THE NON SM HIGGS

Michele Redi

La Thuile, 4 March

WHAT WE KNOW

SM is a gauge theory based on $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$\mathcal{L}_{Kinetic} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}W^b_{\mu\nu}W^{b\mu\nu} + i\sum_{j=1}^{3}\left(\bar{\Psi}^j_L \;\not{D}\Psi^j_L + \bar{\Psi}^j_R \;\not{D}\Psi^j_R\right)$$

$$\Psi_{L,R} = (3,2)_{\frac{1}{6}} \oplus (3,1)_{\frac{2}{3}} \oplus (3,1)_{-\frac{1}{3}} \oplus (1,2)_{-\frac{1}{2}} \oplus (1,1)_{-1}$$

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(3 couplings)

Unbroken gauge symmetry forbids mass terms: vacuum must respect a smaller symmetry

$$SU(3)_c \otimes U(1)_{EM}$$

allowing to write mass terms,

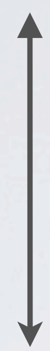
$$\mathcal{L}_{mass} = \sum_{i,j=1}^{3}\left[\bar{u}^i_L M^u_{i,j} u_R + \bar{d}^i_L M^d_{i,j} d_R + \bar{e}^i_L M^e_{i,j} e_R\right] + h.c.$$

$$+m^2_W W^2 + \frac{1}{2}m^2_Z Z^2$$

O(20) parameters

Mass for gauge bosons implies new degrees of freedom

$m_1 = 0$



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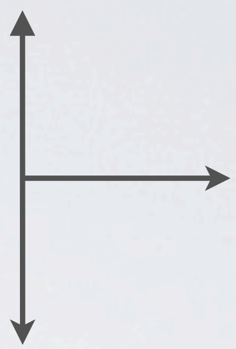

The extra degrees of freedom are Goldstone Bosons

$$SU(2)_L \otimes U(1)_Y \to U(1)_Q$$

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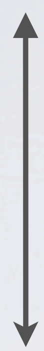

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Important hint:

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx 1 \quad \longrightarrow$$

Custodial Symmetry

$SU(2)_c$

In the SM electro-weak symmetry is broken through a scalar doublet with Y=1/2

$$V(H) = \lambda \left(|H|^2 - v^2 \right)^2$$

$$H(x) = U(x) \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \qquad v = 174\, GeV$$

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VEV breaks symmetry. The Goldstone Bosons in $U(x)$ are eaten giving mass to W & Z. Higgs sector respects custodial symmetry

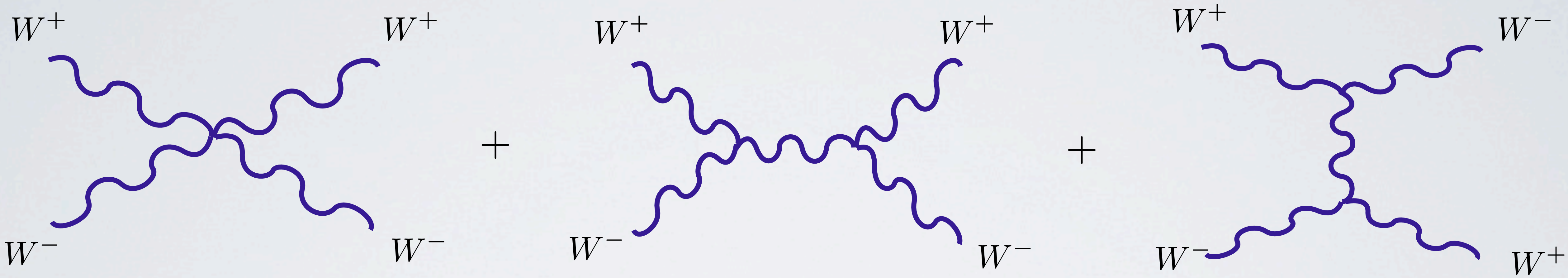
$$\frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}} \longrightarrow \rho \approx 1$$

If SM is correct only unknown is the quartic/mass

$$m_h = \sqrt{\lambda}\, v$$

STRONG DYNAMICS

In principle the Higgs scalar is not even needed, but



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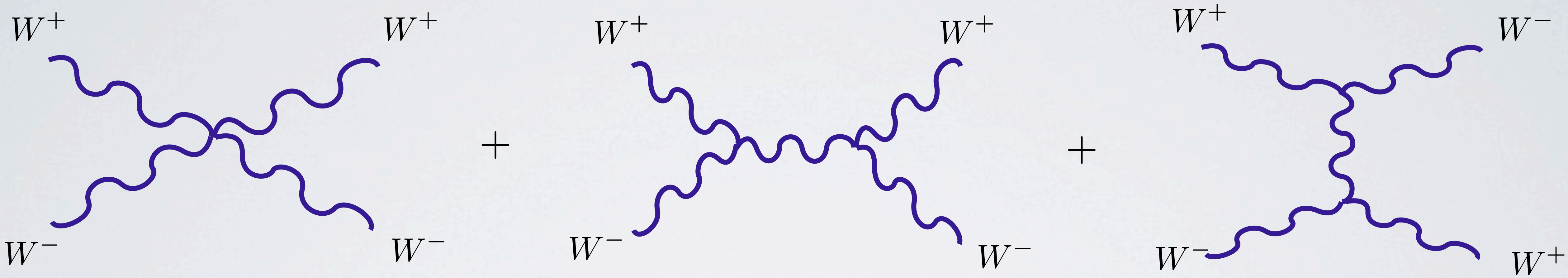

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Interactions become strongly coupled around TeV.

Perturbative unitarity is violated at

$$\Lambda \approx 1.7\,\mathrm{TeV}$$

New physics must appear below Λ

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The 3 Goldstone bosons are the pions.
scattering is unitary because they are composite objects.

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The 3 pions would become longitudinal polarization of W & Z without other effects

$$m_W = g f_\pi \sim 50\,\mathrm{Mev} \qquad\qquad \rho \approx 1$$

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$$f = v$$

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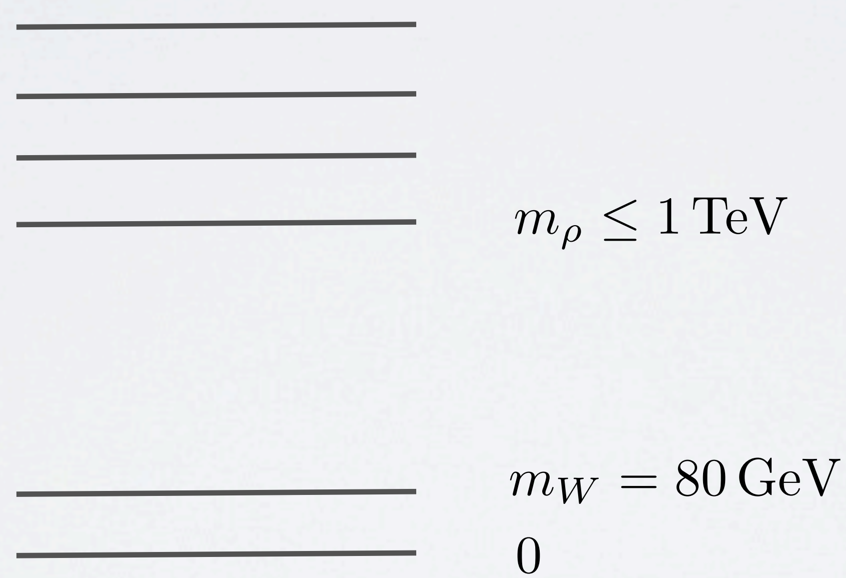

