

# THE HIGGS BOSON

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# THE STANDARD MODEL

- The Standard Model (SM) is currently the most accurate theory for describing interactions between elementary particles, particularly at high energies and on microscopic length scales.
- According to the model shown in the figure, matter is composed of 12 fundamental fermionic fields, each one accompanied by its respective antiparticle
- The SM describes interactions among elementary particles based on the principle of gauge invariance.

## Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.2 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	

**QUARKS** (left side of the table)

**LEPTONS** (left side of the table)

**GAUGE BOSONS VECTOR BOSONS** (bottom right)

**SCALAR BOSONS** (right side)

# THE STANDARD MODEL

- The model requires the laws of physics to remain unchanged even when particle "phases" are altered locally; this necessity dictates the existence of gauge bosons: the photon, the gluon, and the W/Z bosons.
- However, in the Lagrangian equations, a mass term for these mediators would look like:  $\mathcal{L}_{mass} = \frac{1}{2}m^2 \cdot A_\mu A^\mu$ .
- Taking the Abelian U(1) case as an example, under the gauge transformation:  $A_\mu \rightarrow A'_\mu = A_\mu + \partial_\mu \alpha(x)$ , The mass term transforms as:  $\frac{1}{2}m^2 \cdot A_\mu A^\mu \rightarrow \frac{1}{2}m^2(A_\mu + \partial_\mu \alpha(x)) \cdot (A^\mu + \partial^\mu \alpha(x)) \neq \frac{1}{2}m^2 \cdot A_\mu A^\mu$
- So that explicit masses for W and Z bosons would violate the gauge symmetry of the theory
- In the Standard Model, this mechanism is applied to the electroweak gauge symmetry:  $SU(2)_L \times U(1)_Y$
- Therefore, the only mathematical way to preserve the symmetry is that the mass of these mediators is equal to zero.

## Standard Model of Elementary Particles

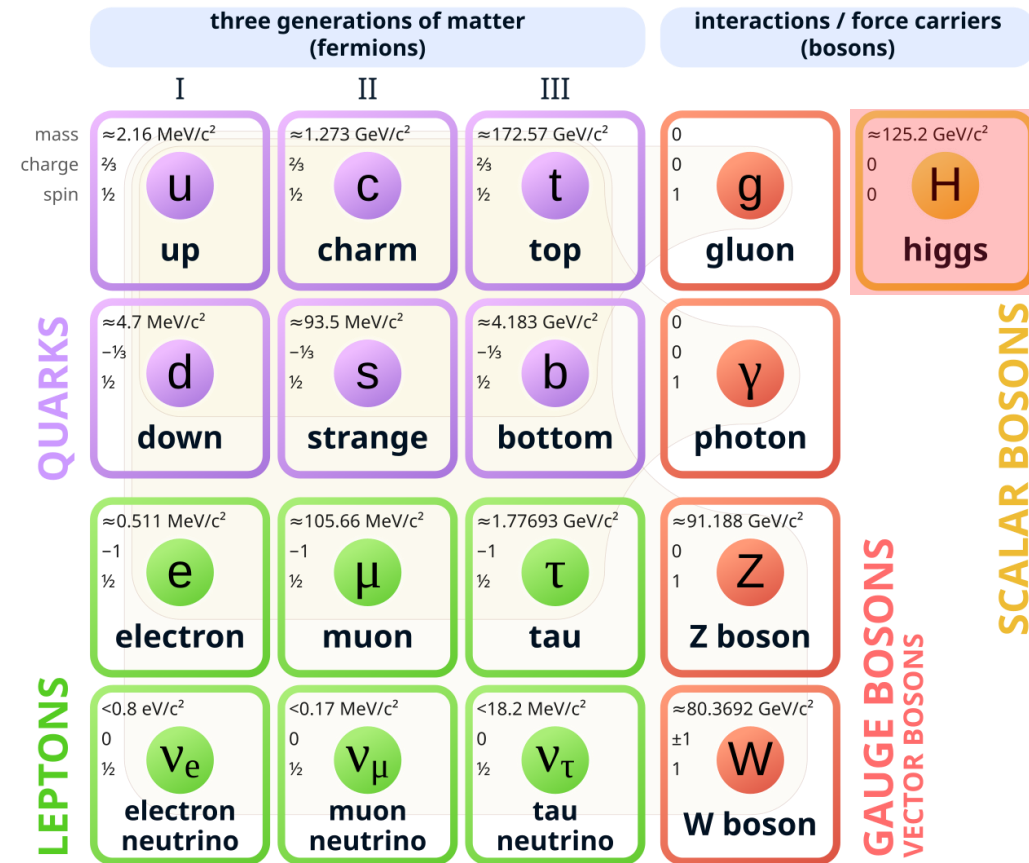
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# THE STANDARD MODEL

