Naturalness of Electroweak Symmetry Breaking in the LHC Era

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- Dark matter
- Cosmological baryon asymmetry
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- Cosmological baryon asymmetry
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- Nearly scale invariant & Gaussian primordial density fluctuations $\Rightarrow$ Inflation

But none of these necessarily points to LHC scales, few×100 GeV – few TeV.

What points to LHC is naturalness problem

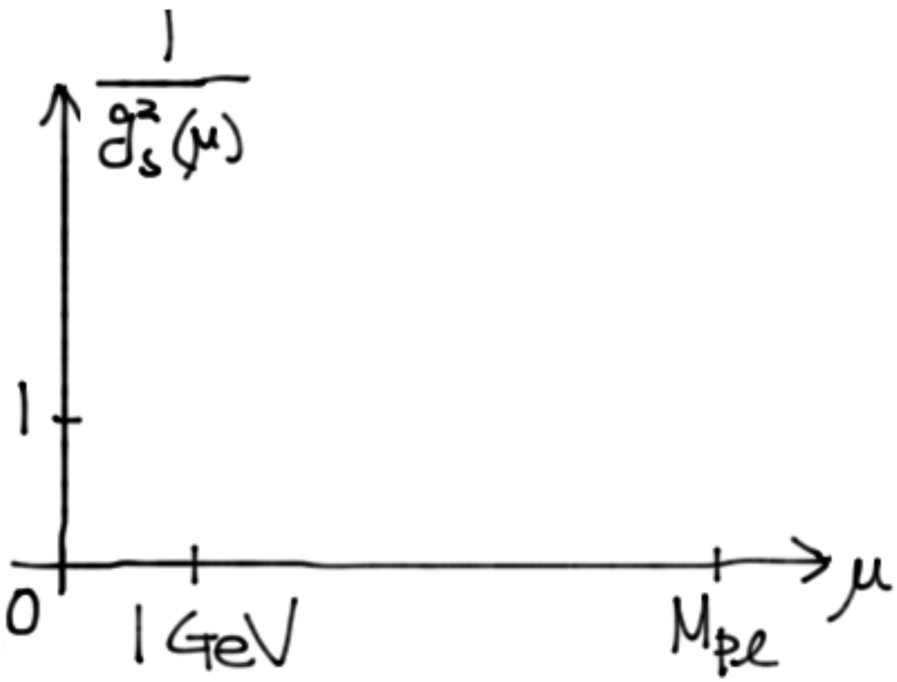
(a.k.a. hierarchy problem,
fine tuning ")

