Alternatives to Electroweak Symmetry Breaking

Alex Pomarol (Univ. Autonoma Barcelona)

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Outline:

- Electroweak symmetry breaking (EWSB): Generalities
- The Higgs mechanism
- Composite Higgs: Pseudo-Goldstone particle (Holographic Higgs)
- EWSB at the LHC

I. EWSB: Generalities

Lets start having a look at the EW sector without any "theoretical prejudice"

Experimental data tell us that particle physics is very well described by a gauge theory:

Gauge SU(3)xSU(2)xU(1)

3 families of

$$\left\{\begin{array}{rl} Q_L: & (3,2,1/3) \\ u_R: & (3,1,4/3) \\ d_R: & (3,1,-2/3) \\ l_L: & (1,2,-1) \\ e_R: & (1,1,-2) \end{array}\right.$$

+ symmetry-breaking terms:

$$m_q\,\bar{q}_L q_R + m_e\,\bar{e}_L e_R + m_W^2 |W_\mu^+|^2 + \frac{1}{2} m_Z^2 Z_\mu^2$$

All information on EWSB:

$$\underbrace{m_q\,\bar{q}_L q_R + m_e\,\bar{e}_L e_R} + m_W^2 |W_\mu^+|^2 + \frac{1}{2} m_Z^2 Z_\mu^2$$

Plenty of information: But, up to now, not very illuminating: Flavor Puzzle
(only the heaviness of the top gives us suggestions on EWSB)

All information on EWSB:

$$m_q\,\bar{q}_L q_R + m_e\,\bar{e}_L e_R + \underbrace{m_W^2|W_\mu^+|^2 + \frac{1}{2}m_Z^2 Z_\mu^2}$$

Focus on this part:

$$m_W^2|W_\mu^+|^2 + \frac{1}{2}m_Z^2(W_\mu^3 c_{\theta_W} - B_\mu s_{\theta_W})^2$$

Absorbing the couplings into the kinetic terms

$$\frac{m_W^2}{g^2}|W_\mu^+|^2 + \frac{1}{2}\frac{m_Z^2 c_{\theta_W}^2}{g^2}(W_\mu^3 - B_\mu)^2$$

Breaks SU(2)xU(1) but preserves a U(1): Q=(T_3+Y)/2

Intriguing experimental relation:

$$\frac{m_W^2}{m_Z^2 c_{\theta_W}^2} \equiv \rho \simeq 1.0$$

Possible origin: A remnant global SU(2) under which (W_1,W_2,W_3) form a triplet = Custodial symmetry

Force equal masses for the $W_{1,2,3}$

But symmetry not respected by gauge boson B

Nor for fermions

Lets, from empirical facts, assume this symmetry

Mass terms: $$\frac{m_W^2}{g^2}\mathrm{Tr}\left[W_\mu - \frac{\sigma_3}{2}B_\mu\right]^2$$ $$W_\mu \equiv \frac{\sigma^a}{2}W_\mu^a$$

Redefinition: $$W_\mu \to \Sigma^\dagger W_\mu \Sigma - i\Sigma^\dagger \partial_\mu \Sigma$$

$$\Sigma = e^{i\sigma_a G_a}$$

2x2 unitary matrix of Det=1

(d.o.f.: 3 real scalars $G_{1,2,3}$)

$$\longrightarrow \quad \frac{m_W^2}{g^2}\mathrm{Tr}\left|\partial_\mu\Sigma + iW_\mu\Sigma - i\Sigma\frac{\sigma_3}{2}B_\mu\right|^2 = \frac{m_W^2}{g^2}\mathrm{Tr}\left|D_\mu\Sigma\right|^2$$

Invariant if: $$\Sigma \to U_L \Sigma U_Y^\dagger$$ $$U_Y = e^{i\sigma_3\theta_Y}$$

Assets:

- EW symmetry realized, ... but not in the vacuum:

$$\langle \Sigma \rangle = 1 \rightarrow U_L U_Y^\dagger$$ broken generators: $T_{1,2}$ and T_3-Y

- No mass term allowed for Σ: $\mathrm{Tr}\Sigma\Sigma^\dagger \sim 1$

  G= Goldstones of the symmetry associated to each broken generator

- "Accidental" larger global symmetry:

$$\Sigma \rightarrow U_L \Sigma U_R^\dagger \qquad U_R \in SU(2)_R$$

broken by the vacuum to a global SU(2) ($U_L = U_R$)

