Recall: SUSY $\rightarrow$ at least 2 Higgs doublets $H_u, H_d$ (+ Singlets ?)

All CP-even Higgs bosons $H_i$ “share” their reduced couplings $\xi_i$ (normalized w.r.t. the SM-like coupling) to electroweak gauge bosons:

$$\sum_i \xi_i^2 = 1$$

The couplings to $b$-quarks, $t$-quarks ($\rightarrow$ gluon-gluon) can be enhanced or reduced, depending on $\tan\beta$ and the Higgs mixing angles.

At present: (mild) excesses of events at ATLAS/CMS for $M_H \sim 140 - 145$ GeV

What if these excesses are confirmed?
MSSM:

In the MSSM (minimal Higgs sector with two Higgs doublets) the mass $M_h$ of the Standard Model-like Higgs Boson is bounded from above by

$$\left( M_{h \text{ upper}} \right)^2 \simeq M_Z^2 \cos^2 2\beta + \frac{m_t^4}{4\pi^2 v^2} \left( \ln \left( \frac{M_{\text{stop}}^2}{m_t^2} \right) + \frac{A_t^2}{M_{\text{stop}}^2} \left( 1 - \frac{A_t^2}{12M_{\text{stop}}^2} \right) \right) + \ldots$$

$$\rightarrow M_h \lesssim 135 \text{ GeV} \text{ if } M_{\text{stop}} \lesssim 3 \text{ TeV}$$

The second “heavy” CP-even Higgs boson $H$ can have a mass in the 140-150 GeV range (with $M_h \sim 115$ GeV, $\tan \beta \sim 8 – 10$), but then its BR into $WW/ZZ$ is small, $< 10^{-2}/10^{-3}$

(Question: could this be enhanced in the case of CP-violation?)

$$\rightarrow \text{Split Susy, extra vector-like matter, extra } U(1)', \text{ NMSSM (}\lambda\text{-Susy)}, \ldots$$
Split SUSY:

Supersymmetry does not solve the Hierarchy Problem, but

— a light gaugino (bino) provides a dark matter candidate
— sparticles lead to gauge coupling unification
→ scalar sparticles like stops can be heavy

\[ M_H \gtrsim 140 \text{ GeV if } M_{\text{stop}} \gtrsim 10^6 \text{ GeV} \]

(D. Alves, E. Izaguirre, Jay G. Wacker, 1108.3390)
Extra Vector-like Matter

— Add extra SU(5) multiplets, keeping perturbative unification at the GUT scale: e.g. one $10 + \overline{10}$ and a superpotential
  \[ W = \ldots + H_u 10 \overline{10} + M_{10} 10 \overline{10} \]

— Assume that the extra scalars and fermions are sufficiently massive in order to comply with negative direct searches and electroweak precision observables ($\gtrsim 300 – 400$ GeV)

→ Rad. corrs. to $M_H$ of the same type as top-stop loops:
  \[ \rightarrow M_H \gtrsim 140 \text{ GeV if } M_{\text{scalar}} \gtrsim 5M_{\text{fermion}} \]

(M. Asano, T. Moroi, R. Sato, T. Yanagida, 1108.2402,
M. Endo, K. Hamaguchi, S. Iwamoto, N. Yokozaki, 1108.3071,
J. Evans, M. Ibe, T. Yanagida, 1108.3437)
Extra U(1)'

If the Higgs doublets carry U(1)' charges:
Extra quartic Higgs couplings from U(1)'-D-terms, extra SM-singlets (see the NMSSM below)

→ Larger SM-like Higgs mass possible

Models must comply with lower bounds on \( M_{Z'} \gtrsim 2 \) TeV, absence of U(1)' anomalies → enlarged field content

Scenarios with \( M_H \gtrsim 140 \) GeV are possible

(E. Ma, 1108.4029)
**NMSSM**

Solution of the $\mu$-problem of the MSSM by an additional gauge singlet superfield $S$ (the simplest Susy extension of the SM with a scale invariant superpotential):

$$W_{MSSM} = \ldots + \mu H_u H_d \quad \rightarrow \quad W_{NMSSM} = \ldots + \lambda S H_u H_d + \frac{\kappa}{3} S^3 \left( + \ldots \right)$$

