With the discovery of the Higgs for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.
Outline

Lecture I
- Introduction: Elements of history
- Elements of SM Higgs theory
- Precision EW tests
- The discovery of the Higgs boson
- An (early) experimental profile of the Higgs boson: The discovery channels

Lecture II
- An (early) experimental profile of the Higgs boson: Complex final states
- An (early) experimental profile of the Higgs boson: Combined measurements
- Rare decay modes
- Rare production modes
- The Higgs width

Lecture III
- Implications of the discovered state
- Search for BSM Higgs and extended sectors
- New trends
- Future Higgs programs
The Discovery
The Birth of a Particle...

Diphoton

ZZ Four leptons

WW (lvlv)

A milestone which has reshaped the field of HEP...

It did not come as a complete surprise!
A Textbook and Timely Discovery

- **Summer 2011**: EPS and Lepton-Photon
  First (and last) focus on limits (scrutiny of the $p_0$)

- **December 2011**: CERN Council
  First hints

- **Summer 2012**: CERN Council and ICHEP
  Discovery!

- **December 2012**: CERN Council
  Beginning of a new era

✓ Strongly Motivated

✓ Significance increased with luminosity to reach unambiguous levels

✓ Two experiments

✓ Several channels
The Standard Model
With one doublet of complex scalar field

\[ L = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} \]
\[ + \bar{\psi} i \gamma \cdot D \psi + h.c \]
\[ + \lambda \bar{\psi} \psi \phi^* + h.c \]
\[ + \frac{1}{2} m^2 \phi^2 - V(\phi) \]

- The elegant gauge sector
- The (less elegant) Higgs sector
  - Non universal interactions not governed by a symmetry
  - Bares most of the free parameters of the SM

... but testable!

+ Dark matter ?
+ BSM ?
The Origins
The Superconductor Analogy

- The universe

<table>
<thead>
<tr>
<th>SC (BCS) Theory</th>
<th>BEH Mechanism</th>
</tr>
</thead>
<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...
- **Condensate**: 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>1957 - Bardeen, Cooper and Schrieffer&lt;br&gt;Phys. Rev. 108 (1957) 1175</td>
<td>1957-59 - Schwinger, Bludman and Glashow introduce W bosons for the weak charged currents...</td>
</tr>
<tr>
<td>1958 - P. W. Anderson&lt;br&gt;Phys. Rev. 112 (1958) 1900&lt;br&gt;SC and gauge invariance</td>
<td>... but local gauge symmetry forbids gauge bosons masses.</td>
</tr>
<tr>
<td>1964 - W. Gilbert Phs. Rev. Lett 12 (1964) 713&lt;br&gt;Thought to be impossible in relativistic theories!</td>
<td></td>
</tr>
</tbody>
</table>
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

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)

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)

Answering Gilbert’s objection

Historical review also in J. Iliopoulos (Higgs Hunting 2012)
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

\[ \varphi = \frac{\phi_1 + i\phi_2}{\sqrt{2}} \quad L = \partial_\nu \varphi^* \partial^\nu \varphi - V(\varphi) \quad V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2 \]

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

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:

\[ \varphi = \frac{\nu + \eta + i\xi}{\sqrt{2}} \quad \text{No loss in generality.} \]

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

Massless scalar
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.
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:

$$L = (D_\nu \varphi)^* D^\nu \varphi - V(\varphi) - \frac{1}{4} F_{\mu \nu} F^{\mu \nu}$$

In terms of the covariant derivative:

$$D_\nu = \partial_\nu - ieA_\nu$$

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:

$$\varphi = \frac{v + \eta + i\xi}{\sqrt{2}}$$

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

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:

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

Then the gauge transformations are:

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

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

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
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:

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

$$\begin{cases} 
D_\mu = \partial_\mu - ig \vec{W}_\mu \cdot \vec{\sigma} - ig' Y B_\mu \\
V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2
\end{cases}$$

The next step is to develop the Lagrangian near:

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Choosing the specific real direction of charge 0 of the doublet is not fortuitous:

$$\phi = e^{-i \vec{\sigma} \cdot \vec{\xi}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

Non electrically charged vacuum

Again choosing the gauge that will absorb the Goldstone bosons $\xi$...
Then developing the covariant derivative for the Higgs field...

