HIGGS-BOSON MASS LIMIT WITHIN THE RANDALL–SUNDRUM MODEL*

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Perturbative unitarity for $W_L^+W_L^- \to W_L^+W_L^-$ scattering is discussed within the Randall–Sundrum model. It is shown that the exchange of massive 4D Kaluza–Klein gravitons leads to amplitudes growing linearly with the CM energy squared. Summing over KK gravitons up to a scale $\overline{\Lambda}$ and testing unitarity at $\sqrt{s} = \overline{\Lambda}$, one finds that unitarity is violated for $\overline{\Lambda}$ below the 'naive dimensional analysis' scale, Λ_{NDA}. It is also shown that the exchange of gravitons can substantially relax the upper limit from unitarity on the mass of the Standard Model Higgs boson — consistency with unitarity for all $\sqrt{s}$ below $\overline{\Lambda}$ is possible for m_h as large as 1.4 TeV, depending on the curvature of the background metric. Observation of the mass and width (or cross section) of one or more KK gravitons at the LHC will directly determine the curvature and the scale Λ_W specifying the couplings of matter to the KK gravitons. With this information and a measurement of the Higgs boson mass it will be possible to determine the precise $\sqrt{s}$ value below which unitarity will remain valid.

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1. Introduction

Even though the Standard Model (SM) of electroweak interactions perfectly describes almost all existing experimental data, nevertheless the model suffers from certain theoretical drawbacks. The hierarchy problem is probably the most fundamental of these: namely, quantum loop corrections in

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the SM destabilize the weak energy scale $\mathcal{O}(1\ \mathrm{TeV})$ if the theory is assumed to remain valid to a much higher scale such as the Planck mass scale $\mathcal{O}(10^{19}\ \mathrm{GeV})$. Therefore, it is believed that the SM is only an effective theory embedded in some more fundamental high-scale theory that presumably could contain gravitational interactions. Models that involve extra spatial dimensions could provide a solution to the hierarchy problem in which gravity plays the major role. The most attractive proposal was formulated by Randall and Sundrum (RS) [1]. They postulate a 5D universe with two 4D surfaces ("3-branes"). All the SM particles and forces with the exception of gravity are assumed to be confined to one of those 3-branes called the visible or TeV brane. Gravity lives on the visible brane, on the second brane (the "hidden brane") and in the bulk. All mass scales in the 5D theory are of order of the Planck mass. By placing the SM fields on the visible brane, all the order Planck mass terms are rescaled by an exponential suppression factor (the "warp factor") $\Omega_0 \equiv e^{-m_0 b_0/2}$, which reduces them down to the weak scale $\mathcal{O}(1\ \mathrm{TeV})$ on the visible brane without any severe fine tuning. To achieve the necessary suppression, one needs $m_0 b_0/2 \sim 35$. This is a great improvement compared to the original problem of accommodating both the weak and the Planck scale within a single theory.

The RS model is specified by the 5-D action:

$$\begin{aligned} S \;=\; & -\int d^4x\, dy \sqrt{-\widehat{g}}\left(2M^3_{\mathrm{Pl}\,5}\widehat{R} + \Lambda\right) \\ & + \int d^4x\, \sqrt{-g_{\mathrm{hid}}}(\mathcal{L}_{\mathrm{hid}} - V_{\mathrm{hid}}) + \int d^4x\, \sqrt{-g_{\mathrm{vis}}}(\mathcal{L}_{\mathrm{vis}} - V_{\mathrm{vis}})\,, \end{aligned} \tag{1}$$

where the notation is self-explanatory, see also [2] for details. In order to obtain a consistent solution to Einstein's equations corresponding to a low-energy effective 4D theory that is flat, certain conditions must be satisfied: $V_{\mathrm{hid}} = -V_{\mathrm{vis}} = 24M^3_{\mathrm{Pl}\,5}m_0$ and $\Lambda = -24M^3_{\mathrm{Pl}\,5}m_0^2$. Then, the following metric is a solution of Einstein's equations:

$$\widehat{g}_{\widehat{\mu}\widehat{\nu}}(x,y) = \left(\begin{array}{c|c} e^{-2m_0 b_0|y|}\eta_{\mu\nu} & 0 \\ \hline 0 & -b_0^2 \end{array}\right). \tag{2}$$

