Elementary particle physics at CERN:
discoveries and new technologies

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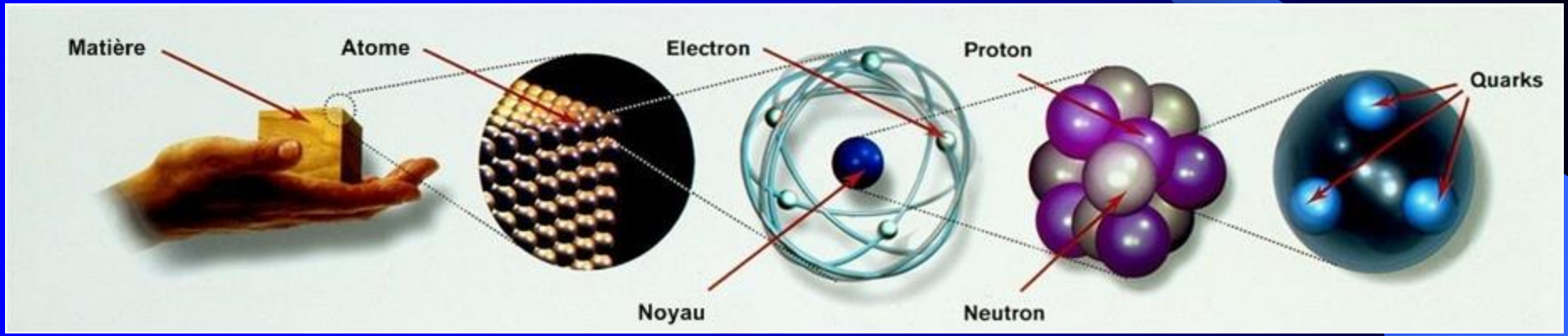
- Elementary particles
- How do we study them at CERN ?
- LHC accelerator
- CMS experiment
- CMS results and still open questions
- Technology transfer of our basic research

Animations and drawings by Dave Barney (CERN)

Elementary particle : what is it ?



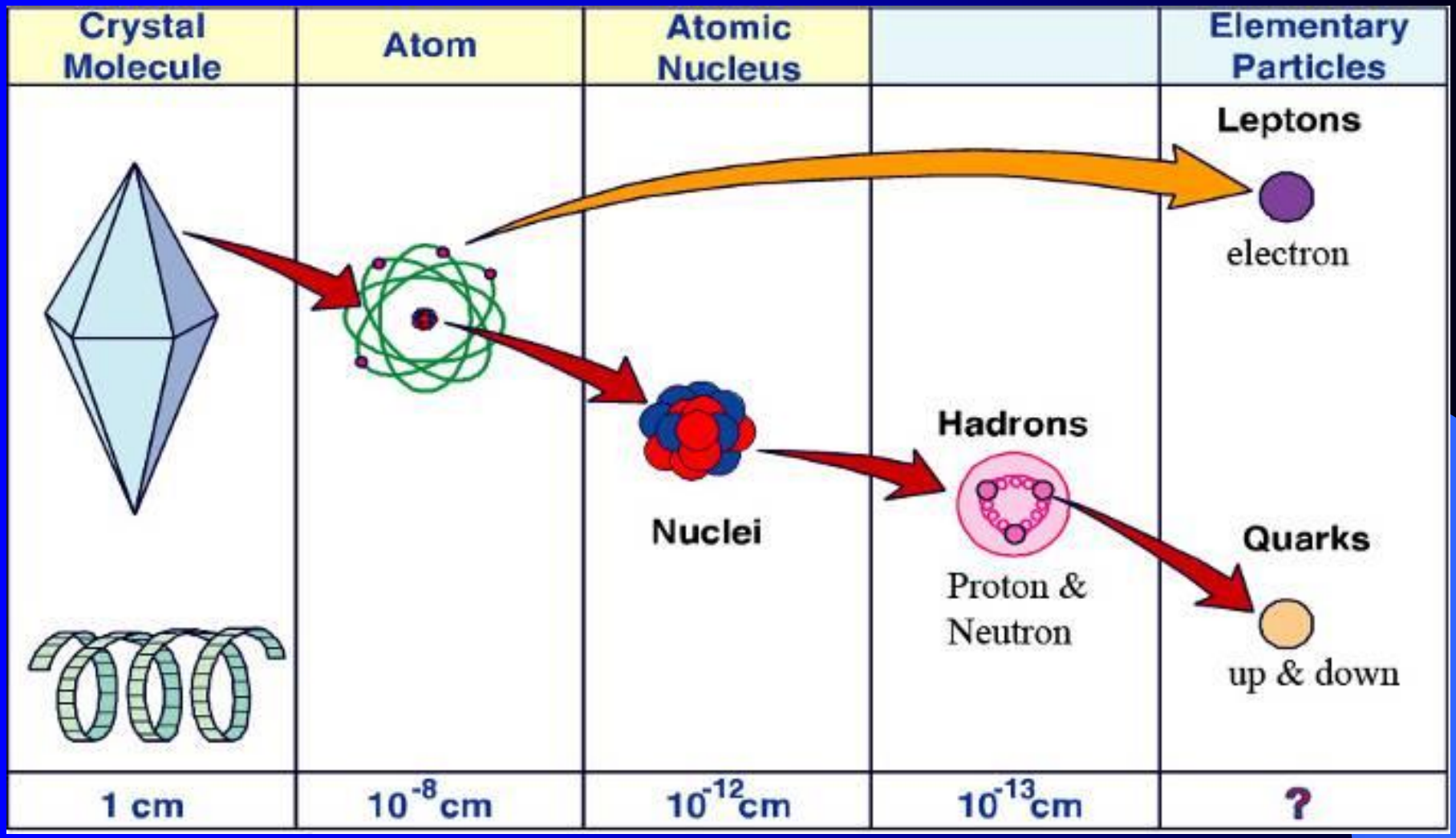
IV - V
A.C.

End of
XIX
century

Beginning of
XX
century

Years
‘60

Our current understanding



$< 10^{-16}$ cm

Universal Lego Bricks

Quarks

up

down

Leptone

elettrone

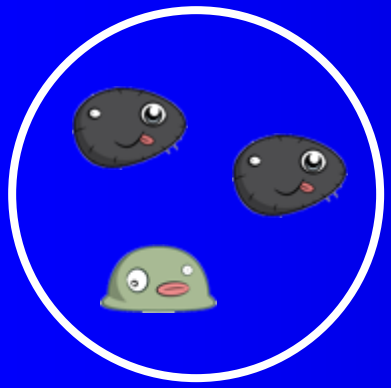
UUD = proton

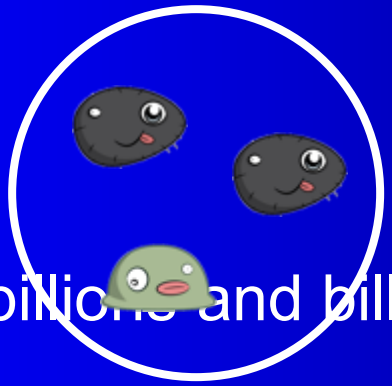
UDD = neutron

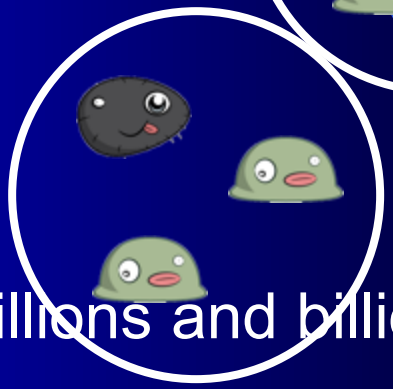
Building an Atom

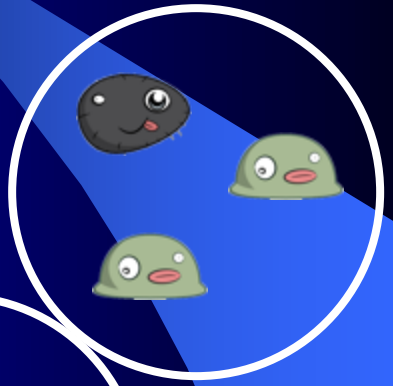
electrons

Helium Atom









protons

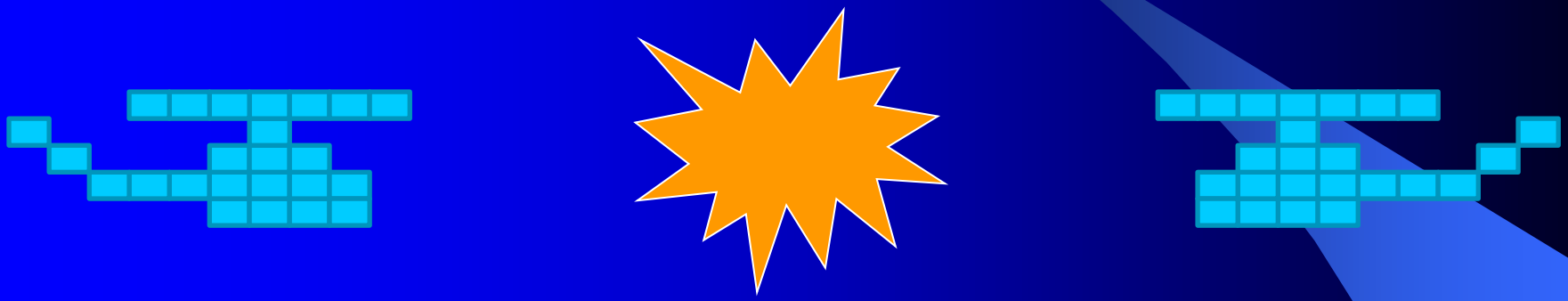
neutrons

Multiply by billions and billions and billions and billions…

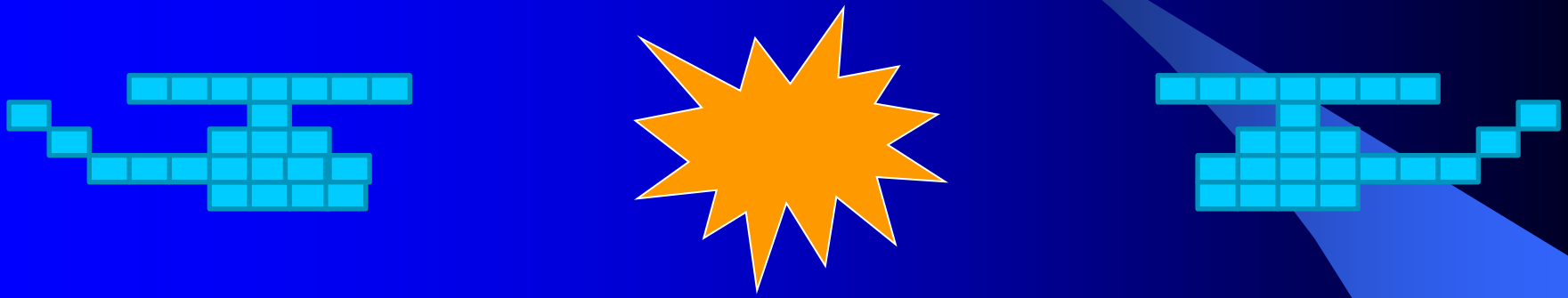
Et voila – the Universe!

How do we study elementary particles at CERN?

Smash things together, see what happens!



Accelerator Energy



Accelerator Energy

$E = mc^2$

The collision energy was used
to create something new, that
did exist but does not any more!

Accelerator Energy

13.7 billion years ago, there were other things in the Universe…

Quarks


up


charm


top


down


strange


bottom

Leptons


electron


muon


tau


electron neutrino


muon neutrino


tau neutrino

There is also anti-matter….

For every type of particle

There is an antiparticle

But, as far as we can tell, there is virtually no anti-matter naturally existing in our Universe…..


up


electron


anti-up


positron


down

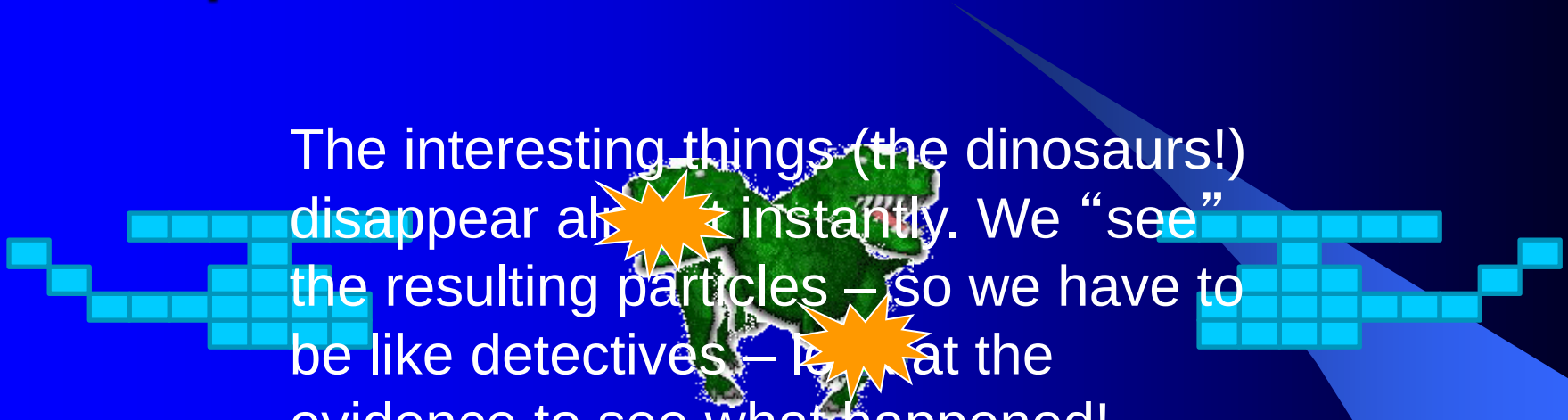

electron neutrino


anti-down


Anti-electron neutrino

Particles and antiparticles have opposite electric charge

And just to make things even more complicated……



The interesting things (the dinosaurs!) disappear almost instantly. We “see” the resulting particles – so we have to be like detectives – look at the evidence to see what happened!

Other particles responsible for interactions

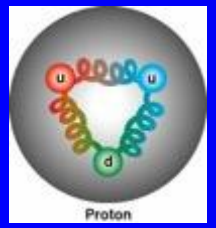
Elementary particle list is not over !!!

There are other particles, representing possible interactions between elementary particles we discussed so far

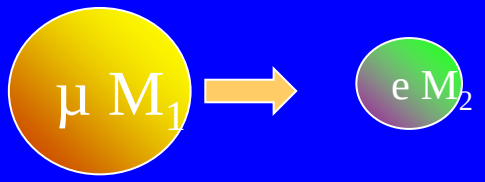
3 major forces that keep together the lego bricks of the matter

Bosons:

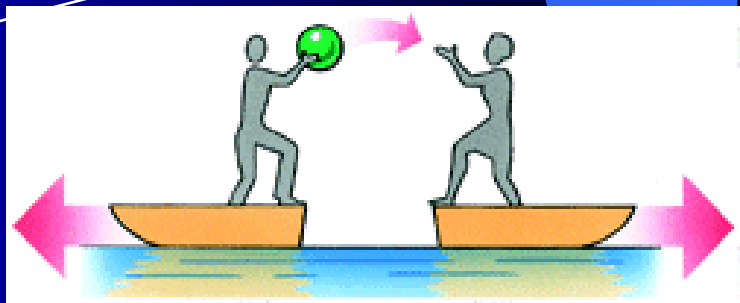
Elettromagnetic ⟷ Photons



Strong ⟷ **Gluons**



Weak ⟷ $W^{+/-}$ e Z^0



The “standard model”

Quarks


up


charm


top


down


strange


bottom

Leptoni


neutrino elettronico

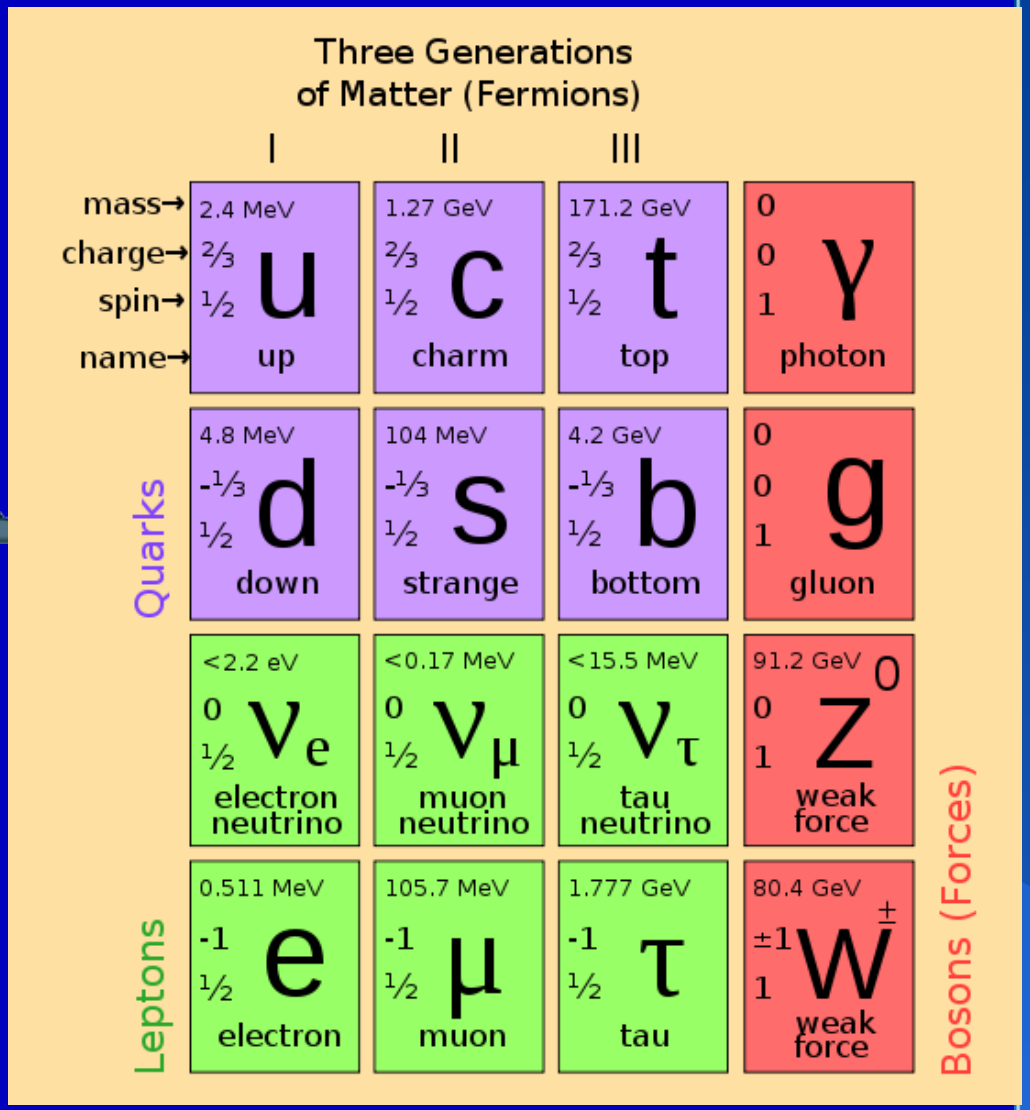

neutrino muonico


neutrino tauonico


elettrone


muone


tauone



How do we do all this in reality?

