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Higgs-radion phenomenology in stabilized RS models

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Abstract. An important general prediction of stabilized brane world models is the existence of a bulk scalar radion field, whose lowest Kaluza-Klein (KK) mode is the scalar particle called the radion. This field comes from the fluctuations of the metric in the extra dimension and the radion mass can be smaller than that of all the massive KK modes of the other particles propagating in the multidimensional bulk. Due to its origin, the radion and its KK tower couple to the trace of the energy-momentum tensor of the Standard Model. These fields have the same quantum numbers as the neutral Higgs field and can mix with the latter, if they are coupled. We present a short review of some aspects of Higgs-radion phenomenology in stabilized brane-world models. In particular, we discuss the possibility of explaining the 750 GeV excess by the production of a radion-dominated state.

1 Introduction to the model

The discovery of the 125 GeV scalar boson [1], rather accurate measurements of its mass [2], still not very precise but compatible with the Standard Model (SM) expectations for the Higgs boson measurements of its properties (see [3]), and the recent observation by the ATLAS and CMS experiments of the 750 GeV diphoton excess [4] attracted much attention to the scalar states predicted by various extensions of the SM. One of such SM extensions that naturally gives rise to extra scalar fields is the Randall-Sundrum model with two branes stabilized by a bulk scalar field [5, 6], which is necessary for the model to be phenomenologically acceptable.

A stabilized brane world model in five-dimensional space-time $E = M_4 \times S^1/Z_2$ with coordinates $\{x^M\} \equiv \{x^\mu, y\}$, $M = 0,1,2,3,4$, $\mu = 0,1,2,3$, the coordinate $x^4 \equiv y$, $-L \le y \le L$ parameterizing the fifth dimension, is defined by an action that is the sum of the action of five-dimensional gravity $g_{MN}(x,y)$ and the action of the stabilizing five-dimensional scalar field $\phi(x,y)$, which also includes potentials on the branes.

The space of extra dimension is the orbifold S^1/Z_2, which is realized as the circle of circumference $2L$ with the points y and $-y$ identified. Correspondingly, the metric g_{MN} and the scalar field ϕ satisfy the standard orbifold symmetry conditions. The branes are located at the fixed points of the orbifold, $y = 0$ and $y = L$, and it is assumed that the SM fields with Lagrangian L_{SM} live on the brane at $y = L$.

This action gives rise to a system of nonlinear differential equations for the metric and the scalar field, which has a background solutions with anti-de Sitter metric and the scalar field depending

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only on the coordinate of extra dimension. The background (vacuum) solution for the Higgs field is standard, all the other SM fields being equal to zero.

Suppose we have a solution for the background metric and the scalar field for an appropriate choice of the parameters of the potentials such that the interbrane distance is stabilized and equal to L. It means that the vacuum energy of the scalar field has a minimum for this value of the interbrane distance. Now the linearized theory is obtained by taking the fluctuations $h_{MN}(x, y)$ of the gravitational field and the fluctuations $f(x, y)$ the scalar field above this background [6].

There are three scalar fields in the linearized theory: the fields $f(x, y)$, $h_{44}(x, y)$ and $\gamma^{\mu\nu} h_{\mu\nu}(x, y)$. However, these fields are not independent, because they are connected by the equations of motion of the linearized theory and a gauge condition [6, 7]. For this reason we can use any one of them to describe the scalar states. Usually, similar to the case of the unstabilized Randall-Sundrum model, the field $h_{44}(x, y)$ is taken and expanded in KK modes, the lowest mode being called the radion field and the higher modes belonging to its KK tower. Thus, one can say that the radion field is the collection of the spin-0 degrees of freedom, coming from the scalar fluctuations of the metric in extra dimension and of the stabilizing scalar field [6, 7]. In a number of studies it was argued that the radion can be significantly lighter than all the other massive KK excitations [8, 9].

