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

Florian Domingo (DESY - Hamburg)

In collaboration with G. Weiglein

Workshop "Implications of LHCb measurements and future prospects"

October, 16th 2013

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: μ-problem

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

- μ : SUSY parameter → Natural Scale: $O(M_{\text{Planck,GUT,etc.}})\ldots$ or Zero!
- LEP Constraints on Chargino masses: $\mu \gtrsim 100\,\text{GeV}$
- Electroweak Symmetry Breaking needs: $\mu \lesssim O(TeV)$
- Additional Gauge-Singlet superfield $\hat{S}$ [Fayet (1975)]

  v.e.v. $\langle S \rangle = s \Rightarrow \mu_{eff} = \lambda s$
- $\mathbb{Z}_3$-symmetry: scale-invariant superpotential ⇒ *No naturalness problem!*

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: μ-problem

$$W_{NMSSM} \ni \lambda \, \hat{S} \, \hat{H}_u \cdot \hat{H}_d$$

- μ : SUSY parameter → Natural Scale: $O(M_{\text{Planck,GUT,etc.}})\ldots$ or Zero!
- LEP Constraints on Chargino masses: $\mu \gtrsim 100\,\text{GeV}$
- Electroweak Symmetry Breaking needs: $\mu \lesssim O(TeV)$
- Additional Gauge-Singlet superfield $\hat{S}$ *[Fayet (1975)]*

  v.e.v. $\langle S \rangle = s \quad \Rightarrow \quad \mu_{eff} = \lambda s$
- $\mathbb{Z}_3$-symmetry: scale-invariant superpotential ⇒ *No naturalness problem!*

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: μ-problem

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

- μ : SUSY parameter → Natural Scale: $O(M_{\text{Planck,GUT,etc.}})\dots$ or Zero!
- LEP Constraints on Chargino masses: $\mu \gtrsim 100\,\text{GeV}$
- Electroweak Symmetry Breaking needs: $\mu \lesssim O(TeV)$
- Additional Gauge-Singlet superfield $\hat{S}$ *[Fayet (1975)]*

  v.e.v. $\langle S \rangle = s \quad \Rightarrow \quad \mu_{eff} = \lambda s$
- $\mathbb{Z}_3$-symmetry: scale-invariant superpotential ⇒ *No naturalness problem!*

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 ~ 125.5 GeV.
  [ATLAS,CMS,TeVatron]

$$\text{MSSM:}\quad m^2_{h_{SM}} \simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left\{\ln\frac{m^2_{\tilde{T}}}{m_t^2} + \frac{A_t^2}{m^2_{\tilde{T}}}\left(1 - \frac{A_t^2}{12 m^2_{\tilde{T}}}\right)\right\}$$

- 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:* $m_{h_{SM}} \lesssim 130$ GeV.
  However: large A_t not favoured by SUSY-breaking + $m_{\tilde{T}} \gtrsim$ TeV stretches Hierarchy.
- NMSSM: *additional tree-level contribution* for large λ, low $\tan\beta$.
  $\Rightarrow$ *NMSSM upper bound:* $m_{h_{SM}} \lesssim 140$ 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 λ).

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): λ, κ, $\tan\beta$, M_A, $\mu_{\rm eff}$, A_κ.

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 ~ 125.5 GeV.
  [ATLAS,CMS,TeVatron]

$$\text{MSSM:}\ \ m^2_{h_{SM}} \simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left\{\ln\frac{m^2_{\tilde{T}}}{m_t^2} + \frac{A_t^2}{m^2_{\tilde{T}}}\left(1 - \frac{A_t^2}{12 m^2_{\tilde{T}}}\right)\right\}$$

- 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:* $m_{h_{SM}} \lesssim 130$ GeV.
  However: large A_t not favoured by SUSY-breaking + $m_{\tilde{T}} \gtrsim$ TeV stretches Hierarchy.
- NMSSM: *additional tree-level contribution* for large λ, low $\tan\beta$.
  $\Rightarrow$ *NMSSM upper bound:* $m_{h_{SM}} \lesssim 140$ 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 λ).

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): λ, κ, $\tan\beta$, M_A, μ_{eff}, A_κ.

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.
  [ATLAS,CMS,TeVatron]

NMSSM: $$m^2_{h_{SM}} \simeq M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left\{\ln\frac{m^2_{\tilde{T}}}{m_t^2} + \frac{A_t^2}{m^2_{\tilde{T}}}\left(1 - \frac{A_t^2}{12 m^2_{\tilde{T}}}\right)\right\}$$

- 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:* $m_{h_{SM}} \lesssim 130$ GeV.
  However: large A_t not favoured by SUSY-breaking + $m_{\tilde{T}} \gtrsim$ TeV stretches Hierarchy.
- NMSSM: *additional tree-level contribution* for large λ, low $\tan\beta$.
  $\Rightarrow$ *NMSSM upper bound:* $m_{h_{SM}} \lesssim 140$ 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 λ).

