Higgs Physics – Lecture 1

Higgs Physics at the LHC – Introduction
Ricardo Gonçalo – LIP
IDPASC Course on Physics at the LHC – LIP, 2 April 2018
**Wednesday, 4 April**

17:00 → 18:30 **Higgs Physics 2**

Discovery of the Higgs boson in the different final states
Case-study of the $H \rightarrow WW$ search
Algorithms, challenges, tools
Combination of search results

Speaker: Dr. Patricia Corde Muño (LIP Laboratorio de Instrumentação e Física Experimental de Partículas)

---

**Wednesday, 11 April**

17:00 → 18:30 **Higgs Physics 4**

- Search for new physics in the Higgs sector.
- The Higgs boson and processes beyond the SM.
- Extensions of the SM, minimal and non-minimal extensions.
- High mass searches.
- MSSM Higgs searches: neutral, charged.
- Light pseudoscalar, resonant and non-resonant Higgs pair production.

---

**Monday, 9 April**

17:00 → 18:30 **Higgs Physics 3**

Models, properties, and interpretation.
Case-study of the coupling strengths.
Case-study of the hypothesis test for different spin-parity assignments.

Speaker: Pedro Vieira de Castro Ferreira da Silva (CERN)
Outlook

• Introduction
• Hard-core theory
  – Lagrangians and symmetries
  – Quantum fields
  – Problems with the Standard Model
• The Higgs mechanism
• The long way to discovery
  – LEP experiments
  – Tevatron experiments
  – Search and Discovery at the LHC
• Higgs boson properties
• Open questions
Introduction

Standard Model particles, interactions, and hard-core theory to set the scene...
Standard model interactions

The interaction of gauge bosons with fermions is (very) well described by the Standard Model.

**Strong**

Only quarks
Never changes flavour

\[ \alpha_s \sim 1 \]

Gluons
massless

**Electromagnetic**

All charged fermions
Never changes flavour

\[ \alpha \sim 1/137 \]

Photon
massless

**Weak Charge Counting**

All fermions
Always changes flavour

\[ \alpha_{W/Z} \sim 1/40 \]

W+, W-
very massive

**Weak Neutral Current**

All fermions
Never changes flavour

\[ \sim Z^0 \]

very massive
Lagrangians, symmetries and all that

Emmy Noether (1882 – 1935)

Leonhard Euler (1707–1783)

Joseph-Louis Lagrange (1736–1813)
Reminder: Lagrangians in classical mechanics

The equations of motion of a system are derived from a scalar Lagrangian function of generalized coordinates and velocities (time derivatives of the coordinates)

$$L(q, \dot{q}) = T - V$$

and from the Euler-Lagrange equations:

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_j} = 0$$
Example

Particle in a conservative potential $V$. The Lagrangian

$$L = \frac{1}{2} m (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) - V(x, y, z)$$

has derivatives (e.g. for $x$)

$$\frac{\partial L}{\partial x} = - \frac{\partial V}{\partial x}, \quad \frac{\partial L}{\partial \dot{x}} = m \ddot{x}, \quad \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{x}} \right) = m \dddot{x}$$

and Euler-Lagrange’s equations

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_j} = 0$$

finally give us Newton’s familiar 2\textsuperscript{nd} law!

$$m \ddot{x} = - \frac{\partial V}{\partial x}, \quad m \ddot{y} = - \frac{\partial V}{\partial y}, \quad m \ddot{z} = - \frac{\partial V}{\partial z} \iff m \dddot{a} = \vec{F}$$
Symmetries and conservation laws

Noether’s theorem:

*If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.*

Simplest case: Coordinates not explicitly appearing in the Lagrangian

⇒ Lagrangian invariant over a continuous transformation of the coordinates

Example: mass \( m \) orbiting in the field of a fixed mass \( M \)

\[
L(r, \phi, \dot{r}, \dot{\phi}) = T - V = \frac{1}{2} m \dot{r}^2 + \frac{1}{2} m r^2 \dot{\phi}^2 + \frac{G M m}{r}
\]

Since the lagrangian doesn’t depend explicitly on \( \phi \) (symmetry with respect to rotations in space), the Euler-Lagrange equation gives

\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\phi}} \right) = 0 \iff \frac{\partial L}{\partial \phi} = m r^2 \dot{\phi} = J
\]

Where the **angular momentum** \( J \) is a constant of motion!
Let’s go to quantum fields...

\[ \frac{1}{\sqrt{2}} \mid \text{cat} \rangle + \frac{1}{\sqrt{2}} \mid \text{mouse} \rangle \]

Richard Feynman (1918 - 1988)

Schrödinger’s cat (???)

