Introduction to the Large Hadron Collider (LHC) to study the elementary particles

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https://conference.ippp.dur.ac.uk/event/793/

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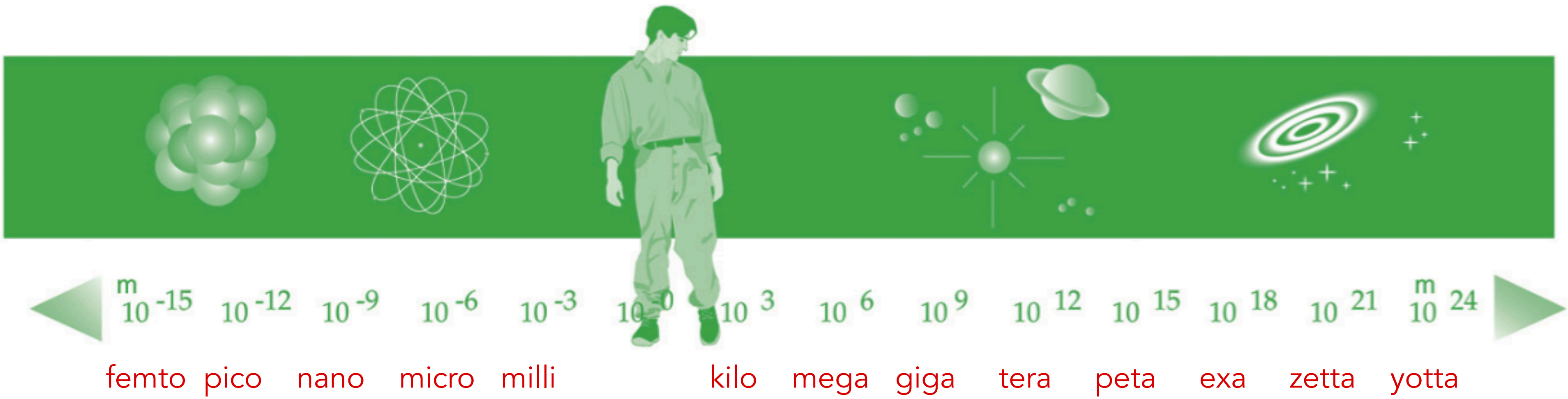
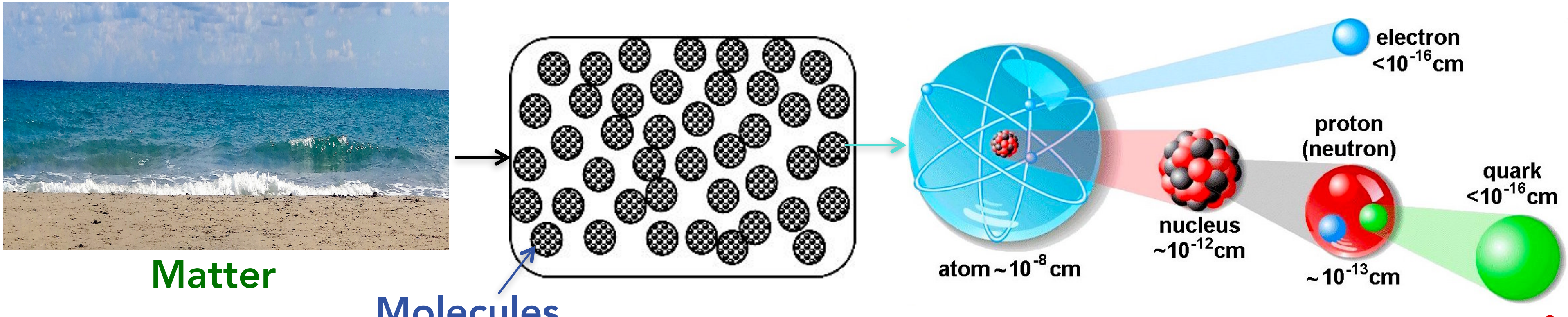
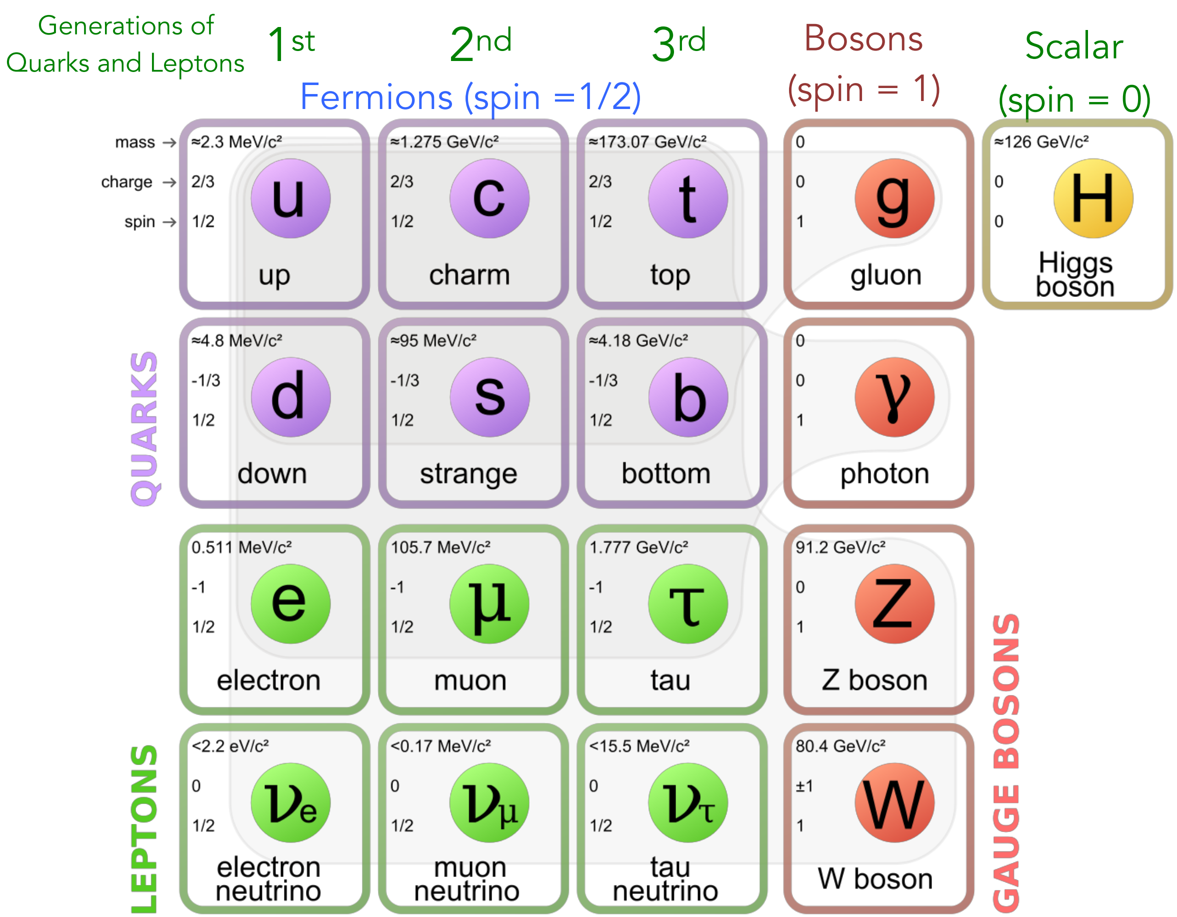
Matter and Particles



- Particle physics studies the tiniest objects of Nature.
- Finding answers of most fundamental questions about the present status of universe.
- Helping us to understand the basic configuration and evolution of universe.



The Standard Model of Particle Physics

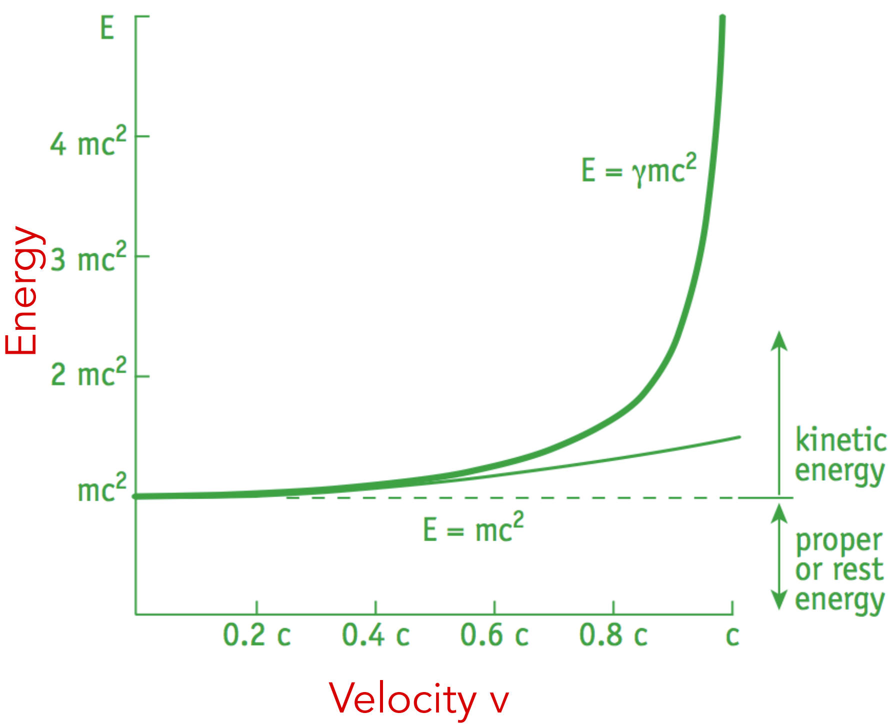


- It is a collection of theories that embodies all of our current understanding of fundamental particles and forces.
- Quarks and leptons are the building blocks of matter, and forces act through carrier particles exchanged between the particles of matter.
- Forces also differ in their strength
- Standard model doesn't include gravity