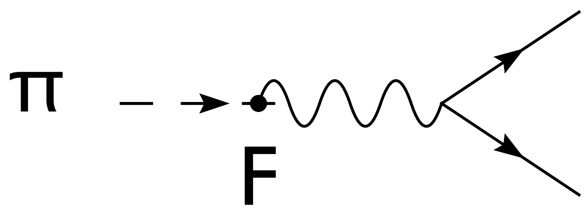
and the gauging of Hypercharge (B-field)

Definition of the decay-constant F of the Goldstones

$$\frac{m_W^2}{g^2} \equiv \frac{1}{4} F^2 \longrightarrow \mathcal{L}_G = \frac{F^2}{4} \mathrm{Tr} |D_\mu \Sigma|^2$$

F ~ 246 GeV

In QCD leads to the pion decay:



Similarly for fermions:

$$m_u \bar{u}_L u_R + m_d \bar{d}_L d_R = \frac{m_u + m_d}{2} \bar{Q}_L Q_R + \frac{m_u - m_d}{2} \bar{Q}_L \sigma_3 Q_R$$

where $Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$ under hypercharge:

$$Q_L \to e^{i\theta_Y/3} Q_L$$

$$Q_R \to e^{i(1/3+\sigma_3)\theta_Y} Q_R$$

introducing Σ
by field redefinitions

$$\frac{m_u + m_d}{2} \bar{Q}_L \Sigma Q_R + \frac{m_u - m_d}{2} \bar{Q}_L \Sigma \sigma_3 Q_R$$

Breaks the custodial symmetry

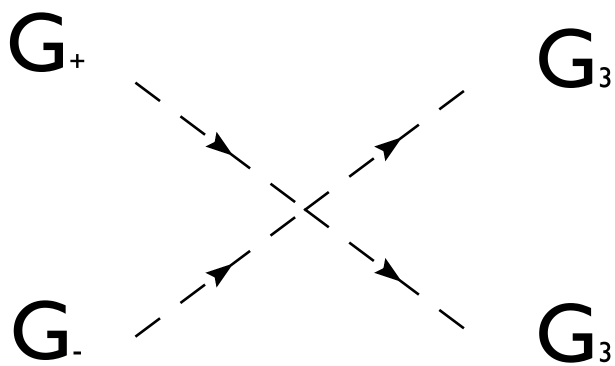
So far, so good...

Nevertheless, unitarity problems:

Lets expand in terms of the Goldstones:

$$\frac{F^2}{4}\mathrm{Tr}|\partial_\mu \Sigma|^2 = F^2\left[\frac{1}{2}(\partial_\mu G_a)^2 + \frac{1}{12}(G_a \overleftrightarrow{\partial_\mu} G_a)^2 + \cdots\right]$$

Self-Interactions



$$= \frac{s}{F^2}$$

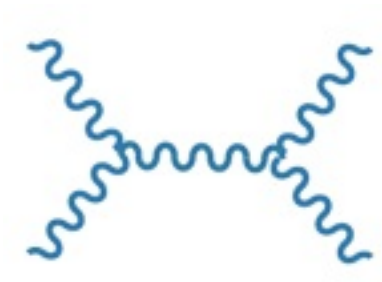
Grows with the energy an violates unitarity at high-energies: $E \gtrsim 1\ TeV$

➔ Theory valid up to energies Λ ~ 1 TeV

Λ= cutoff of the theory

Not a problem associated by introducing Σ

In the unitary gauge Σ=1:

WW→ZZ :  +  $\sim \frac{g^2 s}{4m_W^2}$

at large energies

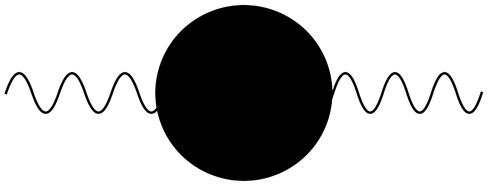
What about quantum corrections (loops)?

The theory can be quantized and loops can be calculated (similar to the chiral lagrangian in QCD)

If infinities appear in loop diagrams, counterterms must be added

If we look for physics at energies $E<\Lambda$, the number of counterterms are finite $\rightarrow$ PREDICTIONS!

Most important effects of quantum corrections are those to the propagator of the gauge boson: Vacuum polarization



$$\equiv \Pi_{ij}(q^2)$$

Highly constrained by LEP!