..not with helicopter collisions, but with elementary particle collisions, driven to very high energy conditions using accelerators !

…but before looking to the LHC (the largest accelerator in the world) in detail… let's clarify :

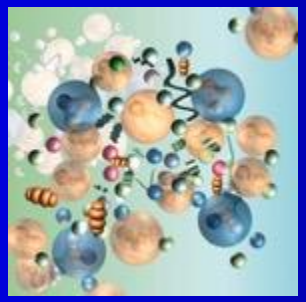
Accellerators = Time machines to go "back in time"

????

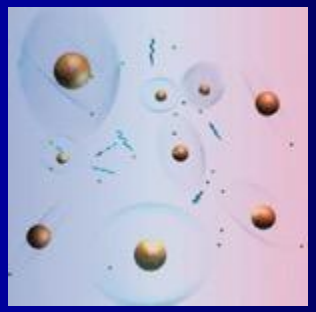
Big Bang Theory

Unified Forces (GUT)

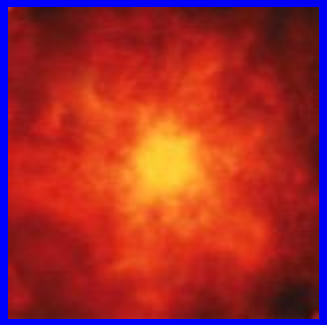
Protons and Neutrons



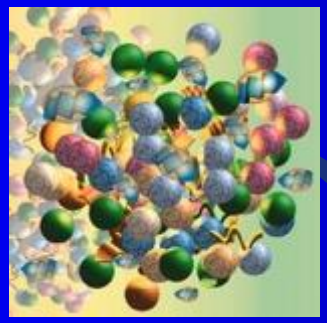
Atoms and Light



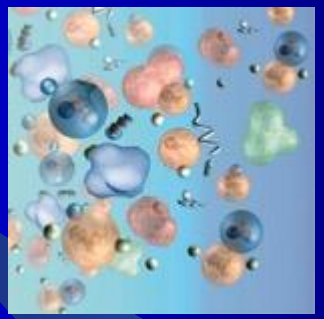
Today



Gravity

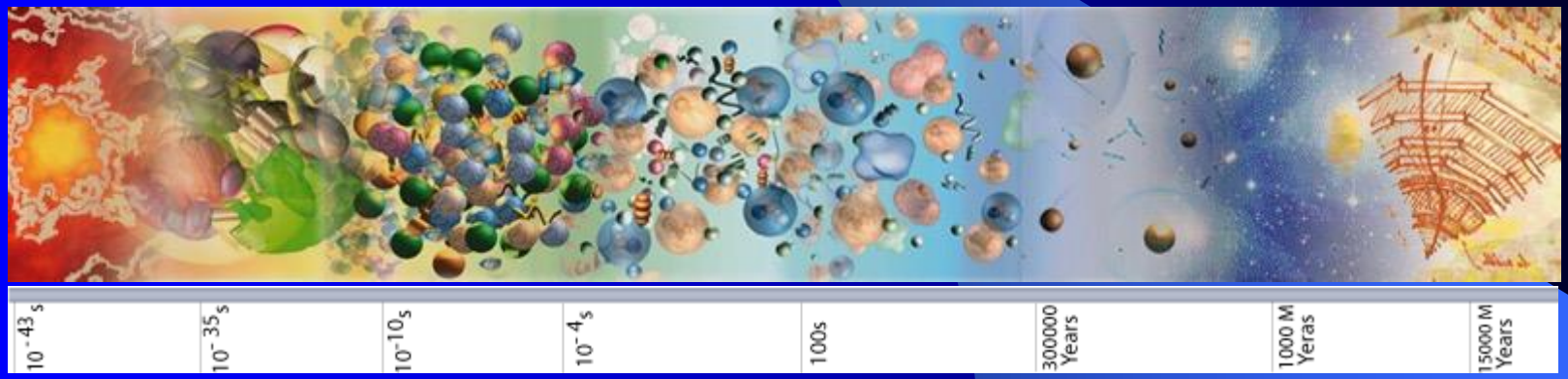


Electroweak



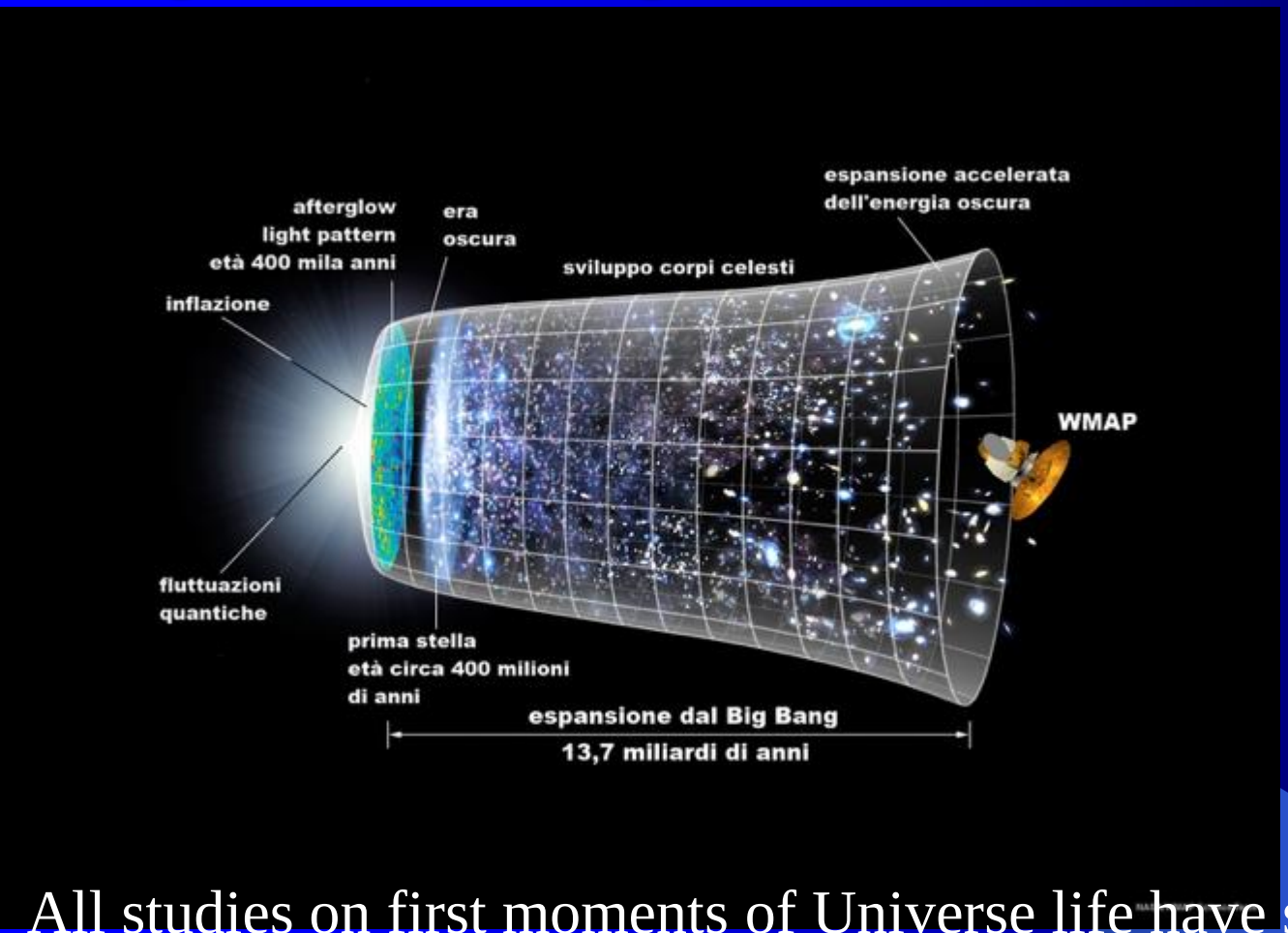
Nuclei

Galaxies



10^{32} K	10^{27} K	10^{15} K	10^{13} K	10^{9} K	6000 K	18 K	3 K
10^{19} GeV	10^{16} GeV	100 GeV	1 GeV	0.1 MeV	0.5 eV		

High E = High T = back in time



$$\langle E \rangle = \frac{3}{2} k_B T$$

Boltzmann constant is managing proportionality between average T and E in a molecule.

All studies on first moments of Universe life have shown the deep connections between cosmology and particle physics.
For that reason, we say that:

Studying the infinite small, we study the infinite big
Studying elementary particles, we study the Universe

… but now let's go back to see how LHC is really done, conceived to produce :

Collisions at **very high E** …

→ meaning to reach **very high T**

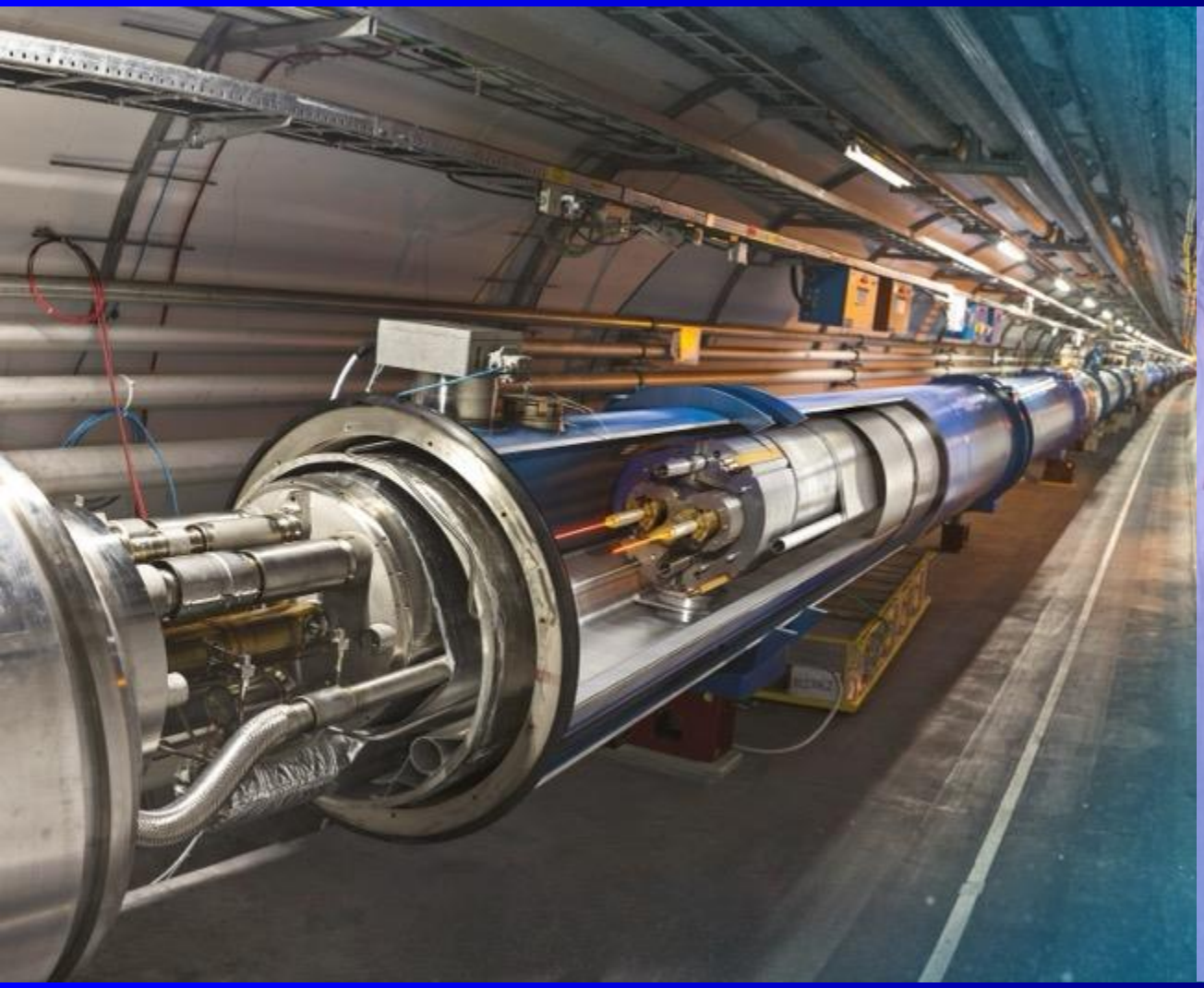
→ meaning to go really **very much "back in time"** !

LHC

Large Hadron Collider

www.cern.ch/lhc

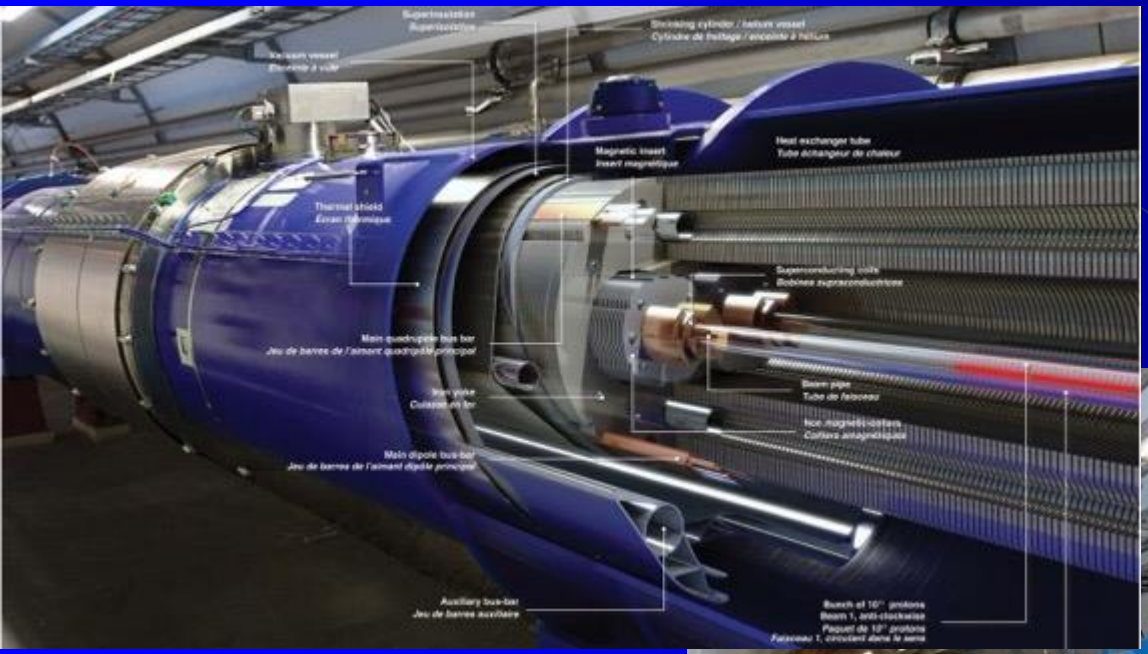
CERN and LHC

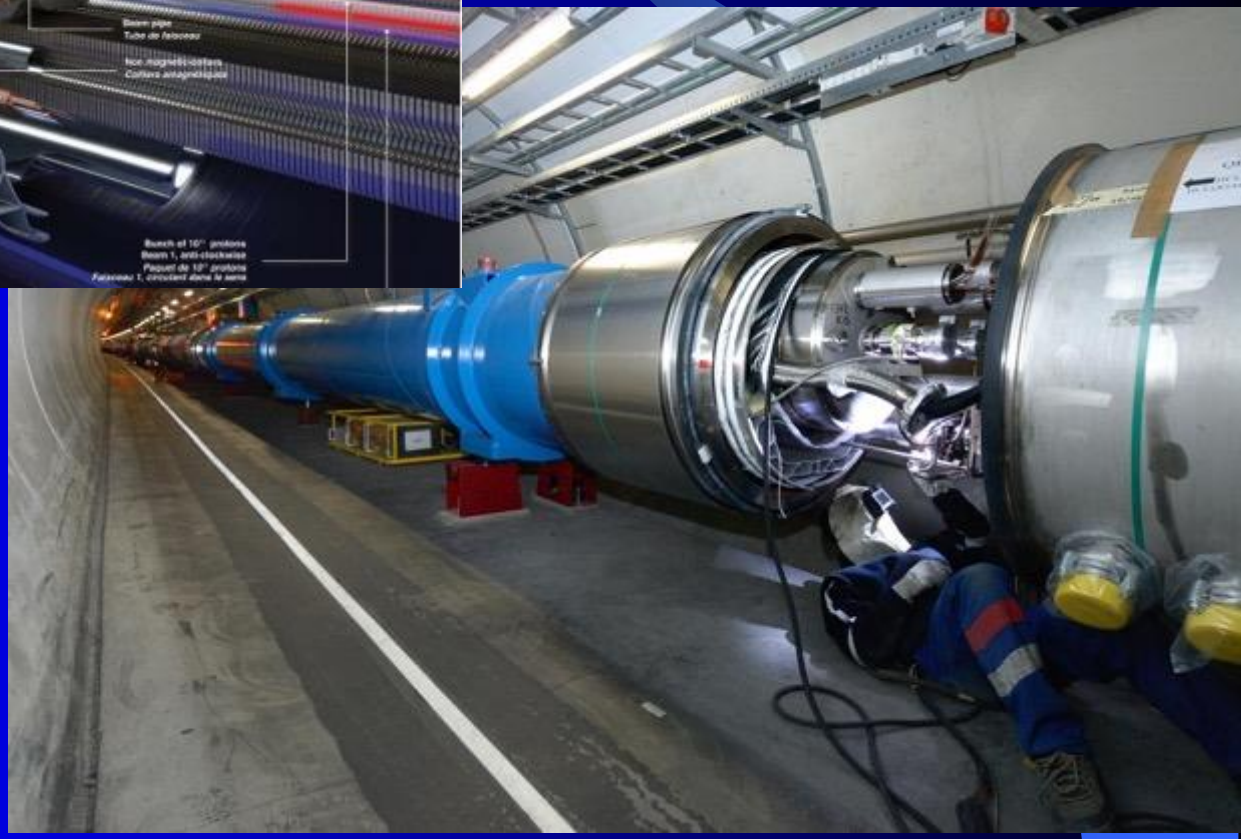


Large Hadron Collider (LHC)

- 27 km in circumference
- About 100 m underground
- 1800 superconducting magnets steer the particles around the ring
- Particles are accelerated to close to the speed of light

Large Hadron Collider (LHC) – a VERY complex facility !





