Title: A Natural Higgs in the N*MSSM

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Abstract: Supersymmetry is a leading candidate for physics Beyond the Standard Model. However, a tree level in the Minimal Supersymmetric Standard Model the Higgs boson should be lighter than the Z boson. LEP did not discover the Higgs boson, so typically large radiative corrections are required to push the Higgs above the LEP lower limit, leading to fine tuning issues. In this talk I will describe how to avoid limits from the searches at LEP and discuss a potential early signal of a 90 GeV Higgs at the LHC.

A Natural Higgs in the N*MSSM

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Dec 8
Perimeter Institute

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Outline

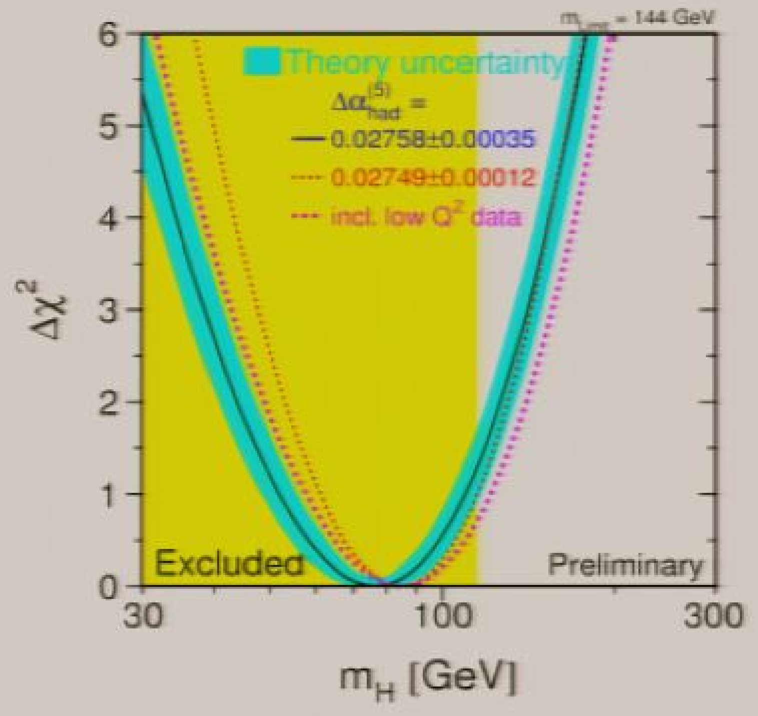
Work in Progress!

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.

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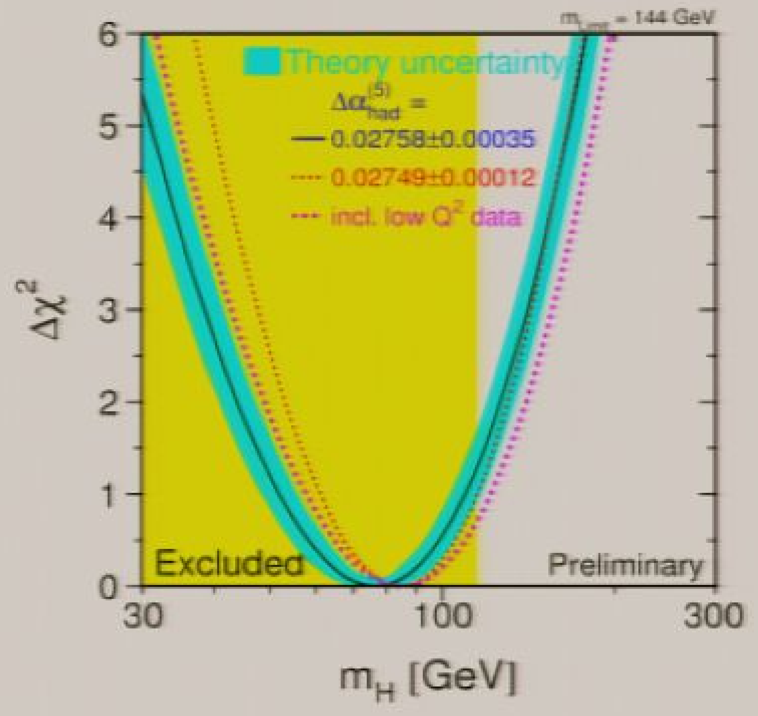

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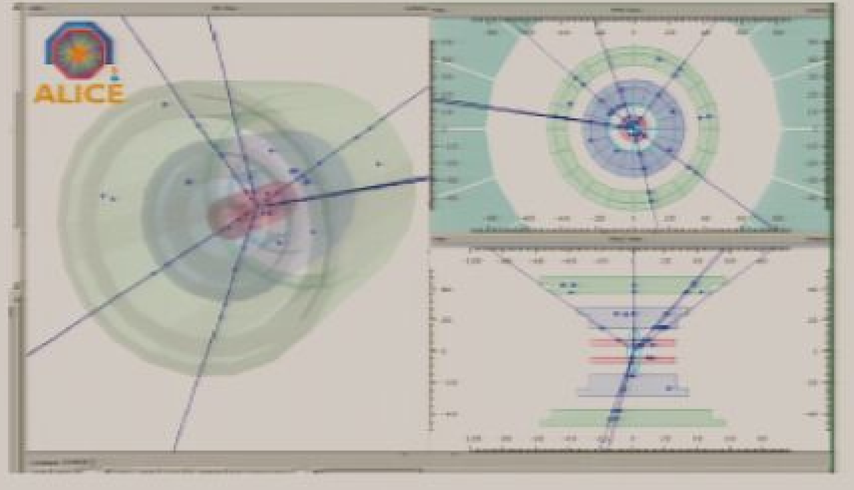
- Direct search at LEP gives a lower bound of 114.4 GeV.

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, Unification etc.)

Supersymmetry?

- Higgs mass at tree level constrained to be less than the Z boson mass
$$m_h^{MSSM} < m_Z^2 \cos^2 2\beta. \tag{1}$$
- 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

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

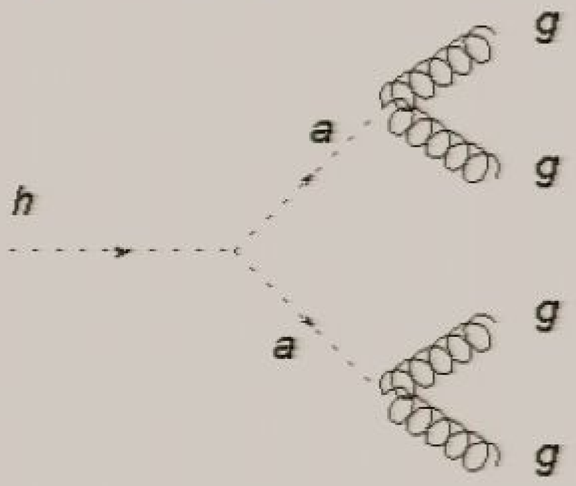
- Need a large stop mass.
- Corrections to Higgs soft mass squared parameter are quadratic

