From an obscure term in an equation to a headline discovery – and beyond

John Ellis
King’s College London
(& CERN)
Programme of Lectures

• Motivations and introduction
• What we know now
• The future?
  – Supersymmetric Higgses
  – Higgs factories
The Standard Model

The matter particles

The fundamental interactions

Gravitation  electromagnetism  weak nuclear force  strong nuclear force

Where does mass come from?

Cosmic DNA
Open Questions within & beyond the Standard Model

• What is the origin of particle masses due to a Higgs boson?
• Why so many types of matter particles?
• What is the dark matter in the Universe?
• Unification of fundamental forces?
• Quantum theory of gravity?
To Higgs or not to Higgs?

• Need to discriminate between different types of particles:
  – Some have masses, some do not
  – Masses of different particles are different
• In mathematical jargon, symmetry must be broken: how?
  – Break symmetry in equations?
  – Or in solutions to symmetric equations?
• This is the route proposed by Higgs
  – Is there another way?
Where to Break the Symmetry?

• Throughout all space?
  – Route proposed by Higgs *et al.*
  – Universal Higgs field breaks symmetry

• Or at the edge of space?
  – Break symmetry at the boundary?

• Not possible in 3-dimensional space
  – No boundaries
  – *Postulate extra dimensions of space*

• Different particles behave differently in the extra dimension(s)
When in trouble, Theorists …

… postulate a new particle:

- QM and Special Relativity: Antimatter
- Nuclear spectra: Neutron
- Continuous spectrum in β decay: Neutrino
- Nucleon-nucleon interactions: Pion
- Absence of lepton number violation: Second neutrino
- Flavour SU(3): Ω⁻
- Flavour SU(3): Quarks
- FCNC: Charm
- CP violation: Third generation
- Strong dynamics: Gluons
- Weak interactions: W⁺, Z⁰
- **Renormalizability:** H
- Dark matter: WIMP/axion?
Completing the Holy Trinity

• Scale hierarchy possible only in theory that can be calculated over many magnitudes of energy

  Renormalizable

• Theorem: (1) vectors (2) fermions (3) scalars

• Need to specify:

  (1) group (2) representations (3) symmetry breaking

  (1) = SU(3) × SU(2) × U(1) [so far]

  (2) = Singlets + doublets + triplets

• Finally:

  (3) A scalar, mechanism of symmetry breaking

Cornwall, Levin & Tiktopoulos; Bell; Llewellyn-Smith
Standard Model Particles: Years from Proposal to Discovery

Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON

Source: The Economist
Summary of the Standard Model

- Particles and $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$ quantum numbers:

<table>
<thead>
<tr>
<th>$L_L$</th>
<th>$\left( \begin{array}{c} \nu_e \ e^- \end{array} \right)<em>L, \left( \begin{array}{c} \nu</em>\mu \ \mu^- \end{array} \right)<em>L, \left( \begin{array}{c} \nu</em>\tau \ \tau^- \end{array} \right)_L$</th>
<th>$(1,2,-1)$</th>
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<tr>
<td>$E_R$</td>
<td>$e_R, \mu_R, \tau_R$</td>
<td>$(1,1,-2)$</td>
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<table>
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<th>$Q_L$</th>
<th>$\left( \begin{array}{c} u \ d \end{array} \right)_L, \left( \begin{array}{c} c \ s \end{array} \right)_L, \left( \begin{array}{c} t \ b \end{array} \right)_L$</th>
<th>$(3,2,+1/3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_R$</td>
<td>$u_R, c_R, t_R$</td>
<td>$(3,1,+4/3)$</td>
</tr>
<tr>
<td>$D_R$</td>
<td>$d_R, s_R, b_R$</td>
<td>$(3,1,-2/3)$</td>
</tr>
</tbody>
</table>

- Lagrangian:

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

\begin{align*}
&+ \ i \bar{\psi} \not\partial \psi + h.c. \\
&+ \ \psi_i y_{ij} \psi_j \phi + h.c. \\
&+ \ |D_\mu \phi|^2 - V(\phi)
\end{align*}

