Establishing a No-Lose Theorem for
NMSSM Higgs Boson Discovery at the LHC

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Abstract

We scan the parameter space of the NMSSM for the observability of at least one Higgs boson at the LHC with 300 fb$^{-1}$ integrated luminosity, taking the present LEP2 constraints into account. We restrict the scan to those regions of parameter space for which Higgs boson decays to other Higgs bosons and/or supersymmetric particles are kinematically forbidden. We find that if $WW$-fusion detection modes for a light Higgs boson are not taken into account, then there are still significant regions in the scanned portion of the NMSSM parameter space where no Higgs boson can be observed at the 5$\sigma$ level, despite the recent improvements in ATLAS and CMS procedures and techniques and even if we combine all non-fusion discovery channels. However, if the $WW$-fusion detection modes are included using the current theoretical study estimates, then we find that for all scanned points at least one of the NMSSM Higgs bosons will be detected. If the estimated 300 fb$^{-1}$ significances for ATLAS and CMS are combined, one can also achieve 5$\sigma$ signals after combining just the non-$WW$-fusion channels signals. We present the parameters of several particularly difficult points, and discuss the complementary roles played by different modes. We conclude that the LHC will discover at least one NMSSM Higgs boson unless there are large branching ratios for decays to SUSY particles and/or to other Higgs bosons.
1 Introduction

Supersymmetric extensions of the standard model generally predict relatively light Higgs bosons. One of the most important tasks of the LHC is the search for Higgs bosons \[1, 2\]. An important milestone in understanding the potential of the LHC was the demonstration that at least one Higgs boson of the minimal supersymmetric standard model (MSSM) would be detectable at the \[\geq 5\sigma\] level throughout all of the MSSM parameter space so long as top squark masses do not exceed 1.5 to 2 TeV and so long as large branching fractions to decay channels containing supersymmetric particles are not substantial.

In the present paper, we study, subject to these same and a few other simplifying restrictions, the detectability of Higgs bosons in the next-to-minimal supersymmetric standard model (NMSSM). In the NMSSM, one Higgs singlet superfield, \(\hat{S}\), is added to the MSSM in order to render unnecessary the bilinear superpotential term \(\mu \hat{H}_1 \hat{H}_2\) by replacing it with \(\lambda \hat{S} \hat{H}_1 \hat{H}_2\), where the vacuum expectation value of the scalar component of \(\hat{S}\), \(\langle S\rangle\), results in an effective bilinear Higgs mixing with \(\mu = \lambda \langle S\rangle\). The detectability of the NMSSM Higgs bosons was first considered in a contribution to Snowmass 96 [3]. The result, using the experimentally established modes and sensitivities available at the time, was that substantial regions in the parameter space of the NMSSM were found where none of the Higgs bosons would have been observable either at LEP2 or at the LHC even with an integrated luminosity of 600 fb\(^{-1}\) (two detectors with \(L = 300\) fb\(^{-1}\) each).

Since then, progress has been made both on the theoretical and the experimental sides. On the theoretical side, the dominant two-loop corrections to the effective potential of the model have been computed \[4, 5\]. These lead to a modest decrease in the mass of the lightest Higgs scalar, holding fixed the stop sector parameters. Inclusion of the two-loop corrections thus increases somewhat the part of the NMSSM parameter space excluded by LEP2 (and accessible at the Tevatron) \[6\], but is of less relevance for the LHC. On the experimental side the expected statistical significances have been improved since 1996 \[1, 2\]. Most notably, associated \(t\bar{t}h\) production with \(h \to bb\) (originally discussed in \[8\]), which in the SM context is particularly sensitive to \(m_h \lesssim 120\) GeV, has been added by ATLAS and CMS to the list of Higgs boson detection modes \[1, 2, 7, 8\]. Analysis of this mode was recently extended \[9\] to \(m_h = 140\) GeV, which, though not relevant in the SM case due to the decline in the \(b\bar{b}\) branching ratio as the \(WW^*\) mode increases, is highly relevant for points in our searches for which the \(WW^*\) mode is suppressed in comparison to the SM prediction. In addition, techniques have been proposed \[10\] for isolating signals for \(WW\) fusion to a light Higgs boson which decays to \(\tau\tau\) or \(WW^{(*)}\).

It turns out that adding in just the \(t\bar{t}h\) process renders the no-Higgs-discovery parameter choices described and plotted in \[3\], including the “black point” described in detail.
there, visible \cite{1}. In the present paper, we search for any remaining parameter choices for which no Higgs boson would produce a \( \geq 5\sigma \) signal. In this search, we perform a scan over nearly all of the parameter space of the model, the only parameter choices not included being those for which there is sensitivity to the highly model-dependent decays of Higgs bosons to other Higgs bosons and/or superparticles. The outcome is that, for an integrated luminosity of 300 fb\(^{-1}\) at the LHC, there are still regions in the parameter space with \(< 5\sigma \) expected statistical significance (computed as \( N_{SD} = S/\sqrt{B} \) for a given mode) for all Higgs detection modes so far studied in detail by ATLAS and CMS, \textit{i.e.} including the \( t\bar{t}h \to t\bar{t}b\bar{b} \) mode but not the \( WW\)-fusion modes. On the other hand, the expected statistical significance for at least one of these detection modes is always above 3.6\( \sigma \) at 300 fb\(^{-1}\), and the statistical significance obtained by combining (using the naive Gaussian procedure) all the non-\(WW\)-fusion modes is at least 4.8\( \sigma \). However, we find that all such cases are quite observable (at \( \geq 10.1\sigma \)) in one of the \(WW\)-fusion modes (using theoretically estimated statistical significances for these modes). For all points in the scan of parameter space, statistical significances obtained by combining all modes, including \(WW\)-fusion modes, are always \( \geq 10.7\sigma \). Thus, NMSSM Higgs discovery by just one detector with \( L = 300 \) fb\(^{-1}\) is essentially guaranteed for those portions of parameter space for which Higgs decays to other Higgs bosons or supersymmetric particles are kinematically forbidden. This represents substantial progress towards guaranteeing LHC discovery of at least one of the NMSSM Higgs bosons.

