PROCEEDINGS OF SCIENCE

Detecting Heavy Higgs Bosons from Natural SUSY at a 100 TeV Hadron Collider

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In supersymmetric (SUSY) models with radiatively-driven naturalness (RNS), the heavier Higgs bosons $H,\ A$ may have TeV-scale masses with the SUSY conserving μ parameter in the few hundred GeV range. Thus, in natural SUSY models there should occur large heavy Higgs boson branching fractions to electroweakinos, with Higgs boson decays to higgsino plus gaugino dominating when they are kinematically accessible. These SUSY decays can open up new avenues for discovery. We investigate the prospects of discovering heavy neutral Higgs bosons H and A decaying into light plus heavy chargino pairs which can yield a four isolated lepton plus missing transverse energy signature at the LHC and at a future 100 TeV pp collider. We find that discovery of heavy Higgs decay to electroweakinos via its 4ℓ decay mode is very difficult at HL-LHC. For FCC-hh or SPPC, we study the $H,\ A \to$ SUSY reaction along with dominant physics backgrounds from the Standard Model and devise suitable selection requirements to extract a clean signal for FCC-hh or SPPC with $\sqrt{s} = 100$ TeV, assuming an integrated luminosity of 15 ab^{-1}. We find that while a conventional cut-and-count analysis yields a signal statistical significance greater than 5σ for $m_{A,H} \sim 1.1 - 1.65$ TeV, a boosted-decision-tree analysis allows for heavy Higgs signal discovery at FCC-hh or SPPC for $m_{A,H} \sim 1 - 2$ TeV.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*This article is based on a recent paper published in Phys. Rev. D [1].

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PoS(EPS-HEP2023)414

1. Introduction

Supersymmetric extensions of the Standard Model (SM) are highly motivated in that they offer a solution to the gauge hierarchy problem (GHP) [2] which arises from the quadratic sensitivity of the Higgs boson mass to high scale physics. SUSY models are also supported indirectly by various precision measurements within the SM: (i) the weak scale gauge couplings nearly unify under renormalization group evolution at energy scale $m_{GUT} \simeq 2 \times 10^{16}$ GeV in the MSSM, but not the SM [3], (ii) the measured value of top quark mass falls within the range needed to initiate a radiative breakdown of electroweak symmetry in the MSSM [4], (iii) the measured value of the Higgs boson mass $m_h \simeq 125$ GeV falls within the narrow range of MSSM predicted values [5], and (iv) precision electroweak measurements actually favor *heavy SUSY* over the SM [6].

In radiatively-driven natural supersymmetric (RNS) models [7], the heavier Higgs bosons may lie in the multi-TeV range while at least some of the electroweakinos (EWinos) are below a few hundred GeV. If SUSY decay modes of the heavy Higgs bosons are allowed, then SM search modes will be suppressed and new avenues for heavy Higgs discovery may open up. This situation was investigated for the case that the lightest EWinos were predominantly gaugino-like [8] and a lucrative $A, H \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to 4\ell + \not{E}_T$ search mode was identified for LHC [9]. However, in RNS models, we expect that the lightest EWinos to be dominantly higgsino-like. Thus, we explore a new possible heavy Higgs discovery channel for SUSY models with light higgsinos. We identify the dominant new SUSY decay mode for heavy neutral Higgs in natural SUSY models as $H,\ A \to \tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$ that proceeds with full gauge strength. Allowing for chargino cascade decays, we can find an analogous clean $4\ell + \not{E}_T$ signature.

To be specific, we will adopt a RNS benchmark (BM) point as listed in Table 1, as generated using Isajet 7.88 [10]. This BM comes from the two-extra-parameter non-universal Higgs model NUHM2 [11]. The NUHM2 model parameter space is given by $m_0, m_{1/2}, A_0, \tan\beta$ along with non-universal Higgs mass soft terms $m_{H_u} \neq m_{H_d} \neq m_0$. Using the EW minimization conditions, it is convenient to trade the high scale soft terms $m_{H_u},\ m_{H_d}$ for the weak scale parameters μ and m_A. This BM point yields $m_{\tilde{g}} \simeq 2.4$ TeV, somewhat beyond the LHC lower limit of 2.2 TeV obtained from a *simplified model analysis*. The heavy neutral Higgs scalars have mass $m_{H,A} \sim 1.2$ TeV which is somewhat beyond the recent ATLAS limit[12] that requires $m_{H,A} \gtrsim 1$ TeV for $\tan\beta = 10$ via an $H,\ A \to \tau^+\tau^-$ search at $\sqrt{s} = 13$ TeV and 139 fb^{-1} of integrated luminosity (while assuming no SUSY decay modes of the heavy Higgs bosons). Also, the SUSY μ parameter is taken to be $\mu = 200$ GeV so that the BM point lies just beyond the recent analyses of the *soft dilepton* plus monojet higgsino signal[13]. For the listed BM point, the lighter EWinos $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^\pm$ are higgsino-like while $\tilde{\chi}_3^0$ is bino-like and $\tilde{\chi}_4^0$ and $\tilde{\chi}_2^\pm$ are wino-like.

