Excessive Higgs pair production from sparticles in the NMSSM

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Higgs production from sparticle decay chains like

$$\chi_2^0 \to \chi_1^0 + H$$

is a well-known possibility, where

χ_1^0 is the "LSP" (lightest Supersymmetric particle, neutralino_1),

χ_2^0 the "NLSP" (next-to-lightest Supersymmetric particle, neutralino_2).

Usually χ_1^0 leads to missing transverse energy

In the NMSSM (with additional singlet-like Higgs states and a singlet-like neutralinos), the neutralino$_1$ can be mostly "singlet-like" and

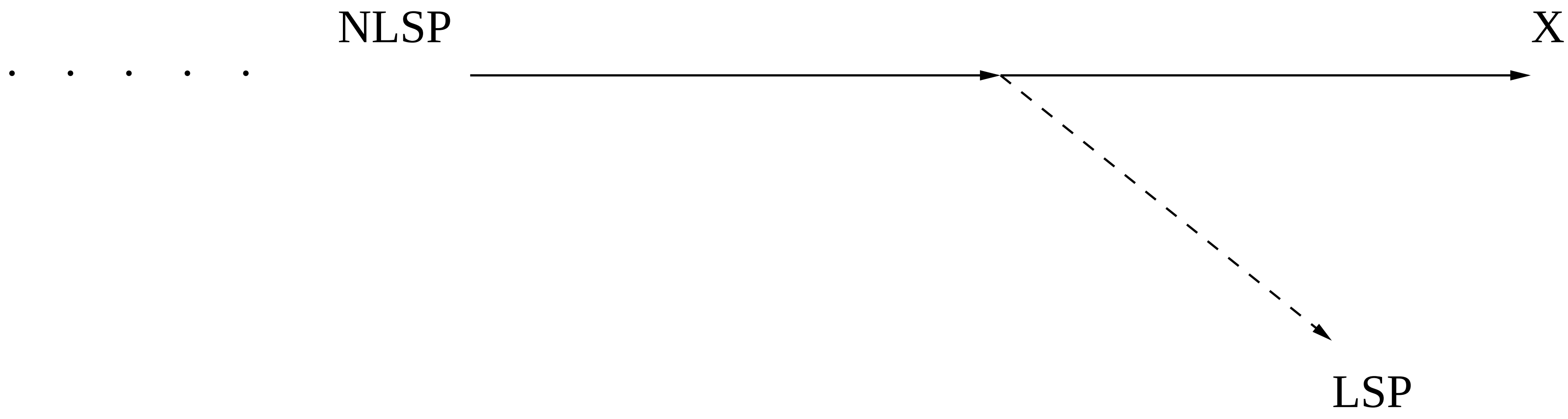
— all sparticle decay cascades contain a Higgs boson
(possibly: H is an additional mostly singlet-like Higgs boson below 125 GeV)

— the missing energy in sparticle decay cascades is strongly reduced

$\longrightarrow$ lower bounds on squark/gluino masses from run 1 at the LHC are considerably reduced

— searches for Higgs pairs (+ jets) at 13/14 TeV are the relevant search channels for Supersymmetry

Consider the kinematics of $\chi_2^0 \to \chi_1^0 + H$ or, more generally, NLSP $\to$ LSP + X:



where "X" decays into SM particles; typically: $X =$ a Higgs boson

If $M_{NLSP} - (M_{LSP} + M_X) \ll M_{NLSP}$, the energy E_{LSP} transferred from the NLSP to the LSP is proportional to the ratio of masses: $\frac{E_{LSP}}{E_{NLSP}} \simeq \frac{M_{LSP}}{M_{NLSP}}$

$\longrightarrow$ If the LSP is light and $M_X \sim M_{NLSP} - M_{LSP}$, little E_T^{miss} energy is transferred to the LSP; E_{NLSP} is carried away by the Higgs

$\longrightarrow$ The E_T^{miss} signature disappears!

(If Higgs decays do not give rise to E_T^{miss})

Instead: Two Higgs bosons per sparticle pair production!

Is such a kinematic configuration possible in the MSSM?