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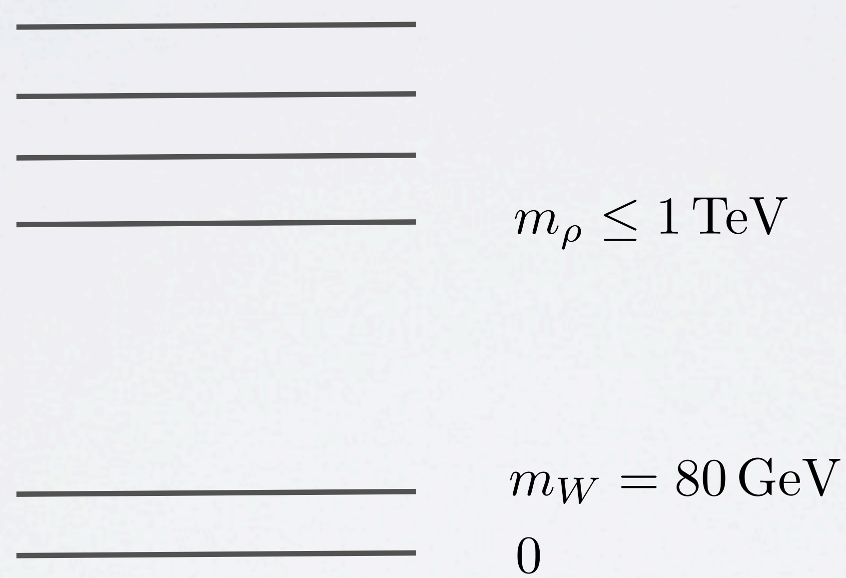
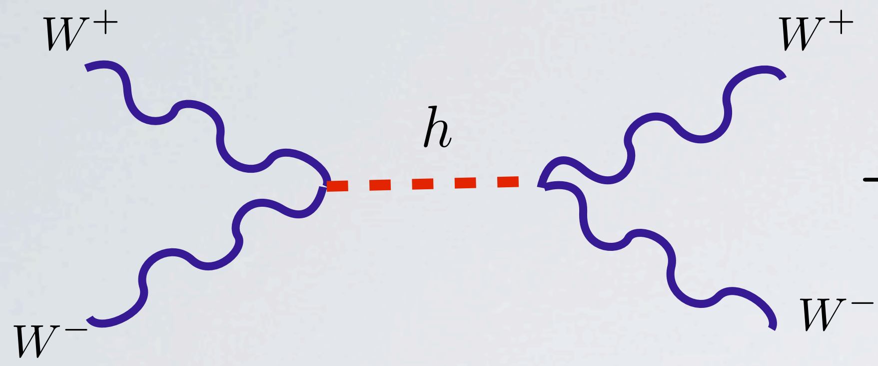


Sadly phenomenologically ruled out:
precision electro-weak measurements and flavor

In the SM:



$+\dots$

$$A(W_L^+W_L^- \to W_L^+W_L^-) \simeq \frac{1}{v^2}\left[s - \frac{s^2}{s-m_h^2} + (s\to t)\right]$$

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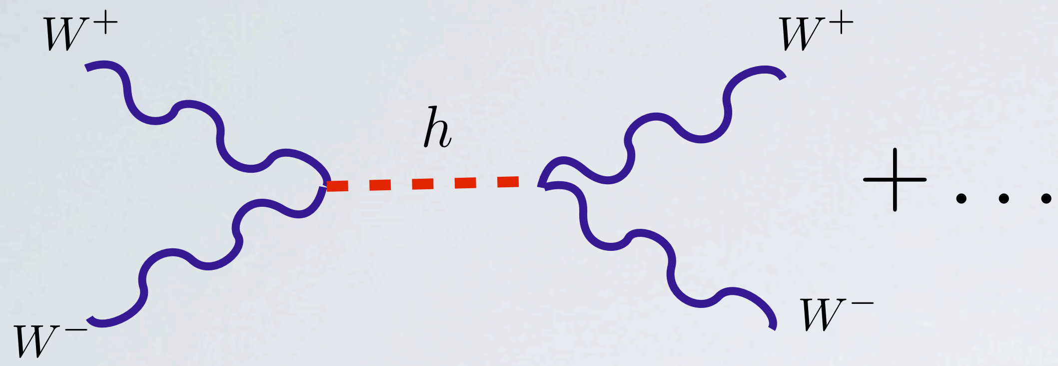

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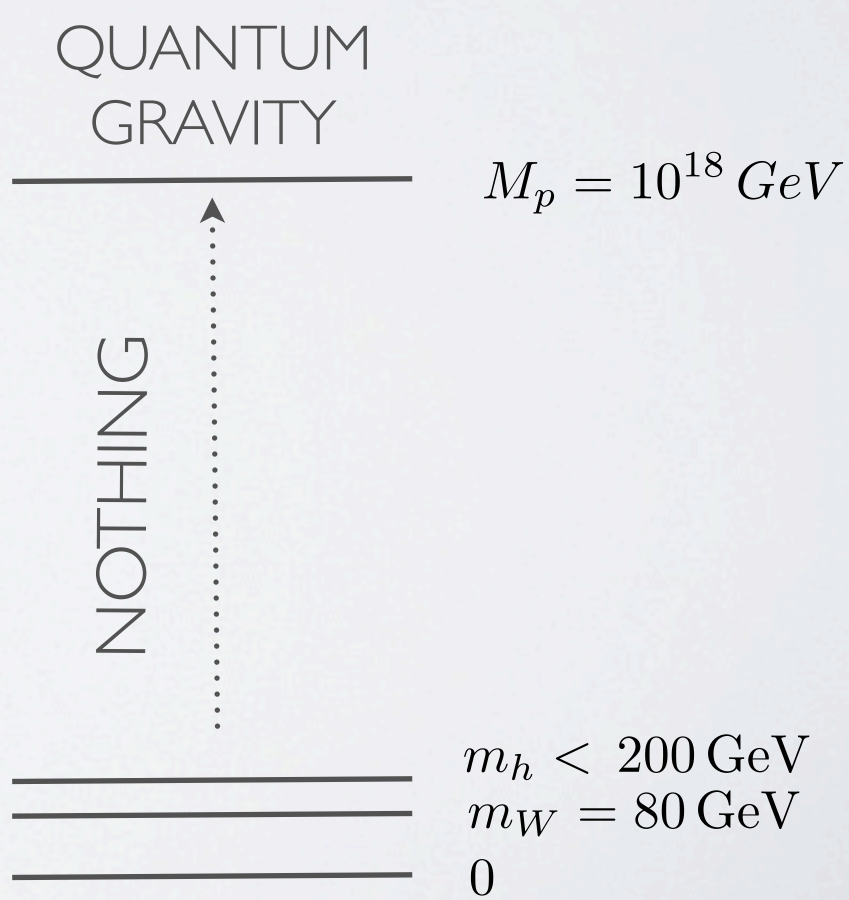
Amplitude does not grow so SM can be valid up to the Planck scale.



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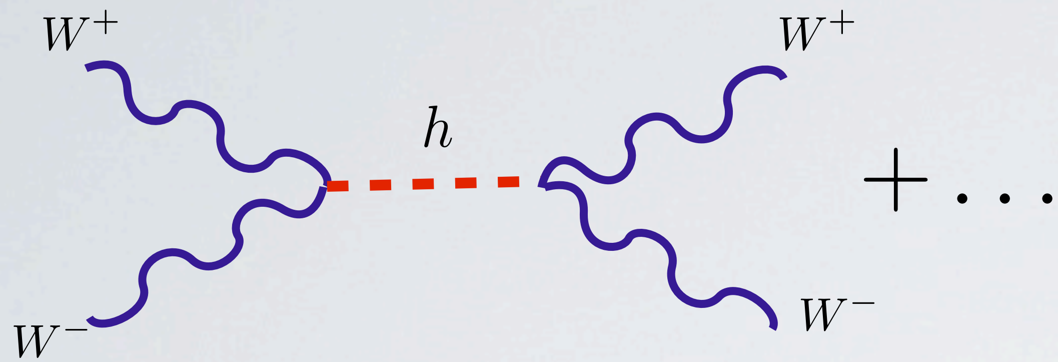

