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Implications of a high mass light MSSM Higgs scalar for SUSY searches at the LHC

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ABSTRACT: The ATLAS and CMS collaborations have both reported an excess of events in the $WW^* \rightarrow \ell^+ \ell^- + E_T^{\text{miss}}$ search channel, which could be the first evidence for the Higgs boson. In the context of the MSSM, the lightest SUSY Higgs scalar h is expected to occur with mass $m_h \lesssim 135$ GeV, depending on the range of SUSY parameters scanned over. Since the $h \rightarrow WW^*$ branching fraction falls swiftly with decreasing m_h , a signal in the WW^* channel would favor an h at the high end of its predicted mass range. We scan over general GUT scale SUSY model parameters to find those which give rise to $m_h \gtrsim 130$ GeV. A value of $m_0 \sim 10 - 20$ TeV is favored, with $A_0 \sim \pm 2m_0$, while the lower range of $m_{1/2} \lesssim 1$ TeV is also slightly favored. This gives rise to an “effective SUSY” type of sparticle mass spectrum. For low $m_{1/2}$, gluino pair production followed by three-body gluino decay to top quarks may ultimately be accessible to LHC searches, while for higher $m_{1/2}$ values, the SUSY spectra would likely be out of range of any conceivable LHC reach. Since the thermal neutralino relic abundance tends to be very high, late-time entropy dilution or neutralino decay to light axinos would be required to gain accord with the measured dark matter abundance.

KEYWORDS: Supersymmetry Phenomenology, Supersymmetric Standard Model, Large Hadron Collider.

1. Introduction

Recent searches for the Standard Model (SM) Higgs boson in the $H_{SM} \rightarrow W^+W^-$ mode have been reported by the ATLAS [1] and CMS [2] collaborations using 35 pb⁻¹ of data, and more recently with 1.7 (1.55) fb⁻¹ of data [3, 4]. The recent analyses allow ATLAS and CMS combined to exclude SM-like Higgs bosons in the mass range 145-288 GeV and 296-466 GeV at 95% CL. Combining these exclusion ranges with the LEP2 limit [5] that $m_{H_{SM}} > 114.4$ GeV, we expect the Higgs to inhabit the low mass range 114.4-145 GeV, as expected by precision electroweak measurements [6], or else the Higgs is very heavy. The low mass Higgs window also corresponds to the range of m_h expected in the Minimal Supersymmetric Standard Model (MSSM), where calculations of the lightest, usually SM-like Higgs boson mass m_h require $m_h \lesssim 135$ GeV [7].

In addition to exclusion limits, searches in the $H_{SM} \rightarrow WW^* \rightarrow (\ell\bar{\nu}_\ell) + (\bar{\ell}'\nu_{\ell'})$ channel have turned up a roughly 2σ excess by ATLAS in events containing no jets, and a similar excess by CMS, but this time in events containing one jet. Also, several events in $H_{SM} \rightarrow ZZ^* \rightarrow 4\ell$ channel with mass $m(4\ell) \sim 120 - 140$ GeV have been reported. As data accrues into the 5-10 fb⁻¹ regime, both experiments should gain sensitivity to the entire low mass range $m_{H_{SM}} \sim 114 - 145$ GeV. If the present excess of WW^* events persists with an enlarged data set, then these events will indicate that the Higgs mass exists on the *high end* of the low mass window, since the Higgs branching fraction to WW^* and ZZ^* drops rapidly with decreasing Higgs mass.

In this note, we examine the implications of an WW^* signal in the context of the MSSM, where the lightest Higgs boson has mass $m_h \lesssim 135$ GeV. In order to gain a substantial rate for $h \rightarrow WW^*$ events, we will then expect $m_h \sim 130 - 135$ GeV in order to maximize the $h \rightarrow WW^*$ branching fraction. By requiring the light Higgs boson h to lie in the 130-135 GeV range, we will find a rather tight correlation of model parameters which then offer some rather distinct predictions for the nature of superparticle signatures which are also expected at LHC.