We study Higgs decays to SUSY particles in natural SUSY models with light higgsinos and examine the discovery potential of the $H,\ A \to 4\ell + \not{E}_T$ signal. This signature could arise from $H,\ A \to \tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$ followed by $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm$. The $Z \to \ell^+\ell^-$ decay should be visible but the leptons from $\tilde{\chi}_1^- \to \ell\nu_\ell\tilde{\chi}_1^0$ are typically very soft in the $\tilde{\chi}_1^\pm$ rest frame. Owing to the TeV scale values of $m_{H,A}$, these soft leptons may be boosted to detectable levels. While such a complicated decay channel appears intractable at HL-LHC, the FCC-hh[14] or the SPPC[15] pp collider operating at $\sqrt{s} \sim 100$ TeV and 15 ab^{-1} should allow for discovery for $m_{H,A} \sim 1 - 2$ TeV with advanced machine learning techniques. We have used boosted decision trees as an illustration.

parameter	NUHM2
m_0	5 TeV
$m_{1/2}$	1.0 TeV
A_0	-8.3 TeV
$\tan\beta$	10
μ	200 GeV
m_A	1.2 TeV
$m_{\tilde{g}}$	2423 GeV
$m_{\tilde{u}_L}$	5293 GeV
$m_{\tilde{u}_R}$	5439 GeV
$m_{\tilde{t}_1}$	1388 GeV
$m_{\tilde{t}_2}$	3722 GeV
$m_{\tilde{\chi}_1^\pm}$	208.4 GeV
$m_{\tilde{\chi}_2^\pm}$	856.7 GeV
$m_{\tilde{\chi}_1^0}$	195.4 GeV
$m_{\tilde{\chi}_2^0}$	208.5 GeV
$m_{\tilde{\chi}_3^0}$	451.7 GeV
$m_{\tilde{\chi}_4^0}$	867.9 GeV
m_h	125.0 GeV
$\Omega_{\tilde{\chi}_1}^{std}h^2$	0.011
$\Delta_{\rm EW}$	25.5

Table 1: Input parameters (TeV) and masses (GeV) for a SUSY benchmark point from the NUHM2 model with $m_t = 173.2$ GeV using Isajet 7.88 [10].

2. Heavy Higgs production at LHC and FCC-hh or SPPC

We will focus on the dominant s-channel heavy neutral Higgs boson production reactions $pp \to H,\ A$ which occurs via the gluon-gluon and $b\bar{b}$ fusion subprocesses. The SusHi program [16, 17] is employed to generate production cross sections, which include QCD corrections at the next-to-next-to-leading order (NNLO) and effects from top and bottom squark loops. We have found that for $\tan\beta = 10$, heavy Higgs boson production via $b\bar{b}$ fusion dominates that from gluon fusion. At the LHC with $\sqrt{s} = 14$ TeV, the total production cross section for H or A is ~ 40 fb for $m_A \sim 800$ GeV. For FCC-hh or SPPC with $\sqrt{s} = 100$ TeV, the cross sections are increased by factors of 70-500 as m_A varies from 800-2000 GeV.

3. Heavy Higgs and sparticle branching fractions

In this Section, we present some updated heavy neutral and charged Higgs branching fractions which we extract from the Isajet 7.88 code [10]. We adopt the benchmark point from Table 1 except now we allow the heavy Higgs mass m_A to vary. Some dominant heavy neutral Higgs decay branching fractions are shown in Table 2 for the benchmark point shown in Table 1. We see again that for the benchmark point the $H,\ A$ decays to SM modes are suppressed compared to decay rates into gaugino plus higgsino.

decay mode	BF
$H \to b\bar{b}$	22.5%
$H \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$	31.2%
$H \to \tilde{\chi}_2^{0}\tilde{\chi}_4^{0}$	12.2%
$A \to b\bar{b}$	22.9%
$A \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$	30.0%
$A \to \tilde{\chi}_1^{0}\tilde{\chi}_4^{0}$	12.2%

Table 2: Dominant branching fractions for heavy Higgs $H,\ A$ for the benchmark point with $m_A = 1200$ GeV.

