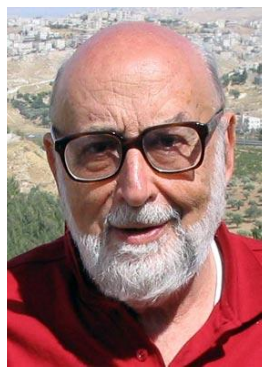
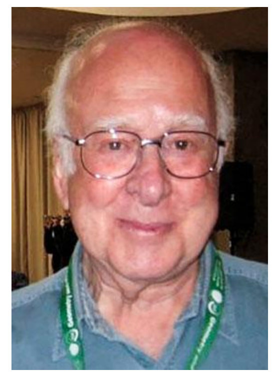
Higgs mechanism
The Nobel Prize in Physics 2013

François Englert


Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.*

Gauge Symmetry in Classical Electrodynamics

Lagrangian density

$$\mathcal{L}(x) = -\frac{1}{4} F^{\mu\nu}(x) F_{\mu\nu}(x) + j_\mu(x) A^\mu(x)$$

Strength tensor

$$F^{\mu\nu}(x) \equiv \partial^\mu A^\nu(x) - \partial^\nu A^\mu(x)$$

$$\partial^\mu \equiv \frac{\partial}{\partial x_\mu}$$

Gauge transformation

$$A^\mu(x) \to A^\mu(x) + \partial^\mu \Lambda(x)$$

$$\mathcal{L}(x) \to \mathcal{L}(x) + j_\mu(x) \partial^\mu \Lambda(x)$$

Action is invariant

$$S \equiv \int d^4x \, \mathcal{L}(x) \to S$$

$$\int d^4x \, j_\mu(x) \partial^\mu \Lambda(x) = -\int d^4x \, \partial^\mu j_\mu(x) \Lambda(x) = 0 \quad \Leftarrow \quad \partial^\mu j_\mu(x) = 0$$

Gauge Symmetry in Quantum Electrodynamics

$$\mathcal{L}(x) = -\frac{1}{4}F^{\mu\nu}(x)F_{\mu\nu}(x) + i\overline{\Psi}(x)(\gamma_\mu\partial^\mu + im)\Psi(x) - e\overline{\Psi}(x)\gamma_\mu\Psi(x)A^\mu(x)$$

Global symmetry

Noether theorm

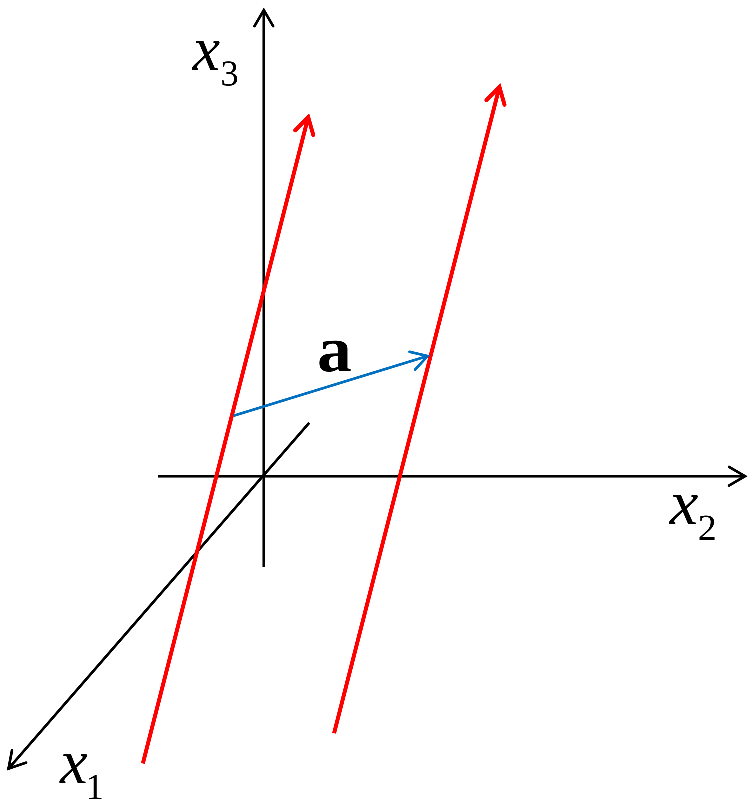
$$\begin{cases} \Psi(x) \to e^{-i\alpha}\Psi(x) \\ \overline{\Psi}(x) \to e^{i\alpha}\overline{\Psi}(x) \end{cases} \qquad \mathcal{L}(x) \to \mathcal{L}(x) \quad \Rightarrow \quad \begin{matrix} j_\mu(x) \equiv e\overline{\Psi}(x)\gamma_\mu\Psi(x) \\ \partial^\mu j_\mu(x) = 0 \end{matrix}$$

