Beyond the Standard Model

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2 approaches:
- precision measurements (effective Lagrangians)
- resonances (particles)

Outline:

today: precision, effective

monday: naturalness

tuesday: addressing naturalness w. new physics

wednesday: DM & the LHC

Eff. SM.: precision tests of the SM

example: Tevatron: $m_W = 80.39 \pm .02$ GeV

0.02 % accurate !!!

and completely uninteresting (by itself).

Why? Don't care about the values of the parameters in the model. We want to know if we understand the physics. e.g. m_W ~~would~~ $= 75.04$ GeV would make me equally happy.

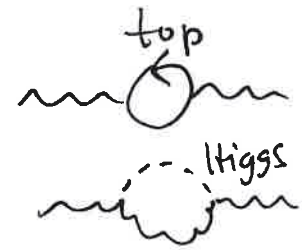
However! SM: $m_W = \underset{\substack{\uparrow \\ \text{LEP}}}{m_Z} \underset{\substack{\uparrow \\ \text{SLC}}}{\cos\theta_W}$ (tree level)

"gfitter" predicts "$m_Z \cos\theta_W$" $= 80.36 \pm 0.02$ GeV

a 0.02 % accurate test of the SM, cool!

accuracy requires

- loop corrections e.g.

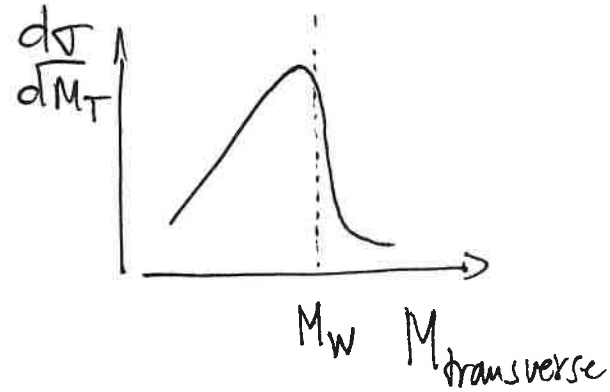


$$\frac{\delta m^2}{m^2} \sim \frac{g^2}{16\pi^2} \sim 1\%$$

$\Rightarrow$ need 2-loop accuracy.

- careful definitions

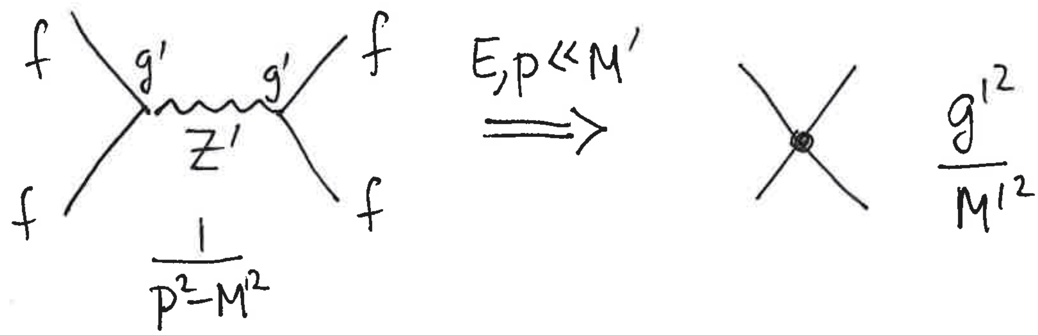
e.g.

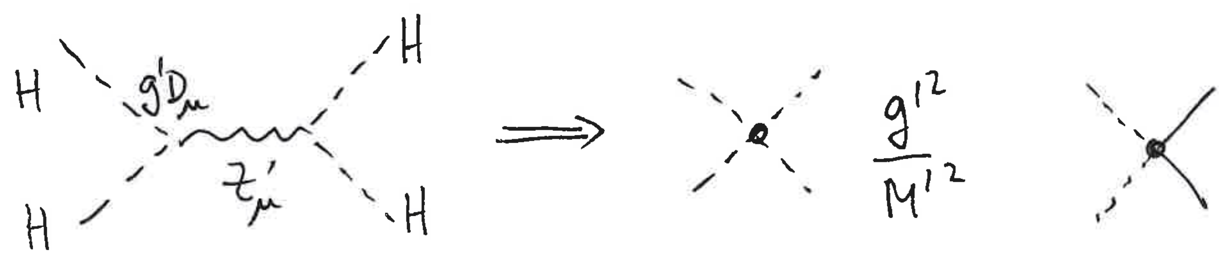


But what does this imply for New Physics?

