The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA
International Atomic Energy Agency

2400-13

Workshop on Strongly Coupled Physics Beyond the Standard Model

25 - 27 January 2012

A minimally symmetric Higgs boson

Ian Low
Northwestern U./ANL

A minimally symmetric Higgs boson

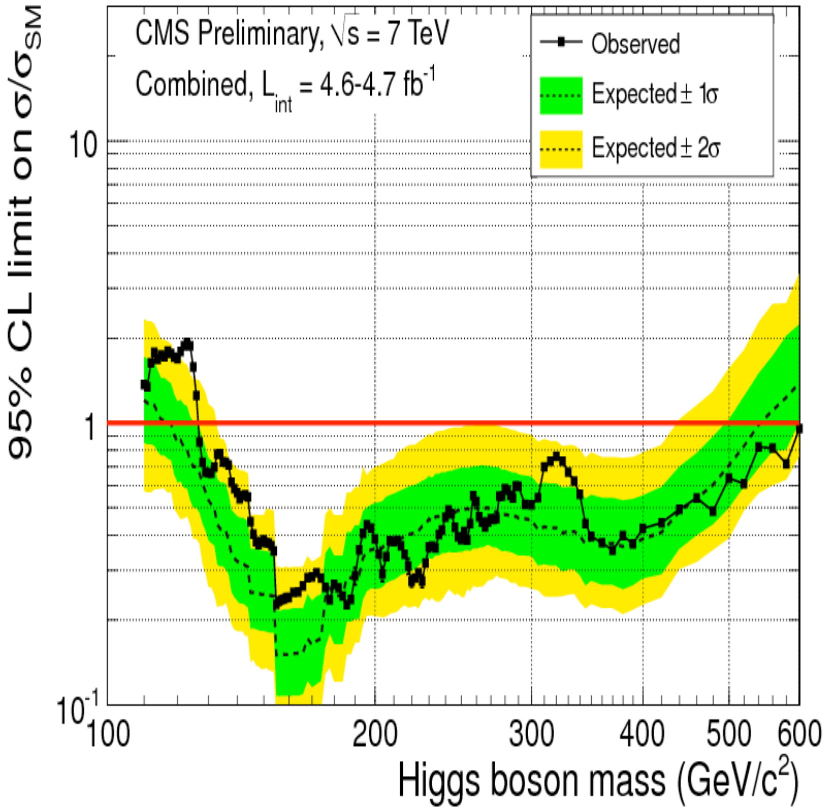
Ian Low @
ICTP Workshop on Strongly Coupled Physics Beyond the Standard Model

