A Higgs Boson Composed of Gauge Bosons

F. J. Himpsel, April 15, 2024

The standard model of particle physics contains a Higgs boson that blemishes 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 has the wrong sign (corresponding to an imaginary mass). A fourth-order term is added, which does not exist for any of the fundamental particles. These terms generate two adjustable parameters. One of them is related to the mass of the Higgs boson.

This construct seems rather artificial, which 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, similar to the electron pairs in superconductors.

Why not gauge boson pairs? The three fundamental interactions of the standard model are transmitted by gauge bosons. The Higgs boson involves the weak interaction, whose gauge bosons are the W^-,Z,W^+. Why not use them?

There is a hitch: Gauge bosons are four-vectors. They point toward a particular direction in space-time. By taking an anisotropic vacuum expectation value (VEV) they seem to violate Lorentz invariance of the vacuum. The standard Higgs boson is an isotropic Lorentz scalar.

Two fixes: 1) Use the isotropic scalar product between pairs of gauge bosons. 2) Instead of giving all “virtual” gauge bosons in vacuum the same VEV, assign each of them an individual expectation value (EV). Then arrange these EVs such that they cancel out when averaging over the vacuum (like the momentum vectors). This is achieved by choosing the EV along the polarization vector of a particular gauge boson. Gauge bosons with opposite polarizations then cancel each other.

Defining the composite Higgs boson: Gauge and Higgs bosons have the same dimension. Therefore, one can define a Higgs pair as superposition of gauge boson pairs using a dimensionless factor (see the next slide). This is not possible for fermion pairs. The factor is chosen by setting the mass Lagrangians of the Higgs and gauge bosons equal to each other, while preserving the result $M_W = \frac{1}{2} g v$ from the standard model.

The Higgs mass: This definition fixes the mass of the Higgs boson as half of its VEV v. The latter can be obtained directly from the measured four-fermion coupling G_F.

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

Standard Higgs:

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

$$\langle H_0 \rangle = v = 2^{-1/4} G_F^{-1/2} = 246.22\,\mathrm{GeV}$$ VEV

$$V_H = -\tfrac{1}{2}\mu^2 \cdot H_0^2 + \tfrac{1}{4}\lambda \cdot H_0^4$$ Higgs potential

Adjustable parameters

Composite Higgs:

$$\boxed{H_0^2 = -g^2 \cdot \Sigma_i (W_0^i W_0^i)}$$ Definition

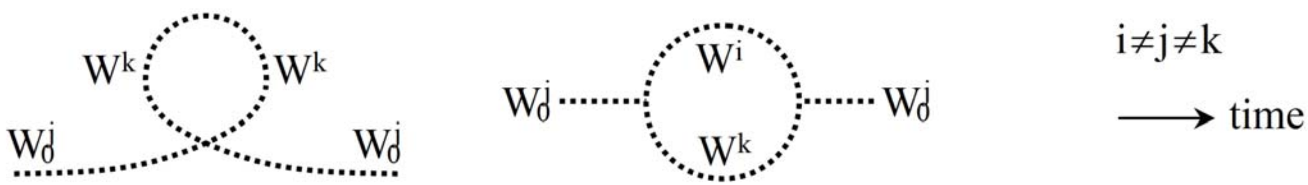
Weak coupling ↑ Scalar product of gauge boson pairs ↑

Why didn't I predict the Higgs mass? Before the discovery of the Higgs boson, I expected a broad resonance near the TeV unitarity limit (as did many others). But as soon as the Higgs particle was found at low energy, I convinced myself that it must involve a much smaller binding energy, such as the gauge boson self-energy. Even though I missed out on predicting the Higgs mass, nobody else has been able to calculate the Higgs mass to this day. (Let me know, if I am wrong.)

