126 GeV Higgs in next-to-minimal Universal Extra Dimensions

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\textbf{ABSTRACT}

The discovery of a Higgs boson and precise measurements of its properties open a new window to test physics beyond the standard model. Models with Universal Extra Dimensions are not an exception. Kaluza–Klein excitations of the standard model particles contribute to the production and decay of the Higgs boson. In particular, parameters associated with third generation quarks are constrained by Higgs data, which are relatively insensitive to other searches often involving light quarks and leptons. We investigate implications of the 126 GeV Higgs in next-to-minimal Universal Extra Dimensions, and show that boundary terms and bulk masses allow a lower compactification scale as compared to in minimal Universal Extra Dimensions.

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1. Introduction

The recent discovery of a Higgs-like boson at the LHC and measurements of its properties open a new window for physics beyond the Standard Model (SM). Both the ATLAS and the CMS Collaborations have measured its mass with precision better than that in the top quark mass (0.5\%):

\[
m_H = \begin{cases} 
125.5 \pm 0.2 \pm 0.5 \text{ GeV}, & \text{ATLAS (0.43\% precision)} \ [1], \\
125.7 \pm 0.3 \pm 0.3 \text{ GeV}, & \text{CMS (0.34\% precision)} \ [2].
\end{cases}
\]

(1)

Measured properties of the boson are consistent with the standard model expectation, which is often parameterized by \( \mu = \sigma / \sigma_{SM} \), the ratio between the SM expectation and the measured value:

\[ \mu = \begin{cases} 
1.30 \pm 0.20, & \text{ATLAS} \ [1], \\
0.80 \pm 0.14, & \text{CMS} \ [2].
\end{cases} \]

(2)

We regard that the discovered boson is actually the Higgs boson in the SM and try to set bounds on new physics models by comparing the measured data and the expected deviation from new physics. In general, the radiative production of the Higgs boson through gluon fusion and its decay to a pair of photons are subject to modification by heavy new colored particles, namely the ‘top partner’ (\( t' \)) \ [3] and electrically charged particles, namely charged gauge bosons and heavy leptons (\( W' \) and \( \ell' \)). Any new physics model which contains such new particles affects the Higgs physics and can be probed by close examination of the Higgs data.

In models with Universal Extra Dimensions (UED) \ [4], all the standard model particles have their Kaluza–Klein (KK) excitations, including new colored particles and electrically charged particles. Among them, the KK excitations of the top quark yield significant corrections to the gluon fusion process due to the largest Yukawa coupling. As the fermionic degrees of freedom in models with extra dimensions are doubled, the KK top quark contribution is also enhanced by a factor of 2. Also, both the KK \( W \) bosons and the KK top quarks contribute to the one-loop induced decay rate to the diphoton. Even though one-loop suppressed, the diphoton channel has been regarded as one of a golden channel. Other decay channels, which are allowed at tree level, are less significantly modified by the KK states so that we may neglect these effects here. There are existing studies on the Higgs production and decay rates in the minimal UED (MUED) model \ [5,6] as well as various 5D \ [7] and 6D extensions \ [8].

In this Letter, we extend the previous studies by including effects of bulk mass parameters \ [9–11] and boundary localized terms \ [12,13] following the philosophy of a recent paper \ [14]. In Ref. \ [14]

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it was shown that bulk masses are strongly constrained for leptons and the first two quark families. Furthermore, non-uniform boundary terms and bulk masses for leptons, and first and second family quarks typically imply large flavor changing neutral currents and are thus strongly constrained [15]. As an important exception, a common boundary parameter for all UED fields is not constrained as it does not induce KK-number violating interactions and only shifts the overall mass scale of the nth Kaluza–Klein mode excitations away from n/R, with R being the compactification radius of the extra dimension.

Constraints on parameters associated with third generation quarks are much weaker, and their phenomenological implications are very different from those with first and second generations. They are particularly important in physics dominated by one-loop corrections, where the large Yukawa coupling of the top plays a crucial role. This applies to electroweak precision tests as well as to Higgs production and decay. We therefore focus on the third generation in the quark sector and consider a UED setup with a common boundary parameter r3 for the first two families (and no bulk masses for those). We allow for a non-zero bulk mass (μt ≠ 0) and a different boundary parameter rL for the third generation. This choice leaves us with rK, rL, μt, and R−1 as parameters to be constrained.

