Graviton Kaluza Klein modes in non-flat branes with stabilised modulus

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We consider a generalised two brane Randall Sundrum model where the branes are endowed with non-zero cosmological constant. In this scenario, we re-examine the modulus stabilisation mechanism and the nature of Kaluza Klein (KK) graviton modes. Our result reveals that while the KK mode graviton masses may change significantly with brane cosmological constant, the Goldberger-Wise stabilisation mechanism, which assumes negligible backreaction on the background metric, continues to hold even when the branes have large cosmological constant. The possibility of having a global minimum for the modulus is also discussed.

I. INTRODUCTION

Gauge hierarchy problem continues to be an unsolved issue in the standard model of elementary particles despite its enormous success in describing Physics up to TeV scale. A solution to the gauge hierarchy problem was proposed by Randall and Sundrum (RS model) by considering an extra dimension compactified into a circle $S^1$ with a $Z_2$ orbifolding [1]. The modulus corresponding to the radius of the extra dimension in such a model can be stabilised via Goldberger-Wise (GW) stabilization mechanism [2]. Both RS and GW model do not invoke any intermediate scale in the theory and are robust against radiative corrections. This resulted into a large volume of work in particle phenomenology and cosmology in the backdrop of Randall-Sundrum warped geometry scenario. In the context of collider Physics, possible role of first Kaluza-Klein (KK) graviton mode have been extensively studied in ATLAS and CMS detectors at LHC which have already set a stringent lower bound for the mass of the first KK graviton to be $m_{n=1} \sim 2.5$ TeV [3, 4]. Various implications of this have been discussed in [5–11].

There have been several efforts to formulate some variants of the original RS model. One such effort addresses a similar warped geometry model with non flat 3-branes in contrast to the original RS model which assumes two flat 3-branes sitting at the two orbifold fixed points. It has been shown in [12] that one can indeed generalise the model with non-zero cosmological constant on the visible 3-brane i.e on our observable universe and can resolve the gauge hierarchy problem concomitantly. In this generalised RS model [13, 14] it has been shown that the 3-branes can be either de-Sitter (dS) or anti de-Sitter (AdS) where the magnitude of the induced cosmological constant and that of the warping parameter are intimately connected. It is therefore crucially important to determine whether in such non-flat warped geometry models, the Goldberger-Wise stabilisation mechanism, which neglects the backreaction of the stabilising field, can still be employed successfully to stabilise the radius of the extra dimension to the desired value $\sim M_\text{Pl}^{-1}$. Moreover it is worth while to explore the effect of the brane cosmological constant on the masses of the graviton KK modes which are expected to play important role in high energy scattering processes. This work is focussed into addressing the following two questions in a generalised RS model:

1. Can the modulus of extra dimension be stabilised to a global minimum for the entire range of values of the cosmological constant in the context of generalised RS model?

2. What are the KK graviton masses for different choices of cosmological constant?

After a brief review of original and generalised RS model in first two sections, we focus into the modulus stabilization conditions as well as the expressions for the modified KK graviton masses due to the presence of non-vanishing brane cosmological constant.

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II. RANDALL SUNDRUM MODEL

In the RS scenario, it is predicted that there exists an extra spatial dimension in addition to the (3 + 1) dimensional observed universe. The corresponding five dimensional bulk space-time is described by a metric

$$ds^2 = \exp (-\kappa r |y|) g_{\mu\nu} dx^\mu dx^\nu - dy^2$$  (1)

where greek indices $\mu, \nu$ run over 0,1,2,3 and refer to the four observed dimensions. The geometry of the extra dimension is $S^1/Z_2$ and is described by the coordinate ‘y’. Here the circle $S^1$ has radius r. $\Lambda$ is the bulk cosmological constant, $k = \sqrt{-\Lambda/12M^2}$. The factor $\exp (-\kappa r |y|)$ is known as the warp factor. The $y = constant$ slices at $y = 0$ and at $y = \pi r$ are known as the hidden and the visible branes, the observable universe being identified with the latter which has a negative brane tension as opposed to the hidden brane with a positive brane tension. It can be shown that a mass parameter $m_0$ of the order of Planck scale is warped to a value TeV on the visible brane following the relation $m = m_0 \exp (-\kappa r \pi)$, for $kr \sim 11.6$. Thus in this picture, the stability of higgs mass against large radiative correction is ensured by the warped geometry of the five dimensional spacetime. In this context the KK graviton mass modes are determined by considering a small fluctuation around the flat metric with its KK decomposition. Some of these modes have masses $m_{n=0} = 0$; $m_{n=1} = 0.383$TeV; $m_{n=2} = 0.702$TeV for $k/M_{pl} \sim 0.1$ [3]. The requirement of $k < M_{pl}$ emerges from the fact that k, which measures the bulk curvature must be smaller than the Planck scale so that the classical solutions of Einstein’s equations in the bulk can be trusted [2].