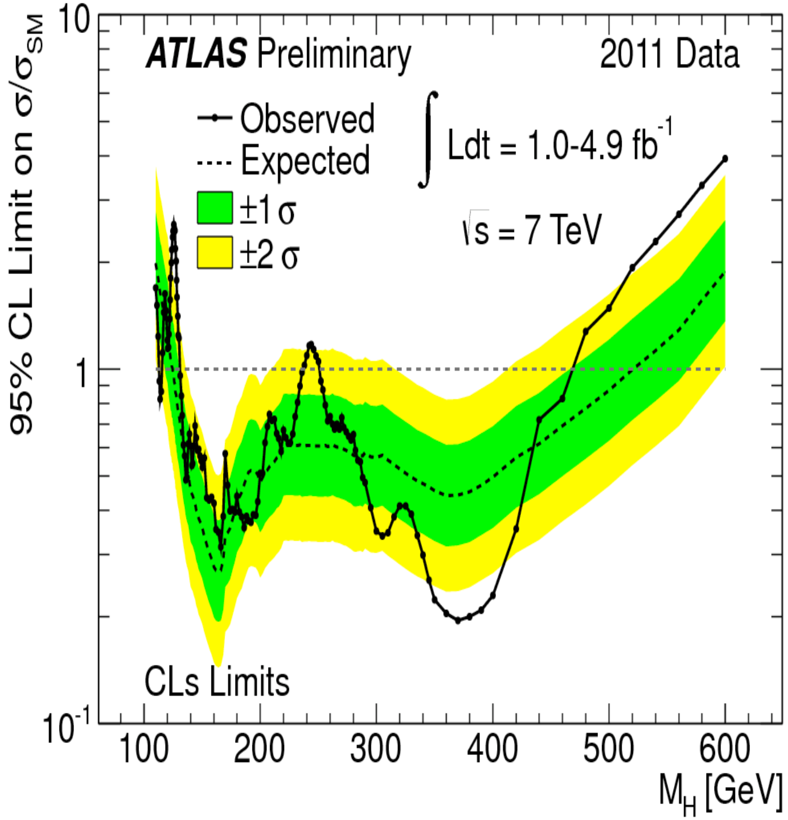
January 26th, 2012

the most important question in our field:

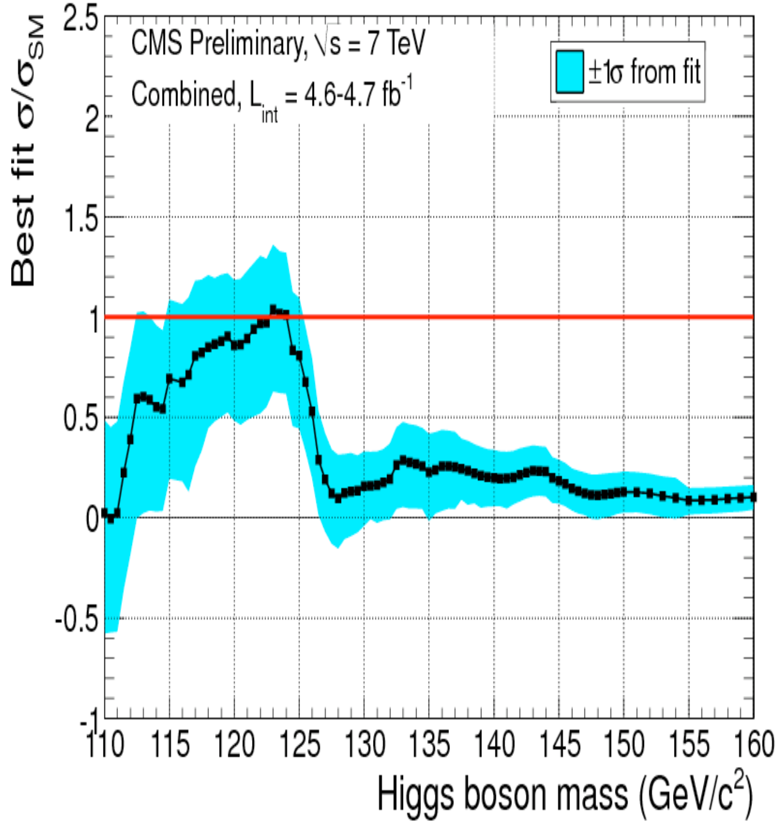
where is the Higgs boson?

