Higgs Bosons in the Next-to-Minimal Supersymmetric Standard Model (NMSSM)

U. Ellwanger, LPT Orsay

Recall: the only explicit mass term in the Lagrangian of the SM appears in the Higgs potential:

$$V_H = -m^2 |H|^2 + \frac{\lambda}{4} |H|^4$$

$$\longrightarrow \langle H \rangle = \sqrt{2} \frac{m}{\lambda} \simeq 174 \text{ GeV}, \qquad M_H = \lambda \cdot \langle H \rangle = ??$$

In the NMSSM:

— all supersymmetric interactions are scale invariant

— all mass terms originate from supersymmetry breaking $\sim M_{\text{SUSY}}$

— the phenomenologically required supersymmetric higgsino mass term $\mu \Psi_{H_u} \Psi_{H_d}$ of the MSSM is replaced by a Yukawa coupling $\lambda S \Psi_{H_u} \Psi_{H_d}$

— S: gauge singlet superfield, $\langle S \rangle \sim M_{\text{SUSY}}$

$$\longrightarrow \mu_{\text{eff}} = \lambda \langle S \rangle \sim M_{\text{SUSY}} \checkmark$$

$\longrightarrow$ more states (w.r.t. the MSSM) in the Higgs and neutralino sectors:

— 3 neutral CP-even Higgs bosons (linear comb. of H_u, H_d and S),

— 2 neutral CP-odd Higgs bosons,

— 5 neutralinos.

The relevant part of the Higgs potential in the MSSM/NMSSM in the approximation $\langle H_u \rangle \gg \langle H_d \rangle$:

$$V_H \simeq \left(m_{H_u}^2 + \mu^2 \right) |H_u|^2 + \frac{g_1^2+g_2^2}{8} |H_u|^4$$

where $m_{H_u}^2 \sim -M_{\text{SUSY}}^2$, μ = higgsino mass term $\equiv \mu_{\text{eff}}$ in the NMSSM

$$\longrightarrow \langle H_u \rangle^2 \sim -4 \frac{m_{H_u}^2+\mu^2}{g_1^2+g_2^2} \stackrel{!}{=} \frac{2M_Z^2}{g_1^2+g_2^2} \qquad \text{or} \qquad -2(m_{H_u}^2 + \mu^2) \stackrel{!}{=} M_Z^2$$

$\longrightarrow$ iff $M_{\text{SUSY}}^2 \sim -m_{H_u}^2 \gg M_Z$: need to tune μ such that

$$-2(m_{H_u}^2 + \mu^2) \simeq M_Z^2$$

Physical Higgs mass: $M_H^2 \sim M_Z^2 + \frac{3m_{top}^2}{4\pi^2 \langle H_u \rangle^2} \ln \left(\frac{M_{\text{stop}}^2}{m_{top}^2} \right) + \ldots$

From $M_H \gtrsim 114$ GeV: need $M_{\text{stop}} \gtrsim 1$ TeV $\rightarrow$ need to tune parameters in order to avoid $m_{H_u}^2 \sim -M_{\text{stop}}^2$ from radiative corrections between the weak and the GUT scale

$\longrightarrow$ "little finetuning problem" of the MSSM

In the NMSSM: The lightest CP-odd Higgs boson A_1 can be light,
$0 < M_{A_1} \lesssim 50$ GeV

⟶ H would decay dominantly as $H \to A_1 A_1$

⟶ LEP constraints on M_H are alleviated; essentially:

Constraints from $H \to 4b$ (if $M_{A_1} \gtrsim 10.5$ GeV) from DELPHI/OPAL

Constraints from $H \to 4\tau$ (if $M_{A_1} \lesssim 10.5$ GeV) from ALEPH

The region 9.5 GeV $\lesssim M_{A_1} \lesssim 10.5$ GeV is particularly interesting:

A_1 would mix with the CP-odd $b\bar{b}$ bound states $\eta_b(nS)$

The mass of the only observed state $\eta_b(1S)$ (BaBar) is below expectations from QCD for the hyperfine splitting $M_{\Upsilon(1S)} - M_{\eta_b(1S)}$

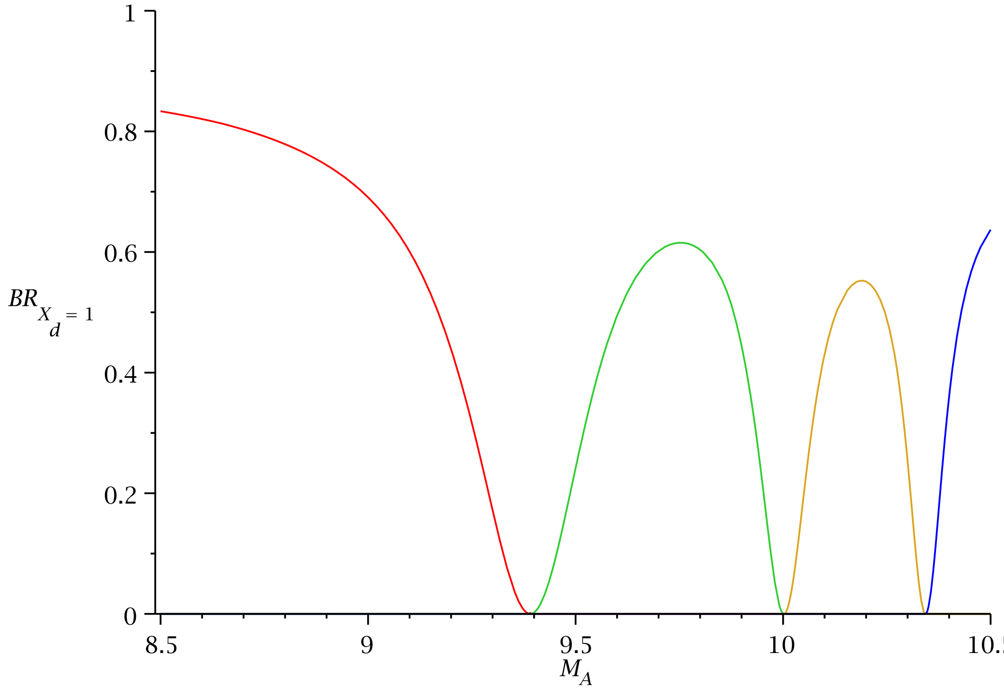
⟶ a hint for $A_1 - \eta_b(1S)$ mixing, if M_{A_1} is in the above range?
(F. Domingo, U. E., C. Hugonie, M. Sanchis-Lozano)

However: the width $\eta_b(nS) \to gg$ is much larger than the width $A_1 \to \tau^+\tau^-$

⟶ a tiny $A_1 - \eta_b(nS)$ mixing angle suffices such that the physical eigenstate decays dominantly into gg (F. Domingo, U. E.)

⟶ For 9.5 GeV $\lesssim M_{A_1} \lesssim 10.5$ GeV, A_1 would decay dominantly as $A_1 \to gg$; ALEPH constraints on $H \to A_1 A_1 \to 4\tau$ do not apply

The $BR(A_i \to \tau^+ \tau^-)$ as function of M_{A_1}



The colors indicate which state $\eta_i \equiv \{\eta(nS),\ A_1\}$ corresponds to A_1: red$\to \eta_1$, green$\to \eta_2$, brown$\to \eta_3$, blue$\to \eta_4$.

A small $BR(A_i \to \tau^+ \tau^-)$ implies a large $BR(A_1 \to g\, g)$!

