The CERN Large Hadron Collider

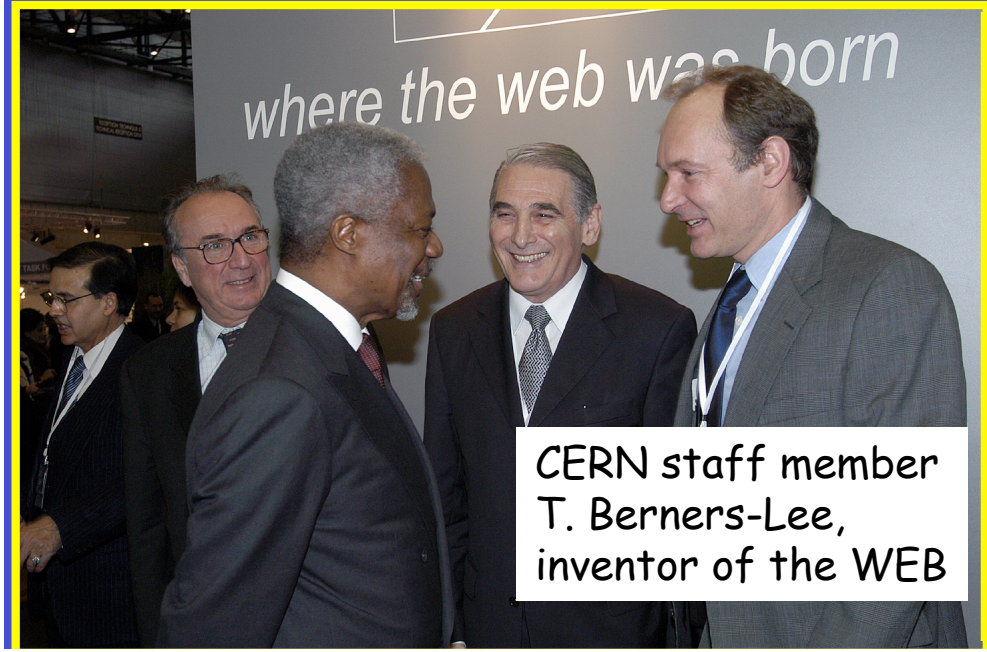
(an instrument to explore the mysteries of the Universe)

Fabiola Gianotti
CERN, Physics Department

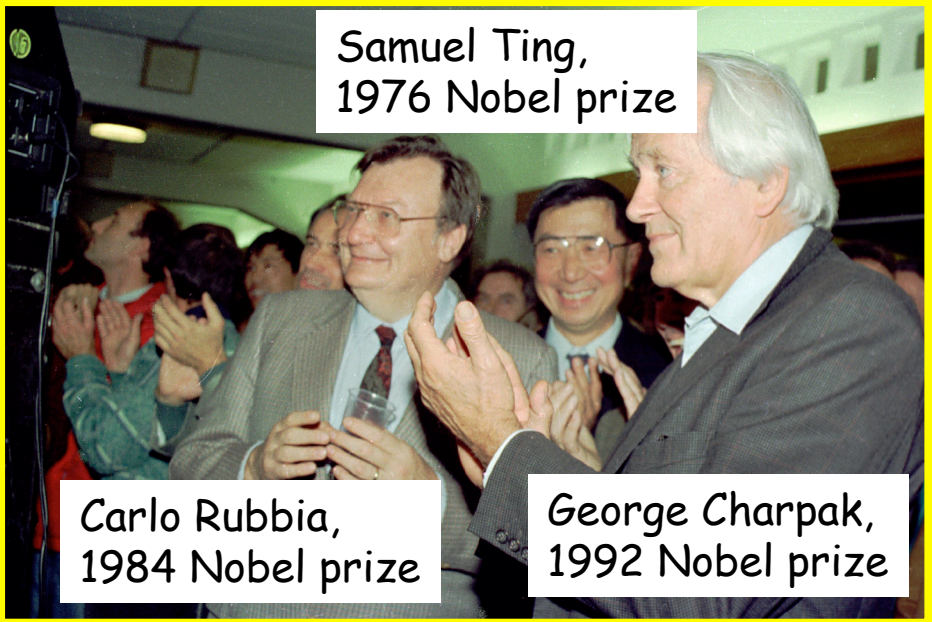
CERN : European Organization for Nuclear Research
The world's largest particle physics laboratory

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


Samuel Ting,
1976 Nobel prize

Carlo Rubbia,
1984 Nobel prize

George Charpak,
1992 Nobel prize

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) cooperation

24 February 1955:
1st meeting of the CERN Council

19 October 2004
CERN celebrates 50 years !

CERN today

Twenty Member States:

Austria	Belgium	Bulgaria	Czech Republic
Denmark	Finland	France	Germany
Greece	Hungary	Italy	Netherlands
Norway	Poland	Portugal	Slovak Republic
Spain	Sweden	Switzerland	United Kingdom

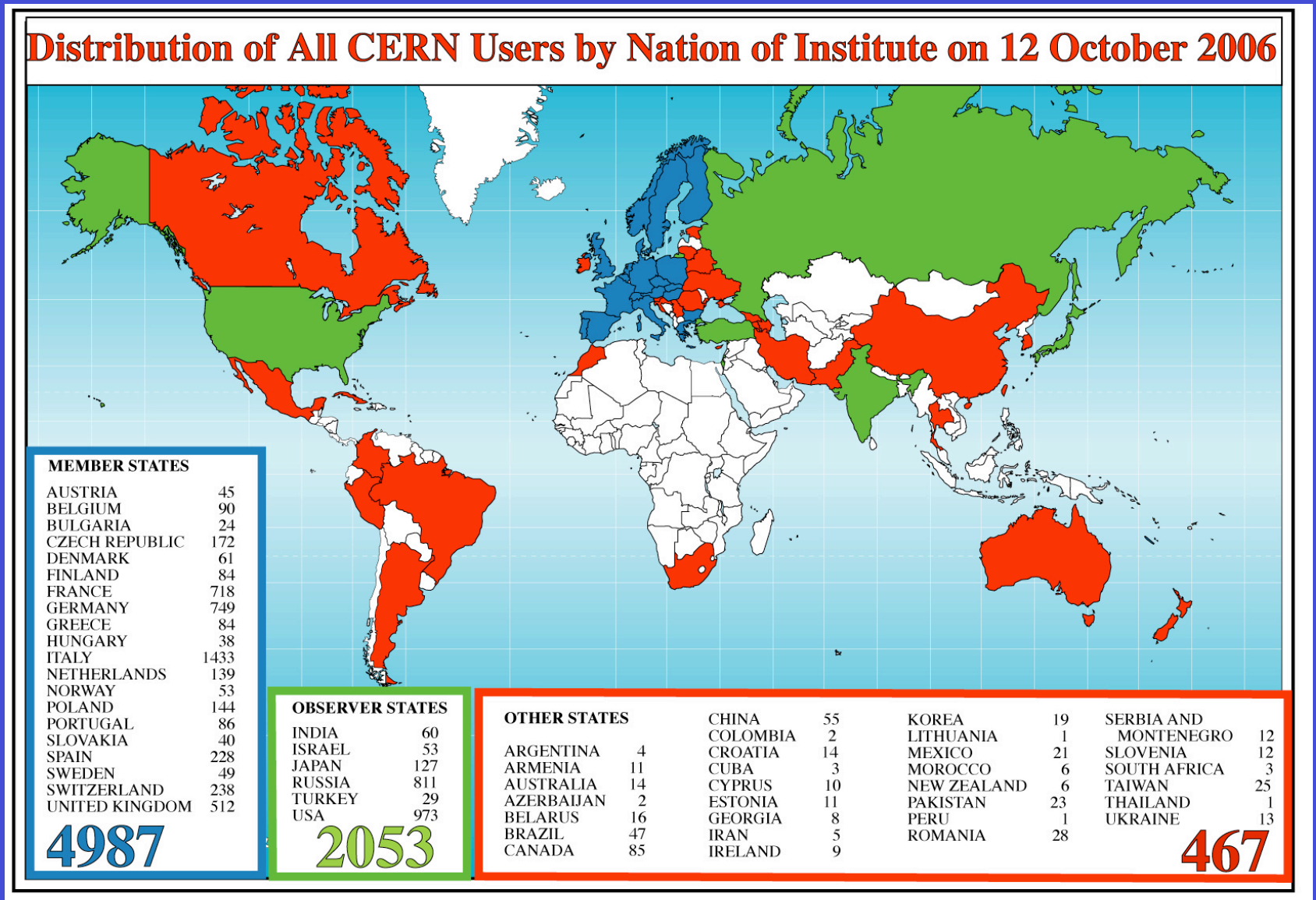
Plus eight Observer States: European Commission, India, Israel, Japan, Russian Federation, Turkey, UNESCO and USA

Budget: ~1000 MCHF (~650 M€): each member states contributes in proportion to its income (e.g. Spain ~8%, ~ 54 M€, ~ one cup of coffe per citizen)

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

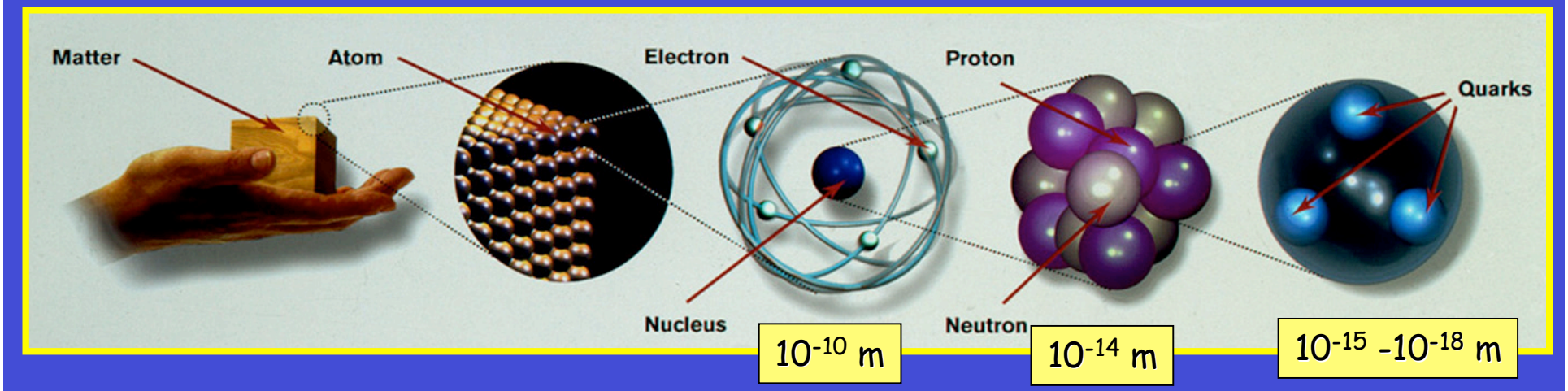
CERN's budget pays for the provision and maintenance of the accelerators and facilities used by the world-wide research community and the salaries of the ~2500 employees

2600 staff, 770 Fellows and Associates, 7500 users (Oct 2006)



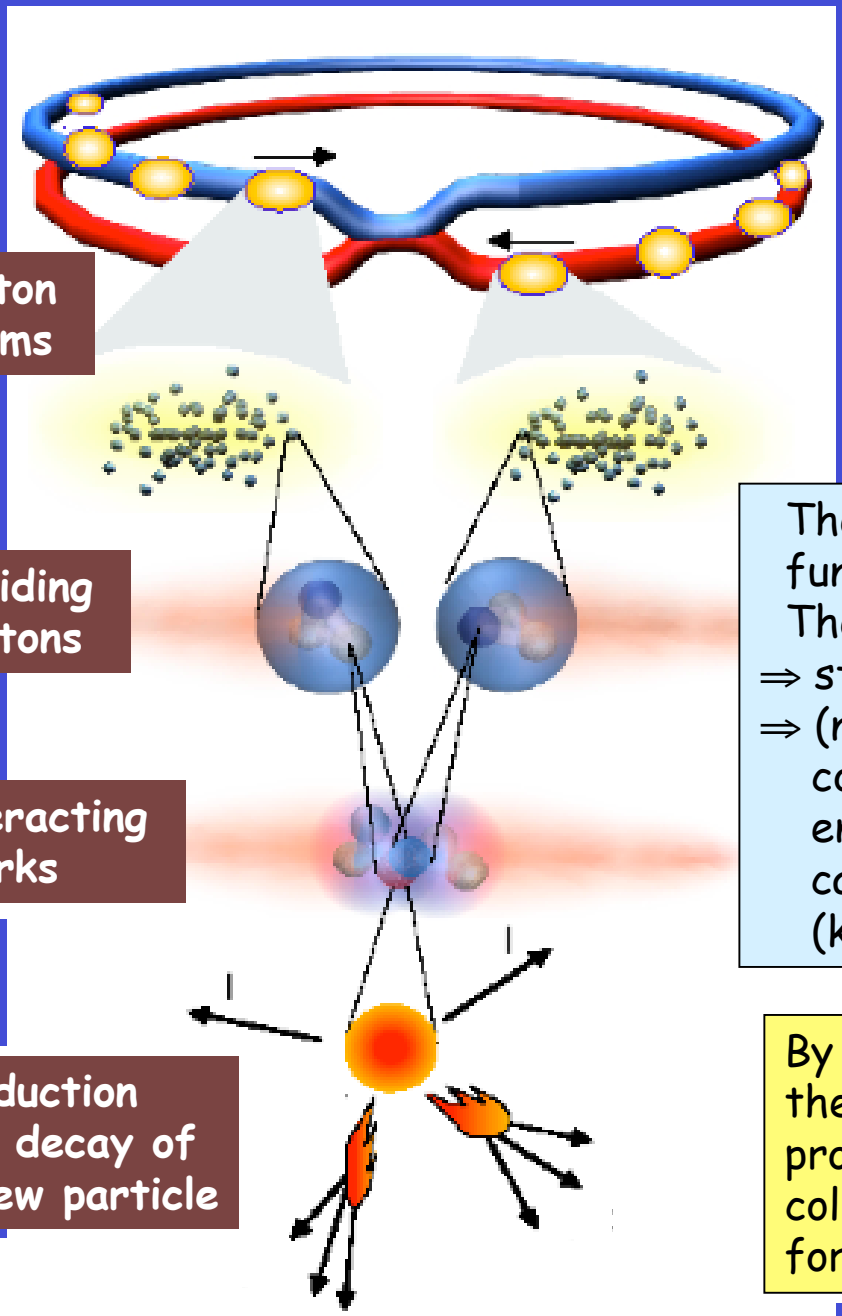
CERN's primary mission is SCIENCE

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 contributes to deciphering the structure and evolution of the Universe (see A. De Rújula's talk)
→ from the infinitely small to the infinitely big ...the two infinities ...

