International Masterclass (CERN IPPOG)

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Tbilisi, Georgia

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Part 1: Fundamentals of Particle Physics

High Energy Physics (a.k.a Particle Physics)

Particle physics is a modern name for centuries old effort to understand the basic laws of nature.

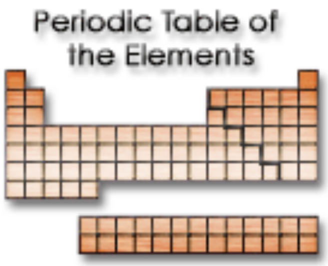
Aims to answer the fundamental question:

What is the universe made of?

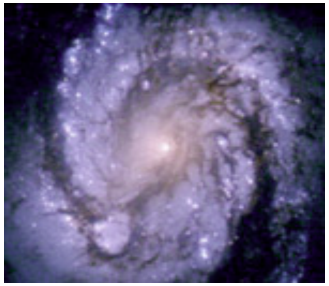
- **A very old question, and one that has been approached in many ways.**
- **The only reliable way to answer this question is by directly enquiring of nature, through experiments.**

Experiments have taught us:

- Complex structures in the universe are made by combining simple objects in different ways
  - Periodic Table

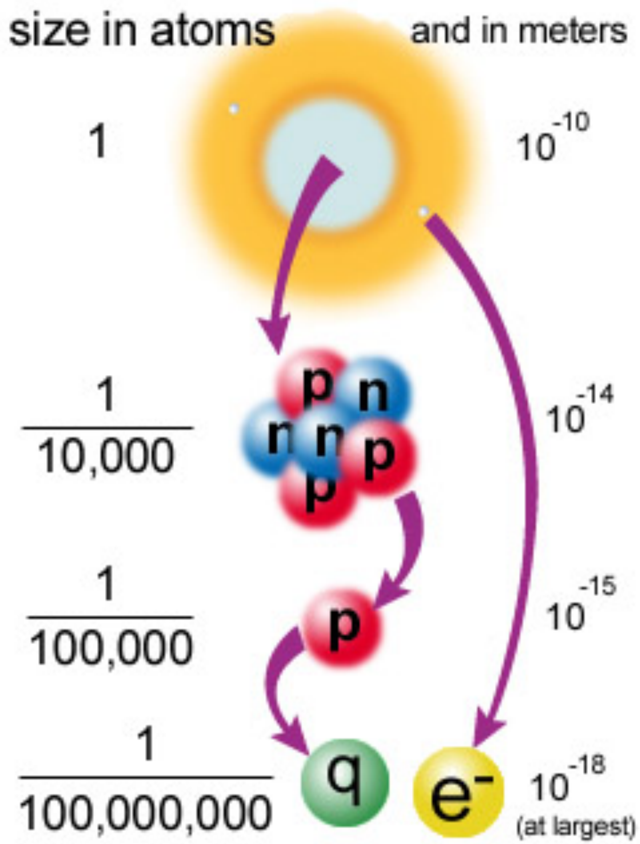


- Apparently diverse phenomena are often different manifestations of the same underlying physics
  - Orbits of stars in galaxes and apples falling from trees

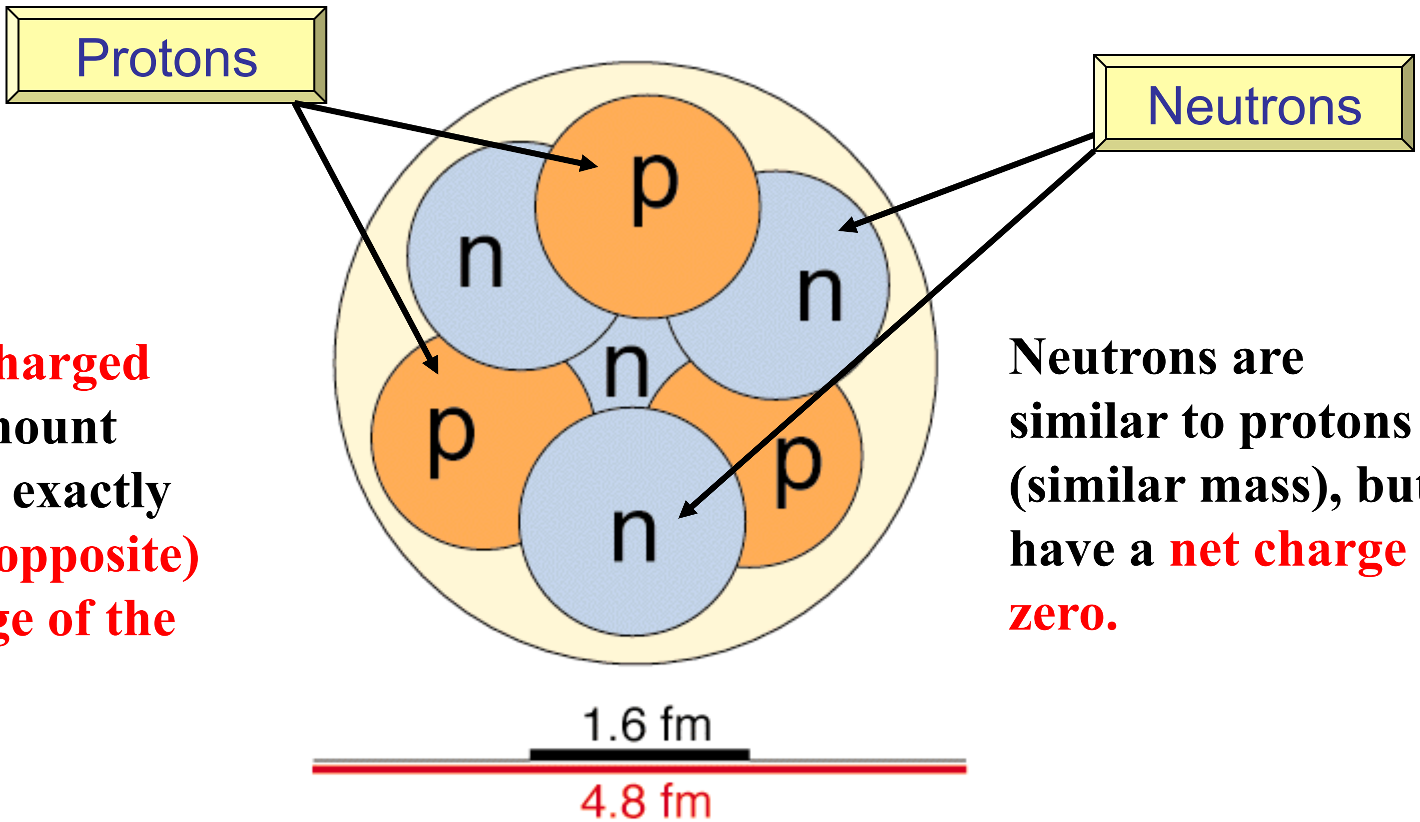


Experiments have taught us:

- **Almost everything is made of small objects that like to stick together**
  - **Particles and Forces**



What's in the Nucleus?



