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Z boson decay to photon plus Kaluza–Klein graviton: large extra dimensional bounds

B.C. Allanach[a], J.P. Skittrall[b]

Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK

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Abstract. We consider the phenomenology of the decay of a Z boson into a photon and a Kaluza–Klein excitation of the graviton in the ADD model. Using LEP data, we obtain an upper bound on the branching ratio corresponding to this process of $\sim 10^{-11}$. We also investigate energy profiles of the process.

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1 Introduction

Nieves and Pal [1] have constructed a theoretical argument to predict the decay width of a Z boson to a photon and a graviton. The ADD model [2–5] predicts a "tower" of massive Kaluza–Klein excitations of the graviton (both massive spin-2 gravitons and massive spin-0 gravi-scalars) when the model is viewed from a four-dimensional perspective [6, 7]. In a previous paper with Sridhar [8], we extended the theoretical argument of Nieves and Pal to predict the decay width of a Z boson to a photon and a Kaluza–Klein graviton state (see Fig. 1) in an ADD model in which the extra dimensions are toroidally compactified with a common compactification radius. We now extend that work by using data from the L3 experiment at LEP1 [9] to estimate the bounds on the size of such extra dimensions that can be achieved by considering this process. The bounds we obtain are comparable with, but not stronger than, those obtained by considering the tree-level processes $e^+e^- \to \gamma\mathcal{G}$ [10] and $p\bar{p} \to \mathcal{G} + \text{jet}$ [11, 12]. (In this paper, we use $\mathcal{G}$ to denote any Kaluza–Klein excitation of the graviton – a massive graviton or gravi-scalar; in the tree-level processes the gravi-scalar contribution is negligible, but in the one-loop Z decay process it dominates.) By using the bounds on the size of such extra dimensions obtained from the processes $e^+e^- \to \gamma\mathcal{G}$ and $p\bar{p} \to \mathcal{G} + \text{jet}$, and, for the case of two extra dimensions, from inverse square law experiments [13, 14], it is therefore possible to predict stronger bounds than those measured by experiment on the contribution from the process $Z \to \gamma\mathcal{G}$ to the decay $Z \to \gamma + \text{missing } E_{\text{t}}$. The weakest such bound constrains the branching ratio to around the 10^{-11} level.

[a] e-mail: B.C.Allanach@damtp.cam.ac.uk
[b] e-mail: J.P.Skittrall@damtp.cam.ac.uk

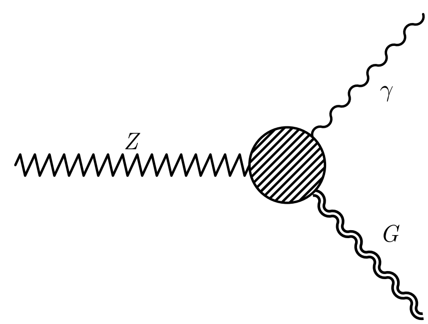


Fig. 1. The decay of a Z boson to a photon and a Kaluza–Klein graviton is one-loop at leading order

We also investigate the energy spectra of events from this decay channel. These spectra may prove useful in model discrimination, possibly indicating an experiment to be performed were ADD discovered. It is particularly notable that the shape of the spectra for $n = 2$ extra dimensions differs from those for $n > 2$ extra dimensions.

2 Existing bounds and bounds from LEP1 data on Z decay

Existing particle physics bounds on the size of extra dimensions come from consideration of the tree-level processes $e^+e^- \to \gamma\mathcal{G}$ [10] and $p\bar{p} \to \mathcal{G} + \text{jet}$ [11, 12]. In our paper with Sridhar [8], we showed that

$$\Gamma_{\text{tot}} = \frac{\alpha^2 G M_Z^{3+n} R^n \pi^{n/2}}{72\pi^2} \times \left[0.00088\left(\frac{7\cdot 5!}{\Gamma\left(\frac{n}{2}+6\right)} + \frac{3\cdot\frac{n}{2}\cdot 5!}{\Gamma\left(\frac{n}{2}+7\right)}\right)\right.$$

