The Higgs Mechanism and the Origin of Mass

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Why do particles have mass?

And what if our best theory were missing the very field that gives it?

A strange universe

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

Mass slows everything down; something hidden must be doing the work.

The missing piece

For decades, the Higgs boson was a rumor.

Could an invisible field be real, or would the Standard Model unravel?

Tonight: follow the trail from paradox to discovery.

Theory: The problem of mass

Gauge symmetry wants light fields; experiments do not.

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.

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

Symmetry protects masslessness.

The forbidden mass term

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

This term breaks gauge invariance.

Fermion mass trouble

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

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.

Symmetry breaking

The vacuum hides the rules our equations respect.

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.

Goldstone modes live along the flat directions.

Goldstone's theorem in action.

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

Build the electroweak story with the Higgs field.

Its vacuum value will complete mass generation.

The Higgs field

A permeating field that lends mass to particles.

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 $\langle \phi \rangle = (0, v/\sqrt{2})^{\mathrm{T}}$.

One direction in the doublet acquires a constant value.

Here we visualize this **vacuum expectation value** with the Higgs potential.

Gauge Boson Masses

Gauge fields absorb Goldstone modes and become massive.

$$m_W = \frac{gv}{2}$$

The Z picks up an analogous mass set by g and g'. A single vacuum scale v controls them both.

Fermion Masses

Yukawa term $-y_f \, \bar{\psi}_L \Phi \psi_R + \text{h.c.}$ turns the VEV 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 at the LHC

Tracking a 125 GeV resonance in clean final states.

A short history of the hunt

Key waypoints on the Higgs road.

- 1964: Higgs mechanism proposed to hide symmetry while giving mass.
- 1980s–2000s: Electroweak precision tests tightened the allowed mass window.
- 2010s: The LHC switched on, turning prediction into experimental chase.

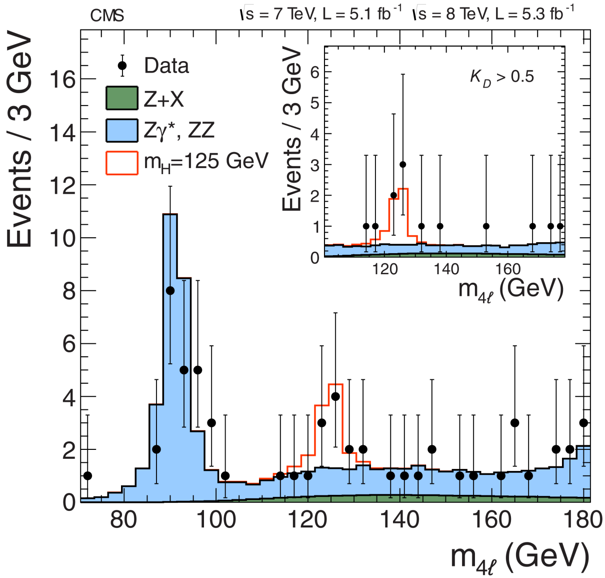
Discovery: Does the Higgs show up?

Where would a Higgs leave a clear bump?

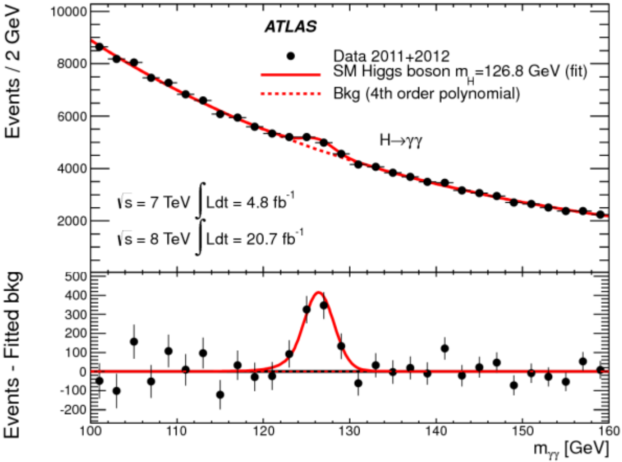
Can we see a narrow signal over huge backgrounds?

Focus on clean final states with precise mass reconstruction.

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



ATLAS Higgs $\rightarrow \gamma\gamma$ Discovery



Two high-energy photons with excellent energy resolution.

A New Boson at 125 GeV

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

Mass reconstructed near 125 **GeV**.

Next: interpret these signals through couplings and rates.

Phenomenology and legacy

How couplings, rates, and open questions line up.

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 $ZZ \to 4\ell$ match predictions.

Coupling strengths follow mass–proportional patterns.

Phenomenology and discovery align.

What would be wrong if this wasn't the Higgs?

Without the Higgs, the Standard Model would fall apart.

No symmetry-preserving way to give mass to W, Z, or fermions.

Precision tests and unitarity would be in tension without this field.

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.

A hidden field became a discovered particle.

Decades of tension collapsed into a 125 GeV signal.

Climax of the story

The bump at 125 GeV was the plot twist.

A once-hypothetical Higgs field revealed itself in data.

Theory, precision tests, and detectors finally converged.

Takeaway

Mass is a consequence of the vacuum structure.

The Higgs discovery resolved the mass paradox and reframed the Standard Model.

Thank you.

Questions?

Key references

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