To study the elementary particles and their interactions:



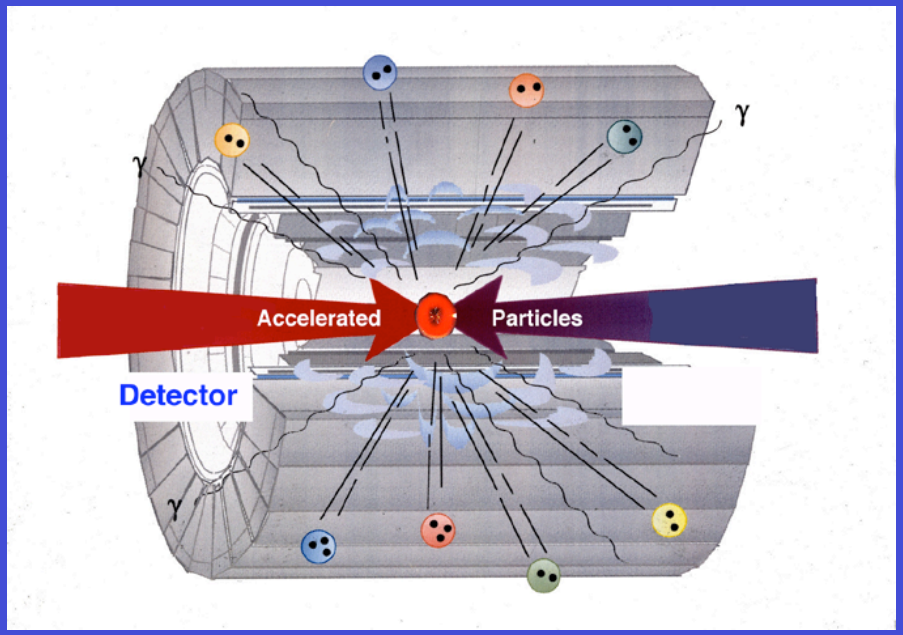
We accelerate two beams of particles (e.g. protons) close to the speed of light and make them collide

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 three 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)

the most powerful accelerator

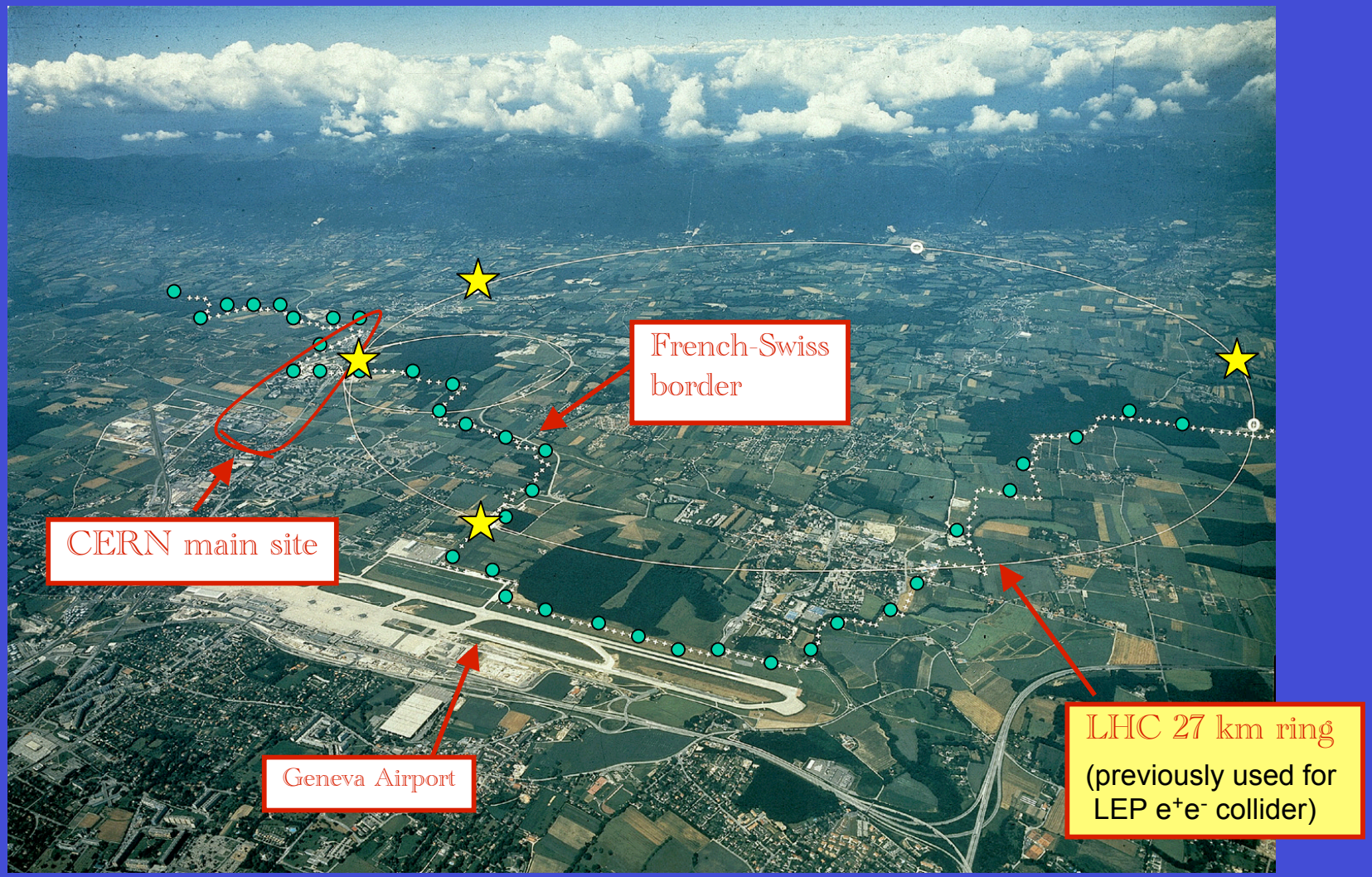
…. and also ….

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…)

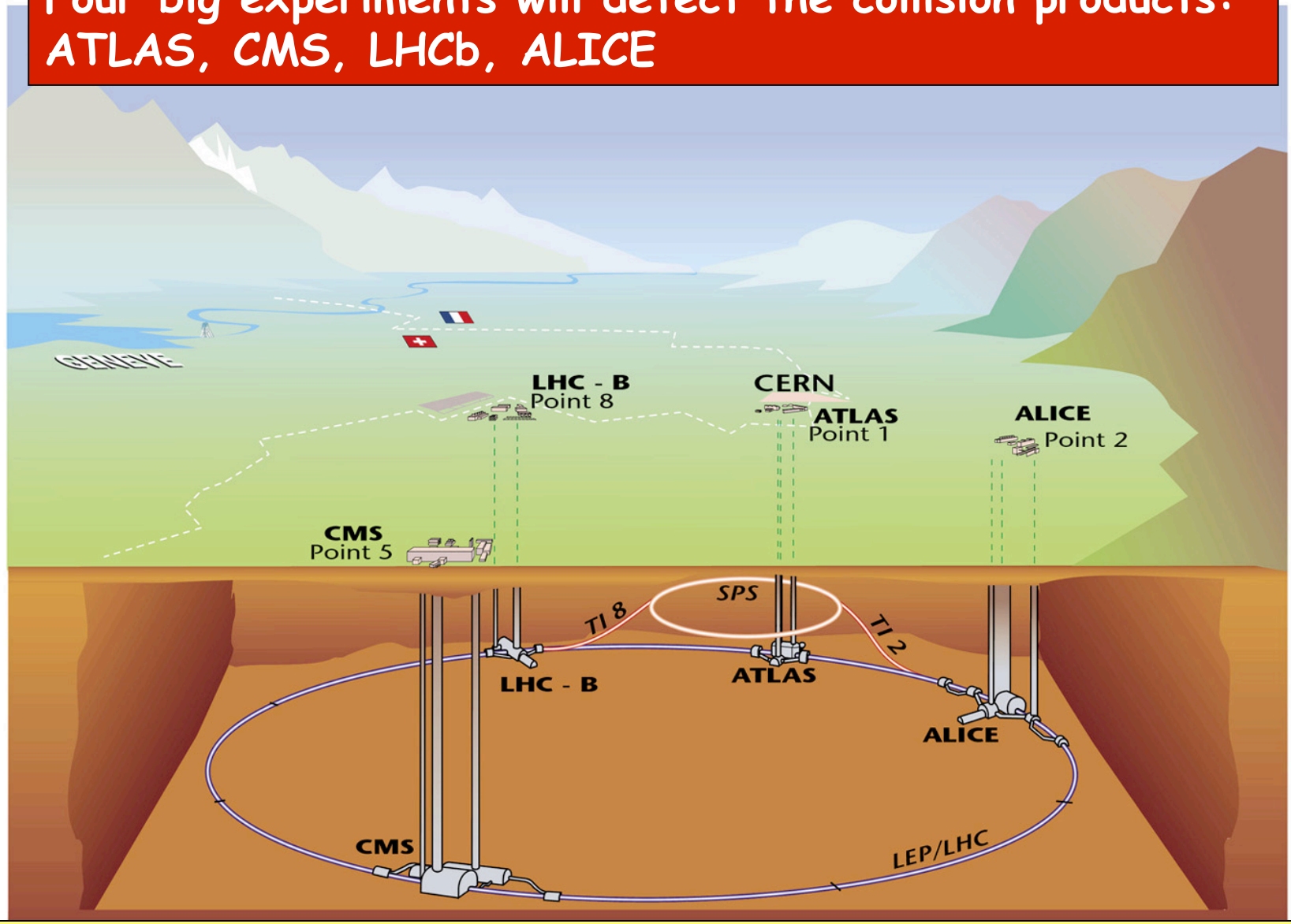
ever achieved in particle physics and one of the most ambitious projects in science in general !