$$
\begin{aligned}
&+0.27\left\{\sum_{j=0}^{\infty}\frac{1}{(j+2)(j+3)(j+4)}\right.\\
&\left.\times\left(\frac{7\cdot(j+5)!}{\Gamma\left(\frac{n}{2}+j+6\right)}+\frac{3\cdot\frac{n}{2}\cdot(j+5)!}{\Gamma\left(\frac{n}{2}+j+7\right)}\right)\right\}\\
&+21\left\{\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\frac{1}{(i+2)(i+3)(i+4)(j+2)(j+3)(j+4)}\right.\\
&\left.\times\left(\frac{7\cdot(i+j+5)!}{\Gamma\left(\frac{n}{2}+i+j+6\right)}+\frac{3\cdot\frac{n}{2}\cdot(i+j+5)!}{\Gamma\left(\frac{n}{2}+i+j+7\right)}\right)\right\}\\
&+\frac{3}{2}\frac{(n-1)}{(n+2)}\left\{\frac{330}{\Gamma\left(\frac{n}{2}+4\right)}-\frac{63\cdot\frac{n}{2}}{\Gamma\left(\frac{n}{2}+5\right)}+\frac{13\cdot\frac{n}{2}\cdot\left(\frac{n}{2}+1\right)}{\Gamma\left(\frac{n}{2}+6\right)}\right.\\
&-\frac{0.97\cdot\frac{n}{2}\cdot\left(\frac{n}{2}+1\right)\cdot\left(\frac{n}{2}+2\right)}{\Gamma\left(\frac{n}{2}+7\right)}\\
&\left.\left.-\frac{0.078\cdot\frac{n}{2}\cdot\left(\frac{n}{2}+1\right)\cdot\left(\frac{n}{2}+2\right)\cdot\left(\frac{n}{2}+3\right)}{\Gamma\left(\frac{n}{2}+8\right)}\right\}\right], \qquad (1)
\end{aligned}
$$

where Γ_{tot} is the total decay width of the Z boson to a photon and any single Kaluza–Klein excitation of the graviton, n is the number of extra dimensions, all of which are toroidally compactified with common radius R, G is Newton's constant in four dimensions, α is the fine-structure constant, and M_Z is the mass of the Z boson. The width has contributions from decay to a photon and a spin-0 gravi-scalar (the part with the $(3/2)(n-1)/(n+2)$ coefficient) and from decay to a photon and a spin-2 Kaluza–Klein graviton excitation (the remainder).

Instead of being expressed in terms of a compactification radius R, it is equivalently possible to express the decay width (and compactification scale) in terms of a mass M_{D}, which is defined such that

$$8\pi R^n M_{\mathrm{D}}^{n+2} G = 1\,, \qquad (2)$$

where again G is Newton's constant in four dimensions. We present bounds using both measures of the compactification scale.

It is possible to obtain experimental bounds on the width of the decay $Z\to\gamma+\text{missing } E_{\text{t}}$ either by direct event selection, or by subtracting from the total Z width the sum of the widths of the "visible" Z decays. The method of direct event selection leads to much stronger bounds with current data, and so it is the method we use in this paper. With both methods (and in the case of the process $e^+e^-\to\gamma\mathcal{G}$), there is a standard model background to experimental data from the process $e^+e^-\to\gamma\nu\bar{\nu}$ [15–19]. The experimental analyses take this background at tree level into account to produce 95% confidence bounds, which we use. Of the one-loop corrections to the background, those involving the process $Z\to\gamma\nu\bar{\nu}$ are of particular relevance to the Z decay case, but the branching ratio for the process $Z\to\gamma\nu\bar{\nu}$ [20] is (at 7.16×10^{-10}) about four orders of magnitude smaller than the L3 experimental bound on the process $Z\to\gamma+\text{missing } E_{\text{t}}$ [9], and so the process $Z\to\gamma\nu\bar{\nu}$ is negligible when analysing current experimental bounds on the process $Z\to\gamma+$ missing E_{t}.

