# Annihilation cross sections and interaction couplings of the dark matter candidates in the warped and flat extra dimensions

**E. O. Iltan** [*]

Physics Department, Middle East Technical University
Ankara, Turkey

## Abstract

We consider a scenario with an additional scalar standard model singlet $\phi_S$, living in a single extra dimension of the RS1 background. The zero mode of this scalar which is localized in the extra dimension is a dark matter candidate and the annihilation cross section is strongly sensitive to its localization parameter. As a second scenario, we assume that the standard model Higgs field is accessible to the fifth flat extra dimension. At first we take the additional standard model singlet scalar field as accessible to the sixth extra dimension and its zero mode is a possible dark matter candidate. Second, we consider that the new standard model singlet, the dark matter candidate, lives in four dimensions. In both choices the KK modes of the standard model Higgs field play an observable role for the large values of the compactification radius $R$ and the effective coupling $\lambda_S$ is of the order of $10^{-2} - 10^{-1}$ ($10^{-6}$) far from (near to) the resonant annihilation.

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[*]E-mail address: eiltan@newton.physics.metu.edu.tr

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The missing matter which is required holds almost 23% [1, 2, 3] of present Universe and it is called dark matter (DM) since it is not detectable by the radiation emitted. The evidence of the existence of DM comes from numerous observations: the galactic rotation curves [4], galaxies orbital velocities [5], the cosmic microwave background anisotrophy [6], observations of type Ia supernova [3]. However the nature of DM is still a mystery. The DM problem can not be solved in the framework of the standard model (SM) and it is inevitable to search new physics beyond in order to provide a dark matter candidate. In the literature, there are many studies which are based on the models beyond the SM in order to understand the nature of DM; DM in the framework of the supersymmetric models [7], the universal and non universal extra dimension (UED and NUED) models [8]-[21], the split UED models [22, 23, 24], the Private Higgs model [25], the Inert doublet model [26]-[33], the Little Higgs model [34], the Heavy Higgs model [35]. The common idea is that a large amount of DM is in the class of nonrelativistic cold DM and the Weakly Interacting Massive Particles (WIMPs) belong to this class. WIMPs, having masses in the range 10 GeV- a few TeV, involve in the weak and gravitational interactions and they are stable in the sense that they do not decay in to SM particles and they play a crucial role in the structure formation of Universe. On the other hand they disappear by pair annihilation (see for example [36, 37] for further discussion). Notice that the stability of WIMPs are ensured by an appropriate discrete symmetry, in various models (for details see for example [38] and references therein).

From the experimental point of view there are two possibilities to detect the DM candidate WIMP: The direct detection of DM, the search for the scattering of DM particles off atomic nuclei within a detector, and the indirect one, the search for products of WIMP annihilations. An upper limit of the order of $10^{-7} - 10^{-6} \, pb$ [39] for the WIMP-nucleon cross section has been obtained in the direct detection experiments. On the other hand since the current relic density could be explained by thermal freeze-out of their pair annihilation the present DM abundance by the WMAP collaboration [40] leads to the bounds for the annihilation cross section.

In the present work we study the annihilation cross section and the related coupling of the DM candidates in the warped and flat extra dimensions. At first, we consider that all SM particles live on the 4 dimensional brane and there exists an additional scalar SM singlet $\phi_S$ which is accessible to a single extra dimension in the RS1 background and its zero mode is a possible DM candidate. As a second scenario we choose the flat extra dimension(s) where the SM Higgs doublet, necessarily the gauge fields, are accessible to a single extra dimension (the fifth one) with two possibilities: the additional SM model singlet scalar field lives in the sixth

extra dimension and its zero mode is a possible DM candidate; the new SM singlet, the DM candidate, lives in four dimensions.

## DM as the zero mode of SM singlet $\phi_S$ which is accessible to a single extra dimension in the RS1 background

The RS1 background[1] [41, 42] is based on the curved extra dimension with the metric

$$ds^2 = e^{-2\sigma}\, \eta_{\mu\nu}\, dx^\mu\, dx^\nu - dy^2\,, \tag{1}$$

where $\sigma = k\,|y|$, $k$ is the bulk curvature constant, the exponential $e^{-\sigma}$, with $y = R\,|\theta|$, is the warp factor. Now we consider that an additional SM singlet $\phi_S$ is accessible to the extra dimension. The compactification of the extra dimension onto $S^1$ orbifold with radius $R$ results in the appearance of KK modes as

$$\phi_S(x, y) = \sum_{n=0}^{\infty} \phi_S^{(n)}(x)\, f_n(y)\,, \tag{2}$$

where the non-vanishing zero mode exists if the fine tuning of the parameters (see [43, 44] and [45] for details)[2] $b$ and $a$

$$b = 2 - \sqrt{4 + a}\,, \tag{3}$$

is reached, and it reads

$$f_0(y) = \frac{e^{b\,k\,y}}{\sqrt{\frac{e^{2\,(b-1)\,k\,\pi\,R}-1}{(b-1)\,k}}}\,. \tag{4}$$

