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
- Nearly scale invariant & Gaussian primordial density fluctuations
Evidence for Physics beyond SM

- Dark matter
- Cosmological baryon asymmetry
- Neutrino oscillation
- Nearly scale invariant & Gaussian primordial density fluctuations

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:

\[ \Lambda_{QCD} \sim 1 \text{ GeV} \ll M_{\text{Pl}} \quad M_{H}^2 \sim -(100 \text{ GeV})^2 \ll M_{\text{Pl}}^2 \]

\[ L = \frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \ldots \]

\[ L = m_H^2 H^\dagger H + \ldots \]
Naturalness Problem of EW scale

Two scales in SM:

\[ \Lambda_{QCD} \sim 1 \text{ GeV} \ll M_{\text{Pl}} \quad m_H^2 \sim (100 \text{ GeV})^2 \ll M_{\text{Pl}}^2 \]

\[ \mathcal{L} = \frac{1}{g_s^2} G_{\mu
u} G^{\mu\nu} + \ldots \]

\[ \text{dim.} = O + \text{"log"} \]

\[ \mathcal{L} = m_H^2 H^\dagger H + \ldots \]

\[ \frac{1}{g_s^2(\mu)} \]

\[ \text{Natural!} \]

\[ -\frac{m_H^2(\mu)}{\mu^2} \]
Naturalness Problem of EW scale

Two scales in SM:

\[ \Lambda_{\text{QCD}} \sim 1 \text{ GeV} \ll M_{\text{Pl}} \quad \frac{m_H^2}{\mu^2} \sim (100 \text{ GeV})^2 \ll M_{\text{Pl}} \]

\[ \mathcal{L} = \frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \cdots \quad \text{dim.} = 0 + \text{"log"} \]

\[ \mathcal{L} = \frac{m_H^2}{\mu^2} h^* h + \cdots \quad \text{dim.} = 2 \]

\[ \frac{1}{g_s^2} (\mu) \]

Natural!

\[ -\frac{m_H^2(\mu)}{\mu^2} \]

\[ \text{Unnatural!} \]

\[ 10^{-32} \]
Heart of problem:

(A) \( \dim[H^+H] = 2 = 4 - 2 \)

(B) \( H^+H \) allowed by all symmetries of SM

\( \Rightarrow \) Quadratically sensitive to UV!
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(B) \( H^+H \) allowed by all symmetries of SM

\[ \Rightarrow \text{ Quadratically Sensitive to UV!} \]

\[ (e.g.) \]
\[ m_{H,\text{uv}}^2 H^+H + \phi^+\phi H^+H \]

\[ \text{new scalar} \]
Heart of problem:

(A) \( \dim[H^+H] = 2 = 4 - 2 \)

(B) \( H^+H \) allowed by all symmetries of SM

\[ m_{H,\text{UV}}^2 H^+H + \phi^+\phi H^+H \]

\( \langle \phi \rangle = \Lambda \)

\[ m_{H,\text{IR}}^2 = \Lambda^2 + m_{H,\text{UV}}^2 \]

Must be tuned if \( m_{H,\text{IR}} \ll \Lambda \)!
Heart of problem:

(A) \( \dim[H^+H] = 2 = 4 - 2 \)  \( \implies \) Quadratically sensitive to UV!

(B) \( H^+H \) allowed by all symmetries of SM

\[ \Phi \Phi \]

Solutions: Negate (A) or (B)!

(A) \( \times \) \( \Omega_H \) with \( [\Omega_H^T \Omega_H] > 4 \)

(e.g.) \( \Omega_H = \bar{\Psi}_T \Psi_T \) "Technicolor"

Not in this session...

(B) New symmetry to forbid \( H^+H \)
Naturally Light Higgs

Plan

(i) Extend SM by a new symm. to kill $H^*H$,
(ii) Break the new symm. in a natural way.

Typically a separate “module”

Focus on (i).
Naturally Light Higgs

Plan
(i) Extend SM by a new symm. to kill $H^+H$,
(ii) Break the new symm. in a natural way.

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

**Spin-0** Nambu-Goldstone boson (NGB)

Unbroken symm. $\equiv$ Rotates particles

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

Spontaneously broken symm. $\equiv$ Rotates vacua

$\Rightarrow$

\[ V(\phi) \]

\[ \phi_1 \rightarrow \phi_2 \]

\[ \text{Broken symm. trans.} \]
Massless particles in QFT

**Spin-0 Nambu-Goldstone boson (NGB)**

Unbroken symm. $\Rightarrow$ Rotates particles

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

Spontaneously broken symm. $\Rightarrow$ Rotates vacua

$\Rightarrow$ Exitations along $\phi_1$

$\Rightarrow$ Massless!

