Abstract

A major focus at the Large Hadron Collider (LHC) will be on Higgs boson studies and it would be an interesting prospect to simultaneously probe for physics beyond the Standard Model (SM) in the Higgs signals. In this work we show as to what extent, the effects of Universal Extra Dimension (UED) can be isolated at the LHC through the Higgs signals. By doing a detailed study of the different uncertainties involved in the measurement of the rates for the process $pp \rightarrow h \rightarrow \gamma\gamma$ we estimate the extent to which these uncertainties can mask the effects of the contributions coming from UED.

Keywords Higgs, Universal Extra Dimension, Kaluza-Klein.

1 Introduction

The much anticipated experiments at the Large Hadron Collider (LHC) are expected to refine our understandings of the Standard Model (SM) further and also shed some light on physics beyond the SM. But most importantly, the LHC is envisioned as the machine to complete the picture of the SM by discovering the Higgs boson, or instead, give a hint into the mechanism responsible for electroweak symmetry breaking. Being a subject of so much speculation and study in particular, one would always want to find out if the study on the Higgs sector itself may reflect information on any kind of new physics beyond the SM. In this work, we explore this above possibility by studying the effects of new physics on the signal of Higgs boson in the light of experiments at the LHC.

Within some models of extradimensions motivated from the framework of string theory [1], non-gravitational fields are also free to propagate in the bulk provided they do not disturb the experimental constraints. One such scenario, referred to as the Universal Extra Dimension (UED) model [2], allows all the SM fields to propagate in the extra dimension. In the effective four dimensional space-time the effects of the extra dimension is felt through the Kaluza-Klein (KK) excitations of these bulk fields which interact with the SM particles (identified as the zero modes of the excitations). At tree level, the momentum along the extra dimensions is conserved, which requires pair production of these Kaluza-Klein (KK) modes at colliders and preventing tree level mixing effects from altering precision electroweak measurements. Values of the compactification
scale are constrained, and it has a lower bound of about 300 GeV \[3\]. The phenomenological implications of UED have been extensively studied in the literature \[2,4–24\].

Direct detection of UED KK states at future colliders requires them to be pair produced due to the KK number conservation and hence already puts a limit on the minimum energy at which the collider should run to produce these particles. The LHC will invariably be able to probe physics at the energy regime unconstrained by precision measurements, where such particle resonances are expected to occur. The main experimental signal for the production and decay of KK excitations at hadron colliders will be the observation of events with multiple leptons and jets of moderately high energies in association with large missing energy \[25\]. This draws a lot of parallels with supersymmetric searches at the hadron colliders and it will prove to be a strong challenge to distinguish the signatures. We refer the readers to \[25\] where one gets a nice review of different interesting signatures at colliders. However, it would be worthwhile to look for its effects in Higgs boson studies whose signals would be extensively studied. There would be possible modifications in the signal, through the modification of Higgs decay properties due to the KK states contributing in the loop mediated decay modes of the Higgs boson. The partial decay widths for \(h \rightarrow gg\), \(h \rightarrow \gamma\gamma\) and \(h \rightarrow \gamma Z\) decay modes which are driven by loops can be substantially modified due to KK excited modes of SM particles running in the loops. There is in fact remarkably significant enhancement in the partial decay width of the Higgs in \(h \rightarrow gg\) due to the excited top quark loops \[26\]. This can greatly enhance the Higgs production at the LHC viz. the \(gg \rightarrow h\) mode of production. The production mode \(gg \rightarrow h \rightarrow \gamma\gamma\) is relevant for the Higgs boson lying in the mass range of 120–150 GeV. Due to the limitations in the resolution of the calorimeter the measurement of the decay width of the Higgs boson in this mass range will be impossible. Thus it would be impossible to study the partial widths \(\Gamma_{gg}, \Gamma_{Z\gamma}\) and \(\Gamma_{\gamma\gamma}\) and look for any kind of UED effects. It would require study of event rates for its production and try to extract the contributions of new physics through the analysis of the rates for the above mentioned process. A study considering rates to identify UED effects in Higgs signals at a linear \(e^+ e^-\) collider has been looked into, in ref \[27\].

