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Higgs Phenomenology of Minimal Universal Extra Dimensions

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Abstract. The minimal model of Universal Extra Dimensions (MUED) is briefly reviewed. We explain how the cross-sections for Higgs production via gluon fusion and decay into photons are modified, relative the the Standard Model (SM) values, by KK particles running in loops, leading to an enhancement of the $gg \to h \to \gamma\gamma$ and $gg \to h \to W^+W^-$ cross-sections. ATLAS and CMS searches for the SM Higgs in these channels are reinterpreted in the context of MUED and used to place new limits on the MUED parameter space. Only a small region of between 1 and 3 GeV around $m_h = 125$ GeV for 500 GeV $< R^{-1} <$ 1600 GeV remains open at the 95 % confidence level.

1 Introduction

The idea of extra dimensions of space is conceptually intriguing and provides a rich framework for building models that go beyond the Standard Model (SM). One class of extra-dimensional theories, proposed by Appelquist, Cheng and Dobrescu [1] in 2001, involves *universal* extra dimensions (UED). In such models all particles can propagate in all dimensions (i.e. in the "bulk"), and the extra dimensions are hidden by compactifying them on a distance scale too small to be probed by our current experiments.

In this note we focus on the simplest possible UED model, Minimal UED (MUED), which has one extra dimension compactified on a circle. The circle has translational symmetry and so there is conserved momentum in the 5th dimension which is discretised because of the periodic boundary conditions; one therefore talks about conserved "Kaluza-Klein" (KK) number n. The extra dimension is then further compactified onto an $S^1/\mathbb{Z}_2$ orbifold (essentially a line segment with particular boundary conditions for the fields). This "orbifolding" is necessary to obtain chiral matter, and it breaks the translational invariance so KK number is only conserved at tree level. There is a remnant reflection symmetry of the orbifold about its midpoint which leads to a KK "parity" $(-1)^n$ being conserved at all orders in perturbation theory.

When MUED is expressed as a 4D effective theory, the different possible KK numbers of a 5D particle manifest themselves as a tower of progressively heavier separate 4D particles, one for each KK number. The zero mode particles are identified with SM particles.

KK parity conservation makes MUED particularly hard to observe at the LHC because it means that $n = 1$ resonances (the lightest new particles predicted by MUED) can only be pair produced and $n = 2$ resonances are typically too heavy to be produced on-shell at LHC energies. However, KK parity ensures that the lightest $n = 1$ KK particle (the "LKP" in analogy to the LSP in SUSY) is stable; for much of the parameter space the LKP is neutral and so it provides an excellent Dark Matter WIMP candidate. This is the main motivation for MUED.

Like all gauge theories in greater than four dimensions, MUED is perturbatively non-renormalisable; the theory must be cut off at a momentum scale Λ above which the new physics of the UV completion is expected to become noticeable. Discounting the mild cutoff dependence at LHC energy scales, MUED has two parameters with values not completely constrained by experiment: the Higgs mass m_h and the inverse compactification radius R^{-1}.

The R^{-1} parameter is already bounded to be less than around 1600 GeV by WMAP observations because it sets the scale of the Dark Matter (DM): if DM were heavier it would lead to the Universe having a measurable positive curvature. Also, m_h is bounded from above by the requirement that DM be neutral. These DM considerations are discussed in detail in [2] and shown in Fig. 4 of this note.

The Higgs mass is required to be greater than 114.1 GeV by the LEP2 Higgs searches and $R^{-1} \gtrsim 300$ GeV in order not to conflict with electroweak precision measurements [3].

In this paper we place new constraints on the parameter space using data from the latest ATLAS and CMS Higgs searches. This idea has been attempted before [4], but without taking into account the effect of MUED on Higgs decay to two photons.[1] This is explained more fully in the following sections.

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[1] Whilst we have been preparing these proceedings, Nishiwaki *et al* have produced new work that includes KK suppression of the $h \to \gamma\gamma$ vertex [9].