Forces	Electromagnetic	Weak	Strong	Gravitation
Carrier	Photon (γ)	$W^{\pm}, Z$	Gluons	Graviton (not yet discovered)
Mass ($\mathrm{GeV/c^2}$)	0	80.4, 91.2	0	expected to be massless
Felt by	quarks and charged leptons	quarks and leptons	quarks	All particles with mass
Strength	1/137	10^{-6}	1	6×10^{-39}
Range (cm)	∞	10^{-16}	10^{-13}	∞

Energy, Speed and Mass

- No particle can travel faster than speed of light in vacuum but there is no limit to the energy a particle can attain.
- If speed of a particle is much lower than speed of light then its kinetic energy is $k=(1/2)mv^2$. For particles travelling at speed of light (c), $k=(\gamma-1)mc^2$ where $\gamma=1/\sqrt{(1-\beta^2)}$; $\beta=v/c$ and `m' is mass of particle at rest. Rest mass of proton is 0.938 GeV/c^2
- Particle physicists do not think about speed, but rather about energy of a particle.



k= 1/2 mv^2	Speed (% c)	Accelerator
50 MeV	31.4	LINAC2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

Mass can transform to energy and vice versa as **$E=mc^2$**

This transformation is happening in each collision **at LHC**

Ref: http://www.phys.unsw.edu.au/einsteinlight/jw/module5_equations.htm

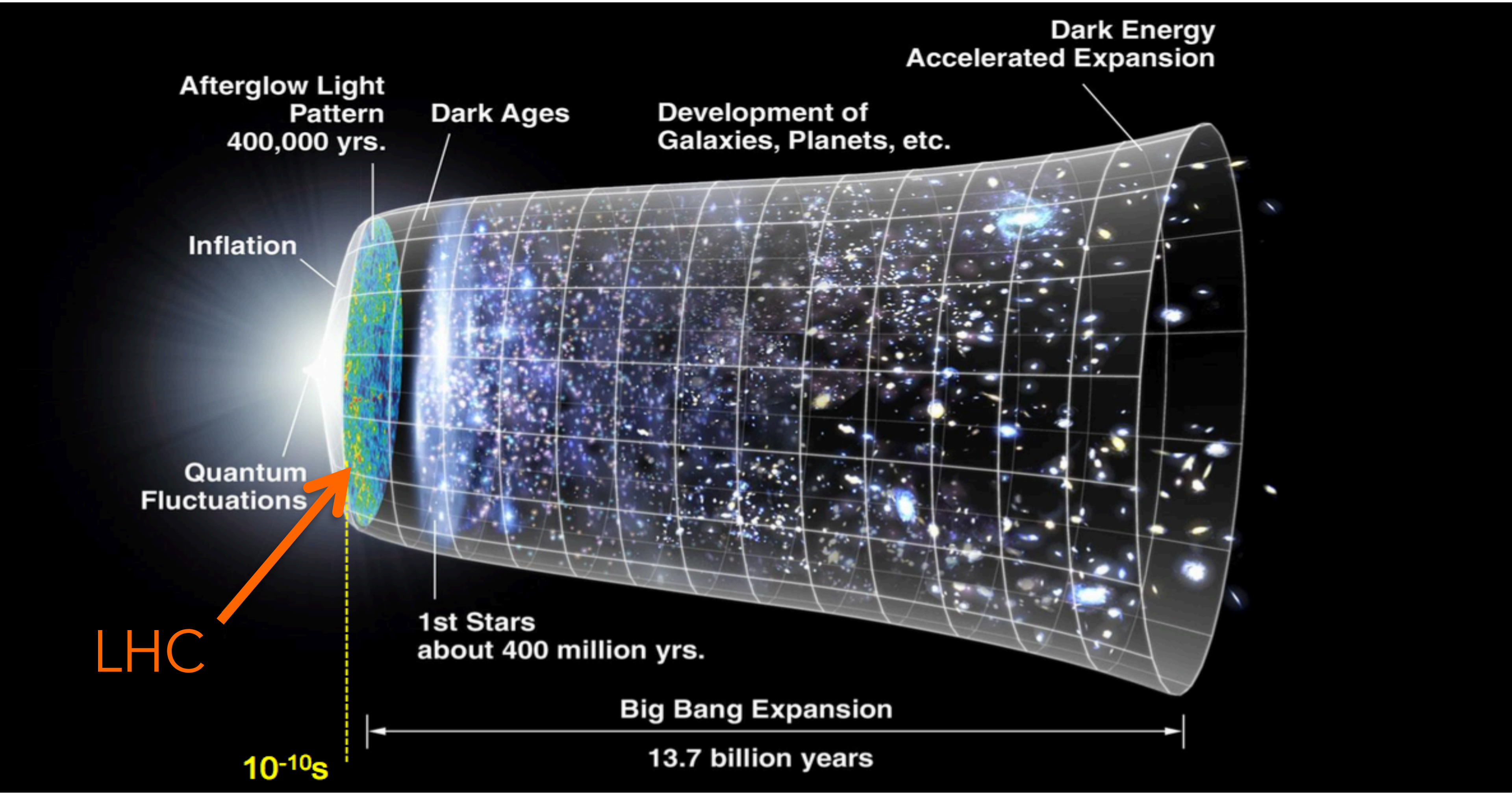
Main Goals of LHC

The Standard Model (SM) summarizes our present knowledge of particle physics and has been tested by various experiments (W, Z, Higgs boson are discovered) but still it leaves many unsolved questions

- The SM does not offer a unified description of all the fundamental forces
  - Supersymmetry — a theory that hypothesizes the existence of more massive partners of the standard particles we know. It could facilitate the **unification of fundamental forces**.
- Cosmological and astrophysical observations have shown that all of the visible matter accounts for only 4% of the Universe. The search is open for particles or phenomena responsible for **dark matter (23%) and dark energy (73%).**
- The LHC will also help us **to investigate the mystery of antimatter**. Matter and antimatter must have been produced in the same amounts at the time of the Big Bang.
- Heavy-ion collisions at the LHC will provide a window onto the state of matter that would have existed in the early Universe, called **'quark-gluon plasma'**. When heavy ions collide at high energies they form for an instant a 'fireball' of hot, dense matter that can be studied by the experiments
- The collision's temperature will exceed 100,000 times that of the centre of the Sun. In these conditions, the quarks are freed again and the detectors can observe and study the primordial soup.
  - Excellent condition to probe the basic properties of particles and explore how they aggregate to form ordinary matter.

LHC and Big Bang

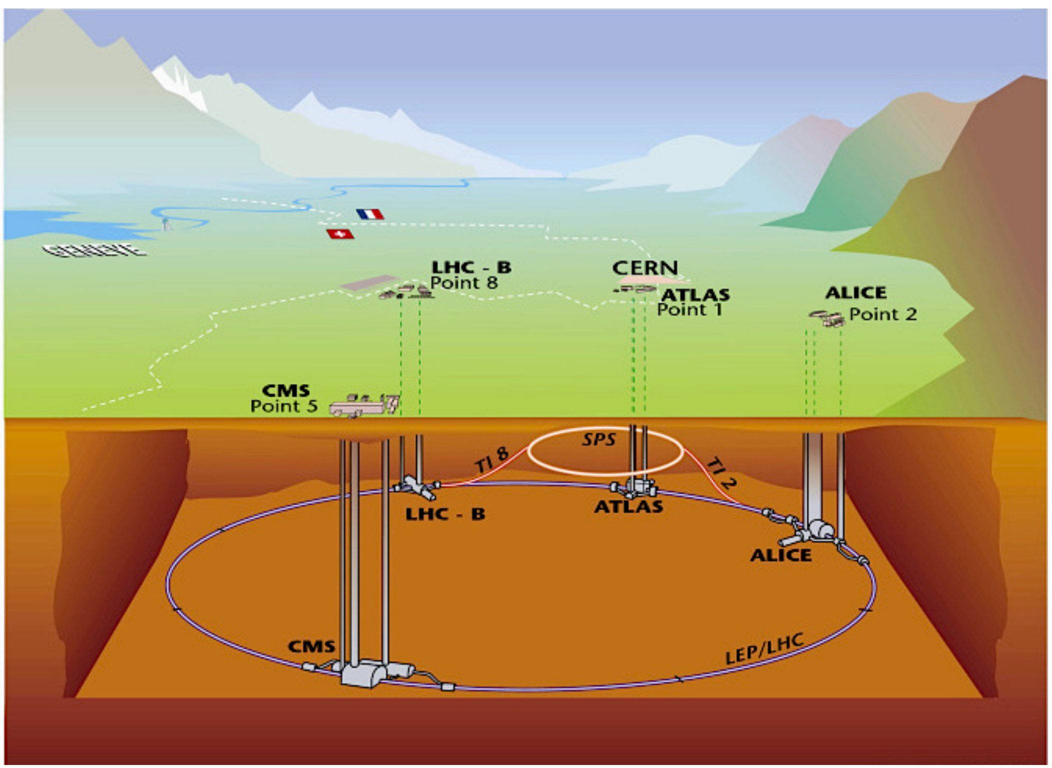
- The energy density and temperature that will be made available in the collisions at the LHC are similar to those that existed a few moments after the Big Bang.
- So LHC is looking very far back into time, just a few moments after the Big Bang.



The LHC

The LHC is located at CERN: Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research) on the Franco-Swiss border near Geneva.