However, the effects would be masked by the different uncertainties which will affect measurements at the LHC and thus make it difficult to differentiate the contributions coming from UED. In this work we look at the dominant mode of Higgs production through the \(gg\)-fusion for a Higgs in the mass range of 120–150 GeV and its subsequent decay into two photons and try to identify the contribution coming from UED and the extent to which these can be identified over the uncertainties that would affect measurements at the LHC. A very similar analysis has been recently carried out, in context of Split Supersymmetry, in identifying additional contributions to the Higgs rate \[28\]. In Section 2 we give a very brief overview about the model in consideration. In Section 3 we discuss the process under consideration and how the signals for the diphoton final states get modified due to UED contributions. In Section 4 we discuss the different uncertainties that would affect the signals. In Section 5 we present our numerical results and finally we summarise and
conclude in Section 6.

2 The Minimal Model

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. Conservation of KK number which is a consequence of momentum conservation along the extra dimension forces the KK particles to be pair produced. Consequently, UED predicts a stable lightest Kaluza-Klein particle (LKP) which would be much like the lightest supersymmetric particle (LSP) and a prospective candidate for dark matter [29, 30]. Bulk and brane radiative effects [31–34] however break KK number down to a discrete conserved quantity, the so called KK parity, \((-1)^n\), where \(n\) is the KK level. KK parity conservation in turn, implies that the contributions to various precisely measured low-energy observables only arise at loop level and are small [4–10].

The KK tower resulting on the four dimensional space-time has a tree level mass given by

\[
m^2_n = m^2 + \frac{n^2}{R^2}
\]

where \(n\) denotes the \(n^{th}\)-level of the KK tower and \(m\) corresponds to the mass of the SM particle in question. This implies a mass degeneracy in the \(n^{th}\)-level of the spectrum at least for the leptons and lighter quarks. This degeneracy is however removed due to radiative corrections to the masses [31–34].

3 Higgs signals and the diphoton mode

If the Higgs exists in the mass range of 120 – 150 GeV, then we should be able to see it during an early phase of the LHC. If that is possible, then it will be interesting to see if there are any indications of new physics in Higgs signal itself, even if the detection of any new particle beyond the SM might not be possible due to their high mass.

The most suggestive channel in this context, for a Higgs boson in the mass range 120 – 150 GeV, is the production of the Higgs through the \(gg\)-fusion channel followed by its decay into the diphotons. In this mode, the (partial) decay width \(\Gamma(h \rightarrow gg)\), gets additional contributions from the KK excitation of the top quark, while the (partial) decay width \(\Gamma(h \rightarrow \gamma\gamma)\) gets additional contributions from the KK excitation of both the top quark and the \(W\)-boson along with its associated Goldstone modes, ghost KK states, and in addition, also due to the charged Higgs tower. It has been shown in quite detail [26] that these loop contributions alter the Higgs decay widths, thus making it distinguishable from the SM Higgs boson. In this work, we are mainly interested in the modification of these partial decay width of the Higgs. Since the KK number is not violated at any of the vertices inside a loop, the contributions come from all the KK-excitations, with a decoupling nature for the higher modes. The combined expressions for the partial decay
width for $h \to gg$ and $h \to \gamma\gamma$ for both UED and SM contributions can be written down as,

$$\Gamma(h \to gg) = \frac{G_F m_h^3}{36\sqrt{2}\pi} \left( \frac{\alpha_s(m_h)}{\pi} \right)^2 |I_q + \sum_n \tilde{I}_{q(n)}|^2$$