In order to clarify the nature of the most difficult points in those portions of parameter space considered, we present, in sect. 4, examples of particularly difficult benchmark points for the Higgs sector of the NMSSM. Apart from the “bare” parameters of the model, we give the masses and couplings of all Higgs scalars, their production rates and branching ratios to various channels (relative to the SM Higgs) and details of the statistical significances predicted for each Higgs boson in each channel. The latter will allow an assessment of exactly what level of improvement in statistical significance will be required in the various different detection modes in order to render marginal modes visible. Of course, our estimates of the expected statistical significances are often somewhat crude (e.g. their dependence on the accumulated integrated luminosity). We believe that our procedures always err in the conservative direction, leading to statistical significances that might be a bit small. Thus, the LHC procedures for isolating Higgs boson signals could provide even more robust signals for NMSSM Higgs boson detection than we estimate here.

The detection modes, which serve for the searches for standard model or MSSM Higgs bosons, include (using the notation \( h, a \) for CP-even, CP-odd Higgs bosons, respectively):
1) $gg \rightarrow h \rightarrow \gamma\gamma$;
2) associated $Wh$ or $t\bar{t}h$ production with $\gamma\gamma\ell^{\pm}$ in the final state;
3) associated $t\bar{t}h$ production with $h \rightarrow b\bar{b}$;
4) $gg \rightarrow h/a$ or associated $b\bar{b}h/a$ production with $h/a \rightarrow \tau\tau$;
5) $gg \rightarrow h \rightarrow ZZ^{(*)} \rightarrow 4$ leptons;
6) $gg \rightarrow h \rightarrow WW^{(*)} \rightarrow l^{+}l^{-}\nu\bar{\nu}$;
7) LEP2 $e^{+}e^{-} \rightarrow Zh$ and $e^{+}e^{-} \rightarrow ha$;
8) $WW \rightarrow h \rightarrow \tau\tau$;
9) $WW \rightarrow h \rightarrow WW^{(*)}$,

where 8) and 9) are those analyzed at the theoretical level in [10] and included in the NMSSM analysis for the first time in this paper. The above detection modes do not employ the possibly important decay channels i) $h \rightarrow hh$, ii) $h \rightarrow aa$, iii) $h \rightarrow h^{+}h^{-}$, iv) $h \rightarrow aZ$, v) $a \rightarrow ha$, vi) $a \rightarrow hZ$, vii) $h,a \rightarrow h^{\pm}W^{\mp}$, viii) $h,a \rightarrow t\bar{t}$ and ix) $t \rightarrow h^{+}b$. The decay modes i)-vii) give high multiplicity final states and deserve a dedicated study [12], while the existing analyses of the $t\bar{t}$ final state signatures are not very detailed. Further, when kinematically allowed, the $t \rightarrow h^{+}b$ signal would be easily observed according to existing analyzes. Thus, in this paper we restrict our scan over NMSSM parameter space to those parameters for which none of these decays are present. In addition, we take the constraints of LEP2 [via the mode 7)] into account, and only accept points for which $5\sigma$ discovery at LEP2 would not have been possible [13, 14].

The Higgs sector of the NMSSM consists of 3 scalars, denoted $h_1, h_2, h_3$ with $m_{h_1} < m_{h_2} < m_{h_3}$, 2 pseudo-scalars, denoted $a_1, a_2$ with $m_{a_1} < m_{a_2}$, and a charged Higgs pair, denoted $h^{\pm}$. Mixing of the neutral doublet fields with the gauge singlet fields in the scalar and in the pseudo-scalar sector can be strong. The scalar mixing can lead to a simultaneous suppression of the couplings of all the $h_i$ to gauge bosons, and hence to a suppression of many of the detection modes above. (Of course, the $a_i$ have no tree-level couplings to gauge boson pairs and the one-loop couplings are too small to yield useful event rates.) The couplings of the Higgs bosons to $t$- or $b$-quarks can be amplified, reduced or even change sign with respect to the standard model couplings. Hence negative interferences can occur among the (loop-) diagrams contributing to $gg \rightarrow h_i$ and $h_i \rightarrow \gamma\gamma$, leading again to suppressions of the above detection modes. A complete simultaneous annihilation of all detection modes is not possible, but simultaneous reduction of all detection modes is possible and it is for such parameter choices that NMSSM Higgs boson discovery is most difficult.

In the next section, we define the class of models we are going to consider, and the way we perform the scan over the corresponding parameter space. In section 3 we describe
our computations of the expected statistical significances of the detection modes 1) – 9) above. In section 4, we present six particularly difficult benchmark points (in table 1) and details regarding their statistical significances in channels 1)-9) in table 2, with a summary of overall statistical significances in table 3. Using these tables, we give a discussion of the properties of these points.

2 NMSSM Parameters and Scanning Procedure

In this paper, we consider the simplest version of the NMSSM [15, 16, 17], where the term $\mu \tilde{H}_1 \tilde{H}_2$ in the superpotential of the MSSM is replaced by (we use the notation $\hat{A}$ for the superfield and $A$ for its scalar component field)

$$\lambda \tilde{H}_1 \tilde{H}_2 \hat{S} + \frac{\kappa}{3} \hat{S}^3,$$

so that the superpotential is scale invariant. We make no assumption on “universal” soft terms. Hence, the five soft supersymmetry breaking terms

$$m_{H_1}^2 H_1^2 + m_{H_2}^2 H_2^2 + m_S^2 S^2 + \lambda A_{\lambda} H_1 H_2 S + \frac{\kappa}{3} A_{\kappa} S^3$$

are considered as independent. The masses and/or couplings of sparticles are assumed to be such that their contributions to the loop diagrams inducing Higgs production by gluon fusion and Higgs decay into $\gamma\gamma$ are negligible. In the stop sector, which appears in the radiative corrections to the Higgs potential, we chose the soft masses $m_Q = m_T \equiv M_{\text{susy}} = 1$ TeV, and varied the stop mixing parameter

$$X_t \equiv 2 \frac{A_t^2}{M_{\text{susy}}^2 + m_t^2} \left(1 - \frac{A_t^2}{12(M_{\text{susy}}^2 + m_t^2)}\right).$$

As in the MSSM, the value $X_t = \sqrt{6}$ – so called maximal mixing – maximizes the radiative corrections to the Higgs masses, and we found that it leads to the most challenging points in the parameter space of the NMSSM.