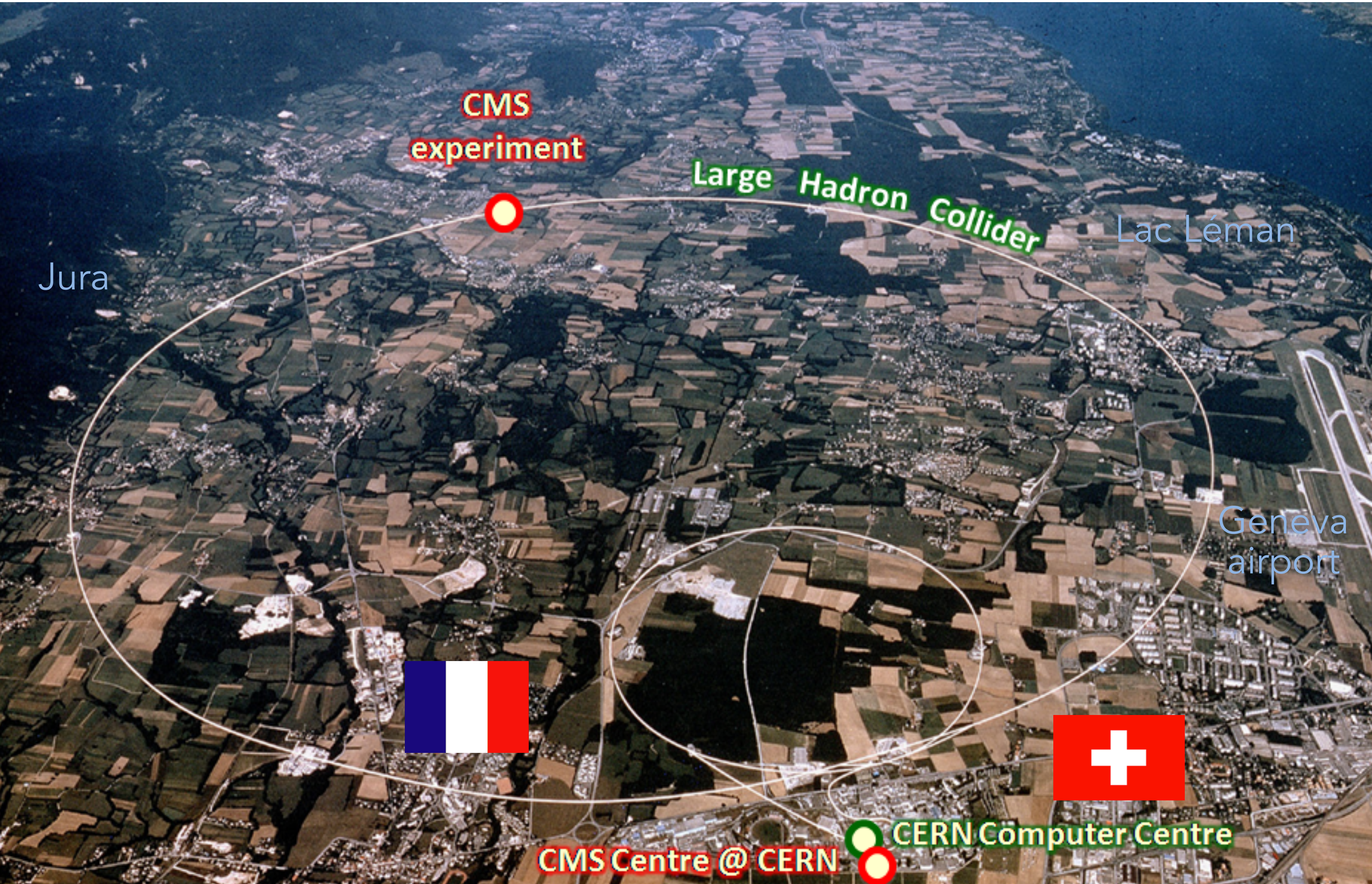
Overall view of the LHC experiments



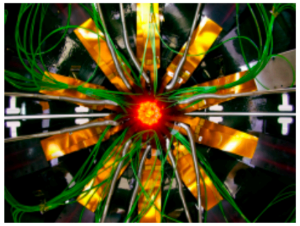
Design parameters of LHC

circumference	26659 m
depth	50 - 175 m
total number of magnets	9600
number of main dipoles	1232
number of quadrupoles	392
temperature	1.9 K (-271.3 C)
beam vacuum pressure	$10^{-13} atm$
nominal p energy	7 TeV
center-of-mass energy	14 TeV
design luminosity	$10^{34}\ cm^2 s^{-1}$
bunches per proton beam	2808
protons per bunch	1.1×10^{11}
turns per second	11245
collisions per second	600 milions
length of each dipole	15 m
weight of each dipole	$\approx 35\ t$
dipole field	8.33 T

An Aerial Layout

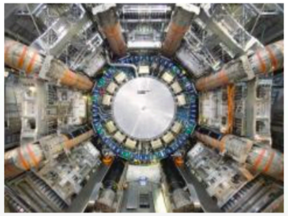


Main Experiments at LHC



ALICE:
Quark-gluon plasma

LHCb:
antimatter



ATLAS and CMS: General purpose, fundamental particles

Many experiments at CERN

AEGIS, **ALICE**, ALPHA, AMS, ASACUSA, **ATLAS**, ATRAP, AWAKE, BASE, CAST, CLOUD, **CMS**, COMPASS, DIRAC, ISOLDE, **LHCb**, LHCf, MOEDAL, NA61/SHINE, NA62, NA63, nTOF, OSQAR, TOTEM, UA9

Why its size is very large?

- The size of an accelerator is related to the maximum energy obtainable.
- In the case of a collider, this is a function of the radius of the machine and the strength of the dipole magnetic field that keeps particles in their orbits.
- The LHC uses some of the most powerful dipoles and radio-frequency cavities in existence.
- The size of the tunnel, magnets, cavities and other essential elements of the machine, represent the main constraints that determine the design energy of 7 TeV per proton beam.

Why underground?

- The Earth's crust provides good shielding for radiation or cosmic rays.

- The LHC re-uses the tunnel that was built for CERN's previous big accelerator, Large Electron–Positron Collider (LEP), dismantled in 2000.

- The underground tunnel was the best solution to house a 27-km circumference machine because it is cheaper to excavate a tunnel rather than acquire the land to build at the surface and the impact on the landscape is reduced to a minimum.

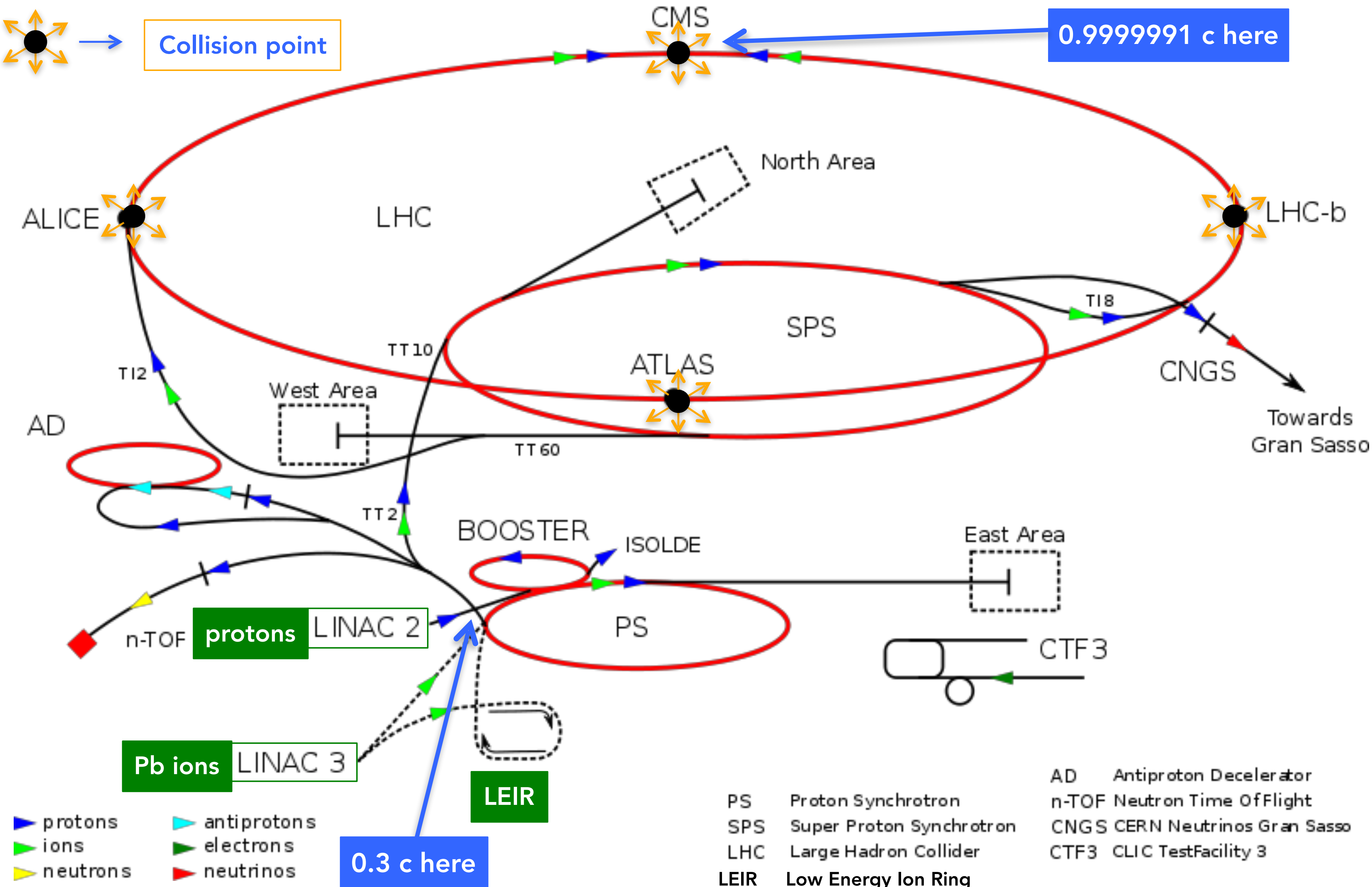
Why hadrons are preferred ?

- An accelerator can only accelerate certain kinds of particles:
  - they need to be charged (as the beams are manipulated by electromagnetic devices that can only influence charged particles).
  - they should have longer life time or they need not to decay. This limits the number of particles to be accelerated to electrons, protons, and ions, plus all their antiparticles.
- The LHC will accelerate two beams of particles of the same kind, either protons or lead ions, which are hadrons.
- In a circular accelerator like LHC, heavy particles such as protons have a much lower energy loss per turn through synchrotron radiation than light particles such as electrons (protons are around 2000 times more massive than electrons).

Why Collider?

