The discovery of the Higgs particle

Luis Roberto Flores Castillo
The Chinese University of Hong Kong

S’Cool LAB Summer Camp 2017
CERN, Switzerland

July 28, 2017
Aiming high
Aiming high

8 km
Aiming high

$9,000,000,000

8 km
Aiming high

$9,000,000,000

8 km

~20 countries
~200 institutions
~30 years
Soñando en grande
“I think we have it” – Rolf Heuer, Director General de CERN
A giant leap for science

Finding the Higgs boson

Scientists prove existence of ‘God particle’

'Momentous' find after 45-year hunt for Higgs boson
Professor weeps as his life's work finally bears fruit
Physicist deserves the Nobel Prize, says Hawking
The Nobel Prize in Physics 2013

François Englert
Université Libre de Bruxelles, Belgium

Peter W. Higgs
University of Edinburgh, UK

"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."

"För den teoretiska upptäckten av en mekanism som bidrar till förståelsen av massans ursprung hos subatomära partiklar, och som nyligen, genom upptäckten av den förutsagda fundamentala partikeln, bekräftats av ATLAS- och CMS-experimenten vid CERN:s accelerator LHC."
What is the Higgs boson?
• ~1869, Mendeleyev published “Principles of Chemistry”
• All that complexity from ~100 “elements”
Fundamental building blocks?

... but all of them are combinations of THREE particles.
Fundamental building blocks?

• Besides those three, …
• Besides those three, …
Fundamental building blocks?

• Besides those three, …

\[ u \text{ up} \]
\[ d \text{ down} \]
\[ \gamma \text{ photon} \]
\[ Z \text{ Z boson} \]
\[ W \text{ W boson} \]
\[ e \text{ electron} \]
Fundamental building blocks?

• Besides those three, …
* Besides those three, ...
Fundamental building blocks?

- Besides those three, …

<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{up}$</td>
<td>+2/3</td>
</tr>
<tr>
<td>$d_{down}$</td>
<td>-1/3</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>0</td>
</tr>
<tr>
<td>$e_{electron}$</td>
<td>-1</td>
</tr>
<tr>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>$Z$</td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td></td>
</tr>
<tr>
<td>$g$</td>
<td></td>
</tr>
<tr>
<td>photon</td>
<td></td>
</tr>
<tr>
<td>Z boson</td>
<td></td>
</tr>
<tr>
<td>W boson</td>
<td></td>
</tr>
<tr>
<td>gluon</td>
<td></td>
</tr>
</tbody>
</table>
Fundamental building blocks?

• Besides those three, ...
• Besides those three, …

![Diagram of fundamental blocks]

- Charge:
  - $u_{up}$: +2/3
  - $d_{down}$: -1/3
  - $\nu_e$ (electron neutrino): 0
  - $e_{electron}$: -1

- Particles:
  - $\gamma$: photon
  - $Z$: Z boson
  - $W$: W boson
  - $g$: gluon
• Besides those three, …
• Besides those three, …

\begin{align*}
\begin{array}{ccc}
    u & \text{up} & \gamma & \text{photon} \\
    d & \text{down} & Z & Z \text{ boson} \\
    \nu_e & \text{electron neutrino} & W & W \text{ boson} \\
    \nu_\mu & \text{muon neutrino} & g & \text{gluon} \\
    \theta & \text{electron} & \mu & \text{muon} \\
    s & \text{strange} & & \\
\end{array}
\end{align*}
Besides those three, ...
Fundamental building blocks?

- Besides those three, …
Fundamental building blocks?

- Besides those three, there are 14 more
- They describe almost all known physical phenomena

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Fermions</th>
<th>Bosons</th>
<th>Force carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>u</td>
<td>γ</td>
<td>photon</td>
</tr>
<tr>
<td>c</td>
<td>c</td>
<td>Z</td>
<td>Z boson</td>
</tr>
<tr>
<td>t</td>
<td>t</td>
<td>W</td>
<td>W boson</td>
</tr>
<tr>
<td>d</td>
<td>d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leptons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \nu_e )</td>
<td>( \nu_e )</td>
<td>( W )</td>
<td>gluon</td>
</tr>
<tr>
<td>( \mu )</td>
<td>( \nu_\mu )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>τ</td>
<td>( \nu_\tau )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: AAAS
• Besides those three, there are 14 more

• They describe almost all known physical phenomena

• In 1964, there was a problem: the model worked only for elementary particles with ZERO mass
“Zero mass”? 