If one respects the existence of the ad-hoc discrete $Z_2$ symmetry $\phi_S \to -\phi_S$ and considers that $\phi_S$ has no vacuum expectation value, the stability of the zero mode scalar $\phi_S^{(0)}$ is guaranteed[3] and it can be taken as a DM candidate which disappears by pair annihilation with the help of the exchange particle. The possible interaction which drives the pair annihilation is

$$\mathcal{S}_{Int} = \int d^5 x \sqrt{g}\, \left( \lambda_{5\,S}\, (\phi_S^{(0)})^2\, (\Phi_1^\dagger\, \Phi_1) \right) \delta(y - \pi R)\,, \tag{5}$$

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[1]Here, the extra dimension, having two boundaries, the hidden (Planck) brane and the visible (TeV) brane with opposite and equal tensions, is compactified onto $S^1$ orbifold with the compactification radius $R$. In this case the low energy effective theory has flat 4D spacetime, even if the 5D cosmological constant is non vanishing. The gravity, having an extension into the bulk with varying strength, is taken to be localized on the hidden brane.

[2]There is another possibility of fine tuning of the parameters $b$ and $a$ for the non-vanishing zero mode, namely $b = 2 + \sqrt{4 + a}$. However we ignore this choice since it is not appropriate for our case since it leads to an effective coupling which is not valid for the perturbative calculation.

[3]The scalar field $\phi_S$ has no SM decay products.

where $\Phi_1$ is the SM Higgs field

$$\Phi_1 = \frac{1}{\sqrt{2}} \left[ \begin{pmatrix} 0 \\ v + H^0 \end{pmatrix} + \begin{pmatrix} \sqrt{2}\chi^+ \\ i\chi^0 \end{pmatrix} \right] , \tag{6}$$

with the vacuum expectation value

$$< \Phi_1 >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} . \tag{7}$$

Here the SM Higgs boson $H^0$ is the exchange particle and the pair annihilation occurs after the electroweak symmetry breaking. In this part of the work we will study the effects of the zero mode scalar localization parameter $a$ and the curvature $k$ on the annihilation cross section.

## DM as the SM singlet (or the zero mode of the SM singlet living in the sixth flat extra dimension) and the Higgs field living in the fifth flat extra dimension

At first, we assume that the SM Higgs doublet and the additional SM model singlet scalar field are accessible to fifth and sixth extra dimension respectively, however the SM fields, except gauge fields, live in four dimensions. The compactification of the extra dimensions on $S_1 \times S_1$ with radii $R$ results in the expansion of the SM Higgs doublet $\Phi_1$ (see eq.(6)) and the new SM singlet $\phi_S$ into their KK modes as

$$\begin{aligned} \Phi_1(x, y) &= \frac{1}{\sqrt{2\pi R}} \left\{ \Phi_1^{(0)}(x) + \sqrt{2} \sum_{n=1}^{\infty} \Phi_1^{(n)}(x) \cos(ny/R) \right\} , \\ \phi_S(x, y) &= \frac{1}{\sqrt{2\pi R}} \left\{ \phi_S^{(0)}(x) + \sqrt{2} \sum_{n=1}^{\infty} \phi_S^{(n)}(x) \cos(nz/R) \right\} , \end{aligned} \tag{8}$$

where $y$ and $z$ are the coordinates of the fifth and sixth extra dimensions. Now, we consider the interaction of the additional scalar singlet with the SM Higgs doublet as

$$\mathcal{L}_{Int} = \left( \lambda_{6S} \, \phi_S^2 \, (\Phi_1^\dagger \, \Phi_1) \right)_{y=0, z=0} . \tag{9}$$

After the electroweak symmetry one gets the interaction term

$$\mathcal{L}'_{Int} = \frac{\lambda_{6S} \, v}{(2\pi R)^2} \, (\phi_S^{(0)})^2 \left( H^{0\,(0)} + \sqrt{2} \sum_{n=1}^{\infty} H^{0\,(n)} \right) , \tag{10}$$

which is responsible for the the annihilation process of $\phi_S^{(0)}$ which we consider as a DM candidate. Here the zero mode and KK mode Higgs fields are intermediate particles which carry the

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annihilation process. Notice that the stability of the DM candidate under consideration is ensured by respecting that the SM singlet scalar $\phi_S$, having no vacuum expectation value, obeys the discrete $Z_2$ symmetry $\phi_S \to -\phi_S$.