$H = \text{NGB of a new broken symm} \Rightarrow M_H = 0$!
Massless particles in QFT

**spin-0** Nambu-Goldstone boson (NGB)

Unbroken symm. = Rotates particles

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

Spontaneously broken symm. = Rotates vacua

\[ \Rightarrow \]

Exitations along \[ \Theta(x) \rightarrow \Theta(x) + 3 \]

"Shift symm."

\[ H = \text{NGB of a new broken symm} \Rightarrow M_H = 0 ! \]
$\text{spin-} \frac{1}{2}$

Chiral symm. $\Leftrightarrow \frac{\Psi}{\Psi_R} \Rightarrow \text{have opposite charges}$

$\Rightarrow m_\Psi = 0$!
Spin $-\frac{1}{2}$

Chiral symm. $= \frac{\Psi}{\Psi_R}$ have opposite charges

$\Rightarrow \; m_\Psi = 0$!

Suppose $M_\Psi \neq 0$.

Then, $\Psi \xrightarrow{\text{boost!}}$ left-handed $\rightarrow$ right-handed
spin-$\frac{1}{2}$

Chiral symm. $= \frac{\psi}{\psi_R}$ have opposite charges

$\Rightarrow m_\psi = 0$

Suppose $M_\psi \neq 0$.

Then, $\psi$,

- left-handed
- charge $+1$

$\Rightarrow$ boost!

$\Rightarrow \psi_R$,

- right-handed
- charge $-1$

Boost shouldn't change charge!

By contradiction, $M_\psi = 0$!
spin-$\frac{1}{2}$

Chiral symm. $\Rightarrow \psi L, \psi R$ have opposite charges

$\Rightarrow m_\psi = 0$ !

Suppose $M_\psi \neq 0$.

Then, $\psi \Rightarrow$ left-handed · charge +1

boost!

$\Rightarrow \psi \Rightarrow$ right-handed · charge -1 !?

Boost shouldn't change charge!

By contradiction, $M_\psi = 0$ !

Must relate $\psi \ (S=\frac{1}{2})$ to $H \ (S=0)$ to get $M_H = 0$.

$\Rightarrow$ Supersymmetry !
Spin-1

Gauge symm $A_\mu \rightarrow A_\mu + \partial_\mu \mathcal{E}$ \implies $m_A^2 A_\mu A^\mu \quad \text{or} \quad m_A = 0$!
Gauge symm $A_\mu \rightarrow A_\mu + \partial_\mu \kappa \Rightarrow m_A^2 A_\mu A^\mu$

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

SUSY?

$|S=0\rangle \xleftarrow{\text{SUSY}} |S=\frac{1}{2}\rangle$

$|S=\frac{1}{2}\rangle \xrightarrow{\text{SUSY}} |S=1\rangle$
spin-1

Gauge symm $A_\mu \rightarrow A_\mu + \partial_\mu \chi \Rightarrow m_A^2 A_\mu A^\mu$

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

$|s=0\rangle \xleftarrow{\text{SUSY}} |s=\frac{1}{2}\rangle \xrightarrow{\text{SUSY}'} |s=\frac{1}{2}\rangle \xrightarrow{\text{SUSY}'} |s=1\rangle$

"N=2 SUSY"

Not chiral ($\text{SUSY} = \text{SUSY}_L$)
($\text{SUSY} = \text{SUSY}_R$)

No!
Need an extra dimension!

\[ (\mu, \nu = 0, 1, 2, 3; M = \mu, 5) \]
Need an extra dimension!

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

\[ H = A_5 \quad \Rightarrow \quad m_H = 0 ! \]

\( A_5 \) unchanged under \( x_\mu - x_\nu \) rotations

Scalar in 4d!
Need an extra dimension!

\[ \mu, \nu = 0, 1, 2, 3 \; \text{and} \; M = \mu, 5 \]

\[ H = A_5 \implies m_H = 0 ! \]

But

5d gauge trans: \( A_5 \rightarrow A_5 + \partial_5 \Sigma \) \( \iff \) \( H \) shifts!

Effectively same as \( H = \text{NGB} \)!
Spin-3/2 (No known working model)

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

(e.g.) \( S = 0 \leftrightarrow S = \frac{1}{2} \leftrightarrow S = \frac{3}{2} \)
Spin-3/2 (No known working model)

Need SUSY (8 extra dim.) to relate to H.

