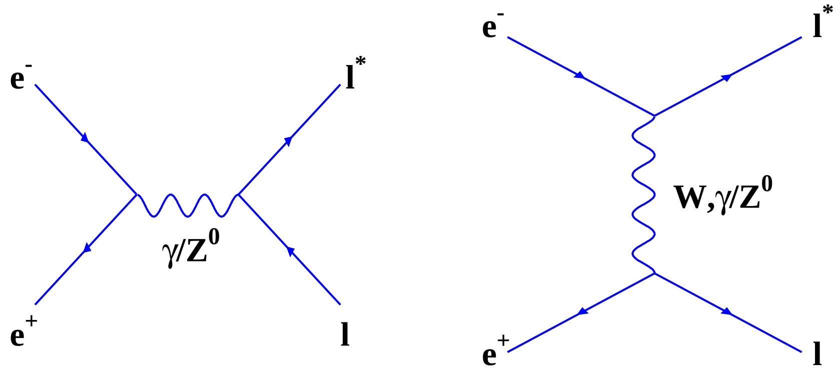
DELPHI: $\sigma(e^+e^- \to tc(u)) < 0.18$ pb at 95% CL

Compositeness

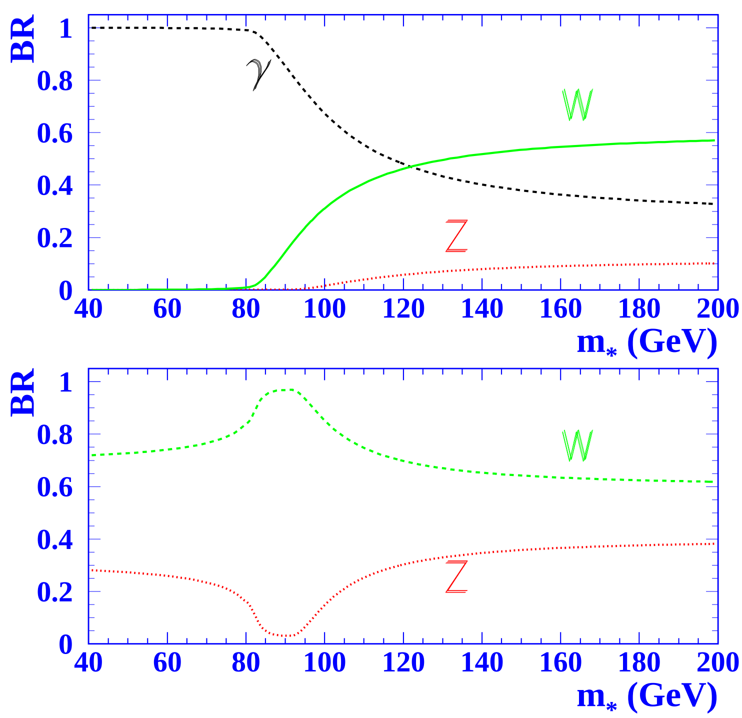
Pair Production



Single Production
$1/\Lambda^2$ suppression



Decays



$$\mathcal{L} = \frac{1}{2\Lambda}\bar{\ell}^{*}\sigma^{\mu\nu} \cdot [g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}]\ell$$

