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Research Article

Relaxing the W' Constraint on Compact Extradimension

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In this paper, we study the constraint on brane tension and compactification scale for models with brane fluctuations using the results from the direct search of W' at 13 TeV LHC, with an integrated luminosity of $36.1 fb^{-1}$, in the case for which branon forms the entire cold dark matter. The inclusion of these brane fluctuations suppresses the KK-mode couplings to brane localised matter fields. Unlike the rigid brane scenario, where the compactification scale gets constrained to $(1/R) > 5.2$ TeV, here we show that compactification scales as small as ~ 1 TeV are allowed for brane tensions of similar strength.

1. Introduction

One of the primary motivations for the search of new physics beyond Standard Model (SM) is to resolve the well-known gauge hierarchy/naturalness problem in connection with the fine-tuning of the Higgs mass against large radiative corrections, the reason being the enormous difference between the electroweak and Planck scales. Among several proposals to address this problem, models with extra spatial dimensions draw special attention. While one such proposal [1–3] solves the hierarchy between the scales by assuming the bulk fundamental scale of the order of electroweak scale, with the apparent hierarchy generated from the volume of the extradimensional space, the other [4] uses a dual interpretation of composite Higgs by assuming a bulk AdS_5 geometry, compactified on a circle of a radius of the order of the Planck scale. Neither of these remarkable solutions are without caveats. The astrophysical [5] and *Large Hadron Collider* (LHC) [6, 7] measurements have placed tight constraints which push these models to the brink of their naturalness.

Apart from these two families of models envisaged to solve the theoretical problems faced by Standard Model, flat extradimensional models with TeV scale compactification [1] and their derivatives are known to contain a plethora of phenomenological observables. A minimal version of such models with Standard Model fields allowed to propagate in the five-dimensional bulk has been facing challenges recently from the LHC [8, 9] and dark matter relic observations [10, 11]. There has been significant effort [12] in solving these problems by modifying the geometry to include strongly coupled gravity in the bulk.

In all the above models, it has been assumed that the segment of the extradimension is protected by very rigid world end branes. Though a dynamical understanding [13–16] regarding the origin of these positive tension branes could be from topological defects (like kinks) that arise in spontaneous symmetry breaking of a real scalar field in the bulk, in the setup of the above models, an effective treatment [17, 18] for the brane is sufficient. Since these branes support localisation of matter fields on to them, any such localised field necessarily couples universally to all the Kaluza Klein (KK) modes, with masses $M_n = n/R$, of the bulk fields. This, along with the recent direct searches for a heavy charged gauge boson decaying into a final state lepton accompanied by a large missing energy at 13 TeV LHC, with an integrated luminosity of $36.1 fb^{-1}$ [19], rules out the compactification scale $(1/R)$ up to 5.2 TeV.

Nevertheless, due to the absence of rigid bodies in relativistic mechanics, any kind of brane necessarily fluctuates. These fluctuations or branons are the Nambu-Goldstone bosons (or pseudo-NG bosons as shown in the next section) of the spontaneously broken translational symmetry in the extradimension due to the presence of the brane. There have been many direct and indirect collider studies [20–22] conducted to look for these particles. These branon modes are also understood [23] to have suppression effect on the gauge boson KK mode coupling with brane localised fields. It has been shown [24–26] that these zero modes, due to their particular interaction structure, are stable and could be responsible for the dark matter (DM) content of the universe. They constitute a wide spectrum ranging from hot to cold DM depending on their mass and the brane tension.

In this paper, we aim to relax the bound from W' direct searches on models with brane localised fermions by including the brane fluctuations. Along with satisfying the LEP observables, we will study the interaction of the KK-1 partner of the W-boson with brane localised fermions in the limiting case where the branon field forms the entire cold dark matter and constrain the compactification scale for given brane tension. In our analysis, we will show that though a large portion of the parameter space gets ruled out, small compactification scale $(1/R)(\sim 1\ \text{TeV})$ for a comparable brane tension (f) is still allowed. The result becomes better on increasing the cutoff scale, but only at the cost of naturalness. Since we work in the limit where domain walls are very thin in comparison with the compactification radius, we will assume $f \gtrsim 1/R$.

