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Identifying new physics contributions in the Higgs sector at linear e^+e^- colliders

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Abstract. Loop-driven decay modes of the Higgs are sensitive to new physics contributions because of new particles in the loops. To highlight this we look at the dilepton–dijet signal in the dominant Higgs production channel at a linear e^+e^- collider. We show that by taking a simple ratio between cross-sections of two different final states such contributions can be very easily identified.

Keywords. Higgs; universal extra dimension; linear collider.

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1. Introduction

Higgs boson discovery will prove to be a crucial ingredient towards understanding the mechanism of electroweak symmetry breaking. Once discovered, a major goal would be to determine its other intrinsic properties, couplings and its total width with high accuracy in a model independent way. The proposed future e^+e^- linear colliders would be instrumental in achieving very precise measurements of the Higgs boson properties.

The partial width of the Higgs decaying to the massless gauge boson is of special interest, since there are no tree level couplings of the Higgs to them and any contribution is generated at the one-loop level. The di-photon partial width gets contribution through massive charged particles in the loops while the gluon–gluon partial width gets contributions from the heavy quarks running in the loops. The effective loop-induced couplings of $H\gamma\gamma$ and Hgg are sensitive to new contributions from particles which appear in various extensions of the SM. Not only do these decay modes provide for a possible probe of new physics particles which are too heavy to be produced directly but they are also sensitive to scales far beyond the Higgs mass. We take up the case of the enhancement in the partial decay width of $H \to gg$ due to additional contributions coming from particles from theories of beyond SM (BSM) physics. Such additional heavy particles are predicted in many different models of BSM physics and here we consider the model of universal extra dimensions (UED) [1] where all the quark flavors of the SM have heavy Kaluza–Klein (KK) excitations. These heavy KK states will modify the form factors which in turn will affect the partial width $\Gamma(H \to gg)$. The UED model, in its simplest form [2], has all the SM particles propagating in a single extra dimension, which is compactified on an S_1/Z_2 orbifold with R as the radius of compactification. The KK tower resulting on the four-dimensional space-time has a tree level mass given by

$$m_n^2 = m^2 + \frac{n^2}{R^2}, \tag{1}$$

where n denotes the nth level of the KK tower and m corresponds to the mass of the SM particle in question.

Since $H \to gg$ proceeds through diagrams containing fermion triangle loops and the coupling is proportional to the zero-mode mass of the fermion even in the case of UED, we consider contributions of the KK tower of the top quark only. The partial decay width for $H \to gg$ with SM and UED contribution is [3],

$$\Gamma(H \to gg) = \frac{G_{\mathrm{F}} m_H^3}{36\sqrt{2}\pi} \left(\frac{\alpha_{\mathrm{s}}(m_H)}{\pi}\right)^2 \; |I_q + \sum_n \tilde{I}_{t^{(n)}}|^2, \tag{2}$$

where G_{F} is the Fermi constant, $\alpha_{\mathrm{s}}(m_H)$ is the running QCD coupling evaluated at m_H and $I_g = \sum_q I_q$, I_q being the contributions of the loop integrals involving the different quark flavors and $\tilde{I}_{t^{(n)}}$ are the additional contributions of the loop integrals for the UED case. These functions are given in ref. [3]. The UED contribution is summed over the first few levels of the KK tower, till the effects of the higher modes decouple and hardly contribute to the amplitude anymore.

2. Channel of interest

We consider the case of a 500 GeV linear e^+e^- collider and calculate the production of a Higgs in association with a Z boson through a process of the form

$$e^+e^- \to Z + H, \tag{3}$$

where Z decays leptonically. In the preceding paragraph we discuss the final states relevant for our study.

1. $e^+e^- \to \ell^+\ell^- +$ two jets, which arises when the Higgs boson decays to a pair of quarks or gluons [3a], which then undergo fragmentation to form a pair of hadronic jets. Clearly, for a Higgs boson in the SM, final state will receive contributions mainly from the decays $H \to b\bar{b}$ and $H \to c\bar{c}$, with a minuscule contribution due to $H \to gg$. However, due to the increase in the partial width for $H \to gg$ due to the extra contribution coming from the additional KK excitations of the top quark in the loops, there will be an enhancement in the overall branching ratio to jets.
2. $e^+e^- \to \ell^+\ell^- + b\bar{b}$, which simply means that the final state in the above contains two tagged b-jets. The decay width for $H \to b\bar{b}$ is roughly the same in SM as well as UED, although the change of the two-gluon decay mode will have a small effect on the branching ratio for the $b\bar{b}$ mode.

