Revisit to Non-decoupling MSSM

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hep-ph/1211.2427, 1212.6311

Partially overlaps with 1211.1955 [hep-ph] by Bechtle, Heinemeyer, Stal, Stefaniak, Weiglein and Zeune (Two days)
Discovery of a Higgs-like Boson at the LHC

Two cleanest channels $\gamma\gamma$, $4\ell$: reconstruction masses at 125 GeV

Dilepton $WW^* \rightarrow 2\ell2\nu$ also consistent with $ZZ^* \rightarrow 4\ell$ at 125 GeV

- $\gamma\gamma$: spin 0 or 2 (Landau-Yang)
- Angular correlation prefers CP-even spin zero $0^+$
- couples to weak gauge bosons ($ZZ^*/WW^*$)
- if it is spin-zero, production from gluon fusion
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The SM Higgs? Likely

Signal strength

- Combination of
  - $W,Z \rightarrow bb$  
    
  - $H \rightarrow \tau\tau$  
    
  - $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$  
    
  - $H \rightarrow \gamma\gamma$  
    
  - $H \rightarrow ZZ^{(*)} \rightarrow 4l$  
    
- Signal strength $\mu = \frac{\sigma}{\sigma_{SM}}$ measured assuming $m_H = 125.5$ GeV
  - Only $\pm 4\%$ change to combined $\mu$ for $\pm 1$ GeV
  - Combined $\mu = 1.30 \pm 0.13$ (stat) $\pm 0.14$ (sys)
  - Compatibility between measurements and SM ($\mu = 1$)
    - Common $\mu$ vs SM: 9%
    - with rectangular QCD scale/PDF constraints: 40%
    - All $\mu_{bb}$, $\mu_{\tau\tau}$, $\mu_{WW}$, $\mu_{\gamma\gamma}$, $\mu_{ZZ}$ vs $\mu = 1$: 8% (5 d.o.f)
    - All $\mu_{bb}$, $\mu_{\tau\tau}$, $\mu_{WW}$, $\mu_{\gamma\gamma}$, $\mu_{ZZ}$ vs $\mu = 1.30$: 13% (4 d.o.f)

- ATLAS also sets limits (95%CL; not used in combination):
  - $H \rightarrow \mu\mu$: $\mu < 9.8$ (20.7 fb$^{-1}$)  
    
  - $H \rightarrow Z\gamma$: $\mu < 18.2$ (4.6 fb$^{-1} + 20.7$ fb$^{-1}$)

Kai Wang, ZIMP, Zhejiang University
The SM Higgs? Likely

Signal Strength

<table>
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<th>H → γγ</th>
<th>ggH</th>
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<tr>
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<tr>
<td>H → bb</td>
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</table>

σ/σ_{SM} = 0.88 ± 0.21

Kai Wang, ZIMP, Zhejiang University
How to interprete the 125 GeV resonance

- Standard Model Higgs boson?
- Composite Higgs?
- ........
- Higgs boson in MSSM
  - the light Higgs boson $h$ at 125 GeV? (push the limit)
  - the heavy Higgs boson $H$ at 125 GeV? while $h$ evades all direct searches (or $h$ around 98 GeV?)

LEP excludes a SM-like Higgs to 114.4 GeV (in both SM and MSSM)

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Pierre Lutz /SACLAY

LEP Jamboree (page 18) 07/22/2002
To evade the LEP bound: reducing \( g_{ZZh} \)

A simple realization: to make \( h \) \( H_d \)-like and take a small \( v_d \)

\[
\begin{pmatrix}
  h \\
  H
\end{pmatrix}
= \begin{pmatrix}
  -\sin \alpha & \cos \alpha \\
  \cos \alpha & \sin \alpha
\end{pmatrix}
\begin{pmatrix}
  \text{Re } H_d \\
  \text{Re } H_u
\end{pmatrix}

\[
\frac{\tan 2\alpha}{\tan 2\beta} = \frac{M_A^2 + m_Z^2}{M_A^2 - m_Z^2}
\]

