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Higgs Sector of Non-minimal Supersymmetric Models at Future Hadron Colliders

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We investigate the potential of current and planned hadron colliders operating at the TeV scale in disentangling the structure of the Higgs sector of non-minimal Supersymmetric extensions of the Standard Model with an extra gauge singlet. We assume universality of the soft Supersymmetry breaking terms at the GUT scale as well as a CP-even Higgs boson with mass around 115 GeV, as suggested by LEP. We find that mixing angles between the doublet and singlet Higgs states are always small. However, concrete prospects exist at both the Tevatron (Run II) and the Large Hadron Collider of detecting at least one neutral Higgs state with a dominant singlet component, in addition to those available from a doublet Higgs sector which is similar to the one of the Minimal Supersymmetric Standard Model.

I. INTRODUCTION

The NMSSM [1, 2] (Next-to-Minimal Supersymmetric Standard Model) is defined by the addition of a gauge singlet Superfield S to the MSSM (Minimal Supersymmetric Standard Model) and a global $\mathbb{Z}_3$ symmetry on the renormalizable part of the Superpotential. It allows to omit the term $\mu H_u H_d$ in the Superpotential of the MSSM (where H_u is the Higgs doublet coupled to the up-type fermions and H_d to the down-type ones) and to replace it by a Yukawa coupling (plus a singlet self coupling), hence solving the so-called 'μ problem' of the MSSM. Apart from the standard quark and lepton Yukawa couplings, the Superpotential of the NMSSM is

$$W = \lambda H_u H_d S + \frac{1}{3}\kappa S^3 + ... \tag{1}$$

and the corresponding trilinear couplings A_λ and A_κ are added to the soft Supersymmetry (SUSY) breaking terms. Once the electroweak (EW) symmetry is broken, the scalar component of S acquires a vacuum expectation value (vev) $s = \langle S \rangle$, thus generating an effective μ term, $\mu = \lambda s$. The Superpotential (1) is scale invariant, and the EW scale appears only through the soft SUSY breaking terms. The possible domain wall problem due to the spontaneous breaking of the $\mathbb{Z}_3$ symmetry at the weak scale is assumed to be solved by adding non-renormalizable interactions which break the $\mathbb{Z}_3$ symmetry without spoiling the quantum stability with unwanted divergent singlet tadpoles [3]. This can be done by replacing the $\mathbb{Z}_3$ symmetry by a discrete R-symmetry, broken by the soft SUSY breaking terms [4].

A similar model, called nMSSM (for new Minimal Supersymmetric Standard Model) has recently been proposed [5], using discrete R-symmetries to forbid the singlet self-interaction in (1). In this model, n-th order singlet tadpole graphs generate a divergent loop-suppressed term in the scalar potential, $V_{\rm tadpole} \sim \frac{1}{(16\pi^2)^n} M_{\rm SUSY}^2 M_P (S+S^*) \equiv \xi^3 (S+S^*)$ $(\xi \sim M_{\rm SUSY})$. This term breaks the dangerous Peccei-Quinn symmetry present when κ is set to 0 in the NMSSM.

The new states in both models are one additional CP-even neutral Higgs S_r (real part of the complex scalar field S), one CP-odd neutral Higgs S_i (imaginary part), as well as one additional neutralino, the 'singlino' $\widetilde{S}$. These states usually mix with the corresponding MSSM states, giving three CP-even neutral ones, two CP-odd neutral Higgses and five neutralinos.

In this study, we focus on the phenomenology of the neutral Higgs sector of the NMSSM and nMSSM at the Tevatron (Run II, $\sqrt{s} = 2$ TeV) and the Large Hadron Collider (LHC, $\sqrt{s} = 14$ TeV). We only consider the 'direct' production channels, namely [6] ($V = W^\pm, Z$, $Q = b, t$ and $q^{(\prime)}$ refers to any possible quark flavour):

$$\begin{aligned} &gg \to \text{Higgs (gluon} - \text{gluon fusion)}, \quad q\bar{q}^{(\prime)} \to V \text{ Higgs (Higgs} - \text{strahlung)}, \\ &qq^{(\prime)} \to qq^{(\prime)} \text{ Higgs } (VV - \text{fusion}), \quad gg, q\bar{q} \to Q\bar{Q} \text{ Higgs (heavy} - \text{quark associated production)}. \end{aligned} \tag{2}$$

Here, we neglect 'indirect' Higgs production via decays/bremsstrahlung off heavy SUSY particles [7].