2. Calculations

In the MSSM, the Higgs sector consists of two doublet fields H_u and H_d , which after the breaking of the electroweak symmetry, result in the five physical Higgs bosons: two neutral CP -even scalars h and H , a neutral CP -odd pseudoscalar A and a pair of charged scalars H^\pm [8]. Over most of the MSSM parameter space the lightest Higgs boson h is nearly SM-like, therefore the SM Higgs search results can be directly applied to h (for exceptions, see Ref. [9]). A calculation of the light (heavy) scalar Higgs boson mass at 1-loop level using the effective potential method gives

$$m_{h,H} = \frac{1}{2} [(m_A^2 + M_Z^2 + \delta) \mp \xi^{1/2}] , \quad (2.1)$$

where m_A is the mass of the CP -odd pseudoscalar A and

$$\xi = [(m_A^2 - M_Z^2) \cos 2\beta + \delta]^2 + \sin^2 2\beta (m_A^2 + M_Z^2)^2. \quad (2.2)$$

The radiative corrections can be approximated as follows

$$\delta = \frac{3g^2 m_t^4}{16\pi^2 M_W^2 \sin^2 \beta} \log \left[\left(1 + \frac{m_{\tilde{t}_L}^2}{m_t^2} \right) \left(1 + \frac{m_{\tilde{t}_R}^2}{m_t^2} \right) \right]. \quad (2.3)$$

Thus, in order to push the value of m_h to its upper limit, we expect we will have to probe very large values of top squark soft masses $m_{\tilde{t}_{L,R}}$ into the multi-TeV range.

For our calculation of m_h , we include the full third generation contribution to the effective potential, accounting for all sparticle mixing effects [10]. The effective Higgs potential, V_{eff} , is evaluated with all running parameters in the \overline{DR} renormalization scheme evaluated at the scale choice $Q_{SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, *i.e.* the mean top squark mass scale. Of particular importance is that the t , b and τ Yukawa couplings are evaluated at the scale Q_{SUSY} using 2-loop MSSM RGEs and including full 1-loop MSSM radiative corrections [11]. Evaluating V_{eff} at this (optimized) scale choice then includes the most important two-loop effects [12]. This calculational procedure has been embedded in the Isajet mass spectra program Isasugra [13], which we use here for our calculations.

Our first goal is to make a thorough scan of the MSSM model parameter space to search for parameter choices leading to the largest values of m_h . We will adopt a GUT scale parameter space for our scan, since this will include the desirable radiative electroweak symmetry breaking (EWSB) constraint, wherein the large top quark Yukawa coupling f_t plays a crucial role in driving the soft SUSY-breaking parameter $m_{H_u}^2$ to negative values, so the electroweak symmetry is appropriately broken. We will also maintain gaugino mass unification, as expected in simple SUSY GUT theories. However, we will avoid a scan over mSUGRA model parameter space, since large values of scalar masses are forbidden beyond the hyperbolic branch/focus point (HB/FP) region. Instead, we will scan over the two-extra-parameter non-universal Higgs model, dubbed NUHM2 [14], with parameter choices:

$$m_0, m_{1/2}, A_0, \tan \beta, \mu, m_A, \quad (2.4)$$

wherein common soft masses of scalars (m_0) and gauginos ($m_{1/2}$) along with the common soft trilinear term (A_0) are stipulated at the GUT scale, while the ratio of Higgs vevs ($\tan \beta$), the bilinear superpotential Higgs parameter (μ) and the CP -odd Higgs mass (m_A) are inputted at the SUSY scale Q_{SUSY} .

3. Results

We employed ISAJET 7.81 to generate 13K random points in the above parameter space, requiring only that the radiative electroweak symmetry breaking is maintained

and the lightest supersymmetric particle (LSP) be electrical and color neutral. Our scan limits are as follows:

$$m_0 : 0 \rightarrow 20 \text{ TeV}, \quad (3.1)$$

$$m_{1/2} : 0 \rightarrow 5 \text{ TeV}, \quad (3.2)$$

$$A_0 : -5m_0 \rightarrow +5m_0, \quad (3.3)$$

$$\tan \beta : 5 \rightarrow 55, \quad (3.4)$$

$$\mu : 0 \rightarrow 10 \text{ TeV}, \quad (3.5)$$

$$m_A : 0 \rightarrow 10 \text{ TeV}. \quad (3.6)$$

We only scan over positive μ values so that we do not stray more than 3σ away from the measured value of the muon anomalous magnetic moment, $(g-2)_\mu$ [15]. We set the mass of the top quark $m_t = 173.3 \text{ GeV}$, in accord with the latest Tevatron combination [16].

