Outline

I. - The roadmap to the discovery  (Lecture I)

1. - Review of basic theoretical foundations
2. - Historical context and perspective
3. - Statistical methods (Part I)
4. - The discovery

II. - An (early) experimental profile of the Higgs boson  (Lecture II)

Measurements of the main properties of the Higgs boson

III. - Implications and future projects  (Lecture III)

- Implications of the discovered state
- Search for BSM Higgs and extended sectors
- Future Higgs programs
Disclaimer

“The” refers to the one discovered
THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES AND SCALAR PARTICLES
8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert and Peter 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”
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Basic theoretical elements
Not the origin of Mass

- Gallilean and Newtonian concept of mass:
  
  Inertial mass (F=ma)  Gravitational mass (P=mg)

Single concept: conserved intrinsic property of matter where the total mass of a system is the sum of its constituents

- Einstein: Does the mass of a system depend on its energy content?
  
  \[ \text{Mass} = \text{rest energy of a system or } m_0 = \frac{E}{c^2} \]

  - Atomic level: binding energy \( \sim O(10 \text{eV}) \) which is \( \sim 10^{-8} \) of the mass

  - Nuclear level (nucleons): binding energy \( \sim 2\% \) of the mass

  - Nucleon level (partons): binding energy \( \sim 98\% \) of the mass

Most of the (luminous) mass in the universe comes from QCD confinement energy

The insight(s) of the BEH mechanism:

Making the weak force weak (short range, or W and Z bosons massive) and allowing fermion masses in the theory
Not explaining the flavor Hierarchy
Replacing mass terms by Yukawa couplings

The BEH sector includes most of the free parameters of the Standard Model

~6 orders of magnitude
Neutrinos are not even on the scale!
The Superconductor Analogy

The universe

<table>
<thead>
<tr>
<th>SC (BCS) Theory</th>
<th>BEH Mechanism</th>
</tr>
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<tbody>
<tr>
<td>Cooper pair condensate</td>
<td>Higgs field</td>
</tr>
<tr>
<td>Electrically charged (2e)</td>
<td>Weak charge</td>
</tr>
<tr>
<td>Mass of the photon</td>
<td>Mass of the W and Z bosons</td>
</tr>
</tbody>
</table>

- The Higgs field is inserted by hand...
- The vacuum has a weak charge

# From SC to SSB in Particle Physics

<table>
<thead>
<tr>
<th>SC (BCS) Theory</th>
<th>Particle Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950 - Landau and Ginzburg</td>
<td>1954 - Yang-Mills theories for non abelian gauge interactions</td>
</tr>
<tr>
<td>JETP 20 (1950) 1064</td>
<td></td>
</tr>
<tr>
<td>1957 - Bardeen, Cooper and Schrieffer</td>
<td>1957-59 - Schwinger, Bludman and Glashow introduce W bosons for the weak charged currents...</td>
</tr>
</tbody>
</table>
| Phys. Rev. 108 (1957) 1175 | ...
| SC and gauge invariance | ... but local gauge symmetry forbids gauge bosons masses. |
| 1958 - P. W. Anderson | |
| SC and gauge invariance | Phys. Rev. 125 (1962) 397 |
| 1963 - P. W. Anderson | Gauge invariance and mass |
| Phys. Rev. 130 (1963) 439 | |
| Gauge field with mass (non relativistic) | 1964 - W. Gilbert Phs. Rev. Lett 12 (1964) 713 |
| | Thought to be impossible in relativistic theories! |
Spontaneous Symmetry Breaking (SSB) in Particle Theory
Nambu (1960) and Goldstone (1961)

Massless scalars occur in a theory with SSB
The symmetry is not apparent (hidden) in the ground state

From a simple (complex) scalar theory with a U(1) symmetry

\[ \varphi = \frac{\phi_1 + i\phi_2}{\sqrt{2}} \]

\[ L = \partial_{\nu} \varphi^* \partial^{\nu} \varphi - V(\varphi) \]

\[ V(\varphi) = \mu^2 \varphi^* \varphi + \lambda (\varphi^* \varphi)^2 \]

The Lagrangian is invariant under: \( \varphi \rightarrow e^{i\alpha} \varphi \)

Shape of the potential if \( \mu^2 < 0 \) and \( \lambda > 0 \) necessary for SSB
and be bounded from below.

Change frame to local minimum frame:

\[ \varphi = \frac{\nu + \eta + i\xi}{\sqrt{2}} \]

No loss in generality.

\[ L = \frac{1}{2} \partial_{\nu} \xi \partial^{\nu} \xi + \frac{1}{2} \partial_{\nu} \eta \partial^{\nu} \eta + \mu^2 \eta^2 + \text{interaction terms} \]

Massless scalar \hspace{1cm} Massive scalar
Digression on Chiral Symmetry

In the massless quarks approximation : $SU(2)_L \times SU(2)_R$ the chiral symmetry is an (approximate) global symmetry of QCD.