We will start the paper by briefly describing the effective low-energy description of the brane and its fluctuation in Section 2 and compute the interactions of W-boson KK modes with the brane localised matter in Section 3. We will, using the 13 TeV LHC data, constrain the model parameters, namely, the brane tension and the compactification radius, and present the results in Section 4.

2. Effective Description of the Brane and Its Goldstone Bosons

In the following, we will briefly review the effective theory [27] understanding of the massive brane fluctuations. Though the origin of the brane is not well understood, topological defects arising from the breaking of the Z_2 symmetry of a scalar $\lambda\phi^4$ theory can form stable domain wall solutions that localise matter fields. For brevity, we will use the low-energy effective description to understand the brane fluctuations and their influence on the W gauge boson interactions.

To that end, we will consider a 3-brane, with coordinates x_μ, $\mu = 0, 1, 2, 3$, embedded in a five-dimensional bulk that is compactified on $M_4 \times S^1 (x_M, M = 0, 1, 2, 3, 5)$, with compactification scale $1/R < M_s$, where M_s is the cutoff scale of the effective model. It is convenient to parametrize the brane as $Y^M = (x^\mu, Y(x))$ with induced metric $g_{\mu\nu} = \partial_\mu Y^M \partial_\nu Y^N G_{MN}$, where G_{MN} is the metric in the bulk and its action could be written as

$$S = -\tau \int_{M_4} \sqrt{g}\, d^4x, \qquad (1)$$

where $\tau = (1/4\pi^2) f^4$ is the brane tension. This particular form of brane parametrisation takes care of the gauge degree of freedom of the Lagrangian under $x \longrightarrow x'$ in addition to the usual bulk coordinate invariance.

In the event of the brane having been created at a certain point $Y(x) = Y_0$, its presence breaks all the isometries involving the direction of the compact S^1. The excitations along that direction corresponding to the zero modes could be parametrised by the Nambu-Goldstone boson field $\omega(x)$. Or in other words,

$$Y(x) = Y(Y_0, \omega(x)) = Y_0 + \left.\frac{\partial Y}{\partial \omega}\right|_{Y=Y_0} \omega(x) + O(\omega^2). \qquad (2)$$

To understand these Nambu-Goldstone bosons or branons that arise on the breaking of this isometry, let us assume a bulk metric of the form

$$G_{MN} = \begin{pmatrix} \tilde{g}_{\mu\nu}(x_\mu, x_5) & 0 \\ 0 & -1 \end{pmatrix}. \qquad (3)$$

Expanding $\tilde{g}_{\mu\nu}(x_\mu, x_5)$ about $x_5 = Y_0$, we get

$$\sqrt{g} = \sqrt{\tilde{g}} \left(1 - \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \omega \partial_\nu \omega + \frac{1}{4} \tilde{g}^{\mu\nu} \partial_Y^2 \tilde{g}_{\mu\nu} \omega^2 + \cdots \right). \qquad (4)$$

Using this, the effective action for the brane could be written as

$$S = \int_{M_4} d^4x \sqrt{\tilde{g}} \left[-\tau + \frac{\tau}{2} \left(\tilde{g}^{\mu\nu} \partial_\mu \omega \partial_\nu \omega - M^2 \omega^2 \right) \right], \qquad (5)$$

where $M^2 = (1/2) \tilde{g}_{\mu\nu} \partial_Y^2 \tilde{g}^{\mu\nu}$ is the mass term due to the explicit breaking. If we had chosen a metric that is independent of the deformation, the branons would have remained massless. This is similar to the explicit chiral symmetry breaking by the quark masses, which leads to massive pions. Since the branons form pseudoscalars on a 3-brane [25], all Lagrangian terms with odd number of branon legs vanish under the parity symmetry. Hence, they are always stable and the massive ones are ideal candidates for cold DM [26].

