BSM physics - Effective Lagrangians - Naturalness - Relaxion

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Monday: precision, $\mathcal{L}_{eff.}$

Tuesday: naturalness, partners

Wednesday: relaxion

BSM at colliders

1. precision measurements
   (effective Lagrangians)
2. resonances (particles)

Effective lagrangians for BSM and precision measurements

Example:

impressive!

ATLAS: $m_W = 80.370 \pm 0.019$ GeV
(Run 1)

Tevatron + LEP $\quad 80.385 \pm 0.015$ GeV

totally uninteresting (by itself)

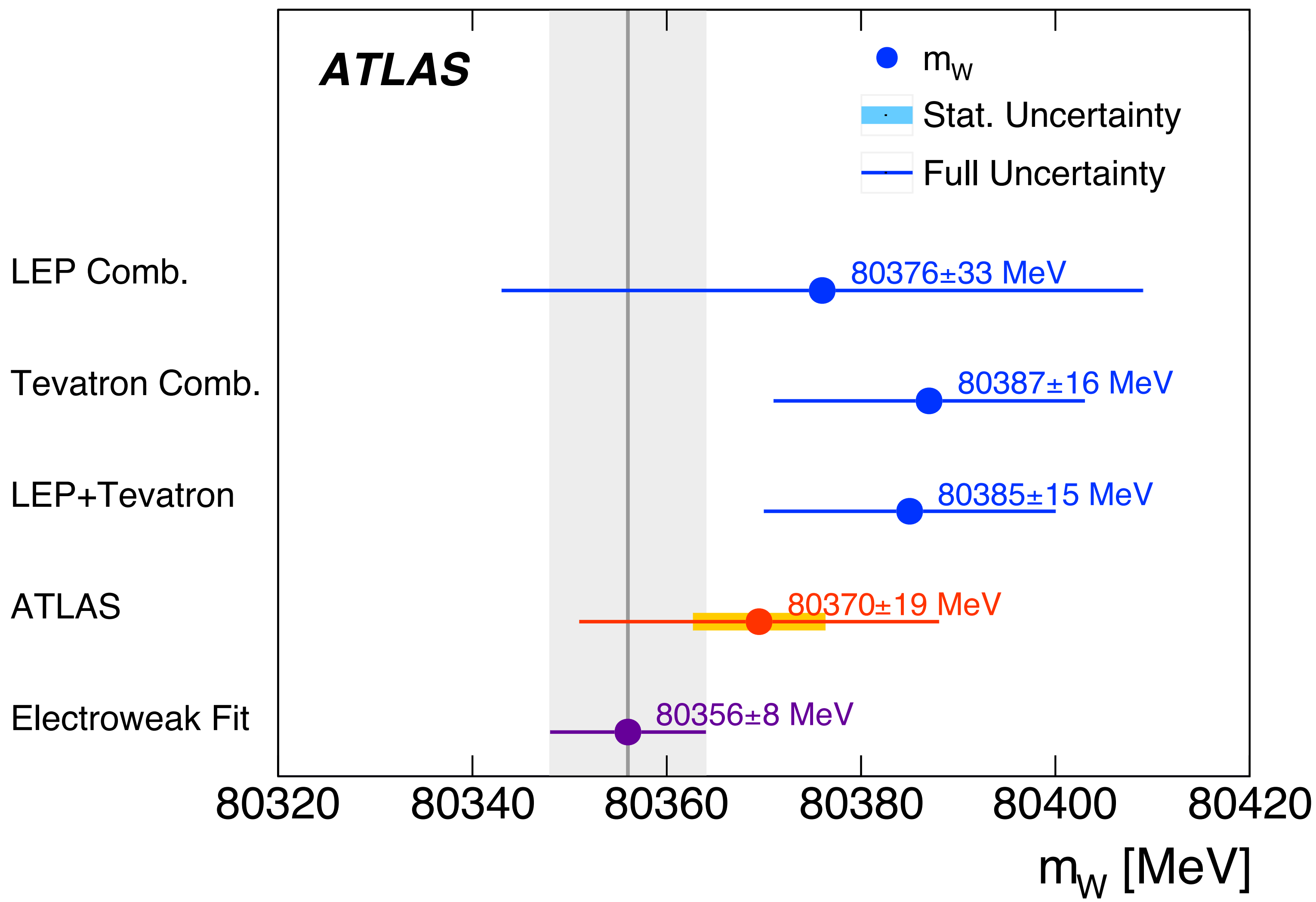
Why? We don't care about the values of masses, parameters. $m_W = 75$ GeV is equally uninteresting