The phenomenology of the radion follows from a simple interaction Lagrangian, which is the product of the trace of the SM energy-momentum tensor and the radion field $r(x)$, divided by a dimensional scale parameter:

$$L_r = -\frac{r(x)}{\Lambda_r} T^\mu_\mu, \tag{1}$$

where the trace includes not only the kinetic terms, but also the interaction terms of the SM fields [10], as well as the terms corresponding to the conformal anomaly of massless gluon and photon fields. Thus, the radion couples to the massless photon and gluon fields via the well-known conformal anomaly in the trace of the energy momentum tensor since the radion also plays the role of the dilaton. When the massive SM fields, as supposed in most of the studies, are taken on the mass-shell, the radion interaction with them, at the lowest order in the SM couplings, is the same as that of the Higgs boson with the replacement of the radion scale by the Higgs vacuum expectation value. Thus, the interaction vertices of the radion with the SM fields are similar to those of the SM Higgs boson except for the anomaly enhanced interactions with gluons and photons. This leads to the corresponding relative enhancement in gluon and photon decay modes and the gluon-gluon fusion production channel of the radion. Various aspects of the decay and production properties of the radion have been touched upon in a number of studies, including a possible mixing of the radion with the Higgs boson, which is important for the radion and Higgs phenomenology [7, 11, 12].

However, if the massive SM fields are not on the mass shell, there appear additional terms in the radion interaction Lagrangian, which contribute, in particular, to the processes with tree level diagrams involving the radion and off-shell fermion lines. The extra terms in the Lagrangian lead to a momentum dependence in the vertices potentially giving additional contributions if virtual fermions participate in the process. For the main radion decay processes the fermions are on-shell and these additional terms in the vertices vanish, but this might not be the case for the radion production.

In the present short review we discuss various aspects of the Higgs-radion phenomenology. First we consider the phenomenology of the single radion production for the cases of on- and off-shell fermions, as well as the associated Higgs boson-radion production. Next we discuss the Higgs-radion mixing due to the merging of the mechanisms of spontaneous symmetry breaking on the brane and of the gravitational bulk stabilization and study the phenomenology of the Higgs-dominated and radion-dominated states arising due to this mixing. Based on these results, we discuss the possibility of explaining the 750 GeV excess by the production of a radion-dominated state.

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2 Single radion and associated Higgs boson-radion production

In all the main radion production processes, there are contributing Feynman diagrams involving off-shell fermions. The radion can be emitted from various fermion currents containing off-shell fermion propagators in various production processes in e^+e^- collisions, as well as in production processes in hadron collisions at the LHC. The off-shell fermions run in the fermion loops of the diagrams of the gluon-gluon fusion production process at the LHC and the gg, $\gamma\gamma$, γZ decay modes of the radion. In all these processes there are additional to the Higgs boson case non-trivial vertices (even for massless fermions) of fermion-radion interactions that follow from the structure of the trace of the gauge invariant SM energy-momentum tensor. One can show that all the contributions to the perturbative amplitudes of physical processes with a single radion are cancelled out due to the corresponding additional terms for both massless and massive off-shell fermions.

For a simple example, the radion production in association with Z boson in e^+e^- collisions, one can show that the matrix element squared is exactly equal to that for the Higgs boson with the replacement $\Lambda_r \to v$ and $m_r \to m_h$. Thus, all the additional contributions are cancelled out. The same property of the cancellation of additional to the Higgs-like contributions takes place for the associated radion and $W^{\pm}$ boson production, for example, $u\bar{d} \to rW^+$.

The property of the cancellation of all the contributions additional to the Higgs-like part also takes place in the case, where an arbitrary number, say N, of gauge bosons is emitted from the line of a massive fermion in association with the radion as shown in Fig. 1. One can show [10] that the sum of

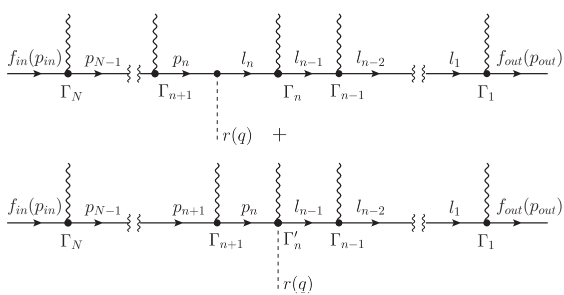

Figure 1. Fermion current radiating the radion and N SM vector gauge bosons in a three-point vertex (upper graph) and in a four-point vertex (lower graph).

all the contributions to the amplitude leads to only the Higgs-like type of the contribution and all the other parts are cancelled out explicitly.

This result can be easily generalized to the loop case. One can find more details in [10].

It turns out that the Higgs boson-radion similarity mentioned above takes place also in the processes of the associated Higgs boson-radion production, although in this case it is more complicated. Namely, it is shown that the perturbative amplitudes of the associated Higgs boson-radion production that do not include the anomalous vertices can be transformed into the corresponding amplitudes of the Higgs boson pair production by a replacement of the radion mass by the Higgs mass and the radion coupling constant by the Higgs field vacuum expectation value, as well as a rescaling of the triple Higgs vertex coupling [13].