The Letter is organized as follows. In the next section, we briefly introduce the next-to-minimal UED (NMUED) model with bulk mass parameters and boundary localized terms. The KK spectra and couplings are collected for the one-loop calculation of the gluon fusion process and radiative decay processes in Section 3 and the electroweak bounds are considered in Section 4. We show our results in Section 5 taking the latest experimental results into account.

2. Next-to-minimal Universal Extra Dimensions

The minimal UED action contains gauge invariant kinetic terms for the bulk fields and Yukawa interaction terms, assuming vanishing boundary localized terms at the cutoff scale. In NMUED, we introduce bulk mass and boundary terms for the third generation and a generic boundary term, which are parameterized as

\[ S_{NMUED} = S_{MUED} + \int d^3x \int_{-L}^{L} dy \{ -M_4 \bar{\Psi}_3 \Psi_3 + \frac{1}{\sqrt{f^2 + \mu_3^2}} \} , \]

where the wave functions f^{\psi_3}_{n} and are given by

\[ f^{\psi_3}_{n} = \begin{cases} 0 & n = 0 \\ \frac{N_{0}^{0}}{k_{0}^{2}} e^{i k_{0} y} & \text{odd } n \\ \frac{k_{n}}{m_{f_{n}}} \cos(k_{n} y) + \frac{\mu_{t}}{m_{f_{n}}} \theta(y) \sin(k_{n} y) & \text{even } n \end{cases} \]

\[ \theta(y) = \begin{cases} -1 & \text{if } y < 0 \\ 1 & \text{if } y > 0 \end{cases} \]

as defined in Ref. [9]. The symbols sin and cos denote sin or sinh and cos or csh, and wave numbers k_n are the solutions of the mass quantization condition

\[ k_{n} \cos(k_{n} L) = (r_{L}(m_{f_{n}})^2 + \mu_{t}) \sin(k_{n} L) \quad \text{for odd } n, \]

\[ r_{K} k_{n} \cos(k_{n} L) = -(1 + r_{L} \mu_{t}) \sin(k_{n} L) \quad \text{for even } n. \]

The chiral zero mode is massless. If "light" (sin and cos) solutions exist, they describe the first and second KK excitations, and their masses m_{f_{n}} are given by

\[ m_{f_{n}} = \sqrt{k_{n}^2 + \mu_{t}^2}. \]

while the "heavy" KK modes (sin and cos solutions) have masses

\[ m_{f_{n}} = \sqrt{k_{n}^2 + \mu_{t}^2}. \]

The normalization factors are given by

\[ N_{0}^{0} = \left\{ \begin{array}{ll} \sqrt{\frac{1}{1+2r_{t} \mu_{t}}} & \text{for } n = 0 \\ \left( L - \frac{\cos(k_{n} L) \sin(k_{n} L)}{k_{n}} + 2r_{t} \sin^{2}(k_{n} L)^{-1/2} \right. & \text{for odd } n, \\ \left. \left( L - \frac{\cos(k_{n} L) \sin(k_{n} L)}{k_{n}} \right)^{-1/2} \right. & \text{for even } n, \end{array} \right. \]

and they are determined from the modified orthogonality relations

\[ \int_{-L}^{L} dy f^{\psi_3}_{m} f^{\psi_3}_{n} [1 + r_{L} \delta(y + L) + \delta(y - L)] = \delta_{mn}. \]

\[ \int_{-L}^{L} dy f^{\psi_3}_{m} f^{\psi_3}_{n} [1 + \delta(y + L) + \delta(y - L)] = \delta_{mn}. \]

A fermion with a right-handed zero mode (i.e. U, D, E) yields analogous results when replacing μt with −μt.

The KK reduction of gauge bosons and scalars has been discussed in Ref. [16]. The fields are decomposed according to

\[ A_{\mu}(x, y) = \sum_{n=0}^{\infty} A^{(n)}_{\mu}(x) f^{A}_{n}(y), \]

\[ H(x, y) = \sum_{n=0}^{\infty} H^{(n)}(x) f^{A}_{n}(y). \]
As expected, the masses and wave functions for scalars and gauge bosons are identical to those of the $Z_2$-even fermions in the limit $\mu_t \to 0.

