The long experimental journey to the Higgs Boson at the LHC
The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, initiated some 30 years ago.

It is a great privilege and pleasure to present now physics results from the first three years of operation.
Remember Einstein’s famous formula for the equivalence between energy and mass

At particle accelerators we produce massive states from kinetic energy, which decay again into lighter particles

\[
\begin{align*}
1 \text{ electron Volt (eV)} &= 1.8 \times 10^{-36} \text{ kg} \\
1 \text{ Tera electron Volt (TeV)} &= 10^{12} \text{ eV} \\
1 \text{ proton mass} &= 938 \times 10^6 \text{ eV} \\
&\approx 0.001 \text{ TeV}
\end{align*}
\]
Experiments at CERN with the Large Hadron Collider allow us to study fundamental particle physics in conditions that we can control, and with measurements that we can reproduce and verify.
The Standard Model of Particle Physics

(i) Constituents of matter: quarks and leptons

(ii) Four fundamental forces
(described by quantum field theories, except gravitation)

(iii) The Higgs field (problem of mass)
A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery for fundamental particles could be solved with the ‘EW symmetry breaking mechanism’ which predicts the existence of a new elementary particle, the ‘Higgs’ particle (theory 1964: R. Brout and F. Englert; P.W. Higgs; G.S. Guralnik, C.R. Hagen and T.W.B. Kibble)

The Higgs (H) particle has been searched for since decades at accelerators … motivated LHC
Why do we need a Higgs?

Elementary particles are point-like, without any internal structure

The natural consequence would be that they are massless, but we know experimentally that this is not the case!

The above-mentioned theorists, together with others, postulated in 1964 a solution which spontaneously breaks this symmetry (initially between the gauge bosons, i.e. the massless photon and the heavy W and Z bosons)

A field was proposed that fills all space (vacuum) that has the following effects:
- Bosons can acquire a mass
- Fermions can acquire a mass
- The weak and the electromagnetic forces are very different in their properties
- A new massive scalar elementary particle (the Higgs, H) must exist (however with a mass that is not predicted by this theory)

The discovery of this H particle would verify this bold theory!
A cartoon ‘illustrating’ the scalar Brout-Englert-Higgs field filling all space that affects elementary particles, and ‘gives’ them their mass by interacting with them.
Announced on 8th October and celebrated on 10th December 2013:

2013 NOBEL PRIZE IN PHYSICS
François Englert
Peter W. 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”
Lagrangian of the Standard Model (SM)…

… only to show that there is a mathematical formulation behind all this!
1984 For the community it all started with the CERN - ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel.

1987 La Thuile Workshop
Many LHC colleagues were already involved in this WS set up by Carlo Rubbia as part of the Long Range Planning Committee.

1989 ECFA Study Week in Barcelona for LHC instrumentation.

1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)

1992 CERN – ECFA meeting ‘Towards the LHC Experimental Programme’ in Evian.

ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1st October 1992, more than 20 years ago.
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60yCERN, 9-Oct-2014
P Jenni (Freiburg and CERN) LHC roadmap to the Higgs

ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1st October 1992, more than 20 years ago

Spokesperson Fabiola Gianotti, celebrating 20 years of ATLAS on 1st October 2012
CERN’s particle accelerator chain

LHC roadmap to the Higgs
Interesting hard (high-pT) events are rare

Collisions at the LHC

Event rate:

\[ N = L \times \sigma \,(pp) \approx 10^9 \text{ interactions/s} \]

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

Event selection:

1 in 10,000,000,000,000

→ Interesting events are very, very rare
→ One needs highly sophisticated instruments to find them
**Detectors for particle physics**

Cover the whole angular range around the collision point to detect as much of the particles produced in the collision as possible.

**Dual role of detectors:**

Select potentially interesting collision events

Provide as much information about these events for the analysis as possible

**A typical cylindrical layout of a collider detector**
The SM is not a complete theory

Some of the outstanding questions in fundamental physics were/are:

(~✓) What is the origin of the elementary particle masses?

What is the nature of the Universe dark matter?

Why is only matter observed in the Universe as primary constituents and not anti-matter?

What are the features of the primordial plasma present ~10 μs after the Big Bang?

What happened in the first moments of the Universe ~10^{-11} s after the Big Bang?

Are there other forces in addition to the known four?
Are there additional (microscopic) space dimensions?