In other words, the explicit amplitude of the associated Higgs boson-radion production process, which contains additional non-standard Feynman graphs and has a complicated structure of the vertices, can be obtained from the well studied result for the pair Higgs boson production by a simple rescaling of the parameters. This property follows from the structure of any massive fermion current emitting the radion and an arbitrary number of any SM gauge bosons. One can find in [13] simple examples of the associated Higgs boson-radion production in fermion-antifermion annihilation and in gluon fusion with only two bosons (*rh* or *hh*) in the final state demonstrating the explicit cancellation. One can show that a similar general property takes place in the case of the associated Higgs boson-radion production by considering a fermion current (or a fermion loop) with the emission of an arbitrary number of SM bosons with all possible permutations. A rigorous proof of this property can be found in paper [13].

3 Higgs-radion mixing and the phenomenology of Higgs-dominated and radion-dominated states

As we have already mentioned, the radion has the same quantum numbers as the neutral Higgs boson. The same is valid for the radion field and its excitations. Thus, these fields can mix with the Higgs field, if they are coupled.

A Higgs-radion coupling was first considered in the unstabilized Randall-Sundrum model by introducing a Higgs-curvature term on the brane that was done in [11]. Then such a coupling and the resulting Higgs-radion mixing in the case of the stabilized model were discussed in paper [7] without taking into account the KK tower of higher scalar excitations. The phenomenology of the Higgs-radion mixing originating from the Higgs-curvature term was also considered in view of the discovery of the Higgs-like boson at the LHC [1], various assumptions about the masses and the mixings of the scalar states having been analyzed in numerous papers. In particular, it was shown that the light radion-dominated state with mass below or above the observed 125 GeV boson is still not completely excluded by all the EW precision constrains and the LHC data.

Below we consider a model, where a Higgs-radion coupling naturally arises due to a mechanism of spontaneous symmetry breaking on the brane involving the stabilizing scalar field. This approach takes into account the influence of the KK tower of higher scalar excitations on the parameters of the Higgs-radion mixing, which turns out to be of importance. It also has the advantage that it modifies only the scalar sector of the model and leaves intact the masses and the coupling constants of the graviton KK excitations.

In brane-world models, the vacuum solution for gravity and the stabilizing scalar field and the vacuum solution for the SM fields are independent. If we consider a brane world model to be an indivisible theory, it is reasonable to believe that there should be a common interconnected vacuum solution for all these fields. To this end we modify the action of the model so that it contains a quartic interaction of the stabilizing scalar field and of the Higgs field, which would connect the stabilization of the extra dimension size and the SM spontaneous symmetry breaking. This can be achieved by replacing the SM Higgs potential by the interaction Lagrangian

$$L_{int}(\phi, H) = -\lambda\left(|H|^2 - \frac{\xi}{M}\phi^2\right)^2, \tag{2}$$

M denoting the fundamental energy scale and ξ being a positive dimensionless parameter. The equations for the background configuration following from such a modified action give a relation between the vacuum value of the Higgs field and the value of the field ϕ on the brane at $y = L$

$$\phi^2(L) = \frac{Mv^2}{2\xi}. \tag{3}$$

This means that in such a scenario the Higgs field vacuum expectation value, being proportional to the value of the stabilizing scalar field on the TeV brane, arises dynamically as a result of the gravitational bulk stabilization.

In this scenario, the linearized theory is obtained by expanding the metric and the scalar field in the standard way and the Higgs field in the unitary gauge about the background solution as

$$H(x) = \begin{pmatrix} 0 \\ \frac{v+\sigma(x)}{\sqrt{2}} \end{pmatrix}. \tag{4}$$

After substituting this representation into the action of the model and keeping the terms of the second order in h_{MN}, f and σ one gets the Lagrangian of this action which is the standard free Lagrangian of the SM (i.e. the masses of all the SM fields are expressed in the same way as usually in terms of the vacuum value of the Higgs field and the coupling constants) together with the standard second variation Lagrangian of the stabilized RS model [6] supplemented by an interaction term of the scalar fields f and σ on the brane coming from interaction Lagrangian (2) [14].

Besides the fields f and σ, there two more scalar fields in the linearized theory, – the fields $h_{44}(x, y)$ and $\gamma^{\mu\nu}h_{\mu\nu}(x, y)$. As we have already mentioned in the Introduction, the fields $f(x, y)$, $h_{44}(x, y)$ and $\gamma^{\mu\nu}h_{\mu\nu}(x, y)$ are not independent and are connected by the equations of motion of the linearized theory and a gauge condition [6, 7].