A light ($\sim$ few GeV) LSP has to be bino-like (higgsinos/winos have charged SU(2) partners)

$\longrightarrow$ Squarks (with hypercharge!) etc. would prefer to decay directly into the LSP, without the NLSP in the decay cascade

$\longrightarrow$ The effect would not be dominant

In the NMSSM, a light singlino-like LSP Ψ_S is natural:

Its mass originates from a Yukawa coupling $2\kappa S \Psi_S \Psi_S$

$\longrightarrow$ $M_{singlino} \sim 2\kappa v_s \sim$ a few GeV if κ is small, $\kappa \sim 10^{-5}...10^{-4}$

A light singlino has very small couplings to squarks, gluinos and all other Susy particles; these will avoid to decay into the singlino

$\longrightarrow$ all decay cascades end "provisionally" in the NLSP, typically the bino; only subsequently the NLSP decays into the singlino-like LSP + Higgs

Which Higgs?

H_{SM}: Has leptonic decays $H_{SM} \to WW^*/ZZ^* \to$ ... which lead to some E_T^{miss}

Worst case with little E_T^{miss}: H_1, a NMSSM specific light Higgs boson with $M_{H_1} < M_Z$ (Just occasionnaly: $H_1 \to \tau^+\tau^- \to \ldots +$ neutrinos)

If squarks decay directly into the bino (no Zs/Ws in the cascades, which decay possibly into neutrinos):

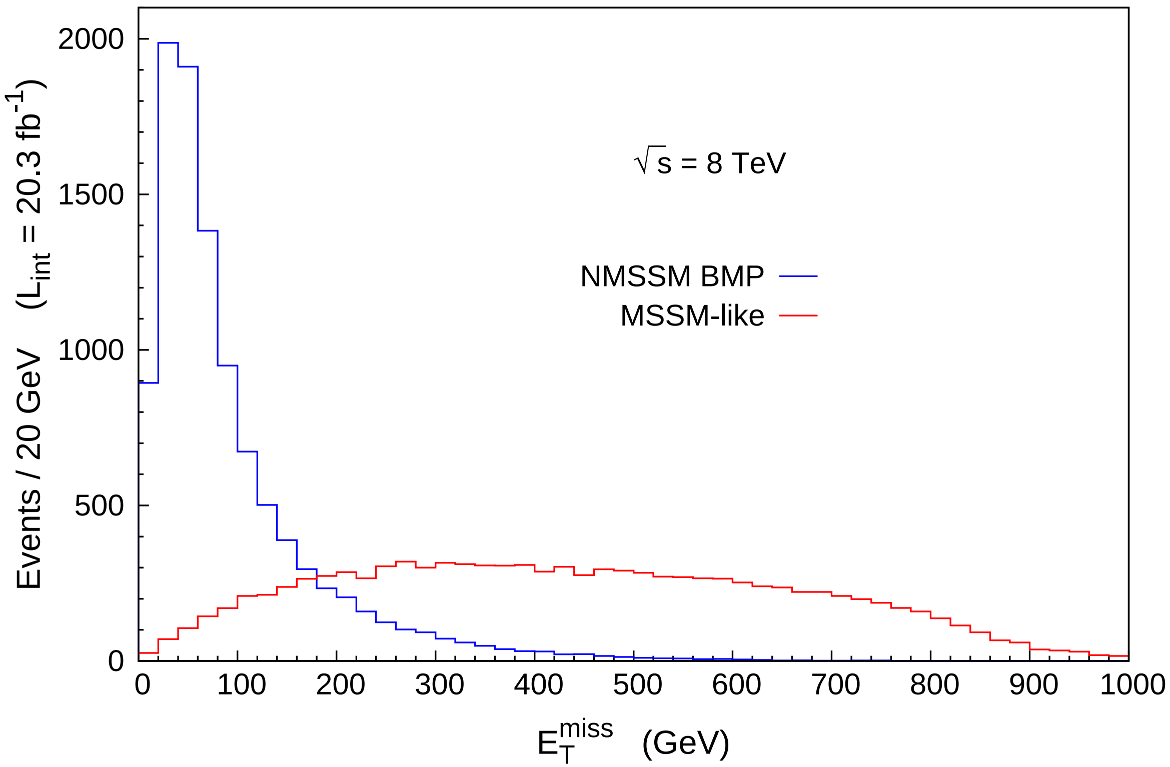
A benchmark point with

$M_{NLSP\equiv bino} \sim 89$ GeV, $M_{H_1} \sim 83$ GeV, $M_{LSP\equiv singlino} \sim 5$ GeV,