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

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

Goal

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



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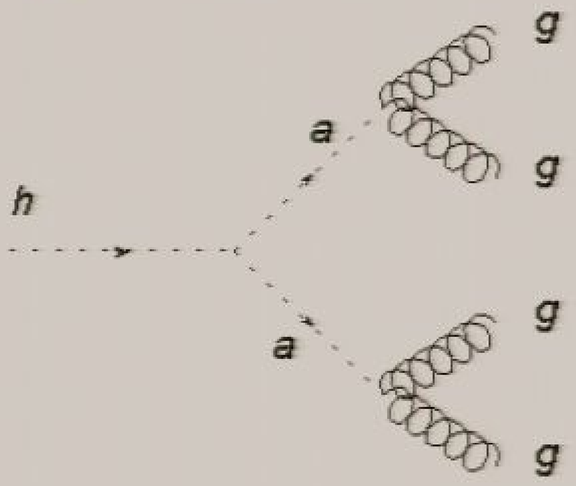
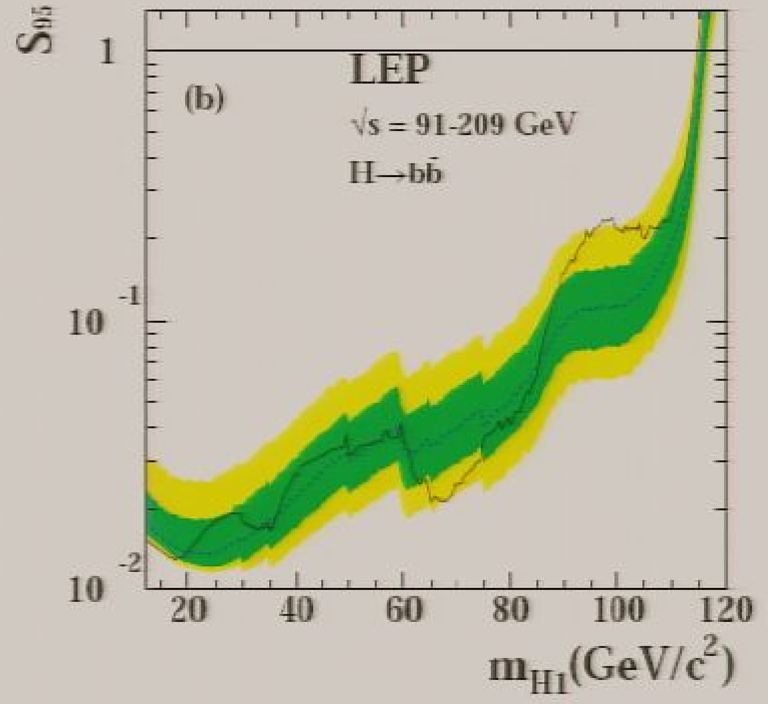


Higgs to b quarks

- $h \to b\bar{b}$ 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.
- Dermisek and Gunion noticed that the two stage cascade can avoid the LEP bounds $h \to b\bar{b}$.
- In the context of the NMSSM, the decay is to a pseudoscalar a_s that mostly lives in a gauge singlet Higgs multiplet.

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

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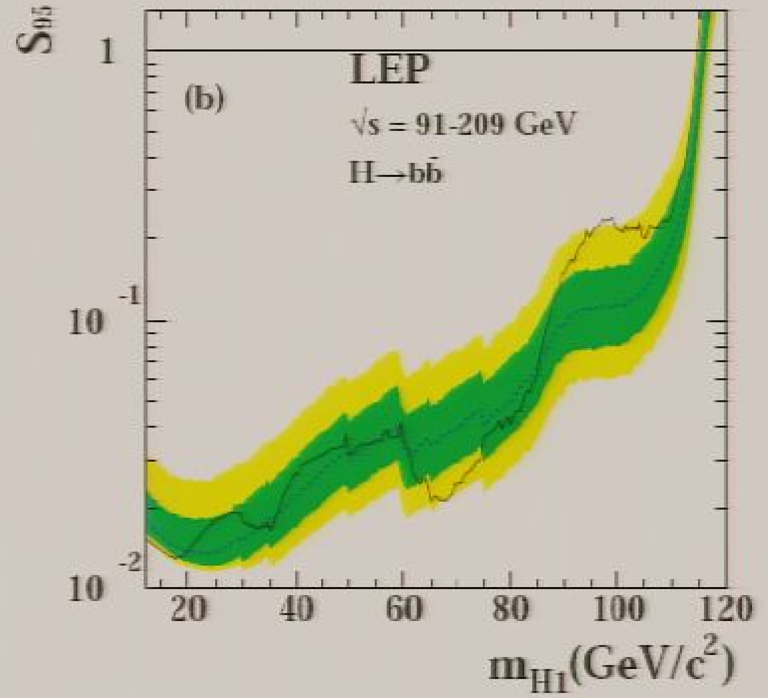

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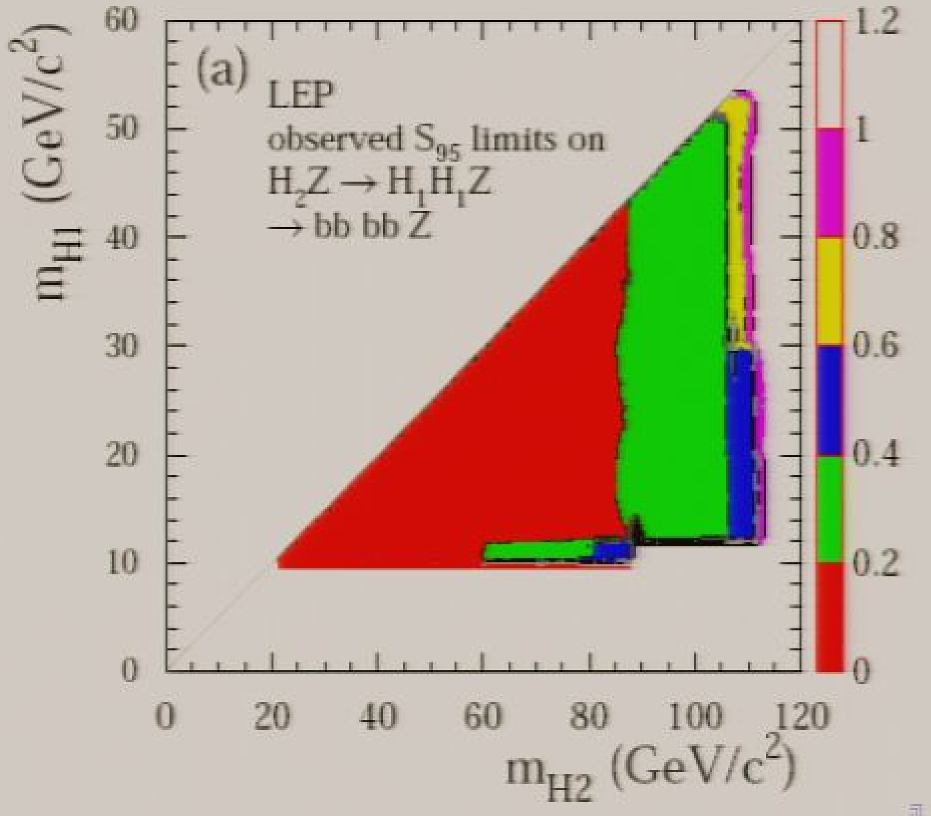
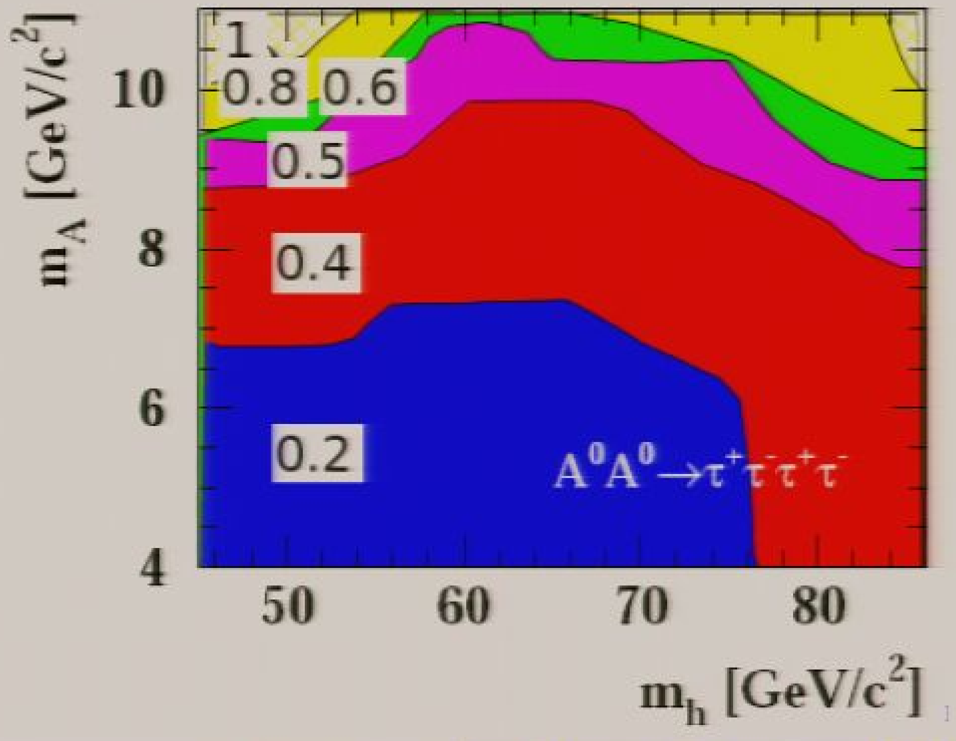
Higgs to 4 b quarks

- 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 constrains for $h \longrightarrow aa \longrightarrow b\bar{b}b\bar{b}$.



