Searches for Extra Dimensions at LEP

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Extra spatial dimensions are proposed by recent theories that postulate the fundamental gravitational scale to be of the same order as the electroweak scale. Different final states and search strategies are used by LEP collaborations to search for the signs of extra spatial dimensions. A brief review of the search strategies and results from all four LEP experiments, ALEPH, DELPHI, L3 and OPAL, is given here. No hints for the existence of extra dimensions are found and limits on the fundamental gravitational scale are derived. The presented results are based on the data collected at LEP in 1998-2000 at centre-of-mass energies from 189 GeV up to 208 GeV. All results reported here are still preliminary.

1 Introduction

1.1 Theoretical Framework

The Standard Model of electroweak interactions has been extremely successful in explaining the physics at its characteristic distance $M_{ew}^{-1}$, where $M_{ew} \sim 10^2$ GeV is the electroweak scale. However, this great success has drawn attention to the hierarchy problem, i.e., the smallness of the electroweak scale as compared to the Planck scale, $M_{Pl} \sim \frac{1}{\sqrt{G_N}} \sim 10^{15}$ TeV, which denotes the characteristic scale of the gravitational interactions.

It has been recently proposed that this problem can be avoided by simply removing the hierarchy. In such models gravity becomes strong near the electroweak scale and gravitational fields can propagate in the $n$ new large extra dimensions, whereas the Standard Model fields are forced to lie on a 3-dim wall in the higher-dimensional space. Gravity thus only appears to be weak since we can only observe its manifestations on this wall. The effective gravitational scale $M_D$ is then connected to the Planck scale through:

\[ M_{Pl}^2 \sim M_D^{2+n} R^n, \]
where $R$ is the size of the additional dimensions, which could be as large as 1 mm. Searches for the manifestations of large extra dimensions at LEP are reviewed below.

1.2 Search Strategy

The phenomenology of large extra dimensions at LEP has already been studied in detail. Direct emission of gravitons leads to missing energy signatures in which a photon or a Z boson is produced with no observable particle balancing its transverse momentum\(^2\)\(^,\)\(^3\), as shown in Figure 1.

The other observable effect is the anomalous production of fermion or boson pairs in $e^+e^-$ annihilation through $s$-channel virtual graviton exchange as presented in Figure 2. The exchange of spin-2 gravitons modifies the differential cross sections of these reactions providing clear experimental signatures\(^3\)\(^,\)\(^4\)\(^,\)\(^5\).

2 Direct Searches

The reaction $e^+e^- \rightarrow \gamma G$ proceeds through $s$-channel photon exchange, $t$-channel electron exchange and four-particle contact interaction. The differential cross section of this process depends on both $M_D$ and $n$ and is given by\(^6\):

$$\frac{d^2\sigma}{dx_Gd\cos\theta_G} = \frac{\alpha}{32s} \frac{\pi^{\delta/2}}{\Gamma(\delta/2)} \left( \frac{s}{M_D} \right)^{\delta+2} f(x_G,\cos\theta_G)$$

with:

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

Figure 1: Direct graviton emission diagram contributing to the process $e^+e^- \rightarrow \gamma G$.

Figure 2: Virtual graviton exchange diagrams.
where $x_\gamma$ is the ratio of the photon energy to the beam energy and $\theta_\gamma$ is the polar angle of the photon. The cross section increases rapidly with smaller photon energies and angles as shown in Figure 3.

The Standard Model background for this reaction is dominated by the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. As an example, Figure 4 shows the expected photon energy spectrum from real graviton production together with data and prediction of the Standard Model background obtained by the L3 experiment. Limits on the parameter $M_D$ as a function of the number of extra dimensions are then derived from a binned likelihood fit to the photon energy distribution. The cross section limits on the real graviton production obtained by DELPHI experiment are depicted in Figure 4.