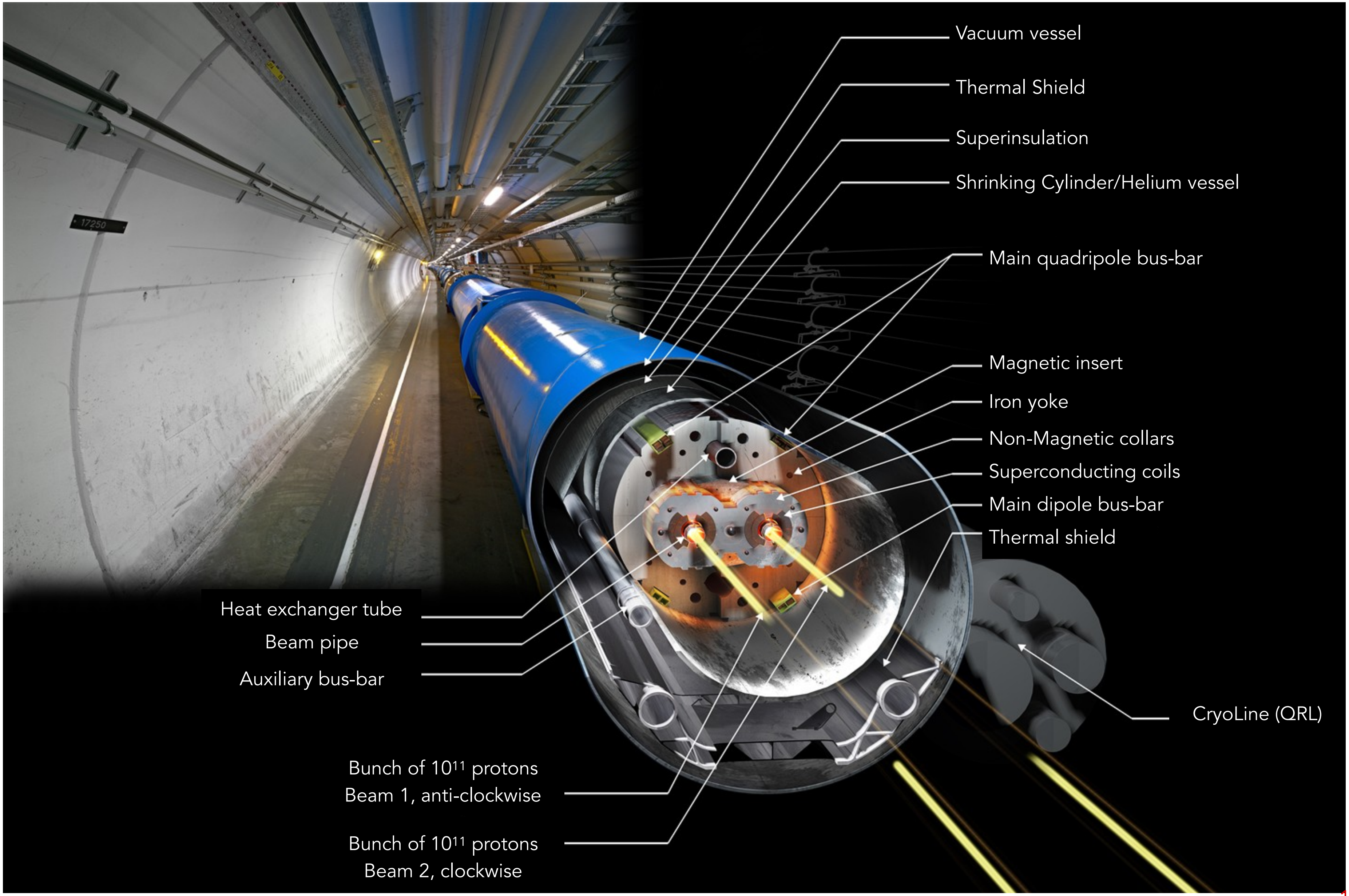
- A collider is a machine where counter-circulating beams collide.
- A collider has a big advantage over other kinds of accelerator where a beam collides with a stationary target.
- The collision energy for 2 colliding beams is the sum of the energies of the two beams.
- A beam of the same energy that hits a fixed target would produce a collision of much less energy.
- The energy available to make new particles in both cases is the centre-of-mass energy. In the first case, it is simply the sum of the energies of the two colliding particles ($E = E_{beam1} + E_{beam2}$), whereas in the second, it is proportional to the square root of the energy of the particle hitting the target ($E \propto \sqrt{E_{beam}}$).

The LHC Accelerator Complex



The LHC tunnel

The LHC beam-pipe



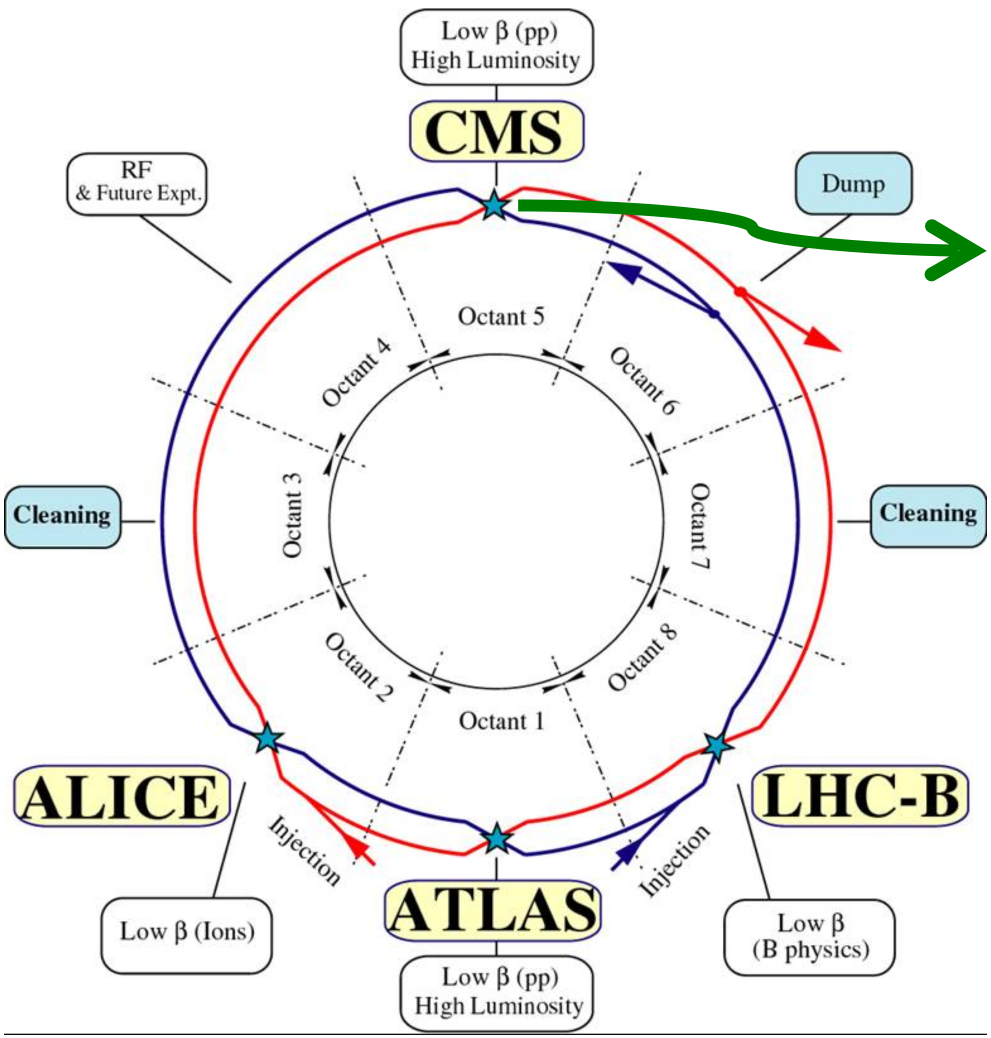
LHC Collision Energy

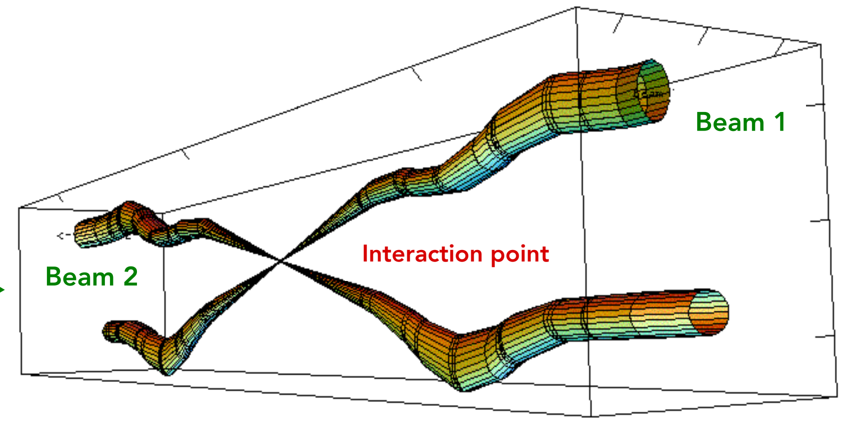
- **It has** never been reached before in lab!
- Each proton beam travel around the LHC at an energy of 7 TeV, and gives collision energy ~14 TeV.
- Lead ions have many protons, and together they give an even greater energy: the lead-ion beams will have a collision energy of ~1150 TeV.
- Compared to the energies we deal with everyday, it is not impressive scale in absolute terms but energy concentration makes particle collisions very special.
    - For example, 1 TeV is about the energy of motion of a flying mosquito but the LHC is very extraordinary because it squeezes energy into a space about a million million times smaller than a mosquito.

Proton Bunches and Collisions

- The protons circulate around the LHC ring in well-defined bunches.
- Under nominal operating conditions, each proton beam has 2808 bunches, with each bunch containing about 10^{11} protons (100 billion), bunch spacing of 25 ns (or about 7 m).
- The bunch size is not constant around the ring. Each bunch gets squeezed and expanded as it circulates around the LHC.
    - It gets squeezed as much as possible around the interaction points to increase the probability of a collision. Bunches of particles measure a few 'cm' long and a 'mm' wide when they are far from a collision point.
    - As they approach the collision points, they are squeezed to about 16 μm to allow for a greater chance of proton-proton collisions.
- Increasing the number of bunches is one of the ways to increase luminosity in a machine.
- The particles are so tiny that the chance of any two colliding is very small. When the bunches cross, there will be a maximum of about 20 collisions between 200 billion particles. Bunches will cross on average about 30 million times per second, so the LHC will generate up to 600 million particle collisions per second.