The chiral symmetry is broken by means of coherent states of quarks (which play a role similar to the cooper pairs in the BCS superconductivity theory).

It is a Dynamical Symmetry Breaking where the pseudo-goldstone bosons are the $\pi^+, \pi^0, \pi^-$ mesons.

And the massive scalar is also there: the sigma!

This is the basis of the construction of an effective field theory ChPT allowing for strong interaction calculations at rather low energy.
Life before the Higgs
Historical review by J. Ellis (Higgs Hunting 2011)

Gauge theories require massless bosons: Yang-Mills theories irrelevant to describe weak interaction?

Nambu Goldstone global SSB implies massless scalar bosons

Can two wrongs make a right?
The Seminal Papers

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)

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

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)

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)

Historical review also in J. Iliopoulos (Higgs Hunting 2012)
\[ L = (D_{\mu} \phi)^* D^\mu \phi - V(\phi) - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} \]

\[ D_{\mu} \phi = \partial_{\mu} \phi - ie A_{\mu} \phi \]

\[ F_{\mu \nu} = \partial_{\mu} A_{\nu} - \partial_{\nu} A_{\mu} \]

\[ V(\phi) = \lambda \phi^* \phi + \beta (\phi^* \phi)^2 \]

\[ \chi < 0, \beta > 0 \]

Peter Higgs
Spontaneous Symmetry Breaking (SSB) with a Local Symmetry

Let the aforementioned continuous symmetry U(1) be local: \( \varphi \rightarrow e^{i\alpha(x)} \varphi \)

The Lagrangian can now be written: \( L = (D_v \varphi)^* D^v \varphi - V(\varphi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \)

In terms of the covariant derivative: \( D_v = \partial_v - ieA_v \)

The gauge invariant field strength tensor: \( F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu \)

And the Higgs potential: \( V(\varphi) = \mu^2 \varphi^* \varphi + \lambda (\varphi^* \varphi)^2 \)

Here the gauge field transforms as: \( A_\mu \rightarrow A_\mu + \frac{1}{e} \partial_\mu \alpha \)

Again translate to local minimum frame: \( \varphi = \frac{v + \eta + i\xi}{\sqrt{2}} \)

\[
L = \frac{1}{2} \partial_\nu \xi \partial^\nu \xi + \frac{1}{2} \partial_\nu \eta \partial^\nu \eta + \mu^2 \eta^2 - v^2 \lambda \eta^2 + \frac{1}{2} e^2 v^2 A_\mu A^\mu - ev A_\mu \partial_\mu \xi - F_{\mu\nu} F^{\mu\nu} + \text{ITs}
\]

Mass term for the gauge field! But…
What about the field content?

A massless Goldstone boson $\xi$, a massive scalar $\eta$ and a massive gauge boson!

Number of d.o.f. : $1$ $1$ $1$
Number of initial d.o.f. : $2$ Oooops… Problem!

But wait! The term $evA_\mu \partial^\mu \xi$ is unphysical

The Lagrangian should be re-written using a more appropriate expression of the translated scalar field choosing a particular gauge where $h(x)$ is real:

$$\varphi = (v + h(x))e^{i \theta(x) \over \nu}$$

Then the gauge transformations are:

$$\varphi \rightarrow e^{-i \theta(x) \over \nu} \varphi \quad A_\mu \rightarrow A_\mu + \frac{1}{ev} \partial_\mu \theta$$

$$L = \frac{1}{2} \partial_\nu h \partial^\nu h - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4} \lambda h^4$$

Massive scalar: The Higgs boson

$$+(1/2)e^2 v^2 A_\mu A^\mu - F^{\mu\nu} F_{\mu\nu}$$

Massive gauge boson

$$+(1/2)e^2 A_\mu A^\mu h^2 + ve^2 A_\mu A^\mu h$$

Gauge-Higgs interaction

The Goldstone boson does not appear anymore in the Lagrangian
SSB and the Standard Model of EW interactions

\[ SU(2)_L \times U(1)_Y \]

The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson \( Z^\mu \).

Of course our model has too many arbitrary features for these predictions to be taken very seriously.
The Neutral Currents

1973: neutral current discovery (Gargamelle experiment, CERN)

Evidence for neutral current events $\nu + N \rightarrow \nu + X$ in $\nu$-nucleon deep inelastic scattering

1973-1982: $\sin^2 \theta_W$
Measurements in deep inelastic neutrino scattering experiments (NC vs CC rates of $\nu N$ events)
Introducing a double of complex scalar fields (4 d.o.f.):
\[ \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^o \end{pmatrix} \]

Setting aside the gauge kinematic terms the Lagrangian can be written:

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

\[ \begin{aligned} D_{\mu} &= \partial_{\mu} - ig \bar{W}_{\mu} \cdot \bar{\sigma} - ig' \frac{Y}{2} B_{\mu} \\ V(\phi) &= \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \end{aligned} \]

