Invisible Higgs in theories of large extra dimensions

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ABSTRACT

We discuss the possibility of detecting a Higgs boson in electron-positron collider experiments if large extra dimensions are realized in nature. In such a case, the Higgs boson can decay invisibly by oscillating into a graviscalar Kaluza-Klein (KK) tower. We show that the search for such a Higgs at an e^+e^- linear collider entails more complications than are usually thought of in relation to an invisibly decaying Higgs.

1. Introduction

Confirming the Higgs mechanism as the underlying principle of electroweak symmetry breaking is one of the main goals of upcoming accelerators. The strategy for Higgs search depends on the decay branching fractions of Higgs (H) to different channels. One possibility is that a Higgs can have a substantial branching ratio for decay into invisible final states. This possibility has been underlined in a number of well-motivated theoretical options (see [1] and references 1-8 there). This talk is based on the Ref. [1].

Theories with large extra spatial dimensions have been popular in recent times. Broadly two such types of models have been studied so far, namely, the Arkani-Hamed-Dimopoulos-Dvali (ADD) [2] and Randall-Sundrum (RS) [3] types. Both of them accomodate extra compact spacelike dimensions, with gravity propagating in the 'bulk', while all the Standard Model (SM) fields are confined to (3+1) dimensional slices or 'branes'. In ADD-type models, one has a factorizable geometry, where the projection on the brane leads to a continuum of scalar and tensor graviton states. The discussion in this talk is related to the ADD-type of models.

An important feature of these models is that the Higgs boson can mix with the graviscalars (the projection of the graviton on the visible brane). One can add to the Lagrangian a mixing term

$$S = -\xi \int d^4x \sqrt{-g_{ind}} R(g_{ind}) H^\dagger H, \tag{1}$$

where H is the Higgs doublet, ξ is a dimensionless mixing parameter, g_{ind}, the induced metric on the brane and R is the Ricci scalar. One can parameterize such mixing by the following term in the Lagrangian:

$$\mathcal{L}_{mix} = \frac{1}{M_P} m_{mix}^3 h \sum_n S_n, \tag{2}$$

where $m_{mix}^3 = 2\kappa\xi v m_h^2$, M_P is the reduced Planck mass, and v is the Higgs vacuum expectation value. κ can be expressed in terms of the number of extra dimensions: $\kappa^2 \equiv 3(\delta-1)/\delta+2$, δ being the number of extra compact spacelike dimensions.

The effects of extra dimensions on the Higgs decay modes are different in the case of large or small extra dimensions. In the case of the large extra dimensions the major effects are due to the closely spaced KK-levels. These lead to the possibly effective 'invisible decays' of the Higgs boson, via oscillation into one or the other state belonging to the quasi-continuous tower of graviscalars [4]. In case of the small extra dimensions the effect comes from the mixing of the Higgs boson with the single radion [3].

2. Higgs invisible decays with scalar-graviscalar mixing

One proceeds by considering the Higgs propagator in the flavor basis and incorporating all the insertions induced by the mixing term. As has been shown in [4], the effect of having a large number of real intermediate states inserted leads to the development of an imaginary term in the propagator. This imaginary part can be interpreted as an effective decay width entering into the propagator following the Breit-Wigner scheme [4][a]:

$$\Gamma_G = 2\pi\kappa^2\xi^2 v^2 \frac{m_h^{1+\delta}}{M_D^{2+\delta}} \frac{2\pi^{\delta/2}}{\Gamma(\delta/2)}, \tag{3}$$

where M_D is the $(4+\delta)$-dimensional Planck scale (also called the string scale). A Higgs boson has a finite probability (proportional to ξ^2) of oscillating into a the invisible states corresponding to the graviscalar tower. The transition is favored when masses of the Higgs and the corresponding graviscalar are close to each other.

Assuming that the graviton KK tower is the only source of the invisible width in the model, we have plotted in Fig. 1 the invisible branching ratio as a function of the mixing parameter. Two masses for the Higgs boson, namely, $m_h = 120$ GeV, and $m_h = 200$ GeV, have been used. The plots have been made for $M_D = 1.5$, 3, and 10 TeV and for $\delta = 2$.

