Footprints of Supersymmetry on Higgs Properties

Takeo Moroi (Tokyo)

Ref:


PPC2015, Deadwood, SD, '15.07.02
1. Introduction
What should we do with future collider experiments?

⇒ Detailed studies of Higgs properties to find a signal of new physics

Expected 1-σ accuracy of Higgs width measurements [%]

[Snowmass 2013 Report (Higgs Working Group); Peskin]

<table>
<thead>
<tr>
<th>√s [GeV]</th>
<th>LHC</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>1400</td>
<td>500</td>
</tr>
<tr>
<td>∫dt L [fb⁻¹]</td>
<td>300</td>
<td>3000</td>
</tr>
<tr>
<td>γγ</td>
<td>10 – 14</td>
<td>4 – 10</td>
</tr>
<tr>
<td>gg</td>
<td>12 – 16</td>
<td>6 – 10</td>
</tr>
<tr>
<td>bb</td>
<td>20 – 26</td>
<td>8 – 14</td>
</tr>
<tr>
<td>ττ</td>
<td>12 – 16</td>
<td>4 – 10</td>
</tr>
</tbody>
</table>

⇒ Hints of BSM physics may be found in Higgs properties (in particular, with e⁺e⁻ colliders)
Today, I discuss what happens in SUSY models

- Higgs decay widths in the minimal SUSY standard model (MSSM)
- Can ILC see a deviation, even if MSSM particles are out of the reach of LHC Run2?

Outline

1. Introduction
2. MSSM Higgs: Brief Overview
3. Partial Decay Widths of MSSM Higgs
4. Summary
2. MSSM Higgs: Brief Overview
The MSSM contains two Higgs doublets, called $H_u$ & $H_d$

$$H_u^0 = v \sin \beta + \frac{1}{\sqrt{2}} (h \cos \alpha + H \sin \alpha + iA \sin \beta) + (\text{NG})$$

$$H_d^0 = v \cos \beta + \frac{1}{\sqrt{2}} (-h \sin \alpha + H \cos \alpha - iA \cos \beta) + (\text{NG})$$

$h$: The lightest Higgs boson

Decoupling limit:

$$\cos(\beta - \alpha) \to 0 \text{ as } m_A \to \infty$$

Higgs vertices (tree level)

$$g_{h\bar{b}b} = -\left(\frac{\sin \alpha}{\cos \beta}\right) g_{h\bar{b}b}^{(\text{SM})} = \left[1 - \cos(\beta - \alpha) \tan \beta + \cdots\right] g_{h\bar{b}b}^{(\text{SM})}$$

$$g_{hZZ} = \sin(\beta - \alpha) g_{hZZ}^{(\text{SM})} = \left[1 - \frac{1}{2} \cos^2(\beta - \alpha) + \cdots\right] g_{hZZ}^{(\text{SM})}$$
Higgs properties depend on $A_t$: $\mathcal{L}_{\text{soft}} = -y_t A_t \tilde{Q}_L \tilde{c}_R H_u + \text{h.c.}$

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2} \left[ \log \frac{m_t^2}{m_t^2} + \frac{A_t^2}{m_t^2} \left( 1 - \frac{A_t^2}{12m_t^2} \right) \right]$$

Four possible values of $A_t$ to realize $m_h \simeq 125.7$ GeV

PL: Positive & Large $A_t$

PS: Positive & Small $A_t$

NL: Negative & Large $|A_t|$

NS: Negative & Small $|A_t|$
Higgs mixing angle

\[
\cos(\beta - \alpha) = \frac{m_Z^2 \sin 4\beta}{2m_A^2} \left( 1 + \frac{\delta M_{11}^2 - \delta M_{22}^2}{2m_Z^2 \cos 2\beta} - \frac{\delta M_{12}^2}{m_Z^2 \sin 2\beta} \right) + \cdots
\]

- \tan \beta = 10
- \hat{M}_f = 5 \text{ TeV}
- \hat{M}_3 = \mu = 5 \text{ TeV}
- GUT relation assumed

\[\Rightarrow \text{Large } A_t \text{ may enhance } \cos(\beta - \alpha)\]
Non-holomorphic interaction is also important