LHC Collisions





- The LHC has 4 interaction points (where the two proton beams cross each other).
- Four main experiments are installed at these points.

General Purpose Detectors: ATLAS and CMS

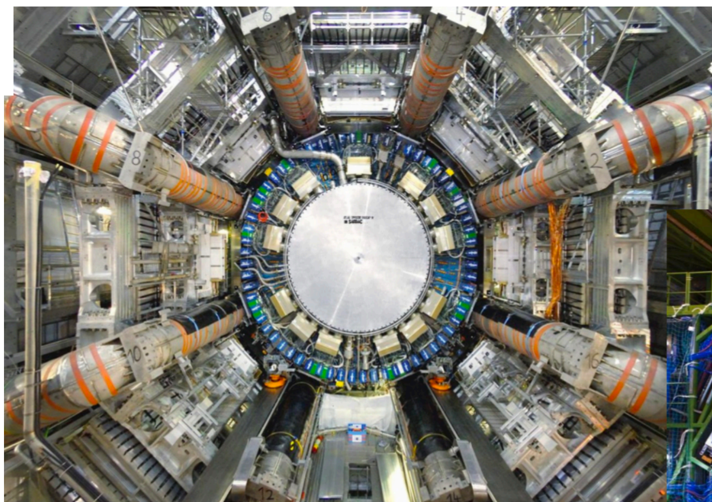
Size	46 m long, 25 m high and 25 m wide
Weight	7000 tonnes
Design	barrel plus end caps
Material cost	540 MCHF
Location	Meyrin, Switzerland.

~3000 Members

38 Countries

177 Institutes

ATLAS



These 2 experiments discovered the Higgs boson in July 2012

CMS

Size	21 m long, 15 high m and 15 m wide
Weight	12 500 tonnes
Design	barrel plus end caps
Material cost	500 MCHF
Location	Cessy, France.

~4300 Members

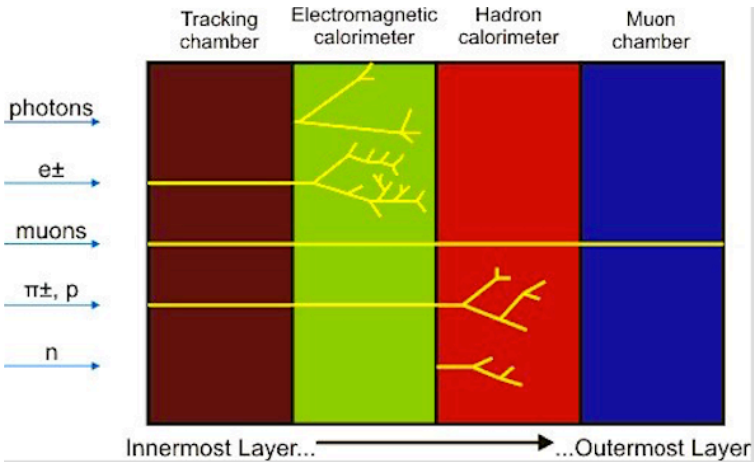
42 Countries

182 Institutes

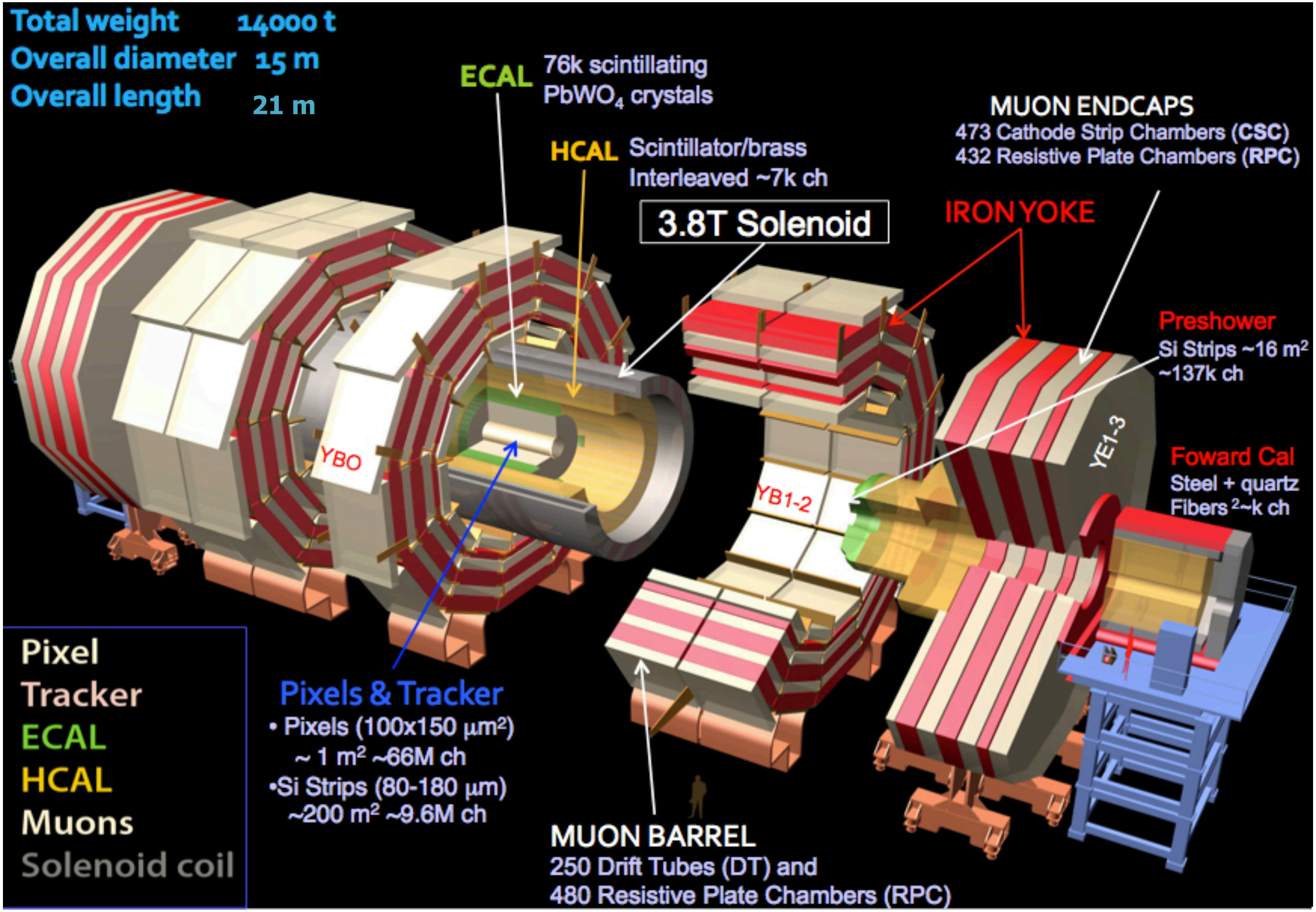
Detectors

- Particle detectors are gigantic digital cameras to see particles and record their information.
- For each collision, need to count, track and characterize all the different particles that were produced in order to reconstruct the full process.
- If the detector is placed inside a magnetic field: the track of the particle gives much useful information.
  - The charge of the particle will be obvious since particles with positive electric charge will bend one way and those with negative charge will bend the opposite way.
  - The momentum of the particle (the 'quantity of motion', which is equal to the product of the mass and the velocity) can be determined:
    - very high momentum particles travel in almost straight lines,
    - low momentum particles make tight spirals.
- The LHC has 4 major detectors ATLAS, ALICE, LHCb, CMS