Though the branon physics is interesting in its own regard, in this paper, we are interested in the influence of branons on the gauge interaction with brane localised fields. From the above action, we could derive the 3 + 1-dimensional, position space, 2-point correlator for the pseudo-Goldstone boson in the time-like region to be [28]

$$\langle \omega(x) \omega(y) \rangle = S_\omega(x - y) = i \frac{1}{\tau} \frac{M}{8\pi |x - y|} H_1^{(2)}(M |x - y|), \qquad (6)$$

where $H_1^{(2)}$ is the Hankel function of the second kind. Note that in the limit $M \longrightarrow 0$, the above propagator becomes

$$\langle \omega(x) \omega(y) \rangle |_{M \longrightarrow 0} = -\frac{1}{\tau} \frac{1}{4\pi^2 |x - y|^2}, \qquad (7)$$

which is the well-known massless scalar propagator and matches with the zero mode kink fluctuation [15]. In the next section, we will analyse the interaction of bulk gauge bosons with the brane localised fermions.

3. Model and W' Interaction

In this model, we assume that the matter fields are localised on the brane and the gauge fields are free to propagate in the bulk. This will not only reduce the effect of the higher dimensional operators causing FCNC but will also allow a rich phenomenology at LHC. The excursion of gauge fields in the bulk of a compactified manifold necessarily brings along the discretised set of KK modes, which couple to the brane and the localised matter fields, depending on their boundary conditions. For phenomenological purpose, we choose Neumann boundary condition at both $x_5 = 0$ and $x_5 = \pi R$, ensuring that the gauge boson has a zero mode which will be identified with the Standard Model gauge boson. With these boundary conditions, the bulk gauge field could be expanded in Fourier series as

$$A_\mu(x_\nu, x_5) = \frac{1}{\sqrt{2\pi R}} A_\mu^{(0)}(x_\nu) + \frac{1}{\sqrt{\pi R}} \sum_{n=1} A_\mu^{(n)}(x_\nu) \cos(M_n x_5), \tag{8}$$

where the masses of the KK modes are given by $M_n = n/R$. Assuming that the gauge boson corresponds to the $SU(2)$ weak sector, the lightest of the KK modes is identified with the Standard Model W-boson gauge field.

The Lagrangian term that corresponds to the interaction of these bulk gauge bosons with the fermion fields is given as

$$g_5 \int d^4x dx_5 \bar{\Psi}(x_\mu) \gamma^\mu \Psi(x_\mu) \left[\xi(x_5 - \omega(x_\mu))\right]^2 A_\mu(x_\mu, x_5), \tag{9}$$

where $\Psi(x_\mu)$ is the brane localised fermions, on a kink with mass m_{kink}, with the extradimensional wave profile $\xi(x_5 - \omega(x_\mu)) = A_0 \cos h^{-1}((m_{\text{kink}}(x_5 - \omega(x_\mu)))/\sqrt{2})$ [13, 15]. Although, for simplicity and to arrive at a closed form analytic solution, we will work in the limit where the wave profile ξ can be replaced by a delta function $\delta(x_5 - \omega(x_\mu))$, it can be shown that the coupling thus obtained matches at a subpercent level (for a kink mass $m_{\text{kink}} \gtrsim 10(1/R)$) to that obtained using the exact form.

Using the plane wave expansion for the gauge bosons, the interaction term above could be rewritten as

$$\begin{aligned} & g_5 \int d^4x \bar{\Psi}(x_\mu) \gamma^\mu \Psi(x_\mu) A_\mu(x_\mu, \omega(x_\mu)) \\ & = g \int d^4x \sum_n \bar{\Psi}(x_\mu) \gamma^\mu \Psi(x_\mu) A_\mu^n(x_\mu) \cos\left(\frac{n}{R}\omega(x_\mu)\right) \\ & = g \int d^4x \sum_n e^{-1/2\left(\frac{n}{R}\right)^2 S_\omega(M_s)} \bar{\Psi}(x_\mu) \gamma^\mu \Psi(x_\mu) A_\mu^n(x_\mu) \\ & = \int d^4x \sum_n g_n \bar{\Psi}(x_\mu) \gamma^\mu \Psi(x_\mu) A_\mu^n(x_\mu), \end{aligned} \tag{10}$$

