EPJ Web of Conferences **191**, 02007 (2018) https://doi.org/10.1051/epjconf/201819102007
QUARKS-2018

Restrictions on the mass of the KK excitation W' from the Higgs boson diphoton decay and the single top production.

Alexey Baskakov[1,*], *Eduard* Boos[1,2,**], *Viacheslav* Bunichev[1], *Maxim* Perfilov[1], and *Igor* Volobuev[1,***]

[1]Skobeltsyn Institute of Nuclear Physics M.V. Lomonosov Moscow State University, Moscow 119991, Russian Federation

[2]Faculty of Physics M.V.Lomonosov Moscow State University Leninskie Gory, Moscow 119991, Russian Federation

Abstract. In the framework of stabilized brane-world models we consider the contribution of the W' boson and the rest of the W boson KK tower to the Higgs boson decay to two photons and to the single top production process. Comparing the signal strengths calculated in this approach with the experimental ones obtained at the LHC and taking into account the expected improvements at future high luminosity HL-LHC, high energy HE-LHC, and FCC-hh projects, we get predictions for the limits on the W' boson mass depending on its coupling to SM fermions.

1 Introduction

The existence of heavy excitations of the Standard Model (SM) gauge bosons is predicted by many theories beyond the SM [1, 2]. In particular, such excitations arise in theories with universal extra dimensions (UED), where some (or all) Standard Model fields can propagate in the bulk of five-dimensional brane-wold models [3, 4]. The lowest KK excitation of the W boson that arises in such theories and will be studied in the present paper is usually called the W' boson.

Here we will consider the scenario, where only gauge fields propagate in the bulk of a stabilized brane-world model [5–7], the distance between the branes is stabilized by a bulk scalar field and a warped bulk metric is, in general, different from that of the Randall-Sundrum model [8]. This assumption looks quite natural, because there is no mechanism for trapping gauge fields on the brane, whereas such a mechanism is well known for fermion fields [9, 10].

Unlike the UED models with the flat bulk [3], stabilized brane-world models give rise to different wave functions for the fields of different tensor type and, for this reason, do not necessarily lead to the KK number conservation. Therefore, a production of single KK states is possible in such a scenario. However, FCNC currents, which are strongly suppressed by the present-day experimental data, do not appear in this case since the neutral currents have the same diagonal structure as in the SM.

*e-mail: a.baskakov@cern.ch
**e-mail: boos@theory.sinp.msu.ru
***e-mail: volobuev@theory.sinp.msu.ru

In the case, where only the SM gauge fields propagate in the Randall-Sundrum bulk, the masses of the KK excitations of the SM gauge bosons have to be larger than 20 TeV in order not to contradict the EW precision data [11]. Such heavy states are obviously out of the reach of the 14 TeV LHC and could be a subject of interest only at future colliders such as FCC 100 TeV Hadron Collider. However,in the stabilized brane-world models, where the warp factor is different from the exponential of a linear function, as it is in the Randall-Sundrum model, the couplings of KK modes to the SM fields can be significantly different from those in the Randall-Sundrum model and, as a result, lighter KK excitations of the SM fields may be allowed [7, 12]. One more possibility is to incorporate various custodial symmetries into the theory in such a way that a few TeV mass scale for the KK gauge bosons would be consistent with both electroweak and flavor precision tests [13].

The excitations of the W boson can contribute to various processes with the Standard Model particles. In particular, in paper [15] the contributions of the W boson KK tower to the single top and muon production processes have been studied. The W boson excitations can also contribute to the diphoton decay of the Higgs boson via the triangle diagrams. The latter is of importance, because the ever growing precision of the measurements by the ATLAS and CMS allows one to use this decay for analyzing finer deviations from the SM predictions and can give new stronger bounds on the W' boson mass.

It turns out that, if only the SM gauge bosons can propagate in the bulk of a stabilized brane-world model, there is a strong correlation between the contributions of the W boson KK tower to these processes, which could give more stringent bounds on the W' boson mass, than obtained only from the scattering processes. In the present paper this possibility will be studied in more detail.