Protons are positively charged and that amount of charge is exactly **equal (and opposite) to the charge of the electron**

Neutrons are similar to protons (similar mass), but have a net charge of zero.

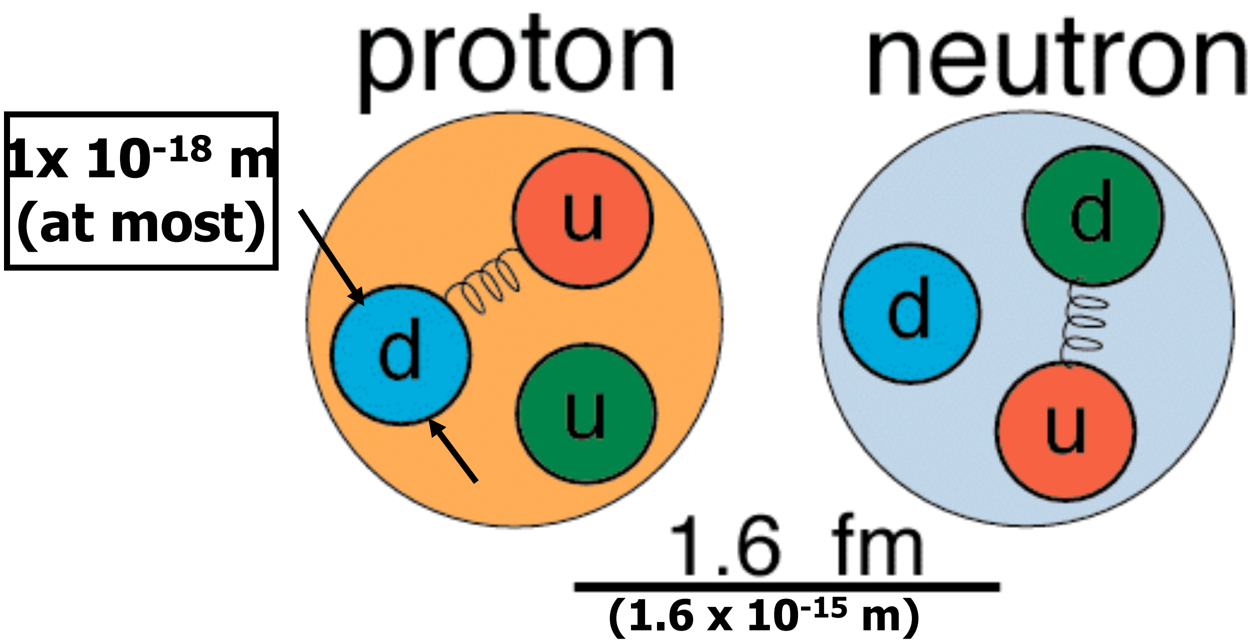
Recall: 1 [fm] = 10^{-15} [m]

Are protons and neutrons fundamental?

By fundamental, we mean are they indivisible?

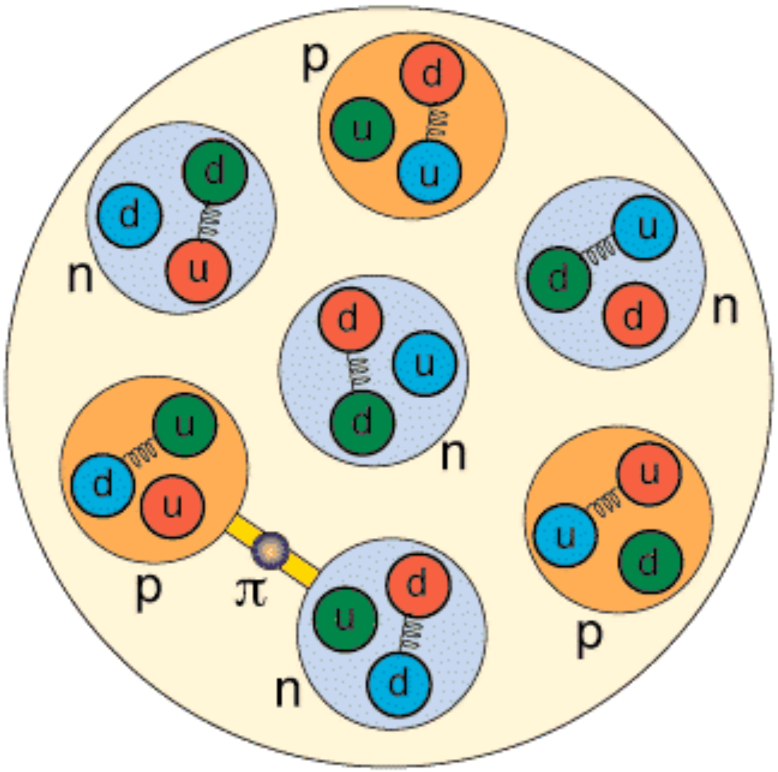
The answer is NO !

Protons and neutrons are made of smaller objects called quarks!



- **Protons**
  2 "up" quarks
  1 "down" quark
- **Neutrons**
  1 "up" quark
  2 "down" quarks

Protons and neutrons



<u>To make a proton:</u>
We bind 2 up quarks of q = +2/3 and 1 down quark of q = -1/3. The total charge is

2/3 + 2/3 + (-1/3) = +1 !

<u>To make a neutron:</u>
We bind 2 down quarks of q= -1/3 with 1 up quark of q = +2/3 to get:

(-1/3) + (-1/3) + (2/3) = 0 !

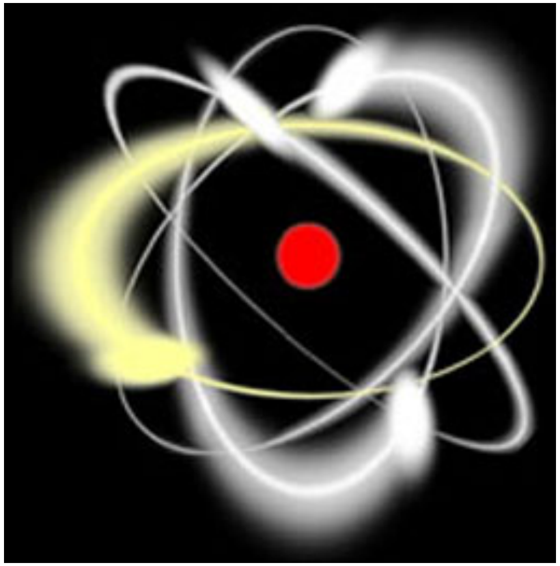
Particles which are made of quarks are called hadrons.
So, protons and neutrons are hadrons.

