

# **The Higgs Mechanism and the Origin of Mass**

2013 Nobel Prize in Physics

Vahid Gorgin

Shahid Beheshti University / Fundamental Physics Faculty

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# Why do particles have mass?

## A strange universe

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

## Why is mass a problem?

Gauge theories love massless fields.

But nature is full of massive particles.

Naive mass terms seem to break our symmetries.

## Gauge bosons and symmetry

Yang–Mills kinetic term keeps the gauge symmetry.

$$\mathcal{L}_{\text{YM}} = -\frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}$$

Symmetry protects masslessness.

## The forbidden mass term

$$\mathcal{L}_{\text{Proca}} = \frac{1}{2} m^2 A_\mu A^\mu$$

This term breaks gauge invariance.

## Fermion mass trouble

$$\mathcal{L}_{\text{Dirac}} = -m\bar{\psi}\psi$$

Left and right chiralities transform differently under  $SU(2) \times U(1)$ .

## The conflict

Gauge symmetry forbids naive mass.

Experiments demand massive  $W$ ,  $Z$ , and fermions.

We need a new idea that keeps the symmetry but generates mass.

## A clue: symmetry can hide itself

Equations stay symmetric.

The ground state can be asymmetric.

Next: a simple scalar field that hides symmetry.

## A symmetry... but a broken ground state

The laws respect the symmetry.

The vacuum does not.

Spontaneous symmetry breaking hides the symmetry in the ground state.

# A Simple Scalar Field

Complex scalar field with symmetric dynamics.

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - \mu^2 |\phi|^2 - \lambda |\phi|^4$$

# The Potential

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

If  $\mu^2 < 0$ , the minimum lies away from  $\phi = 0$ .

## Choosing a Vacuum

The minimum lies on a circle of vacua.

The vacuum picks one direction in field space.

Symmetry is hidden, not destroyed.

## Goldstone Modes

Breaking a continuous symmetry creates massless excitations along the flat directions. Goldstone theorem at work.

## Toward Massive Gauge Bosons

Spontaneous breaking leaves the Lagrangian symmetric.

Its vacuum chooses a direction.

Electroweak gauge fields will use this mechanism.

## Enter the Higgs Field

Next: build the electroweak story where the Higgs field completes mass generation.

## A field that fills space

Introduce the Higgs as an  $SU(2)$  doublet.

A field that is nonzero everywhere in the vacuum.

Its presence reshapes the behavior of gauge and matter fields.

## Choosing the Vacuum

We choose a vacuum  $\langle \phi \rangle = (0, v/\sqrt{2})^T$ .

One direction in the doublet acquires a constant value.

Here we visualize this with the Higgs potential.

## Gauge Boson Masses

Gauge fields absorb Goldstone modes and become massive.

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

Mass arises from interacting with the constant Higgs background.

## Fermion Masses

Yukawa term:  $-y_f \bar{\psi}_L \Phi \psi_R + \text{h.c.}$  VEV turns Yukawa coupling into mass.

$$m_f = \frac{y_f v}{\sqrt{2}}$$

## One Scalar Remains

Goldstone modes are eaten by the gauge fields.

One physical scalar excitation is left.

This is the Higgs boson we aim to discover.

## Why This Matters Experimentally

Masses and couplings are now predicted.

Production and decay rates follow from the Higgs mechanism.

These patterns define concrete search channels.

## Can we see the Higgs?

A scalar with predicted couplings.

Specific rates into  $ZZ$ ,  $\gamma\gamma$ , and other channels.

ATLAS and CMS can test this picture.

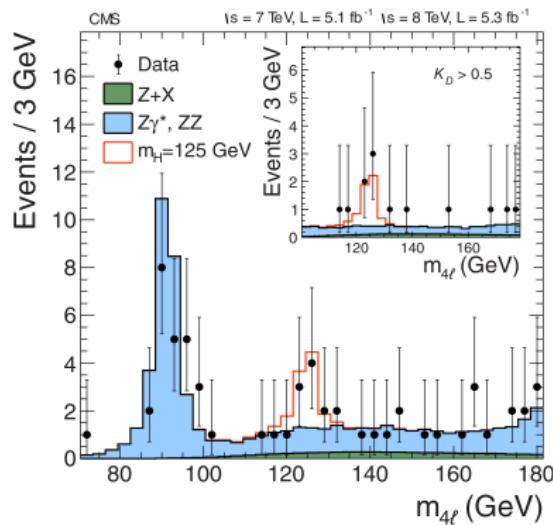
## Discovery: Does the Higgs show up?

Where would a Higgs leave a clear bump?

Can we see a narrow signal over huge backgrounds?

Focus on clean final states with precise mass reconstruction.

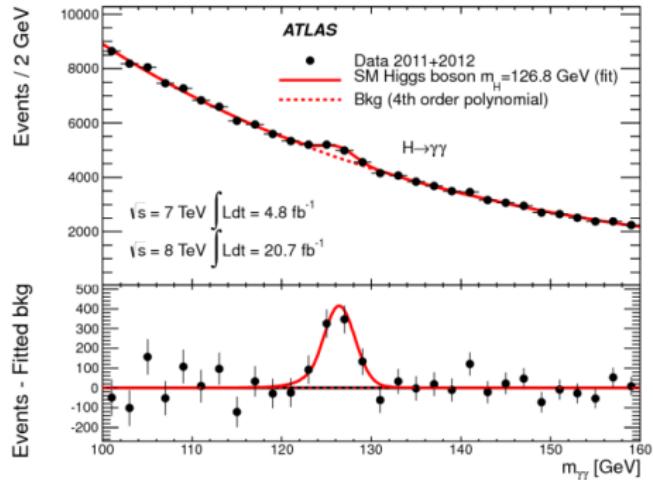
# CMS: Higgs $\rightarrow ZZ \rightarrow 4\ell$



Four clean leptons reconstruct a sharp mass peak.

A small but striking excess near 125 GeV.

# ATLAS Higgs $\rightarrow \gamma\gamma$ Discovery



Two high-energy photons with excellent energy resolution.

A narrow excess emerges near 125 GeV.

## A New Boson at 125 GeV

A narrow resonance appears in  $\gamma\gamma$  and  $ZZ \rightarrow 4\ell$ .

Mass reconstructed near 125 GeV.

Next: interpret these signals through couplings and rates.

## The Higgs couples in proportion to mass

Heavier particles couple more strongly to the Higgs.

Fermion couplings scale like  $m_f$ .

Vector couplings scale like  $m_V^2$ .

## Production

At the LHC, Higgs bosons are produced mainly by gluon fusion.

Vector boson fusion and associated production provide complementary handles.

Each mode favors different experimental signatures.

## Decays

Decay patterns follow from couplings and available phase space.

At 125 GeV, many channels compete.

Some are rare but exceptionally clean.

## Why $H \rightarrow \gamma\gamma$ ?

A loop-induced, rare decay.

No tree-level coupling, but an extremely clean electromagnetic signature.

Small branching ratio, high discovery power.

## Why $H \rightarrow ZZ \rightarrow 4\ell$ ?

Four charged leptons fully reconstruct the Higgs mass.

Backgrounds are tiny and well understood.

This is a golden channel.

## The 125 GeV Fingerprint

Observed rates in  $\gamma\gamma$  and  $ZZ \rightarrow 4\ell$  match predictions.

Coupling strengths follow mass–proportional patterns.

Phenomenology and discovery align.

## A consistent picture emerges

Production and decay patterns fit a 125 GeV Higgs boson.

Theory, phenomenology, and data form a unified story.

This concludes the arc from mechanism to discovery.

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