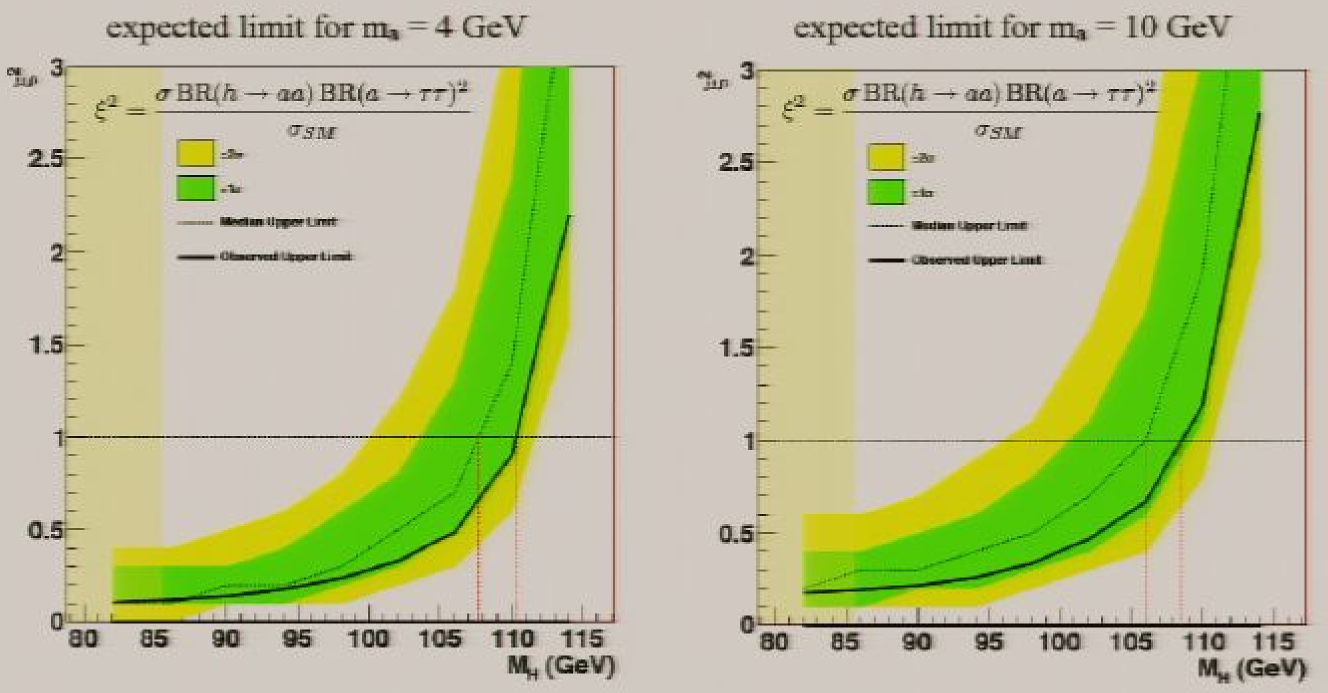
Higgs to 4 τ

- 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 is underway that could close this window.



Kranmer, Beacham, Yavin, Spagnolo

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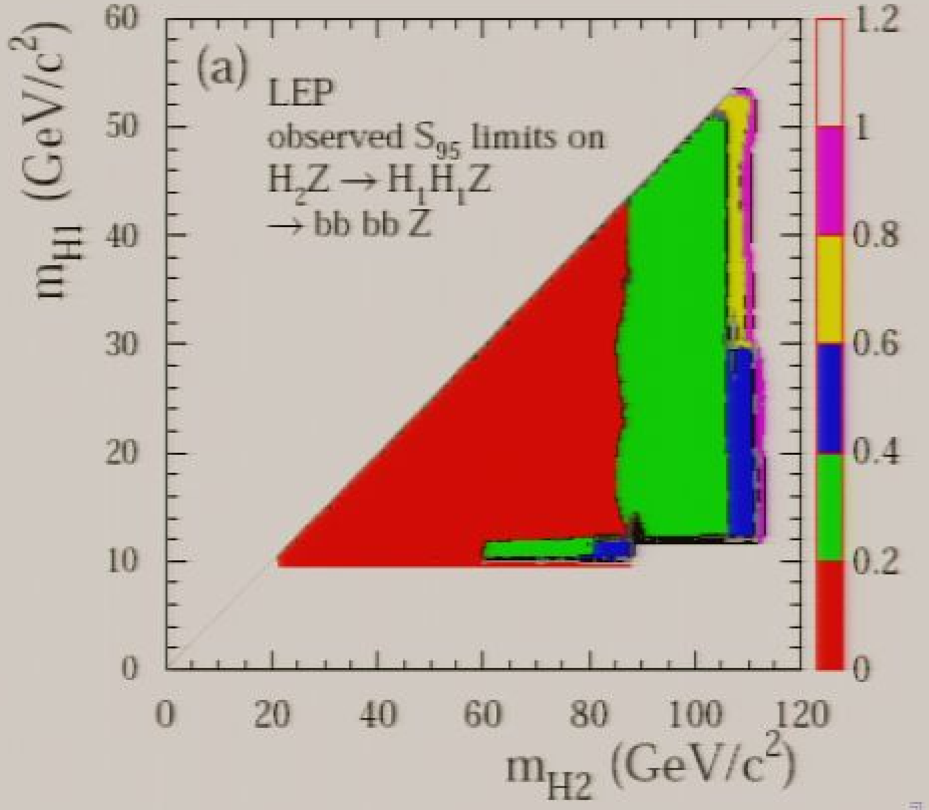
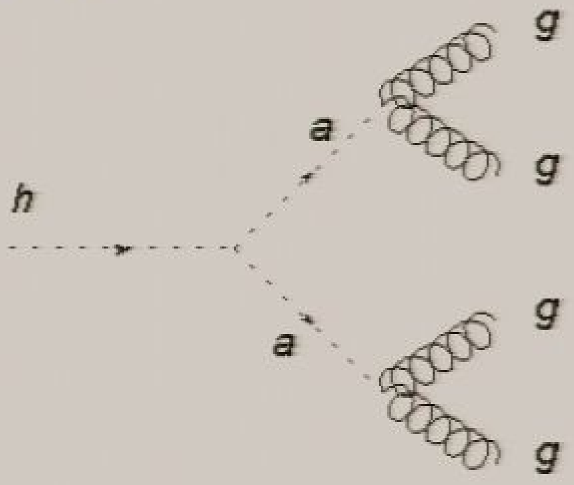


