The CERN Large Hadron Collider

Malika Meddahi – CERN

- What is CERN?
- Why do people do Physics?
- Why is the LHC so special?
- Does it work?

With materials from:
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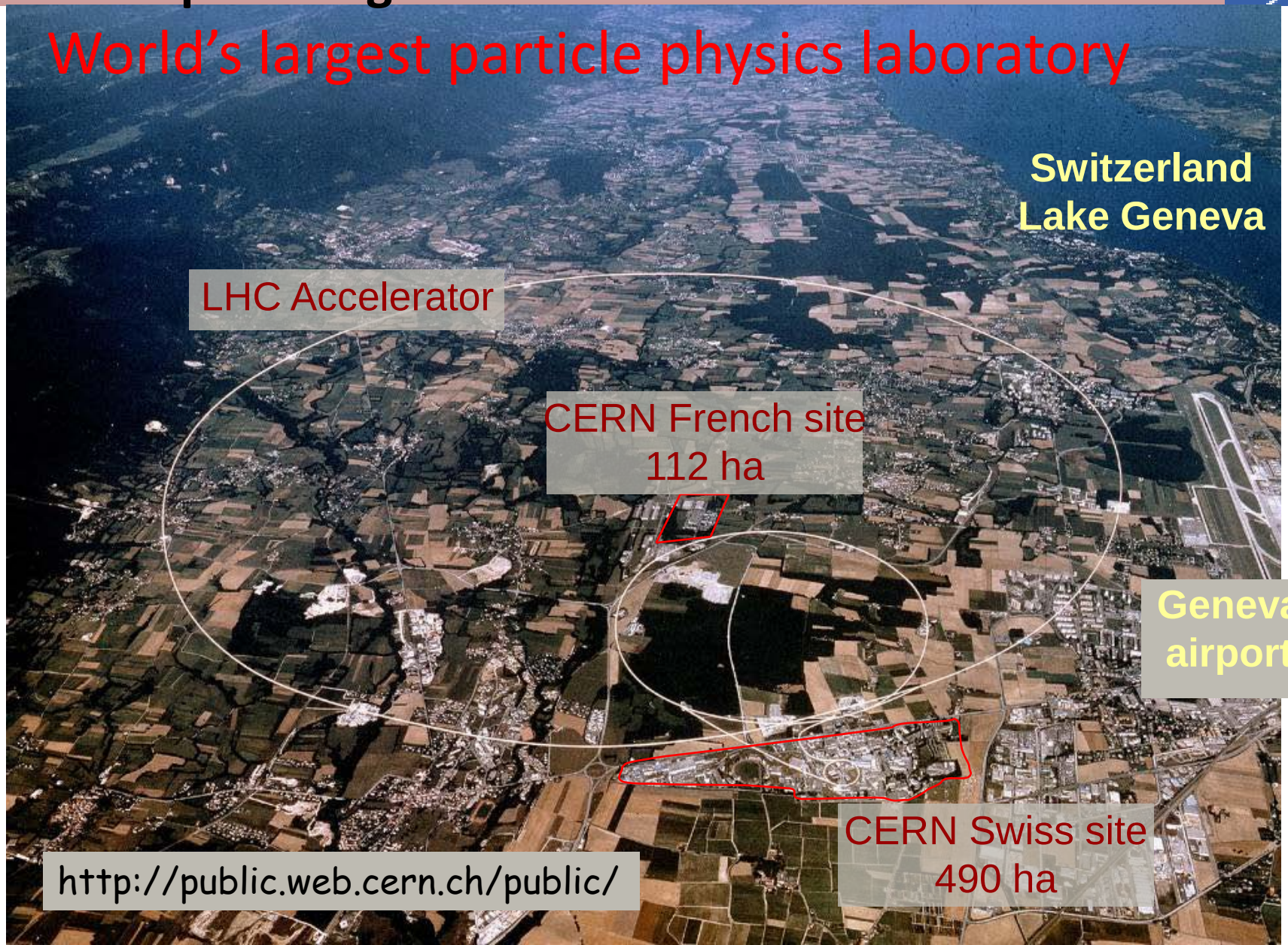
CERN

European Organisation for Nuclear Research



CERN history

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

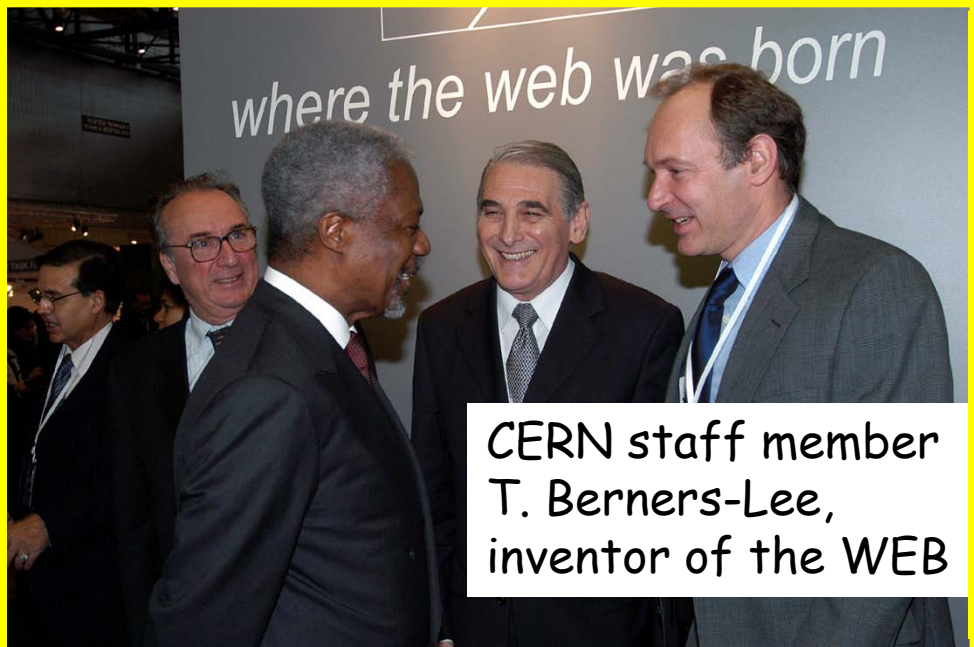
1954 The European Organization for Nuclear Research is founded by 12 countries (the provisional Council is dissolved but the CERN acronym is retained).
CERN becomes one of the first examples of post-war (scientific) cooperation

24 February 1955:
1st meeting of the CERN Council

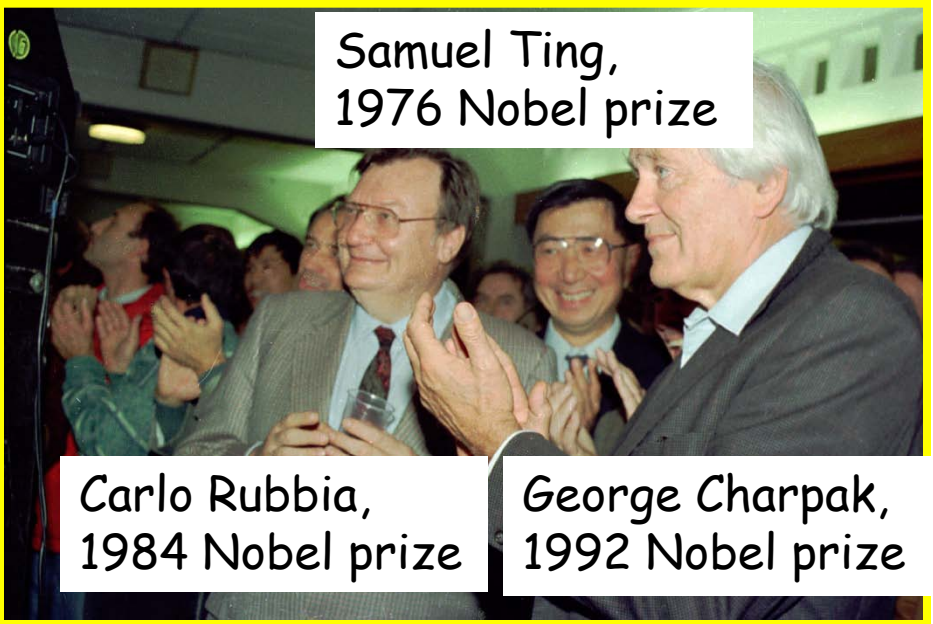
19 October 2004
CERN celebrates 50 years !

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

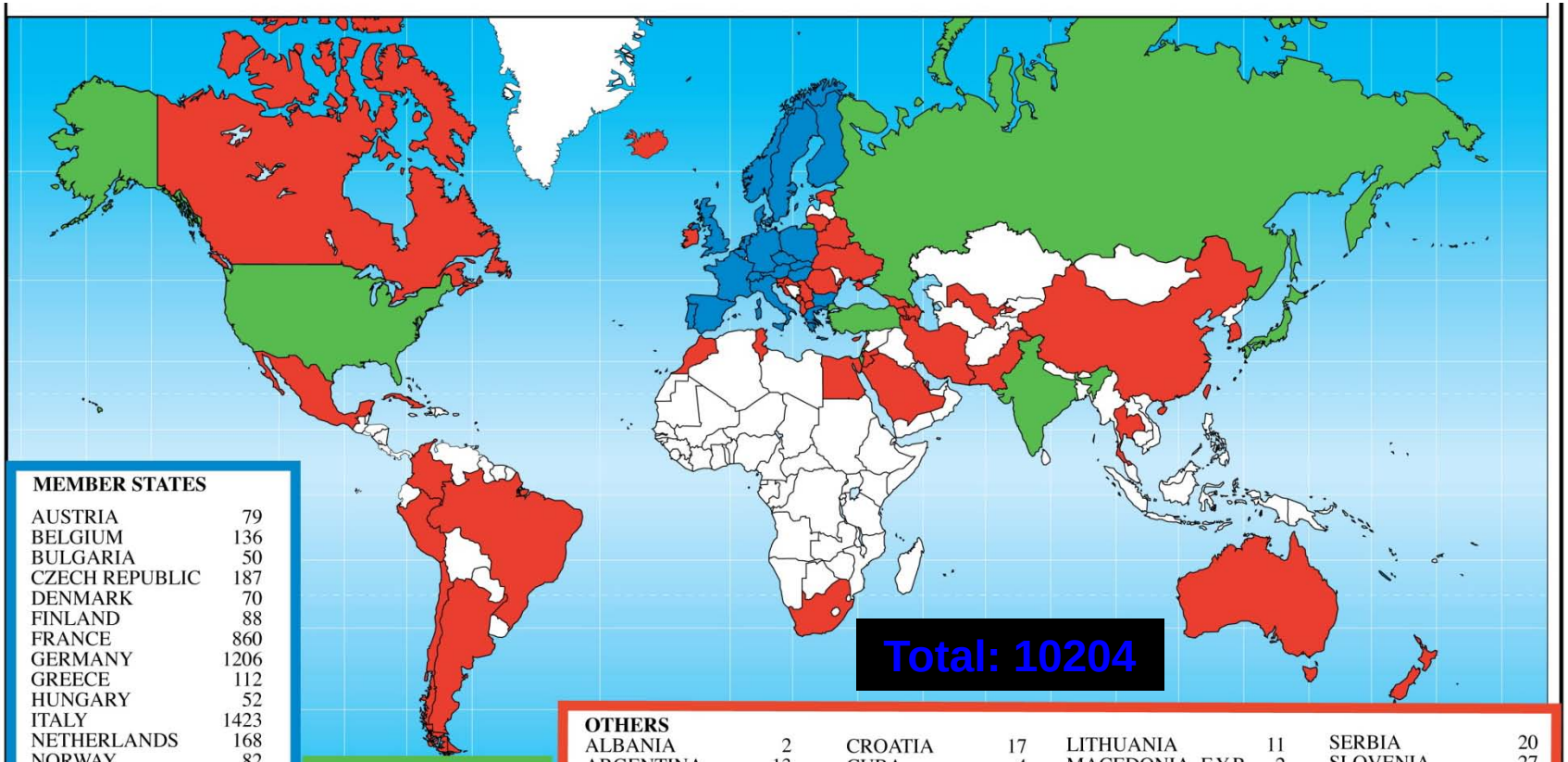


Samuel Ting,
1976 Nobel prize

Carlo Rubbia,
1984 Nobel prize

George Charpak,
1992 Nobel prize

CERN TODAY



MEMBER STATES

AUSTRIA	79
BELGIUM	136
BULGARIA	50
CZECH REPUBLIC	187
DENMARK	70
FINLAND	88
FRANCE	860
GERMANY	1206
GREECE	112
HUNGARY	52
ITALY	1423
NETHERLANDS	168
NORWAY	82
POLAND	196
PORTUGAL	138
SLOVAKIA	62
SPAIN	333
SWEDEN	73
SWITZERLAND	357
UNITED KINGDOM	713

6385

OBSERVER STATES

INDIA	100
ISRAEL	61
JAPAN	212
RUSSIA	841
TURKEY	74
USA	1702

2990

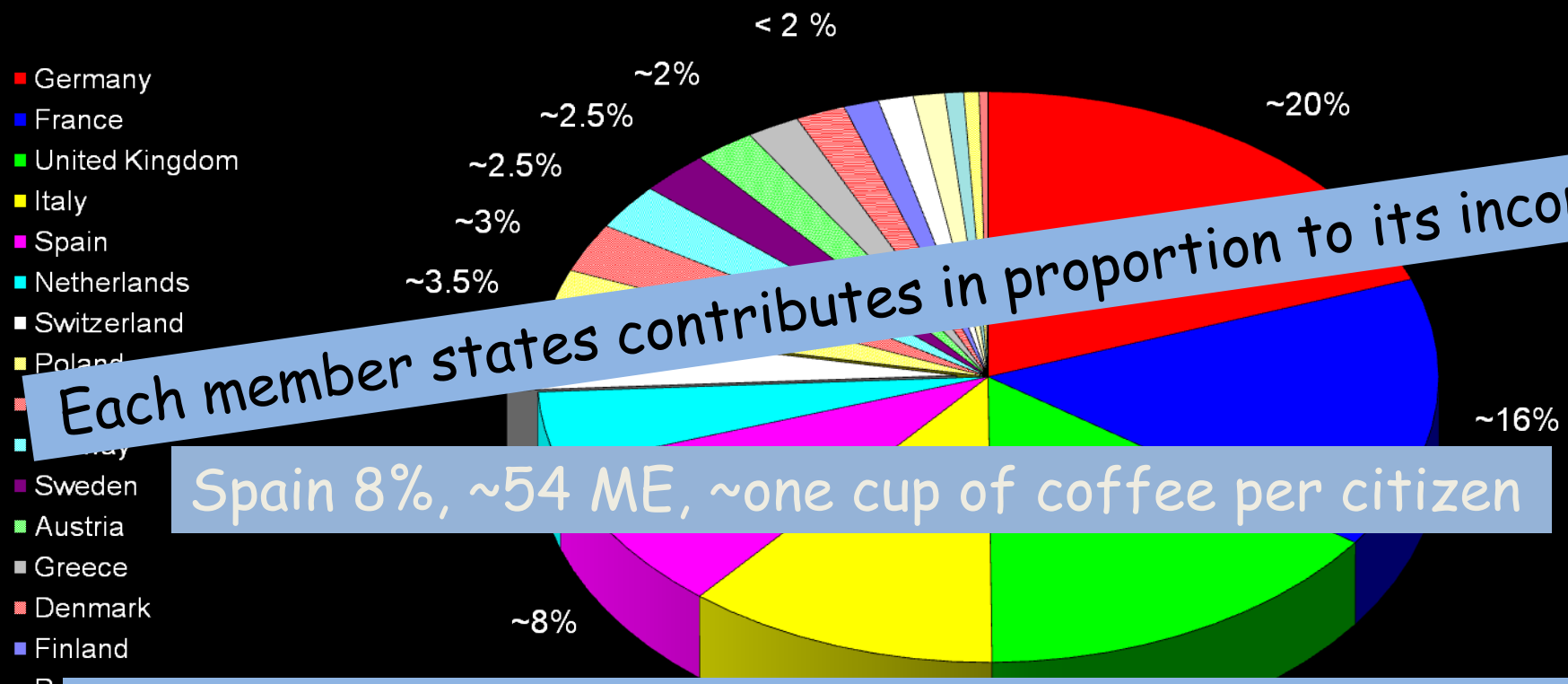
OTHERS

ALBANIA	2	CROATIA	17	LITHUANIA	11	SERBIA	20
ARGENTINA	13	CUBA	4	MACEDONIA, F.Y.R.	2	SLOVENIA	27
ARMENIA	12	CYPRUS	8	MALTA	1	SOUTH AFRICA	10
AUSTRALIA	20	EGYPT	5	MEXICO	32	THAILAND	1
AZERBAIJAN	1	ESTONIA	10	MONTENEGRO	1	TUNISIA	1
BELARUS	21	GEORGIA	8	MOROCCO	5	UKRAINE	18
BRAZIL	78	ICELAND	3	NEW ZEALAND	9	UZBEKISTAN	1
CANADA	152	IRAN	16	PAKISTAN	16		
CHILE	3	IRELAND	14	PERU	2		
CHINA	80	KOREA	74	QATAR	1		
CHINA (TAIPEI)	51	JORDAN	1	ROMANIA	64		
COLOMBIA	11	LEBANON	1	SAUDI ARABIA	2		

829

Snapshot on 10.11.2010

Budget 2011: ~1‘000 MCHF (760 M€ - 1‘100 M$)



Each member states contributes in proportion to its income

Spain 8%, ~54 ME, ~one cup of coffee per citizen

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

Romania (as Candidate for Accession) : + 4.212 MCHF

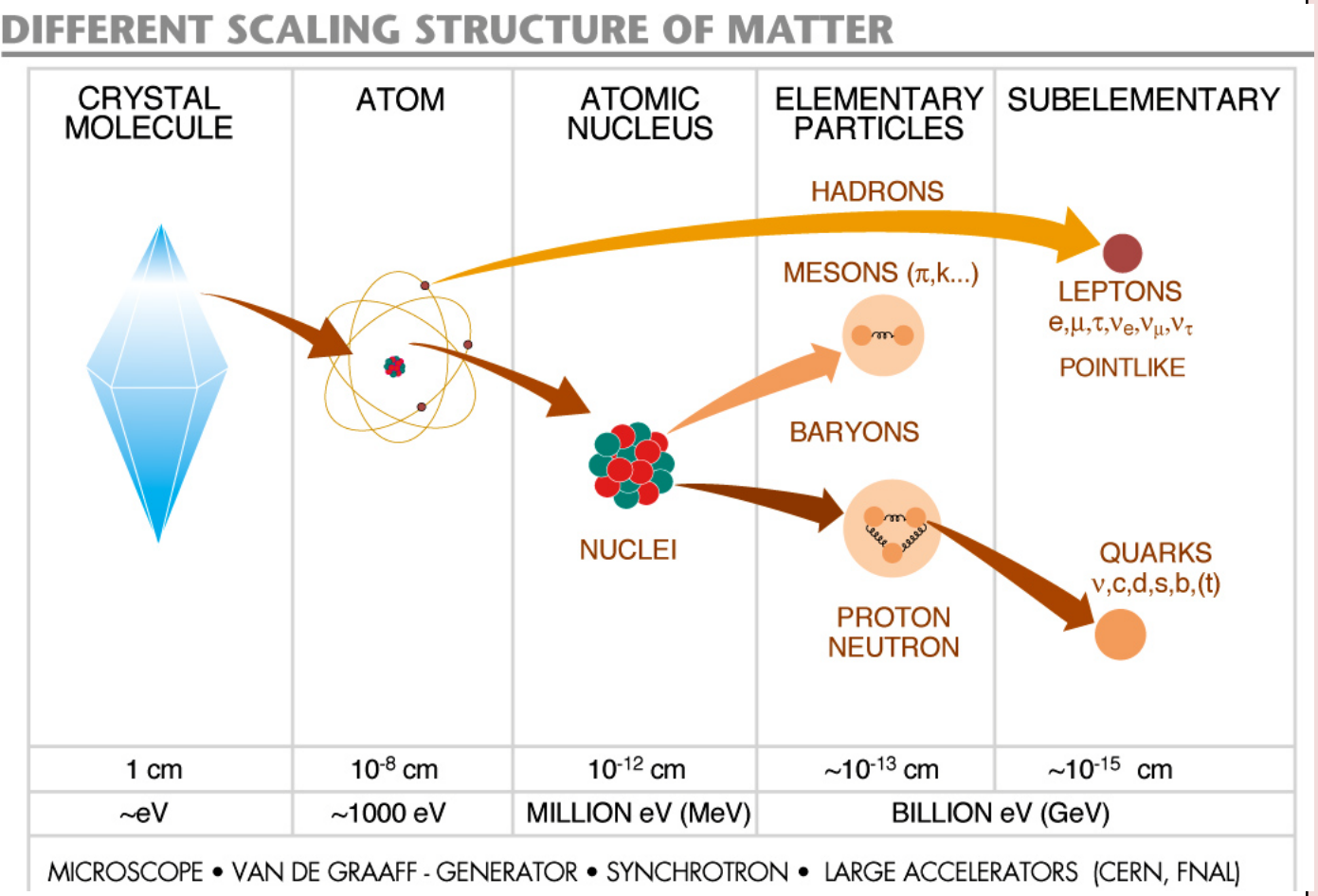
Why do people do Physics?