Local symmetry

$$\begin{cases} A^\mu(x) \to A^\mu(x) + \partial^\mu\Lambda(x) \\ \Psi(x) \to e^{-ie\Lambda(x)}\Psi(x) \\ \overline{\Psi}(x) \to e^{ie\Lambda(x)}\overline{\Psi}(x) \end{cases} \quad \Longrightarrow \quad \mathcal{L}_{\text{int}}(x) = -e\overline{\Psi}(x)\gamma_\mu\Psi(x)A^\mu(x)$$

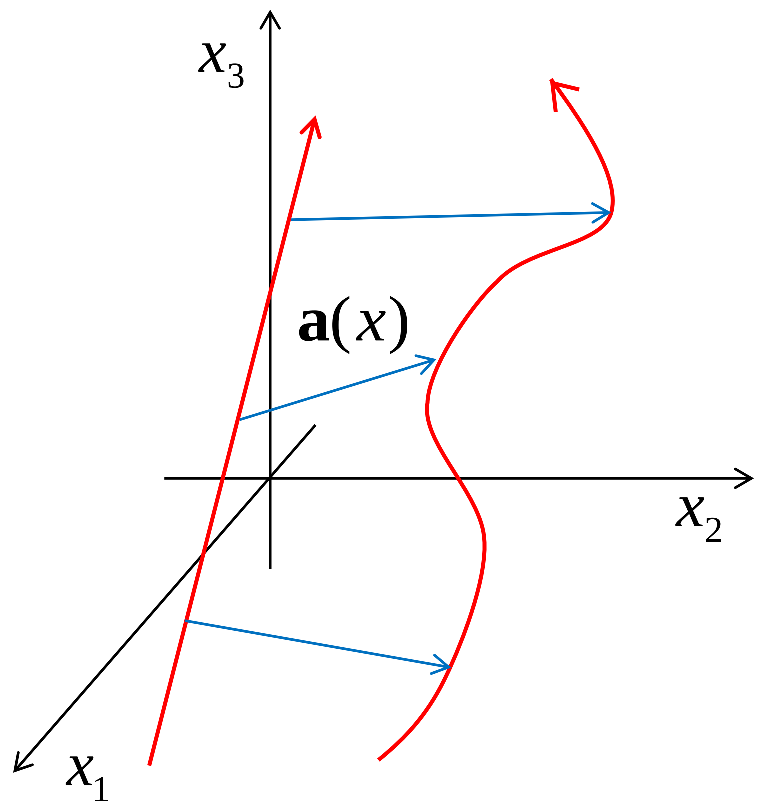
Local Symmetry & Interaction

Global symmetry



free particle trajectory → free particle trajectory

Local symmetry



free particle trajectory → interacting particle trajectory

Yang-Mills Fields

PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. Yang † and R. L. Mills
Brookhaven National Laboratory, Upton, New York