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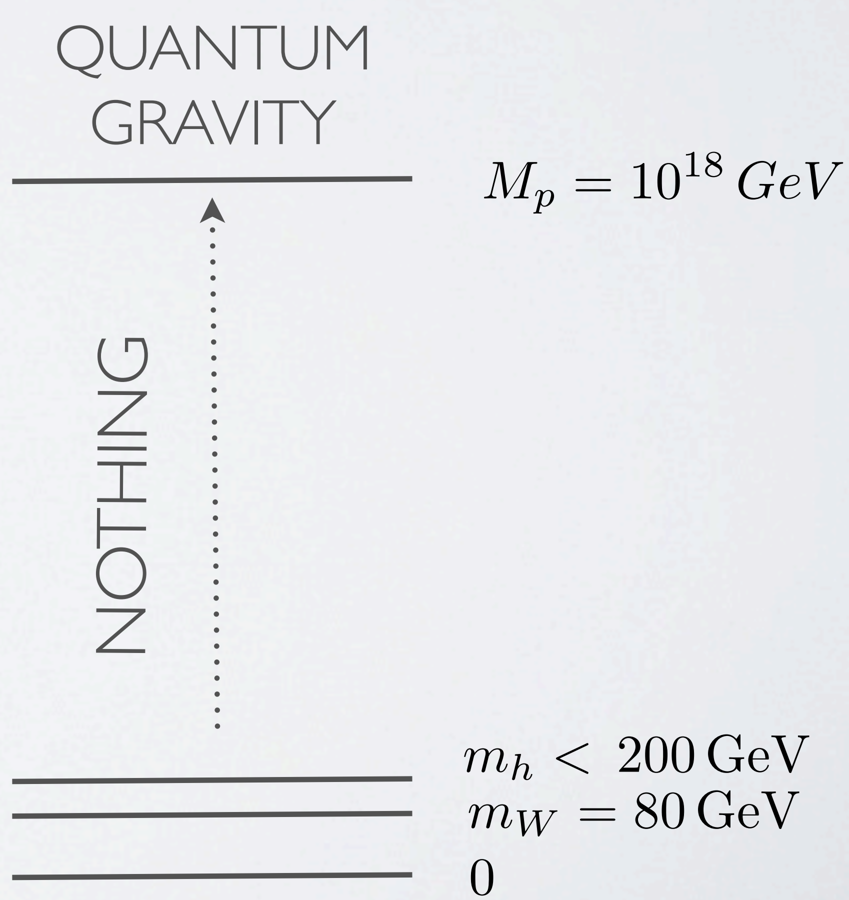
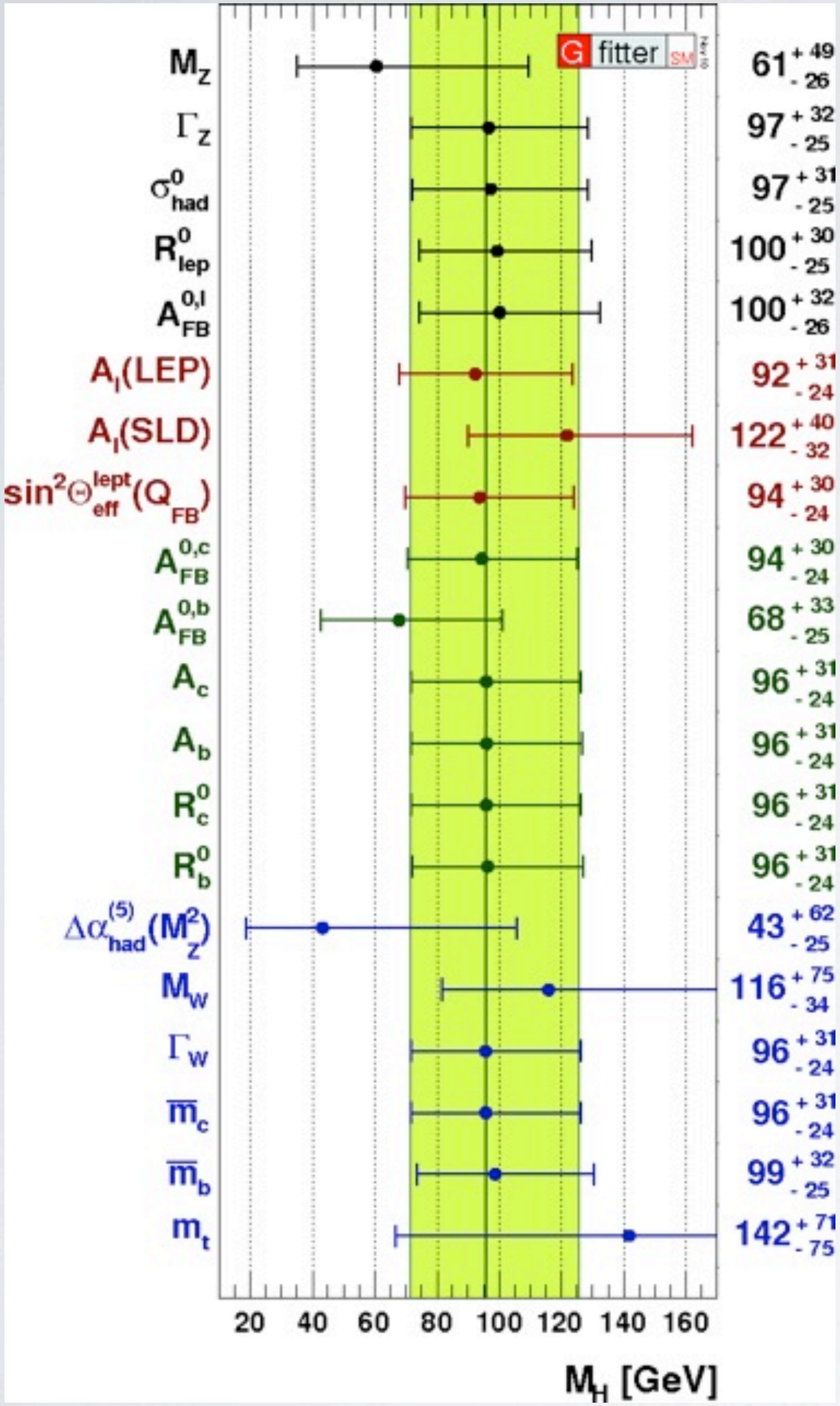
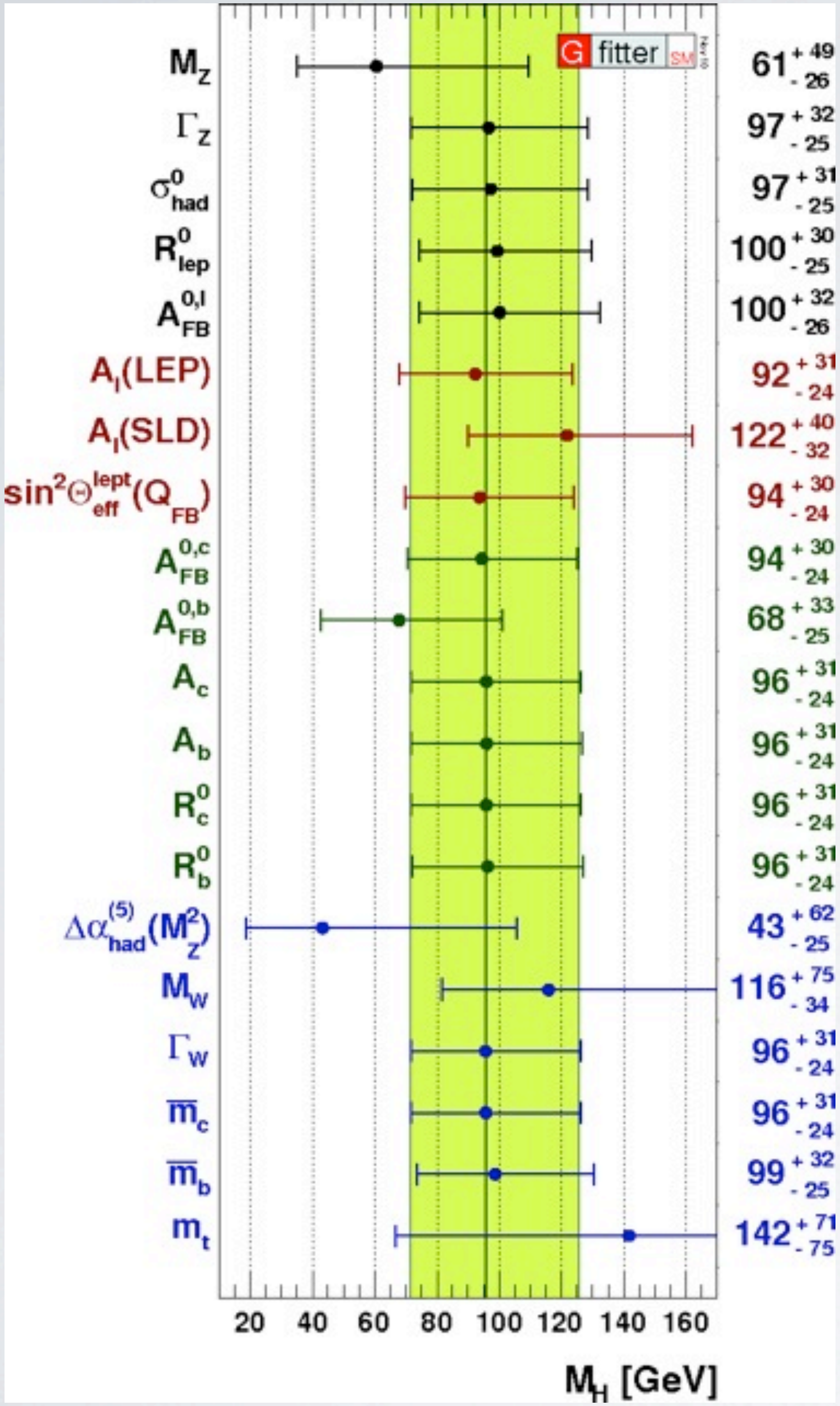
- Hierarchy problem
- Dark Matter
- Origin of Yukawas, CP
- Explains nothing