$\rightarrow$ 3 CP-even Higgs bosons, mixtures of $H_u$, $H_d$ and $S$

$\rightarrow$ Upper bound on the lightest CP-even state, valid also for the general NMSSM with additional Susy mass/tadpole terms:

$$\left( M_{H}^{upper} \right)^2 \simeq \left( M_{H,MSSM}^{upper} \right)^2 + \lambda^2 M_Z^2 \sin^2 2\beta + \ldots$$

(The second tree-level term decreases as $\tan^{-2} \beta$)

Assume $\lambda \lesssim 0.75$ ($\lambda(M_{GUT}) < \infty$), $M_{stop} \lesssim 1$ TeV, $m_{top} \sim 173$ GeV, incl. full electroweak 1-loop and $h_t/\alpha_s$-2-loop corrections (Degrassi, Slavich):

$$M_{H}^{upper} \simeq 138 \text{ GeV}$$
Moreover: \( M_H = M_H^{upper} \) only if \( H - S \)–mixing terms vanish!

Ways out:

a) \( \lambda > 0.75 \) (\( \lambda \)-Susy): either
   — additional matter/gauge interactions such that \( \lambda(Q^2) \) does not increase (strongly) with \( Q^2 \), or
   — accept \( \lambda(Q'^2) \rightarrow \infty \), new strong interactions at \( Q' < M_{GUT} \)
     \( (S = \text{composite field, fat Higgs...}) \)
   \( \rightarrow M_H \sim 200 \text{ GeV} \) possible

b) Drop the (unneccessary) assumption that \( H_{SM} \equiv H_1 \):
   IF \( H_{SM} = H_2 \) (\( H_1 \) mostly singlet, with a mass possibly below 114 GeV):
     Typically \( M_{H_{SM}} > M_H^{upper} \) due to \( H - S \)–mixing!

BUT: The reduced coupling to electroweak gauge bosons \( \xi_2 \) of \( H_2 \) becomes \( \xi_2 < 1 \) due to \( H - S \)–mixing; also: slightly reduced couplings (by 70-90\%) to \( b \)-quarks, \( t \)-quarks/gluon-gluon (U.E., 1108.0157):
Examples ($\lambda \sim 0.7, \tan \beta \sim 2.7$):

<table>
<thead>
<tr>
<th>$M_{H_2}$</th>
<th>140 GeV</th>
<th>145 GeV</th>
<th>150 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi_2$</td>
<td>0.92</td>
<td>0.86</td>
<td>0.73</td>
</tr>
<tr>
<td>$M_{H_1}$</td>
<td>91 GeV</td>
<td>97 GeV</td>
<td>115 GeV</td>
</tr>
<tr>
<td>$\xi_1$</td>
<td>0.40</td>
<td>0.51</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Note: $\xi_1^2 + \xi_2^2 \simeq 1$,
$M_{H_1}$ and $\xi_1$ are consistent with LEP constraints, which are particularly weak for $M_{H_1} \sim 95$ GeV (Dermisek, Gunion)

$\rightarrow M_{H_{SM}} \gtrsim 140$ GeV is possible, but slightly reduced signal rates!
Note:

— $H_1$ could be visible at the Tevatron (if CDF/D0 look for $M_H$ as light as $\sim 100$ GeV)

— The $H_1$ production cross section $\times BR(H_1 \to \gamma\gamma)$ could be enhanced by a factor 6 w.r.t. the SM, if the $H_d$ component of $H_1$ happens to be small (U.E., 1012.1201)
  $\to$ the reduced width for $H_1 \to b\bar{b}$ enhances the $BR(H_1 \to \gamma\gamma)$ by a factor up to 10

Moreover: possibly less $E_T^{\text{miss}}$ in sparticle decay cascades in the NMSSM compared to the MSSM from additional bino $\to$ singlino transitions

  $\to$ An attractive scenario within an attractive model, but:

Finally, after $\sim 35$ years of Susy extensions of the Standard Model, DATA will decide and NOT “naturalness arguments” of theorists (including mine...