[Hall, Rattazzi & Sarid; Hempfling; Carena, Olechowski, Pokorski & Wagner; Choudhury & Gaur; Babu & Kolda]

\[ \mathcal{L}_{\text{eff}} = y_b \bar{b}_R Q_L H_d + \Delta y_b \bar{b}_R Q_L H_u^* + \cdots \]

Bottom-quark mass

\[ m_b = \frac{y_b}{\sqrt{2}} v \cos \beta \left( 1 + \frac{\Delta y_b}{y_b} \tan \beta \right) \equiv \frac{y_b}{\sqrt{2}} v \cos \beta (1 + \Delta_b) \]
$\Delta_b$ is a “non-decoupling” variable, and is proportional to $\tan \beta$

\[ h\bar{b}b \text{ coupling: } \mathcal{L}_{h\bar{b}b} \equiv -g_{h\bar{b}b} h\bar{b}b \]

[Carena, Mrenna & Wagner]

\[
g_{h\bar{b}b} = \left[ \sin(\beta - \alpha) - \frac{\tan \beta - \Delta_b \cot \beta}{1 + \Delta_b} \cos(\beta - \alpha) \right] g_{h\bar{b}b}^{(SM)}
\]
Constraint 1: Perturbativity of $y_b$

- $y_b = \frac{\sqrt{2}m_b}{v \cos \beta (1 + \Delta_b)} \quad \Rightarrow \quad \text{We require } y_b(M_{GUT}) < \infty$

Constraint 2: FCNC via heavy Higgs exchange

[Babu & Kolda]

- $\mathcal{L}_{\text{eff}} \simeq \frac{g m_b}{\sqrt{2} m_W \cos \beta} \left[ \Delta_b^{(\tilde{H})} + O(\Delta_b^2) \right] V_{tb} V_{ts}^* (H + iA) \bar{s}_L b_R$

- $B_s \rightarrow \mu^+ \mu^-$ gives a stringent constraint

Constraint 3: Vacuum stability

[Frere, Jones & Raby; Gunion, Haber & Sher; Casas, Lleyda & Munoz; Kusenko, Langacker & Segre]

- Color & charge breaking vacua exist with large $A_t$
- EWSB vacuum should be long-lived enough (i.e., $S_E \gtrsim 400$)
3. Partial Decay Widths of MSSM Higgs
We calculate $R_F$ using FeynHiggs

$$R_F \equiv \frac{\Gamma(h \rightarrow F)}{\Gamma^{(\text{SM})}(h \rightarrow F)}$$

In our calculation, we have taken account of:

- Higgs mass ($m_h = 125.7$ GeV)
- Flavor constraints (in particular, $B_s \rightarrow \mu^+\mu^-$)
- Perturbativity of $y_b$ up to the GUT scale
- Vacuum stability

Note:

- $R_{ff}$ and $R_{gg}$ may show deviations from 1
- $R_{WW}$ and $R_{ZZ}$ are very close to 1
Parameters

- \( m_{\tilde{Q}} = m_{\tilde{U}} = M_3 = 2, 3, 4, \) and \( 5 \) TeV
- \( m_{\tilde{D}} = m_{\tilde{L}} = m_{\tilde{E}} = \max(m_{\tilde{U}}, |\mu|) \)
- \( M_3 = 3M_2 = 6M_1 \) (approximate GUT relation)
- \( 0.8 \text{ TeV} \leq m_A \leq 6 \text{ TeV} \)
- \( -5 \leq \mu/m_{\tilde{U}} \leq -0.5, \text{ or } 0.5 \leq \mu/m_{\tilde{U}} \leq 5 \)
- \( 5 \leq \tan \beta \leq 50 \)

Numerical calculations

- **FeynHiggs** for Higgs mass and decay widths
- **SuperIso** for flavor observables
- **CosmoTransitions** for vacuum stability
Contours of $R_{bb} - 1: A_t > 0$

- For small $A_t$, $|R_{bb} - 1| \lesssim 0.01$ for $m_A \gtrsim 2 - 3$ TeV
- For large $A_t$, $|R_{bb} - 1|$ can be $O(0.01)$ even for $m_A \sim 5$ TeV
Contours of \( R_{bb} - 1: A_t < 0 \)

**At < 0 & Small |At|**

- \( m_{sfermion} = 5 \text{TeV}, \text{NS} \)

**At < 0 & Large |At|**

- \( m_{sfermion} = 5 \text{TeV}, \text{NL} \)