In order to consider experimental data to derive a bound on the magnitude of the radius of the extra dimensions R, we need to take into account that there will be a cut specifying the minimum photon energy, $E_{\min}$. We can put this into our summation/integration over the Kaluza–Klein states when deriving the overall width, to get

$$
\begin{aligned}
\Gamma_{\text{tot}}=&\frac{\alpha^2 G M_Z^{3+n} R^n \pi^{n/2}}{72\pi^2}\\
&\times\left[\left\{0.00088\left[10\sum_{p=0}^{5}\left(\frac{5!}{(5-p)!\Gamma\left(\frac{n}{2}+p+1\right)}\widehat{E}_{\min}^{5-p}\widehat{E}_{\text{rem}}^{\frac{n}{2}+p}\right)\right.\right.\right.\\
&\left.-3\sum_{p=0}^{6}\left(\frac{6!}{(6-p)!\Gamma\left(\frac{n}{2}+p+1\right)}\widehat{E}_{\min}^{6-p}\widehat{E}_{\text{rem}}^{\frac{n}{2}+p}\right)\right]\\
&+0.27\sum_{j=0}^{\infty}\frac{1}{(j+2)(j+3)(j+4)}\\
&\times\left[10\sum_{p=0}^{5+j}\left(\frac{(5+j)!}{(5+j-p)!\Gamma\left(\frac{n}{2}+p+1\right)}\widehat{E}_{\min}^{5+j-p}\widehat{E}_{\text{rem}}^{\frac{n}{2}+p}\right)\right.\\
&\left.-3\sum_{p=0}^{6+j}\left(\frac{(6+j)!}{(6+j-p)!\Gamma\left(\frac{n}{2}+p+1\right)}\widehat{E}_{\min}^{6+j-p}\widehat{E}_{\text{rem}}^{\frac{n}{2}+p}\right)\right]\\
&+21\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\frac{1}{(i+2)(i+3)(i+4)(j+2)(j+3)(j+4)}\\
&\times\left[10\sum_{p=0}^{5+i+j}\left(\frac{(5+i+j)!}{(5+i+j-p)!\Gamma\left(\frac{n}{2}+p+1\right)}\widehat{E}_{\min}^{5+i+j-p}\widehat{E}_{\text{rem}}^{\frac{n}{2}+p}\right)\right.\\
&\left.\left.-3\sum_{p=0}^{6+i+j}\left(\frac{(6+i+j)!}{(6+i+j-p)!\Gamma\left(\frac{n}{2}+p+1\right)}\widehat{E}_{\min}^{6+i+j-p}\widehat{E}_{\text{rem}}^{\frac{n}{2}+p}\right)\right]\right\}\\
&+\frac{1}{4}\frac{n-1}{(n+2)\Gamma\left(\frac{n}{2}\right)}\left\{\frac{330}{\frac{n}{2}}\widehat{E}_{\text{rem}}^{\frac{n}{2}}-\frac{910}{\frac{n}{2}+1}\widehat{E}_{\text{rem}}^{\frac{n}{2}+1}\right.\\
&+\frac{800}{\frac{n}{2}+2}\widehat{E}_{\text{rem}}^{\frac{n}{2}+2}-\frac{180}{\frac{n}{2}+3}\widehat{E}_{\text{rem}}^{\frac{n}{2}+3}-\frac{26}{\frac{n}{2}+4}\widehat{E}_{\text{rem}}^{\frac{n}{2}+4}\\
&\left.\left.-\frac{10}{\frac{n}{2}+5}\widehat{E}_{\text{rem}}^{\frac{n}{2}+5}-\frac{0.74}{\frac{n}{2}+6}\widehat{E}_{\text{rem}}^{\frac{n}{2}+6}+\frac{0.078}{\frac{n}{2}+7}\widehat{E}_{\text{rem}}^{\frac{n}{2}+7}\right\}\right], \qquad (3)
\end{aligned}
$$

where we have defined $\widehat{E}_{\min}\equiv 2E_{\min}/M_Z$ and $\widehat{E}_{\text{rem}}\equiv 1-\widehat{E}_{\min}$ for notational brevity. (This reduces to (1) in the case $E_{\min}=0$.)