In the limit of small \( v_d \) (large \( \tan \beta, \sin \beta \to 1 \))

Taking \( M_A \to 0, \sin \alpha \to -1 \)

\[
\beta \to \frac{\pi}{2}, \alpha \to -\frac{\pi}{2}, g_{ZZh} \sim \sin(\beta - \alpha) \to 0
\]
Qualitatively, smaller $M_A \rightarrow$ smaller $g_{ZZh}$
Lower bound of $M_A$ from LEP bound on charged Higgs

non-decoupling limit ($M_A \rightarrow m_Z$) may survive the LEP direct search bound (via $Z h$) and charged Higgs search
At tree level, $M_A \rightarrow m_Z$, $M_h \rightarrow M_H$: nondecoupling
With radiative corrections:

$125\text{GeV}$
$h$
$M_{\tilde{\tau}_L} = M_{\tilde{\tau}_R} = 500 \text{ GeV}$
$\mu = 2300 \text{ GeV}$
$A_t = -740 \text{ GeV}$
$\tan\beta = 11$
Large $\tan \beta$ and $\sin \alpha \to -1$ lead to $M_h \simeq M_{11}, M_H \simeq M_{22}$

\[
M_H^2 \simeq \mathcal{M}_{22}^2 \simeq M_A^2 \cos^2 \beta + m_Z^2 \sin^2 \beta \left( 1 - \frac{3}{8\pi^2} y_t^2 t \right)
+ \frac{y_t^4 v^2}{16\pi^2} 12 \sin^2 \beta \left\{ t \left[ 1 + \frac{t}{16\pi^2} (1.5 y_t^2 + 0.5 y_b^2 - 8 g_3^2) \right] \right\}
+ \frac{A_t \tilde{a}}{M^2_{SUSY}} \left( 1 - \frac{A_t \tilde{a}}{12 M^2_{SUSY}} \right) \left[ 1 + \frac{t}{16\pi^2} (3 y_t^2 + y_b^2 - 16 g_3^2) \right]\}
- \frac{v^2 y_b^4}{16\pi^2} \sin^2 \beta \frac{\mu^4}{M^4_{SUSY}} \left[ 1 + \frac{t}{16\pi^2} (9 y_b^2 - 5 y_t^2 - 16 g_3^2) \right] + \mathcal{O}(y_t^2 m_Z^2)
\]

Consequences of Non-decoupling

Non-decoupling scenario may evade all constraints from direct search experiments but ....

- $H^\pm$ are around ($M_{H^\pm}^2 = M_A^2 + m_W^2$ at tree level)
  Is the scenario flavor safe?

- Light Higgs bosons can enhance spin-independent neutralino-nuclei scattering
  If DM consists of only neutralino, how about bounds from direct detection?
Tree level $H^\pm$: $B_u \to \tau \nu$ in 2HDM and SUSY

Farvah Mahmoudi and Oscar Stal

Figure 5: Constraints on $(m_{H^+}, \lambda_{bb})$ from $B^R (B_u \to \tau \nu \tau)$. The highlighted region is excluded at 95% C.L. The y-axis normalization corresponds to $\tan \beta$ in the 2HDM II (for positive values only).

where $\rho V (\rho S)$ are vector (scalar) form factors and $t (w) = m_B^2 + m_D^2 - 2 m_B m_D m^{D_B}$. It has been shown [48] that comparing differential distributions directly would be a superior method to extract the charged Higgs contribution. However, since the collected statistics is still too low, this method has so far not been pursued experimentally. To reduce the uncertainty from the vector form factor, we consider the ratio [47]

$$\xi_D^{\ell\nu} = \frac{BR(B \to D \tau \nu \tau)}{BR(B \to D \nu \tau \nu)}$$

which the 2HDM contributes only to the numerator. The resulting constraints based on $\xi_D^{\ell\nu}$ are shown in Fig. 6 for $m_{H^+} = 100, 200$ GeV. Similarly to other results for $B_u \to \tau \nu \tau$, the 2HDM contribution in Eq. (24) can be twice the SM contribution with opposite sign, leading to the two disjoint exclusion regions as observed in Fig. 6. When $\lambda_{cc} \ll \lambda_{bb}$—like in the 2HDM II at high $\tan \beta$—the effective constraint on $\lambda_{bb}$ can be combined with that from $B_u \to \tau \nu \tau$ to cover fully the cancellation region observed for low $m_{H^+}$.