SM nice but not perfect



SM probability 15 %

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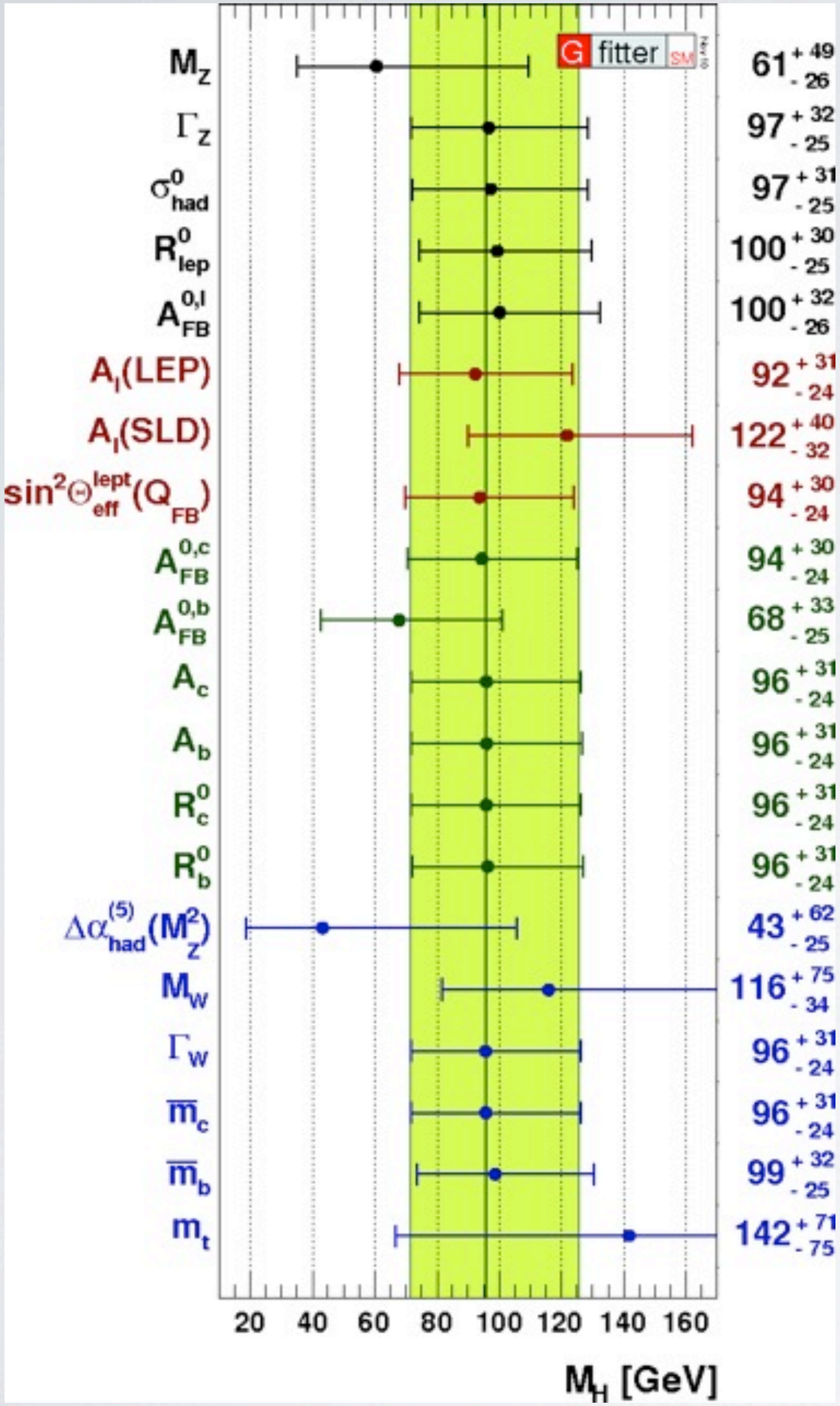

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Just observables related to the Higgs < 2%

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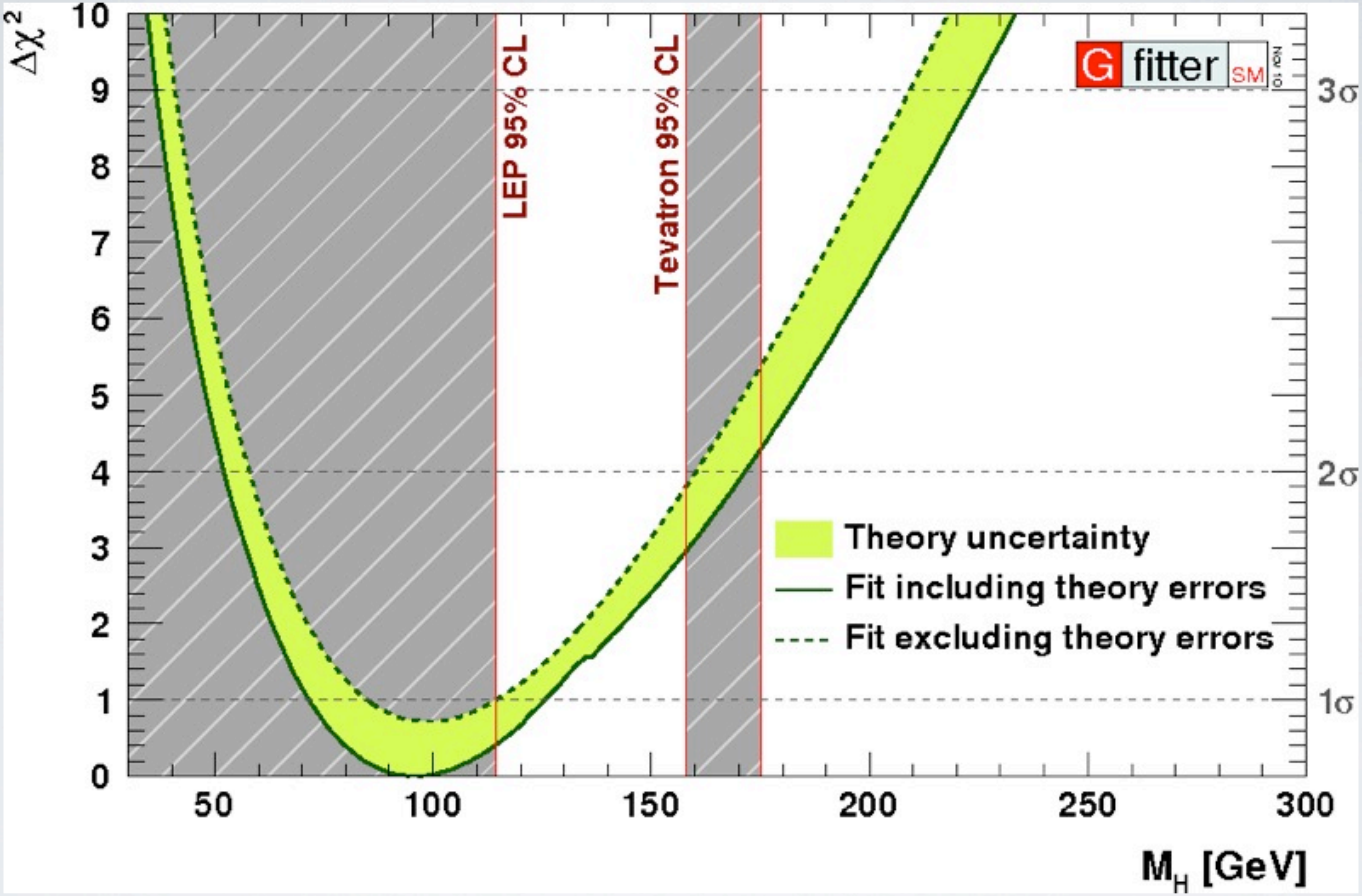