Assuming that the Higgs sector is CP conserving, the independent parameters of the model are thus: $\lambda, \kappa, m_{H_1}^2, m_{H_2}^2, m_S^2, A_{\lambda}$ and $A_{\kappa}$. For purposes of scanning and analysis, it is more convenient to eliminate $m_{H_1}^2, m_{H_2}^2$ and $m_S^2$ in favor of $M_Z$, $\tan \beta$ and $\mu_{\text{eff}} = \lambda \langle S \rangle$ through the three minimization equations of the Higgs potential (including the dominant 1- and 2-loop corrections [8]) and to scan over the six independent parameters

$$\lambda, \kappa, \tan \beta, \mu_{\text{eff}}, A_{\lambda}, A_{\kappa}. $$

We adopt the convention $\lambda, \kappa > 0$, in which $\tan \beta$ can have either sign. The absence of Landau singularities for $\lambda$ and $\kappa$ below the GUT scale ($\sim 2 \times 10^{16}$ GeV) imposes upper
bounds on these couplings at the weak scale, which depend on the value of $h_t$ and hence of $\tan \beta$ [15, 16]. Using $m_{\text{pole}}^{\text{top}} = 175$ GeV, one finds $\lambda_{\text{max}} \sim 0.69$ and $\kappa_{\text{max}} \sim 0.62$ for intermediate values of $\tan \beta$.

For each point in the parameter space, we diagonalize the scalar and pseudo-scalar mass matrices and compute the scalar, pseudo-scalar and charged Higgs masses and couplings taking into account the dominant 1- and 2-loop radiative corrections [5]. We then demand that the Higgs scalars satisfy the LEP2 constraints on the $e^+e^- \to Zh_i$ production mode (taken from [13], fig. 10), which gives a lower bound on $m_{h_i}$ as a function of the $ZZh_i$ reduced coupling. We also impose LEP2 constraints on $e^+e^- \to h_ia_j$ associated production (from [14], fig. 6), yielding a lower bound on $m_{h_i} + m_{a_j}$ as a function of the $Zh_i a_j$ reduced coupling.

In order to render the above-mentioned processes i) – ix) kinematically impossible, we require the following inequalities among the masses:

$$m_{h_3} < 2m_{h_1}, \ 2m_{a_1}, \ 2m_{h^\pm}, \ m_{a_1} + M_Z, \ m_{h^\pm} + M_W;$$
$$m_{a_2} < m_{h_1} + m_{a_1}, \ m_{h_1} + M_Z, \ m_{h^\pm} + M_W; \ m_{h^\pm} > 155\text{GeV}.$$ 

In addition we require $|\mu_{\text{eff}}| > 100$ GeV; otherwise a light chargino would have been detected at LEP2. (The precise lower bound on $|\mu_{\text{eff}}|$ depends somewhat on $\tan \beta$ and the precise experimental lower bound on the chargino mass; however, our subsequent results do not depend on the precise choice of the lower bound on $|\mu_{\text{eff}}|$.) We further note that for the most challenging parameter space points that we shall shortly discuss, $|\mu_{\text{eff}}| > 100$ GeV is already sufficient to guarantee that the NMSSM Higgs bosons cannot decay to chargino pairs so long as the SU(2) soft-SUSY-breaking parameter $M_2$ is also large. In fact, in order to avoid significant corrections to $\gamma\gamma h_i$ and $\gamma\gamma a_i$ couplings coming from chargino loops it is easiest to take $M_2 \gg \mu_{\text{eff}}$ (or vice versa). This is because the $h_i\tilde{\chi}_i^+\tilde{\chi}_i^-$ coupling is suppressed if the $\tilde{\chi}_i^+$ is either pure higgsino or pure gaugino. Since the parts of parameter space that are challenging with regard to Higgs detection typically have $|\mu| \sim (100 - 200)$ GeV, the validity of our assumptions requires that $M_2$ be large and that the chargino be essentially pure higgsino.

Using a very rough sampling, we determined, as expected from previous work [3], that it is only for moderate values of $\tan \beta$ that $< 5\sigma$ signals might possibly occur. From this sampling, we determined the most difficult parameter space regions and further refined our scan to the following:

- $4.5 < |\tan \beta| < 8$ (both signs) in steps of 0.25;
- $0.001 < \lambda < \min[0.21, \lambda_{\text{max}}]$, using 20 points;
• $0.001 < \kappa < \min[0.24, \kappa_{\text{max}}]$, using 20 points;
• $100 \text{ GeV} < |\mu_{\text{eff}}| < 300 \text{ GeV}$ (both signs), in steps of 5 GeV;
• $0 < |A_{\lambda}| < 160 \text{ GeV}$, with $A_{\lambda}$ opposite in sign to $\mu_{\text{eff}}$, using steps of 5 GeV;
• $25 \text{ GeV} < |A_{\kappa}| < 170 \text{ GeV}$, with $A_{\kappa}$ opposite in sign to $\mu_{\text{eff}}$, using steps of 5 GeV.

For those points sampled in this final scan which satisfy all the constraints detailed earlier, we compute the expected statistical significances for the processes 1) to 9) listed in section 1, as described in the next section. As a rough guide, from the $\sim 10^9$ points detailed in the above list, we find about 250,000 that pass all constraints and have $N_{SD} < 5$ (for $L = 300 \text{ fb}^{-1}$) in each of the individual discovery modes 1) – 7). We shall tabulate a number of representative points taken from this final set in section 4.

3 Expected Statistical Significances

From the known couplings of the NMSSM Higgs scalars to gauge bosons and fermions it is straightforward to compute their production rates in gluon-gluon fusion and various associated production processes, as well as their partial widths into $\gamma\gamma$, gauge bosons and fermions, either relative to a standard model Higgs scalar or relative to the MSSM $H$ and/or $A$. This allows us to apply “NMSSM corrections” to the processes 1) – 9) above.

These NMSSM corrections are computed in terms of the following ratios. For the scalar Higgs bosons, $c_V$ is the ratio of the coupling of the $h_i$ to vector bosons as compared to that of a SM Higgs boson (the coupling ratios for $h_iZZ$ and $h_iWW$ are the same), and $c_t$, $c_b$ are the corresponding ratios of the couplings to top and bottom quarks (one has $c_c = c_b$). Note that we always have $|c_V| < 1$, but $c_t$ and $c_b$ can be larger, smaller or even differ in sign with respect to the standard model. For the CP-odd Higgs bosons, $c_V$ is not relevant since there is no tree-level coupling of the $a_i$ to the $VV$ states; $c_t$ and $c_b$ are defined as the ratio of the $i\gamma_5$ couplings for $t\bar{t}$ and $b\bar{b}$, respectively, relative to SM-like strength.

