The Higgs Mechanism and the Origin of Mass

2013 Nobel Prize in Physics

Vahid Gorgin

[Your University / Department]

December 4, 2025

Why do particles have mass?

A strange universe

Imagine a world where all particles move at the speed of light.

Gauge symmetry vs. mass

Gauge symmetry forbids mass terms.

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} \quad \Rightarrow \quad m_W = 0$$

But experiments disagree

We measure massive W and Z bosons.

Theory says: *no mass*.
Experiments say: *big mass*.

Adding mass by hand breaks the theory.

The crisis

Naive mass terms destroy gauge symmetry, renormalizability, and predictivity.

How can a gauge theory have massive bosons?

What if the symmetry is hidden, not broken by hand?

Symmetry in the equations, not in the vacuum

Keep the Lagrangian symmetric.
Let the vacuum pick a direction.

Spontaneous symmetry breaking.

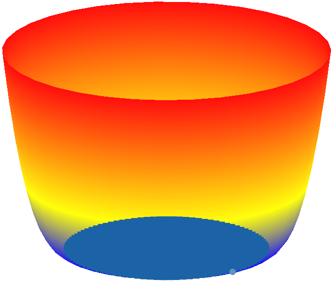
The Higgs field idea

Introduce a complex scalar doublet Φ with potential

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

Choose $\mu^2 < 0 \rightarrow$ the vacuum is not at $\Phi = 0$.

The Mexican hat



$$V(\phi) = \lambda\left(|\phi|^2 - v^2\right)^2$$

Continuum of minima at $\langle 0|\Phi|0\rangle \neq 0$.

Choosing a vacuum

Choose one vacuum direction:

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

The symmetry of the equations survives;
the symmetry of the vacuum does not.

Gauge boson masses from the vacuum

Gauge fields eat Goldstone modes and become massive:

$$m_W = \frac{1}{2} g v, \qquad m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v$$

Mass comes from interaction with an always-on field.

The Higgs boson

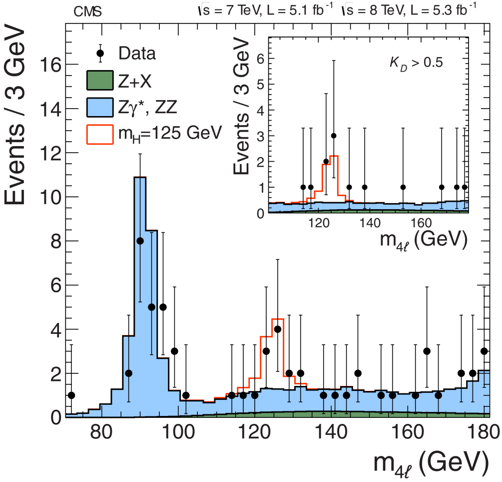
$h(x)$ is a real scalar excitation of the Higgs field.

A vibration of the vacuum itself.

Discovery: Does the Higgs show up?

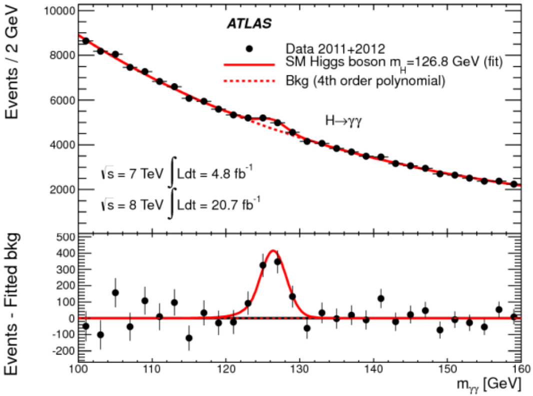
- Where would a Higgs leave a clear bump?
- Can we spot a narrow signal over huge backgrounds?
- Which channels balance sensitivity and precision?

CMS: Higgs $\rightarrow ZZ \rightarrow 4\ell$



- Pristine four-lepton final state, fully reconstructible.
- Tiny branching ratio but excellent mass resolution.

ATLAS Higgs $\to \gamma\gamma$ Discovery



New boson at $\sim$ 125 GeV with properties consistent with a Higgs.

ATLAS-CONF-2012-168, Fig. 1. Combined 7 TeV + 8 TeV diphoton mass spectrum.

A New Boson at 125 GeV

- ATLAS and CMS both see excesses near 125 GeV.
- Combined channels exceed 5σ significance.
- Properties align with a scalar carrying Higgs-like couplings.

Is it the Higgs or a Higgs?

Many models predict extended Higgs sectors:

Two-Higgs-doublet models, SUSY Higgs, singlet portals, . . .

Precision Higgs phenomenology

Measure couplings to W, Z, fermions, and itself.

Look for small deviations from SM predictions.

Higgs as a portal

Higgs couplings may connect the visible sector to dark matter or hidden sectors.

Invisible decays, exotic decays, modified branching ratios.

Open questions

Why is the Higgs so light?
Why this pattern of Yukawa couplings?
Is electroweak symmetry breaking unique?

The Higgs solved one mystery and opened many more.

Takeaway

Mass is not an input;
it is a consequence of the vacuum structure.

The 2013 Nobel Prize celebrates this shift.

Thank you.

Questions?

References I