In the context of modulus stabilisation, it was proposed by Goldberger and Wise that the modulus of the model (i.e. the radius of the extra dimension) can be stabilised to the desired value by introducing a massive scalar field in the bulk. Evaluating the effective modulus potential due to the massive scalar field of mass $m$, one gets the stabilisation condition as $\exp [\kappa r \pi] = (10^{-16}/c_1) [1 + \sqrt{1 - \omega^2 10^{32}}]$ for AdS case due to back-reaction on the background metric can be ignored. Moreover the condition of having a global minimum for the modulus potential was found to be $\delta V_v < k \nu^2$, where $\delta V_v$ is a perturbation on the visible brane tension.

III. GENERALISED RANDALL SUNDRUM MODEL

Present cosmological observation indicates the possible existence of a 4-dimensional cosmological constant (~$10^{-124}$) in Planckian unit. It has been demonstrated [12] that by relaxing the condition of zero cosmological constant (i.e flat 3-brane) it is possible to obtain a more general expression for the warp factor. Starting from a general metric ansatz,

$$ds^2 = \exp [-2A(y)] g_{\mu\nu} dx^\mu dx^\nu - dy^2$$  (2)

one may solve the bulk equations for both anti de-Sitter(AdS) and de-Sitter (dS) 3-branes. The corresponding warp factor for AdS brane is

$$\exp [-A(y)] = \omega \cosh [\ln (\omega/c_1) + ky]$$  (3)

with $c_1 = 1 + \sqrt{1 - \omega^2}$ and $\omega^2 = -\Omega/(3k^2)$ while that for dS brane is

$$\exp [-A(y)] = \omega \sinh [\ln (c_2/\omega) - ky]$$  (4)

with $c_2 = 1 + \sqrt{1 + \omega^2}$ and $\omega^2 = \Omega/(3k^2)$. Here $\Omega$ is the brane cosmological constant and $\omega^2$ is a dimensionless parameter. Just as in the original RS model, this generalised scenario also can address the gauge hierarchy problem for appropriate choices of the parameters which we discuss below.

The scalar mass on the visible brane [12] gets warped through the warp factor. In order to resolve the gauge hierarchy problem it must satisfy, $\exp [-A(\pi r)] = 10^{-16} = m/m_0$. This leads to

$$\exp [-k \pi r] = (10^{-16}/c_1) [1 + \sqrt{1 - \omega^2 10^{32}}]$$  (5)

for AdS case.

$$\exp [-k \pi r] = (10^{-16}/c_2) [1 + \sqrt{1 + \omega^2 10^{32}}]$$  (6)

for dS case.

From the above two relations one can say: (1) real solution of $k \pi r$ exists which resolves the hierarchy problem, (2) the the warping parameter $kr$ depends on cosmological constant. In the following section we employ the GW stabilisation mechanism for the generalised RS model with non-flat branes to derive the new stability condition.
IV. MODULUS STABILISATION FOR NON-FLAT BRANES

To stabilise the modulus $r$ in the context of generalised RS model, we adopt the method proposed by Goldberger and Wise [2]. Let us consider a massive scalar field $\Phi$ in the bulk with quartic interactions on the Planck ($y = 0$) and visible branes ($y = \pi r$). The corresponding action is,

$$S_5 = (1/2) \int d^4 x dy \sqrt{-g_y} (\partial_y \Phi)^2 + m^2 \Phi^2 - \int d^4 x dy \sqrt{-g_y} \lambda_y (\Phi^2 - v_y^2)^2 \delta(y) - \int d^4 x dy \sqrt{-g_y} \lambda_v (\Phi^2 - v_v^2)^2 \delta(y - \pi r)$$

(7)

Here we assume that the scalar field depends only on extra dimensional coordinate. $g_y$ and $g_v$ are the determinants of the induced metric on the hidden and visible brane respectively. The vacuum expectation value of the scalar field on the branes are given by $v_h$ and $v_v$; $\lambda_y$ and $\lambda_v$ are brane tensions.

