# DIRICHLET HIGGS IN EXTRA-DIMENSION CONSISTENT WITH ELECTROWEAK DATA

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We propose a simple five-dimensional extension of the Standard Model (SM) without any Higgs potential nor any extra fields. A Higgs doublet lives in the bulk of a flat line segment and its boundary condition is Dirichlet at the ends of the line, which causes the electroweak symmetry breaking without Higgs potential. The vacuum expectation value of the Higgs is induced from the Dirichlet boundary condition which is generally allowed in higher dimensional theories. The lightest physical Higgs has non-flat profile in the extra dimension even though the vacuum expectation value is flat. As a consequence, we predict a maximal top Yukawa deviation (no coupling between top and Higgs) for the brane-localized fermion and a small deviation, a multiplication of $2\sqrt{2}/\pi \simeq 0.9$ to the Yukawa coupling, for the bulk fermion. The latter is consistent with the electroweak precision data within 90% C.L. for 430 GeV $\lesssim m_{\mathrm{KK}} \lesssim$ 500 GeV.

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## 1. Introduction

The Standard Model (SM), with appropriate extension to take into account the observed neutrino masses, has up to now passed all the experimental tests. In the model, all the masses for fermions and gauge bosons

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are solely from the Higgs mechanism. Currently, the Higgs sector is the only missing part of the model, which is waiting to be tested at the CERN Large Hadron Collider (LHC).

The five dimensional Universal Extra Dimension (UED) model puts all the SM fields in the bulk of a compactified extra dimension $S^1/Z_2$, or equivalently of a line segment [1,2]. The electroweak symmetry breaking is caused by a bulk potential for the Higgs field. The LHC experiment might prove existence of the extra dimension if first few peaks of the Kaluza–Klein (KK) modes are discovered.

Another interesting phenomenological consequence from extra-dimensional theories is a top Yukawa deviation, which is a deviation of the Yukawa coupling between top and physical Higgs fields from the naive SM expectation. Such a deviation generically occurs in a 4-dimensional model too if there are multi-Higgs fields. Recently, it has pointed out that the deviation can be induced from effects of the brane localized Higgs potentials in the context of extra-dimensional theory [3,4] even when there is only one Higgs doublet[1].

In this paper, we point out that an extra dimensional model can predict a maximal top Yukawa deviation and the physical Higgs field can be as heavy as TeV without contradicting the electroweak precision measurements. We define the model compactified on a flat line segment with the Dirichlet boundary conditions (BCs) for a bulk Higgs field at the branes. In this model, the vacuum expectation value of the Higgs is induced from the Dirichlet BC which is generally allowed in higher dimensional theories. It is also shown that the resultant mass spectrum and interactions of the Higgs field are quite similar to the SM when we concentrate on the lowest modes in the KK expansions.

## 2. Setup and model

We consider a simple five-dimensional (5D) SM, compactified on a flat line segment, without adding any extra fields.

Let the SM gauge bosons and the Higgs doublet exist in the 5D flat space-time. The bulk-scalar kinetic action is given by

$$S = -\int d^4x \int\limits_{-L/2}^{+L/2} dz \, |D_M \Phi|^2 \, , \tag{1}$$

where we write 5D coordinates as $x^M = (x^\mu, z)$ with $\mu = 0, \ldots, 3$ and the extra dimension is compactified on a line segment $-L/2 \le z \le L/2$. The five

[1] See Ref. [5] for the top Yukawa deviation in a warped gauge-Higgs unification model.

dimensional gauge covariant derivative is given as $D_M = \partial_M + igT^a W^a_M + ig'YB_M$ with $T^a = \sigma^a/2$ and $Y = 1/2$ on the Higgs doublet field. Our metric convention is $(- + + + +)$. We also impose the KK parity, the reflection symmetry $z \to -z$ on the boundary conditions so that they are equal to each other at both boundaries, as in the UED model.