After an expansion around the background metric we obtain the gravity-matter interactions

$$\mathcal{L}_{\mathrm{int}} = -\frac{1}{\Lambda_W}\sum_{n\neq 0} h^n_{\mu\nu}T^{\mu\nu} - \frac{\phi_0}{\Lambda_\phi}T^\mu_\mu\,, \tag{3}$$

where $h^n_{\mu\nu}(x)$ are the Kaluza–Klein (KK) modes (with mass m_n) of the graviton field $h_{\mu\nu}(x,y)$, $\phi_0(x)$ is the radion field (the scalar quantum degree of freedom associated with fluctuations of the distance between the branes), $\Lambda_W \simeq \sqrt{2} M_{\rm Pl} \Omega_0$, where $\Omega_0 = e^{-m_0 b_0/2}$, and $\Lambda_\phi = \sqrt{3}\,\Lambda_W$. To solve the hierarchy problem, Λ_W should be of order $1-10$ TeV, or perhaps higher [1]. In addition to the radion, the model contains a conventional Higgs boson, h. The RS model solves the hierarchy problem by virtue of the fact that the 4D electro-weak scale is given in terms of the $\mathcal{O}(M_{\rm Pl})$ 5D Higgs vev, $\widehat{v}$, by:

$$v_0 = \Omega_0 \widehat{v} = e^{-m_0 b_0/2} \widehat{v} \sim 1 \text{ TeV} \quad \text{for} \quad m_0 b_0/2 \sim 35\,. \tag{4}$$

However, the RS model is trustworthy in its own right only if the 5D curvature m_0 is small compared to the 5D Planck mass, $M_{\rm Pl\,5}$ [1]. The $m_0 < M_{\rm Pl\,5}$ requirement and the fundamental RS relation $M_{\rm Pl}^2 = 2M_{\rm Pl\,5}^3/m_0$ imply that $m_0/M_{\rm Pl} = 2^{-1/2}(m_0/M_{\rm Pl\,5})^{3/2}$ should be significantly smaller than 1. Hereafter, we will focus on the range: $10^{-3} \lesssim m_0/M_{\rm Pl} \lesssim 10^{-1}$.

The goal of this analysis is to determine the cutoff (defined as some maximum energy up to which the 4D RS theory is well behaved) and to discuss the unitarity limits on the Higgs boson mass taking into account KK graviton exchange; for a detailed discussion see [3].

2. The cutoff

The cutoff can be estimated in a number of ways. One estimate of the maximum allowed energy scale is that obtained using the 'naive dimensional analysis' (NDA) approach [4], the associated scale is denoted by $\Lambda_{\rm NDA}$[1]. One finds

$$\Lambda_{\rm NDA} = 2^{7/6}\pi (m_0/M_{\rm Pl})^{1/3} \Lambda_W\,, \tag{5}$$

where Λ_W was defined in Eq. (3); its inverse sets the strength of the coupling between matter and gravitons. We emphasize that $\Lambda_{\rm NDA}$ is obtained when the exchange of the whole tower of KK modes up to $\Lambda_{\rm NDA}$ is taken into account. Physically, $\Lambda_{\rm NDA}$ is the energy scale at which the theory starts to become strongly coupled and string/M-theoretic excitations appear from a 4D observer's point of view [1]. In this presentation, we show that unitarity in the $J = 0$ partial wave of $W_L^+ W_L^- \to W_L^+ W_L^-$ scattering is always violated in the RS model for energies below the $\Lambda_{\rm NDA}$ scale. We will define $\overline{\Lambda}$ as the largest $\sqrt{s}$ value such that if we sum over graviton resonances with mass below $\overline{\Lambda}$ (but do not include diagrams containing the Higgs boson or radion of the model) then $W_L^+ W_L^- \to W_L^+ W_L^-$ scattering remains unitary in

[1] The 4D condition for the cutoff $\Lambda_{\rm NDA}$ (which corresponds to the scale at which the theory becomes strongly coupled) is $(\Lambda_{\rm NDA}/\Lambda_W)^2 N/(4\pi)^2 \sim 1$, where N is the number of KK-gravitons lighter than $\Lambda_{\rm NDA}$ (implying that they should be included in the low-energy effective theory). For the RS model the graviton mass spectrum for large n is $m_n \simeq m_0 \pi n \Omega_0$, implying $N \sim \Lambda_{\rm NDA}/(m_0 \pi \Omega_0)$ which leads to Eq. (5).