<u>SM effective theory:</u>

<u>example</u>: Z' with mass M', couplings g' to SM fields f, H





$$\mathcal{L}_{eff} \sim \frac{\bar{f}\gamma_\mu f\, \bar{f}\gamma^\mu f}{\Lambda^2} + \frac{H^\dagger D_\mu H\, H^\dagger D^\mu H}{\Lambda^2} \qquad \Lambda \equiv \frac{M'}{g'}$$

$$\frac{H^\dagger D_\mu H\, \bar{f}\gamma^\mu f}{\Lambda^2}$$

<u>Lesson</u>: Heavy new physics can be parameterized by effective couplings suppressed by heavy scale.

$\Longrightarrow$ goal: paramaterize NP by writing all possible effective couplings and bound coefficients from experiment example: $$\frac{H^\dagger D_\mu H \; H^\dagger D^\mu H}{\Lambda^2}$$

$\partial_\mu + igZ_\mu$ $\qquad$ $v+h$

four Higgs scattering, good luck!

but also $$\underbrace{g^2 v^2}_{m_Z^2} \frac{v^2}{\Lambda^2} Z_\mu Z^\mu$$

Z mass correction, no W mass correction.

$$\frac{\delta m_Z^2}{m_Z^2} \sim \frac{v^2}{\Lambda^2}$$

$$2\frac{\delta m_Z}{m_Z} < 0.1\,\%$$

$$\Longrightarrow \quad \Lambda \gtrsim 30\,v \approx 30 \cdot 246\ \mathrm{GeV} \sim 7\ \mathrm{TeV}\ !$$

LEP + Tevatron probed 7 TeV!

$\Lambda = M'/g'$, $g' \sim 1/2$, $1/4$ dropped in calculation $\Rightarrow$ $M_{Z'} \gtrsim 2\ \mathrm{TeV}$

Let's be systematic : order terms by "mass dimension"

$$\mathcal{L}_{eff} = \Lambda^4 + \Lambda^2 H^\dagger H + \underbrace{\lambda (H^\dagger H)^2 + \mathcal{L}^{SM}_{kinetic} + \mathcal{L}^{SM}_{yukawa}}_{\text{SM dimensionless couplings}}$$

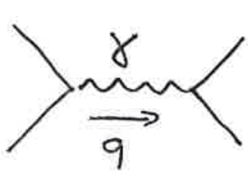
$$+ \frac{(L_L H)^2}{\Lambda} \quad \text{dimension 5, neutrino masses}$$

$$+ \frac{H^\dagger D_\mu H\, H^\dagger D^\mu H}{\Lambda^2} + \frac{H^\dagger D_\mu H\, \bar{e}_R \gamma^\mu e_R}{\Lambda^2} + \frac{H^\dagger \sigma^a H\, W^a_{\mu\nu} B^{\mu\nu}}{\Lambda^2}$$

$$+ \frac{H^\dagger H\, B_{\mu\nu} B^{\mu\nu}}{\Lambda^2} + \frac{H^\dagger H\, W^a_{\mu\nu} W^{\mu\nu}_a}{\Lambda^2} + \ldots \quad > 80 \text{ more at dim 6}$$

$$+ \text{dim} > 6 \quad \ldots$$

an ∞ number of coefficients, predictive ?



