Search for Extra Dimensions at LEP

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Abstract

Recent theoretical scenarios postulate the fundamental gravitational scale to be of the same order as the electroweak scale. In these models the interaction between Standard Model particles and gravitons propagates in extra spatial dimensions. Experimental results on single photon and pair-produced fermions, photons, W and Z bosons at LEP are used to search for sizable effects of extra dimensions. No hints are found and limits on the fundamental scale of gravity are derived.

1 Introduction

Although the Standard Model of electroweak interaction describes the measurements very successfully it is widely assumed that it is only an effective theory. Above a scale $\Lambda \approx$ 1 TeV a new theory takes over - famous candidates are Supersymmetry or strong dynamic symmetry breaking. In particular, the new theory should solve the hierarchy problem and include gravity.

Recent theoretical scenarios [1] propose a fundamental scale, M_D, that propagates the gravitation into extra dimensions and considers the Planck scale as an effective scale in the 'normal' 3+1 dimensions of the order 1 TeV:

$$M^2_{Planck} = R^n M_D^{n+2} \propto G_N^{-1}, \tag{1}$$

where R is the radius of the compactified extra dimensions, n their number and G_N is the Newton constant. These theories escape the hierarchy problem forcing the Standard Model particles to lie on a 3-dimensional wall in the higher-dimensional space and allow weak gravity.

2 Search Strategies for Extra Dimensions

The gravitons couple to the momentum tensor, hence, they can contribute to Standard Model processes. In electron-positron annihilations a direct emission of gravitons, G, could be obtained in the process $e^+e^- \rightarrow \gamma G$ or $e^+e^- \rightarrow ZG$. Indirect exchange of gravitons would lead to an anomalous production rate of fermion or boson pairs due to virtual

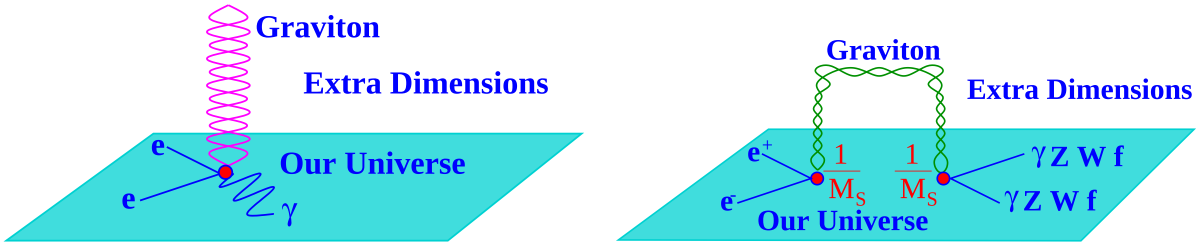

Figure 1: Direct graviton emission contributing to $e^+e^- \rightarrow \gamma G$ (left) and indirect graviton exchange (right).

graviton exchange. Both, indirect and direct processes are illustrated in figure 1. In the following, the results of direct and indirect searches for gravitons in extra dimensions based on e^+e^- annihilation will be presented.

3 Direct Search for Gravitons

The differential cross section for the process $e^+e^- \rightarrow \gamma G$ depends on the number n of extra dimensions and on the scale M_D [2],

$$\frac{d^2\sigma}{dx_\gamma d\cos\theta_\gamma} = \frac{\alpha}{32s}\,\frac{\pi^{n/2}}{\Gamma(n/2)}\left(\frac{\sqrt{s}}{M_D}\right)^{n+2} f(x_\gamma, \cos\theta_\gamma), \tag{2}$$

where x_γ is the ratio of photon to beam energy, θ_γ is the polar angle of the photon and

$$f(x,y) = \frac{2(1-x)^{\frac{n}{2}-1}}{x(1-y^2)}\left[(2-x)^2(1-x+x^2) - 3y^2x^2(1-x) - y^4x^4\right]. \tag{3}$$

The cross section increases rapidly with smaller photon energies and angles. The Standard Model background for this reaction is dominated by $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. Figure 2 shows the recoil mass distribution of the detected single photon averaged for all LEP experiments in good agreement with the Standard Model expectation.

Performing a binned likelihood fit to the photon energy distribution limits on M_D as a function of the number of extra dimensions are obtained [8]. Simultaneously, limits on the compactification radius, R, are derived. The results based on [6, 7, 8, 9] are summarized in table 1. The cross section limits for a real graviton production obtained by the DELPHI collaboration [7] are depicted in Figure 3.