the $J = 0$ partial wave. Unitarity of the S-matrix implies that the partial wave amplitudes $a_J(s)$ must satisfy $|\mathrm{Re}\ a_J| < 1/2$. As we see from Fig. 1, $W_L^+W_L^- \to W_L^+W_L^-$ scattering violates unitarity if Λ_{NDA} is employed as the cutoff. A more appropriate cutoff is determined numerically by requiring

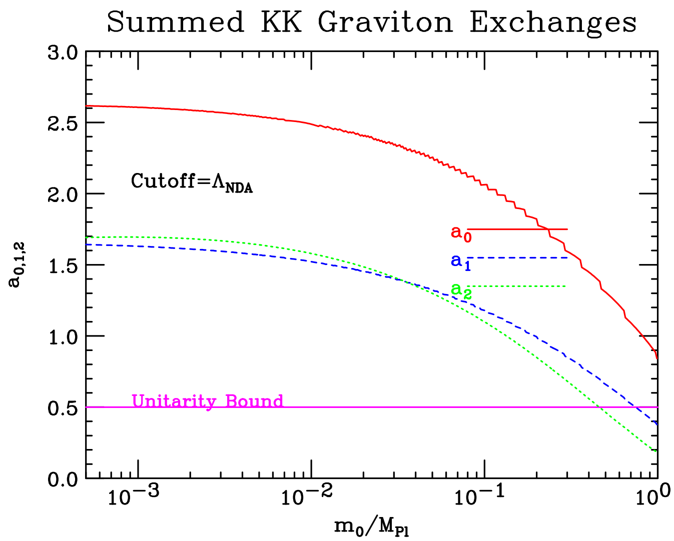

Fig. 1. We plot Re $a_{0,1,2}$ as functions of m_0/M_{Pl} as computed at $\sqrt{s} = \Lambda_{\mathrm{NDA}}$ and summing over all KK graviton resonances with mass below Λ_{NDA}, but without including Higgs or radion exchanges.

$|\mathrm{Re}\ a_{0,1,2}| < 1/2$ for $\sqrt{s} = \overline{\Lambda}$ after summing over KK resonances with mass below $\overline{\Lambda}$. It is important to realize that in the presence of KK gravitons and the radion, the SM cancellation (between Higgs and gauge boson contributions) of terms $\propto s$ in the asymptotic behavior of $a_J(s)$ is spoiled, that is why graviton contributions turn out to be so relevant. In the left-hand plot of Fig. 2, we display the ratio $\overline{\Lambda}/\Lambda_{\mathrm{NDA}}$ as a function of m_0/M_{Pl}, where $\overline{\Lambda}$ is the largest $\sqrt{s}$ for which $W_L^+W_L^- \to W_L^+W_L^-$ scattering is unitary when computed including only the KK graviton exchanges. Results are shown for $J = 0$, 1, and 2. As a function of $\sqrt{s}$, the $J = 0$ partial wave is always the first to violate unitarity and gives the lowest value of $\overline{\Lambda}$. We will cut off our sums over KK exchanges when the KK mass reaches $\overline{\Lambda}$ as determined by the $J = 0$ amplitude. We see that the $\overline{\Lambda}$ so defined is typically a significant fraction of Λ_{NDA}, but never as large as Λ_{NDA}. Still, it is quite interesting that the unitarity consistency limit $\overline{\Lambda}$ tracks the 'naive' Λ_{NDA} estimate fairly well as m_0/M_{Pl} changes over a wide range of values (for a qualitative 'derivation' see [3]). The right-hand plot of Fig. 2 shows the actual values of $\overline{\Lambda}$ and Λ_{NDA} as functions of m_0/M_{Pl} for the case of $\Lambda_\phi = 5$ TeV. Note