where $g = (1/\sqrt{\pi R}) g_5$. For each "n" (KK level), an expansion of the cosine in the dynamical field $\omega(x_\mu)$ leads to an infinite series of even number of branon legs at the vertex. We obtain the second line after contracting all those branon legs leading to loops at the same point in space given by $S_\omega(M_s)$. Note that we have used a hard cutoff for the momentum as the effective theory is valid only up to scales smaller than M_s. Hence, the coupling of the "n^{th}" KK mode of gauge boson with the brane localised fermion becomes

$$g_n = g e^{-(1/2)(n/R)^2 S_\omega(M_s)}, \tag{11}$$

where $S_\omega(M_s)$ is given as

$$S_\omega(M_s) = \frac{1}{\tau} \frac{M}{8\pi l_s} H_1^{(2)}(iM l_s) = \frac{1}{\tau} \frac{M M_s}{8\pi} H_1^{(2)}\left(i \frac{M}{M_s}\right). \tag{12}$$

In the above equation, we have replaced $|x - y|$ in equation (6) with the corresponding Euclidian length scale, $l_s = M_s^{-1}$, which denotes the smallest length that could be probed due to the effective nature of the theory. In the limit where $M/M_s \ll 1$, the above result matches with the expression given in [23] to the first order

$$g_n = g e^{-(1/2)(n/R)^2 S_\omega(M_s)} \Big|_{M \longrightarrow 0} = g e^{-(1/2)(n/R)^2 \left(M_s^2/f^4\right)}. \tag{13}$$

Note that, in the limit where the brane is rigid, $f \longrightarrow M_s$, the effect of the exponential factor in equation (11) becomes small. In this situation, all the KK partners of the gauge boson couple to the brane localised fermions with near Standard Model coupling strengths. On the other hand, at this juncture, owing to the inapplicability of the semiclassical treatment, with the predictions now becoming very sensitive to the ultraviolet completion, we deliberately stay away from such complications. In the region of importance to our study, the interactions of higher KK modes of the gauge bosons could be safely ignored.

On the other hand, it is clear from equation (11) that for a finite tension brane $(f < M_s)$ the couplings of KK-1 state and its heavier partners are smaller than those for the Standard Model W-boson, and hence, the bounds could be relaxed. For that, we need to know the mass of the branon for a given brane tension. If we demand that the annihilation cross section of the branon be such that the observed relic density [10, 11, 26] is reproduced, the mass of the branon and the brane tension get related. This branon mass corresponding to the brane tension could be used in equation (12) to compute the exponential factor in the coupling of KK-1 partner of the gauge boson with the fermions. With these couplings, we can compute the cross section for the processes mediated by W' that would contribute to LEP observables and at LHC. We have performed a global fit of 22 precision observables [29] in terms of the oblique parameters S, T, and V (correction to four-Fermi operator) using the data from [30]. All the data points (both red (or +) and green (or ×)) shown in Figure 1 are set to satisfy the electroweak precision constraint with $\Delta\chi^2 < 1$, Standard