… it took more than 20 years to manufact & install all LHC magnets !

Beyond Pluto – a 10 billion km long ride inside CERN !!!

How do we discover new particlaes with LHC

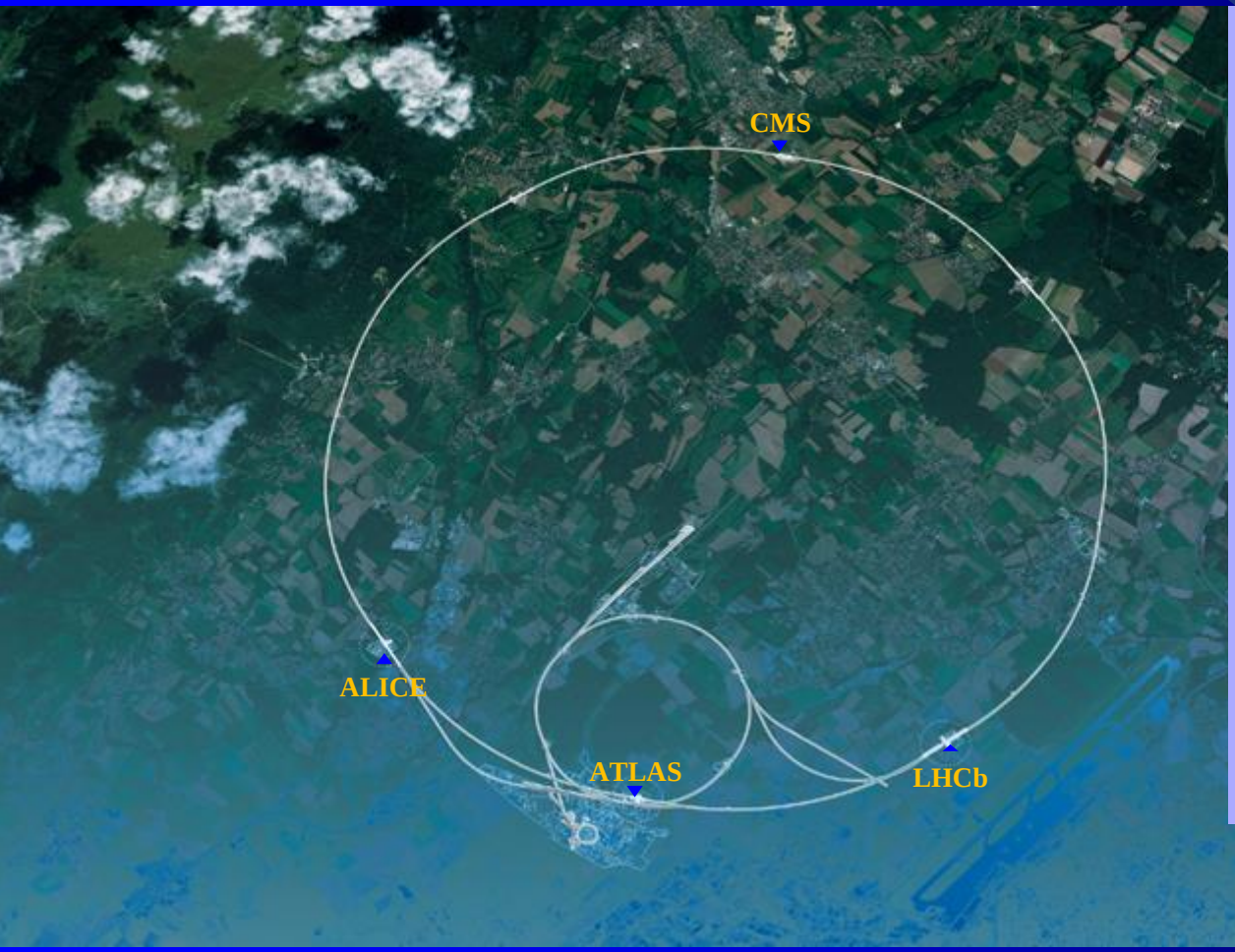
1) We accelerate « bunches » of protons (10^{11}) getting the highest possible cinetic energy: 7 TeV (for single proton)

2) We let collide 2 beams of many « bunches » of protons (2800 bunches)

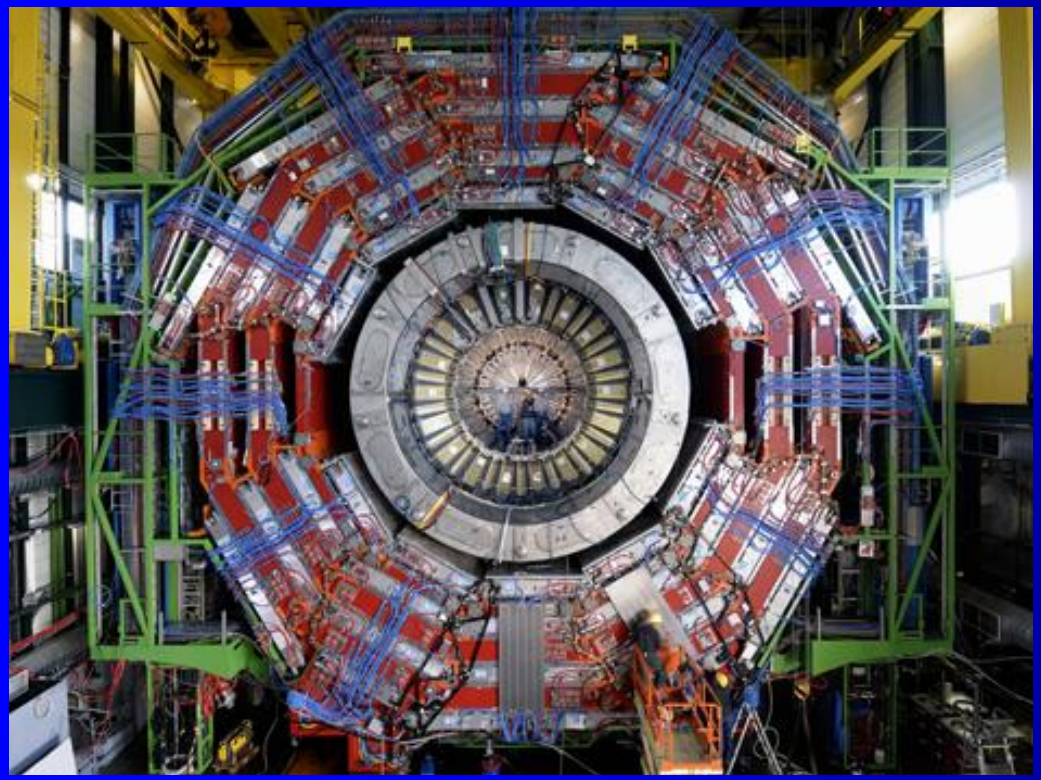
3) The available energy in the collisions proton - proton « E » (E= 2x7 TeV) it's converted in NEW particles of mass « m » following the formula:

$$E = mc^2$$

Giant detectors record the particles formed at the four collision points



Using the **largest and most complex detectors** ever built



To select and record the signals from the 40 million collisions every second, CERN scientists were building huge detectors to measure the tiny particles to an extraordinary precision.

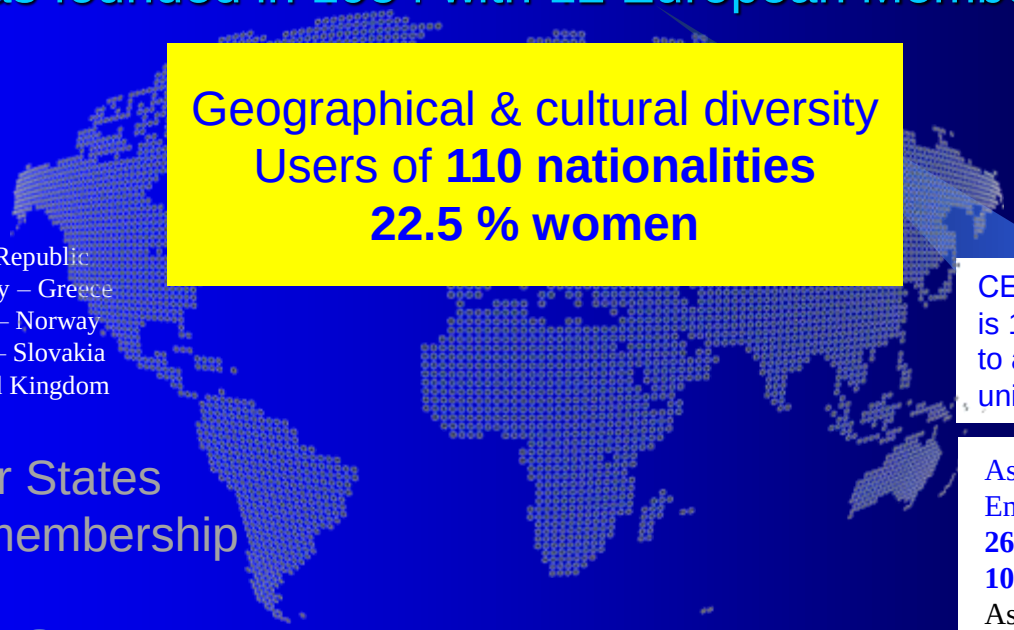
Collaboration

More than **17000 people** work at CERN

Science for peace

CERN was founded in 1954 with 12 European Member States

Geographical & cultural diversity
Users of **110 nationalities**
22.5 % women



23 Member States

Austria – Belgium – Bulgaria – Czech Republic
Denmark – Finland – France – Germany – Greece
Hungary – Israel – Italy – Netherlands – Norway
Poland – Portugal – Romania – Serbia – Slovakia
Spain – Sweden – Switzerland – United Kingdom

3 Associate Member States in the pre-stage to membership

Cyprus – Estonia – Slovenia

8 Associate Member States

Brazil – Croatia – India – Latvia – Lithuania – Pakistan
Türkiye – Ukraine

6 Observers

Japan – Russia (suspended) – USA
European Union – JINR (suspended) – UNESCO

CERN's annual budget is 1200 MCHF (equivalent to a medium-sized European university)

As of 31 December 2023
Employees:
2666 staff,
1002 graduates and fellows
Associates:
12370 users, **1513** others

Around 50 Cooperation Agreements with non-Member States and Territories

Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Belarus – Bolivia
Bosnia and Herzegovina – Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Honduras
Iceland – Iran – Jordan – Kazakhstan – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco – Nepal
New Zealand – North Macedonia – Palestine – Paraguay – People's Republic of China – Peru – Philippines – Qatar
Republic of Korea – Saudi Arabia – Sri Lanka – South Africa – Thailand – Tunisia – United Arab Emirates – Vietnam

Distribution of all CERN Users by the country of their home institutes as of 31 December 2023

Research and Education & Outreach : the CERN Science Gateway

- CERN's new education and outreach centre for all publics aged 5-plus.

- Opening for public: 8th October 2023
- Number of visitors:
- **~ 320 000**

- Immersive exhibitions,
- education labs,
- events and shows.