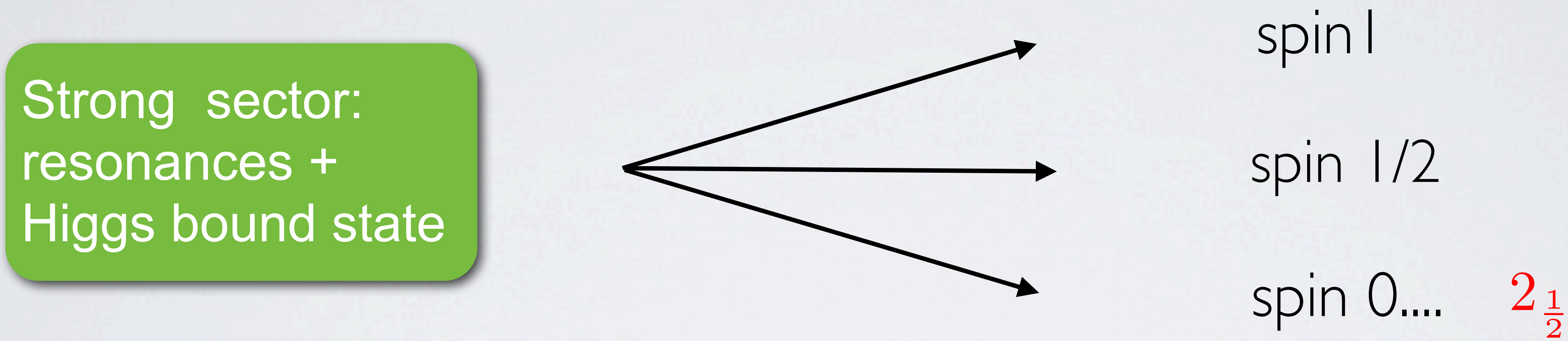
Higgs must be light:

SM ruled out @ 99.7 C.L. if M > 225 GeV (worse in SUSY)

COMPOSITE HIGGS

Georgi, Kaplan '80s

Higgs doublet could be a light remnant of strong dynamics.



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m_ρ $\qquad$ g_ρ $\qquad$ $(1 < g_\rho < 4\pi)$

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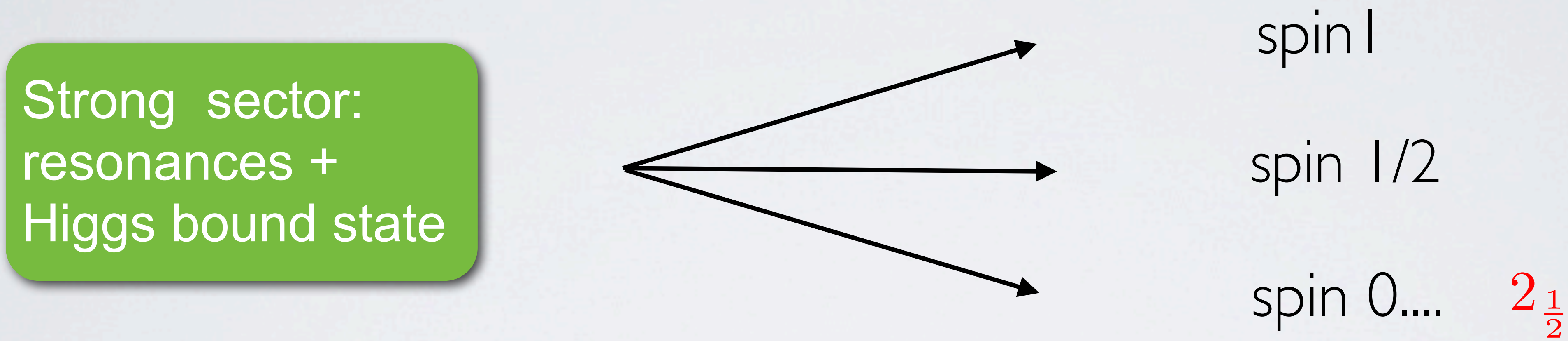

Two parameters:

m_ρ $\qquad$ g_ρ $\qquad$ $(1 < g_\rho < 4\pi)$

- Relieves hierarchy problem

$$\delta m_h^2 \sim \frac{3\,\lambda_t^2}{4\pi^2} m_\rho^2$$

Particularly natural if Higgs is a Goldstone Boson:
Massless at leading order.

Ex: $$\frac{SO(5)}{SU(2)_L \otimes SU(2)_R} \longrightarrow GB = (2,2)$$

Agashe , Contino, Pomarol, '04

Or: $$\frac{SO(6)}{SO(5)} \qquad \frac{SO(6)}{SO(4)\otimes U(1)} \qquad + \ldots$$

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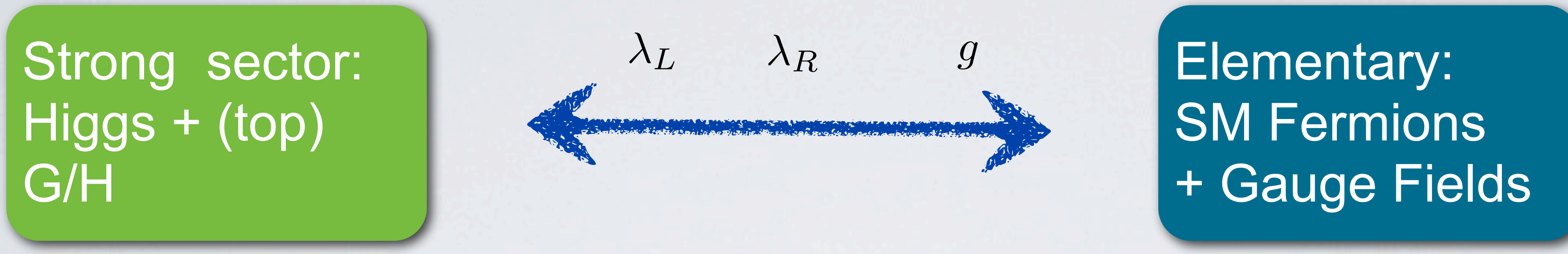
Low energy lagrangian

$$\mathcal{L} = f^2\, D_\mu \Sigma^i D^\mu \Sigma^i + \dots \xrightarrow{SU(2)_L \otimes SU(2)_R} \rho \approx 1$$

$$m_\rho = g_\rho f$$

Goldstone symmetry is broken explicitly by SM couplings



Giudice et al., '07

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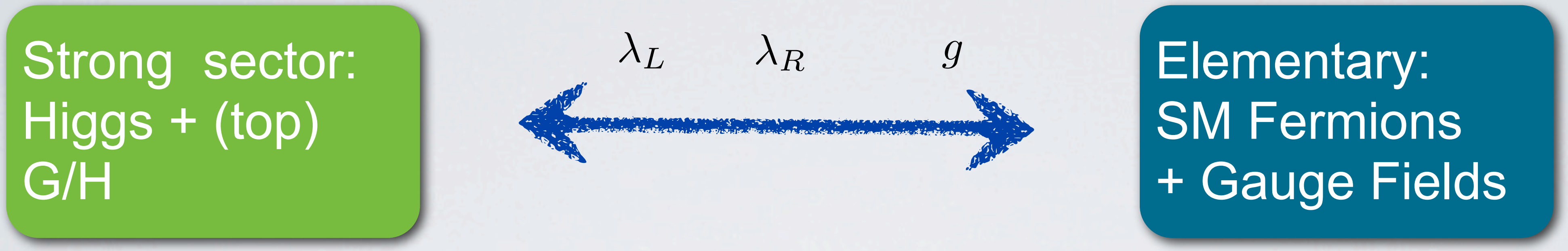


Giudice et al., '07

Two sectors talk through gauging of $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$\mathcal{L}_{gauge} = g\, A_\mu J^\mu$$

