2/1/24 - K. LANE — 20 MINUTE TALK AT FCC WORKSHOP AT ANNECY

3 QUESTIONS ABOUT H(125):
- WHY IS H SO LIGHT?
- WHY DOES IT HAVE SM COUPLINGS?
- ARE THERE MORE (BSM) HIGGSES & WHAT ARE THEIR MASSES?

THE LAST TREASURE - CHARACTERIZE WELL BEYOND MULTI-TeV MODELS

I. ASSUME SCALE-INVARIANT MULTI-HIGGS POTENTIALS + YUKAWA COUPLINGS:

$-V_0(\phi) = \frac{-1}{24} f_{ijkl}\,\phi_i\phi_j\phi_k\phi_l$ (sum over doublets e.g. four generic doublets)

$\mathcal{L}_Y = -Y_{ia}\,\bar{\psi}_{Li}\phi_i\,\psi_{Ra} + h.c.$ (with $\phi_i \equiv$ coupling SU(2) doublet e.g.)

II. A SIMPLEST EXAMPLE - TWO-HIGGS-DOUBLET MODEL (2HDM)

$\phi_i = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}H_i^+ \\ \rho_i + i a_i\end{pmatrix}$ ($a_i \to 0^-$)

$V_0 = \lambda_1|\phi_1^\dagger\phi_1|^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \text{etc.}$

with Z_2 symmetry on $\phi_{1,2} \to \mp\phi_{1,2}$; $\psi_{La} \to \psi_{La}$, $\psi_{Ra} \to -\psi_{Ra}$.

1. When S.I is explicitly broken, $(CP=+1)$ VEV's appear:

$\langle\rho_i\rangle = v_i$ $(i=1,2)$; $v = \sqrt{v_1^2+v_2^2}$ GeV

$v_1 = v\cos\beta$, $v_2 = v\sin\beta$.

2. Consider $H = \rho_1\cos\beta + \rho_2\sin\beta$ (like the EW Goldstone bosons). This linear combo will have SM couplings to W, Z and quarks and leptons.

Consider this H on the ray $\rho_1, \rho_2 \to +\infty$

i.e., "H is (perfectly) aligned" !!
- it has SM couplings.

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3. On the ray $p_1, p_2 = p \to \infty$, H is an eigenstate and it is massless - just like the Goldstone bosons $W^\pm = H_1^\pm \cos\beta + H_2^\pm \sin\beta$ and $Z = A_1^\pm \cos\beta + A_2^\pm \sin\beta$ - eaten by $W^\pm$ and Z, respectively.

i.e. H is the massless dilaton of spontaneously broken scale-invariance.

4. In the one-loop approx'n of S. Coleman and E. Weinberg, scale-invariance is explicitly broken $\to p_i \to p_i + v_i$ ($v_1 = v\cos\beta$, $v_2 = v\sin\beta$; $0 < \beta \leq \pi$). Now, H gets a mass (it's a pseudo-dilaton) — as do all the other

And there results the sum rule

$$M_H^2 = \frac{8\pi^2}{v^2}\left(M_{H'}^4 + 2M_{H^\pm}^4 + 3M_W^4 + M_Z^4\right)$$

massive Higgses **not eaten** by Z and $W^\pm$!

5. The same sort of sum rule holds in any GW model of electroweak interactions ($SU(2)\otimes U(1)$) with complex-doublet Higgses:

$$\Rightarrow \left(\sum M_{BSM}^4\right)^{1/4} = \left[\frac{v^2}{8\pi^2}M_H^2 - 3M_W^4 - M_Z^4\right]^{1/4} = 540\ \text{GeV}$$

i.e. BSM Higgs masses are constrained by $M_H = 125$ GeV

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AGAIN: IN GW MODELS OF THE EW INTERACTIONS, BSM HIGGS MASSES ARE LIGHT BECAUSE H(125) IS LIGHT!