The Higgs sector of the Next-to-Minimal Supersymmetric Standard Model

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Supersymmetry leads always to an extended Higgs sector:

MSSM: 2 SU(2) doublets H_u, H_d (+ higgsinos Ψ_u, Ψ_d) where the vev of H_u generates up-type quark masses ($m_{top} = h_{top}\, v_u$), the vev of H_d generates down-type quark and lepton masses masses ($m_{bottom} = h_{bottom}\, v_d$, $m_\tau = h_\tau\, v_d$).

v_u and v_d contribute to the W and Z boson masses:

$$M_W^2 = \frac{g_2^2}{2}(v_u^2 + v_d^2) \qquad M_Z^2 = \frac{g_1^2 + g_2^2}{2}(v_u^2 + v_d^2),$$

but the ratio $\frac{v_u}{v_d} \equiv \tan\beta$ is model dependent.

Problem: The mass of 125 GeV of the SM-like Higgs boson is not easy to explain (the tree level potential gives $H_{SM} < M_Z$); large unnatural radiative corrections are required to explain $H_{SM} \sim 125$ GeV.

NMSSM: An additional gauge singlet S with a Higgs-to-Higgs coupling $\lambda S H_u H_d$ in the superpotential ($\to$ Yukawa coupling $\lambda S \Psi_u \Psi_d$ to higgsinos)

— whose vev $\langle S \rangle = v_S$ generates masses for the higgsinos (the μ-term of the MSSM)

— allows to explain $H_{SM} \sim 125$ GeV at tree level, no large radiative corrections are required

— Many parameters in the Higgs sector: dimensionless couplings λ, κ; trilinear couplings A_λ, A_κ; v_S, $\tan\beta$

The NMSSM Higgs spectrum (assuming CP-conservation):

— a 3×3 mass matrix for 3 neutral CP-even states H_i
— a 2×2 mass matrix for 2 neutral CP-odd states A_i
— a charged Higgs $H^\pm$

Approximate (!) mass eigenstates:

— a neutral CP-even state H_{125} with a mass of $\sim$ 125 GeV, and couplings similar to (but not necessarily equal to) a SM Higgs boson

— a "heavy" nearly degenerate SU(2) multiplet $H/A/H^{\pm}$ (like in the MSSM), with mass $\gtrsim$ 300 GeV (unless contributions from $H^{\pm}$ to $b \to s + \gamma$ happen to be cancelled by SUSY contributions)

— mostly singlet-like neutral CP-even and CP-odd states H_S, A_S with model dependent masses, possibly below 125 GeV; hardly constrained by previous experiments (LEP)

Note:

— M_{H_S} somewhat below $M_{H_{SM}}$ ($M_{H_S} \sim 80 - 120$ GeV) helps to shift upwards the mass of H_{SM} to $\sim$ 125 GeV through mixing

— A (very) light A_S is natural; a possible pseudo-Goldstone boson of an approximate Peccei-Quinn symmetry

Couplings to $W-$ and $Z-$bosons:

— For all extensions of the Higgs sector involving only SU(2) doublets and singlets, the ratios g_W/g_Z of the couplings of all neutral Higgs states to W/Z bosons are given by $g_2/\sqrt{g_1^2+g_2^2}$, i.e. SM-like!

— Def.: EW gauge couplings $g_i \equiv g_{W_i}$ for each neutral Higgs state

$$H_i = H_{125},\ H,\ H_S$$

→ Measurements of the couplings of H_{125} to W and Z from production and decays can be combined to improve the measurement of g_{125}

→ If $g_{SM} =$ coupling of the SM Higgs boson: the g_i satisfy the sum rule

$$g_{125}^2 + g_H^2 + g_{H_S}^2 = g_{SM}^2$$

→ Since the measured value of g_{125}^2 (incl. error bars) is close to g_{SM}^2, no large values of g_H^2 or $g_{H_S}^2$ (induced by mixing) are allowed

Couplings to Fermions (top- and bottom quarks):

— if the mixings $H_{125} - H_S$ and $H_{125} - H$ are small, all couplings of H_{125} are nearly SM-like

— the couplings of H/A to b-quarks can be strongly enhanced; reason:

$m_b = h_b\, v_d \to h_b = \frac{m_b}{v_d} \gg \frac{m_b}{\sqrt{v_u^2+v_d^2}}$ if v_d is small $\leftrightarrow$ if $\tan\beta = \frac{v_u}{v_d}$ is large