Operation starts this Summer at CERN

LHC is a 27 km accelerator ring, 100 m below ground, across 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 Spanish Universities [including Institut de Física d'Altes Energies (IFAE), Universidad Autónoma de Barcelona] have strongly contributed to the construction of the four experiments

1) Accelerator

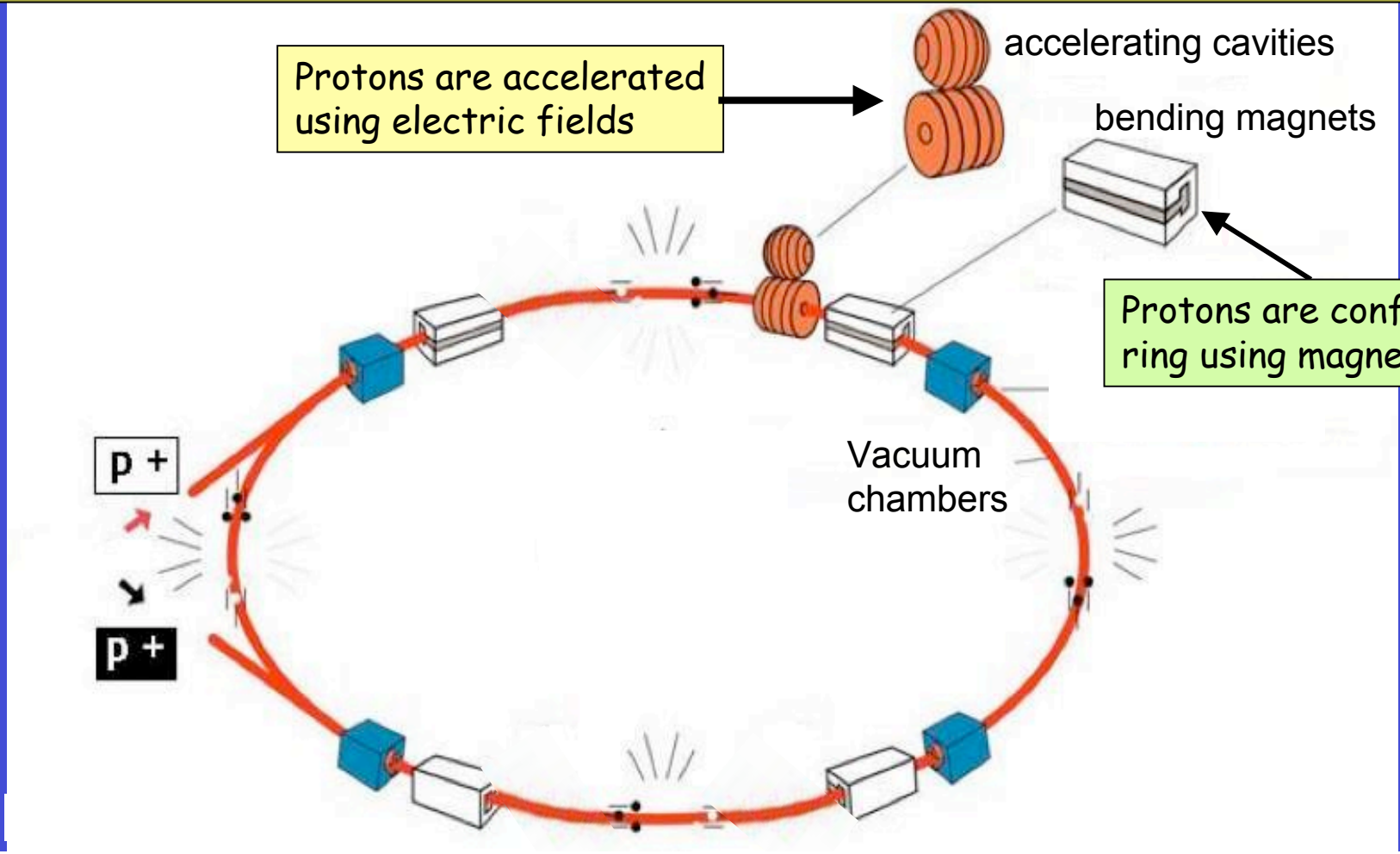
Unprecedented energy: 7 TeV per beam → collision energy = 14 TeV

[1 TeV= 1 Tera electron Volt = 10^{-7} Joule]

7 times higher than most powerful accelerator today (Tevatron at Fermilab/Chicago)

14 TeV corresponds to 20 1-Volt batteries for each star of our galaxy

Huge amount of energy concentrated in the collision point, however little energy on macroscopic scale (1 μJoule is just enough to swat a mosquito)



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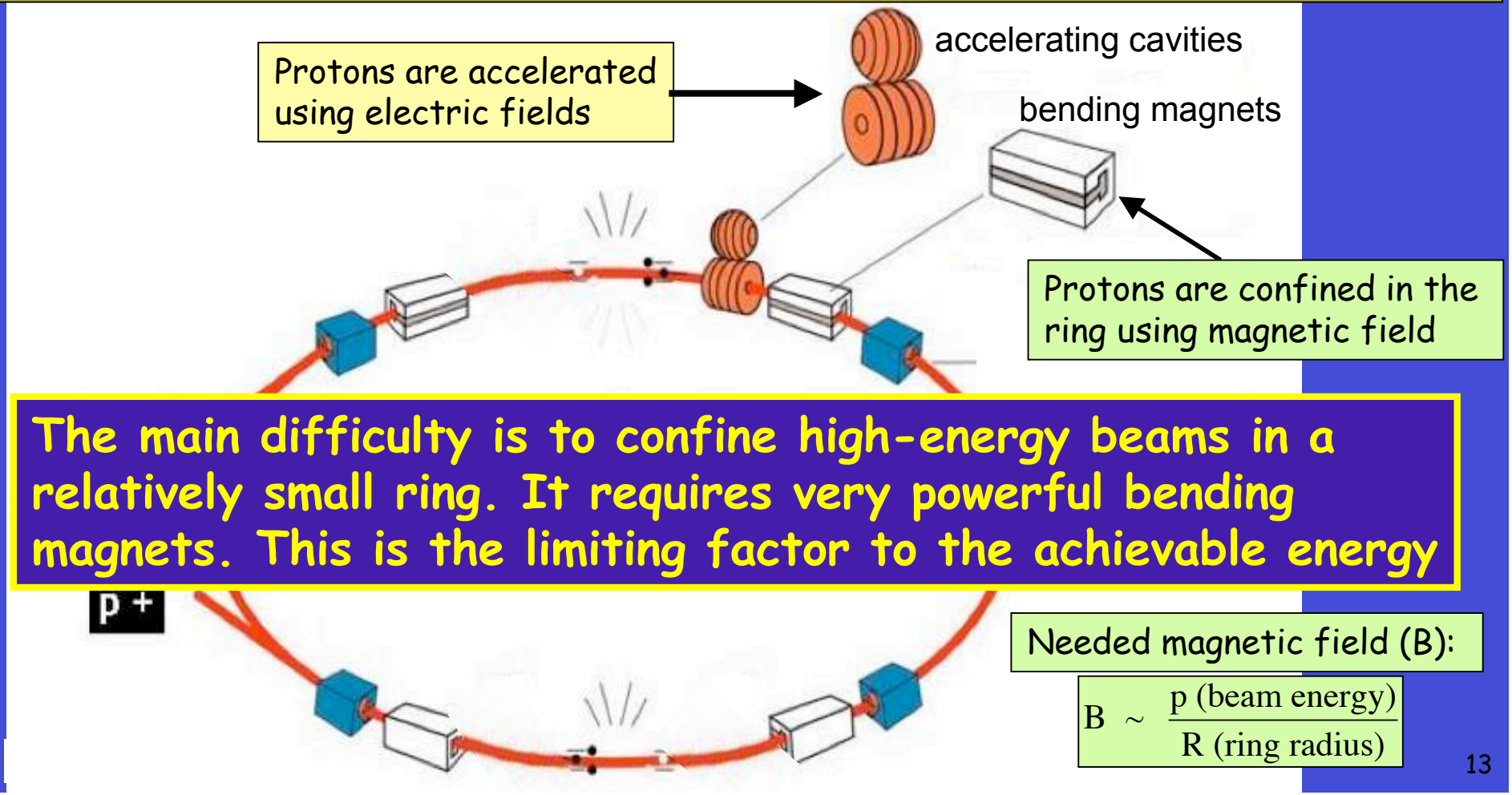
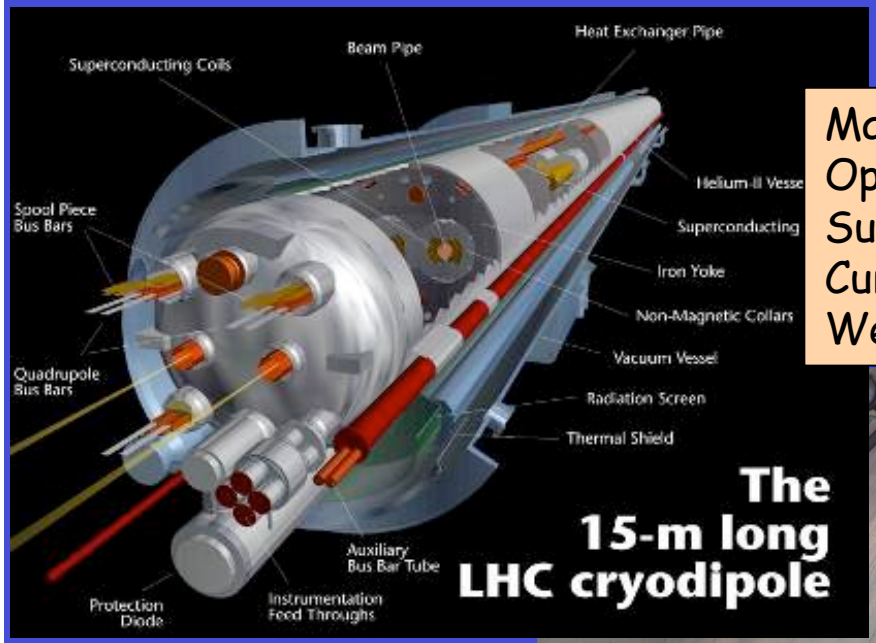


The main difficulty is to confine high-energy beams in a relatively small ring. It requires very powerful bending magnets. This is the limiting factor to the achievable energy

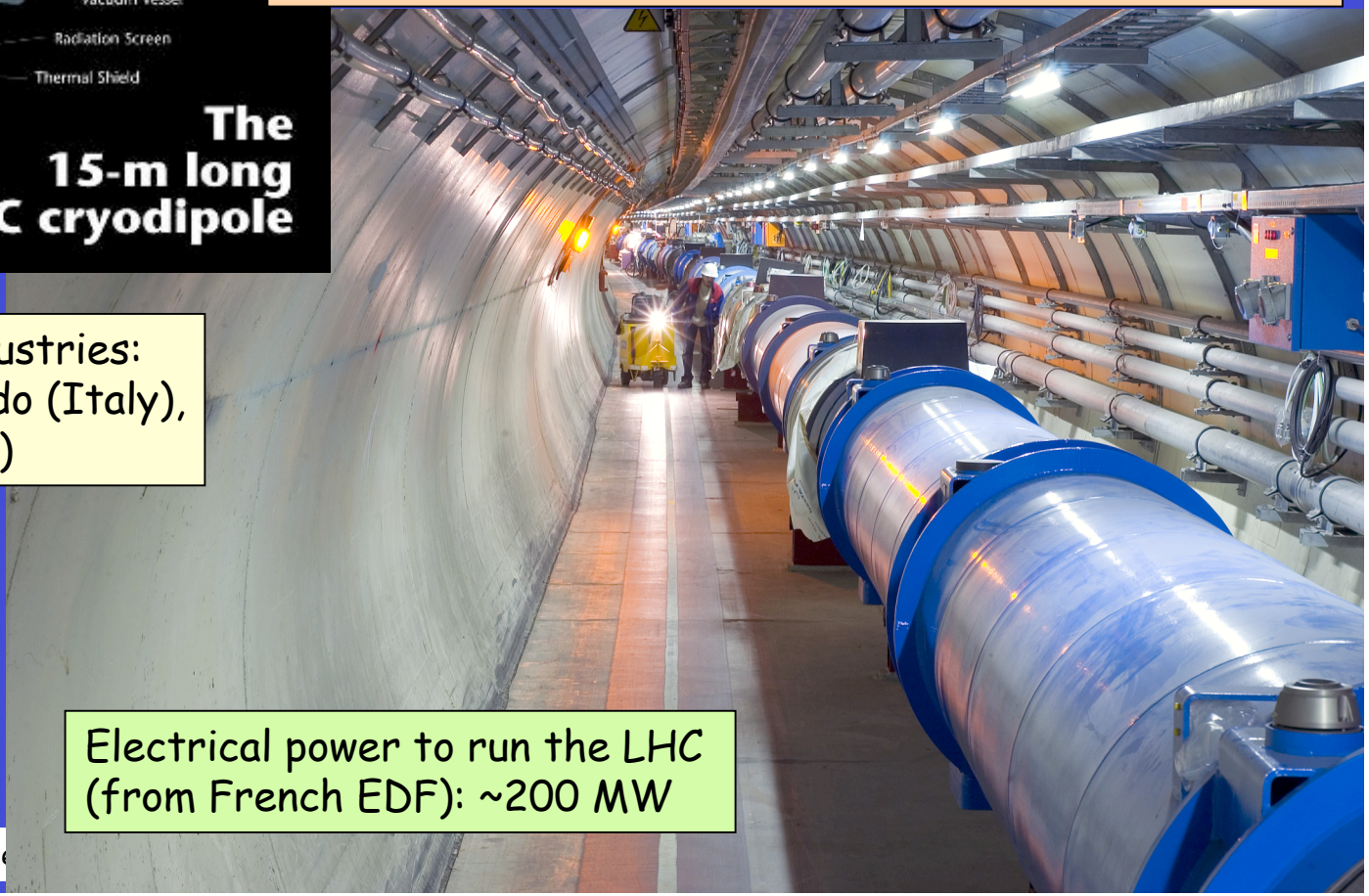
Needed magnetic field (B):

$$B \sim \frac{p \text{ (beam energy)}}{R \text{ (ring radius)}}$$

The most challenging components of the LHC are 1232 superconducting dipole magnets of unprecedented technology