2 Diphoton decay of the Higgs boson

First let us recall the main facts about the decay of the Higgs boson to two photons. It is convenient to represent the amplitude of this process as [16]

$$M(h \to \gamma\gamma) = A\frac{\alpha}{4\pi v}(k_{1\mu}\epsilon_{1\nu} - k_{1\nu}\epsilon_{1\mu})(k_2^{\mu}\epsilon_2^{\nu} - k_2^{\nu}\epsilon_2^{\mu}), \tag{1}$$

where α is the fine structure constant, v is the Higgs field vacuum expectation value, k_1, k_2 and ϵ_1, ϵ_2 are the 4-momenta and the polarization vectors of the photons. The width of the decay $h \to \gamma\gamma$ is given in terms of the dimensionless amplitude A by

$$\Gamma(h \to \gamma\gamma) = \left(\frac{\alpha}{4\pi}\right)^2 \frac{G_F m_h^3}{8\pi\sqrt{2}}|A|^2. \tag{2}$$

The amplitude A, when calculated perturbatively in the SM, depends only on the ratios of the Higgs and loop particle masses and in the lowest order looks like

$$A_{SM} = \frac{4}{3}A_{\frac{1}{2}}(\tau_t) + A_1(\tau_W), \tag{3}$$

where only the dominant contributions of the t-quark and W boson are taken into account, $\tau_i = m_h^2/(4m_i^2)$, and $A_{\frac{1}{2}}$, A_1 are the standard functions for the loop contributions of spin $1/2$ and spin 1 particles [17]. The t-quark contribution $A_{\frac{1}{2}}(\tau_t)$ is real and positive, whereas the W-boson contribution $A_1(\tau_W)$ is real and negative and its absolute value is essentially larger than $(4/3)A_{\frac{1}{2}}(\tau_t)$. Thus, the amplitude A_{SM} is negative. There are also QCD and electroweak corrections to this amplitude that amount to approximately 2% [18] and will be taken into account in our numerical calculations.

In accordance with paper [19], the coupling of the W boson bulk field to the brane Higgs field $h(x)$ can be represented as

$$\frac{2m_W^2}{v\chi_0^2}\left(W^-_\mu(x,L)W^{+\mu}(x,L)\right)h(x), \tag{4}$$

where $W^\pm_\mu(x,L)$ is the value of the W boson bulk field on the TeV brane at $y = L$ and χ_0 is the (constant) wave function in the extra dimension of its zero mode, the SM W boson field.

The expansion of the W boson bulk field in the KK modes has the form

$$W^-_\mu(x,y) = W^-_\mu(x)\chi_0 + \sum_{n=1}^{\infty} W^-_{n\mu}(x)\chi_n(y), \tag{5}$$

where $\chi_i(y)$ denote the wave functions of the modes and the first excitation W_1 should be identified with the W' boson. Then the coupling of the mode $W^-_{n\mu}(x)$ to the Higgs field can be written as

$$\frac{2m_W^2\alpha_n^2}{v}\left(W^-_{n\mu}(x)W^{+\mu}_n(x)\right)h(x) \equiv \alpha_n^2\,\frac{m_W^2}{m_{W_n}^2}\,\frac{2m_{W_n}^2}{v}\left(W^-_{n\mu}(x)W^{+\mu}_n(x)\right)h(x), \tag{6}$$

where $\alpha_n = \chi_n(L)/\chi_0$ is the ratio of the wave functions of the nth and zeroth modes on the brane. Using the latter form of the coupling one can easily find the contribution of the W_n boson to the Higgs decay to two photons, which turns out to be

$$\alpha_n^2\frac{m_W^2}{m_{W_n}^2}A_1(\tau_{W_n}) \simeq -7m_W^2\frac{\alpha_n^2}{m_{W_n}^2}, \tag{7}$$

where we have used the approximate value of the function A_1 for $\tau_{W_n} \to 0$. Thus, the contribution of all the KK tower of the W boson to this decay is given by

$$\Delta A = -7m_W^2\sum_{n=1}^{\infty}\frac{\alpha_n^2}{m_{W_n}^2}. \tag{8}$$

Now we note that the sum in formula (8) is exactly the sum that enters the contribution of the W boson KK tower to low-energy processes with charged currents, when the center of mass energy or momentum transfer are much smaller than the masses of the KK modes and can be dropped from the propagators of the W boson KK modes. This means that there should be a correlation between the contributions of the W-boson KK tower to the Higgs boson decay to two photons and to the single top production process, which can lead to restrictions on the W' boson mass.

