BSM physics in light of LHC8

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CERN Winter School on Supergravity, Strings, and Gauge Theory, 4-8 February 2013

Status of BSM

- TH point of view
- EXP point of view

Higgs ~~BSM~~ physics in light of LHC8

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Spontaneously broken symmetry

Scalar theory $$L = \frac{1}{2}\partial_\mu \phi \, \partial^\mu \phi - V(\phi)$$

Invariant under global symmetry: $\dfrac{\partial V}{\partial \phi}\delta_a \phi = 0 \quad \delta_a \phi = T_a \phi$

Vacuum state: $$\left.\frac{\partial V}{\partial \phi}\right|_{\phi=\langle\phi\rangle} = 0$$

Symmetry spontaneously broken, if vacuum non-invariant: $\langle \delta_a \phi \rangle \neq 0$

$$\left.\frac{\partial^2 V}{\partial \phi^2}\delta_a \phi + \frac{\partial V}{\partial \phi}\partial(\delta_a \phi)\right|_{\phi=\langle\phi\rangle} = 0 \quad \Rightarrow \quad M^2 \langle \delta_a \phi \rangle = 0$$

One massless state for each broken generator.

Realizing symmetries

Vacuum invariant under G
- Physical states in mass-deg multiplets
- Fields transform linearly

Vacuum invariant under $H \subset G \quad (G \to H)$
- Set of equivalent vacua related by symmetry transformation (G/H)
- Physical states in multiplets of H (not of G)
- Massless Goldstones (for each generator of G/H)
- Fields transform non-linearly

In both cases conserved currents (at least classically)

The case of local symmetries: the Standard Model

$G = SU(2)_L \times U(1)_Y \quad H = U(1)_Q \quad Q = T_3 + Y$

Construct the field $\Sigma(x) = \exp[i\sigma_a \chi_a(x)/v]$

v: scale of EW breaking ($v = 246$ GeV)

Local symmetry transformation: $\Sigma \to U_L \, \Sigma \, U_Y^+$

$U_L(x) = \exp[i\lambda_a(x)\,\sigma_a/2] \quad U_Y(x) = \exp[i\lambda_Y(x)\,\sigma_3/2]$

At the origin, $\langle\Sigma\rangle = 1$

Vacuum is left invariant under a transformation with

$\lambda_3 = \lambda_Y, \quad \lambda_1 = \lambda_2 = 0 \quad \Rightarrow \quad G \to H$

$\Sigma^+\Sigma = 1 \quad \Rightarrow$ we cannot write any non-derivative interactions

invariant under $G \quad \Rightarrow \chi_a$ are massless

$\Rightarrow$ they are the Goldstones of G/H

How do χ_a transform under the symmetry?

$$\Sigma \to U_L \Sigma U_Y^+$$

$$\Sigma(x) = \exp(i\sigma_a \chi_a / v)$$

$$U_L(x) = \exp(i\lambda_a \sigma_a / 2) \quad U_Y(x) = \exp(i\lambda_Y \sigma_3 / 2)$$

Expanding in powers of fields:

$$\delta_b \chi_a = (v\delta_{ab} - \varepsilon_{abc}\chi_c)\frac{\lambda_b}{2} + O(\chi^2)$$

$$\delta_Y \chi_a = (-v\delta_{a3} - \varepsilon_{a3c}\chi_c)\frac{\lambda_Y}{2} + O(\chi^2)$$

- Shift of Goldstone symmetry
- Non-linearities
- Transform linearly under $Q = T_3 + Y$, with one neutral and one charged state
- Σ gives the most-general non-linear representation of G

Constructing the Lagrangian

Since $\Sigma^{+}\Sigma = 1,$ the Lagrangian is obtained by expanding in derivatives (low-energy effective theory)

Covariant derivative:

$$\mathrm{D}_{\mu}\Sigma = \partial_{\mu}\Sigma - ig\frac{\sigma_a}{2}W_{\mu}^{a}\Sigma + ig'\Sigma\frac{\sigma_3}{2}B_{\mu}$$