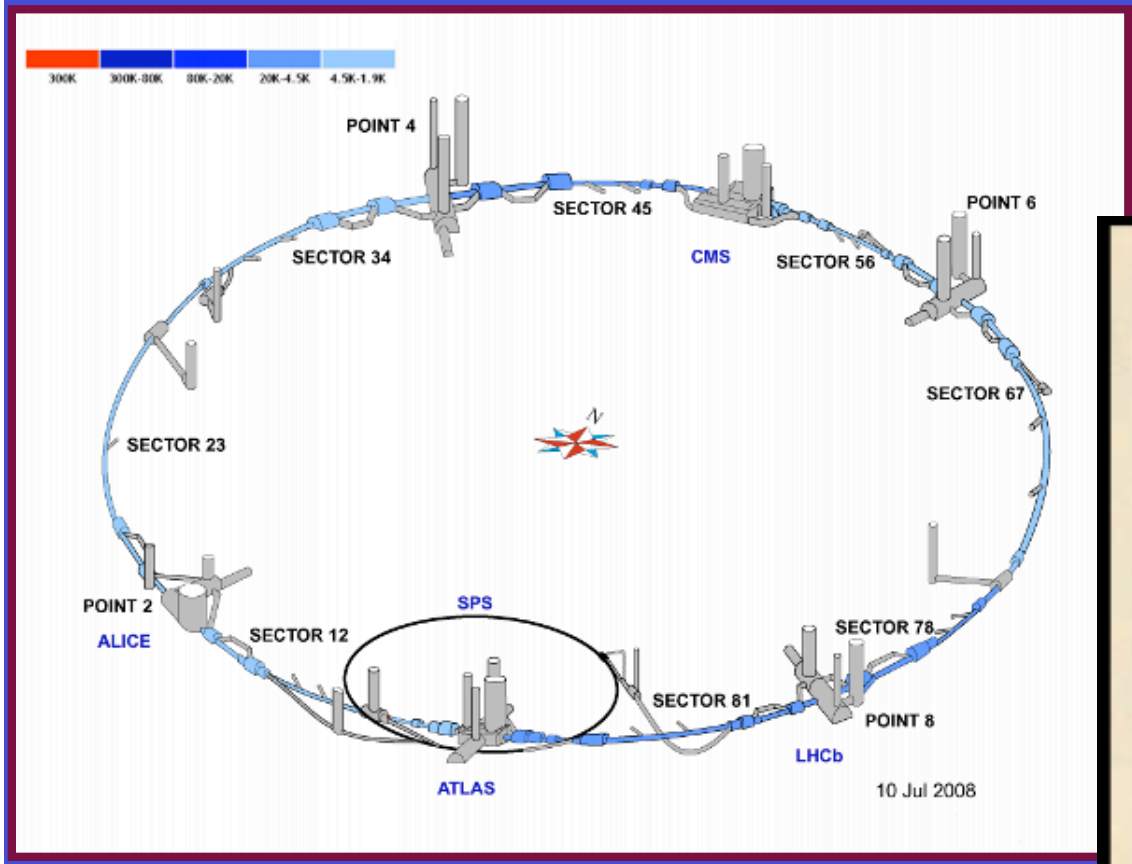
Magnetic field: 8.4 T
Operation temperature: 1.9 K (-270 degrees Celsius)
Superconducting cable: 7600 km of NbTi
Current: 11700 A
Weight: 34 tons



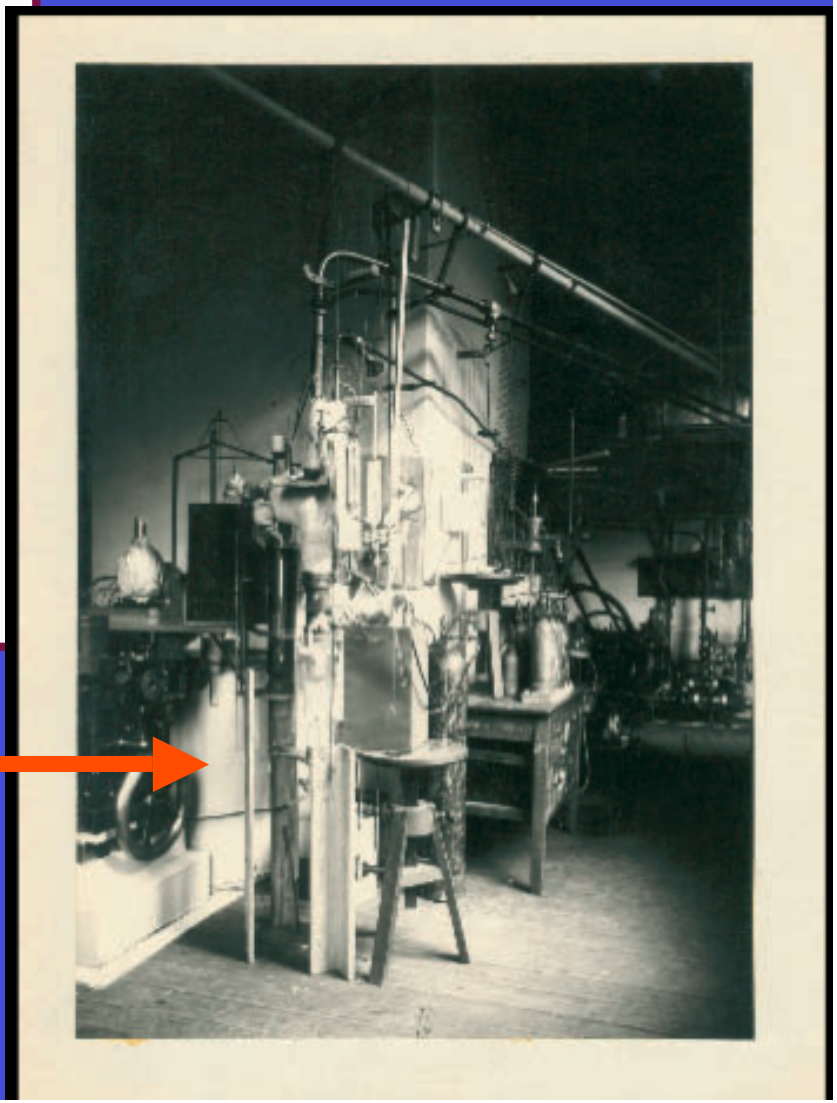
Built by 3 European industries: Alstom (France), Ansaldo (Italy), Babcok-Noell (Germany)

Electrical power to run the LHC (from French EDF): ~200 MW

LHC is the largest cryogenic system on earth, cooler than outer space



Magnets cooled down in a bath of ~120 tons of superfluid Helium



- 100 years ago, on 10 July 1908: Kamerling Onnes first liquefied Helium (60 cm^3 in 1 hour) in Leiden
- LHC today: 32000 He liters liquefied per hour by eight giant cryogenic plants

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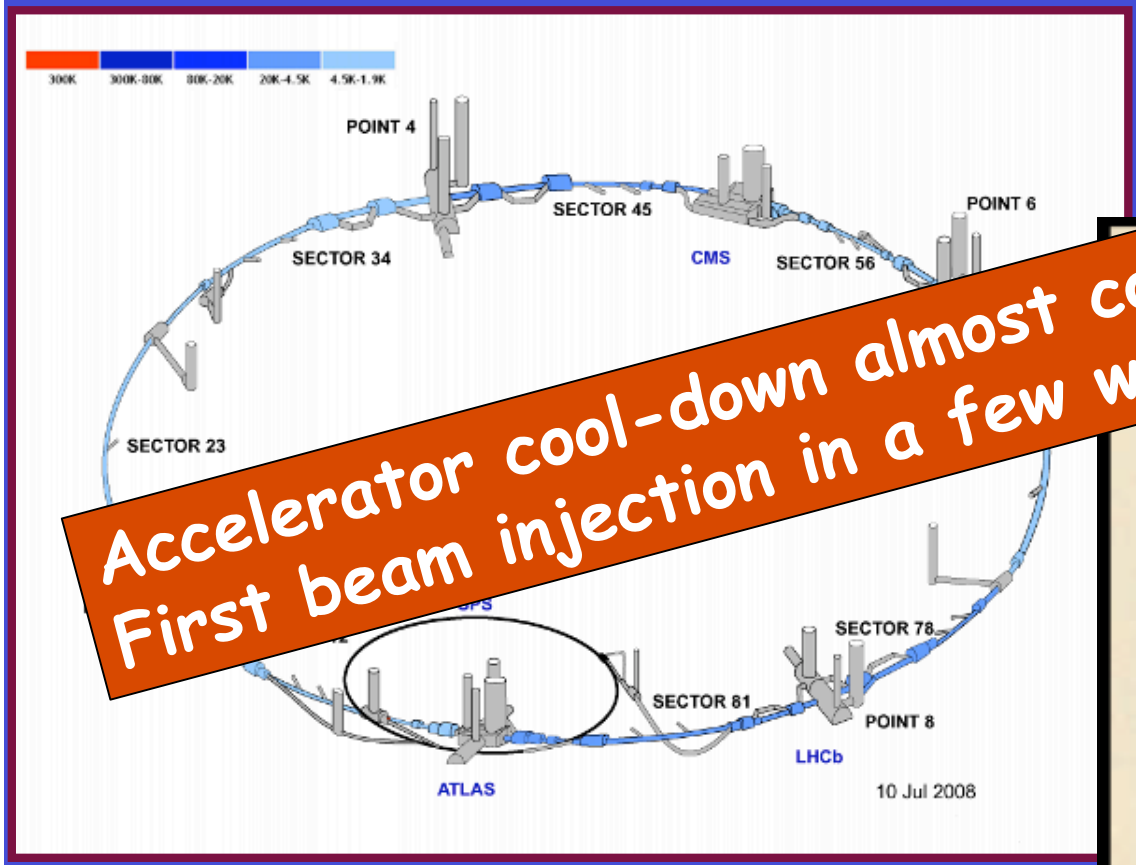
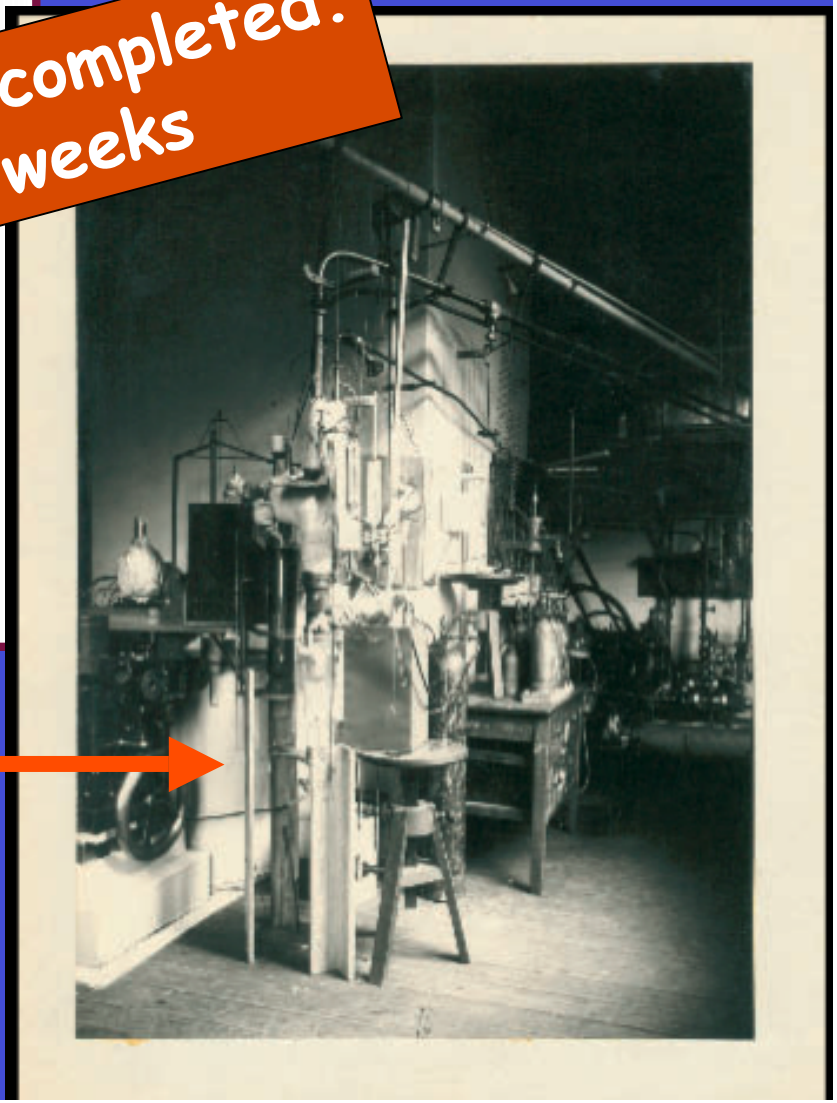


Accelerator cool-down almost completed.
First beam injection in a few weeks

Magnets cooled down in a bath of ~120 tons of superfluid Helium



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Not only high-energy beams … but also very intense beams

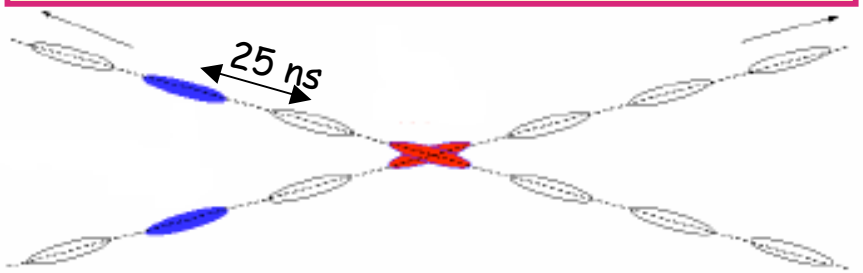
To observe new heavy particles (rare processes …), a huge number of proton-proton collisions is needed.