(e.g.) \[ S = 0 \leftrightarrow S = \frac{1}{2} \leftrightarrow S = \frac{3}{2} \]

SUSY XD

Spin-2 (No known working model)

"Gauge" symm: \[ h_{\mu \nu} \rightarrow h_{\mu \nu} + \phi \xi \nu + \partial \nu \xi \mu \] \( \Rightarrow \)

(or GR!)

\[ m = 0 \]
Spin-$3/2$ (No known working model)

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

(e.g.) $S=0 \leftrightarrow S=\frac{1}{2} \leftrightarrow S=\frac{3}{2}$

Susy XD

Spin-$2$ (No known working model)

"Gauge" symm: $h_{\mu
u} \rightarrow h_{\mu
u} + \not{\omega} \not{\nu} + \not{\nu} \not{\omega}_\mu$ \Rightarrow $m=0$

(or GR!)

Need extra dimensions to get scalar

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

But $H$ shifts under symm.

Same story as spin-$1$ $H=\text{NGB}!$
Spin-3/2 (No known working model)
Need SUSY (& extra dim.) to relate to H.
(e.g.) $S=0 \leftrightarrow S=\frac{1}{2} \leftrightarrow S=\frac{3}{2}$
SUSY XD

Spin-2 (No known working model)
"Gauge" symm: $h_{\mu\nu} \rightarrow h_{\mu\nu} + \partial_{\mu} \xi_{\nu} + \partial_{\nu} \xi_{\mu}$
(or GR!)

Need extra dimensions to get scalar
$h_{55}, h_{56}, \text{etc.} = \text{scalars in 4d} \sim H$

But H shifts under symm.
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!

**SUSY**

$H \xleftarrow{\text{SUSY}} H^\ast \xrightarrow{\text{SUSY}} 2H$

$(s = 0) \quad (s = \frac{1}{2})$

$m_H = 0 \xleftarrow{\text{SUSY}} m_H^\ast = 0$

→ chiral symm.

**H = NGB**

Shift symm.

$H \rightarrow H + \epsilon$

$\Rightarrow \quad m_H^2 > \frac{1}{4}$

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

$$V(H) = \begin{align*}
&\uparrow V(H) \\
&\downarrow (H) = V \\
&H \\
\end{align*}$$

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

$$\sim \lambda_H (H^+ H - V^2)^2$$
EWSB and Higgs mass

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

We want

$$V(H) = \lambda H (H^*H)^2$$

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

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

$H = V + h$

Physical Higgs

Physical Higgs mass
EWSB and Higgs mass

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

We want

$$V(H) = \lambda_H (H^+ H)^2$$

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

$$\sim \lambda_H (H^+ H - V^2)^2$$

$$H = V + h$$

$$\Rightarrow m_h^2 \sim \lambda_H V^2$$

$V = \text{(measured)} \approx 174 \text{ GeV}$

What's $m_h$? = What's $\lambda_H$?
$\lambda h$ in SUSY

(i) SUSY contributions
   - Kills $H^H$

(ii) SUSY contributions
\( \lambda H \) in SUSY

(i) SUSY contributions

Kills \( H^+H \)

and predicts \( \lambda H \sim g_1^2 + g_2^2 \)

\( \Rightarrow M_h^2 \sim \lambda H V^2 \sim m_Z^2 \)

(More precisely \( m_h \leq m_Z \))

(ii) SUSY contributions
$\lambda h$ in SUSY

(i) SUSY contributions

Kills $H^*H$

and predicts $\lambda h \sim g_1^2 + g_2^2$

$\Rightarrow M_h^2 \sim \lambda h v^2 \sim m_Z^2$

(More precisely $m_h \leq m_Z$)

(ii) SUSY contributions

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

or scalar top mass

$\delta \lambda_H \sim \frac{3y_t^4}{4\tan^2\beta} \log \frac{M_{W}}{m_t}$
$\lambda H$ in SUSY

(i) SUSY contributions

Kills $H^4 H$

and predicts $\lambda H \sim g_1^2 + g_2^2$ !

$\Rightarrow M_h^2 \sim \lambda H V^2 \sim M_Z^2$

(More precisely $m_h \leq M_Z$)

(ii) SUSY contributions

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

$\delta \chi_H \sim \frac{3y_t^4}{4t^2} \log \frac{M_t}{M_t}$

Naturalness $\Rightarrow M_t \lesssim 1 \text{ TeV}$

$\Rightarrow M_h^2 \lesssim M_Z^2 + (90 \text{ GeV})^2 = (130 \text{ GeV})^2$
Is $m_h$ upper bound robust?

Do we "expect" additional $\lambda_h$?

(= w/o knowing $m_h > 114.4$ GeV from LEP2)
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Do we "expect" additional $\lambda_H$?

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

$\mu$-problem

$M_H = M_H^\mu = 0$

\[ \Rightarrow \begin{cases} m_H^2 = \mu^2 + \Delta M_H^2 \approx -(100 \text{ GeV})^2 \\ M_H^\mu = \mu \end{cases} \]

 SUSY, chiral symm.
Is $M_h$ upper bound robust?