We can apply this formula to the data of [9] to obtain the bounds on the size of the extra dimensions given in the second and third columns of Table 1.[1]

In addition to particle physics bounds, a stronger experimental bound can be obtained for $n=2$ extra dimensions from inverse square law experiments [13]. (Bounds cannot be directly taken from [13] for $n>2$ extra dimensions, as the bounds derived require the extra dimensions

[1] Reference [9] plots upper limits on the branching ratio for a range of values of $E_{\min}$. The bounds on the size of the extra dimensions we obtain are the strongest that arise from applying (3) across the range of values of $E_{\min}$. For each number of extra dimensions n, the value of $E_{\min}$ that leads to the strongest bound is 30.8 GeV.

Table 1. Bounds on the scales of the extra dimensions (lower limits on the gravity scale M_{D} and upper limits on the radius R), for $n = 2$ to $n = 6$ extra dimensions, for (L3) L3 Z decay data [9], (LEP) combined LEP $e^+e^- \to \gamma\mathcal{G}$ data [10], (CDF) CDF Run II $p\bar{p} \to \mathcal{G} + \text{jet}$ data [11], (ISL) inverse square law experiment data [13]. All limits correspond to a 95% confidence level. The strongest bound for each value of n is shown in bold

n	L3 M_{D} (TeV) >	LEP M_{D} (TeV) >	CDF M_{D} (TeV) >	ISL M_{D} (TeV) >
2	0.18	1.6	1.18	**1.9**
3	0.16	**1.2**	0.99	–
4	0.14	**0.94**	0.91	–
5	0.13	0.77	**0.86**	–
6	0.12	0.66	**0.83**	–

n	L3 R (mm) <	LEP R (mm) <	CDF R (mm) <	ISL R (mm) <
2	15	0.19	0.35	**0.13**
3	7.4×10^{-5}	$\mathbf{2.6 \times 10^{-6}}$	3.6×10^{-6}	–
4	1.8×10^{-7}	$\mathbf{1.1 \times 10^{-8}}$	1.1×10^{-8}	–
5	5.0×10^{-9}	4.1×10^{-10}	$\mathbf{3.5 \times 10^{-10}}$	–
6	4.6×10^{-10}	4.6×10^{-11}	$\mathbf{3.4 \times 10^{-11}}$	–

Table 2. Limits on the total branching ratio of the Z boson to a photon and a Kaluza–Klein graviton/gravi-scalar at the strongest of each of the 95% confidence bounds on the mass scale M_{D} from Table 1 (i.e. the bounds given in bold)

n	Branching ratio bound
2	1×10^{-11}
3	6×10^{-12}
4	2×10^{-12}
5	3×10^{-13}
6	3×10^{-14}

to be asymmetrically sized.) There are also estimates of astrophysical bounds using the temperature profile of the observed collapse of SN1987A (an upper bound is set on the amount of graviton emission as this would affect the resultant temperature) [21–24], which, depending on the assumptions made, give estimates of $M_{\mathrm{D}} \gtrsim 30$ TeV to $M_{\mathrm{D}} \gtrsim 130$ TeV for $n = 2$, and $M_{\mathrm{D}} \gtrsim 2.0$ TeV to $M_{\mathrm{D}} \gtrsim 9.3$ TeV for $n = 3$ (the bounds are comparable with or weaker than the experimental bounds for $n > 3$). There are also cosmological arguments that lead to estimated bounds on the size of extra dimensions [25, 26].

