Where is the Higgs boson?

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(Dated: June 16, 2003)

Abstract

Electroweak precision measurements indicate that the standard model Higgs boson is light and that it could have already been discovered at LEP 2, or might be found at the Tevatron Run 2. In the context of a TeV$^{-1}$ size extra dimensional model, we argue that the Higgs boson production rates at LEP and the Tevatron are suppressed, while they might be enhanced at the LHC or at CLIC. This is due to the possible mixing between brane and bulk components of the Higgs boson, that is, the non-trivial brane-bulk ‘location’ of the lightest Higgs. To parametrize this mixing, we consider two Higgs doublets, one confined to the usual space dimensions and the other propagating in the bulk. Calculating the production and decay rates for the lightest Higgs boson, we find that compared to the standard model (SM), the cross section receives a suppression well below but an enhancement close to and above the compactification scale $M_c$. This impacts the discovery of the lightest (SM like) Higgs boson at colliders. To find a Higgs signal in this model at the Tevatron Run 2 or at the LC with $\sqrt{s} = 1.5$ TeV, a higher luminosity would be required than in the SM case. Meanwhile, at the LHC or at CLIC with $\sqrt{s} \sim 3–5$ TeV one might find highly enhanced production rates. This will enable the latter experiments to distinguish between the extra dimensional and the SM for $M_c$ up to about 6 TeV.

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I. INTRODUCTION

The Higgs boson is the missing link connecting the real world with the unified electroweak (EW) gauge group by spontaneously breaking the latter. Precision measurements of EW observables constrain the Higgs mass below about 200 GeV at 95% C.L. \[1, 2, 3, 4, 5, 6, 7\] within the standard model (SM). Thus, it is expected that a Higgs particle will be discovered at the Run 2 of the Tevatron, provided sufficient luminosity \[8\]. But it is intriguing to notice that the EW observables strongly prefer a SM like Higgs with mass below 114.1 GeV \[5, 7\], which is the present lower limit from LEP 2. The data also indicate that the Higgs boson should have already been discovered \[5\], and the fact that it was not found can be interpreted as new physics crucially affecting the Higgs sector \[7\]. In this work we put forward a model in which the presently missing signal of the lightest Higgs boson is due to a suppression of the Higgs production cross section at LEP and the Tevatron. This suppression arises from the non-trivial ‘location’ of the lightest Higgs boson in a five dimensional space. However, the same feature promises enhancement of the Higgs signal at the CERN Large Hadron Collider (LHC) and possibly at a multi TeV linear collider (CLIC).

The idea that our universe could be confined to a higher dimensional defect has been revived both in field theory \[10\] and string contexts \[11\]. It has been laid on more solid ground in the context of non-perturbative string analyses \[12, 13, 14\], and applied as a possible solution to the gauge hierarchy problem \[15, 16, 17, 18\]. Such a solution relies on the existence of \(n > 0\) additional compact space-like dimensions. In models based on this idea, the four dimensional Planck scale \(M_{Pl}\) becomes an effective quantity and it is related to the fundamental scale \(M\) by the volume of the extra space \(V_n\) via the relation \(M_{Pl}^2 = M^{n+2} V_n\). If one requires \(M = \mathcal{O}(\text{TeV})\) then for \(n = 2\), the compactification radius \(R \sim V_n^{1/n}\) is in the order of a millimeter, but for \(n = 7\) it is less than a fermi, not far from the inverse of a TeV. It is remarkable to notice that with \(\mathcal{O}(\text{TeV}^{-1})\) size extra dimensions the hierarchy problem is indeed nullified, since the fundamental scales \(M \sim 1/R\) are close to TeV.

The string arguments of Ref.s \[12, 14\] also allow the standard gauge and Higgs sectors to penetrate the bulk. If the compactification scale \(M_c = 1/R\) is higher than \(\mathcal{O}(\text{TeV})\), phenomenology does not conflict with this scenario either \[19, 20, 21, 22, 23, 24\]. This makes the inverse TeV size extra dimensional models attractive. Alternatively, the hierarchy problem can be solved with the use a non-factorizable geometry, which has also been proposed in five dimensions. The introduction of an exponential ‘warp’ factor reduces all mass parameters of the order of a fundamental \(M_{Pl}\) of a distant brane to TeV’s on the brane where we live \[25\]. In order to explain large hierarchies among energy scales one simply has to explain small distances along the extra dimension, thus this mechanism requires a Planck scale size extra dimension \[25, 26\].
These intriguing possibilities have opened a new window for the exploration of physics beyond the SM, in particular, the phenomenology of the Higgs sector. In Ref. [27, 28, 29], it is shown that it is possible to obtain electroweak symmetry breaking in an extra-dimensional scenario even in the absence of tree-level Higgs self-interactions. Also, in Ref. [30], we find scenarios in which the radion in the Randall-Sundrum model is contrasted with the SM Higgs boson. Studying several models that lead to a universal rate suppression of Higgs boson observables, Ref. [32] concluded that the Tevatron and LHC will have difficulty finding evidence for extra-dimensional effects. Yet another study of universal extra dimensions [33] conjectures that a suppression of the Higgs rates occurs [34].