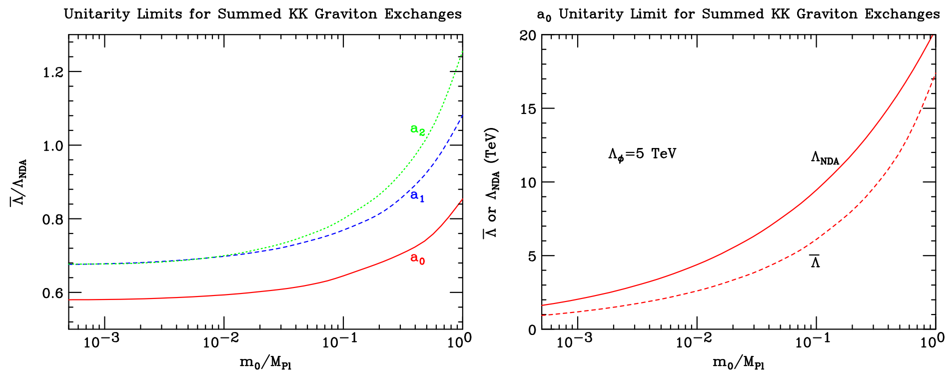

Fig. 2. In the left hand plot, we give $\overline{\Lambda}/\Lambda_{\rm NDA}$ as a function of $m_0/M_{\rm Pl}$, where $\overline{\Lambda}$ is the largest $\sqrt{s}$ for which $W_L^+W_L^- \to W_L^+W_L^-$ scattering is unitary after including KK graviton exchanges with mass up to $\overline{\Lambda}$, but before including Higgs and radion exchanges. Results are shown for the $J=0$, 1 and 2 partial waves. With increasing $\sqrt{s}$ unitarity is always violated earliest in the $J=0$ partial wave, implying that $J=0$ yields the lowest $\overline{\Lambda}$. The right hand plot shows the individual absolute values of $\overline{\Lambda}(J=0)$ and $\Lambda_{\rm NDA}$ for the case of $\Lambda_\phi = 5$ TeV; $\overline{\Lambda}/\Lambda_{\rm NDA}$ is independent of Λ_ϕ.

that for larger $m_0/M_{\rm Pl}$ they substantially exceed the input inverse coupling scale Λ_ϕ, whereas for smaller $m_0/M_{\rm Pl}$ they are both substantially below Λ_ϕ. In other words, using either $\overline{\Lambda}$ or $\Lambda_{\rm NDA}$, one concludes that Λ_ϕ, and equally Λ_W, are themselves not appropriate estimators for the maximum scale of validity of the model. The left-hand plot of Fig. 3 shows Re a_0 as a function of $\sqrt{s}$ for the case of $\Lambda_\phi = 5$ TeV for two different m_h values and with and without radion and/or KK gravitons included. In the case where we include only the SM contributions for $m_h = 870$ GeV, the figure illustrates unitarity violation as Re a_0 asymptotes to a negative value very close to $-1/2$, implying that $m_h = 870$ GeV is very near the largest value of m_h that is allowed by unitarity in the SM. If we add in just the radion contributions (for $m_\phi = 500$ GeV [2] — the ϕ resonance is very narrow and is not shown), then a sharp-eyed reader will see (red dashes) that Re a_0 is a bit more negative at the highest $\sqrt{s}$ plotted, implying earlier violation of unitarity. However, if we now include the full set of KK gravitons, which enter with an increasingly positive contribution, taking $m_0/M_{\rm Pl} = 0.01$ (dotted blue curve) one is far from violating unitarity due to Re $a_0 < -1/2$ for $\sqrt{s}$ values above $m_h = 870$ GeV; instead, the positive KK graviton contributions, which cure the unitarity problem at negative Re a_0 for $\sqrt{s}$ above m_h, cause unitarity

[2] The radion contribution is always negligible in the scenario discussed here if m_ϕ remains in the range $m_\phi \in [10, 1000]$ GeV and Λ_ϕ is above 1 TeV. This is however not true in the context of curvature-Higgs mixing as discussed in [5].

to be violated at large $\sqrt{s}$, but *above* $\overline{\Lambda}$, as Re a_0 passes through $+1/2$. In fact, in the case of a heavy Higgs boson we see that Re a_2 actually violates unitarity earlier than does Re a_0. However, even using Re a_2 as the criterion, unitarity is first violated for $\sqrt{s}$ values above the $\overline{\Lambda}$ value appropriate to the $m_0/M_{\rm Pl} = 0.01$ value being considered, but still below $\Lambda_{\rm NDA}$. In fact, it is very generally the case that unitarity is not violated at $\sqrt{s} = \overline{\Lambda}$ (which is typically a sizable fraction of $\Lambda_{\rm NDA}$) no matter how small we take $m_0/M_{\rm Pl}$. However, as we shall see, unitarity can be violated in the vicinity of $\sqrt{s} \sim m_h$ if m_h is large and $m_0/M_{\rm Pl}$ is sufficiently small.

