A Natural Higgs in the N*MSSM

Daniel J. Phalen
with Aaron Pierce and Markus Luty
phalen@physics.ucdavis.edu

UC Davis

November 3

Outline

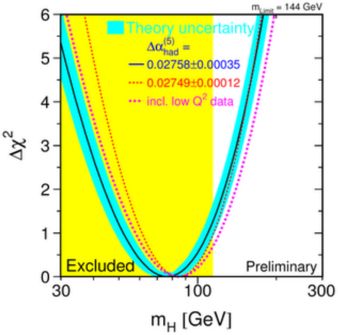
Work in Progress!

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

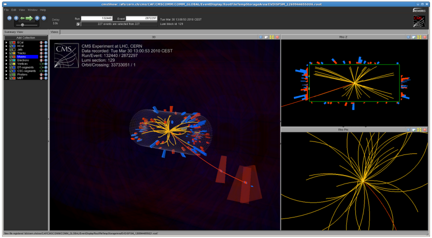
- Can test for mass of Standard Model Higgs with Electroweak precision tests.



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

LHC!

- 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.

Big Hierarchy Problem

- 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
$$m^2_{h,MSSM} < m^2_Z \cos^2 2\beta. \qquad (1)$$
- 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

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

- Need a large stop mass.
- Corrections to Higgs soft mass squared parameter are quadratic

$$\delta m_{H_u}^2 \sim -\tilde{m}_t^2 \log \frac{\Lambda^2}{\tilde{m}_t^2} \tag{3}$$

- $m_Z^2 \sim -|\mu|^2 - m_{H_u}^2$, so need to fine tune μ 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 ~ 1 %
- 3 options:

Big Problem!

- To raise the Higgs mass above the LEP bound, MSSM fine tuning is ~ 1 %
- 3 options:
  1. There is no Supersymmetry.

Big Problem!

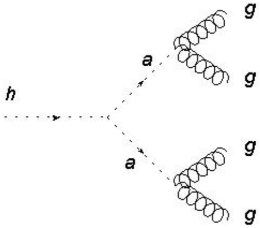
- To raise the Higgs mass above the LEP bound, MSSM fine tuning is ~ 1 %
- 3 options:
  1. There is no Supersymmetry.
  2. We don't understand how fine tuning works (SplitSUSY)

Big Problem!

- To raise the Higgs mass above the LEP bound, MSSM fine tuning is ~ 1 %
- 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 accomodate light higgs.

Goal

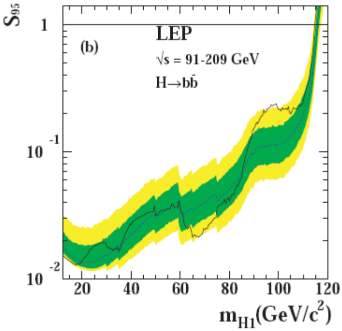
- Avoid the little heirarchy problem by saying the Higgs is light and LEP missed it.
- Exotic Higgs decay $h \rightarrow jets$ to avoid the LEP searches. (Dobrescu, Landsberg, Matchev) (Dermisek, Gunion)(David E. Kaplan and others)(Chang, Fox, Weiner)



Higgs to b quarks

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

$$\xi^2 BR(h \to X) = \frac{\sigma_{Zh}}{\sigma_{SM}} BR(h \to X) \qquad (4)$$



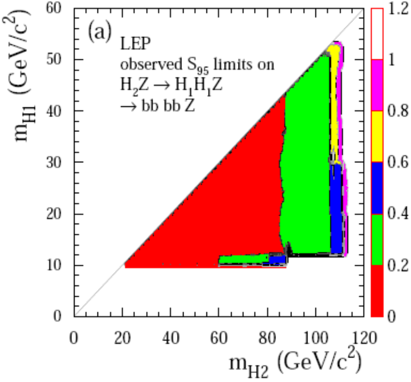
Higgs in the NMSSM

- Suppressing $BR(h \to b\bar{b})$ 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.

$$W \supset \lambda S H_u H_d + \frac{\kappa}{3} S^3 \qquad (5)$$

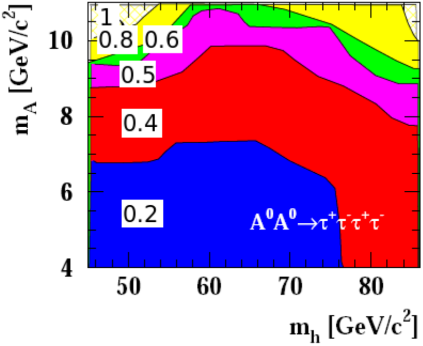
Higgs to 4 b quarks

- 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 $h \to aa \to b\bar{b}b\bar{b}$.