However, just as in the SM and other four-dimensional theories, the Higgs sector remains the least constrained, since it can live either on the brane or in the bulk, each choice being phenomenologically consistent. One way to parametrize this freedom is to consider an extra-dimensional two-Higgs-doublet model (XD THDM) where one doublet lives in the bulk while the other is confined to the brane. The lightest Higgs boson state, which will resemble the SM one, will then be a linear combination of the neutral components of the two doublets. Constraints from electroweak precision data have been applied to such a model, and it was found that the compactification scale is larger than a couple of TeVs [35].

In this paper, we study the ability of present and future colliders to find the lightest Higgs boson in a XD THDM with a single TeV$^{-1}$ size new dimension. In particular, our aim is to estimate the minimal size of the compact dimension for which the lightest Higgs signal is distinguishable from that of the SM (or THDM) at the LHC or at CLIC.

We assume that the SM gauge bosons and one of the Higgs doublets propagate in this compact dimension. The SM $W^\pm$ and $Z$ particles are identified with the zero modes of the five-dimensional gauge boson fields. There is a second Higgs field restricted to the brane together with all the matter fields of the SM. Although the Higgs spectrum includes two CP-even states ($h, H$, with $m_h < m_H$), one CP-odd Higgs ($A$) and a charged pair ($H^\pm$), in this work we focus on the lightest Higgs boson $h$, because most likely this will be the first Higgs state that future colliders will detect. The CP-even Higgses may be the combinations, i.e. brane-bulk mixed states, of the two Higgs doublets.

We derive the Lagrangian for Higgs interactions and apply it to calculate the cross section of the associated production of Higgs with gauge bosons at the LC, as well as the dominant Higgs decays including the possible contributions from virtual KK states. Crucial to our approach is the cumulative effect of the virtual gauge boson KK states, $W^{\pm(n)}$ and $Z^{(n)}$, which contribute to the cross section for the production of the Higgs associated with the $W^\pm$ and $Z$ and to the three-body decay $h \rightarrow V f \bar{f'}$ ($V = W^{\pm(0)}$, $Z^{(0)}$). The corresponding reactions at hadron colliders are studied as well.

We remark that in this scenario, with a low enough compactification scale, the discovery of the extra dimension would probably precede the discovery of the lightest Higgs boson.
Gauge bosons propagating in the new dimension would exhibit unambiguous resonances, for example, in their s-channel production at the LHC. Our focus is on the lightest Higgs because we investigate how much information the various colliders can give us about the Higgs sector with a second Higgs doublet in the bulk. While more exotic processes might provide more useful to this end, we restrict ourselves to $Vh$ production ($V = W^\pm$ or $Z$) because our emphasis is that this dominant search channel is suppressed at the Tevatron (and at LEP), while possibly enhanced at future colliders.

The organization of our paper is as follows. In Section II we present the model that we use to study the brane-bulk mixing of the Higgs boson. Then in Section III we derive formulae for the Higgs production and decays. These include the evaluation of the contribution from virtual $Z^{(n)}$ KK states to the associated production at linear colliders, i.e. $e^+e^- \rightarrow hZ^{(0)}$, as well as to the three-body decay $h \rightarrow V f \bar{f}'$. Results of our calculation for the hadron collider case are also included. The discussion of the implications of our results for present and future colliders appears in Section IV, while the conclusions are presented in Section V.

II. MODELING THE HIGGS LOCATION

To describe the brane-bulk Higgs mixing, we work with a five dimensional (5D) extension of the SM that contains two Higgs doublets. The SM fermions and one Higgs doublet ($\Phi_u$) live on a 4D boundary, the brane, while the gauge bosons and the second Higgs doublet ($\Phi_d$), are all allowed to propagate in the bulk. The constraints from electroweak precision data [35] show that the compactification scale can be of $O$(TeV) (3-4 TeV at 95 % C.L.). The relevant terms of the 5D $SU(2) \times U(1)$ gauge and Higgs Lagrangian are given by

$$\mathcal{L}^5 = -\frac{1}{4} (F_{MN}^a)^2 - \frac{1}{4} (B_{MN})^2 + |D_M \Phi_d|^2 + |D_\mu \Phi_u|^2 \delta(x^5),$$