- Since dawn of humanity, people want to understand the world
  - Why do apples fall on the ground?
  - What is the origin of sunshine, rain, flow of ocean?
  - What are the stars, the moon and …
- In the end: guide its action to our advantages

We've already gone a long way!

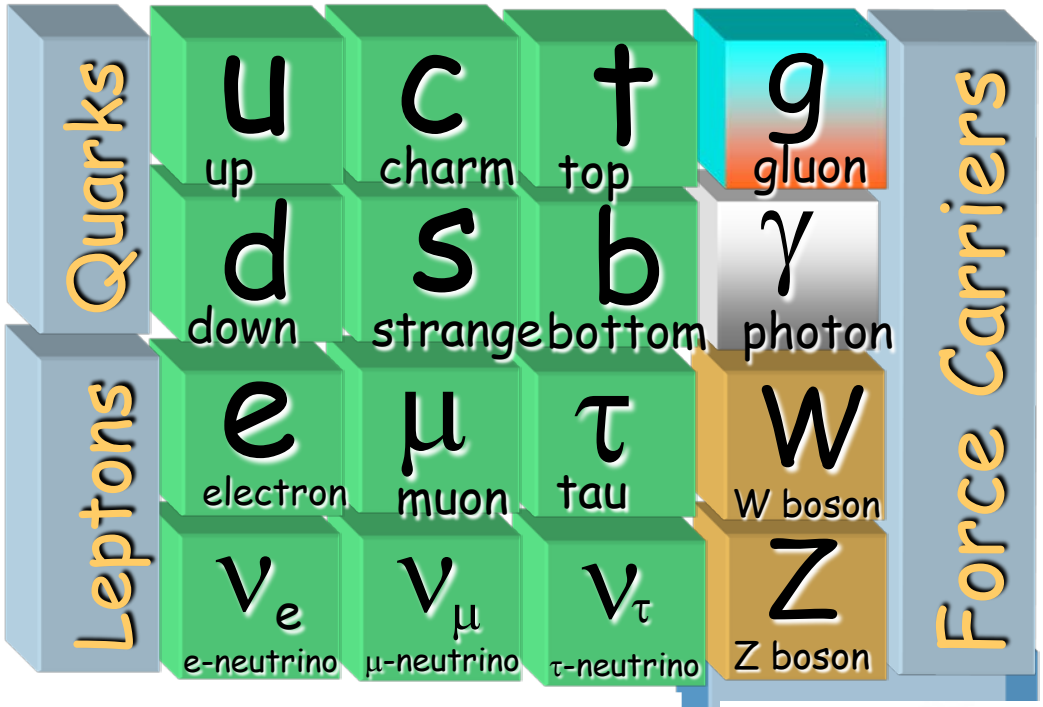
- We are not (less) scared anymore by thunder, lightning, solar eclipse … → result of basic research
- We understand:
  - Mechanics (car, airplanes…)
  - Electricity (Computers, TV, mobile phone….)
  - Thermodynamics (refrigerators…)
  - Optics (glasses, lasers,….)
- Alchemist led us to chemistry and the understanding of
  - Atoms, but they consist of something still smaller
  - Protons, neutrons, electrons, photons…
  - And smaller components, quarks, neutrinos

Particle Physics

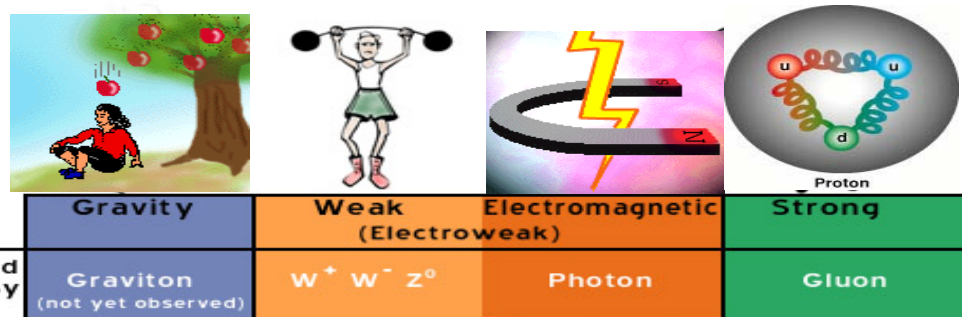


Study the elementary particles (e.g. the building blocks of matter: electrons and quarks) and the forces that control their behaviour at the most fundamental level

The Standard Model



Particles and forces



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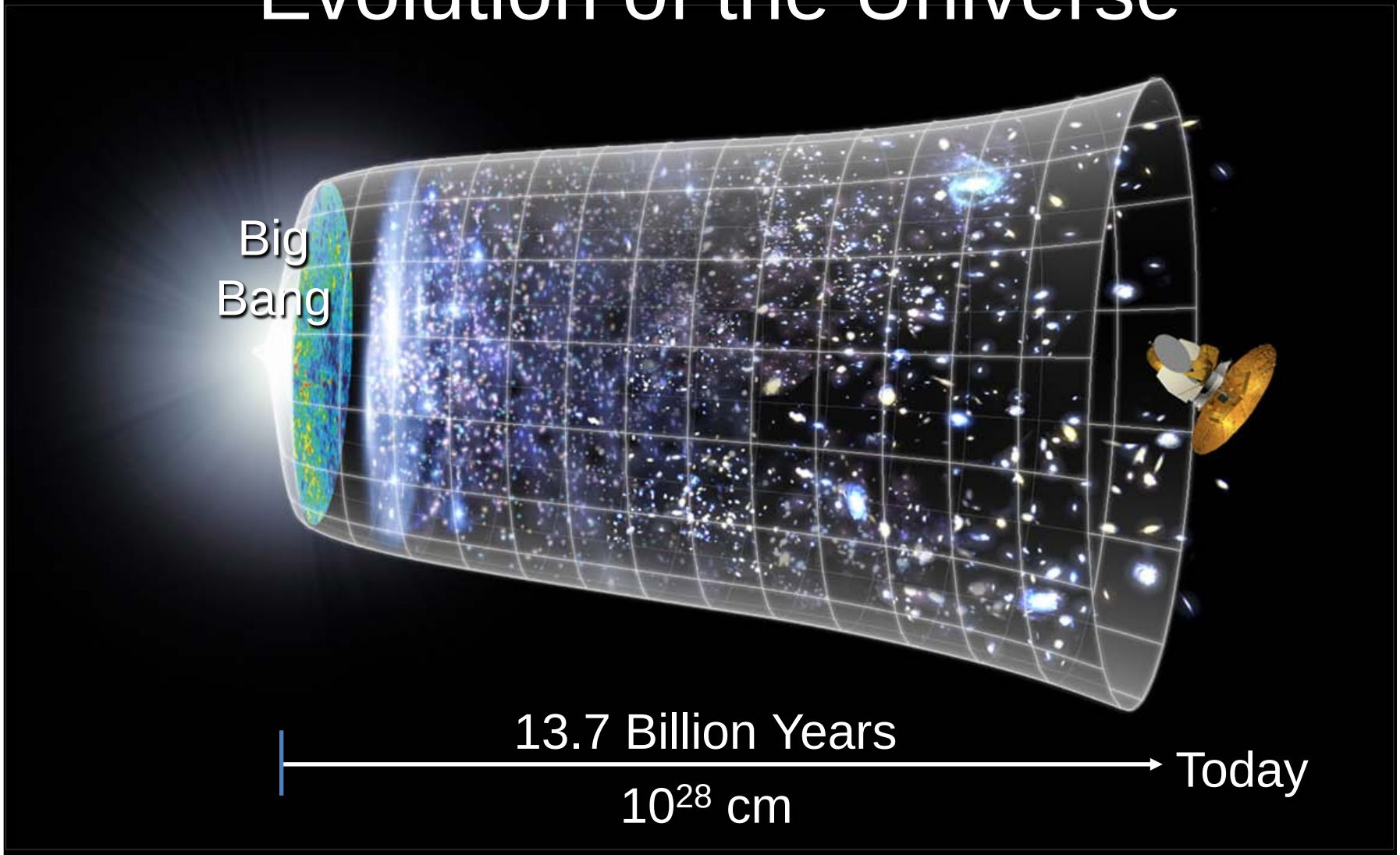
What's next?

Several outstanding questions remain:

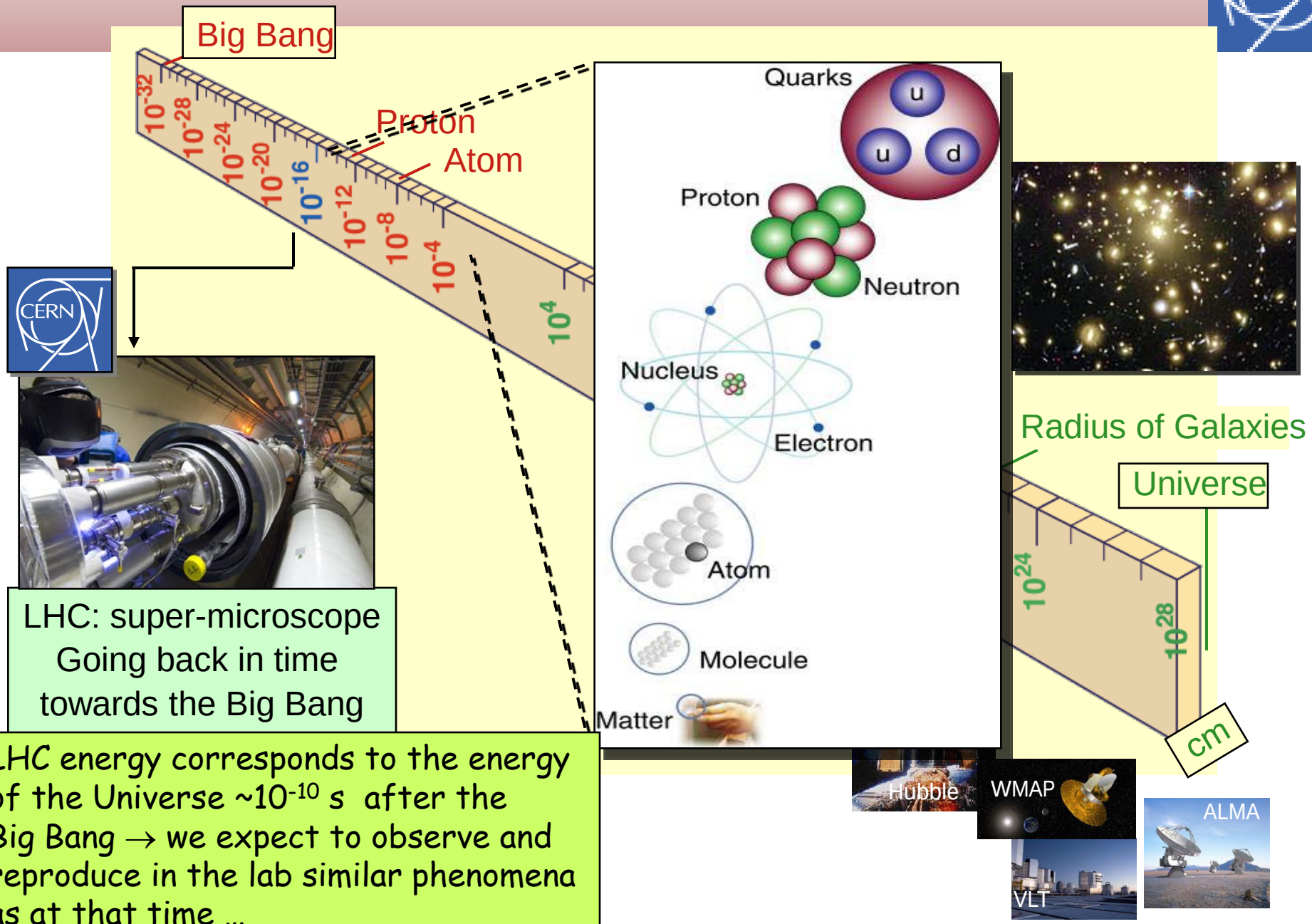
- Why these particles behave like they do?
- What has determined their properties (mass, charge,…)
- Are there other forces in addition to the known 4?
- Is there a final theory?
- What happened in the first moments of the Universe life (10^{-10} s after the Big Bang) ?
- etc…

The small and the very big

Evolution of the Universe



"The two infinities": the very small allows us to understand the very big



LHC: super-microscope
Going back in time
towards the Big Bang

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 …

Why using particle accelerators?

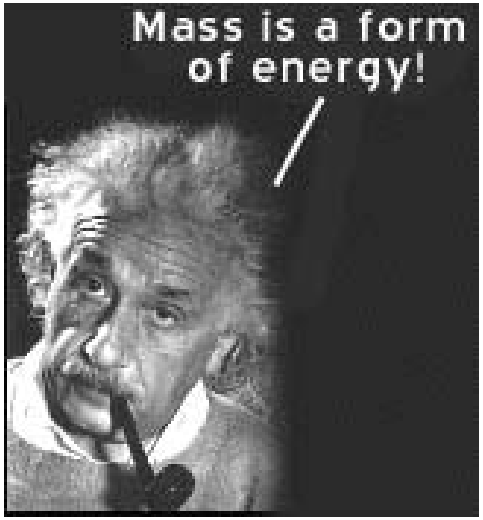
When one accelerates a particle…

It does not necessarily go much faster

Its energy increases, so does its mass

$$E = m c^2$$

In an interaction, it can transform its energy into massive particles, heavier than its initial mass.



…one transforms energy into mass

The units

Expressing 1 proton in different units:

~1.6 x10^{-27} Kg
~1.5x10^{-10} J
~938’000’000 eV

Derivatives:

keV (1’000 eV)
MeV (1’000’000 eV)
GeV (1’000’000’000 eV)
TeV (1’000’000’000’000 eV)

Example: proton at 1 GeV (1’000’000’000 eV) accelerate to almost speed of light → 7000 GeV (7’000’000’000’000 eV)

Energy, mass and temperature

1 electron Volt (eV) ~ 1.6×10^{-19} J

~ 1.8×10^{-36} kg

~ 11'600 °C

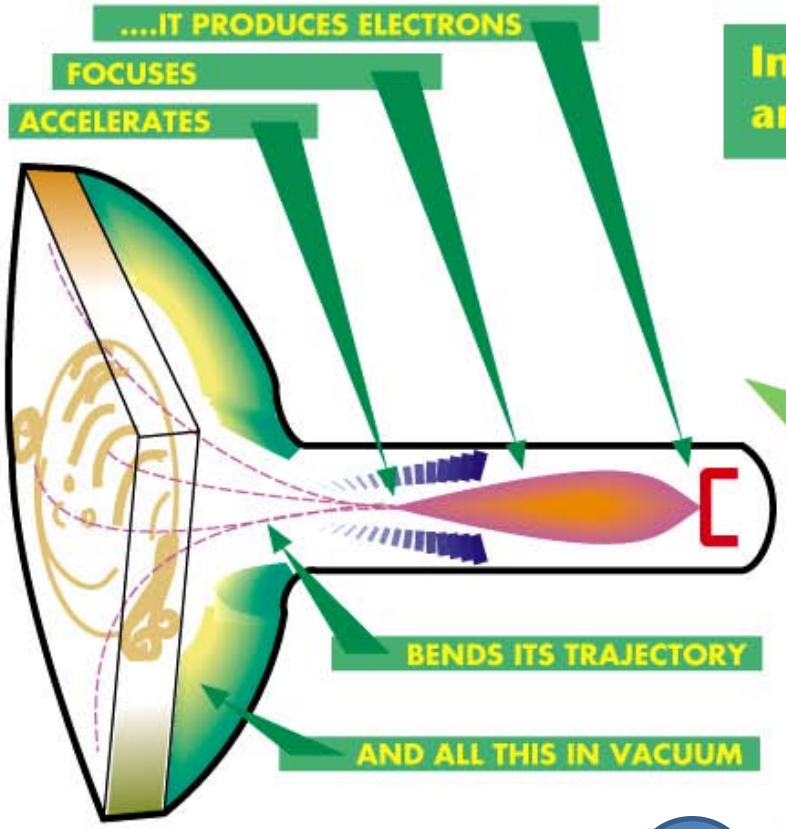
1 Tera electron Volt (TeV) ~ 10^{16} °C

Comparison:

Sun: outside temperature: 6'000 °C

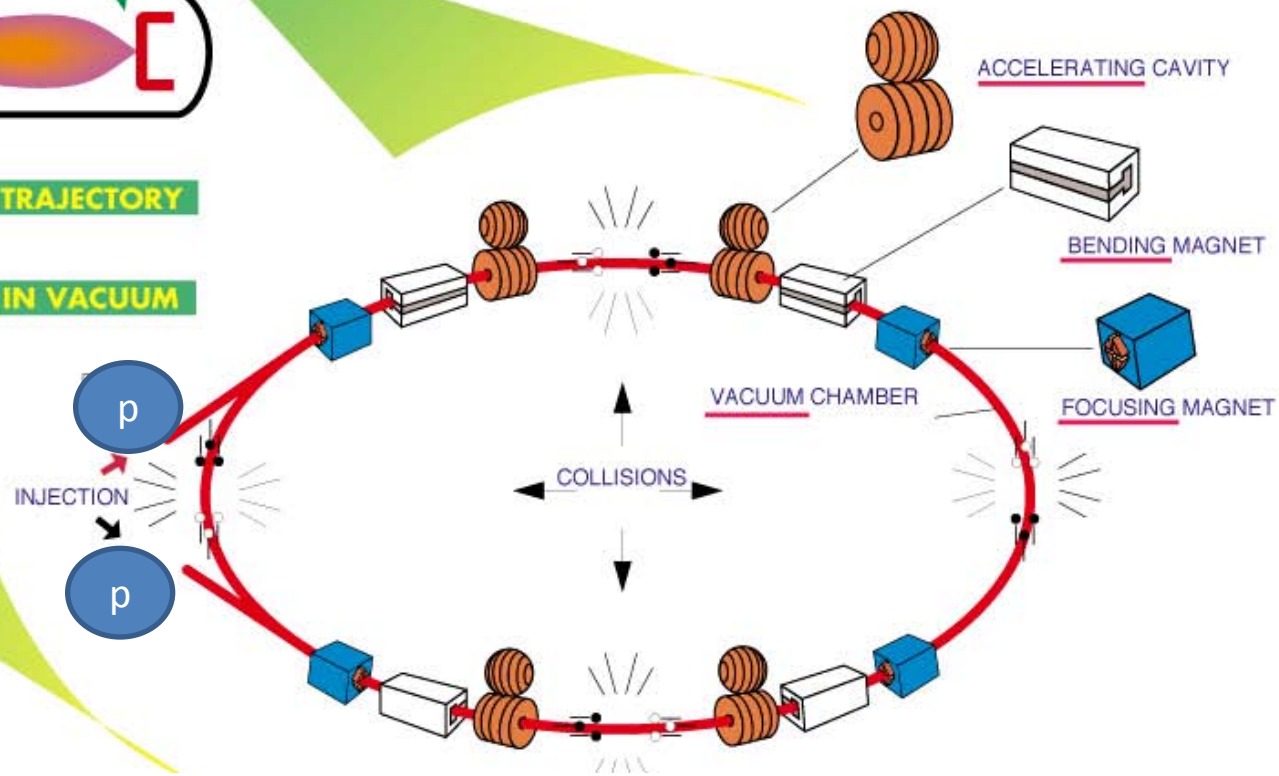
inside temperature: 15-20 10^{6} °C

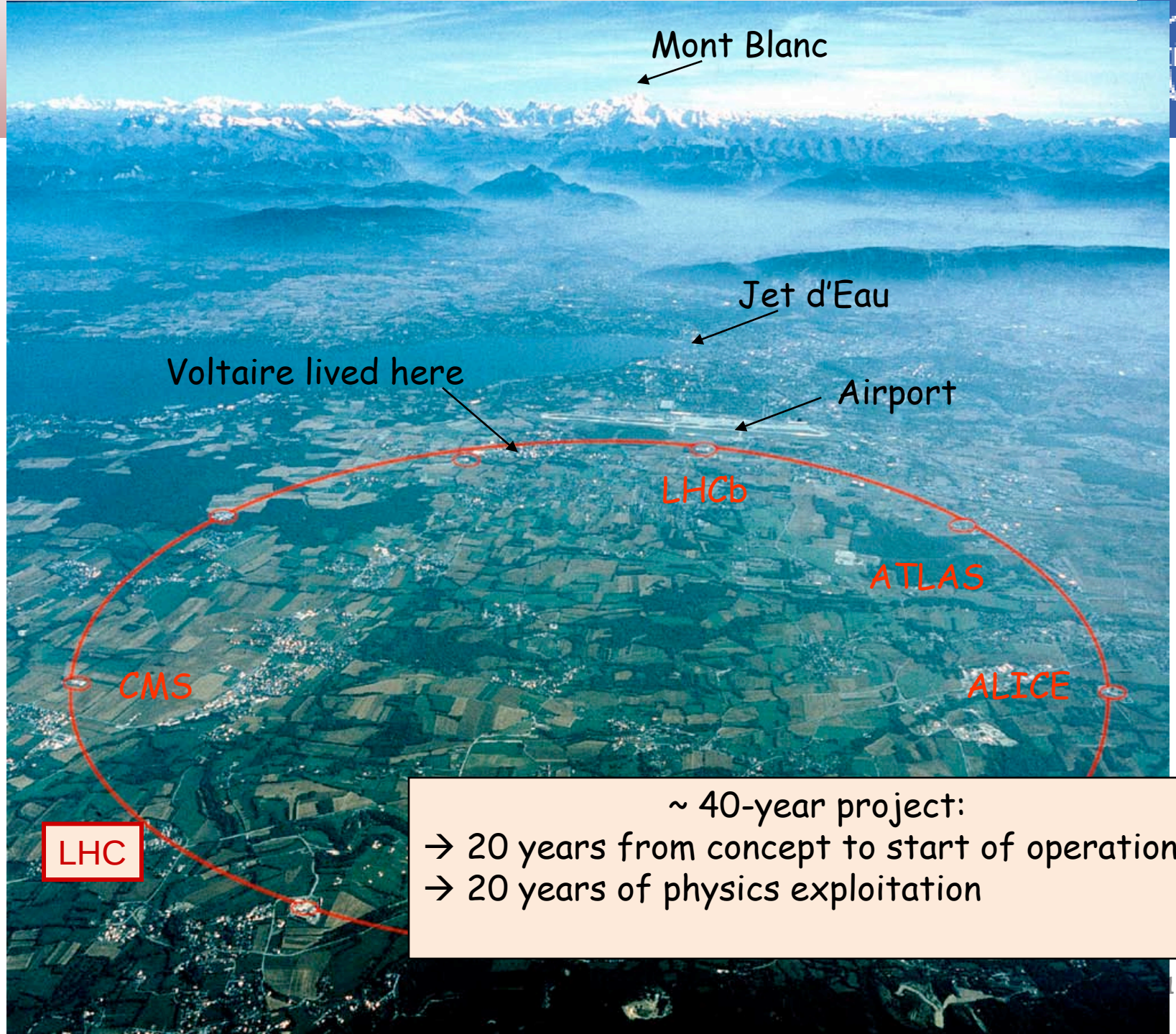
DID YOU KNOW YOUR TELEVISION SET IS AN ACCELERATOR ?



In your TV set, the electrons are accelerated to 20000 volts.

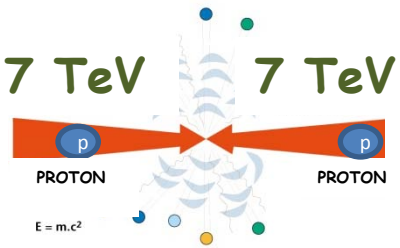
In the LHC the protons are accelerated to 7’000’000’000 eV

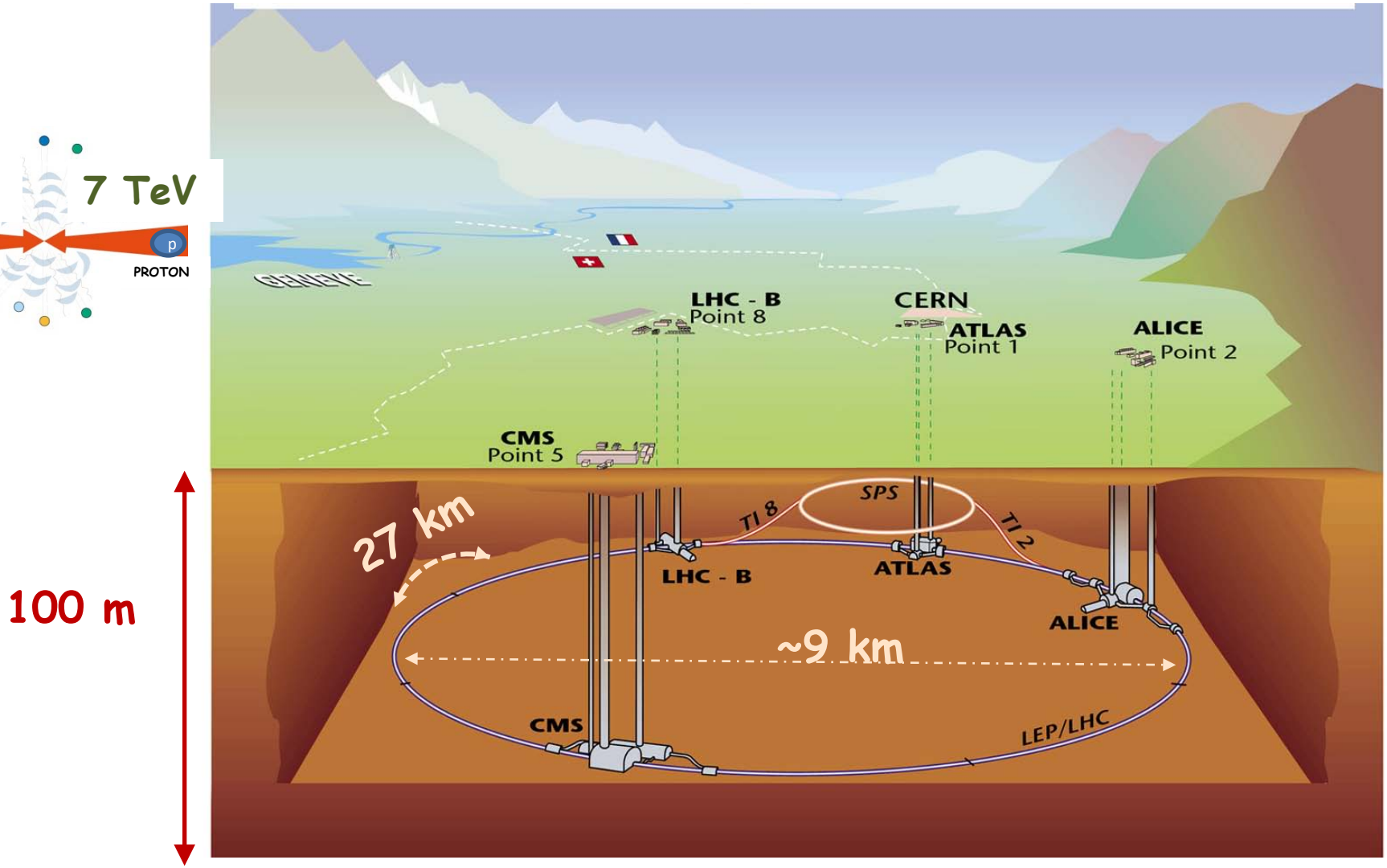




~ 40-year project:
→ 20 years from concept to start of operation
→ 20 years of physics exploitation

The Large Hadron Collider





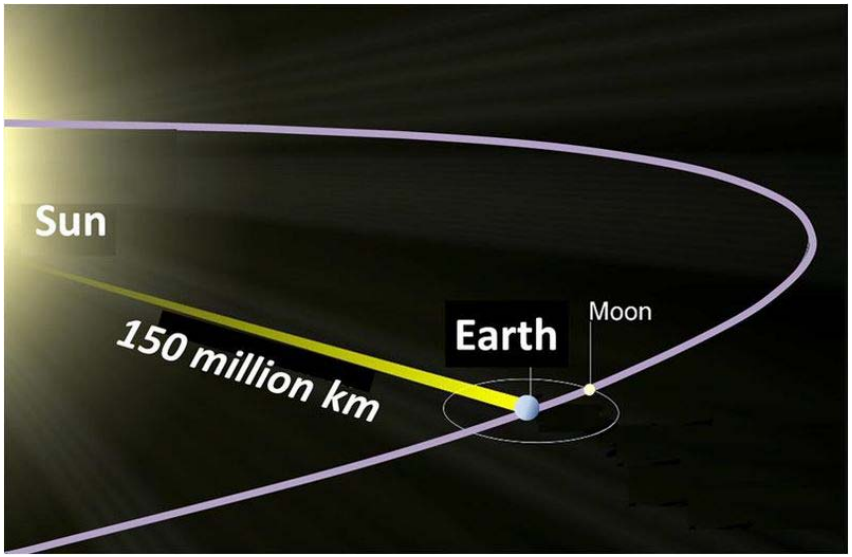
The fastest racetrack on the planet!

Fastest racetrack on the planet: Particles will race around the LHC ring at the speed of light, traveling at almost 300’000 km/s .

In 1 second they will have travelled ~11’000 times the LHC ring.

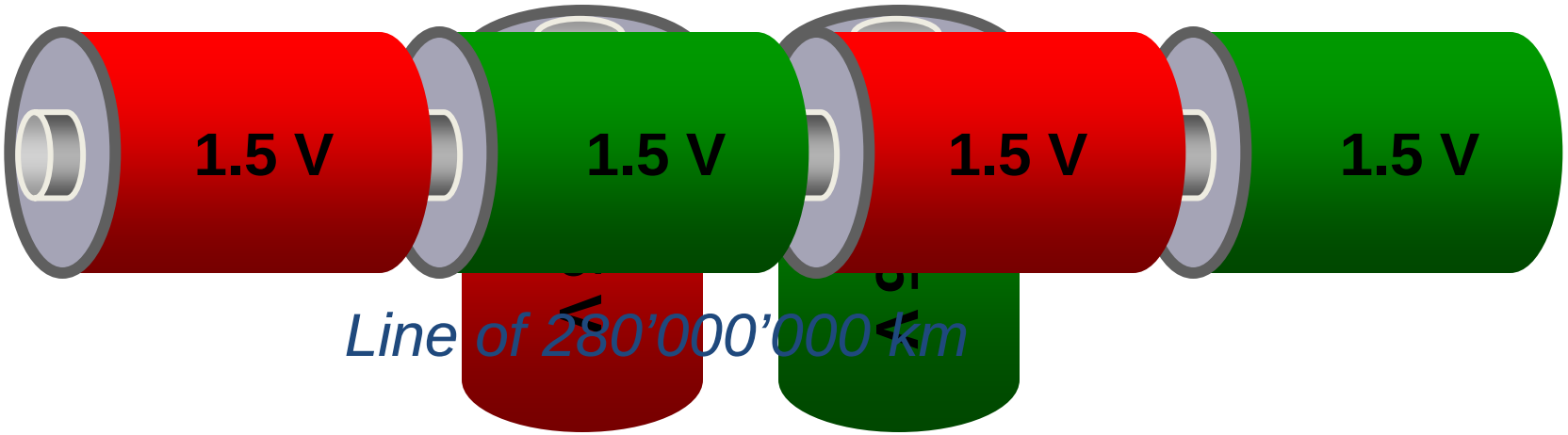
10 hours of LHC travel

100 times
the distance between
the earth and the sun!



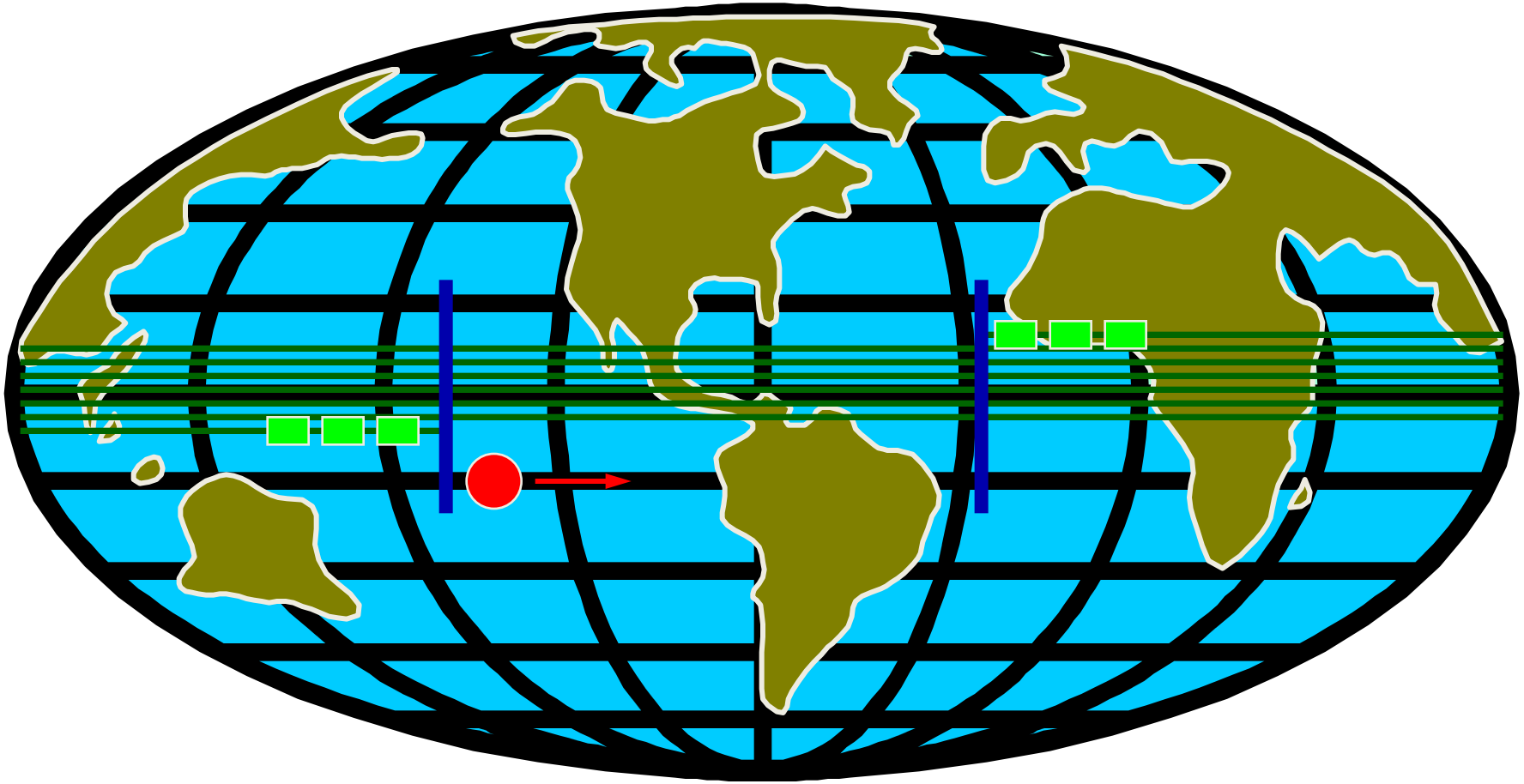
How to make your own 7 TeV accelerator?