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II. PARAMETER SPACE OF THE MODELS

In order to study the Higgs spectrum of both models, we have numerically scanned their free parameter spaces using a similar program as described in Refs. [2, 5]. First, we constrained the soft terms of both models by requiring *universality* at the GUT scale. The independent parameters of the models are then: a universal gaugino mass $M_{1/2}$, a universal mass for the scalars m_0, a universal trilinear coupling A_0, the Yukawa coupling λ and the the singlet self-coupling κ (NMSSM) or the tadpole coefficient ξ (nMSSM). The (well-known) value of the Z-boson mass fixes one of these parameters with respect to the others, so that we end up with *four* free parameters at the GUT scale, i.e., as many as in the MSSM with universal soft terms. In principle, one could choose the same set of free parameters as in the MSSM, i.e., $M_{1/2}$, m_0, A_0 and $\tan\beta(\equiv \frac{h_u}{h_d})$, with s, λ, and κ (ξ) being determined by the three minimisation equations. However, this appears to be not easily feasible, as λ (κ) also influences the running of the renormalization group equations (RGEs) for the soft parameters between the GUT and the weak scale. Therefore, we took the following input parameters: $m_0/M_{1/2}$, $A_0/M_{1/2}$, λ and κ ($\xi/M_{1/2}$). We then integrated numerically the RGEs between the GUT and the weak scale and minimised the two-loop effective potential. This gives $\tan\beta$ and s and the overall scale $M_{1/2}$ is fixed by M_Z. Finally, we imposed the current experimental bounds on (s)particle masses and couplings, especially the LEP limits on the Higgs mass vs. its coupling to gauge bosons, see [8]. Furthermore, we assumed the existence of one neutral CP-even Higgs boson with mass 115 GeV and sufficient coupling to gauge bosons, as suggested by LEP [9].

III. RESULTS

The main result of this numerical analysis, as already pointed out in Refs. [2, 5], is that the additional couplings appearing in (1) are always small: $\lambda(\kappa) < 10^{-2}$ (NMSSM) and $\lambda < 0.2$ (nMSSM). (Higher values would lead to unphysical minima of the scalar potential.) The mixing angles of the additional singlet states (described in Sect. I) to the non-singlet sector, being proportional to these couplings, are always small and the singlet sector of the universal NMSSM/nMSSM is quasi decoupled. (In the non-universal scenario, the outcome may be quite different: see Ref. [10]). Hence, the neutral Higgs sector consists of a quasi pure (qp) CP-even Higgs singlet state, S_r, a qp CP-odd singlet, S_i, and the doublet sector is basically MSSM-like, apart from small perturbations of order $\sim \lambda^2$, so that results known for the Higgs sector of the MSSM are also valid in our case.