We want to understand physics $\Rightarrow$ need to test predictions!

in SM: $m_W = m_Z \cos\theta_W$ (tree level)

m_Z ↑ LEP θ_W ↑ SLC

Electroweak fit : "$m_Z \cos\theta_W$" = 80.356 ± 0.008 GeV



1701.07240v2 [hep-ex]
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a 0.2 per mille test of the Standard Model!

Sub-permille accuracy requires ....

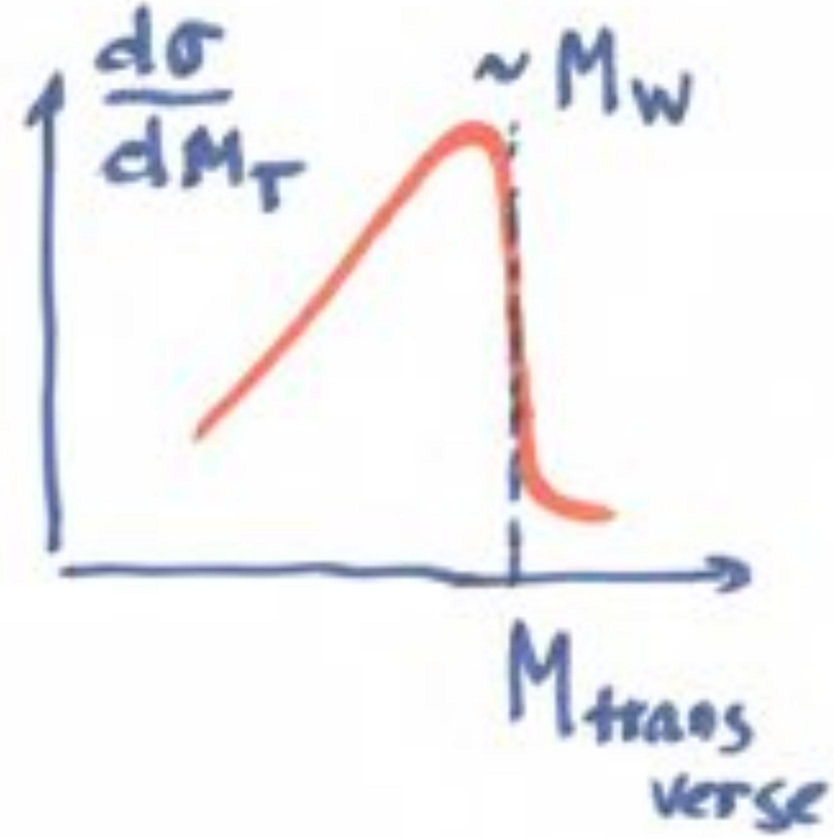
- loops

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

$\Longrightarrow$ need 2 loop accuracy !