- However, experimental evidence has shown that the W and Z bosons have a non-zero mass, creating a fundamental contradiction with the theory.
- To resolve this, the Higgs boson was introduced; the idea is that mediators are not assigned mass directly in the equations, which would destroy the symmetry.
- Instead, the hypothesis is that these particles are born massless but interact with a field that permeates the entire universe: the Higgs Field.
- It is this continuous interaction with the field that effectively confers mass to the particles while keeping the underlying gauge symmetry intact.

## Standard Model of Elementary Particles



# THE POTENTIAL IN THE HIGGS FIELD: MEXICAN HAT

- The Higgs field is a complex doublet under the weak interaction symmetry group

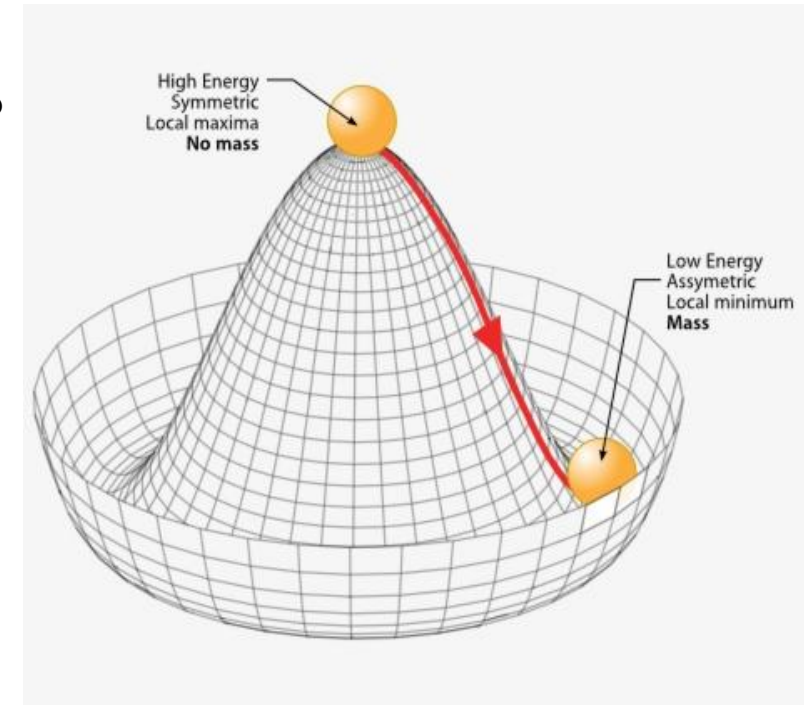
$SU(2)_L$ :  $\phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ , where  $\phi^+$  is a complex field associated with a positive electric charge, and  $\phi^0$  is an electrically neutral complex field.

- In the Higgs field, the form of the potential energy is:  $V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$ 
  - With  $\mu^2 > 0$
  - $\lambda > 0$

- The term  $-\mu^2|\phi|^2$  makes the point  $\phi = 0$  unstable, so the potential has a continuous set of degenerate minima, this is called the spontaneous symmetry breaking. With spontaneous symmetry breaking, 3 of the 4 degrees of freedom are absorbed by the gauge bosons to acquire their mass, leaving only one physical degree of freedom: the Higgs boson.

- The non-zero vacuum expectation value (VEV) is :  $|\phi| = \frac{v}{\sqrt{2}}$ , where  $v = 246 \text{ GeV}$

- By choosing a specific mathematical configuration (the *unitary gauge*), the field simplifies to this form:  $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h(x) \end{pmatrix}$



## HOW BOSONS ACQUIRE MASS?

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- Let's consider the kinetic term:  $|D_\mu \phi|^2$ , where  $D_\mu$  is the covariant derivative is defined as:  $D_\mu = \partial_\mu + igW_\mu^\alpha \tau^\alpha + ig' B_\mu Y$ , which contains the gauge fields:  $W_\mu^1, W_\mu^2, W_\mu^3$  e  $B_\mu$ . This covariant derivative is constructed in such a way that it transforms like the field under local gauge transformations, thereby ensuring the invariance of the theory
- Considering  $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h(x) \end{pmatrix}$ , if we compute the term  $|D_\mu \phi|^2$ , we obtain:
  - $\frac{1}{2} g^2 \cdot v^2 \cdot W_\mu W^\mu$ , which is the mass term for the  $W$  boson
  - $\frac{1}{2} (g^2 + g'^2) \cdot v^2 \cdot Z_\mu Z^\mu$ , which is the mass term for the  $Z$  boson
  - The photon remains massless.