At the two-derivative level

$$L = \frac{v^2}{4}\mathrm{Tr}\left[\left(D_{\mu}\Sigma\right)^{+}\left(D^{\mu}\Sigma\right)\right] + c_T\frac{v^2}{4}\left[\mathrm{Tr}\left(\Sigma^{+}D^{\mu}\Sigma\sigma_3\right)\right]^2$$

$$L = \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu \Sigma\right)^+ \left(D^\mu \Sigma\right)\right] + c_T \frac{v^2}{4}\left[\mathrm{Tr}\left(\Sigma^+ D^\mu \Sigma \sigma_3\right)\right]^2$$

On the vacuum $\langle \Sigma \rangle = 1$

$$L = M_W^2 W_\mu^+ W^{-\mu} + \frac{M_Z^2}{2} Z_\mu Z^\mu$$

$$M_W^2 = g^2 \frac{v^2}{4} \quad M_Z^2 = \left(g^2 + g'^2\right)\left(1 + 2c_T\right)\frac{v^2}{4}$$

- In unitary gauge, $\chi_a(x) = 0 \quad \Rightarrow \quad$ Higgs mechanism
- $\Delta\rho = \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} - 1 \approx -2c_T \quad < 2\times 10^{-3}$ experimentally

$$L = \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu \Sigma\right)^+ \left(D^\mu \Sigma\right)\right] + c_T \frac{v^2}{4}\left[\mathrm{Tr}\left(\Sigma^+ D^\mu \Sigma \sigma_3\right)\right]^2$$

Why is c_T so small ($\approx 10^{-3} \approx$ loop factor)?

Different symmetry properties

$$\mathrm{Tr}\left[\left(D_\mu \Sigma\right)^+ \left(D^\mu \Sigma\right)\right] \to \sum_{a=1}^{3} \partial_\mu \chi_a \partial^\mu \chi_a$$

$$\left[\mathrm{Tr}\left(\Sigma^+ D^\mu \Sigma \sigma_3\right)\right]^2 \quad \to \partial_\mu \chi_3 \partial^\mu \chi_3$$

Neglecting gauging $\mathrm{Tr}\left[\left(\partial_\mu \Sigma\right)^+ \left(\partial^\mu \Sigma\right)\right]$ has a larger global symmetry

The global symmetry of $\mathrm{Tr}\left[\left(\partial_\mu \Sigma\right)^+ \left(\partial^\mu \Sigma\right)\right]$:

$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R : \quad \Sigma \to U_L \, \Sigma \, U_R^+$ with $U_{L,R} \in SU(2)_{L,R}$

The global symmetry is broken into the diagonal part

$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \to \mathrm{SU}(2)_V$ (just like chiral symmetry in QCD)

$\mathrm{SU}(2)_V$ is a global symmetry of the SSB sector preserved by the vacuum $\langle \Sigma \rangle = 1 \quad \Rightarrow$ custodial symmetry

The approximate global $\mathrm{SU}(2)_V$ insures $\rho = \dfrac{M_W^2}{M_Z^2 \cos^2 \theta_W} \approx 1$

ϱ =1 follows from:

1) Global SU(2) under which the generators of $SU(2)_L$ transform as a triplet
2) Charge conservation

$$M^2_{V^0} \rightarrow \begin{pmatrix} W_{3\mu} & B_\mu \end{pmatrix} \begin{pmatrix} M_W^2 & x \\ x & y \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}$$

- Massless photon $\Rightarrow$ $\det(M^2_{V^0}) = 0 \Rightarrow x = \sqrt{M_W^2\, y}$
- Z mass $\Rightarrow$ $\mathrm{Tr}\,(M^2_{V^0}) = M_Z^2 \Rightarrow y = M_Z^2 - M_W^2$
- Mixing angle $\Rightarrow$ $\cos^2\theta_W = \dfrac{M_W^2}{M_Z^2} \Rightarrow \rho = 1$

