HS „Hunting New Physics in the Higgs Sector“

SM Higgs Sector - Test of the Higgs Mechanism

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Outline

Introduction

- $\sim$ 1960: Nambu & Goldstone - SSB in condensed matter physics

$\Rightarrow$ Nambu - application to particle physics?

- 1961: Glashow - EW theory
- 1964: Higgs - SSB in gauge theories $\neq$ non-gauge theories
- 1967: Weinberg & Salam - Higgs mechanism $\rightarrow$ Glashow's EW theory
- 1971: 't Hooft - renormalizable theory
- 1981: W and Z bosons discovery
- 2013: Higgs boson discovery at CERN

$\Rightarrow$ EWSB mechanism dominant theme of elementary particle physics

SSB

Symmetry of $\mathcal{L}$ is *spontaneously broken* if $\mathcal{L}$ is symmetrical, but the physical vacuum does *not* obey the symmetry.

Simple example: thin rod on a table.

$\mathcal{L}$ is invariant under a symmetry, which is not the symmetry of a physical vacuum $\Rightarrow \geq 1$ massless spin-0 particles: Goldstone bosons.

If leptons, quarks and gauge bosons remain weakly interacting up to high energies $\Rightarrow$ the sector in which the EW symmetry is broken must contain ≥ 1 fundamental scalar Higgs bosons of the order 246 GeV.

The Higgs boson mass was the last unknown parameter in the SB sector of the SM.

Why introduce the Higgs boson

1. A theory of massive gauge bosons and fermions requires the existence of a Higgs particle (unitarity)
2. The introduction of mass terms for gauge bosons and fermions violates the $SU(2)_L \times U(1)$ symmetry of the SM $\mathcal{L}$

To explain the existence of massive particles consistently with symmetries of the SM.
$\Rightarrow$ A mechanism, that „breaks“ the gauge symmetry in a specific way;
Higgs mechanism $\Rightarrow$ Higgs particle

How it works

SSB $\Rightarrow$ particle mass generation:

- Scalar field self-interaction $\rightarrow \infty$ number of degenerate ground states with $\phi_0 \neq 0$
- Choice of one ground state as the physical ground state $\rightarrow$ SSB
- Interaction with scalar field in ground state $\Rightarrow$ particle mass

The Goldstone Theorem

Expansion of Φ around the min. of the Higgs potential $\Rightarrow 1$ massive scalar particle (Higgs boson) and 3 massless Goldstone bosons.
The Goldstone bosons are absorbed to give masses to W and Z bosons.

<u>The Goldstone Theorem:</u>
Let
$N = dim$ of algebra of symmetry group of complete $\mathcal{L}$
$M = dim$ of algebra of group, under which the vacuum is invariant after SSB
$\Rightarrow$ There are <u>$N - M$ Goldstone bosons without mass</u>

i.e.: for each spontaneously broken degree of freedom of the symmetry there is one massless Goldstone boson

Gauge theories: no Goldstone bosons

For gauge theories it holds:
Let
$N = dim$ of algebra of symmetry group of complete $\mathcal{L}$
$M = dim$ of algebra of group, under which the vacuum is invariant after SSB
$n =$ number of scalar fields

$\Rightarrow$ There are:
M massless vector fields
$N - M$ massive vector fields
$n - (N - M)$ scalar Higgs fields

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) \ , \ \ V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \ , \ \ \phi \text{ scalar real field}$$

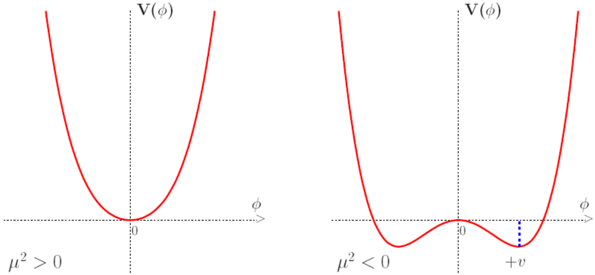
Symmetry $\phi \to -\phi$

1. $\mu^2 > 0 \Rightarrow V(\phi) > 0 \Rightarrow V(\phi)_{\text{min}}$ for $\phi_0 = 0$

$\Rightarrow \mathcal{L}$ of spin-0 particle of mass μ

2. $\mu^2 < 0 \Rightarrow V(\phi)_{\text{min}}$ for $\phi_0^2 = -\frac{\mu^2}{\lambda} \equiv v^2$

$\Rightarrow$ expand around min. v : $\phi = v + \sigma$



$$\Rightarrow \mathcal{L} = \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - (-\mu^2)\sigma^2 - \sqrt{-\mu^2\lambda}\sigma^3 - \frac{\lambda}{4}\sigma^4 + const$$

This is the theory of scalar field of mass $m^2 = -2\mu^2$,
σ^3 and σ^4 being the self-interactions.