- careful definitions

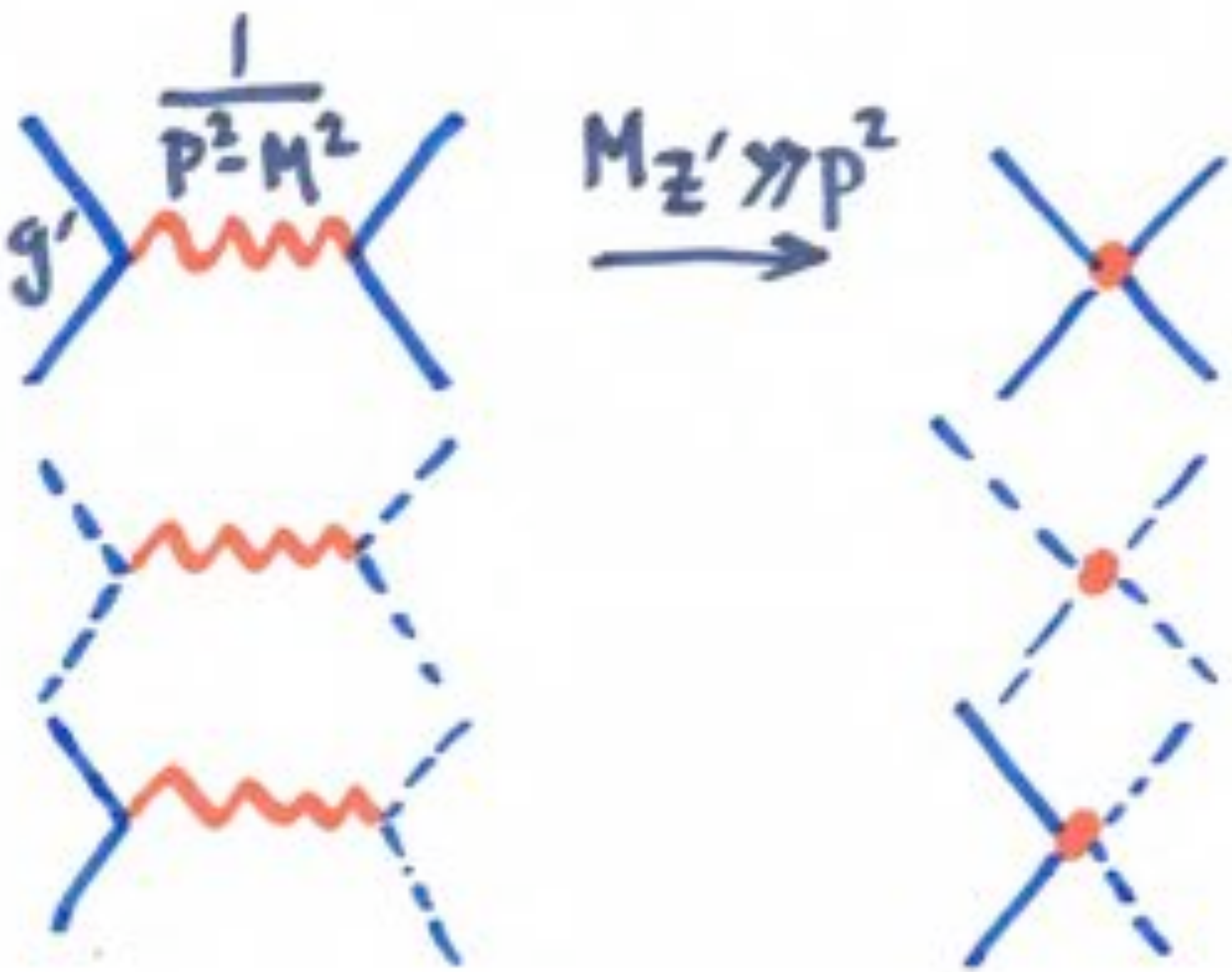
e.g.



- careful experiments

Connection to BSM ?

Z' example :



$$\frac{g'^2}{M_{Z'}^2}$$

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

Lesson: Heavy new physics ($M^2 \gg p^2$) parameterized by effective couplings suppressed by heavy scale

Strategy: parameterize NP by writing all possible effective couplings of SM fields 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! 

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

$$\frac{\delta m_Z^2}{m_Z^2} \simeq \frac{v^2}{\Lambda^2} \qquad v = 246\text{ GeV}$$

no shift in W-mass $\Rightarrow$ $m_W = m_Z \cos\theta$ violated

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

Experimental precision: $\frac{\delta m_W}{m_W} \sim 2.4 \cdot 10^{-4}$

$$\Longrightarrow \frac{v^2}{2\Lambda^2} \lesssim 2.4 \cdot 10^{-4}$$

$$\Longrightarrow \Lambda \gtrsim v \cdot 46 \approx 11\ \text{TeV}$$

indirect precision test probes 11 TeV!