(1)

where the Lorentz indices $M$ and $N$ run from 0 to 4, and $\mu$ runs from 0 to 3. The covariant derivative is given by

$$D_M = \partial_M + ig_5 \frac{Y}{2} B_M + ig_5 \sigma^a \frac{A^a_M}{2}.$$

(2)

Given this definition, the mass dimensions of the fields are: $\text{dim}(\Phi_d) = 3/2$, $\text{dim}(\Phi_u) = 1$, $\text{dim}(A_M) = 3/2$, $\text{dim}(B_M) = 3/2$, and the 5D gauge couplings have a mass dimension of $-1/2$. Bulk fields are defined to have even parity under $x^5 \rightarrow -x^5$, and are expanded as

$$S(x^\mu, x^5) = \frac{1}{\sqrt{\pi R}} \left( S^{(0)}(x^\mu) + \sqrt{2} \sum_{n=1} \cos \left( \frac{n x^5}{R} \right) S^{(n)}(x^\mu) \right).$$

(3)

This decomposition, together with Eq. (1), guarantees that after compactification we obtain the usual 4D kinetic terms for all fields.

Spontaneous symmetry breaking (SSB) of EW symmetry occurs when the Higgs doublets acquire vacuum expectation values (vevs). After SSB the Higgs fields on the brane can be
written as

\[
\Phi_u = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_0^u \\ \Phi_u^- \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} v_u + h \cos \alpha + H \sin \alpha + i \cos \beta A \\ \cos \beta H^- \end{pmatrix},
\]

(4)

\[
\Phi_d^{(0)} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_0^d \\ \Phi_d^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d - h \sin \alpha + H \cos \alpha + i \sin \beta A \\ \sin \beta H^+ \end{pmatrix},
\]

(5)

where the neutral CP-even bosons are denoted by \(h\) and \(H\), and \(h\) is identified with the lightest Higgs: \(m_h < m_H\). The mixing angle \(\alpha\) is introduced to diagonalize the CP-even mass matrix. The CP-odd and charged Higgs fields are denoted by \(A\) and \(H^\pm\), and \(v_u\) and \(v_d\) are the vevs of \(\Phi_u\) and \(\Phi_d^{(0)}\) respectively. Note that the angles \(\alpha\) and \(\beta = \arctan(v_u/v_d)\) parametrize what we call brane-bulk mixing, or higher dimensional ‘location’, of the neutral Higgses.

After performing the KK-mode expansion and identifying the physical states, one derives the interaction Lagrangian for all the vertices of the neutral and charged Higgses. In particular, the interactions \(ZZh\) and \(ZZ^{(n)}h\), which are necessary to calculate the Higgs production in association with a \(Z\), as well as the vertices involving the \(W^\pm\) bosons, are given by the following 4D Lagrangian:

\[
\mathcal{L}^I \supset \frac{g M_Z}{2 c_W} (h \sin(\beta - \alpha) + H \cos(\beta - \alpha)) Z_\mu Z^\mu \\
+ \sqrt{2} \frac{g M_Z}{c_W} (h \sin \beta \cos \alpha + H \sin \beta \sin \alpha) \sum_{n=1}^{\infty} Z^{(n)}_\mu Z^\mu \\
+ g M_W (h \sin(\beta - \alpha) + H \cos(\beta - \alpha)) W^+_\mu W^-\mu \\
+ \sqrt{2} g M_W (h \sin \beta \cos \alpha + H \sin \beta \sin \alpha) \sum_{n=1}^{\infty} \left( W^{+}_{\mu} W^{-}(n)_{\mu} + W^{-}_{\mu} W^{+}(n)_{\mu} \right). \tag{6}
\]

Thus, the vertices \(hZZ\) and \(hWW\) have the same form as in the usual 4D THDM, i.e. proportional to \(\sin(\beta - \alpha)\). Meanwhile the couplings \(hZZ^{(n)}\) and \(hW^+W^\pm(n)\) are proportional to \(\sin \beta \cos \alpha\), vanishing either when \(\beta = 0\) or \(\alpha = \pi/2\), i.e. either when EWSB is driven exclusively by the vev of \(\Phi_d^{(0)}\) or when the CP-even Higgs comes entirely from \(\Phi_d^{(0)}\). Similarly, the couplings of the CP-odd Higgs \(A\) and the charged Higgs resemble the THDM, although new vertices of the type \(H^+W^-Z^{(n)}\) or \(H^+W^-Z^{(n)}\) could be induced.