Our results are shown in Fig. 1, showing the dependence of the generated light Higgs mass on each of the model parameters. Points satisfying LEP2 chargino bound $m_{\widetilde{W}_1} > 103.5 \text{ GeV}$ [17] are shown as blue dots, while those with too low chargino mass $m_{\widetilde{W}_1} < 103.5 \text{ GeV}$ are represented by red crosses. The first thing to note is that our scan over parameter space refines the upper limit on m_h to

$$m_h < 132 \text{ GeV}. \quad (3.7)$$

Thus, if m_h comes in much above 132 GeV, then in a SUSY context we would have to expect some sort of extended Higgs sector, perhaps the NMSSM [18] or theories with vector-like matter [19]. We note that we expect just a few GeV theory error in our m_h calculation. Also, it should be noted that our value of m_h is typically a couple GeV below the corresponding FeynHiggs [20] calculation, mainly due to the fact that we are able to extract and use the two-loop \overline{DR} Yukawa couplings including 1-loop threshold corrections at the Q_{SUSY} scale.

From frame a), we see however that m_h can reach to over 130 GeV only for m_0 very high: for values $m_0 \gtrsim 10 \text{ TeV}$. Thus, if the $h \rightarrow WW^*$ signal comes in at very high values of $m_h \sim 128 - 132 \text{ GeV}$, then we can expect squarks and sleptons to exist in the multi-TeV regime, well beyond LHC reach. In addition, since smuons and muon sneutrinos are expected to be multi-TeV, the value of $(g-2)_\mu$ is expected to be near its SM value. Alternatively, if $m_h \sim 125 \text{ GeV}$, then the corresponding bound on m_0 is only $> 1 \text{ TeV}$.

From frame b), we see that if $m_h \sim 130 - 132 \text{ GeV}$, then rather low values of $m_{1/2} \lesssim 1 \text{ TeV}$ are favored, although some models allow $m_{1/2}$ as high as 2.4 TeV. If the lower portion of the range of $m_{1/2}$ is indeed favored by a heavy Higgs scalar h , then there may be implications for gluino pair searches at the CERN LHC. The gluino mass $m_{\widetilde{g}}$ is shown versus m_h in Fig. 2a). If we require $m_h \gtrsim 130 \text{ GeV}$, then

we find that $m_{\tilde{g}} \lesssim 4$ TeV, with the region around $m_{\tilde{g}} \sim 1$ TeV being slightly more favored. In the region of large m_0 , the LHC7 reach [21] for gluino pair production with 10 fb^{-1} is to about $m_{\tilde{g}} \sim 800$ GeV, while the LHC14 reach [22] with 100 fb^{-1} is to $m_{\tilde{g}} \sim 1400$ GeV. Thus, if $m_h \sim 130 - 132$ GeV, then gluinos might be accessible to LHC searches, but it is also the case that all sparticles could be beyond LHC reach.

In frame *c*), we show m_h vs. A_0/m_0 . Here we see that the value of A_0 is really restricted to $\sim \pm 2m_0$ in order to attain the very largest values of m_h . For these large A_0 values, the top squark mixing is large, which can suppress the lighter stop mass $m_{\tilde{t}_1}$. The mass $m_{\tilde{t}_1}$ is shown versus m_h in Fig. 2*b*), where we see that for $m_h \sim 130 - 132$ GeV, we have $m_{\tilde{t}_1} \sim 2 - 4$ TeV, even though m_0 (and hence $m_{\tilde{u},\tilde{d}}$) is required $\gtrsim 10$ TeV. In fact, the boundary conditions of large m_0 with low $m_{1/2}$ and $|A_0| \sim 2m_0$ have been derived earlier in the case of Yukawa-unified SUSY [23], wherein third generation scalar masses are suppressed relative to first/second generation scalars via RG running. These boundary conditions result in an inverted scalar mass hierarchy (ISMH).

