THEORIES OF ELECTROWEAK SYMMETRY BREAKING

There is little doubt that the electroweak theory
based on the SU(2)xU(1) gauge symmetry
and the Brout-Englert-Higgs mechanism
is the correct effective theory

up to the energies O(100) GeV.

- Crucial for Brout-Englert-Higgs mechanism:

spontaneous breaking of a global symmetry, at least

$$SU(2)\times SU(2)\rightarrow SU(2)$$

of some sector coupled to the weak gauge bosons is the origin of their masses

The BEH mechanism:
Goldstone bosons become the longitudinal modes of the gauge bosons W, Z which acquire masses.

Simple origin of the needed interactions with chiral symmetry (to be spontaneously broken) – self interacting scalar field (Higgs field)

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

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

Big virtue - renormalizability; also easy description of fermion masses

$$SU_L(2) \times SU_R(2) \sim SO(4)$$

$SO(4)$ is spontaneously broken to

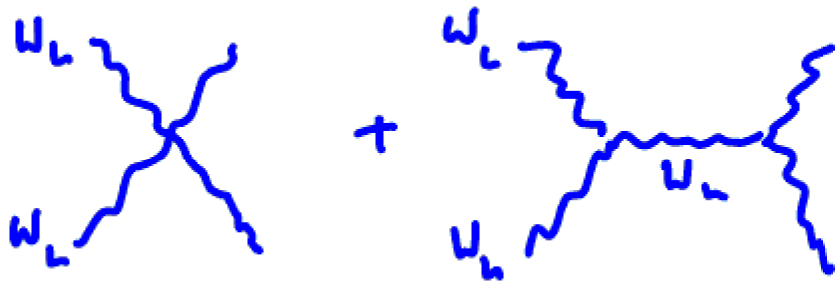
$$SO(3) \sim SU(2)$$

One gets 3 Goldstone bosons and a physical scalar particle

$$\mathcal{H} \approx e^{i\frac{G^a \tau^a}{v}} \begin{pmatrix} v+h & 0 \\ 0 & v+h \end{pmatrix}$$

$$\to v e^{i\frac{G^a \tau^a}{v}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \text{ for } E \ll m_h$$

Unitarity of $W_L W_L (Z_L)$ scattering amplitude in 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

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

Moreover, the hierarchy problem: strong sensitivity of the Fermi scale to the cut-off of the SM (via radiative corrections to the Higgs potential)

GOALS

a)Explain dynamically the origin of the Fermi scale
b) Avoid the hierarchy problem
c) NO CONFLICT WITH ELECTROWEAK DATA (LEP)

IT IS SUPRISING HOW DIFFICULT IT IS TO ANSWER THOSE QUESTIONS BY EMBEDDING THE SM INTO A CONSISTENT AND PREDICTIVE EXTENSION

Big hierarchy problem

Solutions: 1) supersymmetry

Λ can remain to be M_{PL}

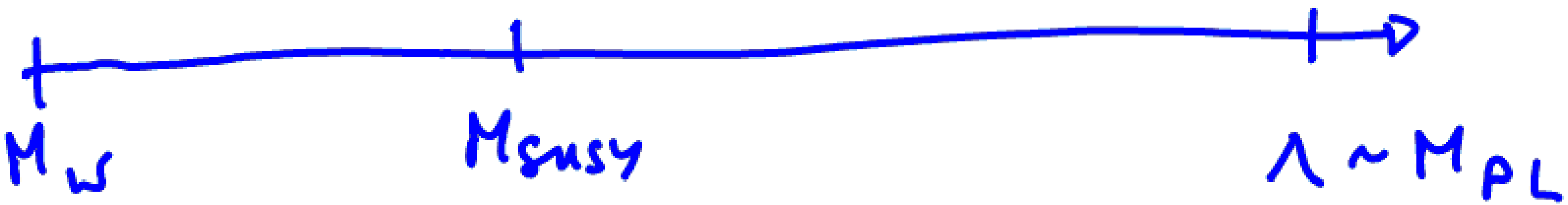
2) Low cut-off Λ by new strong interactions