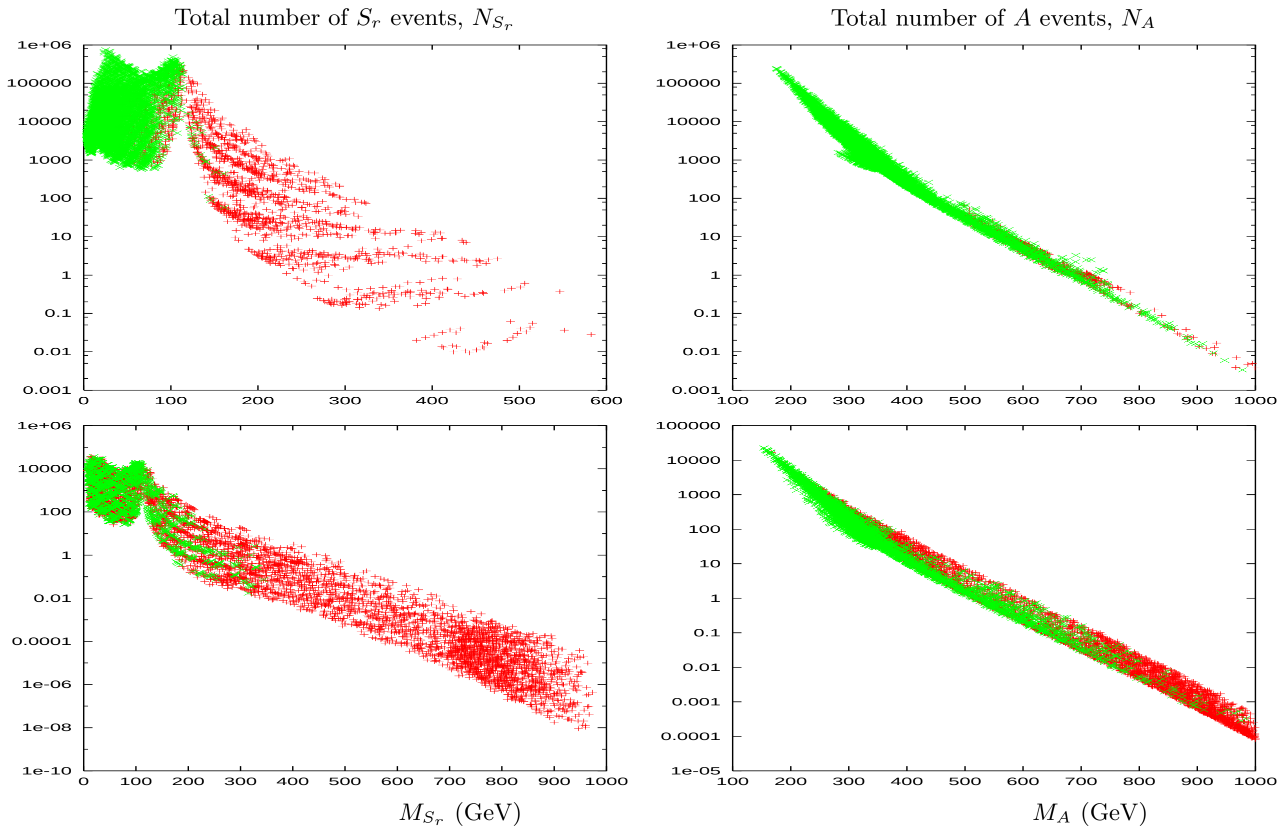
Fixing the mass of the lightest visible (non-singlet) CP-even Higgs at 115 GeV puts further constraints on the parameter space of both models: we find that $\tan\beta$ is always larger than 4, the CP-odd doublet Higgs mass M_A is larger than 160 GeV and $M_{\rm SUSY}$ is larger than 350 GeV. In this limit, the CP-even doublet states are qp interaction eigenstates. The Higgs state with mass 115 GeV is a qp H_u, and the qp H_d is heavy (with mass larger than 300 GeV). On the other hand, the masses of the singlet Higgs states, S_r and S_i, can vary from a few GeV to 1 TeV.

For each of the five neutral Higgs bosons, we have computed the total number of events obtained by summing the rates of all production processes in (2), assuming 15 fb^{-1} for Tevatron (Run II) and 300 fb^{-1} for the LHC, as integrated luminosities. We have plotted these rates versus the mass of the given Higgs states in Figs. 1–2. If, as threshold of detectability of a signal, we assume 100 events, the conclusions are similar in both models.