- gauge interactions
- matter fermions
- Yukawa interactions
- Higgs potential
Status of the Standard Model

- Perfect agreement with all confirmed accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing $< \sim 180$ GeV
- Raises many unanswered questions: *mass? flavour? unification?*
Precision Tests of the Standard Model

Lepton couplings

Pulls in global fit

It works!
The Standard Model Lagrangian

\[ \mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \]

\[ \mathcal{L}_m = \bar{Q}_L i \gamma^\mu D^L_\mu Q_L + \bar{q}_R i \gamma^\mu D^R_\mu q_R + \bar{L}_L i \gamma^\mu D^L_\mu L_L + \bar{l}_R i \gamma^\mu D^R_\mu l_R \]

\[ \mathcal{L}_g = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} \]

\[ \mathcal{L}_h = (D^L_\mu \phi)\dagger (D^L_{\mu} \phi) - V(\phi) \]

\[ \mathcal{L}_y = y_d \bar{Q}_L \phi q^d_R + y_u \bar{Q}_L \phi^c q^u_R + y_L \bar{L}_L \phi l_R + \]

\[ D^L_\mu = \partial_\mu - ig W^{a}_{\mu} T^{a} - i Y g' B_\mu \]  

\[ V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4 \]
The only one who mentioned a massive scalar boson.
The Englert-Brout-Higgs Mechanism

- Vacuum expectation value of scalar field
- Englert & Brout: June 26\textsuperscript{th} 1964
- First Higgs paper: July 27\textsuperscript{th} 1964
- Pointed out loophole in argument of Gilbert if gauge theory described in Coulomb gauge
- Accepted by Physics Letters
- Second Higgs paper with explicit example sent on July 31\textsuperscript{st} 1964 to Physics Letters, rejected!
- Revised version (Aug. 31\textsuperscript{st} 1964) accepted by PRL
But the Higgs Boson

Englert & Brout

Higgs

Guralnik, Hagen & Kibble

Also

Goldstone in
global case

\[ \frac{\partial^\mu}{\partial \mu} \{ \phi^0_0 (\Delta \phi^0_1 - e \phi^0_{A \mu}) \} = 0, \]  \hspace{1cm} (2a)

\[ \{ \partial^2 - 4 \phi^0 \partial V''(\phi^0) \} (\Delta \phi^0_2) = 0, \]  \hspace{1cm} (2b)

\[ \partial^\nu F^\mu\nu = e \phi^0_0 \{ \partial^\nu (\Delta \phi^0_1) - e \phi^0_{A \mu} \}. \]  \hspace{1cm} (2c)

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons. It is to be

We consider, as our example, a theory which was partially solved by Englert and Brout,\textsuperscript{5} and bears some resemblance to the classical theory of Higgs.\textsuperscript{6} Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

\[ \mathcal{L} = -\frac{1}{2} F^\mu\nu \partial_\mu A_\nu - \frac{1}{4} F^\mu\nu F_{\mu\nu} + \frac{1}{2} F^\mu\nu \partial_\mu \phi + \frac{1}{2} \phi^\mu \phi_\mu + i e \phi^0 \phi \bar{q} q A_{\mu}, \]

With no loss of generality, we can take \( \eta_2 = 0 \), and find

\[ (-\partial^2 + \eta_1^2) A_k^T = 0, \]

\[ -\partial^2 \phi_2 = 0, \]

where the superscript \( T \) denotes the transverse part. The two degrees of freedom of \( A_k^T \) combine with \( \phi_1 \) to form the three components of a

FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, \( \langle \phi_1 \rangle \); long-dashed line, \( \varphi_2 \) propagator; wavy line, \( A_\mu \) propagator. (a) \( -2(2\pi)^k i e^2 g_{\mu\nu} \langle \phi_1 \rangle^2 \), (b) \( -2(2\pi)^k i e^2 (q_{\mu} q_{\nu} / \eta_1^2) \times \langle \phi_1 \rangle^2 \).
The Higgs Mechanism

- Postulated effective Higgs potential:
  \[ V[\phi] = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \]