4. Physics Backgrounds and Analysis Cuts

Our signal $pp \to H, A \to \chi_1^{\pm}\chi_2^{\mp} \to 4\ell + \not{E}_T$ contains 4 leptons and missing energy in the final states, where one pair of leptons comes from the decay of a Z-boson. Since the signal rate is too small at the HL-LHC, we will from now on mostly focus our attention on a 100 TeV pp collider.

Our simplified study has been carried out at parton level. The dominant SM background to the $4\ell + \not{E}_T$ events comes from $W^{\pm}W^{\mp}V$, $t\bar{t}V$, Zh and ZZV ($V = W^{\pm}, Z, \gamma$). Notice that the partonic final states from the signal, as well as from all the backgrounds other than $t\bar{t}V$ production, are free of any hadronic activity. We use tree-level matrix elements from the HELAS library in Madgraph to evaluate the backgrounds, and then scale our cross section to NLO with K-Factors calculated using MCFM [18].[1] For the $t\bar{t}V$ background we veto events which contain any b-jets (*i.e.* b-quarks) with $p_T > 20$ GeV and $|\eta(b)| < 2.5$. This serves as a powerful cut in reducing this background. However, with PDF enhancements, we find that this background becomes the second most dominant background at $\sqrt{s} = 100$ TeV. $W^{\pm}W^{\mp}V$ proves to be the most dominant background at all energies.

Since the signal of interest has a final state of $4\ell + \not{E}_T$, we started with a set of minimal cuts on p_T, η and ΔR, labeled as **cuts A** [1]. After applying cuts A, we show the invariant mass and transverse mass distributions obtained (upon summing $b\bar{b}$ and gg initiated processes) in Fig 1. Additional cuts on the invariant masses, transverse mass, and missing transverse energy (**cuts B**) [1] have been applied to improve the statistical significance.

In Fig. 2, we show the signal cross section versus m_A after cuts B at (a) the HL-LHC, and (b) a 100 TeV pp collider. We indeed see from frame (a) that for all values of m_A the signal lies well below the one event level. From Fig. 2(b), we project that at the FCC or at the SPPC with an integrated luminosity of 15 ab^{-1}, several tens of signal events may be expected after cuts B over most of the range of m_A in the figure.

5. Discovery Potential with Cut-and-Count Analysis

In this section, we study the discovery potential of the $4\ell + \not{E}_T$ signal for heavy Higgs bosons at a 100 TeV pp collider using a traditional cut-and-count analysis.

[1]The K-factors that we use are, $K_{WWV} = 1.36$, $K_{t\bar{t}V} = 1.30$, $K_{Zh} = 1.40$ and $K_{ZZV} = 1.40$.