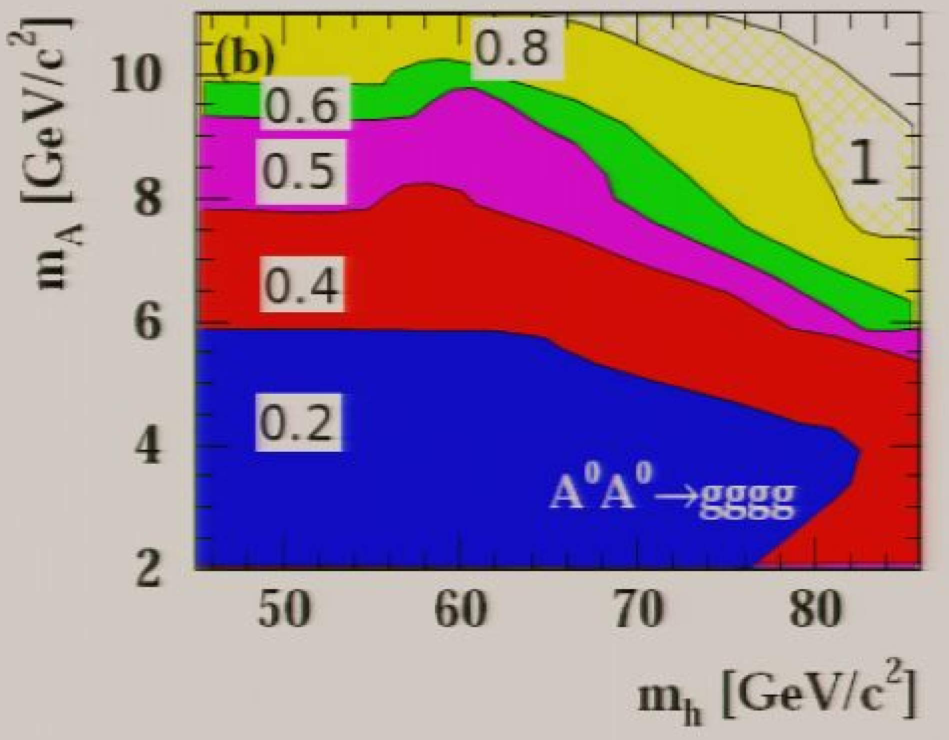
Higgs to 4 *gluons*

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



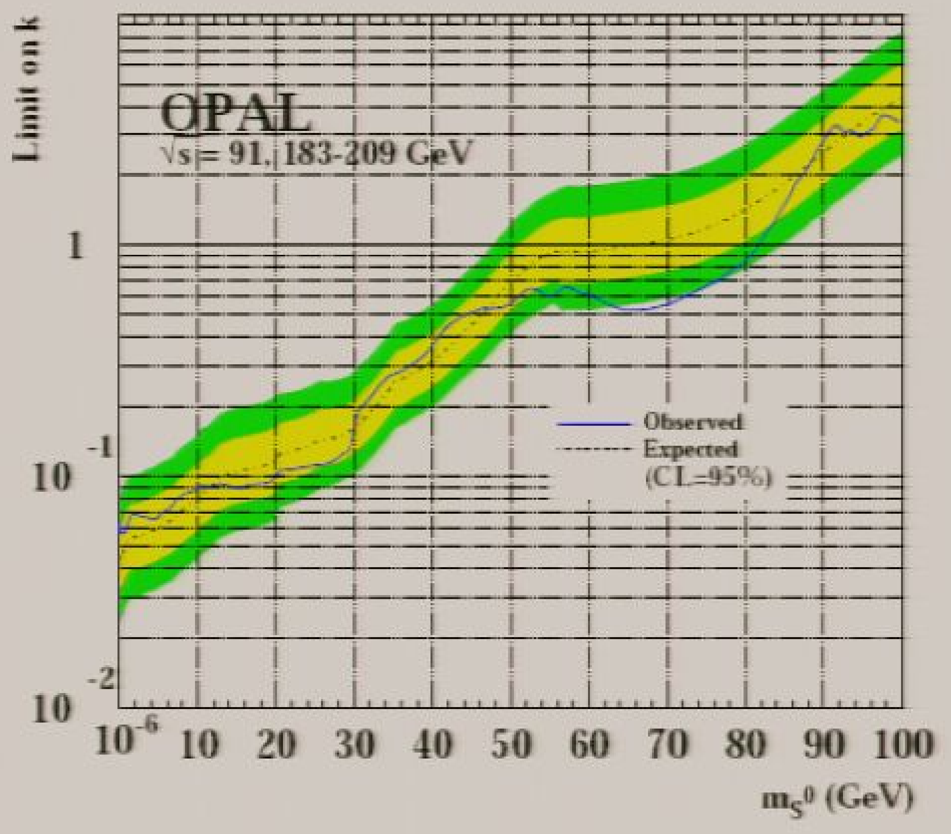
Higgs to 4 *gluons*

- 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."*

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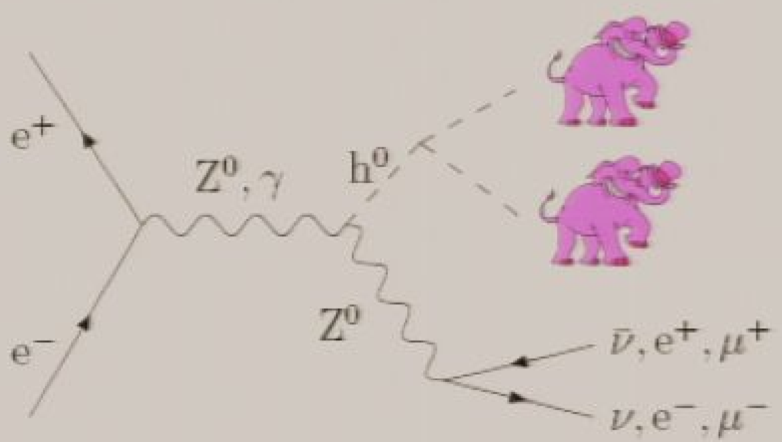
LEP did not look for processes like these either



Higgs to Anything

- 80 higgs bosons produced in association with Z ($m_h = 90 - 100$ GeV).
- Does $h \rightarrow (4+)$ 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.

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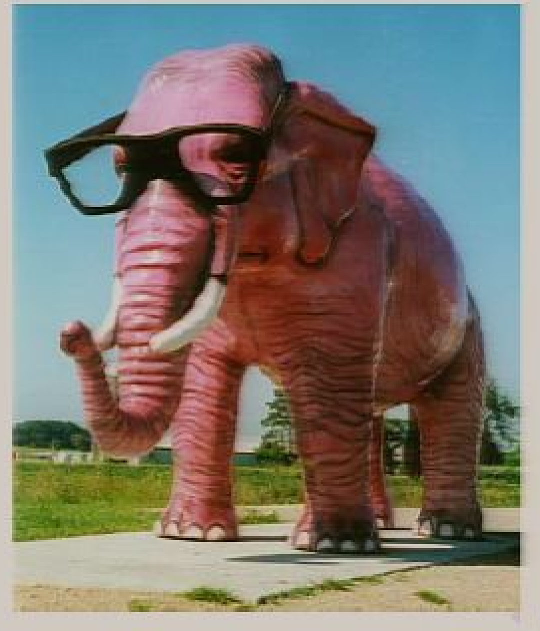
2. Avoid the bound on low mass scalars decaying to b, τ, g.
3. Have the Higgs mass large enough to avoid the bound on $h \longrightarrow anything$.
4. Dodge the Pink Elephants in disguise!



LHC?

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LHC?

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- LHC will not discover $h \rightarrow \mathit{jets}$, so two options if no SM-like higgs is see at LHC:
  1. Either Higgs has prevented its own discovery (Nielsen)
  2. The Higgs is buried in the QCD background.
- May be able to discover the Higgs with γs (More on this later).

Goals

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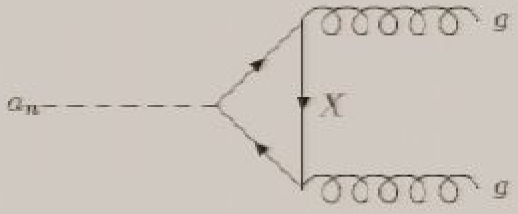
4. Have $N\, scalars \longrightarrow gg$ be dominant decay.