Impact on the fine tuning, comparing the NMSSM to the MSSM

(U. E., G. Espitalier-Noel, C. Hugonie)

Assume universal soft SUSY breaking parameters at the GUT scale
$\longrightarrow$ cMSSM, cNMSSM

Compute the fine tuning measure $\Delta = Max\{\left|\frac{\partial \ln(M_Z)}{\partial \ln(p_i^{\text{GUT}})}\right|\}$,

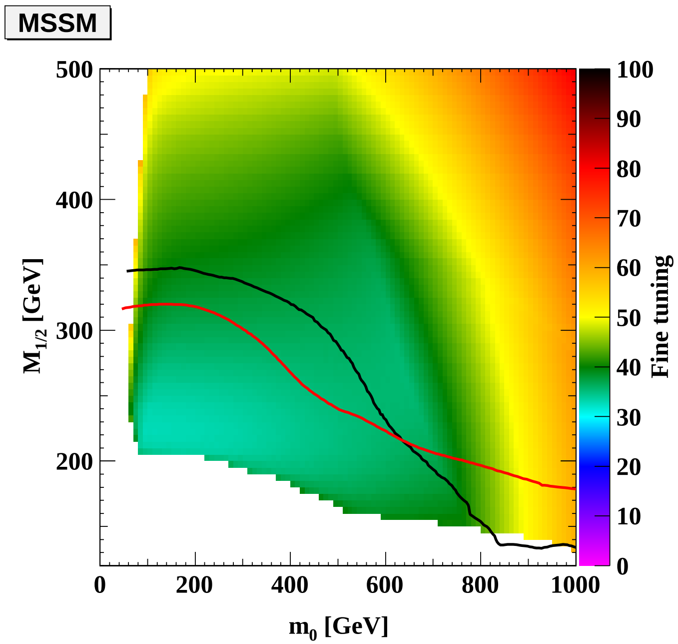
where p_i^{GUT} are the parameters at the GUT scale:

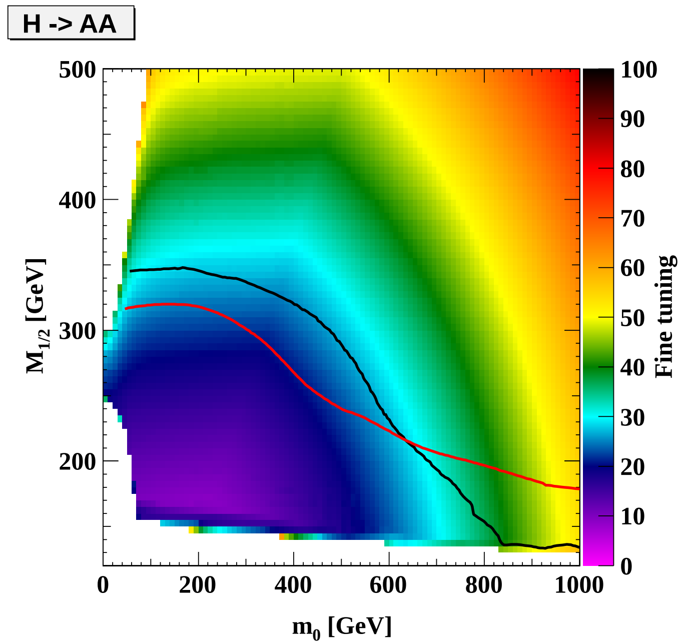
$$p_i^{\text{GUT}} = m_0,\ M_{1/2},\ A_0,\ h_t,\ \ldots$$

Δ should be as small as possible, preferably of $\mathcal{O}(1)$
(Standard Model up to M_{GUT}: $\Delta \sim 10^{14}$!!!)