+

$$\frac{1}{q^2} + \frac{1}{\Lambda^2} = \frac{1}{q^2}\left(1 + \frac{q^2}{\Lambda^2}\right)$$

expansion in $\frac{q^2}{\Lambda^2}$, useful for $q^2 \ll \Lambda^2$

a subtlety, can also get $\frac{v^2}{\Lambda^2}$ from couplings with Higgs.

e.g. • δm_Z^2

• $$\frac{H^\dagger D_\mu H}{\Lambda^2} \bar{e}_R \gamma^\mu e_R \longrightarrow g \frac{v^2}{\Lambda^2} Z_\mu \bar{e}_R \gamma^\mu e_R$$ 

$$\frac{\delta g}{g} \sim \frac{v^2}{\Lambda^2} \qquad \text{LEP}: \Lambda \gtrsim \text{few TeV}.$$

A Non-trivial example:

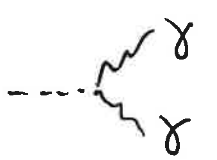
$$\mathcal{L} \sim s_1 \underset{\substack{\uparrow \\ \text{Hypercharge}}}{g'^2} \frac{H^\dagger H B_{\mu\nu}B^{\mu\nu}}{\Lambda^2} + s_2 g^2 \frac{H^\dagger H W^a_{\mu\nu}W^{a\,\mu\nu}}{\Lambda^2} + s_{12} g g' \frac{H^\dagger \sigma^a H W^a_{\mu\nu}B^{\mu\nu}}{\Lambda^2}$$

$$\xrightarrow{\langle H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h\end{pmatrix}} \underbrace{s_1 g'^2 \frac{v^2}{2\Lambda^2} B_{\mu\nu}B^{\mu\nu} + s_2 g^2 \frac{v^2}{2\Lambda^2} W^a_{\mu\nu}W^{a\,\mu\nu}}_{\text{corrections to } SU(2)\times U(1) \text{ kinetic terms, absorb by rescaling } B_\mu,\, W^a_\mu} + \underbrace{s_{12} g g' \frac{v^2}{2\Lambda^2} W^3_{\mu\nu} B^{\mu\nu}}_{SU(2)\text{-violating mixing of } Z,\gamma}$$

$$\text{"}S\text{"} \equiv 16\pi s_{12} \frac{v^2}{\Lambda^2}$$

$$\underbrace{+ s_1 g'^2 \frac{v^2}{\Lambda^2} \frac{h}{v} B_{\mu\nu}B^{\mu\nu} + s_2 g^2 \frac{v^2}{\Lambda^2}\frac{h}{v} W_{\mu\nu}W^{\mu\nu} + s_{12} g g' \frac{v^2}{\Lambda^2}\frac{h}{v} W^3_{\mu\nu} B^{\mu\nu}}$$

$$= \underbrace{4e^2 \frac{v^2}{\Lambda^2}(s_1+s_2+s_{12})}_{\equiv e^2 c_{\gamma\gamma}} \frac{h}{v} \frac{F_{\mu\nu}F^{\mu\nu}}{4} + \underset{\substack{\uparrow \\ c_{\gamma Z}}}{\cdots} \frac{h}{v} F_{\mu\nu} Z^{\mu\nu} + \underset{\substack{\uparrow \\ c_{ZZ}}}{\cdots} \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu}$$