Second, we consider that the SM Higgs doublet is accessible to fifth extra dimension, however, the additional SM model singlet scalar field, the DM candidate, lives in four dimensions. This is the case that the interaction of the additional scalar singlet with the SM Higgs doublet reads

$$\mathcal{L}_{Int} = \left( \lambda_{5\,S}\, \phi_S^2 \, (\Phi_1^\dagger \, \Phi_1) \right)_{y=0}, \tag{11}$$

and the interaction term, which is responsible for the annihilation process, becomes

$$\mathcal{L}'_{Int} = \frac{\lambda_{5\,S}\, v}{2\,\pi\,R}\, \phi_S^2 \left( H^{0\,(0)} + \sqrt{2} \sum_{n=1} H^{0\,(n)} \right), \tag{12}$$

after the electroweak symmetry breaking. Similar to the previous case the zero mode and KK mode Higgs fields play the role of intermediate particles which drive the annihilation process. The stability of the DM candidate is ensured with the above ad-hoc $Z_2$ symmetry and with vanishing vacuum expectation value.

Now, we present the total averaging annihilation rate of DM which is obtained by the annihilation process DM DM$\to H^0 \to X_{SM}$

$$< \sigma\, v_r > \;\; = \;\; \frac{4\,\lambda_S^2\, v^2}{m_S} \frac{1}{(4\,m_S^2 - m_{H^0}^2)^2 + m_{H^0}^2\, \Gamma_{H^0}^2} \Gamma(\tilde{h} \to X_{SM})\,, \tag{13}$$

where $\Gamma(\tilde{h} \to X_{SM}) = \sum_i \Gamma(\tilde{h} \to X_{i\,SM})$ with virtual Higgs $\tilde{h}$ having mass $2\,m_S$ (see [46, 47]) and $v_r = \frac{2\,p_{CM}}{m_S}$ is the average relative speed of two zero mode scalars (see for example [48]). Here the effective coupling $\lambda_S$ model dependent and, for the case that the DM is the zero mode SM singlet $\phi_S$ which is accessible to a single extra dimension in the RS1 background, it reads

$$\lambda_S = \lambda_{5\,S}\, e^{-2\,k\,\pi\,R}\, f_0^2(\pi\,R)\,, \tag{14}$$

where $f_0(y)$ is given in eq.(4). In the case that the SM Higgs field is accessible to the fifth flat extra dimension and the DM candidate is the zero mode of the SM singlet, which is accessible to the sixth one, the total averaging annihilation rate of DM reads

$$< \sigma\, v_r > \;\; = \;\; \frac{4\,\lambda_S^2\, v^2}{m_S} \left| \frac{1}{(4\,m_S^2 - m_{H^0\,(0)}^2) + i\,m_{H^0\,(0)}\, \Gamma_{H^0\,(0)}} \right.$$
$$+ \;\; \sqrt{2} \sum_{n=1} \frac{1}{(4\,m_S^2 - m_{H^0\,(n)}^2) + i\,m_{H^0\,(n)}\, \Gamma_{H^0\,(n)}} \left. \right|^2 \Gamma(\tilde{h} \to X_{SM})\,, \tag{15}$$

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where $m^2_{H^0\,(n)} = m^2_{H^0\,(0)} + \frac{n^2}{R^2}$ and $\lambda_S$ is

$$\lambda_S = \frac{\lambda_{6\,S}}{(2\,\pi\,R)^2}\,. \tag{16}$$

If the DM candidate is the SM singlet, living in four dimensions, $\lambda_S$ becomes

$$\lambda_S = \frac{\lambda_{5\,S}}{2\,\pi\,R}\,, \tag{17}$$

and the annihilation cross section is given in eq.(15).