# HOW FERMIONS ACQUIRE MASS? THE YUKAWA INTERACTION

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- Let's consider the fermionic field  $\psi$ , and the Higgs field  $\phi$
- In the Standard Model, the interaction is described by the Yukawa Lagrangian, which couples the left-handed and right-handed components of the fermionic field:

$$\mathcal{L}_{Yukawa} = -y_f (\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \phi^\dagger \psi_L)$$

- $y_f$ : is a dimensionless constant that indicates the strength of the coupling specific to each particle.
  - $\bar{\psi}_L \psi_R$ : represents the fermionic field.
- The mass of the fermion is given by this equation:  $m_f = y_f \frac{v}{\sqrt{2}}$ .
  - The values of  $y_f$  confer a hierarchy order to the fermion: the top quark is the heaviest ( $y_{top} = 1$ ), and the electron is the lightest ( $y_e = 2.9 \cdot 10^{-6}$ )

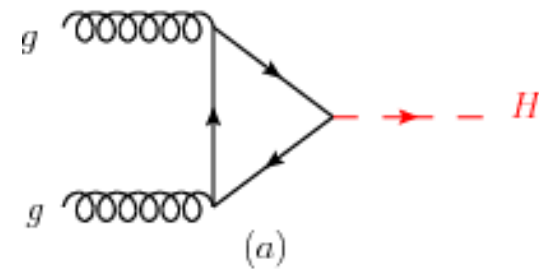
So this mechanism shows that the mass of particles (fermion or boson) is not an intrinsic property. The interaction with the Higgs field allows the particles to acquire mass without violating the gauge symmetries of the Standard Model.

# HIGGS BOSON FORMATION

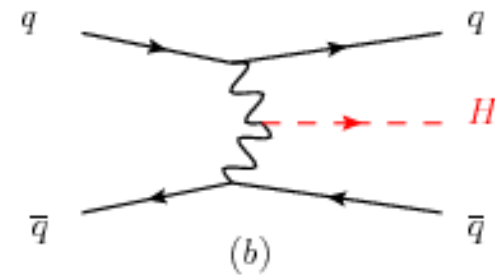
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- The Higgs boson is the quantum of one of the components of a complex scalar field, which is the Higgs field. As a scalar boson, it has spin zero, is its own antiparticle, and is even under a CP symmetry operation
- According to the Standard Model, the Higgs boson can be produced at particle colliders at very high energy through several distinct mechanisms:

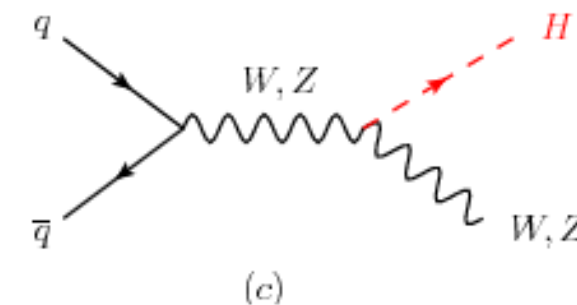
- Gluon Fusion (a): This is the dominant production process. It involves the interaction of two gluons, typically top quark.



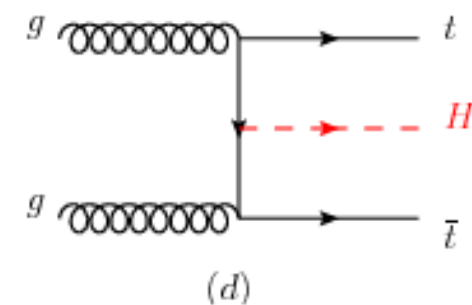
- Vector Boson Fusion (b): Two quarks radiate W or Z bosons that subsequently fuse to create a Higgs boson.



- Associated Production with a Vector Boson (c): Two quarks interact and there is the production of a Higgs boson in association with a W or Z



- Associated Production with a Top-Quark Pair (d): The Higgs is produced alongside a pair of top quarks.



