Electroweak Symmetry Breaking & the Higgs Boson Beyond the Standard Model

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Evidence for Physics beyond SM

- Dark matter
- Cosmological baryon asymmetry
- Neutrino oscillation
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But none of these necessarily points to LHC scales, few×100 GeV – few TeV.

What points to LHC is naturalness problem

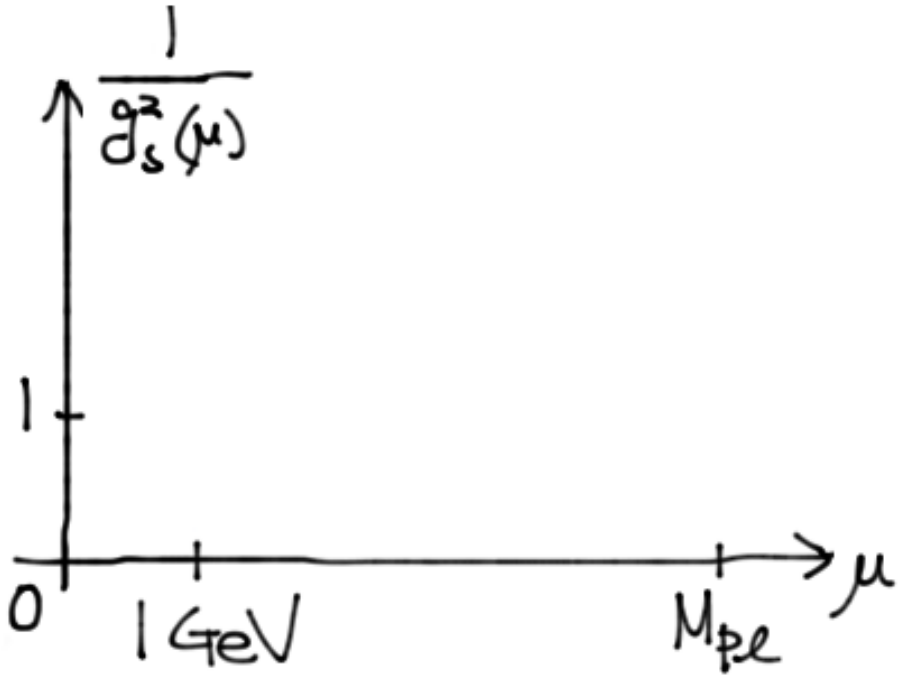
(a.k.a. hierarchy problem,
fine tuning "
)

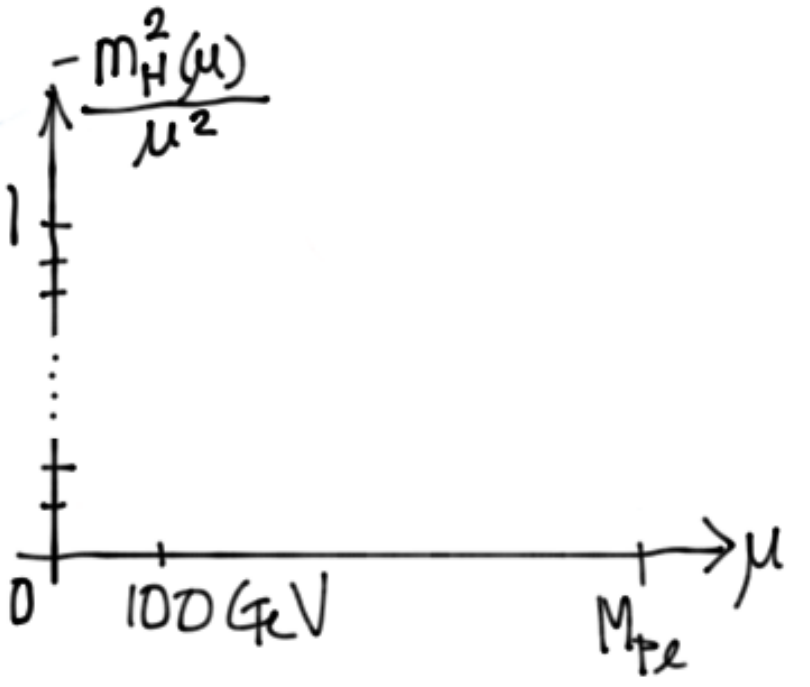
Naturalness Problem of EW scale

Two scales in SM:

$$\Lambda_{QCD} \sim 1\ \text{GeV} \ll M_{Pl} \qquad m_H^2 \sim -(100\ \text{GeV})^2 \ll M_{Pl}^2$$

$$\mathcal{L} = \frac{1}{g_s^2} G_{\mu\nu} G_{\mu\nu} + \cdots \qquad \mathcal{L} = m_H^2 H^\dagger H + \cdots$$





