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Higgs production in association with top quark pair at e^+e^- colliders in theories of higher dimensional gravity

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ABSTRACT: Models with large extra compact dimensions predict exciting phenomenological consequences with gravitational interactions becoming strong at the TeV scale. Such theories can be tested at the existing and future colliders. In this paper, we study the contribution of virtual Kaluza-Klein excitations in the process $e^+e^- \to t\bar{t}H$ at a future linear collider. The exchange of virtual KK gravitons is found to modify the cross-section $\sigma(e^+e^- \to t\bar{t}H)$ from its Standard Model value to a very significant extent. The consequent sensitivity to the effective string scale M_S depends (weakly) on the number of extra-dimensions n and (strongly) on the center-of-mass energy of the collider. For $n = 3$, $M_S \simeq 920\,\mathrm{GeV}$ ($8\,\mathrm{TeV}$) could be probed at machines working at $\sqrt{s} = 500\,\mathrm{GeV}$ ($3\,\mathrm{TeV}$). More importantly, this process can serve to distinguish such models from other sources of new physics.

KEYWORDS: Extra Large Dimensions, Standard Model, Beyond Standard Model, Higgs Physics.

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Contents

1. Introduction

The concept of large extra dimensions and TeV scale gravity introduced by Arkani-Hamed, Dimopoulos and Dvali, often referred to as the ADD model [1] has attracted a lot of attention. In this scenario, the total space-time has $D = 4 + n$ dimensions, with the additional n dimensions compactified. While gravity lives in the entire bulk space-time, the Standard Model (SM) particles are deemed to be confined to the usual four (i.e. $3+1$) dimensions. The 4-dimensional Planck scale, $M_{Pl} \sim 2.4 \times 10^{18}\,\mathrm{GeV}$, is no longer a fundamental quantity but is derived from the size R of the extra dimensions[1] and the *fundamental* Planck scale M_S in the full theory:

$$M_{Pl}^2 \sim R^n M_S^{n+2}\,. \tag{1.1}$$

Thus, for large extra-dimensions, it is possible to have a *fundamental* scale M_S as low as a TeV [1], thereby "solving" the gauge hierarchy problem of the standard model. However, $M_S \sim \mathcal{O}(1\,\mathrm{TeV})$ in a model with a single extra dimension ($n = 1$) necessitates $R \sim 10^{11} mm$, a value that obviously runs counter to astrophysical observations. On the other hand, for $n \geq 2$, we have $R \leq$ mm, a range that is still allowed by gravitational experiments.

The graviton couples to the standard model matter and gauge particles through the energy-momentum tensor, with a strength suppressed by powers of the 4-dimensional Planck scale, M_{Pl}. However, from the 4-dimensional point of view, the massless graviton propagating in the $(4+n)$-dimensional bulk is to be interpreted as a tower of massive Kaluza-Klein (KK) modes of excitations, with spin-2, spin-1 (which decouples) as well spin-0 components. In the context of collider experiments, the mass spectrum of these KK

[1] In principle, each of the extra dimensions could have a different size. For the sake of simplicity though, we shall assume that the radii of the compactified T^n are identical.

modes can be treated as a continuum, as the mass splitting ($\sim 1/R$) between successive modes is about 10^{-4} eV (1 MeV) for $n = 2(6)$. On summing over the KK modes, the effective graviton-exchange contribution to processes involving the standard model particles is only suppressed by powers of $(\sqrt{s}/M_S)$ [1], where $\sqrt{s}$ is the energy available for the process. The Feynman rules for this theory may be developed from a linearized theory of gravity in the bulk and may be found in refs. [2, 3]. These new interactions can give rise to several interesting phenomenological consequences testable at present and future colliders [4] with their effects observed either through production of real KK modes [5, 6, 7], or through the exchange of virtual KK modes in various processes [4].