For the the annihilation cross section $< \sigma\,v_r >$ we respect the restriction

$$< \sigma\,v_r >= 0.8 \pm 0.1\,pb\,, \tag{18}$$

which is constructed in the case that s-wave annihilation is dominant (see [49] for details.). These bounds are coming from the relic density

$$\Omega\,h^2 = \frac{x_f\,10^{-11}\,GeV^{-2}}{< \sigma\,v_r >}\,, \tag{19}$$

where $x_f \sim 25$ [2, 22, 48, 50, 51] and, by the WMAP collaboration [40], the present DM abundance reads

$$\Omega\,h^2 = 0.111 \pm 0.018\,. \tag{20}$$

# Discussion

The present work is devoted to the analysis of the annihilation cross sections of some DM candidates and the couplings that drive these cross sections. Here we consider two scenarios. As a first one, we assume that all SM particles live on the 4 dimensional brane and there exists an additional scalar SM singlet $\phi_S$ which is accessible to a single extra dimension in the RS1 background. In this case the zero mode of the scalar singlet is a candidate of DM and it is localized in the extra dimension (see eq.(4)). The interaction term, which is represented by the action in eq.(5), is responsible for the existence of the vertex DM DM $H^0$ which appears after the elecroweak symmetry breaking. This term drives the annihilation cross section which should be compatible with the present observed DM relic density (eq.(20)) and the strength of the interaction is regulated by the the effective coupling $\lambda_S$ (eq.(14)). The free parameters in this scenario are the Higgs mass $m_{H^0}$, the zero mode scalar mass $m_S$, the curvature

$k$ and the parameter $a$ which plays an essential role in the localization of DM. In our numerical calculations we take Higgs mass around $110 - 120 \, GeV$, the DM candidate mass in the range of $10 - 80 \, GeV$ and we choose two different values for the curvature $k$, $k = 10^7 \, GeV$ and $k = 10^8 \, GeV$. Now we study the localization parameter $a$ dependence of the annihilation cross section $< \sigma v_r >$ and we estimate the range of $a$ by respecting the upper and lower bounds of the current experimental value of the relic abundance, namely $0.7 \, pb \leq < \sigma v_r > \leq 0.9 \, pb$.

In Figs.1 and 2 we plot the localization parameter $a$ dependence of the annihilation cross section $< \sigma v_r >$ for $m_{H^0} = 110 \, GeV$ and $m_{H^0} = 120 \, GeV$. Here the left-right solid (long dashed; dashed; dotted) line represents $< \sigma v_r >$ for $k = 10^{17} - 10^{18} \, GeV \; m_S = 80 \, (m_R; 50; 10) \, GeV$ where $m_R = 55(60) \, GeV$ for $m_{H^0} = 110 \, GeV$ ($m_{H^0} = 120 \, GeV$). We observe that the annihilation cross section strongly depends on the parameter $a$. The $0.5 \, \%$ variation in $a$ results in that $< \sigma v_r >$ changes between the estimated upper and lower bounds. If the mass of the scalar is $m_S = 55 \, GeV$ the resonant annihilation occurs and $a$ reaches the greatest value so that the increase in $< \sigma v_r >$ is appropriately suppressed in order to set it in the estimated range. For $m_S = 50 \, GeV \; a$ is still larger compared to ones for $m_S = 80 \, GeV$ and $m_S = 10 \, GeV$ since this is the case that the scalar mass is near to the resonant annihilation mass. For far from resonant annihilation, heavy scalar mass causes that the ratio in the definition of the annihilation cross section decreases and the parameter $a$ must increase to set the cross section in the region which is restricted by the experimental result (see the curves for $m_S = 80 \, GeV$ and $m_S = 10 \, GeV$). On the other hand the increase in the compactification radius $R$ results in suppression in the parameter $a$. For the SM Higgs mass $m_{H^0} = 120 \, GeV$ the behavior of the annihilation cross section $< \sigma v_r >$ is similar to the previous case. Here the curve for $m_S = 80 \, GeV$ lags the one for $m_S = 50 \, GeV$ since, in this case, the DM scalar with mass $m_S = 50 \, GeV$ is relatively far from the resonant annihilation.