On the other hand, because the fermions are confined to the brane, the Higgs-fermion couplings could take any of the THDM I, II or III versions \cite{36, 37}. However, for the THDM III version the possible FCNC problems would be ameliorated, as the bulk-brane couplings will be suppressed by the factor \(1/\sqrt{2\pi R}\) \cite{38}. Thus, for the flavor conserving couplings one can use the formulae of the widely studied THDM II, which appears for instance in the Higgs Hunters Guide \cite{39}.
III. EXTRA DIMENSIONAL CONTRIBUTION TO HIGGS PRODUCTION AND DECAYS

A. Associated production $h + Z$ at linear colliders

In order to study Higgs production at future colliders, first we derive the cross section for the Bjorken process, namely for $e^+e^- \rightarrow hZ$. The total amplitude includes the contribution of virtual $Z = Z^{(0)}$ and $Z^{(n)}$ states in the $s$-channel. The sum over all KK modes can be performed analytically, which considerably simplifies the final expression. Our result for the cross section is given by

$$\sigma(e^+e^- \rightarrow hZ) = \sigma_{SM} F_{XD}(\alpha, \beta, s).$$

(7)

Here $\sigma_{SM}$ denotes the SM cross section, given by

$$\sigma_{SM} = \frac{G_F M_Z^4}{3\pi} \left( 4s_w^4 - 2s_w^2 + \frac{1}{2} \right) \frac{|k| (3M_Z^2 + |k|^2)}{\sqrt{s} (s - M_Z^2)},$$

(8)

with

$$|k| = \frac{1}{\sqrt{s}} \left( \frac{s + M_Z^2 - m_h^2}{2} \right)^2 - sM_Z^2 \right)^{1/2}$$

(9)

being the 3-momentum of the $Z$ boson.

The extra dimensional contribution is factorized into

$$F_{XD}(\alpha, \beta, s) = [\sin(\beta - \alpha) + 2 \cos \alpha \sin \beta F_{KK}(s)]^2.$$

(10)

The function $F_{KK}$, which arises after summing over all the virtual KK-modes, is given by

$$F_{KK}(s) = 2 \sum_{n=1}^{\infty} \frac{s - M_Z^2}{s - M_n^2} = RA(s) \pi \cot(RA(s)\pi) - 1,$$

(11)

where

$$M_n = \sqrt{n^2/R^2 + M_Z^2},$$

(12)

is the mass of the $n^{th}$ KK level. When neglecting the widths,

$$\Gamma_n = M_n \alpha_g (v_f^2 + a_f^2)/3,$$

(13)

of the KK resonances[46], we can write

$$A(s) = \sqrt{s - M_Z^2}.$$

(14)

(Here $v_f$ and $a_f$ are the SM vector and axial coupling strength of the vector boson to fermions.) This is a reasonable approximation, since $\alpha_g = g^2/(4\pi) \ll 1$. By neglecting only $M_Z \alpha_g$ terms (next to $M_Z$), we can even include the dominant width effect by setting

$$A(s) = \sqrt{c(s - cM_Z^2)/c},$$

(15)
Recently it was pointed out that summing over a large number of KK resonances may jeopardize the unitarity of standard-like extra dimensional models \[40\]. Thus, we mention that the sum in Eq.(11) can also be performed analytically for a finite number of terms with the result:

\[
F_{KK}(s) = 2 \sum_{n=1}^{N} \frac{s - M_Z^2}{s - M_n^2} = RA(s)(\pi \cot(RA(s)\pi) - H_{N-RA(s)} + H_{N+RA(s)}) - 1, \tag{16}
\]

where \(H_x\) is the harmonic number function. (The KK width can also be included as above). Since the \(F_{KK}\) function can be calculated even analytically, we can easily check its sensitivity to the number of KK levels and the inclusion of KK width. Fig.(11) shows that, for a typical set of parameters, \(F_{KK}\) is reasonably insensitive to these, which ensures that our later results are robust against cutoff and width effects of KK levels in the relevant energy range.

These expressions also apply for the process \(qq' \rightarrow W^{\pm}h\) after changing \(\sigma_{SM}\) and \(M_Z\) to \(M_W\) at the appropriate places.