Real graviton emission, at LEP, through the processes $e^+e^- \to G\ \gamma(Z)$, with the G providing missing energy-momentum, have been studied [8, 9]. Negative results lead to a lower bound on $M_S \sim 0.6\,(1.4)$ TeV for $n = 6\,(2)$ [10]. The corresponding search by the D0 [11] and the CDF [12] collaborations (in the jets + $\not{E}_T$ channel) with a data sample of 84 pb^{-1} collected at $\sqrt{s} = 1.8$ TeV, leads to the exclusion, at 95% C.L., of M_S below $1.0, 0.77$ and 0.71 TeV for $n = 2, 4$ and 6 respectively. The CDF Collaboration has also investigated the $\gamma + \not{E}_T$ channel, but the sensitivity is distinctly lower ($M_S > 550$, 581 and 602 GeV for $n = 4, 6$ and 8 respectively). Significant enhancement of the sensitivity is expected at the LHC though. For example, with an accumulated luminosity of 100 fb^{-1}, the jets $+\not{E}_T$ channel can be used to probe M_S upto 9.1, 7.0 and 6.0 TeV for $n = 2, 3$ and 4 respectively [13]. On the other hand, at future e^+e^- linear colliders operating at $\sqrt{s} \sim 0.25 - 1.5$ TeV, processes such as $e^+e^- \to G\ \gamma(Z)$ [6] or Bhabha scattering with radiated gravitons [14] could be sensitive to M_S of upto several TeVs.

In contrast to real graviton production, one may also consider the contribution of virtual graviton exchanges in SM-allowed processes. Several $2 \to 2$ scattering processes have been investigated in the context of both hadronic as well as leptonic colliders [15]–[23]. The best curent limit was obtained from Drell-Yan production at the Tevatron (data collected upto October 2003) with the CDF and D0 collaborations setting limits of $M_S >$ 1.1 TeV and $M_S > 1.43$ TeV respectively (in the convention used by GRW [2]). While Run II(b) Run is expected to improve these bounds by more than a factor of 2 (e.g., combining dilepton and diphoton channel data is expected to probe upto $M_S \lesssim 3.5$ TeV for $n = 2$), at the LHC the sensitivity is enhanced manifold ($M_S \sim 8.3$–13 TeV for $n = 2$–6) [17]. Similarly, at future e^+e^- linear colliders one could expect to probe $M_S \lesssim 5\sqrt{s}$ [24].

The next generation e^+e^- linear colliders is expected to function with a center-of-mass energy ranging from 300 GeV up to about 1 TeV [25, 26, 27]. There is also a possibility of multi-TeV linear collider operating between energy range of 3-5 TeV at CERN [28]. In this paper we will consider the process $e^+e^- \to t\bar{t}H$ to study the effect of low-scale gravity at the proposed linear colliders operating with a center of mass energy 500 GeV and beyond. Within the SM, $t\bar{t}H$ production has been studied in the context of the determination of the top quark Yukawa couplings [29, 30]. Thus, one would be looking for significant deviations from the expectations within the SM as a signal of new physics. However, it should be borne in mind that these processes are unlikely to serve as the dominant discovery channel for KK gravitons, since there exist other simpler channels that are equally (or more) sensitive to such graviton exchanges [4].

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On the other hand, once a discovery is made, the next phase would comprise of confirmatory tests as well as the determination of the parameters of the theory. This can be achieved only through a series of other experiments and this is where the process under discussion would be useful. For one, the enhancement on account of graviton exchanges could, in principle, behave differently with a change in $\sqrt{s}$ than in the case for the simple and well-studied $2 \to 2$ processes. This behaviour will be different for different models of new physics beyond the SM and thus help distinguish between them. Furthermore, such a study could provide us with additional insight into the Higgs mechanism operative in higher dimensional theories.

2. $e^+e^- \to t\bar{t}H$

In this section we study the effect of the graviton exchange in the production of a Higgs particle in association with a pair of top quarks at a Linear Collider. The SM diagrams contributing to this process are well known. We present the Feynman rules relevant for this process in the appendix. In figure 1, we present the additional set of diagrams that arise in the theory under consideration.[2]

The amplitudes corresponding to the diagrams in figure 1 can be easily calculated following the Feynman rules derived in, say, ref. [3]. As mentioned earlier, the gravitational coupling $\kappa \equiv \sqrt{16\pi G_N}$ (G_N being the four-dimensional Newton's constant) can be

