Z boson decay to photon plus Kaluza-Klein graviton in large extra dimensions

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From Strings to LHC – II: Fireflies Ashram, Bangalore
22nd December 2007

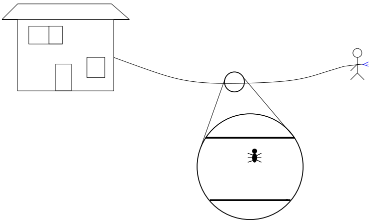
Work in collaboration with Ben Allanach and K. Sridhar:
JHEP11(2007)089 (arXiv:0705.1953), and arXiv:0709.2929

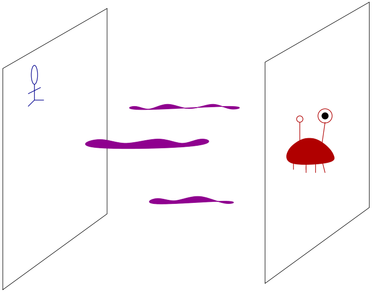
Take-home messages

- $Z \to \gamma\mathcal{G}$ does not beat other bounds on the size of extra dimensions in a toroidally compactified ADD model.
- Other bounds constrain $\Gamma_{Z\to\gamma\mathcal{G}}$. We should not expect to see this event even in a 'Giga-Z' collider ($\mathrm{BR}(\mathrm{Z} \to \gamma\mathcal{G}) \lesssim 10^{-11}$). A signal in this channel may exclude ADD/a signal of ADD may suggest a consistency check in this channel.
- Given a signal of ADD and an appropriate experiment, $Z \to \gamma\mathcal{G}$ may be a useful channel for parameter determination.

Extra dimensional scenarios

- All propose extra dimensions that are "invisible" to the everyday observer.





Universal extra dimensions (UED)

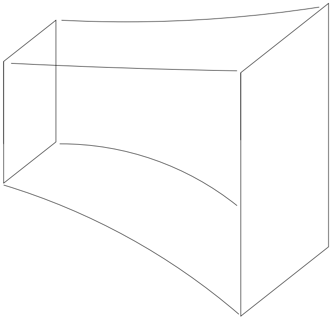
- ‘Normal’ but compactified dimensions.
- Fields have resonant modes from 4D viewpoint.
- Strongly confined by precision measurements from colliders.

ADD model – large extra dimensions

- Evade collider bounds.
- Confine Standard Model fields to $3 + 1$-D world.
- Allow gravity to propagate into “bulk”.
- Get resonant graviton modes.

Randall-Sundrum models – warped extra dimensions

- Extra dimension with curved geometry to suppress measurable effects.
- Exponential factor in metric generates hierarchy.



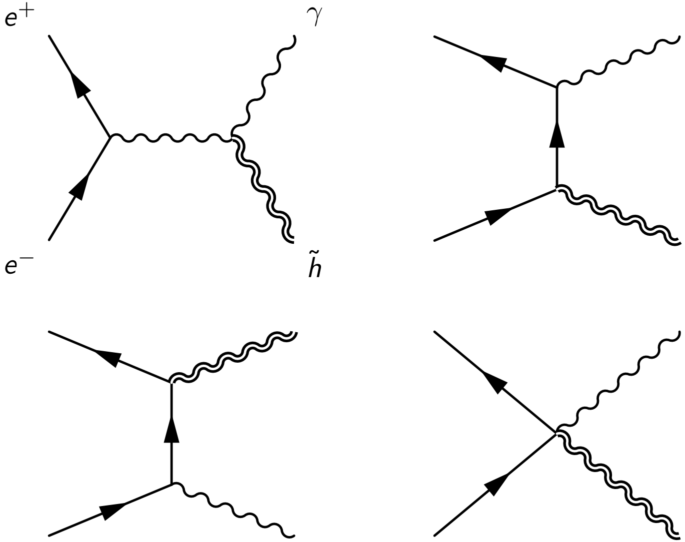
Bounds on ADD

- Gravity experiments.
- SN1987A collapse.
- Cosmological bounds.
- Collider bounds.