Erwin Schrödinger (1887 - 1961)
Now in quantum field theory...

Imagine space as an infinite continuum of balls and springs, where each ball is connected to its neighbours by elastic bands. **Particles are perturbations of this field**.
Generalized coordinates are now **fields** (dislocation of each spring)

\[ q_i \rightarrow \phi_i(x^\mu) \]

In a relativistic theory we must treat space and time coordinates on an equal footing, so the derivatives in the classical equations are now

\[ \frac{d}{dt}, \nabla \rightarrow \partial_\mu = (\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}) \]

In place of a Lagrangian we have a **Lagrangian density** (we call it Lagrangian anyway, just to be confusing)

\[ L(q_i, \frac{dq_i}{dt}) \rightarrow \mathcal{L}(\phi_i, \partial_\mu \phi_i) \]

with:

\[ L = \int \mathcal{L} d^3x \]

The new Euler-Lagrange equation now becomes

\[ \partial_\mu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_i)} \right) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0 \]
Gauge invariance

Take the Dirac Lagrangian for a spinor field $\psi$ representing a spin-$\frac{1}{2}$ particle, for example an electron:

$$\mathcal{L} = i\hbar \bar{\psi} \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi$$

It is invariant under a global U(1) phase transformation like:

$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi} \psi(x)$$

Where $\chi$ is a constant

$$\mathcal{L}' = e^{-iq\chi} e^{iq\chi} (i\hbar \bar{\psi} \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi) = \mathcal{L}$$
$\psi(x) \rightarrow \psi'(x) = e^{iqx} \psi(x)$

\(\chi = \text{constant}\)

\(\chi = \chi(x)\)
Local gauge invariance and interactions

If $\chi = \chi(x)$ then we get extra terms in the Lagrangian:

$$\mathcal{L}' = ie^{-iqx}\bar{\psi}\gamma^\mu[e^{iqx}\partial_\mu\psi + iq(\partial_\mu\chi)e^{iqx}\psi] - me^{-iqx}[e^{iqx}\bar{\psi}\psi]$$

$$= \mathcal{L}' - q\bar{\psi}\gamma^\mu(\partial_\mu\chi)\psi$$

But we can now make the Lagrangian invariant by adding an interaction term with a new gauge field $A_\mu$ which transforms as:

$$A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu \chi$$

We get:

$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^\mu A_\mu\psi$$

A few things to note:

1. Gauge theories are renormalizable, i.e. calculable without infinities popping up everywhere (Nobel prize of t’Hooft and Veltman)
2. The new gauge field $A_\mu$ is the photon in QED
3. The mass of the fermion is the coefficient of the term on $\psi\bar{\psi}$
4. There is no term in $A_\mu A^\mu$ (the photon has zero mass) $\rightarrow$ this is the beginning of the Higgs story...
Now for the problems...
1: Longitudinal gauge-boson scattering

In the absence of the Higgs, some processes have cross sections that grow with the centre of mass energy of the collision... i.e. breaks unitarity!

The Higgs regulates the cross section through negative interference

Feynman diagrams contributing to longitudinal WW scattering
2: Mass of elementary particles and gauge bosons

\[ \mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu \partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu \psi A_\mu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_\gamma A_\mu A^\mu \]

To keep the Lagrangian gauge invariant (against a U(1) local phase transformation) the photon field transforms as:

\[ A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu \chi \]

But the \( A^\mu \) mass term breaks the invariance of the Lagrangian:

\[ \frac{1}{2} m_\gamma A_\mu A^\mu \rightarrow \frac{1}{2} m_\gamma (A_\mu - \partial_\mu)(A^\mu - \partial^\mu \chi) \neq \frac{1}{2} m_\gamma A_\mu A^\mu \]

For the SU(2)_L gauge symmetry transformations of the weak interaction the fermion mass term \( m_e \bar{\psi} \psi \) also breaks invariance!