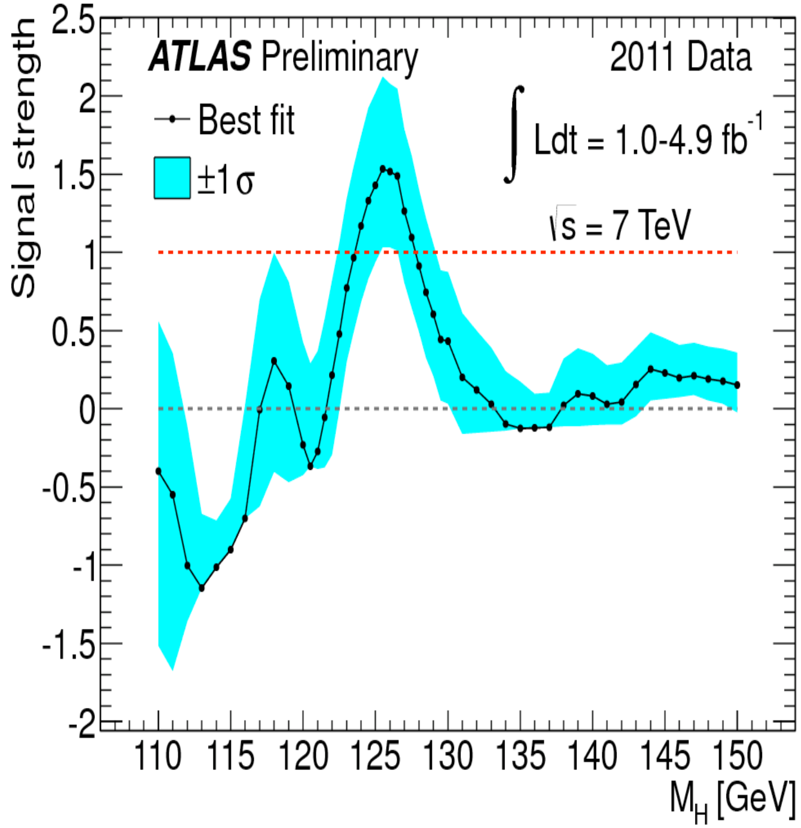
- ATLAS and CMS have done amazing jobs in Higgs searches!
- A ``Standard Model Higgs'' above 130 GeV is pretty much ruled out!!





- both collaborations claimed excesses at around 125 GeV!