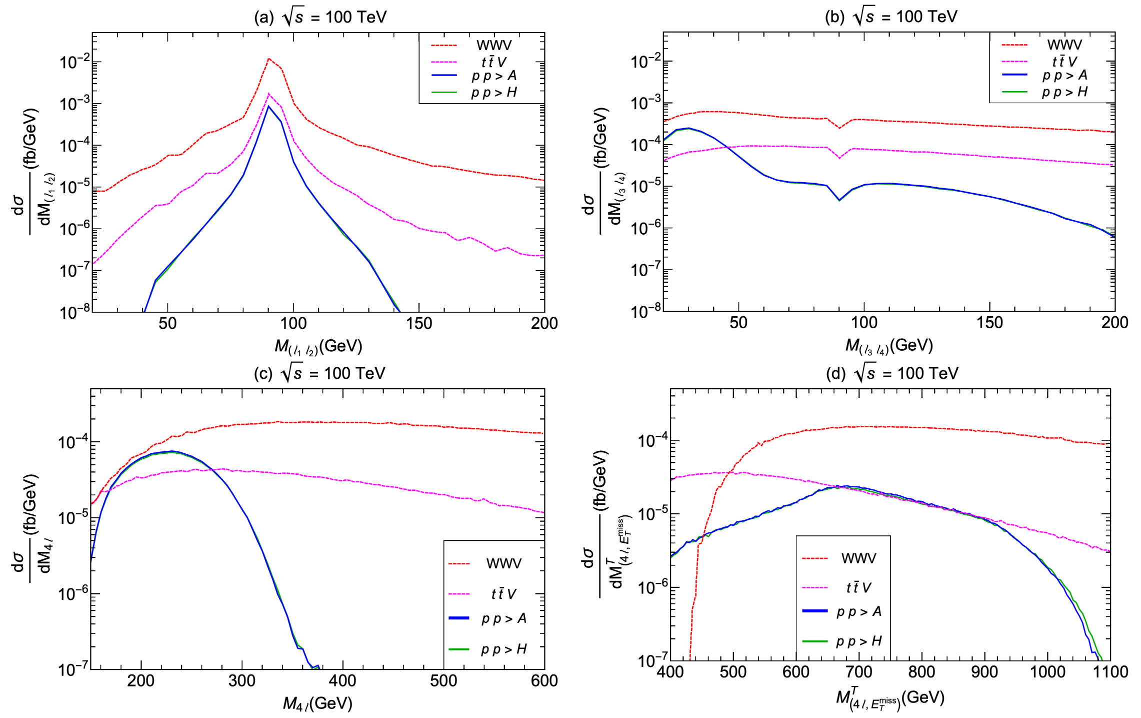

Figure 1: Plots of the (a) invariant mass distribution $M(\ell_1\ell_2)$ of the two leptons that form an invariant mass closest to m_Z,(b) invariant mass distribution of the remaining two leptons, $M(\ell_3, \ell_4)$, (c) invariant mass of the 4ℓ system, and (d) cluster transverse mass distribution of the $4\ell + \not{E}_T$ system, for the Higgs signal $(pp \to H,\ A \to 4\ell + \not{E}_T + X)$, after the cut set A defined in the text. The corresponding contributions from the dominant physics backgrounds are also shown.

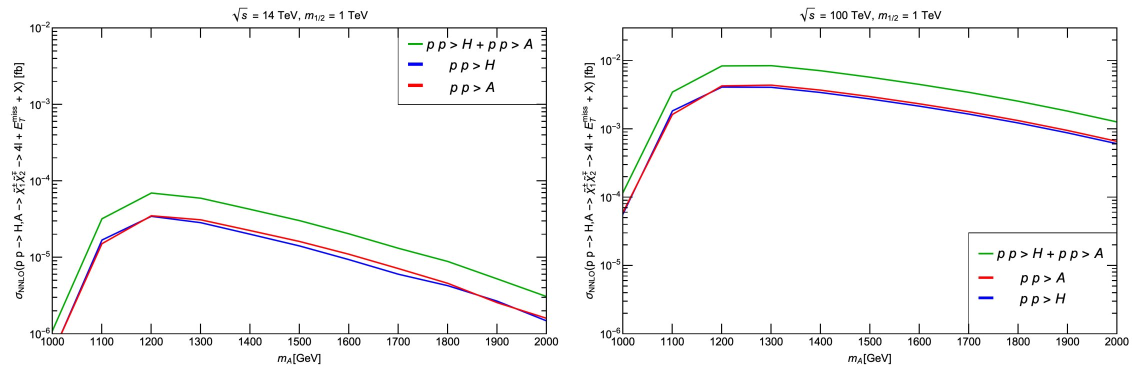

Figure 2: NNLO Cross sections, $\sigma(A)$, $\sigma(H)$, and $\sigma(A)+\sigma(H)$ times the cascade decay branching fractions into the $4\ell + \not{E}_T$ final state in fb vs. m_A for (a) 14 TeV and (b) 100 TeV, after the cut set B defined in the text.

In the left frame of Fig. 3, we present our estimates of statistical significance [19],

$$N_{ss} \equiv \sqrt{(2 \times (N_S + N_B)\ln(1 + N_S/N_B) - 2 \times N_S)},$$

for 1100 GeV $\leq m_A \leq$ 2000 GeV. Our selection cuts work well in removing a large part of the physics background. We see that with a center of mass energy of 100 TeV and integrated luminosity

