Higgs Theory II

The Higgs Mechanism in Weak Interactions

Wolfgang Kilian

University of Siegen

Symmetries and Phase Transitions
Dresden, September 2016

A Simple Fact

Particle Physics is described by a QFT with massive matter and massive vector bosons

$$(d, u, s, c, b, t), \qquad (e, \mu, \tau), \qquad (\nu_1, \nu_2, \nu_3)$$
$$(W^+, W^-, Z^0)$$

and no symmetry beyond the QED and QCD gauge symmetries

A Simple Fact

Particle Physics is described by a QFT with massive matter and massive vector bosons

$$(d, u, s, c, b, t), \qquad (e, \mu, \tau), \qquad (\nu_1, \nu_2, \nu_3)$$
$$(W^+, W^-, Z^0)$$

and no symmetry beyond the QED and QCD gauge symmetries
which is S-matrix equivalent to a different QFT with massless matter and massless bosons and exact gauge symmetry.

A Simple Fact

Particle Physics is described by a QFT with massive matter and massive vector bosons

$$(d, u, s, c, b, t), \qquad (e, \mu, \tau), \qquad (\nu_1, \nu_2, \nu_3)$$
$$(W^+, W^-, Z^0)$$

and no symmetry beyond the QED and QCD gauge symmetries
which is S-matrix equivalent to a different QFT with massless matter and massless bosons and exact gauge symmetry.

This is useful if the high-energy structure exhibits the gauge symmetry, but there are soft breaking terms (masses).

Counting Fields

- A massive spin-1 particle has 3 components (T$+$, T$-$, L)
- A gauge particle (e.g., photon) has 2 components (T$+$, T$-$)

Counting Fields

- A massive spin-1 particle has 3 components (T+, T−, L)
- A gauge particle (e.g., photon) has 2 components (T+, T−)

The extra longitudinal component decouples at high energy.

Counting Fields

- A massive spin-1 particle has 3 components (T+, T−, L)
- A gauge particle (e.g., photon) has 2 components (T+, T−)

The extra longitudinal component decouples at high energy.

⇒ formally equivalent QFT:

- add 1 massless scalar field for each vector and couple its derivative to the gauge field.

$$m_Z Z^\mu(\partial_\mu z) = -m_Z z(\partial_\mu Z^\mu)$$

Counting Fields

- A massive spin-1 particle has 3 components (T+, T−, L)
- A gauge particle (e.g., photon) has 2 components (T+, T−)

The extra longitudinal component decouples at high energy.

$\Rightarrow$ formally equivalent QFT:

- add 1 massless scalar field for each vector and couple its derivative to the gauge field.

$$m_Z Z^\mu (\partial_\mu z) = -m_Z z (\partial_\mu Z^\mu)$$

The new bosons ("Goldstone bosons") do enter the S-matrix.

Counting Fields

- A massive spin-1 particle has 3 components (T+, T−, L)
- A gauge particle (e.g., photon) has 2 components (T+, T−)

The extra longitudinal component decouples at high energy.

$\Rightarrow$ formally equivalent QFT:

- add 1 massless scalar field for each vector and couple its derivative to the gauge field.

$$m_Z Z^\mu(\partial_\mu z) = -m_Z z(\partial_\mu Z^\mu)$$

The new bosons ("Goldstone bosons") do enter the S-matrix.

but the unitary projection of the S-matrix does not contain them as external states. $\Leftrightarrow$ Lorentz Symmetry/BRST

Example: Quark Mass

Quark fields: u_L, u_R, d_L, d_R

in $SU(2)$ multiplets:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \qquad d_R$$

with transformation law ($U_L \in SU(2)$)

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \to U_L \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

Mass terms:

$$m_u \bar{u}_L u_R + m_d \bar{d}_L d_R$$

Gauge-Invariant Quark and Lepton Masses

1. Introduce three scalar fields w^+, w^-, z^0 and a 2×2 matrix

$$\Sigma = \Sigma(w^+, w^-, z^0)$$

2. Define the $SU(2)$ transformation law of w^+, w^-, z such that

$$\Sigma \to U_L \Sigma$$

3. Write invariant mass term

$$\begin{pmatrix} \bar{u}_L & \bar{d}_L \end{pmatrix} \Sigma \begin{pmatrix} m_u \\ 0 \end{pmatrix} u_R + \begin{pmatrix} \bar{u}_L & \bar{d}_L \end{pmatrix} \Sigma \begin{pmatrix} 0 \\ m_d \end{pmatrix} d_R$$