Real graviton production, can also be accompanied by a Z boson instead of a photon, $e^+e^- \rightarrow ZG$. Due to the limited phase space the search for single Z production results in a lower sensitivity to extra dimensions compared to the single photon production. For centre-of-mass energies up to 189 GeV the L3 collaboration determined upper limits on the cross section, σ_{ZG}^{lim}, analyzing only hadronic final states: $\sigma_{ZG}^{lim} > 0.29$ pb, (0.30 pb and 0.30 pb) for n=2(3,4) extra dimensions. The results correspond to the scale $M_{\tilde{D}}$. Following [2], $M_{\tilde{D}}$ is related to but not identical with M_D; $M_{\tilde{D}}^4 = 4M_D^2$ holds for $n = 2$. The preliminary 95% confidence level lower limits on the scale of extra dimensions, $M_{\tilde{D}}$, are 0.6 TeV, 0.38 TeV and 0.29 TeV for $n = 2, 3, 4$ extra dimensions.

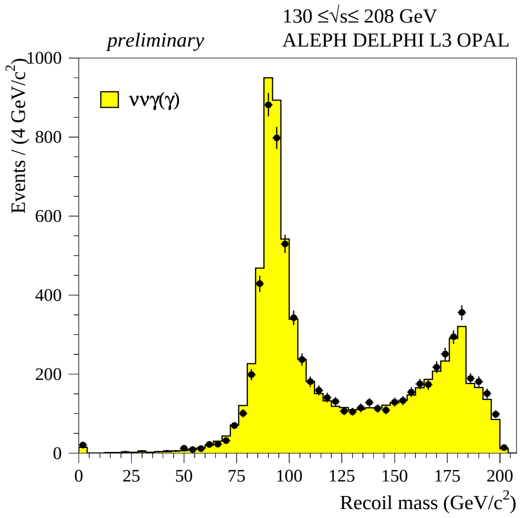

Figure 2: The recoil mass distribution for single photon events based on all available LEP data (see [5]).

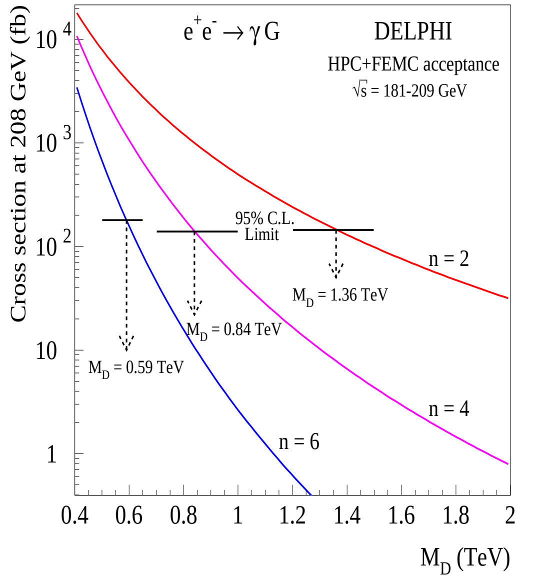

Figure 3: The cross section limit at 95% C.L. for the process $e^+e^- \to \gamma G$ obtained by DELPHI at $\sqrt{s} = 208$ GeV and the expected cross sections for 2, 4 and 6 extra dimensions.

	ALEPH		DELPHI	
δ	M_D [TeV]	R [cm]	M_D [TeV]	R [cm]
2	1.28	$2.9 \cdot 10^{-2}$	1.36	$2.5 \cdot 10^{-2}$
4	0.78	$1.4 \cdot 10^{-9}$	0.84	$1.3 \cdot 10^{-9}$
6	0.57	$5.6 \cdot 10^{-12}$	0.59	$5.4 \cdot 10^{-12}$
	L3		OPAL	
δ	M_D [TeV]	R [cm]	M_D [TeV]	R [cm]
2	1.45	$2.3 \cdot 10^{-2}$	1.09	$4.0 \cdot 10^{-2}$
4	0.87	$1.2 \cdot 10^{-9}$	0.71	$1.6 \cdot 10^{-9}$
6	0.61	$5.2 \cdot 10^{-12}$	0.61	$5.2 \cdot 10^{-12}$

Table 1: The 95% C.L. preliminary lower limits on M_D and the corresponding upper limits on the compactified space R in dependence on the number of extra dimensions derived from single photon production.