We emphasize that our procedure implicitly includes QCD corrections to the Higgs production processes at precisely the same level as the experimental collaborations. First, the ATLAS and CMS collaborations employed Monte Carlo programs such as ISAJET and PYTHIA in obtaining results for the (MS)SM. These programs include many QCD corrections to Higgs production in a leading-log sense. This is the best that can currently be done to implement QCD corrections in the context of experimental cuts and neural-net analyses. Clearly the more exact NNLO results for many of the relevant processes will slowly be implemented in the Monte Carlo programs and increased
precision for Higgs discovery expectations will result. Since our goal is to obtain NMSSM results that are completely analogous to the currently available (MS)SM results, we have proceeded by simply rescaling the available (MS)SM experimental analyses. In doing the rescaling of the Higgs branching ratios we have included all relevant higher-order QCD corrections [20] using an adapted version of the FORTRAN code HDECAY [21]. We now give additional details on our rescaling procedures.

The expected statistical significances for the processes 1) and 6) are computed beginning with results for the SM Higgs boson taken from ref [23], fig.1 (“Expected Observability of Standard Model Higgs in CMS with 100 fb$^{-1}$”). The application of the NMSSM corrections using $c_V$, $c_t$ and $c_b$ [which determine $\Gamma(gg \rightarrow h_i)$, $BR(h_i \rightarrow \gamma\gamma)$ and $BR(h_i \rightarrow WW^*)$] is straightforward in these two cases.

The expected statistical significances for process 2) are taken from the same figure. In ref. [24] one finds that $Wh_i$ and $t\bar{t}h_i$ production contribute with roughly equal weight to the SM signal. This allows us to decompose the expected significance into the corresponding production processes, apply the NMSSM corrections, and then recombine the production processes.

The expected Standard Model Higgs statistical significances for process 3) are taken from table 19-8 in ref. [1], with the extension to Higgs masses above 120 GeV as provided in [9], using a numerical interpolation for Higgs masses below 140 GeV. For the standard model process 5) we again use ref. [1], tables 19-18 and 19-21. In both cases, the application of the NMSSM corrections is straightforward.

The estimation of the statistical significances for the process 4) in the NMSSM requires the most discussion. Figure 19-62 of ref. [1] and fig. 8 of ref. [24] give the 5$\sigma$ contours in the $\tan \beta - m_A$ plane of the MSSM. The critical issue is how much of these 5$\sigma$ signals derive from $gg \rightarrow H + gg \rightarrow A$ production and how much from associated $b\bar{b}H + b\bar{b}A$ production, and how each of the $gg$ fusion and $b\bar{b}$ associated production processes are divided up between $H$ and $A$. For the former, we turn to table 19-35 of ref. [1]. There, we see that it is for cuts designed to single out the associated production processes that large statistical significance can be achieved and that such cuts provide 90% of the net statistical significance of $N_{SD} = 8.9$ (3.9 for $gg$ fusion cuts combined in quadrature with 8.0 for $b\bar{b}H + b\bar{b}A$ associated production cuts) for $m_A = 150$ GeV and $L = 30$ fb$^{-1}$. (For the

\footnote{In our computations however, we neglect the contribution to the $h_i\gamma\gamma$ coupling coming from the charged Higgs loop. Despite the relatively small masses of the $h^+$ for our most problematical points, the charged Higgs loop decouples [22], especially for the small values of $\lambda$ and $\lambda A_3$ characteristic of difficult points for which the actual $h^+h^-h_i$ coupling is only of order a few times $gm_W/(4\sqrt{2})$ [15]. Its contribution would typically only be of order a few percent even though our difficult points have smaller $\gamma\gamma h_i$ coupling than a SM-like Higgs boson by virtue of suppressed $h_iWW$ coupling and/or cancellation between the top and $W$ loop contributions.}
associated production cuts, the table shows that the contribution of the \( gg \) fusion processes to the signal is very small.) The percentage of \( N_{SD} \) deriving from \( gg \)-fusion cuts is even smaller at high \( m_A \). Since we are mainly interested in \( m_H, m_A \in [100 \text{ GeV}, 200 \text{ GeV}] \), we will assume that 90% of the statistical significance along the contours of fig. 19-62 comes from the associated production cut analysis; this will give us a slightly conservative estimate of the associated production \( N_{SD} \) values at still higher \( m_A \). With this choice, the 5\( \sigma \) contour at \( L = 100 \text{ fb}^{-1} \) from fig. 19-62 of ref. \[ \square \] corresponds to a 4.5\( \sigma \) contour for associated \( bbH + bbA \) production alone. Since the values of \( \tan \beta \) along this contour are large, we can separate the \( H \) and \( A \) signals from one another by using the following properties of the MSSM within which fig. 19-62 of ref. \[ \square \] was generated: (a) \( BR(H \rightarrow \tau\tau) \sim BR(A \rightarrow \tau\tau) \sim 0.09 \); (b) the \( bbA \) and \( bbH \) couplings are very nearly equal and scale as \( \tan \beta \); and (c) \( m_A \sim m_H \) within the \( \tau\tau \) mass resolution. As a result, the net signal rate along this contour is approximately twice that for \( bbA \) or \( bbH \) alone. Thus, \( N_{SD} = 2.25 \) would be achieved for \( bbA \) or \( bbH \) along this contour were \( m_A \) and \( m_H \) widely separated.

We can then compute the statistical significance for the \( bbh_i \) and \( bba_i \) signals with \( h_i, a_i \rightarrow \tau\tau \) decay using the following procedure. First, the NMSSM \( bbh_i \) and \( bba_i \) production rates are related to the MSSM \( bbH \) and \( bba \) rates by the factors \( [c_b(h_i)]^2/\tan^2 \beta \) and \( [c_b(a_i)]^2/\tan^2 \beta \), respectively. Next, we account for the fact that the \( \tau\tau \) branching ratios of the NMSSM scalars and pseudo-scalars differ somewhat from the value of 0.09 appropriate for the MSSM \( H \) and \( A \). In particular, \( BR(h_3 \rightarrow \tau\tau) \) is significantly reduced when the \( h_3 \) has large enough mass and large enough \( c_V \) that it acquires a modest \( WW^* \) branching ratio. Typical reductions will be tabulated in table 2. Thus, defining the value of \( \tan \beta \) as a function of \( m_A \) shown by the 100 fb\(^{-1} \) curve of fig. 19-62 in ref. \[ \square \] as \( \tan \beta_{2.25}(m_A) \), we compute \( N_{SD}(h_i) \) for \( L = 100 \text{ fb}^{-1} \) as

\[
N_{SD}(h_i) = 2.25 \left[ \frac{c_b(h_i)}{\tan \beta_{2.25}(m_{h_i})} \right]^2 BR_{\tau\tau}(h_i),
\]

where \( BR_{\tau\tau} \equiv BR(h_i \rightarrow \tau\tau)/BR(H \rightarrow \tau\tau) = BR(h_i \rightarrow \tau\tau)/0.09 \). An exactly parallel procedure is employed for \( N_{SD}(a_i) \).