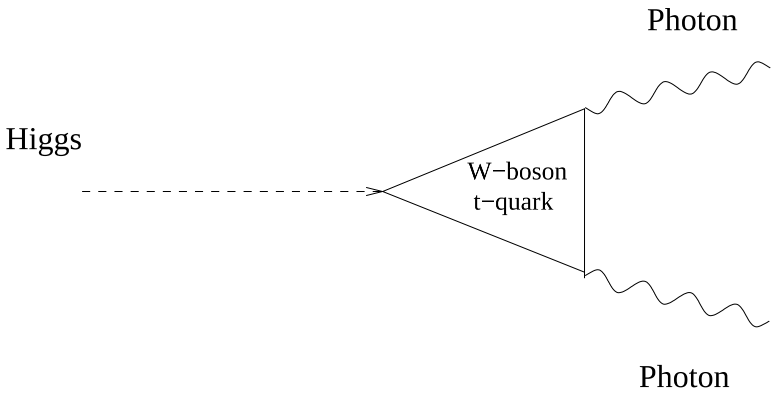
For the coupling of H_{125} to b-quarks, a large Yukawa coupling h_b is compensated by a small H_d component of H_{125}; $g_{H_{125}\, b\, \bar{b}}$ remains SM-like

For H/A, the H_d component is large $\to g_{H/A-b\,\bar{b}}$ can be very large!

— the singlet states H_S, A_S couple only through mixing with H_{125} and/or H/A. The coupling to b-quarks can be very small (if light)

Couplings to $\gamma\gamma$:

SM: induced by top quark/$W^{\pm}$ loops:



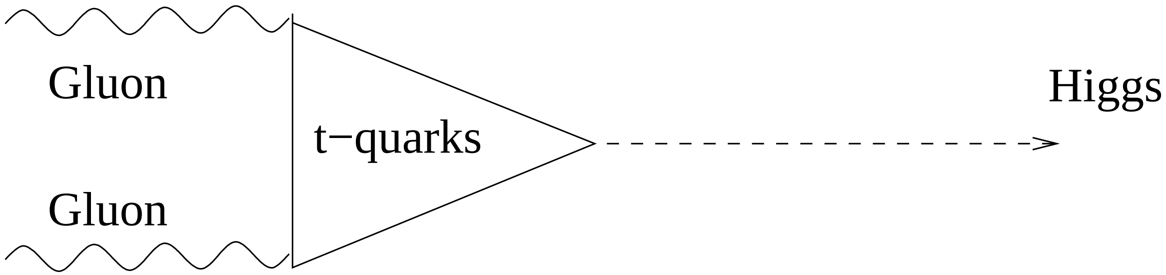
NMSSM: the NMSSM-specific Yukawa coupling $\lambda S \Psi_u \Psi_d$ generates an additional H_S-γ-γ coupling from a loop of charged higgsinos $\Psi_u \Psi_d$; the impact depends on λ and the mixing of H_S with the other Higgs states

Trilinear Higgs couplings:

Originate from the NMSSM-specific term $\lambda S H_u H_d$ in the superpotential; can be large notably for couplings of the mostly singlet-like states H_S, A_S to H/A and H_{125}!

Direct production of the extra Higgs states:

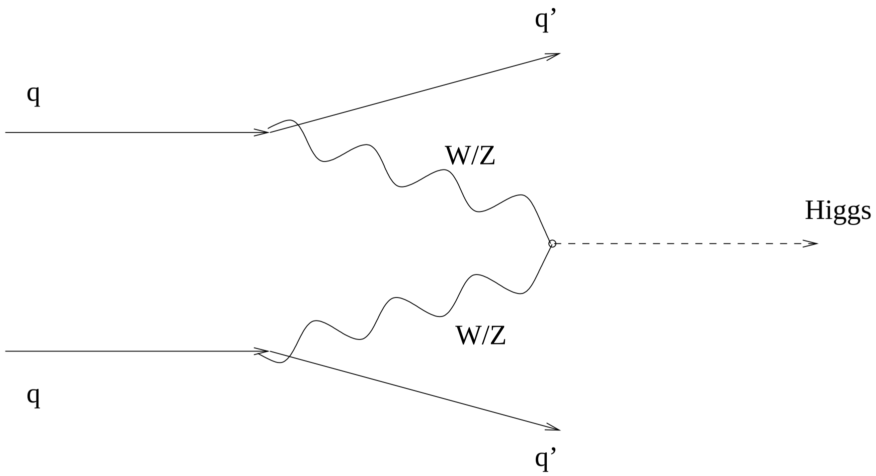
1) Gluon fusion:

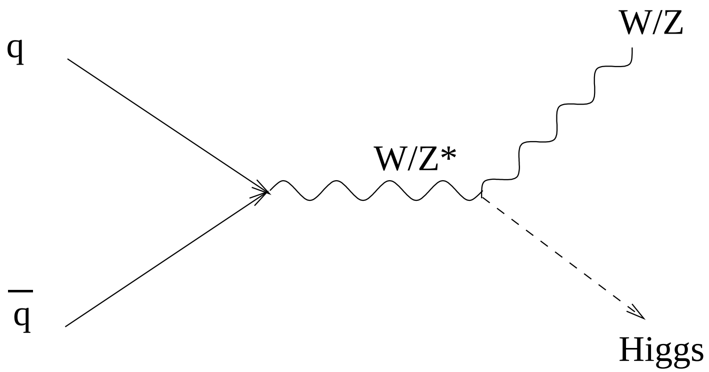


Depends on the coupling of H_i to the top quark (possibly through mixing)

$\longrightarrow$ the production cross section is always below the one of a SM Higgs boson (of the same mass)

2) VBF and associate production with a W/Z boson:

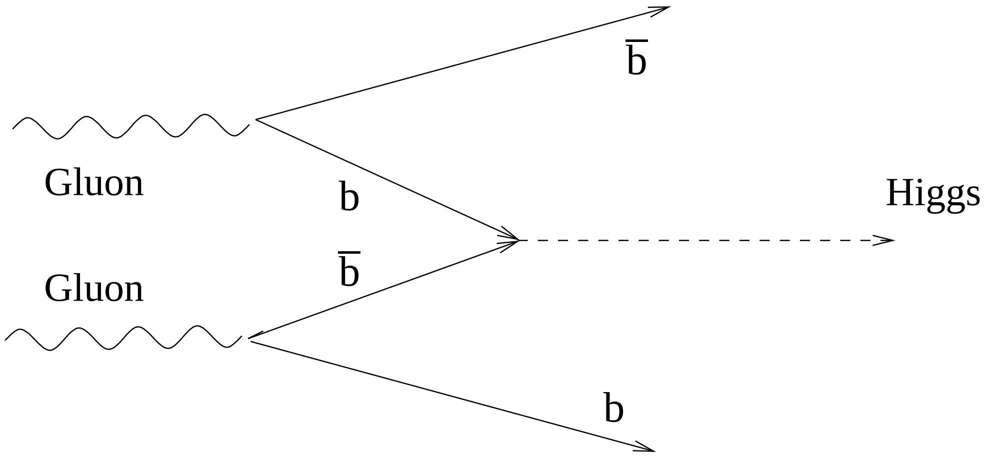




Depends on the coupling of H_i to the W/Z bosons (possibly through mixing)

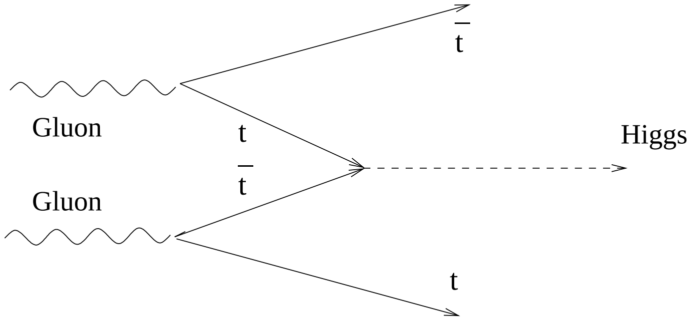
$\longrightarrow$ production cross section always below the one of a SM Higgs boson (of the same mass)

3) Ass. production with b-quarks:



$\longrightarrow$ Can be strongly enhanced for H/A (and for heavy H_S/A_S through mixing) if h_b is large (large $\tan\beta$)

4) Ass. production with t-quarks:



Not enhanced w.r.t. a SM Higgs boson

Decays of the extra Higgs states

The branching fractions can deviate considerably from those of a SM-like Higgs boson of the corresponding mass. In particular

— the branching fraction into $\gamma\gamma$ can be strongly enhanced.
Not (necessarily) since the loop-induced coupling is much larger, but since partial widths into "standard" final states – and hence the total width – are small:

$$BR(H_i \to \gamma\gamma) = \frac{\Gamma(H_i \to \gamma\gamma)}{\Gamma_{Tot}}$$

For $M_H \lesssim 150$ GeV: Γ_{Tot} is dominated by $H \to b\bar{b}$
→ The $BR(H_i \to \gamma\gamma)$ becomes large if the coupling $H_i\, b\, \bar{b}$ is small (notably for $M_{H_S} < 125$ GeV, NOT ruled out by LEP!)

For $M_H \gtrsim 150$ GeV: The $BR(H_i \to \gamma\gamma)$ becomes large if all couplings to $b\,\bar{b}$, $t\,\bar{t}$ and to gauge bosons are small; happens easily for H_S, A_S!