The equation of motion for the scalar field is given by,

$$\Phi''(y) - 4A'(y)\Phi'(y) - m^2\Phi + 4\lambda_v (\Phi^2 - v_v^2)\Phi\delta(y - \pi r) + 4\lambda_y (\Phi^2 - v_y^2)\Phi\delta(y) = 0$$

(8)

For large $\lambda_y$ and $\lambda_v$, one obtains the following two boundary conditions :

$$\Phi(0) = v_h$$
$$\Phi(\pi r) = v_v$$

(9) (10)

Now we discuss the stability mechanism for two different scenarios i.e. AdS and dS branes separately.

1. Anti de-Sitter brane ($\Omega < 0$)

It has been shown in [12] that the magnitude of the cosmological constant on AdS brane is constrained to have an upper bound and must lies between $-10^{-32} < \Omega < 0$. Due to this tiny value of the magnitude of the cosmological constant, we keep terms up to $\omega^2$ order. Differentiation of both sides of eqn.(3) with respect to ‘y’ yields,

$$A'(y) = k[1 - (\omega^2/2) \exp (2ky)]$$

Putting the above expression in eqn. (3), one gets the equation of motion for scalar field in the bulk as,

$$\Phi''(y) - 4k[1 - (\omega^2/2) \exp (2ky)]\Phi'(y) - m^2\Phi = 0$$

This leads to the solution,

$$\Phi(y) = [A \exp ((2 + \nu)ky) + B \exp ((2 - \nu)ky)] - \omega^2/2[A(2 + \nu)/(1 + \nu) \exp ((4 + \nu)ky) + B(2 - \nu)/(1 - \nu) \exp ((4 - \nu)ky)]$$

(11)

Here A, B are arbitrary constants and $\nu = \sqrt{3 + m^2/k^2}$. An effective potential $V_{eff}$ can be obtained by putting the above solution(11) back into the scalar field action (2) and integrating over the extra dimension. This yields an effective modulus potential at the visible brane as,

$$V_{eff} = [2A^2 k(2 + \nu) \exp (2\nu k\pi r) + 2B^2 k(\nu - 2)] - [2A^2 k^2 \exp (2\nu k\pi r) - 2B^2 k^2 (\nu - 2)] - [4A^2 \omega^2 k(2 + \nu)/(1 + \nu) \exp ((2 + 2\nu)k\pi r) - 4B^2 \omega^2 k(2 - \nu)/(1 - \nu)] - [2A B \omega^2 k(4 - \nu^2)/(1 - \nu^2) \exp (2k\pi r)]$$

(12)

The boundary conditions given by eqn(4) and eqn. (10) yield the arbitrary constants A and B in the following form,

$$A = [v_v \exp -((2 + \nu)k\pi r) - v_h \exp ((-2\nu k\pi r)] + \omega^2/2[v_v (2 + \nu)/(1 + \nu) \exp -\nu k\pi r) - v_v (2 - \nu)/(1 - \nu) \exp -3\nu k\pi r) + 2v_v (\nu/1 - \nu^2) \exp -((2 + 3\nu)k\pi r)] + 2v_h (\nu/1 - \nu^2) \exp -((2 - 2\nu)k\pi r)]$$

(13)
\[ B = v_h[1 + \omega^2/(2(2 - \nu)/(1 - \nu))] - A[1 + \omega^2(\nu/1 - \nu^2)] \] (14)