(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

- Baryon number conservation
- Universality of nuclear forces

$$\Psi = \begin{pmatrix} p \\ n \end{pmatrix} \rightarrow \underbrace{\begin{pmatrix} a & b \\ c & d \end{pmatrix}}_{U=U^{+} \,\&\; \det U=1} \begin{pmatrix} p \\ n \end{pmatrix}$$

$$U \in \mathrm{SU}(2)$$

Yang-Mills Fields

Local symmetry

$$\Psi(x) = \begin{pmatrix} p(x) \\ n(x) \end{pmatrix} \qquad \Psi(x) \to U(x)\Psi(x)$$

$$U(x) \in \mathrm{SU}(2)$$

$$\mathcal{L}(x) = -\frac{1}{4}\mathrm{Tr}[F^{\mu\nu}(x)F_{\mu\nu}(x)] + i\overline{\Psi}(x)(\gamma_\mu \partial^\mu + im)\Psi(x) - g\overline{\Psi}(x)\gamma_\mu A^\mu(x)\Psi(x)$$

$$F^{\mu\nu}(x) \equiv \partial^\mu A^\nu(x) - \partial^\nu A^\mu(x) - ig[A^\nu(x), A^\mu(x)]$$

NonAbelian theory $\quad [A^\nu(x), A^\mu(x)] \neq 0$

$$A^\mu(x) \to U(x)A^\mu(x)U^+(x) + \frac{i}{g}U(x)\partial^\mu U^+(x)$$

$$F^{\mu\nu}(x) \to U(x)F^{\mu\nu}(x)U^+(x)$$

Masslessness of Guage Fields

Potential of point-like source $$A^0(x) \sim \frac{1}{|\mathbf{x}|}$$

How to get $$A^0(x) \sim \frac{e^{-m|\mathbf{x}|}}{|\mathbf{x}|}$$?

Proca Lagrangian

$$\mathcal{L}(x) = -\frac{1}{4}F^{\mu\nu}(x)F_{\mu\nu}(x) - \frac{1}{2}m^2 A_\mu(x)A^\mu(x)$$

The mass term breaks gauge invariance!

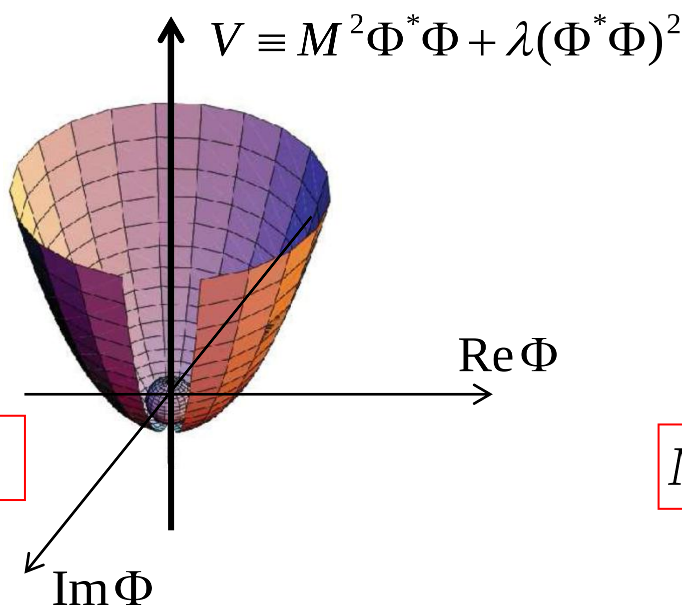
Spontaneous Symmetry Breakdown

$$\mathcal{L}(x) = \left(\partial^\mu \Phi^*(x)\right)\left(\partial_\mu \Phi(x)\right) - M^2 \Phi^*(x)\Phi(x) - \lambda\left(\Phi^*(x)\Phi(x)\right)^2$$

