The Invisible Higgs Decay Width in the ADD Model at the ILC

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In the ADD model of extra dimensions the $H \to$ invisible decay width may become significant. Its detectability at the LHC and ILC will provide significant constraints on the model parameters. In particular we show that the ILC will probably be critical in determining the parameters of the ADD model: the number of dimensions; the D-dimensional Planck mass; and the Higgs-graviscalar mixing parameter.

1. INTRODUCTION

In several extensions of the Standard Model (SM) there exist mechanisms which modify the Higgs production and decay rates. One example is the Randall Sundrum model where the Higgs-radion mixing not only gives detectable reductions or enhancements in Higgs yields, but also allows the possibility of direct observation of radion production and decay [1, 2]. It is also possible for the Higgs rate in visible channels to be reduced as a result of a substantial invisible width. For example, this occurs in supersymmetric models when the Higgs boson has a large branching ratio into the lightest gravitinos or neutralinos. In this paper we discuss the invisible decay width of the Higgs boson in models with large extra dimensions felt by gravity (ADD) [3, 4]. In the ADD models the interaction between the Higgs field H and the Ricci scalar curvature of the induced 4-dimensional metric g_{ind}, generates, after the usual shift $H = (\frac{v+h}{\sqrt{2}}, 0)$, the following mixing term [5]

$$\mathcal{L}_{\rm mix} = \epsilon h \sum_{\vec{n}>0} s_{\vec{n}} \tag{1}$$

with

$$\epsilon = -\frac{2\sqrt{2}}{M_P}\xi v m_h^2 \sqrt{\frac{3(\delta-1)}{\delta+2}}\,. \tag{2}$$

where $M_P = (8\pi G_N)^{-1/2}$ is the Planck mass, δ is the number of extra dimensions, ξ is a dimensionless mixing parameter and $s_{\vec{n}}$ is a graviscalar KK excitation, with mass $m_{\vec{n}}^2 = 4\pi^2\vec{n}^2/L^2$, L being the size of each of the extra dimensions. After signalization of the full mass-squared matrix, the physical eigenstate, h', acquires admixtures of the graviscalar states and vice versa.

As a result, there is a decay width of the Higgs boson arising from its mixing with the closest KK graviscalar levels. These graviscalars are invisible since they are weakly interacting and mainly reside in the extra dimensions, whereas the Higgs resides on the brane. The mixing width $\Gamma_{h\to graviscalar} \sim G(m_h^2)/m_h$ thus effectively corresponds to an invisible decay width for the Higgs boson.

In addition to decay by mixing, a further contribution to the Higgs invisible width from its decays into two graviscalars is also expected. The ratio of the two widths is given by:

$$\frac{\Gamma(h' \to graviscalar\ pairs)}{\Gamma(h \to graviscalar)} = \frac{3(\delta-1)}{2\pi^2(\delta+2)}\xi^2 \left(\frac{m_h}{M_D}\right)^{2+\delta} \frac{\pi^{\delta/2}}{\Gamma(\delta/2)} I \,. \tag{3}$$

This result shows that, even for small values of δ, the pair invisible width will be smaller than the mixing invisible width unless m_h is comparable to M_D (see Figure 1).

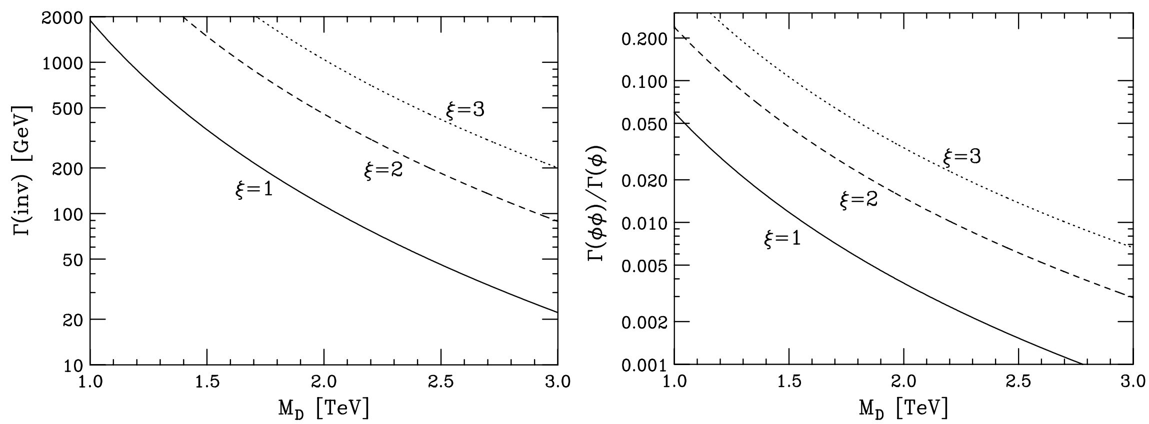

Figure 1: In the left-hand plot, we display the total invisible width of a 1 TeV Higgs boson into one and two graviscalars as a function of M_D for various values of ξ ($\xi = 1$ solid, $\xi = 2$ dashed, $\xi = 3$ dotted). For this plot we have fixed $\delta = 2$. The plot on the right shows the ratio of the two-graviscalars decay width to the one-graviscalar decay width for the same choices of parameters.