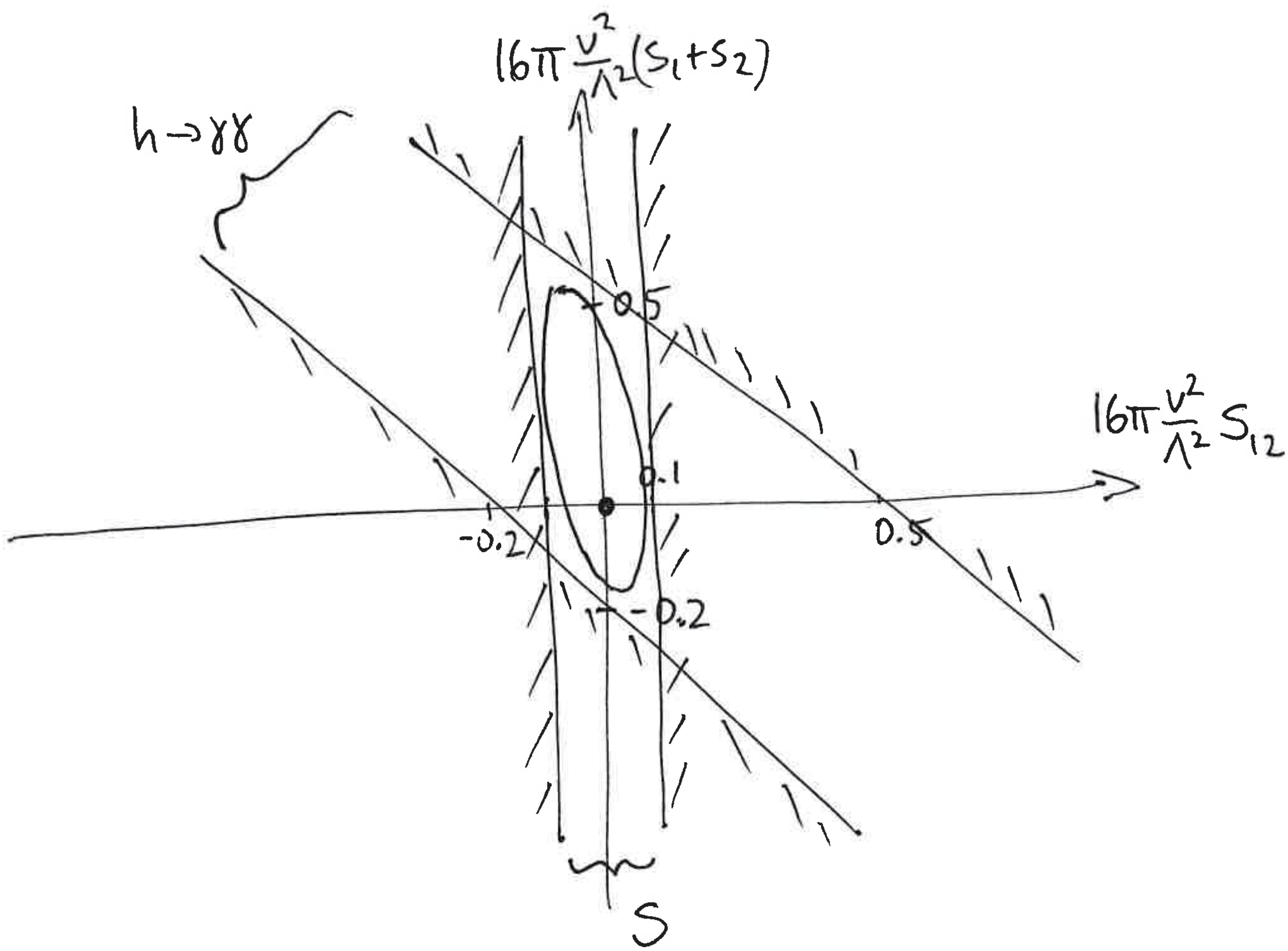
Higgs decays: 

γZ $\quad$ ZZ^*

<u>the data</u>: Precision electroweak $S = -0.03 \pm 0.10$ PDG

95% $h \to \gamma\gamma$ $c_{\gamma\gamma} = 0.014 \pm 0.058$ Falkowski hep-ph/1505.00046

($h \to \gamma Z$: $|c_{\gamma Z}| < 0.2$ much worse than S)



New physics bounds? $s_i = 1 \Rightarrow \Lambda \gtrsim 6\,\text{TeV}$

$s_i = \frac{1}{16\pi^2} \Rightarrow \Lambda \gtrsim 500\,\text{GeV}$

Effective SM

$$\mathcal{L}_{eff} = \Lambda^4 + \Lambda^2 H^\dagger H + \mathcal{L}_4 + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \dots$$

- expansion in $\frac{p, m, v}{\Lambda}$, valid when $p, m, v \ll \Lambda$
- Λ is scale of new physics
- coefficients in $\mathcal{L}$ are free parameters, determined by experiment. <u>But</u> if UV physics is known, can calculate coefficients in terms of UV parameters

e.g. exchange of heavy particle

$$\frac{g^2}{p^2 - M^2} \quad \xrightarrow{p \ll M} \quad \frac{g^2}{M^2} = \frac{c}{\Lambda^2}$$