The next step is to develop the Lagrangian near:
\[ <\phi> = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \]

Choosing the specific real direction of charge 0 of the doublet is not fortuitous:
\[ \phi = e^{-i \sigma \cdot \xi} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix} \]

Non electrically charged vacuum

Again choosing the gauge that will absorb the Goldstone bosons \( \xi \)...
After a few computational steps the Lagrangian will then be written:

\[ \mathcal{L} = \frac{1}{2} \partial_\mu H \partial^\mu H - \frac{1}{2} \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4 \]

+ \frac{1}{2} \left[ \frac{g'^2 v^2}{4} B_\mu B^\mu - \frac{g g' v^2}{2} W^3_\mu B^\mu + \frac{g^2 v^2}{4} \vec{W}_\mu \cdot \vec{W}_\mu \right]

+ \frac{1}{v} \left[ \frac{g'^2 v^2}{4} B_\mu B^\mu H - \frac{g g' v^2}{2} W^3_\mu B^\mu H + \frac{g^2 v^2}{4} \vec{W}_\mu \cdot \vec{W}_\mu H \right]

+ \frac{1}{2v^2} \left[ \frac{g'^2 v^2}{4} B_\mu B^\mu H^2 - \frac{g g' v^2}{2} W^3_\mu B^\mu H^2 + \frac{g^2 v^2}{4} \vec{W}_\mu \cdot \vec{W}_\mu H^2 \right] \]

Massive scalar: The Higgs boson

Massive gauge bosons

Gauge-Higgs interaction
After a few computational steps the Lagrangian will then be written:

\[
\mathcal{L} = \frac{1}{2} \partial_\mu H \partial^\mu H - \frac{1}{2} \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4
+ \frac{1}{2} \left[ \frac{g'^2 v^2}{4} B_\mu B^\mu - \frac{g g' v^2}{2} W_\mu^3 B^\mu H + \frac{g^2 v^2}{4} \vec{W}_\mu \cdot \vec{W}_\mu \right]
+ \frac{1}{v} \left[ \frac{g'^2 v^2}{4} B_\mu B^\mu H - \frac{g g' v^2}{2} W_\mu^3 B^\mu H + \frac{g^2 v^2}{4} \vec{W}_\mu \cdot \vec{W}_\mu H \right]
+ \frac{1}{2v^2} \left[ \frac{g'^2 v^2}{4} B_\mu B^\mu H^2 - \frac{g g' v^2}{2} W_\mu^3 B^\mu H^2 + \frac{g^2 v^2}{4} \vec{W}_\mu \cdot \vec{W}_\mu H^2 \right]
\]

Massive scalar: The Higgs boson
Massive gauge bosons
Gauge-Higgs interaction

Keep this in mind for the next lectures...
First important consequences of the mechanism:

1. Two massive charged vector bosons:

\[ m_W^2 = \frac{g^2 v^2}{4} \]

Corresponding to the then observed charged currents

Thus \( v = 246 \) GeV

2. One massless vector boson:

\[ m_\gamma = 0 \]

The photon corresponding to the unbroken \( U(1)_{EM} \)

3. One massive neutral vector boson \( Z \):

\[ m_Z^2 = \frac{(g^2 + g'^2)v^2}{4} \]
The sector of Fermions

Another important consequence of the Weinberg Salam Model...

A specific SU(2)\textsubscript{L} x U(1)\textsubscript{Y} problem: \( m \bar{\psi} \psi \) manifestly not gauge invariant

\[ m \bar{\psi} \psi = m \bar{\psi} \left( \frac{1}{2} (1 - \gamma^5) + \frac{1}{2} (1 + \gamma^5) \right) \psi = m (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) \]

- neither under SU(2)\textsubscript{L} doublet and singlet terms together
- nor under U(1)\textsubscript{Y} do not have the same hypercharge

Not the case when using Yukawa couplings to the Higgs doublet

\[ \frac{\lambda_{\psi} v}{\sqrt{2}} \bar{\psi} \psi + \frac{\lambda_{\psi}}{\sqrt{2}} H \bar{\psi} \psi \]

Which is invariant under U(1)\textsubscript{EM}

The Higgs mechanism DOES NOT predict fermion masses

...Yet the coupling of the Higgs to fermions is proportional to their masses
Prediction of the Model

Beside the existence of the Z massive neutral gauge boson...

\[ \rho = 1 \]

Protected by custodial symmetry

\[ \frac{M_W}{M_Z} = \rho \frac{g^2}{g^2 + g'^2} = \rho \cos^2 \theta_W \]

F. Wilczek at the LEP Celebration:

The Higgs mechanism is corroborated at 75%
Prediction of the Model

Beside the existence of the $Z$ massive neutral gauge boson...