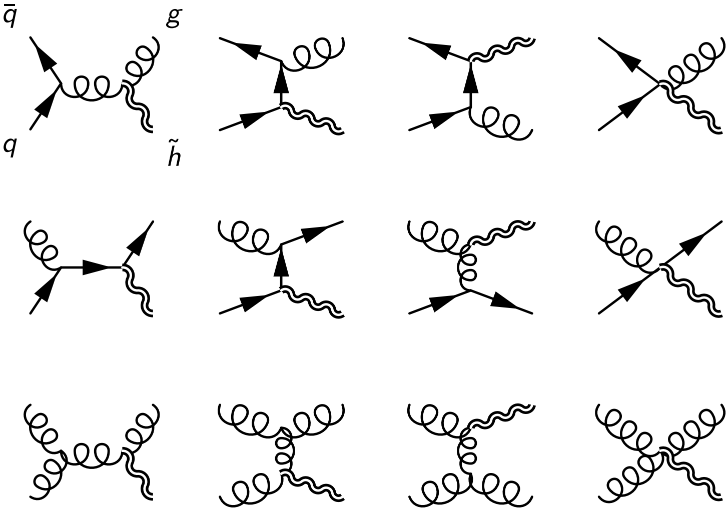
Effective quantum gravity

- $\eta_{\mu\nu} \rightarrow g_{\mu\nu} = \eta_{\mu\nu} + 2\kappa h_{\mu\nu}$.
- Also $\sqrt{g}$ coefficient in $\mathcal{L}$.
- Modify for KK reduction in ADD:
  $\eta_{\mu\nu} \rightarrow g_{\mu\nu} = \eta_{\mu\nu} + 2\kappa(h_{\mu\nu} + \eta_{\mu\nu}\phi)$.
- Redefine in terms of massive fields (Giudice, Ratazzi, Wells / Han, Lykken, Zhang) – get couplings to spin-2 and spin-0 gravitational modes.
- "Kaluza-Klein tower" of massive gravitons/gravi-scalars. Approximate sum by integral.

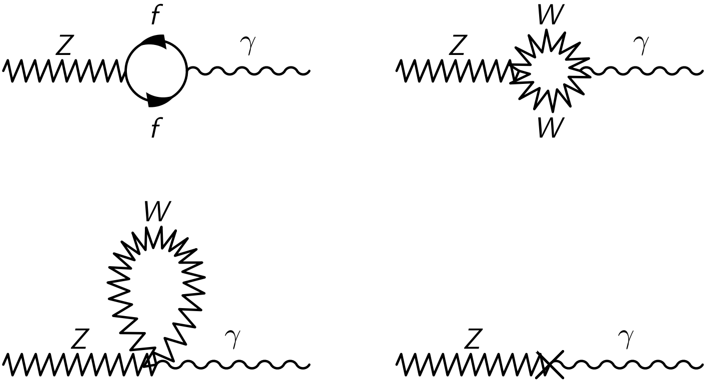
Bounds on ADD: $e^+e^- \to \gamma\mathcal{G}$



Bounds on ADD: $p\bar{p} \longrightarrow$ jet $\mathcal{G}$



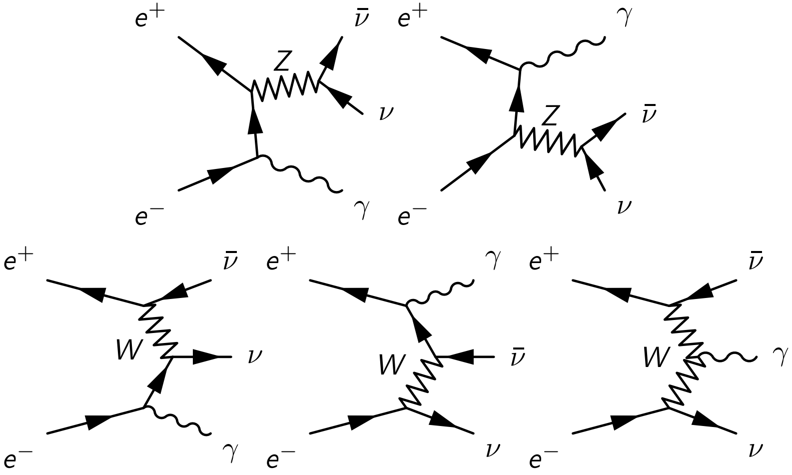
Bounds on ADD: $Z \to \gamma \mathcal{G}$



Bounds on ADD: $Z \to \gamma \mathcal{G}$

- One-loop process.
- Dominated by gravi-scalar decays ($Z \to \gamma\phi$).
- Many Z decays at LEP1.
- Standard Model background $e^+e^- \to \gamma\nu\bar{\nu}$.

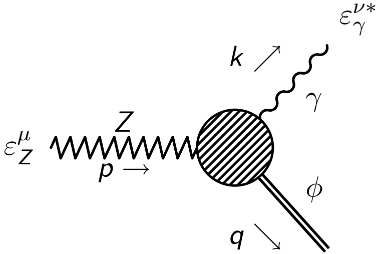
Standard Model background $e^+e^- \to \gamma\nu\bar{\nu}$



Simplifying the calculation

- Unitary gauge with counterterms $\Longrightarrow$ 38 diagrams to evaluate.
- Simplification by Nieves and Pal.
- Amplitude has a general form dictated by Ward-like identities.
- Argument implies that there are terms with identical coefficients, and terms that will cancel.

General form argument example: spin-0 case



- Write $\mathcal{M}^{(\phi)}(q, k) = \varepsilon_\gamma^{\nu *}(k) \varepsilon_Z^\mu(p) F_{\mu\nu}^{(\phi)}(q, k)$.