As a second scenario we take the extra dimension(s) flat and, at first, we assume that the SM Higgs doublet and the additional SM model singlet scalar field are accessible to fifth and sixth extra dimension respectively. Here the zero mode of SM singlet is considered as the DM candidate. This is the case that the annihilation of the DM occurs with the help of the SM Higgs boson and its KK modes after the electroweak symmetry breaking (see eq.(10)). In this scenario we study the behavior of the coupling $\lambda_{6S}$ in six dimensions with respect to the compactification radius $R$, by respecting the current average value of the annihilation cross section, $< \sigma v_r >= 0.8 \, pb$. In the numerical calculations we take the compactification radius $R$ in the range $0.00001 \, GeV^{-1} \leq R \leq 0.005 \, GeV^{-1}$.

Fig.3 represents $R$ dependence of the coupling $\lambda_{6S}$ in six dimension for[4] $m_{H^0} = 110\,GeV$ and $m_{H^0} = 120\,GeV$. Here the upper-lower solid line represents $\lambda_{6S}$ for $m_{H^0} = 110 - 120\,GeV$ $m_S = 80\,GeV$ and the upper-lower long dashed (dashed; dotted) line represents $\lambda_{6S}$ for $m_{H^0} = 120 - 110\,GeV$ $m_S = 60 - 55\,(50; 10)\,GeV$. $\lambda_{6S}$ lies in the range of $10^{-10} - 10^{-6}\,GeV^{-2}$ for the interval of the compactification radius $10^{-5} - 10^{-3}\,GeV^{-1}$ for DM that is far from the resonant annihilation case. In the case of resonant annihilation, $\lambda_{6S}$ is suppressed and it is in the range of $10^{-14} - 10^{-10}\,GeV^{-2}$. $\lambda_{6S}$ is weakly sensitive to the SM Higgs mass for the interval under consideration, i.e. $110\,GeV \leq m_{H^0} \leq 120\,GeV$. It is observed that the coupling $\lambda_{6S}$ changes its behavior for the large values of $R$, $R > 0.004\,GeV^{-1}$, especially in the case that the mass of the DM scalar is far from the resonant annihilation. This variation comes from the readable effects of the intermediate SM Higgs KK modes for the compactification radius in this range. Notice that the Higgs KK mode contribution is suppressed with the decreasing values of the radius $R$.

As a second choice, we assume that the SM Higgs doublet is accessible to fifth extra dimension and the additional SM model singlet lives in four dimensions. Here we study the behavior of the coupling $\lambda_{5S}$ with respect to the compactification radius $R$, by respecting the current average value of the annihilation cross section, $< \sigma v_r > = 0.8\,pb$, similar to the previous case. In Fig.4 we show the $R$ dependence of the coupling $\lambda_{5S}$ for $m_{H^0} = 110\,GeV$ and $m_{H^0} = 120\,GeV$. Here the upper-lower solid line represents $\lambda_{5S}$ for $m_{H^0} = 110 - 120\,GeV$ $m_S = 80\,GeV$ and the upper-lower long dashed (dashed; dotted) line represents $\lambda_{5S}$ for $m_{H^0} = 120 - 110\,GeV$ $m_S = 60 - 55\,(50; 10)\,GeV$. $\lambda_{5S}$ is in the range of $10^{-6} - 10^{-3}\,GeV^{-1}$ for the interval of the radius $R$ $10^{-5} - 10^{-3}\,GeV^{-1}$ in the case that the DM mass is far from the resonant annihilation. If the resonant annihilation occurs $\lambda_{5S}$ decreases up to the range of $10^{-10} - 10^{-8}\,GeV^{-1}$. The effects of Higgs KK modes are observed if the mass of the DM scalar is far from the resonant annihilation and the radius $R$ is large, $R > 0.003\,GeV^{-1}$.

Finally, we plot the the effective coupling $\lambda_S$ for both choices in the second scenario in Fig 5. Here the upper-lower solid line represents $\lambda_S$ for $m_{H^0} = 110 - 120\,GeV$ $m_S = 80\,GeV$ and the upper-lower long dashed (dashed; dotted) line represents $\lambda_S$ for $m_{H^0} = 120 - 110\,GeV$ $m_S = 60 - 55\,(50; 10)\,GeV$. $\lambda_S$ is at the order of magnitude of $10^{-2} - 10^{-1}\,(10^{-6})$ far from (near to) the resonant annihilation. The effects of intermediate KK modes appear for $R > 0.002\,GeV^{-1}$ and these effects are negligible for the resonant annihilation case.

At this stage we would like to present our results

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[4]Notice that, in the following, we denote the zero mode $H^{0\,(0)}$ as $H^0$.