$\Big\{$ $\Lambda = \frac{M'}{g'}$, "typical" Z' $g' \sim 1/2$, $1/4$ dropped in calculation

$\Rightarrow M_{Z'} \gtrsim 3\ \text{TeV}$ similar to direct limits $\Big\}$

systematically... order terms by mass dimension

$$\mathcal{L}_{eff} = \Lambda^4 + \Lambda^2 H^\dagger H + \underbrace{\lambda (H^\dagger H)^2 + \mathcal{L}^{SM}_{kinetic} + \mathcal{L}^{SM}_{Yukawa}}_{\text{dim 4 , coefficients dimensionless}} \leftarrow \text{the SM}$$

$$\text{dim 5} \quad + \frac{(L_L H)^2}{\Lambda}$$

$$\text{dim 6} \left\{ \begin{array}{l} + \dfrac{H^\dagger D_\mu H H^\dagger D^\mu H}{\Lambda^2} + \dfrac{H^\dagger D_\mu H \bar{e}_R \gamma^\mu e_R}{\Lambda^2} + \dfrac{H^\dagger \sigma^a H \, W^a_{\mu\nu} B^{\mu\nu}}{\Lambda^2} \\ + \dfrac{H^\dagger H \, B_{\mu\nu} B^{\mu\nu}}{\Lambda^2} + \dfrac{H^\dagger H \, W^a_{\mu\nu} W_a^{\mu\nu}}{\Lambda^2} + \ldots \end{array} \right.$$

>80 more at dimension 6

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

$\mathcal{L}_{eff}$ has ∞ number of undetermined coefficients

- useful as expansion $\frac{\partial_\mu \partial^\mu}{\Lambda^2} \to \frac{P^2}{\Lambda^2} \ll 1$
- also $\frac{v^2}{\Lambda^2}$
  - δm_Z
  - $\frac{H^\dagger D_\mu H \, \bar{e}_R \gamma^\mu e_R}{\Lambda^2} \to g \frac{v^2}{\Lambda^2} \bar{e}_R Z_\mu \gamma^\mu e_R$ 

$\frac{\delta g}{g} \sim \frac{v^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim$ few TeV (LEP)

non-trivial example:

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

$$\langle H\rangle = \begin{pmatrix} 0 \\ v+h \end{pmatrix} / \sqrt{2}$$

$$\longrightarrow$$

$$\sim \underbrace{\frac{v^2}{\Lambda^2} B_{\mu\nu} B^{\mu\nu} + \frac{v^2}{\Lambda^2} W_{\mu\nu} W^{\mu\nu}}_{\text{absorb into } B_\mu,\, W^a_\mu \text{ field-redefinitions}} + s_{12}\, g g' \frac{v^2}{2\Lambda^2} W^3_{\mu\nu} B^{\mu\nu}$$

SU(2) violating Z-γ mixing

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

$+$ linear h-terms

$$+\; S_{12}\, g g' \frac{v^2}{2\Lambda^2} W^3_{\mu\nu} B^{\mu\nu}$$

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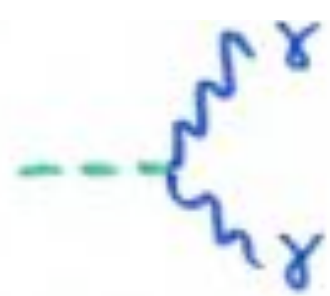
linear h-terms

$$\underbrace{+\; S_1 g'^2 \frac{v^2}{\Lambda^2} \frac{h}{v} B_{\mu\nu} B^{\mu\nu} + S_2 g^2 \frac{v^2}{\Lambda^2} \frac{h}{v} W^a_{\mu\nu} W^a_{\mu\nu} + S_{12}\, g g' \frac{v^2}{\Lambda^2} \frac{h}{v} W^3_{\mu\nu} B^{\mu\nu}}$$

$$= \underbrace{4e^2 \frac{v^2}{\Lambda^2} (S_1 + S_2 + S_{12})}_{\equiv \frac{\alpha}{2\pi} \kappa_\gamma} \frac{h}{v} \frac{F_{\mu\nu} F^{\mu\nu}}{4} + \underbrace{\dots}_{\kappa_Z} \frac{h}{v} F_{\mu\nu} Z^{\mu\nu} + \underbrace{\dots}_{\kappa_{Z\gamma}} \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu}$$

Higgs decays:



γZ $\qquad$ ZZ^*

the data (95% confidence):