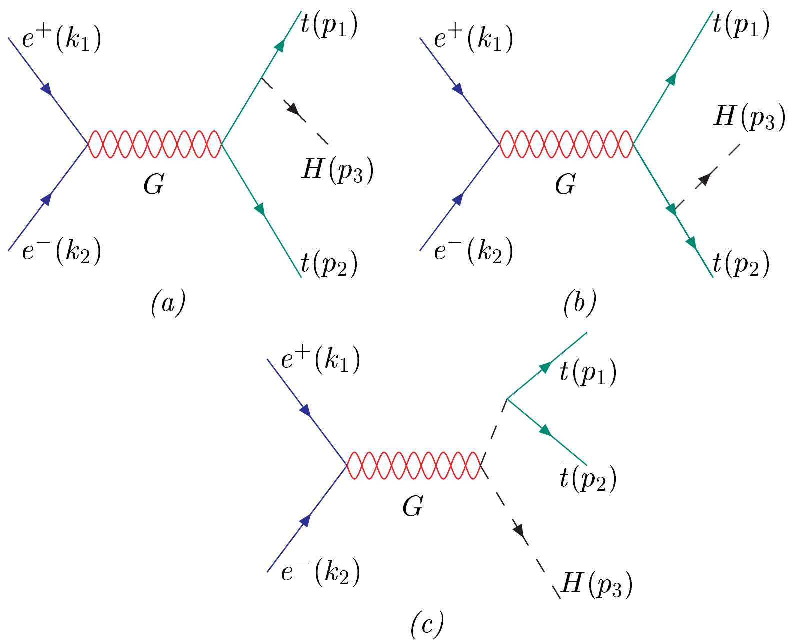

Figure 1: The graviton-mediated diagrams contributing to $e^+e^- \to t\bar{t}H$ at the tree level.

[2]Note that two further diagrams exist. These involve the exchange of the graviscalar with a $f\bar{f}G$ vertex at one end and a $f\bar{f}HG$ vertex on the other. However, since the graviscalar coupling, with or without the Higgs, is proportional to the fermion mass, we may safely neglect such contributions on account of the smallness of m_e.

expressed in terms of the fundamental scale M_S and the size R of the n extra dimensions through

$$\kappa^2 R^n = 16\pi\,(4\pi)^{n/2}\,\Gamma(n/2)\,M_S^{-(n+2)}\,. \tag{2.1}$$

Choosing to work in the de Donder gauge, we have, for the amplitudes,

$$\begin{aligned}
\mathcal{M}_a &= \frac{-\mathcal{G} g m_t \pi}{16 M_W}\,\frac{P^{\mu\nu\alpha\beta}}{(p_1+p_3)^2 - m_t^2}\,[\bar{v}(k_1) C_{\mu\nu} u(k_2)][\bar{u}(p_1)\,(\not{p}_1 + \not{p}_3 + m_t)\chi^a_{\alpha\beta} v(p_2)] \\
\mathcal{M}_b &= \frac{\mathcal{G} g m_t \pi}{16 M_W}\,\frac{P^{\mu\nu\alpha\beta}}{(p_2+p_3)^2 - m_t^2}\,[\bar{v}(k_1) C_{\mu\nu} u(k_2)][\bar{u}(p_1)\,(\not{p}_2 + \not{p}_3 - m_t)\chi^b_{\alpha\beta} v(p_2)] \\
\mathcal{M}_c &= \frac{-\mathcal{G} g m_t \pi}{2 M_W}\,\frac{P^{\mu\nu\alpha\beta}}{(p_1+p_2)^2 - m_H^2}\,[\bar{v}(k_1) C_{\mu\nu} u(k_2)][\bar{u}(p_1)\chi^c_{\alpha\beta} v(p_2)]
\end{aligned} \tag{2.2}$$

