Monoenergetic Photons from annihilating KK Dark Matter

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Direct annihilation: $B^{(1)}B^{(1)} \to \gamma\gamma$

outline:

- Universal Extra Dimensions and the $B^{(1)}$ as a dark matter candidate
- the particle spectrum in 4D
- processes that contribute to $B^{(1)}B^{(1)} \to \gamma\gamma$ (at the one loop level)
- numerical results
- analytical analysis
- observational prospects
- summary

Universal Extra Dimensions

Appelquist, Cheng & Dobrescu '01

- *all* Standard model fields can propagate in the extra dimensions
- compactification on an orbifold
- KK *parity* is still conserved

⟶ The lightest KK-particle (LKP) is stable and thus a dark matter candidate.

Including radiative corrections to KK masses, one finds LKP=$B^{(1)}$. Cheng, Matchev & Schmaltz '02

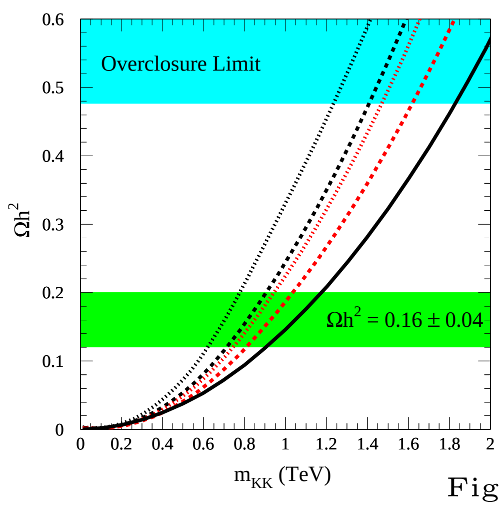


Fig.: Servant & Tait '02

The Kaluza-Klein spectrum

- A 5D scalar field $\Phi(x^\mu, y) \sim \sum_{k=0}^{\infty} \Phi_{(k)}(x^\mu) e^{i \frac{k}{R} y}$ looks from a 4D perspektive like

  $$S = \int d^5x \, (\partial\Phi)^2 - m^2\Phi^2 = \sum_k \int d^4x \, \left(\partial\Phi_{(k)}\right)^2 - m_k^2 \Phi_k^2 \, ,$$

  i.e. it decomposes into a 'KK'-tower of massive states, with

  $$m_k^2 = \left(\tfrac{k}{R}\right)^2 + m^2, \quad k = 0, 1, 2, \ldots$$

- A massless 5D vector field A^M decomposes into a 4D vector A^μ and a 4D scalar A^5. For A^μ one will have a KK-tower as before, while the KK-components of A^5 are 'eaten up' through the vector field acquiring a mass.

$$A^M \longrightarrow \begin{array}{ll} A^\mu_{(0)}, \; A^5_{(0)} & \quad (m = 0) \\ A^\mu_{(k)} & \quad (m = \tfrac{k}{r}, \; k \geq 1) \end{array}$$

The Kaluza-Klein spectrum - II

- In odd dimensions, there are no chiral fermions. Still, a 5D fermion can be written as

$$f = \Pi_R f + \Pi_L f \,,$$

where $\Pi_{R,L} = \frac{1}{2}(1 \pm \gamma^5)$ as usual. Under 4D Lorentz transformations, each of these parts will behave like an ordinary (chiral) 4D spinor.

(More generally, a fermion in $(n+4)$ dimensions transforms like 2^n 4D-fermions under 4D Lorentz transformations.)

- To get the right degrees of freedom at tree level, one assigns for all fields odd resp. even transformation properties under the orbifold projection $y \to -y$.

