Light Higgs scenarios in the NMSSM in view of LHC Run I

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In collaboration with G. Weiglein

Workshop “Implications of LHCb measurements and future prospects”

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Next-to-Minimal Supersymmetric Standard Model - Model and Motivations

Softly-broken SUSY extensions of the SM

- **Hierarchy Problem**: SUSY protects Higgs mass from quadratic high-energy corrections;
- **One-step Unification**: SUSY matter-content ensures convergence of gauge couplings;
- **Dark matter**: WIMP candidate in the presence of R-parity;
- **Top-down approach**: Supergravity, Superstrings, etc.

*But SUSY obviously absent at low-energies: soft-breaking at the ~TeV scale!*

MSSM vs. NMSSM 1: $\mu$-problem

$$W_{\text{MSSM}} \ni \mu \hat{H}_u \cdot \hat{H}_d$$

- $\mu$: SUSY parameter → Natural Scale: $O(M_{\text{Planck,GUT,etc.}})$… or Zero!
- LEP Constraints on Chargino masses: $\mu \gtrsim 100 \text{ GeV}$
- Electroweak Symmetry Breaking needs: $\mu \lesssim O(\text{TeV})$

- Additional Gauge-Singlet superfield $\hat{S}$
  
  $v.e.v. \langle \hat{S} \rangle = s \quad \Rightarrow \quad \mu_{\text{eff}} = \lambda s$  

- $Z_3$-symmetry: scale-invariant superpotential ⇒ *No naturalness problem!*
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[Fayet (1975)]

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\[ W_{NMSSM} \ni \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \kappa \hat{S}^3 \]

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Next-to-Minimal Supersymmetric Standard Model - Model and Motivations (continued)

MSSM vs. NMSSM 2: Little Fine-Tuning

- Accumulating evidence for a SM-Higgs-like particle with mass $\sim 125.5$ GeV.
  
  $$m_{h_{\text{SM}}}^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \left\{ \ln \frac{m_T^2}{m_t^2} + \frac{A_t^2}{m_T^2} \left(1 - \frac{A_t^2}{12m_T^2}\right) \right\}$$

- MSSM tree-level contribution to the mass of the SM-like state $< M_Z$ + only as long as $\tan \beta \equiv \frac{v_u}{v_d} \gg 1$.

- Large top/stop corrections at one-loop: provided large stop masses / trilinear couplings.
  
  $\Rightarrow$ MSSM upper bound for TeV-scale stop parameters: $m_{h_{\text{SM}}} \lesssim 130$ GeV.
  
  However: large $A_t$ not favoured by SUSY-breaking + $m_T \gtrsim$ TeV stretches Hierarchy.

- NMSSM: additional tree-level contribution for large $\lambda$, low $\tan \beta$.
  
  $\Rightarrow$ NMSSM upper bound: $m_{h_{\text{SM}}} \lesssim 140$ GeV. [hep-ph/0612133]

  Less dependent on loop corrections but $\lambda \lesssim 0.7$ (Landau poles) + $\tan \beta \lesssim 3$.

- Alternative mechanism: Singlet-Doublet mixing (large $\lambda$).

The NMSSM Higgs sector

- Singlet $\Rightarrow$ 1 additional CP-even (3 in total) + 1-additional CP-odd (2 in total) states;

- 6 parameters at tree level (against 2 in the MSSM): $\lambda, \kappa, \tan \beta, M_A, \mu_{\text{eff}}, A_\kappa$. 
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Accumulating evidence for a SM-Higgs-like particle with mass $\sim 125.5$ GeV. [ATLAS,CMS,TeVatron]

**NMSSM:**

$$m^2_{h_{SM}} \approx M^2_Z \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3m^4_t}{4\pi^2 v^2} \left\{ \ln \frac{m^2_{\tilde{T}}}{m^2_t} + \frac{A^2_t}{m^2_{\tilde{T}} \left( 1 - \frac{A^2_t}{12m^2_{\tilde{T}}} \right)} \right\}$$

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Exploring the NMSSM parameter space.

**NMSSMTools 4.1.0:** Higgs masses up to leading two-loop double-log order

- Stability of the EWSB-vacuum: positive scalar squared-masses, no deeper minimum; [hep-ph/0406215]
- Landau poles: absence below the GUT scale; [hep-ph/0508022]
- Soft terms at the TeV scale;
- Dark Matter: requirement for a neutralino LSP;
- Limits on supersymmetric particles from LEP;
- Limits from $B$- and $\Upsilon$-physics (under a strong Minimal Flavour Violation hypothesis): $BR(B \rightarrow X_s\gamma)$, $BR(B^+ \rightarrow \tau\nu_\tau)$, $BR(\bar{B}_s \rightarrow \mu^+\mu^-)$, $BR(B \rightarrow X_s\mu^+\mu^-)$, $\Delta M_{d,s}$, $BR(\Upsilon \rightarrow A\gamma)$, $\eta_b(1S) - A$ mixing; [arXiv:0710.3714]
- $(g - 2)_\mu$. [arXiv:0806.0733]

**HiggsBounds 4.0.0**

Limits on Higgs sector at 95% CL combining data from LEP, TeVatron, LHC.


