Higgs bosons in the Next-to-Minimal-Supersymmetric-SM

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The Next-to-MSSM

Why adding a singlet?

MSSM Problems:

1. *The μ problem*:

$$V_{\text{Higgs}}^{\text{MSSM}} = (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2) + \ldots \to v_u^2 = \mathcal{O}(\overbrace{-|\mu|^2}^{\mathcal{O}(?)} \overbrace{-m_{H_u}^2}^{\mathcal{O}(M_{\text{SUSY}})}) \stackrel{!}{=} (248\,GeV)^2$$

2. Tree-level m_h of the Higgs is bounded by the Z mass $m_h < M_Z \Rightarrow$ large radiative corrections are needed.

Solution: *Add a singlet!*

1. One complex field is added, singlet under all gauge fields.
2. The parameter μ is substituted by the VEV of a singlet field, $S \to \langle s \rangle$, of the order of the weak or SUSY breaking scales.
3. New terms contributing to the mass of the lighter Higgs. The mass can reach easily 125 GeV at tree level.

Implications:

1. Extended Higgs Sector.
2. Extended neutralino sector: New scenarios for dark matter candidates.
3. The MSSM as a subspace of parameter space of the NMSSM.

The Higgs sector of the NMSSM

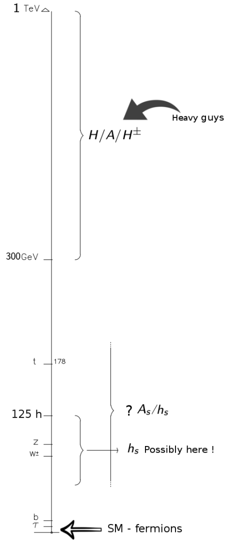
Extended Higgs sector!

Higgs spectrum: Assuming CP-conservation

1. 3 neutral CP-even states H_i, including a 125 GeV one.
2. 2 neutral CP-odd states A, A_S
3. a charged Higgs $H^{\pm}$

In contrast with the MSSM, we have 2 SU(2) doublets **+ 1 gauge singlet** $\rightarrow$ 10 real degrees of freedom!
3 massless Goldstone d.o.f. are absorbed by the gauge bosons through the Higgs mechanism, and there remain **7 physical Higgs bosons**.

The Higgs sector of the NMSSM



These bosons must correspond to

- A neutral CP-even state with a mass $m_h \sim 125$ GeV and couplings similar to those of a SM Higgs boson.
- A heavy nearly degenerate SU(2) multiplet $H/A/H^{\pm}$ (like in the MSSM), with a mass $\gtrsim 300$ GeV.
- Mostly singlet-like neutral CP-even h_s and CP-odd state A_s with model dependent masses, possibly below 125 GeV; hardly constrained by previous experiments (LEP).

A singlet-like CP-even boson h_s below 125 GeV

Particular scenario: a CP-even boson h_s with mass below $m_{h_s} < m_{h_{125}} = 125$ GeV

Why?

- Off-diagonal terms in a matrix (e.g. the mass matrix) tend to increase the gap between the eigenvalues. Therefore, a lighter boson $m_{h_s} < m_{h_{125}}$ pushes up the tree level mass of the SM-like higgs h_{125} (through mixing), requiring smaller radiative corrections to reach the 125 GeV measured value $\Rightarrow$ *Naturalness*.
- $m_{h_s} > 62.5$ preferred to avoid an unseen possibly dominant $h_{125} \to h_s h_s$

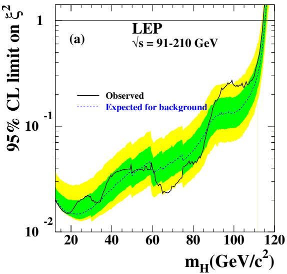
Couplings and decays of h_s

- h_s has small couplings to gauge bosons g_{h_s}: only possible through mixing with the doublets.
- Sum rule: $g_h^2 + g_{h_s}^2 + g_H^2 = 1$. Identifying h with the measured 125 GeV boson, from the LHC Run 1 we have (arXiv:1409.1588):

  $0.85 < g_h$ at $95\% CL \rightarrow$ **we can constrain g_{h_s}**

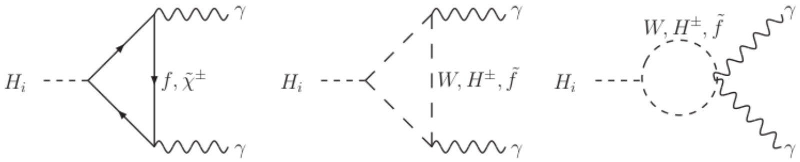
- **Constraints from LEP**

$$\xi^2 = g_X^2 \times \frac{BR(X \to b\bar{b})}{BR(h_{SM} \to b\bar{b})} \qquad (1)$$