The variation of the action is given by

$$\delta S = \int d^4x \int_{-L/2}^{+L/2} dz \times \left[\delta\Phi(\mathcal{P}\Phi_X) + \delta\left(z - \tfrac{L}{2}\right)\delta\Phi(-\partial_z\Phi) + \delta\left(z + \tfrac{L}{2}\right)\delta\Phi(+\partial_z\Phi)\right] , \quad (2)$$

where $\mathcal{P} \equiv \Box + \partial_z^2$. The vacuum expectation value (v.e.v.) of the scalar field, $\Phi^c$, is determined by the action principle, $\delta S = 0$, that is $\mathcal{P}\Phi^c = 0$. The v.e.v. profile is fixed by the BCs. We have normally four choices of combination of Dirichlet and Neumann BCs at $z = \pm L/2$, namely

$$(D, D), \qquad (D, N), \qquad (N, D), \qquad \text{and} \qquad (N, N) , \quad (3)$$

where the $D$ and $N$ means the Dirichlet and Neumann BCs, respectively. Difference choice of BC corresponds to different choice of theory. The theory is fixed once one chooses one of four conditions.

In this paper, we propose to take Dirichlet BCs for the Higgs field. The most general form of the Dirichlet BC is $\delta\Phi|_{z=\pm L/2} = 0$ and $\Phi|_{z=\pm L/2} = (v_1, v_2)$ where $v_1$ and $v_2$ are free complex constants. Without loss of generality, we can always take a basis by an $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ field redefinition so that the boundary condition becomes

$$\delta\Phi(x, z)|_{z=\pm L/2} = 0 , \qquad \Phi(x, z)|_{z=\pm L/2} = \begin{pmatrix} 0 \\ v \end{pmatrix} , \quad (4)$$

where $v$ is a real constant of mass dimension $[3/2]$. The BC (4) sets the v.e.v. to be the fixed value $(0, v)$, while requiring the quantum fluctuation to be vanishing at the boundaries. The general solution of the equation of motion (EOM) takes the form $\Phi^c(z) \sim A + Bz$. The constants $A$ and $B$ are fixed by the BC (4) and the resultant v.e.v. profile becomes flat in the extra dimension

$$\Phi^c(z) = \begin{pmatrix} 0 \\ v \end{pmatrix} . \quad (5)$$

It is remarkable that the v.e.v. of Higgs field and flat profile in the extra-dimensional direction can be realized by taking the most general Dirichlet BC at the branes without contradiction to the action principle. The gauge symmetry is violated by this extra-dimensional BC and the gauge boson masses can be obtained. The constant v.e.v. makes profiles of the SM $W$ and $Z$ bosons to be flat too [3][2]. How about the profiles of quantum fluctuation modes of the Higgs field and the would-be Nambu–Goldstone (NG) bosons?

The Higgs doublet field $\Phi$ is KK expanded as

$$\Phi(x,z) = \begin{pmatrix} \sum_{n=0}^{\infty} f_n^{\varphi}(z)\varphi^{+(n)}(x) \\ v + \frac{1}{\sqrt{2}}\sum_{n=0}^{\infty}\left[f_n^H(z)H^{(n)}(x) + i f_n^{\chi}(z)\chi^{(n)}(x)\right] \end{pmatrix} \tag{6}$$

around the v.e.v. 5. Focusing on $H$, the KK equation is given by $\partial_z^2 f_n^H(z) = -\mu_{Hn}^2 f_n^H(z)$, which has a solution $f_n^H(z) = \alpha_n \cos(\mu_{Hn} z) + \beta_n \sin(\mu_{Hn} z)$. The Dirichlet BC $\delta\Phi = 0$ reads, for the quantum fluctuation

$$f_n^H(z)|_{z=\pm L/2} = 0\,, \tag{7}$$

so that the 5D profile of the quantum mode becomes

$$f_n^H(z) = \begin{cases} \sqrt{\frac{2}{L}}\cos\left(\frac{(n+1)\pi}{L} z\right) & \text{for even } n\,, \\ \sqrt{\frac{2}{L}}\sin\left(\frac{(n+1)\pi}{L} z\right) & \text{for odd } n\,. \end{cases} \tag{8}$$