4 Indirect Searches

4.1 Graviton Exchange in Boson Pair Production

Fermion and boson pair production processes could be affected by the virtual graviton exchange as illustrated in Figure 1. Therefore, deviations from QED and Standard Model predictions can be interpreted within the framework of low scale gravity. In practice, instead of the fundamental scale, M_D, an effective scale M_S is also used. M_S is the cut-off scale to regulate ultraviolet divergencies and corresponds to M_D,

$$M_D^4 = \frac{2}{\pi\lambda} M_S^4, \tag{4}$$

where λ is a parameter of the order $|\lambda| \approx 1$. For its explicit calculation the full theory of gravity must be known.

4.1.1 $\mathbf{e^+e^-} \rightarrow \gamma\gamma(\gamma)$

In general, photon pair production is sensitive to new physics:

$$\frac{d\sigma}{d\Omega} = |e_u + e_t + NewPhysics|^2. \tag{5}$$

There are many candidates for new phenomena that could cause deviations from the Standard Theory. A basic approach to describe deviations is

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{SM} \cdot \left[1 \pm \frac{s^2}{2(\Lambda_\pm^{QED})^4} \sin^2\theta\right], \tag{6}$$

where Λ^{QED} is the cut-off scale of QED. Low scale gravity is only one of the new physics candidates,

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{SM} \cdot \left[1 \mp \frac{s^2}{\pi\alpha} \cdot \frac{\lambda}{2M_S^4} \sin^2\theta + ...\right], \tag{7}$$

and would distorts the angular distribution. Neglecting the 'higher order' terms denoted with '...' the characteristics of Equations (6) and (7) agree.

Analyzing the angular distribution assuming that low scale gravity exists ([2]),

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s}\frac{(1+\cos^2\theta)}{1-\cos^2\theta)} - \frac{\alpha s \lambda}{2\pi M_S^4}(1+\cos^2\theta) + \frac{s^3\lambda^2}{16\pi^2 M_S^8}(1+\cos^2\theta)(1-\cos^2\theta) \tag{8}$$

no discrepancies to QED expectations are obtained and preliminary limits on M_S are derived by all LEP experiments [10]. The results are listed in Table 2.

4.1.2 $\mathbf{e^+e^-} \rightarrow ZZ;\ WW$

Analogously, also the cross section for ZZ production is sensitive to virtual graviton exchange. The OPAL collaboration analyzed the angular distributions of the pair produced Z bosons in leptonic and hadronic four-fermion final states (including b-tagging) and

	M_S [TeV]				
λ	ALEPH	DELPHI	L3	OPAL	LEP comb.
+1	0.80	0.82	0.84	0.81	0.93
−1	0.85	0.91	0.99	0.96	1.01

Table 2: 95% C.L. on the preliminary lower limits on M_S for the LEP experiments derived from photon pair production.

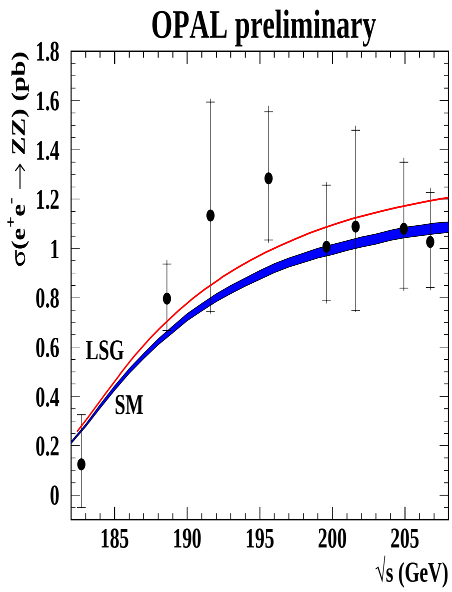

Figure 4: Indirect search for graviton exchange in $e^+e^- \rightarrow ZZ$. The measured total ZZ production cross section together with the Standard Model expectation (lower curve, thickness indicates the theoretical error) and with the cross section corresponding to low scale gravity with the fit result $\lambda/M_S^4 = -2.18$ TeV (upper thin line).