Compositeness

CC Decays

$\ell^*\ell^* \rightarrow \nu\nu$WW, $(f = -f')$

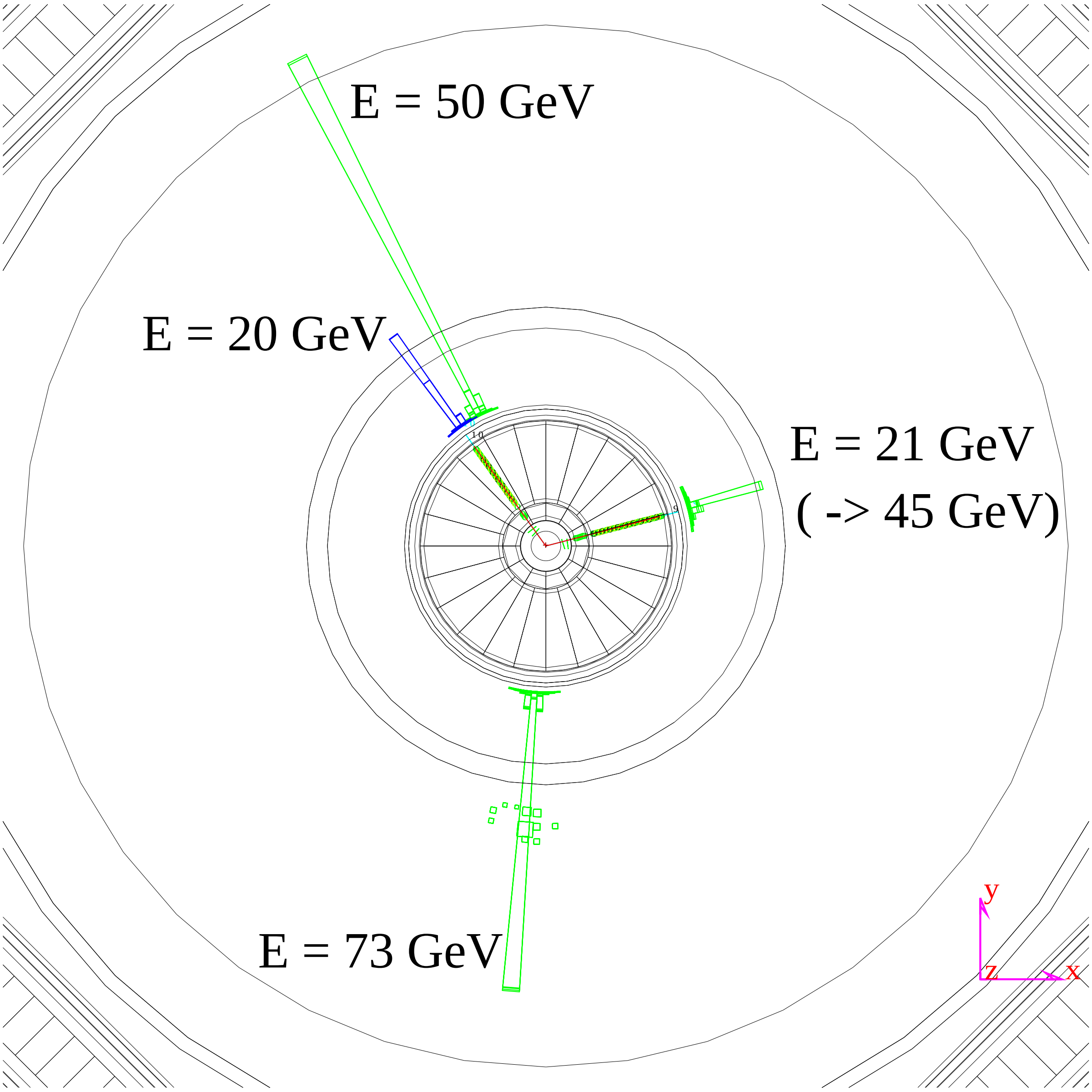
$\nu^*\nu^* \rightarrow \ell\ell$WW, $(f = f')$