Powerful constraint on ~~EW~~ sector:

a global custodial symmetry must be
preserved by the vacuum
(but possibly broken in the interactions
between ~~EW~~ and SM sectors)

Coupling the ~~EW~~ sector to the SM

$$L = -\frac{1}{4}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + i\bar{f}\gamma^{\mu}D_{\mu}f$$

$$+\frac{v^2}{4}\mathrm{Tr}\left(D_{\mu}\Sigma\right)^{+}D^{\mu}\Sigma - \frac{v}{\sqrt{2}}\bar{f}_L\Sigma\lambda_f f_R + \mathrm{h.c.}$$

$$\Sigma = \exp\left(\frac{i\sigma_a\chi_a}{v}\right)$$

$$L = -\frac{1}{4}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + i\bar{f}\gamma^{\mu}D_{\mu}f$$
$$+\frac{v^2}{4}\mathrm{Tr}\left(D_{\mu}\Sigma\right)^{+}D^{\mu}\Sigma - \frac{v}{\sqrt{2}}\bar{f}_L\Sigma\lambda_f f_R + \mathrm{h.c.}$$

Gauge principle:

- Robustness
- Predictivity
- Elegance

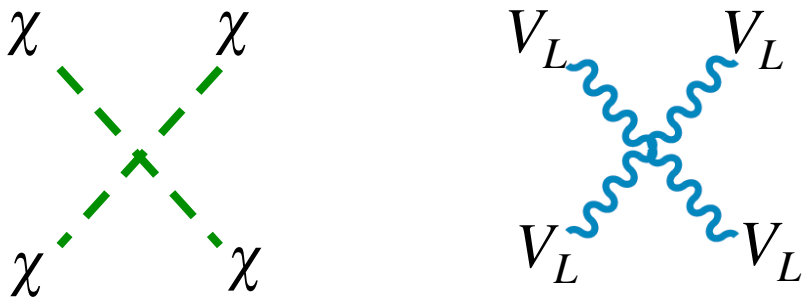
Richness of gauge symmetry is the secret for the complexity of the real world emerging out of the simplicity of the fundamental principles

$$L = -\frac{1}{4}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + i\bar{f}\gamma^{\mu}D_{\mu}f$$

$$+\frac{v^2}{4}\mathrm{Tr}\left(D_{\mu}\Sigma\right)^{+}D^{\mu}\Sigma - \frac{v}{\sqrt{2}}\bar{f}_L\Sigma\lambda_f f_R + \mathrm{h.c.}$$

Equivalence Theorem: $\chi_a \rightarrow V_{aL}^{\mu} + O(M_V^2/E^2)$

$$A(\chi\chi \rightarrow \chi\chi) = A(V_L V_L \rightarrow V_L V_L) + O\left(\frac{M_V^2}{E^2}\right)$$



$$L = -\frac{1}{4}\,\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} + i\,\bar{f}\,\gamma^{\mu}D_{\mu}f$$

$$+\frac{v^2}{4}\,\mathrm{Tr}\left(D_{\mu}\Sigma\right)^{+}D^{\mu}\Sigma - \frac{v}{\sqrt{2}}\,\bar{f}_L\,\Sigma\,\lambda_f\,f_R + \mathrm{h.c.}$$

- Until 2012, *L* could account for all known phenomena
- Gauge symmetry is exact (but non-linearly realized)
- Custodial symmetry broken by g' and $\lambda_u - \lambda_d$
- *L* shows the phenomenon of SSB was established well before the Higgs discovery (propagating particles do not share the full symmetry of interactions)

$$L = -\frac{1}{4}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + i\bar{f}\gamma^{\mu}D_{\mu}f$$

$$+\frac{v^2}{4}\mathrm{Tr}\left(D_{\mu}\Sigma\right)^{+}D^{\mu}\Sigma - \frac{v}{\sqrt{2}}\bar{f}_L\Sigma\lambda_f f_R + \mathrm{h.c.}$$