For example,

$$f^d \sim \sum_{k=0}^{\infty} (\Pi_L f^d)_{(k)} \cos\frac{ky}{R} + \sum_{k=1}^{\infty} (\Pi_R f^d)_{(k)} \sin\frac{ky}{R}$$

The UED spectrum in 5D

Including the first KK level only, one has:

- Fermions $f_{(0)}$, $f^d_{(1)}$, $f^s_{(1)}$
- Gauge Bosons $A^{r\mu}_{(0)}$, $B^{\mu}_{(0)}$, $A^{r\mu}_{(1)}$, $B^{\mu}_{(1)}$
- Mass eigenstates of the scalar spectrum:

$$\begin{aligned} a^0_{(k)} &= \frac{k}{RM_{Z_{(k)}}}\chi^3_{(k)} + \frac{M_Z}{M_{Z_{(k)}}}Z_{5(k)} \\ a^\pm_{(k)} &= \frac{k}{RM_{W_{(k)}}}\chi^\pm_{(k)} + \frac{W_W}{M_{W_{(k)}}}W^\pm_{5(k)} \end{aligned}$$

$$\begin{aligned} G^0_{(k)} &= \frac{M_Z}{M_{Z_{(k)}}}\chi^3_{(k)} - \frac{k}{RM_{Z_{(k)}}}Z_{5(k)} \\ G^\pm_{(k)} &= \frac{M_W}{M_{W_{(k)}}}\chi^\pm_{(k)} - \frac{k}{RM_{W_{(k)}}}W^\pm_{5(k)} \end{aligned}$$

$\rightsquigarrow$Goldstones $G^0_{(0)}$, $G^\pm_{(0)}$, $G^0_{(1)}$, $G^\pm_{(1)}$, $A^5_{(1)}$
Physical scalars $H_{(0)}$, $H_{(1)}$, $a^0_{(1)}$, $a^\pm_{(1)}$

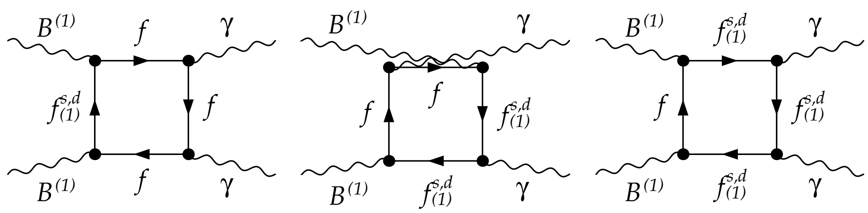
- Gauge fixing terms

$$\begin{aligned} \mathcal{G}^r &= \frac{1}{\sqrt{\xi}}\left[\partial^\mu A^r_\mu - \xi\left(-\frac{\hat{g}\hat{v}}{2}\chi^r + \partial_5 A^r_5\right)\right] \\ \mathcal{G}^Y &= \frac{1}{\sqrt{\xi}}\left[\partial^\mu B_\mu - \xi\left(\frac{\hat{g}'\hat{v}}{2}\chi^3 + \partial_5 B_5\right)\right] \end{aligned}$$

$\rightsquigarrow$ Ghosts $c^\pm_{(0)}$, $c^{3,Y}_{(0)}$, $c^\pm_{(1)}$, $c^{3,Y}_{(1)}$

