Search for Exotics and Extra Dimensions at LEP

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Abstract

Results from various searches for new physical phenomena performed by the four LEP experiments are summarised. Topics presented include the search for contact interactions, a Z′ boson, leptoquarks, excited leptons, technicolour and gravity in extra dimensions.

Many different theoretical ideas of physics beyond the Standard Model attempt to address aspects of nature that remain unexplained. Searches for physical consequences of many models of new physics are performed by the four LEP experiments: ALEPH, DELPHI, L3 and OPAL. This notes summarizes the most recent preliminary results obtained in the search for four-fermion contact interactions, a Z′ boson, leptoquarks, excited leptons, technicolour and gravity in extra dimensions.

During the second phase of LEP running, each experiment recorded a total of approximately 600 pb^{-1} of data. Table 1 shows a break down of the approximate integrated luminosity recorded per experiment at each centre-of-mass energy attained. Not all results presented here include the entire set of data; whenever possible the data set used in each searches is indicated.

The substantial amount of data recorded combined with the highest centre-of-mass energies ever achieved in $\mathrm{e}^+\mathrm{e}^-$ collisions provide a unique environment to look for new phenomena beyond the Standard Model.

year	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})
1996	161-172	~ 20
1997	183	~ 40
1998	189	~ 180
1999	192-202	~ 230
2000	200-209	~ 220

Table 1: Center-of-mass energies and corresponding approximate integrated luminosities recorded per experiment during the second phase of LEP running.

Model name	η_{LL}	η_{RR}	η_{LR}	η_{RL}
$LL^{\pm}$	± 1	0	0	0
$RR^{\pm}$	0	± 1	0	0
$LR^{\pm}$	0	0	± 1	0
$RL^{\pm}$	0	0	0	± 1
$AA^{\pm}$	± 1	± 1	∓ 1	∓ 1
$VV^{\pm}$	± 1	± 1	± 1	± 1
$V0^{\pm}$	± 1	± 1	0	0
$A0^{\pm}$	0	0	± 1	± 1

Table 2: Types of four-fermion contact interactions considered and their corresponding values of η_{ij}. For each model, both constructive (+) and destructive (-) interference between the Standard Model processes and the contact interactions are considered.

1 Four-Fermion Contact Interactions

The mathematical formulation of four-fermion contact interactions is a general framework for describing possible deviations from the Standard Model interactions. At LEP, the experiments search for contact interactions of the form $e^+e^-f\bar{f}$. The general gauge invariant and chiral/flavour conserving Lagrangian used to describe possible contact interactions is given by [1]

$$\mathcal{L}_{\text{contact}} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{ij=\text{L,R}} \eta_{ij} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma_\mu f_j)$$

where g^2 is usually set arbitrarily to 4π by convention, Λ is the energy scale of these new interactions, $\delta = 1$ only for eeee interactions and is zero otherwise, and e_i, f_i are left or right-handed spinors. The parameters η_{ij}, which have values generally between -1 and 1, describe the chiral structure of the interactions . The different models [1] considered and their corresponding values of η_{ij} are presented in table 2.

The existence of four-fermion contact interactions would result in deviations in the di-fermion cross-section and asymmetry measurements from the Standard Model predictions. No deviations are observed. Limits on the energy scale Λ are calculated for different models by fitting the measured di-fermion cross-sections, leptonic forward-backward asymmetries, R_b and R_c at all the center-of-mass energies achieved at LEP. Figure 1 presents graphically the combined LEP results of the fit to different models for the contact interactions $ee\ell\bar{\ell}$, $eeb\bar{b}$ and $eec\bar{c}$ [2]. These particular interactions are only accessible at LEP. The limits Λ^-, Λ^+ correspond to destructive and constructive interference between the Standard Model and contact interactions contributions. Limits for $e^+e^- \to \ell^+\ell^-$ interactions are obtained, assuming lepton universality, by combining results from $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$.

