# LHC vs PHYSICS BEYOND THE SM

WHAT BREAKS THE  ELECTROWEAK SYMMETRY?

IT HAS BEEN A CHALLANGE FOR THE LHC

## ADDRESSING THE GENERAL FRUSTRATION….

## 125 GeV HIGGS AND NOTHING ELSE: IS IT REALLY SHOCKING?

### THE SM HIGGS- LIKE PARTICLE DISCOVERED

FUNDAMENTAL DISCOVERY BUT…SOME OF US KNEW IT ALREADY 20 YEARES AGO.
IT DOES NOT MAKE IT EASIER TO ANSWER THE QUESTION „WHAT BREAKS ELECTROWEAK SYMMETRY?"

### NO SIGNAL OF NEW PHYSICS

BUT… PRECISION LEP DATA, PRECISION FLAVOUR DATA,
WERE POINTING IN THAT DIRECTION. IN THE MSSM: GAUGE COUPLING UNIFICATION

GAUGE COUPLING UNIFICATION IN THE MSSM

AMALDI, de BOER, FURSTENAU '91

$$T_{susy} = 1\ TeV$$

**Superpartner mass mass dependence can be described (in LL approx) by a single effective parameter Tsusy**

$$T_{susy} = |\mu| \left(\frac{m_{\tilde{W}}}{m_{\tilde{g}}}\right)^{3/2} \left(\frac{M_{\tilde{\ell}}}{M_{\tilde{q}}}\right)^{3/19} \left(\frac{M_{A^0}}{|\mu|}\right)^{3/19} \left(\frac{m_{\tilde{W}}}{|\mu|}\right)^{3/19}$$

$$\approx |\mu| \left[\frac{m_{\tilde{W}}}{m_{\tilde{g}}}\right]^{3/2}$$

CARENA, SP, WAGNER ‘93

A HINT FOR EITHER HEAVY OR COMPRESSED SPECTRUM BECAUSE…

For instance, for universal gaugino masses at the GUT scale

$$T_{susy} \simeq |\mu| \left[\frac{\alpha_2(M_Z)}{\alpha_3(M_Z)}\right]^{3/2} \sim \frac{1}{7}|\mu|$$

A HINT FOR EITHER HEAVY O(1) TeV OR COMPRESSED SPECTRUM

SM:

self interacting scalar SU(2) doublet field

$$V = m_H^2 H H^\dagger + \frac{1}{2}\lambda (H H^\dagger)^2$$

$$v^2 = -\frac{m_H^2}{\lambda} \qquad H = \begin{bmatrix} H^0 \\ H^- \end{bmatrix}$$

$$< H^0 >= v$$

3 Goldstone bosons, 1 massive scalar

$$m_h^2 = -2m_H^2 = 2\lambda v^2$$

Higgs potential in the SM: describes but does not explain dynamically the origin of the Fermi scale

**BIG PUZZLE: IS THE VEV A NEW FUNDAMENTAL SCALE OF NATURE OR HAS IT A DYNAMICAL EXPLANATION?**

**IF IT HAS A DYNAMICAL EXPLANATION, THE SM SHOULD BE EMBEDDED INTO A DEEPER THEORY!**

## Analogy (for the mechanism of spontaneous global symmetry breaking)

| strong | electroweak |
| --- | --- |

IN BOTH CASES, CHIRAL SU(2)xSU(2) OF THE SCALAR SECTOR IS SPONTANEOUSLY BROKEN TO SU(2)

| | |
| --- | --- |
| Sigma model | Higgs doublet |
| Dynamical condensate | ? |

# PIONS AS A NAMBU-GOLDSTONE BOSONS OF SPONTANEOUSLY BROKEN SU(2)xSU(2) CHIRAL SYMMETRY

$$\Psi_L = (P_L N_L)^T \qquad \Psi_R = (P_R N_R)^T$$

WE WANT TO CONSTRUCT A LAGRANGIAN FOR NUCLEONS AND PIONS WHICH IS SU(2)xSU(2) INVARIANT

$$\Psi'_L = e^{-i\alpha_L \tau}\Psi_L \qquad \Psi'_R = e^{-i\alpha_R \tau}\Psi_R$$

