Le CERN et le LHC: les buts de physique et les enjeux scientifiques et technologiques

Fabiola Gianotti, CERN, Physics Department
More than 50 years of:

- fundamental research and discoveries (and Nobel prizes in Physics...)
- technological innovation and technology transfer to society
- training and education (young scientists, teachers, school students)
- bringing the world together
A bit of history ...

1952 To restore European science after the war, 11 European countries agree to set up a provisional “Conseil Européen pour la Recherche Nucleaire” (CERN). The Geneva region is selected as the site for the planned laboratory.

1954 The European Organization for Nuclear Research is founded by 12 countries (the provisional Council is dissolved but the CERN acronym is retained). CERN becomes one of the first examples of post-war (scientific) cooperations.

24 February 1955: 1st meeting of the CERN Council

19 October 2004 CERN celebrates 50 years!
CERN today

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| Plus eight Observer States: | European Commission, India, Israel, Japan, Russian Federation, Turkey, UNESCO and USA |

| Budget: | ~1000 MCHF (650 M Euro): each member states contributes in proportion to its income. E.g. France contributes ~15%, but as host country has a return factor of up to 4. |

The Council is the highest authority and has the ultimate responsibility for all important decisions. It controls CERN’s activities in scientific, technical and administrative matters.

CERN's budget pays for the provision and maintenance of the accelerators and facilities used by the research community and the salaries of the 2600 CERN staff.
2600 staff, 770 Fellows and Associates, 7500 users (Oct 2006)

Distribution of All CERN Users by Nation of Institute on 12 October 2006

Thanks also to IN2P3!
CERN primary mission is science

Understand the fundamental laws of nature by studying the elementary particles (the “building blocks” of matter like electrons and quarks) and their interactions.

Particle physics allows us to understand also the evolution and the structure of the Universe (see later) → from the infinitely small to the infinitely big

“Les deux infinis” de Michel Spiro (CS CNRS, 22-23/11/2006) ...
To study 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:

⇒ we can 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 could be. These particles then decay into lighter (known) particles: electrons, photons, etc.

By placing high-tech powerful detectors around the collision point we can detect the collision products and reconstruct what happened in the collision (which phenomena, which particles and forces involved, etc.)
Therefore, we need:

**Accelerators**: underground tunnels (usually rings) containing electric fields to accelerate particles to very high energy (incrementally at each turn), and magnets to bend the beams inside the ring and bring them into collision.

**Powerful giant microscopes to explore the smallest constituents of matter!!**

**Detectors**: massive instruments which register the collision products and allow to identify the produced particles and measure their energy and trajectory.

**Computing**: to store, distribute and analyse the vast amount of data produced by the detectors and thus reconstruct the “event” occurred in the collision.
The **Large Hadron Collider (LHC)** being built at CERN

- the most powerful accelerator
- and also ....
- the most powerful detectors
- the most powerful computing infrastructure
- the widest international collaboration
- the most innovative concepts and technologies
  (cryogenics, rad-hard materials, electronics, data transfer and storage, etc. etc...)

ever achieved in particle physics,
and one of the most ambitious projects in science more in general

**Operation will start in November 2007**
A 27 km accelerating ring, 100 m underground, across French-Swiss border (used until the year 2000 by the LEP e+e− Collider)
Two proton beams will be accelerated in opposite directions up to speed of light. They will collide at four points, where four big experiments are being installed.
Four big experiments will detect the collision products: ATLAS, CMS, LHCb, ALICE
Unprecedented energy: 7 TeV per beam particle → collision energy = 14 TeV

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

Note: a football with the same energy would be moving at 90000 Km/hour
7 TeV corresponds to 10 1-Volt batteries for each star of our galaxy and
to 10^{14} times the temperature in this room

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). They work at 1.9K (-270 degrees)

Built by 3 European industries: Alstom/France, Ansaldo/Italy, Babcock-Noell/Germany

Energy stored in the beams: 350 MJoule (like a TGV at full speed; can melt 500 kg of Cu)
Electrical power to run the LHC (from EDF): 130 MW
(Note: ~same power needed for LHC Computing !)
Detectors for accelerator-based particle physics

Cover (almost) the full solid angle around the collision point to detect as many particles produced in the collision as possible.

A sketch of the CMS detector
Detectors are giant digital cameras which take pictures of the pp collisions at a rate of 40 million per second. Typically 100 pictures/second are recorded. Sophisticated software techniques are used to reconstruct the particle trajectories from the signals left in the various detector elements and hence obtain a “picture of the full event”. The origin of the event (which new particle or phenomenon has produced it) can then be studied.