Just replacing the Pauli matrices:

\[
D_\mu \varphi = \partial_\mu \varphi - \frac{i}{2} \left( gW_\mu^3 + g'B_\mu \quad g(W_\mu^1 - iW_\mu^2) \right) \varphi
\]

Then using:

\[
W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}
\]

\[
D_\mu \varphi = \partial_\mu \varphi - \frac{i}{2} \left( gW_\mu^3 + g'B_\mu \quad \sqrt{2}gW_\mu^+ \right) \varphi = \left( \begin{array}{c} 0 \\ \partial_\mu h \end{array} \right) - \frac{i}{2} \left( \begin{array}{c} \sqrt{2}gW_\mu^+ + \sqrt{2}ghW_\mu^+ \\ -gW_\mu^3 + g'B_\mu \end{array} \right)
\]

For the mass terms only:

\[
(D_\mu \varphi) D^\mu \varphi = \partial_\mu h \partial^\mu h + \frac{1}{4} g^2 v^2 W_\mu^+ W_-^\mu + \frac{1}{8} (W_\mu^3 \quad B_\mu) \left( \begin{array}{cc} g^2 v^2 & -gg'v^2 \\ -gg'v^2 & g'^2 v^2 \end{array} \right) (W_\mu^{3\mu})
\]

Explicit mixing of $W^3$ and $B$. 
After a few computational steps the Lagrangian will then be written:

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

Massive scalar: The Higgs boson

Massive gauge bosons

Gauge-Higgs interaction

Higgs - Gauge main terms relevant for the LHC (and more)

\[ g_{HVV} = \frac{2 M_V^2}{v} \]

\[ g_{HH} = \frac{3 M_H^2}{v} \]

\[ g_{HHH} = \frac{3 M_H^3}{v^2} \]
Without SSB

Not gauge invariant
(Simple dimensional analysis)

\[ m^2 A_\mu A^\mu \]

Not existing vertex

\[ A_\mu A^\mu h \]
With the Higgs Mechanism (and after SSB)

Not only existing but also closely related!

\[(1/2)e^2 v^2 A_\mu A^\mu\]  
\[v e^2 A_\mu A^\mu h\]

Proof of condensate!
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 \( Z \):

\[ m_Z^2 = \frac{(g^2 + g'^2) v^2}{4} \]
Prediction of the Model

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

$$\frac{M_W}{M_Z} = \rho \frac{g^2}{g^2 + g'^2} = \rho \cos^2 \theta_w$$

$$\rho = 1$$

Protected by custodial symmetry

$$m_t^2 + m_b^2 - 2(m_t^2 m_b^2) \log(m_t^2 / m_b^2) / (m_t^2 - m_b^2)$$

F. Wilczek at the LEP Celebration:

The Higgs mechanism is corroborated at 75%
The sector of Fermions

Another important consequence of the Weinberg Salam Model...

A specific \( SU(2)_L \times U(1)_Y \) 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 \( SU(2)_L \) doublet and singlet terms together
- nor under \( U(1)_Y \) do not have the same hypercharge

Not the case when using Yukawa couplings to the Higgs doublet

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

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

The Higgs mechanism DOES NOT predict fermion masses

...Yet the coupling of the Higgs to fermions is proportional to their masses
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 term:

$$\phi^C = i \sigma_2 \phi^* \quad \lambda_u Q_L \phi^C \bar{u}_R = \lambda_u(\bar{u}_L, \bar{d}_L) \begin{pmatrix} v + h \\ 0 \end{pmatrix} d_R + H.C.$$

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

... But not necessary.
Not explaining the flavor Hierarchy

Replacing mass terms by Yukawa couplings

For neutrino masses: introduction of a Dirac right handed neutrino is fine... but how to explain the incredibly large hierarchy?