$$\Gamma(h \to \gamma\gamma) = \frac{G_F}{128\sqrt{2}} \frac{\alpha_{em} m_h^3}{\pi^3} |I_q + I_W + \sum_n \tilde{I}_{q(n)} + \sum_n \tilde{I}_{W(n)}|^2$$

where $G_F$ is the Fermi constant, $\alpha_s(m_h)$ is the running QCD coupling evaluated at $m_h$, $\alpha_{em}$ is the electromagnetic coupling and $I_q, \tilde{I}_{q(n)}$ are the contributions of the loop integrals for the SM and UED case respectively. We consider the contributions from the KK excitation of the top quark as well as the bottom quark as we wish to make precise estimates comparable to uncertainties. We have to include the KK excitations of the $W-$boson and its associated Goldstone modes, ghost KK states and the charged Higgs tower for the diphoton decay channel. The UED contributions include the sum over the KK towers of the respective particle. As the more massive modes in the loop will hardly make significant contributions, we ensure that the sum is terminated as the higher modes decouple. We include all the decay modes affected by UED contributions in the decay package HDECAY [36] to evaluate the relative sensitivities to the branching ratios to the different decay channels of the Higgs boson.

It has to be remembered, however, that the above decay width will not be a directly measurable quantity at the LHC. This is because the width is of the order of keV in the relevant Higgs mass range, which is smaller than the resolution of the electromagnetic calorimeters to be used [37, 38]. Here we try to estimate how the UED contributions may be extracted in this channel, given the rather sizable theoretical as well as experimental uncertainties in the various relevant parameters.

We, therefore, have chosen to do a calculation involving the full process ($pp \to hX \to \gamma\gamma$), that is to say, the production of the Higgs followed by its decay into the diphoton final state. Taking all uncertainties into account, we have tried to find the significance level at which the additional contributions can be differentiated in different regions of the parameter space which in this scenario is the compactification radius $R$. We have confined ourselves to the production of Higgs via gluon fusion. The other important channel, namely gauge boson fusion, has been left out of this study, partly because it is plagued with uncertainties arising, for example, from diffractive production, which may be too large for the small effects under consideration here. In the SM, the loop-induced decay widths of the Higgs boson, including QCD as well as further electroweak corrections, are well-documented in the literature [39–50].

The rate for the inclusive process

$$pp \to h + X \to \gamma\gamma$$

(where Higgs production takes place via gluon fusion) can be expressed in the leading order as

$$N = \frac{\pi^2}{8m_h s} \frac{\Gamma_{h\to 2\gamma}}{\Gamma_{tot}} \int_\tau^1 d\zeta \frac{1}{\zeta} g \left( \zeta, m_h^2 \right) \frac{1}{\zeta} g \left( \frac{\tau}{\zeta}, m_h^2 \right)$$

$$\Gamma_{h\to 2\gamma}, \Gamma_{h\to 2g} \text{ and } \Gamma_{tot} \text{ stand respectively for the diphoton, two-gluon and}$$
total decay widths of the Higgs. The lowest order estimate given above is further multiplied by the appropriate K-factors to obtain the next-to-next leading order (NNLO) predictions in QCD. While the computation of the rate is straightforward, we realise that the various quantities used are beset with theoretical as well as experimental uncertainties [51–53]. We undertake an analysis of these uncertainties in the next section.

4 Numerical estimate: uncertainties

As has already been stated in the previous section, the rate for diphoton production through real Higgs at LHC is given by

\[ N = \sigma(pp \rightarrow h) \times B = \sigma(pp \rightarrow h) \frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma_{\text{tot}}} \]  

(5)