Three families of quarks

	Generations (Increasing mass →)		
	I	**II**	**III**
Charge = **-1/3**	**d** **(down)**	**s** **(strange)**	**b** **(bottom)**
Charge = **+2/3**	**u** **(up)**	**c** **(charm)**	**t** **(top)**

Also, each quark has a corresponding antiquark.
The antiquarks have opposite charge to the quarks

Leptons



- **Electrons** belong to a general class of particles, called "**Leptons**"
- **As far as we can tell, the leptons are "fundamental".**
- **Each charged lepton has an uncharged partner called the "neutrino"**
- **The leptons behave quite differently than the quarks**

    - They don't form hadrons (no binding between leptons)

Three families of leptons

Family	Leptons		Antileptons	
	Q = -1	Q = 0	Q = +1	Q = 0
1	e^-	ν_e	e^+	$\bar{\nu}_e$
2	μ^-	ν_μ	μ^+	$\bar{\nu}_\mu$
3	τ^-	ν_τ	τ^+	$\bar{\nu}_\tau$

3 families, just like the quarks… interesting !!!

This is what we have learned so far:

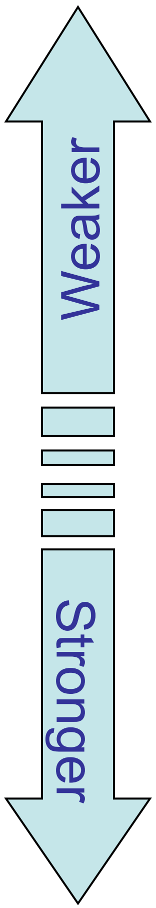
- Quarks and leptons are the most fundamental particles of nature that we know about.

- Up & down quarks and electrons are the constituents of ordinary matter.

- The other quarks and leptons can be produced in cosmic ray showers or in high energy particle accelerators.

- Each particle has a corresponding antiparticle.

Four fundamental forces

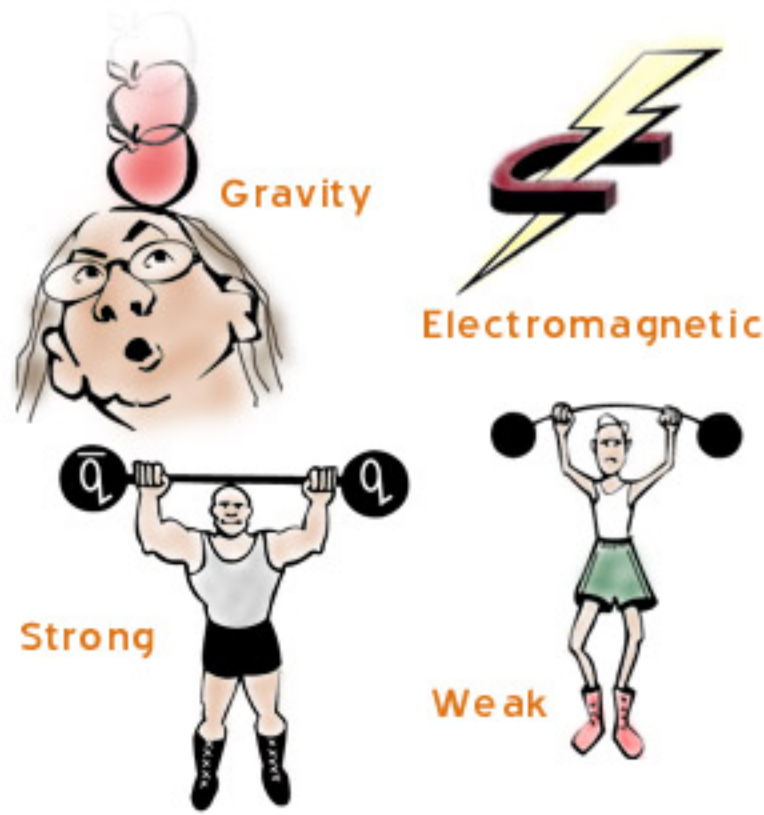


1. **Gravity**

2. **Weak Force**

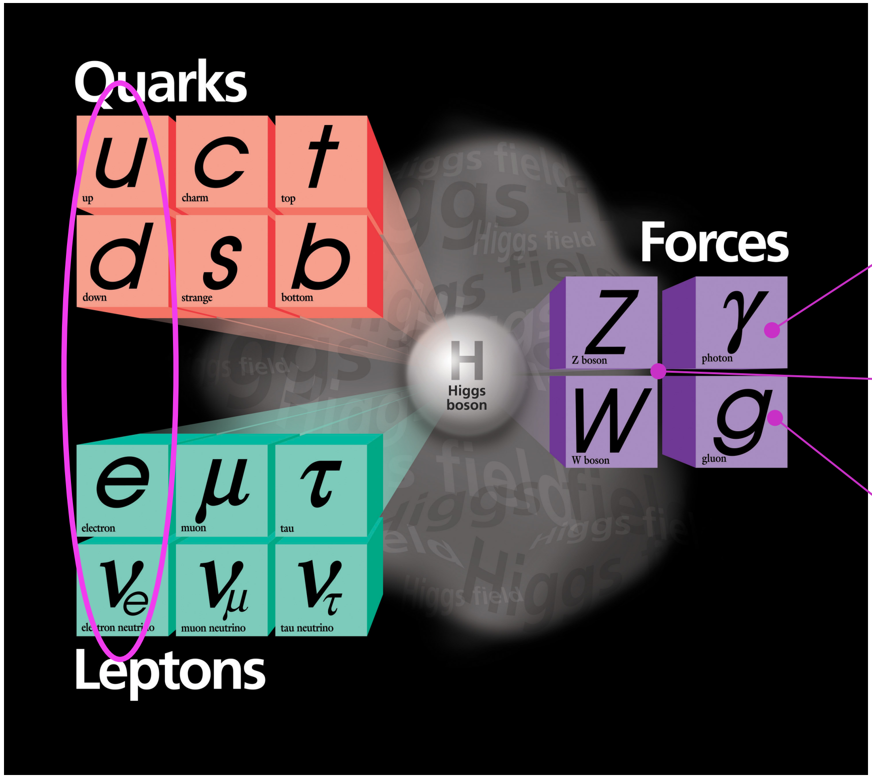
3. **Electromagnetic Force**

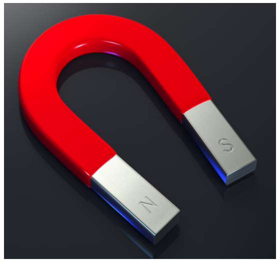
1. **Strong Force**



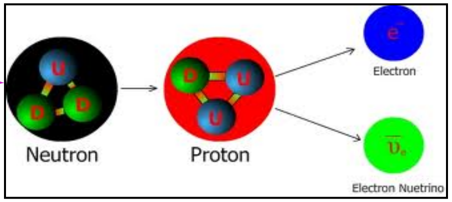
All other forces you know about can be attributed to one of these!