Majorana mass term possible and more natural.
Proof of condensate!

\[ g_{Hff} = \frac{m_f}{v} \]

\[ g_{HVV} = \frac{2M_V^2}{v} \]

Proof of condensate!

\[ g_{HHVV} = \frac{2M_V^2}{v^2} \]

(And masses of fermions)

(And masses of gauge bosons)
Proof of condensate!

\[ g_{Hff} = \frac{m_f}{v} \]

\[ g_{HVv} = \frac{2M_V^2}{v} \]

(Proof of condensate)

\[ g_{HHVv} = \frac{2M_V^2}{v^2} \]

(And masses of fermions)

\[ g_{HHH} = \frac{3M_H^2}{v} \]

(And masses of gauge bosons)

\[ g_{HHHH} = \frac{3M_H^2}{v^2} \]

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

\[ v = -\frac{\mu^2}{\lambda} \]
Very important additional virtue of the Higgs Particle

\[ W_L^+ W_L^- \rightarrow W_L^+ W_L^- \]

Does not preserve perturbative unitarity.

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

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

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!

The origin of the \textbf{No Loose theorem}* at the LHC

\*Approximate
The Pre LHC Era:

*Searches and Importance of Precision*
The Roadmap

1976

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 $evH$ ($ee$) 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 $eH$ ($ee$) 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
Precision EW Measurements

e^+e^- and hadron collider complementarity
Three Machines in three years...

**LEP 1989-2000** $e^+e^-\ 91\text{GeV}, 130-208\text{GeV}

**Tevatron 1987-2011** pp $\sim 2\text{TeV}$

**SLC 1988-1998** $e^+e^-\ 91\text{GeV}$
Experimental Constraint : Electroweak Precision Data and the Higgs Mass

At tree level, the gauge sector of the standard model has 3 free parameters not counting the Higgs mass and the fermion masses and couplings.

Particularly useful set to start is:

1.- The fine structure constant: \( \alpha = 1/137.035999679(94) \times 10^{-9} \)
   Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

2.- The Fermi constant: \( G_F = 1.166367(5) \times 10^{-5} \text{ GeV}^{-2} \times 10^{-5} \)
   Determined from muon lifetime

3.- The Z mass: \( M_Z = 91.1876 \pm 0.0021 \text{ GeV} \times 10^{-5} \)
   Measured from the Z lineshape scan at LEP
There is many more !!

- Numerous observables $O(40)$
- Numerous experiments (with different systematics)
- Within experiments numerous analyses (with different systematics)
- Various theoretical inputs

For the weak mixing angle

Forward-backward asymmetry: asymmetry of the $Z$ decay product angular distribution (for all fermions)

\[ A_{FB}^{0,f} \equiv \frac{n(\theta^\ell<90^\circ)-n(\theta^\ell>90^\circ)}{n(\theta^\ell<90^\circ)+n(\theta^\ell>90^\circ)} \]

Polarisation asymmetry: asymmetry of the rates of the $Z$ decay polarised final-states (can be measured only for $\tau$’s)

\[ P^\tau \equiv \frac{n(\tau_R)-n(\tau_L)}{n(\tau_R)+n(\tau_L)} = -A_t \]

Left-right asymmetry: asymmetry of the cross-sections with incident polarized electron beam

\[ A_{LR} = \frac{\sigma(e_L)-\sigma(e_R)}{\sigma(e_L)+\sigma(e_R)} = A_c \]
W and Top quark mass measurements

Mass of the W Boson

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( M_W ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-0/I</td>
<td>80432 ± 79</td>
</tr>
<tr>
<td>DØ-I</td>
<td>80478 ± 83</td>
</tr>
<tr>
<td>DØ-II (1.0 fb(^{-1}))</td>
<td>80402 ± 43</td>
</tr>
<tr>
<td>CDF-II (2.2 fb(^{-1}))</td>
<td>80387 ± 19</td>
</tr>
<tr>
<td>DØ-II (4.3 fb(^{-1}))</td>
<td>80369 ± 26</td>
</tr>
<tr>
<td>Tevatron Run-0/I/II</td>
<td>80387 ± 16</td>
</tr>
<tr>
<td>LEP-2</td>
<td>80376 ± 33</td>
</tr>
<tr>
<td>World Average</td>
<td>80385 ± 15</td>
</tr>
</tbody>
</table>