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): λ, κ, $\tan\beta$, M_A, $\mu_{\rm eff}$, A_κ.

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 ~ 125.5 GeV.
  [ATLAS,CMS,TeVatron]

NMSSM: $$m^2_{h_{\rm SM}} \simeq M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left\{\ln \frac{m^2_{\tilde{T}}}{m_t^2} + \frac{A_t^2}{m^2_{\tilde{T}}}\left(1 - \frac{A_t^2}{12 m^2_{\tilde{T}}}\right)\right\}$$

- 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:* $m_{h_{\rm SM}} \lesssim 130$ GeV.
  However: large A_t not favoured by SUSY-breaking + $m_{\tilde{T}} \gtrsim$ TeV stretches Hierarchy.
- NMSSM: *additional tree-level contribution* for large λ, low $\tan\beta$.
  $\Rightarrow$ *NMSSM upper bound:* $m_{h_{\rm SM}} \lesssim 140$ 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 λ).

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): λ, κ, $\tan\beta$, M_A, $\mu_{\rm eff}$, A_κ.

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;
- Landau poles: absence below the GUT scale; *[hep-ph/0406215,*
- Soft terms at the TeV scale; *hep-ph/0508022]*
- Dark Matter: requirement for a neutralino LSP;
- Limits on supersymmetric particles from LEP;
- Limits from B- and Υ-physics (under a strong Minimal Flavour Violation hypothesis): $BR(B \to X_s\gamma)$, $BR(B^+ \to \tau\nu_\tau)$, $BR(\bar{B}_s \to \mu^+\mu^-)$, $BR(B \to X_s\mu^+\mu^-)$, $\Delta M_{d,s}$, $BR(\Upsilon \to A\gamma)$, $\eta_b(1S) - A$ 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.
[arXiv:0811.4169,arXiv:1102.1898,arXiv:1301.2345]

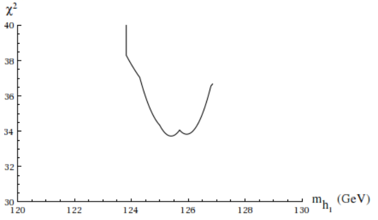
HiggsSignals 1.0.0

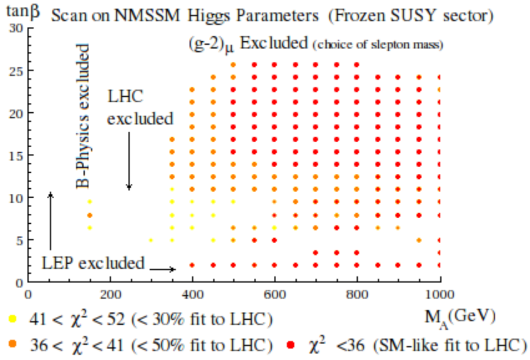
Confrontation of the Higgs sector to the rates measured at TeVatron, ATLAS and CMS ($\sim$ 125 GeV): statistical test. $\Rightarrow$ Definition of a χ^2 test (out of 37 observables)
[arXiv:1305.1933]

The SM and the Decoupling limits

SM-limit

- Singlet decoupling: $\lambda \sim \kappa \to 0$ (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: $M_A \gg M_Z$;

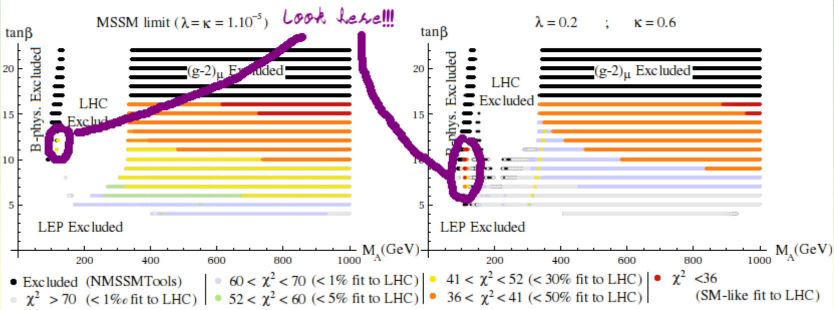
Correct kinematical range for the light doublet ensured through:

* **Loop corrections** (MSSM-like, large $\tan\beta$);
* **λ contribution at Tree-level** (NMSSM specific, low $\tan\beta$).