And through mixing to fermionic states

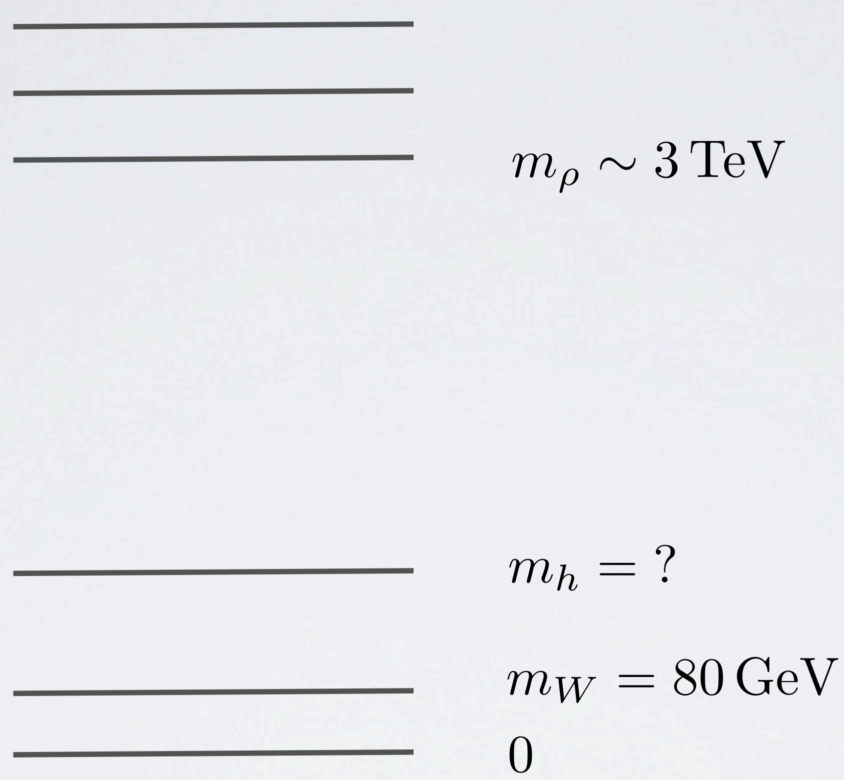
$$\mathcal{L}_{mixing} = \lambda_L \bar{f}_L O_R + \lambda_L \bar{f}_R O_L \longrightarrow y_f \sim \frac{\lambda_L\, \lambda_R}{g_\rho}$$

Potential also generated

$$V(H) \sim N_c \frac{m_\rho^4}{g_\rho^2} \frac{\lambda^2_{t_L, t_R}}{16\pi^2} \hat{V}\left(\frac{H}{f}\right)$$

Main difference from techni-color is that f is not linked to v.

Spectrum:



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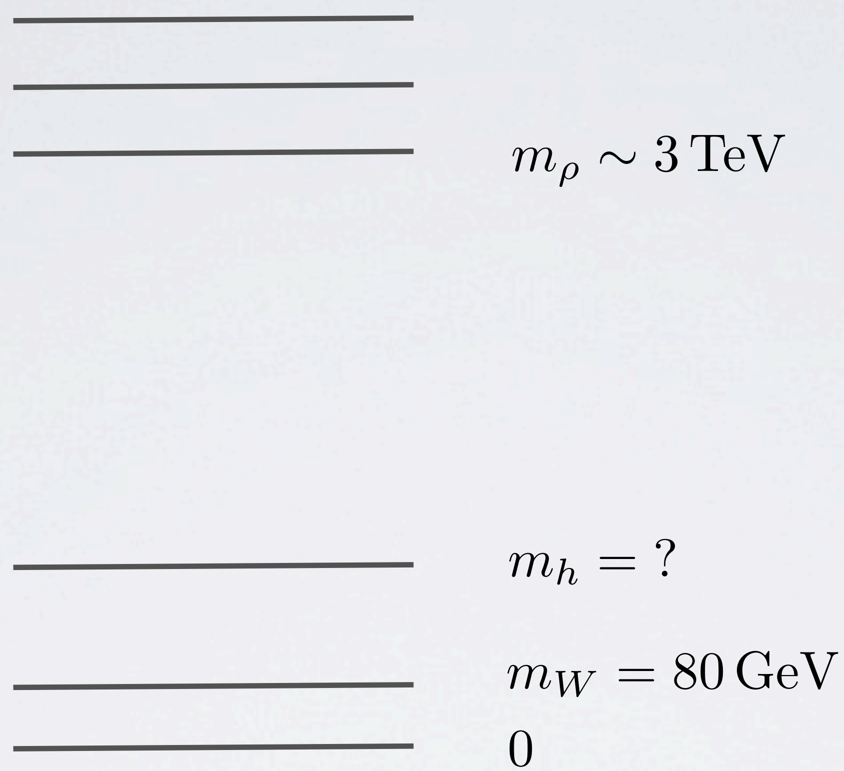
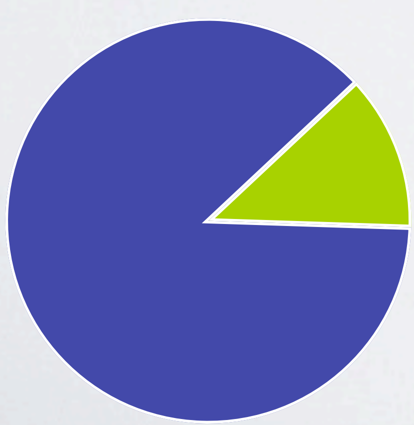


Higgs is angle,



$0 < h < 2\pi f$ → Tuning $\xi = \frac{v^2}{f^2}$

Scenario approaches SM for f >> v.
Precision measurements can be reproduced for $m_\rho > 2.5\mathrm{TeV}$
Flavor problems greatly reduced,

$$C_4^K\, \bar{d}_R^\alpha s_L^\alpha \bar{d}_L^\beta s_R^\beta \qquad\qquad C_4^K \sim \frac{g_\rho^2}{m_\rho^2}\frac{m_d\, m_s}{v^2}$$

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Acceptable pheno at the price of mild tuning,

$f = 500\,\mathrm{GeV}$ $\quad m_\rho = 3\,\mathrm{TeV}$ $\quad \longrightarrow \quad \xi = \dfrac{1}{8}$

($g_\rho \sim 6$ ~QCD)

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Overall models are far from perfect but general picture is compelling and worth taking seriously.

Composite Higgs can be distinguished from SM Higgs:

- Heavy resonances

Mostly coupled to third generation quarks

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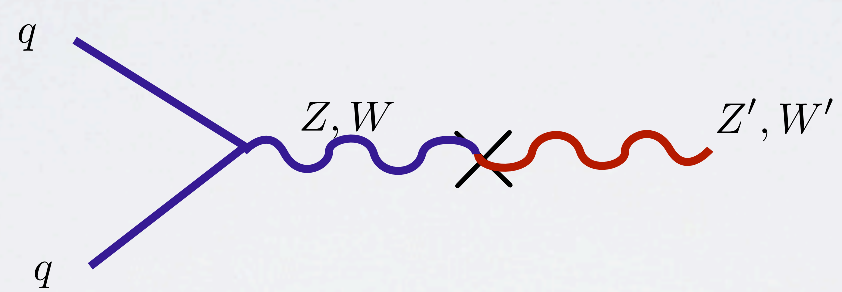
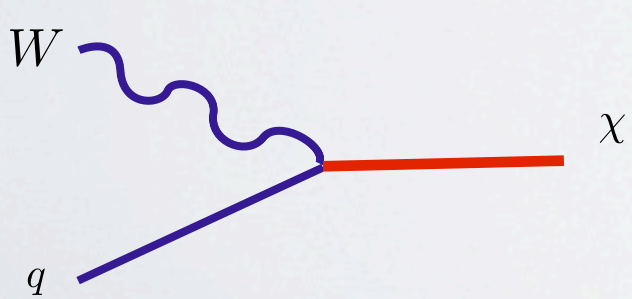
Spin-1: electro-weak and gluon resonances

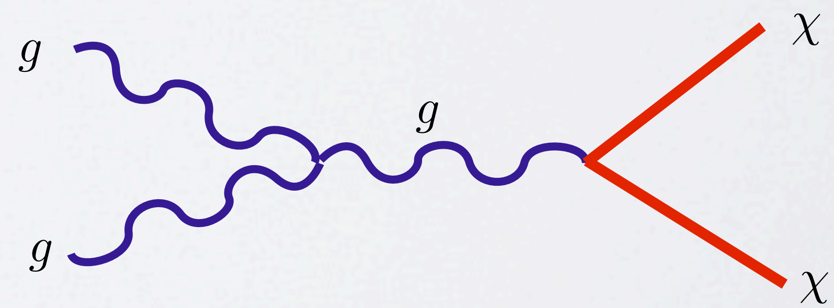
Ex:



Spin-1/2 : Top partners could be lighter + exotic charges

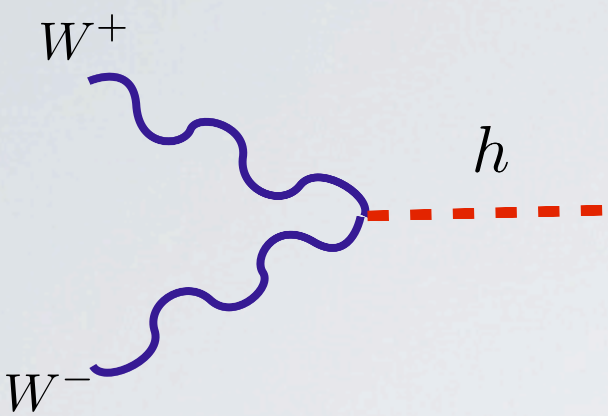


Single

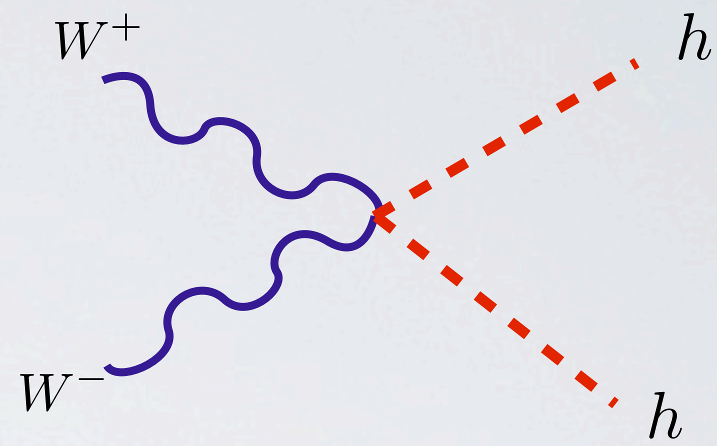


Double

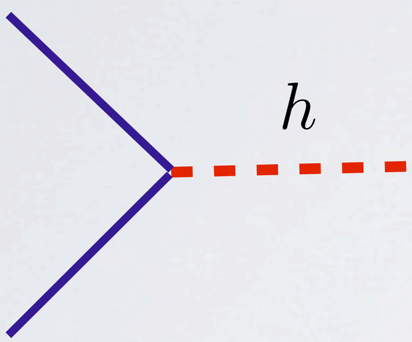
• Modified Couplings



$$= \sqrt{2} i \frac{m_W^2}{v} \, a$$



$$= 2i \frac{m_W^2}{v^2} \, c$$



$$= -\frac{m_f}{\sqrt{2} v} \, b$$

$$\mathrm{SM:} \quad \mathrm{a = b = c = 1}$$

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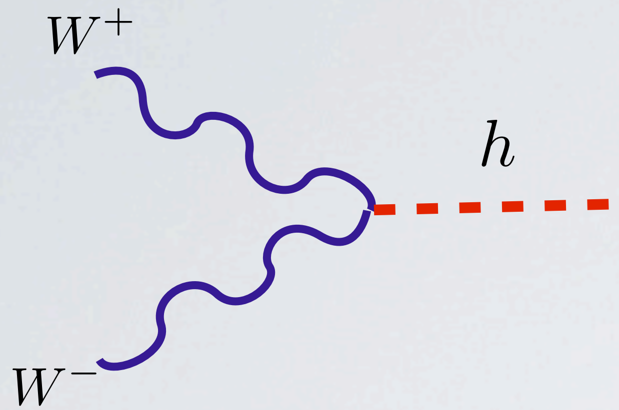

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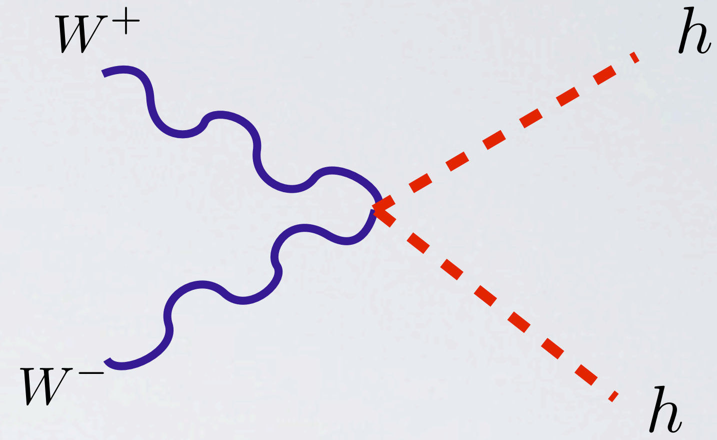

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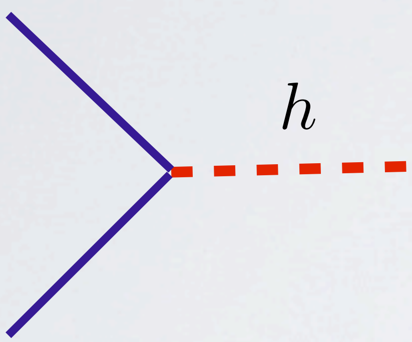

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$$\mathrm{SM:} \quad \mathrm{a = b = c = 1}$$

WW scattering does not unitarize completely.
Unfortunately very hard to see at LHC unless v/f~1.

Contino et al. '10

Deviations from a, b, c=1. Wait ILC...

Higgs quartic increases with strength of the strong dynamics. For example for $\lambda_{t_L} \sim \lambda_{t_R}$

$$\lambda \sim N_c \frac{g_\rho^3 \lambda_t}{16\pi^2} \longrightarrow m_h^2 \sim N_c \, \frac{g_\rho^3 \, \lambda_t}{16\pi^2} v^2$$

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Higgs can be heavy for a strong coupling similar to QCD.

$$100\,\mathrm{GeV} < \mathrm{m_h} < 400\,\mathrm{GeV}$$

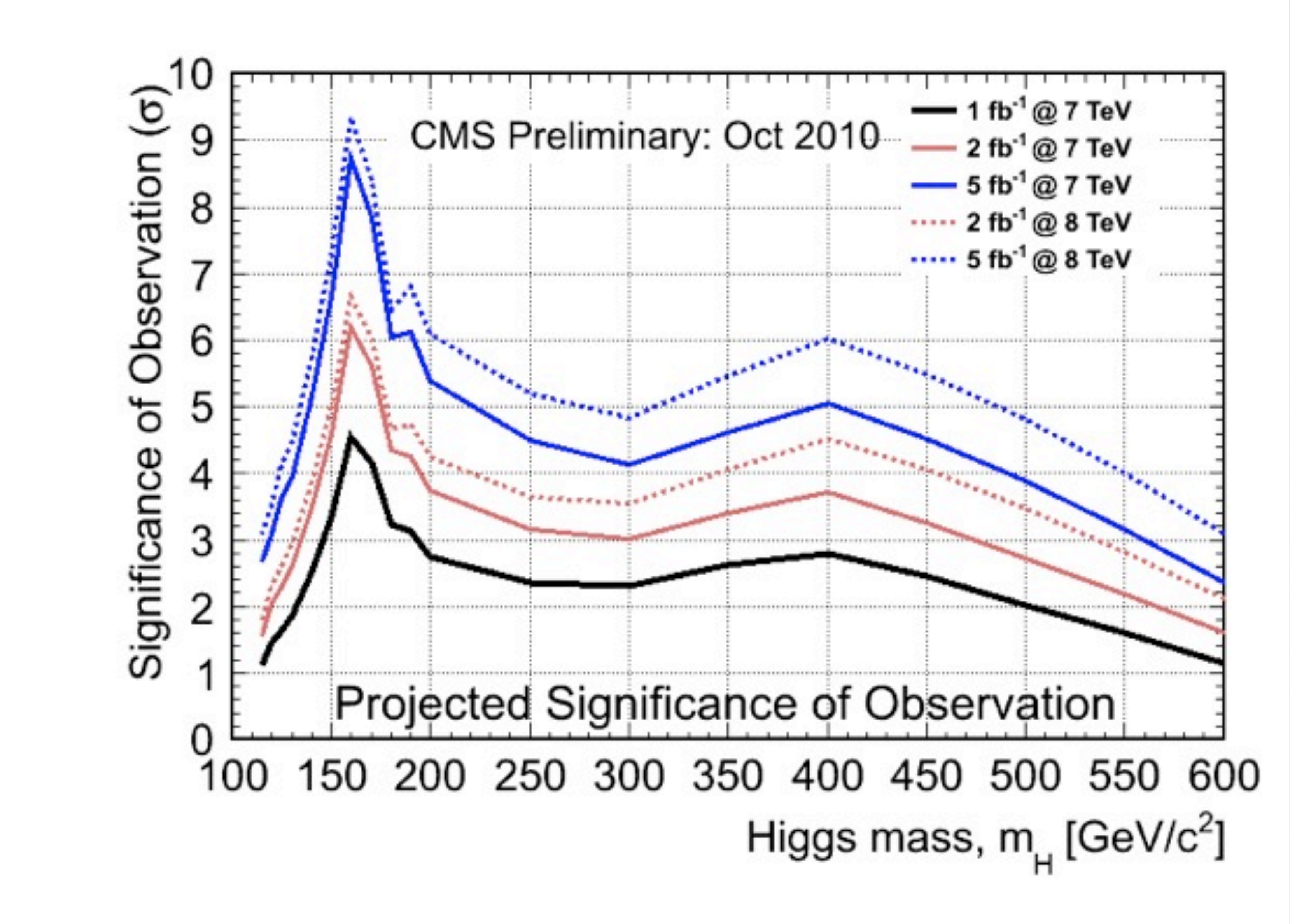
A large coupling is also hinted to minimize the tuning,

$$\xi \sim \frac{v^2}{f^2} \sim g_\rho^2 \frac{v^2}{m_\rho^2}$$

Barbieri et al., '07

Precision measurements could be ok with the contributions from extra-states (positive T).