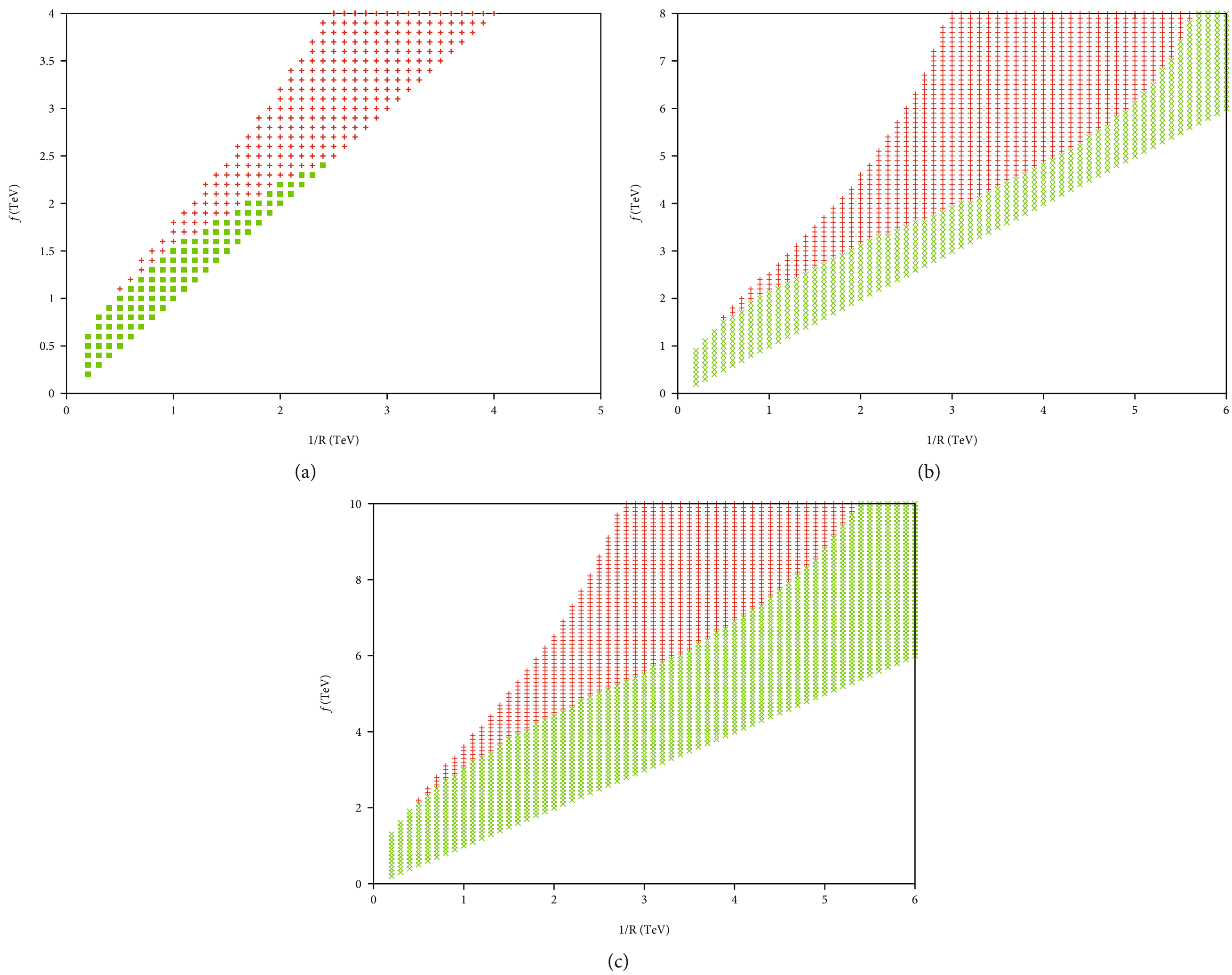

Figure 1: The region, in the plot showing brane tension vs. compactification scale, disallowed by the W' and LEP searches is depicted in red (or +) and the allowed parameter space of the model is shown in green (or ×). We have kept the mass of branon a variable such that the dark matter relic density is always satisfied for a given brane tension. The figures correspond to the cutoff scales $M_s = 5$ TeV, $M_s = 10$ TeV, and $M_s = 20$ TeV, respectively.

Model being $\chi^2 \approx 39.43$. Then, we study the process $pp \longrightarrow W' \longrightarrow e\bar{\nu}_e$, with the mediater mass given as $M_{W'}^2 = (1/R)^2 + M_W^2$, at LHC using Calchep 3.7.4 [31] and then compare this with the observed data [19]. For a given KK-1 mode mass and cutoff M_s, the coupling that satisfies the LHC bound is identified at 95% CL, among the region that is constrained previously by the four-Fermi operator, and the corresponding parameter space is plotted as the green (or ×) region in Figure 1. Similarly, the region satisfied by the LEP observables but not by LHC is plotted as red (or +). Note that in all the plots, though a large section of the parameter space is unfavored, light KK masses (<5.2 TeV) are still allowed for small enough brane tensions.