No magnetic field

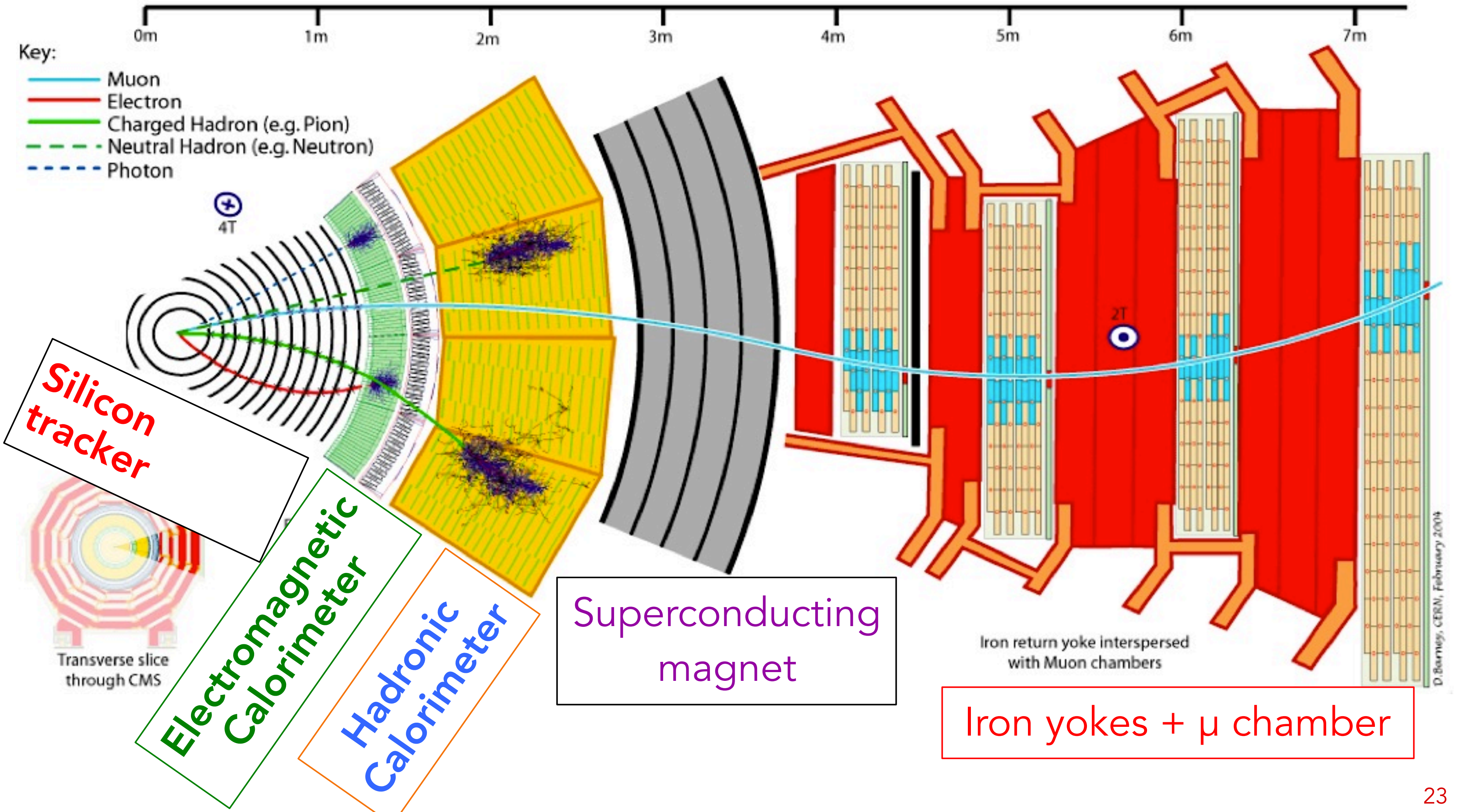


The CMS Detector

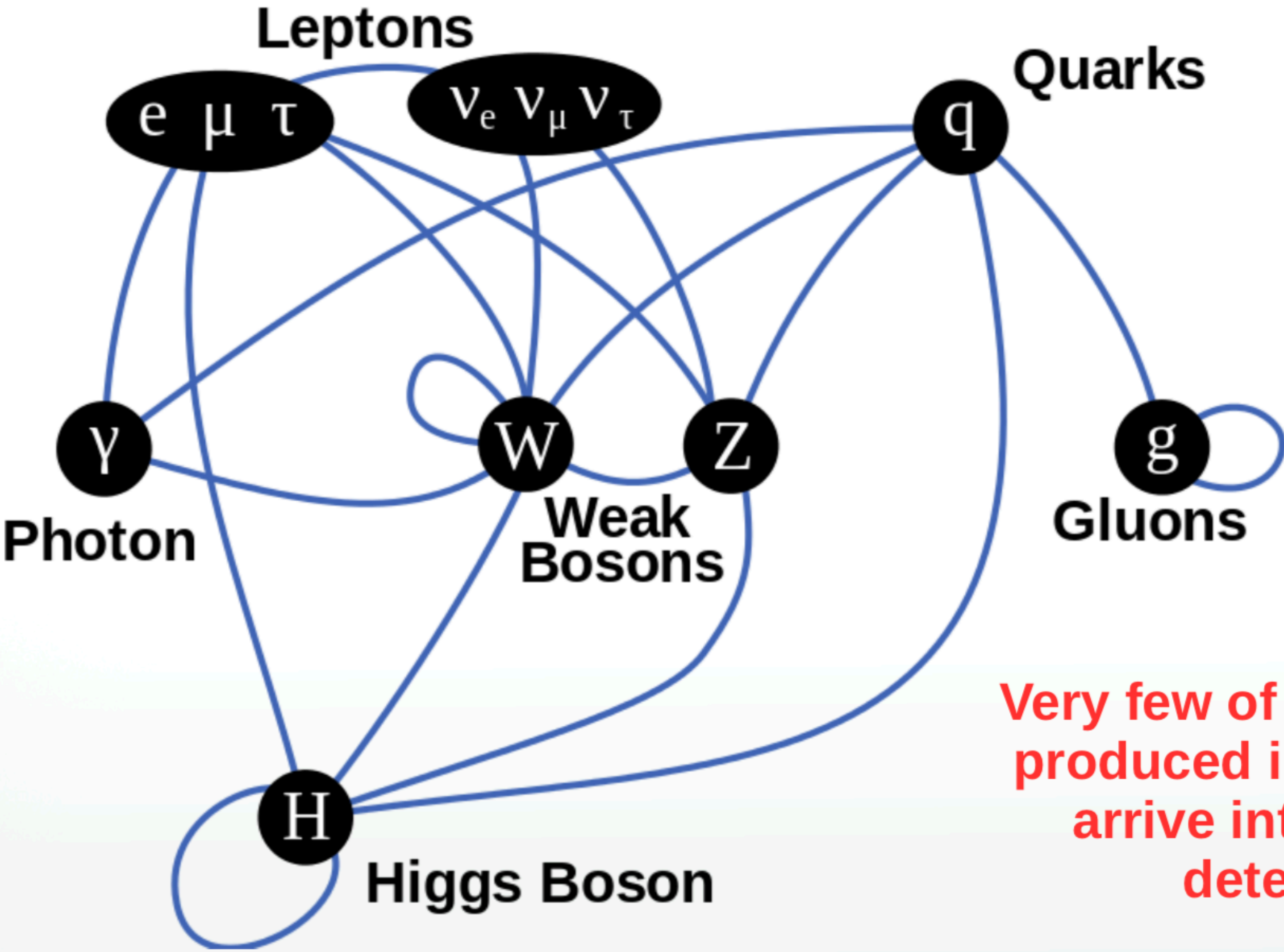


Transverse Slice through CMS

- 85 % - 90 % efficiency for collecting LHC delivered data
- High efficiency and resolution in object (e, μ, tau etc.) reconstruction
- The CMS detector provides good tracking and particle ID all around the interaction point ($0 < \varphi < 2\pi$, $|\eta| < 3$)

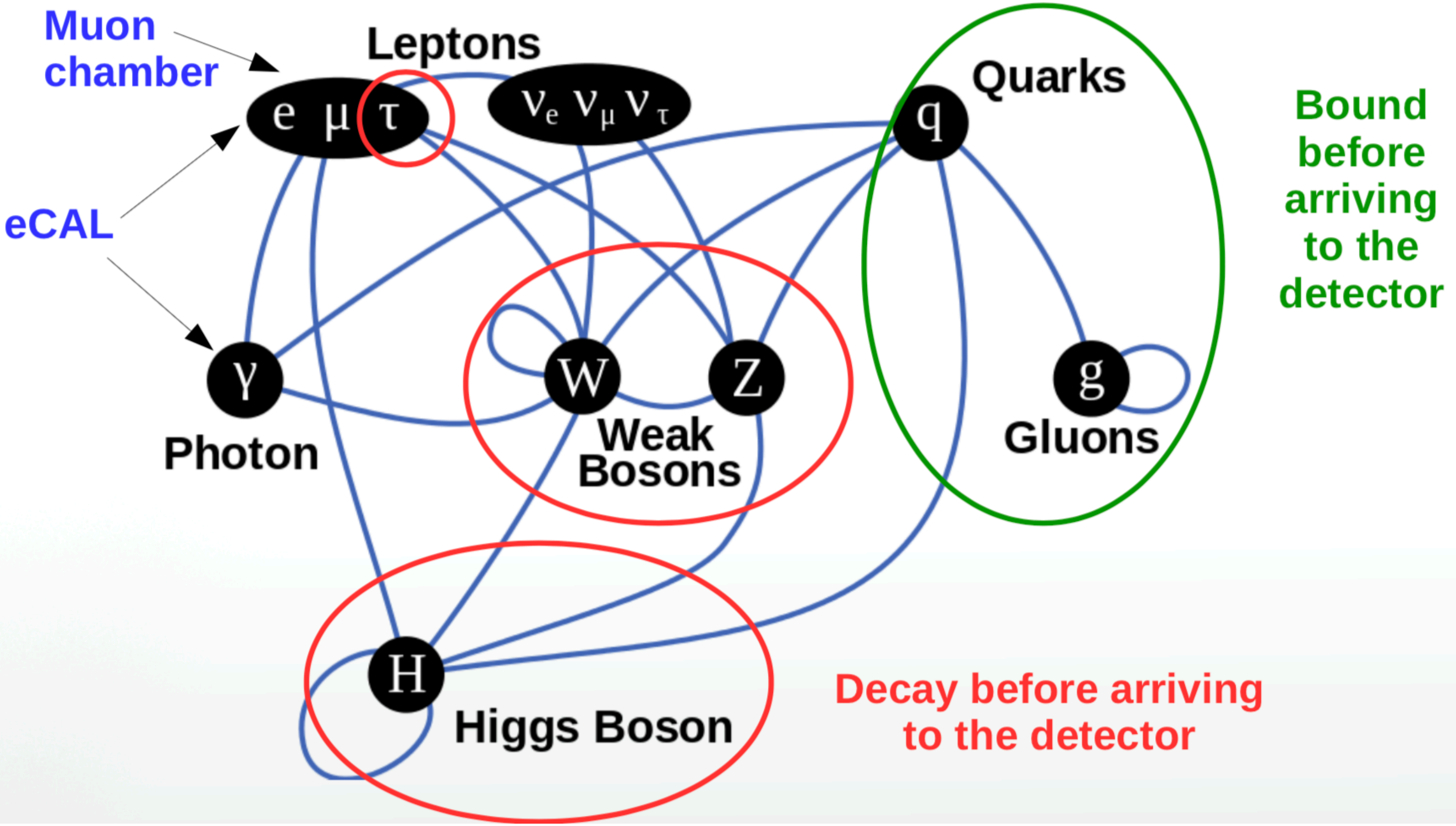


How are particles actually revealed?