A remark is in order here. The coupling in formula (4) mixes the KK modes and should be diagonalized. In paper [19] it was shown that the corrections to the particle masses due to this interaction alter them as follows:

$$m_W \to m_W\left(1+\beta_0\frac{m_W^2}{M^2}\right), \quad m_{W_n} \to m_{W_n}\left(1+\beta_n\frac{m_W^2}{m_{W_n}^2}\right), \tag{9}$$

where M is the fundamental five-dimensional energy scale and the dimensionless parameters β_i are of the order of unity. The corrections to the values of the wave functions on the brane can also be estimated and turn out to be of the same order. Thus, these corrections give a negligible contribution to the amplitude ΔA in formula (8) and can be dropped.

3 Single top quark production in s-channel

The experiments on single top production processes can give a restriction on the the W' boson mass from below. In fact, the range of the W' boson masses that are not experimentally excluded starts from approximately 4 TeV [14]. For this reason, when analyzing the contribution of the W boson KK tower to the single top production processes, we will have to take into account the propagator of the W' boson exactly, i.e. without neglecting the center of mass energy in the denominator, whereas the contribution of the rest of the KK tower will be modeled by a contact interaction. Then the effective interaction Lagrangian of the W boson KK tower in the energy range close to the mass of the W' boson can be written as

$$L_{eff\_W\_KK} = \frac{g\,\alpha_1}{\sqrt{2}}(J^{+\mu}W'^{-}_{\mu} + J^{-\mu}W'^{+}_{\mu}) - \frac{g^2\alpha_1^2}{2m^2_{W'\_sum}}J^{+\mu}J^{-}_{\mu}, \qquad (10)$$

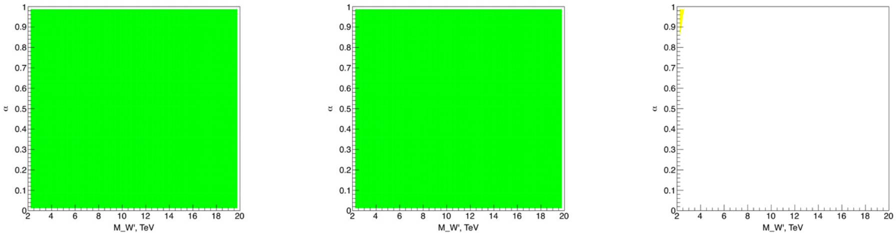
where g is the weak coupling constant, α_1 is the ratio of the wave functions of W' and W on the brane, $J^{\pm\mu}$ is the weak charged current and $m_{W'\_sum}$ is the mass parameter taking into account the contribution of the KK tower above W' [15]. The contact term in Lagrangian (10) is, in fact, Fermi's interaction with the coupling constant $g^2\alpha_1^2/(2m^2_{W'\_sum})$. Explicit calculations in UED models with flat extra dimension and in certain stabilized brane-world models show that this mass is just a little larger than that of the W' boson. In the present paper we will take the value $1.4\,m_{W'}$ for the effective mass of the KK tower above W' that was also used in [15, 20].

4 Phenomenological analysis

The results of the LHC Run 1 for the Higgs boson decay to two photons by the ATLAS and CMS collaborations [21–23] have shown that the signal strength of this process is definitely larger than unity $\mu^{\gamma\gamma}_{Run-1} = 1.14^{+0.27}_{-0.25}$ and $\mu^{\gamma\gamma}_{Run-1} = 1.11^{+0.25}_{-0.23}$. The LHC Run 2 results do not confirm this deviation to the full extent and are $\mu^{\gamma\gamma}_{Run-2} = 0.99^{+0.28}_{-0.26}$ [24] and $\mu^{\gamma\gamma}_{Run-2} = 1.18^{+0.17}_{-0.14}$ [25] by the ATLAS and CMS correspondingly. Nevertheless, at present all the measurements are in accord with the SM predictions due to the uncertainties.

