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Search for one large extra dimension with the DELPHI detector at LEP2

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Abstract

Single photons detected by the DELPHI experiment at LEP2 in the years 1997-2000 are used to investigate the existence of a single extra dimension in a modified scenario with slightly warped large extra dimensions. The data collected at centre-of-mass energies between 180 and 209 GeV for an integrated luminosity of $\sim$ 650 pb^{-1} agree with the predictions of the Standard Model and allow to set a limit on graviton emission in one large extra dimension. The limit obtained on the fundamental mass scale M_D is 1.69 TeV at 95% CL, with an expected limit of 1.71 TeV. These results are preliminary.

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1 Introduction

The Standard Model has been thoroughly tested at the CERN LEP e^+e^- collider [1]. No sign of statistically significant deviations from it or evidences for new physics phenomena beyond it have been found up to the highest LEP energies, ∼209 GeV. Yet the SM cannot be the final picture, because of several theoretical problems. One is known as the hierarchy problem and is related to the observed weakness of gravity in comparison with other interactions. This may be expressed by the observation that the reduced Planck mass, $M_{Pl} = \sqrt{1/G_N} \sim 2.4 \cdot 10^{15}$ TeV, where G_N is Newton's coupling constant, is much larger than the 0.1-1 TeV scale of the electroweak symmetry breaking.

A step towards the solution of this puzzle has been proposed in 1998 by Arkani-Hamed, Dimopoulos and Dvali (ADD) [2], assuming the existence of large extra spatial dimensions (ED). One ED has been proposed since a long time in connection with gravity and its unification with electromagnetism in the classic papers of Kaluza and Klein (KK) [3]. More recently, with the appearence of string theory, several EDs were advocated, but their size was thought to be close to the Planck length, $R \sim 1/M_{Pl} \sim 10^{-33}$ cm. In this case EDs would be completely out of the reach of present and planned colliders. The novel suggestion of ADD was the possible existence of large EDs with a fundamental Planck mass close to the electroweak scale, in fact implying that non-trivial physics "ends" at energies ∼1 TeV. In the ADD model all the SM particles are supposed to live on a 3D brane corresponding to our usual space, while gravitons are allowed to propagate into the bulk. Thus the weakness of gravity is simply due to its dilution in the EDs.

Assuming flat EDs and compactification on a torus, Gauss' law gives

$$M_{Pl}^2 = R^n M_D^{n+2} \tag{1}$$

where R is the radius of the ED and M_D is the fundamental Planck scale in the D-dimensional space-time (D=4+n). With M_D ∼1 TeV, $R \sim 10^{32/n-19}$ m, and as a consequence eq. 1 for n=1 implies a modification of Newton's law over solar system distances which is not observed. So the possibility that n=1 is usually considered to be falsified. On the other hand for $n \geq 2$, $R <1$ mm and tests of gravity are only recently touching these small distances [4]; for $n \geq 3$, $R <1$ nm and no gravity test exists which can falsify the model.

The graviton, confined within flat EDs of size R, has a uniform spectrum of excitations, which, from the point of view of a 4D observer, will be seen as a KK tower of states, with masses uniformly spaced between $1/R(\sim 10^{-32/n}$ TeV) and M_D. In particle collisions at colliders and in the cosmos, gravitons can be emitted, but they disappear immediately into the bulk and are therefore detectable via a missing energy signature. Each KK state is very weakly coupled, yet the number of states is very large, which turns into a sizable cross-section for graviton emission. Astrophysics limits yield strong constraints for n=2,3 based on observations of supernova SN1987A and on the behaviour of neutron stars [5]. These limits are 20-40 TeV and 2-3 TeV, respectively, and seem to rule out the ADD model with M_D=1 TeV. They are however based on many assumptions with differences of a factor of 2-3 between different calculations. For larger n they become much weaker.