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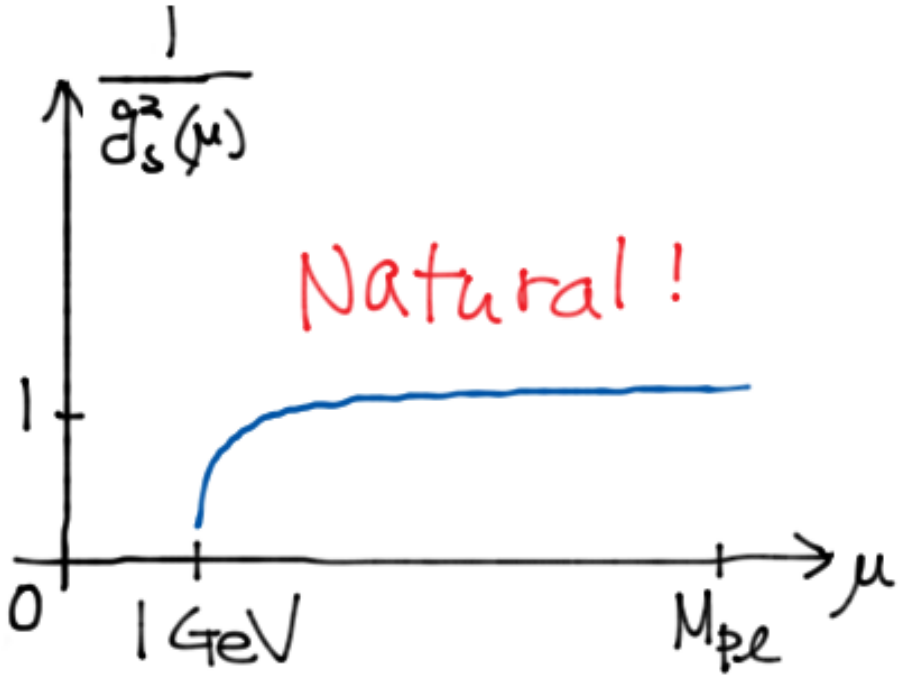

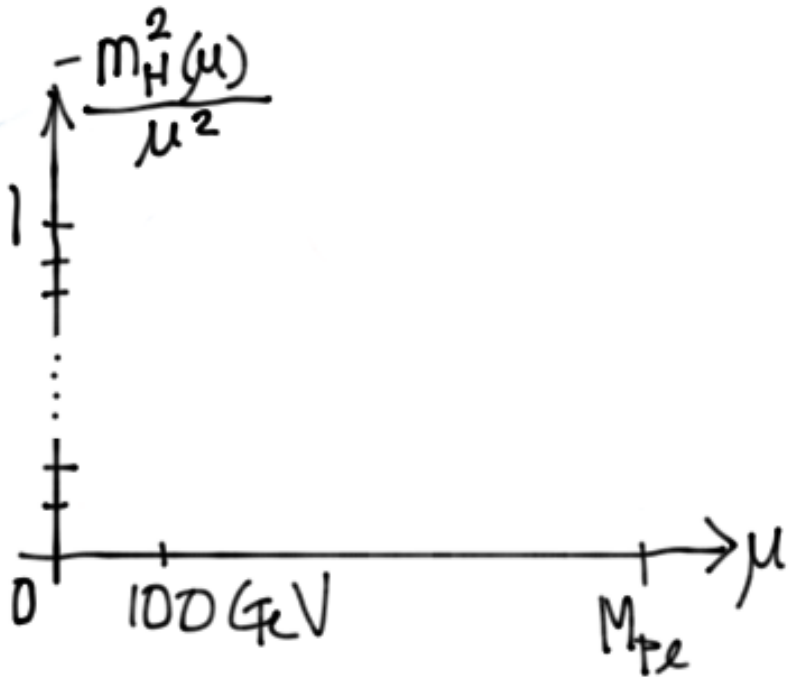

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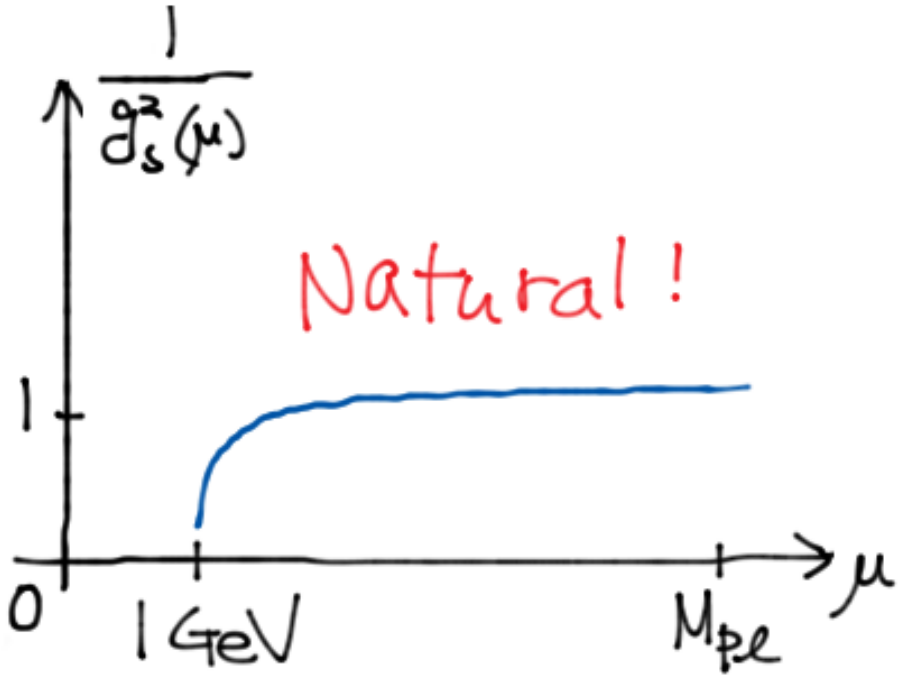