PDG 2018 precision EW fit : $S = 0.02 \pm 0.14$

PDG 2018 Higgs physics : $k_\gamma = 0.87 \pm 0.24$

$k_\gamma^{SM} = 1$

$\Rightarrow \delta k_\gamma^{NP} = -0.13 \pm 0.24$

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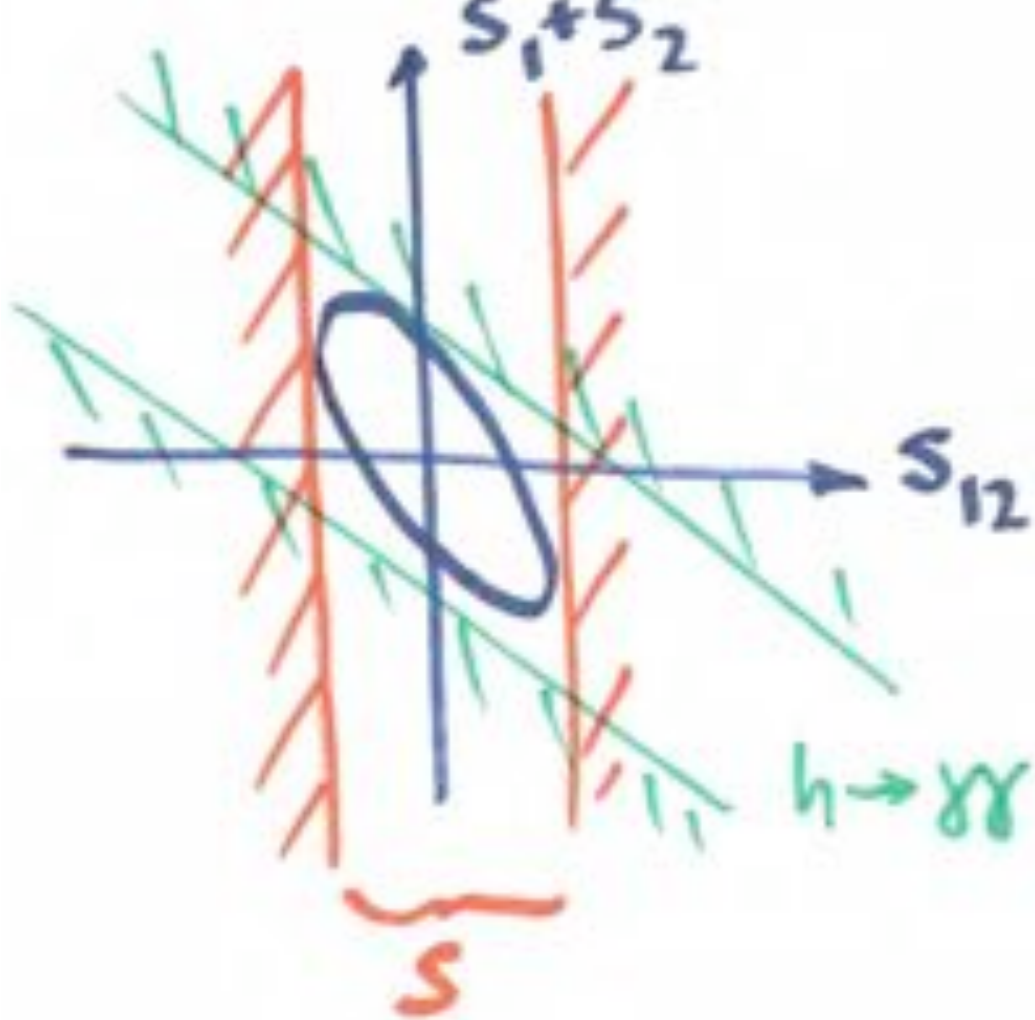