$\sigma^3 \Rightarrow$ reflection symmetry broken; example of SSB

Next step: ϕ_i with $i = 0, 1, 2, 3$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \frac{1}{2}\mu^2(\phi_i\phi_i) - \frac{1}{4}\lambda(\phi_i\phi_i)^2$$

$\mathcal{L}$ invariant under the rotation group $O(4)$, $\phi_i(x) = R_{ij}\phi_j(x)$ for any orthogonal matrix R

$\mu^2 < 0 \Rightarrow V(\phi)_{\text{min}}$ for $\phi_i^2 = -\frac{\mu^2}{\lambda} \equiv v^2$

$\Rightarrow$ expand: $\phi_0 = v + \sigma$, rewrite $\phi_i = \pi_i$ for $i = 1, 2, 3$

$$\Rightarrow \mathcal{L} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}(-2\mu^2)\sigma^2 - \lambda v\sigma^3 - \frac{\lambda}{4}\sigma^4$$
$$+ \frac{1}{2}\partial_\mu\pi_i\partial^\mu\pi_i - \frac{\lambda}{4}(\pi_i\pi_i)^2 - \lambda v\pi_i\pi_i\sigma - \frac{\lambda}{2}\pi_i\pi_i\sigma^2$$

$\Rightarrow$ massive σ boson with $m^2 = -2\mu^2$ & 3 massless pions

Still an $O(3)$ symmetry among the π_i fields

$\rightarrow$ Goldstone Theorem: 3 massless Goldstone bosons for $O(4)$ group

The Higgs Mechanism in an abelian theory

Local symmetry, abelian $U(1)$ case:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + D_\mu\phi^* D^\mu\phi - V(\phi)$$

with $D_\mu = \partial_\mu - ieA_\mu$, $V(\phi) = \mu^2\phi^*\phi + \lambda(\phi^*\phi)^2$.

$\mathcal{L}$ is invariant under the local $U(1)$ transformation

$$\phi(x) \to e^{i\alpha(x)}\phi(x) \qquad A_\mu(x) \to A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x)$$

1. $\mu^2 > 0 \Rightarrow \mathcal{L}$ is the QED $\mathcal{L}$ for charged scalar particle of mass μ & with ϕ^4 self-interactions
2. $\mu^2 < 0 \Rightarrow V(\phi)_{\text{min}}$ for $\langle\phi\rangle_0 = \left(-\frac{\mu^2}{2\lambda}\right)^{1/2} \equiv \frac{v}{\sqrt{2}}$

$\Rightarrow$ expand around $\langle\phi\rangle$:

$$\phi(x) = \frac{1}{\sqrt{2}}[v + \phi_1(x) + i\phi_2(x)]$$

$$
\begin{aligned}
\Rightarrow \mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (\partial^\mu + ieA^\mu)\phi^*(\partial_\mu - ieA_\mu)\phi \\
&- \mu^2\phi^*\phi - \lambda(\phi^*\phi)^2 \\
= &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu\phi_1)^2 + \frac{1}{2}(\partial_\mu\phi_2)^2 \\
&- v^2\lambda\phi_1^2 + \frac{1}{2}e^2v^2A_\mu A^\mu - evA_\mu\partial^\mu\phi_2
\end{aligned}
$$

Observations:

1. Photon mass term in $\mathcal{L}$: $\frac{1}{2}M_A^2A_\mu A^\mu$ with $M_A = ev = -e\mu^2/\lambda$
2. We still have a scalar particle ϕ_1 with mass $M_{\phi_1}^2 = -2\mu^2$
3. Massless particle ϕ_2; a would-be Goldstone boson

Problem:

In the beginning: 4 degrees of freedom; $2 \times \phi$ & $2 \times A_\mu$

Now: 5 degrees of freedom; $1 \times \phi_1$, $1 \times \phi_2$ & $3 \times A_\mu$

$\Rightarrow$ There must be a field which is not physical: $evA_\mu \partial_\mu \phi_2$ to be eliminated

At first order:

$$\phi = \frac{1}{\sqrt{2}}(v + \phi_1 + i\phi_2) \equiv \frac{1}{\sqrt{2}}[v + \eta(x)]e^{i\zeta(x)/v}$$

Freedom of gauge transformations & substituting

$$A_\mu \to A_\mu - \frac{1}{ev}\partial_\mu \zeta(x)$$

All ζ terms disappear from $\mathcal{L}$

$\Rightarrow$ Photon (2 deg. of freedom) absorbed the would-be Goldstone boson (1 deg. of freedom) $\rightarrow$ massive photon (3 deg. of freedom)
$U(1)$ gauge symmetry is spontaneously broken.