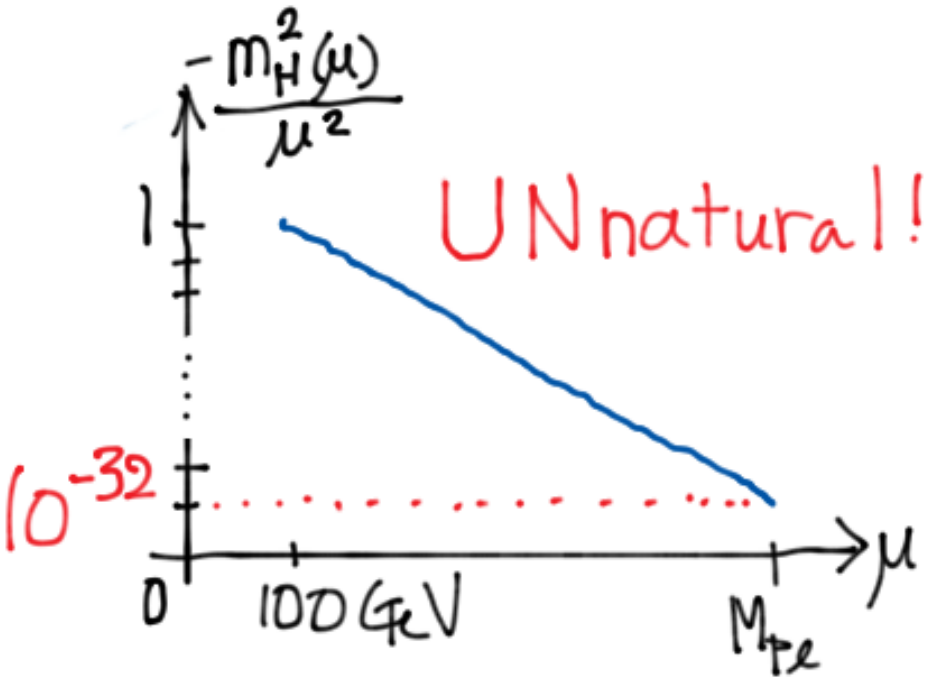

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Must be tuned if $m_{H,IR} \ll \Lambda$!

Solutions: Negate (A) or (B)!

(A) $\cancel{H} \longrightarrow \mathcal{O}_H$ with $[\mathcal{O}_H^\dagger \mathcal{O}_H] > 4$

(e.g.)

$\mathcal{O}_H = \bar{\Psi}_T \Psi_T$ "Technicolor"

Not in this session...

(B) New symmetry to forbid $H^\dagger H$

Naturally Light Higgs

<u>Plan</u>

(i) Extend SM by a new symm. to kill $H^\dagger H$,

(ii) Break the new symm. in a natural way.

Typically a separate "module"

Focus on (i).

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Focus on (i).

Break down (i) in 2 steps:

(i-A) Find a symm. that gives <u>some</u> kind of massless particle X,

(i-B) Relate X to H.

Massless particles in QFT

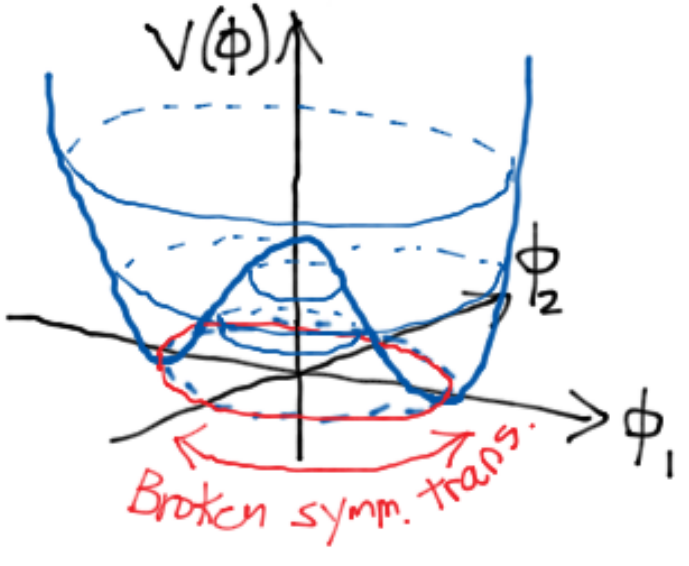
Spin-0 Nambu-Goldstone boson (NGB)

Unbroken symm. ≡ Rotates particles

$\Rightarrow M_{\text{particle } 1} = M_{\text{particle } 2}$, etc.