**B. Associated production \(h + Z, h + W^{\pm}\) at hadron colliders**

When considering Higgs production at hadron colliders, an expression similar to Eq.(7) holds at the parton level for the production cross section of the Higgs in association with a
\( W^\pm \) or \( Z \). To obtain the hadronic cross section \( h_1 h_2 \to hZ \), the partonic cross section must be convoluted with the parton distribution functions (PDFs):

\[
\sigma(h_1 h_2 \to Z h) = \sum_{q\bar{q}} \int_0^1 \int_0^1 f_{q/h_1}(x_1, \hat{s})\sigma(q\bar{q} \to Z h) f_{\bar{q}/h_2}(x_2, \hat{s}) dx_1 dx_2 + q \leftrightarrow \bar{q}.
\]  

(17)

Here \( f_{q/h_i}(x, \hat{s}) \) gives the distribution of a parton \( q \) in the hadron \( h_i \) as a function of the longitudinal momentum fraction \( x \) and the factorization scale, which is chosen to be the partonic center of mass \( \hat{s} \). In our numeric study we use CTEQ4M PDFs \[41\]. The sum in Eq. (17) extends over the light quark flavors \( q = u, d, s, c \).

The large center of mass energy that can be achieved at the LHC also opens up the possibility to produce a Higgs boson in association with KK states, for instance \( hZ^{(1)} \), which will have a very distinctive signature that could allow ‘direct’ detection of the first KK modes at the LHC. This possibility is studied elsewhere.

C. Higgs decays

For Higgs bosons lying in the intermediate mass range, which is in fact favored by the analysis of electroweak radiative corrections, the dominant decay is into \( b\bar{b} \) pairs. In our higher dimensional model this decay width is given by the formulae of the THDM, just as that of the other tree-level two-body modes. On the other hand, for the three-body decays \( h \to Wl\bar{\nu}_l \) and \( h \to Zl^+l^- \), which can play a relevant role at the Tevatron and LHC, the corresponding decay width could receive additional contributions from the virtual KK states. The inclusion of these KK modes leads to the following expression for the differential decay width:

\[
\frac{d\Gamma}{dx}(h \to Wl\bar{\nu}_l) = \frac{g^4 m_h}{3072\pi^3} \left( \frac{x^2 - 4r_w}{1 - x} \right)^{1/2} f_V(x) \left[ \sin(\beta - \alpha) + 2 \cos \alpha \sin \beta F_{KK} \right]^2,
\]

(18)

where \( f_V(x) = x^2 - 12r_w x + 8r_w + 12r_w^2 \), with \( r_w = M_{W}^2/m_h^2 \), and \( 2r_w^{1/2} < x < 1 + r_w \). The \( F_{KK} \) function is given as in Eq. (11), with the replacements \( s \to q^2 = m_h^2(1-x) \) and \( M_Z \to M_W \). A similar expression can be derived for the decay \( h \to Zl^+l^- \).

To study the effect of the KK modes on the decay \( h \to Wl\bar{\nu}_l \), we have evaluated the ratio of the corresponding decay width in the extra dimensional scenario over the SM decay width:

\[
R_{h\rightarrow WW^*} = \frac{\Gamma(h \rightarrow Wl\bar{\nu}_l)_{XD}}{\Gamma(h \rightarrow Wl\bar{\nu}_l)_{SM}}.
\]

(19)

Results for this ratio are shown in Table I for several representative sets of parameters which are chosen as

**A**: \( M_c = 2 \text{ TeV}, \alpha = \pi/3 \),  \( B \): \( M_c = 2 \text{ TeV}, \alpha = \pi/1.28 \),
Where $eta = \pi/4$ remains fixed. We observe that significant deviations from the SM can appear, although this effect is largely due to the difference of the Higgs couplings in the THDM and the SM.

On the other hand, the loop induced decays $h \to \gamma\gamma, Z\gamma$ also receive contributions from the $W^{(n)}$ KK modes. But since the coupling $hWW^{(n)}$ that appears in the loop is proportional to $M_W$, rather than $M_W^{(n)}$, the contribution of the KK states will decouple, as there are no mass factors that could cancel the ones in the numerator. Thus, the KK contribution can be neglected for the decay widths of the loop induced decays.

We conclude that in the intermediate Higgs mass range the decay $h \to b\bar{b}$ will continue to dominate, even more than in the SM case for some values of parameters. In the limit $M_c \gg O(1)$ TeV, one recovers the SM pattern for the Higgs decays.

### IV. IMPLICATIONS FOR HIGGS SEARCHES AT FUTURE COLLIDERS

#### A. The LC case

Because of its simplicity, first we discuss Higgs production at a linear collider. The present bound on the compactification scale is $M_c \gtrsim 3.8$ TeV \cite{12}, for the cases when the Higgs field is either in the bulk or confined to the brane. For the general case of “mixing” one obtains similar bounds \cite{13}.