2 Higgs production and decay

For low and intermediate m_h, the most important Higgs production process at the LHC is gluon-gluon fusion. The lowest order Feynman diagram contributing to this process is the one shown in Fig. 1 (top), with quarks running in the triangle loop. For low m_h, Higgs decay to two photons is the most important channel due to its small background. In Fig. 1 (bottom), two leading order contributions are shown. There are actually many other one-loop diagrams involving $W^{\pm}$ bosons that are not shown; for the full details see [5]. But essentially there is tension between the quark/lepton (dominated by the top quark) and the W contributions to the decay, with the W contribution being dominant in the SM.

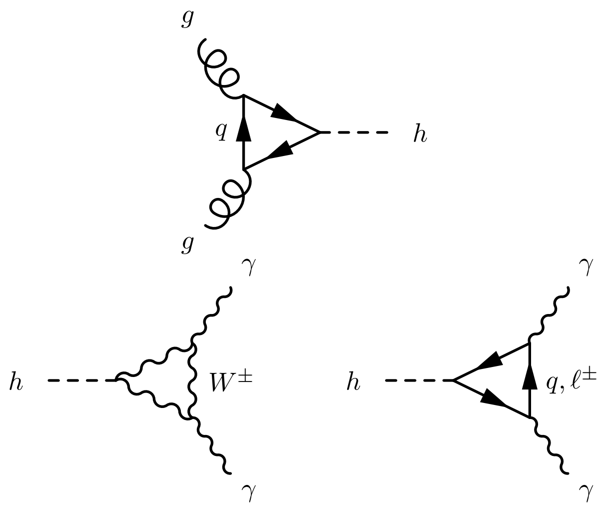

Fig. 1. Representative diagrams involved in Higgs production by gluon fusion (top) and subsequent decay to photons (bottom).

In MUED, KK particles can also flow in the loops. These enhance each of the diagrams shown. The rate of Higgs production is therefore increased relative to the SM. The opposing fermion and W contributions to the diphoton decay are each enhanced, but the fermion enhancement is greater than the W and so the partial decay width to photons is *decreased* for most of the relevant (m_h, R^{-1}) parameter space. The matrix elements for production and decay both take the form

$$\mathcal{M} = \tilde{\mathcal{M}} \times \left(\frac{m_h^2}{2} g^{\mu\nu} - p^{\nu} q^{\mu} \right) \epsilon_{\mu} \epsilon_{\nu},$$

where the ϵ four-vectors are gluon or photon polarisations. We have approximated external particles as being on shell. The scalar parts $\tilde{\mathcal{M}}$ of the matrix elements for $g, g \to h$ and $h \to \gamma, \gamma$ are plotted in Fig. 2 (top and middle) as multiples of the SM values for various values of m_h and R^{-1}.

We used our own implementation of the MUED model in the `LanHEP` and `CalcHEP` software packages in order to calculate these matrix elements and, later, cross-sections. Unlike other implementations, ours includes the effects of radiative corrections to KK particle masses at one-loop because these corrections play a vital role due to the highly-degenerate tree-level MUED mass spectrum [6]. Our model also includes two-loop SM corrections to the ggh and $h\gamma\gamma$ vertices that can be as large as 50 % of the leading order values, although these cancel in the ratios plotted in Fig. 2.