Bottom line: the SM (without the Higgs mechanism) results in wrong calculations and breaks down for massive particles.
The Higgs Mechanism

Robert Brout (1928 – 2011)

Peter Higgs (b. 1929)

François Englert (b. 1932)
• Introduce a SU(2) doublet of spin-0 complex fields

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

• The Lagrangian is

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

• With a potential

• For $\lambda>0$, $\mu^2<0$ the potential has a minimum at the origin

• For $\lambda>0$, $\mu^2<0$ the potential has an infinite number of minima at:

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

The choice of vacuum (lowest energy state of the field) breaks the symmetry of the Lagrangian
\[ V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \]
Electroweak symmetry breaking

• In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass

• Electroweak gauge symmetry is broken:
  – Photon does not have mass
  – W, Z have a large mass

• Higgs mechanism: mass of W and Z results from the Higgs mechanism

• Masses of fermions come from a direct interaction with the Higgs field

see J.Varela’s lecture
The Higgs is significant because it explains why stuff has mass.

Wait, we don't know why stuff has mass?

What is mass?

You just blew my mind.

I know.

The Higgs is significant because it explains why stuff has mass.

For me it's the Ramen diet.
EWK Symmetry Breaking in Pictures

\[ \begin{align*}
W_1 & \quad W_2 \quad W_3 \quad B \\
\uparrow & \quad \downarrow \\
W_1 & \quad W_2 \\
H^+ & \quad H^- \\
W_3 & \quad B \\
\uparrow & \quad \downarrow \\
H^0 & \\
\end{align*} \]
• We have at this point a massive scalar field with vacuum expectation value $v$ and mass
$$m_h = \sqrt{2\lambda v}$$

• 4 gauge fields: $W^{(1)}$, $W^{(2)}$, $W^{(3)}$, and $B^{(1)}$ which transform to give the massive $W^+$, $W^-$ and $Z$, and massless $A$ (the photon)

$$m_W = \frac{1}{2} g_W v$$
$$m_A = 0$$
$$m_Z = \frac{1}{2} v \sqrt{g_W^2 + g^2}$$

$\Leftrightarrow v = 246\text{GeV}$

with $g$, $g_W$ the couplings of electromagnetic and weak forces

• Defining the Weinberg angle as
$$\frac{g}{g_W} = \tan \theta_W$$

we also get the relation between the masses of $W$ and $Z$

$$\frac{m_W}{m_Z} = \cos \theta_W$$

• Fermions get their masses from interaction terms with the Higgs field (Yukawa coupling)
Weak Nuclear Interaction

Electromagnetic interaction

$\gamma$

$W^\pm$

$\frac{d\sigma}{dQ^2} \text{ (pb}/\text{GeV}^2)$ vs $Q^2 \text{ (GeV}^2)$
The Story So Far...

IN THE BEGINNING
THE UNIVERSE WAS CREATED
THIS MADE A LOT OF PEOPLE
VERY ANGRY
AND HAS BEEN WIDELY REGARDED
AS A BAD MOVE

DOUGLAS ADAMS
The Standard Model of particle physics

1a
Ve
Neutrino do Eletrão
0
1/2
u
Up
1/2
1/2
d
Down
1/2

2a
Vμ
Neutrino do Muão
0
1/2
c
Charm
1/2
s
Strange
1/2

3a
Vτ
Neutrino do Tau
0
1/2
t
Top
1/2
b
Bottom
1/2

γ
Fotão
0
1

Z
Bosão Z
0
1

W±
Bosão W
0
1

H
Higgs
0
0

Legend

<table>
<thead>
<tr>
<th>Símbolo</th>
<th>Nome</th>
<th>Carga</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Higgs</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Z</td>
<td>Bosão Z</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>γ</td>
<td>Fotão</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Para cada uma dessas partículas existe uma antipartícula de carga oposta (antimatéria).
What we think we know:

- Higgs mass (was) the only unknown parameter
- We can give mass to $W^\pm$ and $Z$ while keeping the photon massless
- Relation between masses of $W$ and $Z$
- Higgs couples to $W$ and $Z$ with strengths proportional to their masses
- Higgs couples to all fermions with a strength proportional to their mass

\[
m_h = \sqrt{2\lambda v}
\]

\[
\frac{m_W}{m_Z} = \cos \theta_W
\]

\[
g_f = \sqrt{2} \frac{m_f}{v}
\]
Exploring the electroweak scale

- Precision measurements of $m_W$, $m_t$, $m_H$ are stringent tests of the SM at the EW scale
  - E.g. excluding measured $m_H$, global EW fit gives $m_H = 90 \pm 21$ GeV (1.7 $\sigma$ tension) driven in part by $m_{top}$
The Long Way to Discovery
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.
Electron-positron collider up to $s^{1/2} = 209$ GeV
Integrated luminosity: $\sim 700$ pb$^{-1}$

Shutdown: September 2000

**Searches at LEP**

OPAL

ALEPH

DELPHI

L3
Low-mass searches at LEP

The decay branching ratios depend only on $m_H$:

- $m_H < 2m_e$: $H \to \gamma\gamma$ + large lifetime;
- $m_H < 2m_\mu$: $H \to e^+e^-$ dominates;
- $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates;
- $m_H < 3 - 4 \text{ GeV}$: $H \to gg$ dominates;
- $m_H < 2m_b$: $H \to \tau^+\tau^-$ and $c\bar{c}$ dominate;
- $m_H > 2m_b$ up to 1000 GeV/$c^2$: 

$$\begin{align*}
\text{Branching ratio} & \\
\ln m_H & (\text{GeV}/c^2) \quad \ln \text{Branching Ratio} \\
\text{hh} & \quad \text{WW} \\
\text{bb} & \quad \text{ZZ} \\
\text{tt} & \quad \text{gg}
\end{align*}$$
Higher-mass Higgs production at LEP
Higgs decays: focus on 3rd generation

- $H \rightarrow b\bar{b}$, $Z \rightarrow q\bar{q}$: 4-jets - 51%
  - $WW \rightarrow q\bar{q}q\bar{q}$
  - $ZZ \rightarrow q\bar{q}q\bar{q}$
  - QCD 4-jets

- $H \rightarrow b\bar{b}$, $Z \rightarrow \nu\bar{\nu}$: missing energy - 15%
  - $WW \rightarrow q\bar{q}l\nu$
  - $ZZ \rightarrow b\bar{b}\nu\nu$

- $H \rightarrow b\bar{b}$, $Z \rightarrow \tau^+\tau^-$: $\tau$-channel - 2.4%
  - $WW \rightarrow q\bar{q}\tau\nu$
  - $ZZ \rightarrow b\bar{b}\tau\tau$
  - $ZZ \rightarrow q\bar{q}\tau\tau$
  - QCD low mult. jets

- $H \rightarrow \tau^+\tau^-$, $Z \rightarrow q\bar{q}$: $\tau$-channel - 5.1%

- $H \rightarrow b\bar{b}$, $Z \rightarrow e^+e^-$, $\mu^+\mu^-$: lepton channel - 4.9%
  - $ZZ \rightarrow b\bar{b}e\bar{e}$
  - $ZZ \rightarrow b\bar{b}\mu\mu$
Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

Expectation for $m_H=115$ GeV

- 8.4 events

Corresponding excess was not observed

Final verdict from LEP

$m_H > 114.4$ GeV @ 95% CL
LEP’s Final Legacy: the Blue Band Plot

- Decades of searches in many experiments...