The existence of a massive scalar:

The Higgs Particle

Whose mass (as $\lambda$) \textit{was} an unknown parameter of the theory

$$v = -\frac{\mu^2}{\lambda}$$

Historical review of including quantization and renormalization in
J. Zinn-Justin (Higgs Hunting 2010)
Very important additional virtue of the Higgs Particle

\[ W^+ W^- \rightarrow W^+ W^- \]

Does not preserve perturbative unitarity.

Introducing a Higgs boson ensures the unitarity of this process \textbf{PROVIDED} that its mass be smaller than:

\[ \sqrt{4\pi\sqrt{2/3G_F}} \quad \text{v.i.z. approximately 1 TeV} \]

This is not only a motivation for the Higgs mechanism but is also a strong experimental constraint on its mass (if you believe in perturbative unitarity)

...If you don’t, weak force will become strong!

One of the basis of the \textbf{No Loose theorem} at the LHC
Half a Century of Higgs Quest

Pre-LHC Era
First Bounds
Astrophysical and Phenomenological

- Effect on Cosmic Microwave background (0.1 eV < m_H < 100 eV)
  (Sato and Sato, 1975)

- Emission from stars: m_H > 0.7 m_e
  (Sato and Sato, 1975)

- Neutron-electron scattering: m_H > 0.7 MeV
  (Rafelski, Muller, Soff and Greiner; Watson and Sundaresan, 1974)

- Neutron-electron scattering: m_H > 0.7 MeV
  (Adler, Dashen and Treiman; 1974)

- Neutron-nucleus scattering: m_H > 13 MeV
  (Barbieri and Ericson, 1975)

- Nuclear {^{16}\text{O}}(6.05\text{ MeV}) to ground state (0^+ - 0^+) transitions (can occur through Higgs emission): m_H > 18 MeV
  (Kohler, Watson and Becker, 1974)
The Roadmap

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva

The Roadmap

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.
Pre-LEP Bounds

- SINDRUM Collaboration measured $\pi$ to ev $H$ (ee) Yielding a limit on very light Higgs
- CUSB Collaboration $\Upsilon$ to $H\gamma$ yielding limit of $\sim 5-6$ GeV (dependent on high order corrections)
- Jade and CLEO provided bounds on $B$ to $\mu\mu+X$
- CERN-Edimbrgh-Orsay-Mainz-Pisa-Siegen $K$ to $\pi H$ (ee) below $\sim 50$ MeV
- Electron beam dump e to e$H$ (ee) excluded 1.2 MeV to 52 MeV (TH uncertainties free)
Absolute Lower Limit on the Higgs Mass at LEP

**LEP1** $e^+e^-$ at COM $\sim m_Z$
Various decays and topologies
Limit down to below $2m_e$ using acoplanar lepton pairs (Higgs is long lived)

**LEP2** $e^+e^-$ up to 209 GeV
(mostly $b\bar{b}$ and $\tau\tau$ decays)

Excludes SM Higgs with mass below 114 GeV
Electroweak Precision Data and the Higgs Mass

The famous blue band plot!

Fermi Constant \( G_F = 1.166367(5) \times 10^{-5} \text{ GeV}^{-2} \)

Fine structure Constant \( \alpha = 1/137.035999679(94) \)

Z mass \( M_Z = 91.1876 \pm 0.0021 \text{ GeV} \) (LEP)

\[
G_F = \frac{\pi \alpha_{\text{QED}}}{\sqrt{2}m_W^2(1 - m_W^2/m_Z^2)}(1 + \Delta r)
\]

\[
\Delta r \propto \log\left(\frac{m_H}{m_W}\right)
\]

\[
m_H = 94^{+29}_{-24} \text{ GeV}
\]

Is there a Higgs?

\( m_H < 152 \text{ GeV} \) at 95% CL
The LHC Era

1991 December CERN Council: ‘LHC is the right machine for advance of the subject and the future of CERN’ (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002

1994 June Council:
Staged construction was proposed by DG Chris Llewellyn Smith, but some countries could not yet agree, so the Council session vote was suspended until

16 December 1994 Council:
(Two-stage) construction of LHC was approved

From P. Jenni, Erice
Proceedings of LHC Workshop (Aachen, 1990):
\[ \sqrt{s} = 16 \text{ TeV}, 100 \text{ fb}^{-1} \]
20 Years, projecting, constructing and Simulating…
Years of Design, Construction and Commissioning of the LHC
The largest cryogenic system on earth...
The Machine Challenges in a Nutshell

- Unprecedented beam energy and luminosities (for a hadron machine)
- This results in the main LHC challenge: Stored beam energy two orders of magnitude higher than existing machines... 350 MJ (nominal)
- There is of course also the total stored energy in the magnets (11 GJ, enough to melt 15 tons of copper)

Risk of damage is the main concern:

- From the stored beam energy
  (as an indication, a few cm groove in an SPS vacuum chamber from a beam 1% of nominal LHC beam, vacuum chamber ripped open)
  Similar incident at LHC: 3 months stop.

