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.

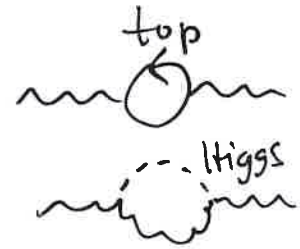
However! SM: $m_W = \underset{\substack{\uparrow \\ \text{LEP}}}{m_Z} \underset{\substack{\uparrow \\ \text{SLC}}}{\cos\theta_W}$ (tree level)

"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.

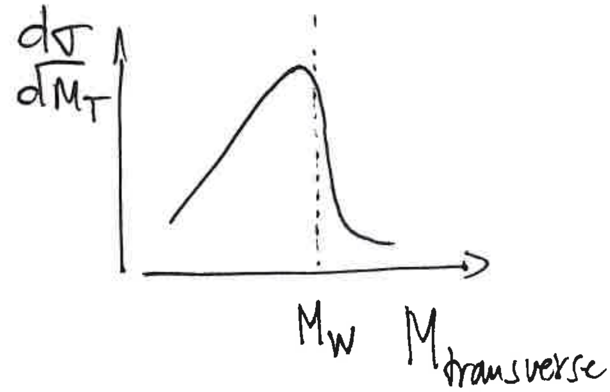


$$\frac{\delta m^2}{m^2} \sim \frac{g^2}{16\pi^2} \sim 1\%$$

$\Rightarrow$ need 2-loop accuracy.

- careful definitions

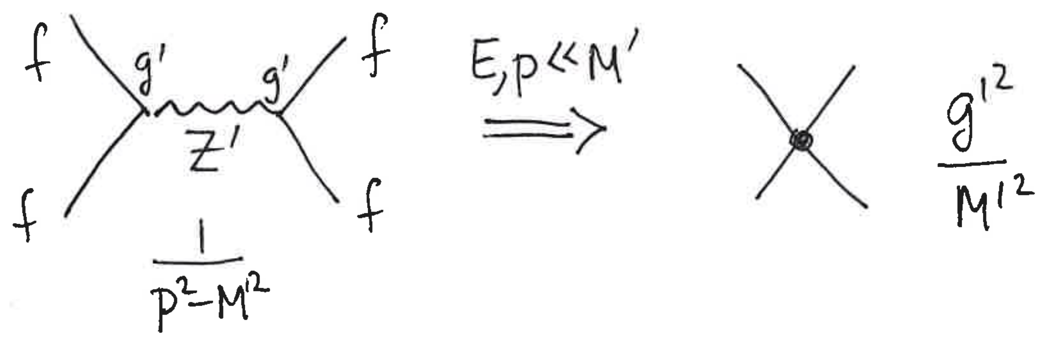
e.g.

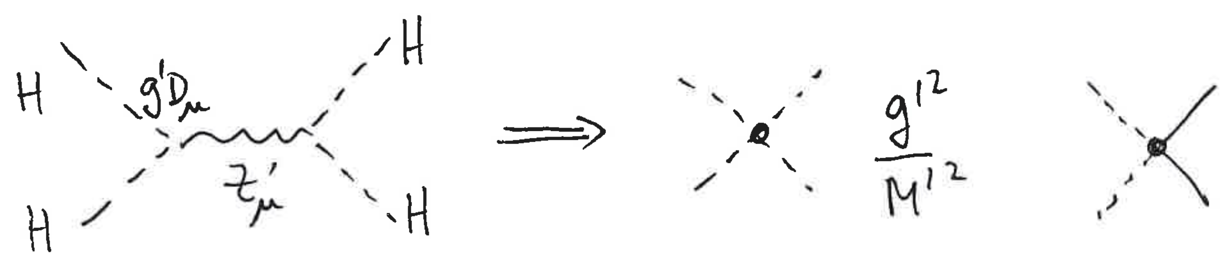


But what does this imply for New Physics?

<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: $$\frac{H^\dagger D_\mu H \; H^\dagger D^\mu H}{\Lambda^2}$$ four Higgs scattering, good luck!

$D_\mu \to \partial_\mu + igZ_\mu$, $H \to v+h$

but also $$\underbrace{g^2v^2}_{m_Z^2}\frac{v^2}{\Lambda^2}Z_\mu Z^\mu$$ Z mass correction, no W mass correction.

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

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

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

LEP + Tevatron probed 7 TeV!

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

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

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

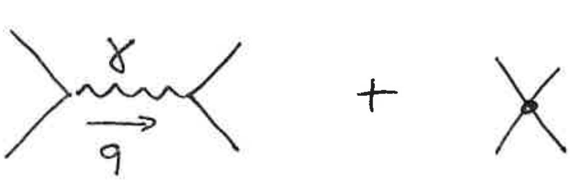
$$+ \frac{(L_2 H)^2}{\Lambda}$$ dimension 5, neutrino masses

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

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

$+$ dim > 6 ...