For $n \geq 2$ limits on graviton emission have been obtained at the LEP collider [6, 7, 8, 9] and at the Tevatron [10]. At LEP the direct graviton emission reaction $e^+e^- \to G\gamma$ (GZ) has been studied: for $n \geq 2$ the photon spectrum peaks at low energies and at small emission angles [11]. No excess with respect to the SM predictions has been found and a combination of the LEP results yielded M_D >1.60 (0.80) TeV for n=2 (6) at the 95% CL [12].

Recently the ADD model has been reconsidered by Giudice, Plehn and Strumia (GPS) [13], who have focused on the IR behaviour of the model in connection with limits at colliders versus gravity and astrophysics constraints. They considered a distorted version of the ADD model with the same properties in the UV region, but satisfying observational and astrophysical limits in the large distance regime. They showed that the introduction of an IR cut-off in the ADD model evades the constraints from astrophysics and gravity for small n and also for n=1, given the energy resolution of the collider experiments. This IR cut-off is equivalent to a slight deformation or warping of the otherwise flat EDs. They started from the Randall and Sundrum type 1 model (RS1) [14] and considered the limit of slightly warped but large ED, resulting in a moderately large total warp factor. In RS1, with the visible brane located at y=0 and the Planck brane at $y = \pi R$, the line element is non-factorizable due to the warping factor

$$ds^2 = e^{2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \tag{2}$$

$$\sigma(y) = \mu|y|. \tag{3}$$

Here μ is a mass parameter due to the warp and y is the coordinate in the extra dimension. The mass parameter has a value 50 MeV $\leq \mu <<$ 1 TeV which introduces an IR cut-off. This cut-off implies a mass of the graviton which is inaccessible for the cosmological processes, but which has no significant implications for the high energy collider signal in the UV region of the KK spectra. In particular, the relation between the fundamental mass scale in 5 dimensions and the 4D Planck mass becomes

$$M_{Pl}^2 = \frac{M_5^3}{2\mu\pi}\left(e^{2\mu R\pi} - 1\right) \tag{4}$$

where R is the radius of the compactified ED. Hence the one ED can still be large, but unobserved as a modification of Newton's law or in the cosmological low energy processes. In this model the hierarchy between the Fermi and Planck scales is generated by two factors, the large ED and warping. It can be seen that for $\mu << R^{-1}$ one obtains the ADD limit, eq. 1.

Since a search for graviton emission with n=1 had not been performed in our previous publication [7] and since the results cannot be inferred from the limits already given for $n \geq$2 owing to the totally different photon energy spectrum [11, 13], we have reanalyzed the DELPHI data and the results will be presented here. The paper is organized as follows. Section 2 recalls briefly the experimental details. The analysis is discussed in Section 3. Section 4 presents the results and the conclusions are given in Section 5.

2 Detector and data preselection

The general criteria for the selection of single-photon events are based mainly on the electromagnetic calorimeters and on the tracking system of the DELPHI detector [15]. All the three major electromagnetic calorimeters in DELPHI, the High density Projection Chamber (HPC), the Forward ElectroMagnetic Calorimeter (FEMC) and the Small angle TIle Calorimeter (STIC), have been used in the single-photon reconstruction. The STIC accepted photons at very small polar angle [1], $2^\circ < \theta < 10^\circ$ ($170^\circ < \theta < 178^\circ$), the FEMC covered intermediate angles, $10^\circ < \theta < 37^\circ$ ($143^\circ < \theta < 170^\circ$), and large angles, $40^\circ < \theta < 140^\circ$, were covered by the HPC. Hermeticity Taggers were used to ensure complete detector hermeticity for additional neutral particles in the angular region not covered by the calorimeters. A detailed description of the trigger conditions and efficiencies of the calorimeters is given in our previous publication [7], where the rejection of events in which charged particles were produced is also discussed.

The single-photon events were selected in two stages. In the first stage events with only one detected photon were preselected and compared to the SM process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. A likelihood ratio method was then used to maximize the sensitivity in the search for graviton production with n=1.