Lower limits at the 95% C.L. from ALEPH, DELPHI and L3 are summarized in Table 1. The expected signal cross section is proportional to $M_D^{-(n+2)}$ and, thus, the limits on $M_D$ fall rapidly with the number of extra dimensions $n$.

The direct graviton production associated with a Z boson can also be used to search for the

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*OPAL has also reported results using data only up to $\sqrt{s} = 189$ GeV.
Table 1: Lower limits at 95% C.L. on the gravitational scale $M_D$ and on the size of extra dimensions $R$, derived from direct graviton searches in the $e^+e^- \to \gamma G$ channel.

| $n$ | ALEPH $M_D$ (TeV) | ALEPH $R$ (cm) | DELPHI $M_D$ (TeV) | DELPHI $R$ (cm) | L3 $M_D$ (TeV) | L3 $R$ (cm) |
|-----|------------------|---------------|--------------------|---------------|----------------|------------|
| 2   | 1.28             | $2.9 \cdot 10^{-2}$ | 1.38               | $2.5 \cdot 10^{-2}$ | 1.45           | $2.3 \cdot 10^{-2}$ |
| 4   | 0.78             | $1.4 \cdot 10^{-9}$ | 0.84               | $1.3 \cdot 10^{-9}$ | 0.87           | $1.2 \cdot 10^{-9}$ |
| 6   | 0.57             | $5.6 \cdot 10^{-12}$ | 0.58               | $5.4 \cdot 10^{-12}$ | 0.61           | $5.2 \cdot 10^{-12}$ |

Table 2: Expected cross sections $\sigma_{ZG}$ for the $ZG$ signal ($M_{D1} = 0.5 \text{ TeV}$), detection efficiency $\varepsilon$, upper limit at 95% C.L. $\sigma_{ZG}^\text{lim}$ on the cross section and lower limit on the scale $M_{D1}$ as a function of the number of extra dimensions $n$.

| $n$ | $\sigma_{ZG}$ (pb) | $\varepsilon$ | $\sigma_{ZG}^\text{lim}$ (pb) | $M_{D1}$ (TeV) |
|-----|-------------------|---------------|------------------|----------------|
| 2   | 0.64              | 0.56          | 0.29             | 0.60           |
| 3   | 0.081             | 0.56          | 0.30             | 0.38           |
| 4   | 0.011             | 0.55          | 0.30             | 0.29           |

Effects of large extra dimensions, complementing the search in the single photon channel. The L3 experiment has searched in the $e^+e^- \to ZG$ channel using only hadronic $Z$ decays selected in data collected in 1998 at $\sqrt{s} = 189 \text{ GeV}$. The signature of this process is an unbalanced hadronic event with a visible mass compatible with that of the $Z$. The reduced sensitivity with respect to the $\gamma G$ channel stems from the limited phase space available for the graviton emission due to the mass of the $Z$. Limits at 95% C.L. on the gravity scale $M_{D1}$ are given in Table 2. The gravity scale $M_{D1}$ is related but not equal to the $M_D$ parameter used in the $\gamma G$ channel, e.g., in the particular case of $n = 2$ the two parameter are related as $M_{D1}^4 = 4M_D^4$.

3 Indirect Searches

3.1 Overview

The pair production of both boson and fermions via virtual graviton exchange can interfere with the Standard Model production of the same final state particles. The cross section can be then written as:

$$\left( \frac{d\sigma}{d\Omega} \right) = \left( \frac{d\sigma}{d\Omega} \right)_{SM} + \frac{\lambda}{M_S} \left( \frac{d\sigma}{d\Omega} \right)_{int} + \frac{\lambda^2}{M_S^2} \left( \frac{d\sigma}{d\Omega} \right)_G,$$

where the first term is the Standard Model contribution, the second term denotes the interference between the Standard Model and graviton exchange diagrams, and the last term comes from the graviton exchange. Here $\lambda$ is a dimensionless parameter order of unity and $M_S$ is a new mass scale (cut-off) related to the effective gravitational scale $M_D$. The exact value of $\lambda$ depends on the details of theory. At LEP most of the experiments use the formalism where $\lambda = +1$ and $\lambda = -1$ cases are considered to allow for both constructive and destructive interference. The dependence of $\lambda$ on the number of extra dimensions, $n$, is believed to be negligible, so that the limits on $M_S$ obtained using this parametrization are assumed to be valid for any $n$. All limits are given at 95% C.L.