Putting \( A \) and \( B \) in expression (12) and minimizing the modulus potential, one gets the condition

\[
\begin{align*}
&[v_v^2 - v_h^2 \exp(-2\epsilon k\pi r)] + \omega^2/2\exp(2k\pi r)[(v_v - v_h \exp(-\epsilon k\pi r))^2 - 8v_v^2 \exp(-\epsilon k\pi r)] \\
&- \omega^2[v_v - v_h \exp(-\epsilon k\pi r)] = 0
\end{align*}
\] (15)

where we use \( \nu = 2 + \epsilon \) with \( \epsilon = m^2/(4k^2) \) and ignore terms proportional to \( \epsilon \). In this approximation eqn. (15) becomes

\[ kr\pi = 4(k^2/m^2) \ln (v_h/v_v) + (16/3)\omega^2(k^2/m^2)(v_v/v_h)^{(2+4/\epsilon)} \] (16)

Here \( r \) is the stabilised distance between the two branes. If we now require that the same \( r \) resolves the gauge hierarchy problem as well, then the following condition holds,

\[ \omega^2 = [16\ln (v_h/v_v) - 100\ln (10)]/[(1/4)10^{32} - (400/3)(v_v/v_h)^{402}] \] (17)

where we take \( m/k \approx 0.2 \). This result reveals that the ratio of the vev of the scalar field at the two branes depend on the brane cosmological constant. From the above relation (17) between brane cosmological constant and vev ratio, we obtain Figure 1 (\( \omega^2 = -\Omega/(3k^2) \)) as,

![FIG. 1: \((v_h/v_v) \) vs \( \Omega \)](image)

Figure 1 demonstrates that for a wide range of values of the brane cosmological constant, the vev ratio varies insignificantly and does not lead to any hierarchical values between the vevs .

2. de-Sitter Brane (\( \Omega > 0 \))

For de-Sitter brane we split the parameter space of cosmological constant into different regimes as following.

- \( 0 \leq \Omega \leq 10^{-32} \):
  
  Using the dS warp factor (1) one gets the scalar field solution for this regime as,

\[
\begin{align*}
\Phi(y) &= [A \exp ((2 + \nu)ky) + B \exp ((2 - \nu)ky)] + \omega^2/2[A(2 + \nu)/(1 + \nu) \exp ((4 + \nu)ky) \\
&+ B(2 - \nu)/(1 - \nu) \exp ((4 - \nu)ky)]
\end{align*}
\] (18)

Now proceeding similarly as in the AdS case, one ends up with the relation between brane cosmological constant and vev ratio as,

\[ \omega^2 = [16\ln (10) - 100\ln (v_h/v_v)]/[(1/4)10^{32} - (400/3)(v_v/v_h)^{402}] \] (19)

This leads to figure 2 (\( \omega^2 = \Omega/(3k^2) \)).
1. $10^{-32} \leq \Omega \leq 1$:

Using the dS warp factor (6), the scalar field solution for this regime is,

$$\Phi(y) = A \exp(-((\nu - 2)ky)_{2}F_{1}(2, 2 - \nu; 1 - \nu; (\omega^{2}/4) \exp(2ky))$$

$$+ B \exp((\nu + 2)ky)_{2}F_{1}(2, 2 + \nu; 1 + \nu; (\omega^{2}/4) \exp(2ky))$$

where $2F_{1}(arg)$ is the hypergeometric function. Keeping terms up to $\omega^{2}$, the above solution of scalar field becomes,

$$\Phi(y) = [A \exp((2 + \nu)ky) + B \exp((2 - \nu)ky)] - \omega^{2}/2[A(2 + \nu)/(1 + \nu) \exp((4 + \nu)ky)$$

$$+ B(2 - \nu)/(1 - \nu) \exp((4 - \nu)ky)]$$

Again proceeding similarly as before, one ends up with the relation between brane cosmological constant and vev ratio as,

$$\omega^{2} = 4(\nu_{v}/v_{h})^{200}$$

This leads to figure 3 ($\omega^{2} = \Omega/(3k^{2})$).

Both Figures 2 and Figure 3 reveals that just as in Ads case, here also the deviation of the vev ratio of the scalar field from that of the GW-value is insignificant even when the brane is endowed with a large positive cosmological constant.