Assuming new physics scale $\Lambda \gg M_W$, we can expand in q/Λ:

$$\mathbf{\Pi_a(q) = \Pi_a(0) + q^2\Pi'_a(0) + \frac{q^4}{2}\Pi''_a(0) + \ldots}$$

SM gauge boson self-energies

$$\Pi_{W+} = \Pi_{W+}(0) + q^2\Pi'_{W+}(0) + \frac{q^4}{2}\Pi''_{W+}(0) + \cdots$$

$$\Pi_{W_3} = \Pi_{W_3}(0) + q^2\Pi'_{W_3}(0) + \frac{q^4}{2}\Pi''_{W_3}(0) + \cdots$$

$$\Pi_{B} = \Pi_{B}(0) + q^2\Pi'_{B}(0) + \frac{q^4}{2}\Pi''_{B}(0) + \cdots$$

$$\Pi_{W_3B} = \Pi_{W_3B}(0) + q^2\Pi'_{W_3B}(0) + \frac{q^4}{2}\Pi''_{W_3B}(0) + \cdots$$

Up to order q^4: **4×3=12** parameters

Masslessness of the photon **-2**

Absorbed by g, g', v^2 **-3**

. ———————————

Independent parameters **7**

Form factors			custodial	$SU(2)_L$
$\hat{T}$	$=$	$\frac{g^2}{M_W^2}\left[\Pi_{W_3}(0)-\Pi_{W^+}(0)\right]$	$-$	$-$
$\hat{U}$	$=$	$g^2\left[\Pi'_{W_3}(0)-\Pi'_{W^+}(0)\right]$	$-$	$-$
V	$=$	$\frac{g^2 M_W^2}{2}\left[\Pi''_{W_3}(0)-\Pi''_{W^+}(0)\right]$	$-$	$-$
$\hat{S}$	$=$	$g^2\,\Pi'_{W_3B}(0)$	$+$	$-$
X	$=$	$\frac{g' g M_W^2}{2}\,\Pi''_{W_3B}(0)$	$+$	$-$
W	$=$	$\frac{g^2 M_W^2}{2}\,\Pi''_{W_3}(0)$	$+$	$+$
Y	$=$	$\frac{g'^2 M_W^2}{2}\,\Pi''_{B}(0)$	$+$	$+$

Keep the leading one in the q^2 expansion: $\hat{S}, \hat{T}, W, Y$

Barbieri, A.P., Rattazzi, Strumia

All these effects nicely parametrized in terms of 4 quantities:

Peskin, Takeushi

Barbieri, AP, Rattazzi, Strumia

$$\boxed{\begin{aligned} \hat{T} &= \frac{g^2}{M_W^2}\left[\Pi_{W_3}(0) - \Pi_{W^+}(0)\right] \\ \hat{S} &= g^2\,\Pi'_{W_3B}(0) \end{aligned}}$$