- Minimum energy at non-zero value:
  \[ \phi_0 = \langle 0 | \phi | 0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ +v \end{pmatrix} \quad v = \sqrt{\frac{-\mu^2}{\lambda}} \]

- Components of Higgs field:
  \[ \phi(x) = \frac{1}{\sqrt{2}} (v + \sigma(x))e^{i\pi(x)} \]

- \( \pi \) massless, \( \sigma \) massive:
  \[ m_H^2 = 2\mu^2 = 2\lambda v \]

- Couple to fermions: on-zero masses:
  \[ M_f = y_f \frac{v}{\sqrt{2}} \]

- After gauging:
  \[ M_W = \frac{g v}{2} \]
Abelian Higgs Mechanism

**Lagrangian**

\[ \mathcal{L} = (D_{\mu}\phi)^+ (D^\mu \phi) - V(|\phi|) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \quad D_{\mu} = \partial_{\mu} - ieA_{\mu} \]

**Gauge transformation**

\[ \phi'(x) = e^{i\alpha(x)} \phi(x) = e^{i\alpha(x)} e^{i\theta(x)} \eta(x) \]
\[ A'_{\mu}(x) = A_{\mu}(x) + \frac{1}{e} \partial_{\mu} \alpha(x) \]

**Choose**

\[ \alpha(x) = -\theta(x) : \quad \phi'(x) = \eta(x) \]

**Rewrite Lagrangian:**

\[ \mathcal{L} = |(\partial - ieA'_{\mu})\eta|^2 - V(\eta) - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} \]

\[ \mathcal{L} = |(\partial_{\mu} - ieA'_{\mu})(v + \frac{1}{\sqrt{2}} H)|^2 - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - V \]

\[ = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + v^2 e^2 A'_{\mu} A'^{\mu} + \frac{1}{2}[(\partial_{\mu} H)^2 - m_H^2 H^2] + \cdots \]

| massive A-field, \( m_A \sim ev \) | neutral scalar, \( m_H \neq 0 \) |
Nambu EB, H, GHK and Higgs

Spontaneous symmetry breaking: massless Nambu-Goldstone boson ‘eaten’ by massless gauge boson

Accompanied by massive particle
Masses for SM Gauge Bosons

- Kinetic terms for SU(2) and U(1) gauge bosons:

\[ \mathcal{L} = -\frac{1}{4} \, G_{\mu\nu}^i G^{i\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

where \[ G_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + i g \epsilon_{ijk} W_\mu^j W_\nu^k \]

\[ F_{\mu\nu} = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i \]

- Kinetic term for Higgs field:

\[ \mathcal{L}_\phi = -|D_\mu \phi|^2 \quad D_\mu = \partial_\mu - i g \sigma_i W_\mu^i - i g' Y B_\mu \]

- Expanding around vacuum:

\[ \phi = <0|\phi|0> + \hat{\phi} \]

\[ \mathcal{L}_\phi \supset -\frac{g^2 v^2}{2} W_\mu^+ W_\mu^- + \frac{g'^2 v^2}{2} B_\mu B_\mu + g g' v^2 B_\mu W_\mu^3 - g^2 \frac{v^2}{2} W_\mu^3 W_\mu^3 \]

- Boson masses:

\[ m_{W^\pm} = \frac{g v}{2} \]

\[ Z_\mu = \frac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}} ; \quad m_Z = \frac{1}{2} \sqrt{g^2 + g'^2} v ; \quad A_\mu = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}} ; \quad m_A = 0 \]
Higgs Boson Couplings

\[ g_2 M_W, \quad g_2 \frac{M_Z}{c_W} \]

\[ \frac{m_f}{v} = \frac{g_2 m_f}{2M_W} \]

\[ \Gamma(H \to f \bar{f}) = N_c \frac{G_F M_H}{4\pi \sqrt{2}} m_f^2, \quad N_C = 3 \quad \text{(1) for quarks (leptons)} \]

\[ \Gamma(H \to VV) = \frac{G_F M_H^3}{8\pi \sqrt{2}} F(r) \left( \frac{1}{2} \right)_Z, \quad r = \frac{M_V}{M_H} \]
Why a Higgs Boson is Needed