Necessary requirement:

$$\langle \Sigma \rangle = 1$$

Gauge-Invariant Quark and Lepton Masses

1. Introduce three scalar fields w^+, w^-, z^0 and a 2×2 matrix

$$\Sigma = \Sigma(w^+, w^-, z^0)$$

2. Define the $SU(2)$ transformation law of w^+, w^-, z such that

$$\Sigma \to U_L \Sigma$$

3. Write invariant mass term

$$(\bar{u}_L \quad \bar{d}_L)\,\Sigma\begin{pmatrix} m_u \\ 0 \end{pmatrix} u_R + (\bar{u}_L \quad \bar{d}_L)\,\Sigma\begin{pmatrix} 0 \\ m_d \end{pmatrix} d_R$$

Necessary requirement:

$$\langle\Sigma\rangle = 1 \qquad \text{or rather} \qquad \int d^4x\,\langle\Sigma^\dagger(x)\,\Sigma(x)\rangle = 1$$

Goldstone Bosons

Possible parameterization:

$$\Sigma = \exp\left(\frac{\mathrm{i}}{v}\sum_{a=1}^{3} w^a \sigma^a\right)$$

v is a known number (muon decay)

$$v = 246 \text{ GeV}$$

- The new scalar fields look like massless Goldstone bosons of spontaneous $SU(2)$ symmetry breaking, in the local QFT
- Parameterization of coset space

$$(SU(2)_L \times SU(2)_R)/SU(2)_{L=R}$$

Properties of the Gauge-Invariant Version

Introduced the electroweak symmetry breaking scale v.

All dimensional quantities are proportional to v
$\Rightarrow$ single parameter describes all relevant directions w.r.t. scaling.

The masses of the unphysical Goldstone bosons are arbitrary.

Properties of the Gauge-Invariant Version

Introduced the electroweak symmetry breaking scale v.

All dimensional quantities are proportional to v
$\Rightarrow$ single parameter describes all relevant directions w.r.t. scaling.

The masses of the unphysical Goldstone bosons are arbitrary. Possible choices (gauges): $m_w = 0$, $m_w = m_W$, $m_w \to \infty$, ...

Properties of the Gauge-Invariant Version

Introduced the electroweak symmetry breaking scale v.

All dimensional quantities are proportional to v
$\Rightarrow$ single parameter describes all relevant directions w.r.t. scaling.

The masses of the unphysical Goldstone bosons are arbitrary. Possible choices (gauges): $m_w = 0$, $m_w = m_W$, $m_w \to \infty$, ...

Caveat

There are irrelevant interactions $\propto 1/v^n$.
The scaling model has a UV cutoff $\sim 4\pi v = 3$ TeV.

Properties of the Gauge-Invariant Version

Introduced the electroweak symmetry breaking scale v.

All dimensional quantities are proportional to v
$\Rightarrow$ single parameter describes all relevant directions w.r.t. scaling.

The masses of the unphysical Goldstone bosons are arbitrary. Possible choices (gauges): $m_w = 0$, $m_w = m_W$, $m_w \to \infty$, ...

Caveat

There are irrelevant interactions $\propto 1/v^n$.
The scaling model has a UV cutoff $\sim 4\pi v = 3$ TeV.

In the formal limit $g \to 0$ there is a range of scaling behavior

$$gv/2 \equiv m_W \ll E \ll \Lambda$$

Scattering amplitudes of Goldstones $\approx$ scattering amplitudes of W_L, Z_L
(Goldstone Boson Equivalence Theorem)

Limitations

The gauge invariant version is convenient for calculations, and it suggests a deeper understanding of the scaling property (= gauge symmetry) in the vector-boson and matter interactions.

But the nonlinearity obstructs scaling beyond TeV energies as long as we can't resolve the origin of the would-be Goldstone bosons.

Limitations

The gauge invariant version is convenient for calculations, and it suggests a deeper understanding of the scaling property (= gauge symmetry) in the vector-boson and matter interactions.

But the nonlinearity obstructs scaling beyond TeV energies as long as we can't resolve the origin of the would-be Goldstone bosons.