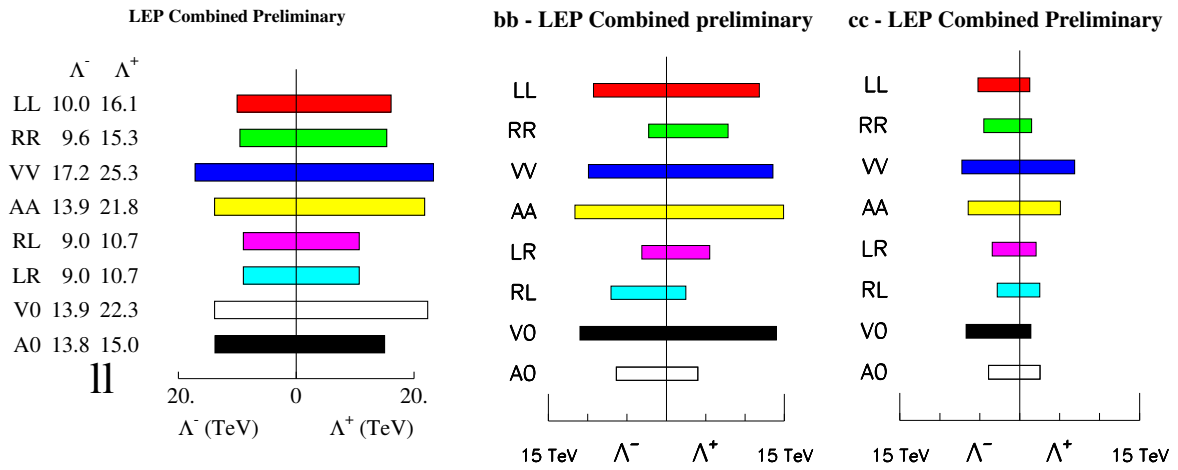

Figure 1: Limits on the energy scale Λ for contact interactions of the form $e^+e^- \to \ell^+\ell^-$ (left), $e^+e^- \to b\bar{b}$ (middle), $e^+e^- \to c\bar{c}$ (right) and for different models of contact interactions interfering destructively (Λ^-) or constructively (Λ^+) with the Standard Model contributions. These limits are calculated assuming $g^2 = 4\pi$. The different bands represent values excluded at 95% confidence level.

2 Z′ Boson

Many different models predict the existence of additional gauge bosons. Precision measurements of LEP data are used to constrain the parameters associated with an extra neutral gauge boson (Z′). In general, an additional neutral boson could mix with the Standard Model Z^0 boson. This mixing can be parameterised by the angle $\theta_{ZZ'}$.

Limits on the mass ($M_{Z'}$) and mixing angle ($\theta_{ZZ'}$) are obtained from measurements, both at the Z^0 pole and at higher energy, of the di-fermion cross-sections and leptonic forward-backward asymmetries. At the Z^0 pole, measured cross-sections and asymmetries are particularly sensitive to the coupling of a possible Z′ to fermions and are therefore most sensitive to the mixing angle $\theta_{ZZ'}$. At high energy, the interference between Z^0 and Z′ is important and the data are consequently particularly sensitive to the mass $M_{Z'}$.

Figure 2 shows examples of two-dimensional limits obtained for four different models: Left-Right Symmetric [5, 6], Sequential Standard Model [7] and E_6 GUT models (χ, ψ, η) [5, 8]. Regions outside the curves are excluded at the 95% confidence level. Table 3 shows the 95% confidence level lower mass limits obtained assuming the Z′ is decoupled from the Standard Model Z^0 ($\theta_{ZZ'} = 0$).

3 Leptoquarks

Leptoquarks are spin 0 or spin 1 particles carrying both lepton and baryon numbers and mediating interactions between quarks and leptons. In general, the total number of possible leptoquark states is reduced to 9 scalar and 9 vector states by assuming that the interaction between a leptoquark, a quark and a lepton be dimensionless, $SU(2) \times U(1)$