γ Decays

$\ell^*\ell^* \rightarrow \ell\ell\gamma\gamma, (f = f')$

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

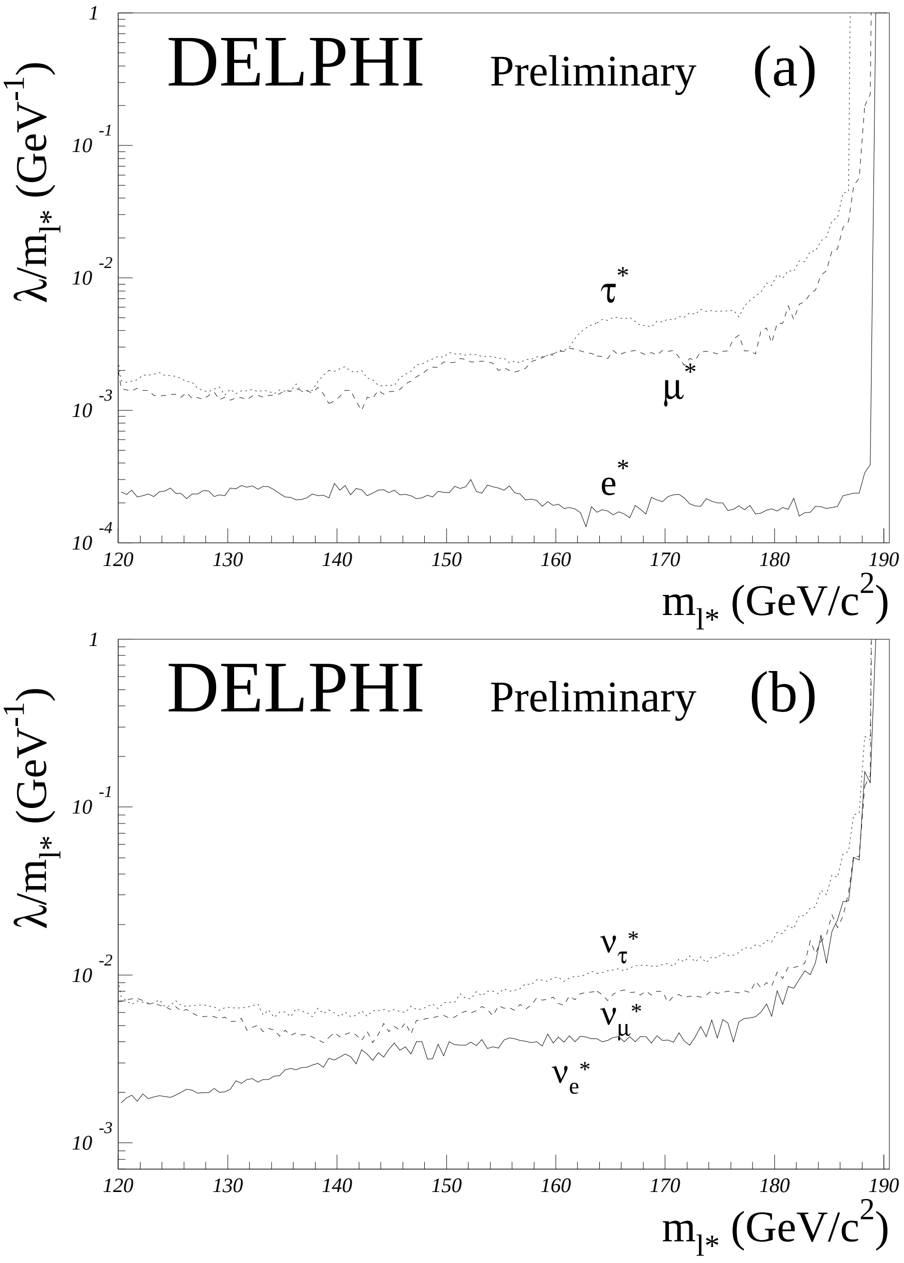
Run # 726808 Event # 3270



Exclusions are close to the kinematic limits

Compositeness

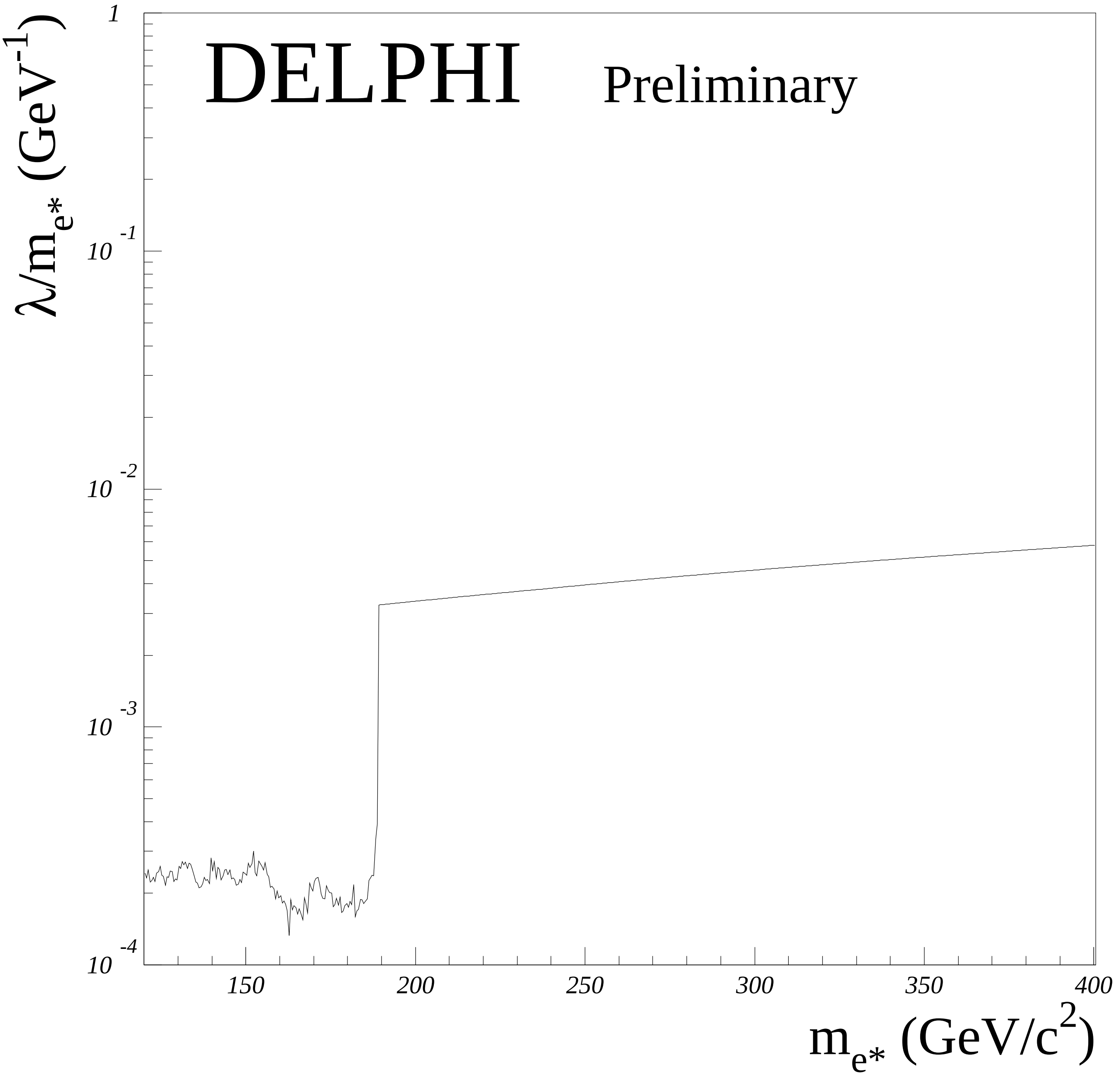
Search for the Single Production of Excited Fermions:



Similar exclusions are reported by ALEPH, L3 and OPAL

Exclusion for Excited Electrons can be extended above the kinematic limits!

$e^+e^- \to \gamma\gamma(\gamma)$



Technicolour

Phenomenology at LEP:

K.Lane, hep-ph/9903369;

implemented by S.Mrenna in PYTHIA

$$e^+e^- \to (\gamma/Z/\rho_T/\omega_T)^* \to f\bar{f}$$

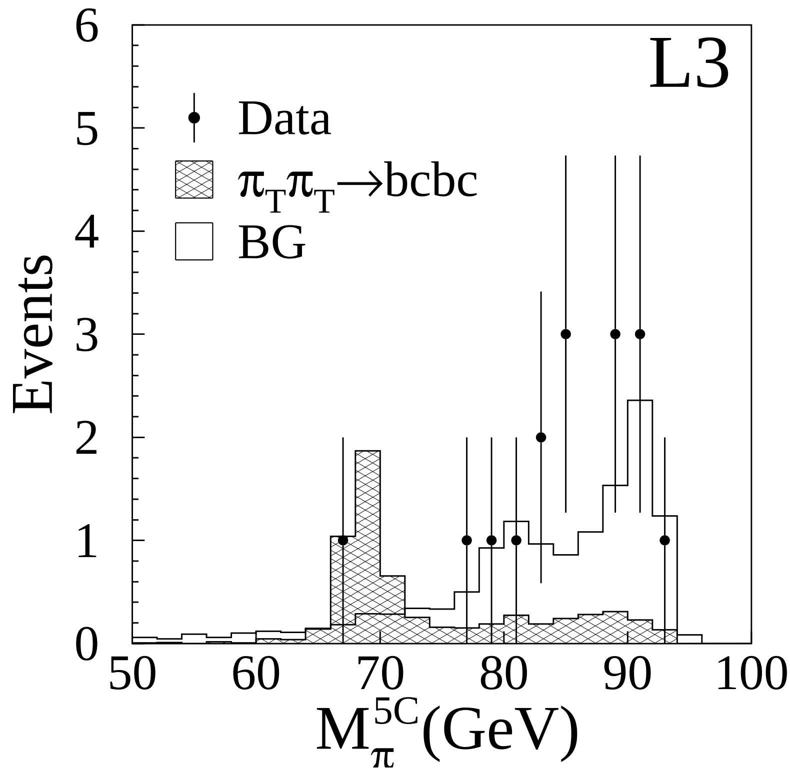
4 model parameters

- Technihadron masses, M_{ρ_T} and M_{π_T}
- Mixing between W_L and π_T, $\sin\chi$
- Technidoublet charge, $Q = Q_U + Q_D$