4. Conclusion

Extradimensional models, whether with flat large compactification radius or warped bulk, offer solutions to the theoretical challenges in Standard Model like fermion mass hierarchy, observed dark matter relic abundance, quadratic sensitivity of Higgs mass with new physics scale, and smallness of the cosmological constant. Though they have interesting phenomenological observables, an alternative to supersymmetric signatures at the *Large Hadron Collider* comes from the universal extradimensional scenario. In all of the above models and their derivatives, a strict understanding of the origin of the brane is hard to come by. To simplify the involved computations in them, it was sufficient to assume rigid branes. On the other hand, the rigidness of the branes comes with divergences which are not physical.

A dynamical explanation for field localisation on brane comes from the studies conducted by Rubakov and Shaposhnikov [13], where they considered domain walls formed by kink fields [32] with Yukawa coupling that lead to the trapping of matter in the potential well created by the kink. The lightest of the matter fields gets localised, whereas the continuum which is heavier than the mass of the kink escapes into the bulk. The presence of these topological defects, on the other hand, breaks the translational symmetry in those directions. This manifests itself as the Goldstone bosons associated with the symmetry.

Rigid branes lead to a very simple but unphysical picture. Including the brane fluctuations, as shown [23], leads to the suppression of bulk gauge field couplings with brane localised matter, thus curing the brane-induced divergences present in the rigid brane models. It was also shown [25, 26] that these fluctuations form good candidate for a wide array of dark matter models, from hot to cold depending on their mass.

In this paper, we considered a generic five-dimensional model with gauge fields in the bulk and fermion zero modes localised to a finite tension brane. We constrained this model using the $p\,p \longrightarrow W' \longrightarrow e\,\bar{\nu}_e$ process while including the coupling suppression due to the branon field. Unlike the previous study [23], where branons were assumed to be massless, in light of hot dark matter being ruled out, we considered massive branons that satisfy the cold dark matter relic and found that a large region of the parameter space, allowed by LEP, is unfavored by the 13 TeV LHC W' direct searches at 95% CL. For small cutoff scales, the LHC data restricts the model to be favorable only in the parameter space with $O(\lesssim 1)$ TeV brane tension and small compactification scale. The results become better when we assumed large cutoff scale.

Compactification scale in the parameter space that is allowed can have their imprints on other observables as well. Branons with mass $M < M_Z/2$ have been searched in the invisible decay widths of Z boson at LEP-I and LEP-II [33], which has successfully excluded the parameter space with branon mass $M < 100$ GeV for similar brane tension. On the other hand, heavier branons could be searched through direct production [33] along with a single photon or Z boson. The future 2 TeV CLIC collider could produce branons of mass $M \lesssim 1$ TeV on shell.

The KK modes of the electroweak gauge bosons can also influence $(g_\mu - 2)$ and charged lepton flavour violating processes like $\mu \longrightarrow e\gamma$ and $\mu \longrightarrow eee$. Efforts have been made [24] to provide an alternative to supersymmetry to solve the dark matter abundance and $(g_\mu - 2)$ simultaneously. Moreover, both the gluonic and electroweak bosons take part in kaon oscillations and other flavour violating rare meson decays. The KK modes of the gauge bosons in parameter space $1/R \lesssim 1$ TeV will contribute to this process significantly. Though it requires further investigation, we might be able to safely say that the suppression in the couplings of KK gauge bosons can lower their impact on the observables. More importantly, branons couple to the fermions via their energy momentum tensor, which become nonuniversal after the Higgs gets vacuum expectation value. Hence, branons could mediate flavour violating processes at 1 loop.

Before concluding, we would also like to note that the branons and KK mode coupling suppression also will have immense impact on the cosmology. In minimal models of baryogenesis through leptogenesis in large extradimensions [34], the renormalisability relies on the finiteness of the KK levels considered. Moreover, the evolution of the universe is influenced by the presence of low-lying KK modes. Such truncations in KK modes appear naturally on making the brane flexible. It is also interesting to study further the influence of branons themselves in these cosmological processes [35].

Data Availability

The data were used to support this study and are available at CERN Document Server (https://cds.cern.ch/). These prior studies (and datasets) are cited at relevant places within the text as references [6, 7, 9, 10, 20].

Disclosure

An earlier version has been presented in arXiv with the following link: http://export.arxiv.org/pdf/1904.08354.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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