Events with a photon in the HPC were selected by requiring a shower having a scaled energy $x_\gamma = E_\gamma/E_{beam}$ >0.06, θ between 45° and 135°, and no charged particle tracks. Photons in the FEMC were required to have a scaled energy x_γ >0.10 and a polar angle in the intervals $12^\circ < \theta < 32^\circ$ ($148^\circ < \theta < 168^\circ$). Single photons in the STIC were preselected by requiring one shower with a scaled energy x_γ >0.30 and with $3.8^\circ < \theta < 8^\circ$ ($172^\circ < \theta < 176.2^\circ$). Additional details about the preselection are given in [7]. In the single-photon event preselection events with more than one photon were permitted to survive only if the other photons were at low angle ($\theta_\gamma < 2.2^\circ$), low energy ($E_\gamma$ <0.8 GeV) or within 3°, 15°, 20° from the highest energy photon in the STIC, FEMC and HPC respectively.

3 Single-photon analysis

The single-photon analysis has been discussed in detail in [7], here we will recall the main points and underline the differences in the present analysis.

Apart from the $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ process, single-photon events can be faked by the QED reaction $e^+e^- \rightarrow e^+e^-\gamma$ if the two electrons escape undetected along the beampipe or if the electrons are in the detector acceptance but are not detected by the experiment. This process has a very high cross-section, decreasing rapidly with increasing energy and polar angle of the photon. Its behaviour together with the rapid variation of efficiencies at low photon energy motivates the different calorimeter energy cuts in the preselection and additional energy-dependent cuts on the polar angle in the FEMC and STIC.

The remaining background from the $e^+e^- \rightarrow e^+e^-\gamma$ process was calculated with a Monte Carlo program [16] and two different event topologies were found to contribute, giving background at low and high photon energy respectively. Either both electrons were below the STIC acceptance or one of the electrons was in the DELPHI acceptance where it was wrongly identified as a photon, while the photon was lost in the holes between the electromagnetic calorimeters.

The contribution from other processes such as $\gamma\gamma$ collisions [17], $e^+e^- \rightarrow \gamma\gamma(\gamma)$ [18], cosmic ray events, $e^+e^- \rightarrow \mu\mu(\gamma)$ [19], $e^+e^- \rightarrow \tau\tau(\gamma)$ [19], and four-fermion events [20] have also been calculated.

The $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ process was simulated by the KORALZ [19] program. A comparison of the cross-section predicted by KORALZ 4.02 with that predicted by

[1] In the DELPHI coordinate system, the z axis is along the electron direction and the polar angle to the z axis is called θ.

NUNUGPV [21] and KK 4.19 [22] showed agreement at the percent level, negligible with respect to the statistical and systematic uncertainties in the present measurement.

Simulated events for the physics processes and backgrounds were generated at the different centre-of-mass energies and passed through the full DELPHI simulation and reconstruction chain [15].

Table 1 shows the total number of observed and expected events in the HPC and FEMC. The numbers are integrated over the LEP energies from 180 to 209 GeV and correspond to an overall luminosity of ∼650 pb^{-1}.

	$N_{observed}$	$N_{e^+e^- \to \nu\bar{\nu}(\gamma)}$	$N_{other\ SM\ background}$
FEMC	705	626±3	49.1
HPC	498	540±4	0.6

Table 1: The number of selected and expected single-photon events.

Fig. 1 shows the x_γ distribution of all preselected single-photon events. As discussed in the previous paper [7], only single photon events in the HPC and FEMC were used for the subsequent analysis, since the E_γ cuts in the STIC, needed to reduce the radiative Bhabha background, reject a large part of the ED signal even in the case n=1.

A likelihood ratio method was used to select the final sample of single-photon events. The photon energy was used as the final discriminating variable and two likelihood functions ($f_S(E_\gamma)$ and $f_B(E_\gamma)$) were produced from the normalized photon energy distributions of the simulated signal and SM background events, after passing through the same selection criteria. The likelihood ratio function was defined as $\mathcal{L}_R = f_S(E_\gamma)/f_B(E_\gamma)$ where an event with $\mathcal{L}_R > \mathcal{L}_R^{CUT}$ was selected as a candidate event. The value of $\mathcal{L}_R^{CUT}$ was optimized to give the minimum signal cross-section excluded at 95% CL in the absence of a signal:

$$\sigma^{min}(\mathcal{L}_R^{CUT}) = \frac{N_{95}^{min}(\mathcal{L}_R^{CUT})}{\epsilon^{max}(\mathcal{L}_R^{CUT}) \times L} \tag{5}$$

where N_{95}^{min} is the upper limit on the number of signal events at 95% CL, ϵ^{max} is the efficiency for the signal and L is the integrated luminosity. This method optimises the background suppression for a given signal efficiency [23] and it is fully described in [24]. The signal shape, $f_S(E_\gamma)$, is the only difference with respect to the previous analysis [7].

The data collected at different centre-of-mass energies were analysed separately and different analyses were made depending on the electromagnetic calorimeter in which the photon was recorded. The final experimental limit was obtained using a Bayesian multi-channel method [24] which combined the results of 20 analyses. The method takes into account all the available information (such as the fraction of the signal and the average background in each subdetector and in each data subsample), and this makes it possible to calculate optimum limits.

The study was done with DELPHI data taken during 1997-2000 runs at e^+e^- centre-of-mass energies from 180 to 209 GeV, grouped in 10 different datasets, corresponding to an integrated luminosity of $\sim$ 650 pb^{-1}, with the subdetectors relevant for the analysis all fully operational.

4 Limit on the production of gravitons

The differential cross-section for $e^+e^- \rightarrow G\gamma$ has been calculated in [11, 13] and is given by

$$\frac{d^2\sigma}{dx_\gamma dcos(\theta_\gamma)} = \frac{\alpha}{32s}\frac{\pi^{\frac{n}{2}}}{\Gamma(\frac{n}{2})}\left(\frac{\sqrt{s}}{M_D}\right)^{n+2} f(x_\gamma, cos(\theta_\gamma)) \quad (6)$$

with

$$f(x,y) = \frac{2(1-x)^{\frac{n}{2}-1}}{x(1-y^2)}[(2-x^2)(1-x+x^2) - 3y^2x^2(1-x) - y^4x^4]. \quad (7)$$

Initial state radiation can produce additional photons that would cause a signal event to be rejected in a single-photon analysis. The expected signal cross section has therefore been corrected with a radiator approximation method [25].

For $n>1$ the differential distribution, eq. 7, is peaked at small E_γ and θ_γ, for n=1 instead a singularity is present at x_γ=1, which makes the distribution qualitatively different from the others. For instance the ratio of the cross-sections, eq. 6 and eq. 7, for n=1 and n=2 is independent of θ_γ, and increases from $\sim$1 at small x_γ to $\sim$30 at x_γ=0.95 for M_D=1 TeV and $\sqrt{s}$=208 GeV. In order to take into account detector effects, the theoretical cross-section has been corrected for efficiency and energy resolution in the calorimeters, using a parameterization developed in the $\nu\bar{\nu}\gamma$ analysis. The theoretical energy distributions for n=1 and 2 smeared in the HPC and FEMC are shown in Fig. 2.

As it can be seen in Fig. 1, the single photon data measured by DELPHI were well compatible with expectations from SM processes and no evidence for graviton production was found.

All DELPHI data with $\sqrt{s}>$180 GeV were used and for each of the 10 bins in $\sqrt{s}$ a limit was calculated after a cut optimization based on the likelihood method described in the previous section. These limits were combined to give a preliminary 95% CL cross-section limit for one extra dimension of 0.171 pb at 208 GeV, with an expected limit of 0.166 pb. The obtained preliminary limit on the fundamental mass scale is $M_D>$1.69 TeV at 95% CL (with 1.71 TeV expected limit) for n=1. As a comparison, the cross-section limits in the previous analysis for n=2-6 varied between 0.14 and 0.18 pb, and the obtained limits for M_D between 1.31 TeV (n=2) and 0.58 TeV (n=6). The same systematic errors were considered as in the previous analysis and the systematic error on the M_D limit in the 1D analysis was estimated to be less than 3%.