The Standard Model

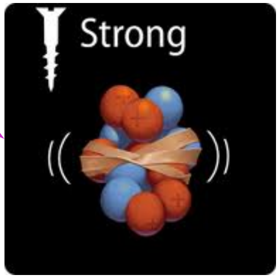




Electromagnetic interaction



Weak interaction



Strong interaction

The Standard Model is a beautiful theory (based on principles of Quantum Physics and symmetries) and arguably one that is most precisely tested.

The Standard Model of Particle and Forces

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

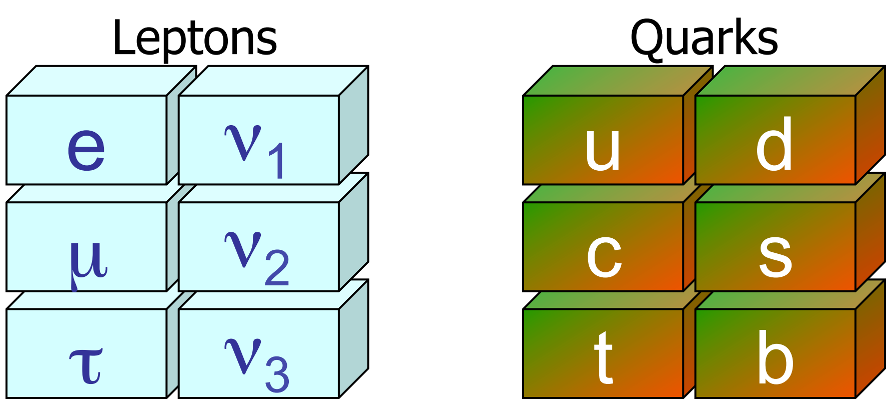
Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

Can exist in free state →



← **Can not exist in free state; only inside hadrons (*e.g. p, n, etc*)**

The Standard Model of Particle and Forces

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

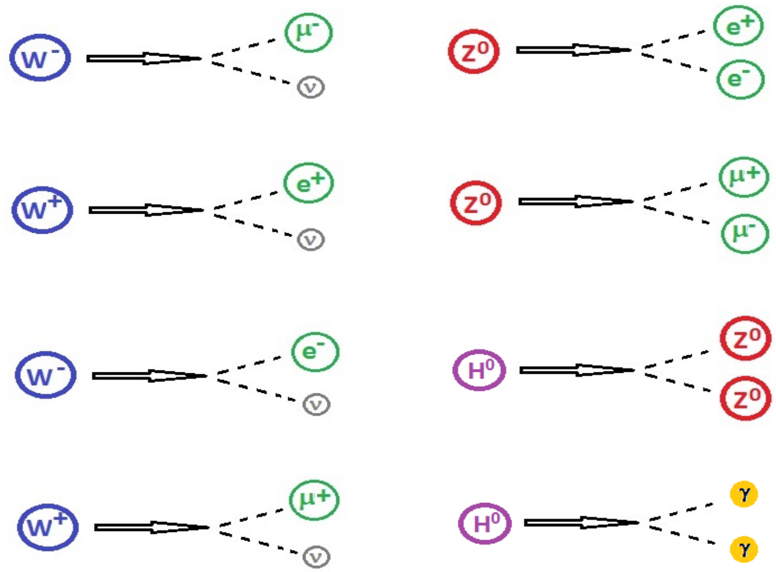
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Particle decays

- Most of the elementary particles are **unstable and decay to lighter particles** the moment they are produced.

- Because of this we do not "see" them directly. Rather we can infer their existence via **decay products**.

- **W, Z and Higgs bosons** are examples of heavy unstable particles that decay immediately:



Conserved quantities:
- energy
- momentum
- mass
- charge

Decays of W boson

- The W bosons are electrically charged:
  - Positively charged W^+ or
  - Negatively charged W^-

- Charge is a conserved quantity, so:

  $W^+ \to e^+ \nu$

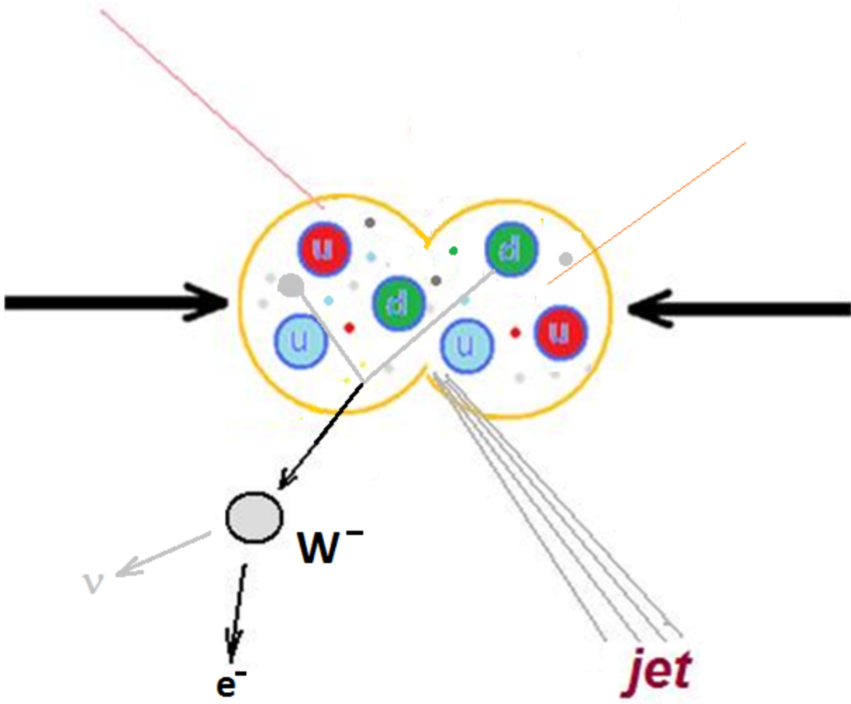
  $W^- \to e^- \nu$

  Or

  $W^+ \to \mu^+ \nu$

  $W^- \to \mu^- \nu$

- Neutrino is undetectible particle. We recognize neutrino via energy imbalance – missing E_T.