$M_{squarks} \sim 860$ GeV, $M_{gluino} \sim 890$ GeV, $M_{stops,sbottoms} \sim 810 - 1060$,

passes all LHC constraints:

Spectrum of E_T^{miss} from squark/gluino production at 8 TeV:



— in the MSSM with a 89 GeV bino as LSP, would be ruled out!

— in the NMSSM with the additional bino $\rightarrow H_1+$ singlino cascade

$\longrightarrow$ Dramatic reduction of the number of events with large E_T^{miss}

(Checked: no strong dependence on NLSP/H1/LSP masses)

The only LHC allowed scenario with all sparticle masses below ~ 1 TeV!

Strongest constraints come from searches for multijets incl. multi-b-jets (searches for RPV), not from standard SUSY searches incl. E_T^{miss}

Possible search strategy at the LHC at 13/14 TeV:

Properties of the final state:

Hard jets + two (boosted) Higgs states with large p_T

Instead of E_T^{miss}, look for remnants of two Higgs bosons: the SM-like H_{125} and/or an additional lighter NMSSM-specific Higgs boson

Have to distinguish

Case I: Simple squark$\to$quark+bino cascade (BMpoint)

Case II: Longer squark decay cascades

Cross section possibly much larger than SM Higgs pair production; up to $\sim$ 5.2 pb for the BMpoint, depending on squark/gluino masses

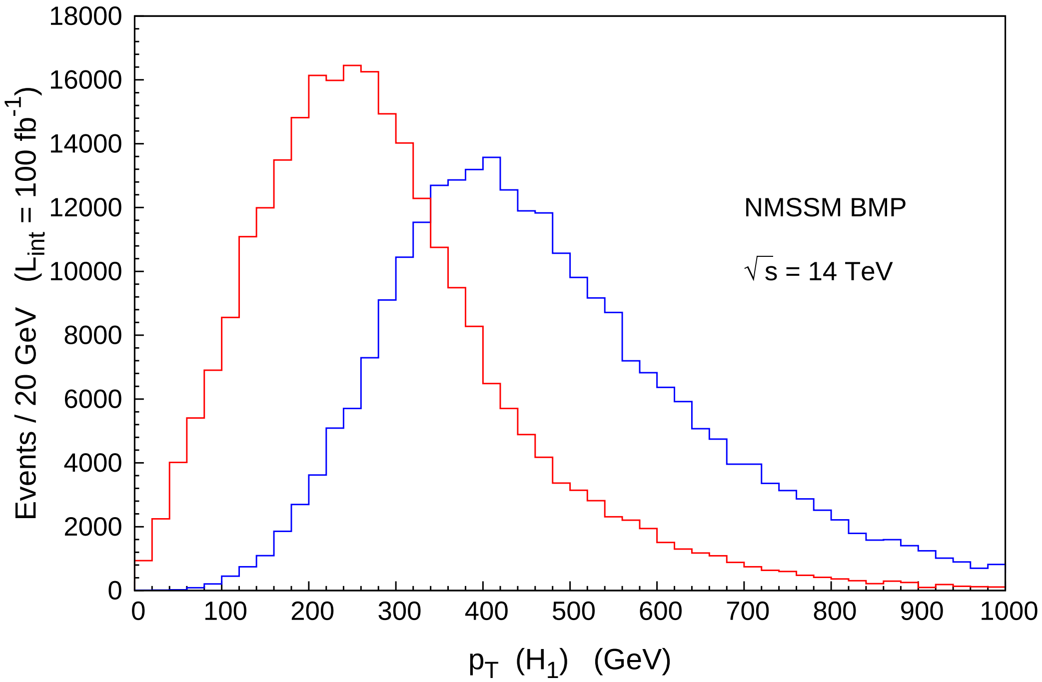
Case I: Simple squark→quark+bino cascade (BMpoint)

