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.

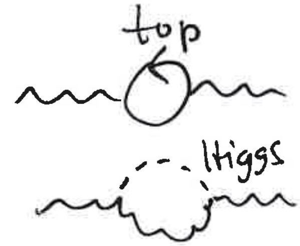
However! SM: $m_W = \underset{\uparrow \atop \text{LEP}}{m_Z} \cos \underset{\uparrow \atop \text{SLC}}{\theta_W}$ (tree level)

"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.

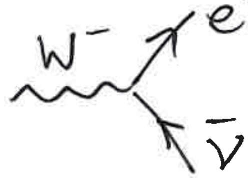


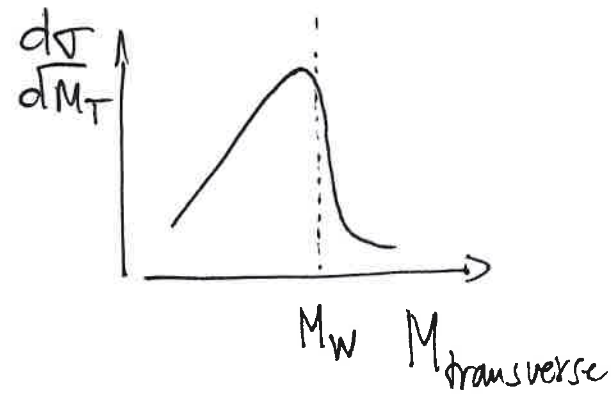
$$\frac{\delta m^2}{m^2} \sim \frac{g^2}{16\pi^2} \sim 1\%$$

$\Rightarrow$ need 2-loop accuracy.

- careful definitions

e.g.

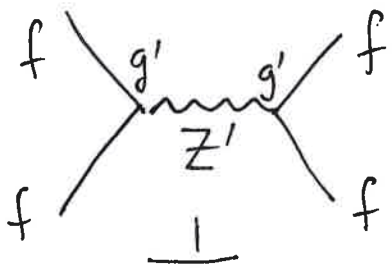




But what does this imply for New Physics?

<u>SM effective theory</u>:

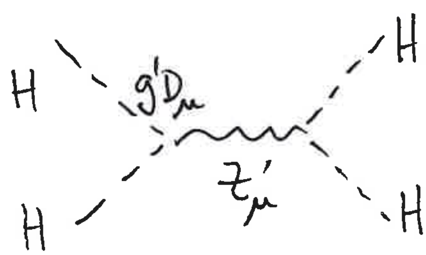
<u>example</u>: Z' with mass M', couplings g' to SM fields f, H



$$\frac{1}{p^2-M'^2}$$

$$\xRightarrow{E,p \ll M'}$$

$$\frac{g'^2}{M'^2}$$



$$\Longrightarrow$$

$$\frac{g'^2}{M'^2}$$

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

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

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

$\Rightarrow$ goal: paramaterize NP by writing all possible effective couplings and bound coefficients from experiment example: $\dfrac{H^\dagger D_\mu H \; H^\dagger D^\mu H}{\Lambda^2}$ four Higgs scattering, good luck!

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

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

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

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

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

LEP + Tevatron probed 7 TeV!

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

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

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

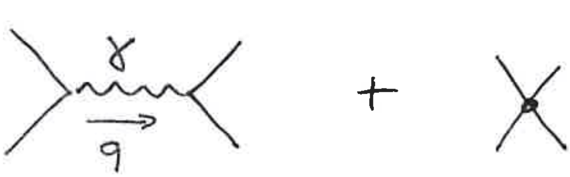
$$+ \frac{(L_L H)^2}{\Lambda} \qquad \text{dimension 5, neutrino masses}$$

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

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

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

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

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

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

A Non-trivial example:

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

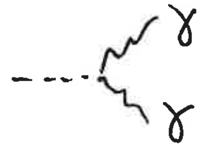
Hypercharge

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

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

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

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

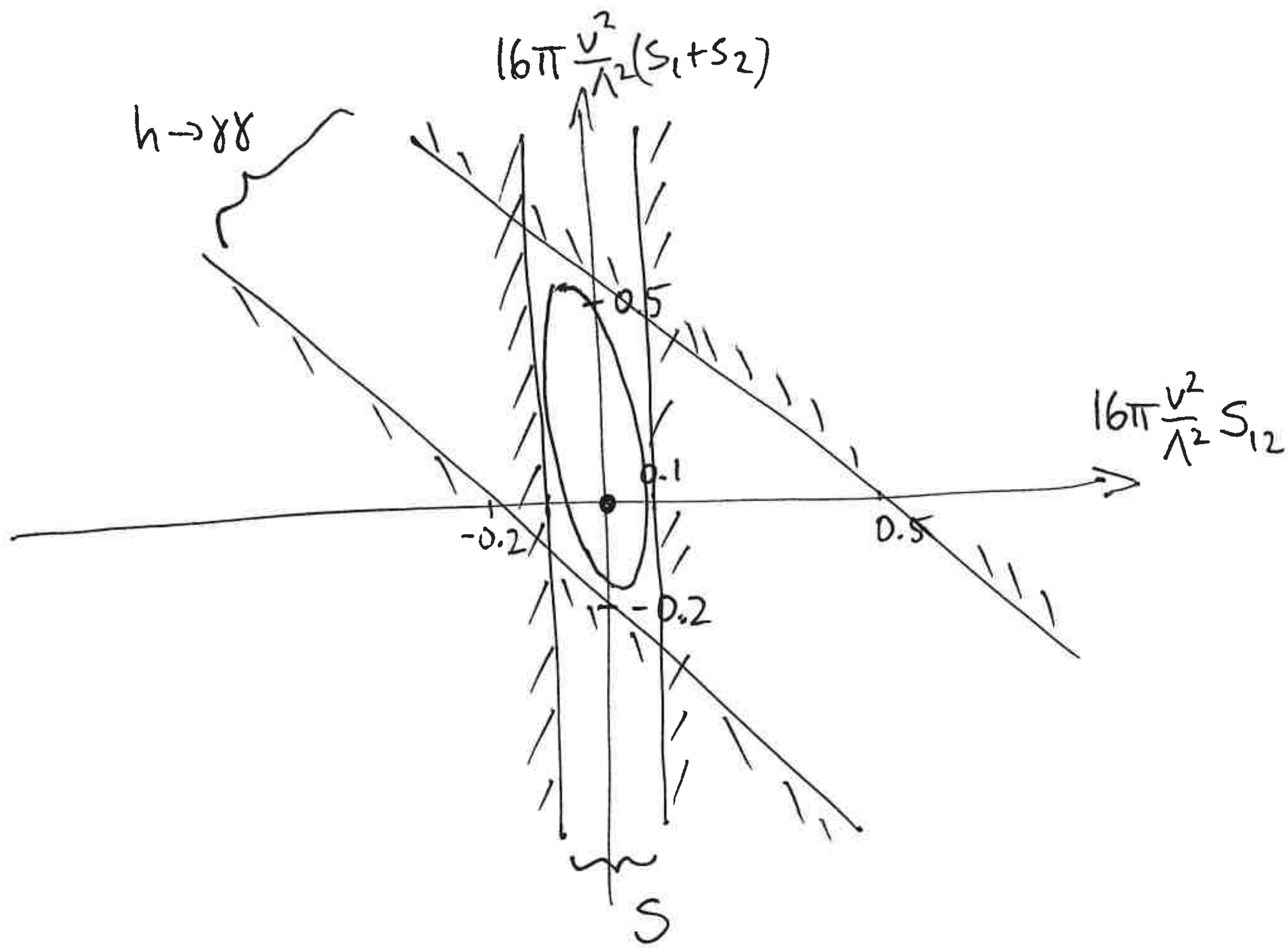
Higgs decays: 

γZ $\quad\quad$ 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? $S_i = 1 \Rightarrow \Lambda \gtrsim 6\,\text{TeV}$

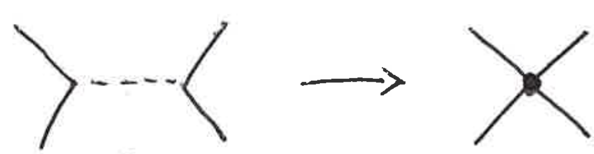
$S_i = \frac{1}{16\pi^2} \Rightarrow \Lambda \gtrsim 500\,\text{GeV}$

Effective SM

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

- expansion in $\dfrac{p, m, v}{\Lambda}$, 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



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

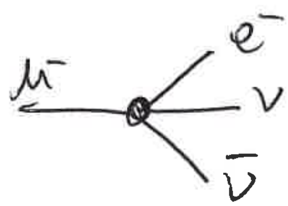
$c \sim$ order 1

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

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

<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 $\quad \frac{(LH)^2}{\Lambda} \longrightarrow m_\nu = \frac{v^2}{\Lambda} \sim 0.1\,\text{eV}$

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

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

or neutrino is Dirac $LH\nu_R$

- gravity couples to energy-momentum

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

$\uparrow$ graviton

Currently no direct evidence for a lower scale.

Indirect? Naturalness

$$\mathcal{L} \sim c_4 \Lambda^4 + c_2 \Lambda^2 H^\dagger H + \cdots$$

cosmological constant

Higgs mass

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

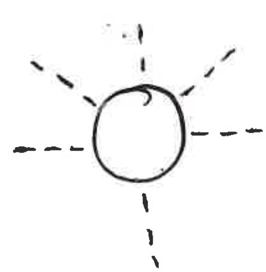
Q: but are they actually generated?

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

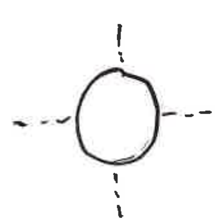
M always downstairs

• yes, at loop level

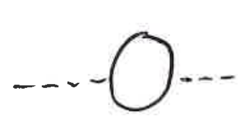
example:



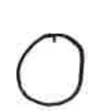
$$\frac{\lambda^6 (H^\dagger H)^3}{M^2} \frac{1}{16\pi^2}$$



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



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



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

*(after regulating + subtracting

the CC: a (relevant?) detour

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

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

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

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

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

different vacua are cosmologically sampled

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

<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.

would 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

2 possible solutions:

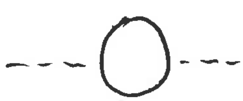
- cancelation because of symmetry (SUSY, Little Higgs)

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

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

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

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

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

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

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

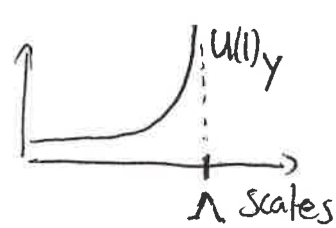
desperate "nightmare" proposal: there are no more massive particles

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

consequences? - no unification

- neutrinos are Dirac $\cancel{\frac{(LH)^2}{\Lambda}}$

- gravity: $\frac{g_{\mu\nu}}{M_{pl}} T^{\mu\nu}$

- Hyperchange coupling 

fortunately, this proposal cannot be true. The SM <u>requires</u> higher scales.