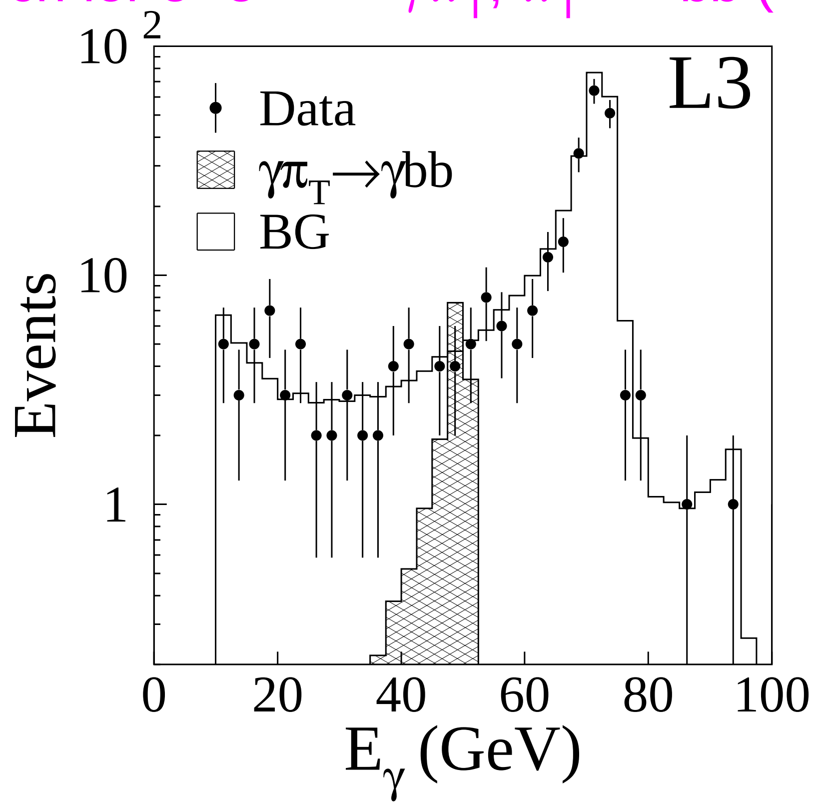
$e^+e^- \to f\bar{f}$	M_{ρ_T}, M_{ω_T}, Q
$e^+e^- \to W_L^+W_L^-$	$\sin^2\chi \cdot \sin^2\chi$
$e^+e^- \to W_L^\pm\pi_T^\mp$	$\sin^2\chi \cdot \cos^2\chi$, M_{π_T}
$e^+e^- \to \pi_T^+\pi_T^-$	$\cos^2\chi \cdot \cos^2\chi$, M_{π_T}
$e^+e^- \to \gamma\pi_T^0$	Q, $\sin\chi$, M_{π_T}
$e^+e^- \to \gamma\pi_T'$	Q, $\sin\chi'$, $M_{\pi_T'}$

Technicolour

Search for $e^+e^- \to \pi_T^+\pi_T^-$, $\pi_T^\pm \to$ bc ($\sim$ 90%)



Search for $e^+e^- \to \gamma\pi_T^0$, $\pi_T^0 \to$ bb ($\sim$ 90%)