We see that the bounds on the scale of the extra dimensions derived from the Z decay process are weaker than other bounds. It is possible therefore for us to use the stronger bounds on the scale to estimate upper bounds on the branching ratio of the Z boson to a photon and a Kaluza–Klein graviton/gravi-scalar, using (1) and [27]. Table 2 gives such an estimate. The estimate is also plotted in Fig. 2, which shows how the decay widths and branching ratios for the process depend upon the scale of the extra

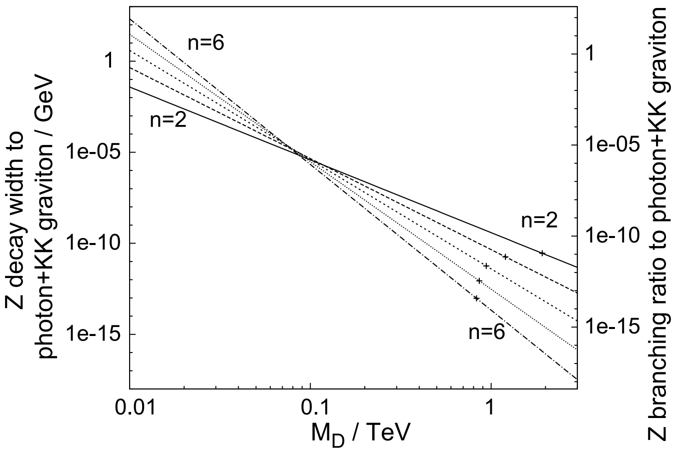


Fig. 2. $\Gamma(Z \to \gamma\mathcal{G})$ and $\mathrm{BR}(Z \to \gamma\mathcal{G})$ as functions of of the mass scale M_{D} of the extra dimensions, for $n = 2$ to $n = 6$ extra dimensions (consecutive values of n correspond to adjacent lines in the plot). The *crosses* plotted show the bounds on the decay width and branching ratio obtained by considering the strongest experimental 95% confidence bounds on M_{D} (i.e. the bold bounds from Table 1)

dimensions (so that the figure is, in effect, a plot of (1)). We note that the largest branching ratio (in the $n = 2$ case) is of the order 10^{-11}, so that we should not expect to see any such events in a Giga-Z collider, if only 10^9 events were collected, indicating the need for an experiment of higher luminosity.

3 Energy profiles of the process

Extra dimensional models are often distinguishable from other "new physics" models by noting that the multiple Kaluza–Klein states predicted by the extra dimensional model give an energy distribution different from, and usually softer than, those corresponding to models predicting single new states. With this in mind, we investigate the energy distribution of the process $Z \to \gamma\mathcal{G}$. It is necessary to recall the caveat that the low branching ratio means that a very high Z luminosity will be required to see such a distribution. The likely main use of such profiles would therefore be in model discrimination subsequent to a signal seen elsewhere. An analysis of the experimental data would also need to take into account the energy profile of the standard model background [18, 19], in addition to any other event selection considerations.

The differential decay width $\mathrm{d}\Gamma/\mathrm{d}E$, where E is the energy of the photon in the centre-of-mass frame, is equal to $-\mathrm{d}\Gamma(E_{\min})/\mathrm{d}E_{\min}$, where $\Gamma(E_{\min})$ is as given in (3) (the minus sign comes from the minimum energy cut corresponding to a lower bound in the integration over the Kaluza–Klein mass states).