- In the first scenario, the annihilation cross section is strongly sensitive to the localization parameter $a$ and $a$ reaches its greatest value in the resonant annihilation case. The increase in curvature $k$ (or the decrease in the compactification radius $R$) forces $a$ to be suppressed.

- In the second scenario, we choose the extra dimension(s) flat and we assume that the SM Higgs doublet is accessible to fifth dimension. Here we consider two different possibilities. In the first we take the additional SM model singlet scalar field which is accessible to the sixth extra dimension and its zero mode is a possible DM candidate. In the second we consider that the new SM singlet, the DM candidate, lives in four dimensions. In both possibilities the KK modes of SM Higgs field play an observable role for large values of the compactification radius $R$, $R > 0.003\,GeV^{-1}$. On the other hand the dimensionfull couplings ($\lambda_{6S}$ for the first choice and $\lambda_{5S}$ for the second choice) are weak and the effective coupling $\lambda_S$, which is the same for both choices, is of the order of $10^{-2} - 10^{-1}$ ($10^{-6}$) far from (near to) the resonant annihilation.

The forthcoming more accurate experimental measurements and the possible observation of the SM Higgs boson at LHC will shed light on the nature of the DM and its annihilation mechanism.

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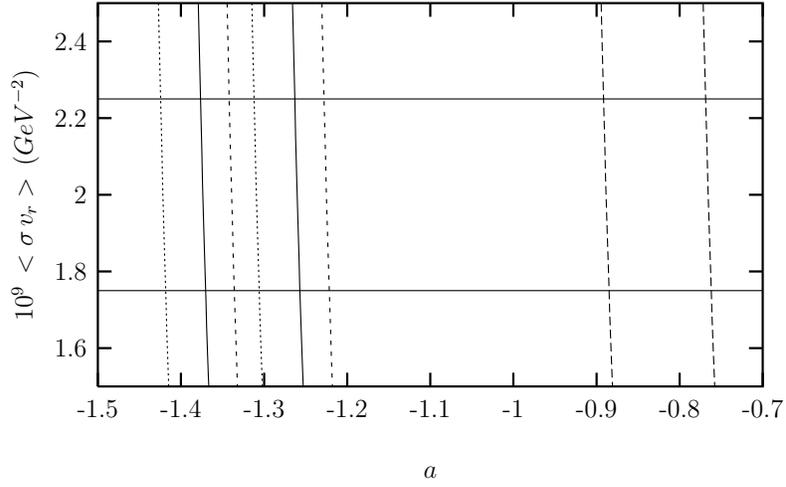
Figure 1: $<\sigma\,v_r>$ as a function of $a$ for $m_{H^0} = 110\,GeV$. Here the left-right solid (long dashed; dashed; dotted) line represents $<\sigma\,v_r>$ for $k = 10^{17} - 10^{18}\,GeV$ $m_S = 80\,(55; 50; 10)\,GeV$.
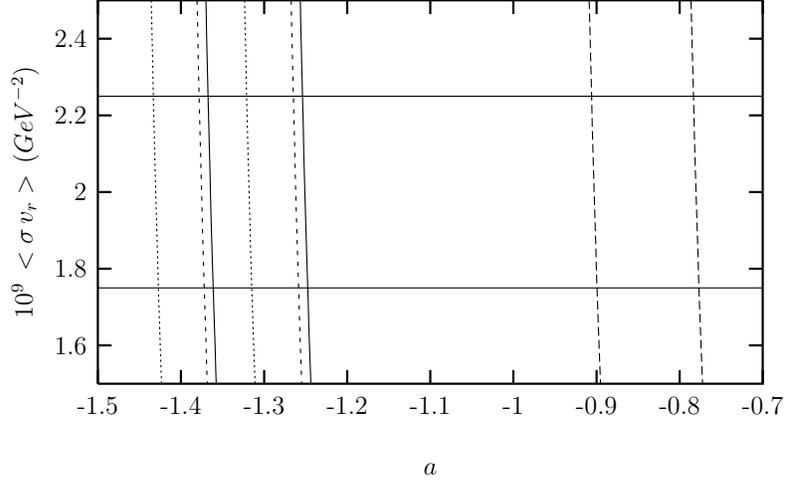
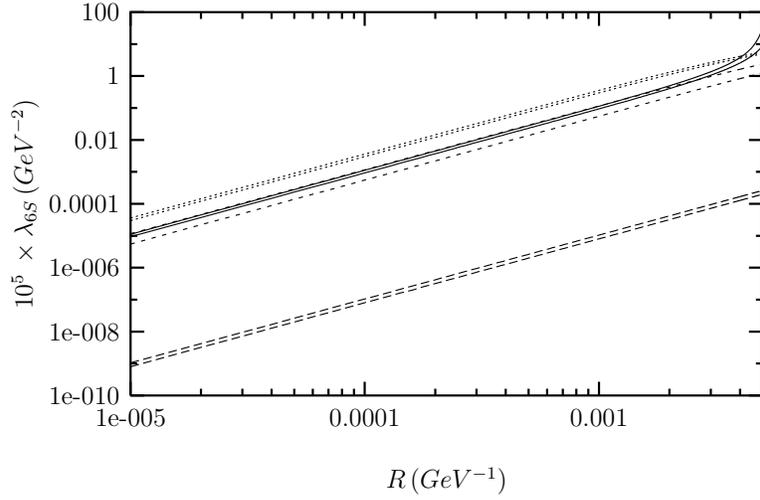Figure 2: The same as Fig1 but for $m_{H^0} = 120\,GeV$ and $m_S = 80\,(60; 50; 10)\,GeV$.