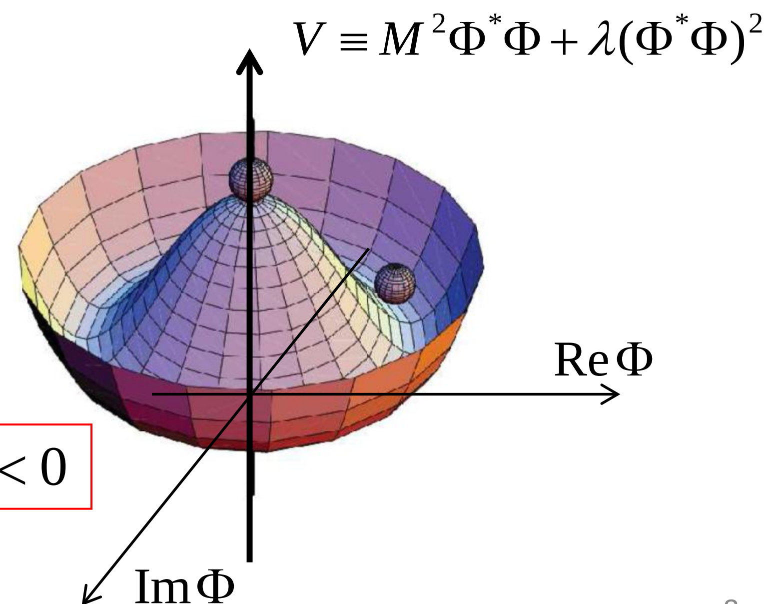
Global symmetry

$$\begin{cases} \Phi(x) \to e^{-i\alpha}\Phi(x) \\ \Phi^*(x) \to e^{i\alpha}\Phi^*(x) \end{cases} \qquad \mathcal{L}(x) \to \mathcal{L}(x)$$

$\lambda > 0$



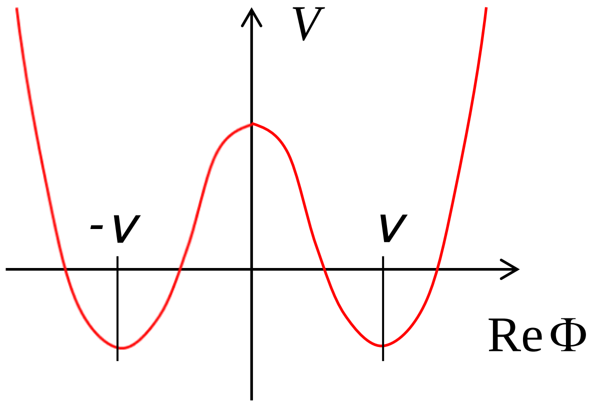
$M^2 > 0$



$M^2 < 0$

Spontaneous Symmetry Breakdown

$M^2 < 0$



$$v \equiv \sqrt{-\frac{M^2}{2\lambda}}$$

New real fields

$$\varphi(x) \equiv \sqrt{2}\left(\mathrm{Re}\,\Phi(x) - v\right), \qquad \chi(x) \equiv \sqrt{2}\,\mathrm{Im}\,\Phi(x)$$

$$\mathcal{L} \to \mathcal{L} = \frac{1}{2}(\partial^\mu \varphi)(\partial_\mu \varphi) - \frac{1}{2}m^2\varphi^2 + \frac{1}{2}(\partial^\mu \chi)(\partial_\mu \chi) - \lambda v \varphi(\varphi^2 + \chi^2) - \frac{1}{2}\lambda(\varphi^2 + \chi^2)^2$$

$m^2 \equiv 2\lambda v^2$

$\chi(x)$ - massless Goldstone field

One Solution of Two Problems

Problems

- masslessness of gauge bosons
- masslessness of Goldstone bosons

Solution

- Higgs mechanism

Higgs mechanism

$$\mathcal{L}(x) = -\frac{1}{4}F^{\mu\nu}(x)F_{\mu\nu}(x) + \left(D^{\mu}\Phi(x)\right)^{*}\left(D_{\mu}\Phi(x)\right) - M^{2}\Phi^{*}(x)\Phi(x) - \lambda\left(\Phi^{*}(x)\Phi(x)\right)^{2}$$