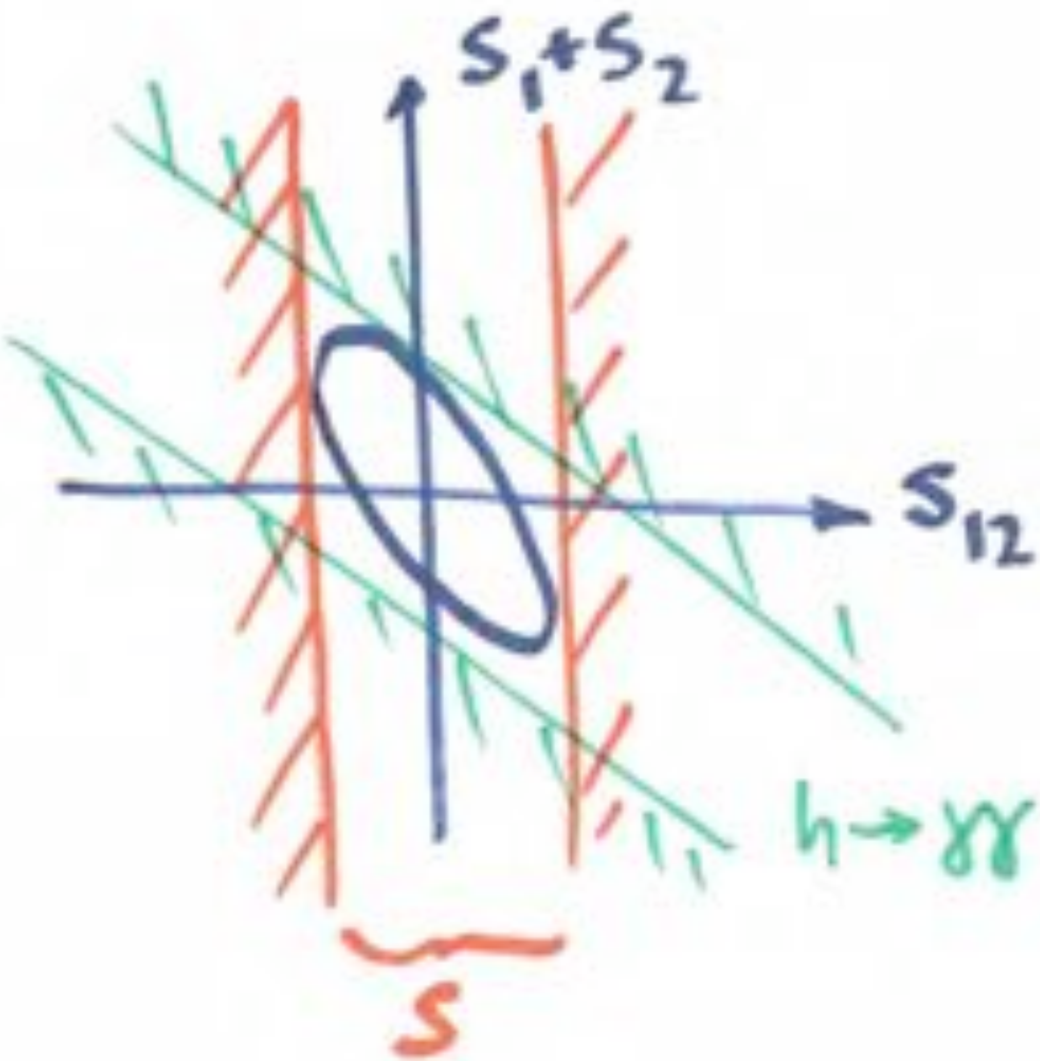

New physics bounds ?

trees $S_i \approx 1 \Rightarrow \Lambda \gtrsim 10$ TeV

loops $S_i \approx \frac{1}{16\pi^2} \Rightarrow \Lambda \gtrsim 1$ TeV

back to 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 $1/\Lambda$, valid when $p, m_{SM}, v \ll \Lambda$
- $\Lambda \sim$ scale of NP
- coefficients free parameters, determined by experiment.

  If UV physics known, calculate coeffs in terms of UV parameters

Assume a non-zero coeff in $\mathcal{L}_6$ measured $\Rightarrow \Lambda$ known

$\Rightarrow$ guarantee of new physics

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

- Historical example: muon decay

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

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

current situation:

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

  $\Rightarrow \Lambda \sim 10^{14}\,\text{GeV} \quad \Rightarrow M \lesssim 10^{15}\,\text{GeV}$

  (or neutrino is Dirac $LH\nu_R$)

- gravity $\quad g_{\mu\nu} \frac{\partial^\mu H^\dagger \partial^\nu H}{M_{pl}}$ $\quad \Lambda \sim M_{pl}$ $\quad$ new physics @ M_{pl}

  graviton

- B physics $R_{K^{(*)}}$?? $\quad \Lambda \approx 30\,\text{TeV}$

$\Rightarrow$ currently no direct evidence for a low NP scale :(

indirect? Naturalness