EVENTUALLY, CHIRAL SYMMETRY IS BROKEN TO VECTOR-LIKE (ISOSPIN) SU(2)

$$\alpha_L = \alpha_R \equiv \alpha$$

$$\Psi' = e^{-i\alpha\tau}\Psi$$

$$\Sigma = \begin{pmatrix} \sigma + i\pi^3 & -i\pi^1 + \pi^2 \\ \pi^2 + i\pi^1 & \sigma - i\pi^3 \end{pmatrix}, \qquad \Sigma \to g_L \Sigma g_R^\dagger$$

$$\mathcal{L} = i\bar{\Psi}\gamma_\mu\Psi - y\bar{\Psi}_L\Sigma\Psi_R - y\bar{\Psi}_R\Sigma^\dagger\Psi_L + \mathcal{L}(\Sigma)$$

Spontaneous symmetry breaking is described by an *ad hoc* ansatz for the potential for the scalar field, giving

$$< \sigma >= f_\pi$$

# SU(2)xSU(2) global symmetry of V(H) :

$$H = \begin{pmatrix} h_1 + i h_2 \\ h_3 + i h_4 \end{pmatrix} \rightarrow \mathcal{H} = \begin{pmatrix} h_1 + i h_2 & -h_3 + i h_4 \\ h_3 + i h_4 & h_1 - i h_2 \end{pmatrix}$$

$$\mathcal{H} \rightarrow \mathcal{H}' = U_L \mathcal{H} U_R$$

$$H^+ H = \frac{1}{2} \mathrm{Tr} \left( \mathcal{H}^+ \mathcal{H} \right) = \det \mathcal{H} = h_1^2 + h_2^2 + h_3^2 + h_4^2$$

OBVIOUS DIFFERENCE: PIONS REMAIN IN THE SPECTRUM
WHEREAS 3 GOLDSTONE HIGGSES ARE EATEN UP BY THE GAUGE FIELDS

$$\mathcal{L}(\Sigma) = \frac{1}{2} Tr \partial_\mu \Sigma \partial^\mu \Sigma^\dagger - \lambda [Tr(\Sigma \Sigma^+) - f_\pi^2]^2$$

$$< \sigma > = f_\pi \qquad \sigma' = \sigma - f_\pi$$

WE GET

$$\mathcal{L} = i\bar{\Psi} \partial_\mu \gamma^\mu \Psi + \frac{1}{2} \partial_\mu \sigma' \partial^\mu \sigma' + \frac{1}{2} \partial_\mu \pi_a \partial^\mu \pi_a$$
$$- y f_\pi \bar{\Psi} \Psi - y \sigma' \bar{\Psi} \Psi + i y \pi_a \bar{\Psi} \tau_a \gamma_5 \Psi$$
$$- \lambda ({\sigma'}^2 + \pi_a^2 + 2 f_\pi \sigma')^2$$

# Important conclusions:

NUCLEONS GET MASSES $m_N = y f \pi$

PIONS REMAIN MASSLES, A SCALAR WITH $m_\sigma^2 = 2\lambda f_\pi^2$

GOLDBERGER-TREIMANN RELATION

$$m_N = g_{\pi NN} f \pi$$

BECAUSE $g_{\pi NN} = y$

GOLDBERGER-TREIMANN RELATION AGREES WITH EXPERIMENT!

$f_\pi$ IS MEASURED IN $\pi \to \mu\nu$ IF WE IDENTIFY

THE LEFT HANDED CHIRAL CURRENT WITH THE HADRONIC WEAK CURRENT, SO THAT

$$\mathcal{L} \sim G_F j^{\dagger a}_{\mu L}(lep) j^{a}_{\mu L}(had) + hc$$

IS THE WEAK INTERACTION FERMI LAGRANGIAN

INDEED

$$j^a_{\mu L} = V - A = \bar{\Psi}\gamma_\mu \tau^a \Psi - \bar{\Psi}\gamma_\mu \gamma_5 \tau^a \Psi$$
$$+[\pi \times \partial_\mu \pi]^a - \sigma \partial_\mu \pi^a + \pi^a \partial_\mu \sigma$$