The results for the $e^+ e^- \to hZ$ cross section, after the inclusion of the virtual $Z$ KK contribution, are shown in Fig. 2. This plot shows the cross section as a function of the center of mass energy ($200 < \sqrt{s} < 4000$ GeV), for $m_h = 120$ GeV and a value of the compactification scale $M_c = 4$ TeV. We plot the SM cross section $\sigma_{SM}$, the THDM cross section $\sigma_{THDM}$, as well as the extra dimensional cross section $\sigma_{XD}$. Three different pairs of $\alpha$ and $\beta$ were chosen to compute $\sigma_{THDM}$ and $\sigma_{XD}$. They are given by

- $a : \beta = \pi/4, \alpha = -\pi/4$,
- $b : \beta = \pi/4, \alpha = 0$,
- $c : \beta = \pi/4, \alpha = 0.241\pi$.

| $m_h$ (GeV) | $R_{hWW^*}$ (set A) | $R_{hWW^*}$ (set B) | $R_{hWW^*}$ (set C) | $R_{hWW^*}$ (set D) |
|------------|----------------------|----------------------|----------------------|----------------------|
| 130        | $6.0 \times 10^{-2}$ | 0.999                | 0.51                 | 0.50                 |
| 140        | $6.0 \times 10^{-2}$ | 0.998                | 0.51                 | 0.50                 |
| 150        | $6.1 \times 10^{-2}$ | 0.996                | 0.50                 | 0.50                 |
| 160        | $6.1 \times 10^{-2}$ | 0.993                | 0.50                 | 0.50                 |

TABLE I: The ratio $R_{hWW^*}$, introduced in Eq. (19), for several sets of parameters A, B, C, D (as defined in the text), and with $\beta = \pi/4$. 

C : $M_c = 2$ TeV, $\alpha = \pi$, while $\beta = \pi/4$ remains fixed. We observe that significant deviations from the SM can appear, although this effect is largely due to the difference of the Higgs couplings in the THDM and the SM.
FIG. 2: SM, THDM and XD cross sections for $e^+e^- \rightarrow hZ$. Each plot corresponds to a different set of values for $\alpha$ and $\beta$ all with $m_h = 120$ GeV and with a compactification scale $M_c = 4$ TeV.

Choice a corresponds to a case in which $\sigma_{THDM} = \sigma_{SM}$; b corresponds to a case where the effect of the mixing due to $\alpha$ in the term involving the KK sum is maximum; c corresponds to values of $\alpha$ and $\beta$ for which $\sigma_{XD}/\sigma_{THDM}$ is larger than 1 above $\sqrt{s} = 2$ TeV.

The first frame of Fig. (2) shows well that the shape of the cross section is determined by the product of $F_{KK}$, as shown in Fig. (1), and the SM cross section.

We can see that in all three cases the cross section of the XD model is always smaller than that of the SM at $\sqrt{s} = 500, 1000$ GeV, and that in order to obtain a larger cross section, one needs energies greater than $\sqrt{s} \sim 2$ TeV. This is understood from the fact that the heavier KK modes, through their propagators, interfere destructively with the SM.
amplitude thus reducing the cross section. We mention that the three cases presented in Fig. 2 are only representative, and that one can find broad regions of parameter space in which $\sigma_{XD} > \sigma_{THDM}$.

Moreover, as Fig. 2 shows, once the center of mass energy approaches the threshold for the production of the first KK state, the cross section starts growing. For instance, with $M_c = 4$ TeV, $\sigma_{SM} \simeq \sigma_{XD}$ for $\sqrt{s} \simeq 2$ TeV. However, one would need higher energies in order to have a cross section larger than that of the SM, which may only be possible at CLIC [45].

According to current studies, when the cross section is 4% larger than the SM cross section, with the estimated precision that could be obtained at the LC [44], it may be possible to distinguish between the SM and XD Higgs scenarios. We can see that this might be possible at CLIC for $M_c = 3-4$ TeV for a broad range of parameter values. It is interesting to note that such deviations in the cross section from the SM prediction arise even when the couplings of the Higgs to the gauge bosons are indistinguishable from the SM couplings.

B. Implications for the Tevatron

After the productive but unsuccessful Higgs search at LEP2, the Run 2 of the Tevatron continues the search until the LHC starts operating. The luminosity that is required to achieve a 5 or 3 $\sigma$ discovery, or a 95% C.L. exclusion limit, was presented by the Run 2 Higgs working group [9]. For instance, with $m_h = 120$ GeV, the corresponding numbers are about 20, 6 and 2 $fb^{-1}$ respectively.