1. **Get hold of ~4’666 trillion batteries ….** For an acceleration to 7 TeV ... in principle...a total voltage of 7 TeV (Trillion Volts) is required
2. **Weld the poles**

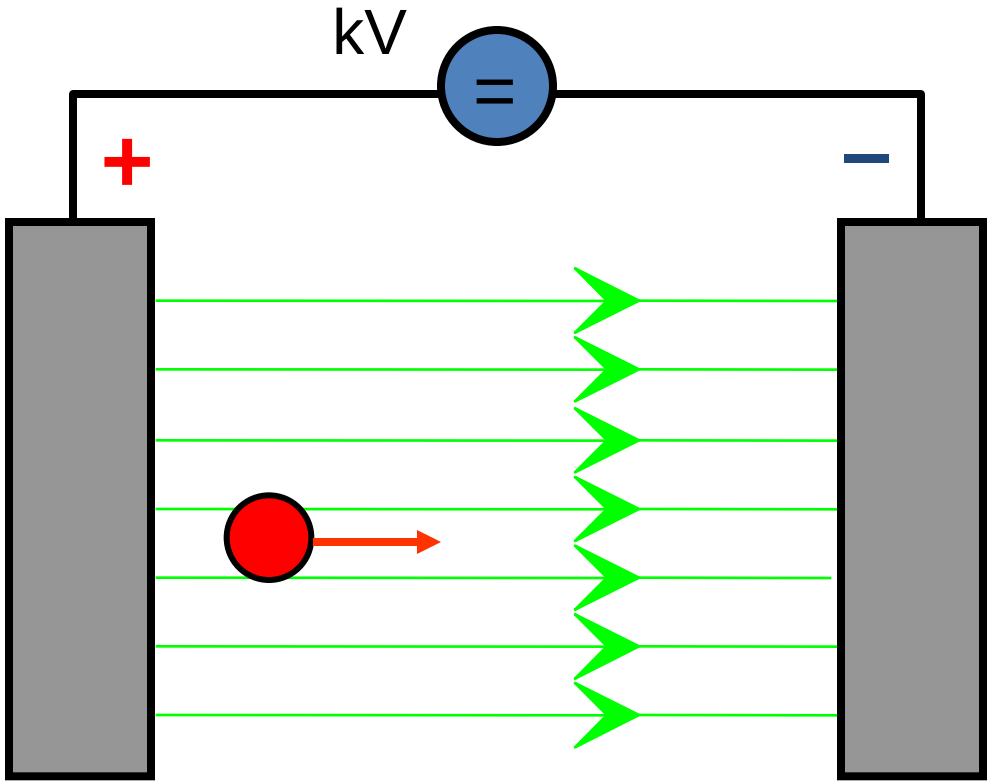


3. **Weld the electrodes at the two extreme ends**
4. **Negociate lands with land owners**

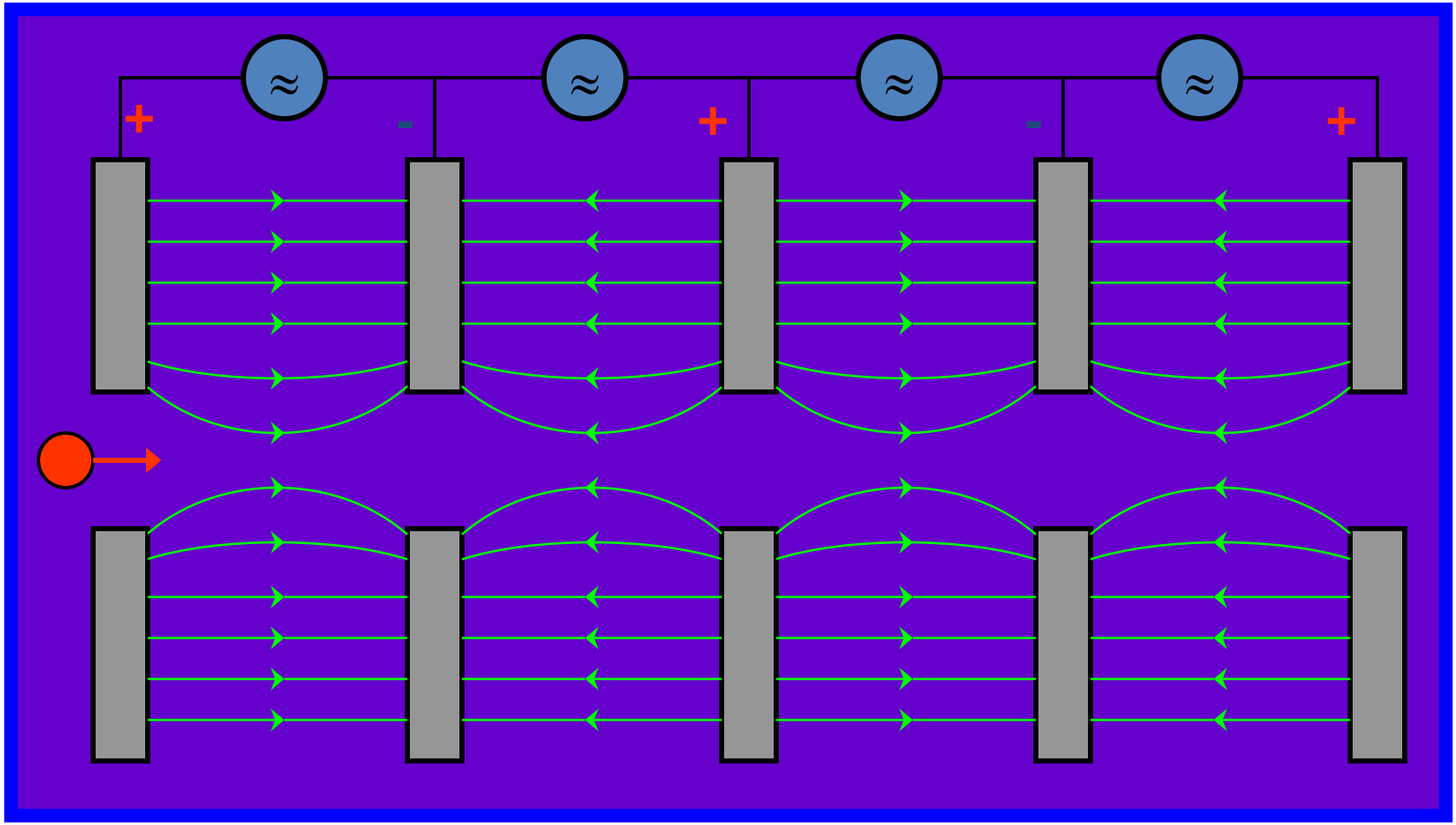
7000 times around the equator



Acceleration in an electrical field



from one cell to an accelerating cavity

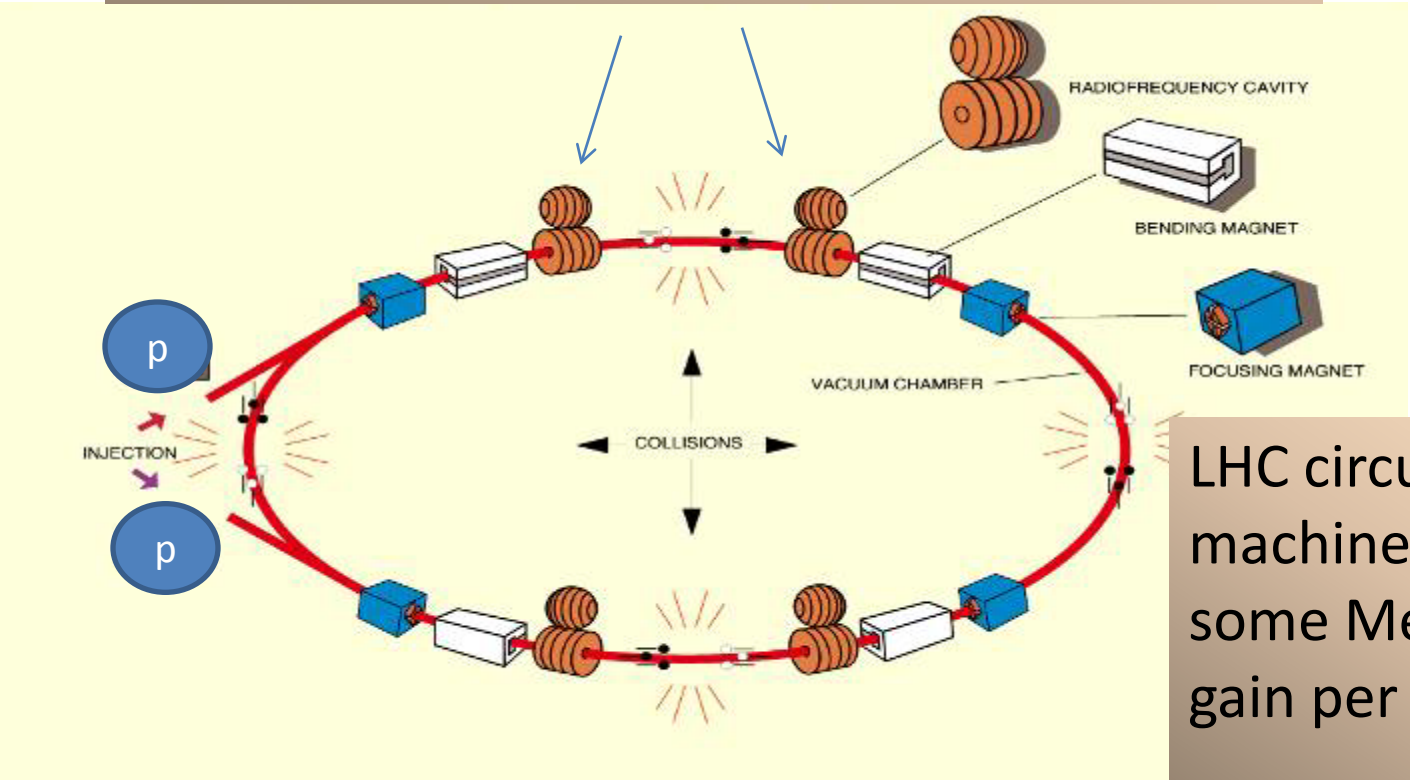


Acceleration to 7 TeV

Maximum electrical field in an accelerator is in the order of ~10 MV/m.

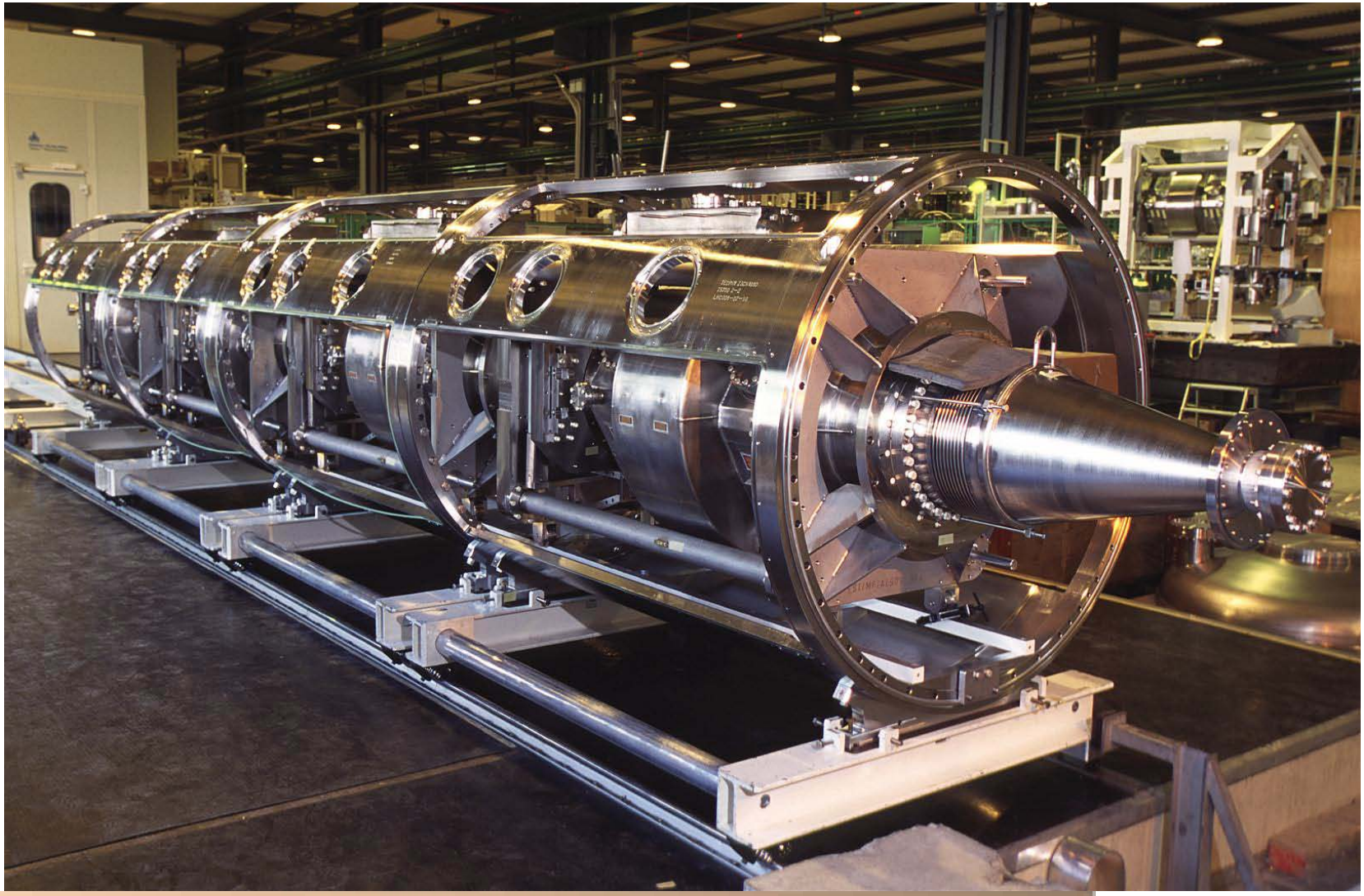
Synchrotron: circular accelerator and many passages in RF cavities

RF Cavities → Boost particles at each turn



LHC circular machine with some MeV energy gain per turn

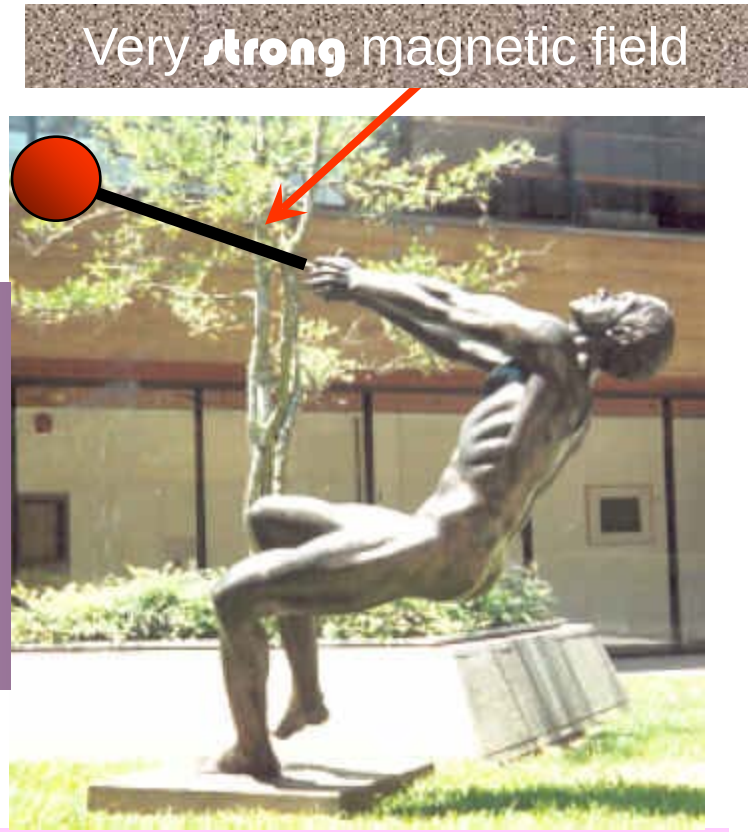
Acceleration to 7 TeV



4 cavities/module - 2 modules/beam - 16 MV (5.5 MV/m)

How to keep particles on the circle?