$$W = \frac{g^2 M_W^2}{2}\,\Pi''_{W_3}(0)$$

$$Y = \frac{g'^2 M_W^2}{2}\,\Pi''_B(0)$$

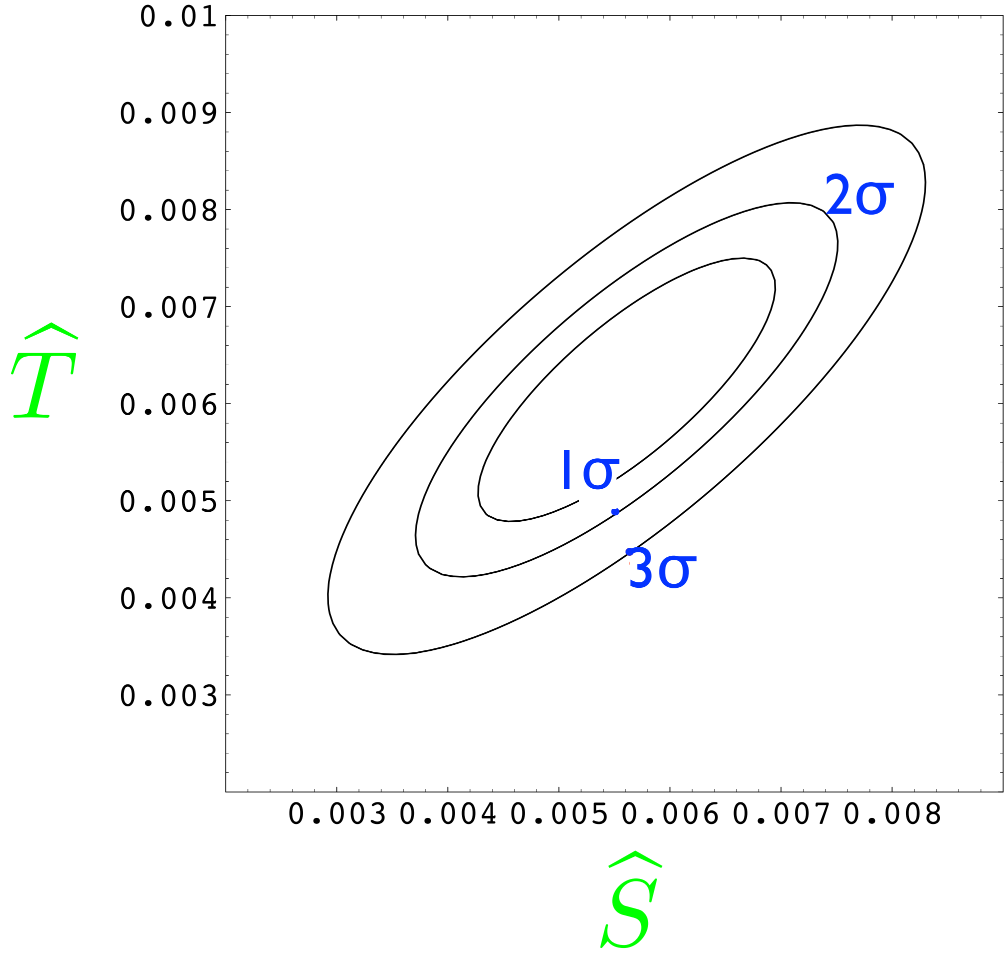
Most important in EWSB physics

$\hat{T}$=0 for custodial invariant theories

From LEP and Tevatron:

$$\hat{S} = g^2 \, \Pi'_{W_3 B}(0)$$

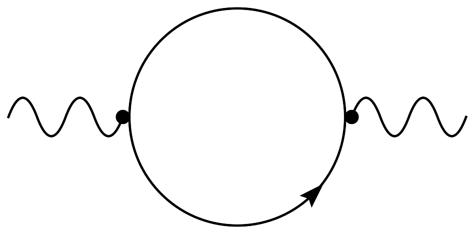
$$\hat{T} = \frac{g^2}{M_W^2} \left[\Pi_{W_3}(0) - \Pi_{W^+}(0) \right]$$



Effects on $\hat{T}$:

- No contribution from loops of Goldstone bosons

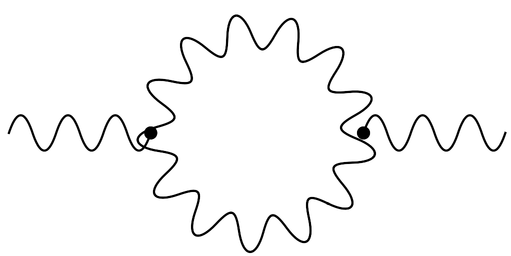
- Largest contribution from the top



$$\hat{T} \simeq \frac{3m_t^2}{16\pi^2 F^2} \simeq 0.008$$

Finite!

- Logarithmic divergent contribution from B-loops

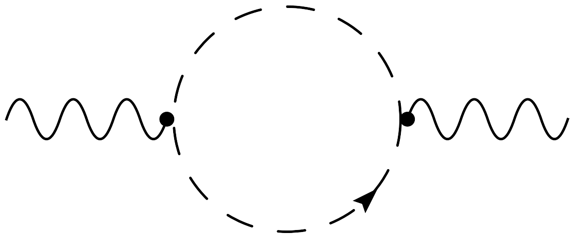


$$\hat{T} \simeq \frac{-3g'^2}{64\pi^2} \ln\left(\frac{\Lambda^2}{m_W^2}\right)$$

Counterterm exists: $c_t F^2\, \mathrm{Tr}^2[\sigma_3 \Sigma D_\mu \Sigma^\dagger]$

Effects on $\hat{S}$:

- Contribution from Goldstone-loops logarithmically divergent

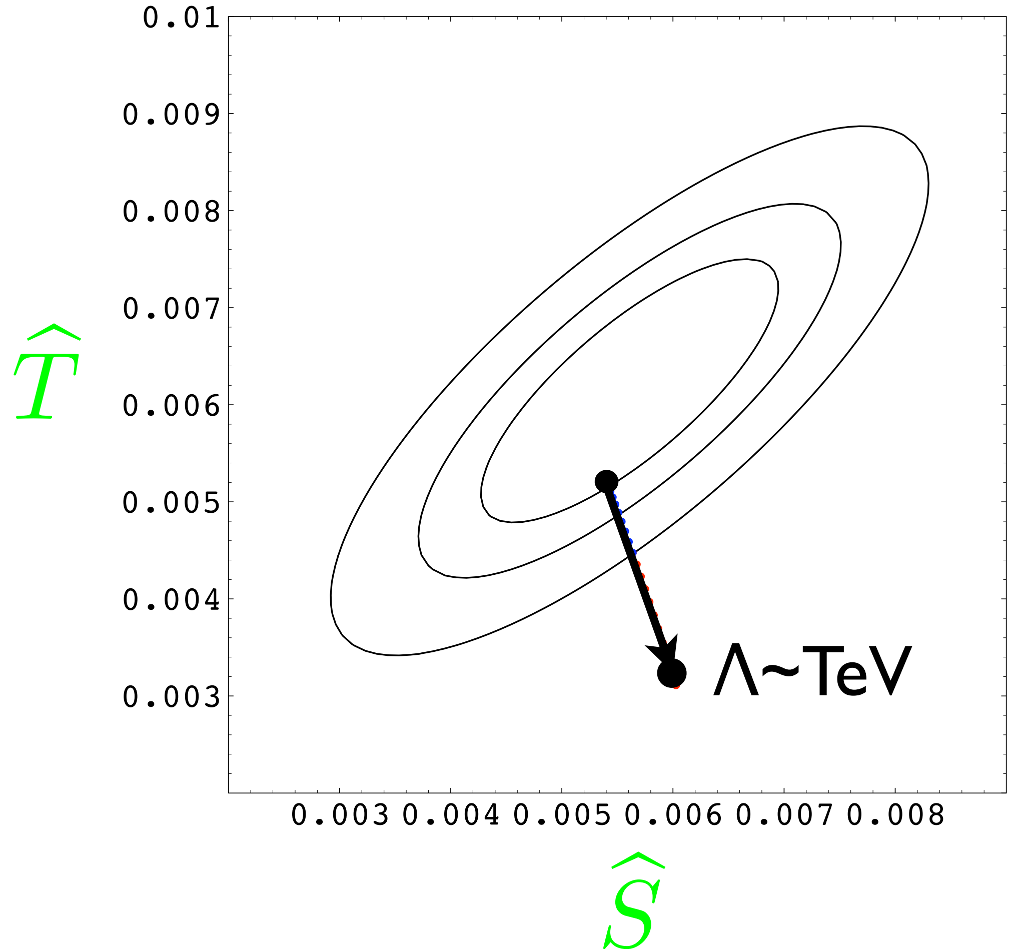


$$\hat{S} \simeq \frac{g^2}{192\pi^2} \ln\left(\frac{\Lambda^2}{m_W^2}\right)$$

Counterterm:

$$c_s \mathrm{Tr}[W_{\mu\nu}\Sigma\frac{\sigma_3}{2}B_{\mu\nu}\Sigma^\dagger]$$

Assuming $c_s = c_t = 0$, we obtain:



EWPT prefers small Λ !

Possible UV-completions of the EW sector

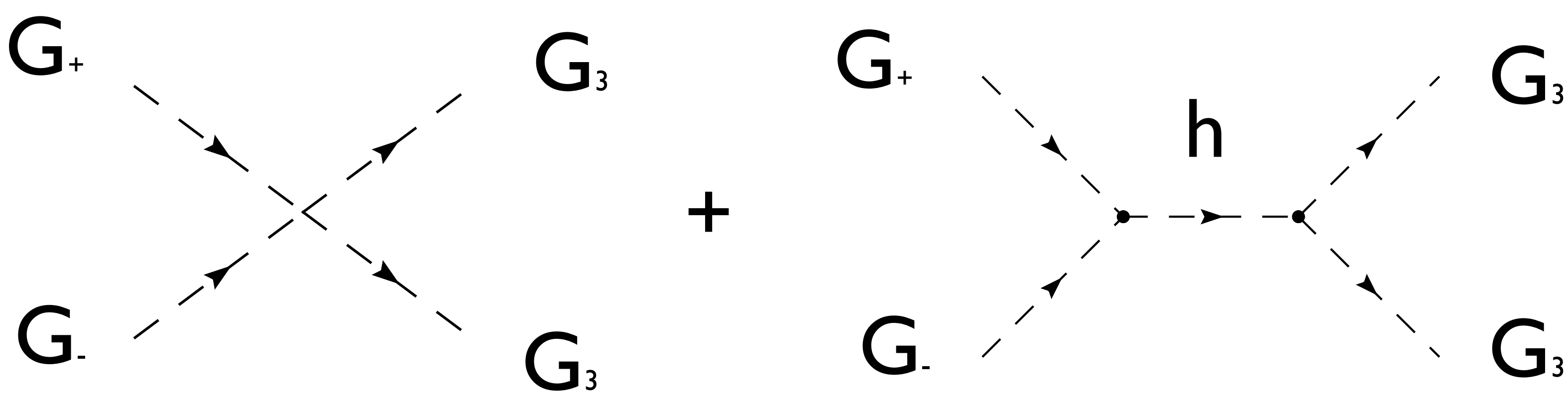
How to recover unitarity?