- From the stored energy in the magnets
  The November 19 2008 incident... (700 m damage area with 39 dipoles and 14 quadrupoles and beam vacuum affected over 2.7 km, 1 year repair)
An approach to high granularity, fast Liq Ar calorimetry using an "accordion" structure

1) BASIC IDEA

In the conventional approach of liquid argon calorimetry, parallel electrodes are connected in parallel (or in series in the ES transformer approach) to form a tower. Instead one could consider a scheme in which the converter plates and electrodes are at ±45 degrees, thus making an "automatic" connection of the elements forming a tower.

In this situation, the incident particle makes an angle of 45 degrees with the converter plates. To first order resolution, similar to the standard case, the energy is recovered by choosing converter plates thinner by \( \sqrt{2} \).

Classical  "Accordion"
An approach to high granularity, fast Liq Ar calorimetry using an "accordeon" structure

1) BASIC IDEA

In the conventional approach of liquid argon calorimetry parallel electrodes are connected in parallel (or in series in the ES transformer approach) to form a tower. Instead one consider here a scheme in which the converter plates and electrodes are at +/- 45 degrees, thus making an "automatic" connection of the elements forming a tower.

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[Diagrams of classical and accordeon structures]
An approach to high granularity, fast Liq Ar calorimetry using an "accordion" structure

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In this situation the incident particle makes an angle of 45 degrees with the converter plates. To first order resolution similar to the standard case is recovered by choosing converter plates thinner by $\sqrt{2}$. 
Years of Design, Construction and Commissioning of Experiments
4 \mu \text{ event ... Standard EW only or Higgs?}

7 \text{ TeV}

2011
4 μ event ... Standard EW only or Higgs?
Three Years at the Energy Frontier

The Discovery!
Center-of-Mass Energy (Nominal)
14 TeV

Center-of-Mass Energy (close to nominal)
13 TeV

Center-of-Mass Energy (2012)
8 TeV

Center-of-Mass Energy (2010-2011)
7 TeV

ALICE
CMS
LHCb
ATLAS
Three Years of LHC operations at the Energy frontier

The LHC
- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K
  (Superfluid He)

\[
\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.O.M Energy</td>
<td>7 TeV</td>
<td>7 TeV</td>
<td>8 TeV</td>
<td>14 TeV</td>
</tr>
<tr>
<td>(N_p)</td>
<td>(1.1 \times 10^{11})</td>
<td>(1.4 \times 10^{11})</td>
<td>(1.6 \times 10^{11})</td>
<td>(1.15 \times 10^{11})</td>
</tr>
<tr>
<td>Bunch spacing / (k)</td>
<td>150 ns / 368</td>
<td>50 ns / 1380</td>
<td>50 ns / 1380</td>
<td>25 ns / 2808</td>
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<tr>
<td>(\epsilon) (mm rad)</td>
<td>2.4-4</td>
<td>1.9-2.3</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>(\beta^*) (m)</td>
<td>3.5</td>
<td>1.5-1</td>
<td>0.6</td>
<td>0.55</td>
</tr>
<tr>
<td>(L) (cm(^{-2})s(^{-1}))</td>
<td>(2 \times 10^{32})</td>
<td>(3.3 \times 10^{33})</td>
<td>(~7 \times 10^{33})</td>
<td>(10^{34})</td>
</tr>
</tbody>
</table>
The first LHC run

2010
O(2) Pile-up events
150 ns inter-bunch spacing

2011
O(10) Pile-up events
50 ns inter-bunch spacing
Design value (expected to be reached at L=10^{34} !)

2012
O(20) Pile-up events
50 ns inter-bunch spacing
Detector Challenges (Highlights)

- **Trigger Challenge**: How to select 400 out of 20M events per second while keeping the interesting (including unknown) physics

- **Computing Challenge**: How to reconstruct, store and distribute 400 increasingly complex events per second (over 100 PB per experiment)

- **Analysis Challenge**: Maintain high (and as much as possible stable) reconstruction and identification efficiency for physics objects (e, μ, τ, jets, $E_T^{mis}$, b-jets) up to the highest pile-up
QCD
QCD

Testing predictions over 8 orders of magnitude!
Overview of Cross Sections

Expected Standard Model and Higgs Productions

Theory and simulation “Next-to...” revolution :
- NNLO PDFs sets
- Calculations at unprecedented order in perturbation theory
- Parton Shower (and Matrix Element matching) improvements
Overview of Cross Sections
Expected Standard Model and Higgs Productions

Theory and simulation “Next-to…” revolution:
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- Parton Shower (and Matrix Element matching) improvements

Production Cross Section,

<table>
<thead>
<tr>
<th>$W$</th>
<th>$Z$</th>
</tr>
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<tbody>
<tr>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$\geq 3$</td>
<td>$\geq 3$</td>
</tr>
<tr>
<td>$\geq 4$</td>
<td>$\geq 4$</td>
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</tbody>
</table>