AND

$$< l\bar{\nu}|\mathcal{L}|\pi > \sim < l\bar{\nu}|j_\mu|0 >< 0|j_\mu|\pi >$$

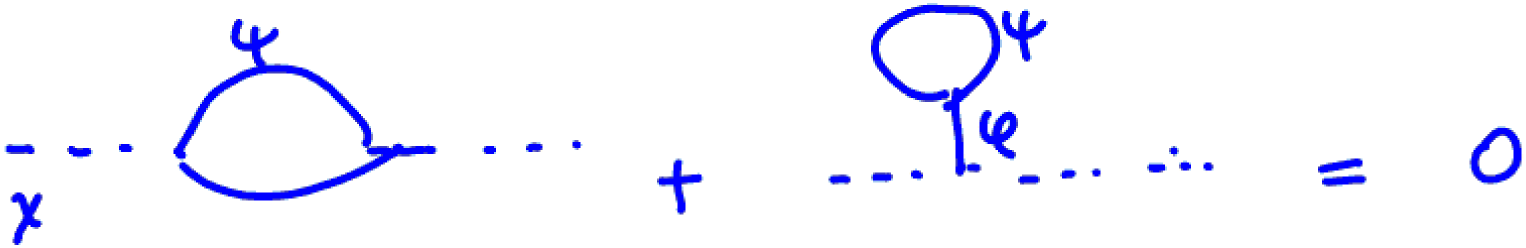
$$< 0|j_\mu|\pi > = < 0|\sigma\partial_\mu \pi|\pi > = f_\pi k_\mu e^{ikx}$$

(THE AXIAL CHARGE-SPONTANEOUSLY BROKEN GENERATOR-DOES NOT ANNIHILATE THE VACCUM)

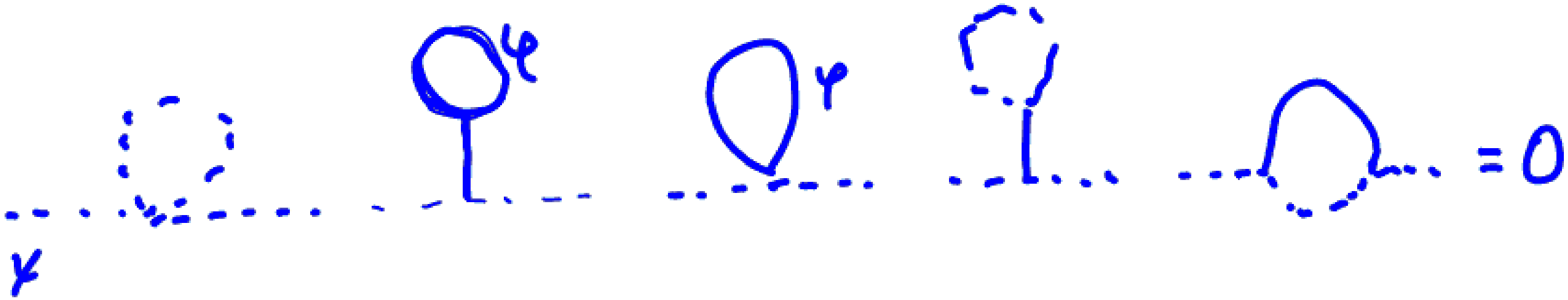
WHY PIONS REMAIN LIGHT AFTER RADIATIVE CORRECTIONS?

LOOP CORRECTIONS TO THE GOLDSTONE BOSON MASSES VANISH

# Corrections to the χ mass (Goldstone)




(no dependence on cut-off Λ !)




fermion - fermion
Boson - boson

cancellations
(conspiracy of couplings)

# GIVING PIONS A MASS:

A SOFT EXPLICIT CHIRAL SYMMETRY BREAKING
(PRESERVING ISOSPIN SYMMETRY)

$$\mathcal{L} \to \mathcal{L} - \mu^3 \sigma$$

ONE GETS

$$m_\pi^2 = \mu^3 / f_\pi$$

(TO BE COMPARED WITH RADIATIVE CORRECTIONS TO THE $\sigma$ MASS)

$$\delta m_\sigma^2 \sim \lambda \Lambda^2$$

( $\Lambda$ -CUT-OFF TO THE EFFECTIVE THEORY)