This means that a flat zero-mode profile in the Neumann BC case is deformed to the cosine function of $f_0^H(z) = \sqrt{2/L}\cos(\pi z/L)$ through the Dirichlet BC. The $n$-mode Higgs mass is calculated as

$$m_{H^{(n)}}^2 = -\int_{-L/2}^{+L/2} dz f_n^H(z)\partial_z^2 f_n^H(z) = \left(\frac{(n+1)\pi}{L}\right)^2, \tag{9}$$

which shows that the lowest ($n = 0$) mode has a KK mass $m_{\rm KK} \equiv \pi/L$. Note that $n = -1$ mode is vanishing. This feature of KK scale Higgs mass is the specific result induced from the Dirichlet BC of Eq. (4). The mass is determined by only the compactification scale of extra-dimension unlike the SM[3]. Profiles of $\chi^{(n)}$ and $\varphi^{(n)\pm}$ are the same as $H^{(n)}$. Note that this

[2] Note that the resultant $Z$ and $W$ masses could be the correct ones due to the custodial symmetry even under the presence of bulk Higgs mass. For simplicity, the bulk potential is assumed to be zero throughout this paper.

[3] We do not have a theoretical constraint on the magnitude of the Higgs mass from the discussions of perturbative unitarity as in the SM since the mass depends on the compactification scale but not on the Higgs self-coupling.

profile can be also realized by introducing an extra *fake Higgs* field $\phi$ at the boundaries, with the interaction with Higgs doublet as $|\phi|^2|\Phi|^2$, and taking a limit of $|\langle\phi\rangle| \to \infty$. This is the similar construction to the Higgsless models.

The tree-level Higgs couplings, $HHH$, $H\chi\chi$, $H\varphi^+\varphi^-$, $HHHH$, $HH\chi\chi$, $HH\varphi^+\varphi^-$, $\chi\chi\chi\chi$, $\chi\chi\varphi^+\varphi^-$, and $\varphi^+\varphi^-\varphi^+\varphi^-$ vanish, since there is no Higgs potential. It means that longitudinal components of gauge bosons $W_{\rm L}$ and $Z_{\rm L}$, only have the gauge interactions.

We take Neumann BC,

$$\partial_z A_\mu(z)|_{z=\pm L/2} = 0\,, \qquad \text{and} \qquad A_z(z)|_{z=\pm L/2} = 0\,, \tag{10}$$

for the bulk gauge bosons. Then the profile of the zero-mode gauge bosons are flat and its KK masses are equal to the SM values $m_Z^2 = (g^2 + g'^2)v^2/2$ and $m_W^2 = g^2v^2/2$, respectively. The mass of the $n$th KK mode is given by

$$m^2_{Z^{(n)},W^{(n)}} = m^2_{Z,W} + \frac{n^2\pi^2}{L^2}\,. \tag{11}$$

Equations (9) and (11) show that bulk fields have the same magnitude of KK mass (at the tree level). We find that the mass of $n$-mode Higgs is the same as the KK mass of gauge bosons with the KK number $n+1$ and the frequency of profile for the $n$-mode Higgs is also the same as that of $n+1$-mode KK gauge bosons which are just results of the Dirichlet BC of the Higgs doublet.

Now we focus on the Higgs mechanism of the zero-mode gauge bosons. How is it possible to occur although the five dimensional fields $\varphi^\pm, \chi$ have no flat KK mode while the lowest mode of the $W^\pm, Z$ are flat? The Higgs v.e.v. itself has a flat profile, and a linear combination of infinite KK modes of $\varphi^\pm$ and $\chi$ must have the flat profile, to be absorbed into $W^{(0)\pm}$ and $Z^{(0)}$, respectively, as the would-be NG bosons. This means that the longitudinal component, $W_{\rm L}^{(0)\pm}$ ($Z_{\rm L}^{(0)}$), is composed by a linear combination of $\varphi^{(n)\pm}$ ($\chi^{(n)}$). We speculate that, for example, $Z_{\rm L}^{(0)}$ absorbs the following field having flat profile along the fifth direction except at the boundary

$$\chi\left(x, \pm\tfrac{L}{2}\right) = 0 \qquad \text{and} \qquad \chi(x,z) = \chi_{\rm NG}(x) \qquad \left(-\tfrac{L}{2} < z < \tfrac{L}{2}\right)\,, \tag{12}$$

which can be realized by the superposition of the infinite numbers of $n$-modes of $\chi^{(n)}$, whose orthogonal linear combination is the physical neutral pseudoscalar. It is given by[4]

$$\chi(x,z) = \chi_{\rm NG} \sum_{m=0}^{\infty} \frac{4(-1)^m}{(2m+1)\pi} \cos\left(\frac{(2m+1)\pi}{L} z\right)\,, \tag{13}$$

[4] See Ref. [6] for a detailed derivation.

where $n = 2m$. In the same way, a linear combination of $\varphi^{(n)\pm}$ is absorbed into $W^{(0)\pm}$, and its orthogonal linear combination becomes physical charged scalar particle. Thus, the infinite numbers of $n$-mode are required for the suitable Higgs mechanism.