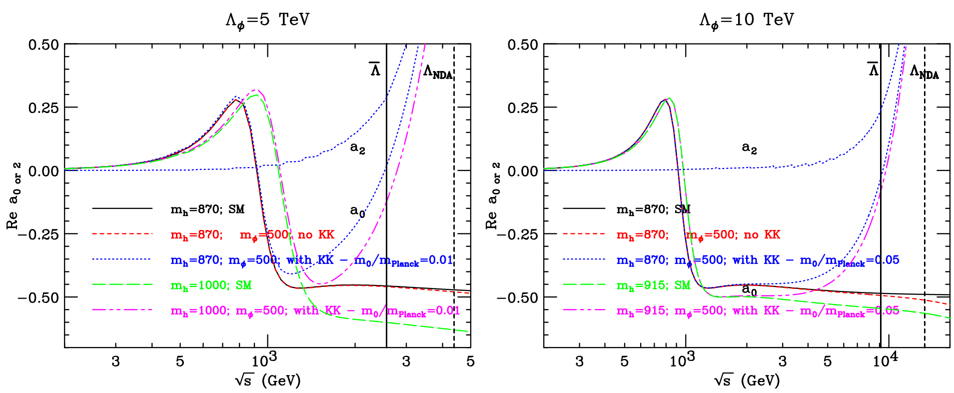

Fig. 3. For $\Lambda_\phi = 5$ TeV — left, $\Lambda_\phi = 10$ TeV — right, we plot Re a_0 as a function of $\sqrt{s}$ for five cases: 1. solid (black) $m_h = 870$ GeV, SM contributions only; 2. short dashes (red) $m_h = 870$ GeV, with an unmixed radion of mass $m_\phi = 500$ GeV included, but no KK gravitons (we do not show the very narrow ϕ resonance); 3. dots (blue) as in 2., but including the sum over KK gravitons taking $m_0/M_{\rm Pl} = 0.01$ ($m_0/M_{\rm Pl} = 0.05$) — Re a_2 is also shown for this case; 4. long dashes (green) $m_h = 1000$ GeV (915 GeV), with an unmixed radion of mass $m_\phi = 500$ GeV, but no KK gravitons); 5. as in 4., but including the sum over KK gravitons taking $m_0/M_{\rm Pl} = 0.01$ ($m_0/M_{\rm Pl} = 0.05$). The $\overline{\Lambda}$ and $\Lambda_{\rm NDA}$ values for $m_0/M_{\rm Pl} = 0.01$ ($m_0/M_{\rm Pl} = 0.05$) are indicated by vertical lines.

Looking again at the left plot of Fig. 3, we observe that if m_h is increased to 1000 GeV, the purely SM plus radion contributions (long green dashes) show strong unitarity violation at large $\sqrt{s}$ due to Re $a_0 < -1/2$. However, if we include the KK gravitons (long dashes and two shorter dashes in magenta), the negative Re a_0 unitarity violation disappears and unitarity is instead violated at higher $\sqrt{s}$. Thus, it is the KK gravitons that can easily control whether or not unitarity is violated for $\sqrt{s} < \overline{\Lambda}$ for a given value of m_h.