The relativistic hammer thrower

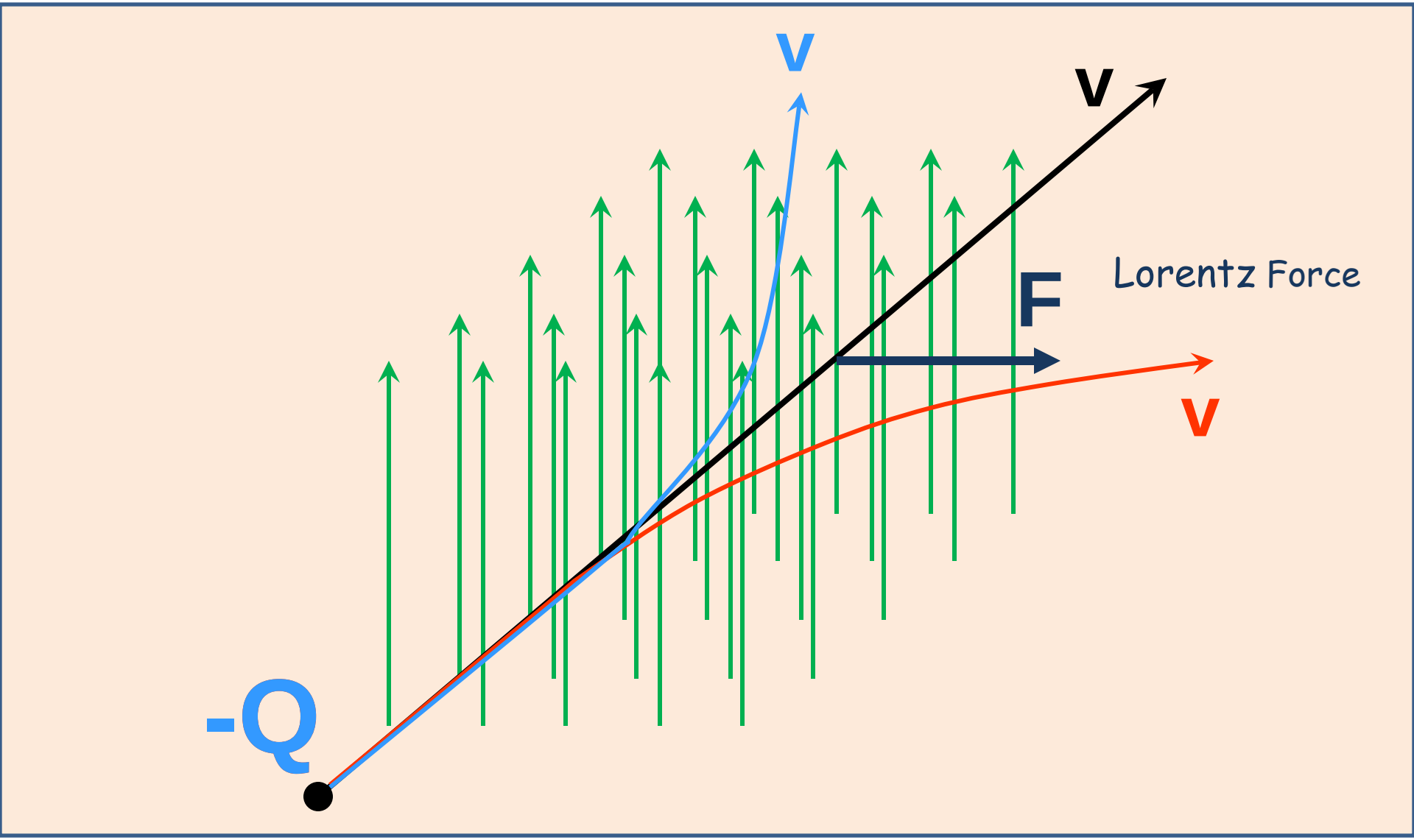


We went to keep particle on a circle - do not want to throw them away…

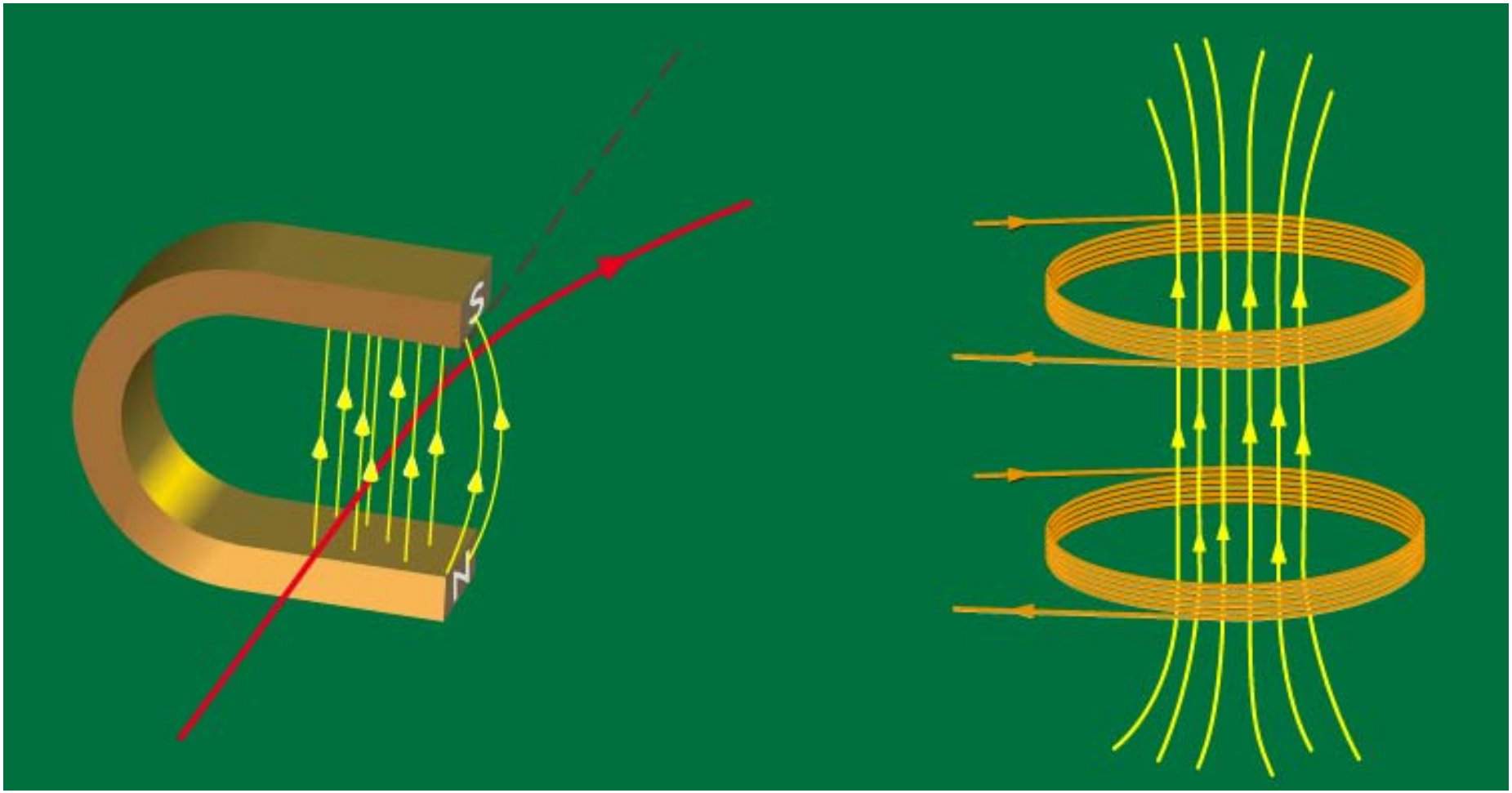
LHC is not only accelerator, also storage ring!

- Magnets deflect protons and keep them on a circle
- While the electrical field accelerates proton and magnetic field increases

Path curvature from magnetic field



Magnetic deflection



What makes LHC so special?

The

Accelera

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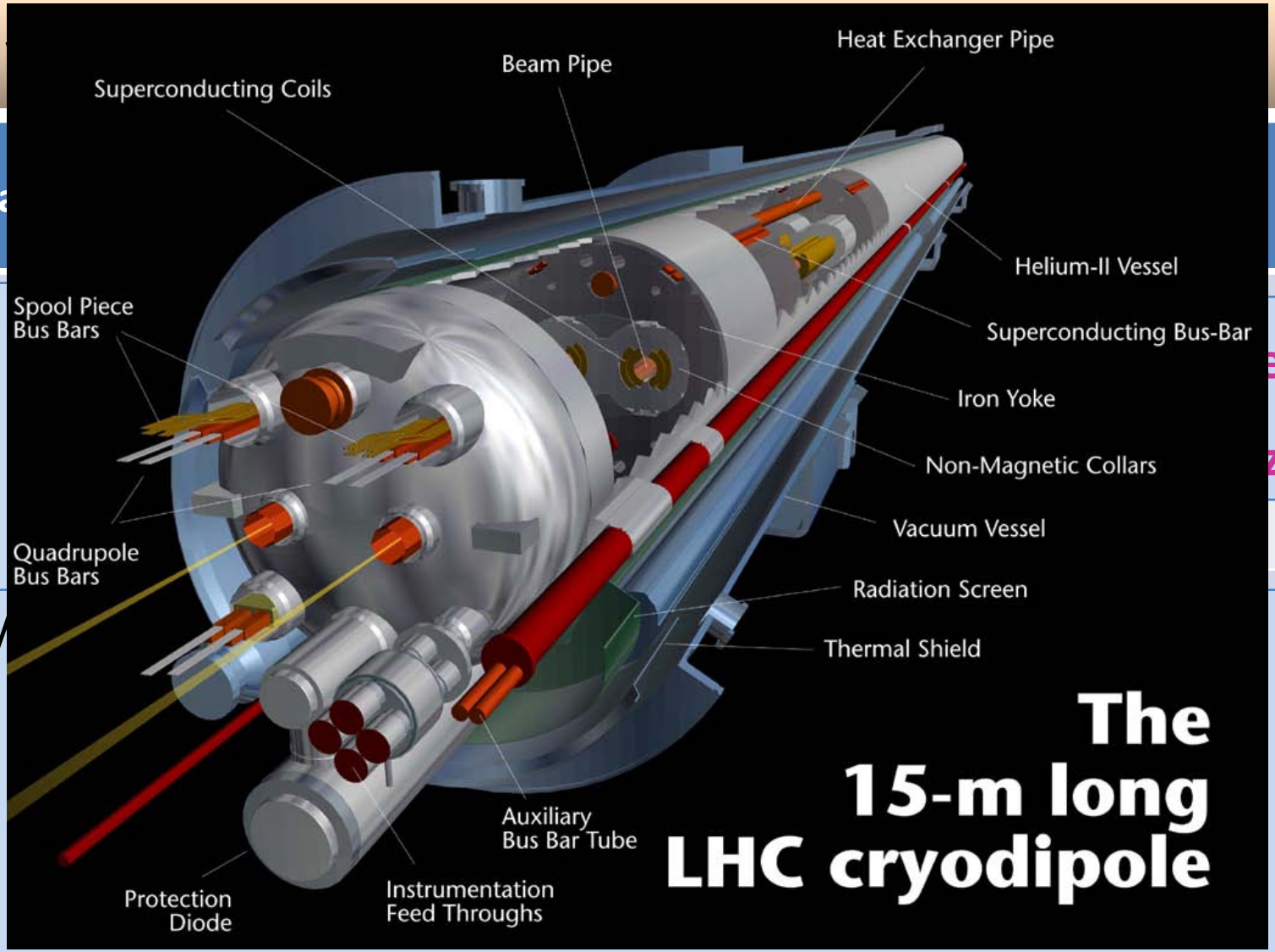


What makes LHC so special?

The largest fridge in the world

- Super Conducting magnets get to high current (13’000 A) with very little voltage
- But they have to be very cold (1.9 K or -271.3 C)
- Technique is called cryogenics – works like a fridge
- Technique is known but :

  Have to cool 40’000 tons to 1.9 K and keep it cold →Takes about …. 1 month

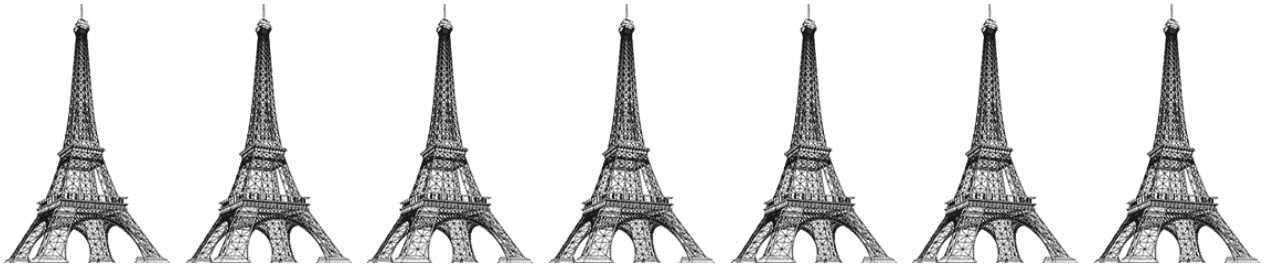
  → Liquid Helium ~ yearly world supply – 120 t
- Largest fridge in the world – even colder than outer space! (2.7 K or -270.5 C)

10’000 magnets

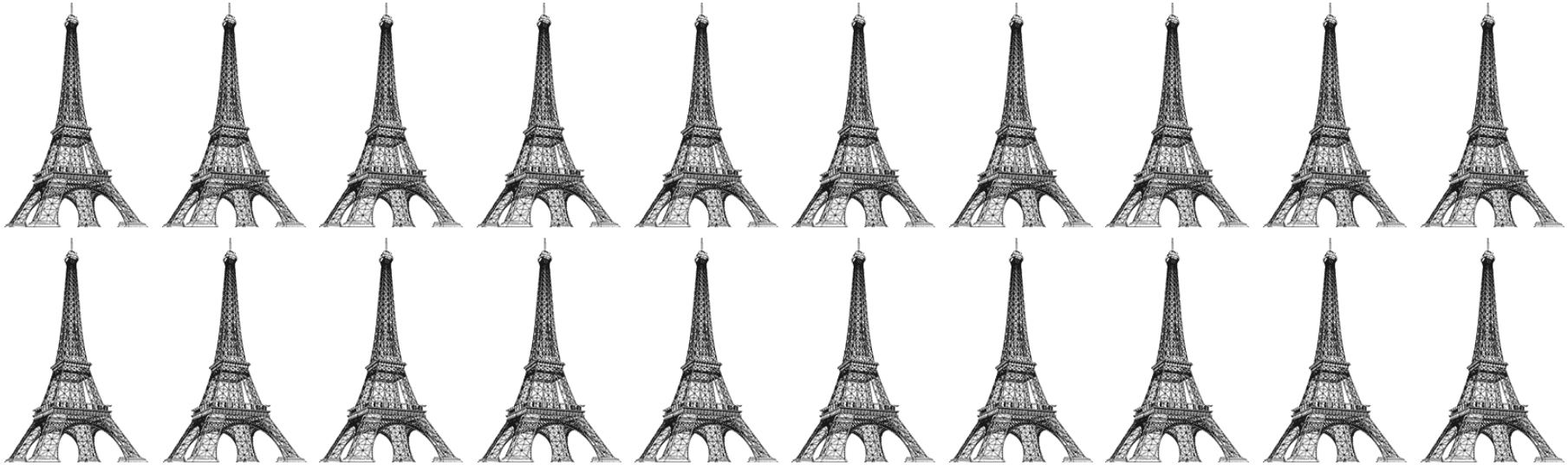
Dipole magnets awaiting their descent down to the LHC

Tons to transport and install

Installed in the tunnel: 50’000 t



Transported over Europe: ~150’000 t



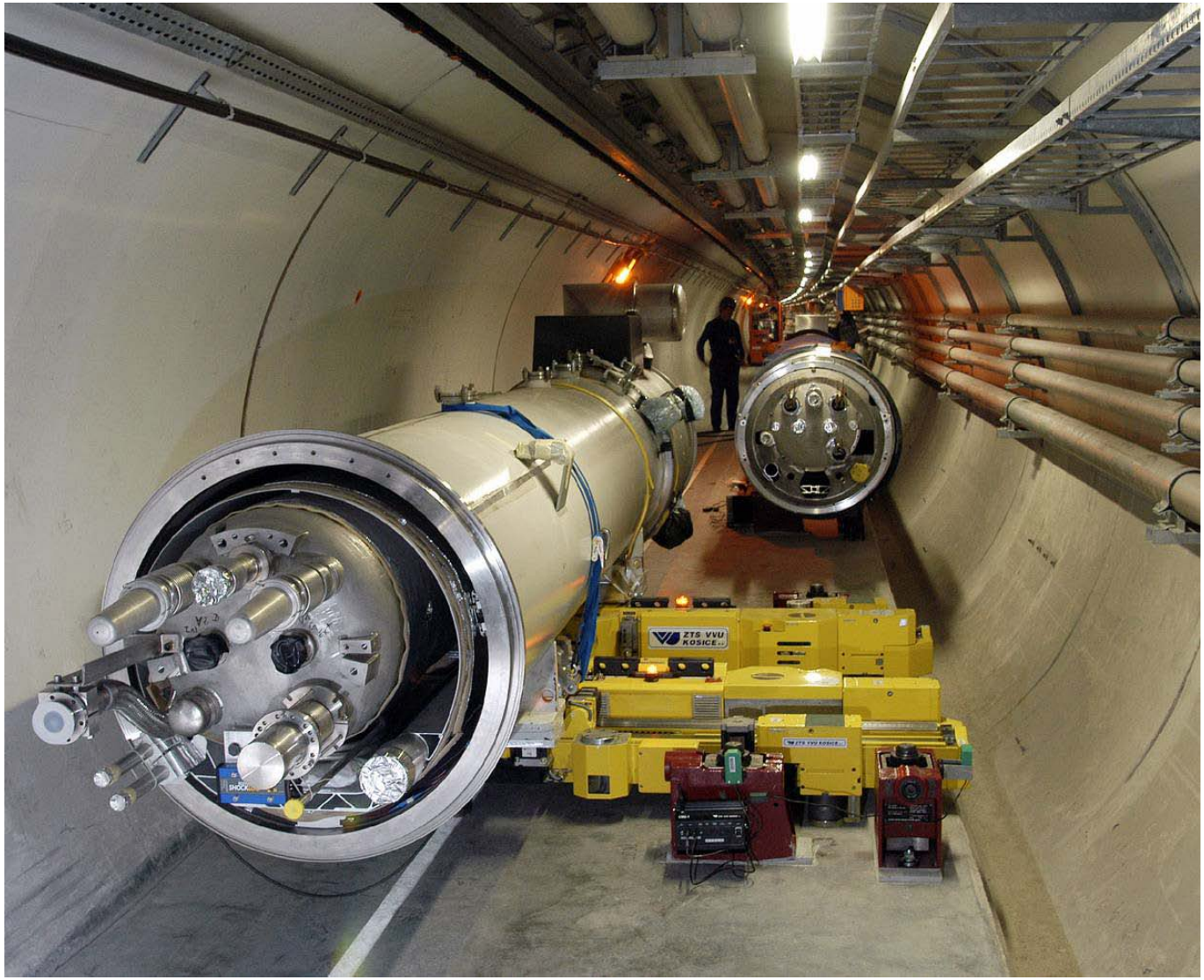
Tricky installation phase

LHC dipole magnet lowered into the tunnel

Magnet installation in the tunnel

Transport in the tunnel with an optical guided vehicle

Magnet installation in the tunnel



All stuck inside the LHC tunnel

Why is the LHC so special?

The emptiest space in the solar system!

Over this journey particles must have the minimum risk to interact with unwanted particles, such as gas molecules …

… because we'd like to keep them for long….

⇒ They must travel in special chamber where ultra high vacuum is established – a cavity as empty as interplanetary space

⇒ The internal pressure of the LHC is 10^{-13} bar, ten times less than the pressure on the moon!

LHC as an energy concentrator

Hunting Higgs particle: Energy of Tera-electron Volt

- One proton in the LHC will have an energy of 7 TeV which is 7’000 billion of electron-volts: Is this really a lot?
- It will only corresponds to 7 times the kinetic energy of a mosquito of 2 mg, flying at 40 cm/s…
- But this energy is concentrated in an object which is one million of a million smaller than a mosquito !

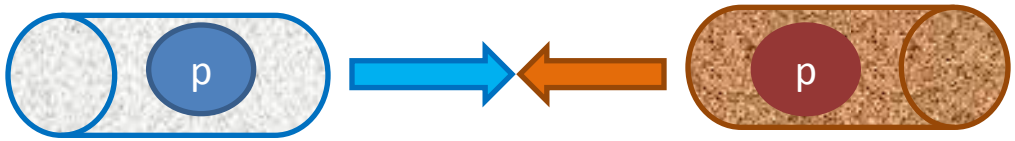
Why is the LHC so special?

Extreme hot and cold!

The hottest spots in the galaxy:

Collision of two beams of protons → generate temperature >100'000 hotter than the heart of the sun, concentrated within a minuscule space **0.020 mm diameter** .... ~ 4 times smaller than a typical a human hair **7 cm long**

Not 1 proton but 2808 bunches of 100'000'000'000 protons each!!!