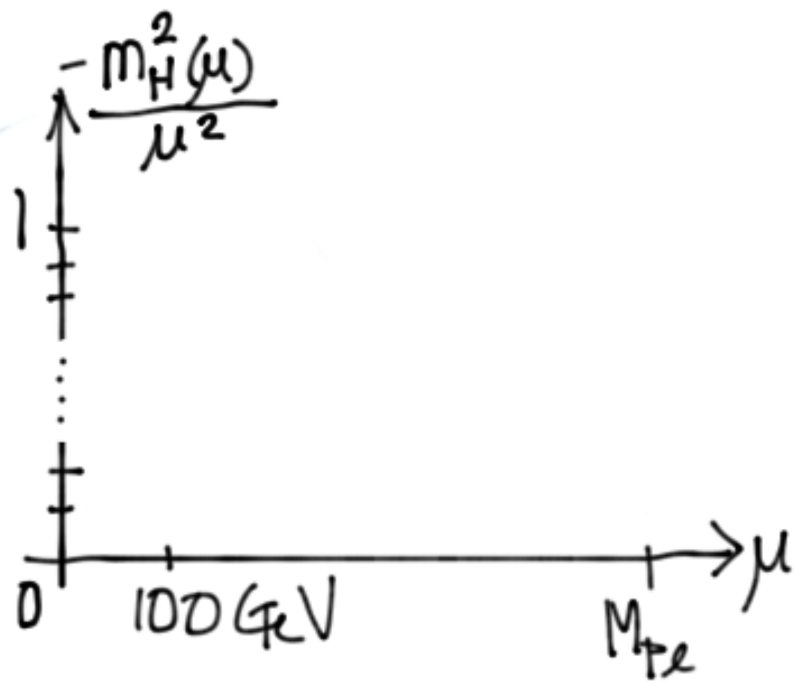
Naturalness Problem of EW scale

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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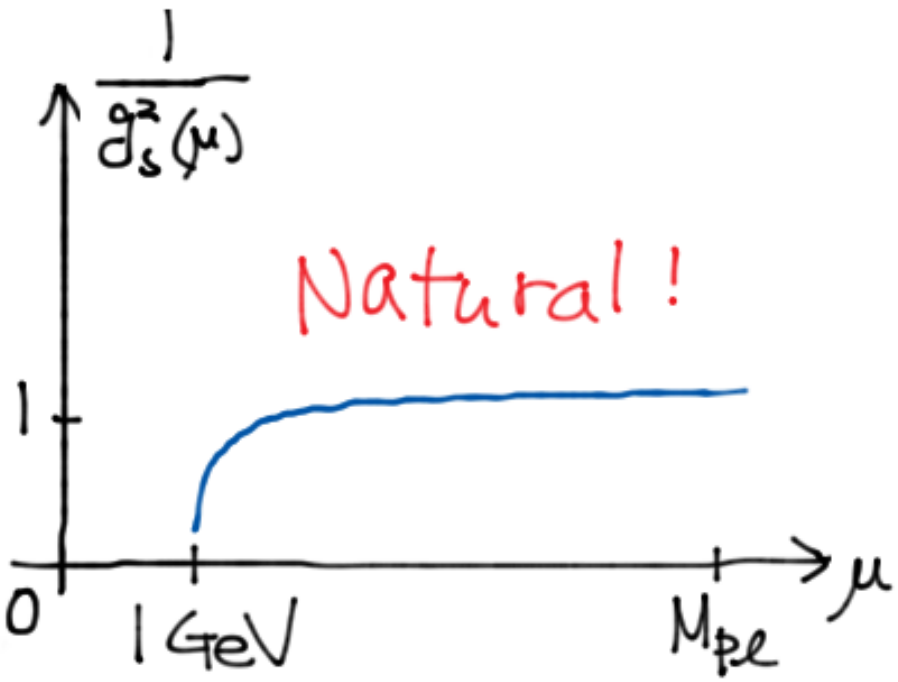

