A Higgs Boson Composed of Gauge Bosons

F. J. Himpsel, Physics Dept., University of Wisconsin Madison

The standard model of particle physics contains a Higgs boson that disturbs the elegance of the theory. It postulates an ad-hoc potential for the Higgs boson. There is a quadratic term that mimics a mass term. But it has the wrong sign (corresponding to an imaginary mass). A fourth-order term is added to introduce a coupling strength. Both terms use adjustable parameters. That's why it took so long to find the narrow Higgs peak in the large energy range of about 100-1000 GeV.

This artificial construct has been a concern to many theorists. As a result, models have been proposed where the Higgs particle is not fundamental but composed of fermion pairs, like the electron pairs in superconductors.

Why not use gauge boson pairs instead?

Gauge bosons transmit the three fundamental interactions. The Higgs boson involves the weak interaction with the gauge bosons W^i (i=1,2,3). Why not use them?

There is a hitch:

Gauge bosons are four-vectors. They point toward a particular direction in space-time. That seems to violate Lorentz invariance of the vacuum. The standard Higgs boson has to be an isotropic Lorentz scalar.

The fix:

Use the isotropic scalar product between pairs of gauge bosons, similar to the scalar combination of fermion pairs.

Defining the composite Higgs boson:

Gauge and Higgs bosons have the same dimension. Therefore, it is possible to define a Higgs *pair* as superposition of gauge boson *pairs* with a dimensionless factor. That is not possible for fermions.

The Higgs mass:

Such a definition fixes the Higgs mass as $M_H = \upsilon/2$ where υ is the vacuum expectation value (VEV) of the Higgs boson. It can be obtained directly from the observed four-fermion coupling G_F.

The resulting value of 123.1 GeV matches the observed Higgs mass of 125.1 GeV within $\approx 2\%$. That is in line with the accuracy of the leading-order approximation used here (given by $\alpha_w = g^2/4\pi \approx 3\%$).

Standard Higgs:

$$H_0 = \langle H_0 \rangle + H$$

$$\langle H_0 \rangle = 246.22\ \text{GeV}$$

H = observed Higgs

VEV: $\langle H_0 \rangle \equiv \upsilon$

Composite Higgs:

Definition from SU(2) gauge bosons:

$$H^2 = -g^2 \cdot \Sigma_i (W^i W^i) \cdot \tfrac{1}{2} (\tfrac{1}{2}\upsilon)^2$$

Pure SU(2)

(...) = scalar product

g = weak coupling

Mass Lagrangian:

$$\tfrac{1}{2} M_H^2 H^2 = -\tfrac{1}{2} M_W^2 \Sigma_i (W^i W^i)$$

$M_H^2 \to (\tfrac{1}{2}\upsilon)^2$ $\qquad$ $M_W^2 \to (\tfrac{1}{2} g \upsilon)^2$

Higgs mass M_H from its VEV υ via the standard result $M_W = \tfrac{1}{2} g \upsilon$

Why didn't I predict the Higgs mass?

Before the discovery of the Higgs boson, many expected a broad resonance approaching the TeV unitarity limit. When it was found with a much lower mass, it became clear that the pair binding energy must be small. That points to the gauge boson self-energy, a correction to the quadratic mass Lagrangian. It also explains the negative sign of the quadratic Higgs potential, which is needed to form a bound state. Although I missed out on predicting the Higgs mass, nobody else has been able to calculate it. (If I am wrong, let me know).