....
Specialized detectors

LHCb

ALICE

LHC roadmap to the Higgs
The LHCb experiment
The LHCb experiment

\[ \tau_B = 1.5 \text{ ps} \]

(proton beam collision point)
ALICE (Status January 2008)

Study primordial plasma of quarks and gluons with heavy ion collisions in the LHC (Pb-Pb, p-Pb)

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P Jenni (Freiburg and CERN)
General purpose detectors
An Example of an Engineering Challenge: CMS Solenoid

CMS solenoid:
- Magnetic length: 12.5 m
- Diameter: 6 m
- Magnetic field: 4 T
- Nominal current: 20 kA
- Stored energy: 2.7 GJ
- Tested at full current in Summer 2006
CMS Electron and Photon calorimeter: 76,000 PbWO₄ crystals

End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS.
[ CMS before closure 2008 ]
As an example:

**ATLAS Collaboration**

39 Countries
178 Institutions
3000 Scientific participants total
(1000 Students)

Age distribution of the ATLAS population
ATLAS

- **Length**: ~ 46 m
- **Radius**: ~ 12 m
- **Weight**: ~ 7000 tons
- ~ $10^8$ electronic channels
- ~ 3000 km of cables

**Tracking** ($|\eta|<2.5$, $B=2T$):
- Si pixels and strips
- Transition Radiation Detector ($e/\pi$ separation)

**Calorimetry** ($|\eta|<5$):
- EM: Pb-LAr
- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

**Muon Spectrometer** ($|\eta|<2.7$):
- air-core toroids with muon chambers
The Underground Cavern at Point-1 for the ATLAS Detector

Length = 55 m
Width = 32 m
Height = 35 m
LHC roadmap to the Higgs
ATLAS End-cap Toroid installation, as an example

The transports and installations were major operations, involving also specialized firms.

The ECTs are 250 tons, 15 m high, 5 m wide.

ECT-A was lowered on 13th June 2007, and ECT-C on 12th July 2007.
The joy in the ATLAS Control Room when the first LHC beam collided on November 23rd, 2009....
First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV
A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly
(first 7 TeV collisions on 30th March 2010)
The experiments record typically 94% of the stably delivered luminosity, and use up to 90% of the LHC luminosity in the final analyses!
Worldwide LHC Computing Grid (wLCG)

WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project’s size.

GRID computing developed to solve problem of data storage and analysis.

LHC data volume per year:
~25 Petabytes

One CD has ~ 600 Megabytes
1 Petabyte = $10^9$ MB = $10^{15}$ Byte

(Note: the WWW is from CERN... )

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P Jenni (Freiburg and CERN)
The Worldwide LHC Computing Grid (WLCG)

Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (12 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

Tier-2 (68 federations of >100 centres):
- Simulation
- End-user analysis
Physics Highlights

ATLAS and CMS have already published together more than 700 papers in scientific journals (and many more as public conference notes…)

The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 300 journal publications together

It is clearly not possible to cover all these results…

No attempt is made to show in a democratic way, for example, CMS and ATLAS results, only examples are given that are meant to represent the others as well where applicable...

Note that all public results are available from the experiments Web pages, and from the CERN Document Server


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P Jenni (Freiburg and CERN)
Very basic measurement: the total cross-section ('measure of the total interaction probability when two protons hit each other')

But remember, only once in about $10^{13}$ of the collisions a detectable Higgs is produced
Well known quark-antiquark resonances (bound states) appear “online”

Data corresponding to ~40 pb\(^{-1}\) collected → re-discovery of the Standard Model

The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear “online”
Jet physics

$\mathbf{m_{jj}} = 4.7 \text{ TeV}$

$\mathbf{p_T^{j}} = 2.3 \text{ TeV}$

$\mathbf{E_T^{\text{miss}}} = 47 \text{ GeV}$
Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

Example: The di-jet cross sections as a function of the jet $P_T$ in rapidity bins

Deviations from QCD at large $p_T$ could hint at substructure inside the quarks (remember the famous Rutherford scattering ~ 100 years ago)
Standard Model Physics

Candidate $Z \rightarrow \mu^+\mu^-$

$W \rightarrow e\nu$ candidate

Today each ATLAS and CMS have in their data more than:

- 100 M $W \rightarrow \mu\nu, e\nu$ events
- 10 M $Z \rightarrow \mu\mu, ee$ events

after all selection cuts

LHC roadmap to the Higgs
Z and W production

Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$
Cross section measurements

\[ \sigma \times B \ [\text{nb}] \]

- CMS, 18 pb\(^{-1}\), 8 TeV
- CMS, 36 pb\(^{-1}\), 7 TeV
- CDF Run II
- D0 Run I
- UA2
- UA1

Theory: NNLO, FEWZ and MSTW08 PDFs

Center-of-mass energy [TeV]