Technicolour

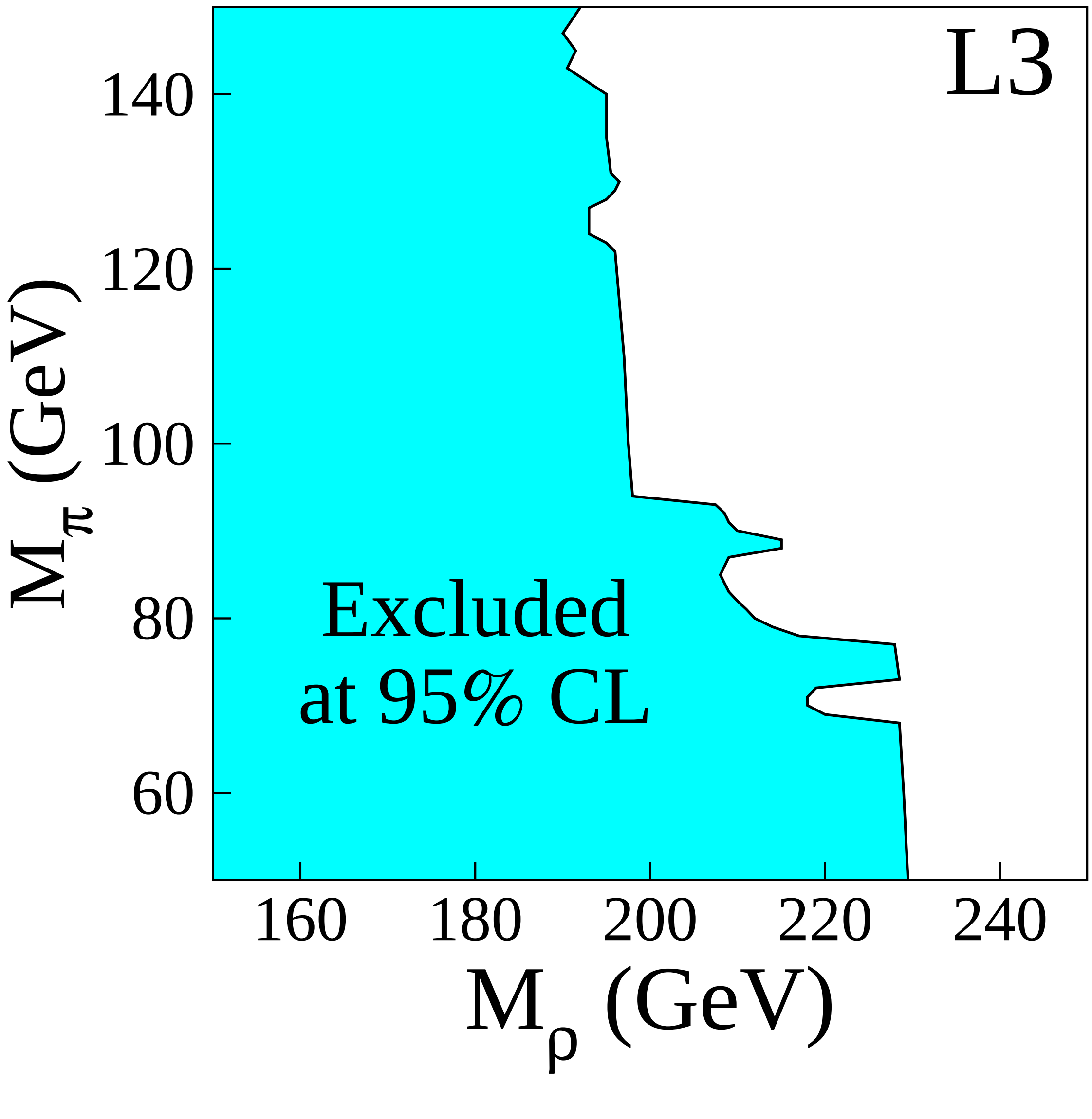
Assumptions

$M_{\rho_T} = M_{\omega_T}$, $M_{\pi_T} = M_{\pi'_T}$

$\sin\chi = \sin\chi'$

$Q = -1, 0, 5/3$

Exclusion in $M_{\rho_T} - M_{\pi_T}$ plane
independent on $\sin\chi$ and Q



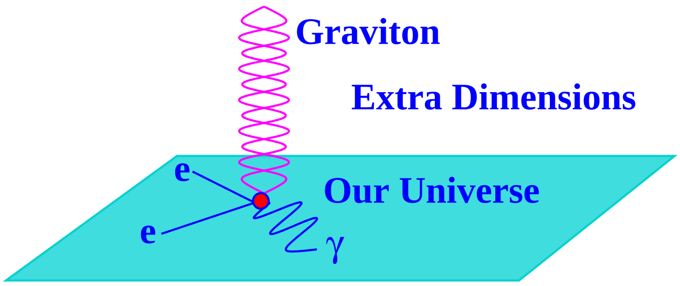
Quantum gravity

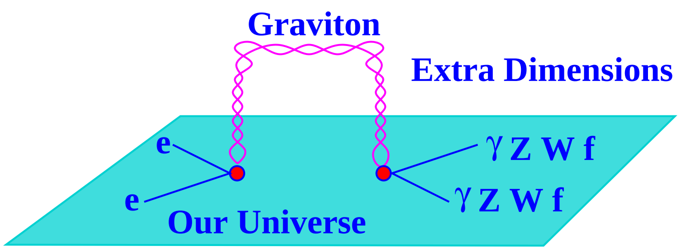
Gravity and extra dimensions

N.Arkani-Hammed *et. al.*, Phys. Lett B429 (1998) 263

- Gravity scale $M_D \sim M_w$,
  if extra dimensions exist
- $G_N^{-1} = 8\pi R^{\delta} M_D^{2+\delta}$
- No experimental exclusions for $\delta > 2$
- KK excitation modes of gravitons appear as massive particles with spin 0, 1 or 2 in our 3 dimensions
- Hierarchy problem is now in smallness of R