Why isn't this the end of the story?

$$L = -\frac{1}{4}\,\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} + i\,\bar{f}\,\gamma^{\mu}D_{\mu}f$$

$$+\frac{v^2}{4}\,\mathrm{Tr}\left(D_{\mu}\Sigma\right)^{+}D^{\mu}\Sigma - \frac{v}{\sqrt{2}}\,\bar{f}_L\,\Sigma\,\lambda_f\,f_R + \mathrm{h.c.}$$

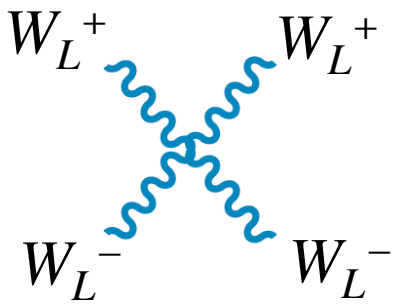
Effective theory:

perturbative expansion valid for $E < 4\pi\,v \approx 3$ TeV

$$\left(\text{Range of validity for Equivalence Theorem: } M_W < E < \frac{8\pi}{g}M_W\right)$$

Expand the leading-derivative term in powers of fields:

$$\frac{v^2}{4}\mathrm{Tr}\left(\partial_\mu \Sigma\right)^+ \partial^\mu \Sigma = \frac{1}{2}\left(\partial_\mu \chi_a\right)^2 + \frac{1}{6v^2}\left[\left(\chi_a \partial_\mu \chi_a\right)^2 - \left(\chi_a \partial_\mu \chi_b\right)^2\right] + O\left(\chi^6\right)$$



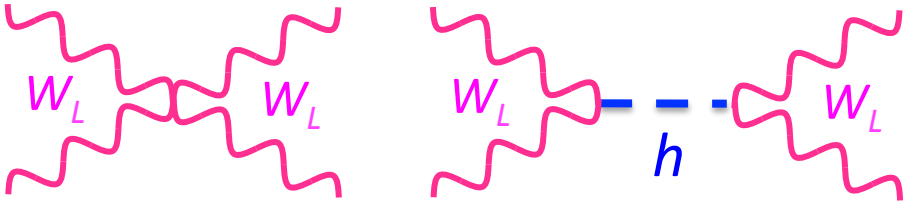
$$A\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{s+t}{v^2}$$

- Violation of perturbative unitarity at high energy
- New phenomena (new d.o.f or new forces) below $4\pi\, v$

What could the new physics be?

Example: take a gauge singlet h

$$L = \left(1 + \frac{2ah}{v} + \frac{bh^2}{v^2} + \ldots\right) \frac{v^2}{4} \mathrm{Tr}\left(\partial_\mu \Sigma\right)^+ \partial^\mu \Sigma$$

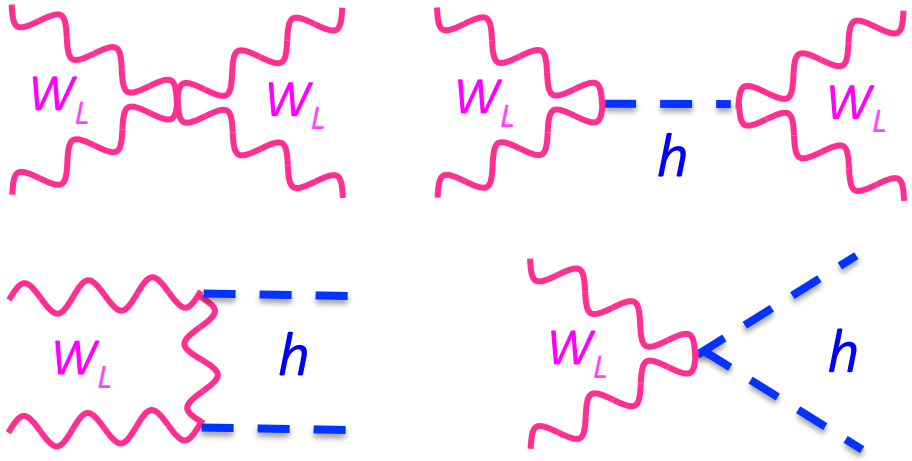


$$A\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) \approx \frac{s}{v^2}\left(1 - \frac{a^2 s}{s - m_h^2}\right) + \left(s \leftrightarrow t\right)$$