– “Mass” is the resistance to transform energy into motion
  Black beach ball vs bowling ball:
    the lower the mass, the larger the speed acquired

– Are there any particles with mass = 0?
  Yes: photons y gluons travel at the speed of light

– What if all elementary particles traveled at light speed?
  • There would be no atoms
  • No clusters of matter (hence: no stars, no planets)
  • No life as we know it

– In 1964, Higgs, Englert+Brout, Guralnik+Hagen+Kibble found a solution by postulating a new field, … and a new elementary particle.
What is the Higgs boson?
What is the Higgs boson?
What is the Higgs boson?
What is the Higgs boson?
What is the Higgs boson?
“For every complex problem there is an answer that is clear, simple, ...
“For every complex problem there is an answer that is clear, simple, and wrong.”

– H. L. Mencken
How was this particle discovered?
Experimental search and discovery

The discovery was achieved in the European Organization for Nuclear Physics (CERN).

**CERN: Conseil Européen pour la Recherche Nucléaire**
[temporary body, but the name stayed]

Founded in 1954 with 12 European countries.

Currently 21 member states.

Home to the world’s largest and most powerful particle accelerator.
The Large Hadron Collider

- 27 km circumference, 50-150 m below ground
- Two proton beams close to the speed of light
- Stored energy: 350 MJ (~TGV at 155 km/h)
The Large Hadron Collider

- \(~1600\) superconducting magnets
- “Bunches” of \(1.15 \times 10^{11}\) protons: 30 microns x several cm
- 40 million bunch crossings per second
The Large Hadron Collider

- Four collision points
- One detector on each
- Discovery: ATLAS, CMS
• ATLAS... before installing most of its components
• ~ 3000 scientists, 180 institutions, 38 countries
• ~ 3000 scientists, 182 institutions, 42 countries
Detectors

- About 100 millions sensors each
- Much beyond a 12-megapixel camera, 40 million pictures/second
One "event"
• Each bunch crossing $\sim$20 $pp$ interactions
• 40 M crossings per second $\times$ 20 $pp$ per crossing, spacing: 600 M $pp/s$
• Fast selection systems (“trigger systems”) keep only 400 collisions/s
• Each $pp$ collision produces hundreds of particles
• If stored in musing CD’s, …
Worldwide LHC Computing Grid

• >170 computing centers

• ~40 countries

• ~250,000 processing cores

• ~120 PB storage (120 million GB)
$H \to \gamma \gamma$
$H \rightarrow \gamma \gamma$

$\sqrt{s} = 7$ TeV $\int L dt = 0.02$ fb$^{-1}$  Apr 18, 2011

**ATLAS** Preliminary

$H \rightarrow \gamma \gamma$ channel
Higgs Physics

$H \rightarrow \gamma \gamma$

ATLAS Preliminary

Higgs channel

$\sqrt{s} = 7$ TeV $\int Ldt = 0.02$ fb$^{-1}$

April 18, 2011

Events / GeV

Data

Background-only

Data - Fit

$M_{\gamma \gamma}$ [GeV]
Candidato a $H$ to $4\mu$, with $m_{4\mu}=125.1$ GeV

$p_T$ (muones) = 36.1, 47.5, 26.4, 71.7 GeV  $m_{12}=86.3$ GeV, $m_{34}=31.6$ GeV. 15 vértices reconstruídos
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
Independent confirmation

ATLAS Preliminary

Data

4l → (*) ZZ → H

Background ZZ, t

Background 2-jets, f

Signal (m_H = 125 GeV)

Syst. Unc.

59
Independent confirmation
Probability < 0.00003% = "5σ" → Discovery!

Combination

ATLAS

CMS

Probability < 0.00003%

= "5σ" → Discovery!
From fundamental science to our daily life
From fundamental physics to daily life

Hadronic therapy for cancer

~30’000 accelerators worldwide
~17’000 for medical applications

>90,000 patients treated (30 facilities)

Medical imaging

e.g. CAT & PET, airport scaners, etc.