Higgs-to-Higgs decays can be relevant, even dominant!

Since the couplings of Higgs bosons to gauge bosons and SM Fermions are quite small (and/or the decays are kinematically suppressed), Higgs-to-Higgs decays can be dominant if kinematically allowed and if the NMSSM-specific Higgs-to-Higgs coupling λ is not too small.

But: exotic decays of H_{125} with too large branching fractions would reduce the observed decays (i.e. signal rates) into the SM-channels below an acceptable level $\rightarrow H_S$, A_S should better have masses above $\sim$ 60 GeV (or λ is really small).

Still: Many possibilities for

$H_i \rightarrow H_j + H_k \rightarrow bb + \gamma\gamma,\ bb + \tau\tau,\ bb + WW,\ \tau\tau + \tau\tau \ldots$

and even

$H \rightarrow HH \rightarrow HHH$ cascades, incl. $H_i \leftrightarrow A_i$

see, e.g., S.F. King et al., arXiv:1408.1120 (PRD)

Tasks

1) Scan the parameter space of the Higgs sector of the NMSSM which is consistent with

— the measured signal rates of H_{125} in all production and decay channels (very important!)

— the (present) absence of signals for additional Higgs bosons with masses below 125 GeV (LEP, searches for $H \to \gamma\gamma$ by ATLAS) or above 125 GeV ($H/A \to \tau\tau$, $H \to \gamma\gamma$ by ATLAS and CMS)
(Note: the MSSM is a subspace of the NMSSM parameter space!)

2) Identify, for the various viable ranges of Higgs masses and decays, incl. Higgs-to-Higgs decays, the most promising

Signal rate = (Production cross section)×(Branching fraction)

for the run II of the LHC.

"Most promising" depends strongly on the final state (the corresponding SM background); many studies incl. simulations are necessary!

Higgs bosons from SUSY particle decay chains

(With A. M. Teixeira, 1406.7221 and 1412.6394)

Higgs production from sparticle decay chains like

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

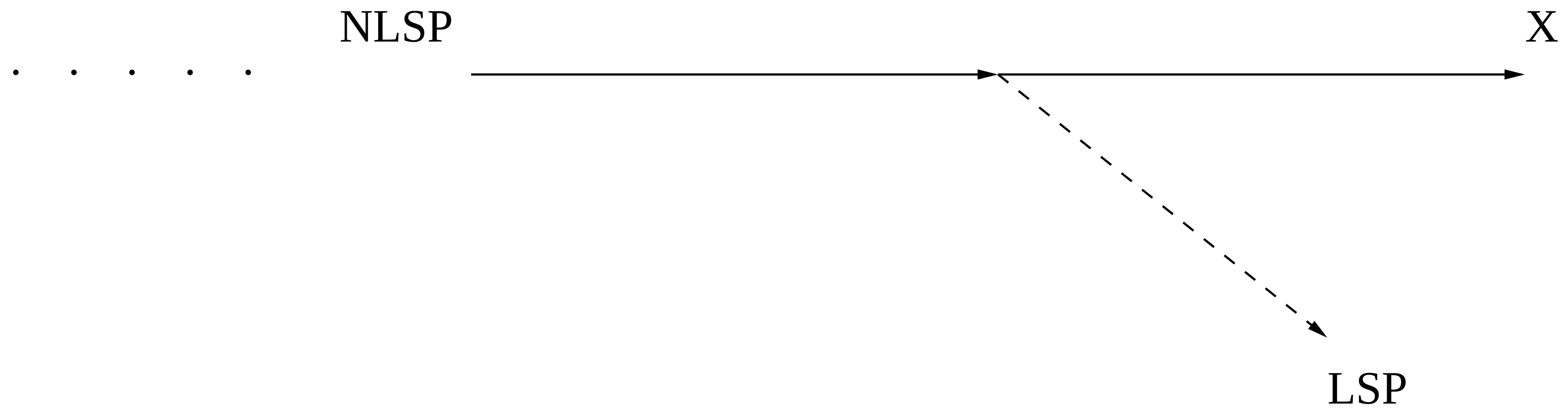
is a well-known possibility, where

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

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: $\frac{E_{LSP}}{E_{NLSP}} \simeq \frac{M_{LSP}}{M_{NLSP}}$

→ 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

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

— 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

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

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

— searches for Higgs pairs (+ jets) at 13/14 TeV are the relevant search channels for Supersymmetry;
two Higgs bosons per sparticle pair production,
a new signature to look for!

At the run II of the LHC

many unexpected (exotic) phenomena

are possible in the NMSSM!