The field $h_{44}(x, y)$ can be expanded in KK modes, which induces the corresponding expansion of the bulk scalar field $f(x, y)$. Substituting the latter expansion into the second variation Lagrangian and integrating over the extra dimension coordinate, one gets an effective four-dimensional Lagrangian. In case the Higgs and the radion masses are much smaller than the masses of the radion excitations one can pass to a low energy approximation in the four-dimensional Lagrangian by integrating out the radion excitation fields. This gives an effective Lagrangian for the interaction of the Higgs field $\sigma(x)$ and the radion field, which we will denote here $\phi_1(x)$, with the SM fields. However, due to the Higgs-radion mixing terms the fields $\sigma(x)$ and $\phi_1(x)$ are not mass eigenstates.

The physical mass eigenstate fields $h(x)$, $r(x)$ are, as usually, obtained by a rotation diagonalizing the mass matrix

$$\begin{aligned} h(x) &= \cos\theta\,\sigma(x) + \sin\theta\,\phi_1(x) \\ r(x) &= -\sin\theta\,\sigma(x) + \cos\theta\,\phi_1(x). \end{aligned} \tag{5}$$

The field $h(x)$ is called the Higgs-dominated field and the field $r(x)$ is called the radion-dominated field. Finally, one gets the effective interaction Lagrangian of the physical scalar fields $h(x)$ and $r(x)$ with the Standard Model fields in the following form [14]:

$$\begin{aligned} L_{h-r} &= \frac{1}{2}\partial_\mu h(x)\partial^\mu h(x) - \frac{1}{2}m_h^2 h^2(x) + \frac{1}{2}\partial_\mu r(x)\partial^\mu r(x) - \frac{1}{2}\mu_r^2 r^2(x) \\ &- \frac{(c\cos\theta + \sin\theta)}{\Lambda_r} h(x)(T^\mu_\mu + \Delta T^\mu_\mu) + \frac{(c\sin\theta - \cos\theta)}{\Lambda_r} r(x)(T^\mu_\mu + \Delta T^\mu_\mu) - \\ &- \sum_f \frac{m_f}{v}\bar{\psi}_f\psi_f(\cos\theta\, h(x) - \sin\theta\, r(x)) + \frac{2M_W^2}{v}(W^-_\mu W^{\mu+})(\cos\theta\, h(x) - \sin\theta\, r(x)) + \\ &+ \frac{M_Z^2}{v}(Z_\mu Z^\mu)(\cos\theta\, h(x) - \sin\theta\, r(x)) + \frac{M_W^2}{v^2}(W^-_\mu W^{\mu+})(\cos\theta\, h(x) - \sin\theta\, r(x))^2 + \\ &+ \frac{M_Z^2}{2v^2}(Z_\mu Z^\mu)(\cos\theta\, h(x) - \sin\theta\, r(x))^2. \end{aligned} \tag{6}$$

The effective four-dimensional interaction Lagrangian (6) expressed in terms of the physical Higgs-dominated $h(x)$ and radion-dominated $r(x)$ fields contains their interactions with the SM fields

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and involves only five parameters in addition to those of the SM: the masses of the Higgs-dominated and radion-dominated fields m_h and m_r, the mixing angle θ, the (inverse) coupling constant of the radion to the trace of the energy-momentum tensor of the SM fields Λ_r and the parameter c that accommodates the contributions of the integrated out heavy scalar modes and is constrained by the other parameters as follows: $0 < c < c_{max} = \frac{(m_r^2 - m_h^2)\sin 2\theta}{m_r^2 \cos^2\theta + m_h^2 \sin^2\theta}$.

There are two possible scenarios, where the observed 125 GeV boson is either a Higgs-dominated state or a radion-dominated state. A detailed statistical analysis carried out in paper [14] shows that the Higgs-dominated state is the strongly preferred scenario.

4 A radion-dominated state as an explanation of the 750 GeV excess

The statistical analysis admits the existence of a heavy radion-dominated state with mass 750 GeV. In order to understand whether the 750 GeV observed excess can be interpreted as a radion-dominated state let us consider the main decay and production properties of such a state that follow from effective Lagrangian.