3. The Higgs-boson mass limit

As we have already seen, the Higgs plus vector boson exchange contributions have a large effect on the behavior of Re a_0 (whereas the radion exchange contributions are typically quite small in comparison). It is particularly interesting to consider cases with a very heavy Higgs boson, focusing on small values of $m_0/M_{\rm Pl}$. For $m_h = 870$ GeV and $\Lambda_\phi = 10$ TeV, the result appears as the left-hand plot of Fig. 4. Note that for the very small value of $m_0/M_{\rm Pl} = 0.0001$, unitarity is only just satisfied for $\sqrt{s} \sim m_h$ and that Re a_0 exceeds $+1/2$ near $\sqrt{s} \sim m_h$. This is a general feature in the case of a heavy Higgs; there is always a lower bound on $m_0/M_{\rm Pl}$ coming purely from unitarity. The right-hand plot of Fig. 4 shows how high we can push the mass of the Higgs boson without violating unitarity. For $m_h = 1430$ GeV, we are just barely consistent with the unitarity limit $|\text{Re } a_0| \leq 1/2$ (until large $\sqrt{s} \gtrsim \overline{\Lambda}$) if $m_0/M_{\rm Pl} = 0.0018$ (and $\Lambda_\phi = 10$ TeV). Any lower value of $m_0/M_{\rm Pl}$ leads to Re $a_0 > +1/2$ at $\sqrt{s} \sim m_h$ and any higher value leads to an excursion to Re $a_0 < -1/2$ at higher $\sqrt{s}$ values (but still below $\overline{\Lambda}$). There are no experimental limits (coming from direct production of KK gravitons) of which we are aware on the $m_0/M_{\rm Pl}$ values considered in Fig. 4 . For such values, the KK gravitons would have very small masses, an experimental analysis in that range of $m_0/M_{\rm Pl}$ is needed.

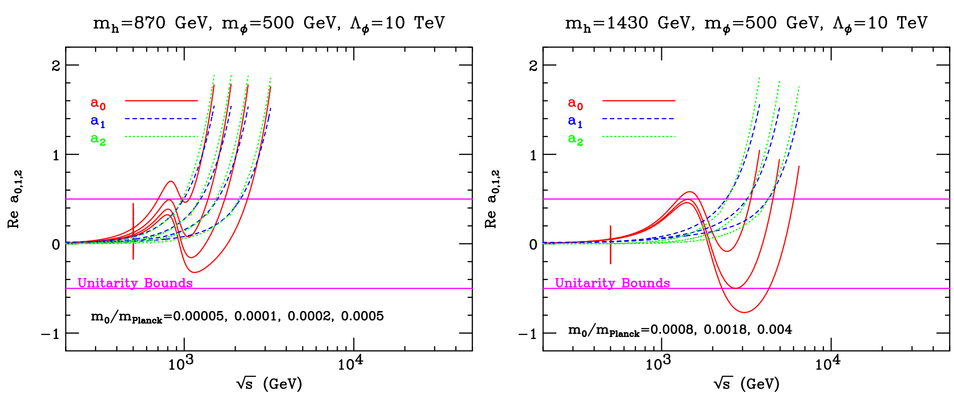

Fig. 4. We plot Re $a_{0,1,2}$ as functions of $\sqrt{s}$ for $m_h = 870$ GeV and $m_h = 1430$ GeV, taking $m_\phi = 500$ GeV and $\Lambda_\phi = 10$ TeV, and for the $m_0/M_{\rm Pl}$ values indicated on the plot. Curves of a given type become higher as one moves to lower $m_0/M_{\rm Pl}$ values. We have included all KK resonances with $m_n < \overline{\Lambda}$ (at all $\sqrt{s}$ values). Each curve terminates at $\sqrt{s} = \Lambda_{\rm NDA}$, where $\Lambda_{\rm NDA}$ at a given $m_0/M_{\rm Pl}$ is as plotted earlier in Fig. 2. The value of $\sqrt{s}$ at which a given curve crosses above Re $a_0 = +1/2$ is always slightly above the $\overline{\Lambda}$ (plotted in Fig. 2) value for the given $m_0/M_{\rm Pl}$.