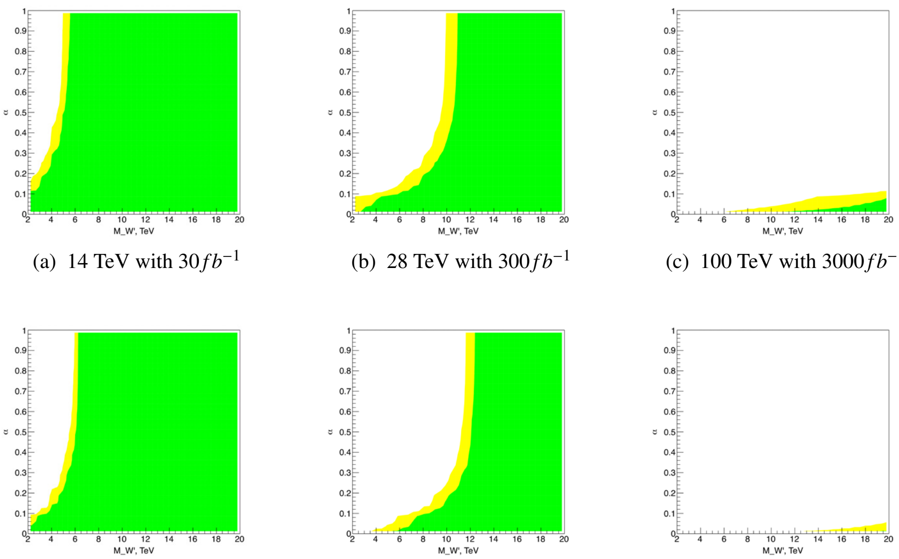
However, if the deviation from the SM is confirmed by further experiments, we may ask a question, whether it is possible to explain the deviations from unity of $\mu^{\gamma\gamma}$ in the framework of the model discussed in section 2? As we have noted above, the SM amplitude of the Higgs boson decay to two photons is negative due to the domination of the W-boson contribution. Therefore, the contribution of the W-boson excitations given by formula (8), which is also negative, will increase the absolute value of the amplitude and lead to an increase of the signal strength. On the other hand the contribution of W' (10) leads to an increase in the production cross section of the single top in s-channel. We give estimates of the experimental accuracies needed to improve the restrictions on the W' mass and discuss the prospects of using the combination of these channels.

The available experimental precision does not allow one to put significant limitations on the mass of the W' boson from diphoton decay of the Higgs boson. In this work we make a scan over $M_{W'}$ in the range from 2 to 20 TeV and over the W' coupling constant α_1 from 0 to 1. Using the standard χ^2 analysis and Eq. 2 and Eq. 8 we obtain possible restrictions on $M_{W'}$ and the coupling constant assuming the experimental value to be $\mu^{\gamma\gamma} = 1.1$ with 10%, 5% and 1% accuracy as shown in Fig. 1. We see that 10% and 5% uncertainties do not allow one to put any significant constraints, while a higher precision excludes practically all the parameter values. A similar situation takes place for other prospective signal strength values. It is so because larger W' masses give a smaller deviation from the SM predictions and



(a) 10% uncertainty (b) 5% uncertainty (c) 1% uncertainty

Figure 1: Restrictions on the $M_{W'}$ and coupling constant from Higgs boson diphoton decay for $\mu^{\gamma\gamma} = 1.1$ with 10%, 5% and 1% precision. Green and yellow areas correspond to the exclusion contours at 68% and 95% CL.



(a) 14 TeV with $30 fb^{-1}$ (b) 28 TeV with $300 fb^{-1}$ (c) 100 TeV with $3000 fb^{-1}$

(d) 14 TeV with $300 fb^{-1}$ (e) 28 TeV with $3000 fb^{-1}$ (f) 100 TeV with $15000 fb^{-1}$

Figure 2: Restrictions on the $M_{W'}$ and coupling constant from single top production for collision energy 14, 28 and 100 TeV with corresponding expected integrated luminocities.

in this parameter range it comes out that the significant signal strength deviation from unity measured with high precision cannot be explained within the discussed model, whereas lower precision or smaller deviation from the SM value of $\mu^{\gamma\gamma}$ allow all the parameter values without any restrictions. This fact makes this channel to work as a trigger, completely excluding W' mass in the range from 2 to 20 TeV in the case of a substantial deviation from the SM with high precision or allowing any mass in the case of a small deviation or a low precision.