Practically for all the values of the mixing parameter $\sin\theta$ the branching ratios are distributed between the modes close to those for the SM Higgs boson, if it had had mass 750 GeV. The NLO corrections are included following the HDECAY code [15]. The dominating decay modes are the decays to heavy SM particles W^+W^-, ZZ boson pairs and the top quark pair. However, for some rather small values of the parameter $\sin\theta$ close to approximately v/Λ_r all the branching ratios are significantly decreased, and the dominating decay mode becomes the mode to two gluons. Also in this region of the parameter space the branching to two photons is significantly increased. Such a property could be easily understood from the structure of the interaction vertices of the radion-dominated state and the SM fermions and gauge bosons (see the Feynman rules in [14]). Indeed all the vertices for the fermions and massive gauge bosons contain the factor $\frac{\cos\theta - c\cdot\sin\theta}{\Lambda_r} - \frac{\sin\theta}{v}$, which becomes very small for $\sin\theta$ close to v/Λ_r. This occurs due to the cancellation of the contributions to the vertices coming from the SM type part of the interactions and the part coming from the trace of the energy-momentum tensor. In contrast, the interaction vertices of the radion-dominated state and the massless gluons and photons have anomaly enhanced contributions and the mentioned cancellation does not take place for small values of the parameter $\sin\theta$ close to v/Λ_r. The corresponding cancellation occurs for the gluon-gluon and photon-photon vertices at much larger values of the parameter $\sin\theta$.

A crucial point for the possible interpretation is the production cross section, which should be in the range from a few to 10 fb. The production cross section for the radion-dominated state has been calculated including the contributions of all the production channels for the radion-dominated state (ggF, VBF, rV, rtt) with the decay to two photons. We have also included the NNLO K-factors taken from the Higgs cross section working group web page [16, 17]. It turned out that, as expected, the gluon-gluon fusion dominates the production cross section in the most interesting region of the parameter space, where the cross section has a maximum. The maximum occurs for the same values of parameters, for which the corresponding gg and $\gamma\gamma$ decay branching ratios have the maximum. As for the branching ratios in the range close to the maximum, the cross section depends very weakly on the the parameter c.

One should note that the parameter region allowed by the signal strength measurements for 125 GeV boson at 8 TeV and 13 TeV LHC energy and presented in Fig. 2 includes the above mentioned region, where the two-photon cross section has a maximum.

However, the interpretation of the observed excess as the radion-dominated state is very problematic or even impossible in the simplest variant of the discussed brane-world models, where only the gravitational degrees of freedom are allowed to propagate in the bulk. Indeed, on can show that the

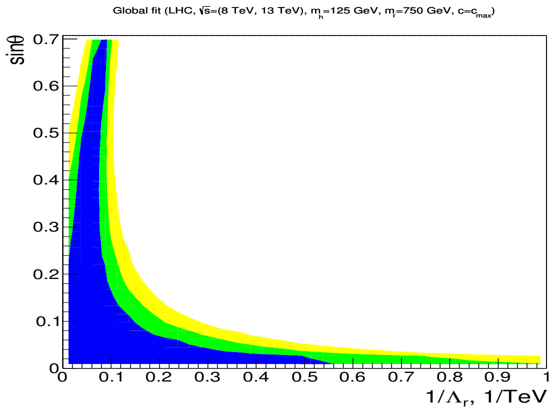

Figure 2. Exclusion contours for the global χ^2 fit in the $(\sin\theta, 1/\Lambda_r)$ plane for the LHC at $\sqrt{s}$ =8 and 13 TeV and m_h=125 GeV, m_r=750 GeV, $c = c_{max}$. The dark, medium and light shaded areas correspond to CL of the fit 65%, 90% and 99% respectively.

cross section has a maximum of about 0.14 fb, which is by a factor of 50 ÷ 100 smaller than what is needed to achieve the observed level of the cross section for the 750 GeV excess. One can easily check that in the other areas of the parameter space the production cross section gets even smaller.

Thus, one has to conclude that in the simplest variant of the model under consideration, where only the gravitational and stabilizing scalar fields propagate in the bulk, the observed excess cannot be understood as a radion-dominated resonance. More details are given in [18].

In order to increase the two-photon signal rate some other heavy particles should propagate in the gluon-gluon-scalar and photon-photon-scalar loop vertices, the scalar in our case being the Higgs-dominated or the radion-dominated states. Such heavy particles in brane-world models could be the excited KK states of those SM fields, which are also allowed to propagate in the multidimensional bulk. However, the calculation of the contributions of the excited states in stabilized brane-world models is not straightforward: the energy-momentum tensor of an excited state of the bulk fields has a component corresponding to the extra dimension, to which the radion couples two times stronger than to the trace of the four-dimensional components [12, 19] thus modifying the overall coupling to the excited state. Moreover, the radion couplings to the energy-momentum tensors of the excited states depend on the radion wave function in the extra dimension as well as on the wave functions of the excited states, which are model dependent. The same problem with the wave functions arises, if one considers the coupling of the bulk Higgs field to the excited states. Thus, taking into account the contributions of the excited KK states of the bulk fields is a complicated problem that needs a special thorough investigation.