where,

$$\begin{aligned}
\mathcal{G} &= \frac{\kappa^2}{16\pi} D(s) = M_S^{-4}\left(\frac{\sqrt{s}}{M_S}\right)^{n-2}\left[\pi + 2i\,P\int_0^{M_S/\sqrt{s}} \frac{y^{n-1}\,dy}{1-y^2}\right] \\
P^{\mu\nu\alpha\beta} &= \eta^{\mu\alpha}\eta^{\nu\beta} + \eta^{\mu\beta}\eta^{\nu\alpha} - \frac{2}{3}\eta^{\mu\nu}\eta^{\alpha\beta} \\
C_{\mu\nu} &= [\gamma_\mu (k_2 - k_1)_\nu + (\mu \leftrightarrow \nu)] \\
\chi^a_{\alpha\beta} &= [\gamma_\alpha (p_1 - p_2 + p_3)_\beta - \eta_{\alpha\beta}(\not{p}_1 - \not{p}_2 + \not{p}_3 - 2m_t)] + (\beta \leftrightarrow \alpha) \\
\chi^b_{\alpha\beta} &= [\gamma_\alpha (p_1 - p_2 - p_3)_\beta - \eta_{\alpha\beta}(\not{p}_1 - \not{p}_2 - \not{p}_3 - 2m_t)] + (\beta \leftrightarrow \alpha) \\
\chi^c_{\alpha\beta} &= m_H^2 \eta_{\alpha\beta} - (p_1+p_2)^\mu p_3^\nu\,[\eta_{\mu\alpha}\eta_{\nu\beta} + \eta_{\nu\alpha}\eta_{\mu\beta} - \eta_{\mu\nu}\eta_{\alpha\beta}]
\end{aligned} \tag{2.3}$$

with $s \equiv (k_1+k_2)^2$. The function $D(s)$ is the resultant of summing over the KK modes of the graviton, and only the principal part of the integral is to be taken.

The cross sections after adding the new amplitudes to the SM are presented in figure 2 as a function of machine energy, and for different Higgs masses. To be specific, we hold the number of extra dimensions to be $n = 3$. In each figure, the solid line represents the standard model predictions and exhibits the expected fall-off with energy. The inclusion of the graviton exchange changes the $\sqrt{s}$-dependence drastically. For relatively large values of M_S, the fall-off persists upto a certain value of $\sqrt{s}$ and thereafter the cross section increases rapidly. And, as expected, the turnaround point (in $\sqrt{s}$) is a monotonic function of M_S. Thus we can expect stronger bounds on M_S as the machine energy increases. Comparing the three panels in figure 2, it is very clear that the ADD contribution is not strongly dependent on Higgs mass. At low energies, the difference in the magnitude of cross-sections for these three values of Higgs masses arises mainly from the phase space. At relatively higher value of $\sqrt{s}$, the cross-sections corresponding to $m_H = 120$ and $200\,\mathrm{GeV}$ become nearly identical. Indeed, the relative difference between the cross sections for any two different values of m_H tends to be smaller in the ADD case than that within the standard model.

Since the integral in $D(s)$ — see eq. (2.3) — is a relatively slowly increasing function of $(M_S/\sqrt{s})$, the amplitudes typically go down as $\sim M_S^{-4}$. This is reflected in figure 3, where we present the total cross-section as a function of M_S for theories with different numbers

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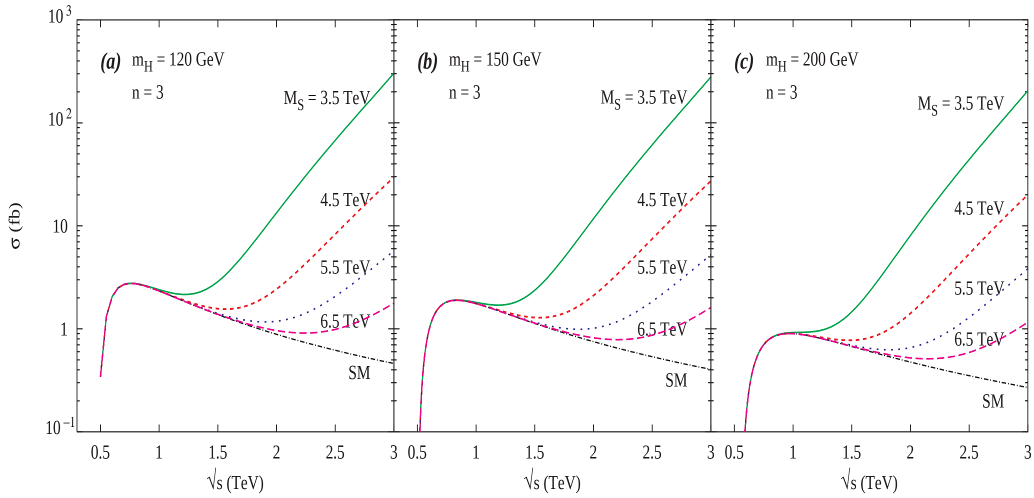