We have performed a parton-level Monte Carlo calculation for the production cross-section, using the MRS [54] parton distribution functions and multiplied the results with the corresponding NNLO K-factors [55–57]. It may be noted that NNLO K-factors are not yet available for most other parameterizations. In estimating the statistical uncertainties in the experimental value [53], MRS (at leading order) distributions have been used by the CMS group while ATLAS uses CTEQ distributions. We have obtained the aforesaid uncertainty by taking the estimate based on MRS and multiplying the corresponding event rate by the NNLO K-factor for MRS. It may also be mentioned that the difference between the NLO estimates of Higgs production using the MRS and CTEQ parameterizations is rather small (\(< 2\%)\), according to recent studies [55]. Therefore, it is expected that the NNLO estimate of uncertainties (where there is scope of further evolution in any case) used by us will ultimately converge to even better agreement with other parameterizations and will not introduce any serious inaccuracy in our conclusions. The programme HDECAY [36], including \(\mathcal{O}(\alpha_s^2)\) contributions, has been used for Higgs decay computations.

| Parameter | Central Value | Present Uncertainty | LHC Uncertainty |
|-----------|---------------|---------------------|-----------------|
| \(m_h\)  | 120. – 150.   | –                   | 0.2             |
| \(m_W\)  | 80.425        | .034                | .015            |
| \(m_t\)  | 172.7         | 2.9                 | 1.5             |
| \(m_b\)  | 4.62          | .15                 | –               |
| \(m_c\)  | 1.42          | .1                  | –               |
| \(m_\tau\)| 1.777        | .0003               | –               |
| \(\alpha_s\)| 0.1187      | 0.002               | –               |

Table 1: Current and projected uncertainties (at LHC) in the values of various parameters. All the masses are given in GeV. The values are extracted from refs [60–62]

The number of two-photon events seen is given by \(\mathcal{L}N\) where \(\mathcal{L}\) is the integrated luminosity. \(\mathcal{L}\)
Table 2: Entries in the second (third) column correspond to experimental (theoretical) uncertainties in the rates as discussed in the text. The total uncertainty in the SM rate including the theoretical and experimental uncertainties along with the errors (different choices) due to parton distributions and renormalisation scale (15%,10% and 5%) are listed for different Higgs boson mass.

| Higgs mass (GeV) | $\delta_{exp}$ (%) | $\delta_{th}$ (%) | PDF+scale uncertainty |
|------------------|--------------------|-------------------|-----------------------|
|                  |                    |                   | (15.0%) | (10.0%) | (5.0%) |
| 120.0            | 8.9                | 8.1               | 19.3% | 15.8% | 13.2% |
| 130.0            | 8.1                | 6.9               | 18.5% | 14.7% | 11.9% |
| 140.0            | 8.6                | 5.6               | 18.3% | 14.4% | 11.6% |
| 150.0            | 11.3               | 4.6               | 19.4% | 15.9% | 13.3% |

is expected to be known at the LHC to within 2%. We include this uncertainty in our calculation, although it has a rather small effect on our conclusions.

The possible sources of theoretical uncertainties can be divided into two general classes: parametric uncertainties and intrinsic uncertainties. The former are related to the fact that, within the SM, each quantity of interest is a function of a set of input parameters, which are known with a finite experimental precision. Any variation of the input parameters within the experimentally allowed range gives rise to an uncertainty on the observable considered. On the other hand, the intrinsic uncertainties have to do with the perturbative treatment of the quantum corrections: scheme dependence, ignorance of higher orders in the perturbative expansion and so on. We have included the NNLO K-factors for the production cross-section $\sigma(gg \rightarrow h)$, available in the literature and assume that our ignorance of more higher order contributions will not introduce a very significant uncertainty.