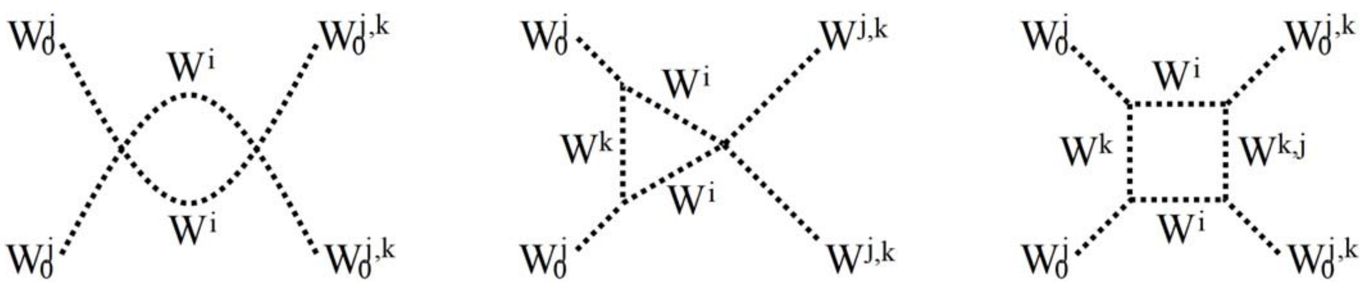
The gauge boson potential: After eliminating the standard Higgs potential, the question arises how to replace it. It turns out that the electro-weak gauge bosons directly interact with each other, leading to quadratic and quartic self-interactions. These replace the standard Higgs potential without containg adjustable parameters.

Diagrams for the potential: The quadratic terms of the gauge boson potential represent their self-energy. The quartic diagrams represent gauge boson scattering. Considering only the gauge bosons of the weak interaction, one obtains three equivalent gauge bosons W^i:

Quadratic:



Quartic:



For the full standard model, the number of diagrams explodes. This set still lacks Goldstones, gauge fixing terms with ghosts, counterterms, and regularization. Nevertheless, all these diagrams are at the one-loop level, which is easily handled by today's codes.

Having a composite Higgs particle adds another layer of complexity.

Therefore, I am looking for help from theorists who are interested in adapting the codes for the standard model to the composite Higgs model.

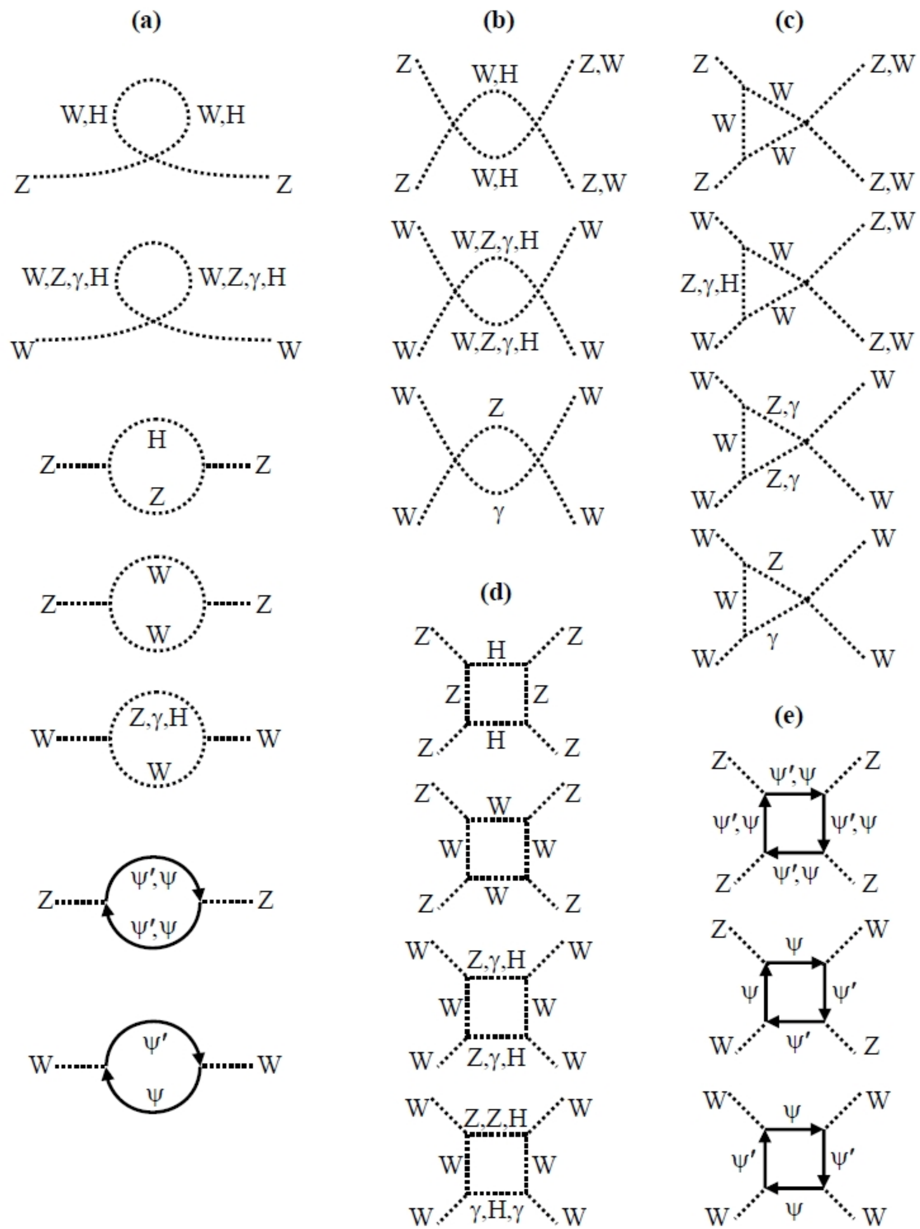
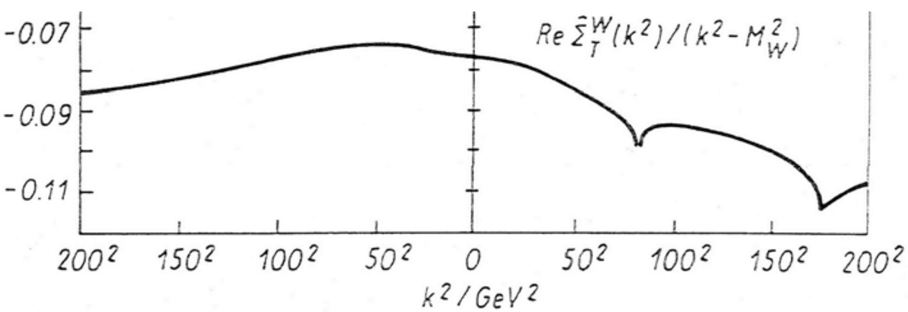
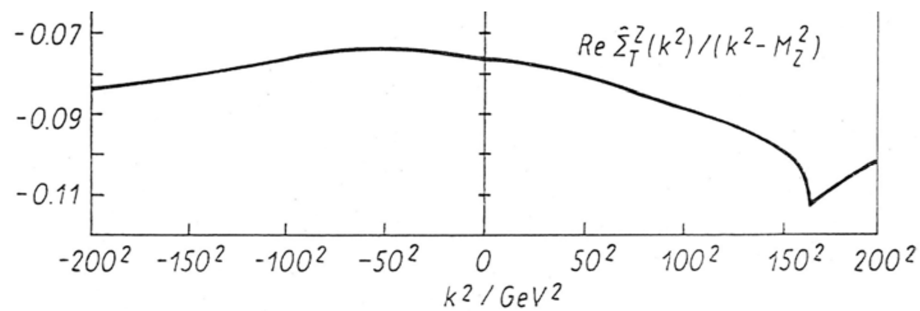