Figure 2: Variation of the cross-section (fb) for $t\bar{t}H$ production with machine energy. The four dashed curves correspond to the ADD predictions for $M_S = 3.5, 4.5,$ 5.5 and 6.5 TeV and $n = 3$, while the solid line represents the standard model expectations. The three panels correspond to three different values of the Higgs mass.

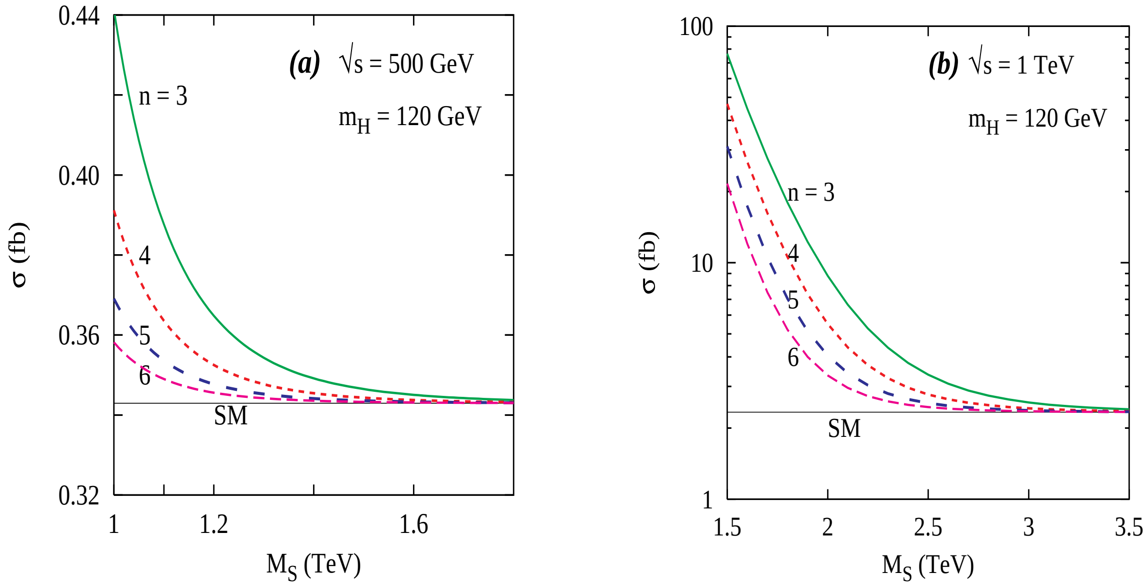

Figure 3: The variation of the cross-section (fb) for $t\bar{t}H$ production with M_S, for a Higgs mass of 120 GeV. The curves correspond to the ADD predictions for $n = 3, 4, 5$ and 6 respectively. Also indicated are the standard model expectations. The left and the right panels correspond to $\sqrt{s} = 500$ GeV and 1 TeV respectively.

of extra dimensions. For comparison, the SM cross-sections are also given. As with simpler processes, here too the graviton contribution decreases with the increase in the number of extra-dimension as long as the machine energy and M_S are held constant.

It is thus obvious that graviton-exchange contributions can significantly alter the predictions for the $e^+e^- \to t\bar{t}H$ cross-section in such models. However, before one can claim

