Exploring the mysteries of the Universe with the Large Hadron Collider (LHC)
More than 50 years of:

- fundamental research and discoveries (and Nobel prizes in Physics...)
- 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

CERN : European Organization for Nuclear Research
The world’s largest particle physics laboratory

CERN staff member T. Berners-Lee, inventor of the WEB

Samuel Ting, 1976 Nobel prize
Carlo Rubbia, 1984 Nobel prize
George Charpak, 1992 Nobel prize
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) cooperation.

24 February 1955: 1st meeting of the CERN Council

19 October 2004 CERN celebrates 50 years!
### Twenty Member States:

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<th>Austria</th>
<th>Belgium</th>
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### Plus eight Observer States:

European Commission, India, Israel, Japan, Russian Federation, Turkey, UNESCO and USA

### Budget:

\(~1000~ \text{MCHF} (~£ 500~ \text{M})\): each member state contributes in proportion to its income (e.g. UK \(~£ 78~ \text{M}, \sim \text{one cup of coffee/citizen})

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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 world-wide research community and the salaries of the \(~2500~ \text{employees}~\).
2600 staff, 770 Fellows and Associates, 7500 users (Oct 2006)
CERN’s 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 decipher the structure and evolution of the Universe (see later)

→ from the infinitely small to the infinitely big ...the two infinities...
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.

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 were involved, etc.)
Therefore, we need 3 things:

**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) 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, new materials, electronics, data transfer and storage, etc. etc...)

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

Operation starts this Summer
The LHC is a 27 km accelerator ring, 100 m below ground, across the French-Swiss border. Two proton beams will be accelerated in opposite directions up to speed of light. They will collide at four points, where four big experiments have been installed.
Four big experiments will detect the collision products: ATLAS, CMS, LHCb, ALICE

Groups from UK Universities (including Edinburgh and Glasgow) and laboratories have strongly contributed to the construction of the four experiments
Unprecedented energy: 7 TeV per beam particle $\rightarrow$ collision energy = 14 TeV

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

Note: huge amount of energy concentrated in the collision point
(14 TeV corresponds to 20 1-Volt batteries for each star of our galaxy and to $10^{14}$ times the temperature in this room)
However: small energy on macroscopic scale (1 µJoule 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 (-270 degrees)

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 French EDF): ~200 MW
Detectors for particle physics

Cover the whole angular range around the collision point to detect as many particles produced in the collision as possible.
Detectors are like 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 then used to reconstruct the particle trajectories from the signals left in the various detector elements and thus 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
- Fast response (~50 ns): 40 million beam-beam collisions per second (1 ns = 10^{-9} s)
- 10^8 electronic channels ("individual signals"): to track ~1000 particles per event
- 3000 km of cables to transfer the detector signals
- Radiation hard: up to 10^6 Gy in the hottest regions after 10 years of operation
- Collaboration: ~ 2100 physicists from 167 Institutions/Universities, from 35 countries from 5 continents (12 UK groups, ~ 220 physicists)
The ATLAS detector superimposed to a 5-storey building
The ATLAS underground cavern (-100 m) in Oct. 2005
Spectacular operations ... installing detector pieces in the underground cavern

October 2004

June 2007

250 tons = 1 Boeing 747
Computing

Each LHC experiment will produce ~ 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 all over the globe.

In Europe, the LHC Computing Grid (LCG) relies on grid infrastructure provided by EGEE (Enabling Grids for E-sciencE). GridPP in the UK (19 Universities, ~ £60M 2001-2011, PL: T. Doyle/Glasgow 2001-2007, now D. Britton/Glasgow, ~ 10000 CPU, ~10 PB)

LCG:
> 250 sites
~ 50 countries
~ 50 000 CPU
~ 30 PB
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: 240 sites, 45 countries, > 40000 processors, ~ 5 PB storage
- Co-funded by the European Commission
- 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.
Scottish contributions to the LHC: examples ...

- Durham, Edinburgh, Glasgow
- Supports Scottish research in growing number of disciplines
- ~1000 CPU, ~100 TB
- Funded by Scottish Funding Council

ATLAS Si strip detector (Glasgow)

LHCb RICH detector (Edinburgh)
ATLAS OVERVIEW WEEK
7-14 JULY 2007, Glasgow

Local Organising Committee:
S. Allwood  S. Ferrag
W. Bell  P. Negus
C. Buttar  V. O'Shea
D. Clements  K. Smith
C. Collins-Tooth  C. Wright

Sponsored by:
The City of Glasgow
CCLRC
The University of Glasgow

www.go-atlas.physics.gla.ac.uk
E-mail: go-atlas@physics.gla.ac.uk
Professor David Saxon, RSE, giving a lecture on Lord Kelvin’s life

A dancing session ....
A few more numbers ……

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

Number of beam-beam collisions per second: 40 million

Number of particles produced per collision: more than 1000
Trajectories reconstructed with ~10 µm precision (1 µm=10^-6 m)

Accelerator temperature: 1.9 K (cooler than outer space)

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

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

Data recorded by experiments in 1 year: 20 km of CD

Number of involved physicists: > 4000 (from the 5 continents!)

Total cost (accelerator plus experiments): ~ 6000 MCHF

The most ambitious project in particle physics ever and one of the most ambitious in science in general
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 and at 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 $\sim 10 \, \mu s$ after the Big Bang?

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

Etc. etc.

The LHC will help elucidate these and other fascinating mysteries ...
The biggest mystery and ... the most famous particle

What is the origin of the particle masses?

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

Postulated in 1964 by prof. Peter Higgs, FRS, FRSE, from University of Edinburgh
This particle has been searched for 20 years at accelerators all over the world and has not been observed yet.

The LHC has enough energy to produce the Higgs particle if it exists ....

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.

We are what we are because the elementary particles have the suitable masses
The Higgs boson in the LHC detectors

H → 4μ in the CMS detector

H → γγ in the CMS detector

H → 2μ2e in the ATLAS detector
Professor Higgs visiting ATLAS ... (4th April 2008)
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”

What is the nature of the Universe Dark Matter?

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 produced abundantly at the LHC!
Back in time towards the Universe’s very first moments .....  

Universe cools down and energy density decreases with time

LHC energy corresponds to the energy of the Universe \( \sim 10^{-10} \) s after the Big Bang \( \rightarrow \) we expect to observe and reproduce in the lab similar phenomena as at that time ...

The two infinities: the infinitely small (elementary particles) allow us to understand the infinitely big (the Universe)
Technology transfer and spin-offs: from fundamental science to everyone’s life

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

Radiography of a bat, recorded with a GEM detector

Applications: medical imaging (e.g. PET), cancer therapy, materials science, airport scanners, cargo screening, food sterilization, nuclear waste transmutation, etc. ... Not to mention the WEB and the GRID ...

Radio-isotope production for medical applications

Hadrontherapy 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 an unprecedented energy scale at the LHC
- Advancing the frontiers of technology (also to the benefit of society)
- Training (students, high-school teachers, young scientists)
- 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)