- Structure is just an accidental fact?
- Fields in Σ can be understood as bound states / new dynamics?
- Spectrum is incomplete?

The Higgs Solution

Imposed restriction (three Goldstone fields):

$$\Sigma^\dagger(x)\,\Sigma(x) \equiv \mathbf{1} \qquad (\text{“London Constraint”})$$

but we need just

$$\langle\Sigma^\dagger\Sigma\rangle\big|_{k=0} = \mathbf{1}$$

Modulus of Σ = extra scalar degree of freedom.

The Higgs Solution

Imposed restriction (three Goldstone fields):

$$\Sigma^\dagger(x)\,\Sigma(x) \equiv \mathbf{1} \qquad (\text{“London Constraint”})$$

but we need just

$$\langle \Sigma^\dagger \Sigma \rangle\big|_{k=0} = \mathbf{1}$$

Modulus of Σ = extra scalar degree of freedom.

Rescale by v:

$$\mathbf{H} = (v + h)\Sigma$$

The extra state h is a BRST singlet and thus does enter the unitary S matrix. There is a new scalar particle (resonance), the Higgs boson. h appears here as a gauge singlet.

The Higgs Solution

Imposed restriction (three Goldstone fields):

$$\Sigma^\dagger(x)\,\Sigma(x) \equiv \mathbf{1} \qquad \text{(“London Constraint”)}$$

but we need just

$$\langle \Sigma^\dagger \Sigma \rangle\big|_{k=0} = \mathbf{1}$$

Modulus of Σ = extra scalar degree of freedom.

Rescale by v:

$$\mathbf{H} = (v + h)\Sigma$$

The extra state h is a BRST singlet and thus does enter the unitary S matrix. There is a new scalar particle (resonance), the Higgs boson. h appears here as a gauge singlet.

Higgs and Goldstones

H happens to allow for a simpler parameterization:

$$H = (v + h)\exp \tfrac{\mathrm{i}}{v} w_a \sigma^a = (v + h')\mathbf{1} - \tfrac{\mathrm{i}}{v} w'_a \sigma^a$$

or

$$H = \begin{pmatrix} v + h' - \mathrm{i}w'_3 & -w'_1 + \mathrm{i}w'_2 \\ -w'_1 - \mathrm{i}w'_2 & v + h' + \mathrm{i}w'_3 \end{pmatrix}$$

Higgs and Goldstones

H happens to allow for a simpler parameterization:

$$H = (v + h) \exp \tfrac{\mathrm{i}}{v} w_a \sigma^a = (v + h')\mathbf{1} - \tfrac{\mathrm{i}}{v} w'_a \sigma^a$$

or

$$H = \begin{pmatrix} v + h' - \mathrm{i}w'_3 & -w'_1 + \mathrm{i}w'_2 \\ -w'_1 - \mathrm{i}w'_2 & v + h' + \mathrm{i}w'_3 \end{pmatrix}$$

or

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

$\Rightarrow$ complex Higgs doublet

$$\phi = \begin{pmatrix} -\sqrt{2}w^+ \\ v + h^0 + \mathrm{i}z^0 \end{pmatrix}$$

(and $\tilde{\phi} = \mathrm{i}\sigma^2\phi^*$)

The Higgs Doublet

The new Higgs doublet is in a linear representation of $SU(2)_L$:

$$\phi \to U_L \phi$$

The model becomes a candidate for scaling beyond Λ.

The Higgs Doublet

The new Higgs doublet is in a linear representation of $SU(2)_L$:

$$\phi \to U_L \phi$$

actually, a linear representation of $SU(2)_L \times SU(2)_R$:

$$\mathbf{H} \to U_L \mathbf{H} U_R^\dagger$$

which is sometimes useful.

The model becomes a candidate for scaling beyond Λ.

The Higgs Potential

Two new interactions, one relevant and one marginal:

$$\mu^2 \mathrm{tr}\left[\mathbf{H}^\dagger \mathbf{H}\right] \quad \text{and} \quad \lambda(\mathrm{tr}\left[\mathbf{H}^\dagger \mathbf{H}\right])^2$$

These determine the minimal Higgs potential.