• Trouble with WW scattering: $M \sim E^2$

→ uncontrollable infinities in loop diagrams can be cancelled by scalar exchange with HWW couplings

\[ M = M_V + M_S \]

\[ \approx \frac{M_H^2}{\rho^2} \left( 2 + \frac{M_H^2}{s-M_H^2} + \frac{M_H^2}{t-M_H^2} \right) \]

• Similar for fermions
A Phenomenological Profile of the Higgs Boson

• First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson \( H \) expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
A Preview of the Higgs Boson @ LHC

• Prepared for LHC Lausanne workshop 1984
Constraints on Higgs Mass

- Electroweak observables sensitive via quantum loop corrections:
  \[ m^2_W \sin^2 \theta_W = m^2_Z \cos^2 \theta_W \sin^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r) \]

- Sensitivity to top, Higgs masses:
  \[ \frac{3G_F}{8\pi^2 \sqrt{2}} m_t^2 \quad \frac{\sqrt{2} G_F}{16\pi^2} m_W^2 \left( \frac{11}{3} \ln \frac{M_H^2}{m_Z^2} + \ldots \right), \quad M_H >> m_W \]

- Preferred Higgs mass: \( m_H \sim 100 \pm 30 \text{ GeV} \)

- Compare with lower limit from direct search at LEP:
  \( m_H > 114 \text{ GeV} \)

and exclusion around \((160, 170 \text{ GeV})\) at TeVatron
Sensitivity to Higgs Mass

- Experimental uncertainty $\Delta M_W \sim 15$ MeV
- Theoretical uncertainty $\sim 4$ MeV
Estimating the Mass of the Higgs Boson

- First attempts in 1990, **1991**

- Easier after the discovery of the top quark
The State of the Higgs: July 2011

- Direct search limit from LEP: \( m_H > 114.4 \text{ GeV} \)
- Electroweak fit sensitive to \( m_t \)
  (Now \( m_t = 173.1 \pm 1.3 \text{ GeV} \))
- Best-fit value for Higgs mass:
  \( m_H = 94^{+29}_{-24} \text{ GeV} \)
- 95% confidence-level upper limit:
  \( m_H < 161 \text{ GeV} \)
- Tevatron exclusion:
  \( m_H < 156 \text{ GeV} \) or \( > 177 \text{ GeV} \)
2011: Combining Information from Previous Direct Searches and Indirect Data

\[ m_H = 125 \pm 10 \text{ GeV} \]
Many production modes measurable if $M_h \sim 125$ GeV
Calculated at Next-to-next-leading order (NNLO) including leading higher-order logs (NNLL)

- Good agreement between theoretical groups
- Significant rise from 7 to 14 TeV
gg $\rightarrow$ Higgs Production at the LHC

- Main remaining uncertainties:
  - Choice of renormalization scale
  - Choice of gluon parton distribution function
VBF Higgs Production at the LHC

- Calculated at NNLO including electroweak corrections at NLO
- Good convergence of perturbation expansion
- Small uncertainties in quark parton dist’ns
Associated V+H Production at the LHC

- Calculated at NNLO including electroweak corrections at NLO
- Good convergence of perturbation expansion
Associated $\bar{t}t+H$ Production

- Calculated at NLO: uncertainties due to
  - Perturbation expansion
  - Choice of parton distributions
Higgs Decay Branching Ratios

• Couplings proportional to masses (?)