Figure 3: $\lambda_{6S}$ as a function of $R$. Here the upper-lower solid line represents $\lambda_{6S}$ for $m_{H^0} = 110 - 120\,GeV$ $m_S = 80\,GeV$ and the upper-lower long dashed (dashed; dotted) line represents $\lambda_{6S}$ for $m_{H^0} = 120 - 110\,GeV$ $m_S = 60 - 55\,(50; 10)\,GeV$.
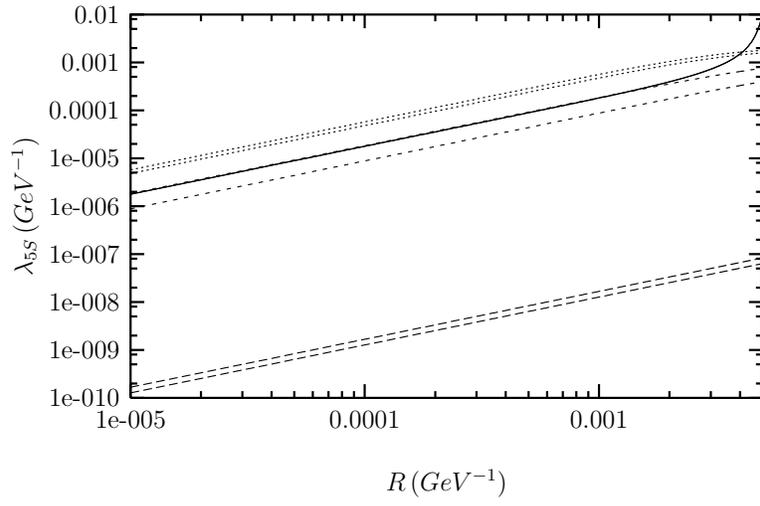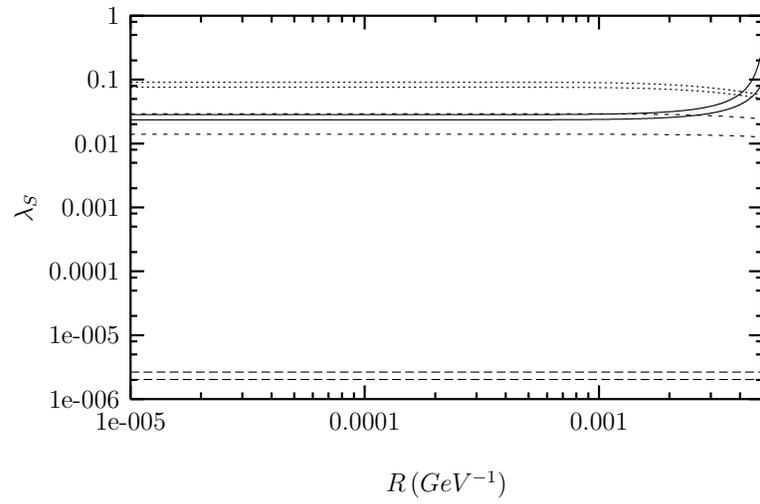
Figure 4: The same as Fig3 but for $\lambda_{5S}$.



Figure 5: The same as Fig3 but for $\lambda_S$.

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