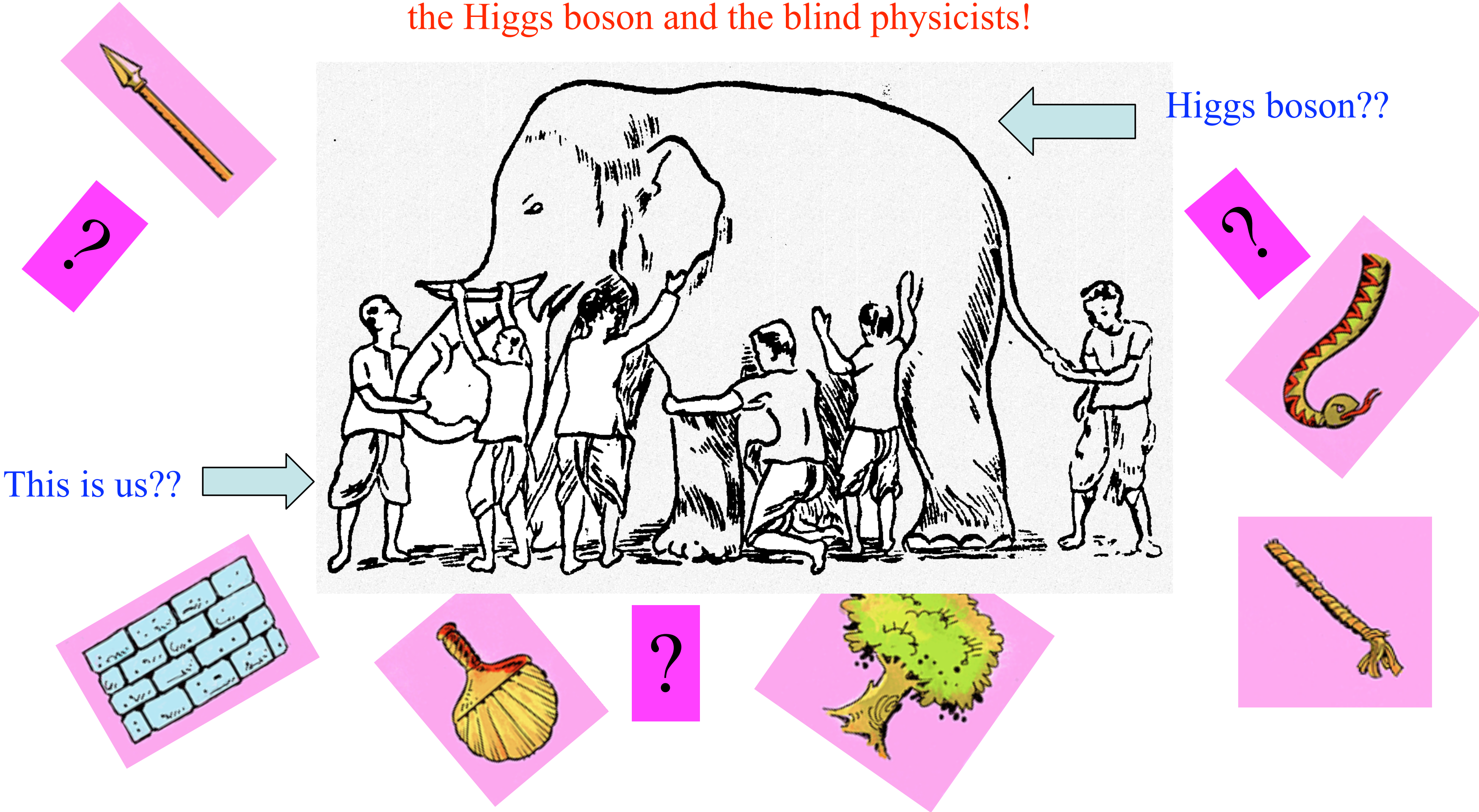


is there a bump? ---> if yes, is it the higgs boson?

what kind of higgs could it be?

---> if not, what is going on!!??

the Higgs boson and the blind physicists!



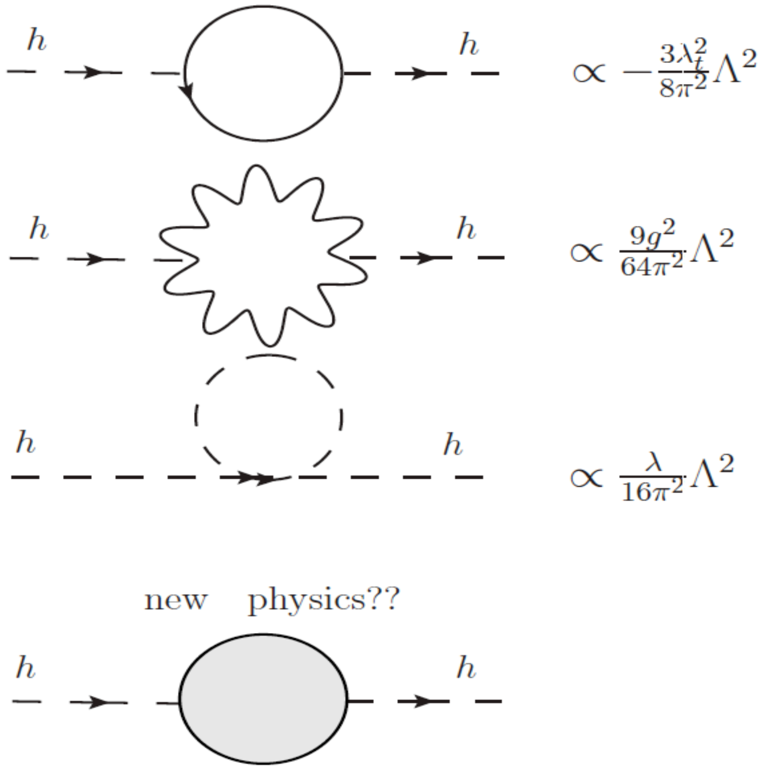
this talk is about the question:

what kind of higgs could it be?

using naturalness as the guiding principle,

1) there should be new physics at the TeV scale.
2) there are only two kinds of higgs!

- one-loop quadratic divergences in the higgs mass must be cancelled by “something” at the TeV scale:



- the whole business of naturalness rests on the assumption that things don’t cancel without a reason!

- so there should be a symmetry reason why the higgs quadratic divergences cancel.

only two classes of models:

1) bosonic global symmetry ----> higgs as a pseudo Nambu-Goldstone boson (PNGB)!

2) fermionic global symmetry -----> supersymmetry

the space of models in both classes of model is quite large….