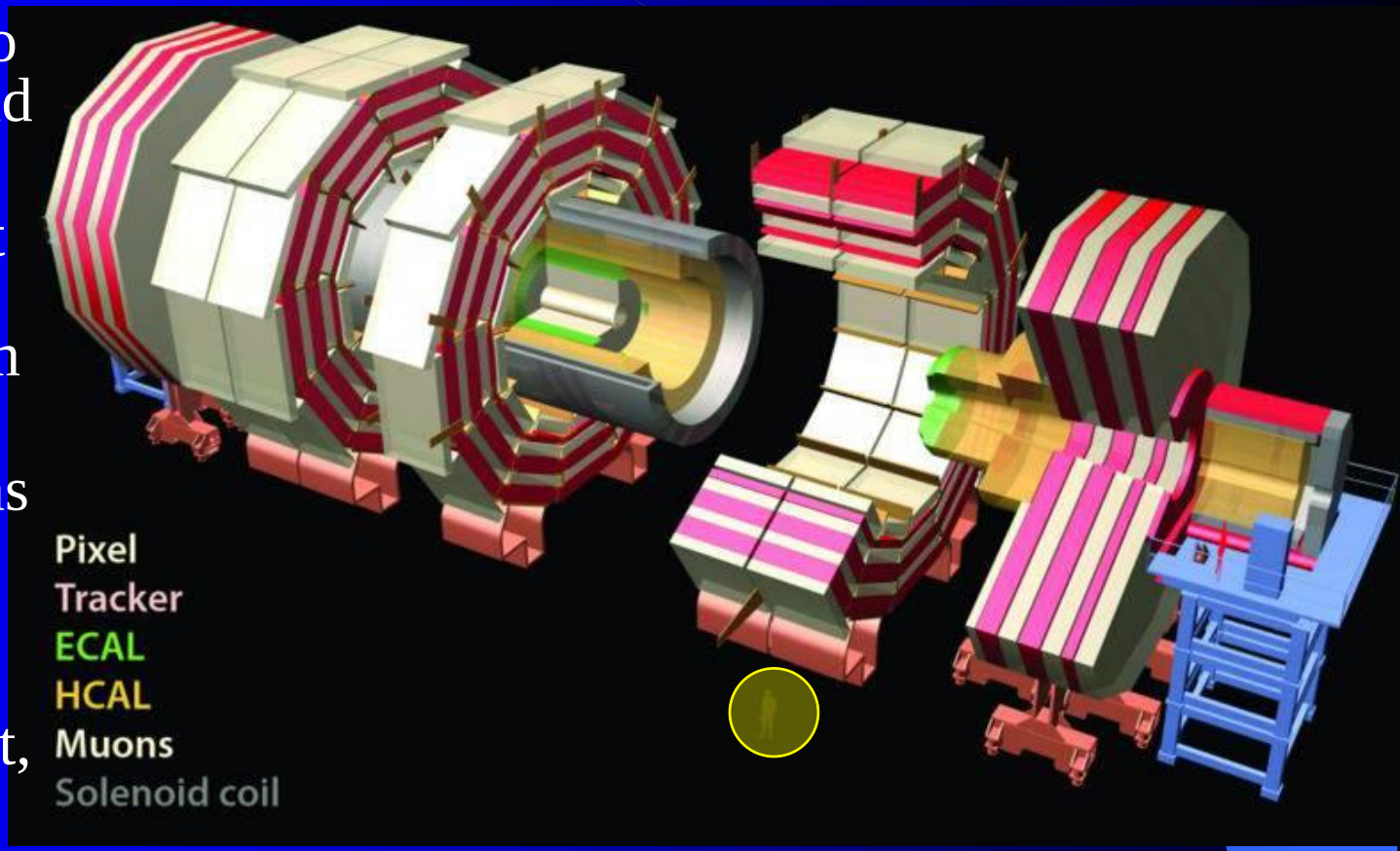
CMS detector

Compact Muon Solenoid

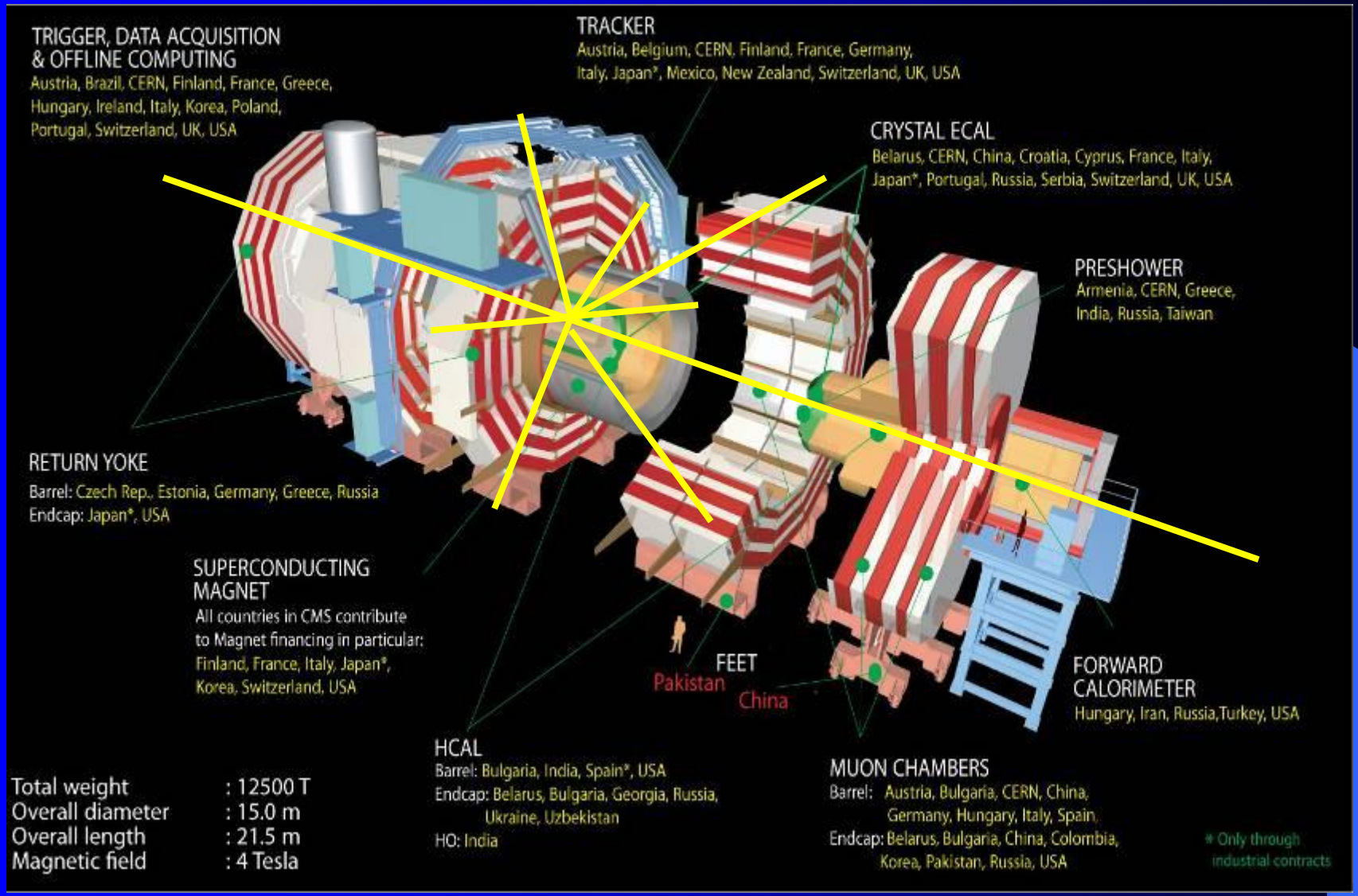
cms.cern.ch

The **huge** CMS detector…..

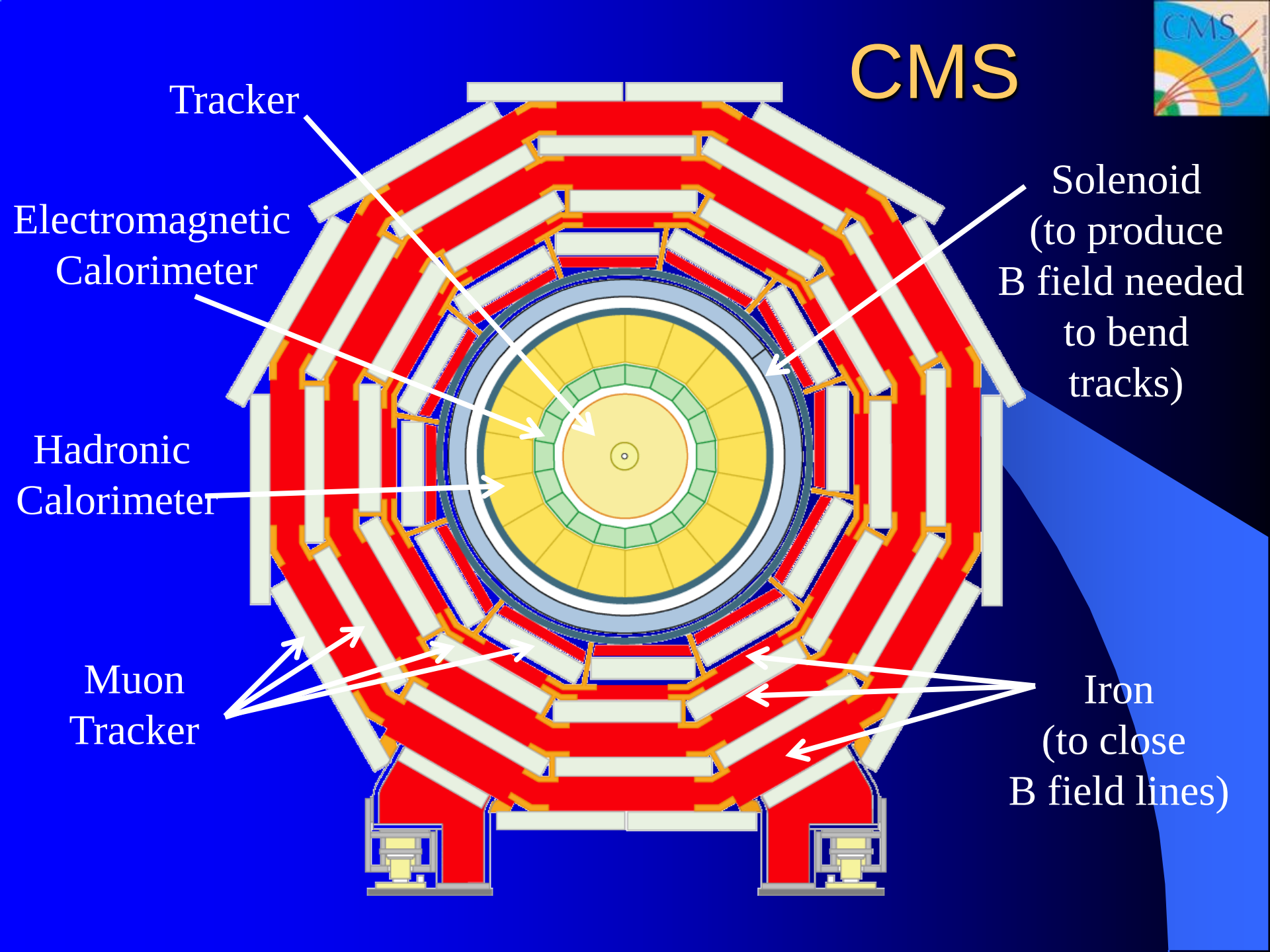
- Took ~3000 scientists and engineers more than 20 years to design and build
- At 100m underground, it is about 15m wide and 21.5m long
- Weighs twice as much as the Eiffel Tower – about 14000t
- Uses the largest, most powerful magnet (3.8T) of its kind ever made



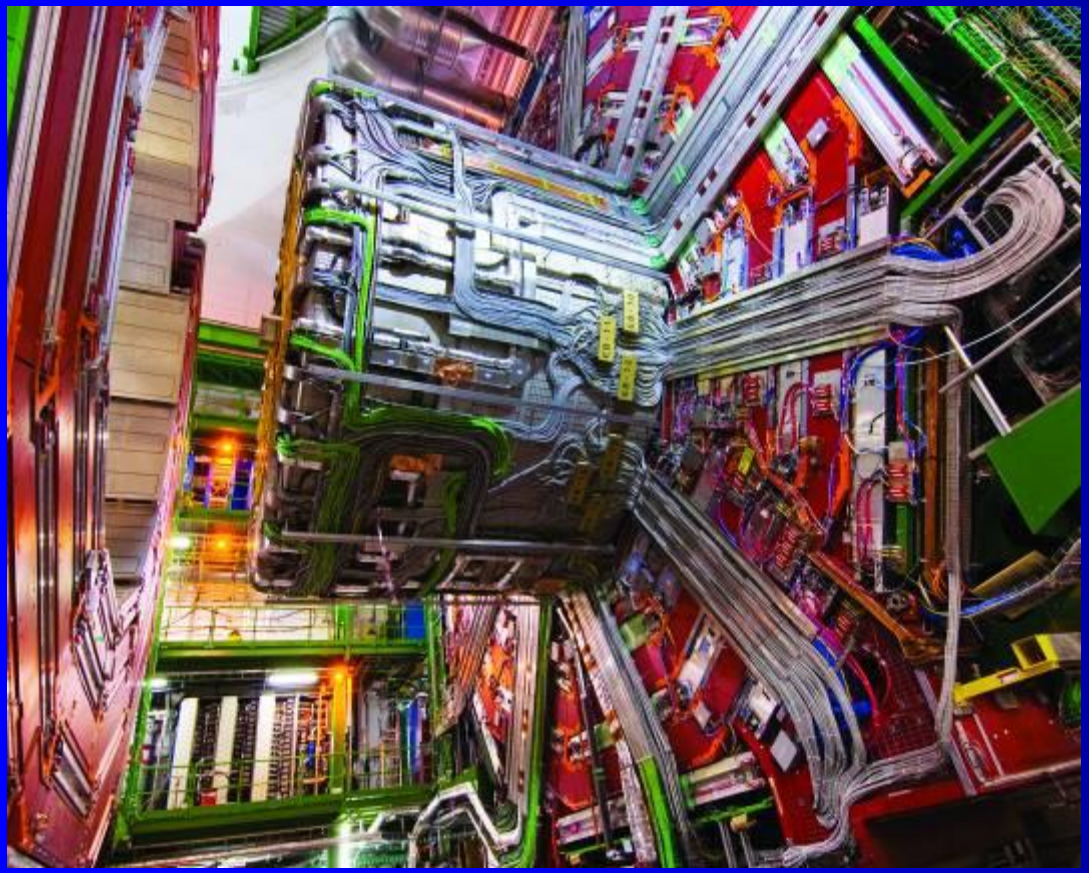
Collisions in CMS



CMS


Tracker
Electromagnetic Calorimeter
Hadronic Calorimeter
Muon Tracker
Solenoid (to produce B field needed to bend tracks)
Iron (to close B field lines)

…is built with incredible **precision**…



- Like a 75 million pixel 3D camera taking 40 million photos per second
- Cabling this central section took ~200 people 6 months!

CMS Cavern 100m underground

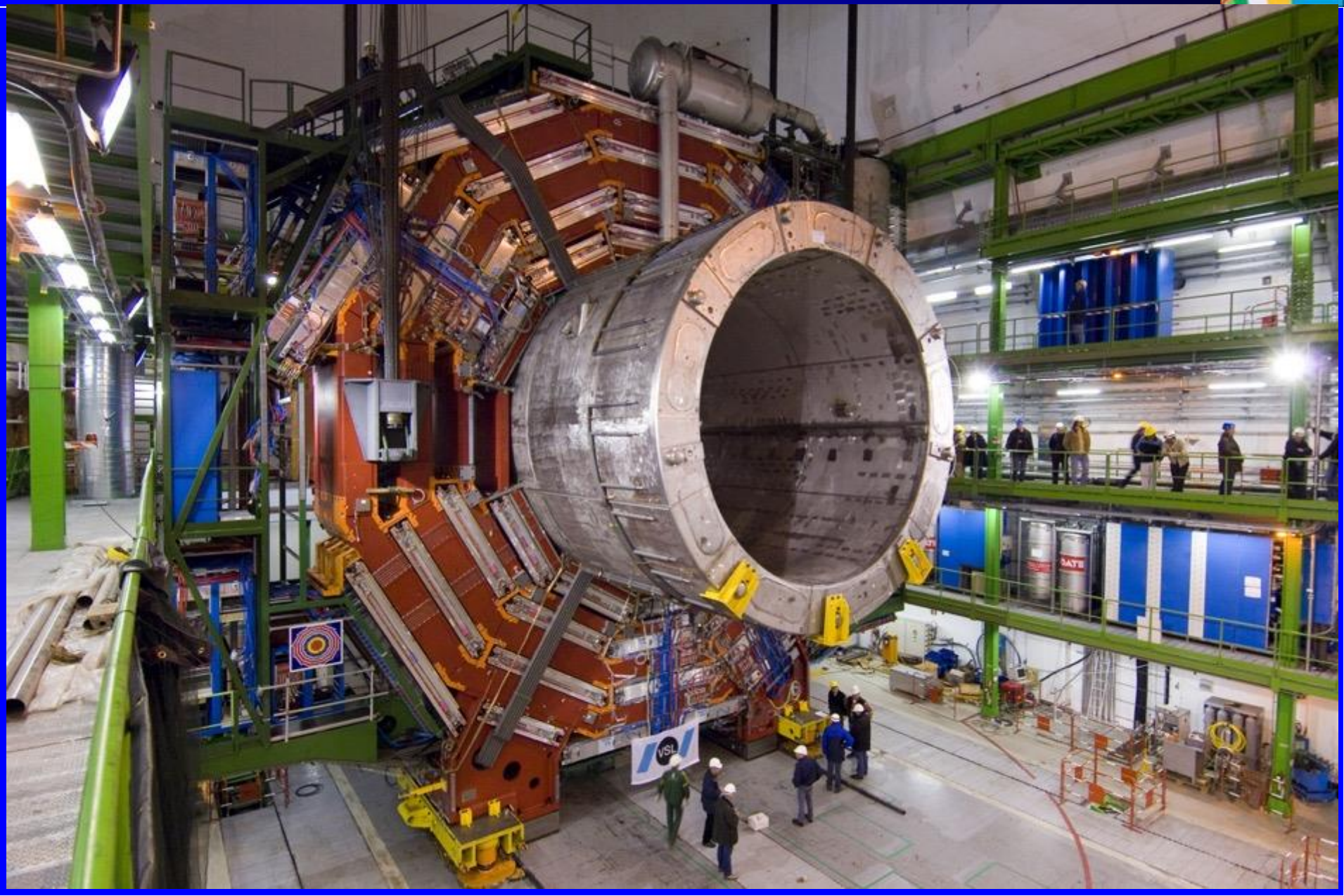
(CERN P5 site in Cessy , Francia)

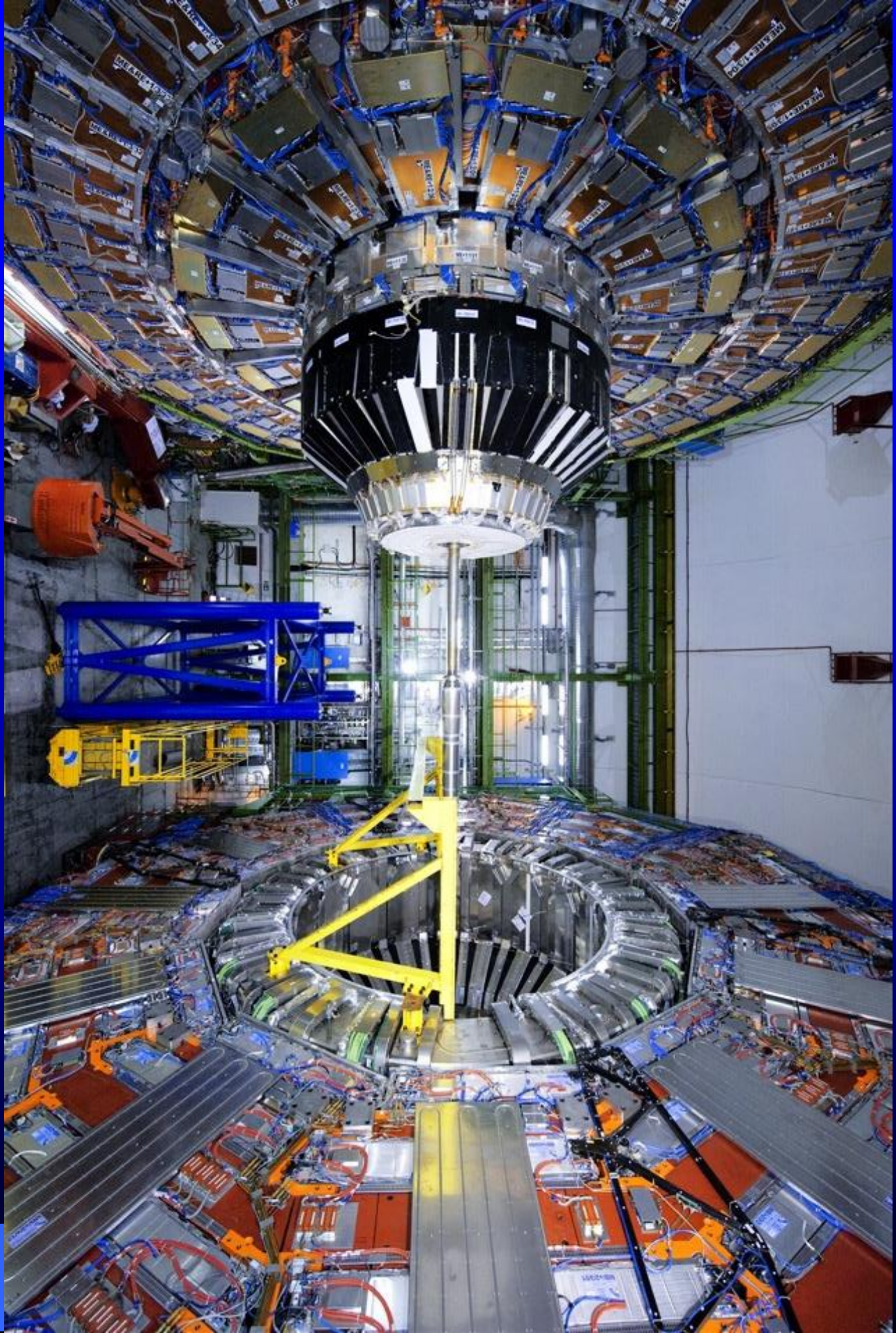
Feb 2005

Almost like Tirana cathedral but 100m underground !