5 Conclusion

In this short review we have presented the results of a systematic study of the radion in stabilized brane-world models. We have shown that, despite the differences in the Higgs boson and radion couplings to off-shell fermions, there is a Higgs boson-radion similarity in the processes involving off-shell fermions and an arbitrary number of gauge bosons that is present at the tree and loop levels.

We have also discussed a new mechanism of Higgs-radion mixing immanent in stabilized brane-world models and based on unifying the spontaneous symmetry breaking on the brane and the gravitational stabilization of the extra dimension size. In the framework of this approach, we have derived the corresponding effective Lagrangian of the interaction of the Higgs-dominated and radion-dominated states that includes a cumulative effect of higher excited scalar states. For special values of the model parameters, it reproduces a number of SM extensions by a singlet scalar boson.

We have shown that the interpretation of the 125 GeV scalar state as the Higgs-dominated state is strongly preferred. However, a rather wide range of the parameter space for the radion-dominated state is allowed by the present data, the allowed regions somewhat growing with the growth of the radion (inverse) coupling constant Λ_r.

We have also studied the possibility of interpreting the 750 GeV excess as a radion-dominated state in stabilized brane-world models and found out that the radion-dominated state mass of 750 GeV is allowed by the 125 Higgs signal strength measurements. But the production cross section of this state is too small to explain the LHC 750 GeV excess.

Acknowledgements

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References

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) ,
S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012)

[2] G. Aad *et al.* [ATLAS and CMS Collaborations], Phys. Rev. Lett. **114**, 191803 (2015)

[3] G. Aad *et al.* [ATLAS and CMS Collaborations], arXiv:1606.02266 [hep-ex]

[4] G. Aad *et al.* [ATLAS Collaboration], *Search for high-mass diphoton resonances in pp collisions at* $\sqrt{s} = 13TeV$ *with the ATLAS detector*, ATLAS-CONF-2015-081,
S. Chatrchyan *et al.* [CMS Collaboration], *Search for High-Mass Diphoton Resonances in pp Collisions at* $\sqrt{s} = 13TeV$ *with the CMS Detector*, CMS PAS EXO-15-004

[5] W. D. Goldberger and M. B. Wise, Phys. Rev. Lett. **83**, 4922 (1999)

[6] E. E. Boos, Y. S. Mikhailov, M. N. Smolyakov and I. P. Volobuev, Mod. Phys. Lett. A **21**, 1431 (2006)

[7] C. Csaki, M. L. Graesser and G. D. Kribs, Phys. Rev. D **63**, 065002 (2001)

[8] C. Csaki, M. Graesser, L. Randall and J. Terning, Phys. Rev. D **62**, 045015 (2000)

[9] C. Charmousis, R. Gregory and V. A. Rubakov, Phys. Rev. D **62**, 067505 (2000)

[10] E. Boos, S. Keizerov, E. Rakhmetov, K. Svirina, Phys. Rev. D **90**, 095026 (2014)

[11] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B **595**, 250 (2001)

[12] C. Csaki, J. Hubisz and S. J. Lee, Phys. Rev. D **76**, 125015 (2007)

[13] E. Boos, S. Keizerov, E. Rakhmetov and K. Svirina, arXiv:1604.00998 [hep-ph]

[14] E. E. Boos, V. E. Bunichev, M. A. Perfilov, M. N. Smolyakov and I. P. Volobuev, Phys. Rev. D **92**, 095010 (2015)

[15] A. Djouadi, J. Kalinowski and M. Spira, Comput.Phys.Commun, **108**, 56 (1998)

[16] S. Dittmaier *et al.* [LHC Higgs Cross Section Working Group Collaboration], arXiv:1101.0593

[17] S. Heinemeyer *et al.* [LHC Higgs Cross Section Working Group Collaboration], arXiv:1307.1347

[18] E. E. Boos, V. E. Bunichev and I. P. Volobuev, arXiv:1603.04495 [hep-ph].

[19] T. G. Rizzo, JHEP **0206**, 056 (2002)