By contrast, the cryogenic distribution system which circulates super fluid helium around the accelerator ring, keeps the LHC at a super cool temperature of 1.9 K

The power stored in the LHC

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

20'000 tons British aircraft carrier at 12 knots

360 MJoule: the energy stored in one LHC beam corresponds approximately to…

90 kg of TNT

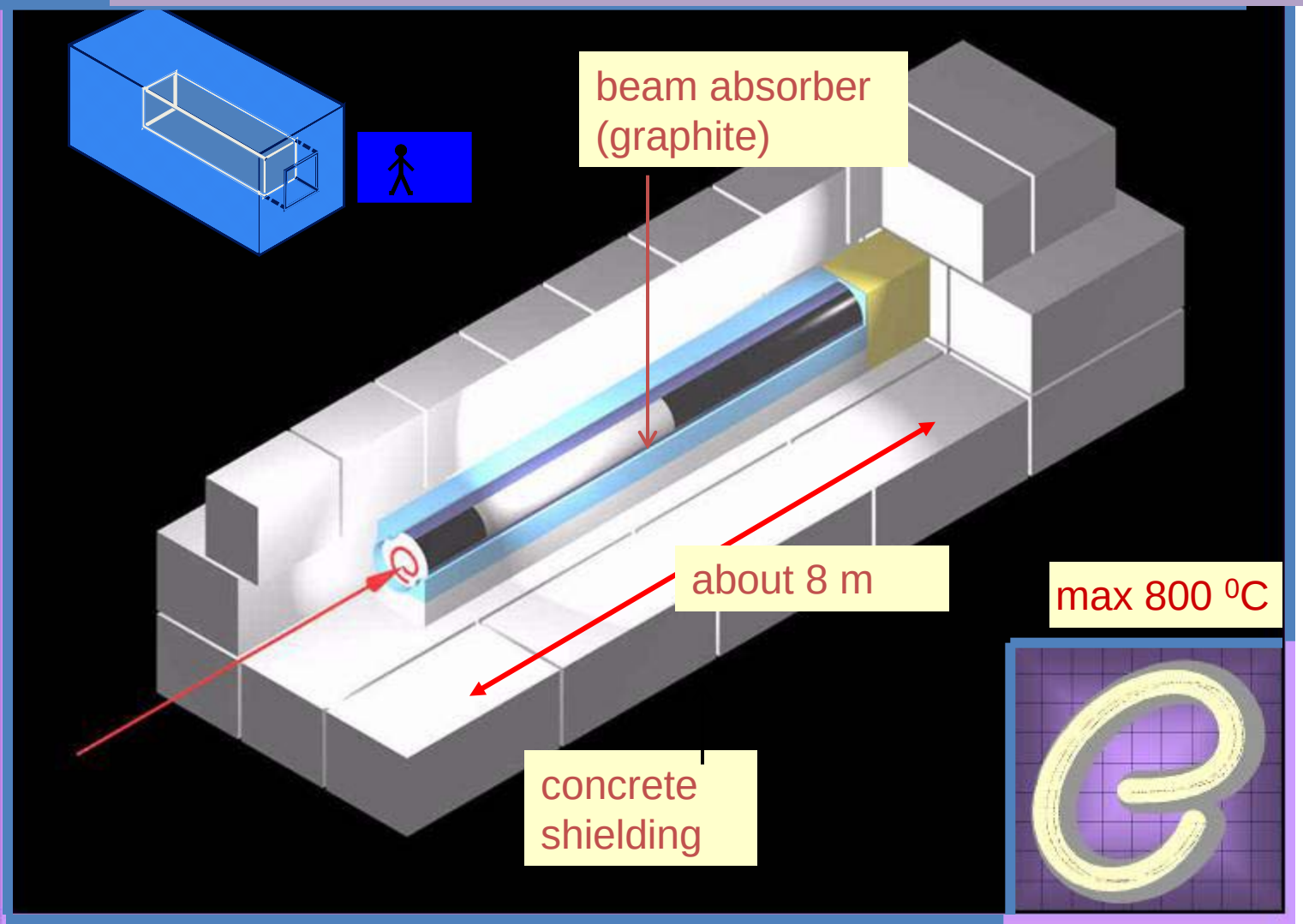
8 litres of gasoline

15 kg of chocolate

With so much stored energy….
…HOW TO STOP THE BEAM?

How do we “kill” the LHC beam?

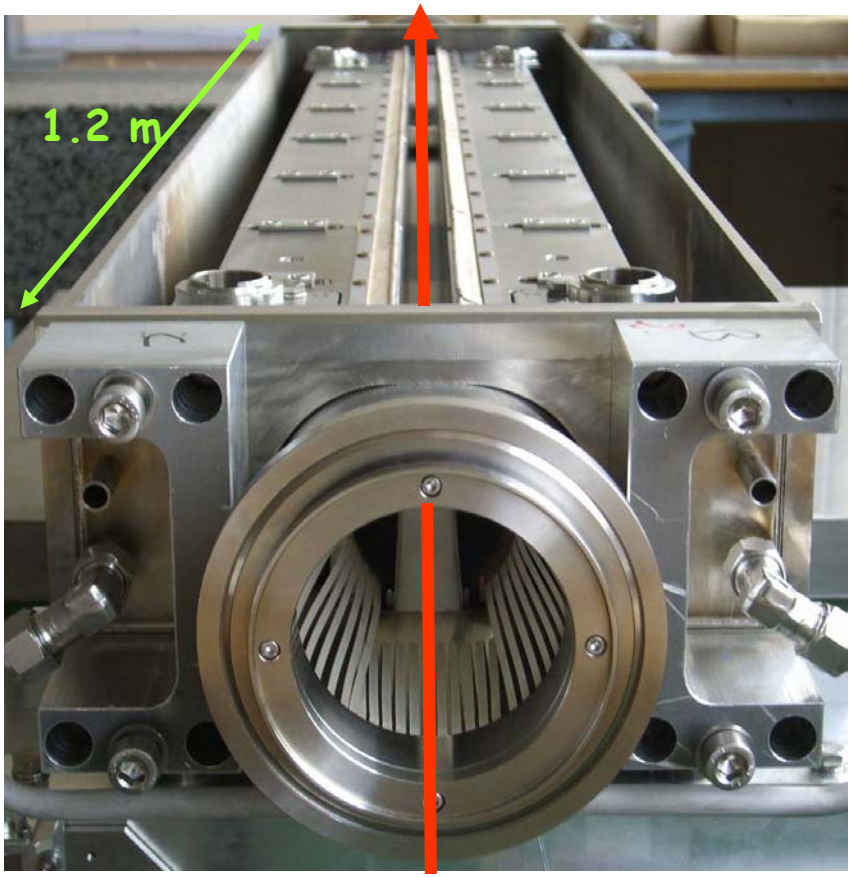
The only component that can stand a loss of the full beam is the beam dump block, all other components would be damaged



about 35 cm

How to protect the magnets?

complex collimation system



- Ensure 'cohabitation' of:
  - 360 MJ of stored beam energy
  - Super-conducting magnets
- Almost 100 collimators and absorbers.
- Alignment tolerances < 0.1 mm to ensure that over 99.99% of the protons are intercepted.

Is LHC really that expensive?

All in Billions	CHF	€	$
LHC	4.6	3	4
Space Shuttle Endeavour (NASA)	1.9	1.3	1.7
Oresund bridge (8km, Sweden/Denmark)	5.7	4	5.3
Burj Khalifa skyscraper (828m, Dubai)	1.6	1.1	1.5
Olympic games of Athens 2004	16	11.2	15
Aircraft carrier	2.9	2	2.7
F1 budget per season	2.3	1.6	2.1

Ingredients to study elementary particles and their interactions

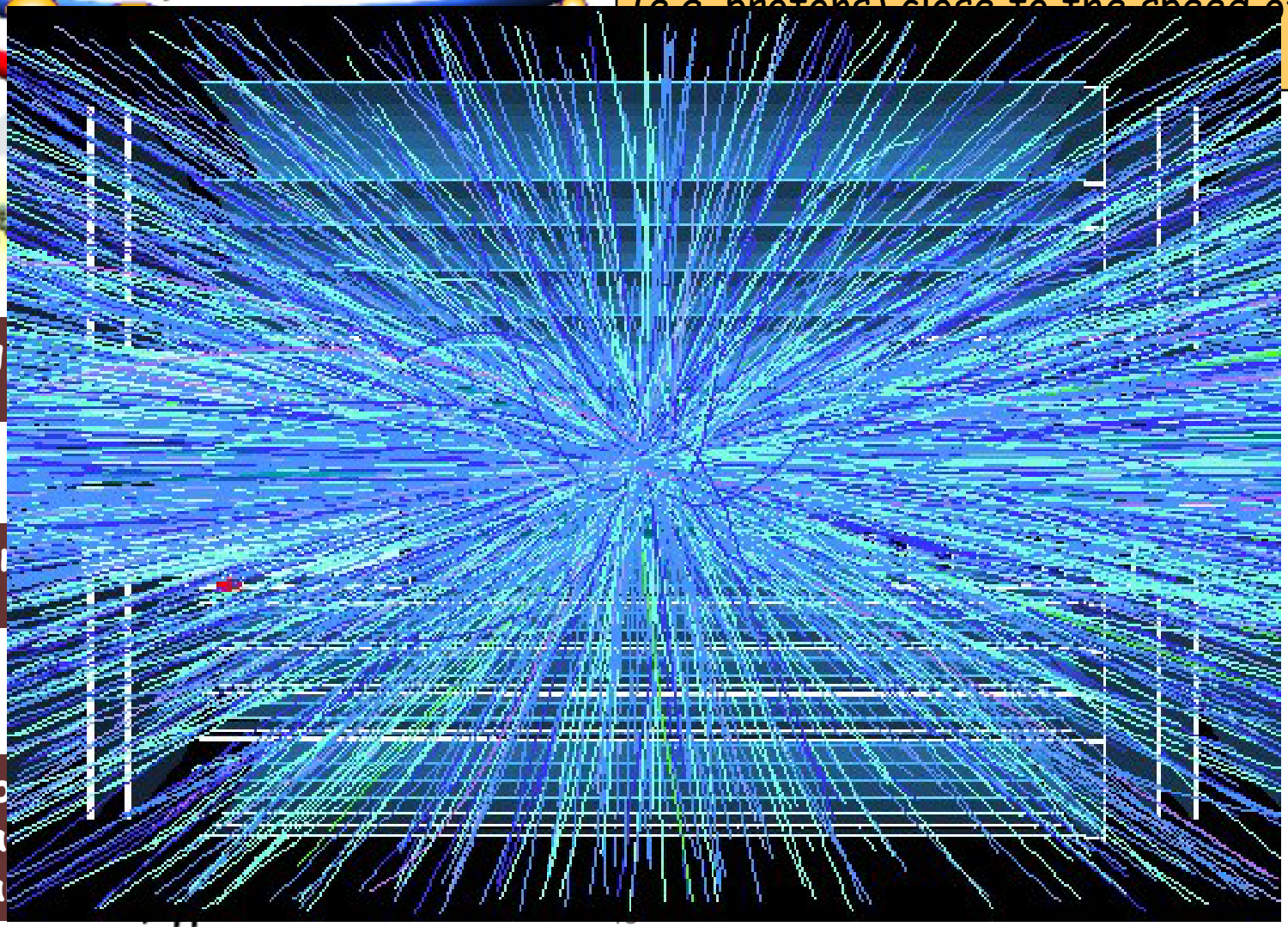
We accelerate two beams of particles (e.g. protons) close to the speed of

proton beams

colliding protons

interacti quarks

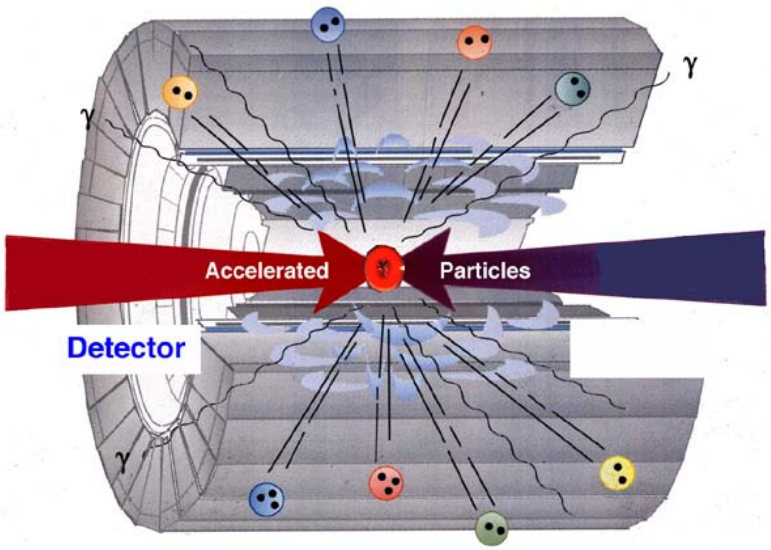
productio and deca a new pa



Remaining ingredients

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

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

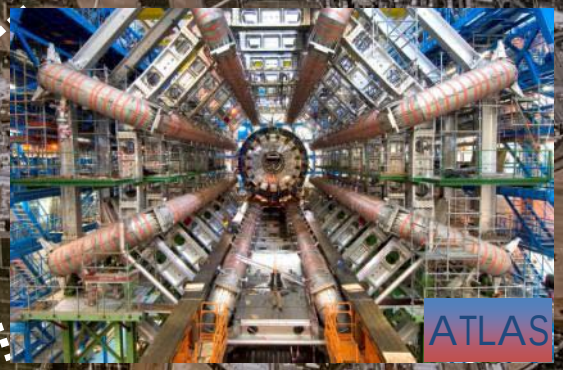


Detectors are like giant digital cameras which take pictures of the pp collisions at a rate of 40 million per second.

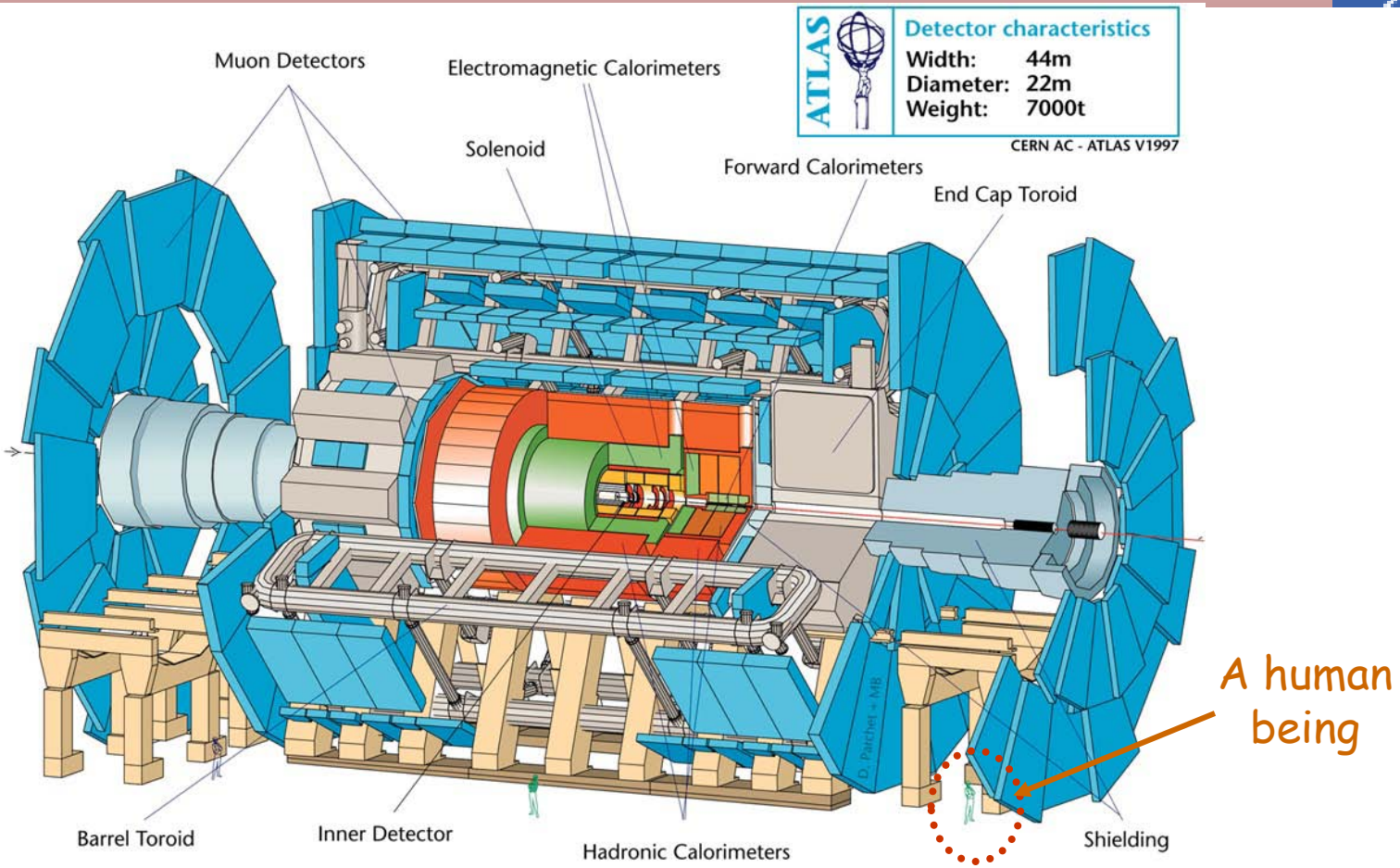
Sophisticated software techniques are then used to reconstruct the particle trajectories from the signals left in the various detector elements and thus obtain a "picture of the full event". The origin of the event (which new particle or phenomenon has produced it) can then be studied