Consequences of this model:

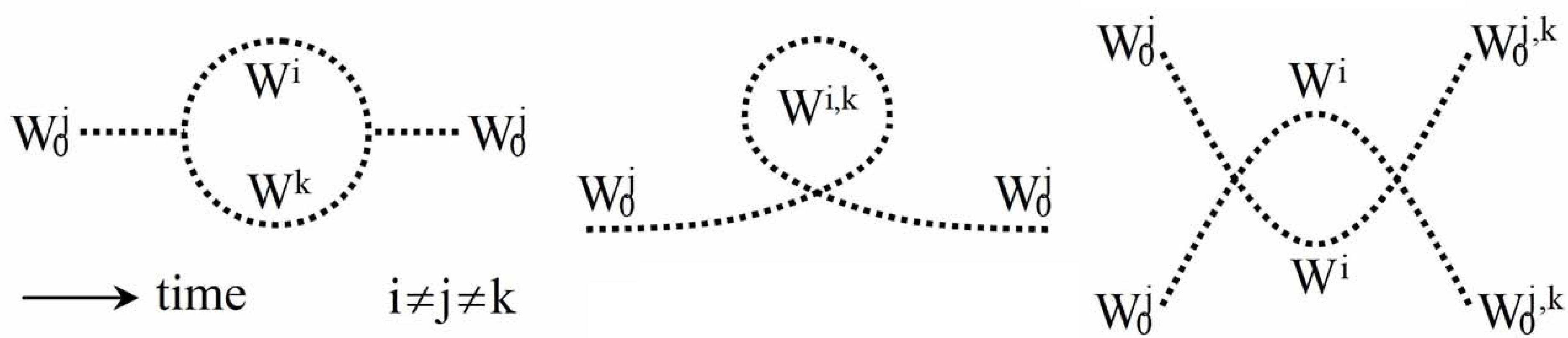
1) The Higgs boson is not an elementary particle. It is a composite of the truly elementary gauge bosons W, Z of the weak interaction.

2) The adjustable Higgs potential is replaced by the quadratic and quartic+biquadratic self-interactions of the W, Z.

3) A simple calculation provides the Higgs mass in leading order.

The gauge boson potential:

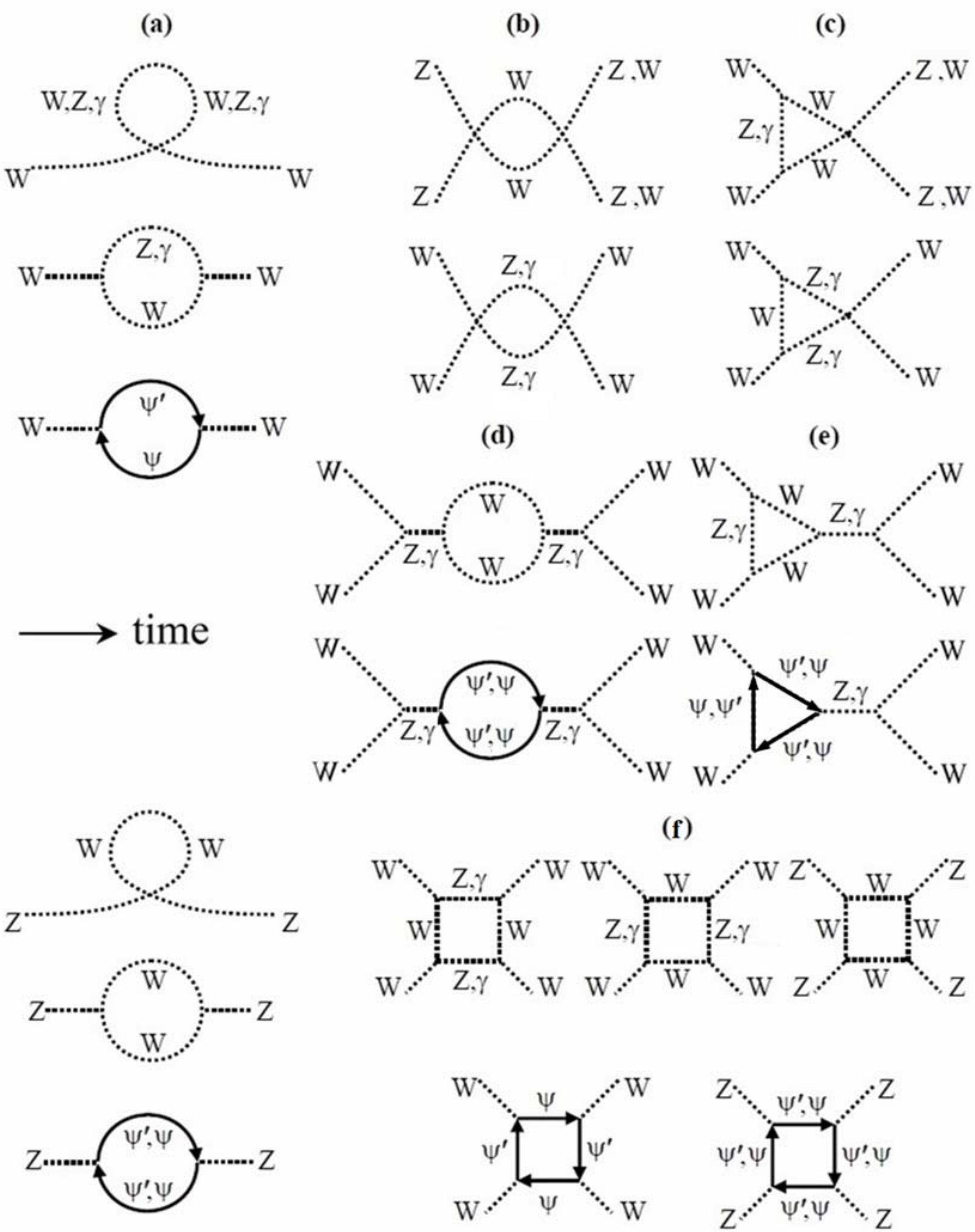
A Higgs-like potential is formed by the one-loop self-interactions of the gauge bosons W^1,W^2,W^3 that transmit the weak interaction. They contain quadratic terms for the gauge boson self-energies (left, center) and biquadratic+quartic terms for their pairs (right). The don't contain any adjustable parameters. Here are some basic diagrams for the SU(2) symmetry of the pure weak interaction:



The SU(2) symmetry forms the simplest example of a Yang-Mills theory, a class of models that have been used extensively in particle theories (including the standard model). It is the topic of a Millenium Prize.

For the full standard model the diagrams proliferate. The SU(2) gauge boson W^3 mixes with the B of the U(1) hypercharge group, forming the Z and the photon γ. The W^1 and W^2 form the charge eigenstates W^+ and W^-.

Internal Higgs lines, Goldstones, counter-terms, and ghosts are omitted.



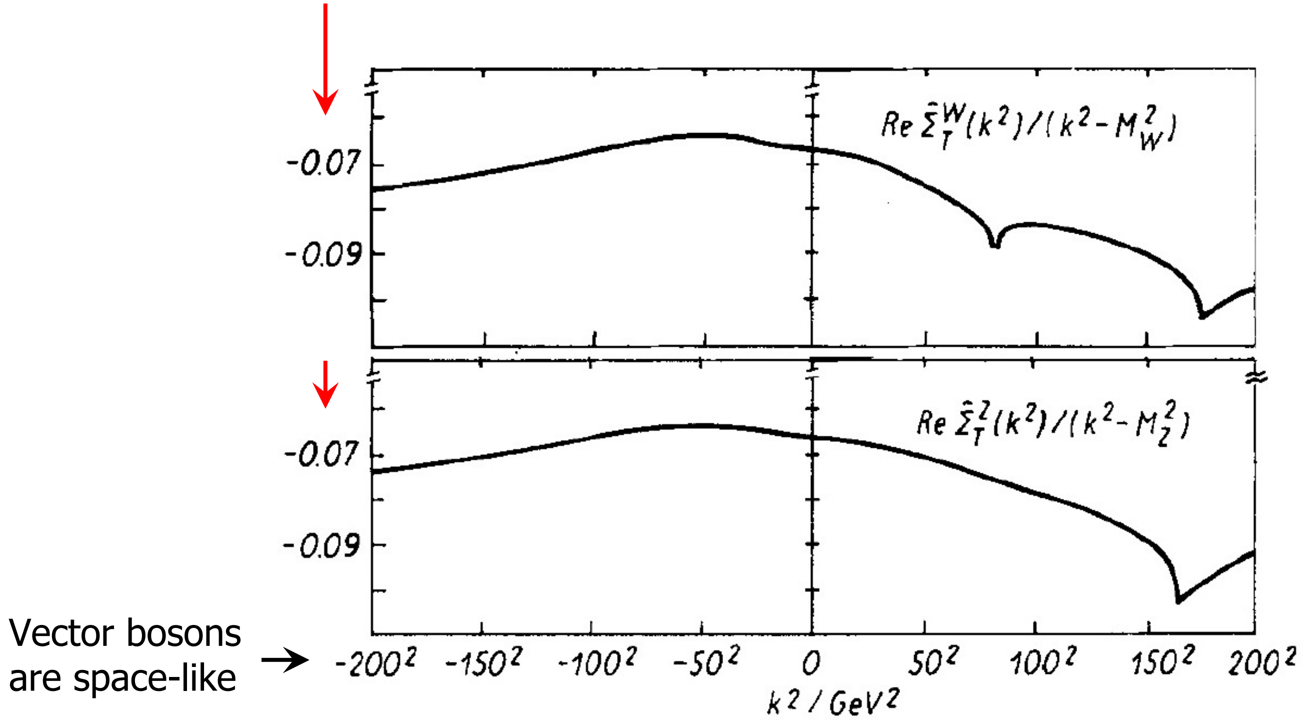
Typical one-loop self-interactions for the weak gauge bosons W, Z in the standard model:

(a) Quadratic diagrams of $O(g^2)$ for the self-energies Σ^W, Σ^Z.
(b)-(f) Biquadratic and quartic terms of $O(g^4)$ involving the scalar pairs (WW),(ZZ) that define the composite Higgs boson. ψ stands for fermions.

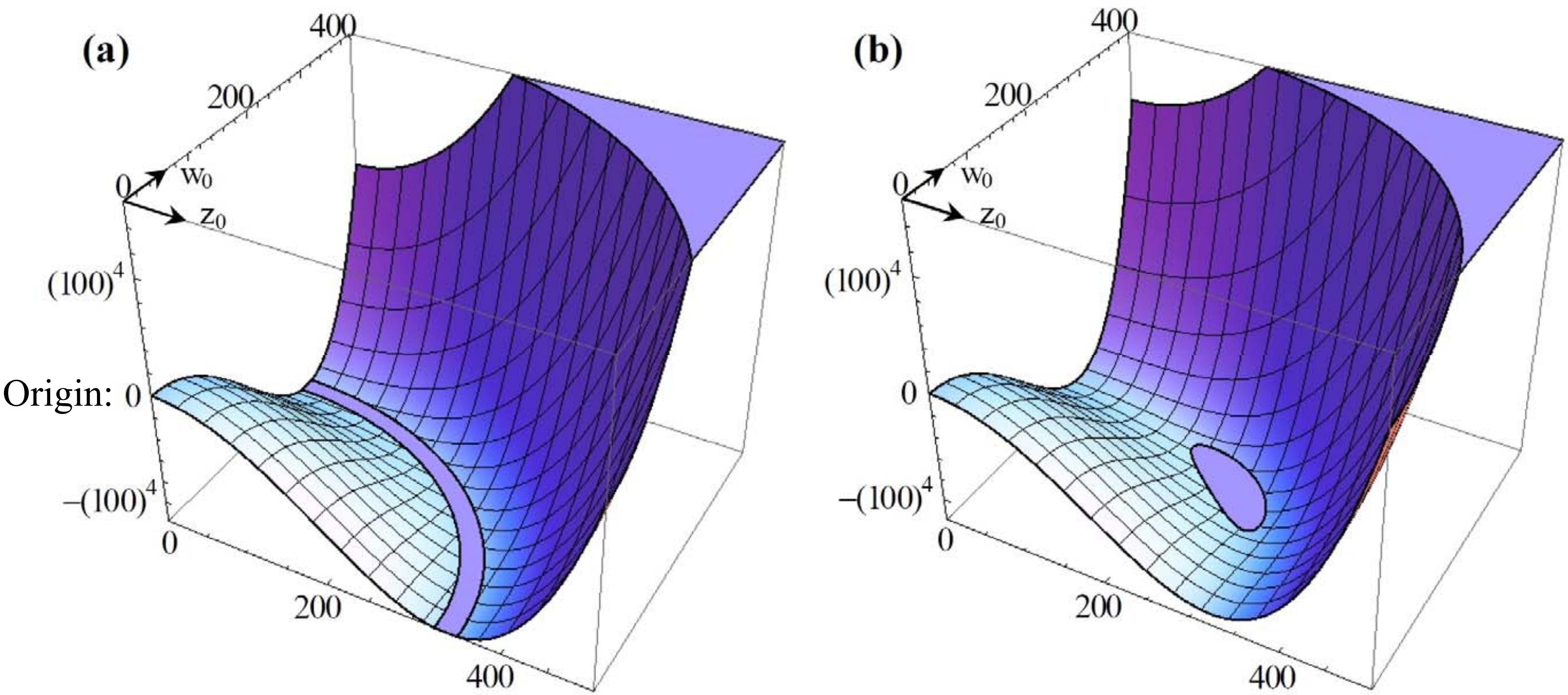
Theoretical test of the model via self-consistency:

Calculating the gauge boson potential from such diagrams will determine whether they have finite VEVs to form a composite Higgs boson. Their quadratic potential needs to be negative (attractive), and the confining biquadratic+quartic potential must be positive (repulsive).

Early results indicate that the quadratic terms (i.e. the self-energies Σ^W, Σ^Z) are indeed negative (from Böhm et al., Fortschr. Phys. 1986, Fig. 10,11):



Before getting into such calculations I tried a phenomenological approach by parametrizing the gauge boson potential and matching as many data as possible. The relevant variables are the scalar products $(W^{+}W^{-})$, (ZZ) describing neutral pairs of gauge bosons. Results are plotted for two different topologies of the potential. Energies are in GeV.



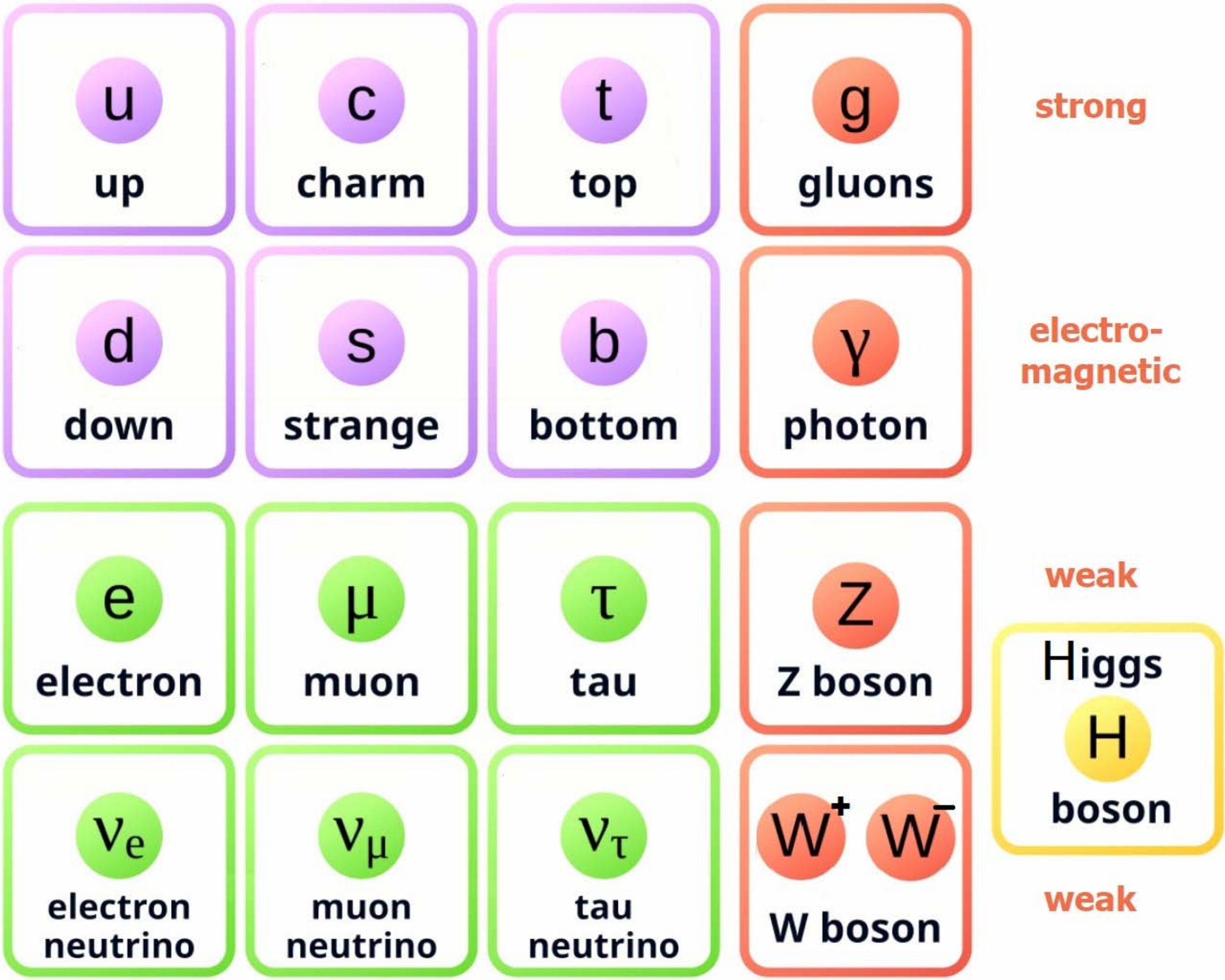
Experimental tests of the composite Higgs model: Since the composite Higgs boson is defined completely in terms of the W,Z gauge bosons, its mass, width, and cross sections can be calculated from first principles.

To observe pairing of Higgs bosons (and gauge bosons) requires energies near the 250 GeV pair threshold. This energy also happens to be equal to the Higgs VEV. Selectivity in producing and detecting Higgs boson pairs will be crucial. Such a "Higgs factory" will take decades to build.

Precision measurements at the pair pole can test next-to-leading order mass corrections of 3%. This path has been successful for the Z at LEP.

Learn from the methods for detecting gluons, the gauge bosons of the strong interaction. In general, composite particles lead to characteristic jets and have signatures in their form factors which are quite different from those of point-like elementary particles.