One possible question is: How should we treat the 5D cutoff energy scale? There exist heavier KK modes than the cutoff scale, and the completely flat profile of the would-be NG boson cannot be obtained without such heavier KK modes. However, a model with a cutoff $\Lambda$ is expected to have an ambiguity of length scale of $\mathcal{O}(\Lambda^{-1})$ in general. We would need an experimental resolution finer than $\mathcal{O}(\Lambda^{-1})$ to distinguish this ambiguity (for example, as the deviation from flat profile in above case), and the ambiguity is negligible in the low energy effective theory.

Let us comment on the KK parity. It is known that the universal extra-dimensional (UED) model has a KK parity conservation. In our setup, the Dirichlet BC is imposed for the Higgs field to take the same value on both $z = \pm L/2$ branes, so that there arises a reflection symmetry. This guarantees the conservation of the KK parity in the gauge and Higgs sector. The existence of the KK parity in the Lagrangian depends on a fermion sector. When the fermions are localized on the 4D branes — brane-localized fermion (BLF) scenario — the KK parity is broken in general. On the other hand, the KK parity is conserved in a bulk fermion (BF) setup. When KK parity exists, the lightest KK particle with odd parity is stable, which can be a candidate for a Dark Matter.

## 3. Top Yukawa deviation

Now let us estimate the top Yukawa deviation. This is a result from the non-flat profile of the physical Higgs field in the extra-dimension. We estimate the BLF scenario at first. The Yukawa interaction for the top quark and the Higgs boson is written as

$$\begin{aligned} -\mathcal{L}_t &= \int_{-L/2}^{+L/2} dz\delta\left(z-\frac{L}{2}\right) y_{t,5}\left[v + f_0^H(z)\frac{H(x)}{\sqrt{2}}\right]\bar{t}(x)t(x) \\ &= y_{t,5}\left[v + f_0(L/2)\frac{H(x)}{\sqrt{2}}\right]\bar{t}(x)t(x)\,. \end{aligned} \tag{14}$$

The top quark mass $m_t$ and effective top coupling in 4D $y_t$ can be obtained as $m_t = y_{t,5}v$ and $y_t = \frac{m_t}{v\sqrt{L}} = \frac{y_{t,5}}{\sqrt{L}}$, where we take $v = v_{\mathrm{EW}}/\sqrt{L}$. On the other hand, the coupling between the top quark and Higgs boson in 4D is given by

$$y_{\bar{t}tH} = y_t f_0^H\left(\frac{L}{2}\right) = y_t\sqrt{\frac{2}{L}}\cos\left(\frac{\pi}{2}\right) = 0\,. \tag{15}$$

This is the maximal top Yukawa deviation, which can be hardly realized in other setups (see for example, Ref. [5]). This maximal top Yukawa deviation is the result of non-flat Higgs profile due to the Dirichlet BC.

Next, in the case of the BF, the Yukawa coupling between the top quark and the Higgs boson is written by

$$- \mathcal{L}_t \;=\; y_{t,5} \int_{-L/2}^{+L/2} dz \left[ v + f_0^H(z) \frac{H(x)}{\sqrt{2}} \right] \bar{t}(x,z) t(x,z) \,. \tag{16}$$

Then the ratio of the top Yukawa coupling in our model to that of the SM, $r_{H\bar{t}t}$, is given by

$$r_{H\bar{t}t} \;=\; \frac{1}{\sqrt{L}} \int_{-L/2}^{L/2} dz f_0^H(z) = \frac{2\sqrt{2}}{\pi} \simeq 0.90 \,. \tag{17}$$

Therefore, the top deviation in the BF setup is 10% decrease from the SM.

