The Higgs boson and our life

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2013 Physics Nobel Prize
CERN : European Organization for Nuclear Research
The world’s largest particle physics laboratory

60 years of:

- fundamental research and discoveries (and Nobel prizes …)
- technological innovation and technology transfer to society (e.g. the World Wide Web)
- training and education (young scientists, school students and teachers)
- bringing the world together (1100 scientists from > 60 countries)
CERN was founded 1954: 12 European States
Today: 21 Member States

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

States in accession to Membership: Romania, Serbia

Applicant States for Membership or Associate Membership:
Brazil, Croatia, Cyprus, Pakistan, Russia, Slovenia, Turkey, Ukraine

Observers to Council: India, Japan, Russia, Turkey, United States of America, European Commission and UNESCO

~ 2300 staff, ~ 1600 other paid personnel
~ 11000 users

Budget (2014) ~1000 MCHF (on average: 1 cappuccino/European citizen):
each Member State contributes in proportion to its income
(CH: ~ 2.5%, ~25 MCHF)
About 11000 users from > 60 countries
CERN’s primary mission is SCIENCE

Study the elementary particles (e.g. the building blocks of matter: electrons and quarks) and the forces that control their behaviour at the most fundamental level

Particle physics at modern accelerators allows us to study the fundamental laws of nature on scales down to smaller than $10^{-18}$ m → insight also into the structure and evolution of the Universe → from the very small to the very big ...
Evolution of the Universe

Big Bang

13.7 Billion Years

10^{28} cm

Today
To study the elementary particles and their interactions:

We accelerate two beams of particles (e.g. protons) close to the speed of light and make them collide.

The colliding protons “break” into their fundamental constituents (e.g. quarks).

These constituents interact at high energy:

- study the way fundamental matter behave
- (new) heavy particles can be produced in the collision ($E=mc^2$). The higher the accelerator energy, the heavier the produced particles can be. These particles then decay into lighter (known) particles: electrons, photons, etc
- reproduce the temperature (~$10^{16}$ K) of the Universe a few instants ($10^{-11}$ s) after the Big Bang.
The Large Hadron Collider (LHC) at CERN

- the most powerful accelerator

- and also ....

- the most high-tech and complex detectors
- the most advanced computing infrastructure
- the most innovative concepts and technologies (cryogenics, new materials, electronics, data transfer and storage, etc. etc...)
- the widest international collaborations

ever achieved in accelerator particle physics.
One of the most ambitious projects in science in general.

- > 25 years from concept to start of operation
- Operation started 20 November 2009
- First data-taking period: April 2010-February 2013
The LHC is a 27 km ring, 100 m below ground, across France/Switzerland
2010-2013: two high-energy proton beams have been circulating in opposite directions, colliding at 4 points, where 4 big experiments had been installed.
Unprecedented collision energy: 8 TeV, 4 times larger than previous collider (Tevatron Fermilab)
Starting in 2015: reach design collision energy of ~14 TeV

Most challenging component: 1232 high-tech superconducting magnets, providing 8.3 T field (to bend 7 TeV beams inside a 27 km ring).
Made of 7600 km of NbTi superconducting cable
On 4th July 2012, ATLAS and CMS announced the discovery of a new particle (Higgs boson).

Switzerland (Universities of Bern, Geneva and Zürich, ETHZ, EPFL, PSI) and CERN have contributed in a very crucial way to the four experiments and the accelerator.
LHC detectors: a big jump in concepts and technologies

- **Size (length 45m, diameter 25m):**
  - to measure and absorb high-energy particles
- **10^8 sensors (providing “individual signals”):**
  - to track ~1000 particles per event and reconstruct their trajectories with ~10 μm precision (1 μm = 10^-6 m)
- **Fast response (~50 ns, 1 ns = 10^-9 s):**
  - 40 million beam-beam collisions per second

Human beings

Giant ultra-fast “digital camera”
~ 3000 scientists from 177 Institutions and 38 Countries

Switzerland:
- 2 Universities (Bern, Geneva): ~ 45 scientists (~ 20 students)
- Very strong contributions to detector construction, operation and now upgrade, software and computing, physics analysis
Age distribution of the ATLAS population

More than 1000 PhD students

- **All**: 2690 (under 35 y: 47.2%)
- **Male**: 81.8% (under 35 y: 44.0%)
- **Female**: 18.2% (under 35 y: 61.3%)

(Status 1.1.2010)
Computing

Each LHC experiment produces ~ 10 PB of data per year. 1 PB = 10^6 GB. This corresponds to ~ 20 million DVD (a 20 km stack ...)