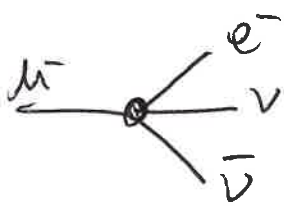
$c \sim$ order 1

Assume that we measured a non-zero coefficient for a term in $\mathcal{L}_6$

$\Rightarrow$ <u>guarantee</u> of new physics at scale M

$$\Lambda \sim \frac{M}{g} \quad \Rightarrow \quad M \sim g\Lambda \leq 4\pi\Lambda \qquad \text{upper bound!}$$

<u>Historical example</u>: muon decay



$$\frac{1}{\Lambda^2} \sim \frac{1}{(200\,\text{GeV})^2}$$

Nature was nice : $M_W = 80\,\text{GeV}$, $g < 1$

<u>current situation</u> :

- neutrino mass $\quad \dfrac{(LH)^2}{\Lambda} \longrightarrow m_\nu = \dfrac{v^2}{\Lambda} \sim 0.1\,\text{eV}$

$$\Rightarrow \Lambda \sim 10^{14}\,\text{GeV}$$

$$\Rightarrow M \sim g\Lambda \leq 10^{15}\,\text{GeV}$$

<u>or</u> neutrino is Dirac $L H \nu_R$

- gravity couples to energy-momentum

e.g. $\dfrac{g_{\mu\nu}\,\partial^\mu H^\dagger \partial^\nu H}{M_{pl}}$ $\Rightarrow$ new physics @ M_{pl}

$g_{\mu\nu}$: graviton

Currently no <u>direct</u> evidence for a lower scale.

Indirect? Naturalness

$$\mathcal{L} \sim \underbrace{c_4 \Lambda^4}_{\text{cosmological constant}} + \underbrace{c_2 \Lambda^2 H^\dagger H}_{\text{Higgs mass}} + \cdots$$

$c_i \sim$ order 1 numbers ? Λ scale of new physics these terms are different, the highest NP scale dominates!

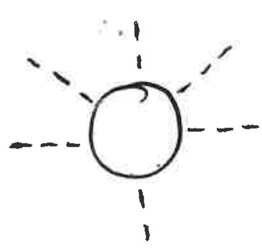
Q: but are they actually generated?

A: • not at tree level $\qquad \frac{1}{p^2 - M^2} \longrightarrow \frac{1}{M^2} + \frac{p^2}{M^4} + \cdots$

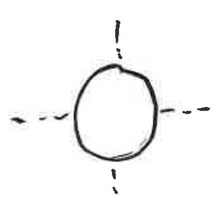
M always downstairs

• yes, at loop level

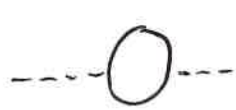
example:



$$\frac{\lambda^6 (H^\dagger H)^3}{M^2} \frac{1}{16\pi^2}$$



$$\lambda^4 (H^\dagger H)^2 \, \mathrm{Log}(M) \frac{1}{16\pi^2}$$



$$\lambda^2 H^\dagger H \, \frac{M^2}{16\pi^2} \quad *$$

$$\frac{M^4}{16\pi^2} \quad *$$

*(after regulating + subtracting

the CC: a (relevant?) detour

expect $\quad CC \sim \sum_i \frac{M_i^2}{16\pi^2}$ dominated by heaviest particles

$M_{pl} \longrightarrow \quad CC \sim 10^{70}\ GeV^4$

experiment: $\quad CC \sim 10^{-50}\ GeV^4$ off by 10^{120} !

$M_{top} \quad \sim 10^{7}\ GeV^4$ still horrible.

<u>is there a way out?</u>

- bosons + fermions have <u>opposite sign</u> $+M_{pl}^4 - M_{pl}^4 + \ldots$

  cancelation requires 10^{120} accident

  $\Rightarrow$ our universe is extremely unlikely

- <u>anthropic principle</u>: a larger CC leads to a lethal universe (not old enough $\rightarrow$ no stars $\rightarrow$ no heavy elements)

  we are alive $\Rightarrow$ CC can only have a value small enough for life.