- supersymmetric theories are all built upon a minimal lagrangian: the MSSM

- the landscape of composite higgs (PNGB) models appear quite diverse:

  SU(4)/Sp(4), SO(5)/SO(4), SU(5)/Sp(5), SU(6)/Sp(6), SO(9)/SO(5)xSO(4), …. etc

  any young hot shot can come up with his/her own symmetry breaking pattern G/H, and becomes famous!

things improved when the SILH paper arrived:

The Strongly-Interacting Light Higgs

G. F. Giudice[a], C. Grojean[a,b], A. Pomarol[c], R. Rattazzi[a,d]

Abstract

We develop a simple description of models where electroweak symmetry breaking is triggered by a light composite Higgs, which emerges from a strongly-interacting sector as a pseudo-Goldstone boson. Two parameters broadly characterize these models: m_ρ, the mass scale of the new resonances and g_ρ, their coupling. An effective low-energy Lagrangian approach proves to be useful for LHC and ILC phenomenology below the scale m_ρ. We identify two classes of operators: those that are genuinely sensitive to the new strong force and those that are sensitive to the spectrum of the resonances only. Phenomenological prospects for the LHC and the ILC include the study of high-energy longitudinal vector boson scattering, strong double-Higgs production and anomalous Higgs couplings. We finally discuss the possibility that the top quark could also be a composite object of the strong sector.

- SILH lagrangian is based on a set of power-counting rules:

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SILH}} \;=\; & \frac{c_H}{2f^2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& -\frac{c_6\lambda}{f^2}(H^\dagger H)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \mathrm{h.c.}\right) \\
& +\frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(D_\nu W^{\mu\nu})^a + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)(\partial_\nu B^{\mu\nu}) \\
& +\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& +\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_s^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu} G^{\mu\nu},
\end{aligned}
$$

- all coefficients in SILH appear to be free parameters and depend on the symmetry breaking pattern in the UV.

now the task is straightforward:

- pick your favorite G/H among
  SU(4)/Sp(4), SO(5)/SO(4), SU(5)/Sp(5), SU(6)/Sp(6), SO(9)/SO(5)xSO(4)….

- compute all the coefficients in the SILH.

- then you have the predictions to compare with data.

the only problems

- every time someone comes up with a new G/H, you need to crank your code again.

- if none of the existing G/H fits the data, we still don't know if composite higgs is ruled out or not.

it would be nice to have a set of predictions that are generic and universal in PNGB higgs models...

is there an analog of MSSM for composite higgs models?

what is the minimal setup for a PNGB higgs?

setup for a minimally symmetric higgs are

- symmetries of the standard model be realized linearly!
  $SU(2)_L xU(1)_Y$ or SO(4) if you'd like custodial symmetry.

- each component of the higgs transforms nonlinearly under a (spontaneously broken) symmetry.
  how these four broken symmetries are embeded inside a particular Lie group G is none of our concerns!

how much can we learn by putting together these two requirements?

- consequences of a spontaneously broken symmetry on goldstone interactions have been studied in the ‘60s by Adler, Nambu, Goldstone, Weinberg, etc.

- although those works are called “soft pion theorems,” a significant part of them does not depend on the particular symmetry breaking pattern!

- one particular important theorem is the Adler’s zero condition:

  on-shell scattering amplitudes of goldstone bosons must vanish in the limit the momentum of one goldstone boson is taken off-shell and soft.

- often this is over-simplified as saying “the goldstone boson is derivatively coupled.”

  it is an over-simplification because it doesn’t do justice to the full power of the Adler’s zero condition.

for now assume only one flavor of goldstone boson and consider 4-pt scattering amplitudes, written in terms of the Mandelstam variables.

- Adler's zero condition forbids a constant term!

$$\mathcal{A}(\pi\pi \to \pi\pi) = c_1 s + c_2 t + c_3 u + \mathcal{O}(p^4)$$

- Bose symmetry implies $c_1 = c_2 = c_3$!

$$\mathcal{A}(\pi\pi \to \pi\pi) = \mathcal{O}(p^4)$$

the argument can be generalized to n-pt amplitudes to show that $O(p^2)$ term always vanishes!

$$\begin{aligned} \mathcal{A}(\pi\pi\cdots \ \to \ \pi\pi\cdots) &= c(p_1 + p_2 + \cdots + p_n)^2 + \mathcal{O}(p^4) \\ &= \mathcal{O}(p^4) \end{aligned}$$

(i've swept some dirt under the rug…..)