The couplings are obtained from overlap integrals of the respective wave functions. As an example, the coupling of a zero mode gauge boson with KK mode fermions follows from

$$S_{\text{eff}} \supset \int d^4x g_s \overline{\psi}_L^{(n)}(y) \gamma^\mu A^{(0)}_\mu \psi_R^{(m)} \psi_L^{(m)} \psi_R^{(m)}$$

$$= \int d^4x \frac{\delta_{nm}}{\sqrt{2(1+\tau/L)}} \overline{\psi}_L^{(n)}(y) \gamma^\mu A^{(0)}_\mu \psi_R^{(m)} \psi_L^{(m)}$$

implying that

$$g_{0mm}^{\text{SM}} = \frac{3\delta_{nm}}{2(1+\tau/L)} = g_{\text{SM}} \delta_{nm},$$

where $g_{\text{SM}}$ is the standard model coupling. All couplings of zero mode gauge bosons to KK fermions are Kaluza–Klein number conserving and of strength $g_{\text{SM}}$, i.e. independent of the fermion KK level. Calculation of the analogous overlap integrals yields the same result for couplings of zero mode gauge bosons to KK gauge bosons, and of the zero mode Higgs to KK mode fermions or gauge bosons. Interactions between the zero mode Higgs and KK fermions are given by the standard model Yukawa couplings if we assume the same mass and boundary terms for $Q_3$, $U_3$, and $D_3$, which is the case in our current study.

$$\frac{1}{\sqrt{2L(1+\tau/L)}},$$

$$\frac{1}{\sqrt{L + r_\phi \sin^2(k_n L)}},$$

$$\frac{1}{\sqrt{L + r_\phi \cos^2(k_n L)}}$$

where the wave numbers $k_n$ are determined by

$$\cot(k_n L) = r_\phi \cot k_n$$

for odd $n$,

$$\tan(k_n L) = -r_\phi \tan k_n$$

for even $n$,

and the corresponding KK masses are

$$m_{k_n} = \sqrt{k_n^2 + m_0^2},$$

where $m_0$ is the zero mode mass ($m_W$, $m_Z$, $m_H$ or zero), which is induced by electroweak symmetry breaking (EWSB). The wave functions satisfy the following orthogonality relation

$$\int_{-L}^L dy f^{A}_n f^{A}_m \left[ 1 + r_\phi \left( \delta(y + L) + \delta(y - L) \right) \right] = \delta_{nm}.$$
in UED models with bulk masses and boundary kinetic terms has
been performed in Ref. [14]. The dominant contributions to S
and T arise from the top-loop corrections to the gauge boson
propagators, while U only receives contributions from gauge boson
and Higgs loops. At one-loop order, the NMUED contributions to the
Peskin–Takeuchi parameters are [14,19]

\[ S_{\text{NMUED}} = \frac{4 \sin^2 \theta_W}{\alpha} \left[ \frac{3 g_{2W}^2}{4(4\pi)^2} \left( \sum_{n} \frac{m_n^2}{m_{h(n)}^2} \right) \right] + \frac{g_{2W}^2}{4(4\pi)^2} \left( \frac{1}{6} \sum_{n} \frac{m_n^2}{m_{h(n)}^2} \right), \quad (27) \]

\[ T_{\text{NMUED}} = \frac{1}{\alpha} \left[ \frac{3 g_{2W}^2}{2(4\pi)^2} \left( \frac{2}{3} \sum_{n} \frac{m_n^2}{m_{h(n)}^2} \right) \right] + \frac{g_{2W}^2 \sin^2 \theta_W}{(4\pi)^2 \cos^2 \theta_W} \left( \frac{5}{12} \sum_{n} \frac{m_n^2}{m_{h(n)}^2} \right), \quad (28) \]

\[ U_{\text{NMUED}} = -\frac{4 \sin^2 \theta_W}{\alpha} \left[ \frac{g_{2W}^2}{4(4\pi)^2} \sin^2 \theta_W \right] \times \left( \frac{1}{6} \sum_{n} \frac{m_n^2}{m_{h(n)}^2} - \frac{1}{15} \sum_{n} \frac{m_n^2 m_n^2}{m_{h(n)}^2 m_{h(n)}^2} \right). \quad (29) \]

Here \( \alpha \) is the fine structure constant, \( \theta_W \) is the Weinberg angle,
and \( g_{\text{ew}} \) is the coupling strength of SU(2)W.