Power growth is cured for $a = 1$

Example: take a gauge singlet h

$$L = \left(1 + \frac{2ah}{v} + \frac{bh^2}{v^2} + \ldots\right) \frac{v^2}{4} \mathrm{Tr}\left(\partial_\mu \Sigma\right)^+ \partial^\mu \Sigma$$



$a = 1$

$$A\left(W_L^+ W_L^- \to h\,h\right) \approx \frac{s}{v^2}\left(a^2 - b\right)$$

Power growth is cured for $b = a^2$

The simplest UV completion

Combine h and Goldstones into a $SU(2)_L$ doublet

$$H = \frac{1}{\sqrt{2}} \exp\left(\frac{i\sigma_a \chi_a}{v}\right) \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$\partial_\mu H^+ \partial^\mu H = \frac{1}{2} \partial_\mu h \, \partial^\mu h + \left(1 + \frac{2h}{v} + \frac{h^2}{v^2} + \ldots\right) \frac{v^2}{4} \mathrm{Tr}\left(\partial_\mu \Sigma\right)^+ \partial^\mu \Sigma + \ldots$$

$a = b = 1$ It restores perturbative unitarity

The simplest UV completion

Combine h and Goldstones into a $SU(2)_L$ doublet

$$H = \frac{1}{\sqrt{2}} \exp\left(\frac{i\sigma_a \chi_a}{v}\right) \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$L = \partial_\mu H^+ \partial^\mu H - V\left(H^+ H\right) \qquad V = \lambda\left(H^+ H - v^2\right)^2$$

Global SO(4) spontaneously broken to SO(3)