Couplings and decays of h_s

- Loop induced coupling to photons: given by the couplings to tops, W **and new SUSY particle loops: mainly charginos**

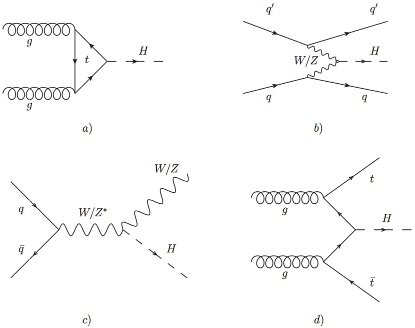


$$\Gamma^{h_s}_{\gamma\gamma} = \frac{\alpha^2 G_F m^3_{h_s}}{128\sqrt{2}\pi^3} \left| \sum_f \mathcal{A}_f^{\gamma\gamma} + \mathcal{A}_W^{\gamma\gamma} + \mathcal{A}_{H^\pm}^{\gamma\gamma} + \overbrace{\sum_{\tilde{f}} \mathcal{A}^{\gamma\gamma} + \sum_{\chi^\pm} \mathcal{A}_{\chi^\pm}^{\gamma\gamma}}^{\mathcal{A}_{SUSY}} \right|^2 \quad (2)$$

.

Production of h_s at the LHC

- Same production modes as a SM higgs: ggF, ttH, VBF and VH.
- ggF is the dominant production mode (by far!), due to suppression of the coupling to gauge bosons.
- New SUSY particle contribution: stops loops. However, this contribution is expected to be rather small.



$$\sigma_{LO}(pp \to h_s) \approx \sigma_0^{h_s} \times \tau_{q,\tilde{q}} \frac{d\mathcal{L}^{gg}}{d\tau_{h_s}}, \quad \text{with } \tau = \frac{4m_{q,\tilde{q}}}{m_{h_s}} \tag{3}$$

$$\sigma_0^{h_s} = \frac{\alpha_S^2 G_F}{288\sqrt{2}\pi} \left| \sum_q g_{h_s qq} A_{1/2}^{h_s}(\tau_q) + \sum_{\tilde{q}} g_{h_s \tilde{q}\tilde{q}} A_0^{h_s}(\tau_{\tilde{q}}) \right|^2 \tag{4}$$

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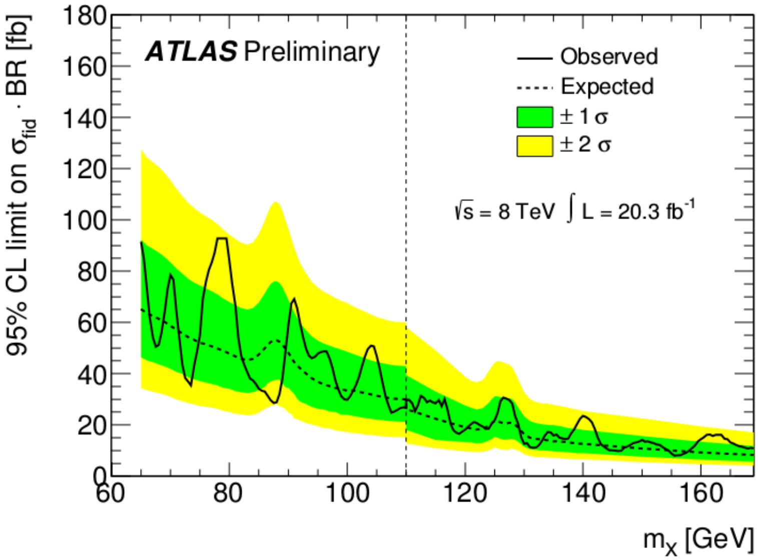
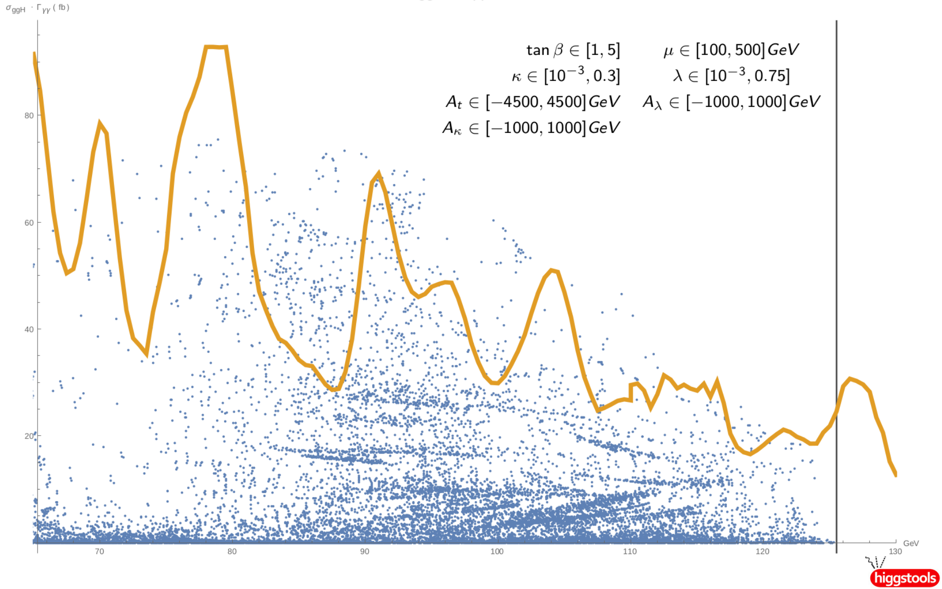
Search strategy: The $\gamma\gamma$ channel