The relatively light top squark mass, along with the large top Yukawa coupling, act to enhance gluino three-body decays $\tilde{g} \rightarrow t\bar{t}\tilde{Z}_i$ (for $i = 1 - 4$) [24] at the expense of three-body decays to first or second generation quarks. Indeed, examining the Isajet sparticle decay table for a variety of models with $m_h \sim 130$ GeV shows that $\tilde{g} \rightarrow t\bar{t}\tilde{Z}_i$ occurs at the 70-80% level when gluino masses are light enough to be accessible to LHC searches.

Meanwhile, in frame *d*), we see that the largest values of m_h occur mainly for the upper range of $\tan \beta \sim 15 - 55$. From frames *e*). and *f*), we see that almost any values of μ and $m_A \sim .1 - 10$ TeV are possible if m_h is restricted to be at its upper range.

In Fig. 3, we show the resultant $h \rightarrow WW^*$, ZZ^* and $\gamma\gamma$ branching fractions versus m_h from our scans over NUHM2 parameter space. Indeed, at the very highest m_h values, we see that $BF(h \rightarrow WW^*) \sim 20\%$, although it drops by nearly an order of magnitude as m_h descends into the 110 GeV range. The branching fraction into ZZ^* drops even faster with decreasing m_h , while the $\gamma\gamma$ branching fraction is nearly constant at $\sim 10^{-3}$. The spread in values comes mainly from the variability in b -quark Yukawa coupling due to its value at Q_{SUSY} , which depends on the entire SUSY spectrum via the threshold corrections.

In Table 1, we show several sample NUHM2 model points with $m_h \sim 130$ GeV. The first two points, one for $A_0 > 0$ and one for $A_0 < 0$, have gluino masses within reach of LHC with dominant $\tilde{g} \rightarrow t\bar{t}\tilde{Z}_1$ decay, so we would expect LHC collider events containing four top quarks plus E_T^{miss} from the escaping neutralinos. The third point has $m_{\tilde{g}} \sim 1800$ GeV. In this case, we would expect LHC to see a light Higgs scalar with $m_h \sim 130$ GeV, but little or no sign of supersymmetry: the SUSY spectrum essentially decouples from LHC searches due to too heavy a mass spectrum.

We also show in Table 1 the standard thermal neutralino dark matter abun-

dance, assuming neutralino-only dark matter, as calculated by IsaReD [25]. We see that $\Omega_{\tilde{Z}_1}^{std} h^2$ is typically 4-5 orders of magnitude larger than the WMAP-measured value [26] of $\Omega_{CDM} h^2 = 0.1123 \pm 0.0035$ (68% CL), so that under a standard cosmology, these points would be excluded. This is similar to what occurs in Yukawa-unified or “effective SUSY” models [37], where a spectrum of lighter gauginos plus multi-TeV scalars results in a standard dark matter abundance which is several orders of magnitude beyond observation. There are several appealing ways around this situation. In one case, one may postulate the existence of additional scalar fields with mass in the 10-100 TeV range and with delayed decays, which occur shortly before BBN begins. This could be the case for instance for light moduli fields of string theory [27], or for saxions from a Peccei-Quinn (PQ) solution to the strong CP problem [28] (or both). In these cases, the scalar fields, which can be produced typically via coherent oscillations, can inject considerable entropy into the early universe, thus diluting all relics present at the time of decay [29, 30, 31, 32]. A more conservative possibility is to choose NUHM2 model parameters with very low μ values such that the lightest neutralino is mixed- or mainly- higgsino-like, or to choose m_A values such that $m_A \sim 2m_{\tilde{Z}_1}$ so that neutralinos annihilation is enhanced via the A -resonance[14].

Another possibility also occurs in the PQ augmented MSSM, where the R -parity odd axinos \tilde{a} are the lightest SUSY particles, and at the MeV scale. In this case, the thermally produced neutralinos would decay via $\tilde{Z}_1 \rightarrow \tilde{a}\gamma$ with lifetimes of order $\lesssim 1$ sec, so that the (non-thermally produced, NTP) axino abundance is $\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1}^{std} h^2$ [33]. Since the factor $\frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \sim 10^{-5}$, the neutralino overabundance is ultimately erased. The remaining dark matter fraction may be built up from a combination of thermally produced axinos [34], along with axions produced via vacuum misalignment [35, 36].