In Table I we summarize the primary implications of our results by showing a number of limits on m_h for the choices of $\Lambda_\phi = 5$, 10, 20 and 40 TeV. The first block gives the very largest m_h that can be achieved, $m_h^{\max}$, without violating unitarity in $W_L^+ W_L^- \to W_L^+ W_L^-$ scattering for some $\sqrt{s} < \overline{\Lambda}$, along with the associated $m_0/M_{\rm Pl}$ value and mass m_1 of the lightest KK graviton. Unfortunately, no Tevatron limits (see [6]) have been given for the associated very small $m_0/M_{\rm Pl}$ values. Even if they end up being experimentally excluded, it is still interesting from a theoretical perspective that in the RS model unitarity can be satisfied for all $\sqrt{s}$ values below the $\overline{\Lambda}$ cutoff of the theory for a Higgs boson mass substantially higher than the usual 870 GeV value applicable in the SM context. One finds that $m_h^{\max}$ is typically of order 1.4 TeV if one chooses the optimal value for $m_0/M_{\rm Pl}$ (for Λ_ϕ in a reasonable range: 5 TeV $\leq \Lambda_\phi \leq$ 40 TeV). It is also noteworthy that the required values of $m_0/M_{\rm Pl}$ are quite consistent with model expectations.

TABLE I

Unitarity limits on m_h for various Λ_ϕ and $m_0/M_{\rm Pl}$ values.

Λ_ϕ(TeV)	5	10	20	40
Absolute maximum Higgs mass				
$m_h^{\max}$(GeV)	1435	1430	1430	1430
required $m_0/M_{\rm Pl}$	1.32×10^{-2}	1.8×10^{-3}	2.3×10^{-4}	2.9×10^{-5}
associated m_1(GeV)	103.2	28.2	7.2	1.8
$m_0/M_{\rm Pl} = 0.005$: Tevatron limit: $m_1 >$??				
$m_h^{\max}$(GeV)	1300	930	920	905
associated m_1(GeV)	39	78	156	313
$m_0/M_{\rm Pl} = 0.01$: Tevatron limit: $m_1 > 240$ GeV				
$m_h^{\max}$(GeV)	1405	930	910	895
associated m_1(GeV)	78	156	313	626
$m_0/M_{\rm Pl} = 0.05$: Tevatron limit: $m_1 > 700$ GeV				
$m_h^{\max}$(GeV)	930	915	900	885
associated m_1(GeV)	391	782	1564	3129
$m_0/M_{\rm Pl} = 0.1$: Tevatron limit: $m_1 > 865$ GeV				
$m_h^{\max}$(GeV)	920	910	893	883
associated m_1(GeV)	782	1564	3128	6257

Table I also gives the $m_h^{\max}$ value achievable for the four Λ_ϕ cases listed above for various fixed $m_0/M_{\rm Pl}$. Also given are the associated m_1 values and the Tevatron direct production limit when available. For some of the cases that are clearly consistent with Tevatron limits, unitarity is satisfied for m_h values as high as ~ 915 GeV.

4. Conclusions

We have discussed perturbative unitarity for $W_L^+W_L^- \to W_L^+W_L^-$ within the Randall–Sundrum theory with two 3-branes and shown that the exchange of massive 4D Kaluza–Klein gravitons leads to amplitudes growing linearly with the CM energy squared. We have found that the gravitational contributions cause a violation of unitarity for $\sqrt{s}$ below the natural cutoff of the theory, $\Lambda_{\rm NDA}$, as estimated using naive dimensional analysis.

In practice, to determine the cutoff the two basic RS model parameters Λ_W and $m_0/M_{\rm Pl}$ must be extracted from experiment, as should be possible at the LHC. If the Higgs mass has also been measured, then the maximum $\sqrt{s}$ for which $W_L^+W_L^- \to W_L^+W_L^-$ scattering obeys unitarity in the RS model can be found from the results of this paper. The most important result obtained here is the determination of the maximal Higgs boson mass allowed by requiring that $W_L^+W_L^- \to W_L^+W_L^-$ scattering be consistent with unitarity for all $\sqrt{s}$ values below the scale $\overline{\Lambda}$ (defined earlier and always close to $\Lambda_{\rm NDA}$): one finds $m_h^{\rm max} \leq 1.4$ TeV — to achieve the upper limit, a particular Λ_W-dependent $m_0/M_{\rm Pl}$ value is necessary.

We should emphasize here that we do not need to consider the effects of the scalar field(s) that are responsible for stabilizing the inter-brane separation at the classical level. These fields are normally chosen to be singlets under the SM gauge groups (sample models include those of Refs. [7,8]), and will thus have no direct couplings to the W_LW_L channel. For the purpose of this work, the only effect of the inter-brane stabilization is to determine the radion mass.

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