### A. Graviton Modes

To study the graviton modes, we decompose the four-dimensional components of the metric into its Kaluza-Klein (KK) modes as,

$$g_{\mu\nu}(x, y) = \sum h_{\mu\nu}^{n}(x)\xi_{n}(y)$$

(21)
Here \( h_{\mu \nu}^{(n)}(x) \) is the \( n \) th KK graviton mode. Plugging back the decomposition in the action and using the appropriate gauge conditions for \( h_{\mu \nu}(x) \) \cite{10}, one gets

\[
S_5 = -(1/4) \int d^4 x dy \sqrt{g} \left[ \partial_M g^{ij} \right] \left[ \partial_M g_{ij} \right]
\]  
(22)

This modified action leads to the equation of motion

\[
\eta^{\mu \nu} \partial_\mu \partial_\nu h_{ij}^{(n)}(x) = m_n^2 h_{ij}^{(n)}(x)
\]  
(23)
The above differential equation for \( x \) dependent part of the metric holds if

\[
\partial_y [\exp(-4A(y)) \partial_y \xi^n] = -m_n^2 \exp(-2A(y)) \xi^n(y)
\]  
(24)
and the orthogonality condition

\[
(1/r) \int \chi^n(y) \chi^m(y) dy = \delta_{mn}
\]
are simultaneously satisfied.

\( m_n \) denotes the mass of \( n \)th KK graviton mode. Solution of eqn. (24) as well as graviton KK modes for AdS and dS branes are now discussed in the following sections.

1. Anti de-Sitter brane (\( \Omega < 0 \))

As mentioned before that the range of cosmological constant on AdS brane is \(-10^{-32} < \Omega < 0 \). Once again keeping terms up to \( \omega^2 \) and using the perturbative expansion of \( \xi(y) \) and \( m_n \) as,

\[
\begin{align*}
\xi(y) &= \xi^0(y) + \omega^2 \xi^1(y) \\
\xi_n &= m_n^0 + \omega^2 m_n^1
\end{align*}
\]  
(25)
(where \( m_n^0 \) is the mass of \( n \)th KK graviton mode on flat branes which is the RS scenario), eqn. (24) becomes,

\[
\left[ \partial_y (\exp(-4ky) \xi^0_n(y)) + \exp(-2ky)(m_n^0)^2 \xi^1_n(y) - \omega^2 \partial_y (\exp(-4ky) \xi^1_n(y)) \right] - \partial_y (\exp(-2ky) \xi^0_n(y) ) = 0
\]  
(26)
Defining the new variable \( z_n = (m_n^0/k) \exp(ky) \), one gets the solution of \( \xi(y) \) as,

\[
\xi_n(y) = (1/N_n) \exp(2ky) [J_2(z_n) + a_n Y_2(z_n) - \omega^2 f_n(z_n^0)]
\]  
(27)
Now demanding the continuity of the graviton wave function at two branes, we get the following boundary conditions

\[
\begin{align*}
\xi_n'(y = 0) &= 0 \\
\xi_n'(y = \pi r) &= 0
\end{align*}
\]
From the first boundary condition and using the approximation \( (m_n / k) \ll 1 \) one can conclude that the co-efficient \( a_n \) is negligible. Thus the solution (27) becomes \( \xi_n(y) = (1/N_n) \exp(2ky) [J_2(z_n^0) - \omega^2 f_n(z_n^0)] \). The other boundary condition yields,

\[
\begin{align*}
\exp(k\pi r)(m_n^0/k) J_1(\exp(k\pi r)(m_n^0/k) ) - 2\omega^2 k f_n(\exp(k\pi r)(m_n^0/k)) \\
- \omega^2 \exp(k\pi r)(m_n^0/k) f_n'(\exp(k\pi r)(m_n^0/k)) \end{align*}
\]  
(28)
which leads to first order correction of graviton KK mass modes as,

\[
\begin{align*}
m_{(n=1)} &= m_{n=1}^0 + 3.5 \times 10^{30} \times \omega^2 \\
m_{(n=2)} &= m_{n=2}^0 + 2 \times 10^{30} \times \omega^2
\end{align*}
\]
2. de-Sitter Brane ($\Omega > 0$)

As before for $10^{-32} \leq \Omega \leq 1$ using eqn. 4, expression for warp factor becomes,

$$\exp [-4A(y)] = \exp (-4ky)[1 - \omega^2 \exp (2ky)]$$

Taking this expression of warp factor and proceeding similarly, one ends up with following graviton mass correction due to brane cosmological constant.

$$m_{(n=1)} = m_{n=1}^0 + (2.5 * 10^{-10})$$
$$m_{(n=2)} = m_{n=2}^0 + (13.44 * 10^{-10})$$

for $\Omega \sim 10^{-20}$

In a similar way we can extend our analysis for very large values of brane cosmological constant ($\Omega$).