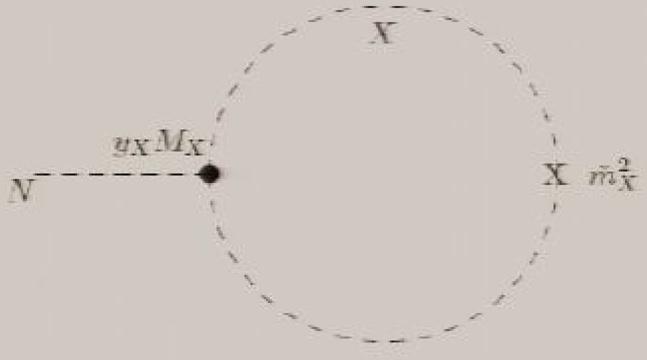
Decaying N

- To decay N field, all models will have have superpotential terms
$$W \supset y_N N X \bar{X} + M_X X \bar{X} \tag{6}$$
- $X\bar{X}$ a vector pair with a weak scale mass and SU(3) quantum numbers (E6SSM).
- Induces loop decay proportional to y_N



Tadpole

- As a result of SUSY breaking, the N field develops a tadpole.



- $\langle N \rangle \sim y_X M_X \tilde{m}_X^2 / m_n^2$.

$h \longrightarrow a_n a_n$

- Consider a coupling in scalar potential

$$\begin{aligned} W &= (\text{SM Yukawas}) + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \frac{1}{2}\lambda S N N \\ &\quad + (N \text{ decay terms}), \end{aligned} \tag{7}$$

  so that $V \supset \lambda\lambda_1(H_u H_d N^* N^* + c.c.)$.
- N gets a tadpole as discussed above.
- The N field mixes with the Higgs.
- a_n mixes with A^0 pseudoscalar and inherits couplings to quarks.
- Since decays to gluons are loop suppressed, (y_X controls both decays) $a \longrightarrow b\bar{b}$ dominates.

Two ways to $h \rightarrow a_n a_n$

- Coupling in scalar potential

$$c v\, h\, a_n\, a_n \tag{8}$$

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

$$\frac{1}{f_{eff}} h\, \partial_\mu a_n\, \partial^\mu a_n \tag{9}$$

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

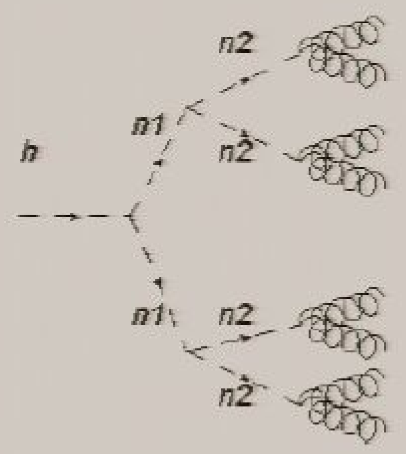
Scalar Potential Coupling: the N3MSSM

- Add two new gauge singlets N_1, N_2 to the NMSSM.
- Idea is to avoid directly mixing with the Higgs.
- Find a parametric limit where this is okay.

$$\begin{aligned} W \;=\; & (\text{SM Yukawas}) + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \frac{1}{2}\lambda_1 S N_1 N_1 \\ & + \frac{1}{2}\lambda_2 N_1 N_2 N_2 + (N_2 \text{ decay terms}), \end{aligned} \tag{10}$$

N3MSSM

Two stage cascade



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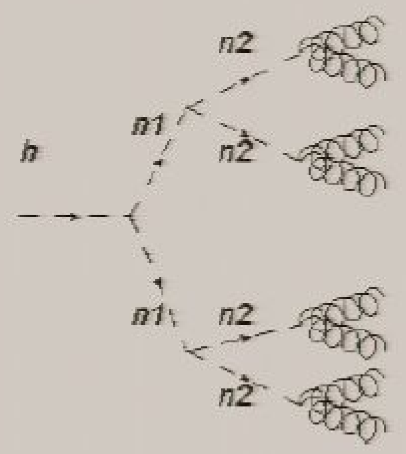

N3MSSM

- $V \supset \lambda\lambda_1(H_u H_d N_1^* N_1^* + c.c.)$.
- Easy to have larger coupling than the b yukawa.

$$\frac{BR(h \to n_1 n_1)}{BR(h \to b\bar{b})} \sim \frac{\lambda\lambda'}{y_b} \tag{11}$$

N3MSSM

- Since different tadpoles control mixing with Higgs, size of tadpole controls $BR(n_1 \longrightarrow b\bar{b})$
- In $y_X \longrightarrow 0$ limit, $BR(n_1 \longrightarrow b\bar{b}) \longrightarrow 0$.

N3MSSM

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- In $y_X \rightarrow 0$ limit, $BR(n_1 \rightarrow b\bar{b}) \rightarrow 0$.
- In $BR(n_2 \rightarrow b\bar{b})$, y_X dependence cancels.
- In $\lambda_2 \rightarrow 0$ limit, $BR(n_2 \rightarrow b\bar{b}) \rightarrow 0$.

Scalar Potential Coupling: the N3MSSM

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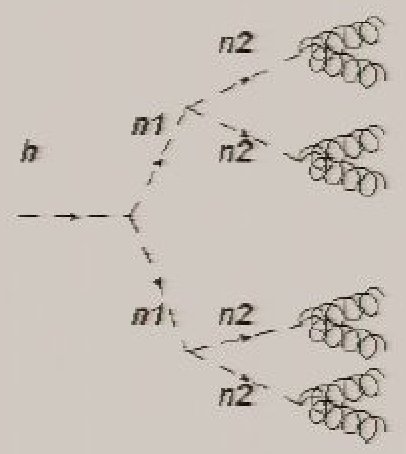

N3MSSM

- Still may have to fine tune scalar masses to be light.
- Parameter space is squeezed to get $m_h > 2m_{n_1} > 4m_{n_2}$.

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

$$\begin{aligned} W &= (\mathrm{SM\ Yukawas}) + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \lambda' S N \bar{N} \\ &\quad + y_N N X \bar{X} + y_{\bar{N}} \bar{N} X \bar{X} + \eta S X \bar{X} \end{aligned} \tag{12}$$

- U(1) charges: $N = +1$, $\bar{N} = -1$.
- X gets weak scale mass from $\langle S \rangle$.

Shift N3MSSM

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

$$\begin{aligned} N &= (v_N + n)e^{ia_n}e^{iA_n} \\ \bar{N} &= (v_{\bar{N}} + \bar{n})e^{-ia_n}e^{iA_n} \end{aligned} \tag{13}$$

- a_n is not present in Higgs part of potential

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Shift N3MSSM

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

$$\frac{1}{f_n} n\,\partial_\mu a_n\,\partial^\mu a_n \tag{14}$$

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

$$\frac{1}{f_{eff}} h\,\partial_\mu a_n\,\partial^\mu a_n. \tag{15}$$

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 $m_s \sim 100$ GeV.
- Pseudoscalar Higgs with $m_{a_s} \sim 100$ GeV
- Charged and other Higgs near 300 GeV.

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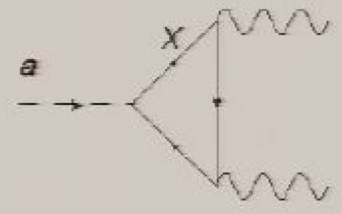
Higgs Discovery

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



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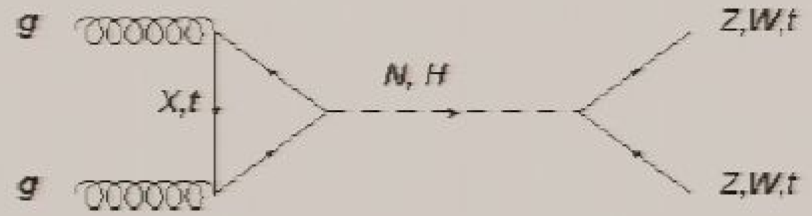
- Chang, Fox, and Weiner believe discovery may be possible with 300 fb^{-1}.