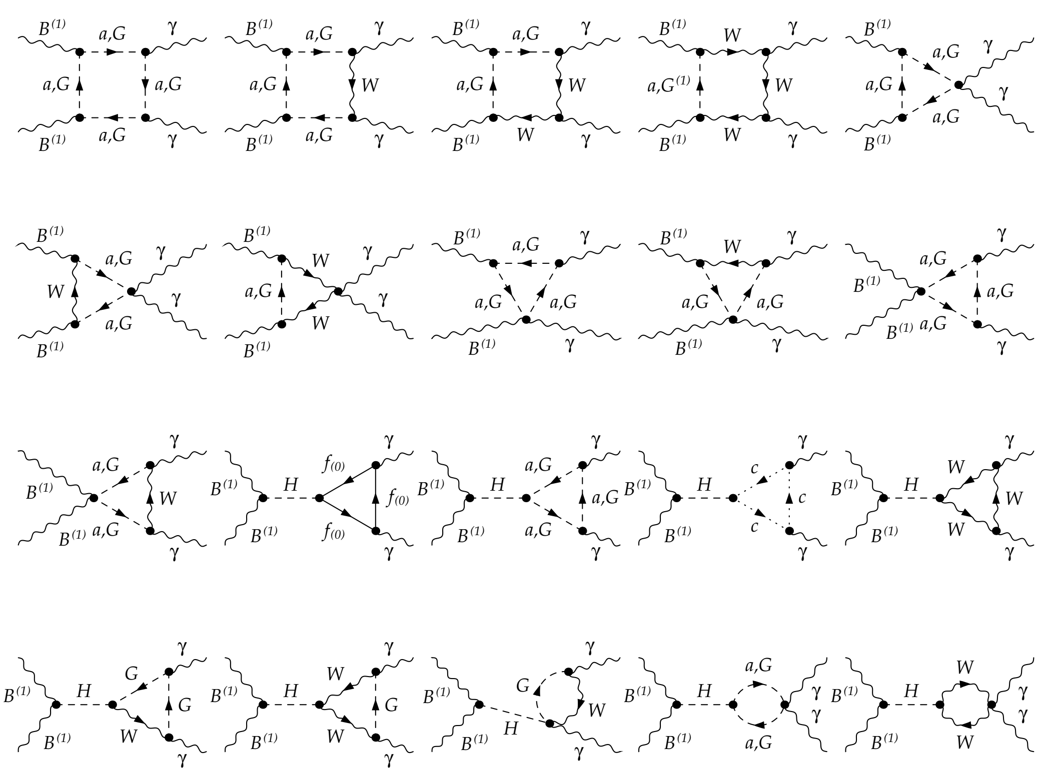
Contributions to $B^{(1)}B^{(1)} \to \gamma\gamma$

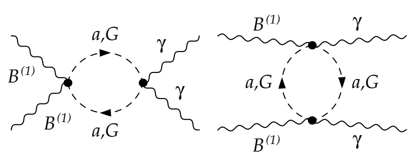
- (charged) Fermion loops:



+ crossings...

- Loops containing scalars:

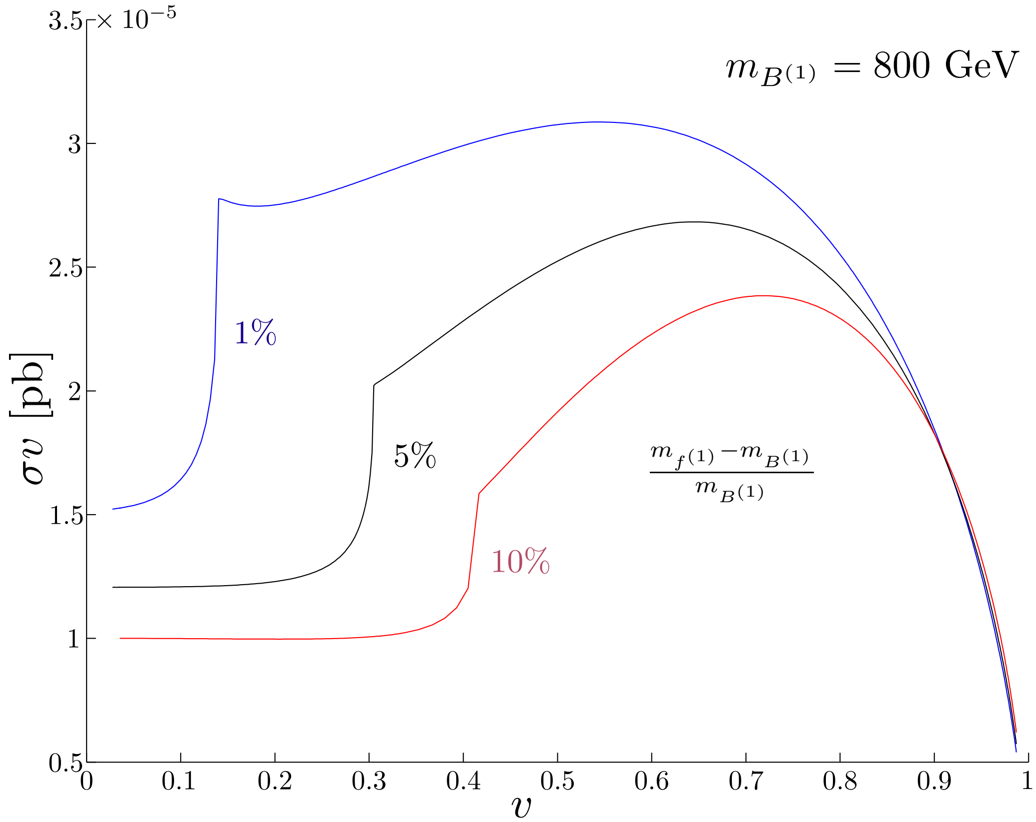




+ crossings & diff. KK levels...

Results for the cross-section

(numerical calculations done with FormCalc)



- $\sigma v \approx const.$ at $v \approx 10^{-3}$
- For $m_{B^{(1)}} = 400$ GeV, one gets 4-5 times higher cross-sections
- Fermion loops alone give about 90% of the total result

Tensor structure of the amplitude

Taking all momenta as ingoing, one has
$\mathcal{M} \equiv \epsilon_1^{\mu_1}\epsilon_2^{\mu_2}\epsilon_3^{\mu_3}\epsilon_4^{\mu_4}\mathcal{M}_{\mu_1\mu_2\mu_3\mu_4}$, with

$$\begin{aligned}\mathcal{M}^{\mu_1\mu_2\mu_3\mu_4} = & \sum_{i_1,i_2,i_3,i_4} \{A^{i_1i_2i_3i_4}\; p_{i_1}^{\mu_1}p_{i_2}^{\mu_2}p_{i_3}^{\mu_3}p_{i_4}^{\mu_4} + \\ & B_1^{i_3i_4}g^{\mu_1\mu_2}p_{i_3}^{\mu_3}p_{i_4}^{\mu_4} + B_2^{i_2i_4}g^{\mu_1\mu_3}p_{i_2}^{\mu_2}p_{i_4}^{\mu_4} + B_3^{i_2i_3}g^{\mu_1\mu_4}p_{i_2}^{\mu_2}p_{i_3}^{\mu_3} + \\ & B_4^{i_1i_4}g^{\mu_2\mu_3}p_{i_1}^{\mu_1}p_{i_4}^{\mu_4} + B_5^{i_1i_3}g^{\mu_2\mu_4}p_{i_1}^{\mu_1}p_{i_3}^{\mu_3} + B_6^{i_1i_2}g^{\mu_3\mu_4}p_{i_1}^{\mu_1}p_{i_2}^{\mu_2} + \\ & C_1\; g^{\mu_1\mu_2}g^{\mu_3\mu_4} + C_2\; g^{\mu_1\mu_3}g^{\mu_2\mu_4} + C_3\; g^{\mu_1\mu_4}g^{\mu_2\mu_3}\}\end{aligned}$$

and $i_{1,2} = 3,4$, $i_{3,4} = 1,2$.

(This is because $\sum_i p_i^\mu = 0$ and $\epsilon_1 \cdot p_1 = \ldots = 0$.)

Crossing symmetry: invariance under $(p_1,\mu_1) \leftrightarrow (p_2,\mu_2)$
and $(p_3,\mu_3) \leftrightarrow (p_4,\mu_4)$

Gauge invariance: $\epsilon_1^{\mu_1}\epsilon_2^{\mu_2}p_3^{\mu_3}\epsilon_4^{\mu_4}\mathcal{M}_{\mu_1\mu_2\mu_3\mu_4} = 0$

C-invariance: The $B^{(1)}f^{(1)}f$ vertex reads $(v_f + a_f\gamma_5)\gamma_\mu$,
giving $M \propto v_f^2 M_v + a_f^2 M_a$.
For $m_{f_{(0)}} \to 0$ one has $M_v = M_a$.

