Bagger ①

Theory points to new physics at TeV scale.

Consider gauge bosons

γ W Z g h

W, Z different. They have mass.
Focus on W_L Z_L

Compute $W_L W_L \to W_L W_L$ in SM

$\sigma \sim s/v^4$ where $v = 250$ GeV.

Unitarity violated ~ 1 TeV.

Something must happen — at CERN LHC!

$\boxed{\text{WHAT?}}$

Let's look at massive $U(1)$ gauge boson.

$$\mathcal{L} = -\frac{1}{4} F_{mn} F_{mn} - \frac{1}{2} m^2 A_m A_m$$

Not gauge invariant!

$$A \to A - \frac{1}{g} \partial \lambda$$

Restore gauge invariance with help of Goldstone boson

$$\pi \to \pi + \lambda v$$

$$D_m \pi = \partial_m \pi + g v A_m$$

$$\mathcal{L} = -\frac{1}{4} F_{mn} F_{mn} - \frac{1}{2} D_m \pi D_m \pi .$$

Gauge invariant! In "unitary gauge"
$\pi \to 0 \Rightarrow$ massive gauge field with

$$m = g v$$

So far, just formalism

Why does this help?

Recall massive gauge field has 3 polarizations

$$\epsilon_T \sim \begin{matrix} (0,1,0,0) \\ (0,0,1,0) \end{matrix}$$

$$\epsilon_L \sim \left(\tfrac{k}{E}, 0, 0, k\right)/m$$

Longitudinal polarization dominates for $k \gg m$.

Also, $D_\mu \pi = \partial_\mu \pi + g v A_\mu$

$\Rightarrow$ equivalence theorem.

$$A_L \rightarrow \pi \qquad k \gg m$$

Use our experience from π physics!

For the SM, the formalism is a bit more complicated.

$$SU(2) \times U(1) \subset SU(2)_L \times SU(2)_R .$$

Goldstone: $\Sigma = e^{i\pi\cdot\tau/v}$

$$\Sigma \to L \Sigma R^\dagger$$

Gauge fields:

$$W_m \to L W_m L^\dagger - \frac{1}{g_L} \cancel{L^\dagger \partial_m L^\dagger} \, \partial_m L \, L^\dagger$$

$$B_m \to R B_m R^\dagger + \frac{1}{g_R} R \partial_n R^\dagger$$

Covariant Derivative:

$$D_m \Sigma = \partial_m \Sigma + g_L W_m \Sigma - g_R \Sigma B$$

$$B_n = B_m \tau_3$$

$$\mathcal{L} = -\frac{1}{4} \operatorname{Tr} W_{mn} W_{mn} - \frac{1}{4} \operatorname{Tr} B_{mn} B_{mn}$$

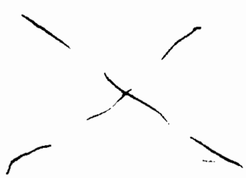
$$- v^2 \operatorname{Tr} D_m \Sigma^\dagger D_m \Sigma$$

In unitary gauge,

$$m_W^2 = m_Z^2 \cos^2\theta$$

$$m_\gamma = 0$$

Let's use this to compute W_L scattering. Because of equivalence theorem we compute $\pi\pi$ scattering



$$\mathcal{L} \sim v^2 \frac{\pi\partial\pi}{v^2} \frac{\pi\partial\pi}{v^2}$$

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

$$\sigma \sim \frac{s}{v^4} \quad ✓$$

Simplicity!

Note that the gauged Lagrangian is nonrenormalizable.

It's an effective Lagrangian valid for energies $E \lesssim 4\pi v$ $\sim 3\,\text{TeV}$

Once we adopt that point of view, we can add other operators, consistent with gauge invariance, and use experiment to determine the coefficients.

$$\Delta\mathcal{L} = g_R^2 v^2 T \left(\operatorname{Tr} \tau_3 \Sigma^\dagger D_n \Sigma\right)^2$$

$$+ g_L g_R S \operatorname{Tr} \Sigma^\dagger W_{mn} \Sigma B_{mn}$$

$$+ \cdots$$

"oblique corrections"

Peskin – Takeuchi

Find strong constraints!