- the simplest lagrangian satisfying these properties is the familiar one:

$$\mathcal{L}_0 = \frac{1}{2}\partial_\mu\pi\partial^\mu\pi + \mathcal{O}(\partial^4)$$

- as is well known, L_0 can be obtained by requiring that there is a constant “shift symmetry” acting on pion:

$$\pi \to \pi + \epsilon$$

- the derivative of pion has simpler transformation under the broken symmetry:

$$\partial_\mu\pi \to \partial_\mu\pi$$

$\partial_\mu\pi$ is the building block of the effective lagrangian!

we have learned a simple yet powerful statement:

independent of the symmetry breaking pattern, self-interactions among goldstones of the same flavor are fixed by Adler's zero condition and Bose symmetry, and must have the form:

$$\mathcal{L}_0 = \frac{1}{2}\partial_\mu \pi \partial^\mu \pi + \mathcal{O}(\partial^4)$$

for a PNGB Higgs, we need to combine this statement with the linearly realized SU(2)xU(1).

- when there are multiple flavors of Goldstones, higher order terms appear in the shift symmetry.

- to warm up, let's consider two flavors of goldstones transforming as a complex scalar under an unbroken U(1):

$$\phi = (\pi_1 + i\pi_2)/\sqrt{2} \quad \rightarrow \quad e^{i\alpha}\ \phi$$

- nonlinear shift symmetry at NLO can be written as

$$\phi \mapsto \phi' = \phi + \epsilon - \frac{c_1}{f^2}(\phi^* \epsilon)\phi - \frac{c_2}{f^2}(\epsilon^* \phi)\phi$$

- when we turn off one of the two flavors , we must return to the single flavor case, π_i -> π_i + ε_i ,

$$\phi \mapsto \phi' = \phi + \epsilon - \frac{c_1}{f^2}(\phi^* \epsilon - \epsilon^* \phi)\phi$$

- to construct the lagrangian, it pays to recall that the derivative of goldstones usually has simpler transformation!

- define the “covariant derivative” of the Goldstone,

$$\mathcal{D}_\mu \phi = \partial_\mu \phi - \frac{d_1}{f^2}(\phi\, \partial_\mu \phi^* - \partial_\mu \phi\ \phi^*)\phi$$

- the form is again fixed by reducing to the single flavor case:

$$\mathcal{D}_\mu \phi\big|_{\pi_{1,2}=0} = \partial_\mu \phi$$

how does the covariant derivative transform under the broken symmetry acting on the goldstone?

- as the name suggests, it should change by a *field-dependent* U(1) rotation under the broken symmetry:

$$\mathcal{D}_\mu \phi \mapsto \mathcal{D}_\mu \phi' = e^{i\alpha\, u(\phi,\epsilon)/f}\ \mathcal{D}_\mu \phi$$

- the field-dependent phase again should have the property:

$$u(\phi,\epsilon)\big|_{\pi_{1,2}=0} = 0$$

$$u(\phi,\epsilon) = \frac{e_1}{f}(\phi^*\epsilon - \epsilon^*\phi)$$

let’s recap here. we postulate

$$\phi \mapsto \phi' = \phi + \epsilon - \frac{c_1}{f^2}(\phi^* \epsilon - \epsilon^* \phi)\phi$$

$$\mathcal{D}_\mu \phi = \partial_\mu \phi - \frac{d_1}{f^2}(\phi\, \partial_\mu \phi^* - \partial_\mu \phi\ \phi^*)\phi$$

$$u(\phi, \epsilon) = \frac{e_1}{f}(\phi^* \epsilon - \epsilon^* \phi)$$

and require

$$\mathcal{D}_\mu \phi \mapsto \mathcal{D}_\mu \phi' = e^{i\alpha\, u(\phi,\epsilon)/f}\ \mathcal{D}_\mu \phi$$

which is not difficult to solve

$$d_1 = -c_1/2$$

$$e_1 = -3i\ c_1/2$$

- the two-deriative effective lagrangian is built out of the covariant derivative:

$$\begin{aligned}\mathcal{L}^{(2)} &= \mathcal{D}_\mu\phi^*\mathcal{D}^\mu\phi \\ &= \partial_\mu\phi^*\partial^\mu\phi - \frac{c_1}{f^2}|\partial_\mu\phi^*\ \phi - \partial_\mu\phi\ \phi^*|^2 + \mathcal{O}(1/f^4)\end{aligned}$$