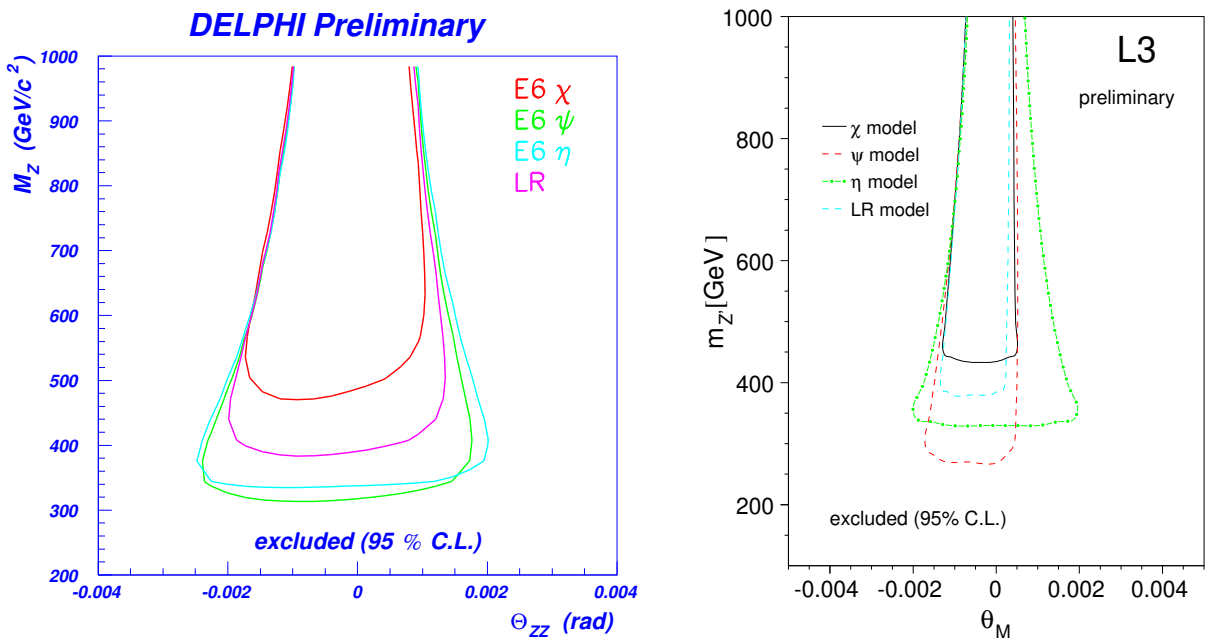

Figure 2: Two-dimensional limits on the mass and mixing angle of Z′ boson obtained by DELPHI [3] and L3 [4] for different models predicting the existence of an additional neutral gauge boson. These preliminary results include the entire data set recorded by the respective experiments. Regions outside the curves are excluded at the 95% confidence level.

	95% CL lower limit on $M_{Z'}$ (GeV)				
	ALEPH	DELPHI	L3	OPAL	LEP
χ	680*	503	460	684	715
ψ	410*	336	275	334	478
η	350*	353	330	451	454
LRS	600*	412	450	469	862
SSM	—	—	1280	—	2090

Table 3: Lower bounds [2–4, 9, 10] on the mass of a Z′ boson for different models assuming $\theta_{ZZ'} = 0$. Results marked with * only include data up to 202 GeV. Although not all the experiments have reported individual mass limits for the SSM model, the LEP electroweak working group has combined the preliminary cross-section and asymmetry measurements of each experiment up to $\sqrt{s} = 209$ GeV and extracted a lower bound on the Z′ mass in the context of the SSM model. Furthermore, in addition to cross-section and asymmetry measurements, limits calculated by ALEPH include their precision measurement of R_b.

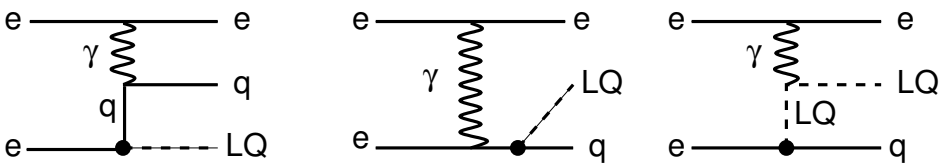

Figure 3: Dominant diagrams at LEP for the single production of first generation leptoquarks.

invariant and conserves baryon/lepton numbers. Under these assumptions, the list of possible leptoquark states can be found in [11]. Leptoquarks are said to be first generation leptoquarks if they only couple to first generation leptons and quarks.

First generation leptoquarks could be singly produced at LEP in association with an electron and a quark which often travel in the forward direction outside the detector acceptance. The dominant diagrams for single production of leptoquarks at LEP are shown in figure 3. The leptoquarks produced then decay to a lepton and a quark resulting in event final states containing a monojet, or one jet and one isolated electron. The production cross-section depends on the mass of the leptoquark M_{LQ}, and on the coupling parameters $g_{L,R}$, where L,R denote the chirality of the lepton it is coupling to. Data analysed are compatible with expectations from the Standard Model. Figure 4 shows an example of limits on the coupling as a function of leptoquark mass obtained for different scalar and vector leptoquark states.

The pair production of leptoquarks at LEP would mainly proceed through an s-channel γ/Z^0 exchange diagram. Given the existing limits on the couplings $g_{L,R}$, the t-channel contribution to the production of first generation leptoquarks is negligible. Thus, the pair production of leptoquarks is independent of the couplings $g_{L,R}$ and only depends on the leptoquark masses. All three generations of leptoquarks could be pair produced. The decay of both leptoquarks results in event final states containing two hadronic jets and two leptons, two jets and one lepton, or two jets and missing energy. Limits on leptoquark masses obtained from pair production searches are shown in table 4.

Leptoquarks could also contribute to the production of two-jet events via a t-channel leptoquark exchange. Limits on leptoquark masses in this case are obtained by fitting the measured $e^+e^- \to q\bar{q}$ cross-section at different centre-of-mass energies. The predicted deviations in the cross-section are calculated assuming one coupling (g_L or g_R) to be equal to $\sqrt{4\pi\alpha_{em}}$ and setting the other to zero. Furthermore, the couplings are assumed to be flavour diagonal. Table 5 presents preliminary mass limits for different leptoquark states obtained from indirect searches.