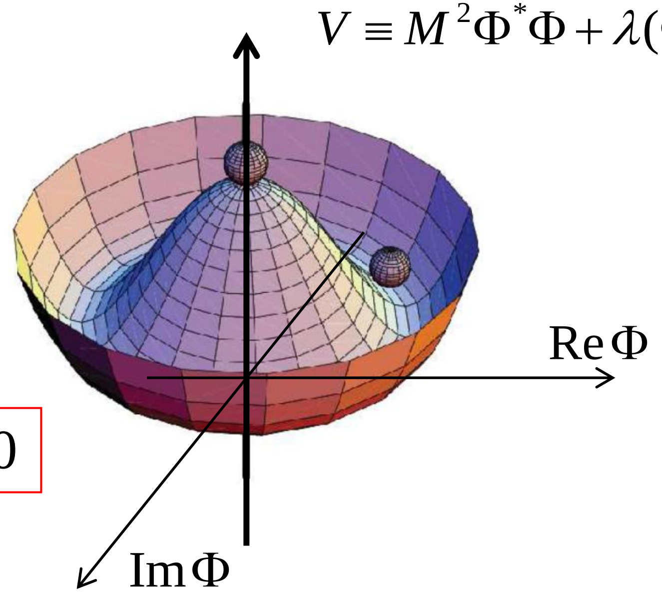
Local gauge symmetry

$$D^{\mu} \equiv \partial^{\mu} + ieA^{\mu}(x)$$

$$\begin{cases} A^{\mu}(x) \rightarrow A^{\mu}(x) + \partial^{\mu}\Lambda(x) \\ \Phi(x) \rightarrow e^{-ie\Lambda(x)}\Phi(x) \end{cases}$$

$$\mathcal{L}(x) \rightarrow \mathcal{L}(x)$$

$$V \equiv M^{2}\Phi^{*}\Phi + \lambda(\Phi^{*}\Phi)^{2}$$



$$M^{2} < 0$$

Higgs Mechanism

New real fields: $H(x),\, B^{\mu}(x),\, \Lambda(x)$

$$\Phi(x) = \frac{1}{\sqrt{2}}\big(H(x)+v\big)e^{i\Lambda(x)/v} \qquad A^{\mu}(x) = B^{\mu}(x) - \frac{1}{ev}\partial^{\mu}\Lambda(x)$$

$$\mathcal{L} \to \mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}m_B^2 B_{\mu}B^{\mu} + \frac{1}{2}(\partial^{\mu}H)(\partial_{\mu}H) - \frac{1}{2}m_{\varphi}^2 H^2 + \frac{1}{2}e^2 B_{\mu}B^{\mu}(H^2 + 2vH) - \frac{1}{4}\lambda H^4$$

$$F^{\mu\nu} \equiv \partial^{\mu}B^{\nu} - \partial^{\nu}B^{\mu} \qquad \boxed{m_B^2 \equiv e^2 v^2} \qquad m_H^2 \equiv 2\lambda v^2$$