Mass of the Top Quark

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( M_t ) [GeV/c(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.40 ± 11.41 (±10.30 ± 4.90)</td>
</tr>
<tr>
<td>DØ-I dilepton</td>
<td>168.40 ± 12.82 (±12.30 ± 3.60)</td>
</tr>
<tr>
<td>CDF-II dilepton *</td>
<td>170.80 ± 3.26 (±1.83 ± 2.69)</td>
</tr>
<tr>
<td>DØ-II dilepton</td>
<td>174.00 ± 2.80 (±2.36 ± 1.49)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.10 ± 7.36 (±5.10 ± 5.30)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.10 ± 5.31 (±3.90 ± 3.60)</td>
</tr>
<tr>
<td>CDF-II lepton+jets</td>
<td>172.85 ± 1.12 (±0.52 ± 0.98)</td>
</tr>
<tr>
<td>DØ-II lepton+jets</td>
<td>174.98 ± 0.76 (±0.41 ± 0.63)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.00 ± 11.51 (±10.00 ± 5.70)</td>
</tr>
<tr>
<td>CDF-II alljets *</td>
<td>175.07 ± 1.95 (±1.19 ± 1.55)</td>
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<tr>
<td>CDF-II track</td>
<td>166.90 ± 9.43 (±9.00 ± 2.82)</td>
</tr>
<tr>
<td>CDF-II MET+Jets</td>
<td>173.93 ± 1.85 (±1.26 ± 1.36)</td>
</tr>
<tr>
<td>Tevatron combination *</td>
<td>174.34 ± 0.64 (±0.37 ± 0.52)</td>
</tr>
</tbody>
</table>

\( \chi^2/\text{dof} = 10.8/11 \) (46%)

Precision of ~0.02%

Precision of ~0.4%

Superb Legacy of Tevatron
Taking the hypothesis of a Minimal Standard Model, small weak radiative corrections (few percent level) to numerous observables can be computed in order to assess the impact of crucial parameters e.g. Higgs and top quark mass.

For example the mass of the W boson:

$$M_W = \frac{M_Z}{\sqrt{2}} \left[ 1 + \sqrt{1 - \frac{4\pi \alpha}{\sqrt{2} G_F M_Z^2 (1 - \Delta r)}} \right]^{\frac{1}{2}}$$

$$\Delta r \propto m_{top}^2, \log \frac{M_H}{M_W}$$
Indirect Predictions of the EW precision

The fit yields:

Predicts the top mass as well as the Higgs boson mass

The fit yields: $94^{+29}_{-24}$ GeV
The Electromagnetic Coupling Constant

\[ \alpha_{QED}(m_Z^2) = \frac{\alpha(0)}{1 - \Delta \alpha_e(m_Z^2) - \Delta \alpha_{had}(m_Z^2) - \Delta \alpha_{top}(m_Z^2)} \]

As mentionned above \( \alpha(0) \) measured with \( \sim 10^{-9} \) precision

The problem is how to evaluate: \( \Delta \alpha_{had}(m_Z^2) \)

The origin of one of the most important uncertainties on the Higgs mass prediction:

The famous blue band plot is named after this contribution
Summary of Pre LHC Era

- No loose theorem: There should be something allowing to either preserve perturbative unitarity or strongly coupled new physics below 1 TeV (approximate no-loose).

- The Higgs boson is a key missing piece of the SM if it exists it should have a mass below 1 TeV approximately.

- If it exists its mass can be indirectly measured to be relatively low of $94^{+29}_{-24}$ GeV
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
4 \mu \text{ event} \ldots \text{Standard EW only or Higgs?} \quad 2011 \quad 7 \text{ TeV}
Three Years of LHC operations at the Energy frontier (in a nutshell)

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)

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

<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 (10^{11})</td>
<td>1.4 (10^{11})</td>
<td>1.6 (10^{11})</td>
<td>1.15 (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>
</tr>
<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(\times10^{32})</td>
<td>3.3(\times10^{33})</td>
<td>(~7\times10^{33})</td>
<td>10(^{34})</td>
</tr>
</tbody>
</table>
The LHC Run 1

2009
- 30 Nov 2009: Collisions at 2.36 TeV
- 20 Nov 2009: First beams in LHC

2010
- 8 Nov 2010: Collisions at 2.36 TeV/nucleon
- 30 Mar 2010: Stable collisions at 7 TeV in LHC

