Probing the Singlet Extended Susy Higgs Model at the LHC

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new:

inclusion of phases
soft masses

vac energy density $\varepsilon = 3560 \text{ MeV/m}^3$
The String Landscape

Weinberg bound: The vacuum energy (Dark Energy) must be less than about $500 \text{ meV}^4$ for life to evolve

“chain inflation” (Freese et al.)
The State of the Universe

half life: \[ \tau = \frac{1}{\sqrt{24\pi G_N (\epsilon_i - \epsilon_f)}} = 5.6 \cdot 10^9 \text{ yr} \left( \frac{(2.3 \cdot 10^{-3} \text{ eV})^2}{(\epsilon_i - \epsilon_f)^{1/2}} \right) \]
The universe should eventually make a phase transition to an exactly Supersymmetric phase.

What can we predict about the future susy phase after the higgs structure is revealed at the LHC?

In quantum mechanics, atomic and molecular binding energies are proportional to the electron mass.

Electromagnetic bound states could occur in the exact susy phase if EWSB is preserved.

In the Minimal Supersymmetric Standard Model (MSSM) and in most of its extensions, electroweak symmetry breaking (EWSB) vanishes in the exact susy limit leaving all fermions massless.

The exception is the “nearly minimal susy std model” where there is a superpotential term linear in the singlet higgs.
Most general renormalizable superpotential with two Higgs doublets and an extra singlet Higgs (Fayet 1975)

\[ W = \lambda \left( S(H_u \cdot H_d - v^2) + \frac{\lambda'}{3} S^3 + \frac{\mu_0}{2} S^2 \right) \]

\( v, \mu_0 \to 0 : \quad W \to NMSSM \) (Next to Minimal Susy)

\( \lambda', \mu_0 \to 0 : \quad W \to nMSSM \) (nearly minimal)

\( \lambda', \mu_0, v \to 0 : \quad W \to UMSSM \)

\[ V_F = \sum_i \left| \frac{\partial W}{\partial \Phi_i} \right|^2 \]

The F terms in the scalar potential are

\[ V_F = \lambda^2 \left( \left| H_u \cdot H_d - v^2 + \lambda' S^2 + \mu_0 S \right|^2 + |S|^2 (|H_u|^2 + |H_d|^2) \right) \]

Add “soft” mass terms: \( m_S^2 |S|^2 + m_H^2 (|H_u|^2 + |H_d|^2) \)
\[ W = \lambda \left( S(H_u \cdot H_d - v^2) + \frac{\lambda'}{3} S^3 + \frac{\mu_0}{2} S^2 \right) \]

\[ v, \mu_0 \to 0 : \quad W \to NMSSM \quad \text{(Next to Minimal Susy Model)} \]
\[ \lambda', \mu_0 \to 0 : \quad W \to nMSSM \quad \text{(Nearly Minimal Model)} \]
\[ \lambda', \mu_0, v \to 0 : \quad W \to UMSSM \quad \text{(extra U(1))} \]

\[ V_F = \lambda^2 \left( |H_u \cdot H_d - v^2 + \lambda' S^2 + \mu_0 S|^2 + |S|^2 (|H_u|^2 + |H_d|^2) \right) \]

Find critical points (all derivatives vanish) (L.C. IJMPA 2008)
Solution 1 (Exact Susy+EWSB)
Solution 2 (Exact Susy no EWSB)
Solution 3 (Broken Susy no EWSB)
Solution 4 (Broken Susy plus EWSB) (like our universe)
Singlet Extended Susy Higgs Model (SESHM)

\[ V_F = \lambda^2 \left( |H_u \cdot H_d - v^2 + \lambda' S^2 + \mu_0 S|^2 + |S|^2 (|H_u|^2 + |H_d|^2) \right) \]

In the SESHM, masses can persist in the susy phase if \( v \) is non-zero!
Critical point conditions

\[ \frac{1}{\lambda^2} \frac{\partial V_F}{\partial S^*} \big|_0 = 0 = (2\lambda' S_0^* + \mu_0^*)(v_0^2 - v^2 + \mu_0 S_0 + \lambda' S_0^2) + S_0(2|v_0|^2 + m_S^2) \]

\[ \frac{1}{\lambda^2} \frac{\partial V_F}{\partial H^*_u} \big|_0 = 0 = v_0^*(v_0^2 - v^2 + \mu_0 S_0 + \lambda' S_0^2) + v_0(|S_0|^2 + m_H^2) \]