Assuming $M_c \geq 2$ TeV, the inclusion of the KK modes decreases the $hW^\pm$ and $hZ$ associated production cross section at the Tevatron. Depending on the actual values of $M_c$, $\alpha$ and $\beta$, the suppression in the parton level cross section may be anything between 1 and 99 percent. For example, if $M_c$ is a few TeV then the $s$-channel process $q\bar{q}' \rightarrow W^\pm h$ can receive a considerable suppression, as it can be inferred from Fig. 2. This is so unless the KK contribution itself is suppressed by $\cos\alpha$ and/or $\sin\beta$ in Eq. (7), in which case the presented model has little relevance. Thus, as a general prediction of this model, we conclude that more than the above listed luminosity is required to find a light Higgs boson. This slims the chances of the Tevatron to find the Higgs of this model.

C. Higgs production at the LHC

The Higgs discovery potential in this model is more promising at the LHC. We illustrate this in Fig. 3 showing the $pp \rightarrow hZ$ differential cross section as the function of the $hZ$ invariant mass $M_{hZ}$. The typical resonance structure displayed by Figs. 1 and 2 is preserved by the hadronic cross section. The resonance peak is well pronounced when $M_{hZ} \sim M_c$. This leads to a large enhancement over the SM (or THDM) cross section.
1. Multiply $10^{-6}$ by $0.01$ for $M_c = 6$ TeV.

The singularity at $M_c = M_{hZ}$ is regulated by the width of the KK mode, which is included in our calculation as given by Eq. (13). Thus, Fig. 3 gives a reliable prediction of the XD cross section even in the peak regions. Depending on the particular values of $\alpha$ and $\beta$ the enhancement is more or less pronounced. For an optimistic set $\alpha = 0$ and $\beta = \pi/2$, the XD production cross section is considerably enhanced compared to the SM at $M_{hZ} = M_c$. This enhancement may be detectable up to about $M_c = 6$ TeV. We estimate that with 100 fb$^{-1}$ for $M_c = 6$ TeV there are about 20 $hZ$ events in the bins around $M_{hZ} \sim M_c$. As Fig. 3 shows, in the SM less than one event is expected in the same $M_{hZ}$ range. It is needless to say that similar results hold for $pp \rightarrow hW^{\pm}$, which further enhances the discovery prospects.

Based on these results, we conclude that in the Bjorken process alone the reach of the LHC may extend to about $M_c = 6$ TeV, depending on the values of $\alpha$ and $\beta$. Finally, we note that the XD contribution to the running of the gauge couplings is important when the effective center of mass energy of the collider is close to $1/R$ [23, 24]. Since not included in this work, this contribution is expected to change our results somewhat for $\sqrt{s} \approx M_c$.

V. CONCLUSIONS

In this work, we studied the extent to which present and future colliders can probe the brane-bulk location of the Higgs boson in a model with a TeV$^{-1}$ size extra dimension. In
this model one Higgs doublet is located on the brane while another one propagates in the bulk. We found that the virtual KK states of the gauge bosons contribute to the associated production of the Higgs with $W^{\pm(n)}$ and $Z^{(n)}$, and at low energies ($\sqrt{s} < 1/R$ GeV) the cross section is suppressed compared to the SM case. Meanwhile at higher energies, i.e. at $\sqrt{s} \sim 1/R$, the cross section can receive an enhancement that has important effects on the discovery of the Higgs at future colliders.

Analysing compactification scales in the range of 2–8 TeV, we concluded that to find a Higgs signal in this model the Tevatron Run 2 and the LC with $\sqrt{s} = 500 - 1500$ GeV are required to have a luminosity higher than in the SM case. Meanwhile, the LHC and possibly CLIC with $\sqrt{s} \sim 3–5$ TeV might have a greater potential to find and study a Higgs signal. Depending on the model parameters, these colliders may be able to distinguish between the extra dimensional and the SM for compactification scales up to about 6 TeV. If this model is relevant for weak scale physics, the LHC should see large enhancements in the associated production rates. Thus, not finding the Higgs at the Tevatron may be good news for the XD Higgs search at the LHC.

Acknowledgments

A.A. was supported by the U. S. Department of Energy under grant DE-FG02-91ER40676. C.B. was also supported by the DOE, under contract number DE-FG02-97ER41022. J.L. D.-C. was supported by CONACYT and SNI (México).