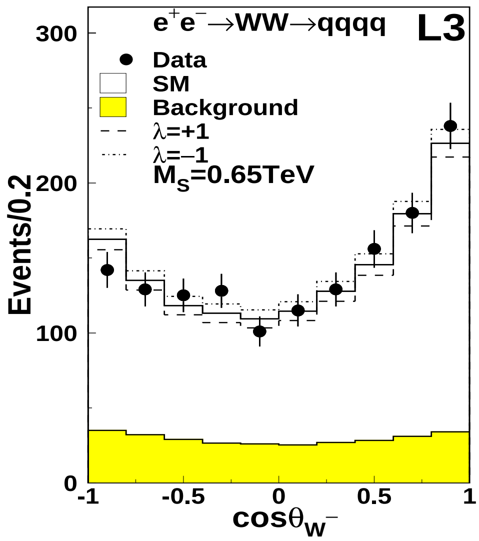

Figure 5: Indirect search for graviton exchange in $e^+e^- \rightarrow W^+W^-$. The distribution of the emission angle of the reconstructed W^- at $\sqrt{s} = 189$ GeV is shown together with the expectation of graviton exchange with M_S=0.65 TeV and $\lambda = \pm 1$.

found $M_S > 0.74$ TeV for $\lambda = +1$ and $M_S > 0.63$ TeV for $\lambda = -1$ at the 95% C.L. [12]. A comparison of the measured Z pair cross sections with the Standard Model expectations and with the case of low scale gravity is shown in Figure 4. Corresponding results from L3 are $M_S > 0.77$ TeV ($\lambda = +1$) and $M_S > 0.76$ TeV ($\lambda = -1$) [11].

The L3 collaboration also performed a search for graviton exchange in WW production using data up to 189 GeV c.m.s. energy. A fit to the angular distributions of W^- in the processes $e^+e^- \rightarrow qqqq$ (see Figure 5) and $e^+e^- \rightarrow qql\nu$ yields $M_S > 0.79$ TeV for $\lambda = +1$ and $M_S > 0.68$ TeV for $\lambda = -1$ at the 95% C.L. [11].

4.2 Graviton Exchange in Fermion Pair Production

As well as boson pair production the fermion pair production is sensitive to low scale gravity. The virtual exchange of gravitons modifies the differential cross section;

$$\frac{d\sigma}{d\cos\theta} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} + B(\cos\theta)\left[\frac{\lambda}{M_S^4}\right] + C(\cos\theta)\left[\frac{\lambda}{M_S^4}\right]^2 . \tag{9}$$

The angular dependence of the parameters B and C results in partial cancellations of the effect in the total cross section and also in the forward-backward asymmetry. Hence, the full sensitivity can only be reached analyzing the differential cross section.

Most sensitive is Bhabha scattering: high statistics and the interferences of graviton exchange with photon and Z exchange in the s- and t-channel allow to set the strongest limits on M_S for indirect measurements. Figure 6 shows the differential cross sections of Bhabha scattering combined for all LEP measurements combined at energies between 189 GeV and 207 GeV. As in Figure 7 illustrated no significant deviation from the Standard Model expectation is obtained and limits on M_S are derived: $M_S > 1.20$ TeV for $\lambda = +1$ and $M_S > 1.09$ TeV for $\lambda = -1$ at the 95% C.L. [13].

5 Summary and Outlook

The LEP collaborations search for signals of extra spatial dimensions. No deviations from the Standard model predictions have been obtained so far and preliminary limits are derived looking for real graviton production as well as for virtual graviton exchange in boson and fermion pair production. The results have to be finalized, especially for the most sensitive channels, $e^+e^- \rightarrow \nu\bar{\nu}\gamma$; e^+e^-, $\gamma\gamma$.

Substantial improvement of our knowledge about extra dimensions is expected with the operation of a linear e^+e^- collider at high energies above 0.5 TeV. Extensive studies are performed to test the potential of a linear collider to detect and to identify extra dimensions. An overview can be found in [14]. Extra dimensions can be discovered in the single photon channel for $M_D = 6.3$ (4.6, 3.6, 3.0, 2.6, 2.2) TeV [$n = 2$ $(3, 4, 5, 6, 7)$] if the electrons are polarized to 80%. With a positron polarization of 60% these discovery reaches can be increased up to a factor 1.25 and without polarized beams they decrease by roughly 20% [15, 16]. The measurements of anomalous single photon cross sections at 500 GeV and 800 GeV allow to determine the number of extra dimensions if M_D is less then 5 TeV [15]. Indirect searches for extra dimensions analyzing anomalous fermion pair cross sections are sensitive up to a cut-off scale of 5 TeV (8 TeV) at a linear collider operating at 0.5 TeV (0.8 TeV) [17]. Again, positron polarization increases the sensitivity.