# KIBBLE PARAMETRIZATION

FOR INSTANCE, U(1) INVARIANT SCALAR THEORY:

$$V = m^2 \Phi\Phi^* + \frac{1}{2}\lambda(\Phi\Phi^*)^2$$

$$\Phi(x) = \frac{1}{\sqrt{2}} \exp^{i\frac{\eta(x)}{v}} (v + \rho(x))$$

KIBBLE

$$\mathcal{L} = \frac{1}{2}\partial_\mu \rho \partial^\mu \rho + \frac{1}{2}\partial_\mu \eta \partial^\mu \eta (1 + \frac{\rho}{v})^2$$

$$-\frac{1}{2} m_\rho^2 \rho^2 - \frac{\lambda}{4}\rho^4 - v\lambda\rho^3$$

$$m_\eta = 0 \qquad m_\rho^2 = \lambda v^2$$

IMPORTANT: IN THIS PARAMETRIZATION WE SEE THE SO-CALLED SHIFT SYMMETRY OF THE LAGRANGIAN

$$\eta(x) \to \eta(x) + \theta$$

WHICH IS IN ONO-TO-ONE CORRESPONDENCE TO THE LINEARLY REALIZED ON THE FIELD $\Phi$ U(1) SYMMETRY.
MASSLESSNESS OF $\eta$ IS NOW OBVIOUS.

ONE CAN DECOUPLE THE $\rho$ FIELD WITHOUT DESTROYING U(1): IT'S NOW REALIZED NON-LINEARLY on $\eta$

NON-LINEAR U(1) AFTER FERMIONS ARE INCLUDED:
TAKE A SIMPLE CHIRAL MODEL

$$\psi_1^L = \begin{pmatrix} \chi_1 \\ 0 \end{pmatrix} \qquad \psi_2^R = \begin{pmatrix} 0 \\ \chi_2 \end{pmatrix} \quad \text{(Weyl fermions)}$$

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - m^2 \phi^* \phi - \frac{\lambda}{4} (\phi^* \phi)^2$$
$$+ i \bar{\psi}_1^L \gamma_\mu \partial^\mu \psi_1^L + i \bar{\psi}_2^R \gamma_\mu \partial^\mu \psi_2^R$$
$$- g \left( \phi \bar{\psi}_2^R \psi_1^L + \phi^* \bar{\psi}_1^L \psi_2 \right)$$

U(1) charges

$\phi : +1 , \quad \psi_1 : -1 , \quad \psi_2 : 0$

NON_LINEAR PARAMETRIZATION AFTER FERMIONS ARE INCLUDED

$$\Phi = \frac{1}{\sqrt{2}}(v+\phi)\exp(i\chi/v)$$

$$-g(\Phi\bar{\Psi}_2\Psi_1 + \Phi^\dagger\bar{\Psi}_1\Psi_2) = -\frac{g}{\sqrt{2}}(v+\phi)\cos\frac{\chi}{v}\bar{\Psi}\Psi - \frac{g}{\sqrt{2}}(v+\phi)i\sin\frac{\chi}{v}\bar{\Psi}\gamma_5\Psi$$

$$\approx \frac{g}{\sqrt{2}}(v+\phi)(1-\frac{\chi^2}{v})\bar{\Psi}\Psi - \frac{g}{\sqrt{2}}(v+\phi)i\chi\bar{\Psi}\gamma_5\Psi$$

TERMS QUADTRATIC IN THE GB FIELD GIVE

The original idea of Nambu – a dynamical origin of the order parameter sigma: fermion- antifermion pair condensation („Cooper pairs”)

$$< \Omega|\bar{\psi}_R^a \psi_L^b|\Omega > \neq 0$$

Beautiful mechanism in QCD: condensation scale (confinement scale) is linked to asymptotic freedom of QCD

$$v/Q = exp(-\pi/b\alpha(Q))$$

BACK TO THE ELECTROWEK THEORY

LET’S FOCUS ON THE „CLASSICAL” IDEAS, THOSE WHICH PREDICT „OBSERVABLE EFFECTS”

STILL, QUITE A SPECTRUM OF POSSIBILIIES

EMBEDDING THE SM INTO A DEEPER THEORY:
NATURALNESS OF THE HIGGS POTENTIAL?

$$|m_H^2| = m_h^2 = 125GeV$$

$$|m_H^2| \sim 10^{-2}TeV$$

$$m_H^2 = m_H^2|_{tree} + \delta m_H^2|_{loop}$$

THE HIGGS POTENTIAL IS NATURAL IF

$$\delta m_H^2|_{loop} \approx m_H^2$$

The naturalness argument for new physics at the EW scale is often expressed in terms of the quadratic cut-off dependence in the scalar sector

$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$


IF WE SEE THE CUT-OFF AS THE SCALE WHERE A NEW PHYSICS OCCURS THEN THE NEW PHYSICS MUST BE NEARBY

The argument can be formulated in terms of renormalized quantities with no reference to a cut-off --->
quadratic sensitivity to thresholds at high energy