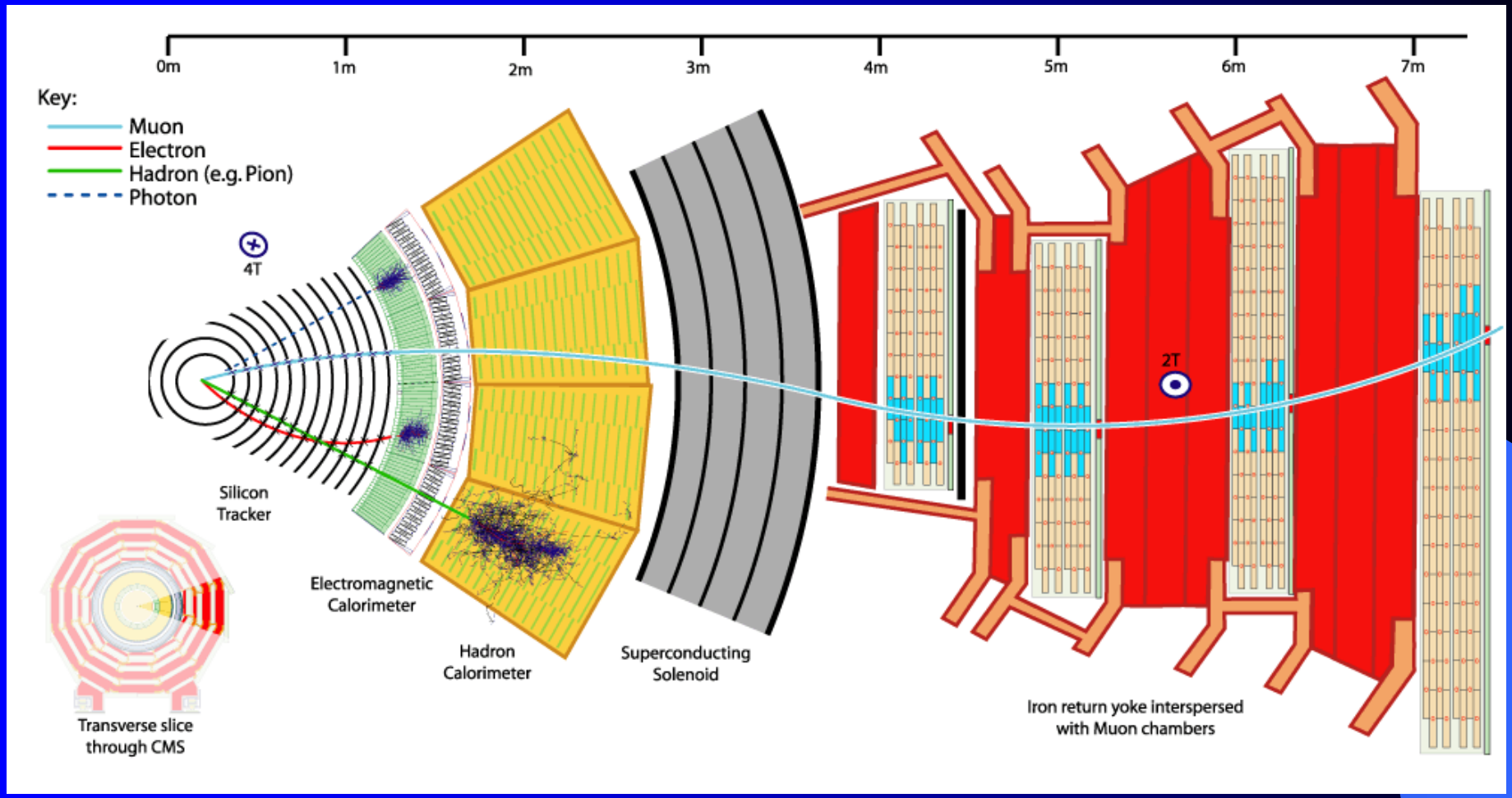
70 m long, 27 m wide & 24 m high

Entirely built in surface and then transferred 100 m underground!

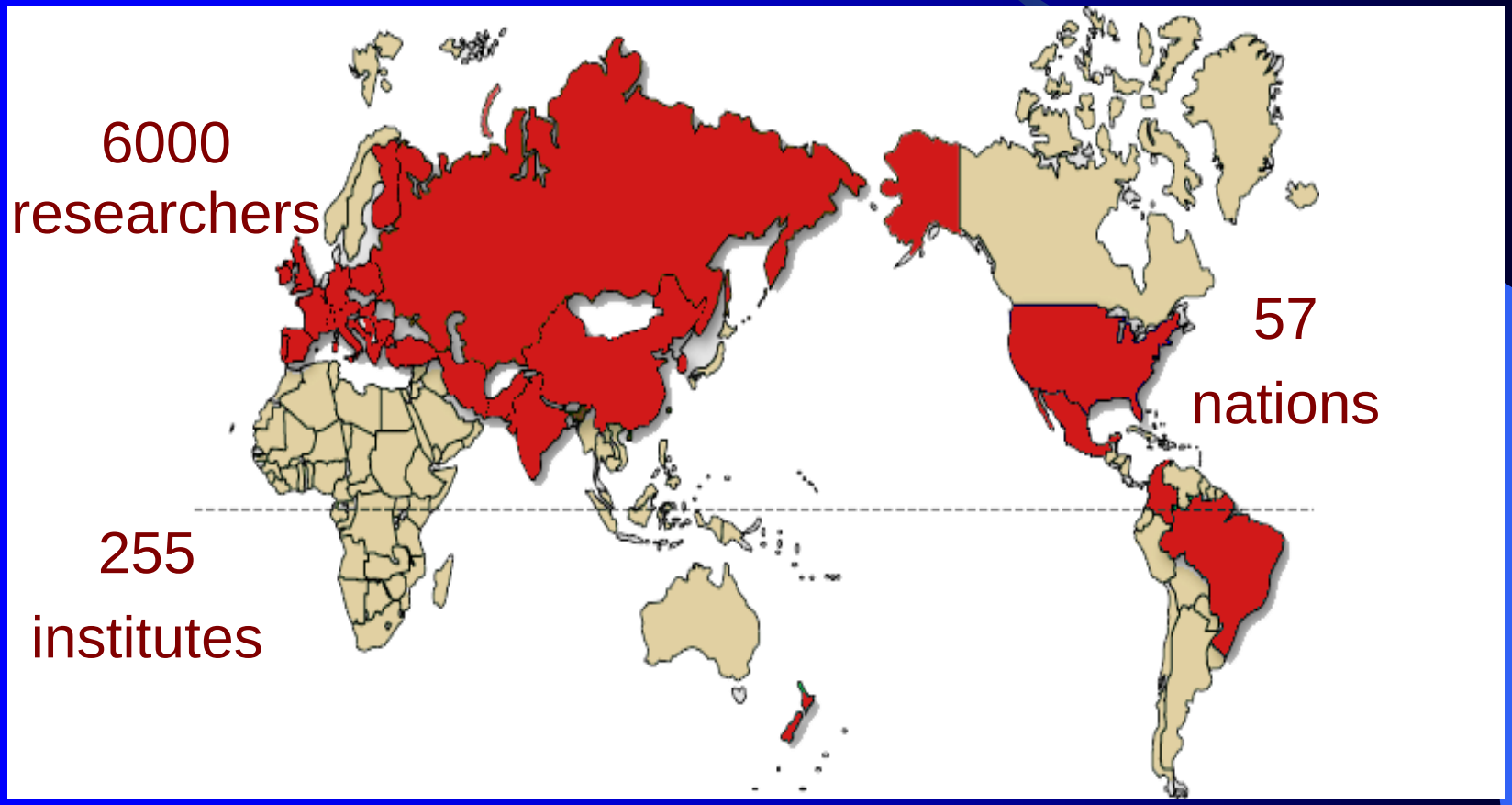




With several different **layers**



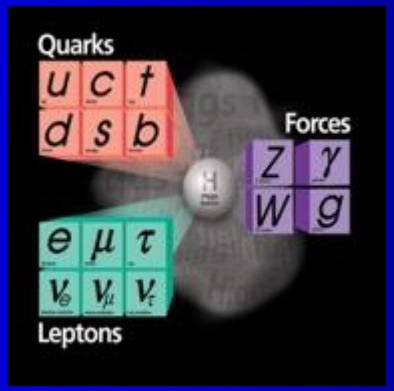
CMS @ CERN: a Global Research



with more than 1000 students (Batchelor, Master and PhD)

Puzzles still to be solved

- **Matter vs Antimatter**
- **Higgs field**
- **Dark Matter and Dark Energy**
- **…**

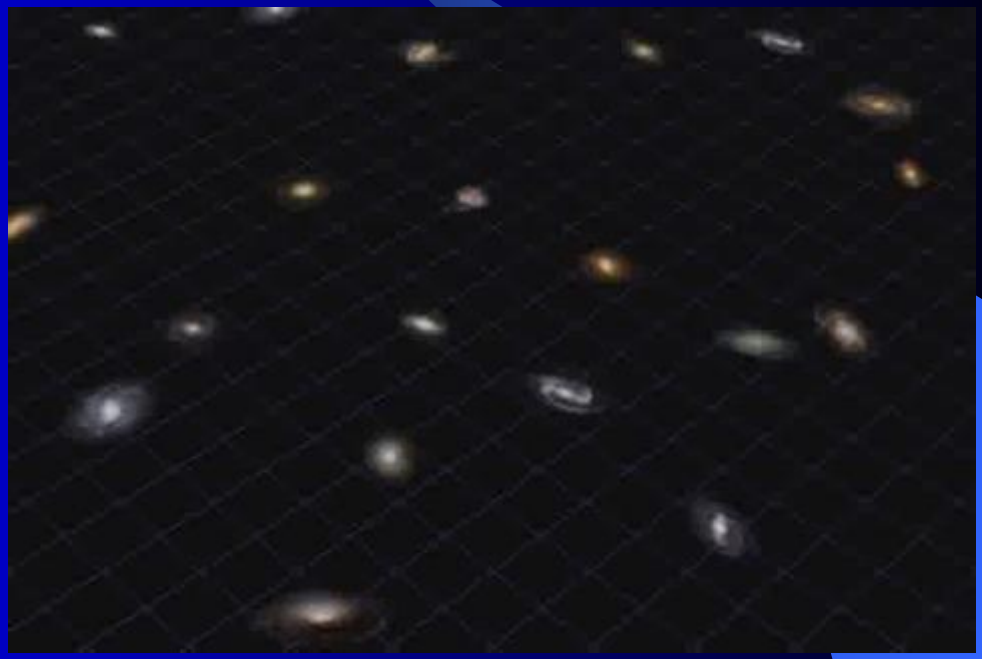


But why are we doing all this?
Don't we already know everything?

In fact we know very little!

The Mystery of Anti-matter

- 14 billion years ago the Big Bang created equal amounts of matter and antimatter
- We exist because there is no antimatter around
- Where has it all gone?
- Why does Nature prefer matter?

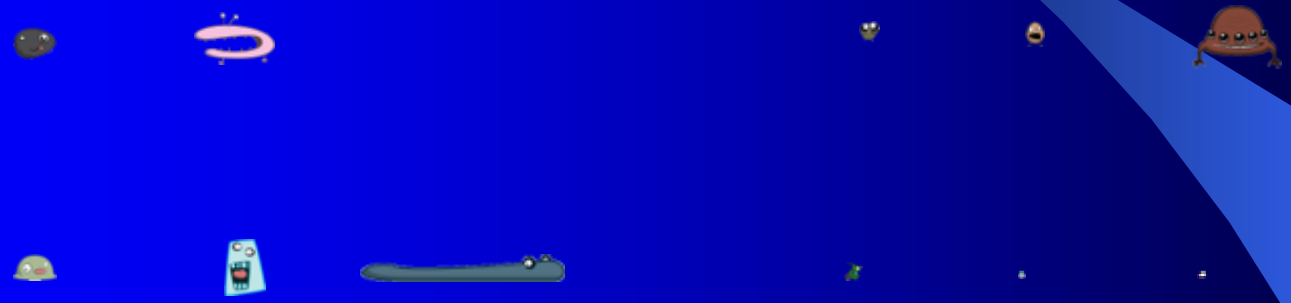


NASA/STScI/G.Bacon

What happened to the anti-matter?

- After more than 50 years of research we know that some particles behave slightly differently from their antiparticles
- The difference is not enough to explain why the Universe is the way it is
- There must be another effect
- As the LHC will produce equal amounts of matter and anti-matter, studying both in detail may give us further insights

THE MYSTERY OF MASS



quarks leptons

The reason *could* be the existence of a new particle, called the “Higgs boson”

The "Standard Model"

The "Standard Model" describes:

- **Properties of single elementary particles**
- **How particles interact with each other**
- **How the forces between particles act**

BUT …

Standard Model is NOT capable to cumpute, nor to predict the mass for ANY of elementary particles !!!

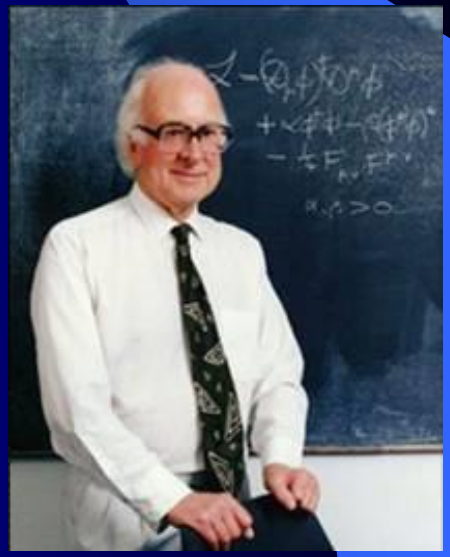
Not for electron

Not for muon

Not for quarks

Not for Z e W

FOR NONE OF THEM !!!!!! ……



Answer to this puzzle is the particle called "Higgs Boson"

… and LHC was the best place to prove if Higgs boson really exists !

Origin of the mass: the Higgs mechanism

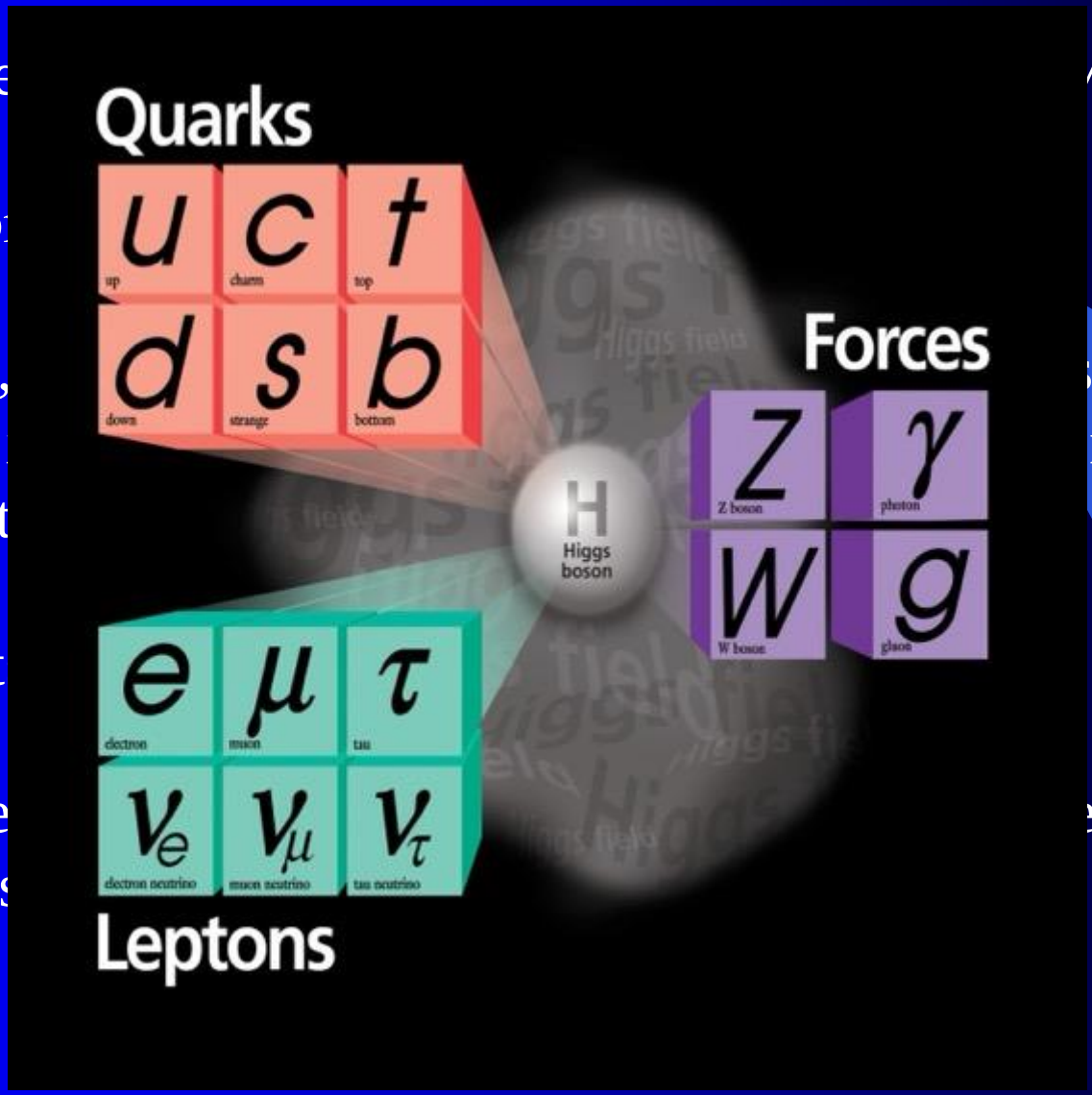
VERY simple MASS !!