Do we “expect” additional $\chi H$?

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

$\mu$-problem

\[
M_H = M_{\tilde{H}} = 0 \quad \Rightarrow \quad \begin{cases} 
M_H^2 = \mu^2 + \Delta M_H^2 \approx -(100 \text{ GeV})^2 \\
\tilde{M}_H = \mu \quad \text{(SUSY)} \\
\tilde{M}_{\tilde{H}} = \mu \quad \text{(Chiral symm.)}
\end{cases}
\]

Is $\mu \not= 0$ necessary?

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

Yes!
Is $m_h$ upper bound robust?
Do we "expect" additional $\lambda H$?
(= w/o knowing $m_h > 114.4$ GeV from LEP2)

$\mu$-problem

\[ m_h = m_H = 0 \quad \Rightarrow \quad \begin{cases} m_H^2 = \mu^2 + \Delta m_H^2 \sim -(100 \text{ GeV})^2 \\ m_H = \mu \quad \text{susy} \\ m_H \downarrow \text{chiral symm.} \end{cases} \]

Is $\mu \neq 0$ necessary?

LEP2 $H$-like chargino searches \( \Rightarrow \) $m_H > 92$ GeV \( \text{Yes!} \)

No tuning in $m_H^2$ b/w $\mu^2$ & $\Delta m_H^2$ \( \Rightarrow \) $\mu \leq \text{few} \times 100$ GeV

\( \Rightarrow \) chiral symm. \sim susy \( \text{Why?} \)

Can't be coincidence!
A solution to $\mu$-problem:

$\mu$ is induced by SUSY

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

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

(from SUSY)
A solution to $\mu$-problem:

$\mu$ is induced by SUSY

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

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

from SUSY

**Bonus:** SUSY \( \Rightarrow \Delta \lambda_H = \alpha^2 \)!
A solution to $\mu$-problem:

$\mu$ is induced by SUSY

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

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

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

How big can $\alpha$ be?

- Precision electroweak tests
  - $\Rightarrow \Lambda_\alpha \geq 10 \text{ TeV}$
  - $\Rightarrow \alpha \leq 2$
  - $\Rightarrow M_h \leq 300 \text{ GeV}$
$\lambda H^2$ in $H = \text{NGB}$

(i) NGB contributions

$\lambda H \to H + 3 \text{ symm.} \Rightarrow V(H) = \text{const.}$

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

(ii) $H \to H + 3 \text{ violating contributions}$
$\lambda H$ in $H = \text{NGB}$

(i) NGB contributions

$\mathcal{L} \ni H \rightarrow H + 3 \text{ symm.} \Rightarrow V(H) = \text{const.}$

No $H^\dagger H$

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

(ii) $H \rightarrow H + 3$ violating contributions

Largest violation = top Yukawa $\bar{Y}_t H Q_{3L} \tau_R$

$\Rightarrow 8\lambda_H \sim \frac{3 Y_t^4}{4 \pi^2} \left( \log \frac{\Lambda_t}{M_t} + O(1) \right)$

\[ \Lambda_t = M_{t'}, M_t \text{ comp., etc.} \]
\[ \lambda H \text{ in } H = \text{NGB} \]

(i) NGB Contributions

\[ \bar{\chi} H \rightarrow H + 3 \text{ symm. } \Rightarrow V(H) = \text{const.} \]

No \( H^* H \)

No \( (H^* H)^2 \)!

(ii) \( H \rightarrow H + 3 \) violating contributions

\[ \bar{\chi} \quad \text{Largest violation} = \text{top Yukawa} \frac{y_t H Q_{3L} L}{O(1)} \]

\[ \Rightarrow 8 \lambda_H \sim \frac{3y_t^4}{4\pi^2} \left( \log \frac{\Lambda_t}{M_t} + O(1) \right) \]

\( \Lambda_t = M_{t'} , M_t \text{ comp., etc.} \)

* No good reason like \( \mu \)-problem for extra \( \lambda_H \).

\[ \Rightarrow M_h^2 \lesssim O(1) \times (90 \text{ GeV})^2 \]

At most a few \( \times \) 100 GeV like SUSY case!
Conclusions

Natural EWSB

With Higgs

- SUSY

No Higgs (e.g. technicolor)

- $H = NGB$

- $m_h < \text{few} \times 100 \text{ GeV}$

  and the lighter the better
Conclusions

Natural EWSB

With Higgs

SUSY

$m_h < \text{few} \times 100 \text{ GeV}
$ and the lighter the better

No Higgs

(e.g. technicolor)

H = NGB

What if we find $m_h = 500 \text{ GeV}$?