IN A FIELD THEORY WITH A CUT-OFF $\Lambda$ AND SOME SCALAR FIELD(S)

$\phi$ (WHICH MAY ACQUIRE VEV(s)), THE 1-LOOP EFFECTIVE POTENTIAL IS

$$\Delta V(\phi) = \frac{1}{32\pi^2}\Lambda^2 Str\mathcal{M}^2(\Phi) + \frac{1}{64\pi^2} Str\mathcal{M}^4(\Phi)\ln(\frac{\mathcal{M}^2(\phi)}{\Lambda^2} + \ldots..$$

CORRECTIONS $\delta m^2$ TO THE MASS PARAMETER OF THE FIELD $\phi$

ARE OBTAINED BY EXPANDING

$$Str\mathcal{M}^2(\phi) = c_2\phi^2 + \ldots \qquad Str\mathcal{M}^4(\phi) = c_4\phi^2 + \ldots.$$

$c_2$ IS DIMENSIONLESS, $c_4$ IS DIMENSIONFUL

IN THE SM

$$\delta m^2 = \frac{3}{64\pi^2}(3g_2^2 + g_1^2 + \lambda - 8y_t^2)\Lambda_{SM}^2$$

FOR SOLVING THE HIERARCHY PROBLEM, ONE NEEDS LOW SM CUT-OFF AND MILD DEPENDENCE OF $\delta m^2$ ON $\Lambda_{NEW}$ OF THE DEEPER THEORY

SUPERSYMMETRY: $c_2 = 0$ BECAUSE OF EQUAL NUMBER OF BOSONIC AND FERMIONIC DEGREES OF FREEDOM AND CORRELATED COUPLINGS

$$\delta m_H^2 = -(3/8\pi^2) y_t^2 M_{stop}^2 \ln(\Lambda_{UV}^2 / M_{stop}^2)$$

DYNAMICAL GENERATION OF THE ELECTROWEAK SCALE (IBANEZ&ROSS)!!

BUT

$$\lambda = \frac{g_{eff}^2}{8} \cos_{2\beta}^2 + \frac{3 y_t^4 \sin_\beta^4}{8\pi^2} \ln(M_{stop}/m_t)$$

$$m_h = 2\lambda v^2 = 125 GeV \to M_{stop} \approx 10 TeV$$

(LEFT-RIGHT STOP MIXING NEGLECTED) FT=1:1000

NMSSM: $$W = \lambda_N S H_u H_d$$

$$\lambda = \frac{g_{eff}^2}{8} \cos^2_{2\beta} + \frac{\lambda_N^2}{4} \sin^2_{2\beta}$$

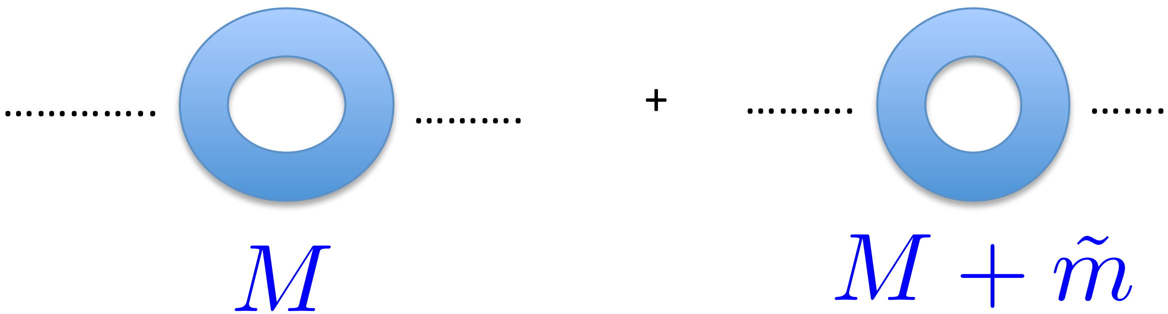
IN THE NMSSM THE HIGGS MASS CAN BE EXPLAINED BY TREE LEVEL EFFECTS AND THE TUNNING IS DETERMINED BY THE LHC EXCLUSION LIMITS ON THE COLORED STATES .

$$M_{stop} = 1TeV \rightarrow FT = 1:50$$

# SUPERSYMMETRY

**UNIQUE FEATURE: CANCELLATION OF QUADRATIC SENSITIVITY TO ARBITRARILY HIGH SCALES**

(FERMION – BOSON CANCELLATIONS)