Spontaneously broken symm. ≡ Rotates vacua

$\Rightarrow$



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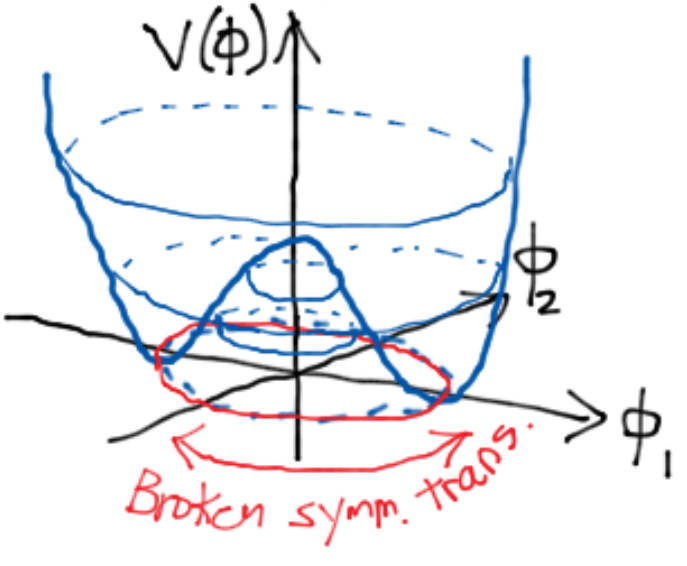

Exitations along ◯

= Massless!

H = NGB of a new broken symm $\Rightarrow m_H = 0$!

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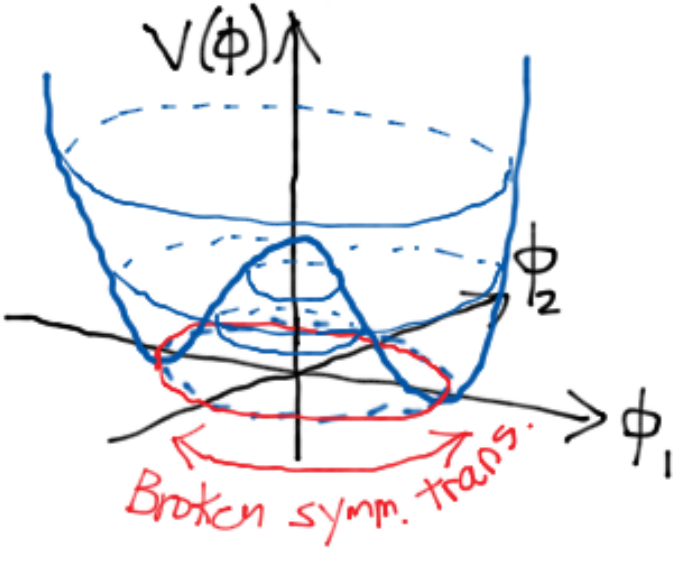

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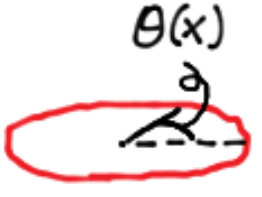

= Massless!

"Shift symm."

$\theta(x) \longrightarrow \theta(x) + \varepsilon$

H = NGB of a new broken symm $\Rightarrow m_H = 0$!

spin-$\frac{1}{2}$

Chiral symm. $\equiv$ ψ_L, ψ_R have opposite charges

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Suppose $m_\psi \neq 0$.

Then,

- left-handed
- charge $+1$

- right-handed
- charge -1 !?

Boost shouldn't change charge!

By contradiction, $m_\psi = 0$!

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· charge −1 !?

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By contradiction, $m_\psi = 0$!

Must relate ψ $(s=\frac{1}{2})$ to H $(s=0)$ to get $m_H = 0$.

$\Rightarrow$ Supersymmetry !

spin-1

Gauge symm $A_\mu \longrightarrow A_\mu + \partial_\mu \varepsilon \implies \cancel{m_A^2 A_\mu A^\mu}$

$m_A = 0!$

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Must relate spin-1 to spin-0 for $m_H = 0$.

SUSY?

$$|s=\tfrac{1}{2}\rangle$$

$$|s=0\rangle \xleftrightarrow{\text{SUSY}}$$

$$|s=1\rangle$$

$$|s=\tfrac{1}{2}\rangle \xleftrightarrow{\text{SUSY}}$$

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SUSY?

$$\begin{tikzcd}
 & |s=\tfrac{1}{2}\rangle \arrow[dr, leftrightarrow, "\text{SUSY}'"] & \\
|s=0\rangle \arrow[ur, leftrightarrow, "\text{SUSY}"] \arrow[dr, leftrightarrow, "\text{SUSY}'"'] & & |s=1\rangle \\
 & |s=\tfrac{1}{2}\rangle \arrow[ur, leftrightarrow, "\text{SUSY}"'] &
\end{tikzcd}$$