A “field” is p

The particles, s.
The stronger r is the
mass they get

That field act

Once discove e of that
field and cons
assignment



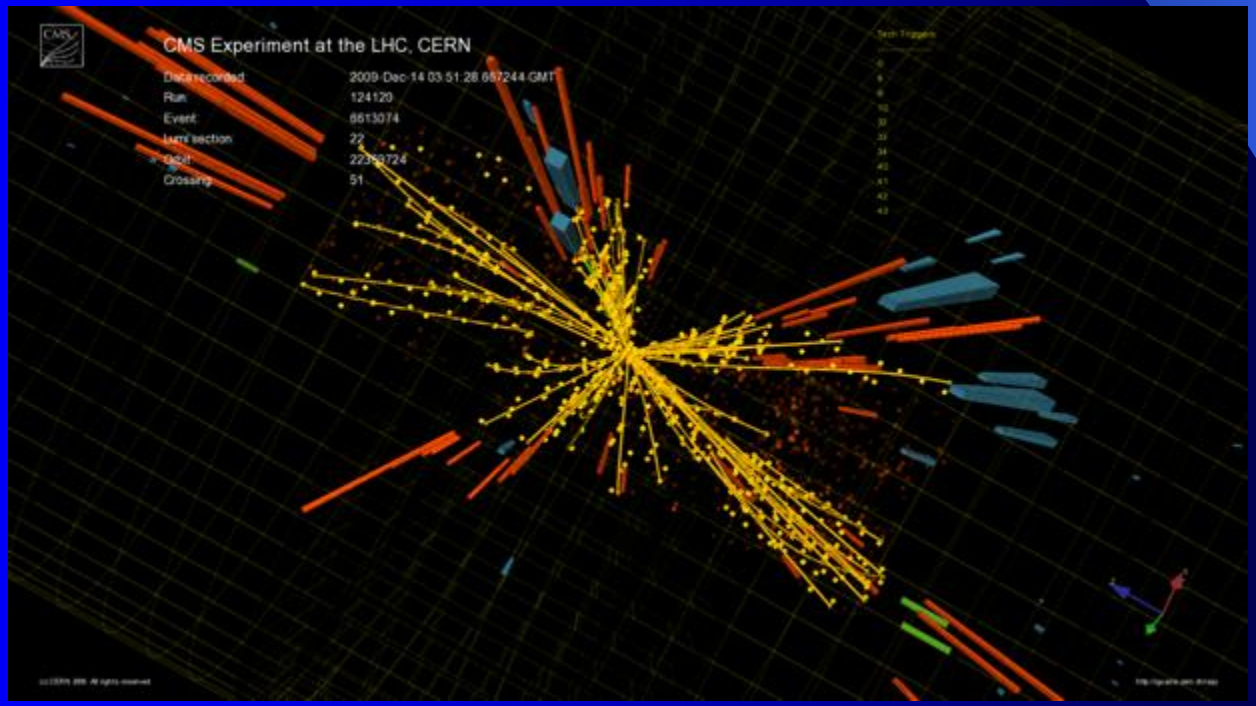
What is really out there? (and in here!)

- Astronomy tells us that the matter we know (i.e. protons, neutrons and electrons) accounts for just 5% of the universe
- The rest is dark matter
- And dark energy

Dark Matter

- "Dark" because we can't detect it directly
- Can tell it's there from effects on galaxies
- Could be made of undiscovered particles → SUPERSYMMETRY
- LHC could create these particles and CMS could (indirectly) detect them

Some risultats of CMS



LHC in first 15 years (2010-2025)

- Dicember 2011: already in RUN1 first solid indications of signal excess (Higgs Boson ?) at 8 TeV (10 fb^{-1})
- 4 Luglio 2012: Discovery of Higgs Boson
- First LHC Technical Stop (TS1) for 2.5 years (2013-15)
- 2015 to 2018: RUN2 collisions @ 13-14 TeV (150 fb-1) to increase precision in Higgs Boson measurements
- Second LHC technical Stop (TS2) (2019-2022)
- 2023 to 2026: RUN3 Collisions @ 14 TeV (300 fb^{-1})

LHC in next 16 years (2025-2041)

- Third LHC Technical Stop (LS3) (2027-2031)
- then LHC operational with higher luminosity till ~ 2041 with RUN4 and RUN5 (3000 fb^{-1}) ... so:

a lot of work for next generations too !

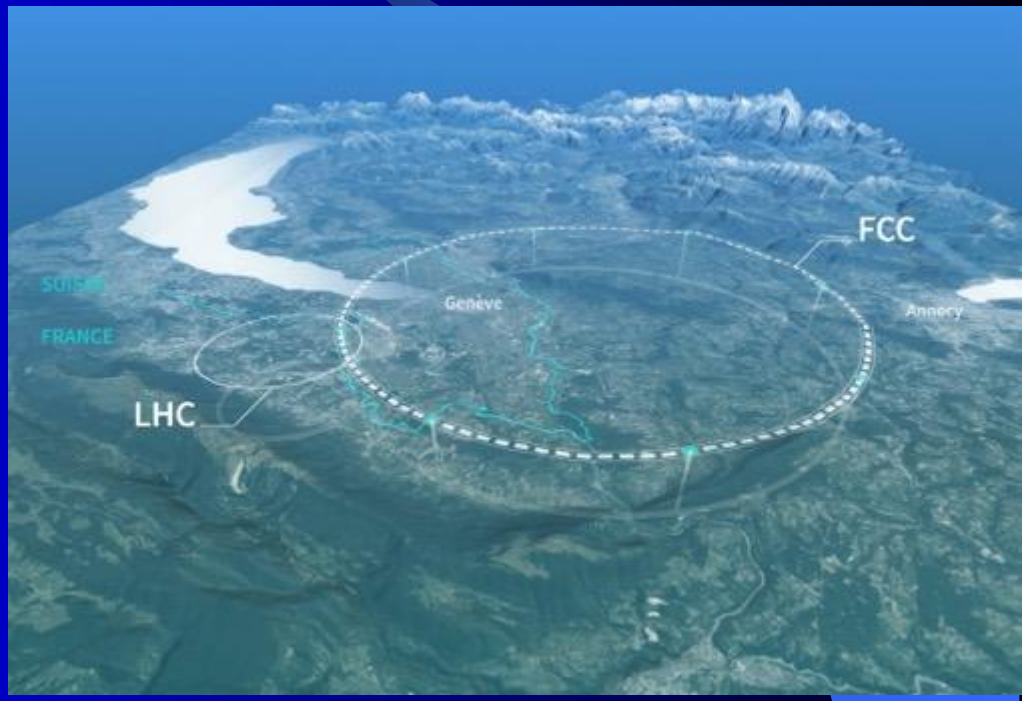
… and for farer (>2041) future : FCC @ CERN

Driven by the **2020 Update of the European Strategy for Particle Physics**

https://home.cern/fr/science/accelerators/future-circular-collider

FCC - ee
FCC - hh

- Technical and financial feasibility study of a **Future Circular Collider - FCC** (report for Spring 2025)
- Accelerator R&D to develop technologies for FCC and for alternative options
- Detector and computing R&D
- Maintain and expand a compelling scientific diversity program
- Continue to support other projects around the world



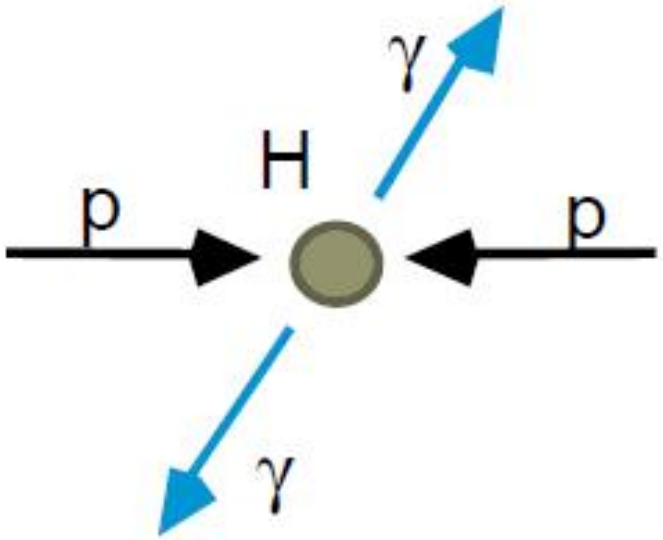
90 km circumference, 200 m depth

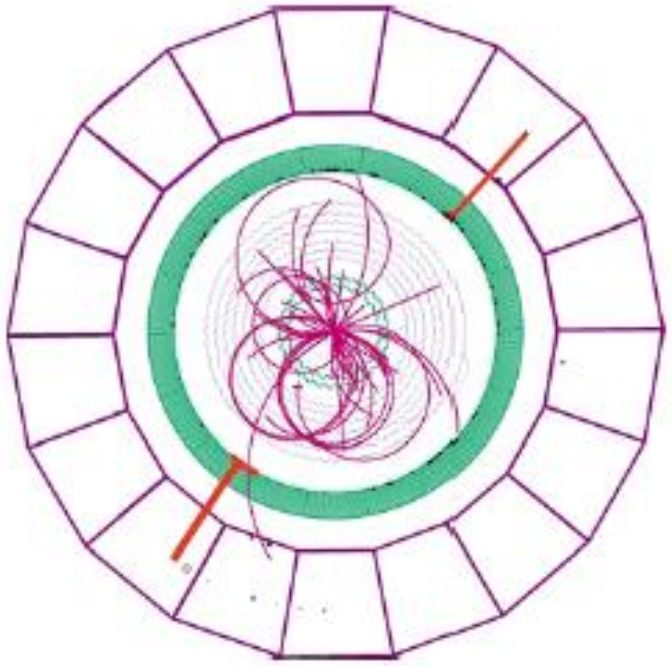
Collision energy up to 100 TeV

Coming back to our helicopters…

If we can produce Higgs Bosons, they are spontaneously and instantaneously «decaying» in other lighter particles, we must be able to see and measure them,
to understand what is going on !