These models are also expected to provide signals in the missing transverse energy at the LHC [6] and in the single γ at the ILC [7]. It is interesting to investigate the interplay of the two classes of signatures and their relevance in pinning down the model parameters, in view of the ILC capabilities in determining the Higgs $\to$ invisible yield with high accuracy.

2. DETECTING THE HIGGS SIGNAL AT THE LHC AND ILC

For a Higgs boson with m_h below the WW threshold, the invisible width causes a significant suppression of the rate in standard visible channels at the LHC. For example, for $\delta = 2$, M_D=500 GeV and m_h=120 GeV, $\Gamma_{h' \to graviscalar}$ is of order 50 GeV for $\xi \sim 1$, *i.e.* far larger than the SM expectation of 3.6 MeV. Even when m_h is beyond the WW threshold, the partial width into invisible states can be substantial, also for M_D values of several TeV as shown in Figure fig:fig1. Therefore, for any given value of the Higgs boson mass, there is a considerable parameter space where the invisible decay width of the Higgs boson could be the first measured phenomenological effect from extra dimensions.

Detailed studies of the Higgs boson signal significance, with inclusive production, have been carried out by the Atlas [8] and Cms [9] experiments. They allow to define the region of parameters where the invisible width would be indirectly revealed by the modifications in the expected decay rates. However, the LHC experiments will also be sensitive to an invisibly decaying Higgs boson through WW-fusion production, with tagged forward jets. A detailed CMS study has shown that, with only 10 fb^{-1}, an invisible channel rate of Γ_{inv}/Γ=0.12-0.20 times the SM $WW \to$Higgs production rate gives a signal exceeding the 5 σ significance for 120 GeV $< m_h <$ 400 GeV [9, 10]. Given that the effective WWh coupling is of SM strength, this defines the region in the ADD parameter space where the Higgs boson signal can be recovered through its invisible decay . It is important to observe that, whenever the

Higgs boson sensitivity is lost due to the suppression of the canonical decay modes, the invisible rate is large enough to still ensure detection through a dedicated analysis.

A TeV-class e^+e^- linear collider (ILC) will be able to detect the Higgs signal regardless of the magnitude of the invisible branching ratio simply by looking for a peak in the Z recoil mass spectrum in $e^+e^- \to ZX$ events. Performing a dedicated search for $e^+e^- \to Z + E_{missing}$, a substantial signal for the Higgsstrahlung production process followed by an invisible Higgs decay can be extracted down to small values of $BR(h \to invisible)$ [11]. An accuracy $0.04 < \delta$BR/BR < 0.025 can be obtained for $0.1 <$ BR < 0.5 at $\sqrt{s}$=350 GeV for L=500 fb^{-1} of integrated luminosity [11]. We have employed these results to determine the portion of the (M_D, ξ) parameter space for which the invisible Higgs signal will be observable at the LHC and ILC at $\geq 5\ \sigma$ level. This is the region above the light grey (yellow) curves in Fig. 2. Not surprsingly, the ILC will be able to detect this signal over an even larger part of the parameter space than can the LHC.