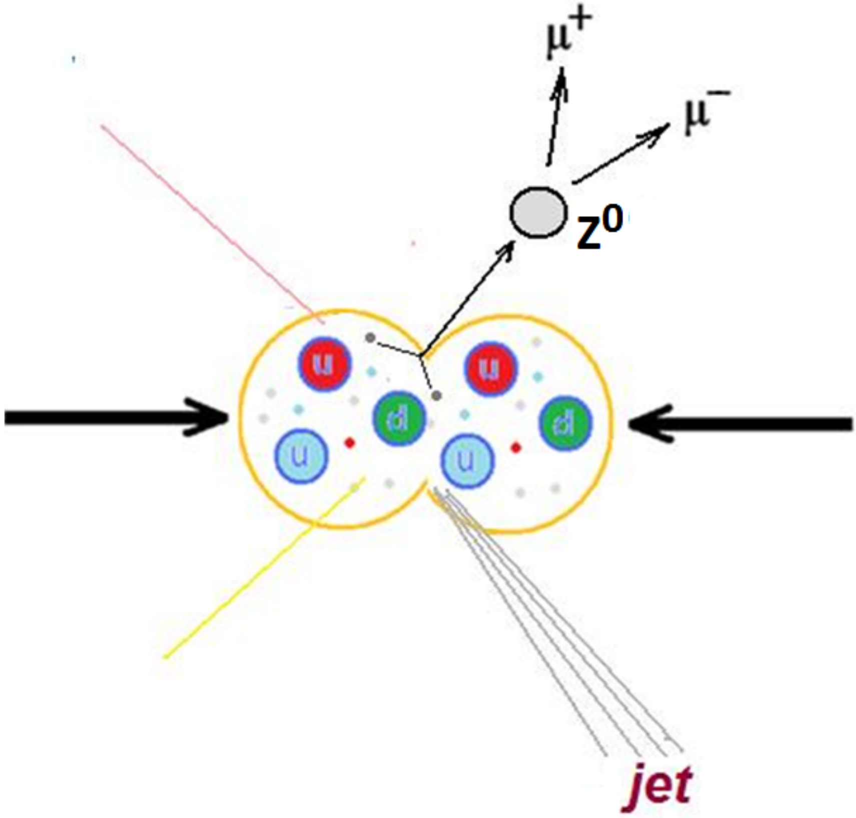


Decays of Z boson

- The Z bosons are electrically charged:
  Z^0

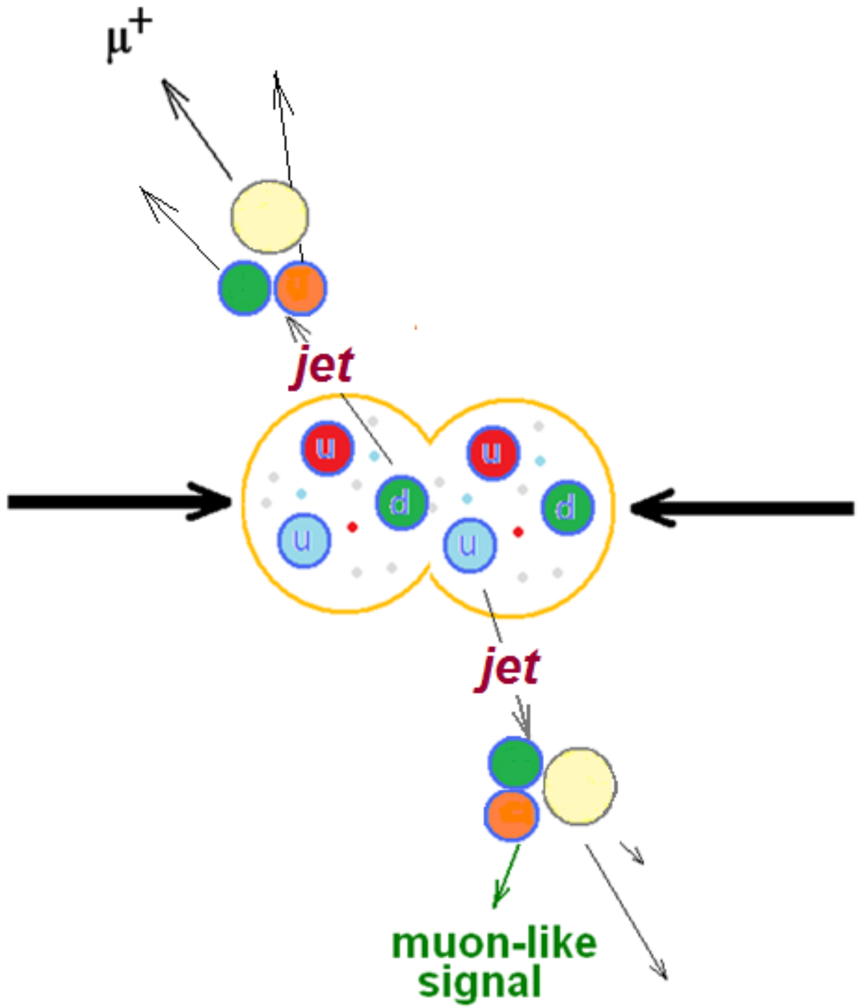
- Charge is a conserved quantity, so:
  $Z^0 \rightarrow e^+ e^-$
  Or
  $Z^0 \rightarrow \mu^+ \mu^-$