General form argument example: spin-0 case

$$\mathcal{M}^{(\phi)}(q,k) = \varepsilon_{\gamma}^{\nu *}(k)\varepsilon_{Z}^{\mu}(p)F_{\mu\nu}^{(\phi)}(q,k)\,. \tag{1}$$

Electromagnetic current conservation implies

$$k^{\nu}F_{\mu\nu}^{(\phi)}(q,k) = 0\,. \tag{2}$$

Expand about $k = 0$, writing

$$F_{\mu\nu}^{(\phi)} = \mathcal{T}_{\mu\nu}^{0} + k^{\alpha}\mathcal{T}_{\mu\nu\alpha}^{1}. \tag{3}$$

Use equation (2) to get

$$\mathcal{T}_{\mu\nu}^{0} = 0, \quad \mathcal{T}_{\mu\nu\alpha}^{1} = -\mathcal{T}_{\mu\alpha\nu}^{1}\,. \tag{4}$$

Considering the possible tensor arrangements that follow this (details omitted), get

$$F_{\mu\nu}^{(\phi)} = (k_{\mu}q_{\nu} - k\cdot q\eta_{\mu\nu})F_{0}^{(\phi)} + (\epsilon_{\mu\nu\alpha\beta}q^{\alpha}k^{\beta})F_{1}^{(\phi)}\,. \tag{5}$$

Horrific decay width $\Gamma_{Z\to\gamma\mathcal{G}}$

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

where $\widehat{E}_{\rm min} \equiv 2E_{\rm min}/M_Z$ and $\widehat{E}_{\rm rem} \equiv 1 - \widehat{E}_{\rm min}$.

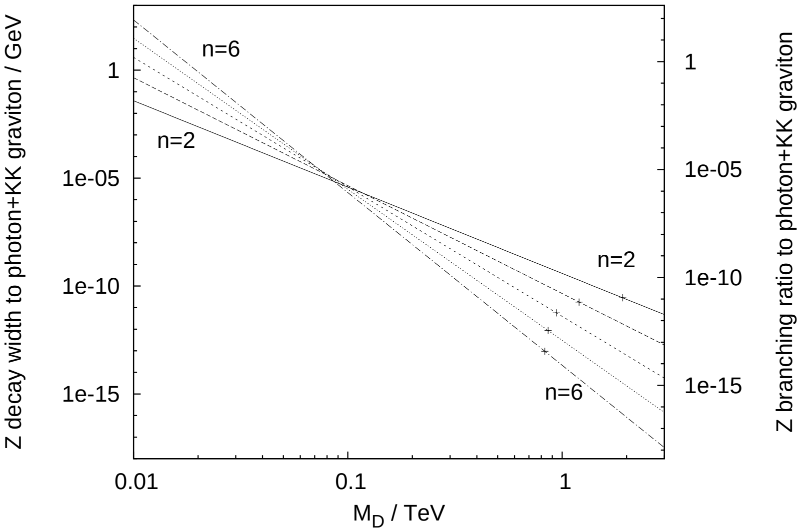
Bounds on ADD: $Z \to \gamma\mathcal{G}$

- Use LEP1 data.
- Either $\Gamma_{\text{tot}} - \Gamma_{\text{vis}}$ or $\gamma + E_{\text{t miss}}$ selection.
- $\gamma + E_{\text{t miss}}$ gives better bounds.
- L3 data with cut on E_γ.

Bounds on ADD: comparison (95% confidence levels)

	L3 Z decay bound ($Z \to \gamma\mathcal{G}$)		Combined LEP $e^+e^- \to \gamma\mathcal{G}$ bound		CDF Run II $p\bar{p} \to \mathcal{G} + \text{jet}$ bound		Inverse square law experiment bound	
n	M_D (TeV) $>$	R (mm) $<$	M_D (TeV) $>$	R (mm) $<$	M_D (TeV) $>$	R (mm) $<$	M_D (TeV) $>$	R (mm) $<$
2	0.18	15	1.6	0.19	1.18	0.35	**1.9**	**0.13**
3	0.16	7.4×10^{-5}	**1.2**	$\mathbf{2.6 \times 10^{-6}}$	0.99	3.6×10^{-6}	—	—
4	0.14	1.8×10^{-7}	**0.94**	$\mathbf{1.1 \times 10^{-8}}$	0.91	1.1×10^{-8}	—	—
5	0.13	5.0×10^{-9}	0.77	4.1×10^{-10}	**0.86**	$\mathbf{3.5 \times 10^{-10}}$	—	—
6	0.12	4.6×10^{-10}	0.66	4.6×10^{-11}	**0.83**	$\mathbf{3.4 \times 10^{-11}}$	—	—

Use of other ADD bounds to constrain $\Gamma_{Z\to\gamma\mathcal{G}}$



Caveat emptor

- Angular distribution given generation from e^+e^-
  - $1 + \cos^2\theta$ when gravi-scalar plus photon produced.
  - $1 + a\cos^2\theta$ $(0 < a < 1)$ when spin-two KK graviton plus photon produced.

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