4 Excited Leptons

Excited states of the known leptons naturally arise in compositeness models which assume fermions have substructure. At LEP, excited leptons (ℓ^*) could be both pair or singly produced. Limits on the mass and coupling of excited leptons are calculated in the framework of the model described in [14]. The gauge invariant Lagrangian describing the

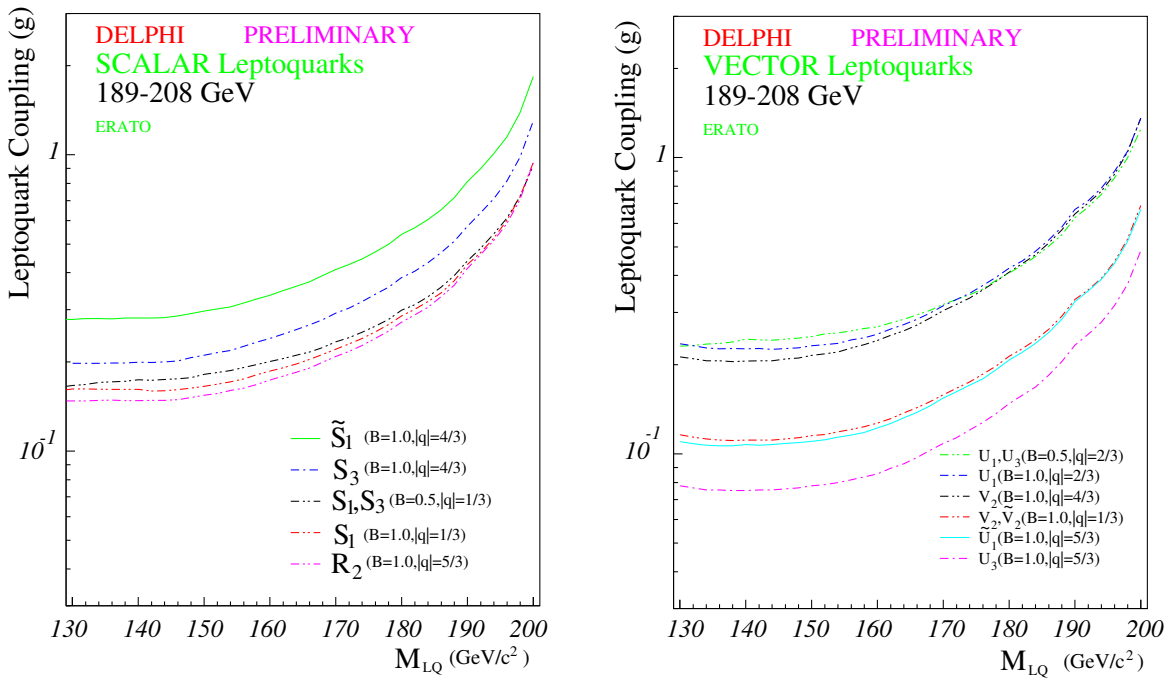

Figure 4: Limits on leptoquark coupling parameters as a function of mass obtained by DELPHI [12] for different scalar (left) and vector (right) leptoquark states. Regions above the curves are excluded at the 95% confidence level.

		OPAL Mass limits (GeV)		
LQ	Q_{em}	1st	2nd	3rd
$\tilde{S}_0$	-4/3	97.6	100.3	98.2
$S_{\frac{1}{2}}$	-2/3	90.9	90.4	87.2
	-5/3	98.7	100.8	99.2
$\tilde{S}_{\frac{1}{2}}$	+1/3	76.5	76.5	76.5
	-2/3	93.9	98.6	94.9
S_1	+2/3	94.7	94.7	94.7
	-4/3	99.2	101.1	99.6

		OPAL Mass limits (GeV)		
LQ	Q_{em}	1st	2nd	3rd
V_0	-2/3	98.7	98.7	96.5
$\tilde{V}_0$	-5/3	101.7	$>$ 102	101.8
$V_{\frac{1}{2}}$	-1/3	98.9	98.7	98.2
	-4/3	101.3	$>$ 102	101.5
$\tilde{V}_{\frac{1}{2}}$	+2/3	98.3	98.3	98.3
	-1/3	99.9	101.4	100.3
	+1/3	100.7	100.7	100.7
V_1	-2/3	98.7	98.7	96.5
	-5/3	101.9	$>$ 102	$>$ 102

Table 4: Lower mass limits of scalar (left) and vector (right) leptoquarks obtained by OPAL [13] from the search of pair produced leptoquarks at $\sqrt{s} = 200 - 209$ GeV. For each leptoquark state considered, 95% confidence level lower bounds on the mass are given for 1st, 2nd and 3rd generation leptoquarks. The column Q_{em} gives the electric charge of each leptoquark.

Scalar LQ		M_{LQ} (GeV)
S_0	$\to e_L u$	789
	$\to e_R u$	639
$\tilde{S}_0$	$\to e_R u$	210
$S_{\frac{1}{2}}$	$\to e_L \bar{u}$	189
	$\to e_R \bar{u}, e_R \bar{d}$	240
$\tilde{S}_{\frac{1}{2}}$	$\to e_L \bar{d}$	-
S_1	$\to e_L u, e_L d$	364

Vector LQ		M_{LQ} (GeV)
V_0	$\to e_L \bar{d}$	1070
	$\to e_R \bar{d}$	167
$\tilde{V}_0$	$\to e_R \bar{u}$	497
$V_{\frac{1}{2}}$	$\to e_L d$	305
	$\to e_R u, e_R d$	227
$\tilde{V}_{\frac{1}{2}}$	$\to e_L u$	176
V_1	$\to e_L \bar{u}, e_L \bar{d}$	664