$\rightsquigarrow$ The total amplitude can be expressed by only four independent functions: A^{3312}, A^{3412}, A^{3421} and B_2^{32}.

Passarino - Veltman decomposition

All appearing loop integrals are of the form

$$\int d^n q \frac{1;\ q_\mu;\ q_\mu q_\nu;\ q_\mu q_\nu q_\rho;\ q_\mu q_\nu q_\rho q_\sigma}{\left[q^2+m_1^2\right]\left[(q+k_1)^2+m_2^2\right]\left[(q+k_1+k_2)^2+m_2^2\right]\left[(q+k_1+k_2+k_3)^2+m_2^2\right]}$$

and usually denoted by $D_0; D_\mu; D_{\mu\nu}; D_{\mu\nu\rho}; D_{\mu\nu\rho\sigma}$. They can all be reduced into the scalar integrals D_0, C_0 and B_0. (Passarino & Veltman '79)

This reduction scheme breaks down, however, if

$$\begin{vmatrix} k_1^2 & k_1\cdot k_2 & k_1\cdot k_3 \\ k_1\cdot k_2 & k_2^2 & k_2\cdot k_3 \\ k_1\cdot k_3 & k_2\cdot k_3 & k_3^2 \end{vmatrix} = 0\,.$$

$\rightsquigarrow$ Use a different reduction scheme, implemented for mathematica in the program LERG-I. (Stuart '95)

'Problem': Appearance of spurious divergences.

Observational prospects

Expected: very narrow γ-ray signal from the center of the galaxy

$\rightsquigarrow$needed: * TeV range telescopes with
* high sensitivity and
* high energy resolution

$\longrightarrow$ HESS, CANGAROO and VERITAS have a sensitivity of about $10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and an energy resolution of 10 - 20 % (at $\sim$ 1 TeV).

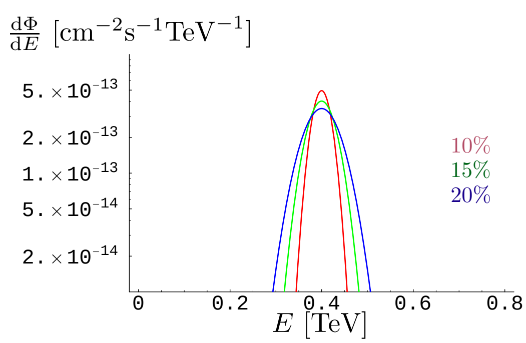
Expected gamma-ray flux:

$$\Phi \approx 1.9\times 10^{-16}\left(\frac{v\sigma}{10^{-30}\mathrm{cm}^3\mathrm{s}^{-1}}\right)\left(\frac{1\mathrm{TeV}}{m_{B^{(1)}}}\right)^2 \int\limits_{\Delta\Omega} J(\Psi)\mathrm{d}\Omega\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

A rough estimate for $m_{B^{(1)}} = 400$ GeV, $\int\limits_{\Delta\Omega} J(\Psi)\mathrm{d}\Omega = 100$ gives

$$\Phi \sim 2\times 10^{-13}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ .$$

(800 GeV $\rightarrow\sim 2\times 10^{-14}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)



Summary

The $B^{(1)}$ is a dark matter candidate that arises naturally in models with universal EDs.

- The monochromatic photon annihilation signal provides a characteristic feature to look for - especially when combined with the expected soft gamma ray spectrum (see also talk by M. Eriksson).
- Since $B^{(1)}B^{(1)} \rightarrow \gamma\gamma$ is loop-suppressed, the expected photon fluxes are rather small. Still, they lie very near the sensitivity of current/planned ACTs.
- For small mass-differences between the $B^{(1)}$ and the other KK masses, one expects a considerably stronger signal.
- Higher fluxes are also obtained for a Halo profile that is more cuspy than NFW near the center - which is actually expected in the vicinity of the black hole.