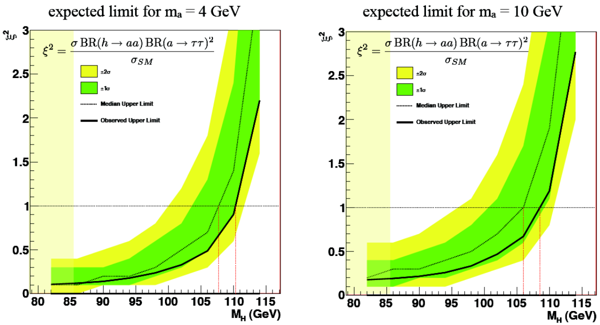
Higgs to 4 τ

- If $m_a < 2m_b$, then $BR(a \to \tau\tau)$ is largest. This is less constrained.
- LEP searches cutoff at 86 GeV, citing that region as 'theoretically inaccessible'.



Higgs to 4 τ

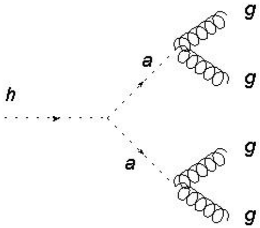
- A new analysis of ALEPH data closed this window.



Kranmer, Beacham, Yavin, Spagnolo

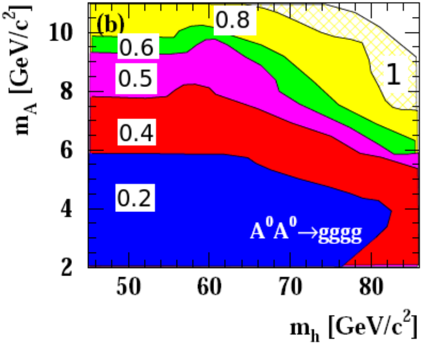
Higgs to 4 *gluons*

- Left with $h \rightarrow aa \rightarrow jjjj$ (Chang, Fox, Weiner).



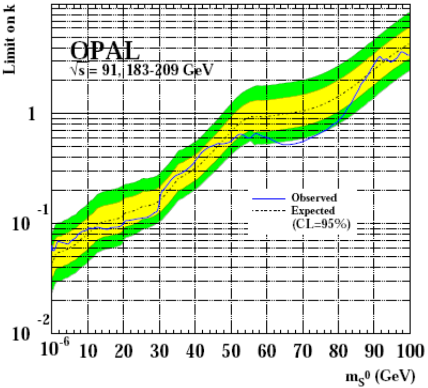
Higgs to 4 *gluons*

- This search only sensitive to low masses when a highly boosted *a* causes the jets to merge.



Higgs to Anything

- OPAL did a model-independent search for the Higgs.
- Looks at recoil spectrum of $Z \to e^+e^-, \mu^+\mu^-$



Higgs to Anything

You may be thinking

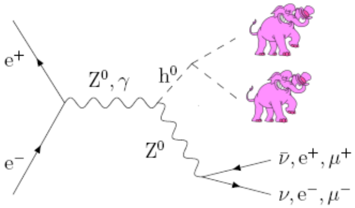
> *"All I need to do is have a higgs mass that is* > 82 *GeV that has an intermediate particle with mass* > 10 *GeV and doesn't decay to b-quarks. LEP hasn't done any of those searches."*

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



Higgs to Anything

- 80 higgs bosons produced in association with Z ($m_h = 90 - 100$ GeV).
- Does $h \to (4+)$ jets qualify as a pink elephant?
- LEP does have SUSY searches for 4 jets + Missing E_T final states (hep-ex/0310054).
- Efficiency for $4j$ signal $1 - 25\%$, So expect ~ 4 events.
- 8 events are seen, consistent with background.

The Game

1. Suppress the branching ratio to b quarks by decaying to an intermediate scalar.

The Game

1. Suppress the branching ratio to b quarks by decaying to an intermediate scalar.
2. Avoid the bound on low mass scalars decaying to b, τ, g.

The Game

1. Suppress the branching ratio to b quarks by decaying to an intermediate scalar.
2. Avoid the bound on low mass scalars decaying to b, τ, g.
3. Have the Higgs mass large enough to avoid the bound on $h \rightarrow anything$.

The Game

1. Suppress the branching ratio to b quarks by decaying to an intermediate scalar.
2. Avoid the bound on low mass scalars decaying to b, τ, g.
3. Have the Higgs mass large enough to avoid the bound on $h \rightarrow anything$.
4. Dodge the Pink Elephants in disguise!

LHC?

- With a low mass higgs decaying to jets, this will be buried in the background.
- May be able to discover the Higgs with γs or via jet substructure (Spencer and friends, Falkowski, Krohn, and others, Nojiri and others).

Goals

1. Goal is that we have $h \rightarrow (\geq 4)$ jets.

Goals

1. Goal is that we have $h \longrightarrow (\geq 4)$ jets.
2. Introduce another gauge singlet field N to the NMSSM, with an effective coupling hNN.
3. Find point where $BR(h \longrightarrow N\, scalars)$ is large.

Goals

1. Goal is that we have $h \to (\geq 4)$ jets.
2. Introduce another gauge singlet field N to the NMSSM, with an effective coupling hNN.
3. Find point where $BR(h \to N\, scalars)$ is large.
4. Have $N\, scalars \to gg$ be dominant decay.