The Higgs Potential

Two new interactions, one relevant and one marginal:

$$\mu^2 \mathrm{tr}\left[\mathbf{H}^\dagger \mathbf{H}\right] \quad \text{and} \quad \lambda(\mathrm{tr}\left[\mathbf{H}^\dagger \mathbf{H}\right])^2$$

These determine the minimal Higgs potential.

- v is replaced by μ^2 as (only!) relevant parameter
- λv determines the Higgs mass m_H
- λ also introduces a Higgs self-coupling.

The Higgs Potential

Two new interactions, one relevant and one marginal:

$$\mu^2 \mathrm{tr}\left[\mathbf{H}^\dagger \mathbf{H}\right] \quad \text{and} \quad \lambda(\mathrm{tr}\left[\mathbf{H}^\dagger \mathbf{H}\right])^2$$

These determine the minimal Higgs potential.

- v is replaced by μ^2 as (only!) relevant parameter
- λv determines the Higgs mass m_H
- λ also introduces a Higgs self-coupling.

In 2012, ATLAS and CMS discovered a scalar particle with $m = 126$ GeV which fits the properties of this Higgs boson, within uncertainties

$\Rightarrow$ talk by Günter Quast

The Standard Model

The combination of all discovered particles with all symmetries is known as the **Standard Model** of particle physics.

- Physical particles in the S matrix: leptons, neutrinos, quarks, gluons, W and Z bosons, Higgs
- Symmetry of the QFT: Lie algebra $SU(3)_C \times SU(2)_L \times U(1)_R$
- Representations: trivial, fundamental, and adjoint.
- Scaling/criticality is automatic

The Standard Model

The combination of all discovered particles with all symmetries is known as the **Standard Model** of particle physics.

- Physical particles in the S matrix: leptons, neutrinos, quarks, gluons, W and Z bosons, Higgs
- Symmetry of the QFT: Lie algebra $SU(3)_C \times SU(2)_L \times U(1)_R$
- Representations: trivial, fundamental, and adjoint.
- Scaling/criticality is automatic, except for the μ^2 term in the Higgs potential

Breakdown of Scaling in the Standard Model

1. Masses of Higgs, W, Z, t quark, lighter quarks, leptons are related to the parameter in the Higgs potential: EWSB
2. Range of weak interactions is set by the W, Z masses.
3. Masses of hadrons/nuclei are set by the QCD singularity
4. Range of strong interactions is set by the pion mass, related to EWSB.
5. Size of atoms is set by the electron mass, related to EWSB.

All free parameters of the Standard Model are known.

Breakdown of Scaling in the Standard Model

1. Masses of Higgs, W, Z, t quark, lighter quarks, leptons are related to the parameter in the Higgs potential: EWSB
2. Range of weak interactions is set by the W, Z masses.
3. Masses of hadrons/nuclei are set by the QCD singularity
4. Range of strong interactions is set by the pion mass, related to EWSB.
5. Size of atoms is set by the electron mass, related to EWSB.
6. [Neutrinos require an extra scale-breaking term of undetermined type and origin, likely inaccessible to experiment.]

All free parameters of the Standard Model are known.

Translation: Superconductor $\leftrightarrow$ Higgs Physics

$$
\begin{aligned}
\text{Cooper pair /} & \\
\text{Ginzburg-Landau field } \psi &= \text{Higgs (doublet) field } \mathbf{H} \\
\text{phase } \theta &= \text{Unphysical Goldstone bosons } (w^+, w^-, z) \\
\text{amplitude fluctuation} &= \text{Higgs boson excitation } h \\
\text{photon} &= \text{weak bosons } (W^+, W^-, Z) \\
\text{Meissner Effect} &= \text{weak boson masses } M_W, M_Z \\
&= \text{short range of weak interactions}
\end{aligned}
$$

What Is the Order Parameter?

What Is the Order Parameter?

- The order parameter is $v = \langle \mathbf{H}(x) \rangle$.

What Is the Order Parameter?

- The order parameter is $v = \langle \mathbf{H}(x) \rangle$.
  Wrong. This is a gauge-dependent operator.

What Is the Order Parameter?

- The order parameter is $v = \langle \mathbf{H}(x) \rangle$.

  Wrong. This is a gauge-dependent operator.

  Right. Because we fix the gauge in calculations.

What Is the Order Parameter?

- The order parameter is $v = \langle \mathbf{H}(x) \rangle$.