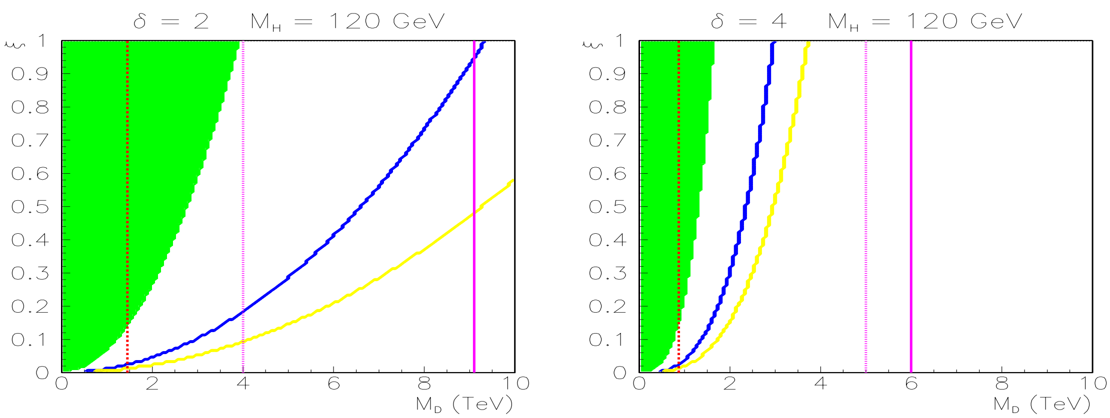

Figure 2: Invisible decay sensitivity in the M_D - ξ plane for $M_h = 120$ GeV and $\delta = 2$ (left) and $\delta = 4$ (right). The green (grey) region indicates where the Higgs signal at the LHC drops below the 5σ threshold in the canonical channels for 100 fb^{-1} of statistics. The blue (yellow) line delimits the region where the invisible Higgs signal at the LHC (ILC) exceeds 5σ significance. The solid vertical line shows the upper limit of direct sensitivity to the model using at the LHC.

3. DETERMINING M_D, ξ AND δ WITH LHC AND ILC DATA

Beyond the observation of deviations of the Higgs decay properties from those expected for the SM boson, it is interesting to combine the data from the Higgs sector with that from direct observation of graviton signals to determine the model parameters, M_D and δ.

The graviton production process is sensitive to M_D and δ. At the ILC, the signature for this process is $e^+e^- \to \gamma + E_{missing}$. This process has been already studied for the case of a 0.8 TeV e^+e^- collider [7]. We have extended this study to a 0.5 TeV and 1 TeV ILC with polarised beams ($\mathcal{P}(\rceil^+) = 0.6$, $\mathcal{P}(\rceil^-) = 0.8$), following the same analysis strategy. The main SM background arise from the process $e^+e^- \to \nu_e\bar{\nu}_e\gamma$. Its cross section has been estimated using the `NUNUGPV` [12], `KK` [13] and `Pandora 2.3` [14] generators and found to be in good agreement. The ratio of the cross section at the two energies give a strong constrain on δ, independent on the absolute value, which is sensitive to M_D. The signal Higgs signals in the invisible channel can then be combined with that in the $\gamma + E_t^{missing}$ channel to determine the fundamental model parameters, M_D, ξ and δ, and ξ. In this study we start from an assumption on the model parameters and then perform a scan of the parameter space. At each point we build a global χ^2 variable based on the observed and reference values for the Higgs visible branching fractions and the the invisible width taking the uncertainties expected for the LHC and the ILC. For the ILC we also add the results of the study of the single γ channel at 0.5 TeV and 1 TeV. This allows to determine the region of parameters compatible with the assumed set of measurements and their accuracies. Some results are shown in Figure 3. It can be observed that the ILC provides significant accuracy for determining the M_D, ξ and δ parameters for most of the δ and M_D plane, except at fairly large values.

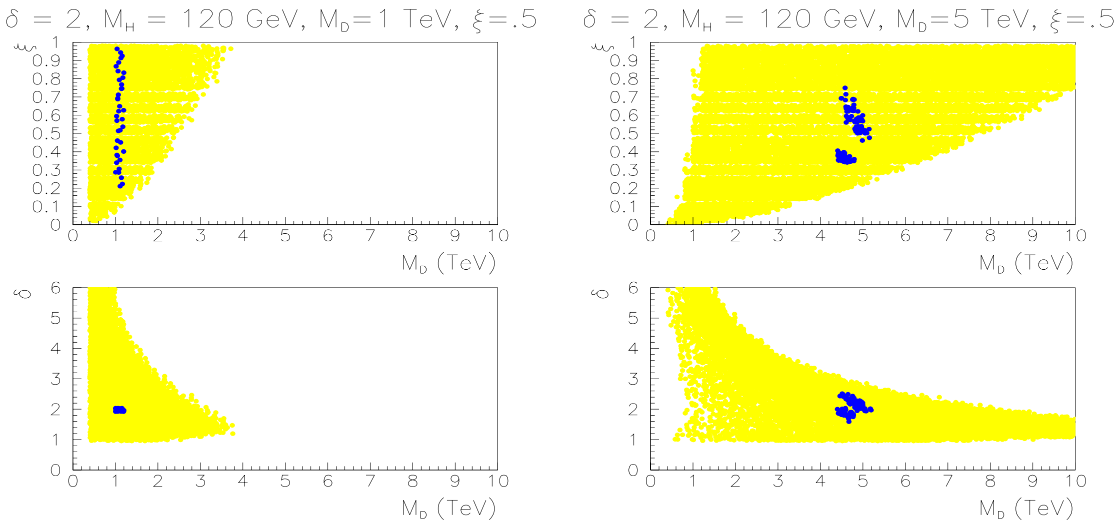

Figure 3: Determination of the model parameters at LHC (yellow) and ILC (blue). The plots give the 95% confidence level contours for different sets of parameters.

Acknowledgments

The work of M.B. was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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