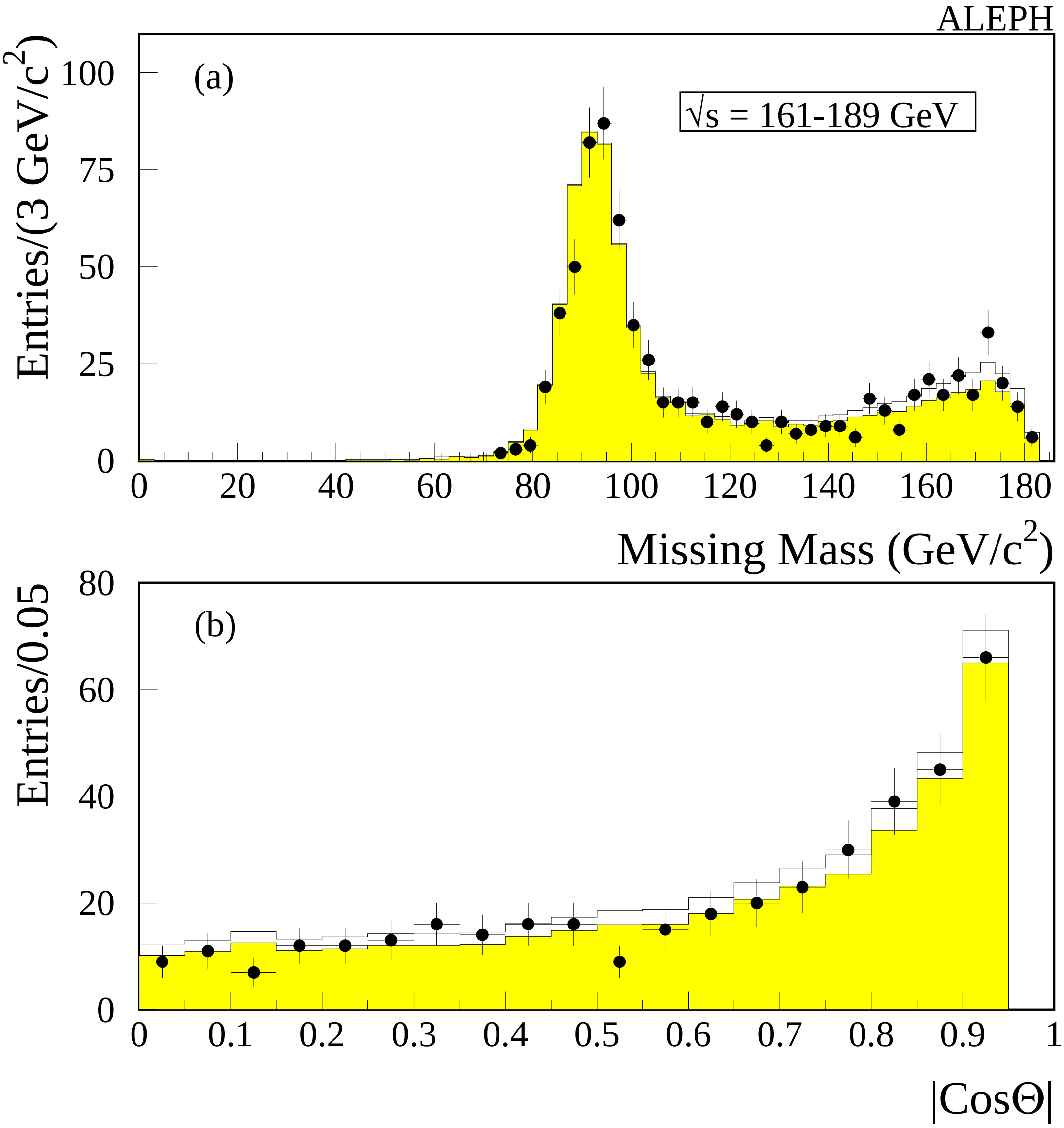
Phenomenology at LEP





Quantum gravity

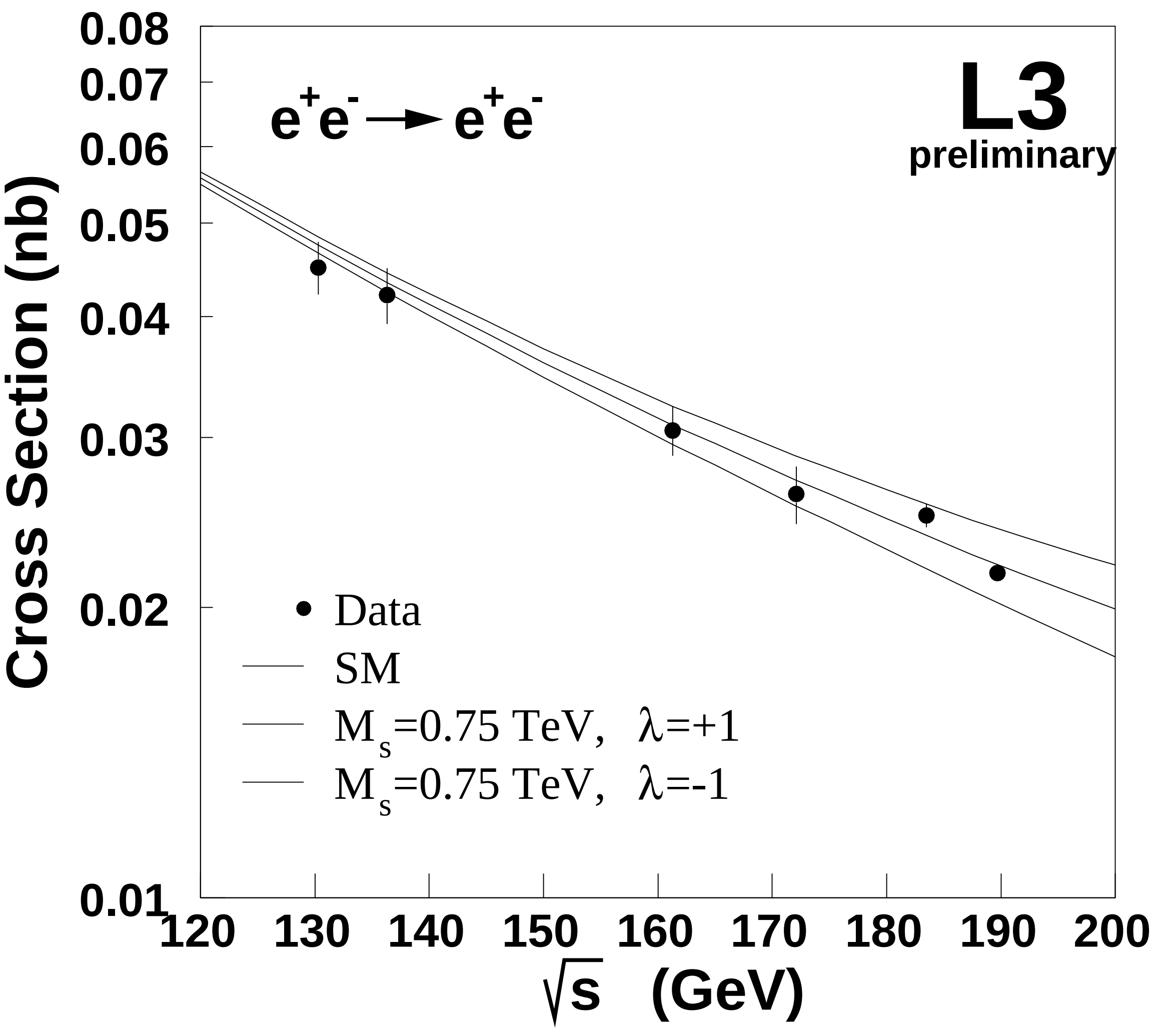
A search for $e^+e^- \to \gamma G$ at LEP



δ	2	3	4	5	6
M_D^{95} (GeV)	990	780	650	550	490
R_{95} (mm)	4.9×10^{-1}	5.4×10^{-6}	1.9×10^{-8}	6.4×10^{-10}	6.9×10^{-11}

Quantum gravity

Virtual effects in $e^+e^- \to e^+e^-$ at LEP



Process	M_S (GeV) $\lambda = +1$	M_S (GeV) $\lambda = -1$
$e^+e^- \to \gamma\gamma$	790	660
$e^+e^- \to e^+e^-$	850	820
Combined	900	860

Conclusions

– no indication for New Physics yet,
Standard Model still rules

– energy frontier will be crossed
1-2 more times in 1999-2000

– analysis of new data is in progress

June 1996	161 GeV ($4 \cdot 11$ pb^{-1})
October 1996	172 GeV ($4 \cdot 11$ pb^{-1})
1997	183 GeV ($4 \cdot 55$ pb^{-1})
1998	189 GeV ($4 \cdot 175$ pb^{-1})
1999	196 GeV ($4 \cdot > 150$ pb^{-1})
2000	200 GeV or more?