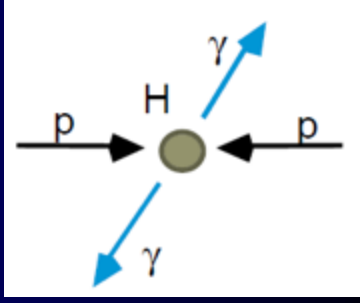
H → 2 photons

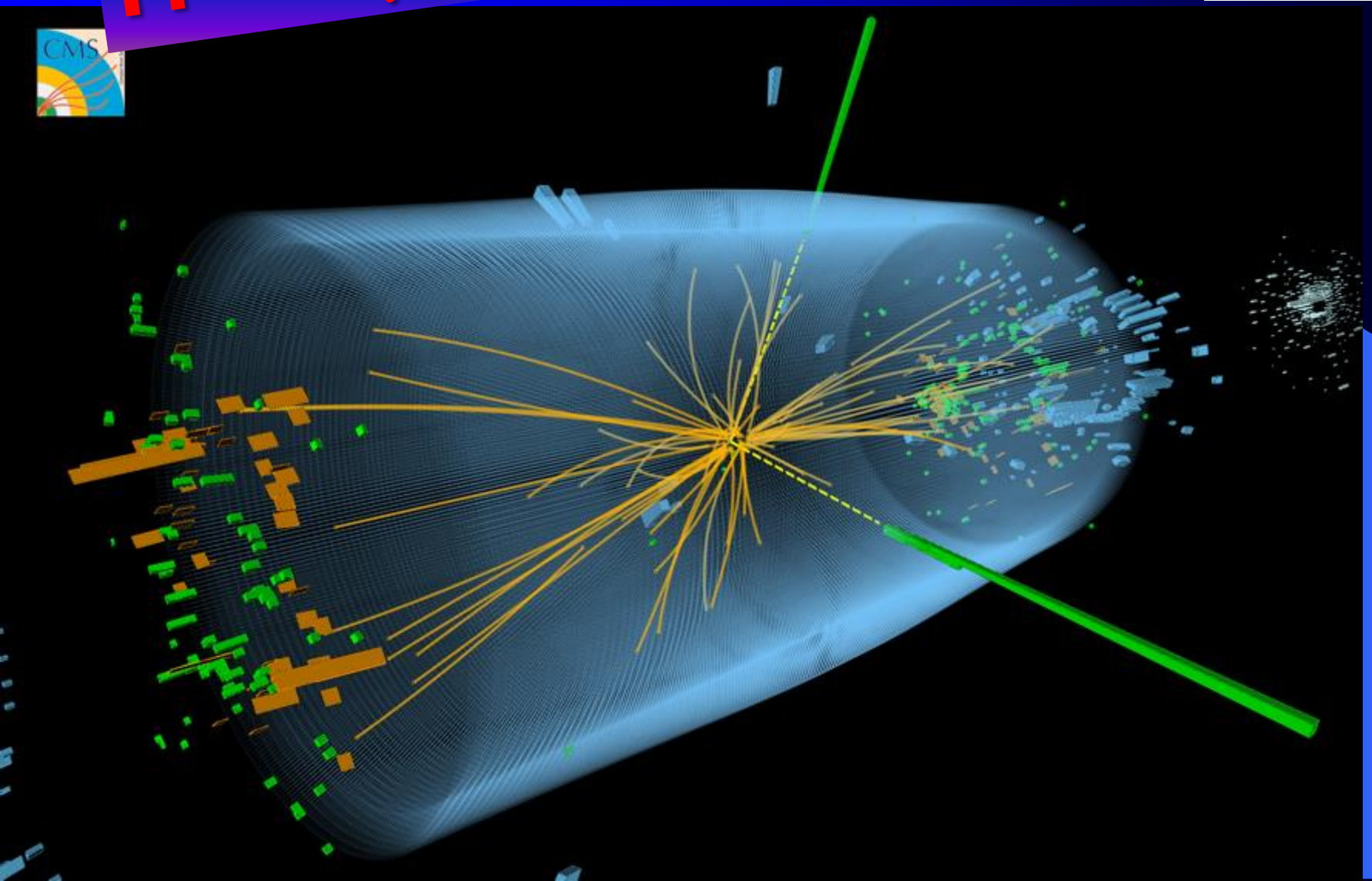




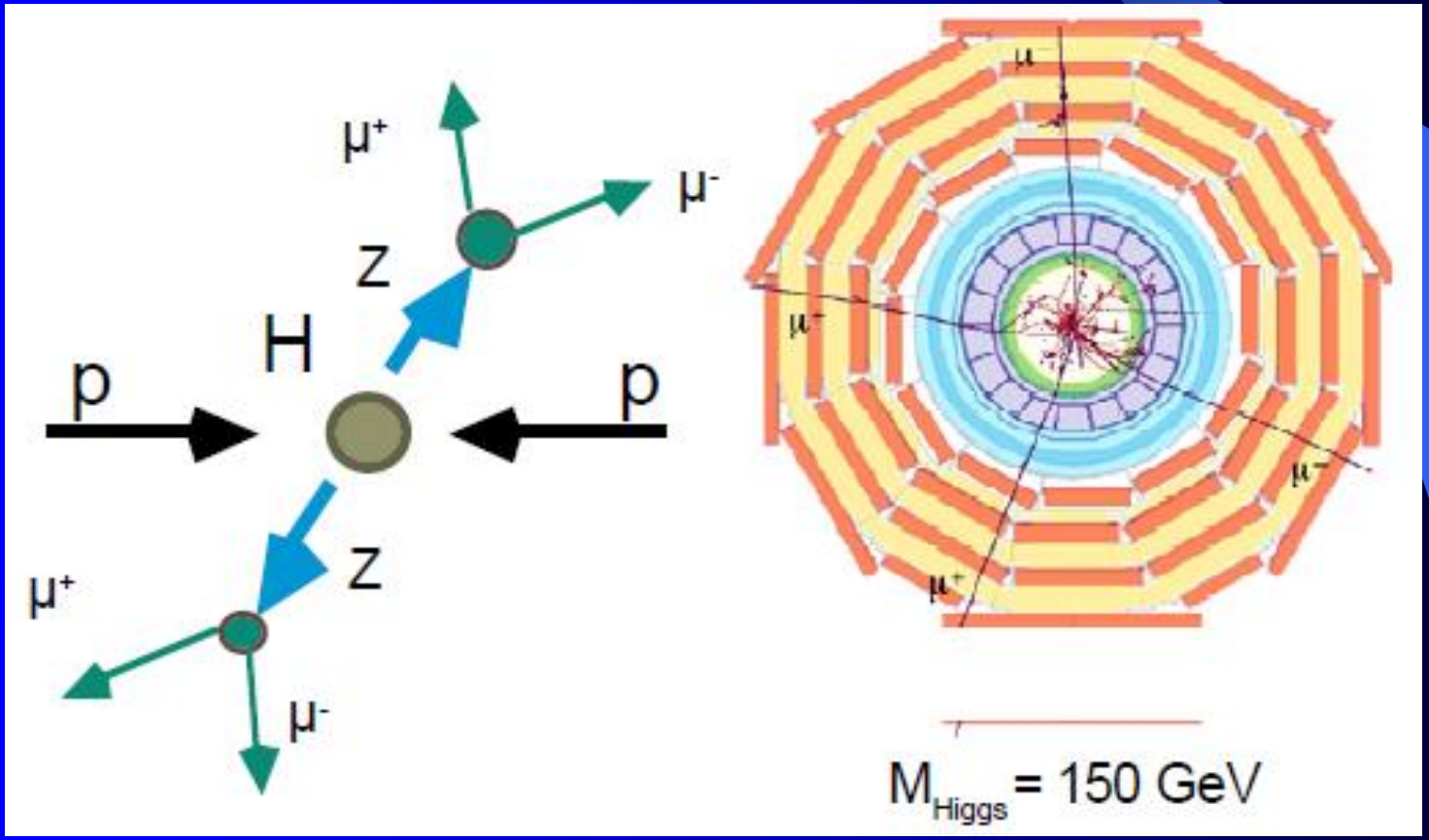
M_{Higgs} = 100 GeV

$H \rightarrow \gamma\gamma$

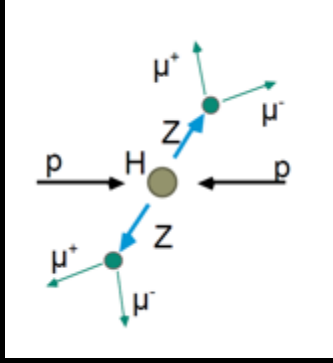




H → Z Z → 4 leptons



$H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$



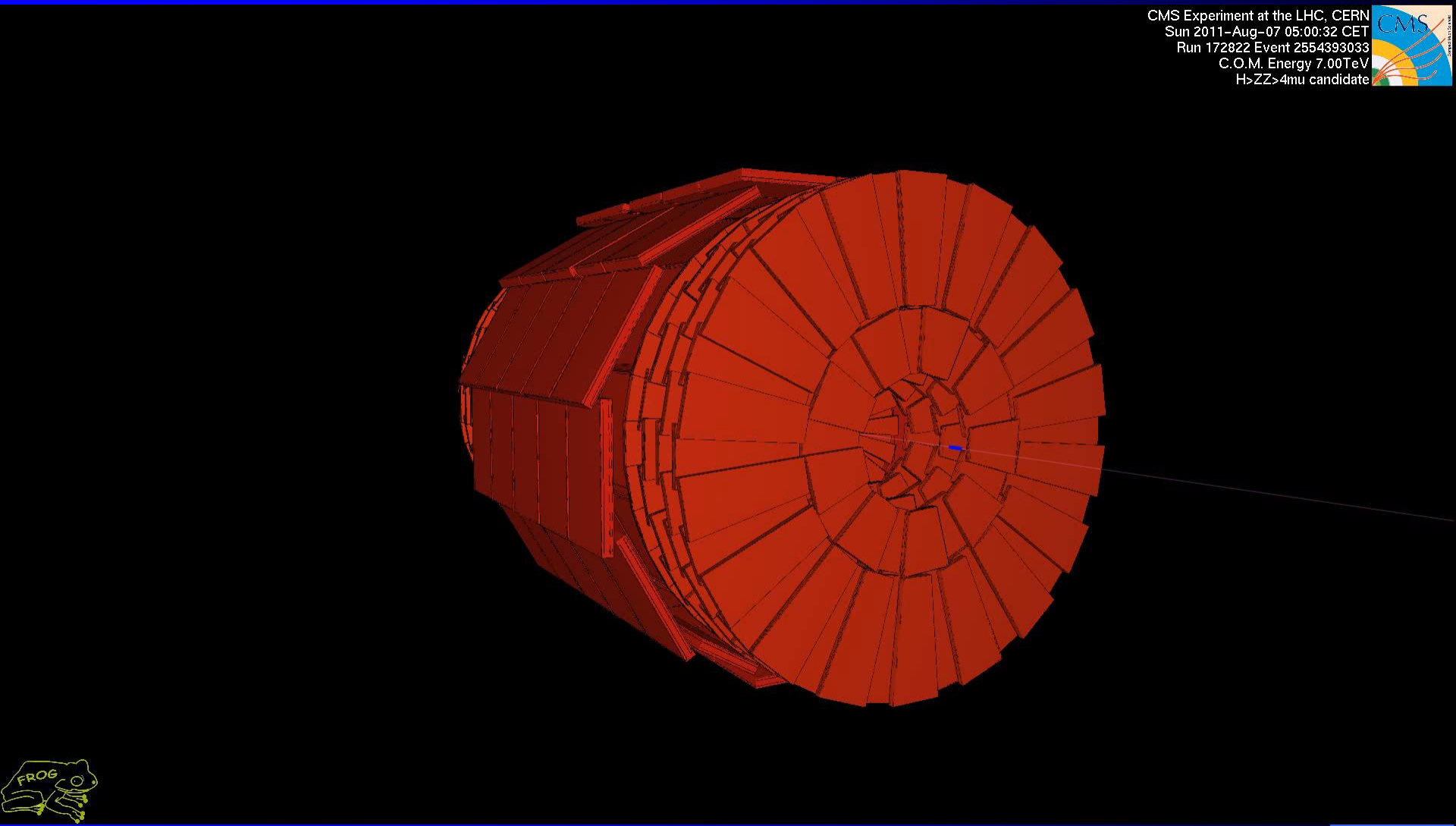
Muon 3, pt: 58.4 GeV

Muon 1, pt: 5.4 GeV

Muon 0, pt: 5.7 GeV

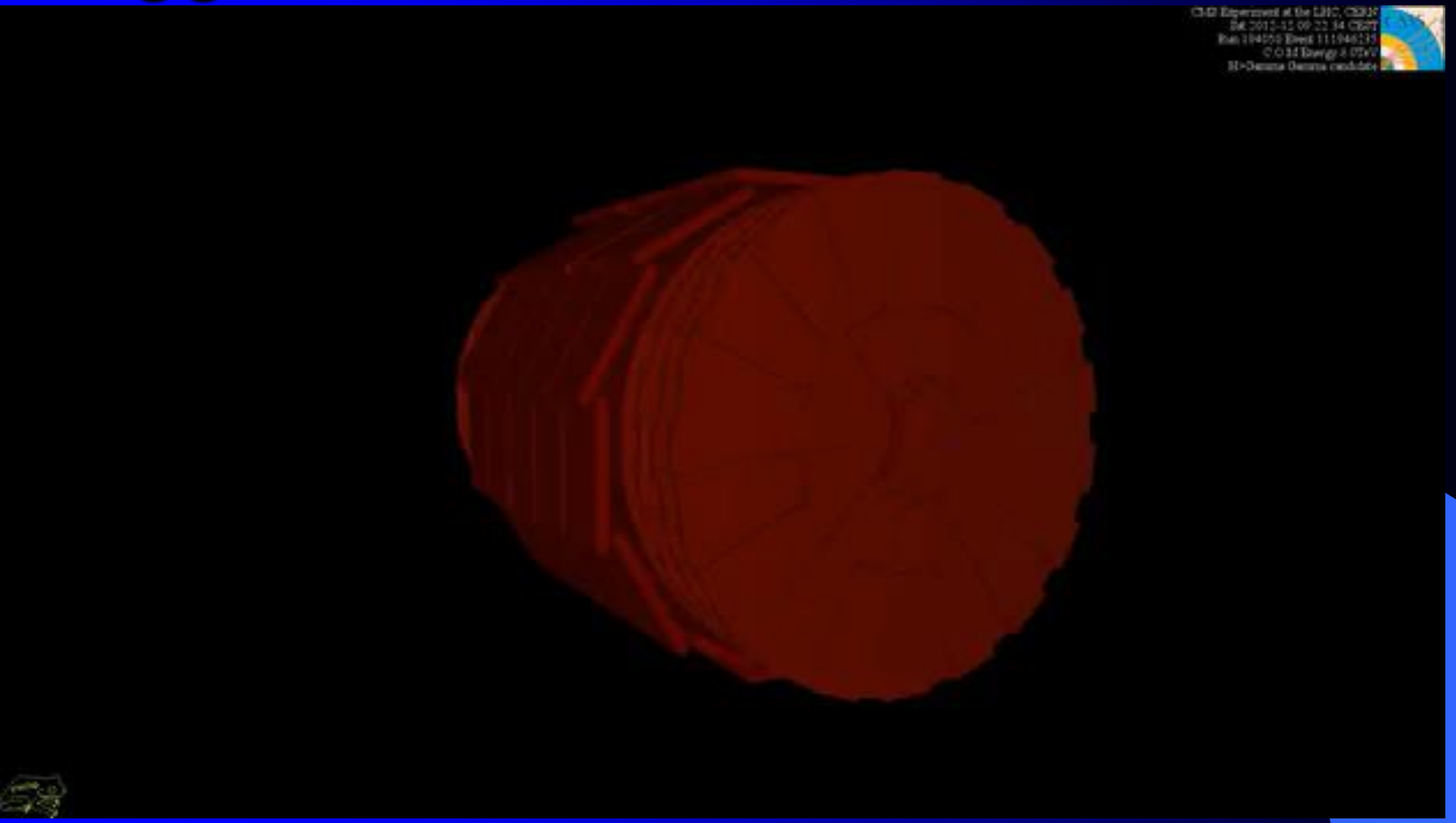
Muon 2, pt: 34.6 GeV

Higgs Boson events



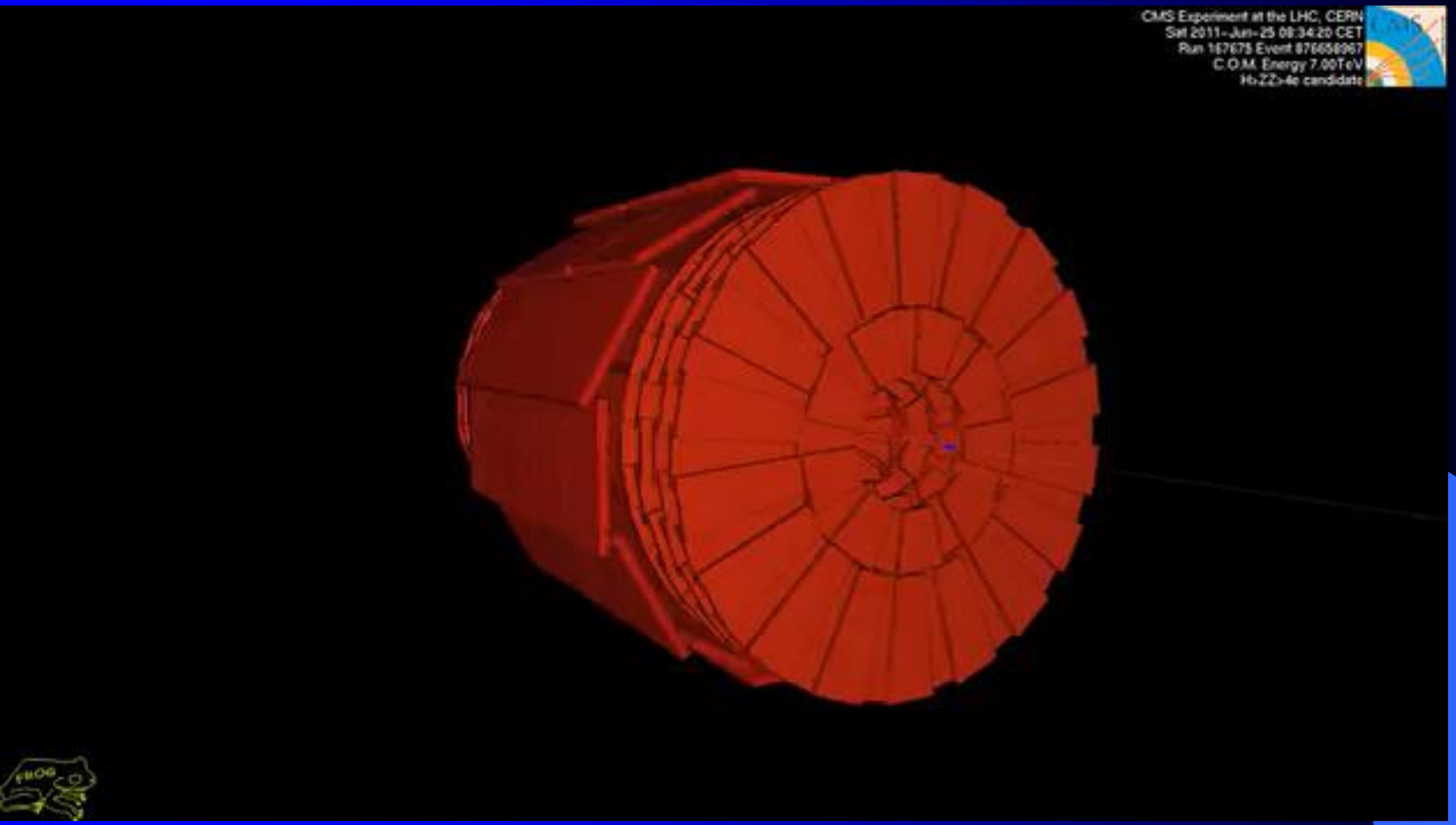
Higgs event (7 TeV, 2011): Higgs decaying in 4 muons

Higgs Boson events



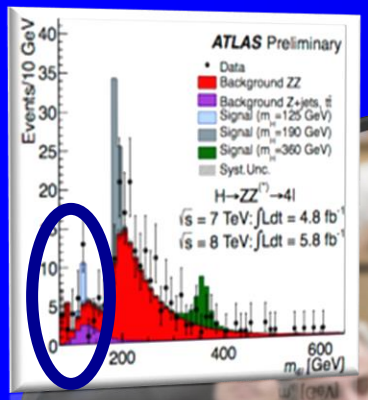
Higgs event (8 TeV): Higgs decaying in 2 photons

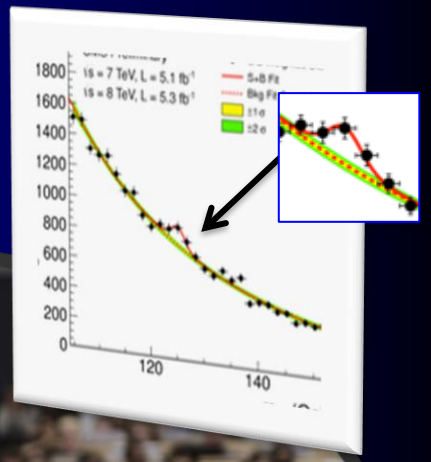
Higgs Boson events



Higgs event (8 TeV): Higgs decaying in 4 electrons

…even being extremely difficult !!





Fabiola Gianotti
ATLAS Spokesperson 2010-2012

Joe Incandela
CMS Spokesperson 2012-2013

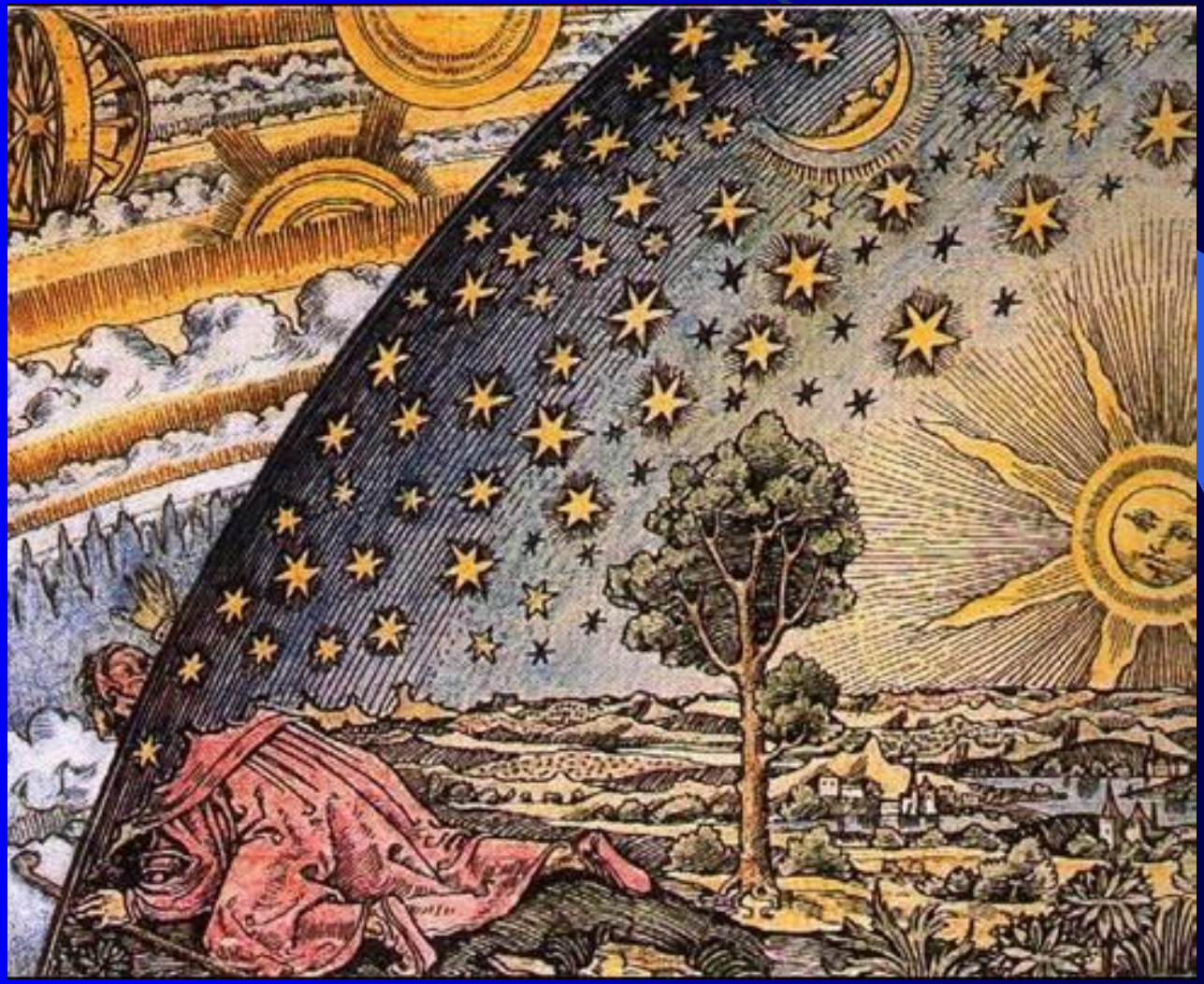
we GOT it !