In order to estimate the total uncertainty in $N$, one has to first obtain the spread in theoretically predicted value in the SM due to the uncertainty in the various parameters used. In addition, however, there is an uncertainty in the experimental values, although the actual level of this will be known only after the LHC run begins, the anticipated statistical spread in the measured value can be estimated through simulations. These two uncertainties, combined in quadrature, are indicative of the difference with central value of the SM prediction which is required to establish any non-standard effect at any given confidence level. We have performed such an exercise, taking the standard model calculation and that with SM + UED contributions. Thus the total uncertainty in $N$ can be expressed as

$$\left(\frac{\delta N}{N}\right)^2 = \left(\frac{\delta N}{N}\right)_{th}^2 + \left(\frac{\delta N}{N}\right)_{exp}^2$$  \hspace{1cm} (6)
where the theoretical component can be further broken up as

\[
\left( \frac{\delta N}{N} \right)^2_{th} = \frac{1}{N^2} \sum_i \sigma^2_{N_i}
\]

where \(\sigma_{N_i}\) stands for the spread in the prediction of \(N\) due to uncertainty in the \(i^{th}\) parameter relevant for the calculation. The sum runs over \(m_h, m_W, m_t, m_b, m_{\tau}\) and \(m_c\), in addition to the uncertainty in the strong coupling \(\alpha_s\). The spread in the predicted value is predicted in each case by random generation of values for each parameter (taken to vary one at a time) within the allowed range. Thus we obtain \(\frac{1}{N^2}\sigma^2_{N_i}\) corresponding to each parameter. This has been listed in Table 1 for different choices of \(m_h\). One has to further include QCD uncertainties arising via parameterization dependence of the parton distribution functions (PDF) \[52\] and the renormalisation scale. Although NNLO calculation reduced such uncertainties, the net spread in the prediction due to them could be as large as \(\sim 15\) percent \[52, 55–59\] in the Higgs mass range \(120 – 150\) GeV. The levels of uncertainties in the various parameters, are presented in Table 1. In that table we have given the uncertainties, wherever they are available, from recent and current experiments like the LEP and the Tevatron. In addition, whatever improved measurement, leading to smaller errors (in, say, \(m_t\) or \(m_W\)) are expected after the initial run of the LHC are also separately incorporated in the table. We have used the estimates corresponding to LHC wherever they are available. In our calculation, we have used three values of the combined uncertainty from PDF and scale-dependence, namely, \(15\%\), \(10\%\) and \(5\%\), the latter two with an optimistic view to likely improvement using data at the LHC. Table 2 contains the finally predicted values of \(\left( \frac{\delta N}{N} \right)\), for the different values of the Higgs boson mass.

![Figure 1](image-url)

Figure 1: Illustrating the effects of UED contributions on the branching ratio of (a) \(h \rightarrow \gamma \gamma\) and (b) \(h \rightarrow gg\).
\( N_{\text{exp}} \) includes statistical uncertainties, as estimated in detector simulations with a luminosity of 100 \( fb^{-1} \) [53]. As has been already mentioned, we have obtained benchmark values of this quantity using the results for CMS presented in ref [53] for MRS distributions at the lowest order, and appropriately improving them with the NNLO K-factors available in the literature. The resulting predictions are listed as \( \delta_{\text{exp}} \) in Table 2 for different values of \( m_h \). Thus one is able to obtain the net (1\( \sigma \) level) uncertainties in the standard model as shown in the last three columns of Table 2.

![Graphs illustrating percentage difference](image)

**Figure 2:** Illustrating the percentage difference over standard model rates for different values of the Higgs mass as a function of the compactification scale \( R^{-1} \). The horizontal lines in each figure corresponds to the confidence levels as labeled. The graphs are shown for different choices of the PDF + scale uncertainty, viz. (a) 5\%, (b) 10\% and (c) 15\%.

Next, the UED contributions via KK excitations-induced diagrams are calculated and added to the standard model amplitude. The observable decay rate obtained therefrom is compared with that predicted in the standard model taking the uncertainty into account at various confidence levels.
Thus one is able to decide whether the UED contributions to the diphoton rate are discernible from the standard model contributions at a given confidence level for a particular $R$. The realistic estimate requires subjecting the predictions to some experimental cuts aimed at maximizing the signal-to-background ratio as well as focusing on kinematic regions of optimal observability. We incorporate the effects of such cuts with the help of an efficiency factor which, on explicit calculation in representative cases, turns out to be approximately 47-53%. The only assumptions required are that the percentage error due to various parameters are the same for uncut rates as those calculated with cuts, and that the standard model and UED contribution suffer the same reduction due to cuts. We have checked that this holds true so long as the kinematic region is not drastically curtailed by the cuts.