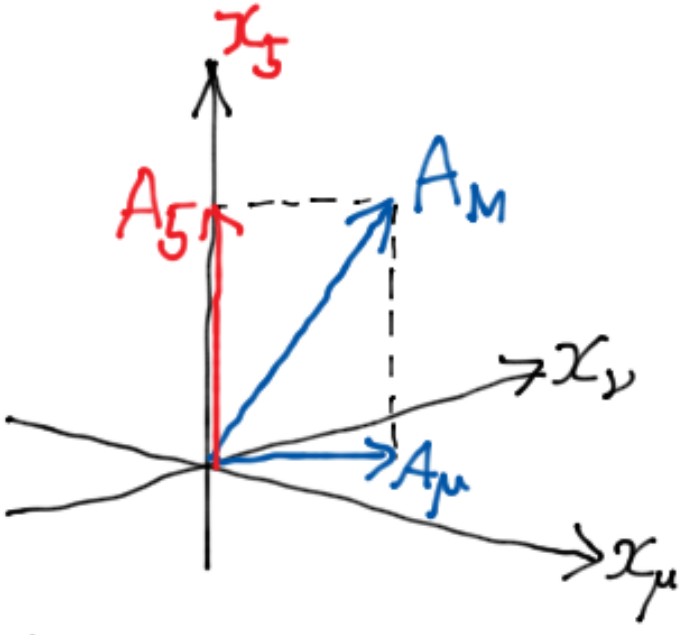
"N=2 SUSY"

Not chiral

$\begin{pmatrix} \text{SUSY} = \text{SUSY}_L \\ \text{SUSY}' = \text{SUSY}_R \end{pmatrix}$

No!

Need an extra dimension!



$(\mu, \nu = 0, 1, 2, 3;\ M = \mu, 5)$

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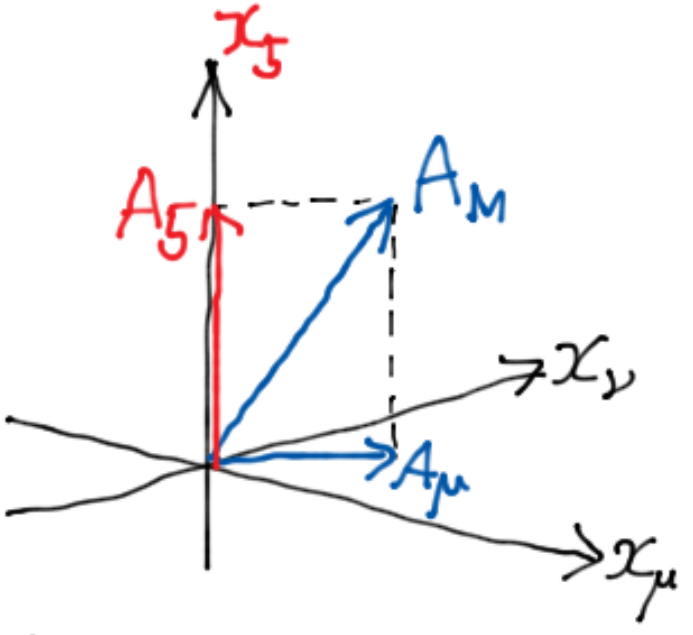

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$A_5 \cdots$ unchanged under x_μ-x_ν rotations

$\equiv$

scalar in 4d!

$$H = A_5 \Rightarrow m_H = 0\ !$$

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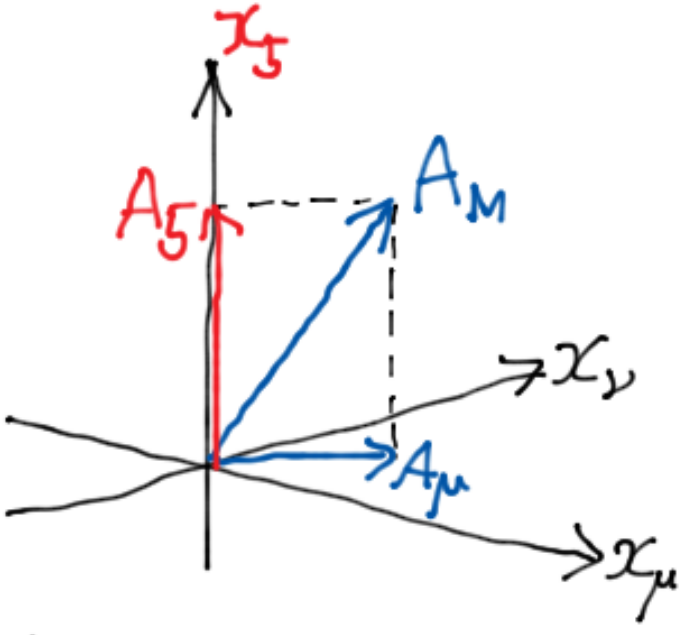

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$$H = A_5 \Rightarrow m_H = 0\ !$$

But

5d gauge trans: $A_5 \to A_5 + \partial_5 \varepsilon \iff H$ <u>shifts</u>!

Effectively same as $H = \text{NGB}$!

Spin-3/2

(No known working model)

Need SUSY (& extra dim.) to relate to H.