Higgs Discovery



- Other Higgs produced in gluon fusion processes at the LHC.
- Decay via mixing with the SM-like higgs to ZZ, W^+W^-, $t\bar{t}$.

Higgs Discovery

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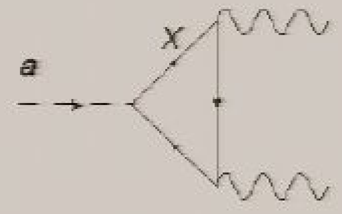

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Mass of the a_n

- U(1) symmetry broken by y_N:

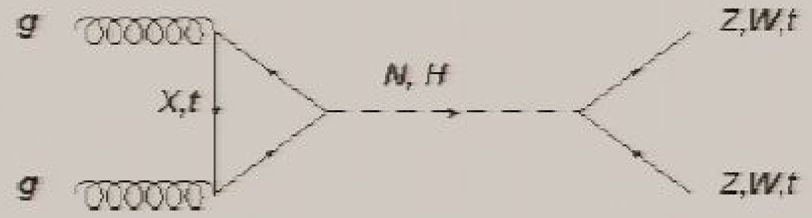
$$y_N N X \bar{X} \tag{16}$$

- Acquires mass via 1-loop Coleman Weinberg potential

$$m_{a_n}^2 \sim \frac{N_c}{16\pi^2}(2 y_N M_X f_n) \log\left(\frac{\tilde{m}_{X_1}\tilde{m}_{X_2}}{m_{X_f}^2}\right). \tag{17}$$

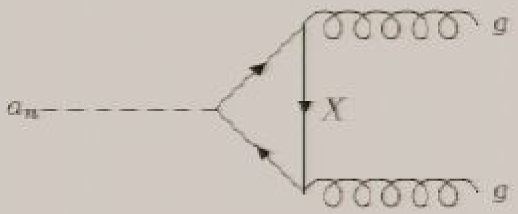
- $m_{a_n}^2$ controlled by $y_N M_X$.
- For $h \to a_n a_n$, require $m_{a_n} \lesssim 30$ GeV.

Higgs Discovery



- Other Higgs produced in gluon fusion processes at the LHC.
- Decay via mixing with the SM-like higgs to ZZ, W^+W^-, $t\bar{t}$.

Lifetime of a_n



- Decay width also controlled by $y_N M_X$.

$$\Gamma(a_n \to gg) \sim \frac{\alpha_s^2}{64\pi^3}\left(\frac{y_N v_N}{\sqrt{2} f_n M_X}\right)^2 m_a^3. \qquad (18)$$

- Decay Length

$$(3.5 \times 10^{-6}\ \mathrm{mm})\left(\frac{1}{y_N}\right)^2\left(\frac{10\ \mathrm{GeV}}{m_a}\right)^3\left(\frac{M_X}{1\ \mathrm{TeV}}\right)^2. \qquad (19)$$

What mass is the X-hadron?

- Require that no displaced vertices are seen at LEP

$$2\frac{m_{X_f}}{y_N} \lesssim 1000 \text{ TeV} \tag{20}$$

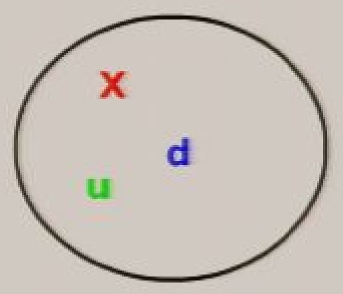
- Have two conditions: $m_{a_n} \sim 30 GeV$ and no displaced vertices.
- With additional assumptions that $\langle N \rangle \sim \langle \bar{N} \rangle$ and $y_N >> y_{\bar{N}}$, find

$$m_{X_f} \lesssim 1 \text{ TeV} \left(\frac{max(m_{a_n})}{20 \text{ GeV}} \right)^{1/2} \left(\frac{f_n}{100 \text{ GeV}} \right)^{1/4} . \tag{21}$$

- Within reach of the LHC!

X-hadrons

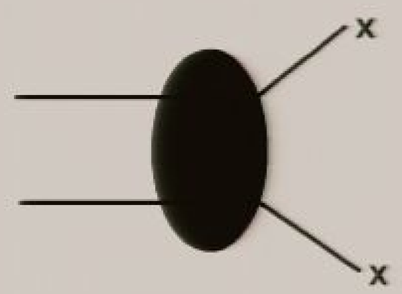
- X-hadron has no decay modes. It could decay via GUT suppressed operators, or via mixing with the light quarks.
- If its lifetime $> 1/\Lambda_{QCD}$, then it will hadronize before it decays, forming a heavy cored ion, like gluinos in Split SUSY.



- 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

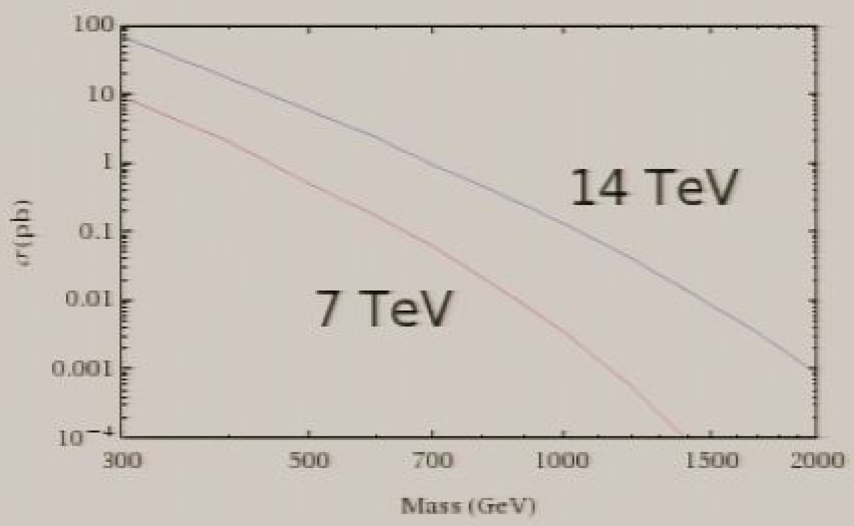
X are produced with strong cross section at the LHC



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.
- Many will be produced at the LHC.



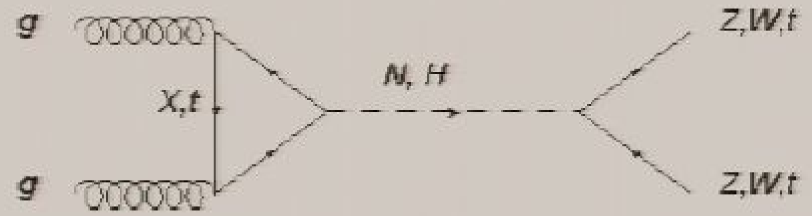
Outlook

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. R-hadrons could be seen early and be a signal of buried higgs.

Work in progress

1. Understand Parameter space of Shift N3MSSM.
2. Understand the X particle cosmology and allowed representations.
3. Classify all allowed decay states that hide the Higgs from LEP (Chiral Color Adjoints).

Higgs Discovery



- Other Higgs produced in gluon fusion processes at the LHC.
- Decay via mixing with the SM-like higgs to ZZ, W^+W^-, $t\bar{t}$.

Shift N3MSSM

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

$$\begin{aligned} N &= (v_N + n)e^{ia_n}e^{iA_n} \\ \bar{N} &= (v_{\bar{N}} + \bar{n})e^{-ia_n}e^{iA_n} \end{aligned} \qquad (13)$$

- a_n is not present in Higgs part of potential

N3MSSM

- Still may have to fine tune scalar masses to be light.
- Parameter space is squeezed to get $m_h > 2m_{n_1} > 4m_{n_2}$.