EWSB sector must contain new states

I. Higgs mechanism

Brute force approach → Find the minimal number of states needed to have well-behaved amplitudes (at high-energies)

Adding a scalar: h with a coupling $hF(\partial_\mu G_a)^2$



$$\frac{s}{F^2} \qquad - \frac{s^2}{s-m_h^2}\frac{1}{F^2} \xrightarrow{\text{large s}} -\frac{m_h^2}{F^2}$$

Do not grow with the energy!

One finds that a single scalar can "repair" all amplitudes

Easy to introduce:

$$\mathcal{L}(\Sigma, \ldots) \to \mathcal{L}(\underbrace{\Sigma(1 + h/F)}_{\frac{\Sigma\,\phi}{F} \equiv \frac{M}{F}}, \ldots)$$

$$\phi = F + h$$

$$\langle\phi\rangle = v = F$$

Why unitarity is restored?

$$M = \phi e^{i\vec{\sigma}\cdot\vec{G}} = \phi(\cos G + i\vec{\sigma}\cdot\frac{\vec{G}}{G}\sin G) \quad \xrightarrow[\text{field redefinition}]{} \quad \phi + i\vec{\sigma}\cdot\vec{G}$$

We have now:

$$\frac{1}{4}\mathrm{Tr}|\partial_\mu M|^2 = \frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2}(\partial_\mu G_a)^2$$

It is just only the kinetic term of four scalar! No self-interactions!

This is usually refer as the linear-model

It was easy, but...

now a mass term is allowed for ϕ:

$$m^2\,\mathrm{Tr}[MM^\dagger] = 2m^2\phi^2 + \cdots$$

and we must have this mass of the order of W-mass

this operator is not protected by any symmetry: Difficult to keep it smaller than other big scales in physics (GUT-scale, Planck-scale,..)

➡ HIERARCHY PROBLEM

requires more stuff at the TeV (SUSY?)

Last redefinition: $M = \sqrt{2}(i\sigma_2 H^*, H)$

where H is a Higgs doublet multiplet (Y=1):

$$H = \frac{1}{\sqrt{2}} \left(\begin{array}{c} G_1 - iG_2 \\ \phi - iG_3 \end{array} \right)$$

Transformation rules: $H \rightarrow U_L H$

$$\rightarrow U_Y H$$

One can proof:

a) $\frac{1}{4}\mathrm{Tr}|D_\mu M|^2 = |D_\mu H|^2$

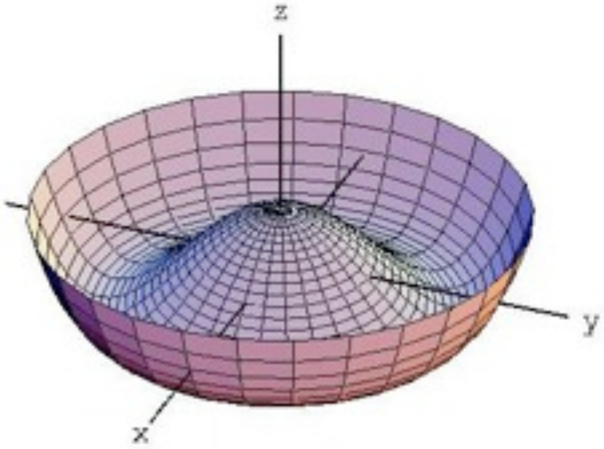
b) $V(M) = \frac{m^2}{4}\mathrm{Tr} M M^\dagger + \frac{\lambda}{16}\mathrm{Tr}^2 M M^\dagger$

equals to $V(H) = m^2|H|^2 + \lambda|H|^4$

Same dimension-4 lagrangian terms as the Higgs of the SM

Custodial symmetry an accidental symmetry of the Higgs potential and interactions with W. Prediction of the Higgs-doublet: ρ=1 (at tree-level)