The CompHEP generator [26] with MSTW2008 PDF [27] has been used for the calculation of the single top s-channel production. The SM cross section is obtained as a sum of s-channel $pp \to t\bar{b}$ and t-channel $pp \to tq\bar{b}$ processes with an additional cut on the light quark

$p_{T_q} < 40GeV$ Eq. 11. The second process allows one to take into account the situation, where t-channel is recognized as s-channel because of the experimental resolution, which does not allow one to register soft quark jets.

$$\sigma_{SM} = \sigma_{t\bar{b}} + \sigma_{tq\bar{b}}(p_{T_q} < 40GeV) \tag{11}$$

The deviation from the SM is tested in the fiducial volume around $M_{W'}$ in $100GeV$ interval, W' width changing with its mass and the coupling being taken into account. The estimated restrictions are presented in Fig. 2. The estimated limitations from Fig. 2 (a) when $\alpha(W') = 1$ are in a good agreement with the recent experimental measurement 4.4 TeV [14]. An increase in the collected data with HL-LHC to 300 fb^{-1} will allow one to improve the limits to 6 TeV, if no deviations from the SM are found. The energy upgrade to 28 TeV will enhance the limits to $9-11$ TeV and the 100 TeV data will be able to finally restrict the W' mass.

5 Results

Within the framework of stabilized brane-world models, the process of the Higgs boson decay to two photons and the single top s-channel production are considered with taking into account the contribution of the W' boson and the rest of the W boson KK tower. The impact of these contributions has been estimated for theW' mass range from 2 to 20 TeV and for the factor α_1 in the W' interaction coupling to the SM fermions from 0 to 1.

The present day experimental data do not allow one to obtain any constraints on the W' mass from the diphoton decay of the Higgs boson. The further improvement of the precision will work as a trigger, either giving no restrictions in the case of small deviations from the SM or excluding the full parameter space in the case of a significant deviation measured with a high accuracy.

The estimates from the restrictions on the single top production are in a good agreement with the present day experimental value of the lower bound of the W' boson mass of 4.4 TeV [14]. The restrictions on the W' boson mass from this process that will be available at the future colliders are also estimated.

6 Acknowledgments

The beginning of the work was supported by grant 14-12-00363 of Russian Science Foundation, the work was completed under the support of grant 16-12-10280 of Russian Science Foundation.

References

[1] J. C. Pati and A. Salam, Phys. Rev. D 10 (1974) 275.
D. B. Kaplan and H. Georgi, Phys. Lett. B 136 (1984) 183.
P. Langacker, R. W. Robinett, and J.L. Rosner, Phys. Rev. D30 (1984) 1470.
P. Langacker and S. Uma Sankar, Phys. Rev. D 40 (1989) 1569.
R. S. Chivukula, E. H. Simmons and J. Terning, Phys. Rev. D 53 (1996) 5258.
M. Cvetic and P. Langacker, Mod. Phys. Lett. A 11 (1996) 1247.
P. Batra, A. Delgado, D. E. Kaplan and T. M. P. Tait, JHEP 0402 (2004) 043.
R. Casalbuoni, S. De Curtis, D. Dolce and D. Dominici, Phys. Rev. D 71 (2005) 075015.

[2] U. Baur, D. Schildknecht and K. H. G. Schwarzer, Phys. Rev. D 35 (1987) 297.
A. Datta, P. J. O'Donnell, Z. H. Lin, X. Zhang and T. Huang, Phys. Lett. B 483 (2000) 203.

[3] T. Appelquist, H. C. Cheng, B. A. Dobrescu, Phys. Rev. D 64 (2001) 035002.
T. G. Rizzo, Phys. Rev. D 64 (2001) 095010.
C. Macesanu, C. D. McMullen, S. Nandi, Phys. Lett. B 546 (2002) 253.