---

\[ \tan \beta \]

\[ m_A \ [\text{GeV}] \]

\[ Br(B_s \rightarrow \mu \mu) \]

\[ \text{Vacuum} \]

---

Allowed

---
The range of $R_{bb}$ and $R_{\tau\tau}$ (all possible $A_t$)

\[ R_{bb} \text{ is sensitive to the bounds on } A_t \text{ (which is from the vacuum stability, } B_s \rightarrow \bar{\mu}\mu, \text{ and perturbativity for small, medium, and large values of } m_A, \text{ respectively).} \]
Maximal and minimal possible values of $R_{ff}$ and $R_{gg}$

$\Rightarrow R_{bb} - 1$ and $R_{\tau\tau} - 1$ can be $O(0.1)$ even if $m_{\tilde{q}}$ is very large

$\Rightarrow$ Deviations from the SM prediction may be seen, even if MSSM particles are out of the reach of LHC13
4. Summary
I studied the decay widths of the MSSM Higgs, requiring:

- Observed Higgs mass \( m_h \approx 125.7 \text{ GeV} \)
- Flavor constraints (in particular, \( B_s \rightarrow \mu^+\mu^- \))
- Vacuum stability \( S_E > 400 \), if CCB vacua exist
- Perturbativity up to the GUT scale

Sizable deviations from the SM prediction are possible

- Deviations become large for the large \( A_t \) case
- \( \Gamma(h \rightarrow \bar{b}b) \) and \( \Gamma(h \rightarrow \bar{\tau}\tau) \) may show \( O(1 \%) \) deviations
- ILC may observe the deviation even if the superparticles are out of the reach of LHC Run2
Backup
The lightest Higgs mass

\[ \mathcal{L}_{\text{soft}} = -y_t A_t \tilde{Q}_L \tilde{t}_R^c H_u + \text{h.c.} \]

Radiative correction to the lightest Higgs mass

[Okada, Yamaguchi & Yanagida, Ellis, Ridolfi & Zwirner, Haber & Hempfling]

\[ \delta m_h^2 \sim \frac{3m_t^4}{2\pi^2v^2} \left[ \log \frac{m_t^2}{m_{\tilde{t}}^2} + \frac{A_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{A_t^2}{12m_t^2}\right) \right] \]
FCNC via heavy Higgs exchange

\[ \mathcal{L}_{\text{eff}} \approx \frac{gm_b}{\sqrt{2}m_W \cos \beta} \left[ \Delta_b^{(H)} + O(\Delta_b^2) \right] V_{tb}V_{ts}^*(s_L b_R) (H + iA) \]

\( B_s \rightarrow \mu^+\mu^- \) is important

- LHCb result is consistent with the SM prediction
  [Bobeth et al. ('13) + LHCb]

\[ -2.3 \times 10^{-9} < \text{Br}(B_s \rightarrow \mu^+\mu^-) - \text{Br}^{(\text{SM})}(B_s \rightarrow \mu^+\mu^-) < 0.6 \times 10^{-9} \]

- Stringent constraint on \( A_t \) is obtained
Vacuum stability

- Color & charge breaking (CCB) vacua exist with large $A_t$

$$\mathcal{L}_{\text{soft}} = -y_t A_t \tilde{Q}_L \tilde{t}_R^c H_u + \text{h.c.}$$

- $M_3 = \mu = m_{\tilde{q}} = 3$ TeV
- $m_A = 3$ TeV
- $\tan \beta = 10$
- $A_t/m_{\tilde{q}} \simeq -2.5$ (NL)

- EWSB vacuum should be long-lived enough (i.e., $S_E \gtrsim 400$)
$S_E$ is evaluated with CosmoTransitions package

$\mu \simeq m_{10} = 5 \text{TeV}, \tan \beta = 20$, PL

$\mu \simeq m_{10} = 5 \text{TeV}, \tan \beta = 20$, PS

⇒ Too large $A_t$ or $\mu$ is excluded by vacuum stability
The range of $R_{bb}$ and $R_{\tau\tau}$ (small $A_t$ only)

$m_{\tilde{Q}}=m_{\tilde{U}}=2\text{TeV}$

$m_{\tilde{Q}}=m_{\tilde{U}}=5\text{TeV}$
This is just for fun...