Higgs VEV can be written as a function of the Higgs potential parameters



$$V(H) = m^2|H|^2 + \lambda|H|^4$$

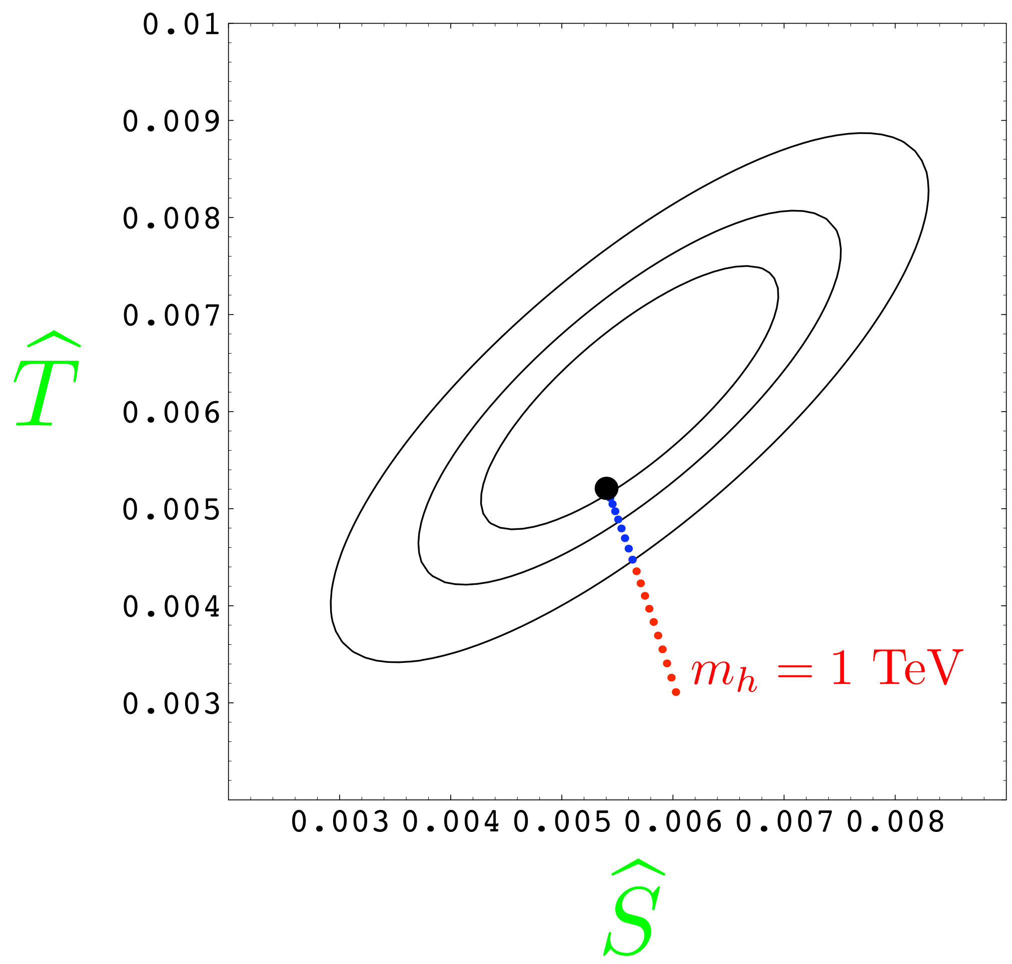
$$v^2 = \frac{-m^2}{\lambda}$$

$$m_h^2 = 2\lambda v^2$$ Physical Higgs mass unknown

Radiative corrections:

Finite contributions to S and T:

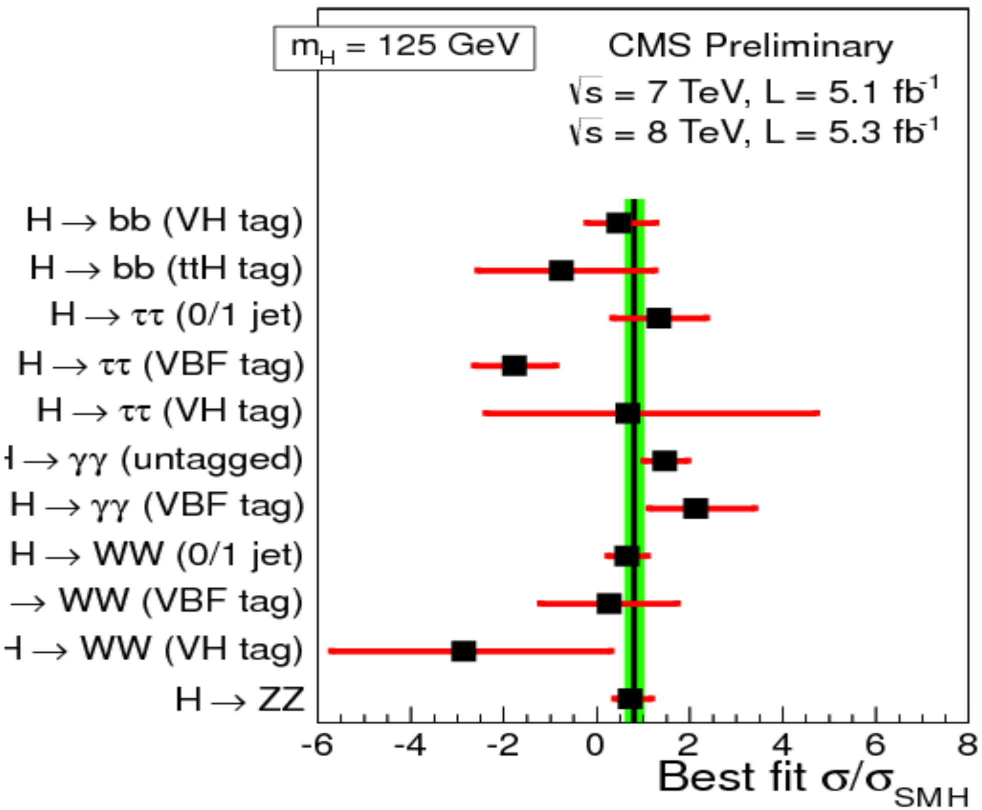
Λ-scale → Higgs mass

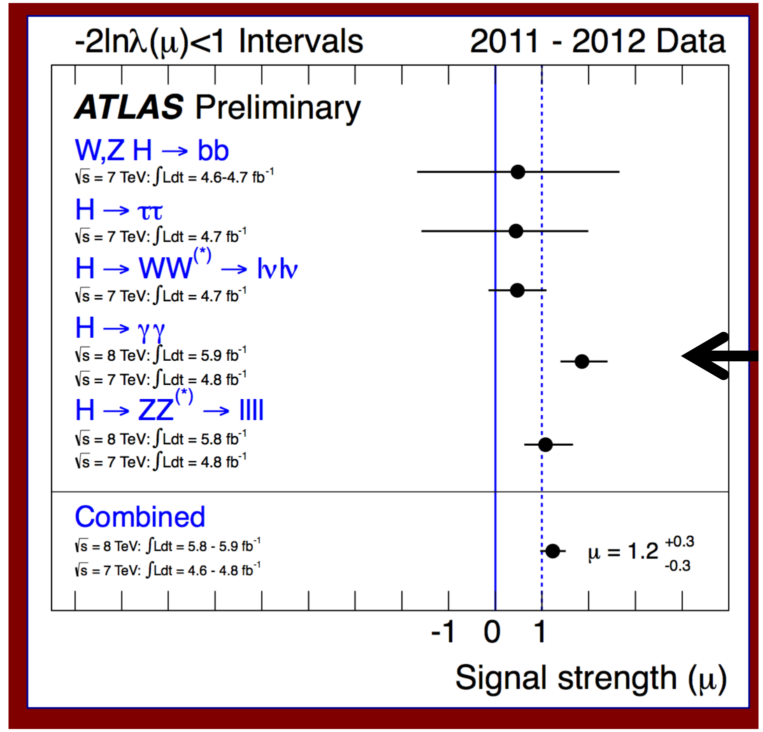


EWPT prefers light Higgs!

After the 4th of July 2012

LHC detected a Higgs-like state:





$$m_H = 126.5\ \mathrm{GeV}$$

Compatible with the SM Higgs predictions!