The effective invisible decay width grows as m_h^3 for $\delta = 2$. This implies that even for $m_h < 2m_W$ total Higgs decay width can be considerably larger than the Standard Model width. As a consequence, even for a light Higgs boson, Higgs resonance may not be very sharp.

3. Detection in e^+e^- collider

It is evident from the Fig. 1 that the Higgs can have a very large invisible branching ratio in the scenario considered here. We investigate the situation at an e^+e^- machine, where the identification of the recoil mass peak against the Z-boson in the Bjorken process is widely known to be a reliable method of detecting the Higgs boson[b]. We therefore concentrate on this process ($e^+e^- \to Z(\to \mu^+\mu^-)h(\to \text{inv})$), also known as the Higgs-strahlung process, at a linear collider with center of mass energy of 1 TeV. The final state we are interested in comprises of a $\mu^+\mu^-$ pair with missing energy/momentum. We do not

[a]Our calculation of the width agrees with [5] where the width is twice the value in [4]. See also talk by J. Gunion in this proceedings.

[b]Possibilities to detect an invisibly decaying Higgs at next generation e^+e^- collider have also been discussed in [6], but only in the context of 4-dimensional models where continuum graviton production does not arise at all.

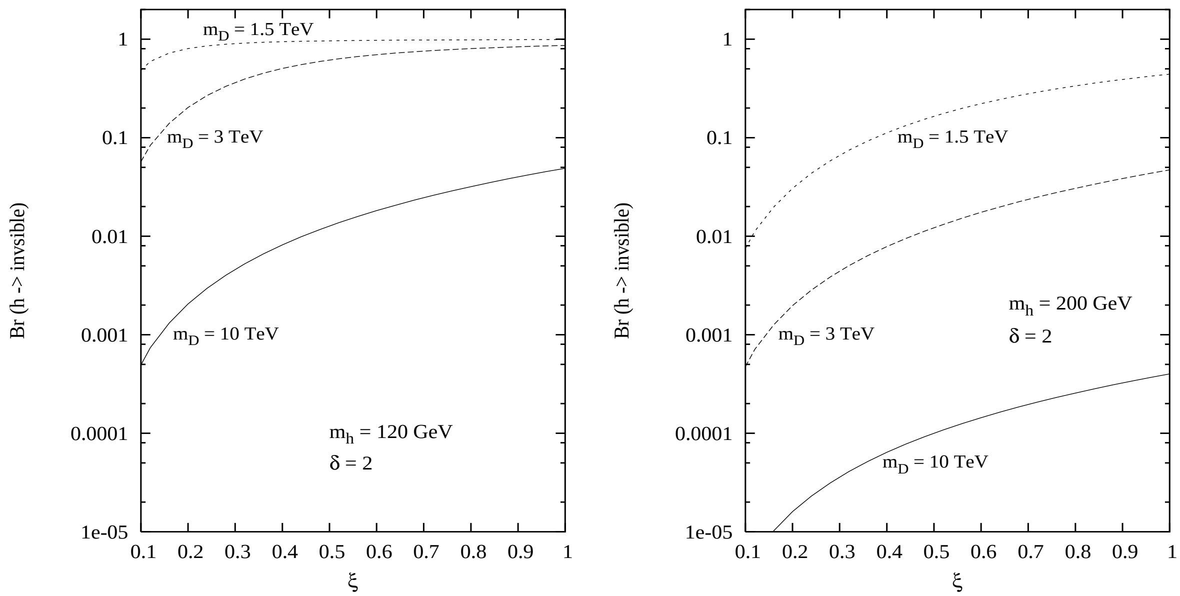

Figure 1: The invisible decay branching ratio of the Higgs boson as a function of the mixing parameter for two representative values of Higgs mass and for one number of extra dimensions, $\delta = 2$.

use the narrow width approximation, but rather treat the Higgs boson as a propagator (inclusive of an invisible width) while calculating the cross-section. We have also taken into account the direct graviscalar production alongside.

A similar final state can arise also in the production of a Z-boson with towers of graviton (spin-2/spin-0). In addition to the SM processes $e^+e^- \to ZZ/WW \to \mu^+\mu^- + \not{E}$, we have included gravitensor production together with a Z-boson, both leading to identical final states.

The ZZ and $Z\nu\bar{\nu}$ backgrounds are eliminated with specific cuts [1]. We find that these criteria work well so long as the invisible Higgs mass is well below 250 GeV or thereabout.