(e.g.) $S=0 \xleftrightarrow[\text{SUSY}]{} S=\frac{1}{2} \xleftrightarrow[\text{XD}]{} S=\frac{3}{2}$

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$m=0$

"Gauge" symm: $h_{\mu\nu} \to h_{\mu\nu} + \partial_\mu \varepsilon_\nu + \partial_\nu \varepsilon_\mu \Longrightarrow \cancel{h_{\mu\nu} h^{\mu\nu}}$

(or GR!) $\cancel{h_\mu{}^\mu h_\nu{}^\nu}$

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Need extra dimensions to get scalar

h_{55}, h_{56}, etc. = scalars in 4d $\sim H$

But H shifts under symm.

Same story as spin-1 $\quad H = \text{NGB}$!

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Spin > 2

No interacting massless particles.

Summary so far

Only 2 ways to have $m_H = 0$ naturally!

SUSY

$$\underset{(S=0)}{H} \xleftrightarrow{\text{SUSY}} \underset{(S=\frac{1}{2})}{\tilde{H}}$$

$$m_H = 0 \xleftrightarrow{\text{SUSY}} m_{\tilde{H}} = 0$$

chiral symm.

H = NGB

Shift symm.

$$H \to H + \varepsilon$$

$$\Rightarrow \cancel{m_H^2 H^\dagger H}$$

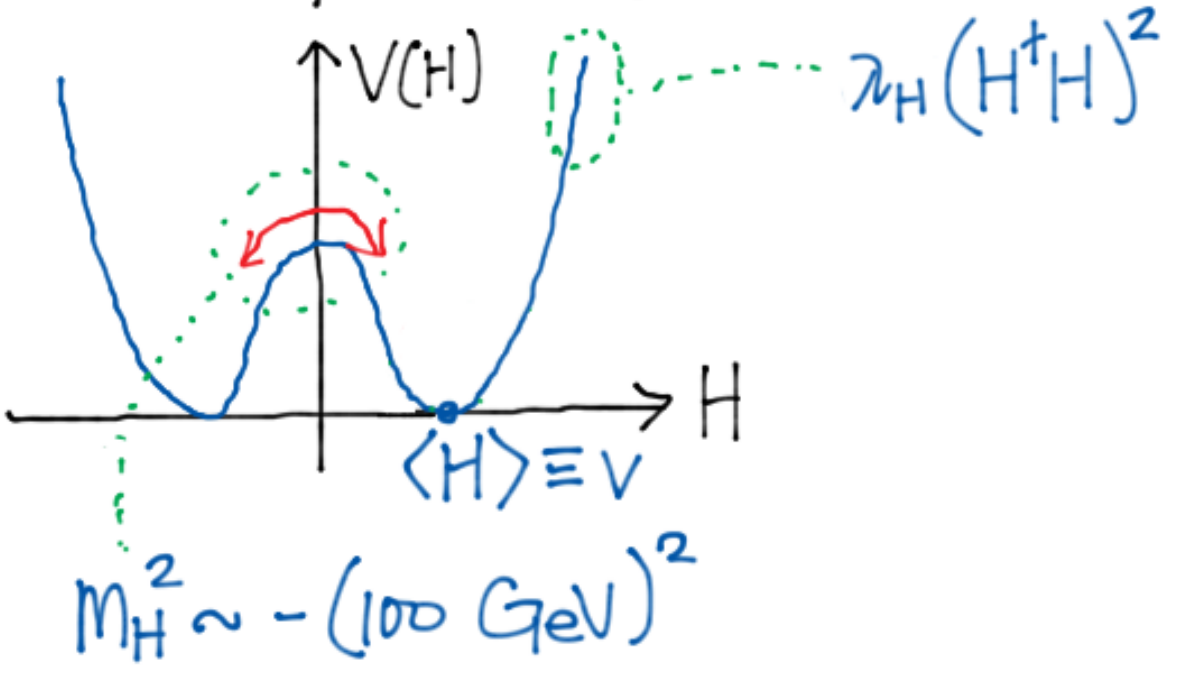
e.g. Composite Higgs
Little Higgs
Twin Higgs
Higgs as A_5

EWSB and Higgs mass

Break the $m_H = 0$ symm. to get $m_H^2 < 0$ for EWSB.

We want

$$V(H) =$$



$$\sim \lambda_H (H^\dagger H - v^2)^2$$

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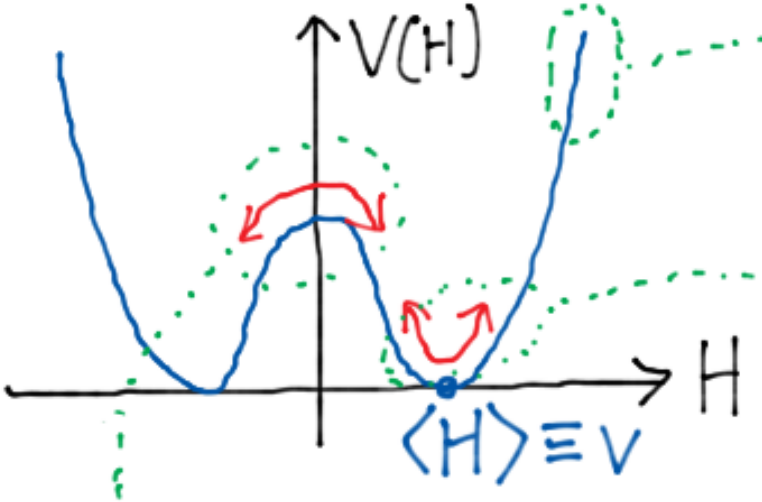
$$V(H) = \lambda_H (H^\dagger H)^2 - m_H^2 (H^\dagger H) + \cdots$$