Goldstone Boson coupling: the Shift N3MSSM

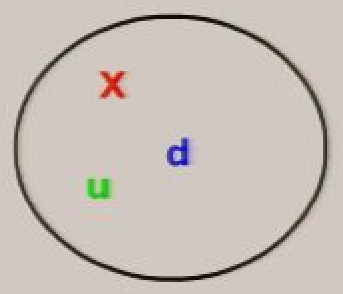
- Use a shift symmetry to keep one of the pseudoscalars from mixing with the Higgs Bosons.
- Pseudoscalar a_n naturally light because a Pseudo-Nambu-Goldstone Boson.
- Superpotential

$$\begin{aligned} W &= (\text{SM Yukawas}) + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \lambda' S N \bar{N} \\ &\quad + y_N N X \bar{X} + y_{\bar{N}} \bar{N} X \bar{X} + \eta S X \bar{X} \end{aligned} \tag{12}$$

- U(1) charges: $N = +1$, $\bar{N} = -1$.
- X gets weak scale mass from $\langle S \rangle$.

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.



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Work in progress

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Scalar Potential Coupling: the N3MSSM

- Add two new gauge singlets N_1, N_2 to the NMSSM.
- Idea is to avoid directly mixing with the Higgs.
- Find a parametric limit where this is okay.
- Goldstone boson coupling

$$\frac{1}{f_{eff}} h \, \partial_\mu a_n \, \partial^\mu a_n \tag{9}$$

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

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 $h \rightarrow anything$.

Higgs in the NMSSM

- Suppressing $BR(h \to b\bar{b})$ branching ratio is a must. However, the b Yukawa is small.
- Dermisek and Gunion noticed that the two stage cascade can avoid the LEP bounds $h \to b\bar{b}$.
- In the context of the NMSSM, the decay is to a pseudoscalar a_s that mostly lives in a gauge singlet Higgs multiplet.

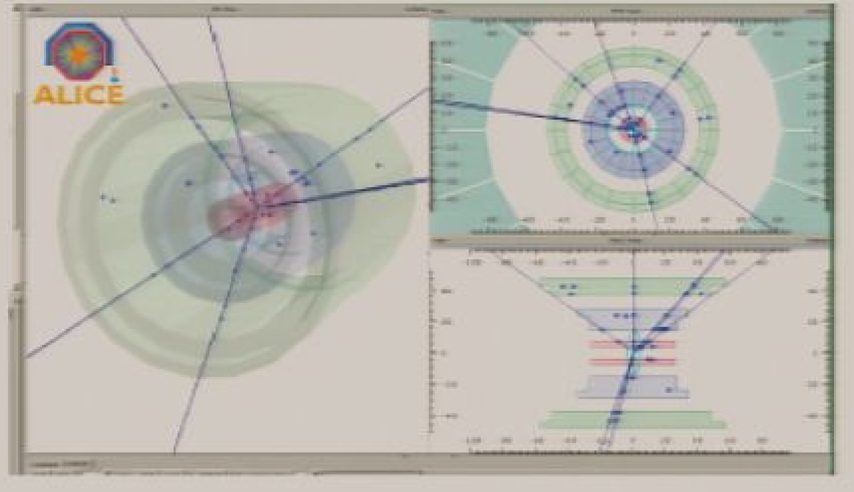
$$W \supset \lambda S H_u H_d + \frac{\kappa}{3} S^3 \tag{5}$$

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.

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.

Supersymmetry?

- Higgs mass at tree level constrained to be less than the Z boson mass

$$m_h^{MSSM} < m_Z^2 \cos^2 2\beta. \qquad (1)$$

- 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

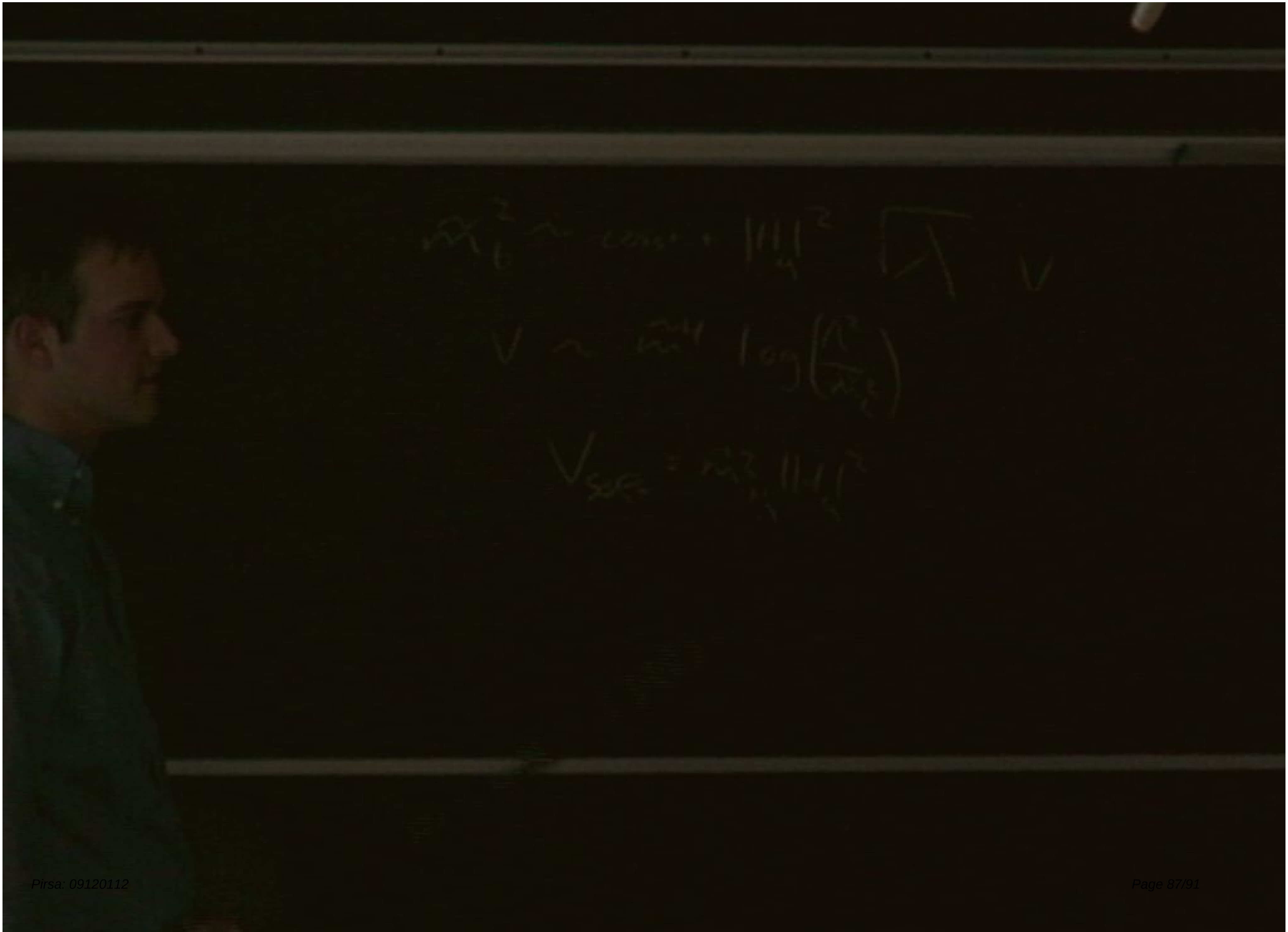
- Corrections to Higgs mass are logarithmic