4. Conclusions

The recent surplus of WW^* events above the SM background, as measured by both ATLAS and CMS experiments, may point to a light MSSM Higgs scalar boson h at the upper edge of its expected mass range: $m_h \sim 128 - 132$ GeV. We have scanned over NUHM2 model parameter space, which maintains the desirable feature of radiative EWSB, while allowing for scalar masses beyond the HB/FP limit: $m_0 \sim 5 - 20$ TeV. By requiring $m_h \gtrsim 128$ GeV, we find that $m_0 \sim 10 - 20$ TeV is required, with $|A_0| \sim 2m_0$. While a wide range of $\tan\beta$, μ and m_A values are allowed, the value of $m_{1/2}$ has a mild preference for the low end of its range.

The associated SUSY particle spectra turns out to be of the “effective SUSY” type [37], with multi-TeV first/second generation scalars, few-TeV third generation scalars and possibly sub-TeV gauginos. In this case, SUSY signatures at LHC should be dominated by gluino pair production, with dominant $\tilde{g} \rightarrow t\bar{t}\tilde{Z}_i$ decays: thus, a

parameter	Pt. 1	Pt. 2	Pt. 3
m_0 [TeV]	18.2	17.246	14.169
$m_{1/2}$ [TeV]	307.8	122.58	712.74
A_0 [TeV]	34.737	-36.576	28.588
$\tan \beta$	51.19	34.9	43.3
μ [TeV]	1.759	9.880	5.660
m_A [TeV]	6.695	7.435	2.189
m_h [GeV]	131.62	131.1	130.4
$m_{\tilde{g}}$ [GeV]	789.0	648.3	1825.3
$m_{\tilde{u}_L}$ [TeV]	18.117	17.139	14.121
$m_{\tilde{e}_L}$ [TeV]	18.218	17.326	14.285
$m_{\tilde{t}_1}$ [TeV]	3.581	3.766	2.957
$m_{\tilde{b}_1}$ [TeV]	9.434	9.763	8.418
$m_{\tilde{\tau}_1}$ [TeV]	8.147	13.078	8.926
$m_{\tilde{W}_1}$ [GeV]	176.0	201.1	568.9
$m_{\tilde{Z}_2}$ [GeV]	174.8	198.8	565.2
$m_{\tilde{Z}_1}$ [GeV]	92.4	93.9	292.2
$\Omega_{\tilde{Z}_1}^{std} h^2$	8.3×10^3	1.7×10^4	1.1×10^3

Table 1: Masses and parameters in GeV/TeV units for several high m_h NUHM2 SUSY models using Isajet 7.82 with $m_t = 173.3$ GeV.

corroborating signal would be in the $4t + E_T^{\text{miss}}$ channel. It is also possible that the entire SUSY spectrum is quite heavy, and beyond LHC reach. The thermal neutralino dark matter abundance is predicted to be far above the WMAP7 measured value (unless very low μ or $m_A \sim 2m_{\tilde{Z}_1}$ is chosen), so that a diminution of neutralinos either via late-time entropy injection or by decays to MeV-scale axinos would be needed to reconcile with the measured dark matter abundance.