Solution 1 (susy+EWSB) : \( v_0 = v \), \( S_0 = 0 \), \( m_S^2 = m_H^2 = 0 \)

Solution 2 (susy): \( v_0 = 0 \), \( S_0 = \frac{-\mu_0 \pm \sqrt{\mu_0^2 + 4\lambda'v^2}}{2\lambda'} \), \( m_S^2 = m_H^2 = 0 \)

Solution 3 : \( v_0 = 0 \), \( (2\lambda' S_0^* + \mu_0^*)(-v^2 + \lambda' S_0^2 + \mu_0 S_0) + S_0 m_S^2 = 0 \)

Solution 4 (broken susy + EWSB)

\[ v_0^*(2\lambda' S_0 + \mu_0)(|S_0|^2 + m_H^2) - v_0 S_0^*(2v_0^2 + m_S^2) = 0 \]  \( \text{(1)} \)

\[ v^2 = v^*^2 = v_0^2 + \lambda' S_0^2 + \mu_0 S_0 + \frac{v_0}{v_0^*}(|S_0|^2 + m_H^2) \]  \( \text{(2)} \)

Solutions 3 and 4 are saddle points, not true minima, in absence of “soft breaking terms”.
\[
\begin{align*}
\langle 0|S|0 \rangle &= S_0 = |S_0|e^{i\phi} \\
\langle 0|H_u|0 \rangle &= \langle 0|H_d|0 \rangle = v_0 = |v_0|e^{i\phi_0} \\
|v_0| &= 175 \text{GeV} \\
\beta &= 2(\phi - \phi_0)
\end{align*}
\]

As $\mu_0 \to 0$, $\beta \to n\pi$

The value of the higgs potential at the broken susy minimum (solution 4) is

\[
V_4(0) = \lambda^2 \left( |S_0|^4 + 2|S_0v_0|^2 + m_H^4 + m_S^2|S_0|^2 + 2m_H^2(|v_0|^2 + |S_0|^2) \right).
\]

Can choose $m_S^2$ to make the vacuum energy in solution 4 agree with the dark energy observation: $(5.9 \pm 0.2) \text{meV}^4$. (At least one of $m_S^2$ and $m_H^2$ must be negative.)
We scan over six real parameters, $\lambda', m^2_S, m^2_H, |S_0|, v, \phi$. Constraint eqs then determine $|\mu_0|, \arg(\mu_0),|v_0|, \arg(v_0)$. Scenario 1: Require $V_4(0) =$ observed dark energy and allow negative soft masses squared.

<table>
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<tr>
<th></th>
<th>minimum</th>
<th>maximum</th>
<th>mean</th>
<th>std dev</th>
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</table>
Space of solutions for $\lambda'$ and $|\mu_0|$ with corresponding values of $v$ color-shape coded requiring that the higgs vacuum energy be equal to the observed value of dark energy.
Space of solutions for soft Higgs masses $m_S^2$ and $m_H^2$ with corresponding values of $v$ color-shape coded requiring that the higgs vacuum energy be equal to the observed value of dark energy.
\[ \beta = 2(\phi - \phi_0) \]
\[ S_0 = |S_0|e^{i\phi} \]
\[ v_0 = |H_u|e^{i\phi_0} \]

As \( \mu_0 \to 0 \), \( \beta \to n\pi \)

Space of solutions for \( \beta \) and \( |S_0| \) with corresponding values of \( v \) color-shape coded requiring that the higgs vacuum energy be equal to the observed value of dark energy.
Summary: Challenges for the LHC

1) Is the $\mu_0$ parameter non zero? (role in CP non-conservation?)

2) Is the $v$-parameter non-zero? (role in a future susy universe?)

$$V_F = v^4 - v^2 (H_u \cdot H_d + \lambda' S^2 + \mu_0 S + h.c.) + \ldots$$

Measure Higgs mixing term $H_u \cdot H_d = H_u^0 H_d^0 - H_u^- H_d^+$

$$V_F = H_u \cdot H_d (v_0^2 - v^2 + \lambda' S_0^2 + \mu_0 S_0)^* + h.c.$$