Table 5: Preliminary LEP combined lower limits [2] on leptoquark masses obtained from fits to the measured $e^+e^- \to q\bar{q}$ cross-section at all centre-of-mass energies. Bounds are expressed at the 95% confidence level. For the state $\tilde{S}_{\frac{1}{2}}$, the predicted cross-section is too small and no limits can be set.

coupling between an excited lepton, a lepton and a gauge boson is given by

$$\mathcal{L} = \frac{1}{2\Lambda}\bar{\ell}^* \sigma^{\mu\nu} \left[g f \frac{\boldsymbol{\tau}}{2} \boldsymbol{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] \ell_L$$

where $\sigma^{\mu\nu}$ is the covariant bilinear tensor, $\boldsymbol{\tau}$ denotes the Pauli matrices, Y is the weak hypercharge, $\mathbf{W}_{\mu\nu}$ and $B_{\mu\nu}$ represent the Standard Model gauge field tensors and the couplings g, g' are the SU(2) and U(1) coupling constants of the Standard Model. The compositeness scale is set by the parameter Λ which has units of energy. Finally, the strength of the $\ell\ell^*$V couplings is governed by the constants f and f'. These constants can be interpreted as weight factors associated to the different gauge groups. The values of f and f' dictate the relative branching fractions of excited leptons to each gauge boson. In order to reduce the number of free parameters, limits are usually calculated for the specific cases $f = f'$ and $f = -f'$.

Excited leptons could be pair produced via an s-channel γ/Z^0 diagram. Since excited leptons would promptly decay to any of the gauge bosons, a large number of final states are possible. Table 6 summarizes the lower mass limits obtained from the search of pair produced excited leptons by all four LEP experiments and for different f, f' assignments. In general, mass limits from pair production searches are set close to the kinematic limit. Limits presented in table 6 sometimes differ between experiments since different data sets were used to calculate the limits, see references [13, 15–18] for further details.

Excited leptons could also be singly produced in association with a Standard Model lepton. Possible event final states may contain isolated leptons and one photon, pairs of hadronic jets and in some cases missing energy from neutrinos. No excesses of events are observed in the data. Limits on the ratio of the coupling to the compositeness scale (f/Λ) as a function of excited lepton mass are calculated. Figure 5 shows typical limits obtained from the single production searches for different f and f' assignments. The predicted single production cross-section of excited electrons is enhanced by the contribution of a

	95% CL Mass Limit (GeV)						
	$f = f'$				$f = -f'$		coupling independent
	DELPHI	OPAL	L3	ALEPH	DELPHI	L3	L3
$\mathbf{e}^*$	103.0	102.9	100.0	94.3	98.0	93.4	93.3
$\boldsymbol{\mu}^*$	103.1	102.9	100.2	94.3	98.0	93.4	93.4
$\boldsymbol{\tau}^*$	102.2	102.8	99.8	94.3	98.0	93.4	92.2
$\boldsymbol{\nu}_{\mathrm{e}}^*$	102.0	99.5	99.1	94.2	102.7	99.4	98.2
$\boldsymbol{\nu}_{\boldsymbol{\mu}}^*$	102.4	99.5	99.3	94.2	102.8	99.4	98.3
$\boldsymbol{\nu}_{\boldsymbol{\tau}}^*$	95.3	91.9	90.5	94.2	102.8	99.4	87.8

Table 6: Lower mass limits obtained from the searches of pair produced excited leptons and for different assignments of f and f'. Bounds from ALEPH [15], DELPHI [16], L3 [17] and OPAL [13, 18] are calculated using different data sets.

t-channel exchange diagram resulting in more stringent limits than for excited muons and taus.

5 Technicolour

Technicolour is a new strong QCD-like interaction that could naturally induce electroweak symmetry breaking. In this framework, the $W^{\pm}$ and Z^0 bosons are condensates of a new family of fermions called technifermions. The phenomenology associated to the existence of technicolour is inferred using the framework of the technicolour "straw-man" model [20], a low energy approximation of technicolour containing a minimum number of free parameters.

Searches for the production of technirho (ρ_{T}) and technipions (π_{T}) are performed. The dominant processes searched for include

$$\mathrm{e^+e^-} \rightarrow \rho_{\mathrm{T}}^{(*)} \rightarrow \begin{array}{l} \pi_{\mathrm{T}}^+\pi_{\mathrm{T}}^- \\ \pi_{\mathrm{T}}^{\pm}W_{\mathrm{L}}^{\mp} \\ W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\mp} \\ \pi_{\mathrm{T}}^0\gamma \\ \mathrm{f\bar{f}} \end{array}$$