The above procedure is conservative in that it assumes no contribution to the \( \tau\tau \) channel \( N_{SD} \) from the \( gg \) fusion processes. However, as we shall describe in the next section, for the most difficult points in parameter space the \( gg \)-fusion rates are very substantially suppressed relative to MSSM values. For these points, essentially 99% of the \( \tau\tau \) channel \( N_{SD} \) would derive from \( bb+\text{Higgs} \) associated production.

In recombining the scalar and pseudo-scalar signals, we must account for the fact that they can have fairly different masses in the NMSSM. In this paper, we have chosen to
recombine the scalar and pseudo-scalar signals at different masses following the procedure of ref. [23], section 5.4, with $\sigma_m \sim 30$ GeV as estimated from fig. 19-61 in [1] at high luminosity and extrapolated to $m_A \lesssim 150$ GeV. This procedure leads to somewhat approximate estimates of the NMSSM statistical significances for this detection mode.

Results for the statistical significances of the $h_i$ signals in modes 8) and 9) were similarly obtained by rescaling the theoretical results of [14] (summarized most conveniently in the last of the listed papers) using the values of $[c_V(h_i)]^2, BR_{\tau\tau}$ and $BR_{WW^*}$.

Using the above procedures, for each point in the parameter space of the NMSSM we obtain the statistical significances predicted for an integrated luminosity of 100 fb$^{-1}$ for each of the detection modes 1) – 9). In order to obtain the statistical significances for the various detection modes at 300 fb$^{-1}$, we multiply the 100 fb$^{-1}$ statistical significances by $\sqrt{3}$ in the cases 1), 2), 3), 5) and 6), but only by a factor of 1.3 in the cases 4), 8) and 9). That such a factor is appropriate for mode 4), see, for example, fig. 19-62 in [1]. Use of this same factor for modes 8) and 9) is simply a conservative guess.

4 Difficult Points

As stated in the introduction we still find “black spots” in the parameter space of the NMSSM, where the expected statistical significances for all Higgs detection modes 1) – 7) are below 5σ at 300 fb$^{-1}$. The reasons for this phenomenon have been described above; see also the corresponding discussion in [3]. However, after including the modes 8) and 9), the points that provide the worst 1) – 6) statistical significances typically yield robust signals in one or the other of the $WW$-fusion modes 8) and 9).

In order to render the corresponding suppression mechanisms of the detection modes reproducible, we present the detailed properties of several difficult points in the parameter space in table 1. The notation is as follows: The bare parameters are as in eq. (2.5), with $m_{H_1}^2, m_{H_2}^2$ and $m_S^2$ fixed implicitly by the minimization conditions. (As noted earlier, with the convention $\lambda, \kappa > 0$ in the NMSSM, the sign of $\tan \beta$ can no longer be defined to be positive.) For the reasons discussed below eq. (2.3) we chose in the stop sector $m_Q = m_T \equiv M_{\text{susy}} = 1$ TeV and $X_t = \sqrt{6}$ for all of the points (1 – 6). We have also fixed $m_{top}^{pole} = 175$ GeV. For both scalar and pseudoscalar Higgs bosons, “gg Production Rate” denotes the ratio of the gluon-gluon production rate with respect to that obtained if $c_t = c_b = 1$, keeping the Higgs mass fixed. For scalar $h_i$, this is the same as the ratio of the $gg$ production rate relative to that predicted for a SM Higgs boson of the same mass. For the scalar $h_i$, $BR_{\gamma\gamma}$ denotes the ratio of the $\gamma\gamma$ branching ratio with respect to that of a SM Higgs boson with the same mass. (A verification of the reduced gluon-gluon
production rates or $\gamma\gamma$ branching ratios would sometimes require the knowledge of the couplings to higher precision than given, for convenience, in table 1.) Also given for the scalar $h_i$ are the ratios $BRb\bar{b}$ and $BRWW^*$ of the $b\bar{b}$ and $WW^*$ branching ratios relative to the SM prediction (as noted above, one has $BR\tau\tau = BRb\bar{b}$).

In table 2, we tabulate the statistical significances for the $h_i$ in all the channels 1) – 9); production of the CP-odd $a_i$ turns out to be relevant only when they add to the $h_i$ signals in process 4). Also note that, all these problematical points are such that $m_{h_1} + m_{a_1} > 206$ GeV, so that $e^+e^- \to h_1 + a_1$ followed by $h_1, a_1 \to b\bar{b}$ would have been kinematically forbidden at the highest LEP2 energy. Hence, for LEP2 mode 7) we only give the statistical significance for $e^+e^- \to Zh_i$. Also tabulated in table 2 are four statistical significances obtained by combining various channels. This combination is done in the Gaussian approximation:

$$N_{SD}^{\text{combined}} = \left[ \sum_i \left( N_{SD}^i \right)^2 \right]^{1/2},$$

where $\sum_i$ runs over the channels $i$ being combined. We give results for the following combinations:

a) $N_{SD}$ obtained by combining LHC channels 1) – 6);

b) $N_{SD}$ obtained by combining LHC channels 1) – 6) and LEP2;

c) $N_{SD}$ obtained by combining LHC channels 1) – 6) with the $WW$-fusion channels 8) and 9);

d) $N_{SD}$ obtained by combining all LHC channels and LEP2, i.e. by combining all channels 1) – 9).

In those cases where there is no LEP2 signal, a)=b) and c)=d). In addition, in our point selection we have required a mass difference of at least 10 GeV between scalar Higgses, so that they yield well separated signals and no statistical significance combination of two different scalar Higgses is needed. All parameter choices for which Higgs boson masses differ by less than 10 GeV yield stronger signals than the cases retained. (The increased net signal strength of overlapping Higgs signals in those channels with limited mass resolution arises as a result of $N_{SD}^{\text{eff}}(1+2) \sim (S_1 + S_2)/\sqrt{B} > \sqrt{S_1^2 + S_2^2}/\sqrt{B}$.)