5. Results

In our analysis, for simplicity we consider a common bulk
mass \( \mu_t = \mu_Q = \mu_\mu = \mu_T \) and a common boundary parameter
\( r_t = r_Q = r_\mu = r_T \), for the third generation of SU(2)W quark dou-
blet \( Q_3 \) and SU(2)W singlets \( B \) and \( T \). This choice, together with
the compactification scale \( R^{-1} \), leaves us with three parameters.
As an additional parameter, we consider a common boundary parame-
ter \( r_g \) for all other fields (i.e. the Higgs, the gauge fields and
leptons, and the first and second family quarks) in order to il-
ustrate how the bounds change in the presence of a common
boundary parameter with only the third family quarks differ-
ing. We present results as bounds on the compactification scale \( R^{-1} \)
as a function of the dimensionless parameters \( \mu_t, r_t \) and \( r_g \). To indi-
cate the effect of a common boundary term, we show constraints
for \( r_g = 0 \) ("vanishing boundary parameter") and \( r_g = 1 \) ("typi-
cal boundary parameter").

The electroweak bounds shown in Fig. 1 are obtained by per-
forming a \( \chi^2 \) fit of the parameters \( S_{\text{NMUED}}, T_{\text{NMUED}}, U_{\text{NMUED}} \)
from Eqs. (27)–(29) to the experimental values given in Ref. [21], \( S_{\text{NP}} \)
= 0.03 ± 0.10, \( T_{\text{NP}} = 0.05 ± 0.12, U_{\text{NP}} = 0.03 ± 0.10, \) for a refer-
cence point \( m_H = 126 \text{ GeV} \) and \( m_t = 173 \text{ GeV} \) with correlation co-
efficients of +0.89 between \( S_{\text{NP}} \) and \( T_{\text{NP}}, \) and −0.54 (−0.83) between
\( S_{\text{NP}} \) and \( U_{\text{NP}} \).

For \( r_g = 0 \), the mass of the first \( U(1)_Y \) KK mode \( \gamma(1) \) (the
usual UED dark matter candidate) is given by \( R^{-1} \). For a large
\( r_t \) and a small \( \mu_t / L \), the first KK bottom partner is lighter than
the \( \gamma(1) \) which implies a charged dark matter and is therefore
excluded. For \( r_g / L \neq 0 \), the same applies, although the mass of the
\( \gamma(1) \) is not given by \( R^{-1} \) anymore, but determined by Eq. (18).

To determine the bounds from Higgs searches, we define the
signal strengths as follows:

\[ \mu_{gg-h-h} \equiv \frac{\hat{\sigma}^{\text{NMUED}}_{gg-h-h}}{\hat{\sigma}^{\text{SM}}_{gg-h-h}} = \frac{|F_{1t}^2| |F_{1W} + 3 Q_2^2 F_{1t}^2|}{|F_{1t}^2|^2 |F_{1W} + 3 Q_2^2 F_{1t}^2|^2}, \quad (30) \]

\[ \mu_{other-h-h} \equiv \frac{\hat{\sigma}^{\text{NMUED}}_{other-h-h}}{\hat{\sigma}^{\text{SM}}_{other-h-h}} = \frac{|F_{1t}^2| |F_{1W} + 3 Q_2^2 F_{1t}^2|}{|F_{1t}^2|^2 |F_{1W} + 3 Q_2^2 F_{1t}^2|^2}, \quad (31) \]

\[ \mu_{gg-h-other} \equiv \frac{\hat{\sigma}^{\text{NMUED}}_{gg-h-other}}{\hat{\sigma}^{\text{SM}}_{gg-h-other}} = \frac{|F_{1t}^2| |F_{1W} + 3 Q_2^2 F_{1t}^2|}{|F_{1t}^2|^2 |F_{1W} + 3 Q_2^2 F_{1t}^2|^2}, \quad (32) \]

\[ \mu_{other-h-other} \equiv \frac{\hat{\sigma}^{\text{NMUED}}_{other-h-other}}{\hat{\sigma}^{\text{SM}}_{other-h-other}} = 1, \quad (33) \]

where “other” production channels are vector boson fusion, and
Higgs radiation off gauge bosons or tops, and “other” decay chan-

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3 In Ref. [14], additional contributions to T and U arise due to lepton bulk mass
terms, which are however shown to be strongly constraint by dilepton searches.
Here, we assume vanishing lepton bulk masses and therefore neglect such contribu-
tions.

