Physics Letters B 784 (2018) 330–335

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The bulk Higgs in the deformed RS model

F. Mahmoudi [a,b,1], N. Manglani [c,d,*], K. Sridhar [e]

[a] Univ Lyon, Univ Lyon 1, CNRS/IN2P3, Institut de Physique Nucléaire de Lyon, UMR5822, F-69622 Villeurbanne, France
[b] Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland
[c] Department of Physics, University of Mumbai, Kalina, Mumbai 400098, India
[d] Shah and Anchor Kutchhi Engineering College, Mumbai 400088, India
[e] Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400 005, India

ARTICLE INFO

Article history:
Received 28 December 2017
Received in revised form 1 August 2018
Accepted 8 August 2018
Available online 10 August 2018
Editor: G.F. Giudice

Keywords:
Warped 5D model
Hierarchy problem
Deformed metric
Higgs

ABSTRACT

Electroweak precision tests allow for lighter Kaluza–Klein (KK) Higgs modes in the deformed Randall–Sundrum (RS) model than in models with custodial symmetry. The first KK mode of the Higgs (h_1) in such a model could have a mass as low as 900 GeV. In this paper, we study the production of h_1 and its subsequent decay to a $t\bar{t}$ pair at the Large Hadron Collider (LHC), in the context of the deformed RS model. We have performed a hadron-level Monte Carlo simulation of the signal and the relevant Standard Model background. We present strategies to effectively suppress the huge SM background and provide a signal that is tractable at the future runs of the LHC.

1. Introduction

One of the most appealing solutions to the large hierarchy between the Planck scale and the electroweak (EW) scale is provided by the Randall–Sundrum (RS) Model [1]. The RS model is a five-dimensional (5D) model with a warped geometry given by the following metric:

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \,, \tag{1}$$

where, $A(y)$ is called the warp factor. The fifth dimension is compactified on an S^1/Z^2 orbifold of radius R and located at the orbifold fixed points, $y = 0$, πR are two 3-branes: the UV and the IR brane, respectively. In the original RS model (RS1), all the Standard Model fields along with the Higgs are localised on the IR brane with only the gravitons being UV-localised. There is essentially only one mass scale to begin with, viz., the Planck scale M_p but scales associated with the IR-localised fields like the electroweak vacuum expectation value, are naturally warped down and a stable solution to the Planck-weak hierarchy results. However, in such a model even other scales that ought to be naturally large, such as the ones that suppress proton decay or flavour-changing neutral currents or provide the desirably small neutrino masses, are warped down. To avoid such issues and with the subsequent realisation that only the Higgs need be IR-localised to address hierarchy, a new class of RS models in which the Standard Model fields are allowed to propagate in the bulk were developed [2–8]. Such bulk models provide us a framework within which to confront experimental observations more realistically. For instance, localising fermions at different points in the bulk provides a tractable approach to Yukawa hierarchy [9–13].

In fact, even the Higgs field need not be exactly localised on the IR brane: the solution to the gauge-hierarchy problem requires that the Higgs be only close to it. Localising the Higgs in the bulk close to the IR brane is sufficient to solve the hierarchy problem, so it is not mandatory to fix it on the IR brane [14]. With a bulk Higgs the mass bounds on the KK gauge boson (m_{KK}) reduces from 12 TeV to 7.2 TeV, i.e. by a factor of $\sqrt{3}$ [15]. Even in this light the phenomenological studies of the Higgs first KK mode are very few and have not got their due attention as compared to other SM field KK excitations.

The bulk RS models are severely constrained by the oblique S and T parameters. The constraints from the S parameter are weakened by localising fermions in the bulk but those coming from the T parameter need more serious consideration. Two different bulk models have been proposed to address this issue:

* Corresponding author.
E-mail addresses: nazila@cern.ch (F. Mahmoudi), namrata.manglani@sakec.ac.in (N. Manglani), sridhar@theory.tifr.res.in (K. Sridhar).
[1] Also Institut Universitaire de France, 103 boulevard Saint-Michel, 75005 Paris, France.

https://doi.org/10.1016/j.physletb.2018.08.007

- The first, referred to as the custodial model, invokes a bulk local symmetry $(SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_y)$ which, in a manner reminiscent of the global custodial symmetry of the SM, ameliorates the fit to the measured T parameter [16,17]. The bound on the lightest m_{KK} comes down to about 3 TeV in such models [18,19]. Due to the larger gauge symmetry of this model, the model has a rich spectrum of new particles. Another issue to contend with in such models is the non-universal correction to the $Z \to b\bar{b}$ vertex induced by the fact that in order to get the magnitude of the top quark mass right in bulk models, the $(t,b)_L$ doublet cannot be localised too far away from the IR brane. In custodial models, this is done by embedding the $(t,b)_L$ doublet in an $SU(2)_L \times SU(2)_R$ bidoublet with a special choice of left- and right-quantum numbers. The bidoublet contains exotic charge $\pm 5/3$ fermions.
- The same problem can be solved in the deformed RS model, without an additional symmetry. In this model, we assume a bulk Higgs i.e. a Higgs not on the IR brane but close to it and introduce an additional scalar field. Due to this extra field, warping of the fifth dimension is strongly modified near the IR brane, while it behaves as pure AdS near the UV brane. This is done using soft wall metrics and a naked singularity generated beyond the IR brane by this scalar field. Proximity of the IR brane to the singularity determines the strength of the modification. The deformation of the metric tends to localise the gauge KK modes closer to the IR brane than in the normal RS model and with the Higgs zero mode localised further out in the bulk its overlap with the gauge KK modes is reduced. This relaxes the electroweak constraints considerably [20,19]. In addition the $Z \to b\bar{b}$ partial width and flavour observables also provide stringent constraints on the gauge KK mass. However even after taking these into account, lower bounds on $m_{KK} \sim \mathcal{O}(1\text{–}2\ \text{TeV})$ are obtained [21] in a reasonably significant part of the parameter space of this model, making it interesting from the LHC perspective.