- Z boson is massive, with M = 91 GeV



Unwanted events – background

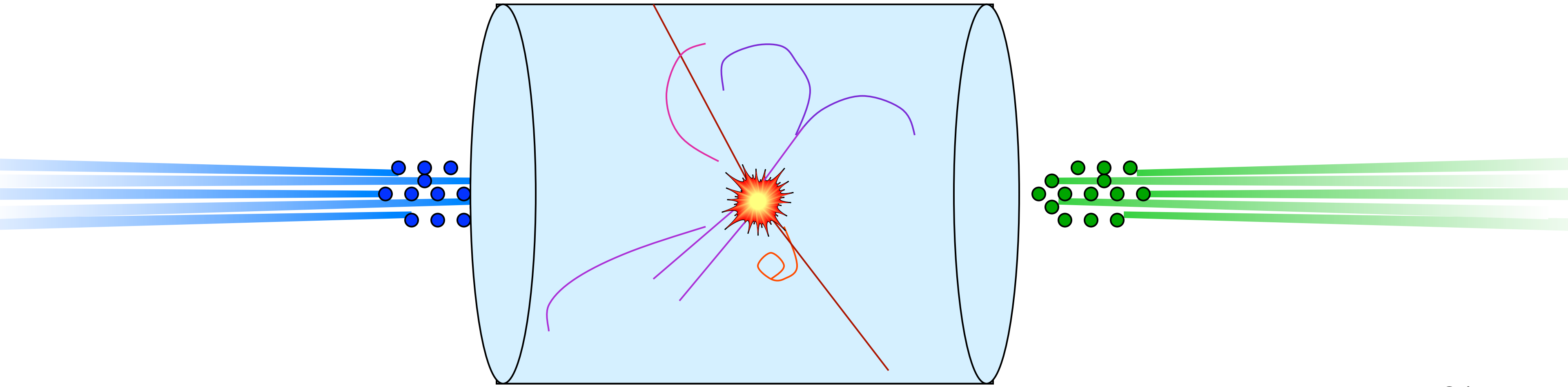
- Often, quarks are scattered by proton collisions.
- As they separate, the binding energy between them converts to sprays of new particles called *jets.* Electrons and muons may be included in jets.
- Software can filter out events with jets beyond our current interest.



How do we know about all of this?

- **The sub-atomic particles are much smaller than visible light wave-length. Therefore, we cannot really "see" them. Not even with most powerful microscope.**

- **To learn about the sub-atomic structure we need to accelerate particles to high energies, collide them and study these collisions.**

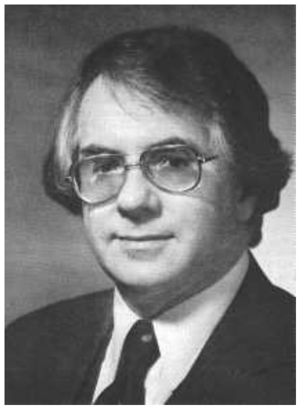
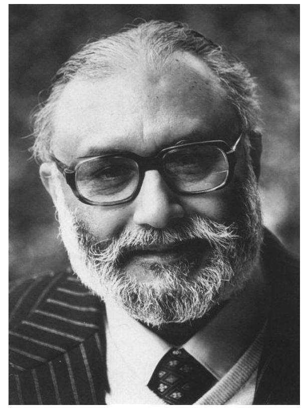
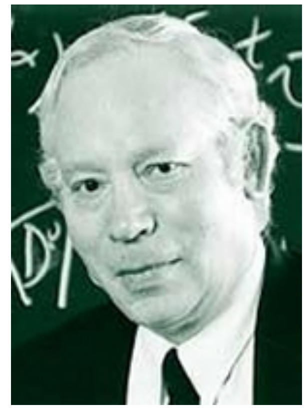


The Standard Model

The Nobel Prize winners

1979 Nobel Prize – GLASHOW, SALAM and WEINBERG

The theory of the unified weak and electromagnetic interaction.

1984 Nobel Prize – RUBBIA and VAN DER MEER

The discovery of the field particles W and Z, communicators of weak interaction.

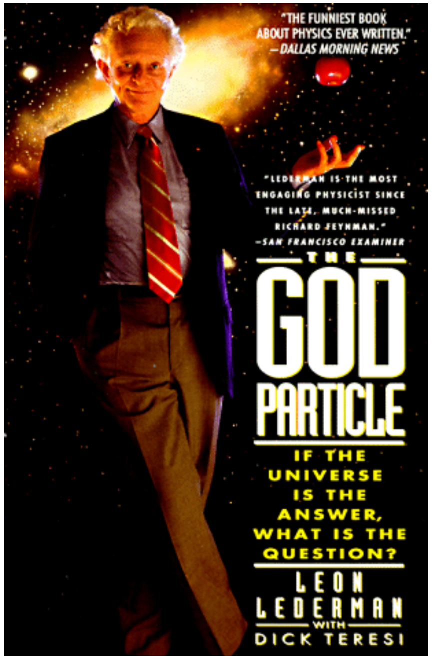

Origin of mass

Where does this mass come from?

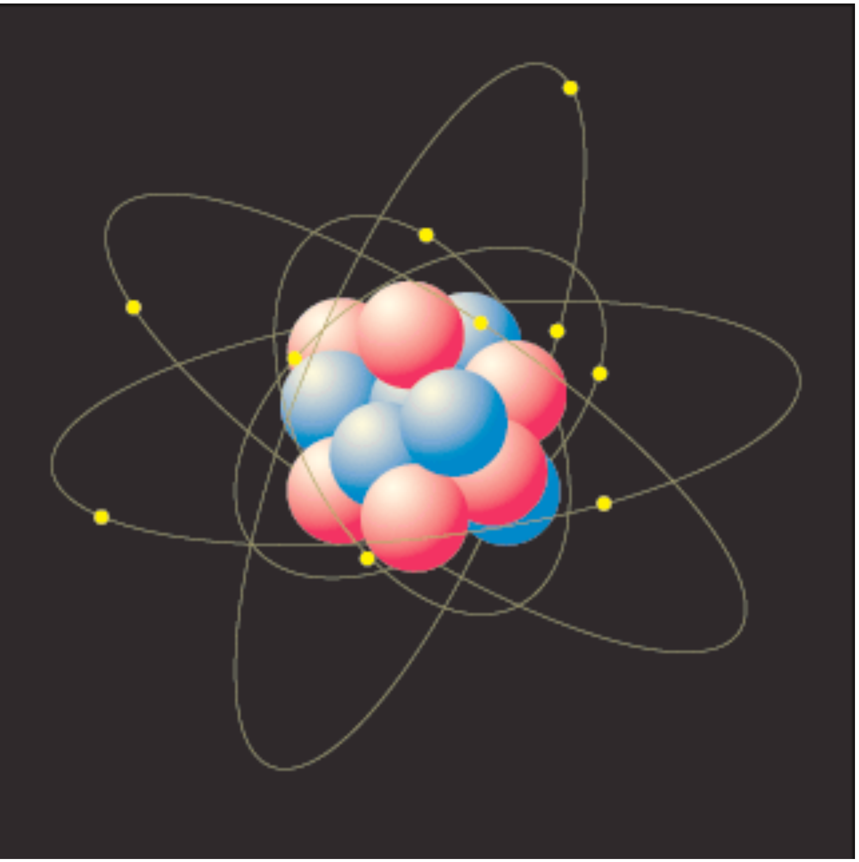
- In the Standard Model, the W and Z and all other massive particles get their mass because **the universe is filled with an energy field, called the Higgs field**, with which they interact.

