A Natural Higgs in the N*MSSM

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November 3
Outline

1. Introduction and motivation
2. LEP searches
3. Models
4. X-hadrons
5. Conclusion
Work in Progress!
The Higgs Boson?

- The Standard Model is extraordinarily successful.
- CKM matrix describes all flavor observables.
- The electroweak sector passes all precision tests.
- Last piece is sorting out the sector responsible for electroweak symmetry breaking.
Electroweak Precision tests

- Can test for mass of Standard Model Higgs with Electroweak precision tests.

  ![Graph showing electroweak precision tests](image)

  - Seems to favor a $\sim 80$ GeV mass Higgs Boson.
  - Direct search at LEP gives a lower bound of 114.4 GeV.
LHC has collisions now!

LHC to probe the Higgs sector.

Low mass Higgs actually one of the toughest discovery modes because no leptons are in the decay.
Reasons to believe there is more to the Higgs than simply symmetry breaking.

The Higgs mass term is the only dimensionful parameter in the Standard Model.

Naturally $m_h^2$ should be near the cutoff of the theory due to large loop corrections.

Need a large tuning to keep the electroweak scale small relative to the Planck scale.
Supersymmetry!

- SUSY can solve this by cancelling quadratic divergences in the corrections to the Higgs mass.
- Can do all kinds of other nice things with it too (Dark Matter, Radiative electroweak symmetry breaking, etc.)
Supersymmetry?

- Higgs mass at tree level constrained to be less than the Z boson mass
  \[ m_{h,\text{MSSM}}^2 < m_Z^2 \cos^2 2\beta. \] (1)

- Need large radiative corrections to lift \( m_h \) above the LEP bound.

- Situation slightly better if extra higgs singlets are added, however there is still an upper limit of \( m_h < 143 \) GeV (Kolda, Kane, Wells)(Espinosa, Quiros).

- No superpartners seen yet.
Little Hierarchy

- Corrections to Higgs mass are logarithmic

\[ \delta m_h^2 \sim \frac{m_t^4}{16\pi^2 v^2} \log \left( \frac{\tilde{m}_t^2}{m_t^2} \right) \]  

(2)

- Need a large stop mass.

- Corrections to Higgs soft mass squared parameter are quadratic

\[ \delta m_{H_u}^2 \sim -\tilde{m}_t^2 \log \frac{\Lambda^2}{\tilde{m}_t^2} \]  

(3)

- \( m_Z^2 \sim -|\mu|^2 - m_{H_u}^2 \), so need to fine tune \( \mu \) to keep the electroweak scale light compared to \( \tilde{m}_{soft} \)
Big Problem!

- To raise the Higgs mass above the LEP bound, MSSM fine tuning is $\sim 1\%$
- 3 options:
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3 options:
1. There is no Supersymmetry.
2. We don’t understand how fine tuning works (SplitSUSY).
3. Have to add new wrinkle to MSSM to accommodate light higgs.
Goal

- Avoid the little hierarchy problem by saying the Higgs is light and LEP missed it.
- Exotic Higgs decay $h \rightarrow jets$ to avoid the LEP searches. 
  (Dobrescu, Landsberg, Matchev) (Dermisek, Gunion) (David E. Kaplan and others) (Chang, Fox, Weiner)
Higgs to $b$ quarks

- $h \rightarrow b\bar{b}$ is most constraining channel for the SM higgs.
- LEP puts limits on

$$\xi^2 BR(h \rightarrow X) = \frac{\sigma_{Zh}}{\sigma_{SM}} BR(h \rightarrow X)$$  \hspace{1cm} (4)
Suppressing $BR(h \rightarrow b\bar{b})$ branching ratio is a must. However, the $b$ Yukawa is small.

Jack Gunion has the NMSSM can avoid the fine tuning issue via a two stage cascade decay of $h$.

In the context of the NMSSM, the decay is to a pseudoscalar $a_s$ that mostly lives in a gauge singlet Higgs multiplet.

$$W \supset \lambda S H_u H_d + \frac{\kappa}{3} S^3$$ (5)
Higgs to 4 $b$ quarks

- $a_s$ inherits its branching ratios from mixing with the $A^0$
- If heavy enough, it will decay to $b\bar{b}$. LEP has stringent constraints for $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$. 