As summarized in table 3, all of the tabulated “benchmark points” have statistical significances below $5\sigma$ for all of the detection modes 1) – 6) at 300 fb$^{-1}$ and 7) at LEP2. In more detail, as tabulated in table 2 and summarized in table 3, the best signals in the modes 1) – 6) for the points #1 – #6 at the LHC are:

- point #1, $N_{SD} = 4.37$ for mode 2) and $h_1$;
• point #2, $N_{SD} = 3.95$ for mode 3) and $h_2$;
• point #3, $N_{SD} = 3.62$ for mode 4) and $h_3$;
• point #4, $N_{SD} = 4.46$ for mode 5) and $h_3$;
• point #5, $N_{SD} = 4.83$ for mode 3) and $h_1$;
• point #6, $N_{SD} = 4.86$ for mode 4) and $h_3$;

Further, for point #3, the combined statistical significance of modes 1) – 6) (also tabulated in table 3) would still be below 5 for any one $h_i$, although $\sqrt{2N_{SD}^{1-6}} > 5$ (as is likely to be relevant by combining ATLAS and CMS data once each detector has accumulated $L = 300 \text{ fb}^{-1}$) for at least one of the $h_i$. However, for all these “difficult” points the $WW$-fusion modes 8) and/or 9) provide (according to theoretical estimates) a decent (sometimes very strong) signal.

The points #1 – #4 differ as to which of the modes 1) – 6) and which $h_i$ yields the largest statistical significance should the $WW$-fusion mode 8) not provide as strong a signal as suggested by the theoretical estimates. To render these points observable without the $WW$-fusion mode 8) would require improvements of all detection modes 2) – 5).

As in [3], we find that difficult points in the parameter space generally have $|\tan \beta| \sim 5$. This is the region of $\tan \beta$ for which the $b\bar{t}h, b\bar{t}a$ signals are still not very much enhanced but yet the $gg \rightarrow h, a$ and $t\bar{t}h, t\bar{t}a$ signals have been suppressed somewhat. In a few cases, however, difficulties also arise for $|\tan \beta|$ as large as 8, as shown in the case of point #5. Also as in [3], the most difficult points are those in which the masses of the $h_i$ and $a_i$ are relatively close in magnitude, typically clustered in a $\sim 60 \text{ GeV}$ interval above $\sim 105 \text{ GeV}$. Such clustering maximizes the mixing among the different Higgs bosons and thereby minimizes the significance of the discovery channels for any one Higgs boson. In particular, it is for strong mixing among the $h_i$ that the statistical significance for discovery modes based on a large $VV$ coupling for any one $h_i$ are most easily suppressed.

Finally, for point #6, we have minimized the statistical significances for the $WW$-fusion modes over the parameter space, while keeping the statistical significances of modes 1) – 6) below 5. One can see that it still gives a strong $10.1\sigma$ signal in mode 8). [Smaller $N_{SD}$ for mode 8) would have been possible if we had allowed stronger signals in modes 1) – 6), in particular had we allowed smaller mass separation, $< 10 \text{ GeV}$, between the two lightest Higgs bosons.] In addition, for point #6 $m_{h_1} = 112 \text{ GeV}$ and the $ZZ$ coupling of $h_1$ is sufficiently large that it would have yielded a $4.8\sigma$ signal at LEP2. Had we taken a top quark mass slightly larger, $m_{top}^{pole} = 178 \text{ GeV}$, we would have found a very similar point with a $h_1$ mass of $\sim 115 \text{ GeV}$, which could have been responsible for the excess observed at LEP2 [20].
5 Discussion and Conclusions

In this paper, we have addressed the question of whether or not it would be possible to fail to discover any of the Higgs bosons of the NMSSM using combined LEP2 and LHC data, possibly resulting in the erroneous conclusion that Higgs bosons with masses below 200 GeV have been excluded. We have demonstrated that, assuming that the decay channels i) – ix) are either kinematically disallowed or render a Higgs boson observable, this is unlikely (at the > 5σ level) to happen. Certainly, there are points in NMSSM parameter space for which the statistical significances for the individual detection modes 1) – 6) (i.e. those analyzed in detail by ATLAS and CMS) are all well below 5σ for integrated luminosity of 300 fb$^{-1}$. However, by combining several of the modes 1) – 6) and 300 fb$^{-1}$ data from both ATLAS and CMS, a > 5σ signal can be achieved based just on modes 1) – 6). Further, we have found that throughout all of the NMSSM parameter space (scanned subject to the earlier listed restrictions) for which such weak signals in modes 1) – 6) are predicted, the theoretical estimates for the WW-fusion modes indicate that an easily detected $WW \rightarrow h \rightarrow \tau \tau$ signal should be present. Thus, our conclusion is that for all of the parameter space of the NMSSM compatible with reasonable boundary conditions for the parameters at the GUT scale (with, of course, non-universal soft terms in general) and such that Higgs pair and SUSY pair decays of the Higgs bosons are kinematically forbidden, at least one of the NMSSM Higgs bosons will be detected at the LHC. This is a big improvement over the results from the earlier Snowmass 1996 study which was somewhat negative without the inclusion of the $t\bar{t}h \rightarrow t\bar{t}b\bar{b}$ mode 3), and the WW-fusion modes 8) and 9).

It is amusing to note that all of our benchmark points for which Higgs discovery is most difficult at the LHC include a Higgs scalar with mass close to 115 GeV (with, however, reduced couplings to the $Z$ boson), which could be responsible for the excess observed at LEP2 [29].

Another important point that appears from our analysis is the fact that the full $L = 300$ fb$^{-1}$ of integrated luminosity (per detector) is needed in order to have robust NMSSM Higgs discovery in the portion of parameter space considered here. Of course, as in the MSSM, it is very possible that only one of the CP-even NMSSM Higgs bosons might be detected at the LHC but that, as studied by Kamoshita et al. in [17], the observation of all the CP-even Higgs bosons of the NMSSM would be possible at the LC by virtue of all having some non-negligible level of $ZZ$ coupling and not having very high masses. Even at the LC, the CP-odd Higgs bosons might escape discovery, although this would not be the case for the parameter choices that we have found which make LHC discovery of even one NMSSM Higgs bosons most challenging. This is because, for such parameters, the
$a_i$ are relatively light and could be readily seen at the LC in the processes $e^+e^- \rightarrow h_ia_j$, $e^+e^- \rightarrow \nu\bar{\nu}a_ia_i$ and $e^+e^- \rightarrow Z^* \rightarrow Za_ia_i$, assuming an integrated LC luminosity of 1000 fb$^{-1}$ and energy $\sqrt{s} \geq 500$ GeV [27].