$A^{\mu}(x)$ - massless vector field – 2 dof

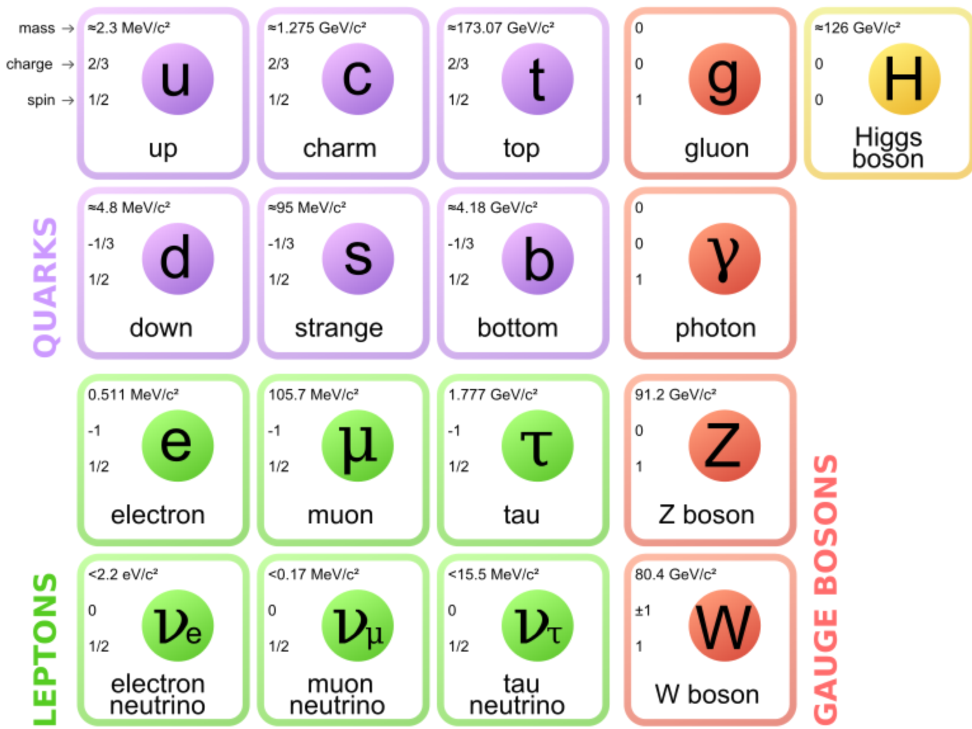
$B^{\mu}(x)$ - massive vector field – 3 dof

$\Phi(x)$ - complex scalar field – 2 dof

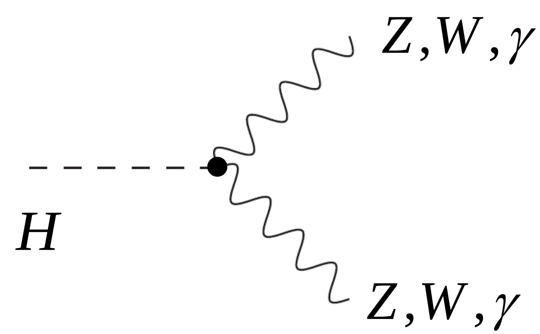
$H(x)$ - real scalar Higgs field – 1 dof