The last $B$ decay we consider is $B_s \to \mu^+ \mu^-$, which has not yet been observed experimentally. The SM prediction for the branching ratio is

$$BR(B_s \to \mu^+ \mu^-)_{SM} = (3.2 \pm 0.5) \times 10^{-9},$$

while the current experimental limit, derived by the CDF collaboration, is [49]:

$$BR(B_s \to \mu^+ \mu^-) < 5.8 \times 10^{-8}$$

at 95% C.L. The gap between the SM prediction and the current experimental limit makes this observable particularly interesting in SUSY, since this difference leaves room for SUSY contributions. In the 2HDM however, we found that the experimental limit can be reached only

$$\tan \beta \sim 10: \epsilon_0^* \text{ and } \epsilon_l \text{ below 1%}$$

MSSM corrections to $d$-type quarks and lepton mass matrix have been neglected

nondecoupling: $M_{H^+} \sim 130$ GeV MSSM prediction: $20\% - 30\%$ smaller than the SM value
Tree level $H^\pm$: $B_u \to \tau \nu$ in 2HDM and SUSY

Farvah Mahmoudi and Oscar Stal

$$\frac{BR(B^+\to \tau^+\nu)_{\text{MSSM}}}{BR(B^+\to \tau^+\nu)_{\text{SM}}} = \left| 1 - \frac{m_B^2}{M_{H^+}^2} \frac{\tan^2 \beta}{(1+\epsilon_0^* \tan \beta)(1+\epsilon_1 \tan \beta)} \right|^2$$

- nondecoupling: $M_{H^+} \sim 130$ GeV, $\tan \beta \sim 10$
- MSSM prediction: $20\% - 30\%$ smaller than the SM, consistent with the new Belle data
- SM prediction: $(0.95 \pm 0.27) \times 10^{-4}$
- World average before 2012: $(1.65 \pm 0.34) \times 10^{-4}$
- Belle: $0.72^{+0.29}_{-0.27} \times 10^{-4}$ (new)
$B \to X_s \gamma$ in general 2HDM

Farvah Mahmoudi and Oscar Stal

- light $H^+$ enhances $B \to X_s \gamma$
- type-II 2HDM: $M_{H^+} > 300$ GeV
- nondecoupling: $M_{H^+} \sim 130$ GeV
  non-trival SUSY setup to cancel $H^+$ contribution
$B \rightarrow X_s\gamma$ in MSSM
Helicity must be flipped in the involved quark states: $m_b$ insertion in SM

- $U(3)_Q \times U(3)_d$ chiral symmetry breaking
- Electroweak symmetry breaking

$$W = Q u^c H_u + Q d^c H_d + \ell e^c H_d + \mu H_u H_d$$

SUSY correction $Q d^c \bar{H}_u$

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<th>Field</th>
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<th>$e^c$</th>
<th>$d^c$</th>
<th>$\ell$</th>
<th>$H_u$</th>
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<td>$0$</td>
<td>$1$</td>
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</tr>
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</table>

$$R[Q d^c \bar{H}_u] : \quad \frac{1}{5} + \frac{7}{5} - \frac{8}{5} = 0$$
$$PQ[Q d^c \bar{H}_u] : \quad 0 + (-1) + 0 = -1$$

SUSY correction must break PQ and $R$-symmetry.
**$B \to X_s \gamma$ in MSSM**

![Diagram](image)

Light stop helps to cancel the $H^\pm$ contribution [Top right figure]

Kai Wang, ZIMP, Zhejiang University
$B \to X_s\gamma$ in MSSM

Helicity must be flipped in involved quark states
Breaking $U(3)_Q \times U(3)_d$ chiral and electroweak symmetries

- $m_b$ insertion
  wino-stop contribution suppressed by Super-GIM if degenerate squark masses.