![Graph showing the correlation between $m_{H1}$ and $m_{H2}$]
Higgs to $4\ \tau$

- If $m_a < 2m_b$, then $BR(a \rightarrow \tau\tau)$ is largest. This is less constrained.
- LEP searches cutoff at 86 GeV, citing that region as 'theoretically inaccessible'.
A new analysis of ALEPH data closed this window.

Kranmer, Beacham, Yavin, Spagnolo
Higgs to 4 gluons

- Left with $h \rightarrow aa \rightarrow jjjj$ (Chang, Fox, Weiner).
This search only sensitive to low masses when a highly boosted $a$ causes the jets to merge.
OPAL did a model-independent search for the Higgs.
Looks at recoil spectrum of $Z \rightarrow e^+ e^-, \mu^+ \mu^-$
You may be thinking

“All I need to do is have a higgs mass that is $> 82$ GeV that has an intermediate particle with mass $> 10$ GeV and doesn't decay to $b$-quarks. LEP hasn't done any of those searches.”
Higgs to Anything

You may be thinking

“All I need to do is have a higgs mass that is $> 82$ GeV that has an intermediate particle with mass $> 10$ GeV and doesn’t decay to $b$-quarks. LEP hasn’t done any of those searches.”

LEP did not look for processes like these either
80 higgs bosons produced in association with $Z$ ($m_h = 90 - 100$ GeV).

Does $h \rightarrow (4+) \text{ jets}$ qualify as a pink elephant?

LEP does have SUSY searches for $4 \text{ jets} + \text{ Missing } E_T$ final states (hep-ex/0310054).

Efficiency for $4j$ signal $1 - 25\%$, So expect $\sim 4$ events.

8 events are seen, consistent with background.
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4. Dodge the Pink Elephants in disguise!
With a low mass higgs decaying to jets, this will be buried in the background.

May be able to discover the Higgs with $\gamma$s or via jet substructure (Spencer and friends, Falkowski, Krohn, and others, Nojiri and others).
1. Goal is that we have $h \rightarrow (\geq 4)$ jets.
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2. Introduce another gauge singlet field $N$ to the NMSSM, with an effective coupling $hNN$.
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2. Introduce another gauge singlet field $N$ to the NMSSM, with an effective coupling $hNN$.
3. Find point where $BR(h \rightarrow N$ scalars$)$ is large.
4. Have $N$ scalars $\rightarrow gg$ be dominant decay.
Two ways to $h \rightarrow a_n a_n$

- Coupling in scalar potential

$$cv \, h \, a_n \, a_n$$  \hspace{1cm} (6)

- Large $BR(h \rightarrow a_n a_n)$ requires $cv \gtrsim 10 \text{ GeV}$.

- Goldstone boson coupling

$$\frac{1}{f_{\text{eff}}} \, h \, \partial_{\mu} a_n \, \partial^{\mu} a_n$$  \hspace{1cm} (7)

- Large $BR(h \rightarrow a_n a_n)$ requires $f_{\text{eff}} \lesssim 400 \text{ GeV}$.
Goldstone Boson coupling: the Shift N3MSSM

- Use a shift symmetry to keep one of the pseudoscalars from mixing with the Higgs Bosons.
- Pseudoscalar $a_n$ naturally light because a Pseudo-Nambu-Goldstone Boson.
- Superpotential

$$W = (\text{SM Yukawas}) + \lambda S H_u H_d + \frac{1}{3} \kappa S^3 + \lambda' S N \bar{N} + \frac{1}{3} \kappa_N N^3$$

$$+ (\text{terms to decay } N)$$

- $U(1)$ charges: $N = +1$, $\bar{N} = -1$.
- $\kappa_N$ breaks the $U(1)$, makes $a_n$ a Pseudo-Nambu-Goldstone boson.
Break the U(1) symmetry. Parameterize the goldstone as

\[ N = (v_N + n)e^{i a_n} e^{i A_n} \]
\[ \bar{N} = (v_{\bar{N}} + \bar{n})e^{-i a_n} e^{i A_n} \]

For \( \kappa_N = 0 \) (\( N^3 \) term), \( a_n \) is not present in Higgs part of potential
After breaking the $U(1)$ symmetry, vertex is

$$\frac{1}{f_n} n \partial_\mu a_n \partial^\mu a_n$$

(10)