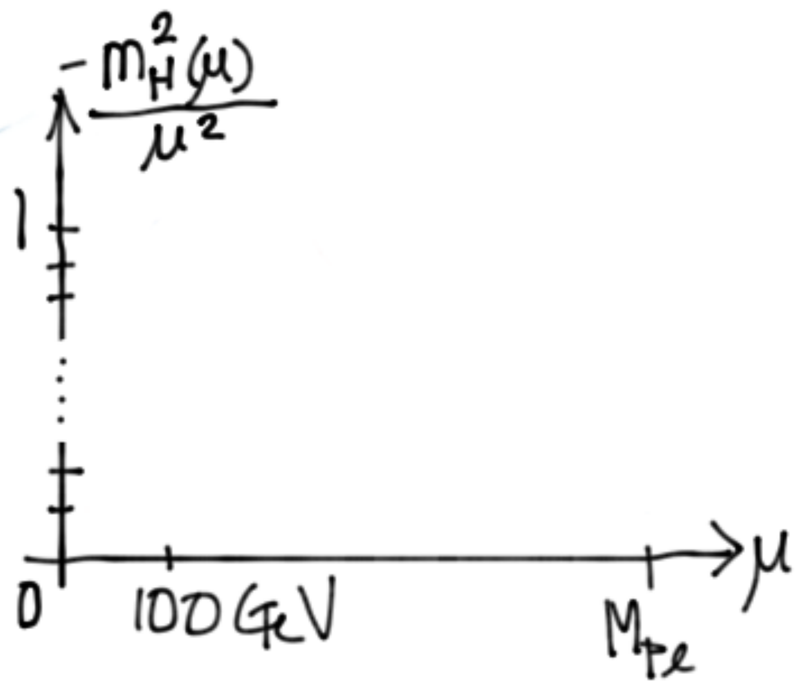

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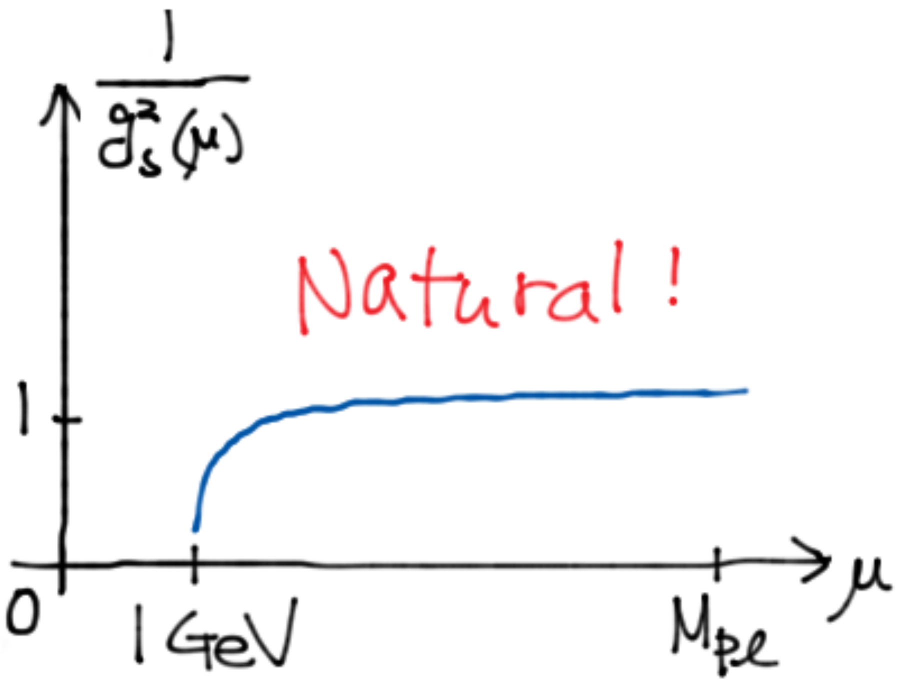

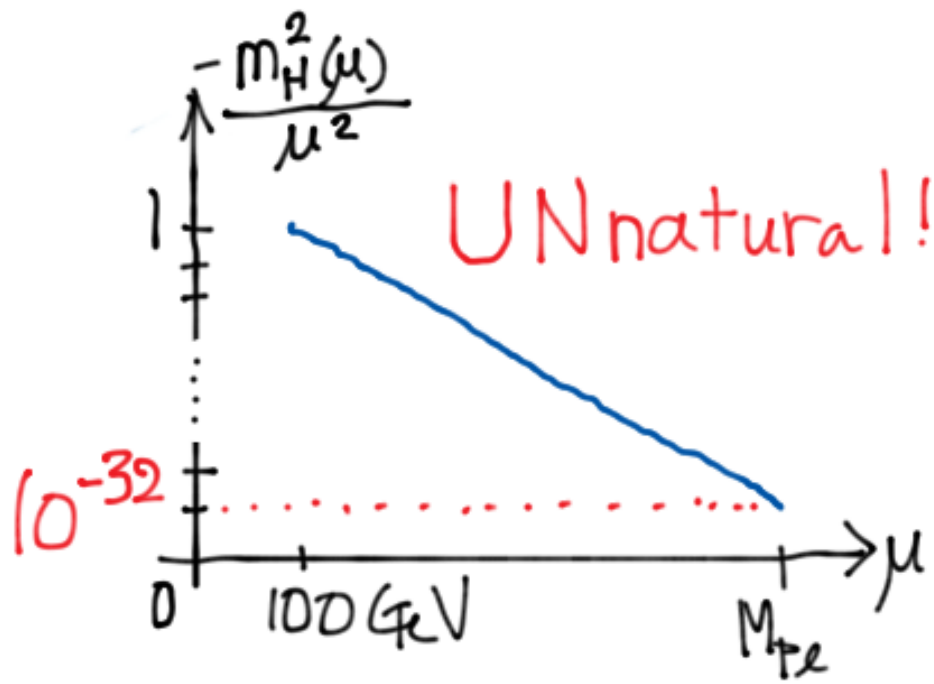

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Solutions: Negate (A) or (B)!