Why this channel?

- Very clean! not large background expected. It remains 'clean' at 14 TeV.
- Good detector resolution!
- Despite of the suppression of the W loop, new SUSY particles could enhance the partial diphoton width, namely charginos and, to a less extent, charged Higgs and stops.
- Also, **a possible suppression in the dominant BR($h_s \to b\bar{b}$) channel could substantially enhance the other channels, notably BR($h_s \to \gamma\gamma$).**
- Given the current limits reported by ATLAS and CMS, particularly those from ATLAS on $\gamma\gamma$ searches for scalar resonances below 125 GeV (ATLAS-CONF-2014-031): **is h_s potentially visible at the LHC Run 2?**


ATLAS Preliminary
Observed
Expected
± 1 σ
± 2 σ
√s = 8 TeV ∫ L = 20.3 fb⁻¹
95% CL limit on σfid · BR [fb]
mX [GeV]
0
20
40
60
80
100
120
140
160
180
60
80
100
120
140
160

$\sigma_{ggH} \cdot \Gamma_{\gamma\gamma}$ (fb)



Take home message:

- In the NMSSM a light mostly singlet-like Higgs boson is very attractive in order to reduce fine tuning.
- As a singlet, its couplings could be really weak...
- **Current data set constraints on its properties.**
- Such a light guy **is potentially visible at the LHC RUN 2 in the diphoton channel!**

Thanks!

Backup

The 3×3 CP-even mass matrix in the basis $\left(H_{d,r}, H_{u,r}, S_r\right)$ reads:

$$\mathcal{M}_S^2 = \begin{pmatrix} g^2 v_d^2 + \mu_{\text{eff}} B_{\text{eff}} \tan\beta & (2\lambda^2 - g^2) v_u v_d - \mu_{\text{eff}} B_{\text{eff}} & \lambda\left(2\mu_{\text{eff}} v_d - (B_{\text{eff}} + \kappa s) v_u\right)\right) \\ & g^2 v_u^2 + \mu_{\text{eff}} B_{\text{eff}} \cot\beta & \lambda\left(2\mu_{\text{eff}} v_u - (B_{\text{eff}} + \kappa s) v_d\right)\right) \\ & & \lambda A_\lambda \frac{v_u v_d}{s} + \kappa s (A_\kappa + 4\kappa s) \end{pmatrix} \quad (5)$$

In the β basis, (corresponding to the MSSM decoupling limit):

$$\begin{pmatrix} h' \\ H' \\ h'_s \end{pmatrix} = \overbrace{\begin{pmatrix} \cos(\beta) & \sin(\beta) & 0 \\ -\sin(\beta) & \cos(\beta) & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{R(-\beta)} \begin{pmatrix} H^0_{d,r} \\ H^0_{u,r} \\ S_r \end{pmatrix} \quad (6)$$

$$\mathcal{M}'^2_{S,h'h'} = M_Z^2 \left(\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 2\beta\right) \quad (7)$$

$$\mathcal{M}'^2_{S,h'h'_s} = \lambda v \left(2\mu - \Lambda \sin 2\beta\right) \quad (8)$$

$$\mathcal{M}'^2_{S,H'h'_s} = -\lambda v \Lambda \cos 2\beta \quad (9)$$

$$\mathcal{M}'^2_{S,h'H'} = -\frac{1}{2} \sin(4\beta) M_Z^2 \left(1 - \frac{\lambda^2}{g^2}\right) \quad (10)$$

$$\mathcal{M}'^2_{S,H'H'} = M_A^2 + M_Z^2 \left(1 - \frac{\lambda^2}{g^2}\right) \sin^2(2\beta) \quad (11)$$

$$\mathcal{M}'^2_{S,h'_s h'_s} = \lambda^2 v^2 \sin 2\beta \left(\frac{M_A^2 \sin 2\beta}{4\mu^2} - \frac{\kappa}{2\lambda}\right) + \frac{\kappa \mu A_\kappa}{\lambda} + \frac{4\kappa^2 \mu^2}{\lambda^2} \quad (12)$$

where we have defined $\Lambda = B + \kappa s = A_\lambda + 2\kappa s$.