2011
- Nov 2011: Pb at 2.76 TeV/nucleon
- 13 Mar 2011: 7 TeV startup

2012
- 5 Apr 2012: 8 TeV at LHC
- 20 Jan 2013: pPb

2013

- Event taken at random
- (filled) bunch crossings
- O(2) Pile-up events
- 0.05 fb\(^{-1}\) at 7 TeV
- O(10) Pile-up events
- ~ 5 fb\(^{-1}\) at 7 TeV
- 50 ns inter-bunch spacing

- O(30) Pile-up events
- ~ 20 fb\(^{-1}\) at 8 TeV
- 50 ns inter-bunch spacing
- **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
# Preamble I: The ATLAS and CMS Detectors In a Nutshell

<table>
<thead>
<tr>
<th>Sub System</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td><img src="image1.png" alt="ATLAS Detector Diagram" /></td>
<td><img src="image2.png" alt="CMS Detector Diagram" /></td>
</tr>
<tr>
<td><strong>Magnet(s)</strong></td>
<td>Solenoid (within EM Calo) 2T 3 Air-core Toroids</td>
<td>Solenoid 3.8T Calorimeters Inside</td>
</tr>
<tr>
<td><strong>Inner Tracking</strong></td>
<td>Pixels, Si-strips, TRT PID w/ TRT and dE/dx</td>
<td>Pixels and Si-strips PID w/ dE/dx</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{p_T}/p_T \sim 5 \times 10^{-4}p_T \oplus 0.01$</td>
<td>$\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4}p_T \oplus 0.005$</td>
</tr>
<tr>
<td><strong>EM Calorimeter</strong></td>
<td>Lead-Larg Sampling w/ longitudinal segmentation</td>
<td>Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation</td>
</tr>
<tr>
<td></td>
<td>$\sigma_E/E \sim 10%/\sqrt{E} \oplus 0.007$</td>
<td>$\sigma_E/E \sim 3%/\sqrt{E} \oplus 0.5%$</td>
</tr>
<tr>
<td><strong>Hadronic Calorimeter</strong></td>
<td>Fe-Scint. &amp; Cu-Larg (fwd) $\gtrsim 11\lambda_0$</td>
<td>Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher</td>
</tr>
<tr>
<td></td>
<td>$\sigma_E/E \sim 50%/\sqrt{E} \oplus 0.03$</td>
<td>$\sigma_E/E \sim 100%/\sqrt{E} \oplus 0.05$</td>
</tr>
<tr>
<td><strong>Muon Spectrometer System</strong></td>
<td>Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4% \text{ (at 50 GeV)}$ $\sim 11% \text{ (at 1 TeV)}$</td>
<td>Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1% \text{ (at 50 GeV)}$ $\sim 10% \text{ (at 1 TeV)}$</td>
</tr>
</tbody>
</table>
Higgs Production at the LHC and Decay
Production modes at the LHC

Cross sections for $m_H = 125.5$ GeV

- Coupling absent at tree level
- Process dominated by a top quark in the loop
  \[ \kappa_g^2 \propto 1 \times 0.6 \kappa_t^2 - 0.07 \times \kappa_t^2 \kappa_b + 0.01 \times \kappa_b^2 \]
- Indirectly measures the Yukawa coupling to the top

Gluon fusion

~0.4 M evts produced at LHC Run 1
Production modes at the LHC

Cross sections for $m_H = 125.5$ GeV

$\sigma(pp \to H + X)$ [pb]

- $pp \to H$ (NNLO+NNLL QCD + NLO EW)
- $pp \to q\bar{q}H$ (NNLO QCD + NLO EW)
- $pp \to q\bar{q}H$ (NLO QCD)

$\sqrt{s}$ [TeV]

~40 k evts produced at LHC Run 1

Properties

- Tree level coupling to the gauge bosons
- Distinctive and challenging topology
- Two forward jets and rapidity gap
Production modes at the LHC

Cross sections for $m_H = 125.5$ GeV

- $pp \rightarrow H$ (NNLO+NNLL QCD + NLO EW)
- $pp \rightarrow q\bar{q}H$ (NNLO QCD + NLO EW)
- $pp \rightarrow WH$ (NNLO QCD + NLO EW)
- $pp \rightarrow ZH$ (NNLO QCD + NLO EW)

~40 k evts produced at LHC Run 1

- Tree level coupling to gauge bosons
- Distinctive topology
- Multiple choices for the decay of the W and the Z boson