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NUHM2: $m_t = 173.3$ GeV

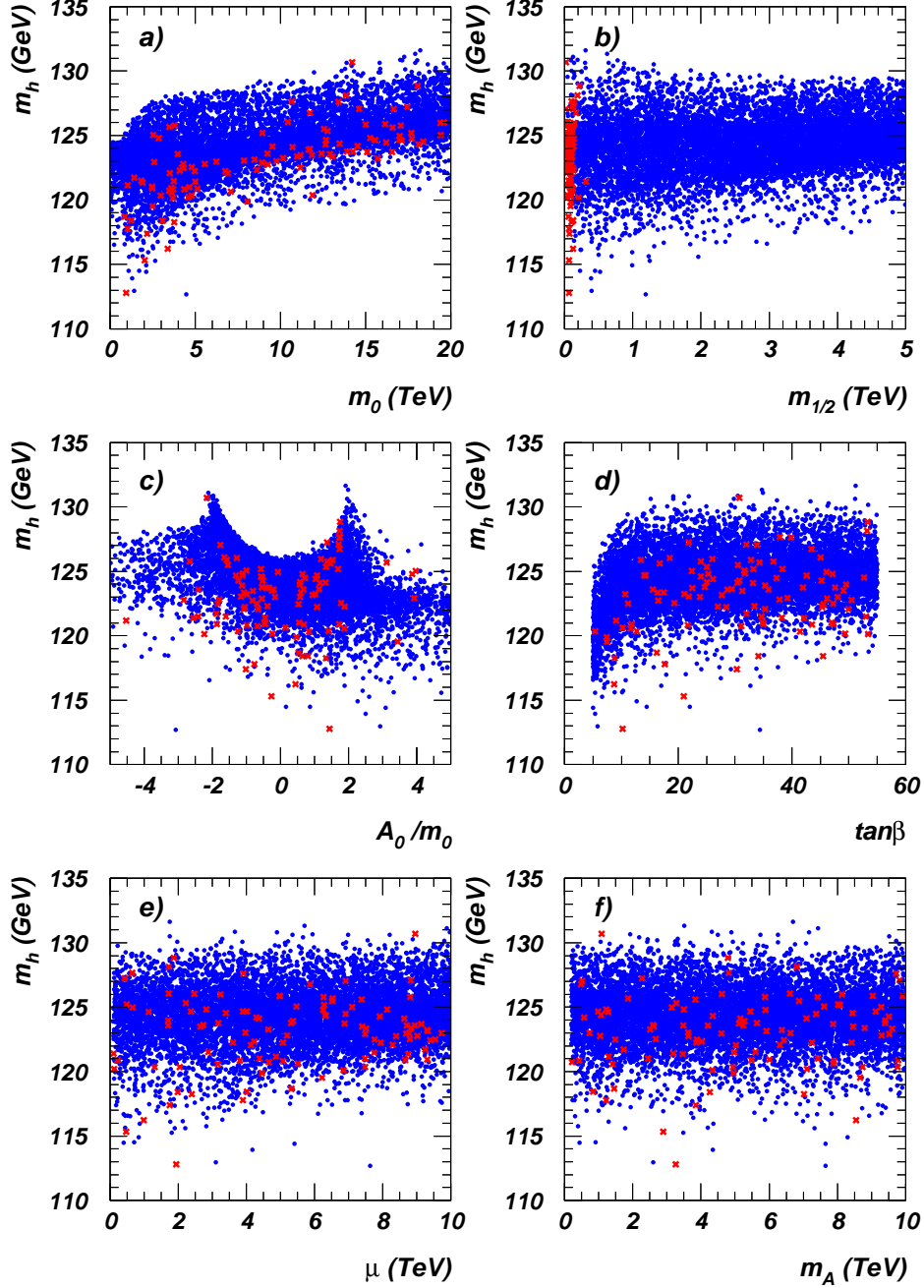


Figure 1: A plot of light Higgs mass m_h versus various SUSY parameters from a scan over NUHM parameter space. Red points have chargino masses $m_{\tilde{W}_1} < 103.5$ GeV, while blue points are LEP2-allowed. We take $m_t = 173.3$ GeV.