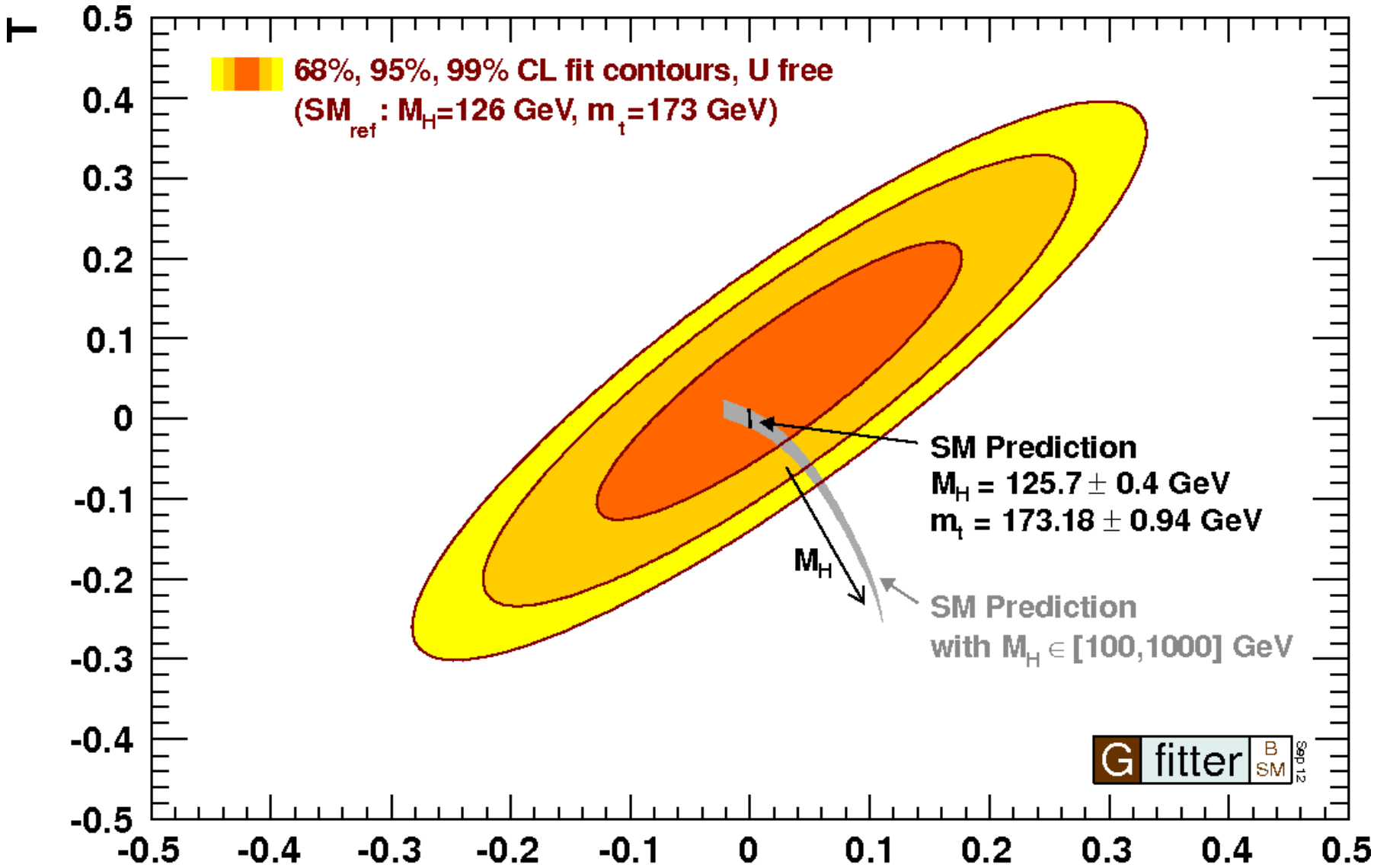
$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

$$H^+ H = \frac{1}{2}\left(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right) \qquad \mathrm{SO}(4) \sim \mathrm{SU}(2) \times \mathrm{SU}(2)$$

$$\left\langle H^+ H \right\rangle = v^2 \quad \mathrm{SO}(4) \to \mathrm{SO}(3) \quad \Rightarrow$$ custodial symmetry!