## 4. Higgs production and decay

Let us consider the Higgs production and decay at LHC experiment. First, we show the Higgs production processes. (We can analyze higher KK Higgs production in the same way.) The SM predicts that the gluon fusion with the top quark 1-loop diagram ($WW$ fusion) dominates when $m_H \equiv m_{H^{(0)}} (= m_{\rm KK}) \leq 1$ TeV ($m_H \geq 1$ TeV). Since the Higgs has the same mass scale as the KK gauge bosons (and also KK fermions in the BF) in our setup, the Higgs mass must be large enough to be consistent with experiments. As shown in the next section, the KK scale must be larger than a few TeV (600 GeV [7]) in BLF (BF) scenario. Anyhow, since the Yukawa couplings of Higgs with the top quark are modified, the processes for the Higgs production must be reanalyzed.

In the BLF scenario, the gluon fusion process is strongly suppressed, since the Higgs is not coupled with the top quark at the tree level. On the other hand, the $WW$ fusion process still exists, but the magnitude decreases because the coupling between $W$ and Higgs is modified as

$$- \mathcal{L}_{WWH} \;=\; \frac{e m_W}{2 \sin\theta_{\rm W}} \frac{1}{2L} \int_{-L/2}^{+L/2} dz f_0^H(z) f_0^{W^+} f_0^{W^-} H(x) W^+(x) W^-(x) + \text{h.c.} \,, \tag{18}$$

where $\theta_{\rm W}$ is the Weinberg angle. The ratio of the $WWH$ coupling in our 5D model to the SM, $r_{WWH}$, is estimated as

$$r_{WWH} \equiv \frac{1}{\sqrt{L}} \int_{-L/2}^{+L/2} dz f_0^H(z)\,. \tag{19}$$

Note that this ratio is the same as $r_{Ht\bar{t}}$ in Eq. (17). To conclude, the Higgs production mainly occurs through the $WW$ fusion in the BLF scenario, which is decreased about 20% compared to the SM due to the suppression by the factor $r_{WWH}^2(= r_{Ht\bar{t}}^2) \simeq 0.81$.

Next, let us consider the BF scenario. Around $m_H = 600 \sim 800$ GeV in the SM ($\sqrt{s} = 14$ TeV), the gluon fusion cross-section is about 10 times larger than the $WW$ fusion. So how is in BF scenario where the coupling between the top quarks and Higgs boson is decreased by 10% from the top Yukawa coupling? It means that the gluon fusion process still exists, but the cross-section (magnitude) decreases 80% (90%) due to $r_{Ht\bar{t}}^2 \simeq 0.81$ ($r_{Ht\bar{t}} \simeq 0.9$) compared to the SM. The $WW$ fusion process is the same as the BLF scenario. Other production processes such as $q\bar{q} \to HW$, $q\bar{q} \to HZ$, and $gg, q\bar{q} \to Ht\bar{t}$ are also suppressed. Therefore, comparing to the SM, the cross-section for the Higgs production in the BF scenario decreases 81% overall, while the branching ratios are not changed.

Finally, let us show the Higgs decay. In the SM, the process $H \to W^+W^-$ dominates when $m_H > 130$ GeV. In our setup, the decay width is estimated quite similarly as in the SM

$$\Gamma_{H\to W^+W^-} \simeq \frac{g^2}{64\pi} \frac{m_H^3}{m_W^2} r_{WWH}^2\,. \tag{20}$$

In the next section, we will see that the Higgs mass must be larger than 6.8 TeV (BLF scenario) and 430 GeV $\lesssim m_H \lesssim$ 500 GeV (BF scenario).