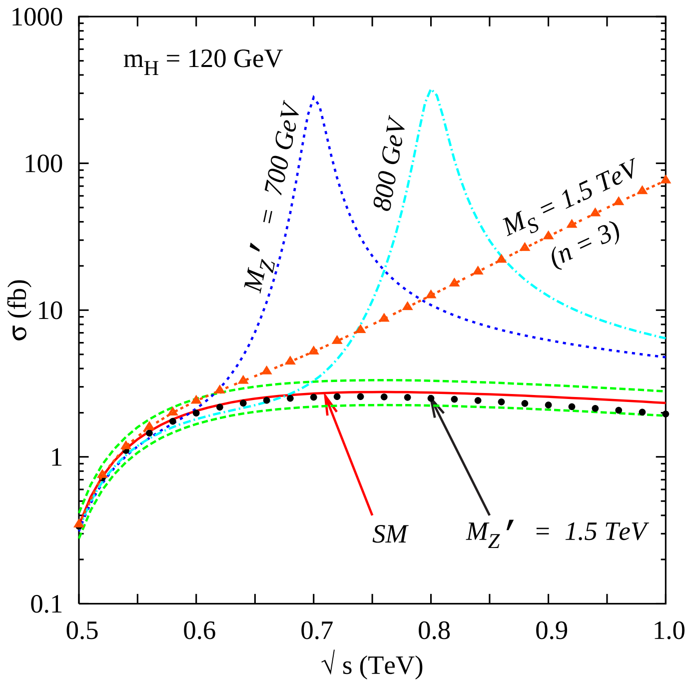

Figure 4: Variation of $\sigma(e^+e^- \to t\bar{t}H)$ with machine energy ($m_H = 120\,\mathrm{GeV}$). The solid curve represents the SM cross-section while the band around it indicates the variation in it wrought by a $\pm 10\%$ deviation in the SM $t\bar{t}H$ coupling. The monotonically increasing curve corresponds to a ADD model with $n = 3$ and $M_S = 1.5\,\mathrm{TeV}$. Also shown are three curves corresponding to a 4-dimensional model with a sequential Z' for different values of the latter's mass.

that any such observed deviation has been occasioned by the exchange of virtual gravitons, one needs to ascertain that such deviations cannot be explained by any other possible 4-dimensional new physics effects (4DNP) going beyond the SM. We proceed to do this next.

Note that, within the SM, the process under discussion is controlled by two relatively undetermined couplings, namely the $t\bar{t}H$ and the ZZH ones. Of these, the latter is expected to be measured to a very great accuracy at such a collider [31]. As for the former, the expected accuracy is far less. In fact, the process under consideration, in itself, is perhaps the best channel for this measurement! In view of this ignorance, let us assume that any 4DNP effect may change the $t\bar{t}H$ coupling by at most 10%. While this may be an underestimate, we shall see that even a somewhat larger uncertainty would not change our conclusions qualitatively.

In figure 4, we display the effect of such a variation in the $t\bar{t}H$ coupling on the cross-section under consideration. The two sidebands around the central (SM) curve represent the cross section expected for an enhancement (reduction) of the $t\bar{t}H$ coupling by 10%. As is immediately obvious, the functional dependence of the cross-section on the center-of-mass energy remains virtually the same as in the standard model for modest changes in this coupling. On the other hand, the functional dependence is markedly different for ADD scenarios. Thus, measurements at two different center of mass energies would clearly distinguish between these two classes of models.

$\sqrt{s}$	M_S in GeV			
TeV	$n = 3$	4	5	6
0.5	920 (880)	855 (825)	810 (785)	780 (750)
1.0	2530 (2470)	2300 (2240)	2140 (2090)	2020 (1970)
3.0	7970 (7680)	7200 (6960)	6680 (6470)	6300 (6100)

Table 1: 3σ exclusion limits on M_S achievable with an integrated luminosity of 500 fb^{-1} for different center-of-mass energies ($\sqrt{s}$). n is the number of extra dimensions and we assume $m_H = 120\,\mathrm{GeV}$. The numbers in parentheses refer to the corresponding (5σ) discovery limits.

As a further example of 4DNP, let us consider an extension of the SM to a model with an extra neutral gauge boson (Z'). For illustrative purposes, we choose to work with a sequential Z', namely one whose couplings to the SM particles are exactly the same[3] as those of the usual Z [32]. In figure 4, we also demonstrate how the $t\bar{t}H$ production cross section may change in the presence of such a Z'. For center of mass energies well below $m_{Z'}$, the cross section would naturally be quite similar to that within the SM. However, as the energy is raised, the cross section starts to grow rapidly, potentially mimicking the effect within an ADD model. However, if the energy is raised further, the resonance structure characteristic of such a Z' would evince itself (as also in other production modes). If the energy were to be raised still further to values much larger than $m_{Z'}$, the cross section would fall as dictated by considerations of partial wave unitarity. Thus, once again, such models are easily distinguishable from ADD-like ones.