- this process can be continued order-by-order in 1/f:

$$\mathcal{D}_\mu\phi = \partial_\mu\phi + \phi\frac{\partial_\mu\phi^*\ \phi - \partial_\mu\phi\ \phi^*}{2|\phi|^2}\left(1 - \frac{\tilde{f}}{|\phi|}\sin\frac{|\phi|}{\tilde{f}}\right)$$

$$\mathcal{L}^{(2)} = \mathcal{D}_\mu\phi\mathcal{D}^\mu\phi = \partial_\mu\phi^*\partial^\mu\phi - \frac{|\partial_\mu\phi^*\ \phi - \partial_\mu\phi\ \phi^*|^2}{4|\phi|^2}\left(1 - \frac{\tilde{f}^2}{|\phi|^2}\sin^2\frac{|\phi|}{\tilde{f}}\right)$$

$$\tilde{f} = f/\sqrt{6c_1}$$

a few comments:

- we managed to derive the two-derivative lagrangian without referring to any symmetry breaking pattern.

- the only undetermined parameter, c_1, reflects the arbitrariness in the normalization of “f”.

$$\mathcal{D}_\mu\phi = \partial_\mu\phi + \phi\frac{\partial_\mu\phi^*\,\phi - \partial_\mu\phi\,\phi^*}{2|\phi|^2}\left(1 - \frac{\tilde{f}}{|\phi|}\sin\frac{|\phi|}{\tilde{f}}\right)$$

$$\mathcal{L}^{(2)} = \mathcal{D}_\mu\phi\mathcal{D}^\mu\phi = \partial_\mu\phi^*\partial^\mu\phi - \frac{|\partial_\mu\phi^*\,\phi - \partial_\mu\phi\,\phi^*|^2}{4|\phi|^2}\left(1 - \frac{\tilde{f}^2}{|\phi|^2}\sin^2\frac{|\phi|}{\tilde{f}}\right)$$

$$\tilde{f} = f/\sqrt{6c_1}$$

a few comments:

- the sign of c_1 is not fixed:
  a positive sign implies a compact G/H, while a negative sign implies a non-compact G/H.

- if UV completion is a concern, $c_1 > 0$ and the sign of the dim-6 operator is negative.

$$\mathcal{D}_\mu \phi = \partial_\mu \phi + \phi \frac{\partial_\mu \phi^* \, \phi - \partial_\mu \phi \, \phi^*}{2|\phi|^2} \left(1 - \frac{\tilde{f}}{|\phi|} \sin \frac{|\phi|}{\tilde{f}} \right)$$

$$\mathcal{L}^{(2)} = \mathcal{D}_\mu \phi \mathcal{D}^\mu \phi = \partial_\mu \phi^* \partial^\mu \phi - \frac{|\partial_\mu \phi^* \, \phi - \partial_\mu \phi \, \phi^*|^2}{4|\phi|^2} \left(1 - \frac{\tilde{f}^2}{|\phi|^2} \sin^2 \frac{|\phi|}{\tilde{f}} \right)$$

$$\tilde{f} = f / \sqrt{6 c_1}$$

- one could introduce another object that transforms non-homogeneously like a gauge field:

$$\mathcal{E}_\mu \mapsto e^{-iu}\mathcal{E}_\mu e^{iu} - ie^{-iu}\partial_\mu e^{iu} = \mathcal{E}_\mu + \partial_\mu u(\phi, \epsilon)$$

$$\mathcal{E}_\mu = \frac{i}{\alpha}\frac{\partial_\mu\phi^*\,\phi - \partial_\mu\phi\,\phi^*}{|\phi|^2}\sin^2\frac{|\phi|}{2\tilde{f}}$$