- By July 2010:
  - LEP+Tevatron+SLD limits
  - Higgs excluded $m_h<114.4$ GeV at 95% CL
  - Plus between 158 and 175 GeV

\[ \Delta \chi^2 \]

\[ m_{\text{limit}} = 158 \text{ GeV} \]

\[ \Delta \alpha_{\text{had}}^{(5)} = \]

- $0.02758 \pm 0.00035$
- $0.02749 \pm 0.00012$
- incl. low $Q^2$ data

CERN-PH-EP-2010-05
Proton-anti-proton collider at $s^{1/2}=1.96$ TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb$^{-1}$ of data for analysis
Higgs production at the Tevatron

(fermion annihilation and vector boson scattering)
Most sensitive searches

- At **low mass** use $h \rightarrow bb$ final states
  - associated production with $W$ or $Z$
  - challenging: b-tagging, jet resolution
  - backgrounds: top, $W/Z+heavy$ flavour di-bosons

- At **high mass** use $H \rightarrow WW$ final states
  - benefit from high gluon-gluon cross section
  - challenging: lepton acceptance, missing energy
  - backgrounds: top, di-bosons
The final stand of the Tevatron

• By the end of its lifetime, the Tevatron had very sophisticated analyses of a huge number of channels

• By that time the LHC was collecting data and analysing it very fast

• The CDF and D0 experiments obtained a significant excess of around 3 standard deviations in the mass range $115 < M_H < 140$ GeV

• Not enough to claim discovery, but consistent with the LHC results
Proton-proton (and Heavy Ion) collider $s^{1/2} = 7, 8, 13$ TeV so far
Operation started 2008
Physics data from 2010
Expected closure 2035
Luminosity so far: about 150 fb$^{-1}$ per experiment for ATLAS and CMS
At the LHC

\[ \sigma(pp \rightarrow H^+X) \text{ [pb]} \]

\[ \sqrt{s} = 8 \text{ TeV} \]

LHC HIGGS XS WG 2016

H (NNLO+NNLL QCD)

→ pp \rightarrow \ell^+\ell^-H (NNLO QCD)

→ pp \rightarrow W^+H (NNLO QCD + NLO EW)

→ pp \rightarrow ZH (NNLO QCD + NLO EW)

→ pp \rightarrow B 

→ pp \rightarrow \ell^+\ell^- (NNLO QCD + NLO EW)

→ pp \rightarrow W^+H (NNLO QCD + NLO EW)

→ pp \rightarrow ZH (NNLO QCD + NLO EW)

→ pp \rightarrow t\bar{t}H (NLO QCD)

→ pp \rightarrow \ell^+\ell^- (NNLO QCD + NLO EW)

→ pp \rightarrow W^+H (NNLO QCD + NLO EW)

→ pp \rightarrow ZH (NNLO QCD + NLO EW)

→ pp \rightarrow t\bar{t}H (NLO QCD)

→ pp \rightarrow \ell^+\ell^- (NNLO QCD + NLO EW)

→ pp \rightarrow W^+H (NNLO QCD + NLO EW)

→ pp \rightarrow ZH (NNLO QCD + NLO EW)

→ pp \rightarrow t\bar{t}H (NLO QCD)

→ pp \rightarrow \ell^+\ell^- (NNLO QCD + NLO EW)

→ pp \rightarrow W^+H (NNLO QCD + NLO EW)

→ pp \rightarrow ZH (NNLO QCD + NLO EW)

→ pp \rightarrow t\bar{t}H (NLO QCD)
It takes time to get it right

**Discovery channels**

- Discovery was made in ATLAS and CMS with about 5 fb\(^{-1}\) of 7 TeV data and 20 fb\(^{-1}\) of 8 TeV data per experiment; several channels combined

\[ h \to \gamma \gamma; h \to ZZ^* \to 4\ell; h \to WW^*; h \to \tau^+\tau^-; h \to b\bar{b} \]

- This means about 400,000 Higgs bosons produced in about 8,000,000,000,000,000 (8 \times 10^{15}) proton collisions
  - Only about 4,000 events with Higgs bosons contributed to the discovery
Combining Higgs Channels

Production

\[ g \quad \text{Primary production} \quad t, q, \bar{q} \]  

\[ W/\bar{W}, Z/\bar{Z}, H \]

\[ \times K_g^2 \]

Decay

\[ H \times K_W^2 \]

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow ZZ \]

\[ H \rightarrow WW \]

Backgrounds +

\[ \times K_{t}^2 \]

\[ \times K_{W}^2 \]

\[ \times K_{Z}^2 \]

\[ \times K_{g}^2 \]