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

(e.g.) $\mathcal{O}_H = \bar{\Psi}_T \Psi_T$ "Technicolor"

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

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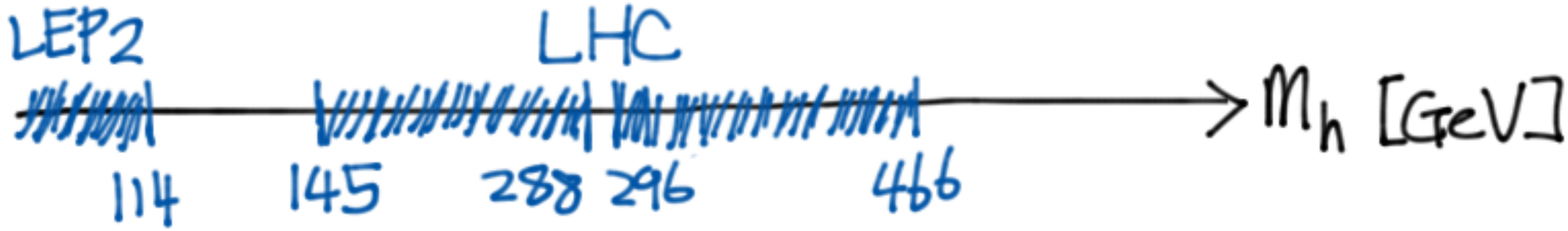
  (e.g. MSSM $\Rightarrow m_h \ll m_{H^0, H^\pm, A^0}$)

$\Longrightarrow$ BSM Higgs $\simeq$ SM Higgs unless contrived

$\Longrightarrow$



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Precisely Light Higgs (B) or No Higgs (A) !

Naturally Light Higgs

Plan

(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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Typically a separate "module"

Focus on (i).

Break down (i) in 2 steps:

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

(i-B) Relate X to H.

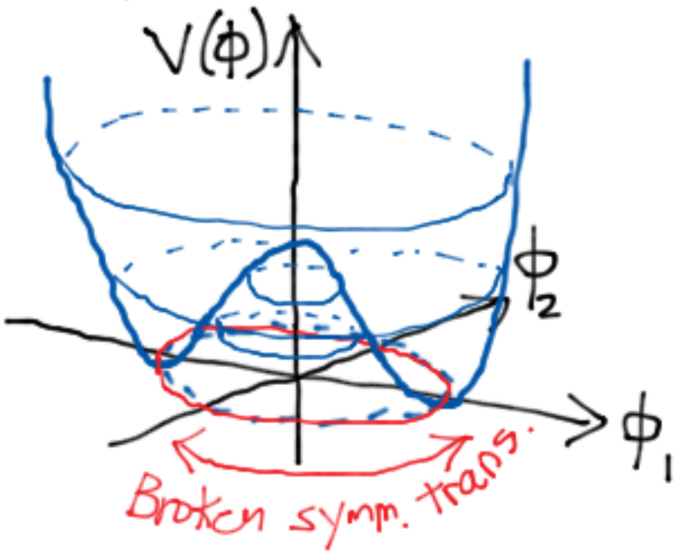
Massless particles in QFT

<u>spin-0</u> 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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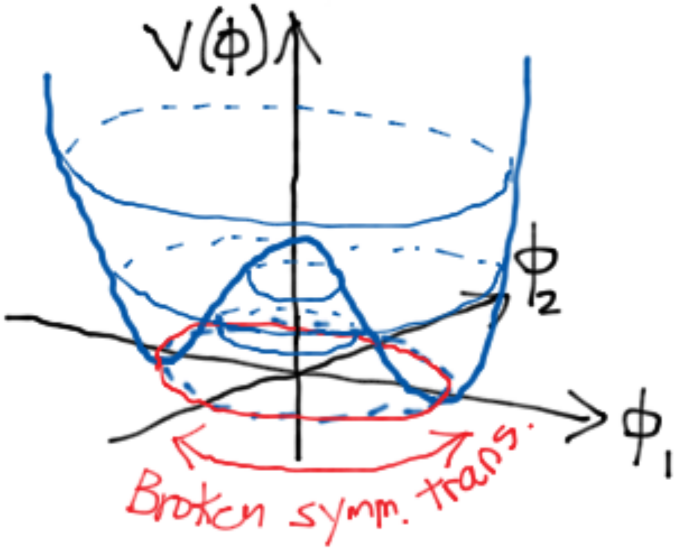

Exitations along

= Massless!