- the non-homogeneous term also allows us to couple higgs to a composite scalar/fermion:

$$(\partial_\mu \Phi^* - i\mathcal{E}_\mu \Phi^*)(\partial^\mu \Phi + i\mathcal{E}^\mu \Phi)$$

$$i\bar{\psi}\not{\partial}\psi + \bar{\psi}\not{\mathcal{E}}\psi$$

studying how the higgs couples to a new scalar/fermion could test of the composite nature, if any, of these new states.

next I will just show results for a PNGB higgs doublet:

$$H \mapsto H' = H + \epsilon + \frac{c_1}{f^2}\left[(\epsilon^\dagger H + H^\dagger \epsilon)H - 2(H^\dagger H)\epsilon\right]$$

$$\begin{aligned}\mathcal{L}^{(2)} &= \mathcal{D}_\mu H^\dagger \mathcal{D}^\mu H \\ &= \partial_\mu H^\dagger \partial^\mu H + \frac{c_H}{2f^2}\mathcal{O}_H + \frac{c_r}{2f^2}\mathcal{O}_r + \frac{c_T}{2f^2}\mathcal{O}_T\end{aligned}$$

again we have rescaled f: $f \to f/\sqrt{c_1}$

at leading order: $c_H = 1/6\ , \quad c_T = -1/2\ , \quad c_r = -4c_H\ .$

again for compact coset, the signs are fixed.

in case you are curious about the all-order expressions:

$$c_H = \frac{f^2}{H^\dagger H}\left(1 - \frac{\sin\frac{\sqrt{H^\dagger H}}{f}}{\frac{\sqrt{H^\dagger H}}{f}}\right)$$

$$c_T = -2\frac{f^3}{(H^\dagger H)^{3/2}}\sin\frac{\sqrt{H^\dagger H}}{f}\ \sin^2\frac{\sqrt{H^\dagger H}}{2f}$$

$$c_r = -4c_H$$

- if one would like to impose the custodial symmetry, the higgs is a vector under SO(4).

- two-derivative lagrangian is the same as SU(2)xU(1), by setting $c_T = 0$.

- the four-derivative lagrangian will differ, because of the SO(4) symmetry acting on the SU(2) and U(1) gauge fields.

- notice that O_r is not in SILH,

$$\frac{c_r}{2f^2}\mathcal{O}_r \equiv \frac{c_r}{2f^2} H^\dagger H (D_\mu H)^\dagger D^\mu H$$

which is removed by a field-redefinition

$$H \to H + a(H^\dagger H)H/f^2$$

c_H , c_r , and c_T are related to 4-pt amplitudes of pion scattering, and their ratios are independent of the normalization of “f”!

- two additional operators in SILH also have their coefficients and signs fixed by the nonlinear shift symmetry,

$$+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(D_\nu W^{\mu\nu})^a + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)(\partial_\nu B^{\mu\nu})$$

this is because they arise from the following term after integrating out a heavy vector:(hep-ph/0703164)

$$-\frac{1}{4g_\rho^2}F_{\mu\nu}(\bar{\mathcal{E}})F^{\mu\nu}(\bar{\mathcal{E}})$$

$$\bar{\mathcal{E}}_\mu = A_\mu + \mathcal{E}_\mu(\Pi, D_\nu)$$

- ratio of c_W and c_B is independent of mass parameters!

  their sum contribute to *S* parameter.

- I believe the following two operators in SILH are also fixed by the nonlinear shift symmetry

$$\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R$$

$$\frac{c_g g_s^2}{16\pi^2 f^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu} G^{\mu\nu}$$

"empirical data" certainly support this assertion.

summary:

- the self-interaction of goldstone bosons is an infrared property, dictated by the IR quantum number, instead of the symmetry breaking pattern in the UV.

- CCWZ way of writing down goldstone interactions requires a top-down thinking by specifying a priori the symmetry breaking pattern in the UV.

  there is an alternative!