~ $\tilde{m}\ln\Lambda$

Generic features of the scalar sector in (perturbative or non-perturbative) extensions of the SM with elementary ( 2HDM, supersymmetry) or composite scalars

- more than one scalar

- none of the scalars couple to *WW* and to fermions exactly like the SM Higgs boson (because of the mixing between them). THE ELECTROWEAK BASIS DOES NOT COINCIDE WITH THE MASS EIGENSTATE BASIS

BUT ONLY O(1%) EFFECTS IN THE HIGGS COUPLINGS FOR 1 TeV NEW MASS SCALE

$$g_{hVV} = \sin(\beta - \alpha)$$

$$g_{htt} = \frac{\cos\alpha}{\sin\beta} \qquad g_{hbb} = -\frac{\sin\alpha}{\cos\beta}$$

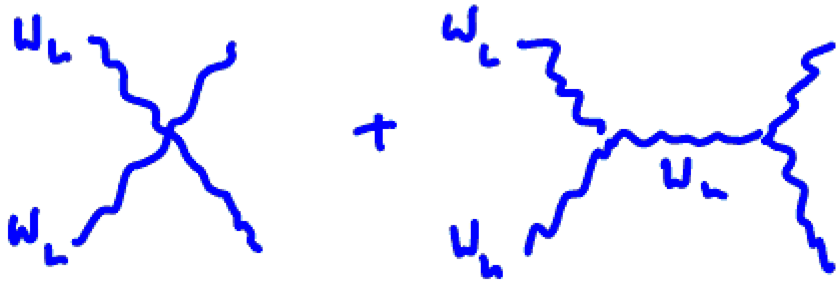
DECOUPLING LIMIT: $\alpha = \beta - \pi/2$

------→ SM COUPLINGS

H,A heavier than 500 GeV

ADD INFO ON H AND A AS A FUNCTION OF THE HIGGS COUPLINGS

# Unitarity of $W_L W_L (Z_L)$ scattering amplitude SM:




$\sim \frac{s}{v^2}$

violates unitarity
around $\sqrt{s} \sim 1.5$ TeV


$\sim - \frac{s}{v^2} \frac{s}{s - m_h^2}$

restores
unitarity

ANOTHER „SOLUTION” TO THE NATURALNESS PROBLEM: HIGGS DOUBLET AS A GOLDSTONE BOSON AND, IN CONSEQUENCE, THE HIGGS PARTICLE AS A PSEUDO-GOLDSTONE

GENERAL STRUCTURE OF THE MODELS:

THE EWSB SECTOR HAS AN EXTENDED GLOBAL SYMMETRY, WITH ITS SU(2) SUBGROUP GAUGED BY THE SM . THAT GLOBAL SYMMETRY IS SPONTANEOUSLY BROKEN, LEAVING AT LEAST CHIRAL SU(2)xSU(2) AS UNBROKEN SUBGROUP

GOLDSTONE BOSON MASS REMAINS ZERO AFTER RADIATIVE CORRECTIONS (FOLLOWS FROM THE SHIFT SYMMETRY)

AFTER SOFT EXPLICIT BREAKING OF GLOBAL SYMMETRY WE GET A POTENTIAL FOR THE GOLDSTONE BOSON (HIGGS DOUBLET) FROM RADIATIVE CORRECTIONS AND EWSB IS BROKEN

THIS IDEA APPEARS IN MANY L MORE SPECIFC APPROACHES TO EWSB

**OFTEN LINKED TO A NEW CONFINING STRONGLY INTERACTING SECTOR WITH EXTENDED GLOBAL SYMMETRY; IT IS DESCRIBED BY EFFECTIVE THEORY OF COMPOSITE STATES, A LA (PION, NUCLEON)**
**SIGMA MODEL**

**BUT THERE IS ROOM FOR IT IN MODELS WITH ELEMENTARY SCALARS AS WELL**
**e.g. LITTLE HIGGS**

**IT CAN EVEN BE COMBINED WITH SUPERSYMMETRY- DOUBLE PROTECTION (SUPERSYMMETRIC TWIN HIGGS)** PHILOSOPHY: SAVE SUSY (AVOID EXP BOUNDS ON COLORED PARTICLES) and provide UV COMPLETION TO „EFFECTIVE" TWIN HIGGS