First, at Tevatron the non-singlet CP-even Higgs with mass 115 GeV, the qp H_u, is of course always visible, but the other non-singlet CP-even state, the qp H_d, is not, as it is too heavy. The non-singlet CP-odd state, the qp A, will be visible if it is light enough ($M_A < 300-400$ GeV for a total number of events $N_A > 100$). The singlet CP-even state, the qp S_r, will also be visible up to masses of ~ 300 GeV if $\lambda \gtrsim 10^{-3}$ (so that this state is not too decoupled), particularly when it is quasi mass degenerate with the qp H_u state (notice the peaks at $M_{S_r} \sim 115$ GeV). On the other hand, the singlet CP-odd state, the qp S_i, will remain invisible at Tevatron. To render this manifest, we have plotted in Fig. 1 the total number of events produced at Tevatron with S_r in the final state, N_{S_r} (two left plots) in green (light) when the corresponding A state is also visible ($N_A > 100$) and in red (dark) when it is not ($N_A < 100$). Similarly, we did for A (two right plots), with green (light) when the corresponding S_r is visible ($N_{S_r} > 100$) and red (dark) when it is not ($N_{S_r} < 100$). The upper plots correspond to the NMSSM and the lower ones to the nMSSM. From these plots it is easy to see in which cases one, two or three Higgs states will be visible (with more than 100 produced events) at Tevatron.

At LHC, on the other hand, due to the large center of mass energy available, all three non-singlet states, H_u, H_d and A, will be visible. In the singlet sector, the S_r should be visible if its mass is $\lesssim 600$ GeV and λ is not too small. In the NMSSM, this covers most of the parameter space. Moreover, the CP-odd singlet, S_i should be visible for an appreciable part of the parameter space, at least for the NMSSM. These results are shown in Fig. 2, with the same lay out and colour coding as for Fig. 1, but this time for S_r and S_i at LHC.

Finally, it should be noted that the discovery areas of multiple Higgs boson states identified in Figs. 1–2 are indeed associated to the same regions of parameter space. However, a first glance at the total number of CP-odd


Total number of S_r events, N_{S_r}

Total number of A events, N_A

FIG. 1: Total number of events produced through processes (2) at the Tevatron (Run II) after 15 fb^{-1} in the NMSSM (upper plots) and nMSSM (lower plots) for the CP-even singlet S_r (left plots) and the CP-odd non-singlet A (right plots) as a function of the produced Higgs mass. (For an explanation of the colour coding, see the text).

non-singlet A produced at Tevatron in both models (Fig. 1, right-hand plots) might indicate that nearly all the parameter space of the models is already covered by the CP-even singlet S_r search at Tevatron, as all the plotted points are in green (light). This is however not the case, as one can check from the left-hand plots (N_{S_r} vs. M_{S_r} at Tevatron), where a lot of points are still under the 100 events threshold. The fact that one sees only green (light) points on the right-hand plots is due to the very high density of points plotted, green (light) points being plotted after red (dark) ones. Hence, there are red (dark) areas, uncovered by the S_r searches, behind green (light), covered, ones. This remark applies also for associated S_r, S_i searches at LHC (Fig. 2).

IV. CONCLUSIONS AND FINAL REMARKS

The conclusions of this preliminary study are that, although the singlet sector of non-minimal models tends to decouple from the rest of the spectrum in the universal case, quasi pure singlet states could still be found at future hadron colliders. One has to remember that a very light CP-even Higgs state is not excluded by LEP searches if its coupling to gauge bosons is small enough. Such a Higgs state should be looked for at Tevatron (Run II) where up to three neutral Higgses could be found in our models (the CP-even non-singlet H_u with mass 115 GeV, and the CP-odd non-singlet A and CP-even singlet S_r if their mass is small enough). On the other hand, the large center of mass energy of LHC will allow us to see at least the three non-singlet Higgses (H_u, H_d and A) and its huge luminosity will trace the CP-even singlet state up to masses of $\lesssim$ 600 GeV and, in some cases, the CP-odd one, making the whole neutral Higgs spectrum visible.