Detectors in the LHC

Exploration of a new energy frontier
Proton-proton collisions at E_{CM} = 14 TeV



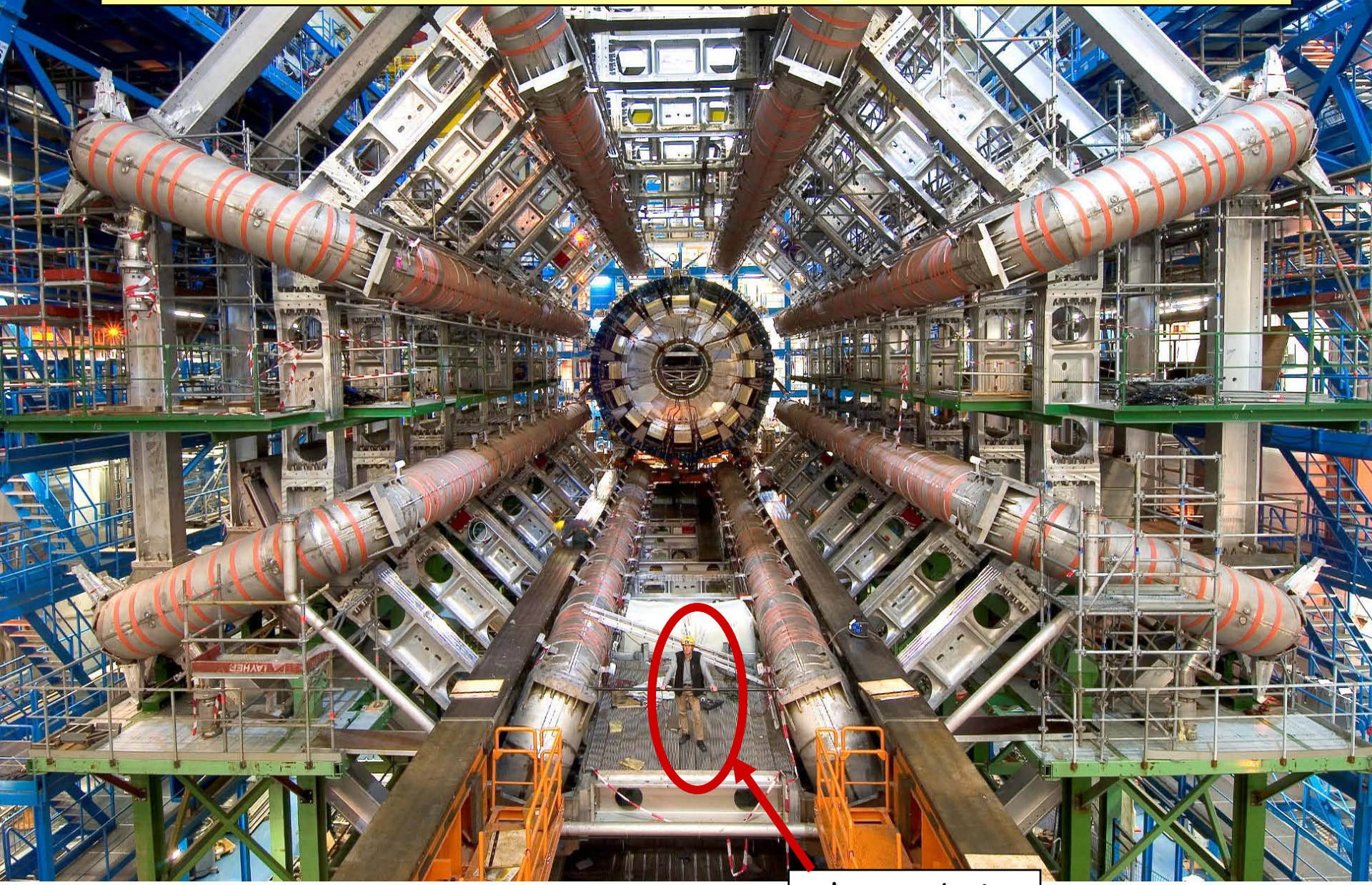
ATLAS detector



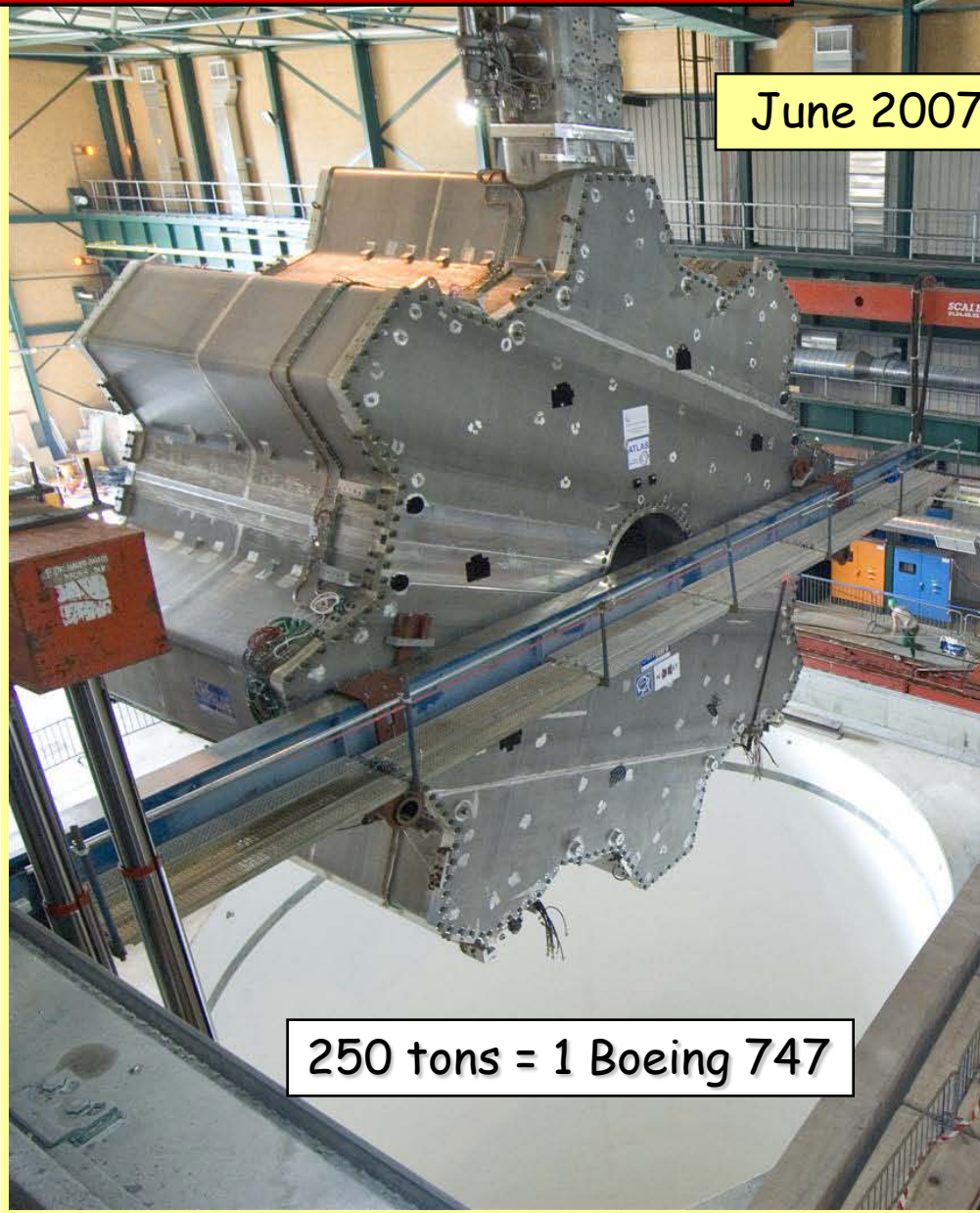
- 10^8 electronic channels ("individual signals"): to track ~1000 particles per event and reconstruct their trajectories with ~10 μm precision (1 μm=10^{-6} m)
- Collaboration: ~ 2200 physicists from 169 Institutions/Universities, from 37 countries from 5 continents … and 450 PhD students

ATLAS cavern (-100 m) in June 2003

October 2005: Barrel toroid magnet system in place

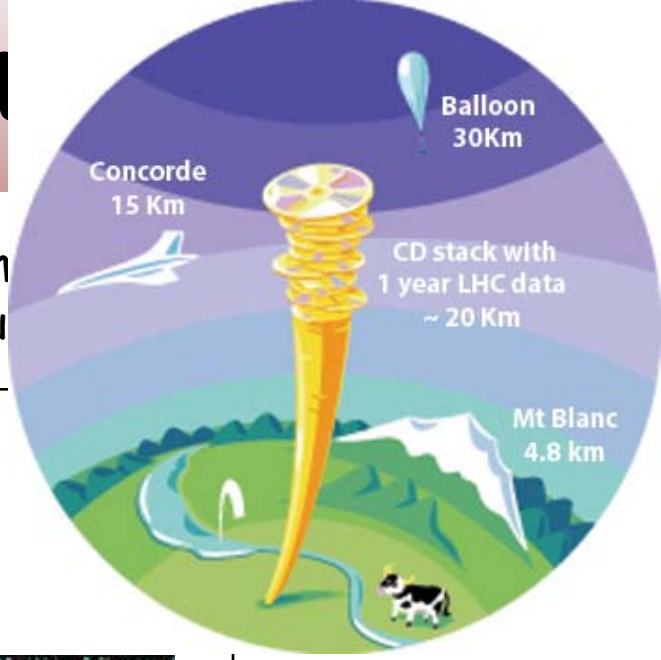


Spectacular operations … installing detector pieces in the underground cavern



June 2008: installation completed → closure of the LHC beam pipe inside the ATLAS cavern

Last ingredient: Comput



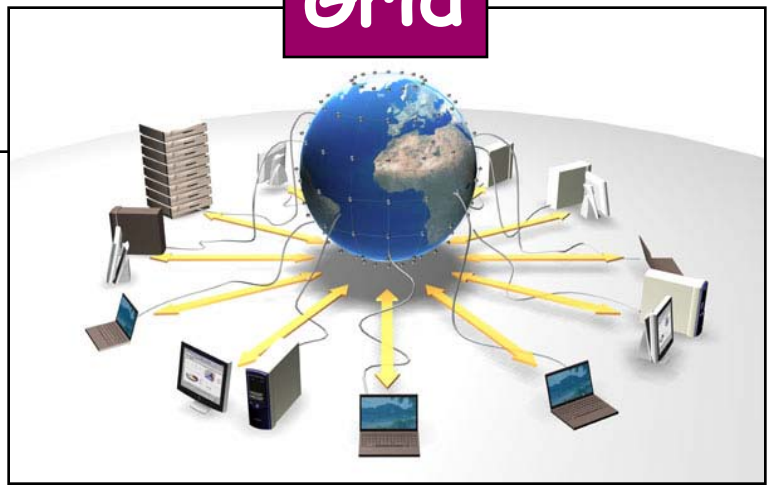
Computing: to store, distribute and analyse the vast an
by the detectors and thus reconstruct the "event" occu

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.

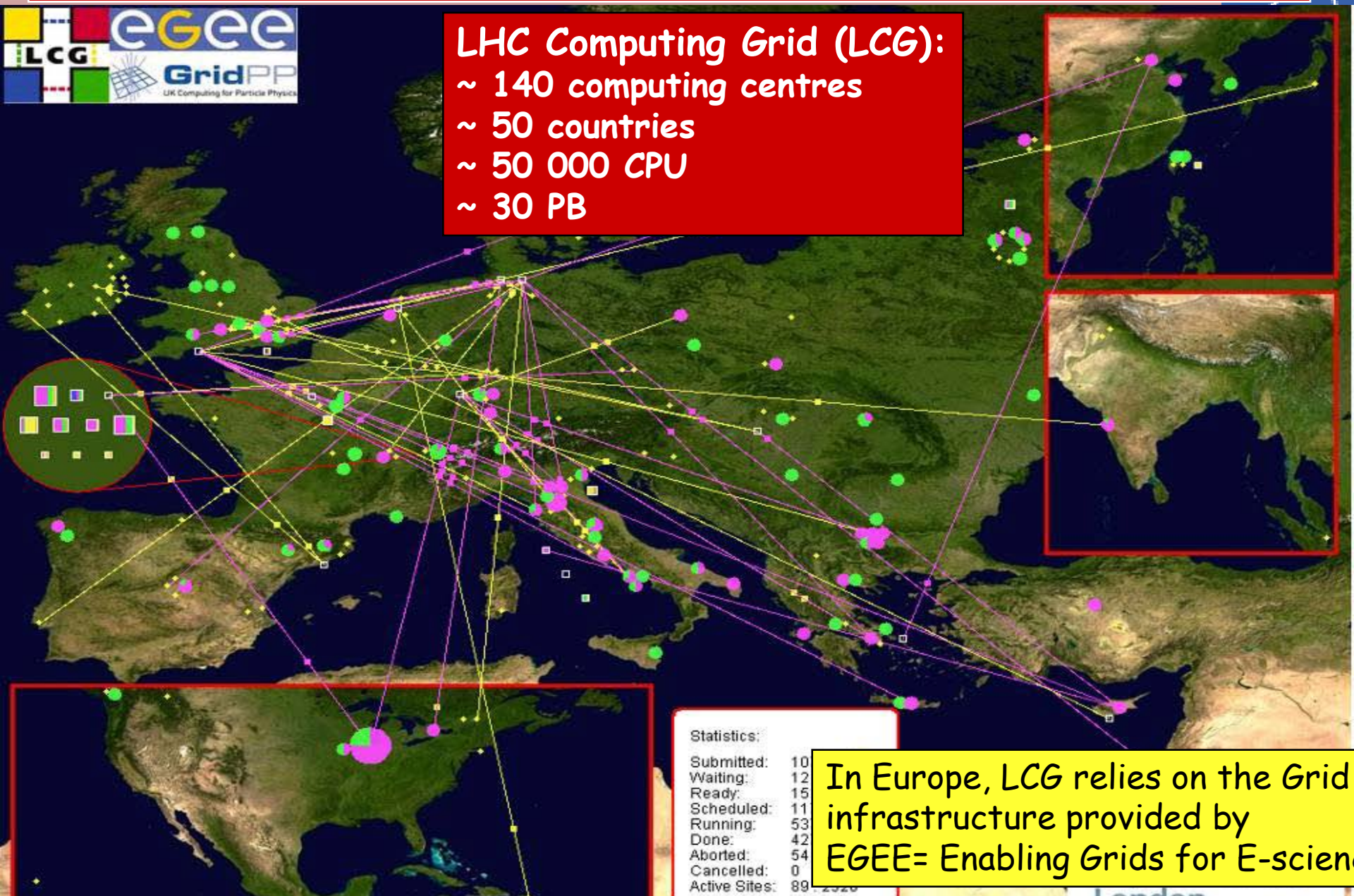
The experiment international Collaborations are spread all over the world → computing resources must be distributed.

Grid



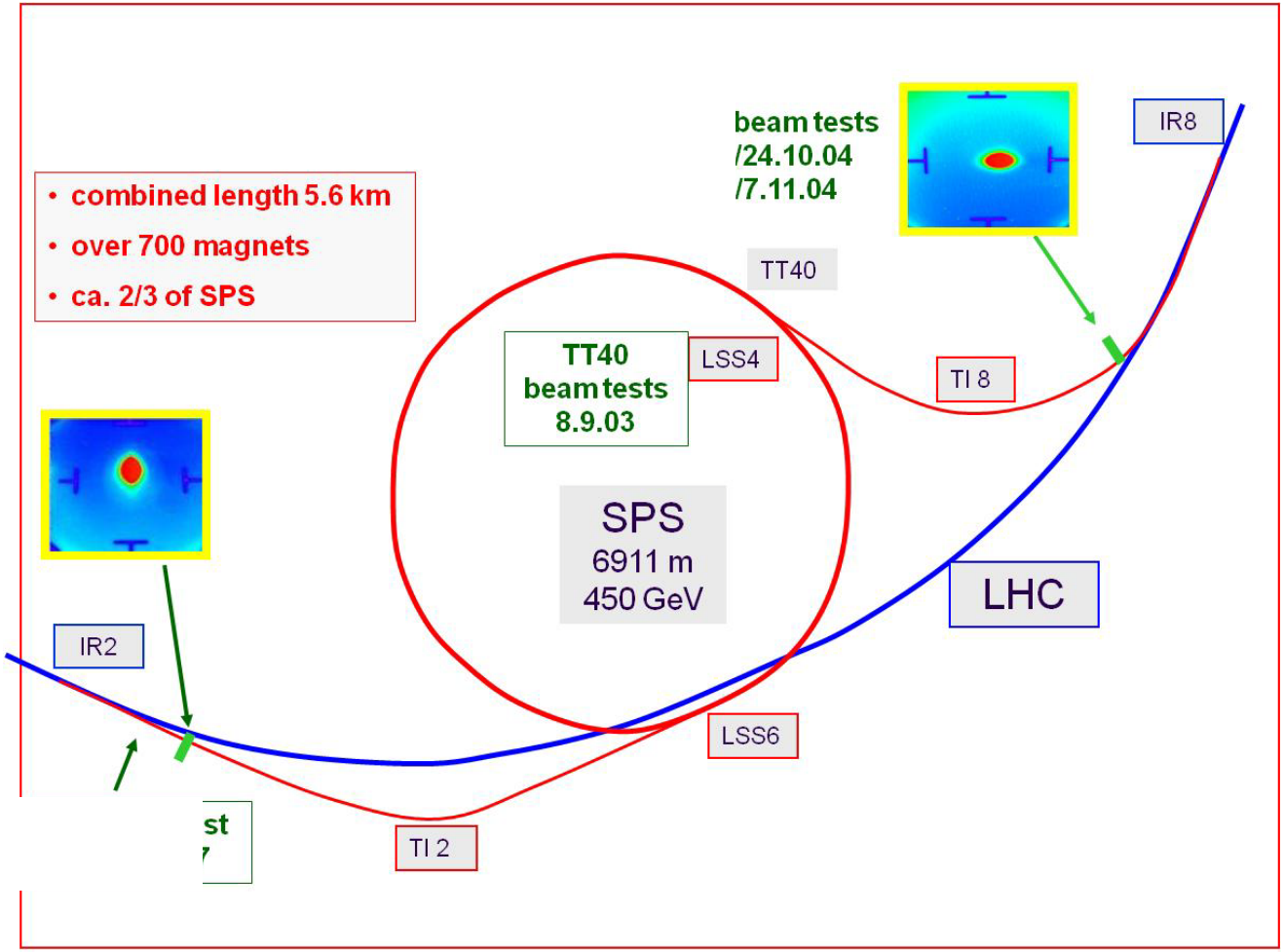
Cooperation of many computer centres all over the world is needed