Properties
Production modes at the LHC

Cross sections for $m_H = 125.5$ GeV

- $pp \to H (\text{NNLO+NNLL QCD + NLO EW})$
- $pp \to q\bar{q}H (\text{NNLO QCD + NLO EW})$
- $pp \to WH (\text{NNLO QCD + NLO EW})$
- $pp \to ZH (\text{NNLO QCD + NLO EW})$
- $pp \to t\bar{t}H (\text{NLO QCD})$

Top associated production

$\sim 3$ k evts produced at LHC Run 1

Properties

- Tree level coupling to top quark
- Complex topology with two top quarks in the final states
- Many possible decay modes, relatively low stats
Non Universal Higgs Couplings and Decay Channels

Yukawa coupling to fermions

\[
H \rightarrow f \rightarrow f' \quad \alpha \frac{m_f}{v}
\]

Main channels

- Dominant: \(bb\) (57%)
- Most sensitive \(\tau \tau\) (6.3%)
- Incredibly difficult (3%)
- Low stat but eventually... \(\mu \mu\) (0.02%)
Non Universal Higgs Couplings and Decay Channels

**Coupling to Gauge bosons**

\[ \alpha \propto \frac{2m_v^2}{v} \]

**Main channels**

- The ZZ channel \((3\%)\)
- The WW channel \((22\%)\)

W and Z decay channels typically to leptons
Non Universal Higgs Couplings and Decay Channels

Coupling to photons (and $Z$ and $\gamma$)

- The $\gamma\gamma$ channel (0.2%)
  \[ \kappa_{\gamma} \propto 1.6 \times k_{W}^{2} - 0.7 \times k_{t} k_{W} + 0.1 \times k_{t}^{2} \]

- The $Z\gamma$ channel (0.2%)
  \[ \kappa_{Z\gamma} \propto 1.12 \times k_{W}^{2} - 0.15 \times k_{t} k_{W} + 0.03 \times k_{t}^{2} \]
Non Universal Higgs Couplings and Decay Channels

Self couplings

Extremely difficult channels requiring at least one Higgs boson off mass shell
Non Universal Higgs Couplings and Decay Channels

**Self couplings**

\[ \propto \frac{3m_H^2}{v} \]

\[ \propto \frac{3m_H^2}{v^2} \]

“A Gift of Nature”

Fabiola Gianotti (July 4, 2012 CERN)
## Panorama of Main Higgs Analyses

<table>
<thead>
<tr>
<th>Channel categories</th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ZZ (llll)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>WW (lνlν)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>bb</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$Z\gamma$ and $\gamma\gamma^*$</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu\mu$ and ee</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Invisible</td>
<td>✓ (monojet)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
The Discovery Channels
### Panorama of Main Higgs Analyses

<table>
<thead>
<tr>
<th>Channel categories</th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>γγ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ZZ (llll)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>WW (lνlν)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ττ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>bb</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Zγ and γγ*</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>μμ and ee</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Invisible</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- ggF: Production via gluon-gluon fusion
- VBF: Production via vector boson fusion
- VH: Production via vector boson + Higgs
- ttH: Production via top-quark pair

*Note: Diagrams not included in text representation.*
The two Main discovery Chaneels

An excellent chanel for a Higgs boson near 125 GeV

The Golden chanel over a large range in mass

Inclusive approximate number of selected signal events

\[ n_s \sim 500 \quad \quad \quad n_s \sim 20 - 30 \]

Very simple channels, with excellent mass resolution (unambiguous signatures)
The Discovery and the Measurement are fully lead by two channels

- s/b ratio ranging from few % to approximately 30%
- Uses exclusive production (VBF, VH and ttH) not for the mass measurement
- Uses Higgs pT as discriminating variable

ATLAS

\[ m_H = 125.4 \pm 0.27 \]
\[ Z = 5.2 \ (4.6) \ \sigma \]
\[ \mu = 1.18 \pm 0.27 \]

CMS

\[ m_H = 124.7 \pm 0.34 \]
\[ Z = 5.7 \ (5.2) \ \sigma \]
\[ \mu = 1.14 \pm 0.26 \]
Background
From jets

