Higgs Theory III

Symmetries Beyond the Higgs?

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Symmetries and Phase Transitions
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The Standard Model: Blessing or Curse?

Blessing

With the Standard Model, we can explain, predict and calculate all properties of elementary particles and matter.

The only limitations are

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The Higgs Sector

Minimal Higgs Sector?

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The matrix **H** is a constrained complex matrix (8 entries, 4 parameters).

Straightforward extension: unconstrained matrix. Or:

$$\tilde{\phi} \neq \mathrm{i}\sigma^2\phi$$

Observable:

- extra heavier neutral scalar H^0, couplings to WW, ZZ suppressed
- extra charged scalar H^+, H^-
- extra neutral scalar A^0 with negative (charge)-parity.

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Higgs Singlet Model

The value μ^2 may be the expectation value of another field,

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so the scalar sector contains a gauge singlet.

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$\Rightarrow$ The true (effective) gauge symmetry may be larger than $SU(3)_C \times SU(2)_L \times U(1)_R$. This might indicate new fermions, vector (gauge) bosons and scalar (Higgs) bosons beyond the SM.

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Quark transitions like $s \leftrightarrow d$ are possible in the SM, but very much suppressed. This can be precisely checked in data.

Any BSM effect that changes this pattern is immediately excluded

For extended Higgs sectors: condition on the possible couplings to matter multiplets

The Relevance of the Relevant Direction

Common Lore of Higgs Physics: there is a

1. **Hierarchy Problem:** why is $\mu \ll M_{\text{Planck}}$?
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My personal view:

The argument should not involve calculational methods or perturbation theory. Either version can be rephrased as:

3. The parameter space of the SM has a relevant direction. If generated by a fundamental theory with much higher characteristic scale, why is it critical down to the electroweak scale?

Possible Solutions

- The SM with its strange hierarchy(ies) is nevertheless the most probable parameter set under the condition that our world does exist.

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- The model should be replaced by a different QFT where the relevant direction emerges naturally like in QCD.

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- There is another symmetry that eliminates the relevant direction.
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One, all, or none of those?

Solution I: New Strong Interactions

If the Higgs potential parameter is not fundamental, there should be new strong interactions in the Higgs sector. The Higgs particle is an (accidentally?) low-lying bound state.

Dealing With a Strongly Interacting Higgs Sector

Convenient realization of the Composite Higgs idea: Use the ordinary SM Lagrangian, but continue to work with

$$h \quad \text{and} \quad \Sigma(w^+, w^-, z)$$

separately. Introduce new terms in this parameterization where h is a gauge singlet.

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Unless Higgs interactions *do* deviate significantly from the SM, this is operationally equivalent to the conventional SM/EFT with a Higgs-doublet representation:

$$\mathbf{H} = (\tilde{\phi} \quad \phi)$$

and adding higher-dimensional interactions in the Lagrangian.
Nothing to gain or lose.

Solution II: New Symmetry

Fermion masses (Majorana masses) and mass-like mixing terms (Dirac masses) can be excluded by symmetry if the fields are in different complex representations of some symmetry:

$$\text{mass term} = m\,\bar{f}_L f'_R$$

This does not apply to scalars.

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- Formalism with Grassmann parameters: handle like Lie algebra/group
- Result: scalars in complex representations are forced to behave critical, no mass allowed.

The Minimal Supersymmetric Standard Model

- Sleptons (scalars w/o QCD interactions)
- Squarks (scalars w/ QCD interactions)
- Gauginos (fermions in adjoint representation)
- 2nd Higgs doublet
- Higgsinos (similar to heavy leptons)

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$\Rightarrow$ Hierarchy problem?

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Apart from SUSY, there is no symmetry that can protect scalar masses in four-dimensional relativistic quantum field theory.

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The extra dimension must be closed or finite in extension, or the SM fields can propagate just a finite distance in the extra direction.

If the Poincaré symmetry is extended, the previous arguments lose their validity.

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The particles that belong to fields that can propagate in the extra dimension will develop resonances.

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- The extra D has flat metric, so extended Poincaré symmetry (Arkani-Hamed, Dimopoulos, Dvali)
- The extra D has curved metric. All scaling properties are reshuffled. Exponentially suppressed masses $m = \exp(-\lambda)M$ can be natural. (Randall-Sundrum)

Summary, Part III

- Scaling, symmetry, and also scaling and symmetry breaking are interleaved and dependent on each other.
- Relativistic QFT is the only known good description of particle physics. The Higgs mechanism reconciles apparent symmetric with non-symmetric phenomena.
- All of this might just be an effective description emerging from universality. We have no idea whether there is an UV cutoff or what are the symmetries of the fundamental interactions, if any.

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- All of this might just be an effective description emerging from universality. We have no idea whether there is an UV cutoff or what are the symmetries of the fundamental interactions, if any.
- There are good reasons to expect new phenomena within reach – and good reasons not to.

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