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

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

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

A Non-trivial example:

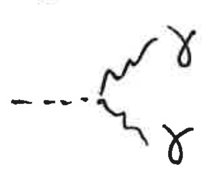
$$\mathcal{L} \sim \underset{\substack{\uparrow \\ \text{Hypercharge}}}{s_1 g'^2} \frac{H^\dagger H B_{\mu\nu}B^{\mu\nu}}{\Lambda^2} + s_2 g^2 \frac{H^\dagger H W^a_{\mu\nu}W^{a\,\mu\nu}}{\Lambda^2} + s_{12} g g' \frac{H^\dagger \sigma^a H W^a_{\mu\nu}B^{\mu\nu}}{\Lambda^2}$$

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

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

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

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

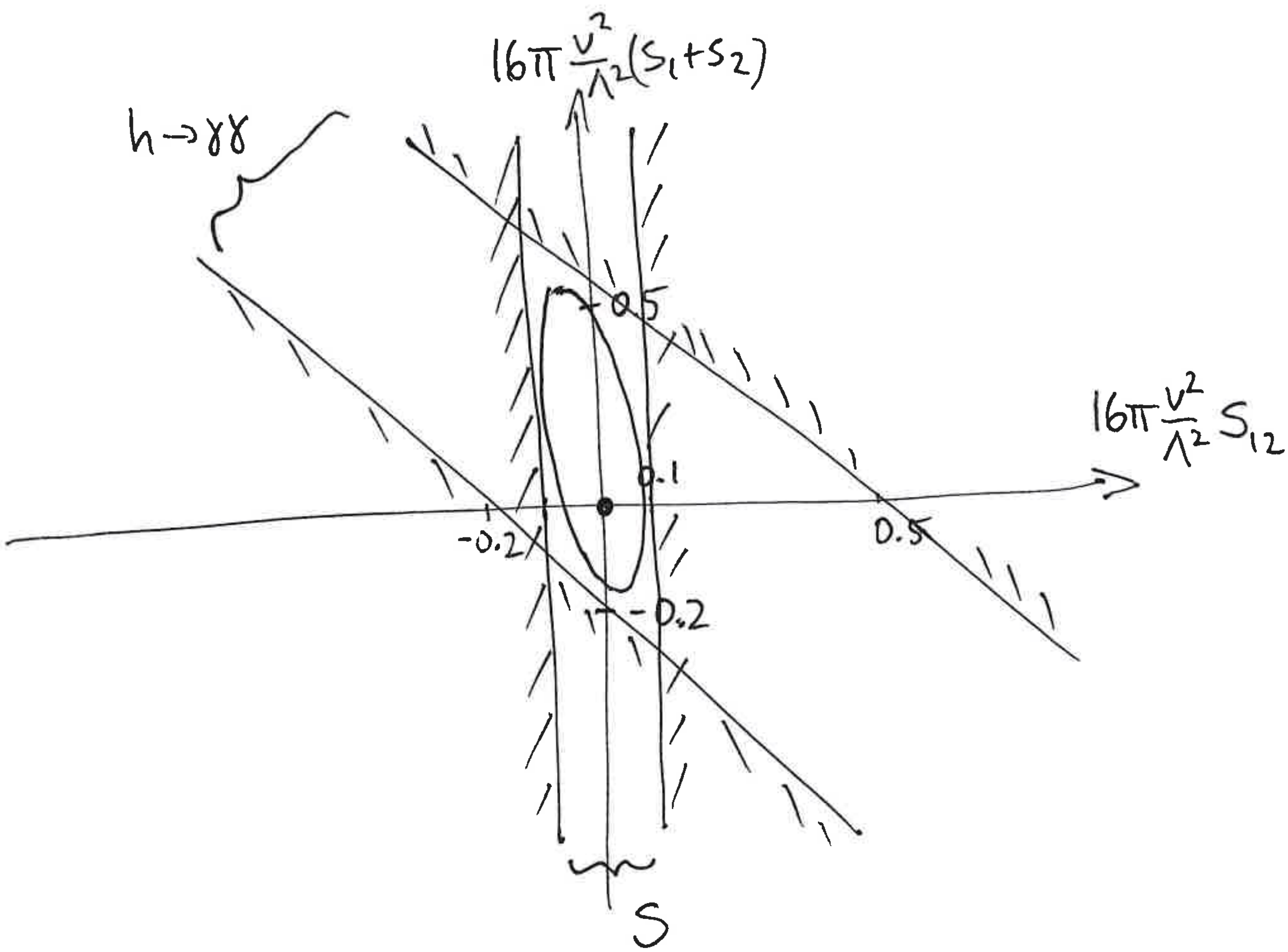
Higgs decays: 