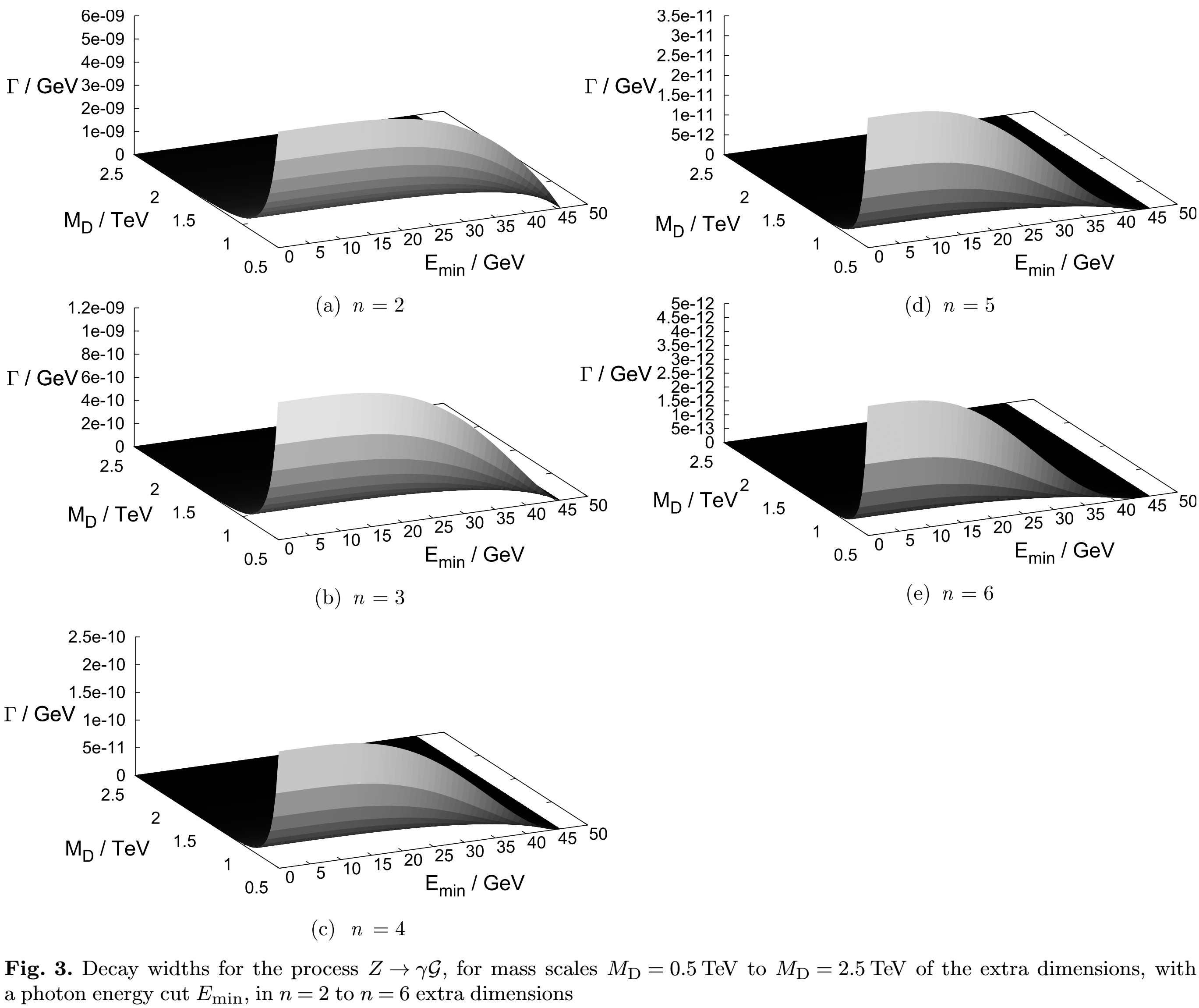
Figures 3 and 4 illustrate the energy profiles of the decay processes for $n = 2$ to $n = 6$ extra dimensions.

It is most obvious from the general profile plots that if such energy profiles could be obtained from an experiment and there were an indication of a toroidally-compactified ADD model, it should be possible to distinguish between $n=2$ and $n>2$ extra dimensions because of the non-zero energy derivative as $E \to M_Z/2$ in the $n=2$ case.

It is also possible to see a distinction between the profiles for other numbers of extra dimensions, if we observe that taking an energy derivative of (3) keeps a factor of R^n, so that one can obtain a parameter independent of the scale of the extra dimensions by considering $(1/\Gamma)\,\mathrm{d}\Gamma/\mathrm{d}E$. This is illustrated in Fig. 5. A detailed investigation of the number of events required for distinction between the numbers of extra dimensions is beyond the scope of this paper. However, this does show that given a signal of the ADD model, it may be possible to distinguish between possible numbers of extra dimensions if it were possible to obtain a sufficiently high number of Z decays.