$\Lambda(x)$ - disappeared due to the guage invariance

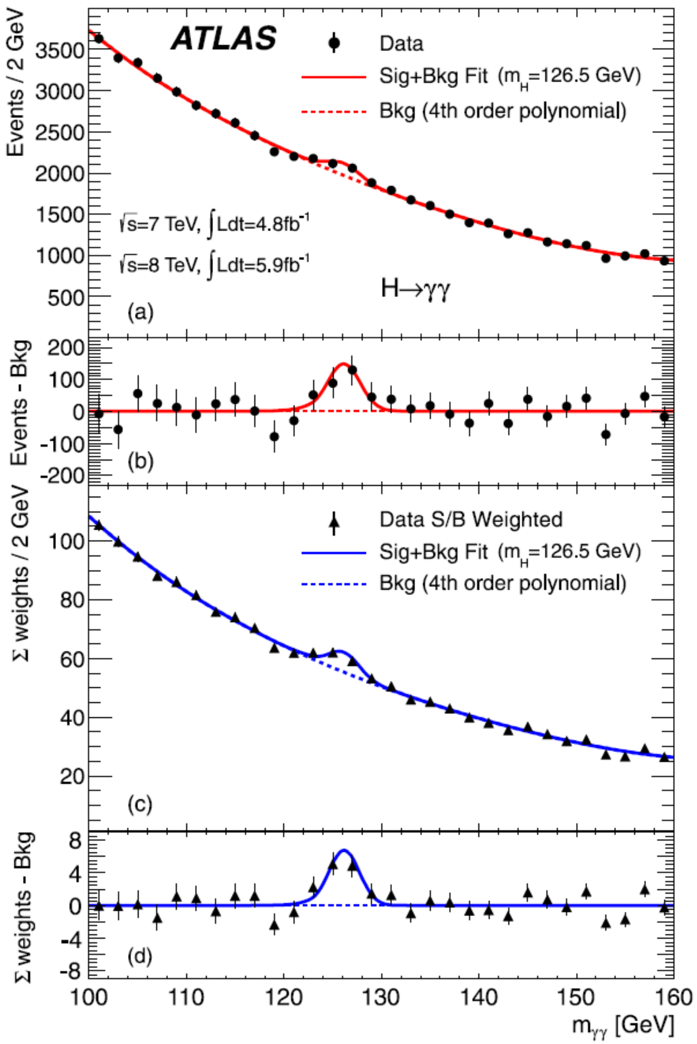
Higgs Boson in the Standard Model



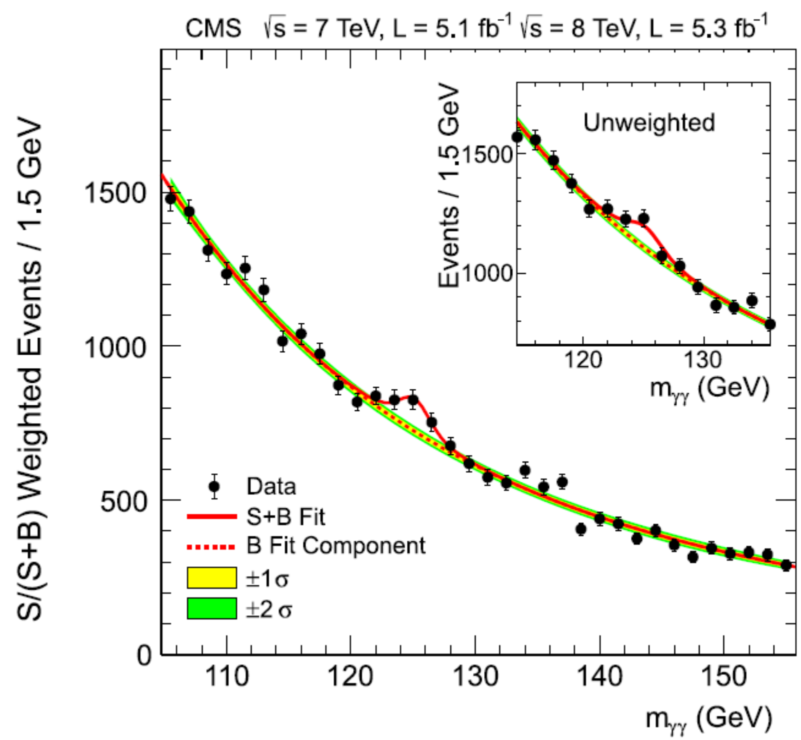
$$\mathcal{L}_{\text{int}} = e^2 v B_\mu B^\mu H$$



Observation of Higgs Boson – CERN 2012



$$pp \to H + X \quad @ \quad LHC$$



$$m_H = 125 \text{ GeV}$$

Candidates for the Nobel Prize

VOLUME 13, NUMBER 9 — PHYSICAL REVIEW LETTERS — 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

Volume 12, number 2 — PHYSICS LETTERS — 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 — PHYSICAL REVIEW LETTERS — 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

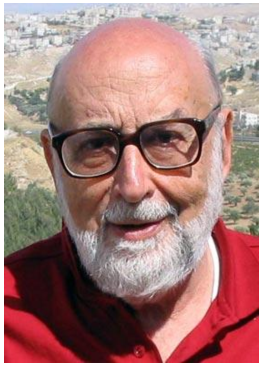
VOLUME 13, NUMBER 20 — PHYSICAL REVIEW LETTERS — 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Robert Brout died on May 3, 2011

Nobel Prize 2013



François Englert

Peter W. Higgs