- Multiverse: fundamental theory has $> 10^{120}$ vacua with different values for CC

different vacua are cosmologically sampled

$\Rightarrow$ $> 10^{120}$ different universes, some with $CC \lesssim 10^{-50}\,\mathrm{GeV}^4$

anthropics: of course, we live in a habitable one

predictions?
- CC is likely close to maximum habitable value
- fundamental theory must allow $> 10^{120}$ vacua.

}.

could the Higgs mass term also be small by anthropics? need to show that life cannot exist with heavier Higgs

(see e.g. "Weakless universe")
hep-ph/0604027

back to Higgs naturalness problem:

In the Standard Model, the Higgs mass term gets contributions from all scales.

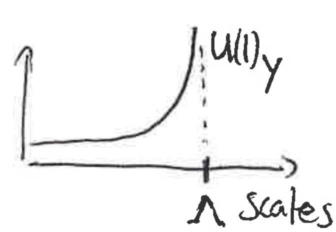
$$\sum_{\text{all scales}} c_i \frac{\lambda_i^2}{16\pi^2} M_i^2 \sim (\text{largest scale in theory/Nature})$$

desperate "nightmare" proposal: there are no more massive particles

$$\Rightarrow \quad \text{smaller} + -\frac{3}{8\pi^2}\lambda_t^2 m_t^2$$

consequences? - no unification

- neutrinos are Dirac $\cancel{\frac{(LH)^2}{\Lambda}}$
- gravity: $\frac{g_{\mu\nu}}{M_{pl}} T^{\mu\nu}$
- Hypercharge coupling



fortunately, this proposal cannot be true. The SM requires higher scales.

2 possible solutions:

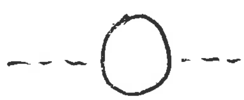
- cancelation because of symmetry (SUSY, Little Higgs)

 $\sum c_i \lambda_i^2 \left(M_i^2 - (M_i^2 + \delta M_i^2) \right) \frac{1}{16\pi^2}$

$$\approx \sum \delta M_i^2$$

requires $\delta M_i \lesssim 4\pi\, m_{Higgs}$

predicts "partners" with relations between couplings, masses

e.g.  top  top partner $\quad m_{\substack{top \\ partner}} \lesssim 4\pi\, m_{Higgs}$

- Higgs is composite particle

 sum up to compositeness scale only

$$\sim \underbrace{\frac{\lambda^2}{16\pi^2}}_{O(1)} M_{composite}^2 \sim M_{composite}^2$$

Natural Higgs mass from symmetries:

idea: invent symmetry which prevents UV physics from generating $m_{UV}^2 H^\dagger H$ term

why doesn't this problem arise for electrons?

SM: e_R, $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

Dirac mass: $m_{UV} e_R^\dagger e_L$ not gauge invariant

Majorana mass $m_{UV} e_R e_R$ "

not a mass $e_R^\dagger e_R$ not Lorentz-invariant

writing a mass <u>requires</u> Higgs doublet

$$\lambda_e \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}^\dagger H e_R + h.c.$$

$$\Rightarrow \quad m_e = \lambda_e v \lesssim v$$

$\lambda_e \sim 10^{-6}$ is "technically natural" 't Hooft: a small parameter is technically natural if setting it to zero leads to a new symmetry

Here: "chiral symmetry" $e_R \to e^{i\theta} e_R$

all other fields unchanged

$\bar{e}_R \not{D} e_R$ invariant

$\lambda_e \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}^\dagger H e_R$ not invariant

λ_e is the only parameter which breaks e_R chiral symmetry.

Consequence: any loop diagrams which might generate the effective coupling $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}^\dagger H e_R$ must be proportional to λ_e.

$\Longrightarrow$ at worst, can get $\underbrace{\lambda_e \log\left(\frac{M_{pl}}{M_{weak}}\right) \frac{g^2}{16\pi^2}}_{\text{1 loop correction}} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}^\dagger H e_R$

"running coupling"

Apply this idea to Higgs doublet?