FIT

R. Gonçalo - Physics at the LHC

17.04.19
The $p_0$ Discovery Plot

- $p_0$ is the combined probability that the background fluctuates to look like signal
- Translated into the one-sided Gaussian probability

- This corresponds to a probability of **1 in 3.5 million** that this was a false positive from fluctuating backgrounds
2013 Physics Nobel Prize Higgs for the Higgs Boson Discovery

François Englert, Belga, born 1932, U. Libre de Bruxelles

Peter Higgs, English, born 1929, Univ. of Edimburgh

"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"
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

www.elsevier.com/locate/physletb

Two quotations from the experimental papers presented in this publication:

"... The search for the Higgs boson, the only elementary particle in the Standard Model that has not yet been observed, is one of the highlights of the Large Hadron Collider physics program."

- ATLAS Collaboration

"... The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent... with expectations for a standard model Higgs boson."

- CMS Collaboration

Best wishes!
[Signature]
Peter Higgs
What we have found out since
A (quick) foretaste of the next few lectures
Spin and Parity

- First concern after observation!
- Some observable quantities sensitive to $J^P$: for example angle between leptons from $W$ decay in $H\rightarrow WW$
- Pure $J^P = 0^-, 1^+, 1^-$, and $2^+$ excluded with $97.8, 99.97, 99.7$, and $99.9\%$ Confidence Level (ATLAS arXiv 1307.1432; CMS Phys. Rev. D 92, 012004)
• **Mass:** around 125GeV
  Was the only unknown SM parameter 😊
• For a while, different mass values were being measured in ATLAS and CMS, and in different channels
• Numbers evolved with accumulated statistics
• Current most precise value from ATLAS+CMS has 0.2% precision!

\[
m_{H} = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}
\]
Cross section compared to SM expectation

$$\frac{\sigma_{\text{meas}} \cdot BR}{\sigma_{\text{SM}} \cdot BR}$$
Probing the 125 GeV Higgs
The Run 1 legacy

- **Mass** – Higgs mass measured with 0.4% accuracy:
  - \( m_H = 125.09 \pm 0.21 \) (stat.) \( \pm 0.11 \) (scale) \( \pm 0.02 \) (other) \( \pm 0.01 \) (theory) GeV

- **Couplings**:
  - \( ggF \) with \( H \rightarrow ZZ, \gamma\gamma, WW \) **observed** by individual experiments
  - \( VBF \) and \( H \rightarrow \tau\tau \) observed with \( >5\sigma \) significance by ATLAS+CMS combination
  - \( ttH, VH \) production and \( H \rightarrow bb \) **not observed** during Run1

- **Couplings compatible with SM**:
  - Signal strength: \( \mu_{VBF+VH}/\mu_{ggF+ttH} = 1.06 \pm 0.35^{+0.27}_{-0.27} \)
  - Coupling modifiers broadly consistent with SM but still large uncertainty

\[ \mu = (\sigma \times BR)_{\text{Obs}} / (\sigma \times BR)_{\text{SM}} \]

### Significance (\( \sigma \))

<table>
<thead>
<tr>
<th>Product</th>
<th>Obs.</th>
<th>Expect.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>5.4</td>
<td>4.7</td>
</tr>
<tr>
<td>VH</td>
<td>3.5</td>
<td>4.2</td>
</tr>
<tr>
<td>ttH</td>
<td>4.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Decay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>5.5</td>
<td>5.0</td>
</tr>
<tr>
<td>( H \rightarrow bb )</td>
<td>2.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Run 2: Higgs boson mass

- Mass measurement from CMS $H \rightarrow ZZ^* \rightarrow 4l$:
  \[ m_{H}^{ZZ^*} = 125.26 \pm 0.20 \text{ (stat)} \pm 0.08 \text{ (syst)} \text{ GeV} \]

- New Measurements from ATLAS
  - $H \rightarrow \gamma\gamma$: \[ m_{H}^{\gamma\gamma} = 124.93 \pm 0.40 \text{ GeV} \]
  - $H \rightarrow ZZ^* \rightarrow 4l$: \[ m_{H}^{ZZ^*} = 124.79 \pm 0.37 \text{ GeV} \]

- Run 1+2 combination from ATLAS:
  \[ m_{H} = 124.97 \pm 0.19 \text{ (stat)} \pm 0.13 \text{ (syst.)} \text{ GeV} \]
Differential Higgs boson cross sections

- Reached a new phase in the exploration of the Higgs sector!