- Fluctuation of Higgs filed gives physical particle – **Higgs boson.**

- Fermilab's Leon Lederman co-authored a book on the subject called ***The God Particle***.



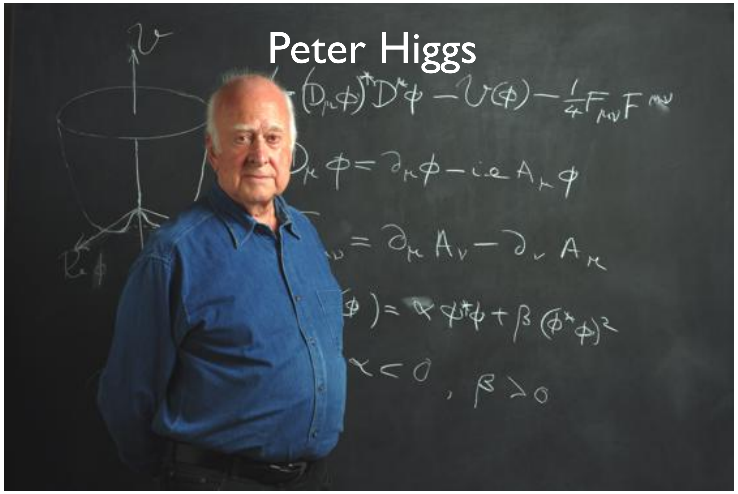
Higgs coupling to matte

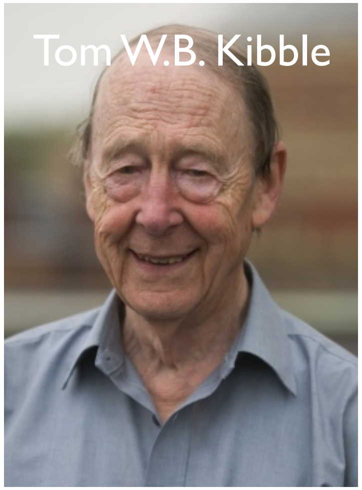


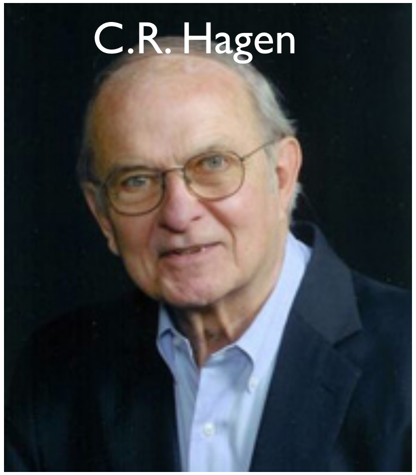
Without Higgs :

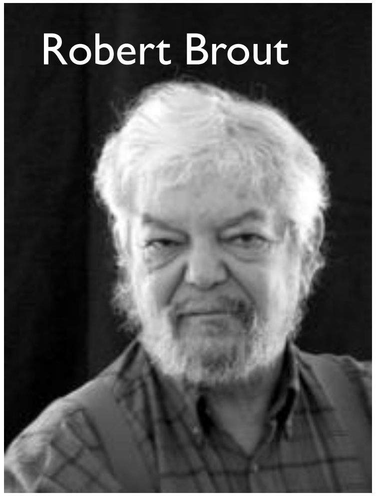
- Electron and nucleus have no mass, so
- We have no atoms, so
- There is no life!!!

The Higgs particle was predicted in 1964 as a consequence of a mechanism that gives mass to the W and Z bosons without destroying Electroweak the symmetry.





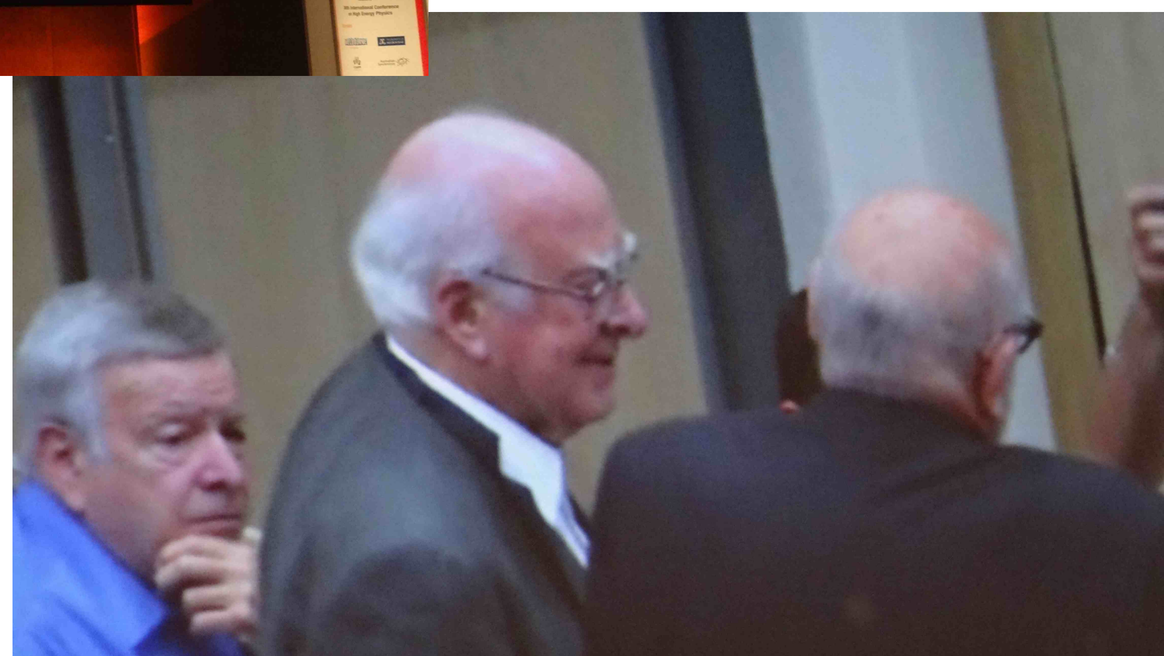




Announcement of Higgs discovery on July 4, 2012

CERN Director General, ATLAS and CMS spokespersons

Peter Higgs *et al.*



Screenshots taken at the Melbourne Convention Center where the ICHEP'12 conference took place and the New Boson Discovery was announced on July 4, 2012