$m_{uv}^2 H^\dagger H$ is invariant under Lorentz + gauge + any "chiral" $e^{i\theta_H}$ symmetry. ☹

<u>However</u>: Supersymmetry

take 2 Higgs doublets
$$\left.\begin{array}{l} H_u \xleftrightarrow{\quad\ \ } \tilde{H}_L \\ H_d^* \xleftrightarrow[\quad]{\text{susy}} \tilde{H}_R \end{array}\right\} \text{Dirac fermion "Higgsino"}$$

$$\mu^2\left(H_u^\dagger H_u + H_d^\dagger H_d\right) \xleftrightarrow{\text{susy}} \mu\left(\tilde{H}_L^\dagger \tilde{H}_R + \tilde{H}_R^\dagger \tilde{H}_L\right)$$

- fermion mass is "technically natural" because it breaks chiral symmetry
$$\tilde{H}_R \to e^{i\theta}\tilde{H}_R$$
$$\tilde{H}_L \to \tilde{H}_L$$

- supersymmetry: boson masses = fermion superpartner masses

exact supersymmetry requires: all SM particles have superpartners
all interactions have "

e.g. top $\longleftrightarrow$ stop

$$\lambda_t \begin{pmatrix} t_L \\ b_L \end{pmatrix}^\dagger H\, t_R \longleftrightarrow |\lambda_t|^2\, H^\dagger H\, \tilde{t}_R^\dagger \tilde{t}_R$$

top sector

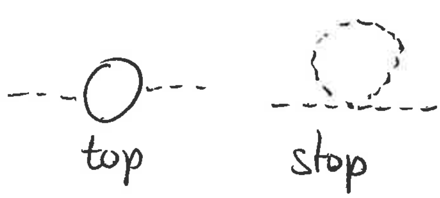
$$= + \frac{|\lambda_t|^2}{16\pi^2} m_{\tilde{t}}^2 - \frac{|\lambda_t|^2}{16\pi^2} m_t^2 = 0 \qquad (*)$$

for unbroken SUSY.

(more precisely, $\tilde{t}_L, \tilde{t}_R$, numerical factors in $(*)$ missing but SUSY guarantees that  $= 0$)

No superpartners at LHC1 $\Rightarrow$ break SUSY by giving superpartners masses $\sim \text{TeV}^2 \sim m_0^2$.

m_0^2 only source of SUSY breaking $\Rightarrow$ Higgs mass corrections must be proportional to m_0^2

e.g. 

$$= -\frac{3}{4\pi^2} \lambda_t^2 m_{\tilde{t}}^2 \log \frac{M_{UV}}{m_{\tilde{t}}} = \delta m_H^2$$

if $\delta m_H^2 \lesssim m_H^2 = (125\,\text{GeV})^2$ there is no fine tuning (f.t.)

$$\text{f.t.} \equiv \left| \frac{\delta m_H^2}{m_H^2} \right| \approx 40 \left[\frac{m_{\tilde{t}}}{\text{TeV}} \right]^2 \left[\frac{\log(M_{UV}/m_{\tilde{t}})}{10} \right]$$

"somewhat unnatural"

is there a symmetry that protects the photon mass?

$m^2 A_\mu A^\mu$ not gauge invariant $A_\mu \to A_\mu + \frac{\partial_\mu \theta}{e}$

photon couplings allowed but special because of gauge inv.

$\bar{\Psi}(\partial_\mu + ieA_\mu)\gamma^\mu \Psi \qquad \psi \to e^{-i\theta}\psi$

could the Higgs have a shift symmetry?

$H \to H + (\text{const})$

- forbids $m^2 H^\dagger H$ ☺
- also forbids $\begin{pmatrix} t_L \\ b_L \end{pmatrix}^\dagger H\, t_R$ ☹ (allows only $\partial_\mu H$ couplings)

scalars with shift symmetry are Nambu-Goldstone bosons

the arise from spontaneous breaking of global symmetries.