Although the decay we are investigating is of a real Z boson in the centre-of-mass frame, which has a uniform angular distribution, the angular distribution does not remain uniform if one takes into account the production process $e^+e^- \to Z$ and considers the process $e^+e^- \to Z \to \gamma\mathcal{G}$ at the Z resonance. In this case, the decay to a photon and a spin-0 gravi-scalar has a $1+\cos^2\theta$ angular distribution, and the decay to a photon and a spin-2 KK graviton has a $1+a\cos^2\theta$ angular distribution, where $0<a\leq 1$ depends upon the KK mass and attains its maximum value of 1 in the limit of a zero KK mass.

We have assumed a uniform distribution in the calculations in this paper. The L3 data used to derive the novel bounds in this paper has angular cuts to exclude regions near the beam, meaning that taking the angular distribution into account would result in our expecting a smaller number of events (by a factor of about 0.9) than we should expect assuming a uniform distribution. This means that the bounds we have derived are stronger than those that would be derived by taking the angular distribution into account. (However, even the slightly strong bounds we have derived are still weaker than bounds from other processes.)



(a) $n=2$

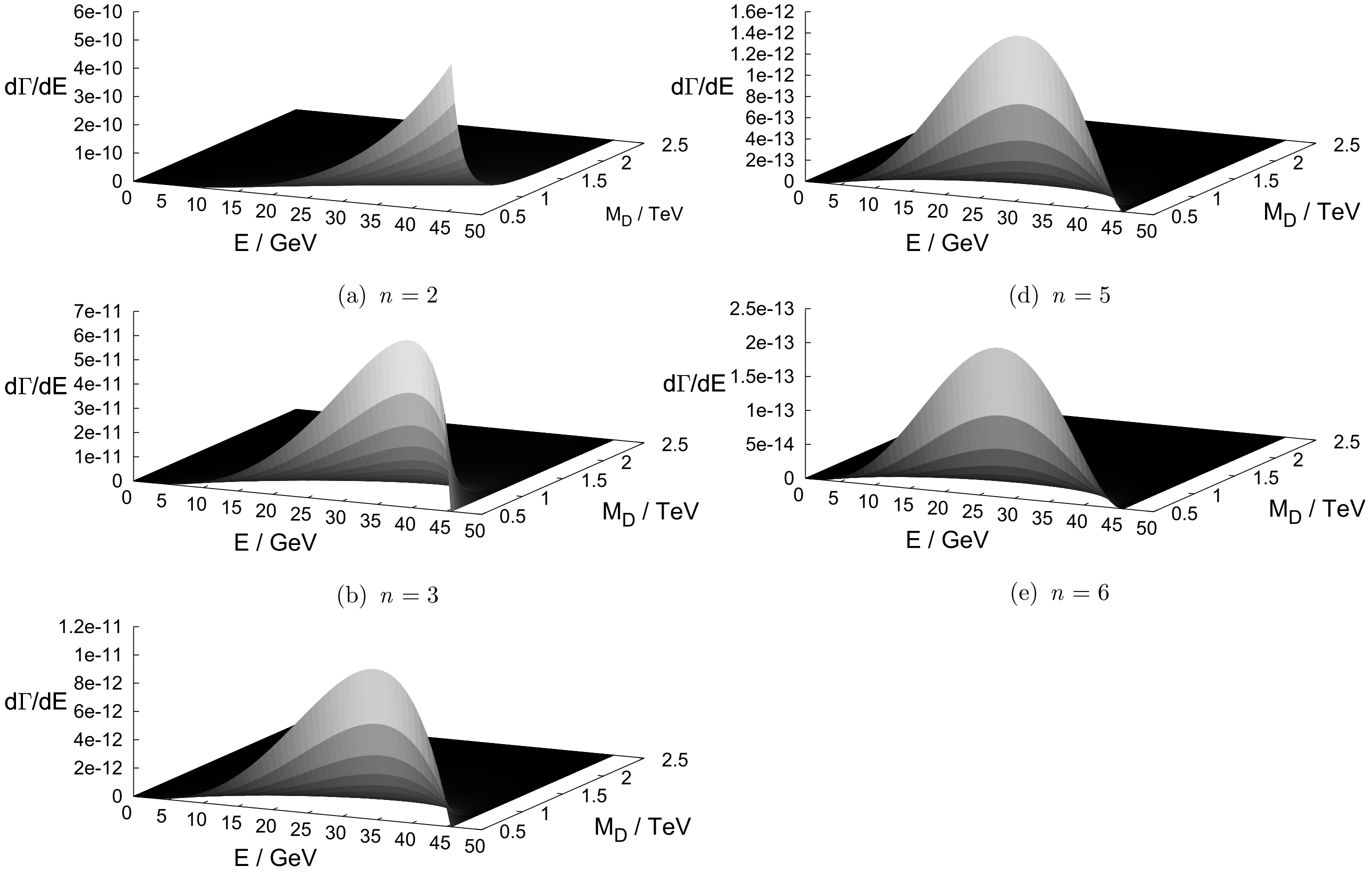
(b) $n=3$

(c) $n=4$

(d) $n=5$

(e) $n=6$

Fig. 3. Decay widths for the process $Z \to \gamma\mathcal{G}$, for mass scales $M_\mathrm{D}=0.5$ TeV to $M_\mathrm{D}=2.5$ TeV of the extra dimensions, with a photon energy cut E_min, in $n=2$ to $n=6$ extra dimensions



(a) $n = 2$

(b) $n = 3$

(c) $n = 4$

(d) $n = 5$

(e) $n = 6$