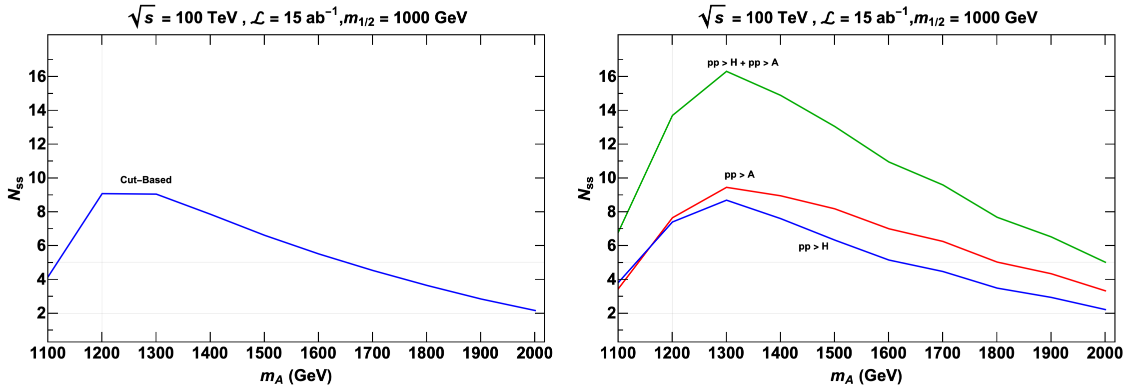

Figure 3: Statistical significance plots for the $H,\ A \to 4\ell + \not{E}_T$ signal at a 100 TeV hadron collider with the traditional cut-based analysis (left) as well as a BDT analysis (right).

of $\mathcal{L} = 15$ ab^{-1}, we have enough events to claim a 5σ discovery for $m_A \sim 1.1 - 1.65$ TeV. We also obtain a 95% CL exclusion limit for the $H,\ A \to 4\ell + \not{E}_T$ signal for values of m_A extending out as far as 2 TeV.

6. Improvement with Boosted Decision Trees

We apply boosted decision trees (BDT) for which algorithms are included in the ToolKit for MultiVariate Analysis (TMVA) [20], a multivariate analysis package included with ROOT. For this study, we have used the following variables for training and testing, (i) the invariant mass $M(4\ell)$, (ii) the invariant masses $M(\ell_1, \ell_2)$ and $M(\ell_3, \ell_4)$, and (iii) $\not{E}_T$, missing transverse energy.

We have generated signal files for each value of m_A along with the backgrounds at 100 TeV after applying the cut set **B**, except that we have now relaxed the cut on $\not{E}_T$ to be $\not{E}_T > 200$ GeV before passing the samples for training and testing.

The right frame of Fig. 3 shows the individual contributions from each of H and A for the BDT analysis along with the significance from the combined H and A signal. This may be compared to the significance shown in the left frame for the traditional cut-based analysis. By using the BDT analysis, we would be able to discover H and A at the 5σ level via $H,\ A \to 4\ell + \not{E}_T$ channel for $m_A \sim 1 - 2$ TeV – a considerable improvement in range of m_A over the usual cut-based method!

7. Conclusions

We have examined heavy neutral Higgs boson discovery as motivated by natural SUSY models with light higgsinos. In such models, the heavy Higgs $H,\ A$ decays to electroweakinos are almost always open since the lightest higgsinos are expected to have masses below ~ 350 GeV range whilst the H and A bosons can have TeV-scale masses.

In our analysis we have focused on production of the heavy Higgs bosons with a mass ($m_H \simeq m_A$) between 1 TeV and 2 TeV. While a signal (in the $4\ell + \not{E}_T$ channel) is not likely to be observable at HL-LHC, prospects are much better at FCC-hh or SPPC. The best case for discovery is near $m_A \simeq 1.2 - 1.3$ TeV that has a balance between kinematics of leptons in the final state and production cross sections. A 100 TeV hadron collider offers promise to discover a heavy neutral Higgs boson via one of its dominant SUSY decay modes in natural SUSY models with a mass $\sim 1-2$ TeV. With a conventional cut-based analysis, we are able to obtain a $N_{ss} > 5$ statistical significance over a range $m_A \sim 1.1 - 1.65$ TeV.

The chargino and neutralino discovery channel for heavy Higgs bosons at high energy hadron colliders offers an important opportunity to discover the heavy neutral Higgs bosons via their decay into EWinos. An upgrade to a 100 TeV hadron collider seems essential for heavy Higgs H and A discovery via the natural SUSY $4\ell + \not{E}_T$ channel.

Acknowledgements

I am grateful to H. Baer, V. Barger, R. Jain, D. Sengupta and X. Tata, for a very enjoyable collaboration.

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