$\sigma_{tot}$

$\sigma_{tot}$ (7 TeV CMS measurement)
$\sigma_{tot}$ (8 TeV CMS measurement)
$\sigma_{tot}$ (7 TeV Theory prediction)
$\sigma_{tot}$ (8 TeV Theory prediction)
$\sigma_{tot}$ (CMS 95%CL limit)

$\sigma_{W}$
$\sigma_{Z}$

$\sigma_{W}$ (19.3 fb$^{-1}$)
$\sigma_{Z}$ (19.6 fb$^{-1}$)

$\sigma_{W}$ (4.9 fb$^{-1}$)
$\sigma_{Z}$ (4.9 fb$^{-1}$)

$\sigma_{W}$ (5.0 fb$^{-1}$)
$\sigma_{Z}$ (5.0 fb$^{-1}$)

$\sigma_{W}$ (36.19 pb$^{-1}$)
$\sigma_{Z}$ (36.19 pb$^{-1}$)

$\Delta R(\gamma, l) > 0.7$
$E_T^{\gamma} > 30$ GeV
$E_T^{\gamma} > 16$ GeV
$|\eta^{\gamma}| < 2.4$

$\sigma_{Higgs}(M_H = 120$ GeV$)$

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$\sigma_{Higgs}(M_H = 120$ GeV$)$
\( \gamma\gamma \) channel basic facts:

\[
\begin{align*}
N_s & \sim O(500) \text{ per experiment} \\
\text{Signal purity} & \sim 2\% - 60\%
\end{align*}
\]
**γγ channel basic facts:**

- **Ns ~ O(500) per experiment**
- **Signal purity ~ 2% - 60%**
The Di-Photon Channel Historical Prospective

Photon decay modes of the intermediate mass Higgs
ECFA Higgs working group
C. Seez and T. Virdee
L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

A report is given of studies of:
(a) $H \rightarrow \gamma \gamma$ (work done by C. Seez and T. Virdee)
(b) $W H \rightarrow \gamma \gamma$ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range ($90 < m_H < 150$ GeV/c$^2$).
The study of the two photon decay mode is described in detail.
The Di-Photon Channel Historical Prospective

1991 Analysis
First EAGLE (ATLAS) note
diphoton channel
The Di-Photon Channel Historical Prospective

1991 Analysis
First EAGLE (ATLAS) note
diphoton channel
The Di-Photon Channel Historical Prospective

1991 Analysis
First EAGLE (ATLAS) note
diphoton channel

16 TeV, 100 fb⁻¹

Moriond 2013 Analysis
ATLAS diphoton channel

7 - 8 TeV, ~25 fb⁻¹
4l channel basic facts:

\[
\begin{aligned}
N_s &\sim O(15-20) \text{ per experiment} \\
\text{Signal purity} &> 1.5
\end{aligned}
\]
$H \rightarrow 4e$

4l channel basic facts:

\[ N_s \sim O(15-20) \text{ per experiment} \]

Signal purity $> 1.5$
The ZZ Channel Historical Prospective

Fig. 10
The ZZ Channel Historical Prospective
The ZZ Channel Historical Prospective

CMS

\( \sqrt{s} = 7 \, (8) \) TeV, \( L = 5.1 \, (12.2) \) fb\(^{-1} \)

\[ m_{4\ell} \] (GeV)

Events / 3 GeV

- Observed
- \( Z+X \)
- \( Z^{\prime} \), ZZ
- \( m_{t} = 126 \) GeV

\[ K_0 > 0.5 \]

\( m_{4\ell} \) (GeV)

Events per GeV for 10\(^{15}\) pb\(^{-1}\)

- \( m_{t} = 150 \) GeV, 193 events
- \( m_{t} = 130 \) GeV, 60 events
- \( m_{t} = 170 \) GeV, 60 events

\( m_{4\ell} \) (GeV)

Fig. 10

7 - 8 TeV, \( \sim 25 \) fb\(^{-1} \)
Significance \( \sim 7 \) \( \sigma \)

16 TeV, 100 fb\(^{-1} \)
Significance \( \sim 6 \) \( \sigma \)
$H \rightarrow WW^{(*)}$

$ll + 2\nu$

0, 1, 2 jet Channel

ATLAS-CONF-2013-030

lvlv channel basic facts:

- $N_s \sim O(300)$ per experiment
- Signal purity $\sim 5\%$ and $40\%$
The Birth of a Particle

Diphoton

Clear excesses in these three channels

How to quantify these excesses?
How to Quantify the significance of an excess?

Starting from PRL Cover Plot
Statistical Interpretation
How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio...

Likelihood Definition:

\[ L(\mu, \theta) = f_b \psi_b(M_{\gamma\gamma}) + f_s \psi_s(M_{\gamma\gamma}) \]

Simplified

\[ \mu \propto f_s \]

\[ n_s = \mu \sigma Br L \varepsilon \]
Definition of the Test Statistic

\[ \lambda_\mu = \lambda(\mu, \theta) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \theta)} \]

\[ q_\mu = -2 \ln \lambda_\mu \]
Statistical Interpretation
How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio...