Fig. 4. Differential decay widths $\mathrm{d}\Gamma/\mathrm{d}E$ for the process $Z \to \gamma\mathcal{G}$, where E is the energy in the centre-of-mass frame of the photon produced, for mass scales $M_\mathrm{D} = 0.5$ TeV to $M_\mathrm{D} = 2.5$ TeV of the extra dimensions, in $n = 2$ to $n = 6$ extra dimensions

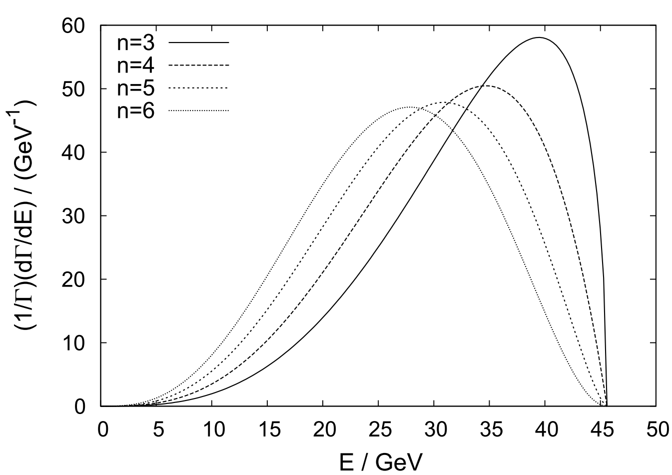


Fig. 5. Differential energy profiles $\mathrm{d}\Gamma/\mathrm{d}E$, normalised by $1/\Gamma$ to be independent of the extra dimensions scale, for $n = 3$ to $n = 6$ extra dimensions

The bounds derived on the branching ratio of $Z \to \gamma\mathcal{G}$ do not have an angular dependence, but it may be necessary if using such bounds to test or exclude this ADD scenario to take into account the Z production process in a particular experiment, to determine whether it is necessary to consider angular distributions.

4 Conclusions

We have shown that for a toroidally-compactified ADD model with a common radius for the extra dimensions, the branching ratio for the process $Z \to \gamma\mathcal{G}$ is not more than 10^{-11} – sufficiently small for the process not to be observed in a Giga-Z collider without a significant luminosity upgrade. No such decays of on-shell Z bosons should be expected at the LHC. This suggests a possible experimental search strategy in the event that it would become necessary to distinguish ADD from another suspected scenario beyond the standard model (namely an investigation of this relatively “clean” experimental decay channel – a significant excess of events would rule out this ADD model). This branching ratio also constitutes a test that ADD would have to fulfill, were there some indication of ADD from one of the other search channels.

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