For fixed m_0, $M_{1/2}$ (universal scalar and gaugino masses) we look for the minimum of Δ as function of A_0, $\tan(\beta)$, ...; the minimal value of Δ can be represented in the plane m_0, $M_{1/2}$ for the cMSSM and the cNMSSM

Δ in the plane $m_0 - M_{1/2}$ for the cMSSM and the cNMSSM:





$\longrightarrow$ for $M_{1/2} \lesssim 400$ GeV and $m_0 \lesssim 800$ GeV, the amount of fine tuning in the cNMSSM ($\gtrsim 10$) can be considerably less than in the cMSSM ($\gtrsim 33$) due to lower possible values of M_H due to allowed $H \rightarrow A_1 A_1$ decays

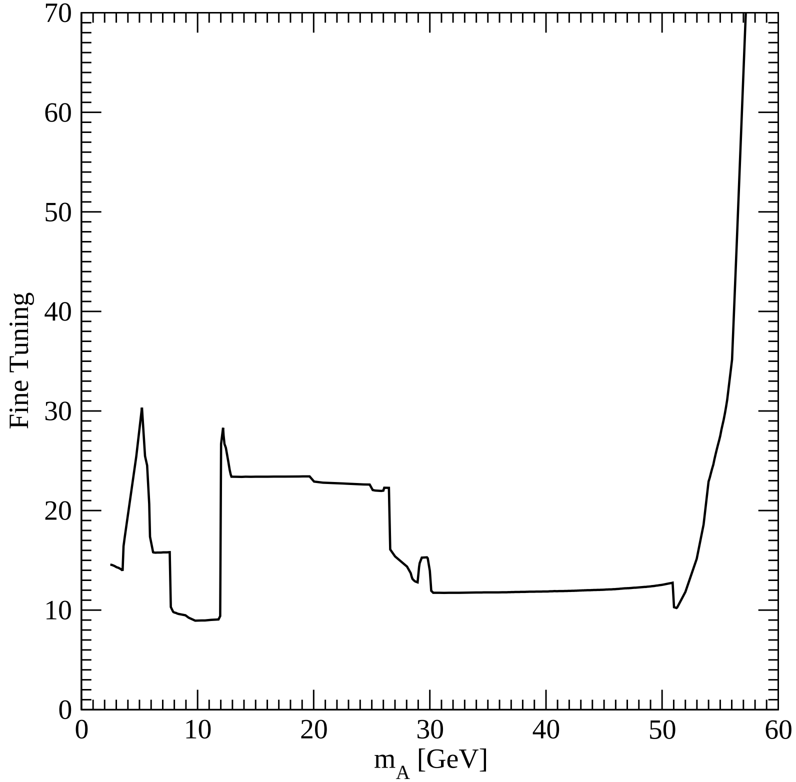
Curves: lower bounds on $M_{1/2}$, $m_0{}^*$ from $L^{int} \simeq 35$ pb^{-1} at the LHC :

Black: ATLAS, interpreted within the cMSSM with $\tan\beta = 3$, $A_0 = 0$

Red: CMS, interpreted within the cMSSM with $\tan\beta = 10$, $A_0 = 0$

*Not necessarily applicable to the cNMSSM, notably for a singlino-like LSP

Dependence of the Fine Tuning Δ on M_{A_1} in the cNMSSM:



$\longrightarrow$ Δ is particularly low for

a) $M_{A_1} \sim 10$ GeV (H can be light due to the absence of constraints from $H \to 4\tau$, just from the remaining non-vanishing $BR(H \to b\bar{b})$)

b) 30 GeV $\lesssim M_{A_1} \lesssim$ 50 GeV (weak constraints on M_H from $H \to 4b$)

For any value of M_H, M_{A_1}, the search for a SM-like Higgs boson decaying as $H \to A_1 A_1 \to xx\,xx$ is a challenge at the LHC

Numerous studies on the final states $4b$, $2b\,2\tau$, 4τ, $2\tau\,2\mu$ by

M. Almarashi, A. Belyaev, M. Carena, L. Cavicchia, S. Chang, K. Cheung, R. Dermisek, U. E., P. J. Fox, R. Franceschini, J. Gunion, T. Han, S. Hesselbach, G. Y. Huang, C. Hugonie, S. Lehti, M. Lisanti, S. Moretti, S. Munir, A. Nikitenko, P. Poulose, I. Rottländer, V. S. Rychkov, M. Schumacher, C. H. Shepherd-Themistocleous, J. Song, T. Stelzer, J. G. Wacker, C. M. Wagner, N. Weiner, S. Wiesenfeldt, S. Willenbrock, Q. Yan

$\longrightarrow$ No “No-lose theorem”!