– www, GPS, cloud computing.

– In the long term, unexpected applications: 1897: the electron.
... and beyond
What is next?

CERN:
- Below the Geneva area
- *Conceptual Design Study* in preparation
- 80 – 100 km

China:
- Qinhuangdao (秦皇岛)
- Strong local support
R.o.l. of large science projects?

Example: The Fermilab collider (Tevatron)

- Detectors, upgrades: 2x$500M + $300M = $1,300M
- Operations: ~ 20 years x $100M/year = $2B

• TOTAL: $4B
Economic Impact

• PhD graduates:
  – $2.2M (US Census Bureau, 2002) = $2.8M (2012)
  – 1414 graduados: $3.96 B

Source: Jonh Womersley slides, FCC Kickoff Meeting, Geneva
Economic Impact

• PhD graduates:
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• Superconducting magnets
  – Mass-produced for the first time for the Tevatron
  – Current value of the SCM industry: $1.5B/year
  – MRI industry (the major costumer of SCM): $5B/year
  – It would likely have succeeded anyway, but it is fair to claim an acceleration of 1-2 years: $5B - $10B

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- Cloud computing: $150B/year (Gartner)
  - Large investment in linux, PC clusters, networking, etc.
  - Assuming Tevatron gave only a 3-month speed-up: $40B

Source: Jonh Womersley slides, FCC Kickoff Meeting, Geneva
SM Higgs production

Gluon fusion (dominant at LHC)

Vector boson fusion

Associated production with Z/W (Higgs-strahlung)

Associated production with top

$\sigma(pp \to H + X)$ vs $M_H$ for different production mechanisms.

$\sqrt{s} = 8$ TeV
**SM Higgs production**

**Gluon fusion** (dominant at LHC)

**Vector boson fusion**

**Associated production with Z/W** (Higgs-strahlung)

**Associated production with top**

![Graph showing SM Higgs production](image)

- **Gluon fusion** (dominant at LHC)
- **Vector boson fusion**
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- **Associated production with top**

\[
\sigma(pp \rightarrow H + X) [pb]
\]

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\[
M_H [GeV] \]

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\[
\sim 2000 \text{ fb at } m_H = 125 \text{ GeV}
\]

\[
\text{In 5fb}^{-1}: \sim 100k \text{ produced!}
\]
Branching ratios

SM Higgs decays

Direct coupling to massive particles

(WW, ZZ, tt, bb, ττ)

Through a triangle loop to massless ones

(gg, γγ)
Branching ratios

SM Higgs decays

Direct coupling to massive particles

(WW, ZZ, tt, bb, ττ)

Through a triangle loop to massless ones

100,000 Higgs bosons produced... times ~0.002 BR to γγ, ~ 200 Higgs to be found via γγ search
Introduction

Cross section times BR

- WW, ZZ split into decay modes
- Targeting production modes can improve sensitivity
- Not yet the full story!
  - Missing: triggers, efficiencies, resolutions, background cross sections, rejection for each, etc.
  - Low $m_H$: $\tau\tau$ is largest (cons: detection and backgrounds)
  - High $m_H$: $ll\nu\nu$ most sensitive
- Experimentally, $100 < m_H < 200$ is accessible in the most ways
- All modes labeled in the plot (and more) have been studied; here, we’ll focus on three
Introduction

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Limits and $p_0$ plots

- Null search results do provide valuable information:
  What signal sizes can be ruled out?
- Need reliable background estimations
  - Always a probabilistic statement
    - Need to state the “CL” (95%)
- Being a random process, uncertainty bands are needed
- “Expected”: median of limits if the signal does not exits
- Observed: from the actual dataset
  - Too few events $\rightarrow$ “strong” limit
  - Too many events $\rightarrow$ “weak” limit
• **Too many events** may also, instead, represent a signal

• … do they?

We quantify it by the probability that background alone would produce an excess as large as observed (or larger)

→ “Local” $p_0$

• Instead of quoting $p_0$, we refer to it using the “number of sigmas” that it would represent in a Gaussian tail.

  – 1 sigma → $p_0 = 16\%$
  – 3 sigma → $p_0 = 0.13\%$
  – 5 sigma → $p_0 = 2.9 \times 10^{-7}$