We now summarise our results for different cases in the following table (for $k/M_{pl} \sim 0.1$).

| $\Omega$  | $kr$  | $v_h/v_v$ | $m_{(n=1)} = (m_{n=1}^0 + \Delta m_n)(TeV)$ | $m_{(n=2)} = (m_{n=2}^0 + \Delta m_n)(TeV)$ |
|----------|------|----------|---------------------------------|---------------------------------|
| $10^{-32}$ | $\sim 11$ | 1.446 | (0.383+0.03) | (0.702+0.02) |
| 0       | $\sim 11$ | 1.445439771 | 0.383 | 0.702 |
| $10^{-20}$ | $\sim 10$ | 1.3700 | (0.383+0.44) | (0.702+0.55) |
| 100     | 0.095 | $\sim 1$ | 10.5263 | 21.0526 |
| 625     | 0.039 | $\sim 1$ | 25.641 | 51.282 |
| $10^4$  | 0.0099 | $\sim 1$ | 101.01 | 202.02 |

**TABLE I:** Warping parameter ($kr$), vev ratio ($v_h/v_v$) and graviton mass modes ($m_n$) for a wide range of cosmological constant ($\Omega$)

From the above table, it is evident that the ratio of $v_h$ and $v_v$ is of the order of unity for the entire chosen range of values of brane cosmological constant. This condition justifies the fact that the back-reaction of the stabilising scalar field on background spacetime can be neglected even in the presence of brane cosmological constant. From eqn.(29), it is easy to see that $\delta V_e < kv_v^2$. This immediately ensures that the minimum is a global one. Similar argument also holds for dS brane.

\[ \delta V_e = 12 M^4 k [\omega^2 \exp (2 kr \pi)]/[1 + \sqrt{(1 - \omega^2)} + (\omega^2/2) \exp (2 kr \pi)] \] (29)

Since for AdS brane, $\omega^2 = -\Omega/(3k^2)$ therefore from eqn.[20], it is easy to see that $\delta V_e < kv_v^2$. This immediately ensures that the minimum is a global one. Similar argument also holds for dS brane.

V. CONCLUSION

We now summarize the findings and the implications of our results.

- We have demonstrated that the extra dimensional modulus can be stabilised by Goldberger-Wise mechanism for a wide range of values of cosmological constant both in de-Sitter and anti-de-Sitter region. It has been shown in [2] that if the vev ratio of the scalar field in the bulk is of the order $\sim 1.46$ or less than that, then one can safely ignore the back reaction of the scalar field on background spacetime for the purpose of modulus stabilisation. Now from our above table it is evident that since the vev ratio lies between 1 < ($v_h/v_v$) < 1.46 for the entire parameter space of cosmological constant, therefore the back reaction can be sagely ignored even in the “Generalised Randall Sundrum Scenario”. In this sense the Goldberger-Wise stabilisation mechanism is extremely robust against the extent of non-flatness of our universe. Our result also reveals that even for non-flat branes the modulus potential continues to yield a global minimum ensuring a robust modulus stabilisation against perturbations.

- We have derived the modifications of the KK graviton mass modes due to the presence of a non-zero cosmological constant on the brane in the generalised Randall Sundrum scenario. We found that the masses of the graviton
KK modes increases with brane cosmological constant and may deviate significantly from the values estimated in RS scenario as the values of the brane cosmological constant increases. During this analysis, we restricted the choice of the parameters in a region so that the gauge hierarchy problem can simultaneously be resolved. In the context of the present epoch of our universe (visible 3-brane), these results indicate that due to extreme smallness of the value of the cosmological constant ($10^{-124}$ in Planckian unit), the warped model resembles very closely to the RS model with graviton KK mode masses $\sim$ TeV. However this scenario will change significantly in epoch with a large cosmological constant.

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