[1] T. Takeuchi, W. Loinaz, N. Okamura and L. C. Wijewardhana, arXiv:hep-ph/0304203.
[2] M. S. Chanowitz, arXiv:hep-ph/0304199.
[3] P. Langacker, arXiv:hep-ph/0304186.
[4] J. Erler, arXiv:hep-ph/0212272.
[5] P. Langacker, J. Phys. G 29, 1 (2003).
[6] S. Villa, arXiv:hep-ph/0209359.
[7] M. S. Chanowitz, Phys. Rev. D 66, 073002 (2002).
[8] H. J. He, Y. P. Kuang, C. P. Yuan and B. Zhang, arXiv:hep-ph/0211229.
[9] M. Carena et al., arXiv:hep-ph/0010338.
[10] V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B 125, 136 (1983).
[11] I. Antoniadis, Phys. Lett. B 246, 377 (1990).
[12] J. Polchinski, Phys. Rev. Lett. 75, 4724 (1995).
[13] J. D. Lykken, Phys. Rev. D 54, 3693 (1996).
[14] P. Horava and E. Witten, Nucl. Phys. B 475, 94 (1996).
I. Antoniadis, S. Dimopoulos and G. R. Dvali, Nucl. Phys. B 516, 70 (1998).
N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429, 263 (1998).
I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 436, 257 (1998).
N. Arkani-Hamed, S. Dimopoulos and J. March-Russell, Phys. Rev. D 63, 064020 (2001).
A. Pomarol and M. Quiros, Phys. Lett. B 438, 255 (1998).
I. Antoniadis, S. Dimopoulos, A. Pomarol and M. Quiros, Nucl. Phys. B 544, 503 (1999).
A. Delgado, A. Pomarol and M. Quiros, Phys. Rev. D 60, 095008 (1999).
C.D. Carone, Phys. Rev. D 61, 015008 (2000).
K. R. Dienes, E. Dudas and T. Gherghetta, Phys. Lett. B 436, 55 (1998).
K. R. Dienes, E. Dudas and T. Gherghetta, Nucl. Phys. B 537, 47 (1999).
L. Randall and R. Sundrum, Phys. Rev. Lett. 83, 3370 (1999).
N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali and N. Kaloper, Phys. Rev. Lett. 84, 586 (2000);
G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B 544, 3 (1999).
T. Han, J. D. Lykken and R. Zhang, Phys. Rev. D 59, 105006 (1999).
For a list of experimental bounds see:
Y. Uehara, Mod. Phys. Lett. A 17, 1551 (2002);
N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Rev. D 59, 086004 (1999);
E. Mirabelli, M. Perelstein and M. Peskin, Phys. Rev. Lett. 82, 2236 (1999);
C. Balazs et. al, Phys. Rev. Lett. 83, 2112 (1999);
J. L. Hewett, Phys. Rev. Lett. 82, 4765 (1999);
T. G. Rizzo, Phys. Rev. D 59, 115010 (1999);
K. Aghase and N. G. Deshpande, arXiv:hep-ph/9902263;
L.J. Hall and D. Smith. Phys. Rev. D 60, 085008 (1999);
S. Cullen, M. Perelstein, Phys. Rev. Lett. 83, 268 (1999).
P. Nath, Y. Yamada and M. Yamaguchi, Phys. Lett. B 466, 100 (1999).
P. Nath and M. Yamaguchi, Phys. Rev. D 60, 116006 (1999);
M. L. Graesser, Phys. Rev. D 61, 074019 (2000).
B. Grzadkowski and J. F. Gunion, Phys. Lett. B 473, 50 (2000).
G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B 595, 250 (2001);
D. Dominici, B. Grzadkowski, J. F. Gunion and M. Toharia, arXiv:hep-ph/0206197;
J. L. Hewett and T. G. Rizzo, arXiv:hep-ph/0202155.
J. D. Wells, arXiv:hep-ph/0205328.
T. Appelquist and B. A. Dobrescu, Phys. Lett. B 516, 85 (2001).
F. J. Petriello, JHEP 0205, 003 (2002).
M. Masip and A. Pomarol, Phys. Rev. D 60, 096005 (1999).
[36] J. L. Diaz-Cruz and G. Lopez Castro, Phys. Lett. B 301, 405 (1993).
[37] J. L. Diaz-Cruz and J. J. Toscano, Phys. Rev. D 62, 116005 (2000).
[38] Y. Sakamura, arXiv:hep-ph/9912511.
[39] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, “The Higgs Hunter’s Guide,” SCIPP-89/13.
[40] R. S. Chivukula, D. A. Dicus, H. J. He and S. Nandi, Phys. Lett. B 562, 109 (2003) arXiv:hep-ph/0302263.
[41] H. L. Lai et al., Phys. Rev. D 55, 1280 (1997).
[42] T. G. Rizzo and J. D. Wells, Phys. Rev. D 61 (2000) 016007 arXiv:hep-ph/9906234.
[43] A. Muck, A. Pilaftsis and R. Ruckl, arXiv:hep-ph/0209371.
[44] M. Battaglia and K. Desch, arXiv:hep-ph/0101165.
[45] R. W. Assmann et al., SLAC-REPRINT-2000-096.
[46] The width of the $n$-th KK state is defined as its total decay rate into a SM fermion pair.