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

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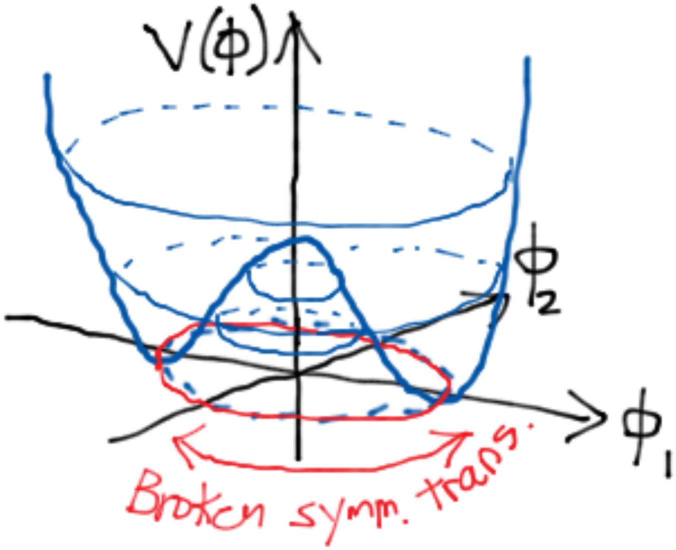

Exitations along 

= 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,

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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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boost! $\Longrightarrow$

- right-handed
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Boost shouldn't change charge!

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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SUSY?

$$|s=0\rangle \xleftrightarrow{\text{SUSY}} |s=\tfrac{1}{2}\rangle$$

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

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SUSY?

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

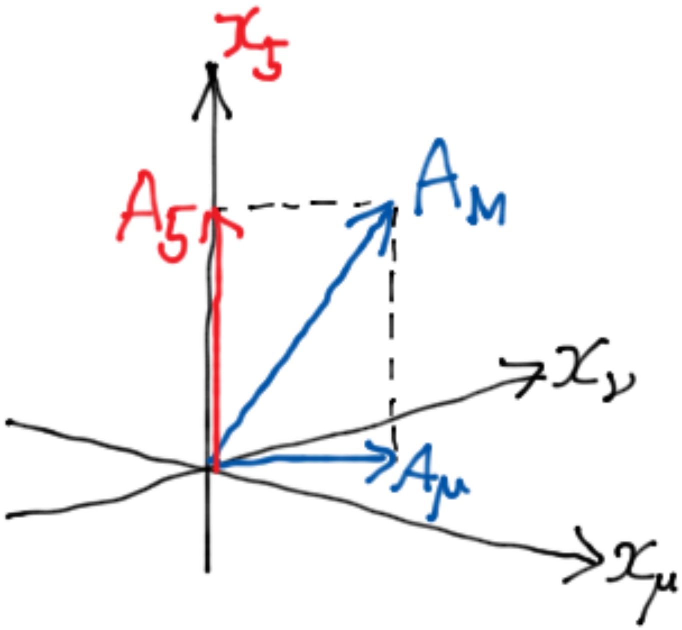
"$N=2$ SUSY"

Not chiral

$\left(\begin{array}{l}\text{SUSY} = \text{SUSY}_L \\ \text{SUSY}' = \text{SUSY}_R\end{array}\right)$

No!

Need an extra dimension!



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

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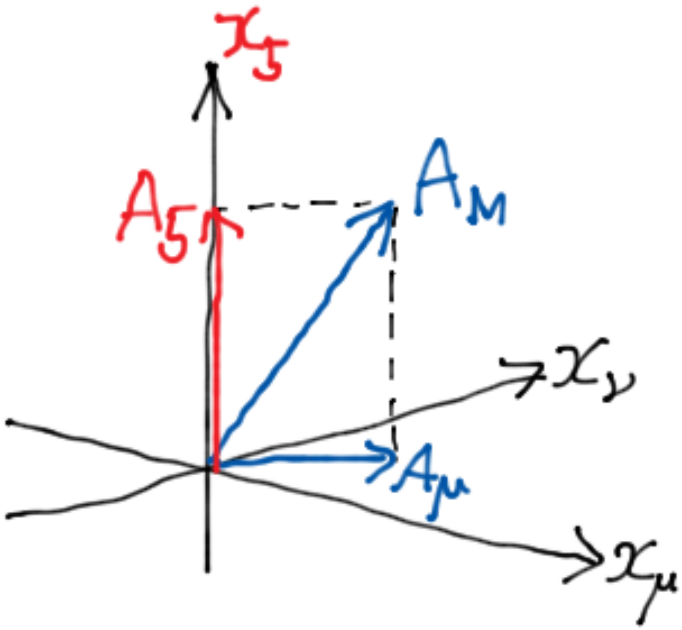

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A_5 ⋯ unchanged under x_μ-x_ν rotations

$\parallel\!\mid$

Scalar in 4d!

