Snowmass2021 - Letter of Interest
Collider Phenomenology of the NMSSM Higgs Sector

Thematic Areas:

■ (EF08) BSM: Model specific explorations
■ (EF01) EW Physics: Higgs Boson properties and couplings
■ (EF02) EW Physics: Higgs Boson as a portal to new physics

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The Next-to-Minimal Supersymmetric extension of the Standard Model (NMSSM) [1,2] is a well-motivated model for physics Beyond the Standard Model (BSM); it may not only solve the hierarchy problem of the electroweak scale [3–7], but also solve the μ-problem [8] of the MSSM, alleviate the fine-tuning associated with the 125 GeV Higgs boson and the tension implied by the current lack of evidence for superpartners below the weak scale (see e.g. [9–12]), and provide a dark matter candidate [13–23].

The NMSSM augments the field content of the MSSM by a SM-singlet chiral superfield $\widehat{S}$; this extends the particle content by singlet scalar and pseudo-scalar bosons $H^{\rm S}$ and $A^{\rm S}$, which mix with their corresponding Higgs-doublet counterparts, and a singlet fermion, the singlino $\widetilde{S}$, which mixes with the neutralinos. The addition of these singlet states leads to relevant modifications of the NMSSM Higgs sector's collider phenomenology compared to the MSSM (or more general 2HDMs) [13,16,24–36]. After electroweak symmetry breaking, the physical states are three neutral CP-even Higgs bosons (h_{125}, h, and H), two neutral CP-odd states (a and A), and one charged Higgs boson ($H^\pm$). We identify h_{125} with the observed 125 GeV Higgs boson, and order the remaining states by masses $m_h < m_H$, and $m_a < m_A$. In order to be compatible with Higgs precision data [37,38], h_{125} must have mass $m_{h_{125}} \simeq 125$ GeV and its couplings to pairs of SM particles must be similar to those of the SM Higgs boson. In the NMSSM, there are two ways to achieve SM-like couplings of h_{125}: in the *decoupling* limit, the non-SM-like neutral Higgs scalars have masses much larger than that of the observed SM-like Higgs boson, while in the *alignment-without-decoupling* limit [29], the parameters of the theory conspire to suppress the mixing of the SM Higgs interaction eigenstate with the non-SM-like neutral scalar interaction eigenstates. This latter alignment-without-decoupling limit is of particular interest for phenomenology, since it does not require the mass of the non-SM-like Higgs bosons to be large compared to the electroweak scale, and hence, they may be accessible at the LHC. We note that Refs. [32, 36] demonstrated that, in random scans of the parameter space, requiring compatibility with the phenomenology of the observed 125 GeV Higgs bosons selects the region of parameter space where the alignment conditions are approximately satisfied, even in regions where one naïvely might have expected the decoupling limit to suffice to realize a 125 GeV state with SM-like couplings.

The admixture of the singlet-interaction states $H^{\rm S}$ and $A^{\rm S}$ to the neutral mass eigenstates reduces their direction production cross sections, since $H^{\rm S}$ and $A^{\rm S}$ do not directly couple to SM particles. On the other

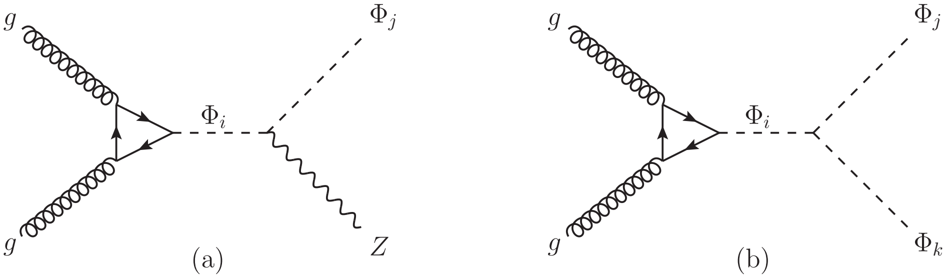

Figure 1: Illustration of di-boson decay processes. The Φ_i stand for any of the NMSSMS's neutral Higgs bosons. CP-conservation demands that for diagram (a) one of the states must be CP-even and the other one CP-odd, e.g. ($gg \to A \to Zh$) or ($gg \to H \to Za$). For diagram (b), either all three states must be CP-even, e.g. ($gg \to H \to hh_{125}$), or two of them must be CP-odd and one CP-even, e.g. ($gg \to A \to ah_{125}$).

hand, the presence of the additional states introduces new interactions and decay channels. In particular, resonant di-boson production processes appear prominently [26, 27, 29–36], where a heavy Higgs decays into two lighter Higgs bosons or a light Higgs and a Z boson as illustrated in Fig. 1. The trilinear couplings corresponding to such decays are controlled by the SM gauge couplings and the dimensionless NMSSM parameters λ and κ. In particular, the dimensionless coupling between the singlet and doublets, λ, takes values $\lambda \simeq 0.65$ in the alignment limit. Due to these large couplings, if kinematically accessible, di-boson decays will play a large role for the decay patterns of the non SM-like Higgs bosons in the NMSSM; typically the branching ratios remain large, $\mathcal{O}(10\,\%)$, even if decays into pairs of top quarks are kinematically allowed.

While di-boson decays have been used extensively to search for BSM Higgs bosons at the LHC, the experimental collaborations have focused their efforts on decays into two SM(-like) states, such as $H \to h_{125}h_{125}$ [39–57], $H \to ZZ$ [58–67], $H \to WW$ [68–76], and $A \to Zh_{125}$ [39, 77–80]. These decay modes have the advantage of particles with known masses and branching ratios in the final state (i.e., Z, W, and h_{125}), however, the corresponding branching ratios are suppressed by alignment. In general, alignment (without decoupling) suppresses the trilinear coupling between two SM(-like) states and one non-SM-like state [29, 35]. Instead, the trilinear couplings unsuppressed by alignment involve at least two non-SM-like states. The most promising di-boson decay modes of the (non-SM-like) NMSSM Higgs bosons at the LHC are ($H \to h_{125}h$), ($H \to Za$), ($A \to h_{125}a$), and ($A \to Zh$). While these channels are more challenging than those relying on the decays of H/A into two SM(-like) modes, the associated branching ratios are much larger, and while they do involve states with unknown masses and branching ratios, the presence of one state with known mass and decay patterns (Z or h_{125}) makes it easier to identify such processes at colliders than decays not involving SM-like states (such as $H \to hh$, $H \to aa$, and $A \to ha$).

The prospects for probing the NMSSM at the LHC using such di-boson decays has been explored in the literature, see, for example, Refs. [13,16,24–33,36]. However, most of these studies focused on the potential of one, or a few, particular channel(s) to probe certain parameter regions of the NMSSM parameter space. Reference [36] took a first step towards a more comprehensive study, investigating how well the region of NMSSM parameter space compatible with the phenomenology of the observed Higgs boson and featuring new Higgs bosons with masses $\lesssim 1\,\text{TeV}$ could be explored in future LHC runs by combining conventional search channels for BSM Higgs bosons (such as $H/A \to bb/\tau\tau/ZZ$) with these more NMSSM specific di-boson channels [such as ($H/A \to h_{125}h/a$), ($H/A \to Za/h$)]. However, Ref. [36] partially relied on rather crude extrapolations of the future LHC sensitivity. Further work exploring the sensitivity of the LHC or other future colliders to the NMSSM, and in particular, the complementarity between different search channels, are highly motivated; we are planning to undertake such studies.

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