The results of a simulated pp collision in the ATLAS detector (transverse view)
One example: the ATLAS detector

LHC detectors are much more complex, performing and challenging than those at previous/present accelerators → a big jump in concepts and technologies

- Size (length 45m, diameter 25m): to measure and absorb high-energy particles
- $10^8$ electronic channels (“individual signals”): to track ~1000 particles per event
- Fast response (~50 ns): 40 million beam-beam collisions per second ($1 \text{ ns} = 10^{-9} \text{ s}$)
- Radiation hard: up to $10^6$ Gy in the hottest regions after 10 years of operation
- Collaboration: ~1800 physicists, 164 Institutions/Universities, 35 countries from 5 continents
Eight big (25m long, 100 tons each) superconducting coils surround the central calorimeters (CNRS/IN2P3 labs: Annecy, Clermont, Grenoble, LAL/Orsay, Paris VI-VII)

The ATLAS underground cavern in Oct. 2005
The core of ATLAS: the Pixel detector

- 3 layers at ~5cm, 10cm, 13cm from the beam line
- made of ~80 million high-tech Si pixels 50\,\mu m wide, 400\,\mu m long, 250\,\mu m thick (0.25\,\mu m CMOS technology)

Each one of these modules contains ~45000 pixel sensors
30 November 2006: lowering a slice (400 tons) of the CMS detector in the underground cavern through the access shaft
One of the ATLAS end-cap calorimeters being moved to its final position
Computing

The LHC experiments will produce 10-15 PB of data per year. 1 PB = $10^6$ GB (~ 1 billion events/year recorded, each event has ~ 100 000 signals)
This corresponds to ~ 20 million CD (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 (CERN provides ~20% of the resources)
• The **World Wide Web** provides seamless access to information that is stored in many millions of different geographical locations.

• The **Grid** provides seamless access to computing power and data storage capacity distributed over the globe.

• The **LHC Computing Grid (LCG)** relies on grid infrastructure provided by **EGEE** = Enabling Grids for E-sciencE and **OSG** = US Open Science Grid.

A map of the worldwide LCG infrastructure operated by EGEE and OSG.

~120 computing centers
~40 countries
LCG computing centres: hierarchical structure by Tiers:

- 1 Tier-0: the biggest/central centre: CERN
- 11 Tier-1: large centres (e.g. CC-IN2P3/CNRS de Lyon)
- ~40 Tier-2: federations of smaller centres
LCG resources at Lyon Tier-1 (2007 → 2010):
Disk: ~ 1.6 → 8 PB
Tape: ~ 1.5 → 10 PB
CPU: ~ 2000 → 12000 of today’s fastest processors
This is ~5% of total LCG resources

Fabiola Gianotti, CS CNRS
The LHC Computing Grid has been the driving force for EGEE (most of the EGEE hardware resources do actually come from LCG)

- EGEE is now a global effort, and the largest Grid infrastructure world-wide: > 180 sites, 40 countries, >24000 processors, ~ 5 PB storage
- Co-funded by the European Commission (~130 M€ over 4 years)
- EGEE already used for > 20 applications, e.g. Astrophysics, Chemistry, Earth Science (climate, ...), Finance, Fusion, Geophysics, Life sciences (medical imaging, drug discovery), Particle physics, etc.
A few more numbers related to the LHC.....

Number of turns of the LHC ring made by protons in one second: ~ 11000

Number of proton-proton interactions per second: 1 billion

Number of particles produced per collision: more than 1000

Machine temperature: 1.9 k (-271 degrees)
The largest cryogenic system in the world, cooler than outer space....

Weight of CMS experiment: ~ 13000 tons (30% more than the Tour Eiffel)

Amount of cables used to transfer the detector signals in ATLAS: ~ 3000 km

Data collected by CMS in 1 second: equivalent to 10000 Encyclopedia Britannica

Total cost (accelerator plus experiments): ~ 5000 MCHF
WHY ???
The elementary particles and their interactions are described by a theory (the **Standard Model**) which has been verified with extremely high precision over the last 35 years by experiments at CERN (e.g. LEP) and other labs all over the world.
However, several open questions and mysteries remain…

What is the origin of the particle masses?

What is the nature of the Universe dark matter?

What is the origin of the Universe matter-antimatter asymmetry?

What are the constituents of the Universe primordial plasma ~10 µs after the Big Bang?

What happened in the first instants of the Universe life (10⁻¹⁰ s after the Big Bang)?

Etc. etc.

The LHC will help solve these and other mysteries … and . . . determine the future course of accelerator-based particle physics.
What is the origin of the particle masses?

Mass of top quark (heaviest elementary particle observed) ≈ mass of Gold atom
Electron mass is 300,000 times smaller than top-quark mass
WHY ???