At design operation:

Protons per bunch	10^{11}
Number of bunches per beam	2808
Total number of protons	10^{14}
Bunch spacing	25 ns

~ 30 times higher than achieved so far

Protons in the two beams are grouped in bunches, 2808 bunches per beam, separated by 25 ns (1 ns = 10^{-9} s)



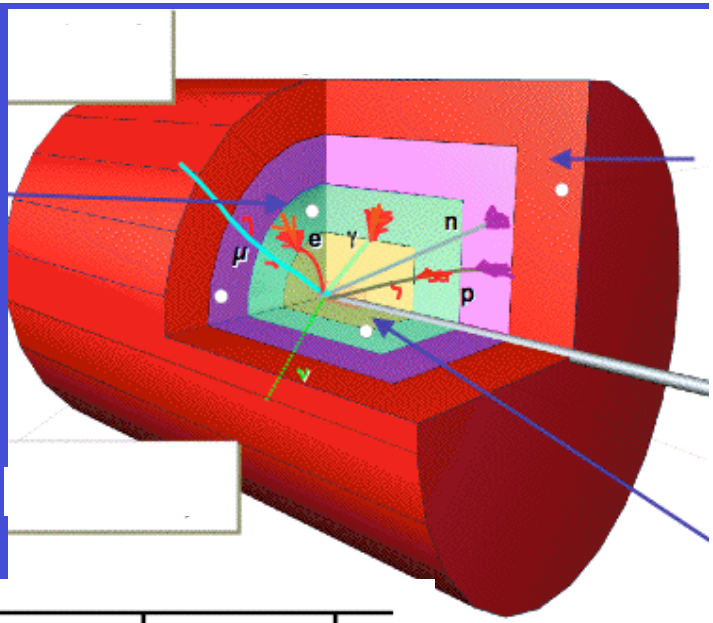
Energy stored in one beam : 360 MJ
(consequence of particle energy and beam intensity)
~200 times higher than at the Tevatron

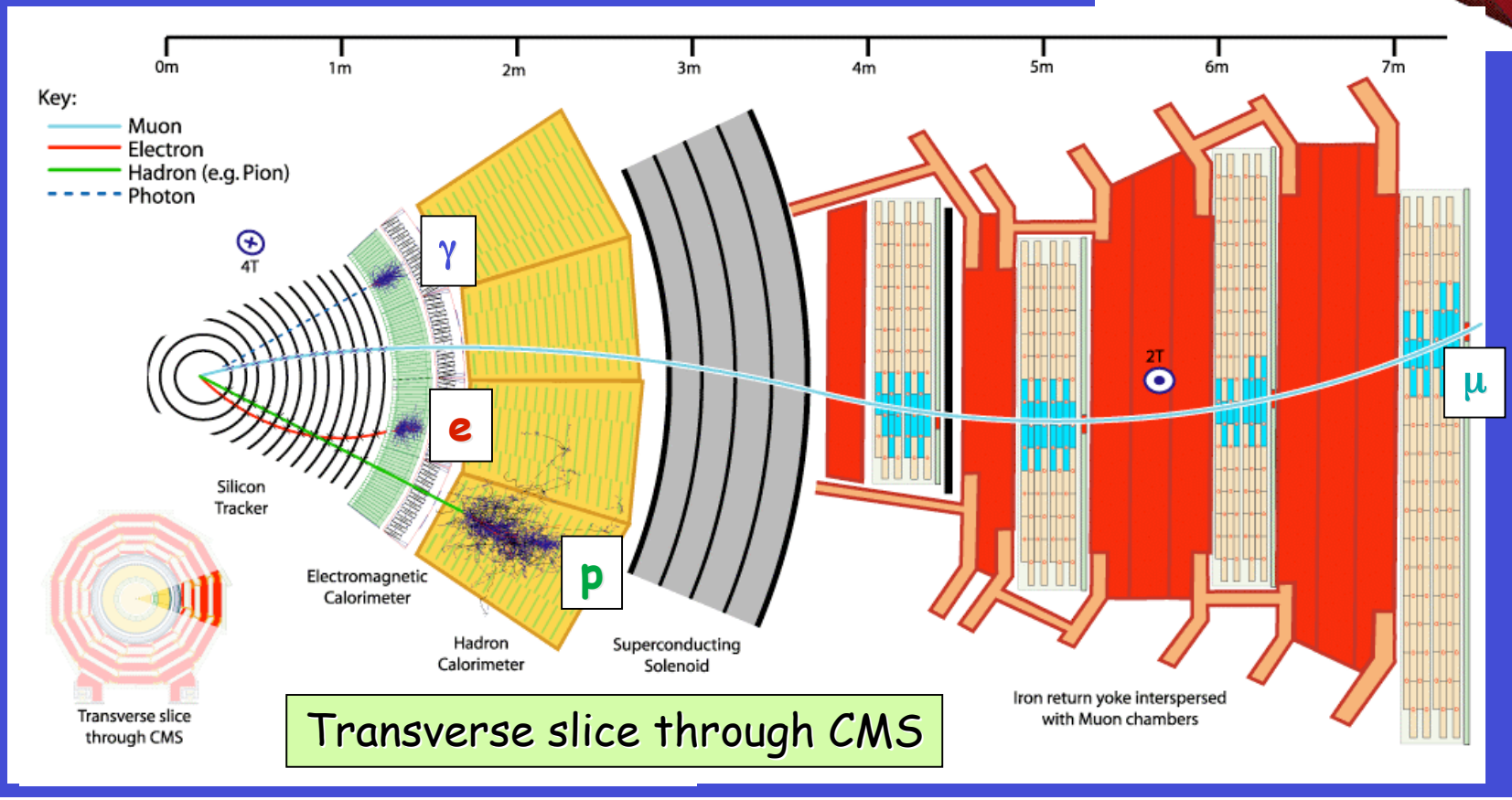
90 kg of TNT

British aircraft carrier at 12 knots

2) Detectors for particle physics

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

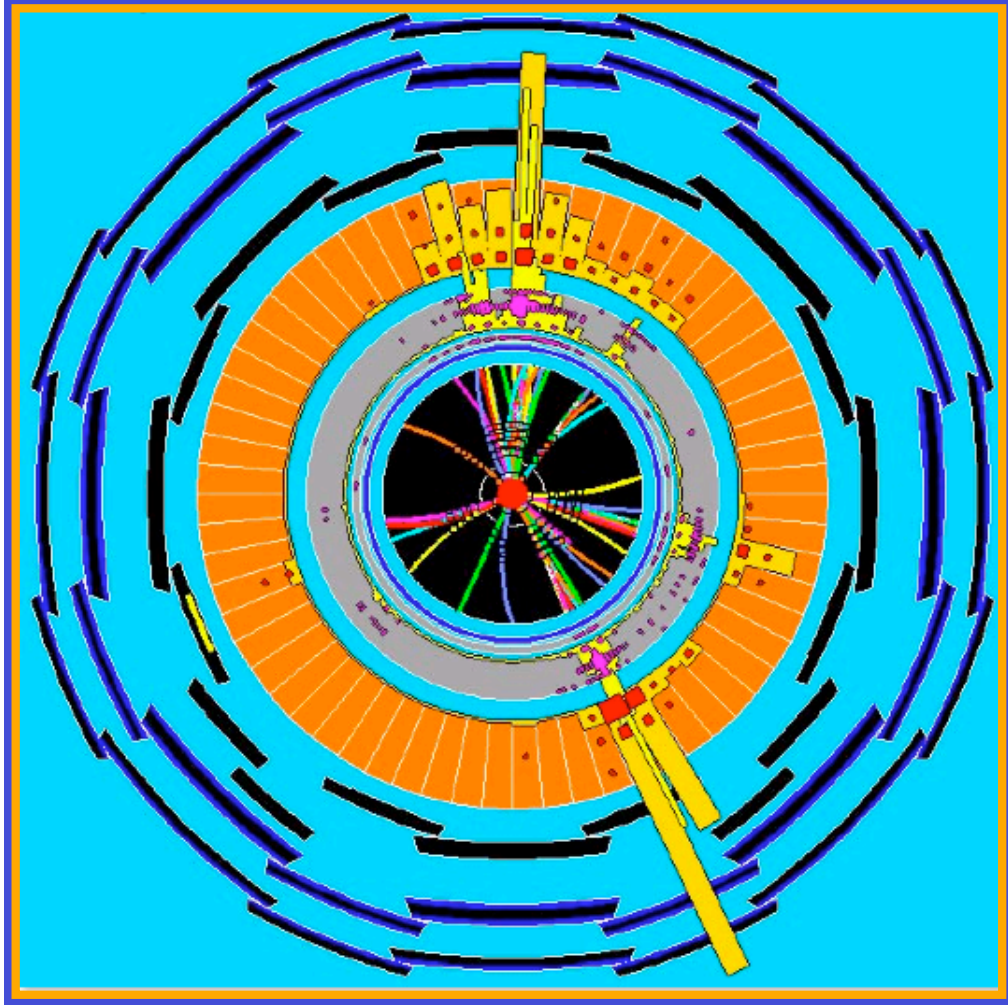




Transverse slice through CMS

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

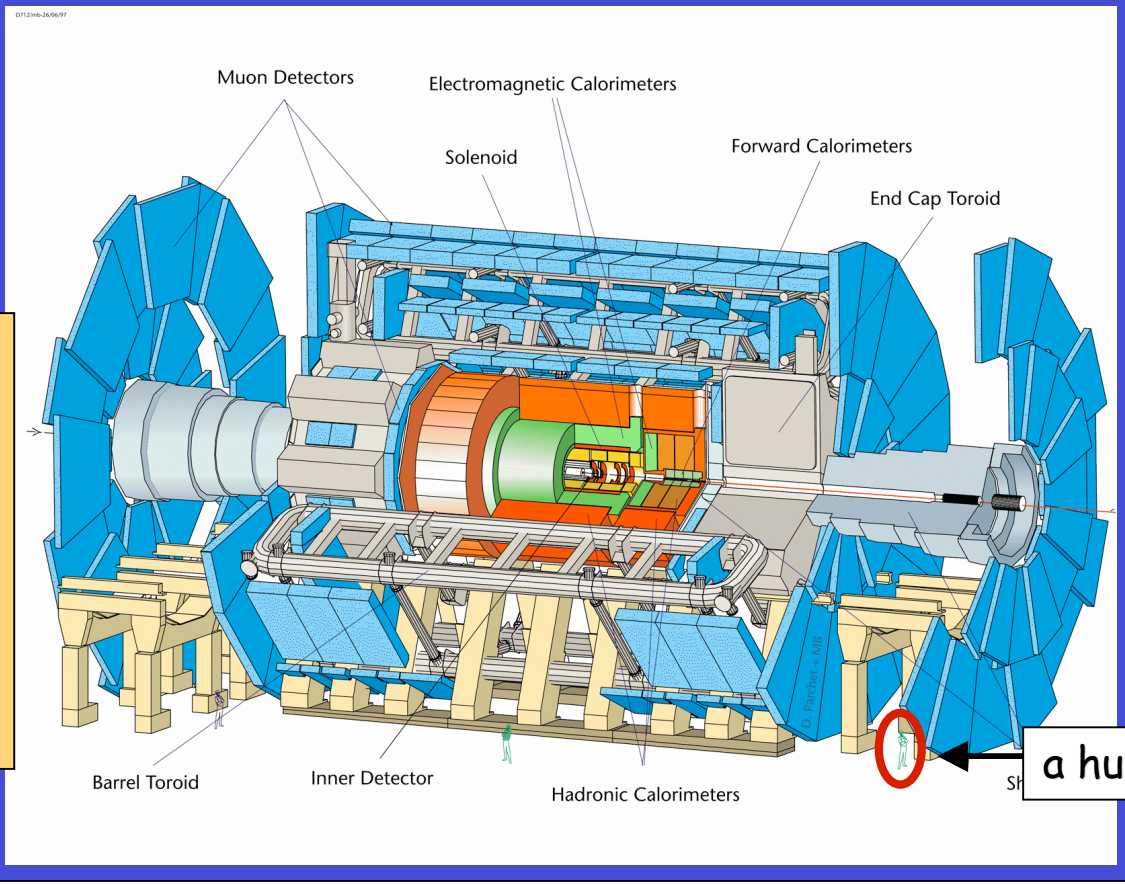
Sophisticated software techniques are then used to reconstruct the particle trajectories from the signals left in the various detector elements and thus obtain a "picture of the full event". The origin of the event (which new particle or phenomenon has produced it) can then be studied