## HIGGS BOSON DECAYS

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Once produced, the Higgs boson can decay through several channels. The branching ratios depend on its mass: for  $m_H \simeq 125$  GeV, the main channels are:

- $H \rightarrow b\bar{b}$  ( $\sim 58\%$ ),
- $H \rightarrow WW^*$  ( $\sim 21\%$ ),
- $H \rightarrow gg$  ( $\sim 8.5\%$ ),
- $H \rightarrow \tau^+\tau^-$  ( $\sim 6\%$ ),
- $H \rightarrow ZZ^*$  ( $\sim 2.6\%$ ),
- $H \rightarrow \gamma\gamma$  ( $\sim 0.2\%$ )

The fact that the Higgs boson decays through these channels is what made its experimental verification possible, as it allowed physicists to detect and measure the particles into which it decayed.

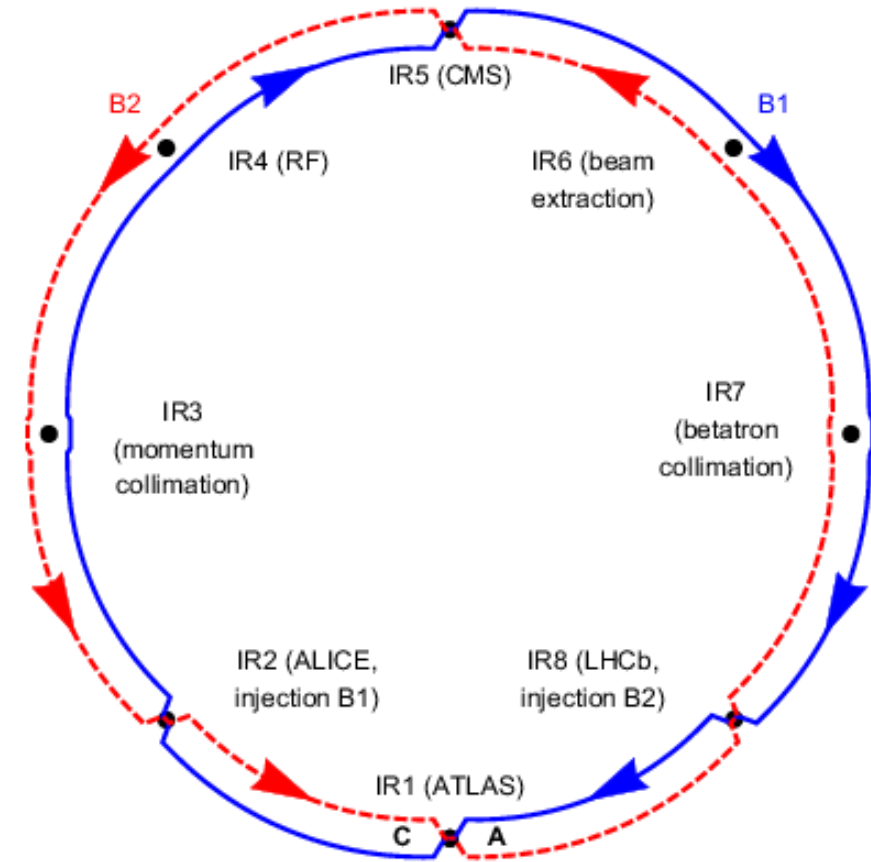
# THE HIGGS BOSON DISCOVERY

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# LARGE HADRON COLLIDER

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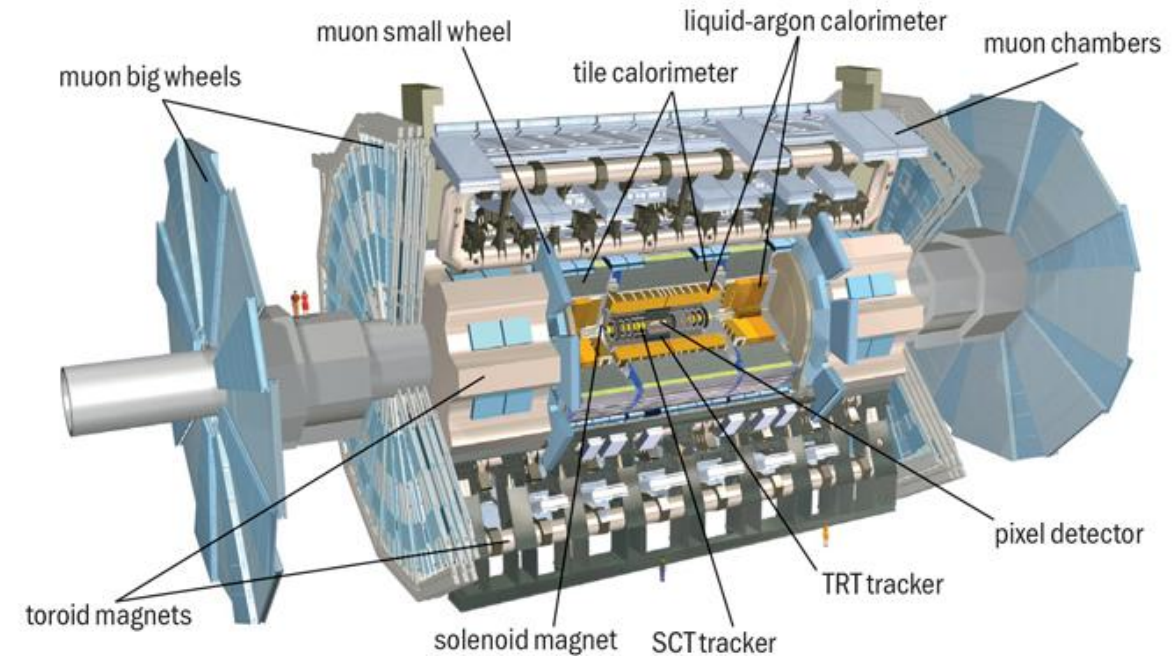
- Is the world's largest and highest-energy particle accelerator
- Located in a 27 km circumference underground tunnel at the CERN accelerator complex in Geneva.
- Inside it, charged particles such as protons are accelerated to speeds close to the speed of light and made to collide with an energy of  $\sqrt{s} = 13.6$  TeV inside the ATLAS and CMS detectors.
- Through these high-energy collisions, particles described by the Standard Model are produced, including the Higgs boson, with production rates depending on their respective cross sections.