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



Putting it all together

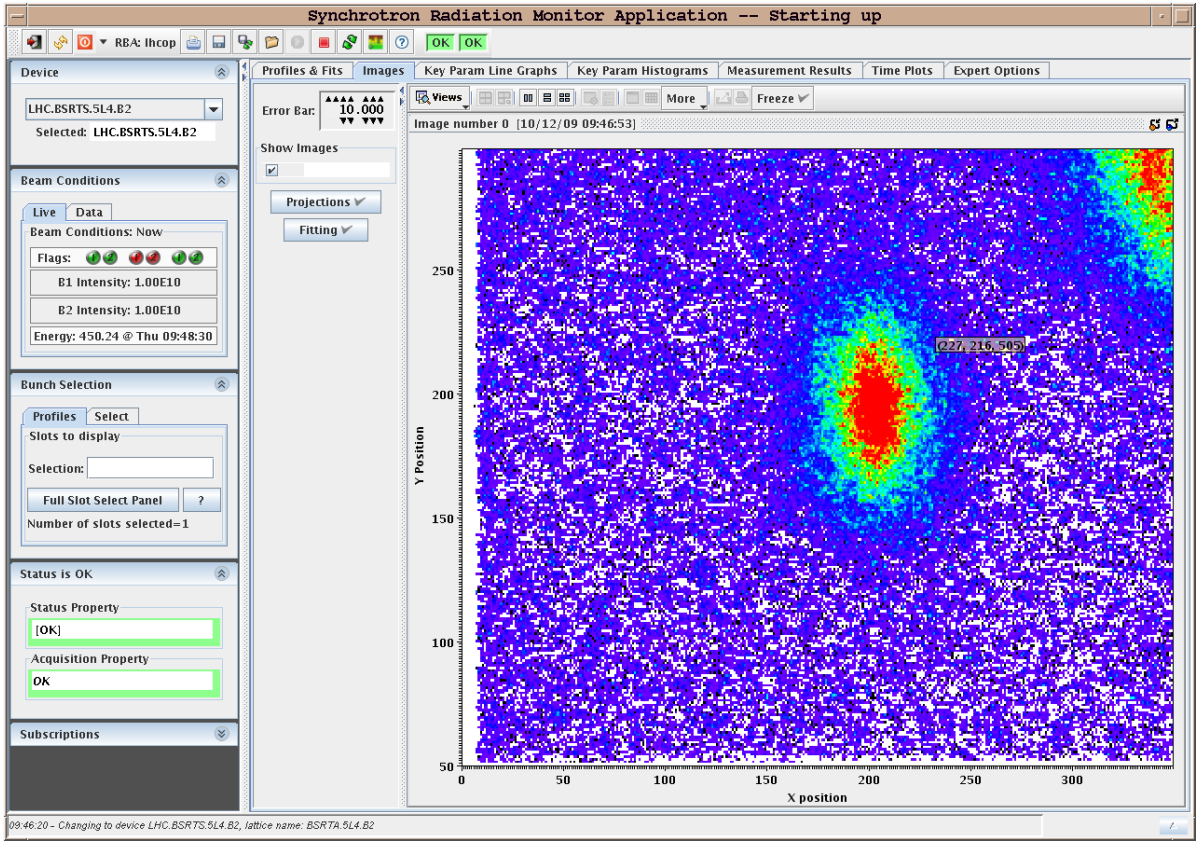
- 1982 : first studies for the LHC project
- 2008 : beam commissioning



Protons visible by eye

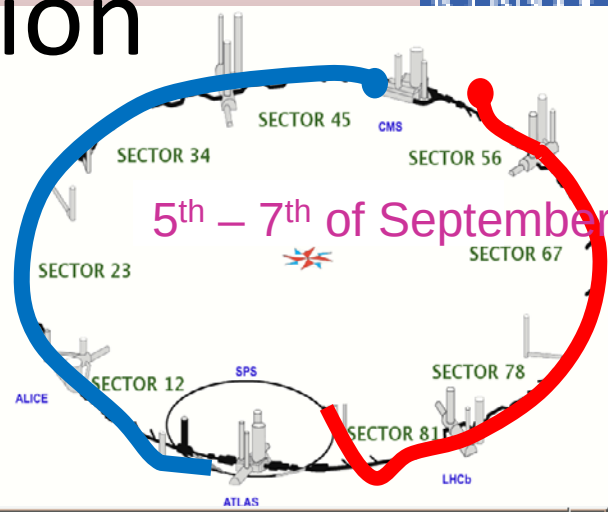
The LHC momentum and magnetic fields are sufficiently strong for the protons to emit visible synchrotron light that can be used to image the beams in real-time.

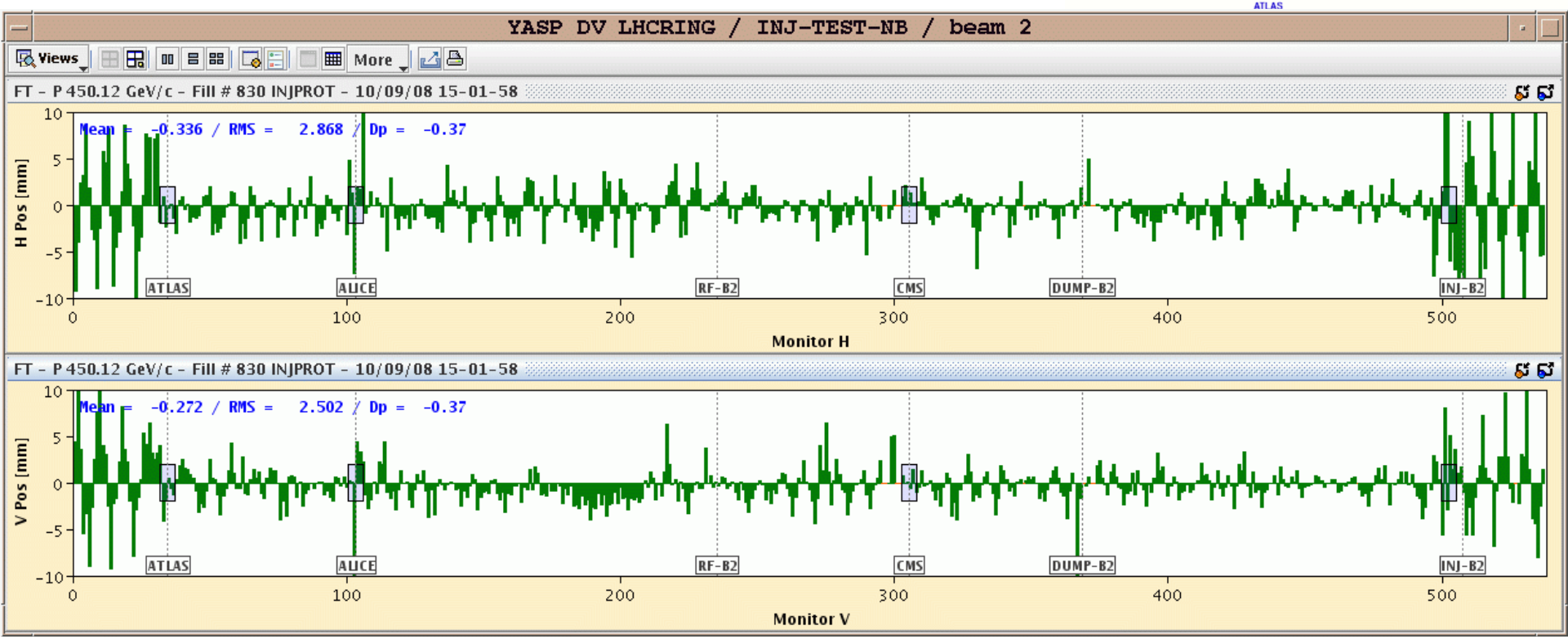
The energy loss per turn is 7 keV at 7 TeV.



Beam trajectory correction

- PRECISION OF THE BEAM POSITION IN THE RING = **1.5 mm**
- PRECISON OF THE BEAM POSITION AT THE INTERACTION POINT = **0.010 mm**



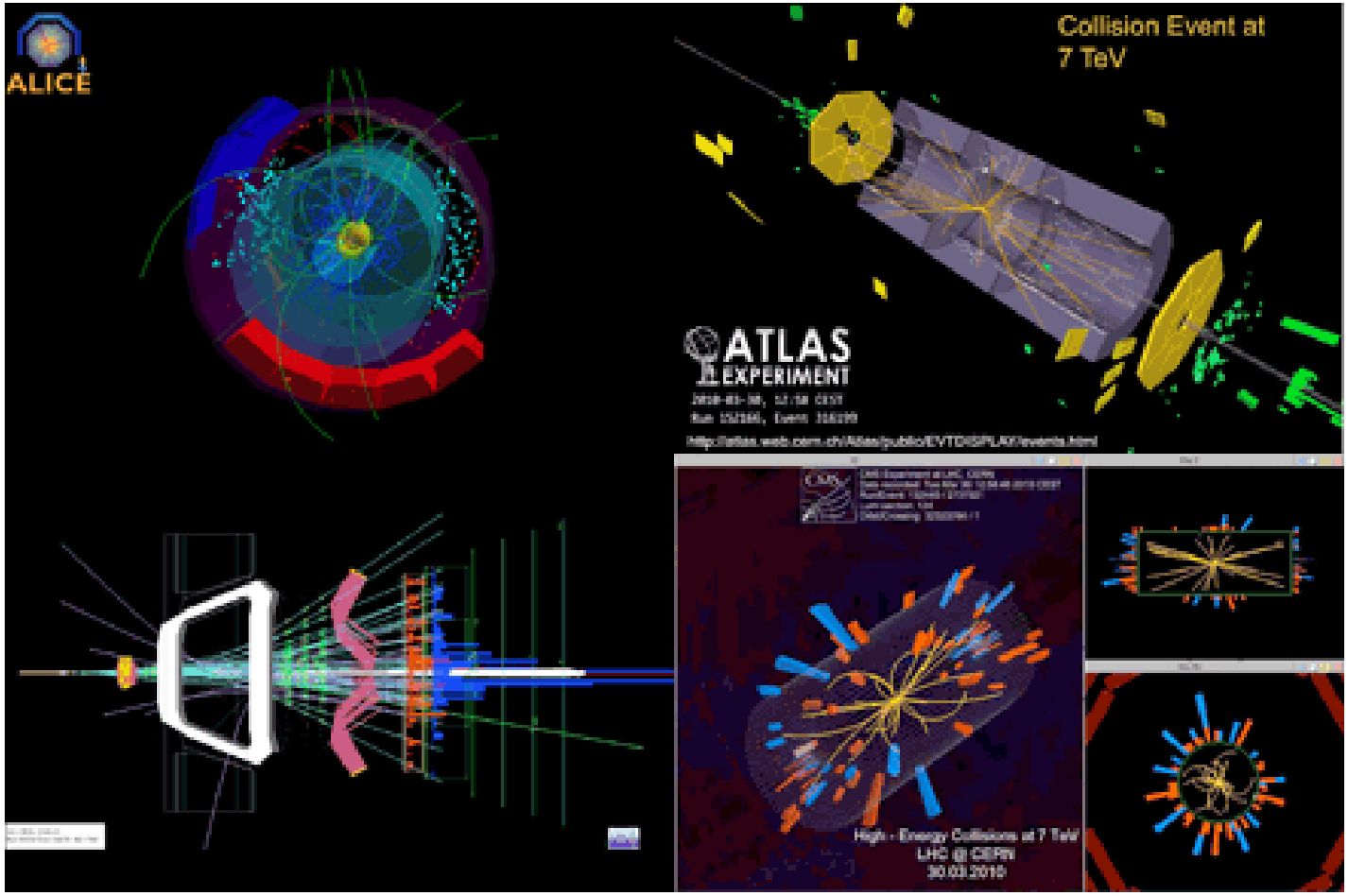


2011 LHC beam parameters

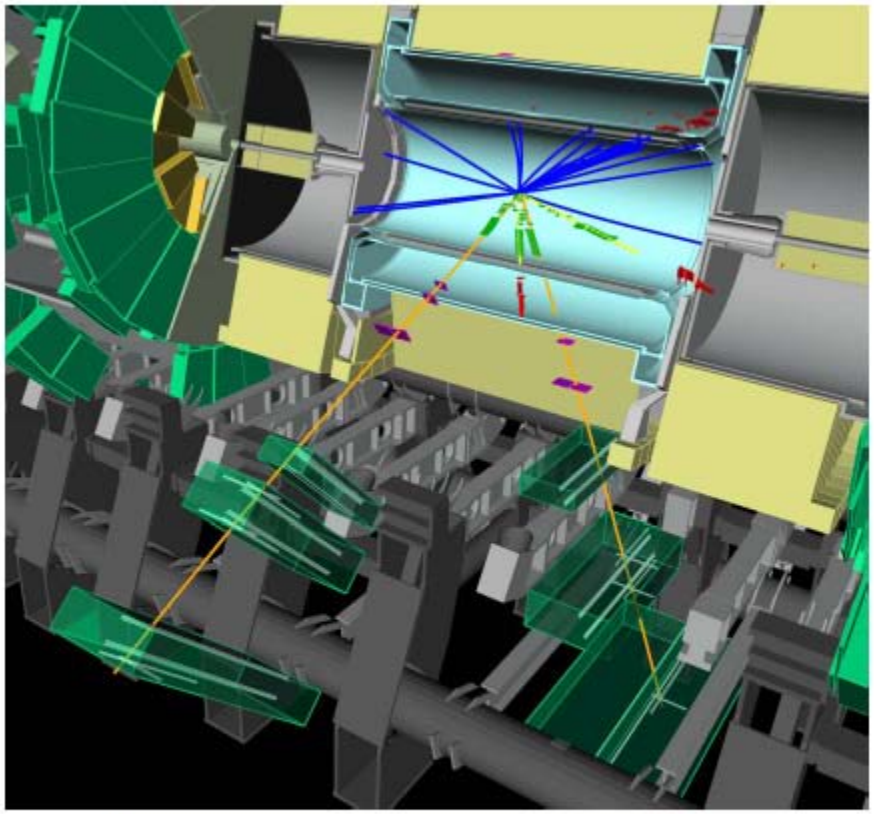
	2011	Nominal
Energy [TeV]	3.5	7
beta* [m]	1.5	0.55
Transverse beam size at IP [microns meter]	around 60	~16
Bunch current [protons]	1.2e11	1.15e11
Number of bunches	~920	2808
Stored energy [MJ]	~75	360
Event rate (evt/s)	10^8	10^9
Peak luminosity [$cm^{-2}s^{-1}$]	~1.5×10^{33} (achieved so far 2.5e32)	10^{34}

30 March 2010: First 7 TeV collisions

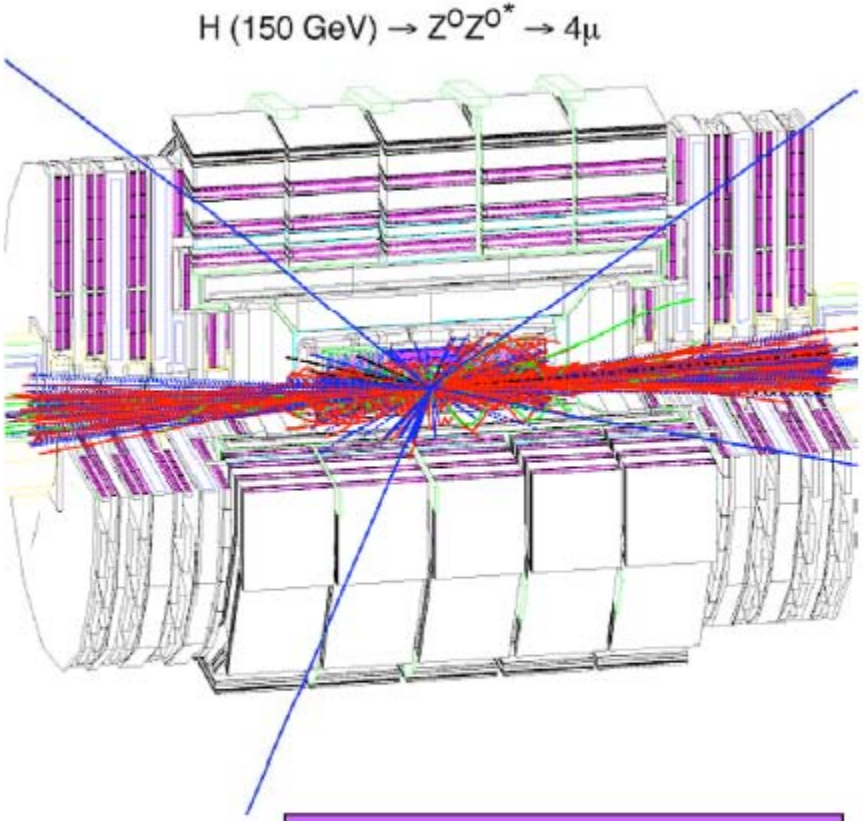
7 TeV collision events seen by the LHC's four major experiments (clockwise from top-left: ALICE, ATLAS, CMS, LHCb).



What they really, really want…

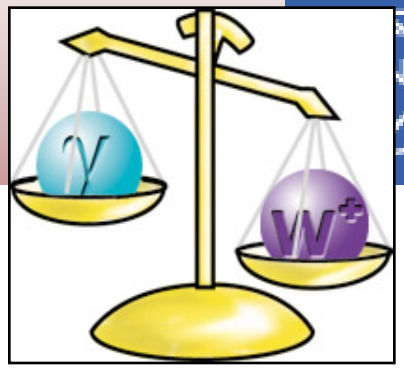


Simulation of a 130 GeV mass
$H \rightarrow \mu\mu$ ee event in ATLAS

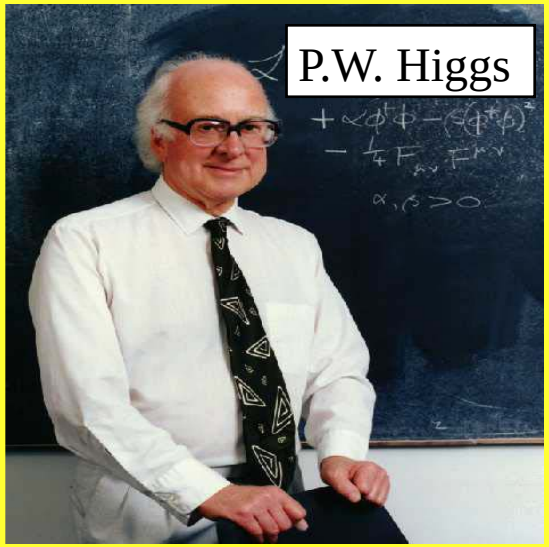


Simulation of a 150 GeV mass
$H \rightarrow \mu\mu\ \mu\mu$ event in CMS

What is the origin of the particle masses ?



Mass of top quark (heaviest elementary particle observed) ≈ mass of Gold atom
Electron mass is ~350000 times smaller: why ???



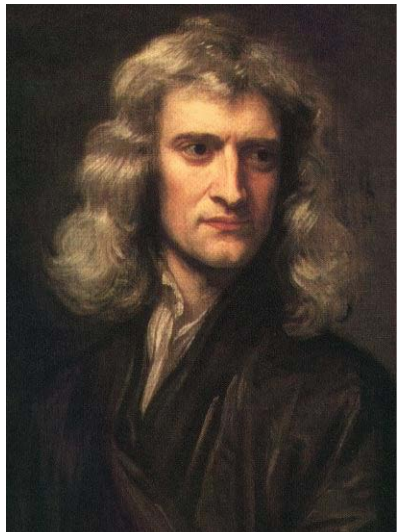
The mass mystery could be solved (at least in part) by the "Higgs mechanism", which also predicts the existence of a new elementary particle:
the Higgs

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.

CERN and the LHC

- Seeking answers to fundamental questions about eleme
particles and the Universe. A new era of discoveri with
the exploration of an unprecedented energy LHC
- Advancing the frontiers of technolog benefit of society)
- Training (students, high-school ung scientists)
- Bringing nations togeth cience

EXCITING TIMES ARE AHEAD OF US

"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)