The results of a simulated pp collision in the ATLAS detector (transverse view, the beams are perpendicular to the screen)

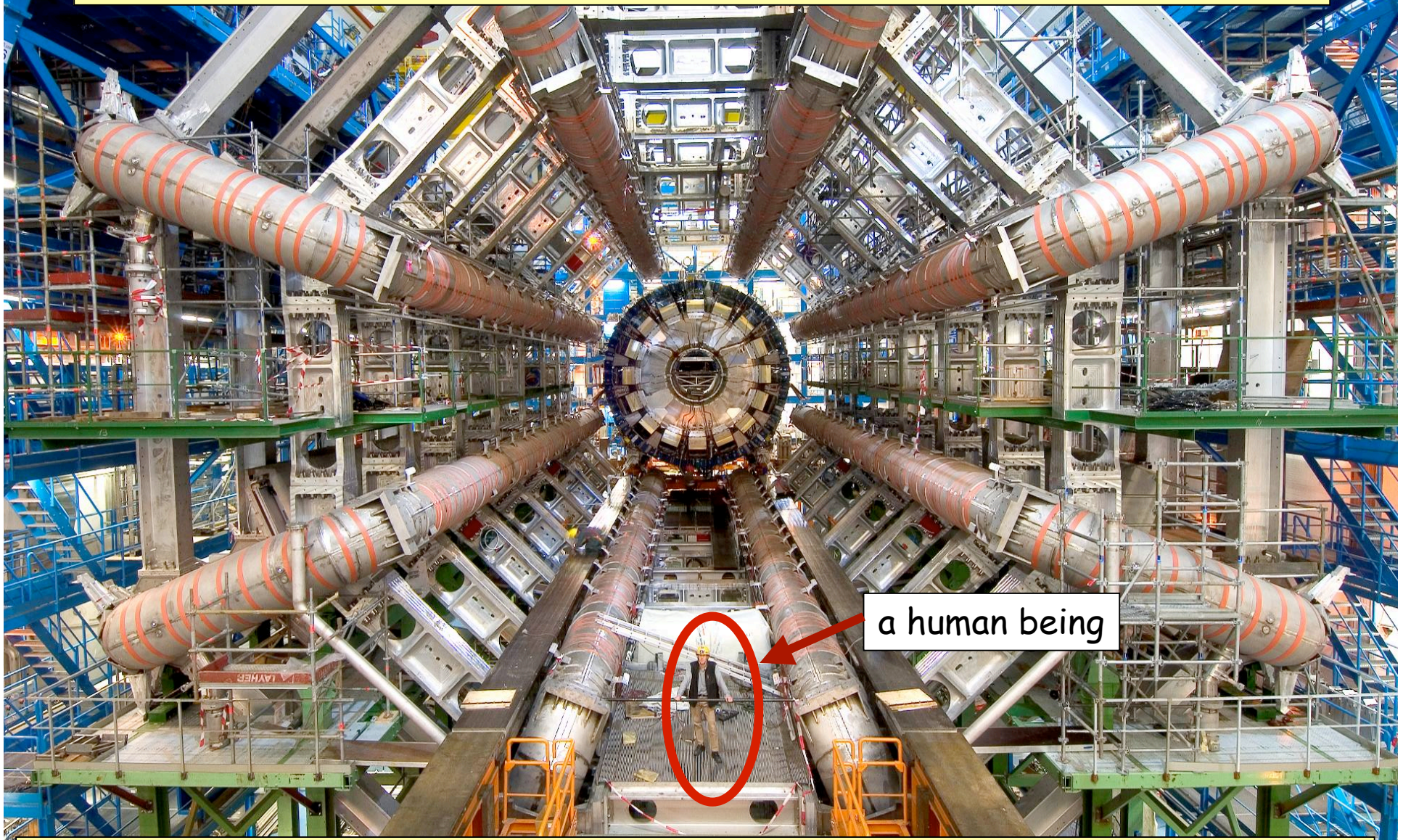
One example: ATLAS

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



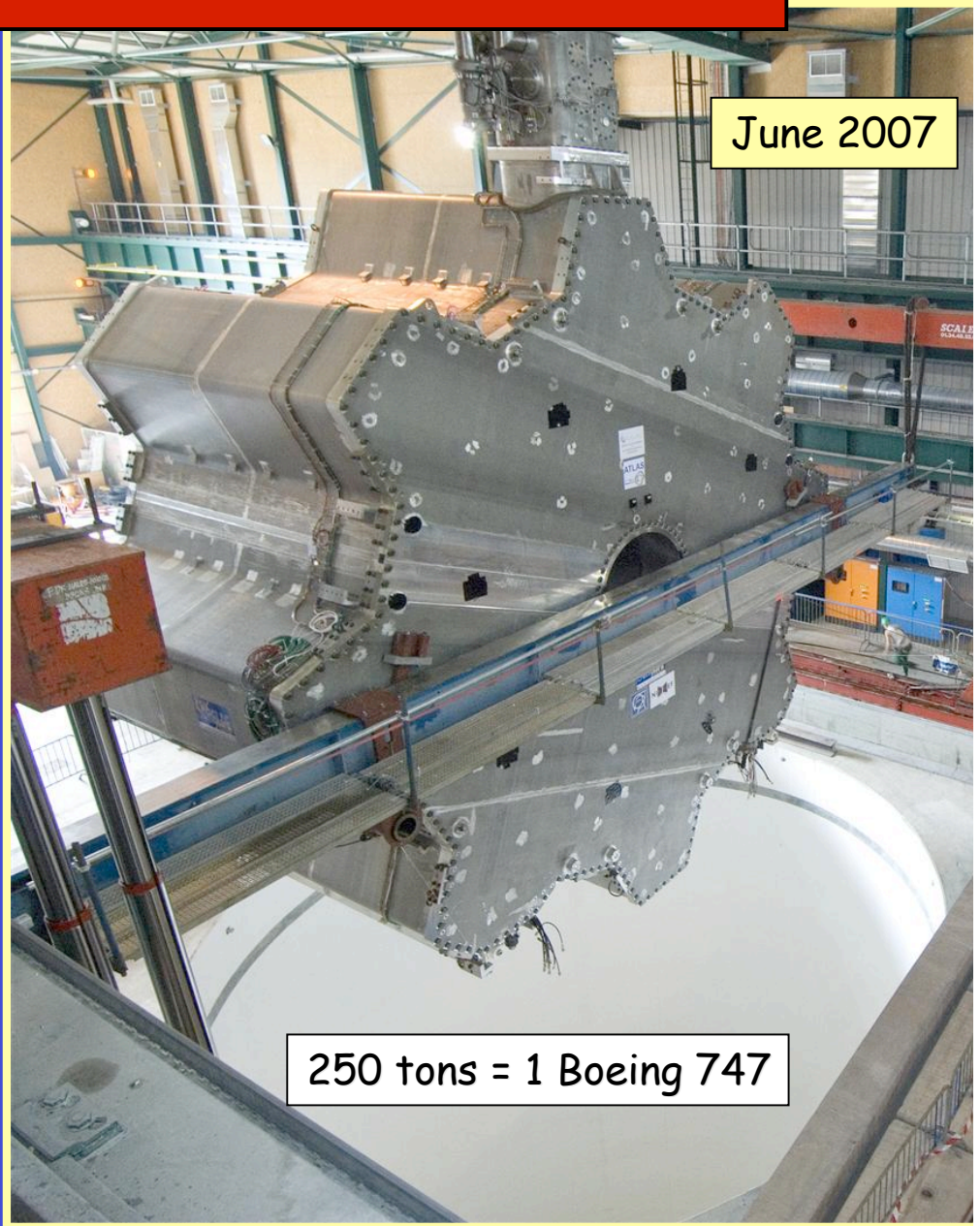
- Size (length 45m, diameter 25m): to measure and absorb high-energy particles
- Fast response (~50 ns): 40 million beam-beam collisions per second (1 ns = 10^{-9} s)
- 10^8 electronic channels ("individual signals"): to track ~1000 particles per event and reconstruct their trajectories with ~10 μm precision (1 μm=10^{-6} m)
- Radiation hard: up to 10^6 Gy in the hottest regions after 10 years of operation
- Collaboration: ~ 2200 physicists from 169 Institutions/Universities, from 37 countries from 5 continents … and 450 PhD students

The ATLAS underground cavern (-100 m) in Oct. 2005

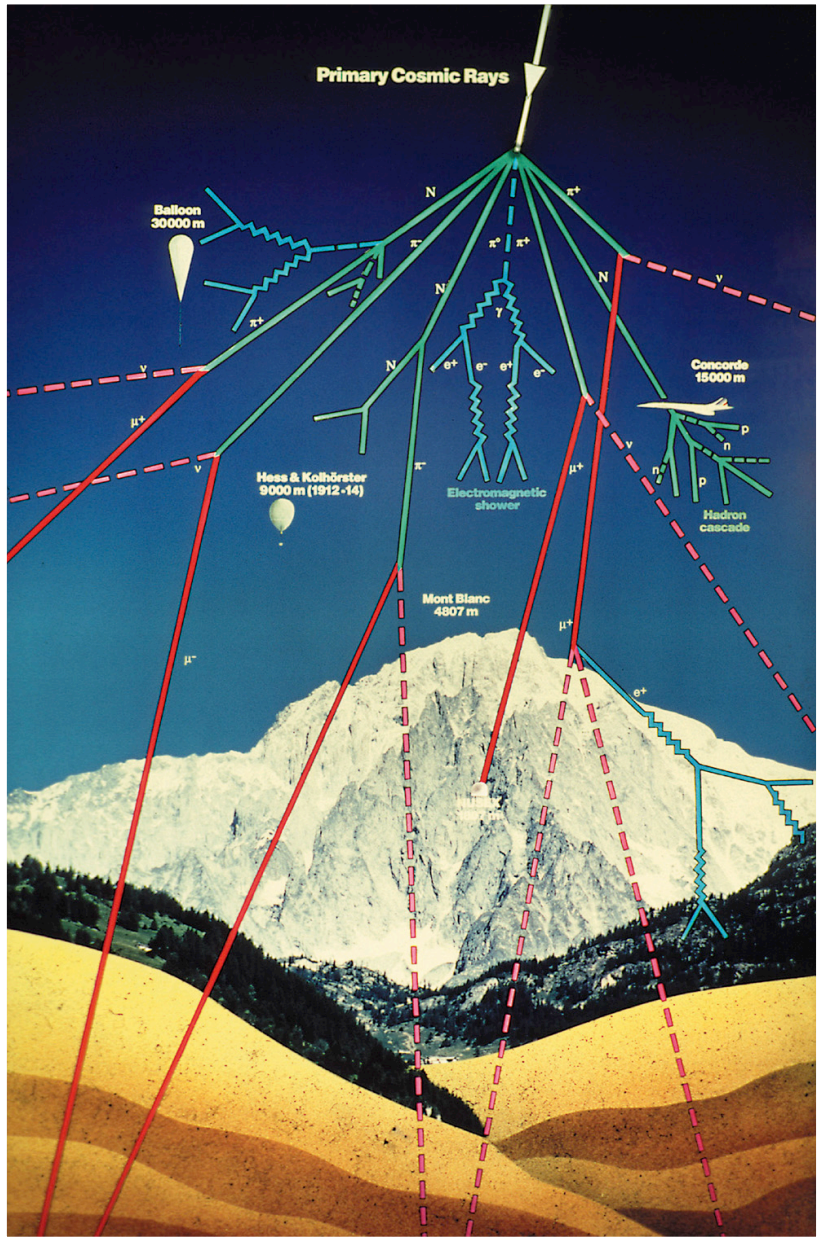


Vacuum vessels of magnet coils built by Felguera Construcciones Mecanicas (Oviedo)
Major contribution of a group from IFAE (led by M.Bosman and M.Cavalli-Sforza) to Tilecal calorimeter