Signal
Isolated Photon Identification

**ATLAS Simulation** \( \sqrt{s} = 8 \, \text{TeV} \)

- \( H \rightarrow \gamma \gamma \) (ggF), \( m_H = 125 \, \text{GeV} \)
- calo-isolation < 4 GeV
- calo-isolation < 6 GeV + track-isolation < 2.6 GeV

Number of primary vertices

---

PV reconstruction

**ATLAS**

\[ \int L \, dt = 20.3 \, \text{fb}^{-1}, \, \sqrt{s} = 8 \, \text{TeV} \]

- \( H \rightarrow \gamma \gamma \) (ggF), \( m_H = 125 \, \text{GeV} \)
- \( Z \rightarrow \ell \ell \), MC (\( \rho \)-reweighted)
- \( Z \rightarrow \ell \ell \), MC
- \( Z \rightarrow \ell \ell \), Data

Number of primary vertices

---

Bkg rejection

**ATLAS**

\[ \int L \, dt = 20.3 \, \text{fb}^{-1}, \, \sqrt{s} = 8 \, \text{TeV} \]

- \( \gamma \gamma + \text{DY} \)
- \( \gamma j \)
- \( jj \)
Interesting Facts about the $\gamma\gamma$ Channel

- Main production and decay processes occur through loops:

  ![Diagram of production and decay processes through loops.]

  Excellent probe for new physics!

  \[ 1.6 \times A_W^2 - 0.7 \times A_t A_W + 0.1 \times A_t^2 \]

  ... Not so obviously enhanced (e.g. SM4)

  A priori potentially large possible enhancement...

  Seldom larger yields: e.g. NMSSM (U. Ellwanger et al.) up to x6, large stau mixing (M. Carena et al.), Fermiophobia...

- High mass resolution channel

- If observed implies that it does not originate from spin 1: Landau-Yang theorem

- If observed implies that its Charge Conjugation is +1 (assuming C and P separately conserved)
Improving Sensitivity and Probing Production Modes

Performing analysis with *categories*

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphoton selection</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}H$ leptonic</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}H$ hadronic</td>
<td></td>
</tr>
<tr>
<td>VH dilepton</td>
<td>$(Z\bar{H} \rightarrow \ell\ell)$</td>
</tr>
<tr>
<td>VH one-lepton</td>
<td>$(W\bar{H} \rightarrow \ell\nu)$</td>
</tr>
<tr>
<td>$VH E_T^{miss}$</td>
<td>$(Z\bar{H} \rightarrow \nu\nu; \ W\bar{H} \rightarrow f\nu)$</td>
</tr>
<tr>
<td>VH hadronic</td>
<td>$(W\bar{H} \rightarrow jj; Z\bar{H} \rightarrow jj)$</td>
</tr>
<tr>
<td>VBF tight</td>
<td>$(qqV \rightarrow jjH)$</td>
</tr>
<tr>
<td>VBF loose</td>
<td>$(qqV \rightarrow jjH)$</td>
</tr>
<tr>
<td>Untagged</td>
<td>$(gg \rightarrow H)$</td>
</tr>
</tbody>
</table>
Why Categories?

Let’s take a simple example with two categories:

- C1: s=12 and b=60
- C2: s=18 and b=40

Inclusively we have a significance of 3

Separating in two categories:

- C1 2.85 \( \sigma \)
- C2 1.55 \( \sigma \)

Combined significance: 3.24
Analyses in Categories

Resolving an over-constrained linear system of \( N(>5) \) equations and 5 unknowns

\[
\begin{pmatrix}
\alpha_a \\
\vdots \\
\alpha_N
\end{pmatrix} =
\begin{pmatrix}
\varepsilon_{ggF}^1 \alpha_{ggF}^1 L^1 & \varepsilon_{VBF}^1 \alpha_{VBF}^1 L^1 & \varepsilon_{VH}^1 \alpha_{VH}^1 L^1 & \varepsilon_{tH}^1 \alpha_{tH}^1 L^1 \\
\vdots & \vdots & \vdots & \vdots \\
\varepsilon_{ggF}^N \alpha_{ggF}^N L^N & \varepsilon_{VBF}^N \alpha_{VBF}^N L^N & \varepsilon_{VH}^N \alpha_{VH}^N L^N & \varepsilon_{tH}^N \alpha_{tH}^N L^N
\end{pmatrix}
\begin{pmatrix}
\mu_{ggF} O_{ggF}^{SM} \\
\mu_{VBF} O_{VBF}^{SM} \\
\mu_{VH} O_{VH}^{SM} \\
\mu_{tH} O_{tH}^{SM}
\end{pmatrix}
\]
The Importance of the Higgs Boson Transverse Momentum
The Discovery and the Measurement are fully lead by two channels