Very few of the particles produced in a collision arrive intact to the detectors

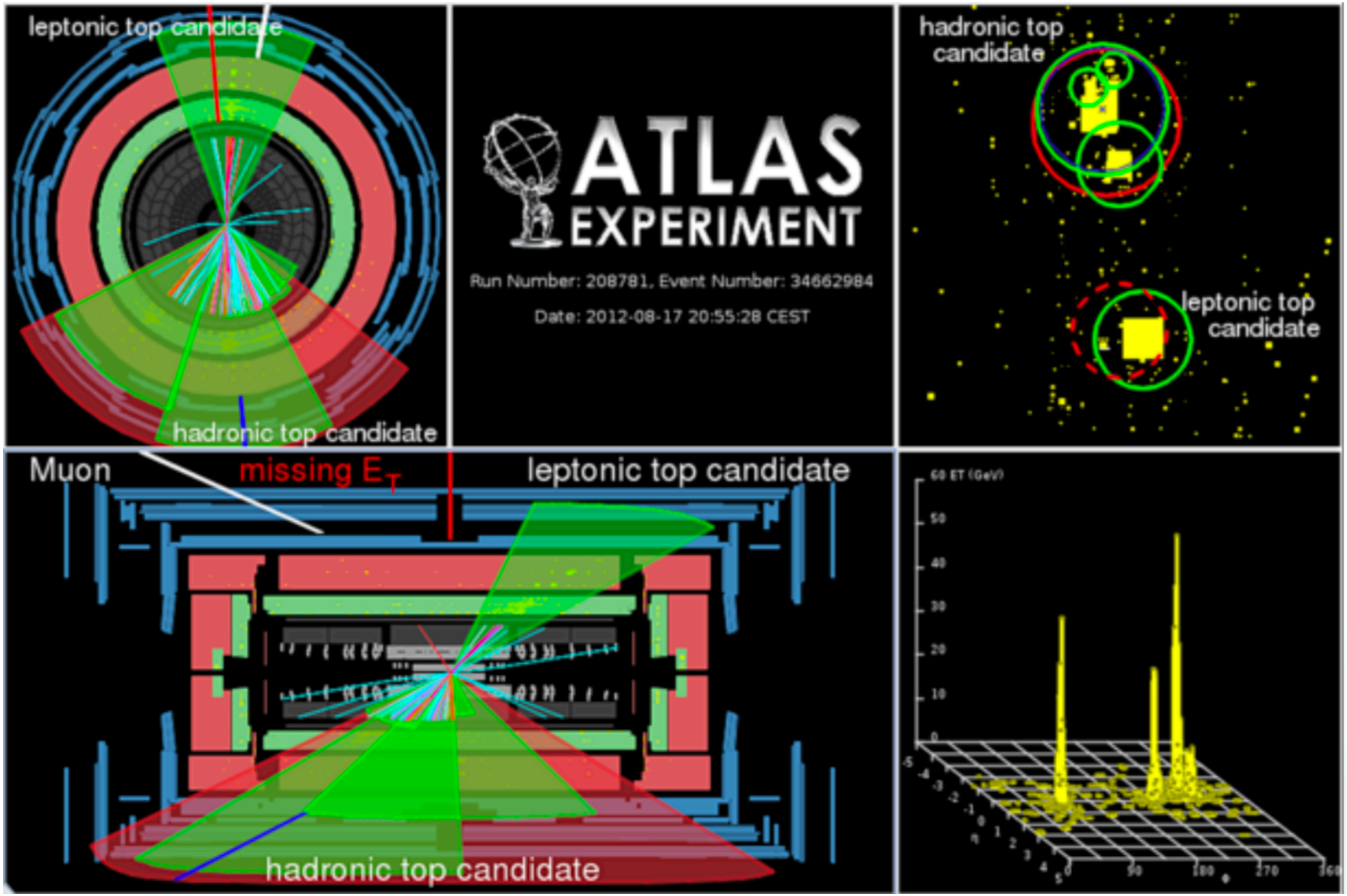
How are particles actually revealed?



LHC Collision Data

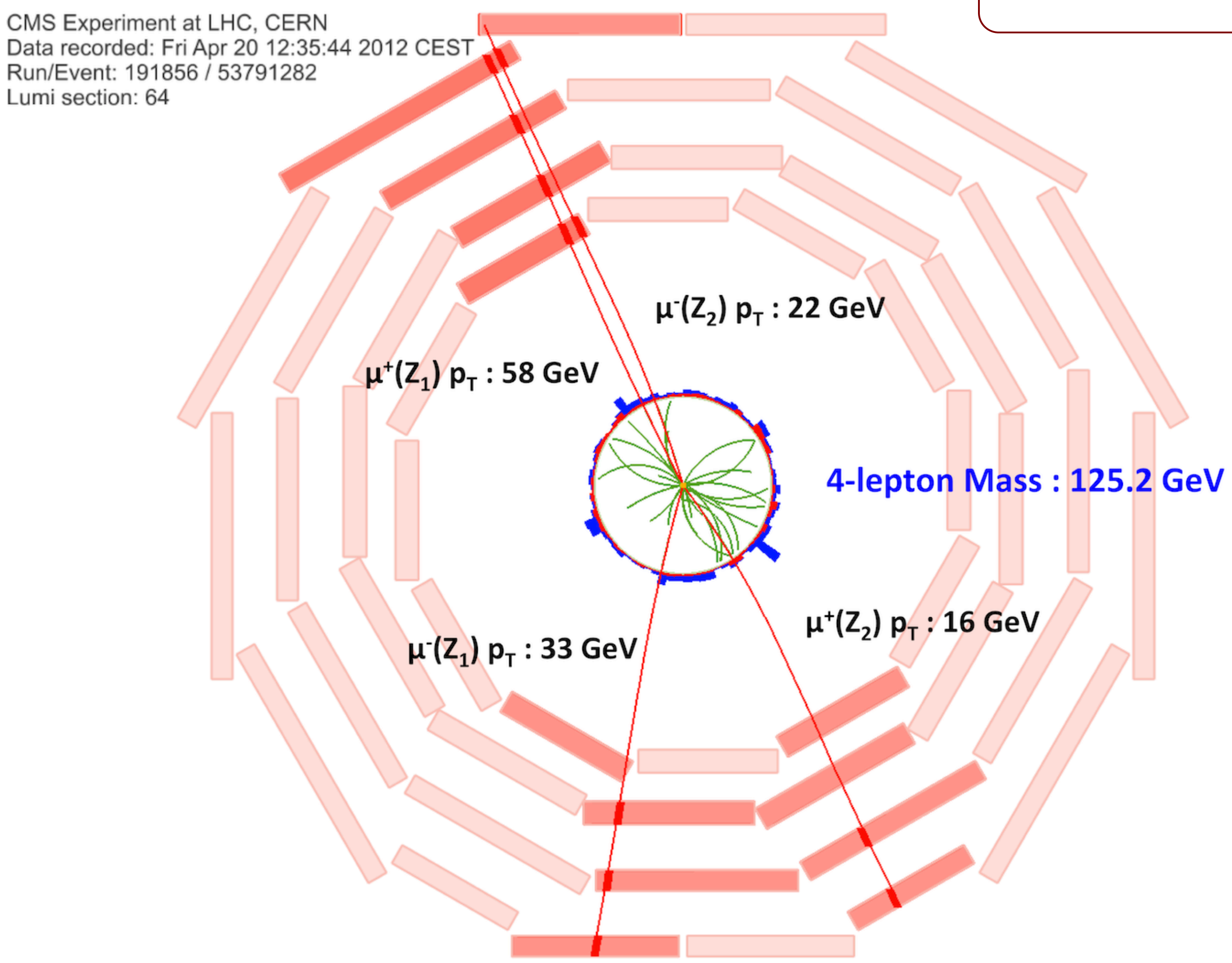
- LHC detectors are gigantic digital cameras that examines the millions of collisions per second and identifies various elementary particles.
- Each collision generates particles that often decay in complex ways into even more particles. Electronic circuits record the passage of each particle through various sub-detectors as a series of electronic signals, and send the data to the CERN Data Centre (DC) for digital reconstruction. The digitized summary is recorded as a \`collision event'.
- LHC experiments produce about **15 petabytes of raw data each year** that must be stored, processed, and analyzed in more detail for various physics interests.
- **Data from the LHC experiments will be distributed around the globe with the Worldwide LHC Computing Grid (WLCG)**
  - UK is part of the WLCG project
- To achieve the physics goals, sophisticated algorithms are applied successively to the raw data collected by each experiment in order to extract physical quantities and observables of interest that can be compared to theoretical predictions.

What do we actually see



Event Display of Higgs boson

$H \to ZZ^* \to 4\mu$



LHC Timeline and Additional Info

~ 25 Years

1983	First studies for the LHC project
1988	First magnet model (feasibility)
1994	Approval of the project by the CERN Council
1996 -1999	Series production of the magnets
1998	Declaration of Utilité Publique and start of civil engineering
1998 - 2000	Main production contracts
2004	Start of the installation of the LHC
2005 - 2007	Installation of the magnets in the LHC tunnel
2006 - 2008	Hardware commissioning
2008 - 2009	Beam commissioning
2009 - 2035	Physics

An international effort, the Sun never sets on the LHC project!

More than 10,000 members (physicists, engineers, technicians, students and support staff)

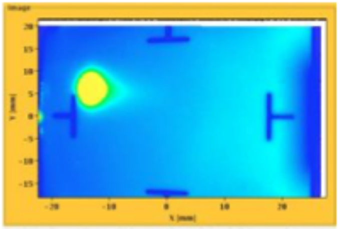
More than 100 countries

100's of Institutes

CERN and the UK: https://international-relations.web.cern.ch/stakeholder-relations/states/united-kingdom

LHC Timeline and Additional Info

August 2008
First injection test



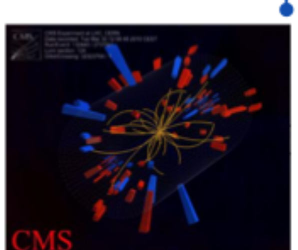
Sept. 10, 2008
First beams around

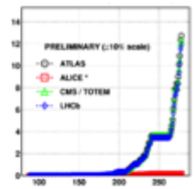
Sept. 19, 2008
Incident

Repair and Consolidation

November 29, 2009
Beam back

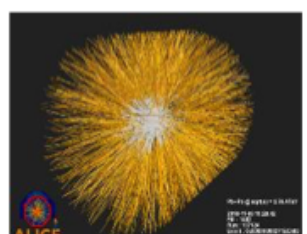
March 30, 2010
First collisions at 3.5 TeV





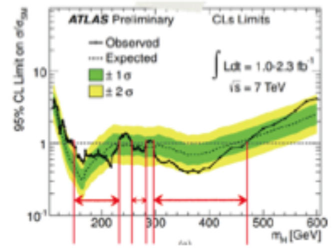
October 14, 2010
L= $1\times10^{+32}$
248 bunches

November 2010
Pb^{82+} Ions



June 28 2011
1380 bunches

1380

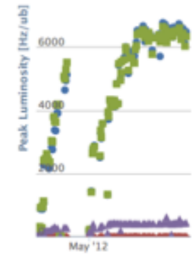


October, 2011
$3.5\times10^{+33}$, 5.7 fb^{-1}

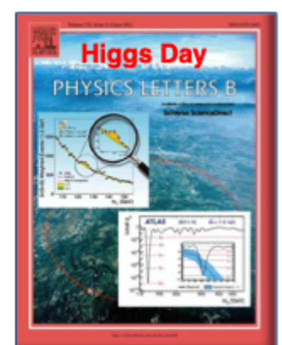
First Hints!!