This study makes clear the importance of continuing to expand the sensitivity of existing modes and continuing to develop new modes for Higgs detection at the LHC in order not to have to wait for construction of a linear $e^+e^-$ collider for detection of at least one of the SUSY Higgs bosons. In particular, study of modes i) – ix) and SUSY pair channels should all be pushed. The problematical points that we have emphasized here are unlikely to be substantially influenced by $t\bar{t}$ or SUSY decays since all the Higgs masses are below $\sim 200$ GeV so that $t\bar{t}$ decays will be kinematically highly suppressed (one of the top quarks would have to be virtual) and SUSY pair decays are quite unlikely to be significant given LEP2 limits on the masses of SUSY particles. However, by allowing Higgs (in particular, pseudoscalar) masses such that one or more of the channels i)-vii) are kinematically allowed we have found points for which discovery in modes 1)-9) will not be possible [12]. Thus, a full “no-lose” theorem for NMSSM Higgs boson discovery at the LHC will require exploring additional discovery modes sensitive to those portions of parameter space for which Higgs decays to other Higgs bosons are important, and might necessitate combining results from both the ATLAS and CMS detectors and/or accumulating more integrated luminosity.

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Table Captions

**Table 1:** We tabulate the input bare model parameters, the corresponding Higgs masses, and the corresponding Higgs couplings, relative to SM Higgs boson coupling strength, for 6 benchmark points. Also given for the CP-even $h_i$ are ratios of the $gg$ production rate and various branching fractions relative to the values found for a SM Higgs of the same mass. For the CP-odd $a_i$, “gg Production Rate” refers to the value relative to what would be found if both the $b\bar{b}$ and the $t\bar{t} \gamma_5$ couplings had SM-like strength.

**Table 2:** Scalar Higgs statistical significances, $N_{SD} = S/\sqrt{B}$, in various channels for the 6 benchmark points. For each individual Higgs, we give (in order): $N_{SD}$ for the channels 1) – 9) described in the text; Gaussian combined $N_{SD}$ for non-$WW$-fusion LHC channels; combined $N_{SD}$ for non-$WW$-fusion LHC channels plus LEP2; combined $N_{SD}$ for all LHC channels, including the fusion channels $WW \rightarrow h \rightarrow \tau\tau$ and $WW \rightarrow h \rightarrow WW^{(*)}$ channels; and combined $N_{SD}$ for all LHC channels plus LEP2.

**Table 3:** Summary for all Higgs bosons. The entries are: maximum non-$WW$ fusion LHC $N_{SD}$; maximum LHC $WW$ fusion $N_{SD}$; best combined $N_{SD}$ after summing over all non-$WW$-fusion LHC channels; and best combined $N_{SD}$ after summing over all LHC channels. The Higgs boson for which these best values are achieved is indicated in the parenthesis. One should refer to the preceding table in order to find which channel(s) give the best values.
### Table 1

| Bare Parameters | 1    | 2    | 3    | 4    | 5    | 6    |
|-----------------|------|------|------|------|------|------|
| $\lambda$       | 0.0340 | 0.0450 | 0.0230 | 0.0230 | 0.1330 | 0.0230 |
| $\kappa$        | 0.0198 | 0.0248 | 0.0129 | 0.0069 | 0.1459 | 0.0114 |
| $\tan\beta$     | 6.00  | 5.25  | -5.5  | 5.75  | -8    | -6   |
| $\mu_{#text{eff}}$ (GeV) | 140   | -110  | 115   | -235  | 100   | 150  |
| $A_{\lambda}$    | -35   | 25    | -95   | 40    | -135  | -100 |
| $A_{\kappa}$     | -150  | 70    | -90   | 80    | -75   | -110 |

| Scalar Masses and Couplings | 1    | 2    | 3    | 4    | 5    | 6    |
|-----------------------------|------|------|------|------|------|------|
| $m_{h_1}$ (GeV)             | 115  | 100  | 103  | 113  | 114  | 112  |
| $c_{V}$                     | -0.66 | 0.32  | -0.34 | 0.67  | -0.87 | -0.71 |
| $c_{t}$                     | -0.65 | 0.30  | -0.31 | 0.65  | -0.81 | -0.66 |
| $c_{b}$                     | -1.07 | 0.66  | -1.27 | 1.16  | -4.50 | -2.40 |
| gg Production Rate          | 0.39  | 0.08  | 0.08  | 0.39  | 0.56  | 0.36  |
| $BR_{\gamma\gamma}$        | 0.43  | 0.26  | 0.09  | 0.38  | 0.05  | 0.11  |
| $BR_{bb} = BR_{t\bar{t}}$   | 1.12  | 1.08  | 1.10  | 1.12  | 1.18  | 1.15  |
| $BR_{WW} (\ast)$            | 0.42  | 0.25  | 0.08  | 0.37  | 0.04  | 0.10  |

| $m_{h_2}$ (GeV)             | 125  | 114  | 114  | 126  | 144  | 122  |
| $c_{V}$                     | -0.74 | -0.83 | 0.79  | -0.73 | 0.46  | 0.59  |
| $c_{t}$                     | -0.72 | -0.74 | 0.70  | -0.71 | 0.57  | 0.54  |
| $c_{b}$                     | -1.49 | -3.28 | 3.46  | -1.47 | -6.66 | 2.24  |
| gg Production Rate          | 0.46  | 0.44  | 0.40  | 0.45  | 1.18  | 0.23  |
| $BR_{\gamma\gamma}$        | 0.33  | 0.08  | 0.07  | 0.34  | 0.01  | 0.10  |
| $BR_{bb} = BR_{t\bar{t}}$   | 1.30  | 1.18  | 1.18  | 1.32  | 3.06  | 1.31  |
| $BR_{WW} (\ast)$            | 0.32  | 0.08  | 0.06  | 0.33  | 0.01  | 0.09  |

| $m_{h_3}$ (GeV)             | 205  | 153  | 148  | 201  | 202  | 155  |
| $c_{V}$                     | -0.14 | -0.46 | -0.51 | -0.15 | 0.18  | -0.39 |
| $c_{t}$                     | -0.30 | -0.63 | -0.67 | -0.32 | 0.17  | -0.55 |
| $c_{b}$                     | 5.80  | 4.17  | 4.20  | 5.53  | 0.68  | 5.12  |
| gg Production Rate          | 0.31  | 0.84  | 0.95  | 0.33  | 0.02  | 0.80  |
| $BR_{\gamma\gamma}$        | 0.13  | 0.05  | 0.05  | 0.15  | 0.98  | 0.03  |
| $BR_{bb} = BR_{t\bar{t}}$   | 308.66 | 5.83  | 3.92  | 274.41 | 13.97 | 8.12  |
| $BR_{WW} (\ast)$            | 0.18  | 0.07  | 0.06  | 0.21  | 0.96  | 0.05  |