The light-doublet scenario

~ 125 GeV state identified to the second CP-even doublet state

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

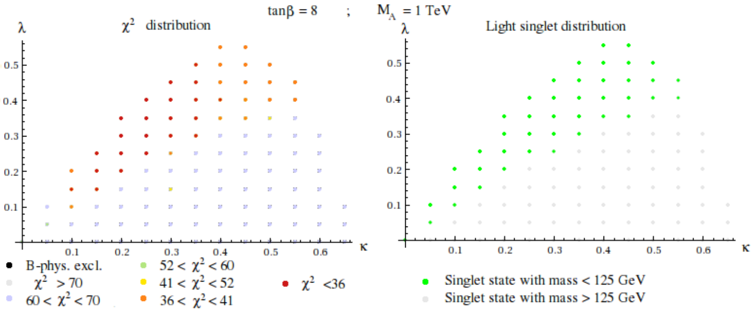


The light-singlet scenario

CP-even singlet state under ~ 125 GeV

- Singlet-like state (h_1) with mass in the range ~ [63, 120] GeV;
- Uplift of the doublet Higgs (h_2) mass through singlet mixing; *[arXiv:1210.1976]*
- Could explain a (now debatable) hint in $h_2 \to \gamma\gamma$; *[arXiv:1112.3648]*
- Best fit: $\chi^2 \sim 33.4$;
- Low energy/LEP limits safe (decoupling singlet ⇒ *vanishing production cross-section*);
- h_1 decays in the $b\bar{b}$, $\tau\tau$ channel

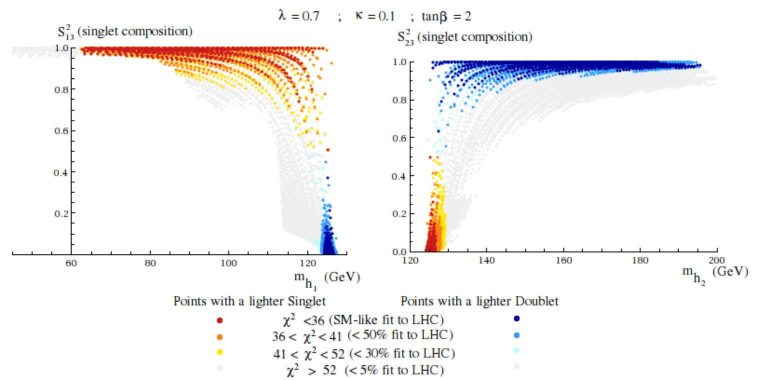
  ⇒ possible searches (provided production cross section does not vanish)!



The low $\tan\beta$ / large λ region

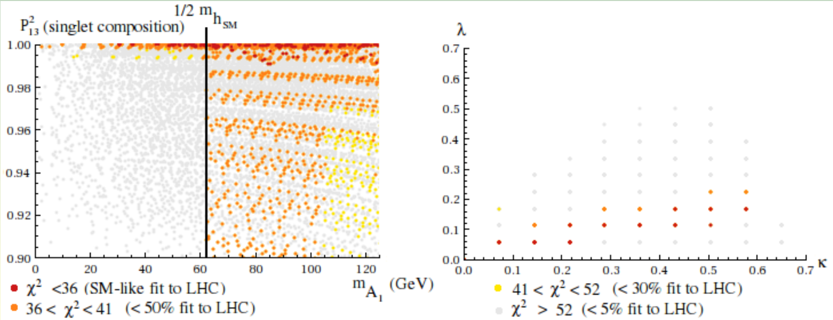
- **No need for large stop effects** ($m_{\tilde{T}} \sim 350$ GeV, $A_t \sim -100$ GeV below);
- Lightest Higgs state may be doublet or singlet or a strong admixture

m_{h_1} (GeV)	125.3 D	79.3 S	125.3 S/D
m_{h_2} (GeV)	174.5 S	125.4 D	125.4 S/D
$S_{13}^2 = 0.1$	0.1%	98.9%	50.3%
χ^2 (LHC/37)	33.5	33.4	35.0



The light (pseudo)scalar scenario (mass $< m_{h[125]}/2$)

- **Unconventional Higgs decays**: $h_1[125\text{ GeV}] \to 2A_1$ ($h_2[125\text{ GeV}] \to 2h_1$);
- **But:** no observed suppression of the conventional decays
  $\Rightarrow$ BR(h[125 GeV] $\to$ inv.) $\lesssim 20\%$; *[arXiv:1302.5694]*
- Therefore A_1 (h_1) under $\sim$ 62 GeV must be dominantly **singlet**
  + moderate λ (vanishing singlet-doublet coupling);
- Search in $h_1[125\text{ GeV}] \to 2A_1 \to 2(b\bar{b})$ provided BR$\sim 20\%$. *[arXiv:1309.4939]*



Conclusion

- 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 $h_1 \to \tau\tau$ channel.
- Unconventional Higgs decays $h[125\text{ GeV}] \to 2A_1/h_1$: 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…