The interesting case $M_{A_1} \approx 10$ GeV where $A_1 \to gg$ would be particularly challenging: hopeless???

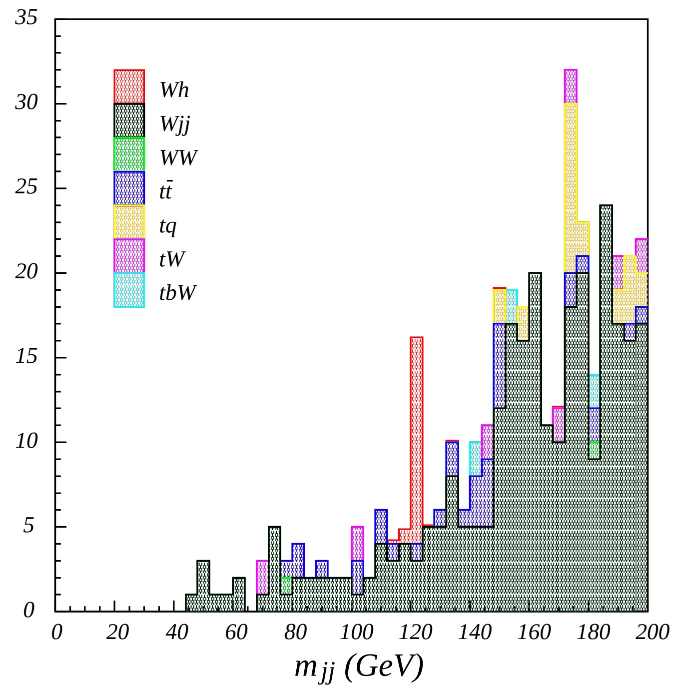
New development: use Jet Substructure:

Ch.-R. Chen, M. Nojiri, W. Sreethawong; A. Falkowski, D. Krohn, L.-T. Wang, J. Shelton, A. Thalapillil; B. Bellazzini, C. Csaki, J. Hubisz, J. Shao; D. Kaplan, M. McEvoy; Ch. Englert, T. Roy, M. Spannowsky

Ass. H production with $W^{\pm}$, require isolated lepton from $W^{\pm} \to l^{\pm} + \nu$

Consider $H \to A_1 A_1 \to 2$ (fat) jets j from each A_1

Require $p_{T_j} > 100$, 50 GeV (or 200 GeV) $\longrightarrow$ boosted Higgs
Look for substructure in j with $m_j \lesssim 12$ GeV: $j(A_1) = \{j_1, j_2\}$ (Gluons):
Undo the last recombination step of the clustering algorithm from j_1, j_2 to j, require $m_{j_1} \sim m_{j_2} \ll m_j$



Then: Look for peak in $m_{jj} \sim m_H$:
(Here: $m_H = 120$ GeV, L=30 fb^{-1},
from Chen, Nojiri, Sreethawong,
arXiv:1006.1151)
Seems feasable!

Conclusions

— In a large part of the parameter space of the NMSSM, no Higgs would be visible in standard search channels due to Higgs-to-Higgs decays

— These regions in the parameter space are well motivated by a lower Higgs mass compatible with LEP constraints
$\longrightarrow$ lower fine tuning

— For a no-lose theorem, conclusive results are required for $H \to A_1 A_1$, $A_1 \to 2b,\ 2\tau,\ 2\mu,\ gg$ (and combinations thereof)
for all possible values of M_H, M_{A_1}

— The analysis of Jet Substructure can be of great help,
not only for "fat" jets due to $A_1 \to gg$, but also for $A_1 \to 2\tau$, $A_1 \to 2b$!