where W_{L} indicates the longitudinal component of the W boson. The cross-section of the three first final states shown above only depend on $\mathrm{M}_{\rho_{\mathrm{T}}}$, $\mathrm{M}_{\pi_{\mathrm{T}}}$ and $\mathrm{N_D}$, the number of technicolour doublets. For $\mathrm{M}_{\rho_{\mathrm{T}}} > 2\mathrm{M}_{\pi_{\mathrm{T}}}$, the $\pi_{\mathrm{T}}^+\pi_{\mathrm{T}}^-$ final state dominates. In addition to the technirho exchange diagram, the reaction $\mathrm{e^+e^-} \rightarrow \pi_{\mathrm{T}}^0\gamma$ can also proceed via the exchange of a techniomega (ω_{T}) and is therefore model dependent. The cross-section $\mathrm{e^+e^-} \rightarrow \pi_{\mathrm{T}}^0\gamma$ depends, in addition to $\mathrm{M}_{\rho_{\mathrm{T}}}$, $\mathrm{M}_{\pi_{\mathrm{T}}}$ and $\mathrm{N_D}$, on the mass scale $\mathrm{M_V}$, the technicolour coupling constant $\alpha_{\rho_{\mathrm{T}}}$ and the sum of the charges of the U and D techniquarks ($\mathrm{Q_U} + \mathrm{Q_D}$). Finally, the $\mathrm{f\bar{f}}$ final state is in general suppressed. Many of the decay final

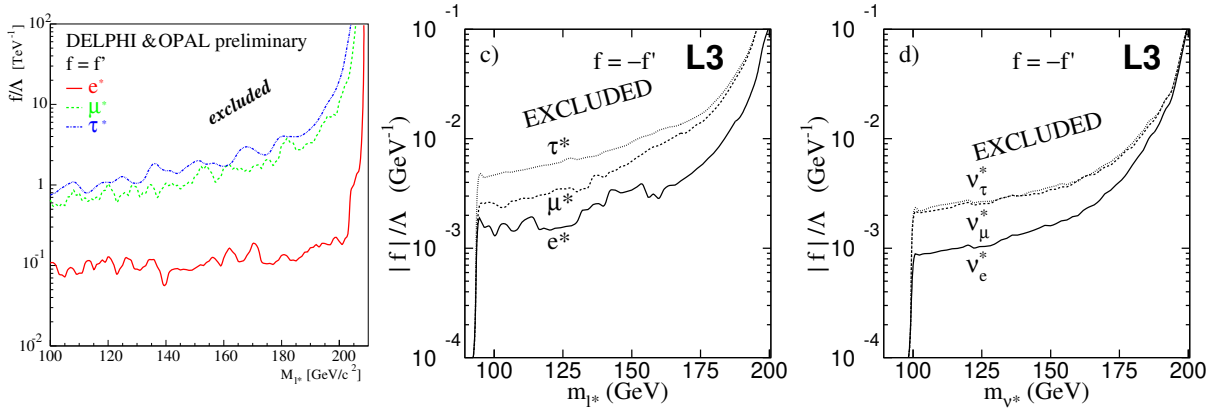

Figure 5: Limits on the ratio of the coupling to the compositeness scale (f/Λ) as a function of excited lepton mass for different f and f' assignments. Regions above the curves are excluded at the 95% confidence level. The combined results [19] from DELPHI and OPAL (left) include data recorded at $\sqrt{s} = 189 - 208$ GeV while limits from L3 [17] (center, right) were calculated using data at $\sqrt{s} = 192 - 202$ GeV and are expressed in GeV^{-1}.

	95% CL limits on M_{π_T} (GeV)	
N_D	DELPHI	OPAL
2	79.8	62.0
9	89.1	77.0

Table 7: Lower limits on M_{π_T} for different values of N_D obtained by DELPHI [21] and OPAL [22].

states considered lead to topologies similar to the Standard Model production of W pairs. Also, since approximately 90% of technipions decay to b quarks, b-tagging is an important part of the search for technicolour.

In the final states considered, no hint of the existence of technicolour is found. Examples of exclusion regions in the (M_{π_T}, M_{ρ_T}) plane obtained at LEP are shown in figure 6. The grey regions are excluded at the 95% confidence level. Limits presented from DELPHI [21] (top left) were calculated for the maximal $W_L - \pi_T$ mixing case, $N_D = 2$. Figure 6 (top right) shows the exclusion regions obtained by OPAL [22] for the theoretically preferred value $N_D = 9$, and assuming $(Q_U + Q_D) = 5/3$. Finally, bounds presented from L3 [23] (bottom) are valid for any value of N_D and for $(Q_U + Q_D) = 0, 1, 5/3$. Limits on the technipion mass can be extracted from these exclusion plots and are summarised in table 7.