Mixing of $N, \bar{N}$ CP even scalars produces $h \rightarrow a_n a_n$:

$$\frac{1}{f_{\text{eff}}} h \partial_\mu a_n \partial^\mu a_n.$$ 

(11)
Decaying $N$

- To decay $N$ field to gluons, all models will have superpotential terms

$$W \supset y_N N X \bar{X} \quad (12)$$

- $X \bar{X}$ a vector pair with a weak scale mass and SU(3) quantum numbers (E6SSM).
- $X$ mass comes from the vev of $N$.
- Induces loop decay proportional to $y_N$

\[ \begin{tikzpicture}
  \node (X) at (0,0) {$X$};
  \node (an) at (-1,0) {$a_n$};
  \node (g1) at (1,1) {$g$};
  \node (g2) at (-1,1) {$g$};
  \draw[->] (an) -- (X);
  \draw[->] (X) -- (g1);
  \draw[->] (X) -- (g2);
\end{tikzpicture} \]
Higgs spectrum

- SM-like Higgs with $m_h \sim 90$ GeV.
- Pseudoscalar $a_n$ with $m_{a_n} \sim 30$ GeV
- Singlet CP-even higgs with $m \sim 100$ GeV.
- Charged and other Higgs can be heavy.
Decays of $a_n$ can produce photons if $X$ a $\mathbf{5}$. 

$BR(a \rightarrow \gamma\gamma) \sim 10^{-2} BR(a \rightarrow gg)$.

Chang, Fox, and Weiner believe discovery may be possible with 300 fb$^{-1}$. 
Can try to use jet substructure methods for discovering the a boosted higgs. (Nojiri, Falkowski)

I don’t believe Nojiri. They look for the $a$ jets and their substructure. Will for the most part have small $p_T$ and I think they underestimate backgrounds from detector mismeasurement. Comments?

Falkowski looks for a big Higgs fat jet with smaller $a_n$ substructure inside. They claim it can be seen with $30 \text{ fb}^{-1}$.

Both look for $m_a < 2m_b$. This model could have $m_a > 2m_b$, so the substructure could look much different. More study would be needed.
Since we are trying to keep it natural, the only relevant scale here is the SUSY soft scale scale $\sim$ weak scale.

- **X** gets mass from the vev of $N$, so mass should be less than a TeV.

- **Within reach of the LHC!**
X-hadrons

- X-hadron has no decay modes. It could decay via GUT suppressed operators, or via mixing with the light quarks.
- If its lifetime $> 1/\Lambda_{QCD}$, then it will hadronize before it decays, forming a heavy cored ion, like gluinons in Split SUSY.

- If $X$ lifetime is long enough ($> 1$ ps) it will produce displaced vertices or charged tracks in the detector.
- If X-hadron is charged, it could be stopped inside the detector.
$X$ are produced with strong cross section at the LHC

If long lived enough, $X$ hadronizes. It could be seen as a massive particle in the muon chamber, or some could be stopped inside the detector.
Stopped X hadrons decay later when no collision happening.
If detected as CHAMPS, then signal acceptance is \( \sim 25\% \) (CMS) (Thanks Max).
Smoking Gun?

- Can we find the $a_n$ pseudoscalar?
- Can have $a$-strahlung processes:
Smoking Gun?

- Cross section for $XXa_n$ production can be order 0.1 pb.
- Remember the $a_n$ decays via a loop.
- If the X particle has electric charge, then the $a_n$ will decay to photons $\approx 1\%$ of the time.
- The X hadrons in the event make this a zero background sample. Assume acceptance is still 25%, then there will be some excess in about $30 \text{ fb}^{-1}$ that could be observed. It depends on the coupling $a_nXX$, as well as large systematic uncertainties.
- At least 60% of the acceptance reduction is from triggers. Will Triggering on the photons help increase the signal acceptance? These could be very low energy $\gamma$s.
Can solve the little hierarchy problem of SUSY by hiding the higgs below the LEP bound.

Simple way to do that via decays $h \rightarrow 4 \text{ jets}$, but then buried at the LHC in background.

LHC will see low mass superpartners!

X-hadrons in CHAMP searches could be seen early and be a signal of buried Higgs.
Another way to avoid the hierarchy problem is to have the Higgs couple to some new vector like matter.

The loop of the vector matter raises the Higgs mass above the LEP bound, but doesn’t contribute to destabilizing $m_Z$.

Can get Higgs-strahlung:

Cross section $\sim 10$ fb for light X, $m_h \sim 120$ GeV.

Can look for $h \rightarrow bb$!