Loop corrections to $\Delta\rho$ from top quark

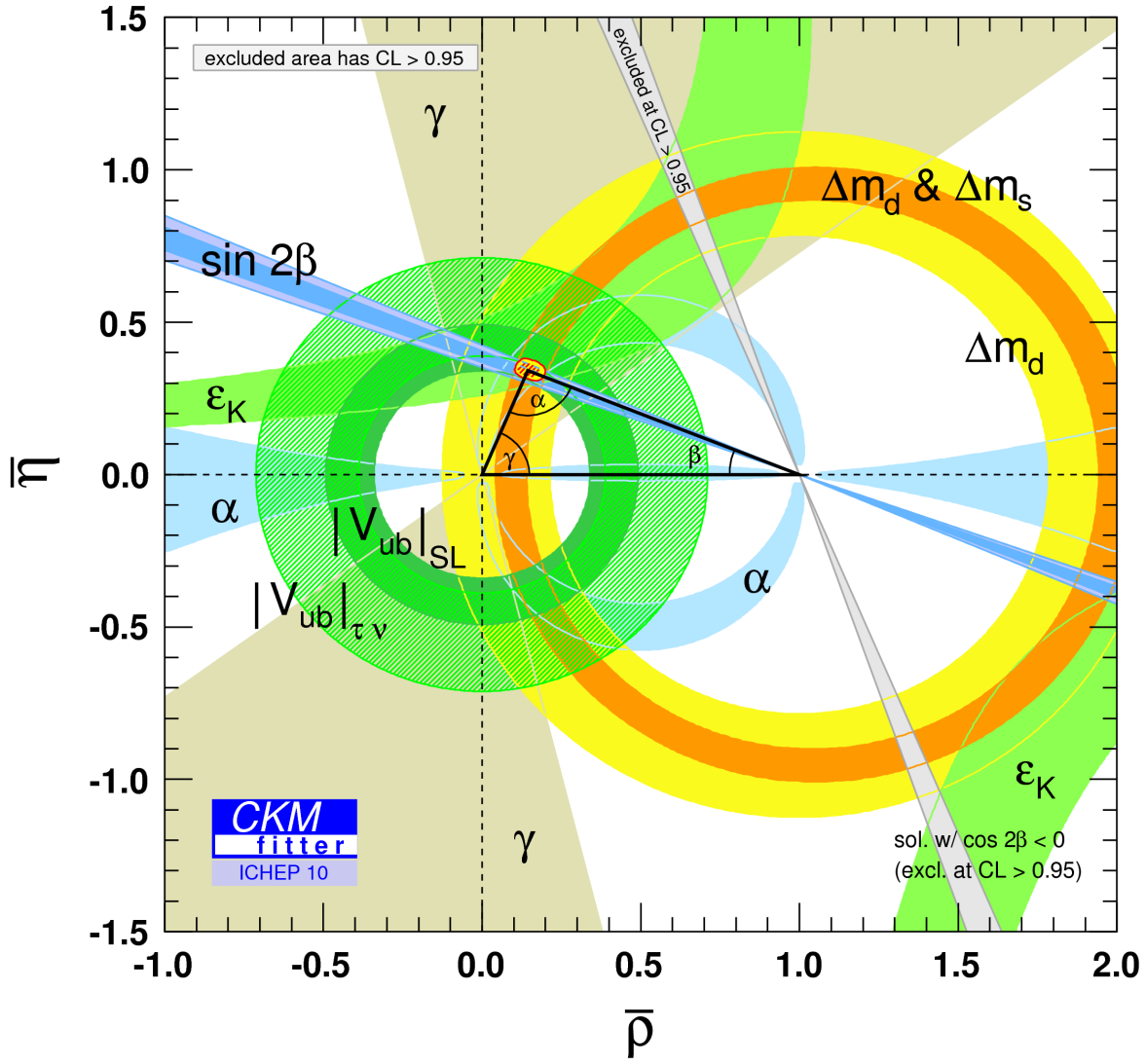
$$\Delta\rho = \frac{3G_F}{8\sqrt{2}\pi^2}\left(m_t^2 - m_b^2\right) \approx 10^{-2}$$



$$T \approx \frac{\Delta\rho}{\alpha(M_Z)}$$

Higgs successfully accounts for the flavor structure

$$L = -H^{+}\,\bar{q}_L\,\lambda_u u_R - H\,\bar{q}_L\,\lambda_d d_R - H\,\bar{\ell}_L\,\lambda_e e_R + \text{h.c.}$$



- A priori no unique solution to ~~EW~~
- Experimental data shows that the solution must be the Higgs or something very similar

$$L = -\frac{1}{4}\,\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} + i\,\bar{f}\,\gamma^{\mu}D_{\mu}f$$

$$+ D_{\mu}\,H^{+}D^{\mu}\,H - \lambda\left(H^{+}H - \frac{v^{2}}{2}\right)^{2}$$

$$-H^{+}\,\bar{q}_{L}\,\lambda_{u}\,u_{R} - H\,\bar{q}_{L}\,\lambda_{d}\,d_{R} - H\,\bar{\ell}_{L}\,\lambda_{e}\,e_{R} + \mathrm{h.c.}$$

This is by far the simplest solution; and yet, it leaves too many unresolved questions