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Jenni (Freiburg and CERN)
LHC roadmap to the Higgs
Inclusive $t\bar{t}$ cross section [pb]

ATLAS+CMS Preliminary

July 2014

TOPLHCWG

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004

$m_{t\bar{t}} = 172.5$ GeV, PDF $\pm \alpha_s$ uncertainties according to PDF4LHC


JHEP 02 (2014) 024

LHC roadmap to the Higgs
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics.
Very happy faces after the announcement of the discovery on 4th July 2012 at CERN and at ICHEP Melbourne
Candidate for a $H \rightarrow \gamma\gamma$ event
- Small cross-section: $\sigma \sim 40 \text{ fb}$
- Expected S/B ~ 0.02
- Simple final state: two high-$p_T$ isolated photons
- Main background: $\gamma\gamma$ continuum (irreducible) and fake $\gamma$ from $\gamma j$ and $jj$ events (reducible)
- Small cross-section: $\sigma \sim 40 \text{ fb}$
- Expected S/B $\sim 0.02$
- Simple final state: two high-$p_T$ isolated photons
- Main background: $\gamma\gamma$ continuum (irreducible) and fake $\gamma$ from $\gamma j$ and $jj$ events (reducible)

CMS

$H \rightarrow \gamma\gamma$

$S/(S+B)$ weighted sum

- Data
- $S+B$ fits (weighted sum)
- B component
- $\pm 1\sigma$
- $\pm 2\sigma$

$\mu = 1.14^{+0.26}_{-0.23}$

$\hat{m}_H = 124.70 \pm 0.34 \text{ GeV}$

B component subtracted

arXiv:1407.0558v1[hep-ex]
sub. to Euro. Phys. Jour. C
Candidate for a $H \rightarrow ZZ^* \rightarrow \mu\mu \mu\mu$ event
**H → ZZ(*) → 4l (4e, 4μ, 2e2μ)**

- Rare process, small cross section: \( \sigma \sim 2\text{-}5 \text{ fb} \)
- However: pure: \( S/B \sim 1 \)
- 4 leptons:
- Main background: \( ZZ(*) \) (irreducible)
  - In addition: \( Zbb, Z+jets, tt \) with two leptons from b-quarks or jets

**ATLAS**

\[ H \rightarrow ZZ^* \rightarrow 4l \]

- \( \sqrt{s} = 7 \text{ TeV} \), \( \mathcal{L} = 4.5 \text{ fb}^{-1} \)
- \( \sqrt{s} = 8 \text{ TeV} \), \( \mathcal{L} = 20.3 \text{ fb}^{-1} \)

- Data
- Signal (\( m_h = 125 \text{ GeV} \), \( \mu = 1.51 \))
- Background \( ZZ^* \)
- Background \( Z+jets, t\bar{t} \)
- Systematic uncertainty

**CMS**

\[ \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1}; \sqrt{s} = 8 \text{ TeV}, L = 19.7 \text{ fb}^{-1} \]

- Data
- \( m_{H} = 126 \text{ GeV} \)
- \( Z\gamma^*, ZZ \)
- \( Z+X \)

- \( D_{\text{inv}}^\text{bin} > 0.5 \)

**Graphs**

- **ATLAS** and **CMS** graphs showing event counts and mass distributions.

**References**

- Phys. Rev. D89 (2014) 092007
https://indico.cern.ch/event/343941/

Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET
How significant is the signal for the new particle?

Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs signal:

- **Mass**
  - ATLAS: $125.36 \pm 0.37$ (stat) $\pm 0.18$ (syst) GeV
  - CMS: $125.03 \pm 0.26$ (stat) $\pm 0.14$ (syst) GeV

- **Signal strength**
  - $\mu = 0$ background only hypothesis
  - $\mu = 1$ SM Higgs hypothesis

- ATLAS: $1.30 \pm 0.18$
- CMS: $1.00 \pm 0.13$
Is the new particle a Higgs boson?

1) To accomplish its job (providing mass) it interacts with other particles (in particular W, Z) with strength proportional to their masses.

2) It has spin zero (scalar).

‘ATLAS and CMS have verified the two main fingerprints for a Higgs …’ (F Gianotti)

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Rejection (C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^-</td>
<td>97.8%</td>
</tr>
<tr>
<td>1+</td>
<td>99.97%</td>
</tr>
<tr>
<td>1^-</td>
<td>99.7%</td>
</tr>
<tr>
<td>2+</td>
<td>99.9%</td>
</tr>
</tbody>
</table>
Birth and evolution of a signal: $H \rightarrow 4l$

$\sqrt{s} = 7$ TeV $\int Ldt = 0.05$ fb$^{-1}$ Apr 24, 2011

**ATLAS** Preliminary
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel

- Signal ($m_H = 125$ GeV)
- Background $ZZ^{(*)}$
- Background $Z+\text{jets, } t\bar{t}$
- Data

Data - Background

**LHC roadmap to the Higgs**

60yCERN, 9-Oct-2014
P Jenni (Freiburg and CERN)
Searches Beyond the Standard Model
(just an example out of very many…)
Dark Matter in the Universe

Astronomers found that most of the matter in the Universe must be invisible Dark Matter.