The caveat of our analysis is that we have not performed a full Higgs decay analysis in the NMSSM/nMSSM. One may question whether the additional Higgs states would actually be visible. For example, they would certainly couple to singlinos – $\tilde{S}$ is always the Lightest Supersymmetric Particles (LSP) in our context – hence decay into the latter and thus remain undetected. This should however not be the case. In fact, the coupling of the singlet states to ordinary matter are generally stronger in comparison (of order λ, whereas those to two singlinos are $\sim \lambda^3$). So that, in the end, the main decay channels of singlet Higgs states should be those into detectable fermions and gauge bosons.

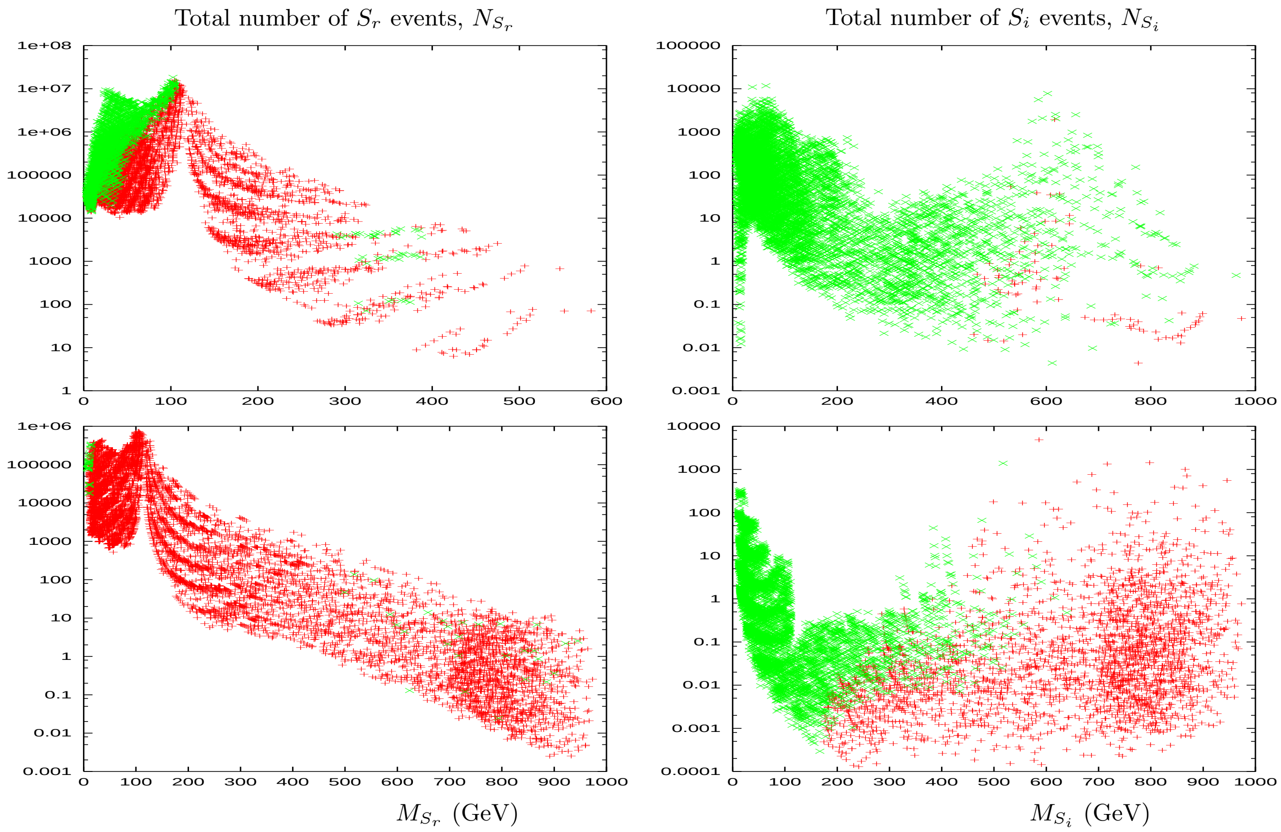


FIG. 2: As Fig. 1 for the CP-even singlet S_r (left plots) and the CP-odd singlet S_i (right plots), at LHC after 300 fb^{-1}.

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