Accessing the LHC /LC Higgs Wedge.

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Motivations and Procedures

There is a region starting at $m_{A^0} \sim 200$ GeV at $\tan \beta \sim 6$, widening to $2.5 < \tan \beta < 15$ at $m_{A^0} = 500$ GeV for which the LHC cannot directly observe any of the heavy MSSM Higgs bosons.

$5\sigma$ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A^0}, \tan \beta]$ parameter plane, assuming maximal mixing and an integrated luminosity of $L = 300\text{fb}^{-1}$ for the ATLAS detector. This figure is preliminary.
This wedge is not covered at the LC. In fact, the LC wedge for $t\bar{t} + H^0, A^0$ and $b\bar{b} + H^0, A^0$ is even larger. Further, $e^+e^- \rightarrow ZH^0H^0$ and $e^+e^- \rightarrow ZA^0A^0$ only cover up to $m_{A^0} = 150$ GeV ($m_{A^0} = 250$ GeV) at $\sqrt{s} = 500$ GeV ($\sqrt{s} = 800$ GeV) using 20 events in $L = 1$ ab$^{-1}$.

For $\sqrt{s} = 500$ GeV (dashes) and $\sqrt{s} = 800$ GeV (solid) the maximum and minimum $\tan\beta$ values between which $t\bar{t}h$ and $b\bar{b}h$ final states both have fewer than 50 events for decoupled $h$ (a) $L = 1000$fb$^{-1}$ or (b) $L = 2500$fb$^{-1}$.\[\]
In this region, the $h^0$ will be observed and its couplings measured to a certain level of accuracy. (We will consider LHC only and LHC + LC.)

Will we be able to indirectly determine $m_{A^0}$ from these precision measurements?

The issue: How much model dependence is there in the $h^0$ branching ratios, etc., that might prevent an interpretation in terms of $m_{A^0}$ of the observations.

Main difficulty: There are choices of parameters for which the $h^0$ has completely standard model couplings to gauge bosons and fermions independent of $m_{A^0}$.

Main question: Can observations of other SUSY parameters guarantee that we are not in this situation?
Main Ingredient: Higgs Mass Matrix

\[ M^2 = \begin{pmatrix} M_{11}^2 & M_{12}^2 \\ M_{12}^2 & M_{22}^2 \end{pmatrix} = \begin{pmatrix} m_A^2 s_\beta^2 + m_Z^2 c_\beta^2 & -(m_A^2 + m_Z^2) s_\beta c_\beta \\ -(m_A^2 + m_Z^2) s_\beta c_\beta & m_A^2 c_\beta^2 + m_Z^2 s_\beta^2 \end{pmatrix} + \delta M^2 \]  

(1)

It is diagonalized by rotation angle \( \alpha \) determined by

\[ \sin 2\alpha = 2c_\alpha s_\alpha = 2 \frac{M_{12}^2}{\sqrt{(\text{Tr}M^2)^2 - 4\text{Det}M^2}} \]  

(2)

\[ \cos 2\alpha = c_\alpha^2 - s_\alpha^2 = \frac{M_{11}^2 - M_{22}^2}{\sqrt{(\text{Tr}M^2)^2 - 4\text{Det}M^2}} \]  

(3)

where

\[ \sqrt{(\text{Tr}M^2)^2 - 4\text{Det}M^2} = m_{H^0}^2 - m_{h^0}^2. \]  

(4)

Writing

\[ \sin 2(\beta - \alpha) = 2 \sin(\beta - \alpha) \cos(\beta - \alpha) = \sin 2\beta \cos 2\alpha - \cos 2\beta \sin 2\alpha \]  

(5)
we obtain

$$\cos(\beta - \alpha) = \frac{(M_{11}^2 - M_{22}^2) \sin 2\beta - 2M_{12}^2 \cos 2\beta}{2(m_{H^0}^2 - m_{h^0}^2) \sin(\beta - \alpha)} \quad (6)$$

$$= \frac{2m_Z^2 \sin 2\beta \cos 2\beta + (\delta M_{11}^2 - \delta M_{22}^2) \sin 2\beta - 2\delta M_{12}^2 \cos 2\beta}{2(m_{H^0}^2 - m_{h^0}^2) \sin(\beta - \alpha)} \quad (7)$$

Exact decoupling corresponds to $\cos(\beta - \alpha) = 0$, which is obtained by zeroing the numerator, equivalent (assuming $\tan \beta \neq 1$) to requiring

$$2m_Z^2 \sin 2\beta + (\delta M_{11}^2 - \delta M_{22}^2) \tan 2\beta - 2\delta M_{12}^2 = 0. \quad (8)$$

To evaluate where exact decoupling occurs and how rapidly one moves away from exact decoupling as SUSY parameters change, one needs the best available expressions for the $\delta M_{ij}^2$'s. We have used those employed in hep-ph/0106116 (Carena, Haber, Logan, Mrenna).

One finds many decoupling solutions at all $\tan \beta$ values in the wedge region, although the difficulty of finding solutions consistent with $m_{h^0} \gtrsim 113$ GeV (the LEP limit for an exactly SM-like coupled $h^0$) increases at lower $\tan \beta$ values.
Important parameters for our scanning:

- $m_{\text{SUSY}}$
- $\tan \beta$
- $\mu, A_t, A_b$

Note: at the decoupling limit, there is no dependence on $m_{A^0}$.