γZ $\quad\quad$ ZZ^*

the data: 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? $s_i = 1 \Rightarrow \Lambda \gtrsim 6\,\text{TeV}$

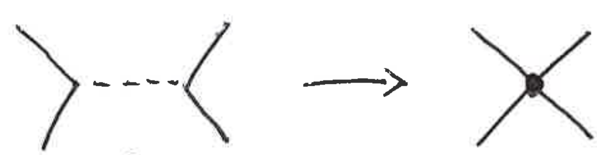
$s_i = \frac{1}{16\pi^2} \Rightarrow \Lambda \gtrsim 500\,\text{GeV}$

Effective SM

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

- 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



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

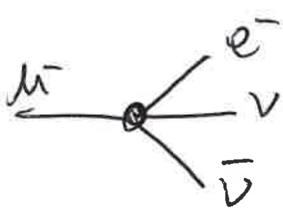
$c \sim$ order 1

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

$\Rightarrow$ guarantee of new physics at scale M

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

Historical example: muon decay



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

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

current situation :

- 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 LHv_R

- gravity couples to energy-momentum

$$\text{e.g.} \quad \underbrace{g_{\mu\nu}}_{\text{graviton}} \frac{\partial^\mu H^\dagger \partial^\nu H}{M_{pl}} \Rightarrow \text{new physics @ } M_{pl}$$

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

Indirect? Naturalness

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

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

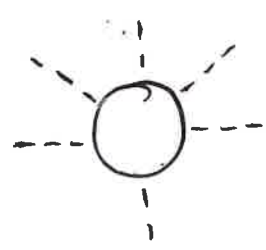
Q: but are they actually generated?

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

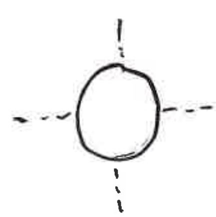
M always downstairs

• yes, at loop level

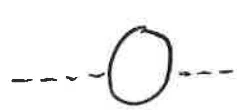
example:



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



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



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

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

*(after regulating + subtracting

§ the CC: a (relevant?) detour

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

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

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

$M_{top} \qquad \sim 10^{7}\ \mathrm{GeV}^4$ 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 $\to$ no stars $\to$ no heavy elements)

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

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

different vacua are cosmologically sampled

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

<u>anthropics</u>: 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

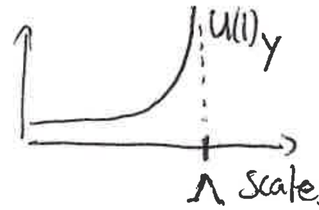
back to <u>Higgs naturalness problem</u>:

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

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

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

$\Rightarrow$  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 <u>requires</u> 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

$m_{\substack{top\\partner}} \lesssim 4\pi\, m_{Higgs}$

- 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

$$\left.\begin{array}{l} H_u \xleftrightarrow{} \tilde{H}_L \\ H_d^* \xleftrightarrow{\text{susy}} \tilde{H}_R \end{array}\right\} \text{Dirac fermion "Higgsino"}$$

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

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

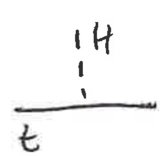
- supersymmetry: boson masses = fermion superpartner masses

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

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

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. 

top stop

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

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"

why doesn't the photon get a mass from UV physics?

What is the symmetry that prevents it?

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

but photon couplings allowed $(\partial_\mu + ieA_\mu)\psi \quad \psi \to e^{-i\theta}\psi$

Can the Higgs have a shift symmetry?

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

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

scalars with a shift symmetry are Nambu-Goldstone bosons

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

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

T mass breaks $SU(3)$ symmetry

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

t, 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

top partner(s) — $SU(2)$ partner(s)

 $$= \sum -\lambda_i^2 M_i^2 = -\frac{\lambda_t^2}{16\pi^2}\left(m_T^2 - m_{top}^2\right) + \frac{g^2}{16\pi^2}\left(m_{W'}^2 - m_W^2\right)$$

$+ \ldots$

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

$\Longrightarrow$ expect $\begin{cases} \underline{\text{top partners}} & \text{usually colored, couple to 3rd generation + Higgs} \\ \underline{SU(2)\text{ partners}} & W', Z', \text{couple to Higgs, 3rd generation} \end{cases}$

masses? the lighter the more natural.