We also need to worry about filtering out the Higgs effects from continuum gravitensor contributions. The first step for this is to reconstruct the recoiled invariant mass which peaks at the Higgs mass modulo the Higgs width and detector resolution. The other important factor is the height of the peak against the continuum background. It is determined by the Higgs-graviscalar mixing ξ, the same quantity which also determines the Higgs width, making the width large for $\xi = O(1)$. This causes the invisible decay recoil mass distribution to lose its sharp character even for a Higgs mass of the order of 120 GeV.

In Fig. 2 we have plotted the recoil mass distribution for the $\mu^+\mu^- + \not{E}$ events including the SM, gravitensor and invisibly decaying Higgs production. The results are presented for three different values of the number of extra dimensions. In the two sets of plots, corresponding to Higgs masses 120 GeV (left) and 200 GeV (right), the different degrees of visibility of the peak is quite obvious. We have chosen $m_D = 1.5$ TeV, $\xi = 1$ and $\sqrt{s} = 1$ TeV. To take into account a realistic detector resolution we have assumed a Gaussian spreading of muon energy [7]. The visibility of the peak for the lower Higgs

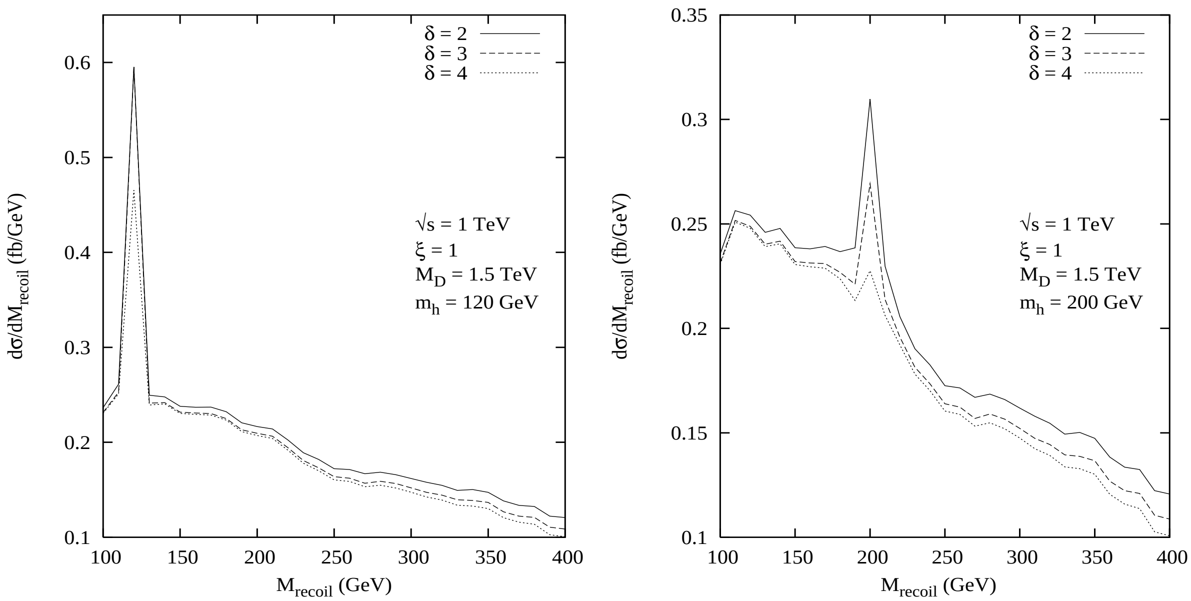

Figure 2: Recoil mass distribution for invisible Higgs for different values of δ, superposed over the SM and gravitensor contributions, for $m_D = 1.5$ TeV and $\xi = 1$.

mass is largely due to the angular cut [1]. For a heavier Higgs, however, reconstruction of the peak appears to be difficult.

4. Summary

We have investigated the detection prospects of a Higgs boson that has mixing with a tower of graviscalars in a scenario with large compact extra dimensions. This causes the Higgs to develop an invisible decay width. In the context of a linear e^+e^- collider such invisibility brings in additional problems in reconstructing the Higgs boson as a recoil mass peak against an identified Higgs boson.

5. References

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