let's perform a last transformation in CP-even Higgs space, via a certain matrix T such that it takes us to the mass eigenbasis, i.e. $(h', H', S) \xleftarrow{T} (h, H, h_s)$.

$$\begin{pmatrix} T_{h',h} & T_{h',H} & T_{h',h_s} \\ T_{H',h} & T_{H',H} & T_{H',h_s} \\ T_{h'_s,h} & T_{h'_s,H} & T_{h'_s,h_s} \end{pmatrix} \begin{pmatrix} h \\ H \\ h_s \end{pmatrix} = \begin{pmatrix} h' \\ H' \\ h'_s \end{pmatrix} \tag{13}$$

RECALL that one can define the limit NMSSM → MSSM + Pure singlet as the limit

$$\begin{pmatrix} T^{\mathrm{MSSM}}_{2\times 2} & 0 \\ 0 & 1 \end{pmatrix} \tag{14}$$

Higgs reduced couplings in the β-basis,

$$g_{d,i} = T_{h',i} - \tan\beta\, T_{H',i}, \quad g_{u,i} = T_{h',i} + \cot\beta\, T_{H',i}, \quad g_{V,i} = T_{h',i} \tag{15}$$

Contributions in the loop induced decay to photons

$$\sum_f \mathcal{A}_f^{\gamma\gamma} \approx \mathcal{A}_t^{\gamma\gamma} = \frac{4}{3}\left(T_{i,h'} - \tan\beta\, T_{i,H'}\right) A_{1/2}^h(\tau_t) \tag{16}$$

$$\mathcal{A}_W^{\gamma\gamma} = T_{ih'} A_1^h(\tau_W) \tag{17}$$

$$\mathcal{A}_{H^\pm}^{\gamma\gamma} = \frac{M_W^2}{M_{H^\pm}^2} \lambda_{h_i H^+ H^-} A_0^h(\tau_H^\pm) \tag{18}$$

$$\mathcal{A}_{\chi^\pm}^{\gamma\gamma} = \frac{M_W}{m_\chi^\pm} g_{h_i \chi^+ \chi^-} A_{1/2}^h(\tau_{\chi^\pm}) \tag{19}$$

$$g_{h_i \chi_j \chi_k} = \tag{20}$$

$$T_{is'} \frac{\lambda v}{M_W} U_{j2} V_{k2}$$

$$+ T_{ih'} \sqrt{2}\left(\sin\beta\, U_{j1} V_{k2} + \cos\beta\, U_{j2} V_{k1}\right)$$

$$+ T_{iH'} \sqrt{2}\left(\cos\beta\, U_{j1} V_{k2} - \sin\beta\, U_{j2} V_{k1}\right)$$

$$\sum_{\tilde{f}} \mathcal{A}_{\tilde{f}}^{\gamma\gamma} = \sum_{\tilde{f}_j} \frac{g_{h_i \tilde{f}_i \tilde{f}_j}}{m_{\tilde{f}_i}^2} N_c Q_{\tilde{f}_i} A_o^{h_i}(\tau_{f_{\tilde{f}_i}}) \tag{21}$$

$$\begin{aligned} g_{h_i \tilde{t}_1 \tilde{t}_1} \quad = \quad & T_{ih'} \Big[(\cos^2\beta - \sin^2\beta) M_Z^2 \left(\frac{1}{2}\cos^2\theta_T - \frac{2}{3}\cos 2\theta_T \sin^2\theta_W\right) + m_t^2 \\ & - \frac{1}{2}\sin 2\theta_T\, m_t (A_t - \mu\cot\beta) \Big] \\ & + T_{iH'} \Big[-2\sin\beta\cos\beta M_Z^2 \left(\frac{1}{2}\cos^2\theta_T - \frac{2}{3}\cos 2\theta_T \sin^2\theta_W\right) + m_t^2 \cot\beta \\ & - \frac{1}{2}\sin 2\theta_T\, m_t (A_t \cot\beta + \mu) \Big] \end{aligned}$$