Given that the deformed RS model is a viable alternative to the actively investigated custodial RS model, it is worthwhile to also subject the deformed RS model to a more critical scrutiny, specially from the point of view of collider searches. A couple of studies of collider signals in the deformed model have been published [22, 23], but, other collider signals in the deformed model are crying out for attention.

In this paper, we study the production of the first KK mode of Higgs within the framework of deformed RS model. A similar study for the same process within the custodial RS model was published by us earlier [24]. However, the significantly lower mass range available for the first KK mode of the Higgs in the deformed RS model and the much smaller production cross sections as compared to custodial RS model makes the collider analysis more challenging. Not only do the lower cross sections pose a challenge but at the lower mass end, the Standard Model backgrounds also turn out to be a very serious problem. It is to address these challenges that we have to alter the analysis from the previously studied custodial case [24].

The paper is structured as follows: In Section 2 we provide a brief introduction to the deformed RS model along with a brief description of the constraints. In Section 3 we give a detailed explanation regarding the signal and background simulations and the strategies used to suppress the background effectively. In Section 4 we summarise the results.

2. Bulk Higgs in deformed RS model

The action for a bulk Higgs and other scalars fields (ϕ) in a 5D theory is given by [14]:

$$S_5 = \int d^4x dy \sqrt{-g}\Big[-|D_M H|^2 - \frac{1}{2}|D_M \phi|^2 - V(H,\phi) - \Sigma_\alpha (-1)^\alpha 2\lambda^\alpha (H,\phi)\delta(y-y_\alpha)\Big], \quad (2)$$

where $\lambda^\alpha (\alpha = 0, 1)$ are the brane potentials for the UV and the IR branes respectively, which are of the form $\lambda^0(\phi_0, H) = M_0|H|^2$ and $-\lambda^1(\phi_1, H) = -M_1|H|^2 + \gamma|H|^4$. Here ϕ_α is the vacuum expectation value of the field ϕ at the two boundaries of the fifth dimension $y = y_\alpha$.

The $V(H,\phi)$ is the 5D scalar potential having a quadratic mass term with the coefficient $M(\phi)$ and H is the 5D Higgs field having the notation:

$$H(x^\mu, y) = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ h(y) + \xi(x^\mu, y)\end{bmatrix},$$

where $h(y)$ is the Higgs background and $\xi(x^\mu, y)$ can be expanded as a series of the Higgs KK modes. For a small Higgs mass, we can assume that the vacuum expectation value (vev) is almost entirely carried by the zero mode (h_0), hence the zero mode profile is the same as the vev profile.

The differential equations for the profiles of $h(y)$ and $\xi(y)$ are obtained by varying the 5D action of the scalar fields given in Eq. (2)

$$h''(y) - 4A'(y)h'(y) - \frac{\partial V}{\partial h} = 0, \quad (3)$$

with the boundary conditions

$$\frac{h'(y_\alpha)}{h(y_\alpha)} = \frac{\partial \lambda^\alpha(h)}{\partial h}|y = y_\alpha. \quad (4)$$

Similarly, for $\xi(y)$ we have

$$\xi''(y) - 4A'(y)\xi'(y) - \frac{\partial^2 V}{\partial h^2}\xi(y) + m_n^2\, e^{2A}\xi(y) = 0, \quad (5)$$

with the boundary conditions

$$\frac{\xi'(y_\alpha)}{\xi(y_\alpha)} = \frac{\partial^2 \lambda^\alpha(h)}{\partial h^2}|y = y_\alpha. \quad (6)$$

After simplifying the above differential equations, we can obtain the solutions for the profiles of h_0 and h_1.

The profile equations for the h_0 and fermion zero modes ($t_0^{L,R}$) as given in Refs. [23,21] are

$$f_0^h = N_0^h e^{aky - A(y)},$$
$$f_0^{t_{L,R}} = N_0^{t_{L,R}} e^{(0.5\mp c)A(y)}. \quad (7)$$

Using these profile equations we fix the value of the fermion mass parameter (c) by fitting the top quark mass [19]. We fit the 5D Yukawa (y_5) to the SM Yukawa (y_4) using these profiles ($y_4 = y_5 \int_0^{y_1} f_0^h f_0^{t_L} f_0^{t_R} dy$) by multiplying the 5D Yukawa with the profile overlap integral for the profiles of the zero-mode Higgs to the zero-mode left handed top quark and the zero-mode right handed top quark. The coupling modifier (y_{100}/y_4) for the h_1 coupling to the zero-mode top quarks is given as the ratio of the profile overlap for KK Higgs first mode with the top quarks to the profile overlap of KK Higgs zero mode with the top quarks ($y_{100} = y_4 \times \frac{\int_0^{y_1} f_1^h f_0^{t_L} f_0^{t_R} dy}{\int_0^{y_1} f_0^h f_0^{t_L} f_0^{t_R} dy}$).