m_h^2 Physical Higgs mass

$m_H^2 \sim -(100\ \text{GeV})^2$

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$H = v + h$ Physical Higgs

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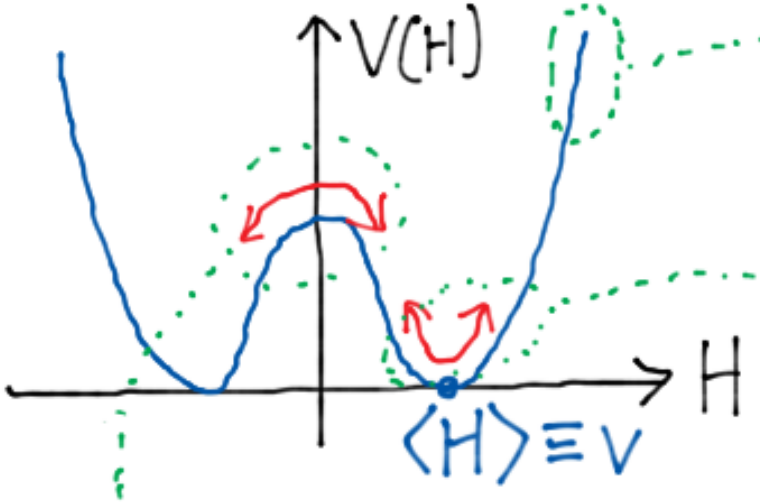

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$\sim \lambda_H v^2 h^2 + \dots$

$\Rightarrow \underline{m_h^2 \sim \lambda_H v^2}$ $\qquad v = (\text{measured}) \simeq 174\ \text{GeV}$

What's m_h? = What's λ_H?

λ_H in SUSY

(i) SUSY contributions

Kills $H^\dagger H$

(ii) ~~SUSY~~ contributions

λ_H in SUSY

(i) SUSY contributions

Kills $H^\dagger H$

and predicts $\lambda_H \sim g_1^2 + g_2^2$!

$$\Longrightarrow m_h^2 \sim \lambda_H v^2 \sim m_Z^2$$

(More precisely $m_h \leq m_Z$)

(ii) ~~SUSY~~ contributions

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$$\delta m_H^2 \sim -(100\ \text{GeV})^2 \rightarrow \text{EWSB}$$

$\delta\lambda_H \sim$ 

$$\sim \frac{3y_t^4}{4\pi^2} \log \frac{m_{\tilde{t}}}{m_t}$$

scalar top mass

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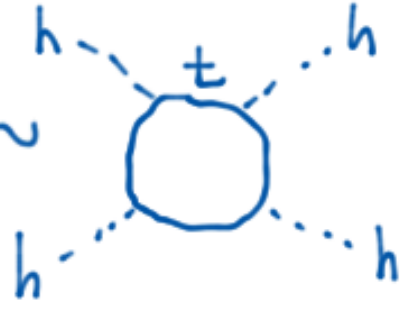

$$\sim \frac{3y_t^4}{4\pi^2} \log \frac{m_{\tilde{t}}}{m_t}$$

scalar top mass

$\|$

cutoff for SM !

Naturalness $\Rightarrow m_{\tilde{t}} \lesssim 1$ TeV

$$\Rightarrow \underline{m_h^2 \lesssim m_Z^2 + (90\ \text{GeV})^2 \simeq (130\ \text{GeV})^2}$$

Is m_h upper bound robust?

Do we "expect" additional λ_H?

(= w/o knowing $m_h > 114.4$ GeV from LEP2)

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μ-problem

$$m_H = m_{\tilde{H}} = 0 \Longrightarrow \begin{cases} m_H^2 = \mu^2 + \Delta m_H^2 \sim -(100\ \text{GeV})^2 \\ m_{\tilde{H}} = \mu \end{cases}$$

SUSY ← Δm_H^2

Chiral symm. ← $m_{\tilde{H}}$

SUSY ← m_H

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SUSY chiral symm.

$\Delta m_H^2 \leftarrow$ ~~SUSY~~

$m_{\tilde{H}} \leftarrow$ ~~Chiral symm.~~

Is $\mu \neq 0$ necessary?

LEP2 $\tilde{H}$-like chargino searches $\Rightarrow$ $m_{\tilde{H}} > 92$ GeV

Yes!

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No tuning in m_H^2 b/w μ^2 & Δm_H^2 $\Rightarrow$ $\mu \lesssim$ few $\times$ 100 GeV

$\Rightarrow$ ~~Chiral symm.~~ $\sim$ ~~SUSY~~ Why?

Can't be coincidence!