1990 – 2000 wreaked havoc on theory ...

Precision measurements are consistent, however, with a Higgs boson.

$$\varphi = h\, e^{i\pi\cdot\tau/v}$$

$$\langle h\rangle = v$$

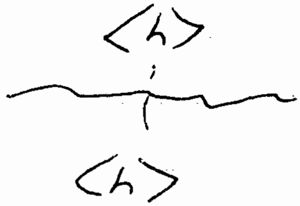
Fundamental spin zero particle, h.

precision data $\quad m_h \lesssim 250$ GeV
direct search $\quad m_h \gtrsim 115$ GeV

Close at hand!

The Higgs unitarizes WW scattering

Also gives mass to gauge bosons



$m^2 \sim g^2 v^2$

Also gives mass to fermions!

Will be discovered at LHC — if it is there!

It is possible that the Higgs is all we'll find.

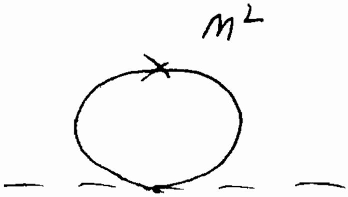
<u>Problem</u>: Nothing keeps m_h at the TeV scale.

Gauge bosons ~ gauge symmetry
Fermions ~ chiral symmetry
Scalar particles ~ NOTHING.

To see the problem, consider a toy theory with two scalars

One massless, h, - - - -
one massive, H, ———

$$\mathcal{L} = \partial h \partial h + \partial H \partial H + M^2 H^2 + \lambda h^2 H^2$$



$$\delta m_h^2 = \frac{\lambda}{16\pi^2} M^2$$

Interactions drive up scalar mass.

Gravity wants to drive it all the way to M_p!

For Higgs to be light, requires tuning

$$\frac{m_W^2}{M_p^2} \sim 10^{-32} \quad !$$

Options

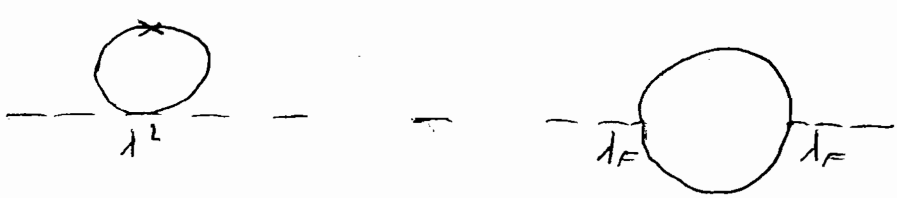
1. Live with it
2. Find mechanism

Two possibilities are motivated by strings

① Add a new fermionic dimension to spacetime

$$\Phi(x,\theta) = \underbrace{h(x)}_{\text{boson}} + \theta^\alpha \underbrace{\chi_\alpha(x)}_{\text{fermion}} + \theta^\alpha\theta_\alpha \underbrace{F}_{\text{aux.}}$$

Power series truncates.



boson loop

fermion loop

Cancel!

New fermionic dimension
changes spacetime symmetry

Poincaré → SUSY!

Bose - Fermi symmetry.

SUSY is a symmetry that
protects spin-zero scalar
fields! Just like
gauge symmetry, chiral
symmetry...

2 Add new bosonic
dimensions to spacetime.
Assume 1 xd of $R \sim 1/\text{TeV}$.

$$\Phi(x,y) = h_0(x) + \sum_{n\neq 0} h_n(x) \cos\left(\frac{ny}{R}\right)$$

boson — no bosons!

An extra dimension stabilizes Higgs by lowering UV cutoff ...

In each case, lots to see at LHC!

Scorecard:

stabilize Higgs	✓✓
dark matter	✓✓
neutrino mass	✓✓
CP violation	✓✓
inflaton	✓
dark energy	? (SUSY ✓)