$H = A_5 \Rightarrow m_H = 0$!

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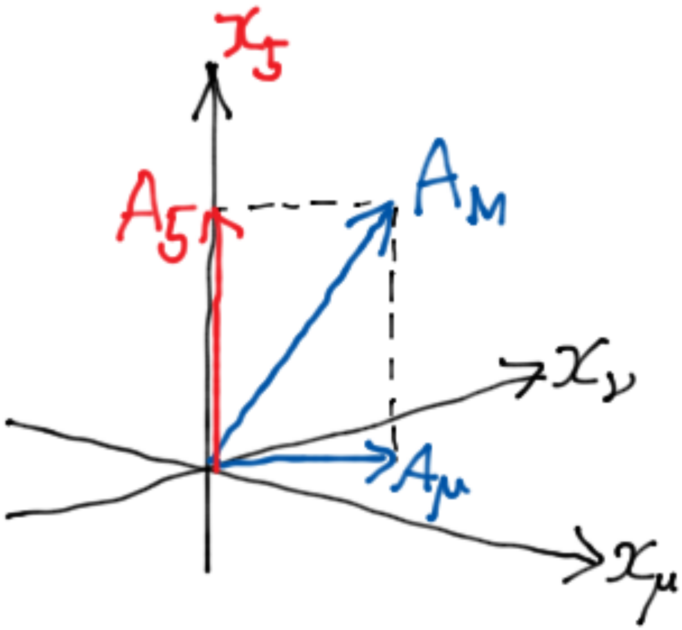

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$\parallel\!\!\!\!\!\;|$

Scalar in 4d!

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But

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

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

Spin-3/2

(No known working model)

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

(e.g.) $S=0 \underset{\text{SUSY}}{\longleftrightarrow} S=\frac{1}{2} \underset{\text{XD}}{\longleftrightarrow} S=\frac{3}{2}$

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Spin-2

(No known working model)

$m=0$

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

(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.

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

spin > 2 No interacting massless particles.

Summary so far

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

$\boxed{\text{SUSY}}$

$$H \xleftrightarrow[\text{SUSY}]{} \tilde{H}$$

$(S=0) \qquad (S=\frac{1}{2})$

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

↑

chiral symm.

$\boxed{H = \text{NGB}}$

Shift symm.

