

# The Higgs Mechanism and the Origin of Mass

2013 Nobel Prize in Physics

Vahid Gorgin

[Your University / Department]

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# 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.*

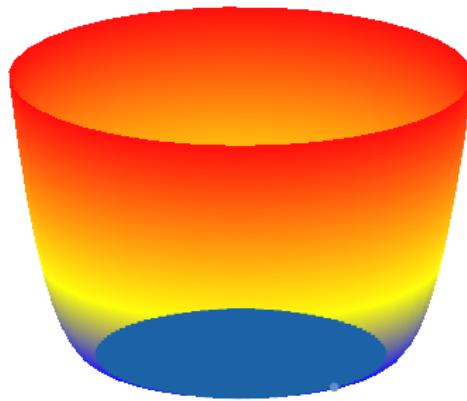
## The Higgs field idea

Introduce a complex scalar doublet  $\Phi$  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



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

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:

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

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.

## From idea to experiment

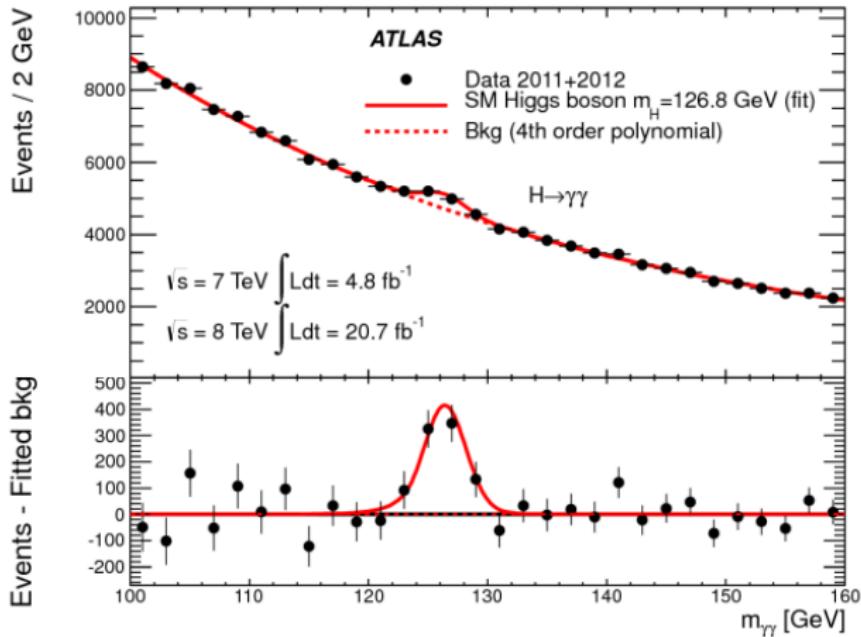
- 1964: mechanism proposed.
- 1980s–2000s: colliders push the energy frontier.
  - LHC built to finally test the Higgs idea.

## The search at the LHC

Look for a new scalar around  $\sim 100\text{--}1000\,\text{GeV}$ .

Decay channels:  $\gamma\gamma$ ,  $ZZ^*$ ,  $WW^*$ ,  $\tau\tau$ ,  $b\bar{b}$ .

# Discovery: July 4, 2012



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

The last missing piece of the  
Standard Model.

## 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