- $v_d$ insertion (not important due to large $\tan\beta$)

- $v_u$ insertion (effectively $10 \cdot 5^c \cdot H_u^*$-like coupling)

- chargino penguins from $v_u$ insertion destructively interfere with the SM and charged Higgs if $\mu A_t < 0$

- light stop helps the cancellation as $\frac{\mu A_t}{M_{\tilde{t}}^2}$

- gluino penguins important: enhanced by $\mu \tan\beta, M_{\tilde{g}}/m_b$
$B_s \rightarrow \mu^+ \mu^-$ in MSSM

- SM: $(3.27 \pm 0.23) \times 10^{-9}$ due to small muon mass $m_\mu^2/m_{B_s}^2$
- LHCb: $3.2^{+1.5}_{-1.2} \times 10^{-9}$ (Nov. 12, 2012)
- MSSM: leading Higgs penguin diagrams $\propto \tan^6 \beta$
- if $\tan \beta \sim 10$, all 1-loop diagrams have to be considered: e.g., charged Higgs diagrams $\propto \tan^4 \beta$
- nondecoupling $\rightarrow$ light $M_A$

$B_s \rightarrow \mu^+ \mu^-$ is even more sensitive as the neutral Higgs bosons are all light: $\tan^6 \beta/M_A^4$ (Chao-Shang Huang, Wei Liao, Qi-Shu Yan, Shou-Hua Zhu, 2000)
General Constraints

- $M_H : 125 \pm 2 \text{ GeV}$
- $R_{\gamma\gamma} = \sigma_{\gamma\gamma}^{\text{obs}} / \sigma_{\gamma\gamma}^{\text{SM}} : 1 \sim 2$
- LEPII+Tevatron+LHC Higgs search bounds
- $\text{BR}(B \to X_s \gamma) < 5.5 \times 10^{-4}$
  - Experimental: $(3.43 \pm 0.22) \times 10^{-4}$
  - SM NNLO: $(3.15 \pm 0.23) \times 10^{-4}$
  - FeynHiggs SM NLO prediction: $(3.8) \times 10^{-4}$
- $\text{BR}(B_s \to \mu^+ \mu^-) < 6 \times 10^{-9}$
  - Experimental upper limit: $4.2 \times 10^{-9}$
  - SM prediction $(3.27 \pm 0.23) \times 10^{-9}$
  - SUSYFlavor SM prediction $4.8 \times 10^{-9}$ (Hadronic parameters ?)
- SUSYFlavor2.01, FeynHiggs2.9.2, HiggsBound3.8.0
\[
M_{\tilde{Q}_{1,2}} = M_{\tilde{u}_{1,2}} = M_{\tilde{d}_{1,2,3}} = M_{\tilde{L}_{1,2,3}} = M_{\tilde{e}_{1,2,3}} = 1 \text{ TeV},
\]
\[
M_1 = 200 \text{ GeV}, M_2 = 400 \text{ GeV}, M_3 = 1200 \text{ GeV}.
\]
\[
M_{\tilde{Q}_3} = M_{\tilde{t}} = 200 \text{ GeV, 300 GeV, 500 GeV and 1TeV}.
\]

\[
M_A : 95 \sim 150 \text{ GeV}
\]
\[
\tan \beta : 1 \sim 30
\]
\[
\mu : 200 \text{ GeV} \sim 3 \text{ TeV}
\]
\[
A_u = A_d = A_\ell : -3 \sim 3 \text{ TeV}
\]

Light stau enhances the diphoton but irrelevant to \(b \rightarrow s\) transition.
$M_{t_L} = M_{t_R} = 1000$ GeV
$M_A : 95$ GeV $-$ $150$ GeV
$tan\beta : 1$ $-$ $30$

$M_{t_L} = M_{t_R} = 500$ GeV
$M_A : 95$ GeV $-$ $150$ GeV
$tan\beta : 1$ $-$ $30$