**HiggsSignals 1.0.0**

Confrontation of the Higgs sector to the rates measured at TeVatron, ATLAS and CMS ($\sim 125$ GeV): statistical test. $\Rightarrow$ Definition of a $\chi^2$ test (out of 37 observables)

[arXiv:1305.1933]
The SM and the Decoupling limits

**SM-limit**
- Singlet decoupling: $\lambda \sim \kappa \rightarrow 0$ (MSSM limit);
- Decoupling of the heavy-doublet states: $M_A \gg M_Z$;
- Heavy SUSY sector;
- Large $\tan \beta$ to fit the observed mass.

**Decoupling limit**
Decoupling of the heavy-doublet states: $M_A \gg M_Z$;
Correct kinematical range for the light doublet ensured through:
* **Loop corrections** (MSSM-like, large $\tan \beta$);
* **$\lambda$ contribution at Tree-level** (NMSSM specific, low $\tan \beta$).
The light-doublet scenario

\[ \sim 125 \text{ GeV state identified to the second CP-even doublet state} \]

- Possibility already considered in the MSSM; \[ [\text{arXiv:1112.3026}] \]
- Doublets: 1 CP-odd and 1 CP-even in \[ \sim 75 - 100 \text{ GeV} \], charged Higgs at \[ \sim 110 \text{ GeV} \];
- Best fit: \[ \chi^2 \sim 33.7 \];
- LEP \[ \Rightarrow h_1 \] has vanishing couplings to gauge bosons \[ \Rightarrow b \bar{b}, \tau \tau \] channels only;
- Marginally consistent with LEP \( (e^+ e^- \rightarrow hA \rightarrow 4b, 2b2\tau) \);
- Fine-tuned B-physics (light charged Higgs vs. SUSY effects);
- Severely threatened by LHC’s \( gg, b \bar{b} \rightarrow h, H, A \rightarrow \tau \tau \) and \( t \rightarrow H^+ b \) searches.
The light-singlet scenario

**CP-even singlet state under \( \sim 125 \) GeV**

- Singlet-like state \((h_1)\) with mass in the range \(\sim [63, 120]\) GeV;
- Uplift of the doublet Higgs \((h_2)\) mass through singlet mixing; \[arXiv:1210.1976\]
- Could explain a (now debatable) hint in \(h_2 \rightarrow \gamma\gamma;\) \[arXiv:1112.3648\]
- Best fit: \(\chi^2 \sim 33.4;\)
- Low energy/LEP limits safe (decoupling singlet \(\Rightarrow\) vanishing production cross-section);
- \(h_1\) decays in the \(b\bar{b}, \tau\tau\) channel
  \(\Rightarrow\) possible searches (provided production cross section does not vanish)!

![Graphs showing \(\chi^2\) distribution and light singlet distribution](image)
The low $\tan\beta / \text{large } \lambda$ region

- No need for large stop effects
  ($m_{\tilde{T}} \sim 350$ GeV, $A_t \sim -100$ GeV below);
- Lightest Higgs state may be doublet or singlet or a strong admixture

<table>
<thead>
<tr>
<th></th>
<th>$m_{h_1}$ (GeV)</th>
<th>$m_{h_2}$ (GeV)</th>
<th>$S_{13}^2$</th>
<th>$\chi^2$ (LHC/37)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>125.3 D</td>
<td>174.5 S</td>
<td>0.1</td>
<td>33.5</td>
</tr>
<tr>
<td></td>
<td>79.3 S</td>
<td>125.4 D</td>
<td>98.9%</td>
<td>33.4</td>
</tr>
<tr>
<td></td>
<td>125.3 S/D</td>
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$\chi^2$ values indicate the goodness of fit with respect to the LHC data.
The light (pseudo)scalar scenario (mass $< m_{h[125]}/2$)

- **Unconventional Higgs decays:** $h_1[125 \text{ GeV}] \rightarrow 2A_1$ ($h_2[125 \text{ GeV}] \rightarrow 2h_1$);
- **But:** no observed suppression of the conventional decays
  $\Rightarrow$ BR($h[125 \text{ GeV}] \rightarrow \text{inv.}$) $\lesssim 20\%$;  
  [arXiv:1302.5694]
- Therefore $A_1 (h_1)$ under $\sim 62 \text{ GeV}$ must be dominantly **singlet**
  + moderate $\lambda$ (vanishing singlet-doublet coupling);
- Search in $h_1[125 \text{ GeV}] \rightarrow 2A_1 \rightarrow 2(b\bar{b})$ provided BR$\sim 20\%$.  
  [arXiv:1309.4939]
The NMSSM Higgs sector offers several unconventional possibilities as compatible with TeVatron/ATLAS/CMS results as a SM-like Higgs boson.

- **Light-doublet scenario** tightly surrounded by existing limits.
- **Light-singlet scenario** natural uplift of the SM-like mass; search in $h_1 \rightarrow \tau\tau$ channel.
- **Unconventional Higgs decays** $h[125\text{ GeV}] \rightarrow 2A_1/h_1$: configuration limited by success of conventional searches; can be looked for in the $4b$ final state.

**LHCb Higgs searches are useful probes of unconventional scenarios!**

- Other marginally compatible possibilities…