Outputs

- Stop and sbottom masses
- Light Higgs boson mass

Note: even if $A_t$ and $A_b$ are large, what is important is whether the output stop and sbottom masses are reasonable enough that the approximations being employed are acceptable.
Results for $\tan \beta = 6$

For $\tan \beta = 6$, we plot $\mu$, $\min(m_{b_1}, m_{t_1})$, $A_t$ and $A_b$ as a function of $m_{\text{SUSY}}$ for various small bands of $m_{h^0}$. 
Results for $\tan \beta = 6$.
Note how the decoupling solutions tend to lie in fixed bands of $X_t/\mu$, $X_b/\mu$ and $\mu/m_{\text{SUSY}}$.

For $\tan \beta = 6$, we plot $X_t/\mu$, $X_b/\mu$, $\mu/m_{\text{SUSY}}$ and $A_t/A_b$ as a function of $m_{\text{SUSY}}$ for various small bands of $m_{h0}$. 
Results for $\tan \beta = 8$

For $\tan \beta = 8$, we plot $\mu$, $\min(m_{\tilde{b}_1}, m_{\tilde{t}_1})$, $A_t$ and $A_b$ as a function of $m_{\text{SUSY}}$ for various small bands of $m_{h^0}$. 

Decoupling Solutions, $\tan \beta = 8$
Results for $\tan \beta = 8$. Note how the decoupling solutions tend to lie in fixed bands of $X_t/\mu$, $X_b/\mu$ and $\mu/m_{\text{SUSY}}$.

For $\tan \beta = 8$, we plot $X_t/\mu$, $X_b/\mu$, $\mu/m_{\text{SUSY}}$ and $A_t/A_b$ as a function of $m_{\text{SUSY}}$ for various small bands of $m_{h0}$. 

Decoupling Solutions, $\tan \beta = 8$
Implications

Even if we do not see the $A^0$ or $H^0$ (or $H^\pm$) at the LHC and LC, if we could approximately determine $m_{A^0}$ this would:

- Allow us to know where to focus the $\gamma\gamma$ collider.
- Allow us to know where to focus the $\mu^+\mu^-$ collider.
- Allow us to know to what energy we must increase the LC $\sqrt{s}$.
- Give us important information regarding MSSM boundary conditions.

Our results show that if $\mu$ is large then there is a distinct possibility that the $h^0$ could be completely decoupled, implying independence of all its properties on the value of $m_{A^0}$.

Note: This does not mean that all of the $h^0$ properties will be the same as for the SM $h_{SM}$. For example, stop and sbottom loops affect $\Gamma(h^0 \rightarrow gg)$ and $\Gamma(h^0 \rightarrow \gamma\gamma)$. However, the SUSY-loop correction, $\Delta\lambda_b$, vanishes in the exact decoupling limit.
Fractional deviations of the $gg$ branching ratio for the decoupling scenarios. Note: The deviations are large enough to affect the branching ratios to the standard channels because of changes in the total $h^0$ width.

We present a scatter plot of the percentage deviations of $\Gamma(h^0 \rightarrow gg)$ in the exact decoupling scenarios.
CONCLUSIONS

• If, we observe that the $h^0$ has completely standard model couplings (*i.e.* not just branching ratios), then there are two possibilities:

1. $m_{A^0}$ is very large — $m_{A^0} \gtrsim 600$ GeV or so putting it outside the LC reach and outside the LHC reach unless $\tan \beta$ is large;
2. we are close to one of the exact decoupling scenarios found here, in which case $m_{A^0}$ could be any value above $\sim 150$ GeV.

• Obviously, it would be important to determine which of the above is correct, since the 2nd alternative would imply we should still search for the $A^0$ by raising the machine energy or using $\gamma \gamma$ or $\mu^+ \mu^-$ collisions.

• To make this assessment we must have quite a bit of information about the overall SUSY scenario. It would appear that we need:

  – observations of the heavier charginos/neutralinos whose masses are of order $\mu$
    (in many scenarios),
- observations of the 1st two generations of squarks (which more or less determine $m_{SUSY}$),
- observations of the lightest stop and sbottom squarks,
- information from, say, the chargino sector to determine $\tan \beta$.

Only with all this information would we have a good idea of whether or not we are in a decoupling scenario.

- These are a lot of if’s.

- Further, even if we are only near the decoupling zone, the properties of the $h^0$ will have reduced sensitivity to $m_{A^0}$.

- We will study these scenarios further to see if we can find easier techniques for using other SUSY observations to allow us to know when decoupling is present.

- We will also study if some precision couplings might still reveal the mass of the $H^0, A^0, H^\pm$.

The most obvious coupling of this type is $h^0 \rightarrow \gamma\gamma$ which has some sensitivity to the mass of the $H^\pm$ through the corresponding loop contribution. Probably,
however, this is overwhelmed by the usual $W$-loop contribution (which is full SM strength in the decoupling scenarios).