The mass mystery could be solved by the “Higgs mechanism”, which predicts the existence of a new elementary particle: the Higgs particle

This particle has been searched for 20 years at accelerators all over the world and has not been observed yet.
The LHC has sufficient energy/intensity to produce it.

Note: a world without “Higgs” would be a very strange one! Atoms (and thus all of us) would not have the size they have, the neutron could be lighter than the proton, chemistry may not exist, etc.
What is the nature of the Universe’ Dark Matter?

Recent astrophysical measurements indicate that the Universe is made of:
- 5% of known matter
- 25% of “dark matter” (no known particle can explain it)
- 70% of “dark energy”

Today we understand only 5% of the Universe composition.

Supersymmetry (a particle physics theory) predicts new (heavy) elementary particles, not yet observed. Among them the neutralino, our present best candidate for the Universe dark matter (its predicted features are in agreement with astrophysics observations and cosmological predictions).
It is expected to be light enough to be abundantly produced at the LHC!
Back in time toward the Universe first instants ….

Universe cools down and energy density decreases with time

LHC energy corresponds to the Universe energy \( \sim 10^{-10} \text{ s} \) after the Big Bang

\[ \rightarrow \text{we expect to observe/reproduce in the lab similar phenomena as at that time } \]

\[ \rightarrow \text{SURPRISES ???} \]

Les deux infinis de M.Spiro….
## CNRS/IN2P3 contribution to the LHC experiments

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<th>ALICE</th>
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<td>79</td>
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<td>3</td>
<td>5</td>
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<td>N. of CNRS/IN2P3 labs</td>
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<td>Financial contribution (MCHF) to construction (material)</td>
<td>~8%</td>
<td>4.5%</td>
<td>~11%</td>
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<tr>
<td>% of experiment cost</td>
<td>~8%</td>
<td>4.5%</td>
<td>~11%</td>
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- **Original ideas and high-tech contributions to the detectors** (e.g. the ATLAS electromagnetic calorimeter)
- **Strong involvements also in software and computing developments**
- ~5% contribution to LCG resources
- **Intense initiatives for international cooperations** (e.g. with Vietnam, China, Korea, …)
- **Management and responsibility positions in the experiment organizations**

Note: big contributions also from CEA/Saclay

**CNRS/IN2P3 is in excellent position to capitalize on the investments and exploit in the best way the LHC data and physics**
Technology transfer and spin-offs: from fundamental science to everyone’s life

Ultimate performance is required in particle physics → leading-edge technologies (accelerators, detectors, electronics, ...) developed at CERN and collaborating Institutes. Used for huge number of applications: medical and industrial imaging (e.g. PET), cancer therapy, materials science, X-ray lithography, ion implantation for artificial hips, airport scanners, etc. Not to mention the WEB and the GRID ...

Radiography of a bat, recorded with a GEM detector

Radio-isotope production for medical applications

Hadrotherapy for cancer treatment
CERN and the LHC

- Seeking answers to fundamental questions about elementary particles and the Universe. A new era (of discoveries ?) will start with the exploration of the TeV energy scale at the LHC
- Advancing the frontiers of technology (also to the benefit of society)
- Training the scientists of tomorrow
- Bringing nations together through science

"Nati non fummo a viver come bruti ma per seguir virtute et conoscenza", Dante Alighieri (1265-1321), Divina Commedia, Inferno, Canto XXVI

“What we know is a droplet, what we don’t know is an Ocean”, Isaac Newton (1643-1727)
SPARE SLIDES
Data Handling and Computation for Physics Analysis

event filter (selection & reconstruction)

reconstruction

reconstruction

processed data

analysis objects (extracted by physics topic)

interactive physics analysis

interative physics analysis

analysis

batch physics analysis

event reprocessing

event summary data

event reprocessing

raw data

event simulation

detector

simulation
EGEE: Steady growth over the lifetime of the project

> 180 sites, 40 countries
> 24,000 processors,
~ 5 PB storage

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• The Collaboration
  – 4 LHC experiments
  – ~120 computing centres
  – 12 large centres
    (Tier-0, Tier-1)
  – ~40 federations of smaller
    “Tier-2” centres
  – ~30 countries
• Memorandum of Understanding
  – Agreed in October 2005, now being signed
• Resources
  – Commitment made each October for the coming year
  – 5-year forward look
There are four fundamental forces that keep matter together:

3. **Weak Force** - Involved in beta decay and is responsible for radioactive decay. Exchanged particles: Z\(^0\), W\(^+\), W\(^-\) (W bosons). Observed in sun (\(\beta^+\) decay) and atomic levels (\(\beta^-\) decay).

The exchange of particles is responsible for the force.
How would a Higgs particle appear in the experiments?

One example...

\[ H \rightarrow \mu\mu\mu\mu \]
\[ m_H = 150 \text{ GeV} \]

+20 min bias