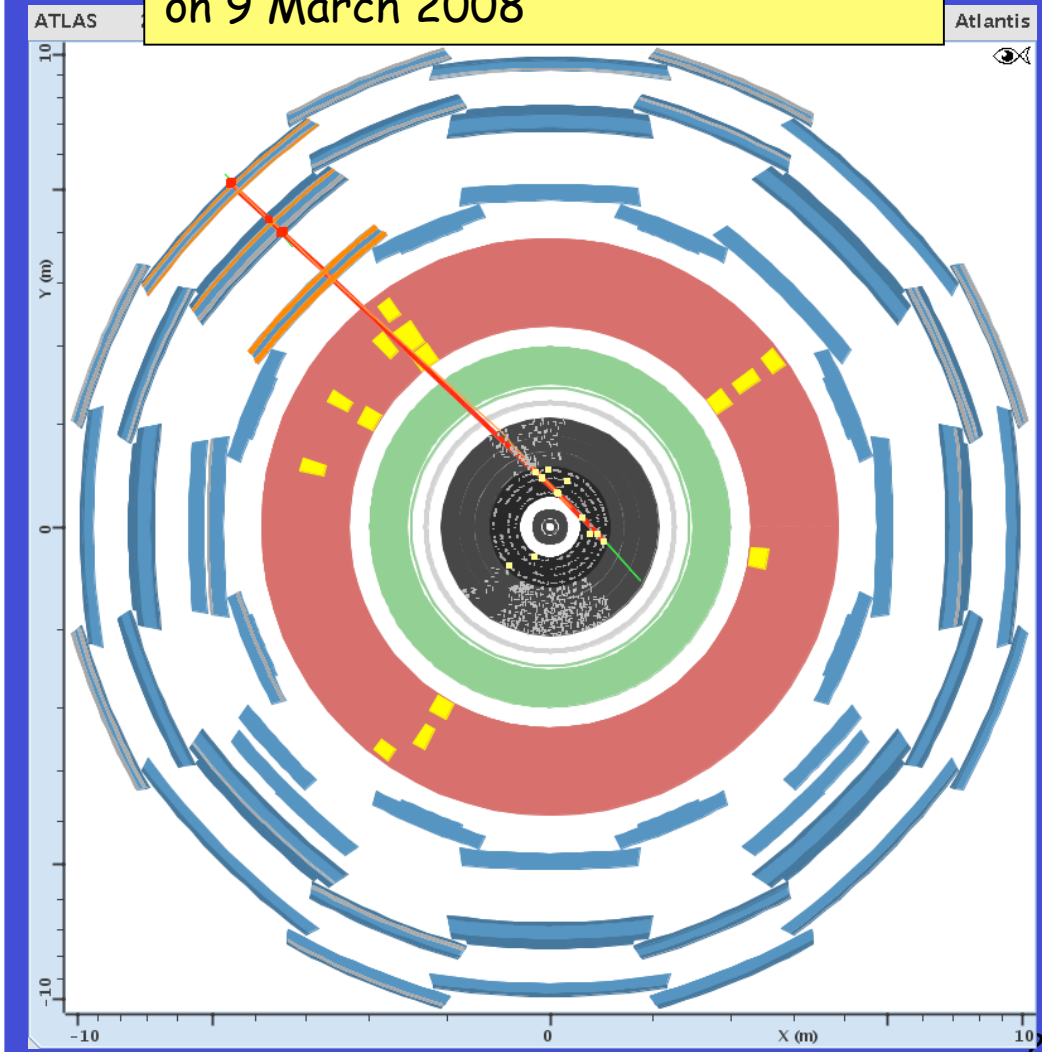
Spectacular operations … installing detector pieces in the underground cavern



The four LHC detectors are now operational in their underground caverns and being commissioned with cosmics rays to prepare for first beams

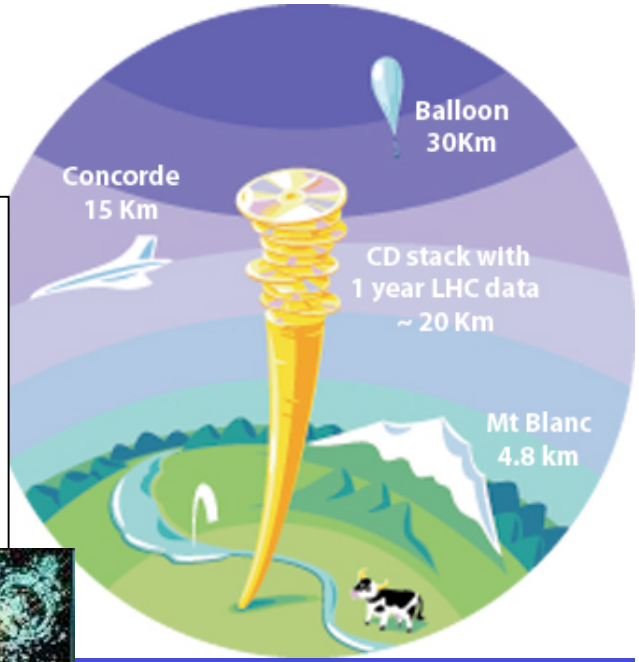


A cosmic muon recorded by ATLAS on 9 March 2008



3) 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 …)



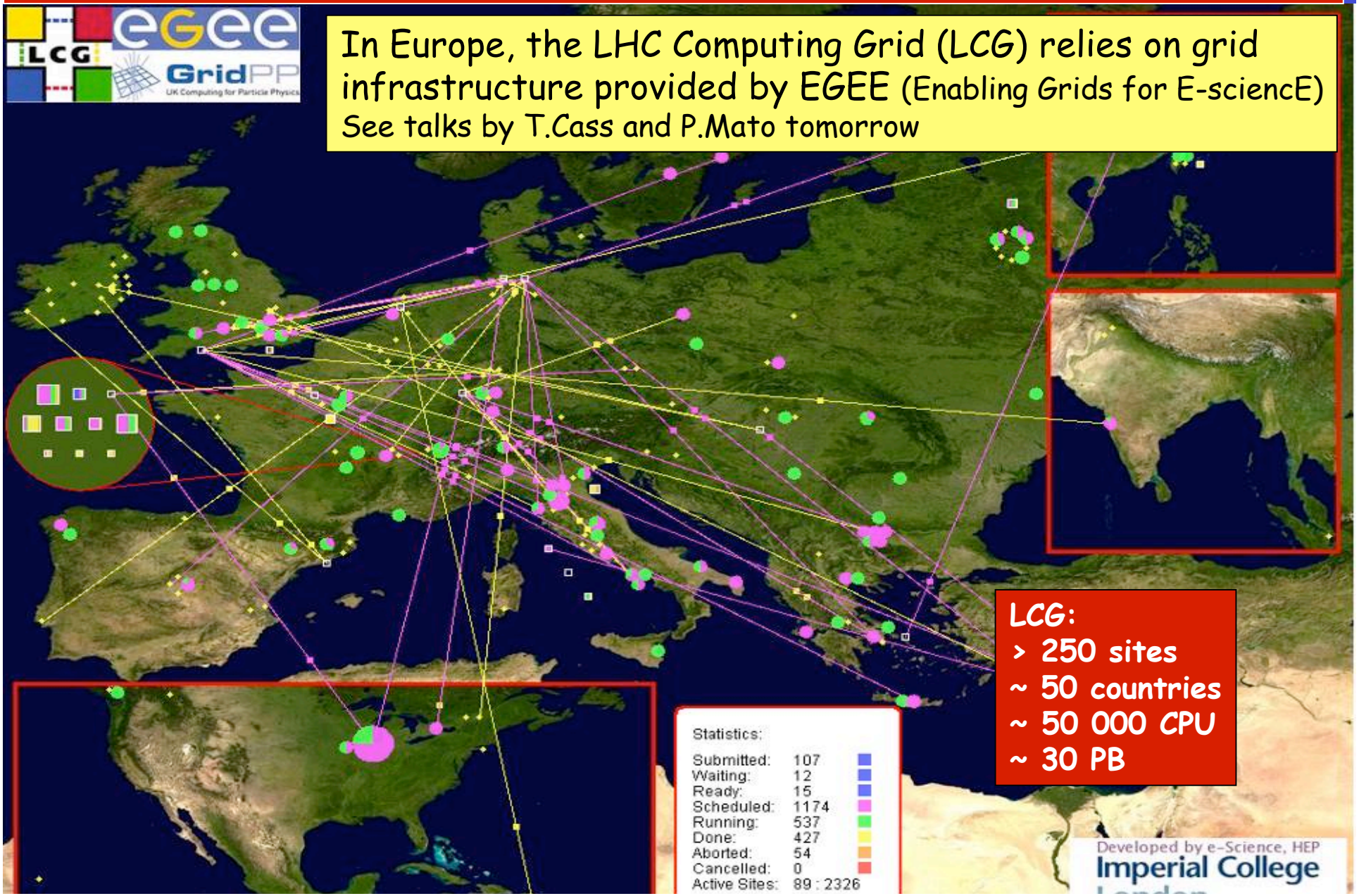
Data analysis requires computing power equivalent to ~100 000 today's fastest PC processors.

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 →

Grid

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

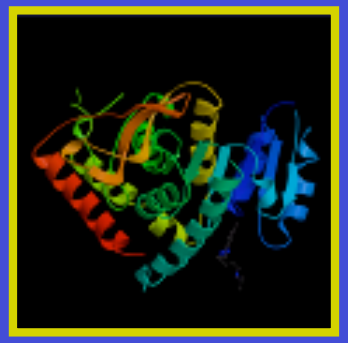
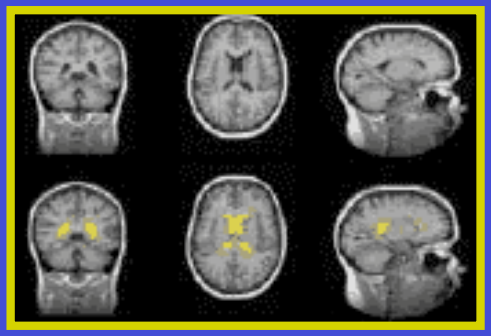


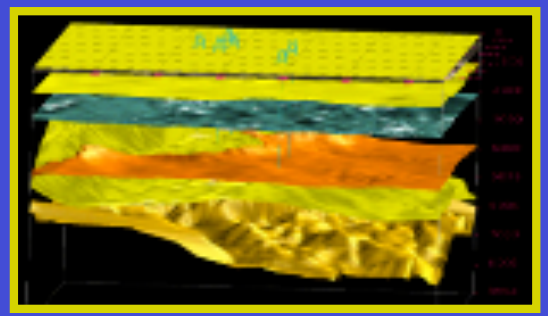
The LHC Computing Grid has been the driving force for EGEE

(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 (~100 M€ 2004-2010)
- 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 .....

Number of magnets in the accelerator: ~ 10000 (~ 7000 are superconducting)

Length of filaments of dipole magnet superconducting cable: enough to go 5 times to the sun and back plus a few trips to the moon

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

Collision energy: ~ 10^{14} times the temperature in this room

Beam cross section at the collision point: ~ 4 times smaller than that of a typical a human hair

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

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

Total cost (accelerator plus experiments) : ~ 6000 MCHF

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One of the most ambitious projects in science ever

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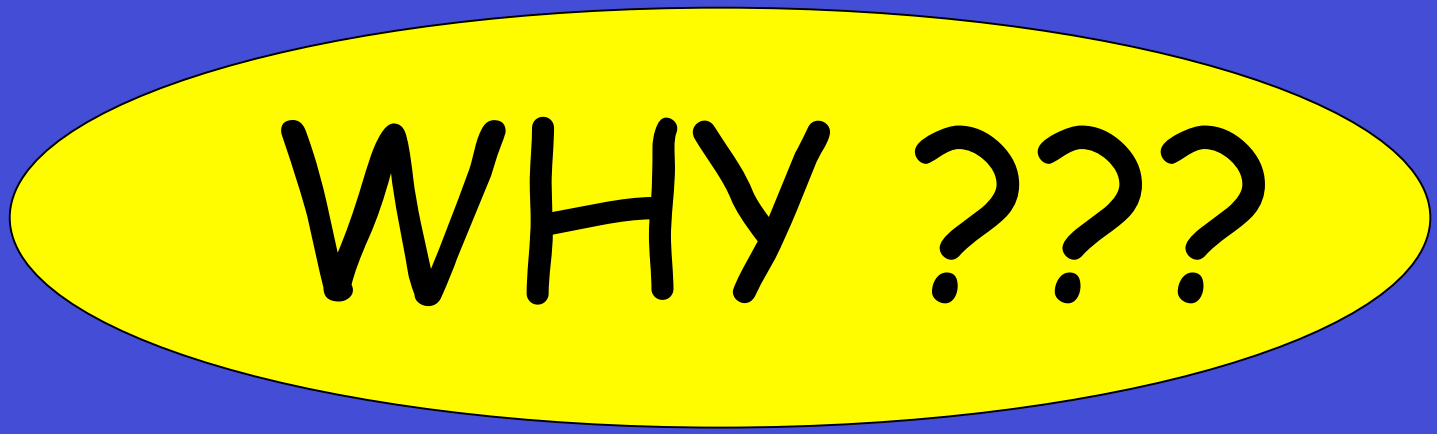
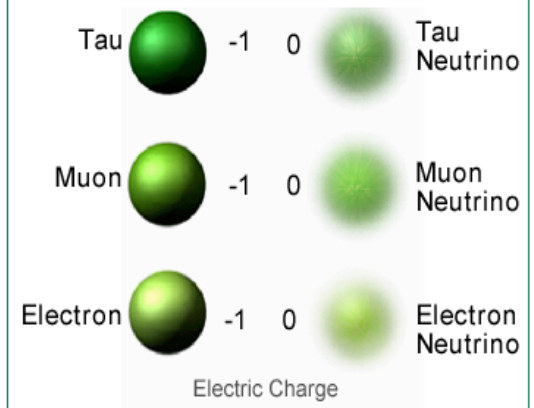

WHY ???