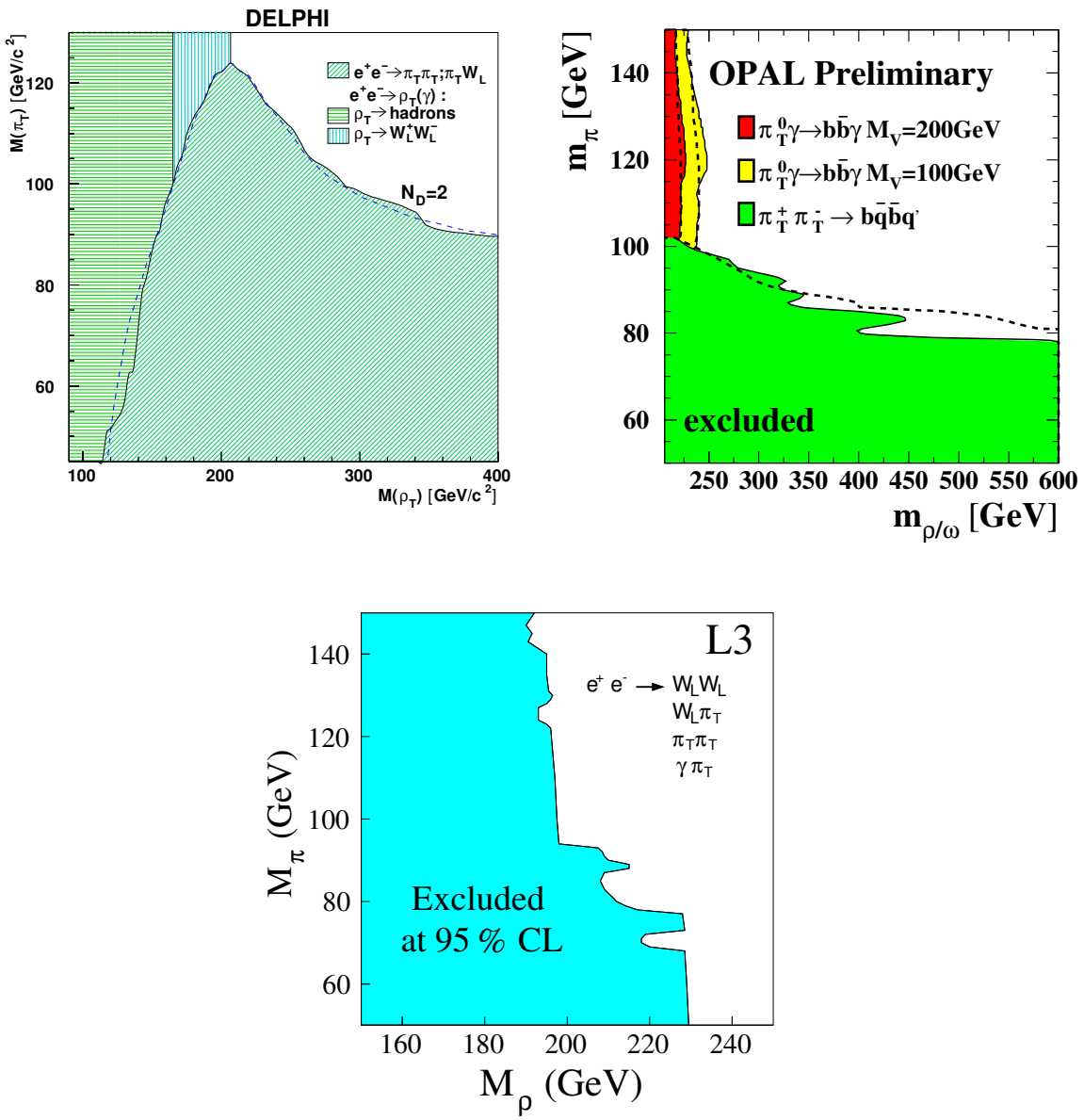

Figure 6: Excluded regions in the (M_{π_T},M_{ρ_T}) plane obtained by DELPHI ($\sqrt{s}$ = 192 – 208 GeV, top left), OPAL ($\sqrt{s}$ = 200 – 209 GeV, top right) and L3 ($\sqrt{s}$ = 189 GeV, bottom). Grey areas are excluded at 95% confidence level.

	Limits on M_D (TeV)					
	Number of extra dimensions					
	2	3	4	5	6	7
ALEPH (189-209 GeV)	1.28	0.97	0.78	0.66	0.57	—
DELPHI (181-209 GeV)	1.38	—	0.84	—	0.58	—
L3 (189 GeV)	1.02	0.81	0.67	0.58	0.51	0.45
OPAL (189 GeV)	1.09	0.86	0.71	0.61	0.53	0.47

Table 8: Lower bounds on M_D from ALEPH [25], DELPHI [26], L3 [27] and OPAL [28]. Limits are calculated at the 95% confidence level.