Higgs Boson discovery

Experimental and Theoretical phisicists: VERY happy !

in summary….

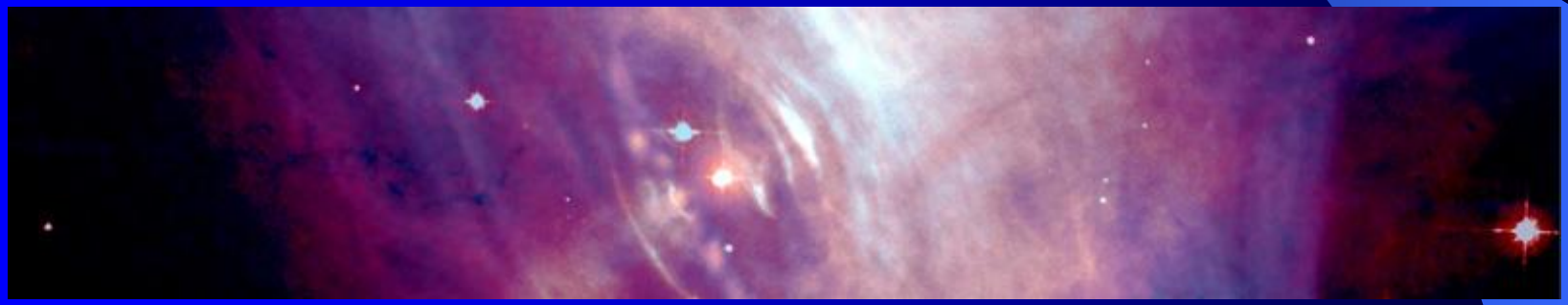
CMS experiment and Large Hadron Collider (LHC) are moving physics in never explored lands !



and….

New processes and new particles could change our knowledge about Energy, Matter, Space

We can learn new things concerning fundamental forces managing our Universe since its creation and that will define its future evolution



First 2 Runs of LHC with p-p collisions already showed the great potentiality of that research !

…. and the game will be still ongoing for a while (Run 3, 4, 5) !!!!

Supersimmetry

Antimatter

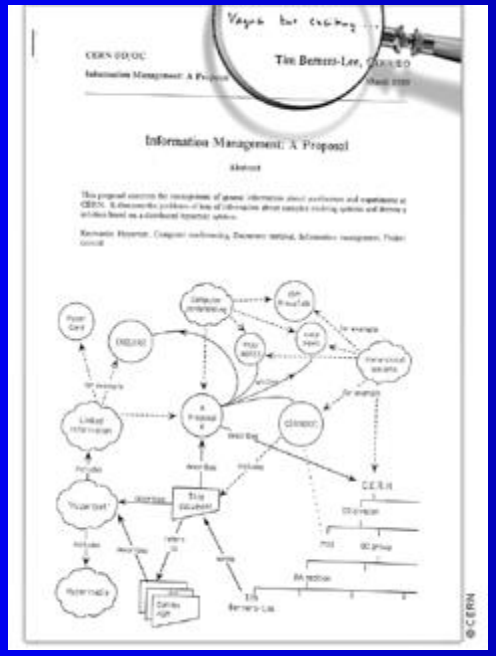
Dark Matter/Energy

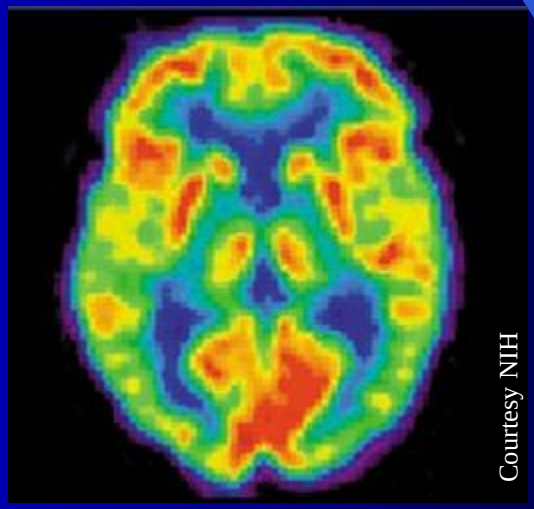
?

Possible discoveries of phenomena predicted by the theory

Possible discoveries of completely unexpected phenomena !

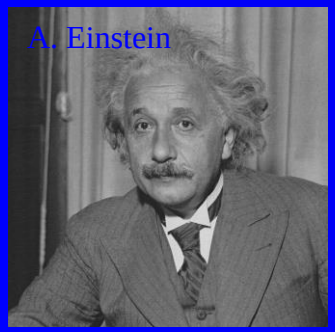
Technology transfer applications





But what does CERN and its particles, accelerators and detectors have to do with everyday life?

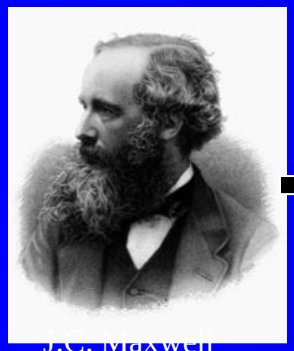
Fundamental research has always been a driving force for innovation



Relativity

100% SCIENCE

For GPS to work, we have to take into account the correction due to time dilation. Otherwise, there would be a position error of around 10m after just 5 minutes of travel-time!



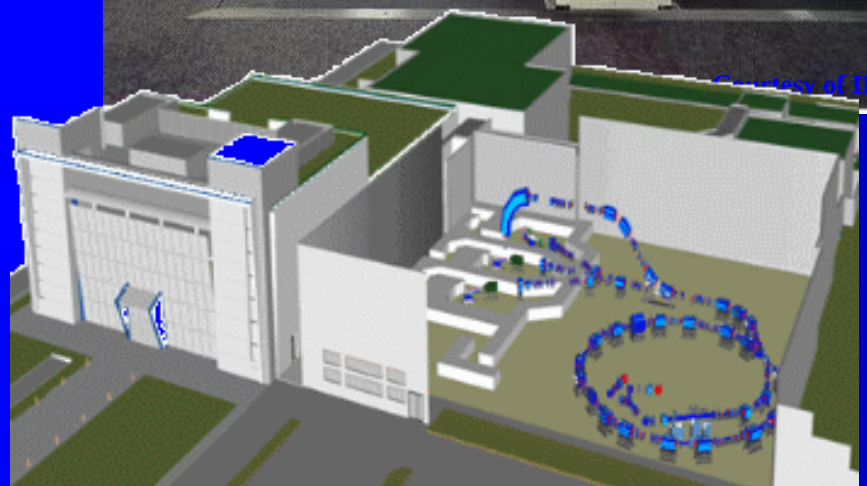
Electromagnetism

100% SCIENCE

Telephones use electromagnetic waves to communicate

Accelerators

Developed in research laboratories and now routinely used in hospitals for medical treatments



about 9000 of 17000 accelerators in operation in the world are used for medical applications

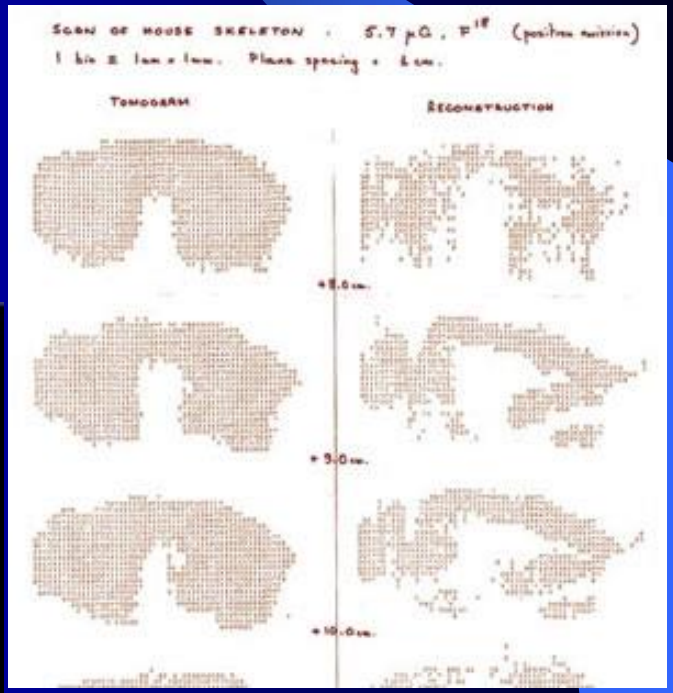
Hadroterapy is more and more applied for cancer therapy

CNAO (Centro Nazionale Adroterapia Oncologica) Pavia

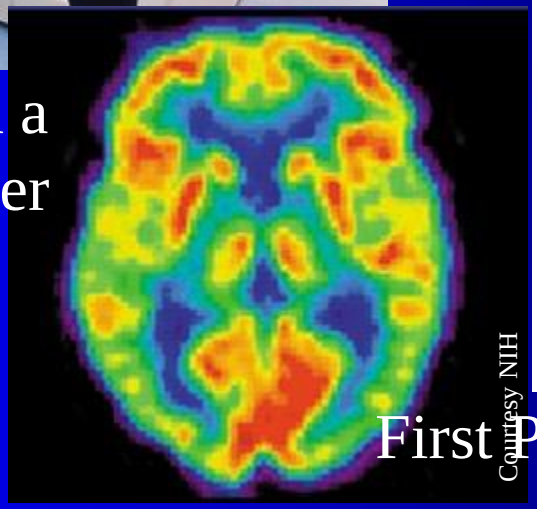
Particle detectors

Developed in research laboratories and now routinely used for medical imaging

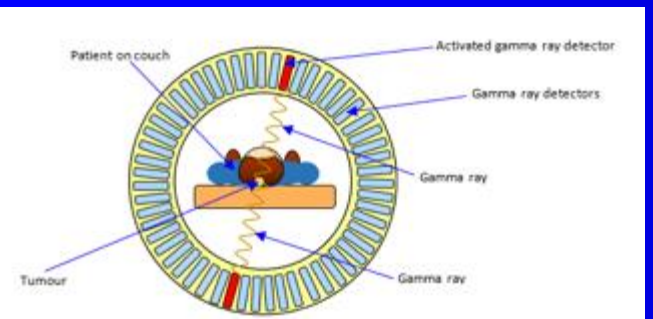
PET (Positron Emission Tomography) using antimatter (positrons) !!!



Images recorded in a modern PET scanner

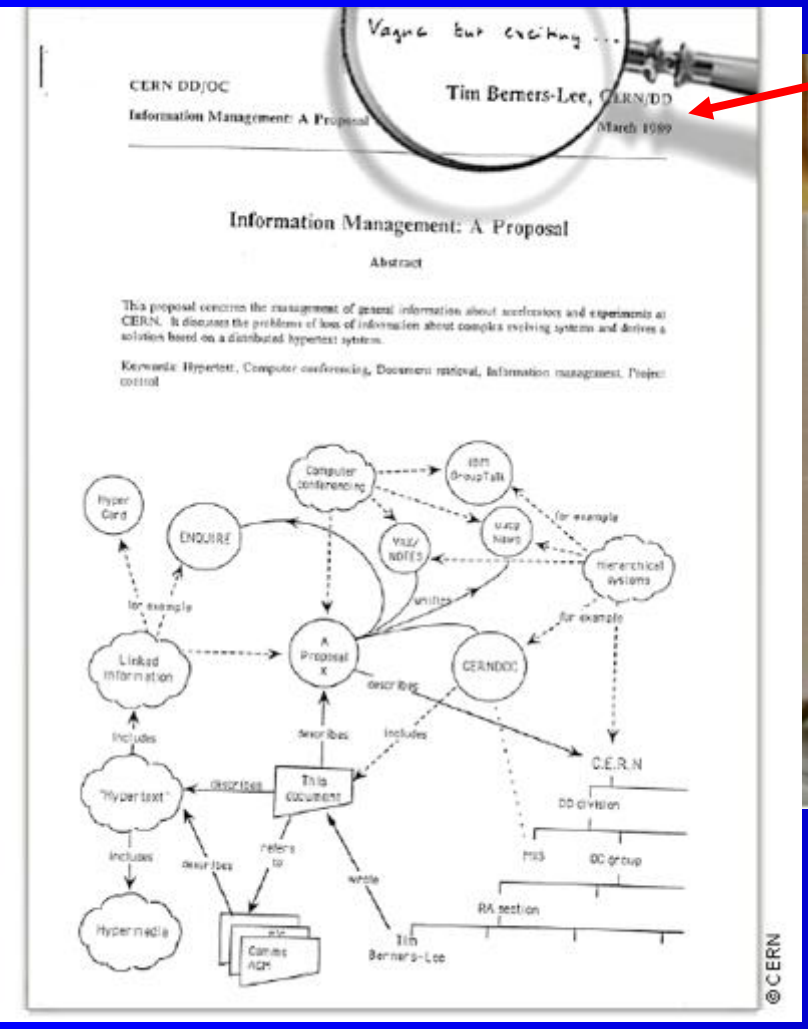


Courtesy NIH



First PET images at CERN 1975 !

Other “minor” spinoff … WWW already 35 year old !


Vague but exciting ...

CERN DD/OC

Tim Berners-Lee, CERN/DD

Information Management: A Proposal

March 1989

Information Management: A Proposal

Abstract

This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext system.

Keywords: Hypertext, Computer conferencing, Document retrieval, Information management, Project control

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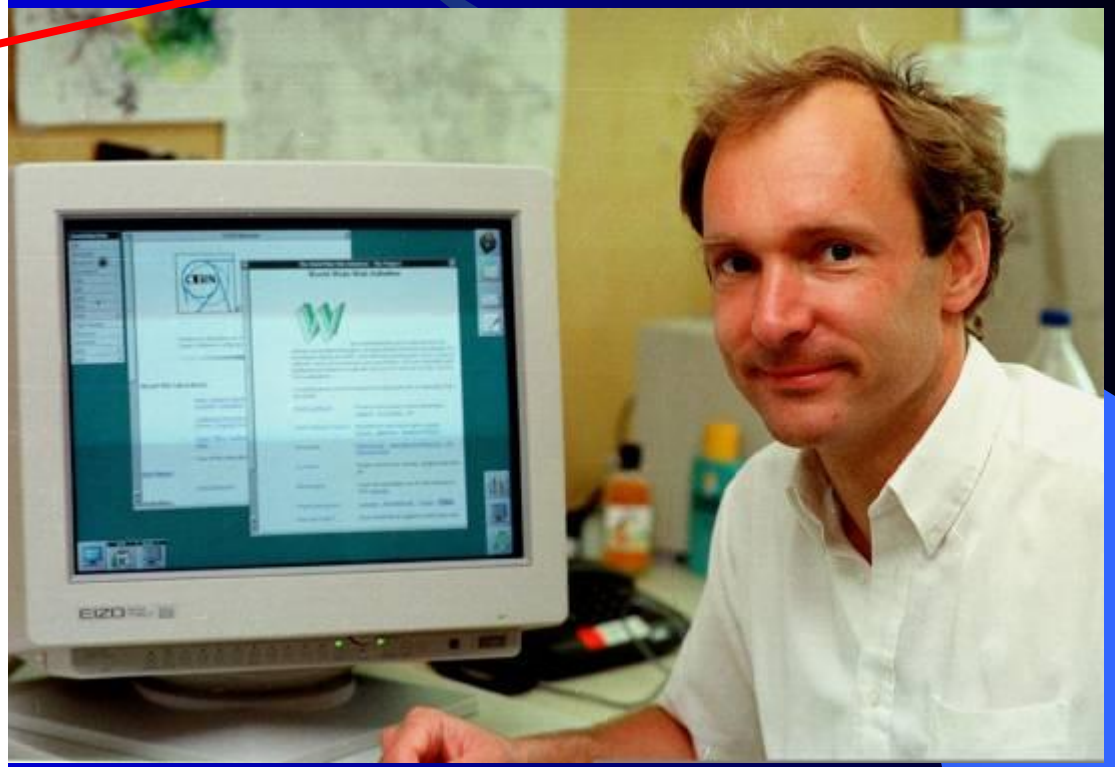

https://

So…

to answer to our first question at very beginning:

what do we do at CERN?

Basic research in the elementary particle physics to understand:

What is the universe made of ?
How did the universe begin ?

… with “some” technology transfer also in very different domains …
… and mostly with education and training of next generation researchers, enthusiastically collaborating independently of their **nationality, ethnicity, skin color, religion** !

…or, in a single sentence:

we try to discover "new particles" using particles, accelerators and new technologies !

Thank you for your attention

Aiming having triggered your curiosity (!?!),
I wait you for a visit to CMS at CERN !