Figure 4 Irreducible one-loop self-interactions of the observable SU(2) gauge bosons in the standard model: (a) Quadratic diagrams of $O(g^2)$ for the self-energies Σ^W and Σ^Z, (b)-(e) diagrams of $O(g^4)$ representing scattering between the neutral gauge boson pairs $(W_0^+ W_0^-)$ and $(Z_0 Z_0)$. They generate the quadruple vertex corrections $\Lambda^{WW}, \Lambda^{WZ}, \Lambda^{ZZ}$. Left-handed fermion doublets are labeled (ψ, ψ').

Theoretical test of the model: The most important test will be proving its self-consistency by calculating the gauge boson potential from such diagrams. That will determine whether the gauge bosons have finite VEVs which can be transferred to the composite Higgs boson. The quadratic potential needs to be negative (attractive) and the quartic potential must be positive (repulsive).

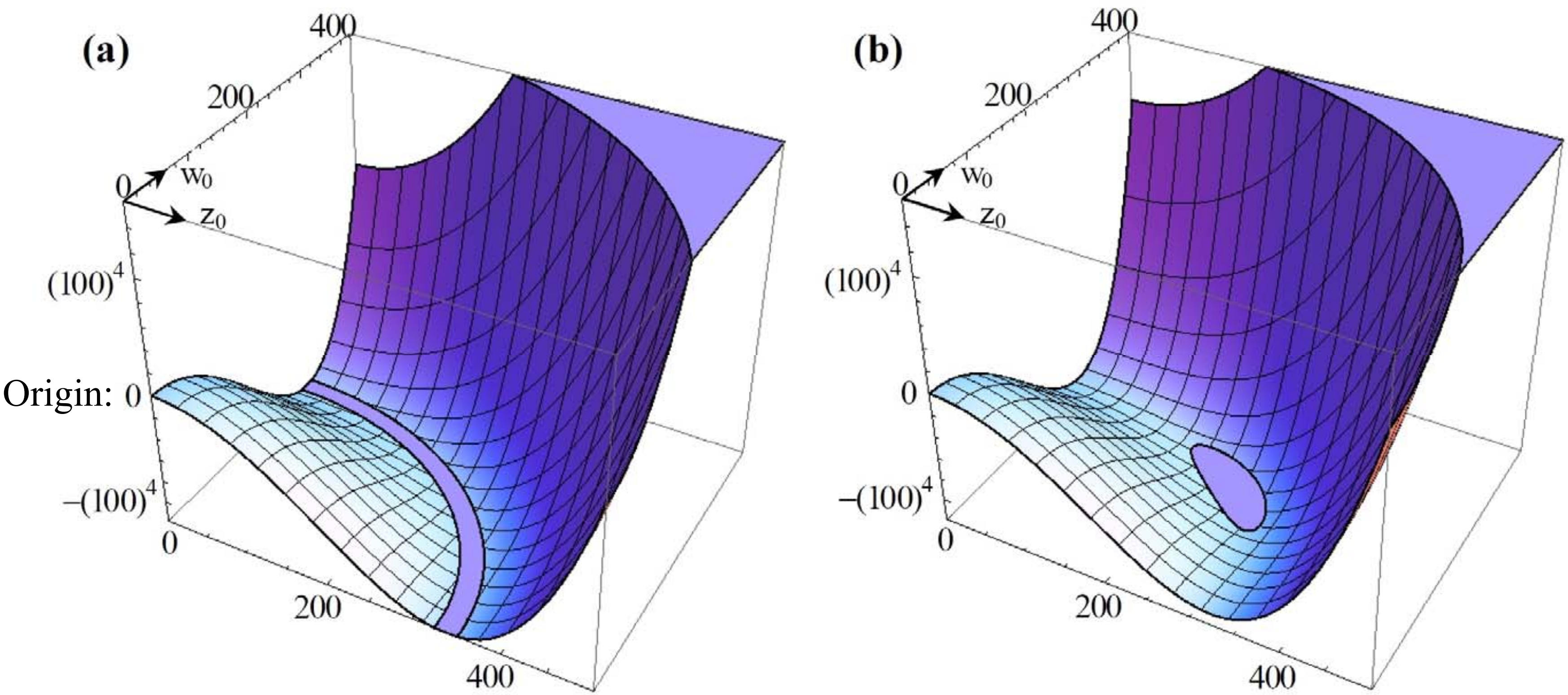
There are signs that the quadratic terms (i.e. the self-energies Σ^W, Σ^Z) are indeed negative:





Additional hints come from the observed masses of the W,Z,H bosons. They tend to be somewhat smaller than those calculated in leading order, i.e. for "bare" particles. This difference represents their self-energy.

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 scalar products of the gauge boson pairs (W^+W^-) and (ZZ). Some results are plotted below for two parameter sets with different topologies of the potential. Energies are in GeV.



From pairs to single bosons: Linear couplings, such as the Higgs-fermion coupling, require taking the "square root" of the equation defining the composite Higgs boson. For this purpose one can use a Taylor expansion. The Higgs boson $H_0 = v + H$ is decomposed into its VEV v and the observable Higgs boson H. The latter represents small oscillations about the VEV. A Higgs pair is then approximated by the three terms at the beginning of a Taylor series: $H_0^2 = v^2 + 2vH + H^2$ The mixed term provides the desired linear relation, and the last term generates the mass Lagrangian of the observable Higgs boson.

The same concept can be used for gauge boson pairs. In the equation defining the composite Higgs boson, the leading term connects the VEV of a Higgs pair to the VEVs of gauge boson pairs. Likewise, the mixed term provides a linear connection between a single Higgs and single gauge bosons. The last term describes the mass Lagrangians of the observable Higgs and gauge bosons. It determines the Higgs mass in terms of the gauge boson masses.

Experimental tests of the composite Higgs model:

To observe pairing of Higgs bosons (and gauge bosons) will require energies beyond the 250 GeV threshold. This energy also matches the Higgs VEV. Such energies require a new accelerator, which is unlikely to happen in my lifetime. Selectivity in producing and detecting Higgs bosons will be crucial for such a "Higgs factory".

That would also allow a comparison of precise mass measurements with next-to-leading order mass shifts of the order $\alpha_{weak} = g^2/4\pi \approx 3\%$.

One could learn from the methods that were used to observe gluons, the gauge bosons of the strong interaction. More generally, composite particles have signatures in scattering that are very different from those of point-like elementary particles.