Notice that in our setup $m_H = m_{\rm KK} \gg m_W$, and the Higgs decay process would become equivalent to the process $H \to \varphi_{\rm NG}^+ \varphi_{\rm NG}^-$ (where $\varphi_{\rm NG}^\pm$ is the NG mode absorbed by the lowest mode of $W^\pm$), if the NG boson equivalence theorem is applicable in the mass spectrum. Since there is no Higgs potential in our model at all, $H$ cannot couple to $\varphi^+\varphi^-$, which means that $H$ would decay into $W^+W^-$ only through the transverse mode of $W^\pm$, that would lead to a suppressed decay width $\Gamma_{H\to WW} \simeq \frac{g^2}{64\pi} m_H r_{WWH}^2$. But is it true? These would-be NG bosons $\varphi_{\rm NG}^\pm$ are absorbed into $W^\pm$, and their wave function profiles are given by Eq. (12). It is the linear combination of all the higher KK modes, which means a lot of heavier KK modes (than the Higgs mass) are included. Obviously, the higher KK mode components

($n \geq 2$) in $\varphi_{\rm NG}$ (with the profile of Eq. (12) and being absorbed into $W^\pm$) are heavier than the Higgs mass, thus, the physical decay process has been estimated as Eq. (20).

## 5. Electroweak precision measurements

Finally, let us estimate constraints from electroweak (EW) precision measurements on this setup. As for the BLF scenario, the present experimental data requires, that the KK scale, that is equal to Higgs mass in our setup, must be larger than a 6.8 TeV at the 95% confidence level [8]. To fit $S$ and $T$ parameters [9] in such a super-heavy Higgs scenario, some extensions of the model, such as matter content, might be required.

In the BF case, we estimate $S$ and $T$ parameters defined as $\alpha S \equiv 4e^2[\Pi_{33}^{\rm new\prime}(0) - \Pi_{3Q}^{\rm new\prime}(0)]$ and $\alpha T \equiv \frac{e^2}{s^2c^2m_Z^2}[\Pi_{11}^{\rm new}(0) - \Pi_{33}^{\rm new}(0)]$, where $s = \sin\theta_{\rm W}$ and $c = \cos\theta_{\rm W}$. $\Pi_{XY}(q^2)$ is the vacuum polarization and $\Pi'_{XY}(q^2)$ means $d\Pi_{XY}/dq^2$ at $q^2 = 0$. The $\Pi_{11}$ and $\Pi_{33}$ are represented by $\Pi_{11} = \frac{s^3}{e^2}\Pi_{WW}$ and $\Pi_{33} = \frac{s^3}{e^2}[c^2\Pi_{ZZ} + 2sc\Pi_{ZA} + s^2\Pi_{AA}]$, respectively. In our setup, $S$ and $T$ parameters are approximately estimated as [2, 10]

$$S \simeq \frac{1}{6\pi}\log\left(\frac{m_H}{m_{H,\rm ref}}\right) + \sum_{n=1}^{\infty}\frac{1}{4\pi}f_S^{\rm KK-top}\left(\frac{m_t^2}{n^2m_{\rm KK}^2}\right), \tag{21}$$

$$T \simeq -\frac{3}{8\pi c^2}\log\left(\frac{m_H}{m_{H,\rm ref}}\right) + \sum_{n=1}^{\infty}\frac{3m_t^2}{16\pi^2v_{\rm EW}^2}\frac{1}{\alpha}f_T^{\rm KK-top}\left(\frac{m_t^2}{n^2m_{\rm KK}^2}\right), \tag{22}$$

where $v_{\rm EW} = 174$ GeV, $m_H = m_{\rm KK}$[5], $m_{H,\rm ref}$ is the reference Higgs mass taken as $m_{H,\rm ref} = 117$ GeV, and

$$f_S^{\rm KK-top}(z) = \frac{2z}{1+z} - \frac{4}{3}\log(1+z), \tag{23}$$

$$f_T^{\rm KK-top}(z) = 1 - \frac{2}{z} + \frac{2}{z^2}\log(1+z). \tag{24}$$

The first terms in both $S$ and $T$ parameters correspond to the absence of the SM Higgs contributions (as explained in footnote 5), and the second termes are the KK top ones. Since a contribution to $S$ and $T$ parameter from the KK Higgs modes are small at $m_{\rm KK} \lesssim 500$ GeV[6], we drop the

[5] Here we approximate the absence of the SM Higgs by making its mass to be KK scale $m_H \to m_{H^{(0)}} = m_{\rm KK} = \pi/L$, as the first KK Higgs $H^{(0)}$ has coupling to the SM zero modes very close to the SM value, universally multiplied by $2\sqrt{2}/\pi \simeq 0.9$. Higher KK modes $H^{(n)}$ ($n \geq 1$) are neglected as we will discuss in footnote 6.