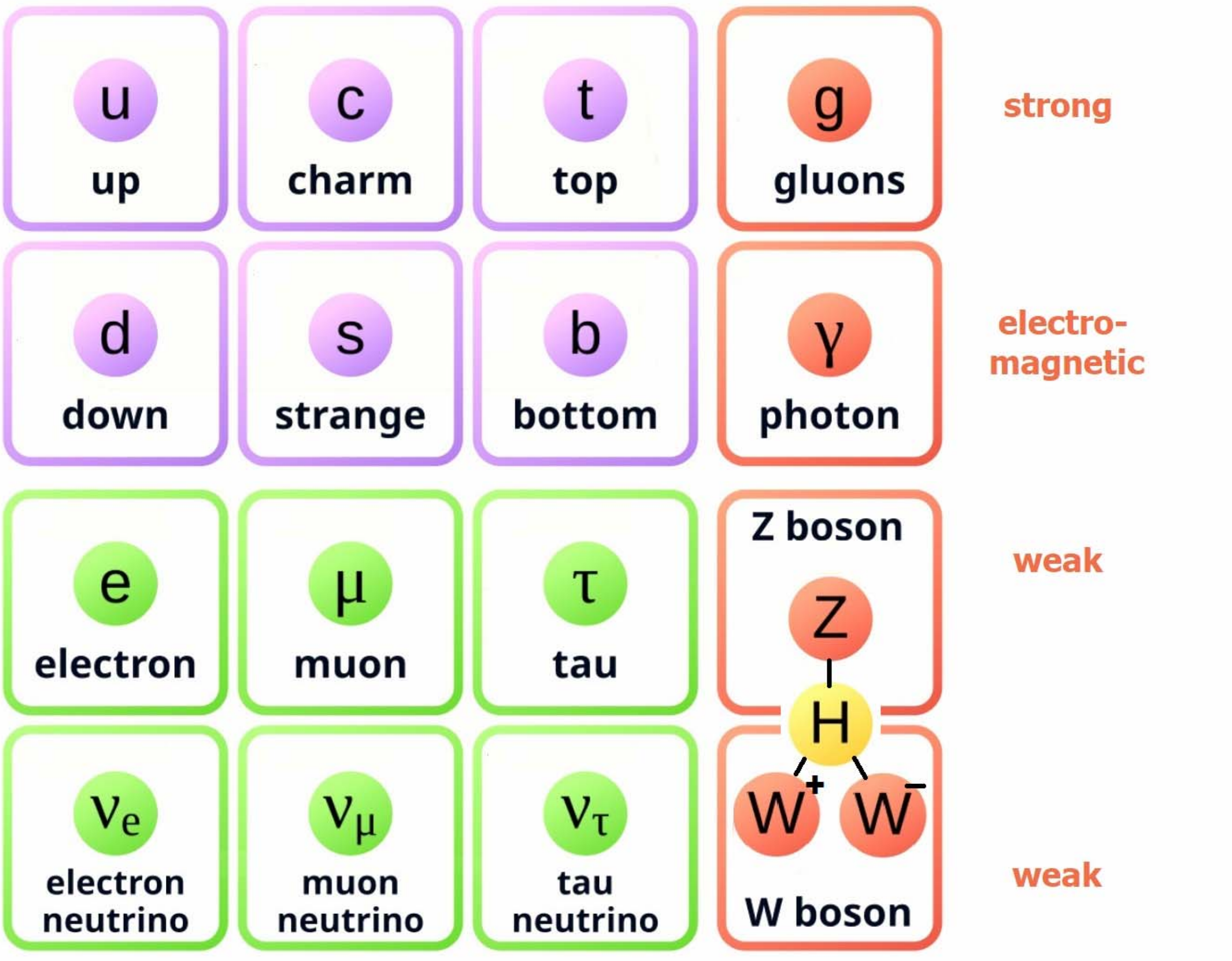
The bigger picture: Simplify this …



Sticks out

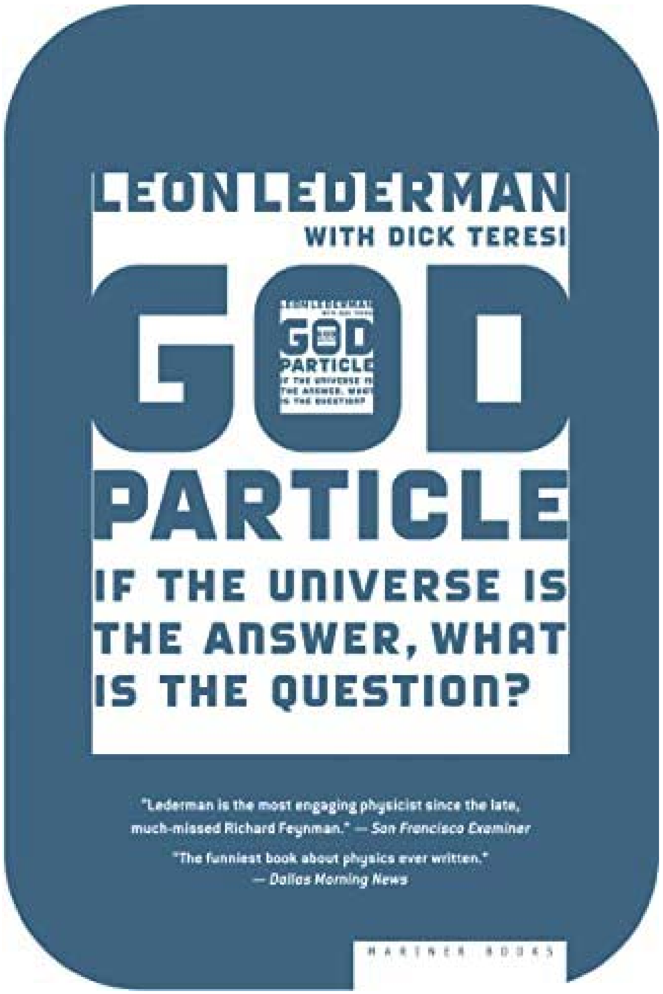
The Elementary Particles: Standard Model

… to that:



The Elementary Particles: Proposed

The Higgs particle loses some of its lustre by not being elementary, but one may still call it the God particle:



The Holy Trinity

W^+

W^-

Z

Extra 1: Two Lagrangians

Gauge invariance is is a crucial criterion for defining the Lagrangian in gauge theories. For the mass Lagrangians one can argue that they must be gauge-invariant, because mass is an observable.

An explicitly gauge-invariant Lagrangian is obtained by replacing the fields H, W^i in the mass Lagrangian with the fields H_0, W_0^i. Those are massless (as required by gauge invariance), but have finite VEVs. In addition, one needs 3 Goldstones as part of the Higgs field to match the gauge fields W^i.

Notice that the fields H, W^i are given in the unitary gauge, whereas the massless fields correspond to the Landau gauge. Transitions from one gauge to another are tricky.

Extra 2: Connect the two definitions

Expand the gauge-invariant definition into a series:

$$H_0^2 \quad = \quad (\upsilon + H)^2 \quad = \upsilon^2 + 2\upsilon H + H^2 \ldots$$

$$(W_0^i W_0^i) = (\langle W_0^i \rangle \langle W_0^i \rangle) + 2(\langle W_0^i \rangle W_0^i) + (W^i W^i) \ \ldots$$

This resembles two truncated Taylor series if $H/\upsilon \ll 1$.
Indeed, the observed Higgs field H must represent small oscillations around a large VEV υ. Otherwise the VEV would hardly be noticeable.

Comparing the two Taylor series above term by term yields 3 relations:

- The leading terms connect the VEVs of Higgs and gauge boson pairs.
- The mixed products yield a linear relation between Higgs and gauge bosons. That is needed for a standard Yukawa coupling to fermions.
- The last terms form the definition via mass Lagrangians on Slide 4 .

Extra 3: Peter Higgs and his boson

After emphasizing the drawbacks of the standard Higgs boson, it is appropriate to recall the history of the 1964 Higgs papers. Apparently, a referee suggested to include an example for the consequences of the new concept. That led to the simplest possible Higgs potential (the bi-quadratic "Mexican Hat" potential found in textbooks).

While Peter Higgs became famous for his boson, the crucial achievement was the Brout-Englert-Higgs mechanism of symmetry breaking. It was recognized eventually with a well-deserved Nobel Prize.

This mechanism solves a long-standing puzzle, why symmetry plays a crucial role in particle physics, but is broken in the real world. In essence, the equations remain symmetric, but our universe has selected a particular, non-symmetric solution. It's like having your cake and eating it too.