Finally, it should be remarked that the ongoing experiments at Tevatron will improve the existing limits on extra dimensions before LHC comes into operation.

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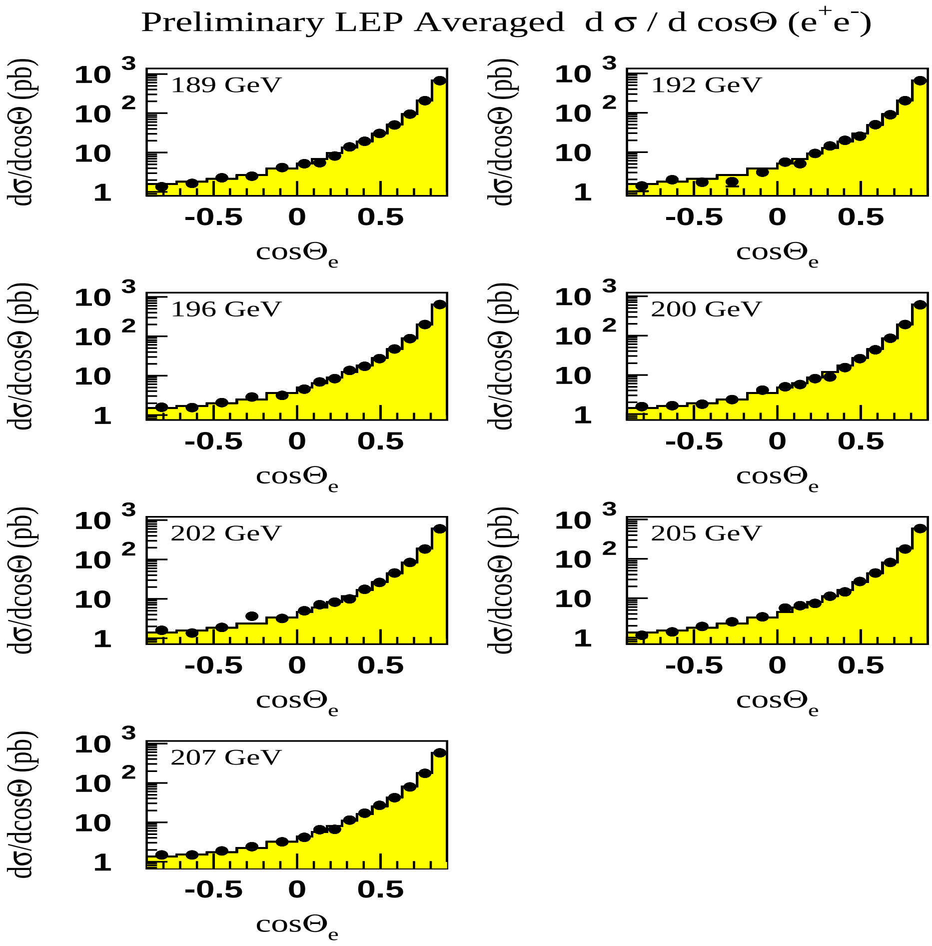

Figure 6: LEP averaged differential Bhabha cross sections for energies of 189 - 207 GeV. The Standard Model predictions (solid histograms) are calculated with BHWIDE.

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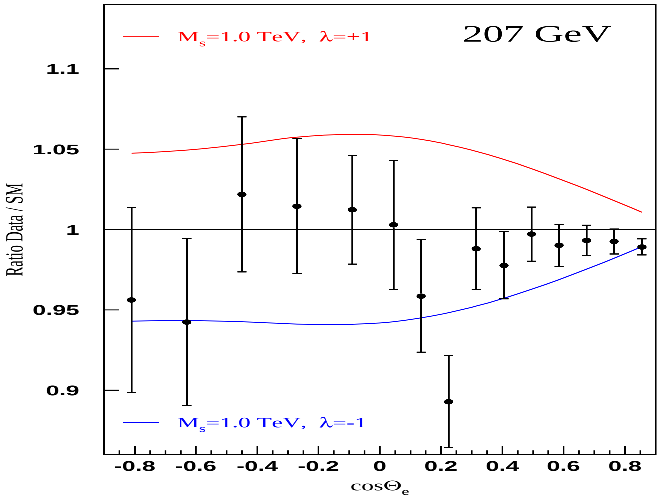

Figure 7: The ratio of the LEP averaged differential Bhabha cross section at $\sqrt{s}$ = 207 GeV compared to the Standard Model. The effects of virtual graviton exchange are also shown.

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