This is the Higgs Mechanism which allows to generate masses for the gauge bosons.

The Higgs Mechanism in the SM

Non-abelian case of the SM.
We need to generate masses for $W^{\pm}$ and Z bosons, but the photon should remain massless, and QED must stay an exact symmetry.
$\Rightarrow \geq 3$ degrees of freedom for scalar fields
We choose a complex $SU(2)$ doublet of scalar fields ϕ

$$\Phi = \left(\phi^{+}, \phi^{0}\right)^{\mathsf{T}} \ , \ Y_{\phi} = +1$$

To the SM $\mathcal{L}$ from previously, but where we ignored the strong interaction part

$$\mathcal{L}_{SM} = -\frac{1}{4} W^{a}_{\mu\nu} W^{\mu\nu}_{a} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \overline{L} i D_{\mu} \gamma^{\mu} L + \overline{e}_{R} i D_{\mu} \gamma^{\mu} e_{R} \ \cdots$$

we add the invariant terms of the scalar field part

$$\mathcal{L}_{S} = (D^{\mu}\Phi)^{\dagger}(D_{\mu}\Phi) - \mu^{2}\Phi^{\dagger}\Phi - \lambda(\Phi^{\dagger}\Phi)^{2}$$

Performing the same exercise as previously we achieve our goal.

The Higgs particle in the SM

The kinetic part of the Higgs field $\frac{1}{2}(\partial_\mu H)^2$ comes from the term with $|D_\mu \Phi|^2$, the mass and self-interaction parts - from the scalar potential $V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$

$$V = \frac{\mu^2}{2}(0, v+H)\begin{pmatrix} 0 \\ v+H \end{pmatrix} + \frac{\lambda}{4}\left|(0, v+H)\begin{pmatrix} 0 \\ v+H \end{pmatrix}\right|^2$$

Using $v^2 = -\mu^2/\lambda$ we have:

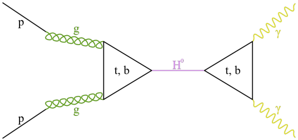
$$\Rightarrow V = -\frac{1}{2}\lambda v^2 (v+H)^2 + \frac{1}{4}\lambda(v+H)^4$$

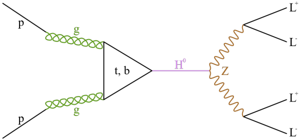
$$\begin{aligned} \Rightarrow \mathcal{L}_H &= \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V \\ &= \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4 \end{aligned}$$

$$\Rightarrow M_H^2 = 2\lambda v^2 = -2\mu^2$$

Test of the Higgs Mechanism

What to look for?
The Higgs decay channels.





Higgs boson couples $\propto$ mass of particle.
$\Rightarrow$ Preferred decays: into heavy fermions & gauge bosons.

High-precision tests of the SM

Experimentally determined are:

- 3 gauge coupling constants
- Masses of weak vector bosons and fermions
- Quark mixing angles

Recently also the Higgs mass.

At high energies the EW constants & the strong coupling constant are small enough $\Rightarrow$ 1st order corrections suffice.
For more precise results: higher order terms: radiative corrections.
Measurements and theoretical predictions are at 0,1% precision and better.
$\Rightarrow$ Accurate tests of the SM.
$\Rightarrow$ Small deviations from theory of the minimal SM can be detected.

Verification of the Higgs Mechanism

4th July 2012: LHC experiments ATLAS & CMS - $M_H \approx 125\,\text{GeV}$.
March 2013: official press release by CERN.

To verify the Higgs Mechanism as the mechanism which allows to generate particle masses without violating gauge principles:

1. Discover the Higgs particle
2. Measure its coupling to gauge bosons and fermions: couplings $\propto m^2$ of particles?
3. Determine its spin and parity quantum numbers
4. Measure its trilinear and quartic self-couplings

Open questions

SM very successful so far:

- tested to highest accuracy
- Higgs particle was the last missing piece of SM

Problems:

1. Higgs Mechanism in SM designed to solve specific problem; non-generalizable
2. At high energy scales M_H receives large quantum corrections $\Rightarrow$ hierarchy problem
3. SM does not have a DM candidate
4. SM does not incorporate gravity

$\Rightarrow$ SM is an effective low-energy theory; embedded in a more fundamental theory.
Higgs data still allows interpretations within BSM theories.
These BSM theories can solve some problems of SM.

Thank You for Your attention!

Any questions/remarks?