COULD WE GET LUCKY?



A heavy Higgs would rule out SM and hint to compositeness!

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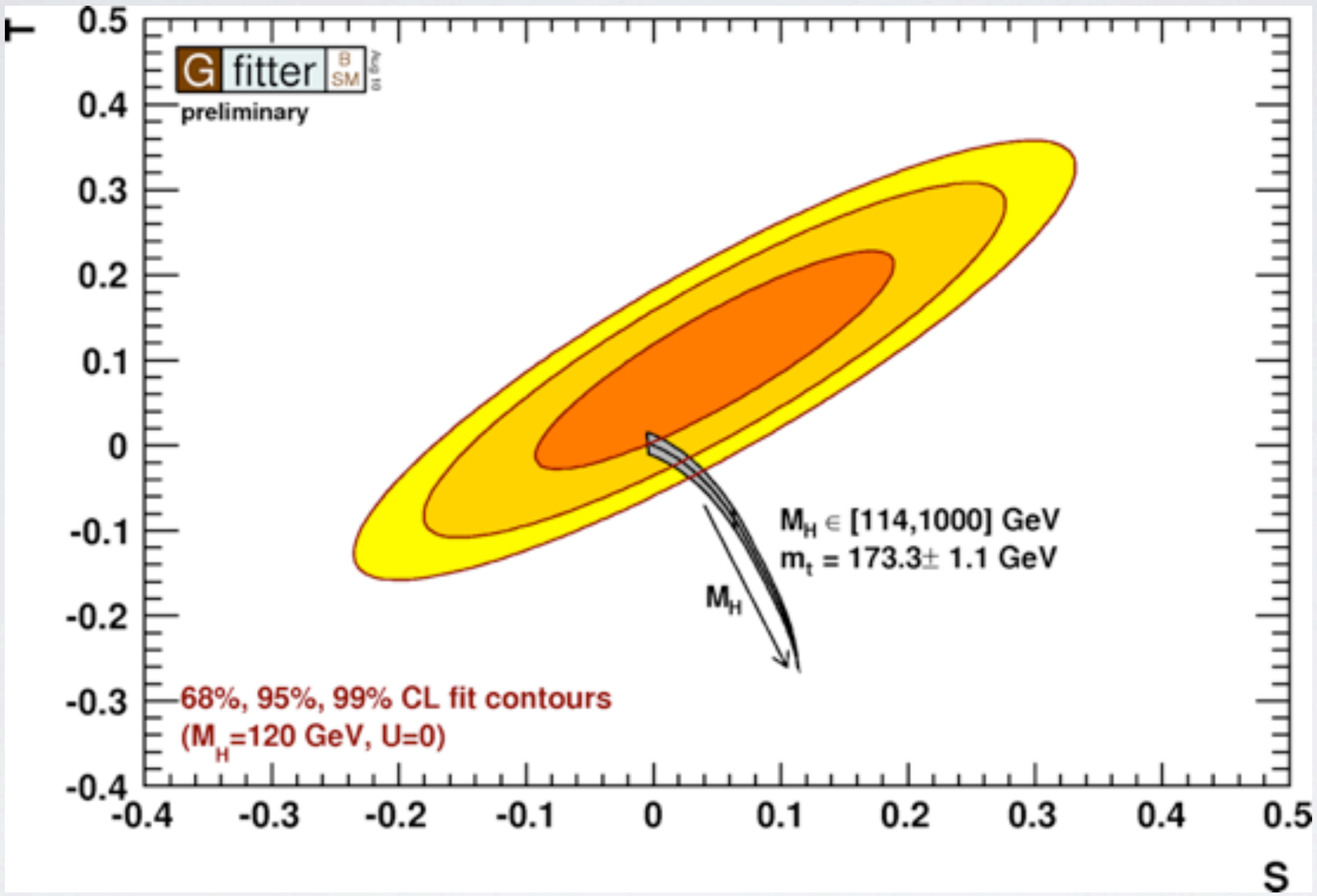
- 2011-12 will be VERY exciting!

Technicolor issues:

- *Precision Measurements*



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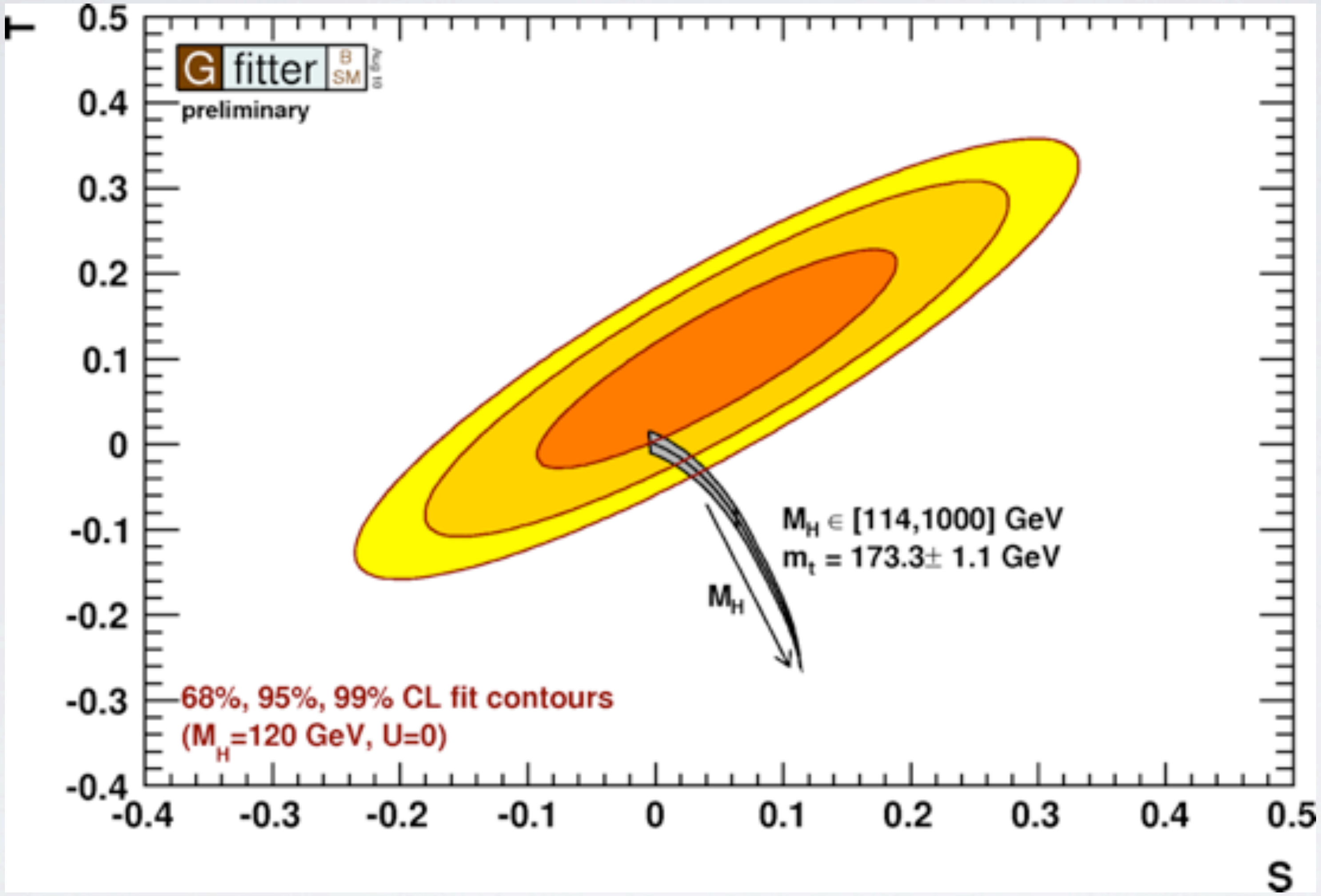

- Flavor Bounds

Unacceptable Flavor Changing Neutral Currents generated unless miracles happen.