4 A naive dimensional analysis of the boundary parameter yields \( r/L \lesssim 12/\Lambda R \),
where \( \Lambda \) is the UED cutoff scale, and \( AR \) gives an estimate for the number of KK
levels below the cutoff scale [12].
nels are $ZZ$, $WW$, $bb$, and $ττ$. Ref. [22] performs a global Bayesian analysis on the ATLAS [23] and CMS [24] Higgs data and provides values of signal strengths and their correlations. We use this data to perform a $χ^2$ test of the UED predictions and plot the constraints in Fig. 2 where no correlation between the ATLAS and CMS results is assumed.

Compared to the electroweak constraints and the CMS bounds, the ATLAS bounds are weaker. The main reason for this lies in that ATLAS (CMS) observes an enhanced (reduced) rate in the di-photon channel as compared to the standard model expectation. The UED model predicts an enhancement of the cross section for $gg → h → γγ$. The other channels do not have a strong effect on the $χ^2$ fit because of the larger errors. Therefore, the constraints shown in Fig. 2 are dominated by the measurements at CMS. We note that the bound from electroweak precision tests is comparable with the bound from direct Higgs searches.

6. Summary and outlook

UED is an attractive extension of the standard model based on higher dimensions providing a viable dark matter candidate and rich phenomenology at the LHC. As an effective theory, UED models could be extended from the minimal realization by incorporating boundary localized operators and bulk masses. In this Letter, we focus on the extra terms associated with the third generation of quarks, which are particularly relevant for the radiative production and decay of the Higgs boson through the Kaluza–Klein quarks and $W$-bosons. Including electroweak precision tests as well as the latest measurements on the Higgs boson at the LHC (ATLAS and CMS), we explicitly show the allowed range of parameter space in next-to-minimal UED for the Kaluza–Klein photon dark matter candidate. Our results show that NMUED allows for a lower compactification scale than in MUED, where $R^{-1} < 500$ GeV is excluded at 95% C.L. [6]. This allowed parameter space will be probed by the LHC14.

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5 To be more precise, the decay rate $h → γγ$ is reduced due to negative interference of the KK top and KK $W$ loop contributions with the standard model contribution, but the production cross section $gg → h$ is enhanced and leads to an enhancement of the overall cross section. The UED cross sections for $gg → h →$ other are enhanced even more, which again is partially reflected in some search channels at ATLAS, but not at CMS.

6 The analysis in Ref. [6] is based on earlier ATLAS and CMS Higgs data. With the data set used here, these bounds are expected to increase. In the $0 = m_t = r_t = r_{ττ}$ limit of our analysis, we find $R^{-1} ≲ 700$ GeV excluded. To our knowledge, the currently strongest published MUED bound from other collider searches is $R^{-1} ≲ 715$ GeV [25].


[24] CMS Collaboration, Updated measurements of the Higgs boson at 125 GeV in the two photon decay channel, CMS-PAS-HIG-13-001; CMS Collaboration, Properties of the Higgs-like boson in the decay $H \to ZZ\to 4\ell$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV, CMS-PAS-HIG-13-002; CMS Collaboration, Evidence for a particle decaying to $W^+W^-$ in the fully leptonic final state in a standard model Higgs boson search in pp collisions at the LHC, CMS-PAS-HIG-13-003; CMS Collaboration, Search for SM Higgs in $W^+W^- \to 3\ell3\nu$, CMS-PAS-HIG-12-039; CMS Collaboration, Evidence for a particle decaying to $W^+W^-$ in the fully leptonic final state in a standard model Higgs boson search in pp collisions at the LHC, CMS-PAS-HIG-12-042; CMS Collaboration, Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV, CMS-PAS-HIG-12-045; CMS Collaboration, Search for the standard model Higgs boson produced in association with W or Z bosons, and decaying to bottom quarks for HCP 2012, CMS-PAS-HIG-12-044; CMS Collaboration, Search for Higgs boson production in association with top quark pairs in pp collisions, CMS-PAS-HIG-12-025; CMS Collaboration, Search for the Standard-Model Higgs boson decaying to tau pairs in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV, CMS-PAS-HIG-13-004; CMS Collaboration, Search for the standard model Higgs boson in the Z boson plus a photon channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV, CMS-PAS-HIG-13-006; CMS Collaboration, Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV, CMS-PAS-HIG-13-005.