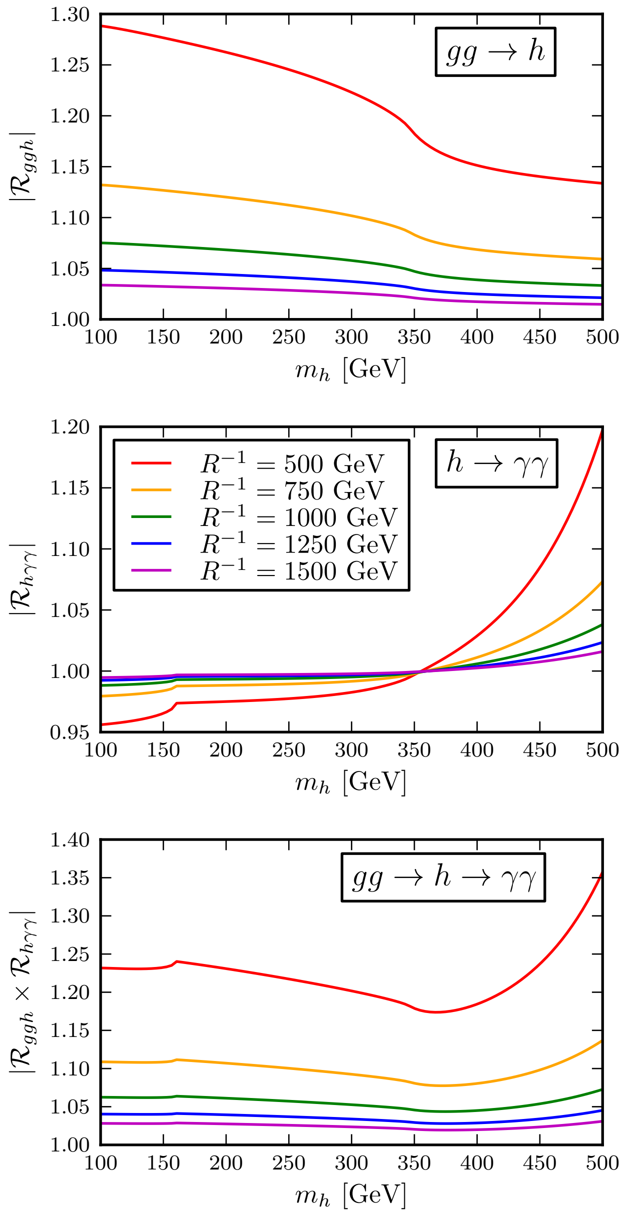

Fig. 2. Ratios of the scalar parts of matrix elements for Higgs production and decay, where $\mathcal{R} = \tilde{\mathcal{M}}_{\mathrm{MUED}}/\tilde{\mathcal{M}}_{\mathrm{SM}}$. For each graph, on the RHS, from top to bottom, the curves represent R^{-1} values of 500, 750, 1000, 1250 and 1500 GeV.

Overall, the enhancement of the Higgs production amplitude is greater than the suppression of the Higgs decay to two photons and so the MUED cross-section for $gg \to h \to \gamma\gamma$ is always enhanced relative to the Standard Model's. This is shown the bottom graph in Fig. 2. This means that our model is more sensitive to experimentally-determined Higgs mass limits that the SM and this sensitivity can be used to constrain the parameter space further.

In addition to $gg \to h \to \gamma\gamma$, we also looked at $gg \to h \to W^+W^-$, which is particularly important in the intermediate Higgs mass range. The gluon fusion part of the process is enhanced as before, but decay to two Ws can proceed via a tree-level diagram so KK particles have no leading order effect on the decay part.

3 Limits on parameter space

We looked at the latest ATLAS and CMS SM Higgs searches and reinterpreted the analyses for MUED. The results of the searches are expressed in terms of $\mu \equiv \sigma_{95\%}/\sigma_{\rm SM}$, where $\sigma_{95\%}$ is the cross-section for a particular Higgs production and decay process that has currently been ruled out at the 95 % confidence level, and $\sigma_{\rm SM}$ is the SM cross-section for that same process.

One can place limits on MUED by calculating $\mu_{\rm MUED} = \sigma_{\rm MUED}/\sigma_{\rm SM}$ for different values of (m_h, R^{-1}) and seeing whether it is larger than the existing limit. We used the latest limits shown in Fig. 3 of [7] for ATLAS and Fig. 6 (top) of [8] for CMS. We combined the limits from the two experiments statistically for each of channels of interest (diphoton and W^+W^-) using

$$\mu_{\rm comb} = \left(\frac{1}{\mu^2_{\rm ATLAS}} + \frac{1}{\mu^2_{\rm CMS}}\right)^{-\frac{1}{2}}.$$

This does not take into account systematic errors but it does give a good estimate of the combination *in lieu* of the official combination from ATLAS and CMS.