A solution to μ-problem:

μ is induced by $\cancel{\text{SUSY}}$

Add a scalar S with $\Delta\mathcal{L} = \alpha S \tilde{H}\tilde{H}$

Then, $m_S^2 \sim -(100\ \text{GeV})^2 \Rightarrow \mu = \alpha\langle S\rangle \sim 100\ \text{GeV}$

from $\cancel{\text{SUSY}}$

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Bonus: SUSY $\Rightarrow \Delta\lambda_H = \alpha^2$!

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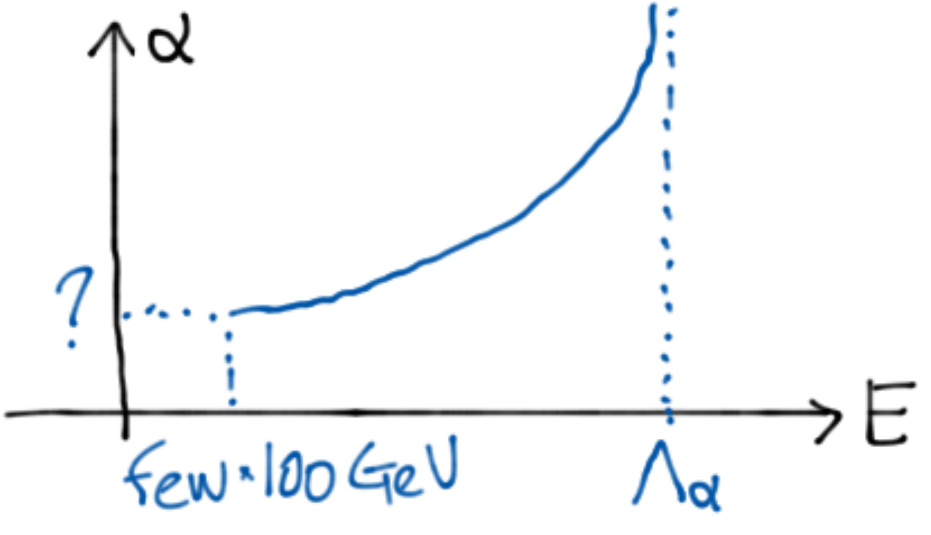
How big can α be?



Precision electroweak tests

$\Rightarrow \Lambda_\alpha \gtrsim 10\ \text{TeV}$

$\Rightarrow \alpha \lesssim 2$

$\Rightarrow m_h \lesssim 300\ \text{GeV}$

λ_H in H=NGB

(i) NGB contributions

$H \to H + \varepsilon$ symm. $\Rightarrow V(H) = \underline{\text{const.}}$

No $H^\dagger H$

No $(H^\dagger H)^2$!

(ii) $H \to H + \varepsilon$ violating contributions

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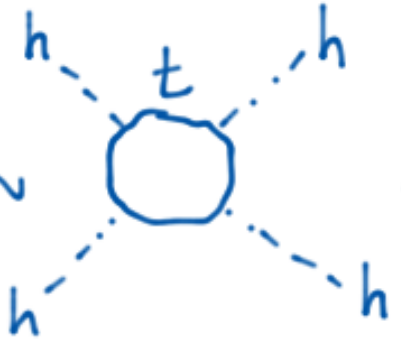
(ii) $H \to H + \varepsilon$ violating contributions

Largest violation = top Yukawa $\underbrace{y_t}_{O(1)} H \bar{Q}_{3L} t_R$

$\Rightarrow \delta\lambda_H \sim$ 

$\sim \dfrac{3y_t^4}{4\pi^2}\left(\log\dfrac{\Lambda_t}{m_t} + O(1)\right)$

$\Lambda_t = M_{t'}, M_{t\,\text{comp.}}$, etc.

λ_H in H=NGB

(i) NGB contributions

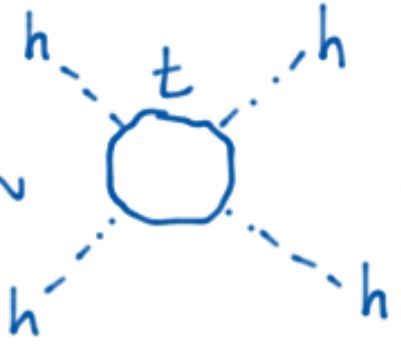
$H \to H + \varepsilon$ symm. $\Rightarrow V(H) = \underline{\text{const.}}$

No $H^\dagger H$

No $(H^\dagger H)^2$!

(ii) $H \to H + \varepsilon$ violating contributions

Largest violation = top Yukawa $\underbrace{y_t}_{O(1)} H \bar{Q}_{3L} t_R$

$\Rightarrow \delta\lambda_H \sim$ 

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$\Lambda_t = m_{t'}, m_{t\,\text{comp.}}$, etc.

* No good reason like μ-problem for extra λ_H.

$\Rightarrow \underline{m_h^2 \lesssim O(1) \times (90\ \text{GeV})^2}$

At most a few × 100 GeV like SUSY case!

Conclusions

Natural EWSB

- With Higgs
  - SUSY
  - H = NGB

  $m_h <$ few × 100 GeV

  and the lighter the better

- No Higgs (e.g. technicolor)

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What if we find $M_h = 500$ GeV?