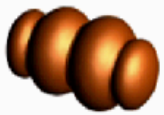
The elementary particles and their interactions are described by a theory (the Standard Model) which has been verified with extremely high precision over the last 35 years by experiments at CERN and at other labs all over the world (see J.Virdee's talk)

Leptons

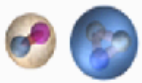


Strong

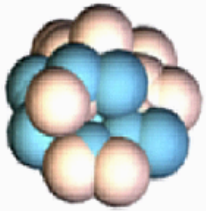
Gluons (8)



Quarks



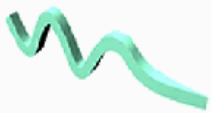
Mesons
Baryons

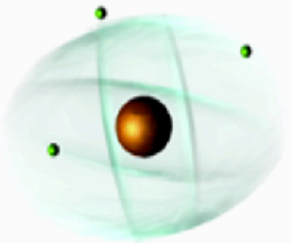


Nuclei

Electromagnetic

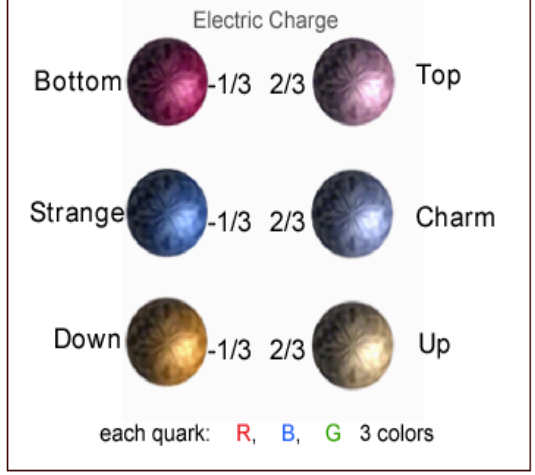
Photon





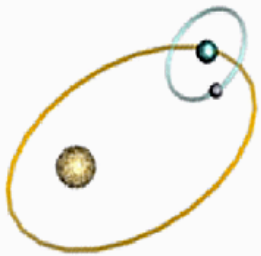
Atoms
Light
Chemistry
Electronics

Quarks



Gravitational

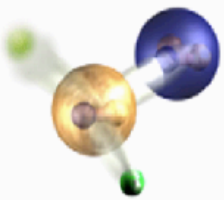
Graviton ?



Solar system
Galaxies
Black holes

Weak

Bosons
(W,Z)



Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

However, several open questions and mysteries remain ….

What is the origin of the particle masses ?	ATLAS, CMS
What is the nature of the Universe dark matter ?	ATLAS, CMS
What is the origin of the Universe matter-antimatter asymmetry ?	LHCb
What are the constituents of the Universe primordial plasma ~10 μs after the Big Bang ?	ALICE
What happened in the first moments of the Universe life (10^{-10} s after the Big Bang) ?	ATLAS, CMS
Etc. etc.	

The LHC will help elucidate these and other fascinating mysteries …
(see J.Virdee's and A. De Rújula's talks)

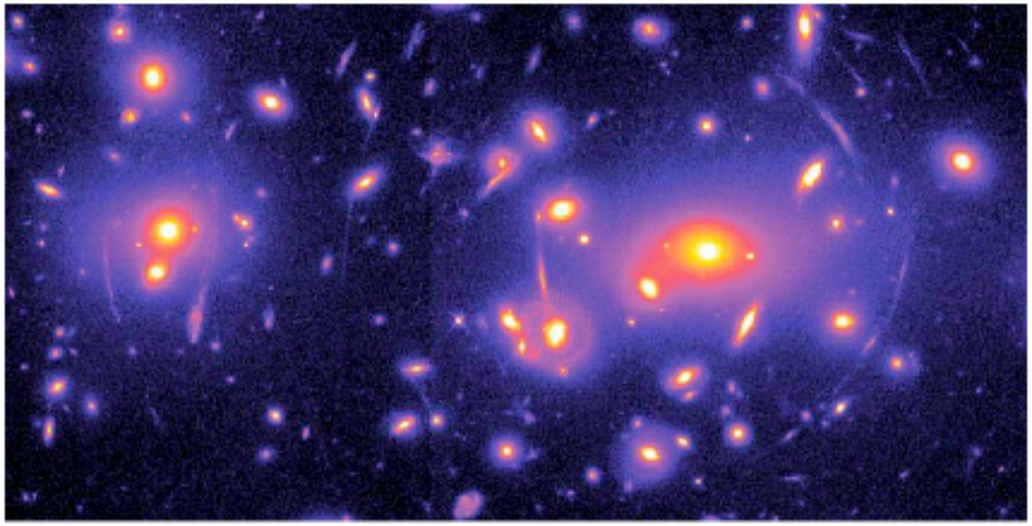
What is the nature of the Universe Dark Matter ?

Recent astrophysical measurements indicate that the Universe is made of:

- 5% of known matter
- 25 % of "Dark Matter" no known particle can explain it.

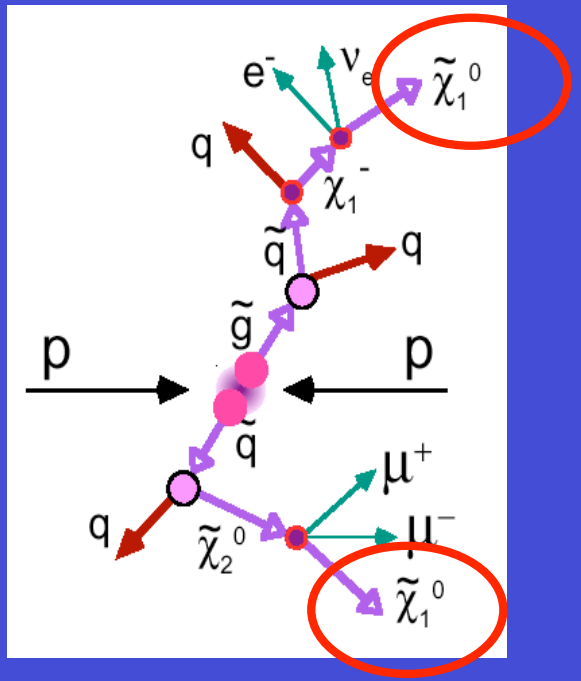
DM density in our galaxy: ~1 particle per cup of coffee

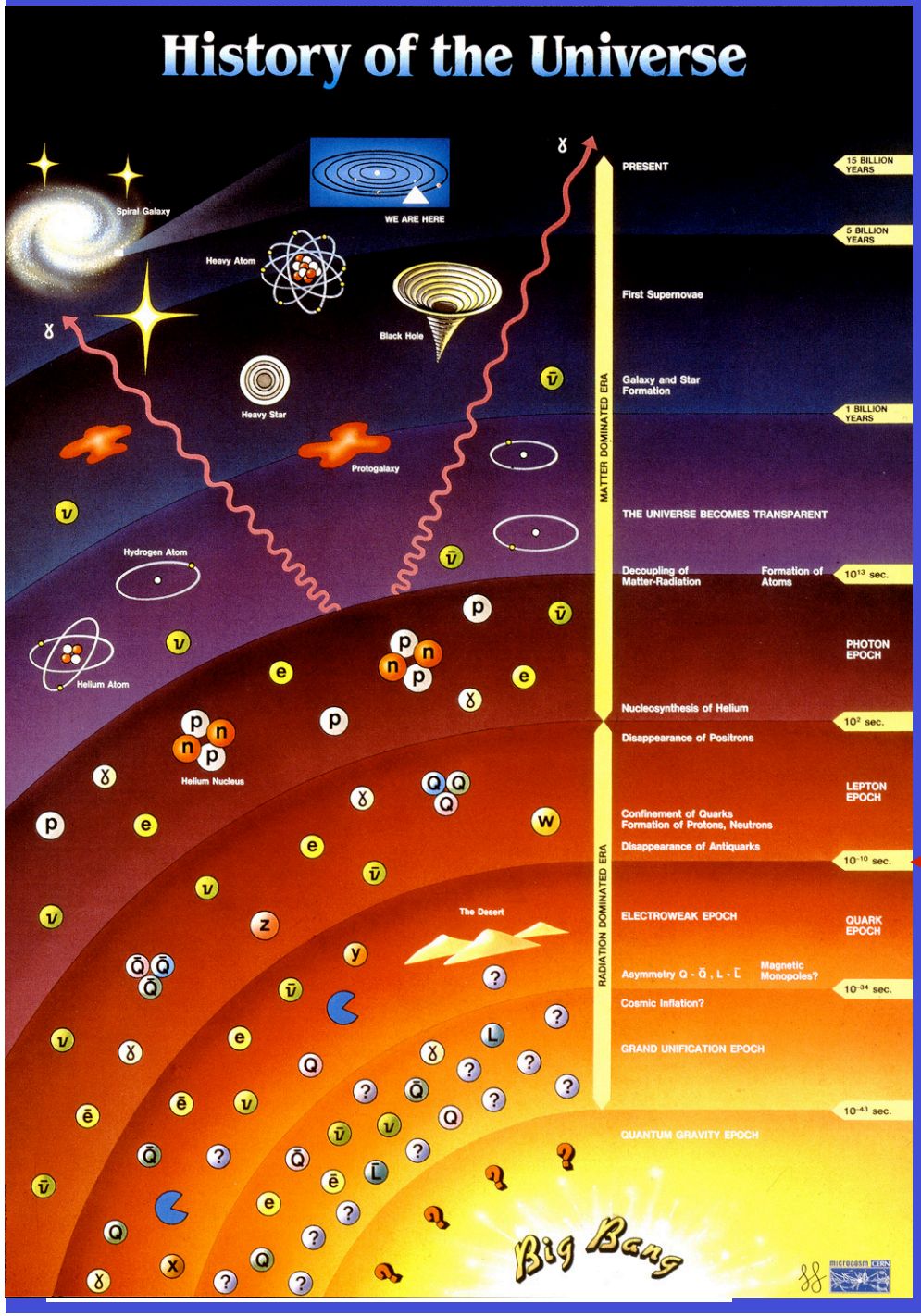
- 70% of "Dark Energy"



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 produced abundantly at the LHC !





Back in time towards the Universe's very first moments .....

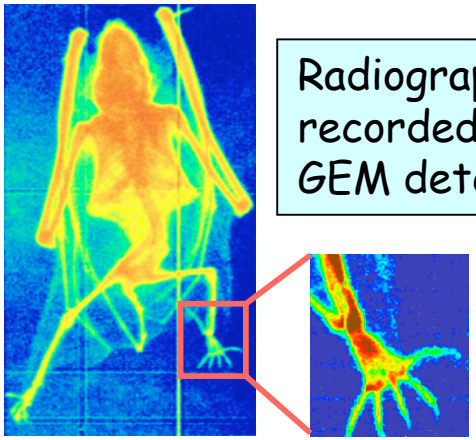
Universe cools down and energy density decreases with time

LHC energy corresponds to the energy of the Universe ~10^{-10} s after the Big Bang → 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

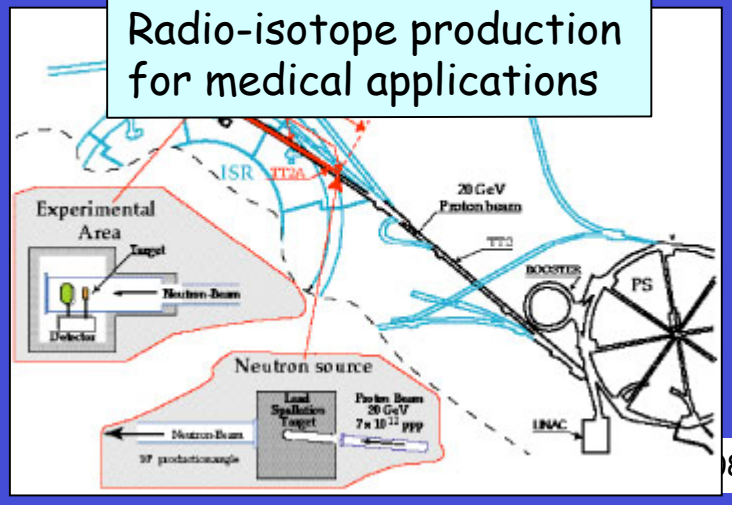
Extreme performance required in particle physics → cutting-edge technologies developed at CERN and collaborating Institutes and then transferred to society.



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 …

Hadrontherapy for cancer treatment



Radio-isotope production for medical applications

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)