6 Gravity in Extra Dimensions

Recently, a new scenario has been proposed which tries to explain the large difference between the energy scale of gravity and the other forces. The framework developped by Arkani-Hamed, Dimopoulos and Dvali [24] assumes that the universe is made of extra dimensions in which Standard Model particles are confined to a 4-dimensional "wall". In this scenario, only gravitons can propagate in the extra dimensions. Furthermore, the Planck mass in 4 dimensions (M_{Pl}) can be related to the Planck mass in 4+n dimensions (M_D) by the relation $M_{Pl}^2 = R^n M_D^{n+2}$, where n is the number of extra dimensions and R is the size of these extra dimensions. The hierarchy between the scale of gravity and the other forces is removed under the assumption that M_D is similar to the electroweak scale. Under these circumstances, extra dimensions could be "large" enough to be probed in collider experiments. The existence of low scale gravity in extra dimensions would manifest itself by the direct and indirect production of gravitons. In 4-dimensions, gravitons would appear as massive, non-interacting stable particles with a wide range of possible masses.

Gravitons could be produced in the reaction $e^+e^- \to G\gamma$ which would result in single photon final states with missing energy. The cross-section for such process is proportional to $(\sqrt{s}/M_D^2)^n$. Data are in good agreement with the Standard Model predictions and thus limits on the value of the Planck mass in 4+n dimensions, M_D, are calculated. Table 8 shows the lower limits on M_D obtained by each LEP experiment as a function of the number of extra dimensions.

Deviations due to the existence of low scale gravity could also be observed in the di-fermion and di-boson production cross-sections. The graviton contribution ($e^+e^- \to G^* \to f\bar{f}, VV$) can be parameterised as a function of λ/M_s^4 where λ depends on the details of the theory of quantum gravity (number of extra dimensions, compactification, etc.) and M_s is a UV cut-off set to the string scale, presumed to be $\mathcal{O}$(TeV) in these models [29]. The di-electron final state is the most sensitive channel to possible contributions from graviton exchange. Figure 7 shows an example of likelihood curves for different final states studied, obtained from a fit to data recorded at $\sqrt{s} = 183 - 209$ GeV by OPAL . Resulting limits on M_s obtained by some of the LEP experiments can be found in table 9 for $\lambda/M_s = \pm 1$.

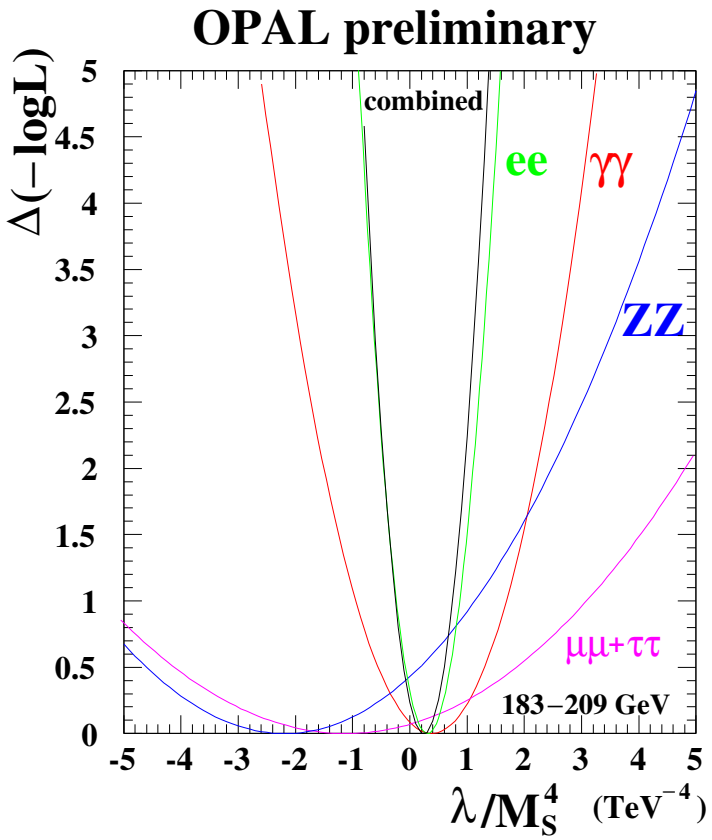

Figure 7: Likelihood curves obtained from a fit to OPAL data recorded at $\sqrt{s} = 183 - 209$ GeV [30] for different final states studied.

$e^+e^- \to e^+e^-$

	Limits on M_s (TeV)	
	$\lambda = -1$	$\lambda = +1$
L3	0.98	1.06
OPAL	1.00	1.15

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

	Limits on M_s (TeV)	
	$\lambda = -1$	$\lambda = +1$
DELPHI	0.70	0.77
L3	0.99	0.84
OPAL	0.89	0.83

Table 9: Lower bounds on M_s assuming $\lambda = \pm 1$ obtained by DELPHI [31], L3 [4,32] and OPAL [9,30]. The 95% confidence level limits are calculated using $e^+e^- \to e^+e^-$ (left) and $e^+e^- \to \gamma\gamma$ (right) event final states.

7 Summary

Recent preliminary results on various searches performed at LEP have been summarised. These represent only a subset of the work involved in the pursuit of physics beyond the Standard Model. Much work remains to finalise preliminary results from individual experiments and publish the final LEP combined limits of many searches. Data analysed by the four LEP experiments are in agreement with the Standard Model predictions.

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