- Differential cross sections:
  - Higgs $p_T$ sensitive to new physics in gluon-fusion loop
  - Number of jets sensitive to modeling of radiation and different production modes
Últimas novidades!!

FÍSICA DE PARTÍCULAS
Bosão de Higgs revela que relação mantém com o quark *top*
Investigadores portugueses participaram na descoberta.

FÍSICA DE PARTÍCULAS
Bosão de Higgs visto (finalmente) a desintegrar-se em quarks *bottom*
Descoberta anunciada no Laboratório Europeu de Física de Partículas (CERN) é um passo fundamental para perceber como o bosão de Higgs faz com que as partículas fundamentais adquiram massa.
Casting a wider net
Going beyond the standard model

But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see but has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?
Many possible theories

There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, ...)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC and most have a connection to the Higgs boson
Additional Higgs bosons?

Diphoton rate – Run I

Selected diphoton sample

- Data 2011+2012
- Sig+Bkg Fit ($m_h = 126.8$ GeV)
- Bkg (4th order polynomial)

*ATLAS* Preliminary

$H \rightarrow \gamma\gamma$

$\sqrt{s} = 7$ TeV, $\int L dt = 4.8$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $\int L dt = 20.7$ fb$^{-1}$

Diphoton rate – Run II

*ATLAS* Preliminary

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
Higgs + Dark Matter

- Used 79.8 fb\(^{-1}\) of 13 TeV data
  - High \(E_{T}^{\text{miss}}\) (>150GeV) and b-tagging to suppress backgrounds
  - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets

- Signal benchmark: Type-II 2HDM + U(1)\(_{Z'}\) symmetry (Z'-2HDM)

- Main backgrounds: tt, W/Z+jets

- Excluded region in \(m_A - m_{Z'}\) plane
Charged Higgs: $H^+ \rightarrow tb$

- Explored single-lepton and dilepton $tt$ final states
  - In range $m_{H^+}: 200 \rightarrow 2000$ GeV
- $36.1 \text{ fb}^{-1}$ of 13 TeV data

- Events categories: $N_{\text{jets}}$ and $N_{\text{b-tags}}$
  - Allow to constrain backgrounds in simultaneous fit

- BDTs trained in signal regions
  - Separate signal and background for 18 mass points
  - Matrix method used in single-lepton channel

- Extracted limits on $\sigma \times \text{BR}$ and on $m_{H^+}$ - $\tan \beta$ plane for two MSSM scenarios
The triple Higgs coupling $\lambda_{HHH}$ can be probed through di-Higgs production.

Very suppressed in SM!
- Negative interference between LO diagrams
- Cross section 1500x less than ggF

Wide range of decay BR and channel purity

$bb\tau\tau$ analysis:
- Used 36 fb$^{-1}$ of 13 TeV data
- Final state BR($bb\tau\tau$)=7%
- Non-Resonant 95% CL limit:
  - $\mu < 12.7$ observed (14.8 expected)

Combination: at ≈10 x SM sensitivity
- with 3% of the HL-LHC luminosity analyzed

Di-Higgs combination plot [here](#)
Implications for 2HDM

- $H(125)$ assumed to be light CP-even neutral scalar $h$ in 2HDM

- $h$ production and decay same as for SM Higgs boson
A bit of fun...

- What if...
  - At higher orders, Higgs potential doesn’t have to be stable
  - Depending on $m_t$ and $m_H$ second minimum can be lower than EW minimum $\Rightarrow$ tunneling between EW vacuum and true vacuum?!

- “For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about $10^{16}$ GeV, where primordial inflation could have started in a cold metastable state”, I. Masina, arXiv:1403.5244 [astro-ph.CO]
The universe seems to live near a critical condition
JHEP 1208 (2012) 098
Why?! Explained by underlying theory? Anthropic principle?
Questions?

Thank you for your interest!

jgoncalo@lip.pt