Note, however, that both the sets of alternative models considered here are renormalizable ones. One might, instead, consider a generic *effective* field theory characterized by (a multitude of) higher-dimensional operators [33, 34, 35] giving rise to cross-sections increasing with energy (see, e.g., figure 2 of ref. [35]). Clearly, *any single experiment* such as the one discussed here *cannot* distinguish between such scenarios from the ADD one. This criticism applies equally well to the more canonical probes of the ADD scenario. However, if one considers the totality of experimental signatures of ADD, it is highly improbable that such higher dimensional operators produce similar energy-dependence of the cross sections in all the channels considered. In fact, the importance of considering many alternative signatures for ADD, such as the one we have considered here, is precisely in eliminating explanations based on *ad hoc* higher dimensional operators. We thus do not compare our results with such models here.

Now that a method of distinguishing has been delineated, we may try to estimate the sensitivity of the process under consideration. To this end, we display, in table 1, the 3σ exclusion limit on M_S for different machine energies and number of extra dimensions. In estimating these limits we assume an integrated luminosity of 500 fb^{-1}, detection efficiency of 80% and a 2% systematic error. We would, however, like to point out that, in the absence of a detailed simulation, such estimates are necessarily very crude ones. Furthermore, while estimating the SM tth cross-sections we have not considered QCD and EW corrections, which has been computed by several groups [36, 37].

[3]The corresponding results for a Z' with a different set of couplings are qualitatively very similar.

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That the exclusion limits vary strongly with the available energy is but a consequence of the structure of the theory (in particular, the momentum dependence of the couplings) and could have already been expected from figures 2 or 3. What is also remarkable is that the exclusion (discovery) limits on M_S are only weakly dependent on the number of extra dimensions.

3. Summary

In this paper we have studied the implications of KK graviton contribution to the process $e^+e^- \to t\bar{t}H$, which has been studied in the standard model. The spin-2 mode of KK gravitons contribute to this process substantially. It is likely though that the existence of low-energy quantum gravity may be discovered through more direct channels as studied by several groups. Nevertheless, this process will be an independent confirmation for such a discovery. We have shown both 3σ exclusion limit and 5σ discovery limit for the string scale M_S obtainable at typical linear collider energies assuming the benchmark integrated luminosity of 500 fb^{-1}.

Acknowledgments

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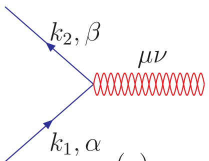
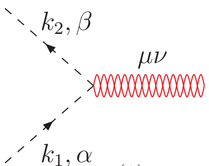
A. Feynman rules for graviton exchange

In this section we list the leading-order, i.e. $\mathcal{O}(\kappa)$, Feynman rules relevant for this analysis. Detailed Feynman rules can be found in ref. [3, 38]. Following the symbols used in ref. [3] we have:



$$: -i\frac{\kappa}{8}\,\delta_{\alpha\beta}\left[\gamma_\mu\,(k_{1\nu}+k_{2\nu}) + \mu \leftrightarrow \nu - 2\eta_{\mu\nu}\,(\not{k}_1 + \not{k}_2 - 2m_f)\right]$$

(a)



$$: -i\frac{\kappa}{8}\,\delta_{\alpha\beta}\,(m_\Phi^2\eta_{\mu\nu} + C_{\mu\nu,\rho\sigma}k_1^\rho k_2^\sigma)$$

(b)

Figure 5: Three-point fermion-fermion-Graviton (a) and scalar-scalar-Graviton (b) Feynman rules. The KK states are denoted by double sinusoidal curves. m_f and m_Φ are masses of the fermion and scalar particles, $\kappa = \sqrt{16\pi G_N}$ and $C_{\mu\nu,\rho\sigma} = \eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \eta_{\mu\nu}\eta_{\rho\sigma}$.

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