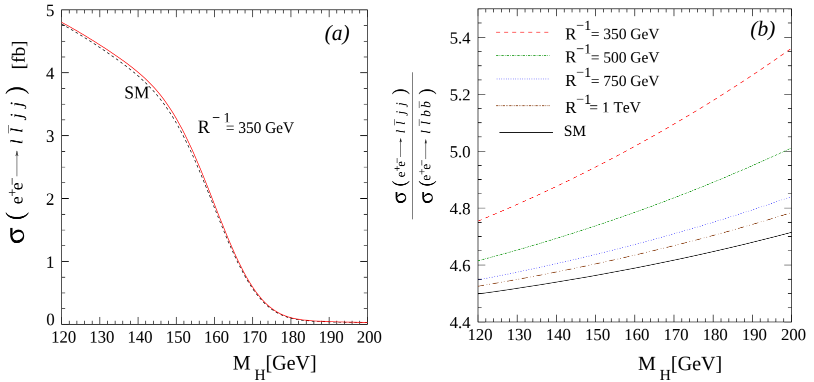

Figure 1. The curves are generated for $\sqrt{s} = 500$ GeV linear e^+e^- collider. (**a**) Shows the cross-section. (**b**) Shows the ratio of cross-sections between two final states for different values of the compactification radius.

In our subsequent analysis, we have imposed a few kinematic acceptance cuts on the final-state particles, viz.,

1. The final-state leptons should have transverse momentum $p_{\mathrm{T}}^{(\ell)} > 10$ GeV and pseudo-rapidity $\eta^{(\ell)} < 3.0$. The final-state jets should have transverse momentum $p_{\mathrm{T}}^{(J)} > 10$ GeV and pseudo-rapidity $\eta^{(J)} < 2.5$.
2. The final-state jets should be clearly separated from each other, so we impose a cut: $\Delta R_{JJ} (\equiv \sqrt{\Delta\eta_{JJ}^2 + \Delta\phi_{JJ}^2}) > 0.4$.

In figure 1a, we illustrate our result for the process discussed above, namely,

$$e^+e^- \to \ell^+\ell^- + \text{two jets}$$

at a $\sqrt{s} = 500$ GeV, e^+e^- collider. The solid line denotes the UED-included cross-section where we have chosen the value of $R^{-1} = 350$ GeV which gives a greater enhancement compared to values of R^{-1} greater than the above, while the dashed line denotes the SM contribution only. It should be noted that the graph shows the excess cross-section after removing the non-Higgs part of the standard model contributions (such as $e^+e^- \to ZZ, ZZ^*$ etc.). The continuum background ($\gamma^*\gamma^*$, Z^*Z^*) too can be easily neglected as it lies below 10^{-3} fb (in the bins of $b\bar{b}$ invariant mass) and would hardly affect the rates for the signal in consideration. The cross-section shown in figure 1a makes it clear that it is very hard to see the differences by just looking at the rates. The cross-sections for $\ell^+\ell^-$ + two jets final state are almost identical in the two cases. As the cross-sections look very similar, it would require very precise measurements to form a distinction between the two cases. However, if we consider the ratio of the two processes, viz. $\frac{\sigma(e^+e^- \to \ell^+\ell^- \ + \text{ two jets})}{\sigma(e^+e^- \to \ell^+\ell^- + b\bar{b})}$ we can see that the difference between the two cases becomes more prominent. In figure 1b we plot this ratio for different values of the compactification scale R^{-1}. We find that the ratio differs from that of the SM throughout the mass range of 120 GeV $\leq m_H \leq$ 200 GeV with the lines converging towards the SM value as R^{-1} is increased. In fact this highlights the decoupling nature of the higher levels of the

KK tower and justifies our termination of the sum of KK towers in the loop, to values where the contributions become negligibly small. The ratios tend to diverge more as the Higgs mass increases. This is because the branching ratios of $H \to gg$ and $H \to b\bar{b}$ become comparable and the enhancement in the $H \to gg$ mode starts playing a more significant role in the 2-jet final state. However, there is a caveat. For comparatively higher Higgs masses, cross-sections for both the above processes are small. Hence, we need higher luminosity to differentiate between the SM and the UED cases in a statistically significant way. The robustness of this method is, nevertheless, highlighted in the fact that although the $H \to gg$ branching ratio is more than an order smaller than that of $H \to b\bar{b}$ in the intermediate mass range for the Higgs boson, we are still able to identify the difference due to the UED contribution which would have been otherwise very difficult to see, by just looking at the cross-sections. The ratios are not susceptible to uncertainties like different efficiency factors associated with particle identifications as they would cancel out. The efficiency factors will however give a more realistic estimate of the events that will be observed at the experiments and which gives us an estimate of the uncertainties in the statistics.

In fact the above analysis can be used to identify other new physics scenarios which play a similar role in modifying the partial width of the Higgs to massless gauge bosons. It can also be used to distinguish scalars of other theories which behave similar to the Higgs boson. Radions predicted in models of warped extra dimensions [4] have similar couplings like the Higgs boson. A major difference is the enhanced coupling of radion to gluons through the trace anomaly. The above analysis proves useful in distinguishing radions from Higgs boson quite effectively [5].

3. Summary

This talk was based on the work done with Anindya Datta and further details can be obtained from ref. [6].

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