- The order parameter is $v^2 = \langle \mathbf{H}^\dagger \mathbf{H} \rangle \big|_{k=0}$.

What Is the Order Parameter?

- The order parameter is $v = \langle \mathbf{H}(x) \rangle$.

- The order parameter is $v^2 = \langle \mathbf{H}^\dagger \mathbf{H} \rangle \big|_{k=0}$.
  Right. This is nonlocal and gauge-invariant.

What Is the Order Parameter?

- The order parameter is $v = \langle \mathbf{H}(x) \rangle$.

- The order parameter is $v^2 = \langle \mathbf{H}^\dagger \mathbf{H} \rangle \big|_{k=0}$.
  Right. This is nonlocal and gauge-invariant.
  Wrong. There are Higgs fluctuations at all scales.

What Is the Order Parameter?

- The order parameter is $v = \langle \mathbf{H}(x) \rangle$.

- The order parameter is $v^2 = \langle \mathbf{H}^\dagger \mathbf{H} \rangle \big|_{k=0}$.

This makes no sense. The QFT is a calculational device. None of this is observable, i.e., a property of the S matrix.

What Is the Order Parameter?

- The order parameter is $v = \langle \mathbf{H}(x) \rangle$.

- The order parameter is $v^2 = \langle \mathbf{H}^\dagger \mathbf{H} \rangle \big|_{k=0}$.

This makes no sense. The QFT is a calculational device. None of this is observable, i.e., a property of the S matrix.

The W,Z,Higgs, and quark and lepton masses are observables. They are all proportional to the parameter v. These are candidates for an order parameter.

What About an Electroweak Phase Transition?

What About an Electroweak Phase Transition?

Caution!

Temperature (and density) is zero. Nonzero temperature breaks Lorentz invariance. Many arguments don't apply.

What About an Electroweak Phase Transition?

Caution!

Temperature (and density) is zero. Nonzero temperature breaks Lorentz invariance. Many arguments don't apply.

Nevertheless, let's pretend ...

Let $v \to 0$, keeping all other parameters fixed. What would happen?

What About an Electroweak Phase Transition?

Caution!

Temperature (and density) is zero. Nonzero temperature breaks Lorentz invariance. Many arguments don't apply.

Nevertheless, let's pretend ...

Let $v \to 0$, keeping all other parameters fixed. What would happen?

- $m_h = \lambda v$: if the Higgs mass goes to zero, Higgs-field fluctuations diverge.

Upside Down

1. If $v \to 0$, QCD would take over. Pions would mix with w, z, exchange their role, and pions would render W, Z massive. We would be left with massless w, z Goldstones and massless photons and leptons.

Upside Down

1. If $v \to 0$, QCD would take over. Pions would mix with w, z, exchange their role, and pions would render W, Z massive. We would be left with massless w, z Goldstones and massless photons and leptons.
2. Ignoring QCD, weak $SU(2)_L$ would confine, so we would see only $SU(2)_L$ invariant (bound) states.

Upside Down

1. If $v \to 0$, QCD would take over. Pions would mix with w, z, exchange their role, and pions would render W, Z massive. We would be left with massless w, z Goldstones and massless photons and leptons.

3. Massless photons and leptons do not allow the definition of an S matrix. In the IR, we would not obtain a particle interpretation.

Upside Down

1. If $v \to 0$, QCD would take over. Pions would mix with w, z, exchange their role, and pions would render W, Z massive. We would be left with massless w, z Goldstones and massless photons and leptons.

3. Massless photons and leptons do not allow the definition of an S matrix. In the IR, we would not obtain a particle interpretation.

In the early universe, there is finite temperature and finite density, so the above arguments are irrelevant.

Upside Down

In the early universe, there is finite temperature and finite density, so the above arguments are irrelevant.

(The problem of electroweak phase transition is left to the reader. . .)

Properties of the Higgs Particle

The Higgs boson arises from the combination $(v + h)$ in the SM Lagrangian.

Properties of the Higgs Particle

The Higgs boson arises from the combination $(v + h)$ in the SM Lagrangian.

$\Rightarrow$ The Higgs particle has direct couplings to all massive particles. The coupling strength is proportional to the particle mass.

Properties of the Higgs Particle

The Higgs boson arises from the combination $(v + h)$ in the SM Lagrangian.