Two ways to $h \longrightarrow a_n a_n$

- Coupling in scalar potential

$$c v \, h \, a_n \, a_n \tag{6}$$

- Large $BR(h \to a_n a_n)$ requires $cv \gtrsim 10$ GeV.
- Goldstone boson coupling

$$\frac{1}{f_{eff}} h \, \partial_\mu a_n \, \partial^\mu a_n \tag{7}$$

- Large $BR(h \to a_n a_n)$ requires $f_{eff} \lesssim 400$ 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

$$W = (\text{SM Yukawas}) + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \lambda' S N \bar{N} + \frac{1}{3}\kappa_N N^3 + (\text{terms to decay N}) \quad (8)$$

- U(1) charges: $N = +1$, $\bar{N} = -1$.
- κ_N breaks the U(1), makes a_n a Pseudo-Nambu-Goldstone boson.

Shift N3MSSM

- Break the U(1) symmetry. Parameterize the goldstone as

$$\begin{aligned} N &= (v_N + n)e^{ia_n}e^{iA_n} \\ \bar{N} &= (v_{\bar{N}} + \bar{n})e^{-ia_n}e^{iA_n} \end{aligned} \tag{9}$$

- For $\kappa_N = 0$ (N^3 term), a_n is not present in Higgs part of potential

Shift N3MSSM

- After breaking the U(1) symmetry, vertex is

$$\frac{1}{f_n} n \, \partial_\mu a_n \, \partial^\mu a_n \tag{10}$$

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

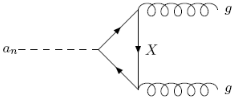
$$\frac{1}{f_{eff}} h \, \partial_\mu a_n \, \partial^\mu a_n . \tag{11}$$

Decaying N

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

$$W \supset y_N N X \bar{X} \tag{12}$$

- $X\bar{X}$ 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

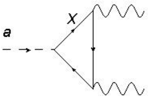


Higgs spectrum

- 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.

Higgs Discovery

- Decays of a_n can produce photons if X a **5**.



- $BR(a \to \gamma\gamma) \sim 10^{-2} BR(a \to gg)$.
- Chang, Fox, and Weiner believe discovery may be possible with 300 fb^{-1}.

Faster Discovery

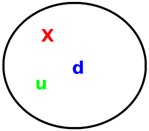
- Can try to use jet substructure methods for discovering the a boosted higgs. (Nojiri, Falkowski)
- I don't believe Nojiri. They look for the a jets and their substructure. Will for the most part have small p_T and I think they underestimate backgrounds from detector mismeasurement. Comments?
- Falkowski looks for a big Higgs fat jet with smaller a_n substructure inside. They claim it can be seen with 30 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.

What mass is the X?

- 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

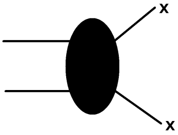
- X-hadron has no decay modes. It could decay via GUT suppressed operators, or via mixing with the light quarks.
- If its lifetime $> 1/\Lambda_{QCD}$, then it will hadronize before it decays, forming a heavy cored ion, like gluinos in Split SUSY.



- 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.

Production at LHC

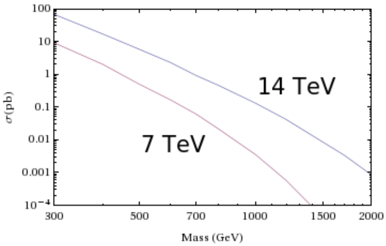
X are produced with strong cross section at the LHC



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.

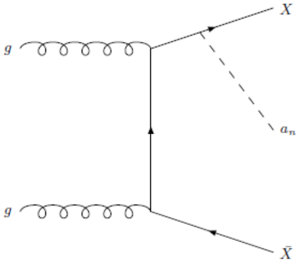
Production at LHC

- 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?

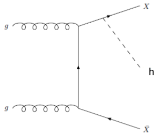
- Cross section for XXa_n production can be order 0.1 pb.
- Remember the a_n decays via a loop.
- If the X particle has electric charge, then the a_n will decay to photons $\approx 1\%$ of the time.
- The X hadrons in the event make this a zero background sample. Assume acceptance is still 25%, then there will be some excess in about 30 fb^{-1} that could be observed. It depends on the coupling $a_n XX$, 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 γs.

Outlook

1. Can solve the little hierarchy problem of SUSY by hiding the higgs below the LEP bound.
2. Simple way to do that via decays $h \longrightarrow 4$ jets, but then buried at the LHC in background.
3. LHC will see low mass superpartners!
4. X-hadrons in CHAMP searches could be seen early and be a signal of buried Higgs.

Work in progress

1. Another way to avoid the heirarchy problem is to have the Higgs couple to some new vector like matter.
2. The loop of the vector matter raises the Higgs mass above the LEP bound, but doesn't contribute to destabilizing m_Z.
3. Can get Higgs-strahlung:



4. Cross section ∼10 fb for light X, $m_h \sim 120$ GeV.
5. Can look for $h \to bb$!