Data analysis requires computing power equivalent to ~100 000 today’s fastest PC processors.

The experiment international Collaborations are spread all over the world → computing resources must be distributed.

Cooperation of many computer centres all over the world is needed.
The Grid provides seamless access to computing power and data storage capacity distributed over the globe.

Worldwide LHC Computing Grid (WLCG): ~ 160 computing centres
~ 35 countries

Switzerland:
CERN Tier-0
Tier-2 in Manno

~350k CPU cores
~170 PB disk
Number of turns of the LHC ring made by protons in one second: ~ 11000

Number of beam-beam collisions per second at design operation: 40 million
Beam cross section at the collision point: 16 μm (~ 4 times smaller than that of a typical human hair)

Magnets work at 1.9K (~ -271 degrees C) → LHC is cooler than outer space

Energy stored in the beams (~350 MJ): like a British aircraft carrier at 12 knots

The CMS experiment weighs more (13000 tons) and contains more iron than the Tour Eiffel

3000 km of cables used to transfer the signals from the ATLAS detector to the control rooms

Each LHC experiment produces ~ 10 PB of detector data per year (1 PB = 10^6 GB)
This corresponds to ~ 20 million DVD (a 20 km stack ...)

Cost: ~ 8000 MCHF

Etc. etc.
The elementary particles and their interactions are described by a very successful theory: the **Standard Model**. All particles foreseen by the SM have been observed, and the SM predictions have been verified with extremely high precision over the last 35 years by experiments at CERN and other labs all over the world.
Several outstanding questions in fundamental physics ...

What is the origin of the elementary particle masses?
Related to the Higgs boson ✔

What is the nature of the Universe dark matter?

Why is there so little antimatter in the Universe?
(Nature’s favouritism allowed us to exist …)

What are the features of the primordial plasma permeating the Universe \( \sim 10 \mu s \) after the Big Bang?

What happened in the first moments of the Universe life \( (10^{-11} \text{ s} \) after the Big Bang)?

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

Etc. etc.

LHC built to address these and other fundamental questions
What is the origin of the particle masses?

Photon is massless (pure energy), W and Z bosons have x 100 proton mass
Mass of top quark (heaviest elementary particle observed) ≈ mass of Gold atom
Electron mass is ~350000 times smaller

WHY ???

Proposed explanation (Brout, Englert, Higgs et al., 1964),
“Brout-Englert-Higgs mechanism”: origin of masses
~ 10^{-11} s after the Big Bang, when “Higgs field” became active → particles acquired masses proportional to the strength of their interactions with the Higgs field

Consequences: existence of a Higgs boson
This particle has been searched for > 30 years at accelerators all over the world
→ finally found at the LHC!

The 1st link to our life

Note: world without the BEH mechanism would be very strange
Atoms may not exist, and the Universe would be very different
Once produced the Higgs boson is expected to decay into known particles, for instance into two photons → looked at the $\gamma\gamma$ spectrum in our data.

What did we observe?

Peak ("resonance") at $m_{\gamma\gamma}$ around 125 GeV (~130 x proton mass) indicates the production of a (new) heavy particle.
Once produced the Higgs boson is expected to decay into known particles, for instance into two photons \( \rightarrow \) looked at the \( \gamma\gamma \) spectrum in our data

\( \gamma\gamma \) data

- It was not easy to find: one detectable Higgs particle produced every \( 10^{12} \) pp collisions
  \( \rightarrow \) required ingenuity and a huge amount of meticulous experimental work
    (in large part made by young people)
- As of today, each experiment has recorded about 700 Higgs events
  (out of 5 billion events total)

Peak ("resonance") at \( m_{\gamma\gamma} \) around 125 GeV (\(~130 \times \) proton mass) indicates the production of a (new) heavy particle
Both experiments have shown since then that the new particle is consistent with a Higgs boson.
Will the Higgs boson change our life? It did already!