5 Conclusions

We have re-analysed single-photon events detected with DELPHI at LEP2 during 1997-2000 at centre-of-mass energies between 180 and 209 GeV to study graviton production with n=1 large extra dimensions, motivated by the model of Giudice, Plehn and Strumia [13]. Since the measured single-photon cross-sections are in agreement with the expectations from the SM process $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$, the absence of an excess of events has been used to set a preliminary limit of 1.69 TeV at 95% CL on the fundamental mass scale for n=1 ED.

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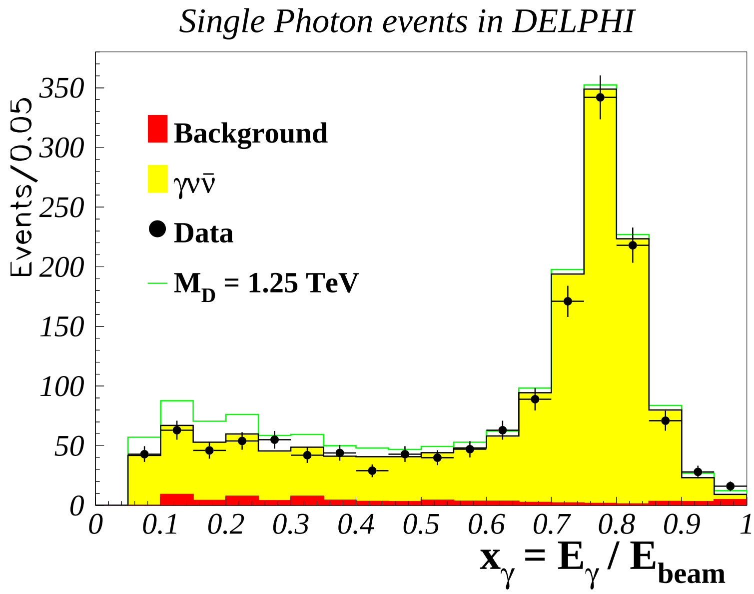

Figure 1: x_γ of selected single photons. The light shaded area is the expected distribution from $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$ and the dark shaded area is the total background from other sources. Indicated in the plot is also the signal expected from $e^+e^- \to G\gamma$ for n=1 and M_D=1.25 TeV.

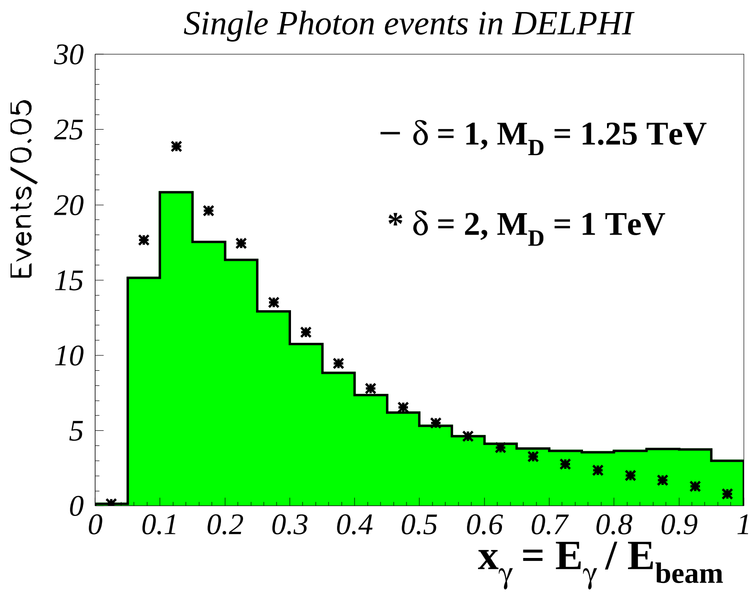

Figure 2: x_γ of expected single photons in the HPC and FEMC from $e^+e^- \to G\gamma$ with n=1, M_D=1.25 TeV and n=2, M_D=1 TeV, corrected for calorimeter efficiency and resolution. MC expectations are normalized to the luminosity of the combined data set in Fig. 1.