5 Numerical estimate: discussions

Our purpose is to see at what confidence levels one can distinguish the UED effects on $h \rightarrow \gamma\gamma$, $gg$. With this in view, we estimate the excess in the rates due to the UED contributions and calculate the fractional difference with that predicted for standard model. It is worth noting that for the mass range of the Higgs boson that we consider, the partial decay width of the $h \rightarrow \gamma\gamma$ mode falls below the SM value while that of the $h \rightarrow gg$ mode is greater than that of the SM contribution. To highlight the dependence, we plot the branching ratios for these two modes in figure 1. This suggests that the UED contribution will have a slight suppression as the rate for the process in consideration is proportional to the product of the above branching ratios. In figure 2 we show the contour plots for the three choices of PDF + scale uncertainty. We can see from figure 2(a), which has the most optimistic choice of 5% for the PDF + scale uncertainty, that at the $2\sigma$ confidence level, one can see excess over the SM rate for values of compactification scale as large as $R^{-1} \simeq 630, 690, 710, 660$ GeV for Higgs mass $m_h = 120, 130, 140, 150$ GeV respectively, while at $1\sigma$ confidence level, these go up to $R^{-1} \simeq 990, 1050, 1090, 1020$ GeV for Higgs mass $m_h = 120, 130, 140, 150$ GeV respectively. For the more conservative choices of PDF + scale uncertainty, these numbers for $R^{-1}$ will go down and as shown in figure 2(c), where the choice for PDF + scale uncertainty is taken as 15%, the $2\sigma$ ($1\sigma$) confidence level limits $R^{-1} \simeq 450(780), 490(810), 500(830), 500(810)$ GeV for Higgs mass $m_h = 120, 130, 140, 150$ GeV respectively. With improvements in the measurement resolutions and lower uncertainties, this reach can be improved further. We must point out that although the better convergence of the NNLO result over the NLO calculations do suggest a better understanding of the theoretical result, our ignorance of corrections beyond NNLO limits our complete knowledge of the intrinsic theoretical error. The updated lower bounds on the compactification scale [63,64] ($\gtrsim 600$ GeV for $m_h = 115$ GeV and top quark mass of 173 GeV at 90% C.L.), which depends on the Higgs mass and the top quark mass, however suggest that the visible effects at the LHC would be marginal and one really needs a better hold on the different uncertainties to highlight the large deviations that are expected in the UED predictions.
6 Summary and conclusions

We have explored the signals for the intermediate mass range of the Higgs boson production through the $gg \rightarrow h$ channel and its subsequent decay to two photons. Both the production and decay channel get contributions through loops due to the absence of tree level couplings. The excited KK modes of the SM particles would give additional contribution to these decay modes, thus altering the decay rates. We have performed a detailed analysis of the rates for the inclusive process $gg \rightarrow h \rightarrow \gamma\gamma$ incorporating the different uncertainties that would affect measurements at LHC. We find that one can have observable enhancements in the allowed range of the parameter space of UED to distinguish effects of UED contributions in the Higgs signals by studying the rates for the inclusive process considered in this work. We show that although the rates (after including UED contributions) differ from the standard model prediction substantially, large uncertainties, both theoretical (we have neglected the intrinsic theoretical error in the Higgs production cross section from corrections beyond NNLO assuming it to be small) as well as experimental, have a large role to play. These uncertainties combine to dilute the substantially significant deviations from SM coming from new physics contributions and are seen to be marginal [63,64]. However, with better luminosity and improvements in the theoretical calculations and experimental measurements, this channel can provide for new physics effects in the Higgs signal itself.

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