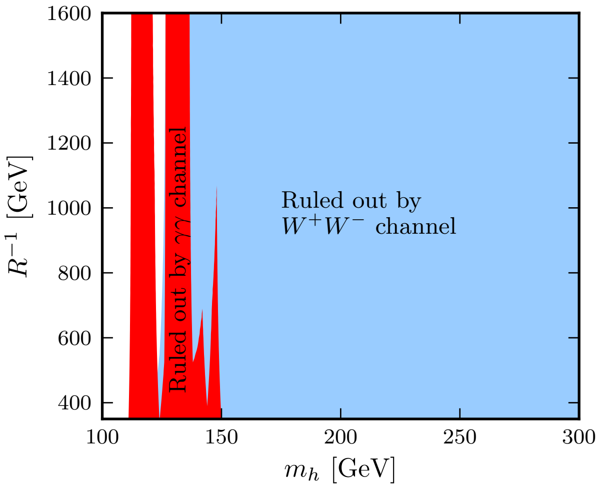

Fig. 3. Regions of MUED parameter space ruled out at the 95 % confidence level by combination of ATLAS and CMS Higgs searches using the diphoton (red) and W^+W^- (blue) channels.

The parameter space ruled out by the Higgs search data is shown in Fig. 3. All of the parameter space for $m_h >$ 111 GeV is ruled out except for a small region around 125 GeV – this is due to the excess of events observed by ATLAS and CMS recently in this region.

For completeness, in Fig. 4 we show the limits on the MUED parameter space from the Higgs analysis presented here together with existing limits from other constraints. In addition to those constraints described in Section 1, electroweak precision fits from LEP prefer a Higgs with a mass in the window delineated on the graph by the two blue hyperboloids.

What is left is a very narrow region of parameter space with m_h around 125 GeV and 700 GeV $< R^{-1} <$ 1600 GeV.

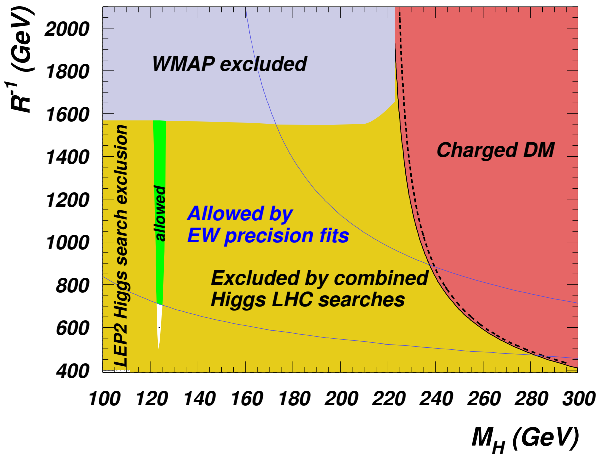

Fig. 4. Constraints on MUED parameter space. Purple and pink show regions ruled out by DM considerations. Gold denotes the region excluded by the Higgs search analysis presented here and also the existing LEP2 limit. Points between the blue hyperboloids agree with LEP EW precision fits to a 95 % CL.

4 Conclusions

We have used the latest ATLAS and CMS Higgs search data to constrain the parameter space of MUED. We have improved on an earlier analysis by including the effects of the KK modes on the Higgs decay to two photons and by also including the radiative corrections to the KK masses. Full details will be given in [5].

We eagerly await the official limit combination from ATLAS and CMS, although details of the combination will become moot (for our purposes!) if the 125 GeV excess goes away when extra data is collected in 2012. If this happens, we will be able to rule out MUED completely at the 3σ limit by the end of the year. If the excess remains and we discover the Higgs there, this should allow us to make a prediction as to the value of R^{-1}.

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