— Require four hard jets, e.g. with $P_T \geq 400,\ 200,\ 80,\ 80$ GeV from $2 \times (\tilde{q} \to q + bino \to q + singlino + H_1$ and/or $\tilde{g} \to q + \tilde{q} \to ...)$

— Ask for two b-jets and two τ_h ($M_{2\tau} < 120$ GeV); try to reconstruct the a priori unknown Higgs (H_1) mass from two b-jets

The results below are based on simulations with MadGraph5+1j, Pythia, Delphes

P_T of the leading and next-to-leading Higgs bosons H_1, $M_{H_1} = 83$ GeV:



(Blue: leading Higgs; red: Next-to-leading Higgs boson)

Analyse the final state twice:

First:

— since the H_1 decay products are boosted, look for two "slim" b-jets and two τ_h using anti-k_T jet-finding algorithm with small cone size $R = 0.15$ (simulation assumes calorimeter cells with $\Delta\varphi,\ \Delta\eta \simeq 0.1$)

Define a $2b$ pseudo-jet $2bPJ$ as the sum of both b-tagged jets (assumed: 70% b-tag efficiency)

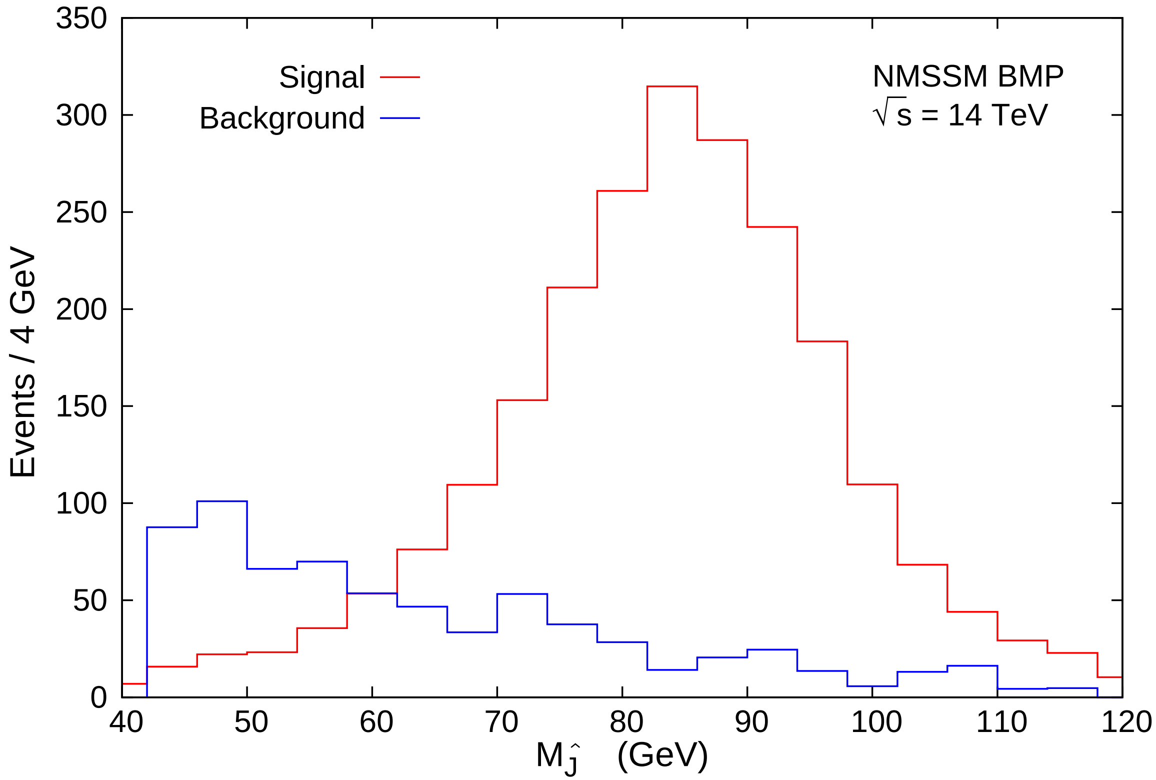
Second:

— Apply the anti-k_T jet-finding algorithm again, with $R = 0.5$

→ The two boosted b-jets tend to merge into a single fatter jet $\hat{J}$;

Look for the jet $\hat{J}$ with $p_T > 400$ GeV closest in ΔR to the previously found $2bPJ$

Invariant mass of $\hat{J}$ (event numbers after $100 fb^{-1}$ at 14 TeV):

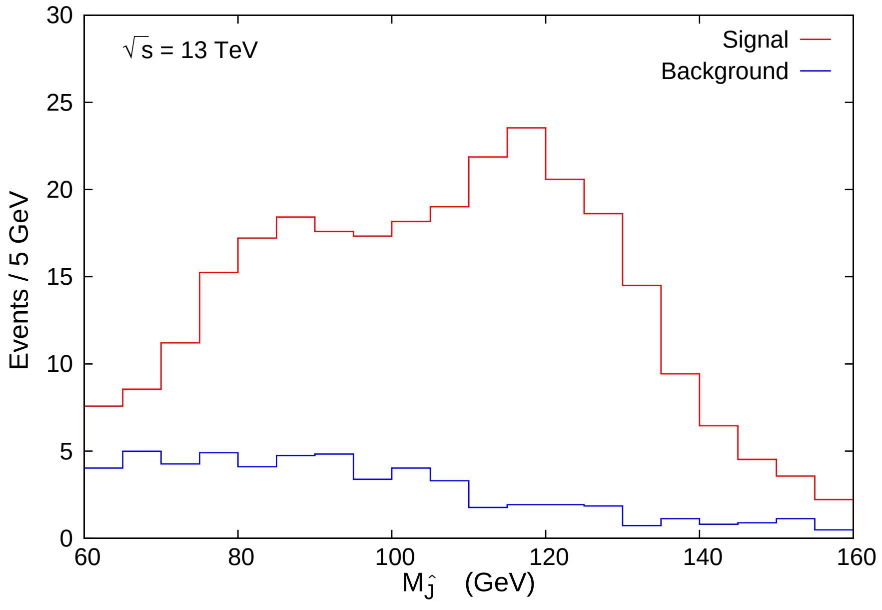


→ The signal is there!   Recall: $M_{H1} = 83$ GeV

Of course: for heavier squarks/gluinos the H_1 production cross section (here: ~ 5.2 pb) would go down; for different M_{H_1} the height of the peak remains the same.

Dominant background from QCD: 2 jets + $b\bar{b}$ + 2 fake τ's:
the 2-τ fake rate at $R = 0.15$ is much larger than the (1-τ fake rate)^2;
"thin" jets from boosted partons use to come in pairs!

Case of a 130 GeV bino with branching fractions both into H_1 with $M_{H_1} = 83$ GeV, and H_{125}:



$\rightarrow$ "Twin peaks" are possible
(Here: ~ 1 TeV squarks/gluinos, harder cuts to suppress background)

Case II: Longer squark decay cascades

$\tilde{q} \to q + \tilde{g}$, $\tilde{g} \to t + \tilde{t}$, $\tilde{t} \to t$ + bino, bino $\to H_{125}+$ singlino:

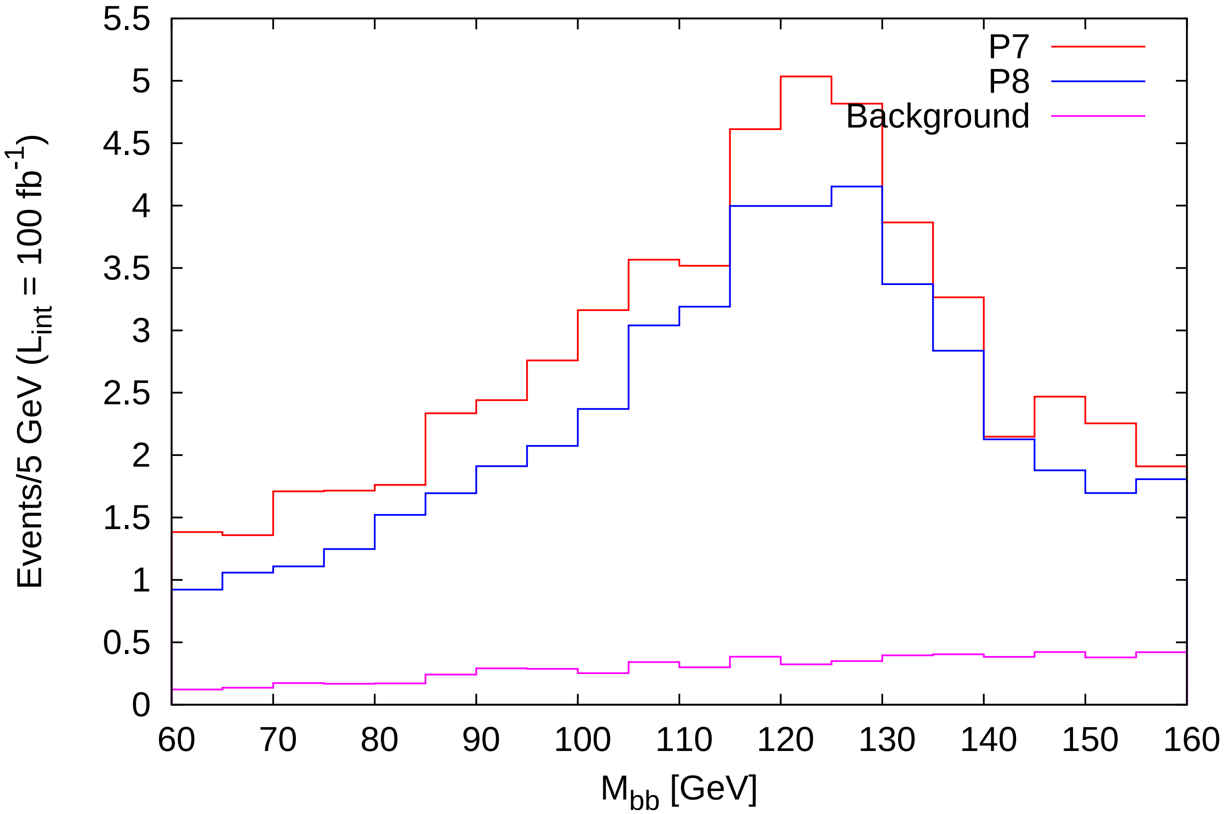
Higgses are less boosted, $H \to b\bar{b}$ gives two separate jets visible with $R = 0.4$ jet algorithms ($\to$ less fake 2τ backgrounds, similar from $t\bar{t}$+jets) $2b$-jet invariant mass M_{bb} should peak at M_{Higgs}

Examples (from "to appear"):

Benchmark point P7:
$\tilde{q}_{1.5\,TeV} \to q + \tilde{g}_{1.3\,TeV} \to q + t + \tilde{t}_{750\,GeV} \to q + t + \bar{t}$+bino,
bino $\to H_{125}$+singlino

Benchmark point P8: same with $t \leftrightarrow b$, $M_{\tilde{q}} = 1.4\,TeV$, $M_{\tilde{g}} = 1.2\,TeV$

Some E_T^{miss} from leptonic t/b-decays $\longrightarrow$ heavier squarks/gluinos to comply with constraints from run I (still below the MSSM-bounds)
$\longrightarrow$ smaller cross sections $\sim 1-3$ fb^{-1}



M_{bb} for the benchmark points P7 and P8

After cuts on four hard jets with $P_T \geq 400,\ 300,\ 200,\ 100$ GeV and requiring two hadronic τ-leptons with combined $P_T \geq 100$ GeV

$\longrightarrow$ Visible after a few 100 fb^{-1} luminosity

Conclusions:

In the NMSSM with a light singlino LSP, standard SUSY search strategies can fail due to "missing" E_T^{miss}

$\longrightarrow$ The present scenario is consistent with constraints from run I with both squark and gluino masses of ~ 900 GeV

$\longrightarrow$ Production cross sections up to ~ 5 pb at 13/14 TeV are possible (compared to ~ 30 fb for Standard Model Higgs pair production)

Dedicated search strategies for Higgs pairs plus many jets are required

$\longrightarrow$ may lead to a discovery of both Supersymmetry and, possibly, of additional NMSSM specific Higgs bosons