Relate to Higgs mass hypothesis

Not a measurement of mass
Not a measurement of cross section
How to Read Higgs Observation Estimates

\[ \lambda_0 = \frac{L(0, \hat{\theta}(0))}{L(\hat{\mu}, \hat{\theta})} \]

\[ q_0 = -2 \ln \lambda_0 \]

\[ p_0 \text{ Probability that a background only experiment be more signal like than observed} \]
The beginning of the $p_0$ Era

For the PLHC 2011 Perugia Conference in spring 2011

Discussion of the $p_0$ with LEE on data... at 127 GeV!

No attention paid... of course it was a fluctuation!
The First fb$^{-1}$ in the p$_0$ Era

EPS-HEP Grenoble 2011

ATLAS Preliminary

Observed
Expected
$\int Ldt = 1.0-1.2 \, fb^{-1}$
$\sqrt{s} = 7 \, TeV$

Observed
Expected
$\int Ldt = 1.0-1.2 \, fb^{-1}$
$\sqrt{s} = 7 \, TeV$

CMS Preliminary, $\sqrt{s} = 7 \, TeV$
Combined, $L_{\text{int}} = 1.1 \, fb^{-1}$

Interpretation requires look-elsewhere effect correction
The First LHC Combination

HCP - Paris 2011

No other combinations to follow in order to ensure independence!
The CERN december 2011 Council Meeting

The first evidence
As a Layman: We have it!
Discovery Announced
ATLAS 2011 + 2012 Data
$\int L \, dt \sim 4.6-4.8 \, fb^{-1}$, $\sqrt{s} = 7 \, TeV$  $\int L \, dt \sim 5.8-5.9 \, fb^{-1}$, $\sqrt{s} = 8 \, TeV$

- Expected Combined
- Expected $H \to ZZ^* \to 4l$
- Expected $H \to bb$
- Observed Combined
- Observed $H \to ZZ^* \to 4l$
- Observed $H \to bb$
- Expected $H \to \gamma\gamma$
- Expected $H \to WW^* \to 4l$
- Expected $H \to tt$
- Observed $H \to \gamma\gamma$
- Observed $H \to WW^* \to 4l$
- Observed $H \to tt$
- Observed $H \to bb$

CMS
$\sqrt{s} = 7 \, TeV$, $L = 5.1 \, fb^{-1}$  $\sqrt{s} = 8 \, TeV$, $L = 5.3 \, fb^{-1}$

- Combined obs.
- Exp. for SM H
- $H \to \gamma\gamma$
- $H \to ZZ$
- $H \to WW$
- $H \to tt$
- $H \to bb$
Additional Material
The sector of Fermions (Fermionic neutral current)

Taking a closer look at the neutral current interaction part of the Lagrangian:

\[
L_L = -\frac{1}{2} \bar{\psi}_L \gamma_\mu \begin{pmatrix} g W^\mu_3 & + g' Y_L B^\mu \\ 0 & -g W^\mu_3 & + g' Y_L B^\mu \end{pmatrix} \psi_L \quad L_R = -\frac{1}{2} \bar{\psi}_R \gamma_\mu \begin{pmatrix} g' Y_R B^\mu & 0 \\ 0 & 0 \end{pmatrix} \psi_R
\]

\[
-2L_{\text{leptons}}^{\text{NC}} = \bar{\nu}_L \gamma_\mu \left[ (c_W g - s_W g' Y_L) Z^\mu + (s_W g + c_W g' Y_L) A^\mu \right] \nu_L
\]

In the lepton sector:

\[
+ \bar{\epsilon}_L \left[ (-c_W g - s_W g' Y_L) Z^\mu + (-s_W g + c_W g' Y_L) A^\mu \right] \epsilon_L
\]

\[
+ \bar{\epsilon}_R \gamma_\mu \left[ -s_W g' Y_R Z^\mu + c_W g' Y_R A^\mu \right] \epsilon_R
\]

1.- Eliminate neutrino coupling to the photon: \( g \sin \theta_W = -g' Y_L \cos \theta_W \)

2.- Same coupling \( \epsilon_R \) and \( \epsilon_L \) to the photon: \( g' Y_R = 2 g' Y_L \)

3.- Link to the EM coupling constant \( e \): \( g \sin \theta_W = e \)

\( Y \) the hypercharge is chosen to verify the Gell-Mann Nishijima formula:

\[
Q = I_3 + \frac{Y}{2}
\]
The sector of Fermions (kinematic)

Another important consequence of the Weinberg Salam Model...