Perturbative physics up to 10 TeV (LEP)

How low Λ can be? $\Lambda \gtrsim 10$ TeV (LEP)

Little hierarchy problem

Supersymmetry :



Quadratic sensitivity of the Higgs potential to M_{susy}

MSSM

$$\frac{1}{2}M_Z^2 \approx -(m_{H_u}^2 + \mu^2)|_{tree} + 0.1 M_{SUSY}^2 \ln \frac{\Lambda_{MSSM}}{M_{SUSY}}$$

$$10^{-2}\text{TeV} \quad \text{vs} \quad O(1)\text{TeV}|_{tree} + O(1)\text{TeV}$$

constrained by m_h > 114 GeV

for $\Lambda_{MSSM} \sim M_{GUT}$

„Little" supersymmetric hierarchy problem

- **Supersymmetry**

- Dynamical generation of the Higgs potential in terms of the soft supersymmetry breaking parameters (to be explained by a still deeper theory) and quantum corrections to the scalar potential

OTHER VIRTUES OF SUPERSYMMETRY

- **Rationale for elementary scalars –two Higgs doublets**

- **No conflict with precision eletroweak data (only loop effects, with SM couplings)**

- **Unification of gauge couplings (room for GUTs)**

STRONGLY INTERACTING PHYSICS AS THE ORIGIN OF THE FERMI SCALE ?

<u>CHALLENGES:</u>

TO BE CONSISTENT WITH LEP PRECISION DATA, THE ON-SET OF NEW STRONG INTERACTIONS ABOVE 10 TeV.

BUT WHAT UNITARIZES WW AMPLITUDE AT 1.5 TeV, THEN?

HOW TO MAKE A STRONGLY INTERACTING THEORY CALCULABLE?

Hundreds of theoretical models but only few basic concepts

Little hierarchy problem in strongly interacting theories with low cut-off Λ

M_W ← perturbative → $\Lambda \gtrsim 10$ TeV

Avoid quadratic sensitivity of the Higgs potential to Λ!

Solutions:

- higgsless models
- higgs doublet as a pseudo-Goldstone boson

Higgs doublet as a pseudo-Goldstone includes

Little Higgs

Composite Higgs

Higgs as A_5

AdS/CFT

. . . .

Higgs doublet is a (pseud-Goldstone) of an extended global symmetry in the Higgs-top sector

SIMPLE EXAMPLE: GLOBAL SO(5) → SO(4) AT SCALE f

SO(4) IDENTIFIED WITH SU(2)xSU(2) OF THE HIGGS SECTOR OF THE SM

4 GOLDSTONE BOSONS IDENTIFIED WITH THE HIGGS DOUBLET H

THE SINGLET IN A SCALAR FIVE-PLET BREAKS SO(5)

$$\phi \equiv (H, S)$$

HIGGS DOUBLET AS A (PSEUDO-)GOLDSTONE BOSON:

- $m_H^2|_{tree} = 0\,!$

- cut-off to SM is given by the scale of breaking of the global symmetry

- fermion-fermion and boson–boson cancellations are responsible for the vanishing potential of the Goldstone boson; hence new fermions

But how to get the potential ? (explicit breaking)

STRONGLY COUPLED BEYOND SM:

Higgsless models and models with light Higgs doublet as a pseudo-Goldstone boson (more interesting)

New developments based on new ideas for delaying the on-set of uncalculabe strongly coupled theory to higher Λ (> 10 TeV); with perturbative physics below that scale;

The main advantage:
saturation of unitarity in $W_L W_L$ is postponed in calculable way (perturbative) by exchange of new vector bosons

THE ORIGIN OF NEW VECTOR BOSONS:

- Kaluza-Klein modes of compactified extra dimensions

- New gauge interactions (deconstructed version of extra dimensional models; without physical (real) extra dimensions)

One gets massive W, Z and tower of *n* W_i', Z_i';

Striking experimental signatures related to the presence of three physical scales:

$\langle H \rangle = v$, $\langle \phi \rangle = f$, $\Lambda \sim 4\pi f$

breaks SU(2)xU(1) | breaks SO(5) | cut-off to perturbative physics

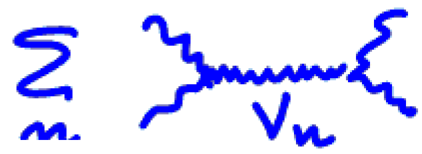
$v/f \leq 10$ for v to be natural

1) New fermions – to protect Goldstone nature of H above scale f

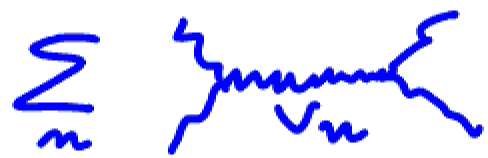
heavy top quark T, $m_T \sim O(f)$

2) Partial unitarization of the WW scattering by the light Higgs boson

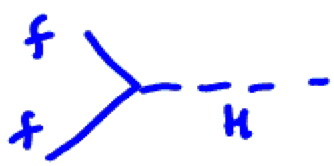
$$A_{WW} \sim \frac{s}{v^2} - \left(1 - \frac{v^2}{f^2}\right)\frac{s}{v^2}\frac{t}{t-m_h^2} +$$



$$\approx \frac{s}{f^2} +$$



3) Higgs boson couplings to fermions



$$Y\left(1 - \frac{v^2}{f^2}\right)^{\frac{1}{2}}$$

Difficulties

- Consistency with precision electroweak (tree level mixings)

- $$\frac{\Lambda}{M_{KK}} \sim \frac{4\pi}{g_n} \approx \underline{1}$$

$$M_{KK} \sim g_n f$$

$$\Lambda \sim 4\pi f$$

DOUBLE PROTECTION FOR THE HIGGS POTENTIAL

Supersymmetry plus spontaneously broken at low scale f global symmetry (by perturbative interactions);

Higgs doublet is a Nambu-Goldstone boson;

no strongly interacting new physics

Two welcome features

$$m_H^2|_{tree} = 0$$

$$\ln \Lambda_{MSSM} \rightarrow \ln f$$

in the Higgs potential

One-loop corrections to Higgs potential must be proportional to $M_{SUSY}^2 f^2$ and are finite

Therefore they are FINITE!

$$\Delta V \sim \mathrm{STr}\, \mathcal{M}^4 \ln \Lambda_{uv} + \ldots$$

$$\mathrm{STr}\, \mathcal{M}^4(\mathcal{H}) \sim y_t^2\, m_{\tilde{q}}^2\, \mathcal{H}^2$$

forbidden by SU(3)

$$\mathrm{STr}\, \mathcal{M}^4(\mathcal{H}) \sim y_t^2\, f^2\, \mathcal{H}^2$$

forbidden by supersymmetry

1 - loop

$$\delta m_h^2 \approx -\frac{3}{8\pi^2} y_t^2 \left[(M_{soft}^2 + f^2) \times \ln (M_{soft}^2 + f^2) - M_{soft}^2 \ln M_{soft}^2 - f^2 \ln f^2 \right]$$

SUMMARY

LHC WILL DISCOVER THE PHYSICS RESPONSIBLE FOR THE DYNAMICAL ORIGIN OF THE FERMI SCALE

SUPERSYMMETRY REMAINS TO BE THE LEADING CANDIDATE BUT…

Each approach to the physics at TeV scale has its generic, model independent, experimental signatures

The mere discovery of a Higgs boson is not enough for understanding the mechanism of electroweak symmetry breaking