- no survivors when assuming 200GeV and 300GeV stop,
  reduced $gg \rightarrow H$ (cancels top-quark loop)
- red: $M_H : 125 \pm 2$ GeV, $R_{\gamma\gamma} : 1 - 2$, and combined direct
  search bounds
- blue: $B \rightarrow X_S \gamma$
- black: $B_S \rightarrow \mu^+ \mu^-$

Typical survival points are $M_A \sim 140 \sim 150$ GeV, $tanh \beta \sim 10$
\[
t \rightarrow bH^+ \text{ at the LHC}
\]

Assuming \( \text{BR}(H^+ \rightarrow \tau^+ \nu_\tau) = 100\% \)

\[
\begin{align*}
\text{Br}(t \rightarrow bH^+) & \quad M_{H^+}(\text{GeV}) \\
\end{align*}
\]

ATLAS Observed CLs
Data2011 7 TeV 4.6 fb\(^{-1}\)

Way below the ATLAS bounds
$H$ is most $H_u$ and $v_u \gg v_d$ which dominates $v$

- $Htt$ is close to 1: $gg \to H$ similar to SM rate
- $HWW$ is similar to SM: $\Gamma(H \to \gamma\gamma)$ similar to SM values (W-loop dominates)
- $\Gamma(H \to WW^* \to 2\ell2\nu)$ and $\Gamma(H \to ZZ^* \to 4\ell)$ similar to SM values

Decay BRs may be similar to SM. Light stau can enhance the diphoton partial width. Reduced $Hbb$ can also enhance the $R_{\gamma\gamma}$
Large PQ and $R$-symmetry breaking to suppress the flavor violation would lead to large correction in $\Delta m_b$. 
The results are consistent with either the background hypothesis, or the SM Higgs hypothesis. The best-fit $\mu$ value at 125 GeV is $\mu = 0.7 \pm 0.7$.

No Enhanced $\tau^+\tau^-$ observed!
$b \bar{b}$ Channel

$b$ has large error bar

But $\mu \simeq 1$ at CMS
New $H \to hh$ Channel

Highly fine-tuned though

\[ M_{t_L} = M_{t_R} = 500 \text{ GeV} \]
\[ \mu = 2800 \text{ GeV} \]
\[ A_t = -650 \text{ GeV} \]
\[ \tan \beta = 12 \]

- $e^+ e^- \to Ah$ with $A \to b\bar{b}$, $A \to hZ$ for $M_h \sim 20$ GeV, $b$s are soft. Evade the LEPII search of $4b + 2b2\tau$

- $WH/ZH$ with $H \to hh \to 2b2\tau + 4b + 4\tau$ combined requires $100 \text{ fb}^{-1}$ at 14 TeV LHC. (gluon fusion requires $300 \text{ fb}^{-1}$)
DM Direct Detection

Stop may significantly enhance the scattering crosssection

\[ \frac{M_{\tilde{\chi}_L}}{M_{\tilde{\chi}_R}} = 500 \text{ GeV} \]

\[ \frac{M_{\tilde{\chi}_L}}{M_{\tilde{\chi}_R}} = 1000 \text{ GeV} \]

Irrelevant if neutralino dark matter is not the only DM

Drees and Nojiri
MSSM: $m_h > 120 \text{GeV}$ is nontrivial $\Rightarrow$ nondecoupling

LEP bounds: \[ \begin{align*} g_{ZZh} &\downarrow \Rightarrow \text{small } M_A \\ m_{H^+} &\Rightarrow M_A > 80 \text{GeV} \end{align*} \]

Is the scenario flavor safe as $m_{H^+} \sim m_A$? The strong constraint comes from $b \to s$ transition:
(1) large PQ and R symmetry breaking with $\mu A_t < 0$
(II) a light stop $M_{\tilde{t}} \sim 500 \text{ GeV}$

Consequence:
\[ \begin{align*} (I) &\Rightarrow \text{large } \Delta m_b \Rightarrow R_{\tau\tau} \uparrow \Rightarrow H \to hh \text{ to make } R_{\tau\tau} < 1 \\ (II) &\Rightarrow \text{strongly constrained by XENON100} \end{align*} \]

Thank you!