[4] T. Gherghetta and A. Pomarol, Nucl. Phys. B 586 (2000) 141.
K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, Phys. Rev. D 77 (2008) 015003.
K. Agashe, G. Perez and A. Soni, Phys. Rev. D 75 (2007) 015002.
K. Agashe, H. Davoudiasl, G. Perez and A. Soni, Phys. Rev. D 76 (2007) 036006.
A. L. Fitzpatrick, J. Kaplan, L. Randall and L. T. Wang, JHEP 0709 (2007) 013.
B. Lillie, L. Randall and L. T. Wang, JHEP 0709 (2007) 074.
G. Burdman, L. Da Rold, O. Eboli and R. Matheus, Phys. Rev. D 79 (2009) 075026.

[5] W. D. Goldberger and M. B. Wise, Phys. Rev. Lett. **83**, 4922 (1999) [hep-ph/9907447].

[6] O. DeWolfe, D. Z. Freedman, S. S. Gubser and A. Karch, Phys. Rev. D **62**, 046008 (2000) [hep-th/9909134].

[7] E. E. Boos, Y. S. Mikhailov, M. N. Smolyakov and I. P. Volobuev, Mod. Phys. Lett. A **21**, 1431 (2006) [hep-th/0511185].

[8] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999) [arXiv:hep-ph/9905221].

[9] V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B **125** (1983) 136.

[10] V. A. Rubakov, Phys. Usp. 44 (2001) 871.

[11] H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Lett. B 473 (2000) 43.

[12] E. E. Boos, Y. S. Mikhailov, M. N. Smolyakov and I. P. Volobuev, Nucl. Phys. B 717 (2005) 19.

[13] K. Agashe, S. Gopalakrishna, T. Han, G. Y. Huang and A. Soni, Phys. Rev. D **80**, 075007 (2009) doi:10.1103/PhysRevD.80.075007 [arXiv:0810.1497 [hep-ph]].

[14] A. M. Sirunyan *et al.* [CMS Collaboration], JHEP **1805** (2018) no.05, 148 doi:10.1007/JHEP05(2018)148 [arXiv:1803.11116 [hep-ex]].

[15] E. E. Boos, V. E. Bunichev, M. A. Perfilov, M. N. Smolyakov and I. P. Volobuev, JHEP **1406** (2014) 160 doi:10.1007/JHEP06(2014)160 [arXiv:1311.5968 [hep-ph]].

[16] A.I. Vainshtein, M.B. Voloshin, V.I. Zakharov and M.A. Shifman, Sov. J. Nucl. Phys. 30 (1979) 711.

[17] A. Djouadi, Phys. Rept. **457** (2008) 1 [hep-ph/0503172].

[18] G. P. Lepage, P. B. Mackenzie and M. E. Peskin, arXiv:1404.0319 [hep-ph].

[19] A. Muck, A. Pilaftsis and R. Ruckl, Lect. Notes Phys. **647** (2004) 189 [hep-ph/0209371].

[20] E. E. Boos, M. A. Perfilov, M. N. Smolyakov and I. P. Volobuev, Theor. Math. Phys. 170 (2012) 90.

[21] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **76** (2016) no.1, 6 [arXiv:1507.04548 [hep-ex]].

[22] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. C **74** (2014) no.10, 3076 [arXiv:1407.0558 [hep-ex]].

[23] G. Aad *et al.* [ATLAS and CMS Collaborations], JHEP **1608** (2016) 045 [arXiv:1606.02266 [hep-ex]].

[24] M. Aaboud *et al.* [ATLAS Collaboration], arXiv:1802.04146 [hep-ex].

[25] A. M. Sirunyan *et al.* [CMS Collaboration], arXiv:1804.02716 [hep-ex].

[26] E. Boos *et al.* [CompHEP Collaboration], “CompHEP 4.4: Automatic computations from Lagrangians to events,” Nucl. Instrum. Meth. A **534** (2004) 250

[27] A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt, “Parton distributions for the LHC,” Eur. Phys. J. C **63** (2009) 189