| Pseudo-Scalar Masses and Couplings | 1    | 2    | 3    | 4    | 5    | 6    |
|------------------------------------|------|------|------|------|------|------|
| $m_{a_1}$ (GeV)                    | 191  | 112  | 130  | 130  | 113  | 145  |
| $c_{t}$                            | 0.03  | -0.03 | -0.10 | -0.01 | -0.10 | -0.16 |
| $c_{b}$                            | 1.16  | -0.83 | -2.95 | -0.19 | -6.55 | -5.77 |
| gg Production Rate                 | 0.00  | 0.00  | 0.03  | 0.00  | 0.31  | 0.08  |
| $m_{a_2}$ (GeV)                    | 206  | 141  | 137  | 198  | 174  | 158  |
| $c_{t}$                            | 0.16  | 0.19  | -0.15 | 0.17  | -0.07 | -0.05 |
| $c_{b}$                            | 5.89  | 5.18  | -4.64 | 5.75  | -4.59 | -1.65 |
| gg Production Rate                 | 0.02  | 0.07  | 0.06  | 0.02  | 0.03  | 0.00  |

| Charged Higgs Mass | 1    | 2    | 3    | 4    | 5    | 6    |
|--------------------|------|------|------|------|------|------|
| $m_{c}$ (GeV)      | 221  | 162  | 157  | 213  | 157  | 167  |
| Point          | 1    | 2    | 3    | 4    | 5    | 6    |
|---------------|------|------|------|------|------|------|
| \( N_{SD}(1) \) | 3.74 | 0.35 | 0.13 | 3.18 | 0.62 | 0.83 |
| \( N_{SD}(2) \) | 4.37 | 0.59 | 0.22 | 3.92 | 0.85 | 1.22 |
| \( N_{SD}(3) \) | 2.79 | 0.85 | 0.85 | 3.03 | 4.83 | 3.30 |
| \( N_{SD}(4) \) | 0.08 | 0.07 | 0.76 | 0.09 | 4.52 | 0.40 |
| \( N_{SD}(5) \) | 0.83 | 0.00 | 0.00 | 0.64 | 0.12 | 0.16 |
| \( N_{SD}(6) \) | 1.10 | 0.09 | 0.03 | 0.90 | 0.16 | 0.22 |
| \( N_{SD}(7) \) | 0.00 | 3.37 | 3.40 | 3.29 | 0.00 | 4.79 |
| \( N_{SD}(8) \) | 9.29 | 1.22 | 1.59 | 8.93 | 16.78 | 10.08 |
| \( N_{SD}(9) \) | 2.39 | 0.00 | 0.00 | 1.74 | 0.41 | 0.49 |

\[
\sqrt{\sum_{i=1}^{6}[N_{SD}(i)]^2} = 6.54, 1.09, 1.17, 5.99, 6.69, 3.65
\]

\[
\sqrt{\sum_{i=1}^{7}[N_{SD}(i)]^2} = 6.54, 3.55, 3.59, 6.84, 6.69, 6.02
\]

\[
\sqrt{\sum_{i=1-6,8,9}[N_{SD}(i)]^2} = 11.61, 1.64, 1.97, 10.89, 18.07, 10.73
\]

\[
\sqrt{\sum_{i=1}^{9}[N_{SD}(i)]^2} = 11.61, 3.75, 3.93, 11.38, 18.07, 11.75
\]

| Point          | 1    | 2    | 3    | 4    | 5    | 6    |
|---------------|------|------|------|------|------|------|
| \( N_{SD}(1) \) | 3.69 | 0.83 | 0.61 | 3.62 | 0.22 | 0.55 |
| \( N_{SD}(2) \) | 4.01 | 1.25 | 0.92 | 3.93 | 0.05 | 0.74 |
| \( N_{SD}(3) \) | 2.49 | 3.95 | 3.58 | 2.30 | 0.99 | 1.77 |
| \( N_{SD}(4) \) | 0.16 | 2.76 | 2.93 | 0.16 | 3.62 | 2.99 |
| \( N_{SD}(5) \) | 1.84 | 0.16 | 0.11 | 1.94 | 0.56 | 0.20 |
| \( N_{SD}(6) \) | 1.44 | 0.22 | 0.16 | 1.46 | 0.38 | 0.18 |
| \( N_{SD}(7) \) | 0.00 | 3.31 | 3.31 | 0.00 | 0.00 | 0.00 |
| \( N_{SD}(8) \) | 15.39 | 15.17 | 13.46 | 15.05 | 7.41 | 9.89 |
| \( N_{SD}(9) \) | 5.79 | 0.63 | 0.44 | 6.05 | 0.19 | 0.82 |

\[
\sqrt{\sum_{i=1}^{6}[N_{SD}(i)]^2} = 5.32, 4.80, 4.64, 5.83, 4.76, 5.37
\]

\[
\sqrt{\sum_{i=1}^{7}[N_{SD}(i)]^2} = 5.32, 4.80, 4.64, 5.83, 4.76, 5.37
\]

\[
\sqrt{\sum_{i=1-6,8,9}[N_{SD}(i)]^2} = 17.65, 16.00, 14.28, 17.40, 8.34, 10.56
\]

\[
\sqrt{\sum_{i=1}^{9}[N_{SD}(i)]^2} = 17.65, 16.00, 14.66, 17.40, 8.34, 10.56
\]
Table 3

| Point Number | 1  | 2  | 3  | 4  | 5  | 6  |
|--------------|----|----|----|----|----|----|
| Best non-WW fusion $N_{SD}$ | 4.37 ($h_1$) | 3.95 ($h_2$) | 3.62 ($h_3$) | 4.46 ($h_3$) | 4.83 ($h_1$) | 4.86 ($h_3$) |
| Best WW fusion $N_{SD}$ | 15.39 ($h_2$) | 15.17 ($h_2$) | 13.46 ($h_2$) | 15.05 ($h_2$) | 16.78 ($h_1$) | 10.08 ($h_1$) |
| Best combined $N_{SD}$ w.o. WW-fusion modes | 6.54 ($h_1$) | 5.05 ($h_2$) | 4.76 ($h_2$) | 6.31 ($h_2$) | 6.69 ($h_1$) | 5.37 ($h_3$) |
| Best combined $N_{SD}$ with WW-fusion modes | 17.65 ($h_2$) | 16.00 ($h_2$) | 14.28 ($h_2$) | 17.40 ($h_2$) | 18.07 ($h_1$) | 10.73 ($h_1$) |

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