‘Supersymmetric’ particles?
Searches for heavy W and Z like particles

These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs

W': Lepton + ETmiss


Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons

\[ \sigma B \text{ [pb]} \]

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

\[ G^* \rightarrow \ell \ell \]

--- Expected limit

- Expected ± 1σ
- Expected ± 2σ

Observed limit

\[ k/M_{Pl} = 0.1 \]
\[ k/M_{Pl} = 0.05 \]
\[ k/M_{Pl} = 0.03 \]
\[ k/M_{Pl} = 0.01 \]

\[ ee: \int L dt = 20.3 \text{ fb}^{-1} \]
\[ \mu\mu: \int L dt = 20.5 \text{ fb}^{-1} \]


R Sundrum
L Randall
F Gianotti

LHC roadmap to the Higgs
First signs of new physics could also come from accurate measurements of clean processes for which the Standard Model makes very precise predictions.

Measured deviations could indicate that something more than just the known SM processes are at play.
CMS 95% CL exclusion limits (in TeV units)

Similar results exist from ATLAS
LHC Schedule and Upgrade

2009
LHC start-up $\sqrt{s} = 900\text{GeV}$

2010
$\sqrt{s} = 7\text{TeV}$ rising to $8\text{TeV}$, $\mathcal{L} = 6 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$, bunch spacing 50ns

2013
Go to design energy and nominal luminosity

2015
$\sqrt{s} = 13\text{–}14\text{TeV}$, $\mathcal{L} = 1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, bunch spacing 25ns

2018

2020
LS2
Injector and LHC Phase-I upgrade to full design luminosity

2022
LS3
HL-LHC Phase-II upgrade, crab cavities, new IR, ...

2025
$\sqrt{s} = 14\text{TeV}$, $\mathcal{L} = 2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, bunch spacing 25ns

... 2035

3000 fb$^{-1}$

~20 fb$^{-1}$

≥50 fb$^{-1}$

≥300 fb$^{-1}$

LHC roadmap to the Higgs
It was a very long road from first dreams to the fantastic scientific instrument we have now with the LHC and its experiments, and many visionaries deserve credit for it…

Herwig Schopper, CERN DG 1981 - 1988

Carlo Rubbia, CERN DG 1989 - 1993
Giorgio Brianti, first LHC Project Leader, until 1993

Sir Chris Llewellyn Smith, CERN DG 1994 - 1998
Lorenzo Foa († 2014), Research Director 1994 - 1998
Lyn Evans, LHC Project Leader 1994 - 2008
CERN Council President 1994 – 1996 Hubert Curien (here with Japanese Minister Kaoru Yosano and DG Christopher Llewellyn Smith, June 1995)
Luciano Maiani, CERN DG 1999 - 2003
Roger Cashmore, Research Director 1999 – 2003

Robert Aymar, CERN DG 2004 - 2008
Jos Engelen, Research Director 2004 - 2008

Rolf Dieter Heuer, CERN DG since 2009
Sergio Bertolucci, Research Director since 2009
Steve Myers, Director of Accelerators and Technology 2009 – 2013
(here shown together with the ATLAS and CMS Spokespersons Fabiola Gianotti and Joe Incandela, on the famous 4th July 2012)
The journey into new physics territory has just only begun, and for sure, exciting times are ahead of us!

LHC has been a great topic for 30 years now, from first dreams to a first discovery, half of CERN age...

Thank you for your attention.
Further reading:

The Higgs Boson

ARTICLE

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider

M. Della Negra, 1 P. Jenni, 2 T. S. Virdee 2*

The search for the standard model Higgs boson at the Large Hadron Collider (LHC) started more than two decades ago. Much innovation was required and diverse challenges had to be overcome during the conception and construction of the LHC and its experiments. The ATLAS and CMS Collaboration experiments at the LHC have discovered a heavy boson that could complete the standard model of particle physics.

http://www.sciencemag.org/content/338/6114/1560.full.html

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider
M. Della Negra et al.
Science 338, 1560 (2012);
DOI: 10.1126/science.1230827