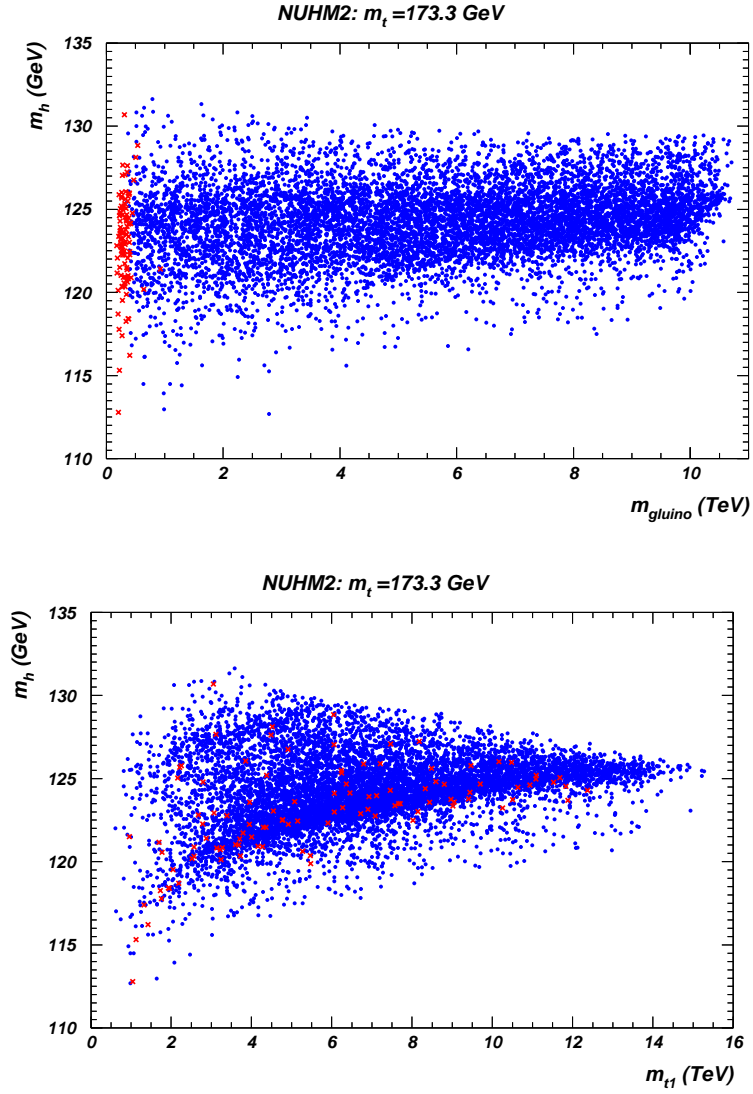


Figure 2: A plot of light Higgs mass m_h versus $m_{\tilde{g}}$ (upper) and $m_{\tilde{t}_1}$ (lower) from a scan over NUHM2 parameter space. We take $m_t = 173.3$ GeV.

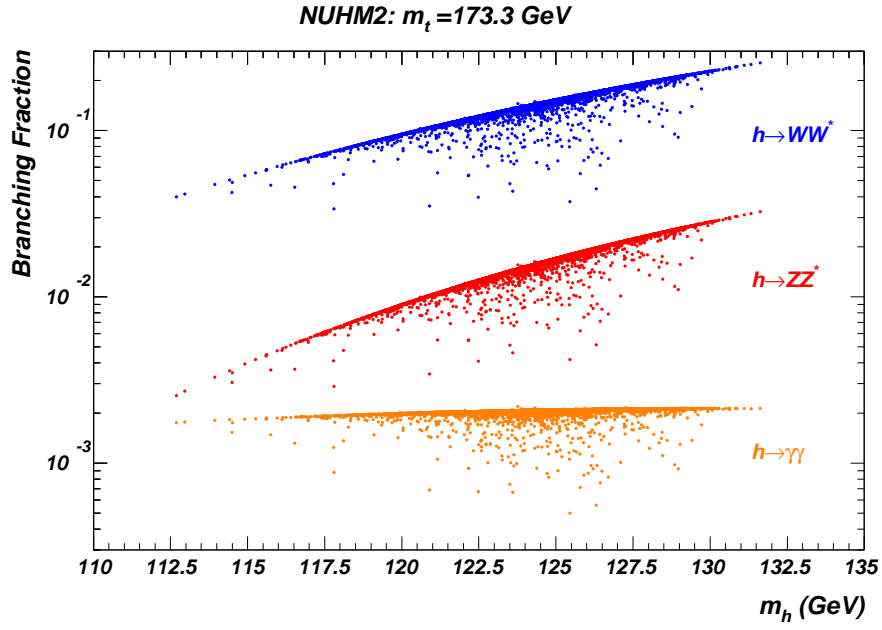


Figure 3: A plot of $BF(h \rightarrow WW^*)$, $BF(h \rightarrow ZZ^*)$ and $BF(h \rightarrow \gamma\gamma)$ versus m_h from a scan over NUHM2 parameter space for $m_t = 173.3$ GeV.