Among many fermion and boson-pair final states studied at LEP, the most sensitive channels involve Bhabha scattering $e^+e^- \to e^+e^-$ and the photon-pair production $e^+e^- \to \gamma\gamma(\gamma)$. 
Figure 5: Ratio of the differential cross section of the process $e^+e^- \rightarrow e^+e^-$ including virtual graviton exchange to the Standard Model expectation for (a) $\lambda = +1$ and (b) $\lambda = -1$. The solid curves show the Born level prediction and the dotted curves show the prediction including radiative corrections.

Table 3: Lower limits at 95% C.L. on $M_S$ obtained by L3 and OPAL using Bhabha scattering process.

| Model          | L3   | OPAL |
|----------------|------|------|
| $M_S(\lambda = +1)$ (TeV) | 1.06 | 1.00 |
| $M_S(\lambda = -1)$ (TeV)   | 0.98 | 1.15 |

### 3.2 Bhabha Scattering

The dominant diagram contributing to the reaction $e^+e^- \rightarrow e^+e^-$ is the $t$-channel photon exchange and the interference between this diagram and the virtual graviton exchange is predicted to be large. This combined with the large statistics of the selected Bhabha sample at LEP makes this channel particularly sensitive. The ratio of the differential cross section including extra-dimensional effects to the Standard Model expectation is given in Figure 5. The maximum deviation from the Standard Model is observed in the central polar angle region and reaches the value of about 4% for $M_S = 1$ TeV.

Two LEP experiments, L3 and OPAL, have searched for the virtual graviton exchange effects with Bhabha samples selected using all available LEP2 dataset. Figure 5 shows the measured cross section distributions for the two experiments. None of the two experiments see any significant deviations from the Standard Model expectations and the derived limits are summarized in Table 3. The limits on the $M_S$ are of the order of 1 TeV.

### 3.3 Photon-Pair Production

The reaction $e^+e^- \rightarrow \gamma\gamma(\gamma)$ proceeds via $t$- and $u$-channel QED diagrams and the cross section in the presence of the virtual graviton exchange is given by

$$
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s} \frac{1 + \cos^2 \theta}{(1 - \cos^2 \theta)} - \frac{\alpha \lambda s}{2\pi M_S^2} (1 + \cos^2 \theta) + \frac{\lambda^2 s^3}{16\pi^2 M_S^4} (1 + \cos^2 \theta) (1 - \cos^2 \theta). \tag{5}
$$
Figure 6: Left: Bhabha cross section measured by the L3 experiment as a function of $\sqrt{s}$. Standard Model curve as well as the predictions from the virtual graviton exchange are also shown. Right: Ratio of the measured differential cross section to the Standard Model prediction obtained by OPAL at different centre-of-mass energies. The points show data, whereas the dashed and dotted lines show the 95% C.L. limits for $\lambda = +1$ and $\lambda = -1$ respectively.

Figure 7: Total cross section measurements for the reaction $e^+e^- \to \gamma\gamma$ (\gamma) from (left) OPAL and (right) L3.

All four LEP collaborations have used this channel to search for the effects of the gravitons propagating in extra dimensions. As an example, Figure 6 shows the total and differential cross section distributions for the $\gamma\gamma$ final state measured by L3 and OPAL. Results from all four LEP experiments agree very well with the Standard Model prediction. Limits on the cut-off scale $M_S$ are then computed using both the total number of the selected events and the distribution of the polar angle of the event, which is defined as $\cos\theta^* = |\sin(\theta_{\gamma_1} - \theta_{\gamma_2})/\sin(\theta_{\gamma_1} + \theta_{\gamma_2})|$. The limits obtained by the LEP experiments are shown in Table 4.