Little Higgs theories

$\Rightarrow$

- make $\mathcal{L}$ invariant under global symmetry, break global symmetry spontaneously such that H = pseudo-Nambu-Goldstone boson

e.g. $SU(3)$ broken to $SU(2)$

$\Rightarrow$ get doublet of $SU(2)$ as NGB : H

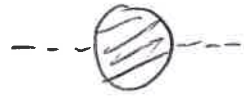
- $SU(2)_W$ is unbroken $SU(2)$ inside $SU(3)$

$\Rightarrow$ all particles in $SU(2)$ representations must be getting partners to fill out $SU(3)$ representations.

e.g. $\begin{pmatrix} t_L \\ b_L \\ T \end{pmatrix}$ $\leftarrow$ top quark partner, colored

- T not seen at LHC1 $\Rightarrow$ $T_{mass} \gtrsim 1\,\text{TeV}$

T mass breaks $SU(3)$ symmetry

$\Longrightarrow \quad \delta m_H^2 =$  t, T $\sim \frac{\lambda_t^2}{16\pi^2} m_T^2 \log \frac{M_{UV}}{m_T}$

similar fine-tuning issues as in SUSY.

precise value of f.t. model-dependent but

f.t. $\gtrsim$ 10-100 typical.

Partner models summary

$$= \sum -\lambda_i^2 M_i^2 = -\frac{\lambda_t^2}{16\pi^2}\underbrace{(m_T^2 - m_{top}^2)}_{\text{top partner(s)}} + \frac{g^2}{16\pi^2}\underbrace{(m_{W'}^2 - m_W^2)}_{\text{su(2) partner(}}$$

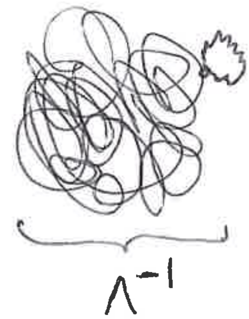
$+ \ldots$

partners of SM particles with biggest couplings to Higgs have biggest contribution to naturalness problem. Thus we need these to be light.

$\Longrightarrow$ expect
- top partners — usually colored, couple to 3rd generatio + Higgs
- su(2) partners — W', Z', couple to Higgs, 3rd generation

masses? the lighter the more natural.

Composite Higgs



short distance quantum corrections affect the constituents, not the Higgs

if constituents are fermions with chiral symmetry to protect their masses then there is no sensitivity to UV physics.

dimensional analysis: Higgs only exists below Λ, Higgs mass is not protected by any symmetry below Λ

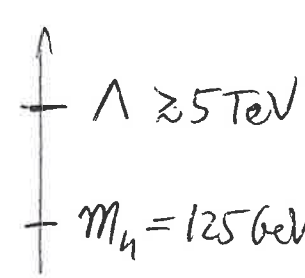
$\Rightarrow$ loops of composite states generate Higgs mass

$$m_H^2 \sim$$

$$\sim \frac{g^2}{16\pi^2}\Lambda^2 \sim \Lambda^2$$

strong coupling

but we need a separation between m_H and Λ because of bounds from precision measurements



Compare with QCD bound states

Λ^{comp}

$p\ n$	$1/2$	1 GeV	
ρ	1	770 MeV	
$\sigma = f_0$	0^+	~ 500 MeV	$\leftarrow$ the "Higgs"
$\pi^+\ \pi^0$	0^-	140 MeV	

$\uparrow$ spin $\quad \nwarrow$ parity

lesson: $m_\sigma \sim \Lambda$, as expected.

But π are lighter, why?

approximate Nambu-Goldstone bosons of $SU(2)_L \times SU(2)_R$ chiral symmetry breaking.

Lesson:
- It is possible to get composite scalars which are lighter but they need to be protected by a symmetry. Implement the symmetry requires partners ...
- scalars could also be a little lighter than Λ by some mild fine-tuning $\mathcal{O}(1\%)$.

Summary:

- the Higgs is an exploration machine. Go explore, expect to be surprised.

- the SM Higgs is unnatural. Finding no new physics which protects the Higgs mass would be very strange. Well-motivated are searches in the Higgs sector and anything that couples strongly to Higgs: top, W, Z partners.

- surprises can be anywhere, cast a wide net.

- Dark Matter - WIMP

  if dark matter is a weakly coupled particle which interacts with the SM (with weak couplings) thermal freeze-out predicts its mass in the 100 GeV - 10 TeV range. It or its "friends" in the dark sector can be produced at LHC

$\Longrightarrow$ missing energy signals