Extreme performance required in particle and nuclear physics → cutting-edge technologies developed at CERN and collaborating Institutes, and then transferred to society.

Applications: medical imaging (e.g. PET), cancer therapy, materials science, airport scanners, cargo screening, food sterilization, nuclear waste transmutation, analysis of historical relics, etc. ...not to mention the GRID-based computing and the WEB ..

Hadron Therapy

Accelerating particle beams
~30'000 accelerators worldwide
~17'000 used for medicine

>100000 patients treated worldwide (45 facilities)
>50000 in Europe (14 facilities)

The 2nd link to our life

Imaging
e.g. PET scanner

Detecting particles
CERN and the LHC

- Seeking answers to fundamental questions about elementary particles and the Universe → a new era has started with the exploration of an unprecedented energy scale at the LHC and the discovery of a Higgs boson: a big step forward in fundamental science
- Training: students, high-school teachers, young scientists
- Advancing the frontiers of technology, also to the benefit of other fields and society
- Promoting diversity (gender, age, ethnicity, ...) as a strength and asset for a richer and more stimulating environment, better science and peace
SPARES
Birth and evolution of a signal

**CMS:** $H \rightarrow 4l$

**ATLAS:** $H \rightarrow l\nu l\nu$

In Dec 2012, CMS used data at $\sqrt{s} = 7$ TeV with a luminosity of 5.1 fb$^{-1}$ and at $\sqrt{s} = 8$ TeV with a luminosity of 19.6 fb$^{-1}$ to analyze the signal $m_H = 126$ GeV. The plot shows $m_{4l}$ with the data points and contributions from various processes such as $Z\gamma^*, ZZ$, and $Z+X$.

For ATLAS, the analysis at 06.04.2012 included the process $H \rightarrow WW'^{(*)} \rightarrow e\nu\mu\nu$ with 0/1 jets. The plot illustrates the distributions in $m_\tau$ and $m_{4l}$ with different signal contributions highlighted, including data, $WW$, $WZ/ZZ/W\gamma$, $t\bar{t}$, single top, $Z+\text{jets}$, and $W+\text{jets}$, with a focus on the $H$ signal with a mass of 125 GeV.
Unprecedented energy: 4 TeV per beam particle \(\rightarrow\) collision energy = 8 TeV

(1 TeV = 10^{-7} \text{ Joule})

2015 \(\rightarrow\) collision energy to \(\sim \) 14 TeV

Note: huge amount of energy concentrated in the collision point

(14 TeV corresponds to \(10^{14}\) times the temperature in this room)

However: small energy on macroscopic scale (1 \(\mu\)Joule is just enough to swat a mosquito)

The most challenging components of the LHC are 1232 high-tech superconducting magnets, providing a field of 8.3 T (needed to bend 7 TeV beams inside a 27 km ring).

7600 km of NbTi superconducting cable

Work at 1.9K (-271 degrees)

Built by 3 leading European industries: Alstom (France), Ansaldo (Italy), Babcock-Noell (Germany)

Electrical power to run the LHC (from French EDF): \(~\)200 MW
Business emails sent 3000PB/year (Doesn’t count; not managed as a coherent data set)

Google search 100PB

Facebook uploads 180PB/year

LHC data 15PB/yr

US Census

Climate DB

Nasdaq

YouTube 15PB/yr

Kaiser Permanente 30PB

In 2012: 2800 Exabytes created or replicated
1 Exabyte = 1000 PB

Total (2010-2013) ATLAS data (including simulated data): 140 PB

Imagine a room full of people quietly chattering ... this is like space filled only with the Higgs field ...
a well known actor walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step ... the actor is like a particle traversing the Higgs field
this increase his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field ...
Imagine now that a rumour crosses the room ... it creates the same kind of clustering, but this time among the people in the room. In this analogy, these clusters are the Higgs particle.