[6] In the UED model, contributions from the KK Higgs to $S$ parameter become dominant at $m_{\rm KK} \gtrsim 600$ GeV. However, such region of KK scale is excluded by the electroweak precision measurement at 90% C.L. as shown in Fig. 1.

corresponding terms. We have not truncated the KK sum but performed it for infinite modes. Generically this is known to be a good strategy that does not spoil the five-dimensional gauge symmetry at short distances. Notice that contributions from KK top loops, which are dominant contributions, are positive. The $(S, T)$ plot in this setup is presented in Fig. 1. We plot the parameters in a region of 300 GeV $\leq m_H \leq$ 1 TeV, and take the reference Higgs mass as 117 GeV. We find that the first KK scale $m_H = \pi/L$ is constrained to be

$$430 \text{ GeV} \lesssim m_H \lesssim 500 \text{ GeV}, \tag{25}$$

within 90% C.L. This numerical analysis is given with the KK sum until 11th KK state, which is enough to evaluate the parameters, because contributions from higher KK modes to the parameters become negligibly tiny.

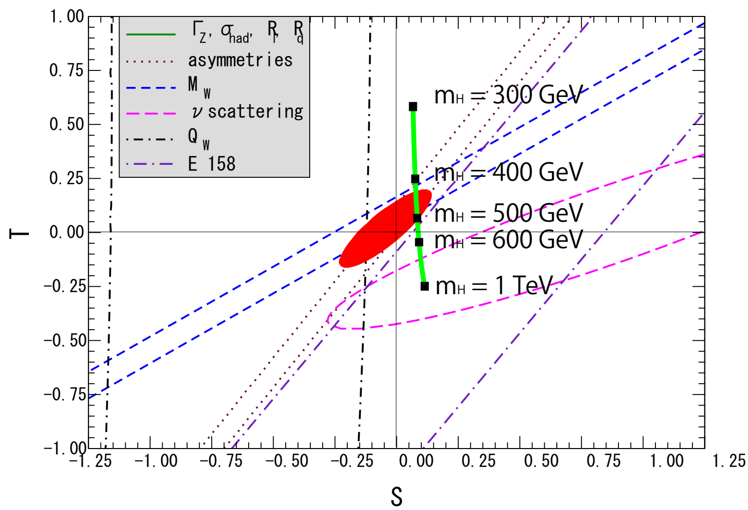


Fig. 1. $S$ and $T$ plot in this setup: Contours show $1\sigma$ constraints (39.35%) from various inputs except for the central one representing 90% C.L. allowed by all data [11].

## 6. Summary and discussions

We have proposed the 5D SM with the Higgs doublet and gauge bosons living in the bulk of the line segment. We take a Dirichlet (Neumann) boundary condition for the Higgs (gauge) field. The vacuum expectation value of the Higgs is induced from the Dirichlet BC, which is generally allowed in higher dimensional theories, and the BC causes the electroweak symmetry breaking in this model. Under the simple BC, we have naturally obtained the non-flat profile of the lightest Higgs $H$. The mass of the physical Higgs boson is induced from the bulk quadratic terms and depends only on the compactification scale of the extra-dimension. We note that there is no Higgs self-coupling unlike the SM. In the BLF case, the maximal top deviation is realized, that is, top quark does not interact with physical Higgs boson, while in the BF case, 10% deviation is predictive. We have shown that the Higgs decay width as large as its mass. The BF setup is consistent with $S$ and $T$ parameters. This model does not have unnatural large couplings nor any fine-tunings.

Finally, we comment on unitarity in our model. Here, the gauge symmetry is violated by the extra-dimensional BC. However, the five dimensional gauge symmetry will be restored as an energy scale becomes much higher than the KK scale. We note that in several models of orbifold/boundary symmetry breaking, it has been shown that the longitudinal gauge boson scattering *etc.* are indeed unitarized by taking into accout Kaluza–Klein mode contributions [12,13,14,15,16,17,18]. Therefore, it would be expected that the bulk gauge boson scattering is unitarized in such a region of our model (above the KK scale but lower than the five-dimensional cut-off scale) by taking into account all the relevant KK modes. It would be worth studying this issue further.

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