A specific $\text{SU}(2)_L \times \text{U}(1)_Y$ problem: $m\bar{\psi}\psi$ manifestly not gauge invariant

$$m\bar{\psi}\psi = m\bar{\psi}\left(\frac{1}{2}(1 - \gamma^5) + \frac{1}{2}(1 + \gamma^5)\right)\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

- neither under $\text{SU}(2)_L$ doublet and singlet terms together
- nor under $\text{U}(1)_Y$ do not have the same hypercharge

Fermion mass terms are forbidden

Not the case when using Yukawa couplings to the Higgs doublet

Then after SSB one recovers:

$$\frac{\lambda_\psi}{\sqrt{2}}\bar{\psi}\psi + \frac{\lambda_\psi}{\sqrt{2}}H\bar{\psi}\psi$$

Which is invariant under $\text{U}(1)_{EM}$

Very important: The Higgs mechanism DOES NOT predict fermion masses

...Yet the coupling of the Higgs to fermions is proportional to their masses
But wait...

The coupling to the Higgs fields is the following:

\[ \lambda_d (\bar{u}_L, \bar{d}_L) \begin{pmatrix} 0 \\ v + h \end{pmatrix} d_R + H.C. = \lambda_d \bar{Q}_L \, \phi \, d_R \]

Can be seen as giving mass to down type fermions...

To give mass to up type fermions, need to use a slightly different coupling:

\[ \phi^C = i \sigma_2 \phi^* \]

\[ \lambda_u Q_L \, \phi^C \, \bar{u}_R = \lambda_u (\bar{u}_L, \bar{d}_L) \begin{pmatrix} v + h \\ 0 \end{pmatrix} d_R + H.C. \]

One doublet of complex scalar fields is sufficient to accommodate mass terms for gauge bosons and fermions!

... But not necessary.
The picture is now almost complete...

<table>
<thead>
<tr>
<th>Field</th>
<th>$I_3$</th>
<th>$Y$</th>
<th>$Q$</th>
<th>SU(2)$_L \times$U(1)$_Y$</th>
<th>SU(3)$_C$</th>
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<tr>
<td>$(\nu^L, e^L)$</td>
<td>$1/2, -1/2$</td>
<td>-1</td>
<td>$(0, -1)$</td>
<td>$(2, -1)$</td>
<td>1</td>
</tr>
<tr>
<td>$e^R$</td>
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<td>-2</td>
<td>-1</td>
<td>$(1, -2)$</td>
<td>1</td>
</tr>
<tr>
<td>$(u^L, d^L)$</td>
<td>$1/2, -1/2$</td>
<td>-1</td>
<td>$(2/3, -1/3)$</td>
<td>$(2, 1/3)$</td>
<td>3</td>
</tr>
<tr>
<td>$u^R$</td>
<td>0</td>
<td>$4/3$</td>
<td>$2/3$</td>
<td>$(1, 4/3)$</td>
<td>3</td>
</tr>
<tr>
<td>$d^R$</td>
<td>0</td>
<td>$-2/3$</td>
<td>$-1/3$</td>
<td>$(1, -2/3)$</td>
<td>3</td>
</tr>
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<td>$(1, 0)$</td>
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<td>0</td>
<td>-</td>
<td>$(3, 0)$</td>
<td>1</td>
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<td>g</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>$(1, 0)$</td>
<td>8</td>
</tr>
<tr>
<td>H</td>
<td>$(1/2, -1/2)$</td>
<td>1</td>
<td>-</td>
<td>$(2, 1)$</td>
<td>1</td>
</tr>
</tbody>
</table>
Running Quartic Coupling : Triviality

The (non exhaustive though rather complete) evolution of the quartic coupling:

\[ 32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots \]

In the case where the Higgs mass is large (large \( \lambda \)):\n\[ M_H^2 = 2\lambda v^2 \]

The first term of the equation is dominant and due to diagrams such as:

![Diagram](image)

\[ \frac{d\lambda(Q^2)}{dt} = \frac{3}{4\pi^2} \lambda^2(Q^2) \rightarrow \frac{1}{\lambda(Q^2)} = \frac{1}{\lambda(Q_0^2)} - \frac{3}{4\pi^2} \ln \left( \frac{Q^2}{Q_0^2} \right) \]

Triviality condition to avoid such pole: \[ 1/\lambda(Q) > 0 \]

Then

\[ M_H^2 < \frac{8\pi^2v^2}{3\log \left( \frac{\Lambda^2}{v^2} \right)} \]
Local vs. Global Probability

Look Elsewhere Effect

(over)Simplified View

Probability of observing an excess at one specific mass (in absence of signal)...

What is the probability of observing an excess at least as large as observed within a mass range?

Trial factor ~ Number of possible independent outcomes within a mass range... (dependence on the significance)
Local vs. Global Probability

Look Elsewhere Effect

Approximate Formula

Based on counting the numbers of up-crossings

Then applying the very simple following formula (Z is the local significance)

\[ P_{\text{global}} = P_{\text{local}} + N \times e^{-\frac{Z^2}{2}} \]

Trial factor ~ Here the dependence is explicit...