$\Rightarrow$ The Higgs particle has direct couplings to all massive particles. The coupling strength is proportional to the particle mass.

$\Rightarrow$ The Higgs particle decays into the heaviest particles that are kinematically possible.

$$
\begin{aligned}
&H \to b\bar{b} \qquad \text{dominant} \\
&H \to W^{+}(W^{-}) \to 4 \text{ fermions} \\
&\ldots
\end{aligned}
$$

Production and Detection of the Higgs particle

The Higgs particle does not couple directly to (light) matter particles.

Unsuppressed couplings: W, Z, t.

Production and Detection of the Higgs particle

The Higgs particle does not couple directly to (light) matter particles.

Unsuppressed couplings: W, Z, t.

$\Rightarrow$ Indirect coupling to matter via virtual excitation of W, Z, t.

- Production: $pp \to gg \to (t\bar{t} \to) \quad h$
- Discovery: $h \to (t\bar{t}, W^+W^- \to) \quad \gamma\gamma$

Production and Detection of the Higgs particle

The Higgs particle does not couple directly to (light) matter particles.

Unsuppressed couplings: W, Z, t.

$\Rightarrow$ Indirect coupling to matter via virtual excitation of W, Z, t.

- Production: $pp \to gg \to (t\bar{t} \to) \quad h$
- Discovery: $h \to (t\bar{t}, W^+W^- \to) \quad \gamma\gamma$

All coupling strengths are known.

The Higgs Mechanism in Experiment

$$W^+W^- \to ZZ$$

without Higgs:

- transversal polarization: gauge-boson interaction, determined by group structure + asymptotically safe
- longitudinal polarization: Goldstone-boson interaction / irrelevant operator, asymptotically unbounded
  - $\Rightarrow$ calculated amplitude violates unitarity bound for $E \gtrsim 1$ TeV

The Higgs Mechanism in Experiment

$$W^+W^- \to ZZ$$

without Higgs:

- transversal polarization: gauge-boson interaction, determined by group structure + asymptotically safe
- longitudinal polarization: Goldstone-boson interaction / irrelevant operator, asymptotically unbounded

  $\Rightarrow$ calculated amplitude violates unitarity bound for $E \gtrsim 1$ TeV

The Higgs Mechanism in Experiment

$$W^+W^- \to ZZ$$

without Higgs:

- transversal polarization: gauge-boson interaction, determined by group structure + asymptotically safe
- longitudinal polarization: Goldstone-boson interaction / irrelevant operator, asymptotically unbounded
  - $\Rightarrow$ calculated amplitude violates unitarity bound for $E \gtrsim 1$ TeV

Higgs exchange:

$$W^+W^- \to (h \to) \quad ZZ$$

restores unitarity in the calculated amplitude $\Rightarrow$ asymptotically safe

The Higgs Mechanism in Experiment

$$W^+W^- \to ZZ$$

without Higgs:

- transversal polarization: gauge-boson interaction, determined by group structure + asymptotically safe
- longitudinal polarization: Goldstone-boson interaction / irrelevant operator, asymptotically unbounded
  - $\Rightarrow$ calculated amplitude violates unitarity bound for $E \gtrsim 1$ TeV

Higgs exchange:

$$W^+W^- \to (h \to) \quad ZZ$$

restores unitarity in the calculated amplitude $\Rightarrow$ asymptotically safe

Summary, Part II

- In the QFT, the apparently broken gauge symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

  can be rewritten as exact. This is a formal manipulation which explicitly realizes the observed pattern of interactions.
- If we add a single observable scalar state, symmetry and scaling can be extended beyond the intrinsic cutoff of 3 TeV. This is the Higgs mechanism.
- The associated Higgs particle has a well-defined pattern of interactions.
- The resulting **Standard Model** has three relevant directions as sources of broken scaling.

Summary, Part II

- In the QFT, the apparently broken gauge symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

  can be rewritten as exact. This is a formal manipulation which explicitly realizes the observed pattern of interactions.
- If we add a single observable scalar state, symmetry and scaling can be extended beyond the intrinsic cutoff of 3 TeV. This is the Higgs mechanism.
- The associated Higgs particle has a well-defined pattern of interactions.
- The resulting **Standard Model** has three relevant directions as sources of broken scaling. Only one is understood.