$$H \to H + \varepsilon$$

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

e.g. Composite Higgs

Little Higgs

Twin Higgs

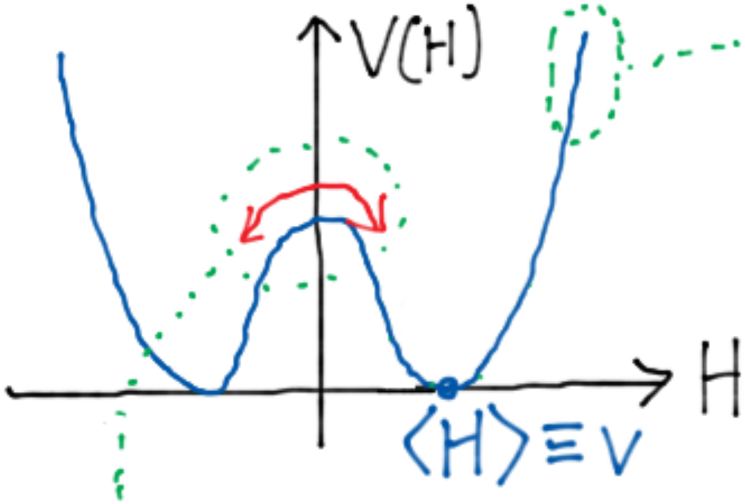
Higgs as A_5

EWSB and Higgs mass

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

We want

$V(H) =$



$\lambda_H (H^\dagger H)^2$

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

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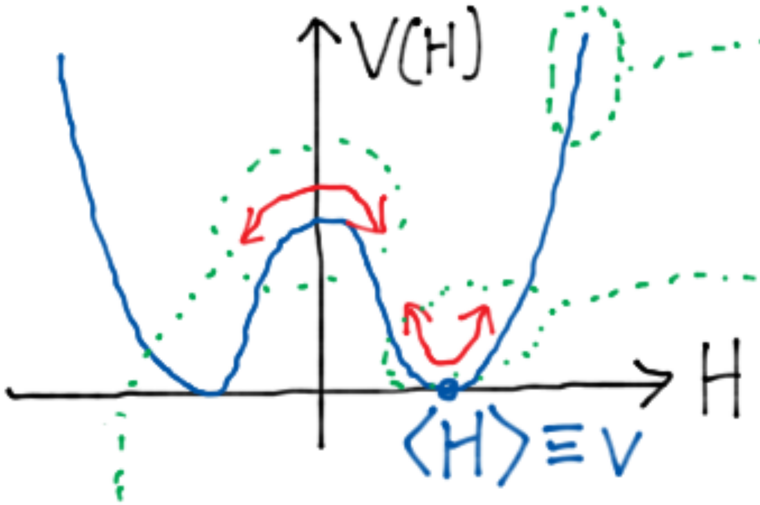

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$H = v + h$ Physical Higgs

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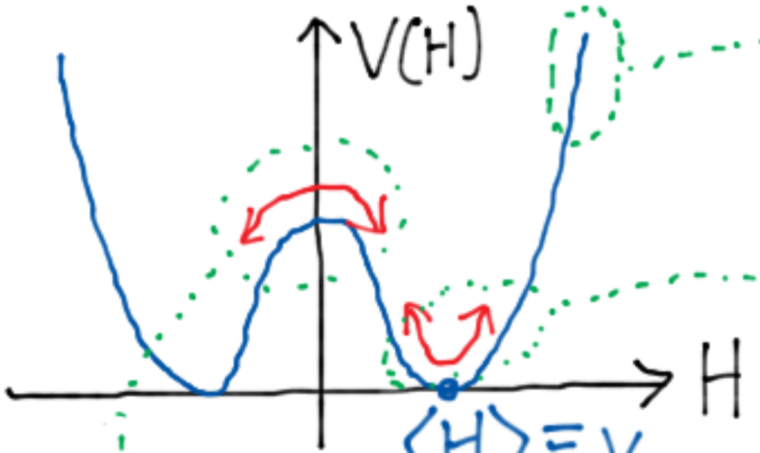

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$\sim \lambda_H v^2 h^2 + \cdots$

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

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 $m_h \leq m_Z$)

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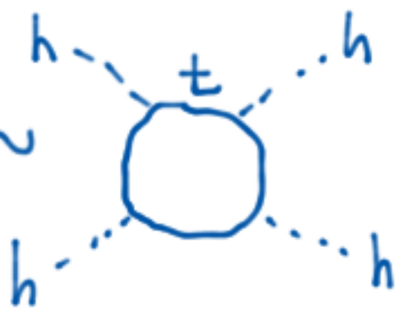
(ii) $\cancel{\text{SUSY}}$ contributions

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

$\delta\lambda_H \sim$ 

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

scalar top mass

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scalar top mass

$\parallel$

cutoff for SM!

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

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

λ_H in H=NGB

(i) NGB contributions

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

No $H^\dagger H$

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

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

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

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

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

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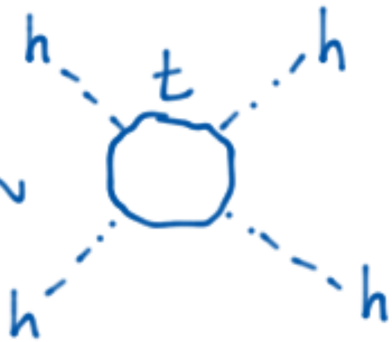

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$\Rightarrow$ $m_h^2 \lesssim O(1) \cdot (90\ \text{GeV})^2$

At most ~100-200 GeV like SUSY case!

Summary

Natural EWSB

No Higgs

$m_{\rho_{TC}} = 2\text{-}3$ TeV

New Symm. for $m_H = 0$

SUSY

H = NGB

$m_H = 100 \sim 200$ GeV

$m_{\tilde{t}, t', \text{etc.}} \lesssim 1$ TeV

Completely consistent with all data! stay tuned...