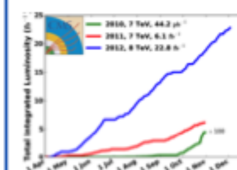
November 2011
Second Ion Run

March 14th 2012
Restart
with Beam

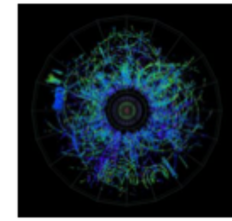


May 2012
Ramping
Performance





Nov. 2012
End of p^{+} Run 1

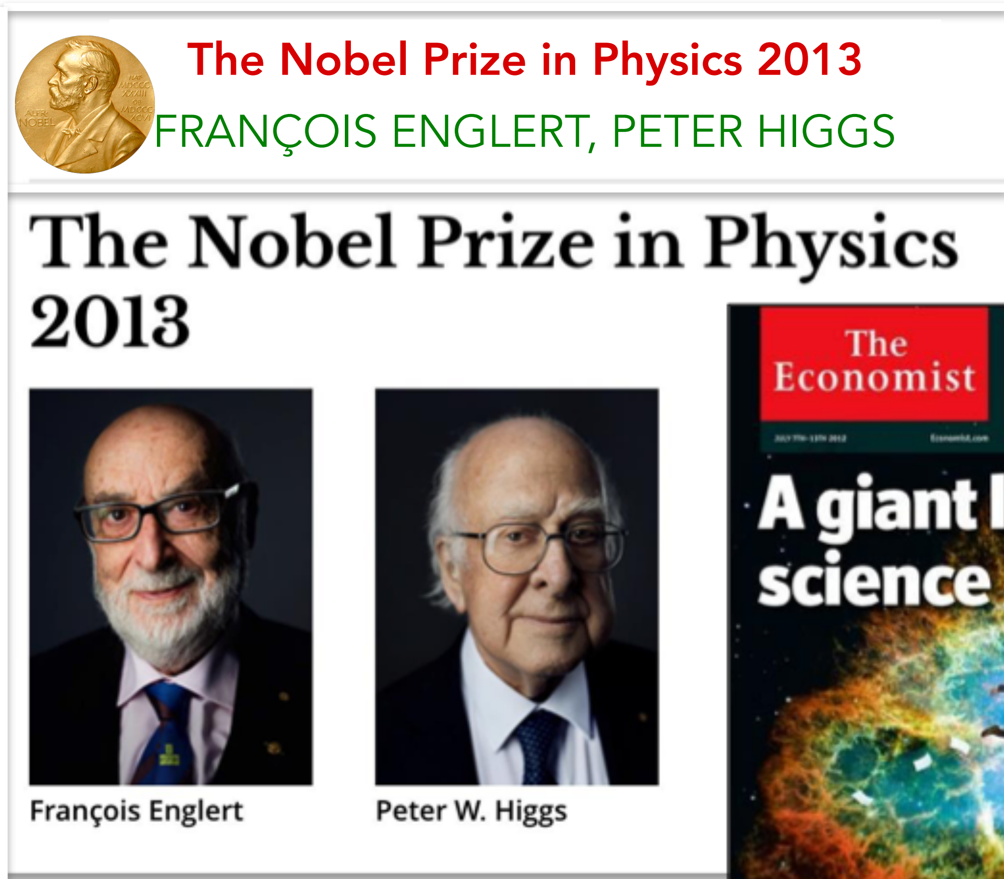


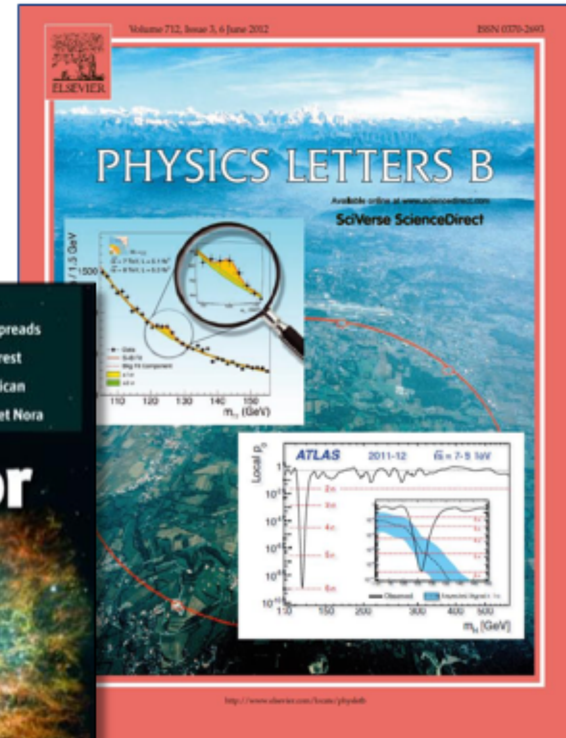
Feb. 2013
$p\text{-}Pb^{82+}$
New Operation Mode

LS1

2008 | 2009 | 2010 | 2011 | 2012 | 2013

Highlights of LHC

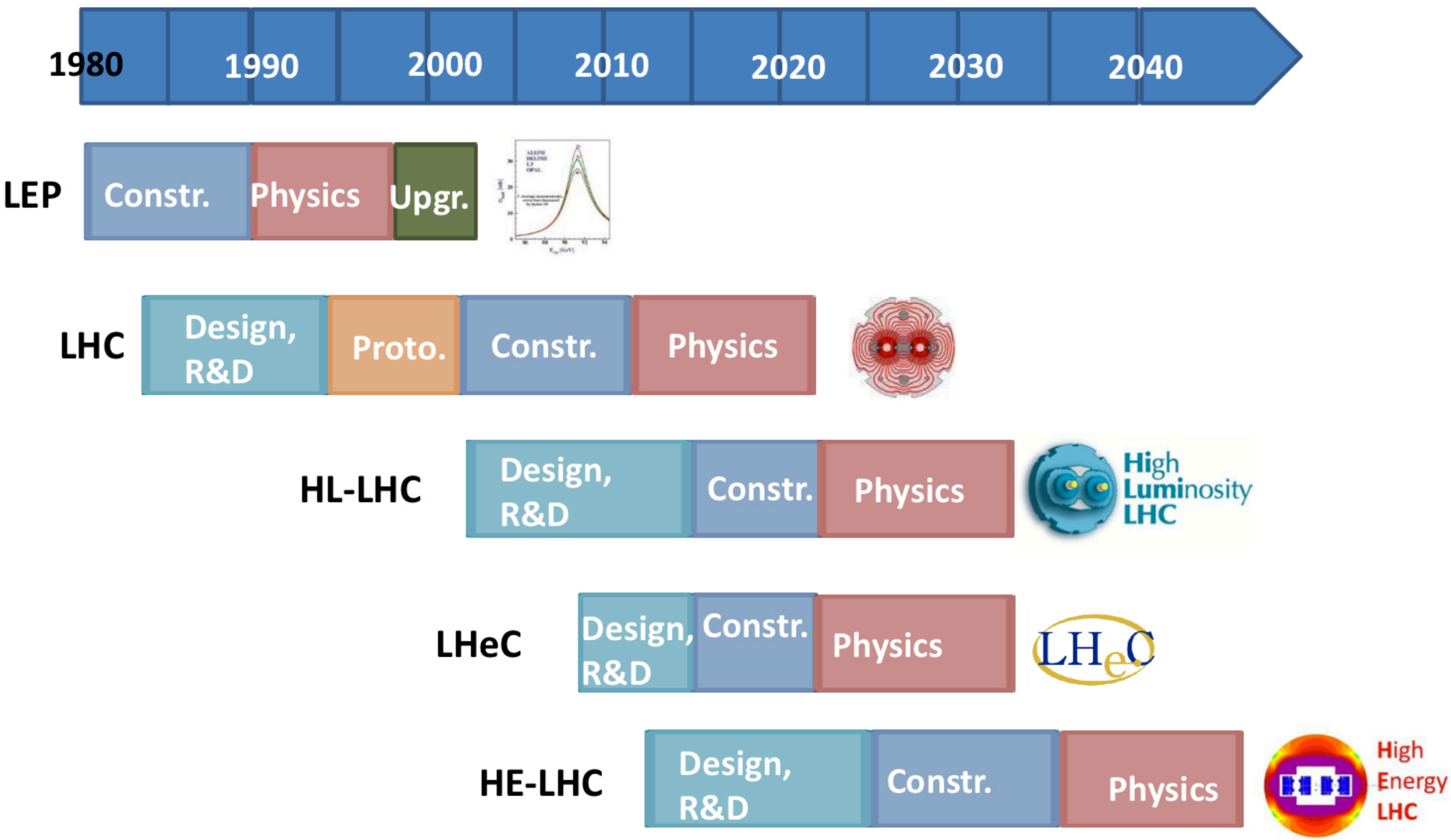




Future Plans for LHC

Future is opportune, exciting and very well planned ☺️

Ask questions to know this great effort to understand the UNIVERSE



Other research activities at CERN

Computer Science

- The WWW as we know it was invented in CERN in 1989
- Invented by Tim Berners-Lee, a British scientist
- Made available to the public in 1993

A lot of the developements made by particle physics, are just byproducts of some completely different research

Medical

- Hadron therapy for cancer treatment

Opportunities at CERN

- Students & Educators site:
  - https://home.cern/students-educators
- High-school students internship programme (hssip)
  - http://hssip.web.cern.ch/

Thank you!