# ATLAS DETECTOR

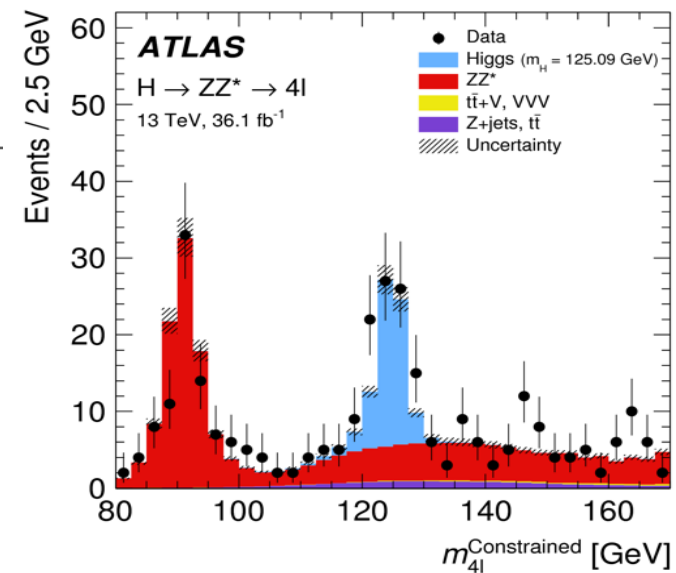
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- The collision of charged particles is in a point called IP (interaction point)
- The new particles produced propagate in all directions
- Inside the ATLAS detector, there is a system of sub-detectors:
  - Inner detector: measure the momentum and trajectory of charged particles
  - Calorimeters: measure the energy of electrons, photons, and hadrons
  - Muon Spectrometer: measure the momentum of muons
- Subsequently, particle reconstruction is performed by integrating the collected data: the energy deposits in the calorimeters are matched with the corresponding tracks measured by the inner detector to identify each particle



# DETECTION OF THE HIGGS BOSON

- After being produced, the Higgs boson survives for about  $10^{-22}$ s before decaying.
- The main channels on which the data analysis has focused are:
  - Two-photon channel:  $H \rightarrow \gamma\gamma$
  - Four-lepton channel:  $H \rightarrow ZZ^* \rightarrow 4l$
- Although  $H \rightarrow b\bar{b}$  is the most probable decay, it cannot be used in hadronic colliders because many bottom quarks are produced, which makes it more difficult to isolate the signal. The  $\gamma\gamma$  and  $ZZ^* \rightarrow 4l$  channels are called Golden Channels because they offer a very clean experimental signal
- Subsequently, the invariant mass of the final-state particles is calculated. The resulting invariant mass should correspond to the mass of the parent particle. So if the Higgs boson did not exist, the invariant mass distribution would show no peak around 125 GeV, but would instead be smoothly distributed
- In addition to determining the mass, further analyses of the spin and other properties were necessary.
- The existence of the Higgs boson was confirmed in 2012 with a significance of  $5\sigma$ . This discovery was awarded the Nobel Prize in Physics in 2013 to Peter Higgs and François Englert.



Thanks for the attention

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