• Important couplings through loops:
  \[
  \text{gluon} + \text{gluon} \rightarrow \text{Higgs} \rightarrow \gamma\gamma
  \]

Many decay modes measurable if \( M_h \sim 125 \text{ GeV} \)
Higgs Decays

- Estimates of uncertainties in branching ratios

<table>
<thead>
<tr>
<th>Partial width</th>
<th>QCD</th>
<th>Electroweak</th>
<th>Total</th>
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<tr>
<td>$H \rightarrow bb/\text{cc}$</td>
<td>$\sim 0.1–0.2%$</td>
<td>$\sim 1–2%$ for $M_H \lesssim 135 \text{ GeV}$</td>
<td>$\sim 1–2%$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$\sim 1–2%$ for $M_H \lesssim 135 \text{ GeV}$</td>
<td>$\sim 1–2%$</td>
<td></td>
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<tr>
<td>$H \rightarrow \text{tt}$</td>
<td>$\sim 5%$</td>
<td>$\lesssim 2–5%$ for $M_H &lt; 500 \text{ GeV}$</td>
<td>$\sim 5%$</td>
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<tr>
<td></td>
<td></td>
<td>$\sim 0.1(M_H/1 \text{ TeV})^4$ for $M_H &gt; 500 \text{ GeV}$</td>
<td>$\sim 5–10%$</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>$\sim 10%$</td>
<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
</tr>
<tr>
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<tr>
<td>$H \rightarrow \text{WW/ZZ} \rightarrow 4f$</td>
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<td>$\sim 0.5%$</td>
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<tr>
<td></td>
<td></td>
<td>$\sim 0.17(M_H/1 \text{ TeV})^4$ for $M_H &gt; 500 \text{ GeV}$</td>
<td>$\sim 0.5–15%$</td>
</tr>
</tbody>
</table>

- QCD @ NNNLO
- EW @ NLO
- Total decay rate
  $\sim 4.2 \text{ MeV}$ for 126 GeV
Higgsdependence Day!
• Mass measurements: $125.6 \pm 0.3$ GeV
• Signal strengths ~ SM in many channels
• Frontiers:
  – VBF significance $2\sigma$ in several channels, $3\sigma$ combined
  – Decay to $\tau\tau$ emerging, limits on $\tau\tau$ ($\mu\tau$, $e\tau$)
  – Decay to $b\bar{b}$bar emerging (CMS, Tevatron)
  – Indirect evidence for $t\bar{t}$bar coupling
    (search for $t\bar{t}$bar + H/W, $Z\gamma$)
Higgs Mass Measurements

- CMS $\gamma\gamma$ and ZZ* measurements consistent
Higgs Mass Measurements

- Tension in ATLAS $\gamma\gamma$ and $ZZ^*$ measurements
Comparison with Electroweak Fit

Quite consistent: $\Delta \chi^2 \sim 1.5$
Comparison with Electroweak Fit

Quite consistent: $\Delta \chi^2 \sim 1.5$
Theoretical Constraints on Higgs Mass

- Large $M_h \rightarrow$ large self-coupling $\rightarrow$ blow up at low-energy scale $\Lambda$ due to renormalization

\[
\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2v^4} \log \frac{Q}{v}
\]

- Small: renormalization due to t quark drives quartic coupling $< 0$ at some scale $\Lambda$ $\rightarrow$ vacuum unstable

- Vacuum could be stabilized by Supersymmetry

Vacuum Instability in the Standard Model

- Due to radiative corrections due to top quark

- Lifetime $\gg$ age of the Universe
Vacuum Instability in the Standard Model

- Very sensitive to $m_t$ as well as $M_H$

- Present vacuum probably metastable with lifetime $>>$ age of the Universe

Evidence that Couplings $\sim$ Mass
Without Higgs …

… there would be no atoms
  – Electrons would escape at the speed of light

… weak interactions would not be weak
  – Life would be impossible: there would be no nuclei, everything would be radioactive

The discovery of the Higgs Boson is a big deal
‘God Particle’ no big Deal

• Peter Higgs as quoted in the London Times:

  “A discovery widely acclaimed as the most important scientific advance in a generation has been “overhyped”, the British scientist behind it has said.”
The Stakes in the Higgs Search

• How is gauge symmetry broken?
• Is there any elementary scalar field?
• **Likely portal to new physics**
• Would have caused phase transition in the Universe when it was about $10^{-12}$ seconds old
• May have generated then the matter in the Universe: **electroweak baryogenesis**
• A related **inflaton** might have expanded the Universe when it was about $10^{-35}$ seconds old
• Contributes to today’s **dark energy**: $10^{60}$ too much!