**ATLAS**

\[ m_H = 125.4 \pm 0.27 \]

\[ Z = 8.1 \ (6.2) \ \sigma \]

\[ \mu = 1.66^{+0.44}_{-0.37} \]

**CMS**

\[ m_H = 125.6 \pm 0.45 \]

\[ Z = 6.8 \ (6.7) \ \sigma \]

\[ \mu = 0.93 \pm 0.29 \]

- High s/b ratio from approximately 1.5 up to more than 10
- Uses exclusive production (VBF, VH and ttH)
- Uses Higgs pT as discriminating variable
- Uses angular variables to discriminate background
Key features

- One Z allowed to be off-mass shell ($m_H < 180$ GeV)
- low $p_T$ lepton reconstruction very important
- Invariant mass selections also important to optimize low mass selection
- Main Background ZZ from Monte Carlo or from high mass data
- Other backgrounds (Zbb and top) data driven (small)

Electrons

Muons
Analysis of in the $H \rightarrow 4\ell$ Channel

- Use distributions of 2 production and 3 decay angles
- ... and the $Z_1$ and $Z_2$ masses

*Combination of this information through LO Matrix Element based event probabilities or MVA*

*In the COM frame*
Analyses in Categories

Less sensitive in low statistics categories...

$H \rightarrow ZZ^* \rightarrow 4l$

4$\ell$ selection

- High mass two jets
  - VBF

- Low mass two jets
  - VBF enriched
  - $W(\rightarrow jj)H, Z(\rightarrow jj)H$

- Additional lepton
  - VH enriched
  - $W(\rightarrow l\nu)H, Z(\rightarrow ll)H$

- ggF
  - ggF enriched

... will improve rapidly

\[ \mu_{\text{ggF}+b\bar{b}H+t\bar{t}H} \times \frac{B}{B_{\text{SM}}} \]

ATLAS

- $H \rightarrow ZZ^* \rightarrow 4l$
- $s=7$ TeV $\int L dt = 4.5$ fb$^{-1}$
- $s=8$ TeV $\int L dt = 20.3$ fb$^{-1}$

2D model ggF

$m_H = 125.36$ GeV

$68\%$ CL

$95\%$ CL
Bright Future for Higgs analyses at Run 2

Run: 209109
Event: 76170653
2012-08-24 09:31:00 CEST

ATLAS

**ATLAS**

\( H \rightarrow ZZ^* \rightarrow 4l \)

\( L = 7 \text{ TeV} \int \text{Ldt} = 4.5 \text{ fb}^{-1} \)

\( L = 8 \text{ TeV} \int \text{Ldt} = 20.3 \text{ fb}^{-1} \)

**VBF enriched category**

\( 110 < m_{ll} \text{ (GeV)} < 140 \)

**Purity (S/(S+B))**

- **gF, VBF, t\bar{t}H, VH Purity**
- **VBF purity**
The Most Precise Measurement at Run I!!

- Statistics dominated Measurement
- Systematic uncertainties completely dominated by calibration uncertainties
- Compatibility of the four measurements masses O(10%)
- Tension between ATLAS 4l and $\gamma\gamma \sim 2\sigma$
**EW Precision Fit after the discovery**

Important to have the Higgs mass, the current uncertainty is irrelevant in the fit

Summary

- Key phenomenological and TH aspects on the role of the Higgs boson in the SM

- Reviewed basics of discovery channels
  - Production and decays in the $\gamma\gamma$ and ZZ channels are compatible with the expectation from SM Higgs boson
  - Clear evidence of coupling to vector bosons W and Z through the decays
  - Strong indirect evidence of the coupling to fermions (top) through the production
  - Already strong indications of the VBF production
  - Already extremely precise measurements

- Interplay between direct measurements and EW precision data