3.4 Combined Limits

The OPAL experiment have produced combined limits on $M_S$ using the following indirect search channels: $e^+e^-, \gamma\gamma$ and ZZ (using data collected at $\sqrt{s} = 189 - 208$ GeV), and $\mu^+\mu^-$ and $\tau^+\tau^-$. ALEPH limits are based on only data collected in 1998-99 at $\sqrt{s} = 189 - 202$ GeV.
Table 4: Lower limits at 95% C.L. on $M_S$ obtained using $\gamma\gamma$ channel.

| Model          | ALEPH | DELPHI | L3  | OPAL |
|----------------|-------|--------|-----|------|
| $M_S(\lambda = +1)$ (TeV) | 0.81  | 0.82   | 0.83| 0.83 |
| $M_S(\lambda = -1)$ (TeV)   | 0.82  | 0.91   | 0.99| 0.89 |

Figure 8: Negative log likelihood curves for each channel used in the OPAL combination and the combined likelihood curve.

(only $\sqrt{s} = 189$ GeV data). The combined limit as obtained by summing log likelihood curves from different channels is: $M_S(\lambda = +1) > 1.03$ TeV and $M_S(\lambda = -1) > 1.17$ TeV. Figure 8 shows that this limit is largely dominated by the $e^+e^-$ channel.

In addition, a combined limit has been obtained by using the full LEP2 dataset for the two most sensitive $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \gamma\gamma(\gamma)$ search channels. The obtained results are summarized in Table 5. These limits are “unofficial”, i.e., they are not endorsed by the LEP experiments. However, they give a good indication of the expected combined LEP sensitivity to effects of the virtual graviton exchange.

3.5 TeV Strings

It has been recently shown that the additional effects due to string excitations in a string theory of extra dimensions might compete and even overwhelm the effects of the virtual graviton exchange.

The Standard Model Bhabha scattering cross section is then modified as:

$$ \frac{d\sigma}{d\cos\theta} = \left( \frac{d\sigma}{d\cos\theta} \right)_{SM} \left| \frac{\Gamma(1 - \frac{s}{M_{Str}^2})\Gamma(1 - \frac{t}{M_{Str}^2})}{\Gamma(1 - \frac{s}{M_{Str}^2} - \frac{t}{M_{Str}^2})} \right|^2, $$

where $M_{Str}$ is the string scale.

The L3 experiment has used cross sections and forward-backward asymmetries from the $e^+e^- \rightarrow e^+e^-$ channel measured using the full LEP2 dataset to derive the following limit on the string scale: $M_{Str} > 0.57$ TeV.

4 Conclusion

The four LEP experiments have searched for signs of extra dimensions by looking for both real graviton production and effects of the virtual graviton exchange. No deviations from the
Table 5: “Unofficial” lower limits on the $M_S$ cut-off scale.

| Process                      | $M_S(\lambda = +1)$ (TeV) | $M_S(\lambda = -1)$ (TeV) |
|------------------------------|---------------------------|---------------------------|
| Bhabha scattering            | 1.13                      | 1.28                      |
| QED photon pairs             | 0.95                      | 1.14                      |
| Combined $e^+e^-$ and $\gamma\gamma$ | 1.13                      | 1.39                      |

Standard Model are found and preliminary limits in excess of 1 TeV are set. The limits on the cut-off mass scale $M_S$ are similar to those obtained at TEVATRON$^{15}$, whereas the searches for the real graviton production provide the best exclusion limits on new fundamental scale of gravity $M_D$. All results from LEP experiments discussed in this paper were taken from papers submitted to the 2001 Winter Conferences. However, they are still up-to-date, as limits determined using the most sensitive channels, $\nu\bar{\nu}\gamma$, $e^+e^-$ and $\gamma\gamma$, have not been changed or finalized since$^{14}$.

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