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

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

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

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



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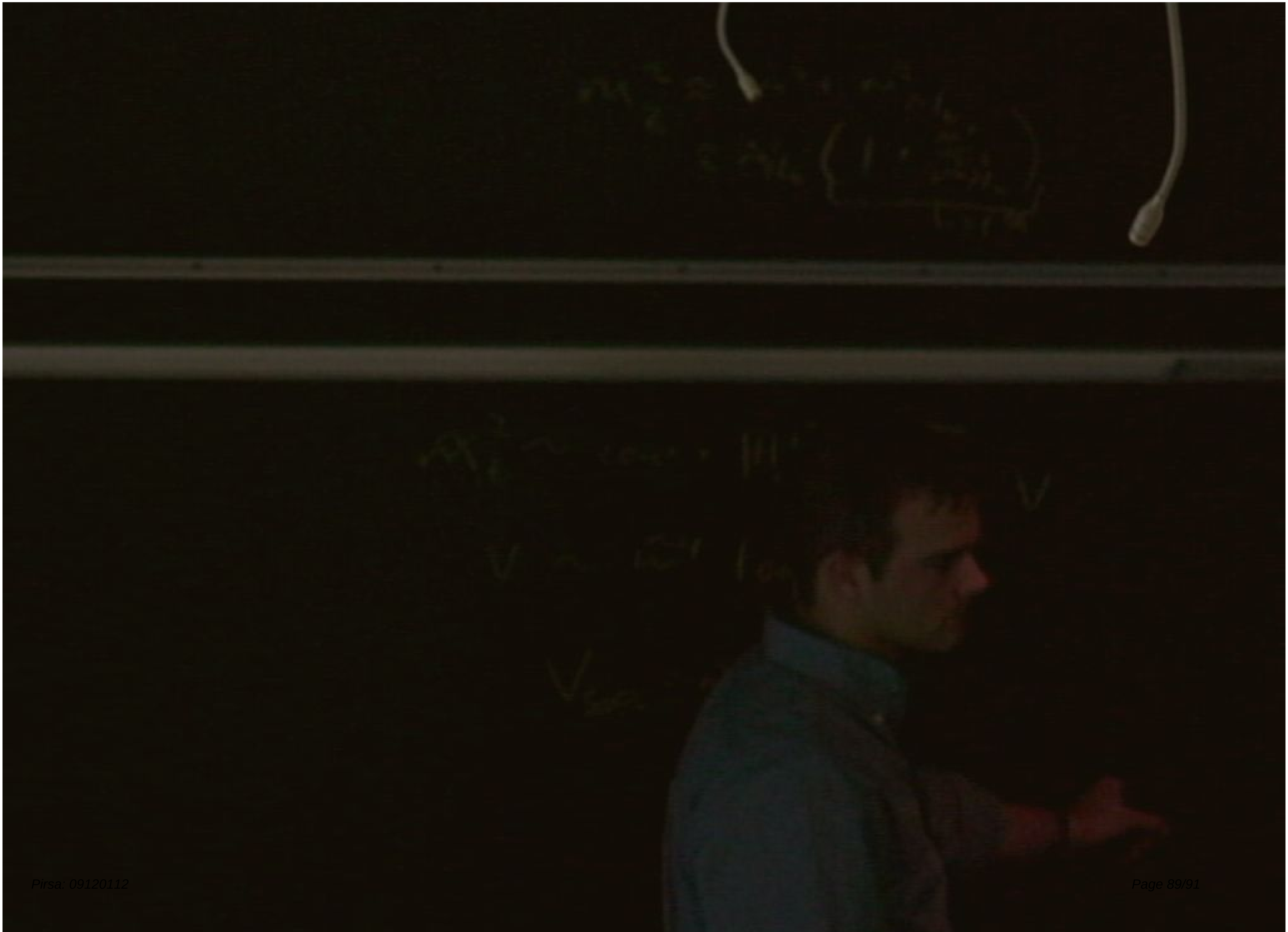

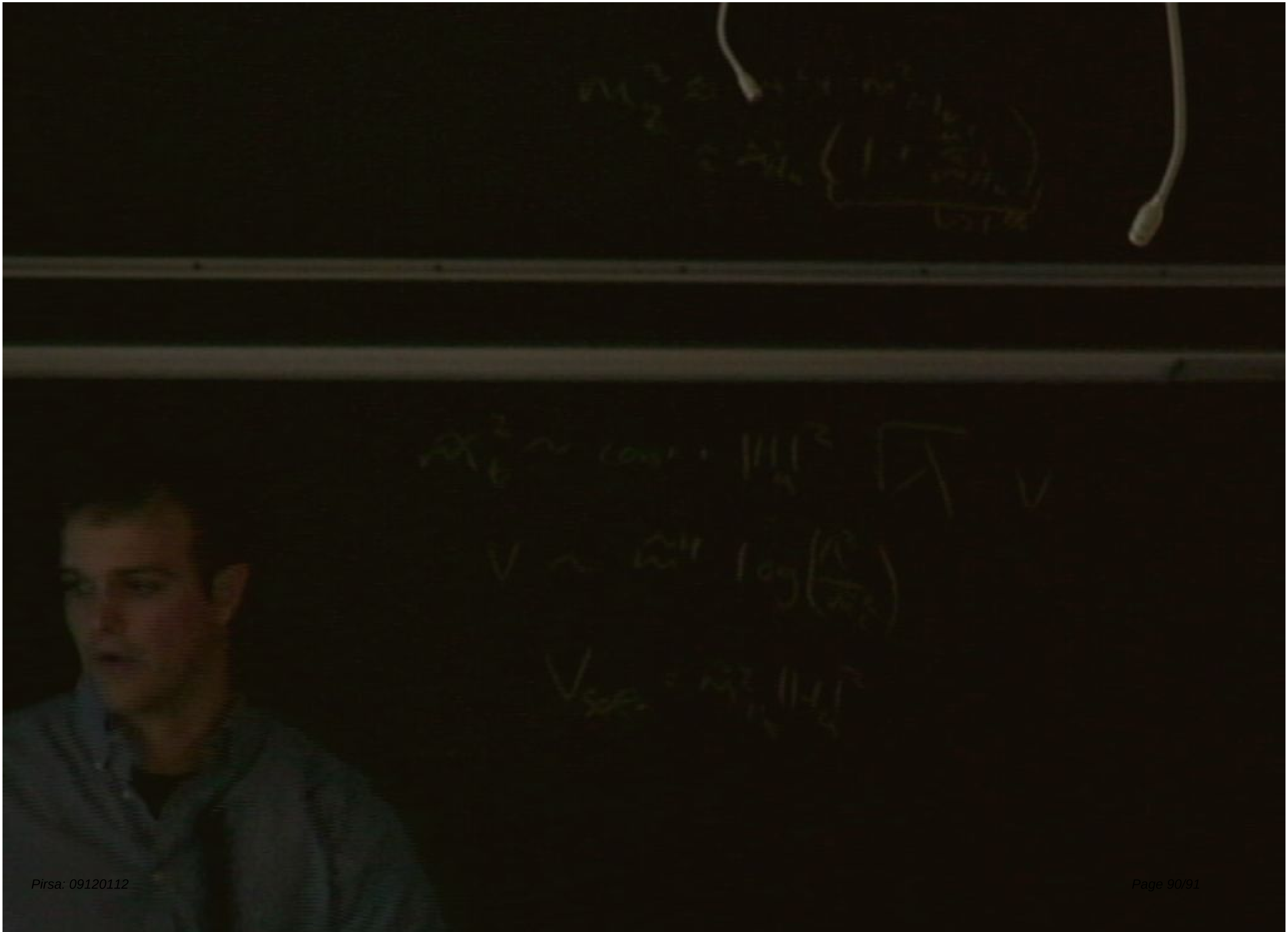
$\delta m_t^2 \sim \text{const} \cdot \|H_u\|^2$
V
$V \sim \tilde{m}^4 \log\left(\frac{\Lambda^2}{\tilde{m}^2}\right)$
$V_{\text{eff}} = m^2_{H_u} \|H_u\|^2$

Little Hierarchy

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