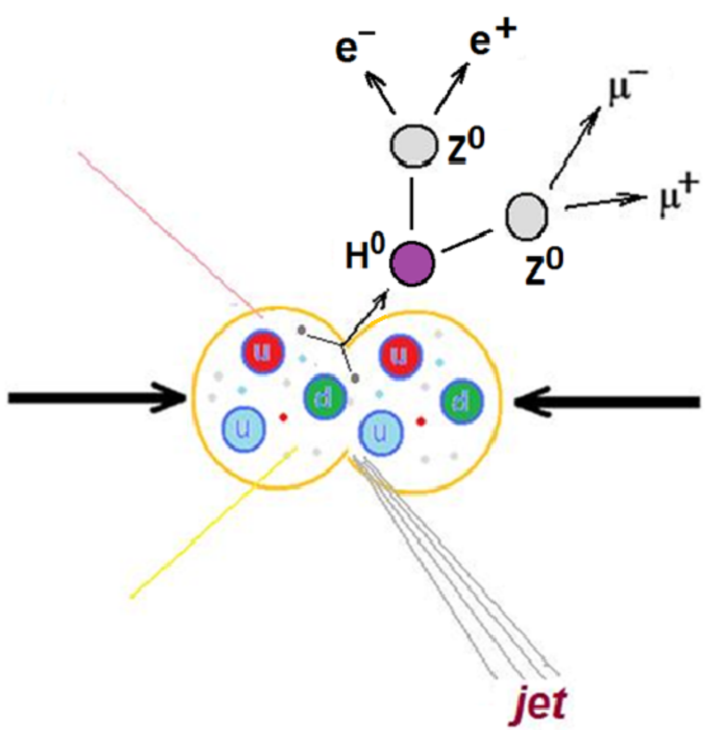
Peter Higgs and Francois Englert received Nobel Price in 2013.

Higgs decays

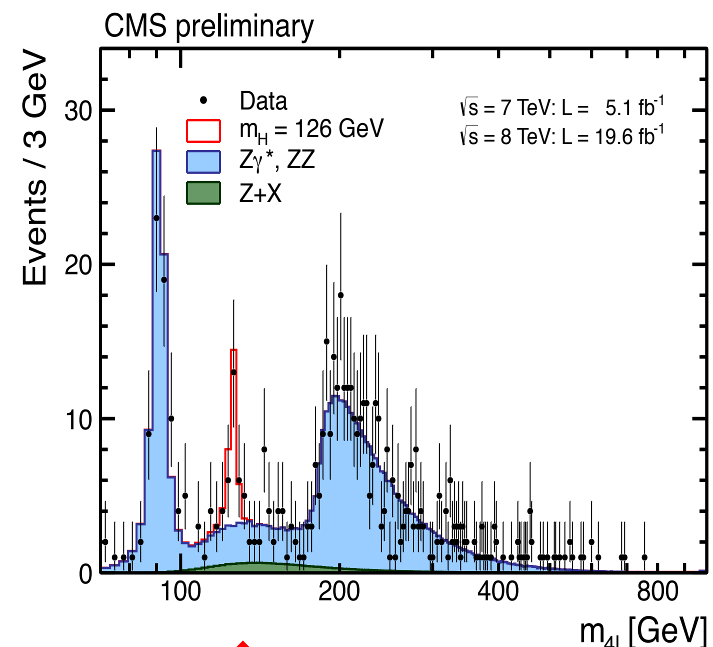
- **Like W and Z bosons, Higgs boson is unstable and immediately decayd to lighter particles. E.g.**

$$H \to ZZ \to 4\ell$$

- **At the end of this decay chain, we have $e^+e^-e^+e^-$ or $\mu^+\mu^-\mu^+\mu^-$ or $e^+e^-\mu^+\mu^-$**



$$H \to ZZ \to 4\ell$$

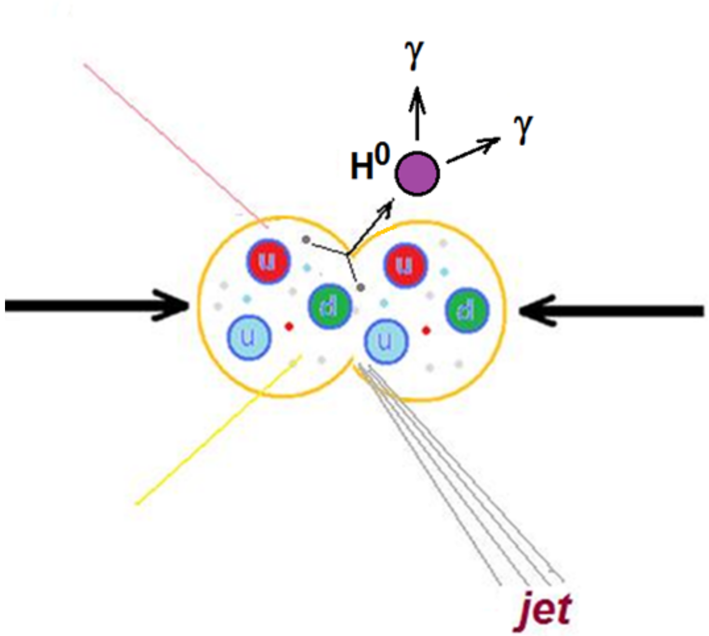


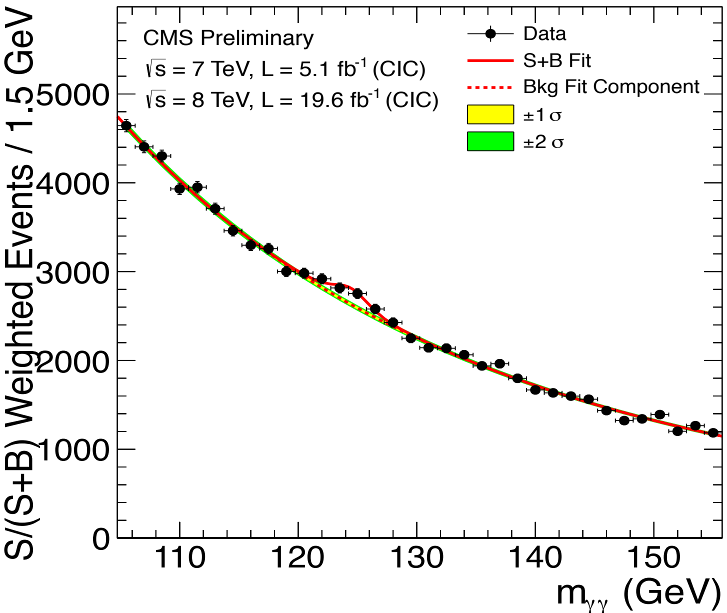
Higgs peak at ~125 GeV

Higgs decays

- **Another decay channel of Higgs:**

$$H \to \gamma\gamma$$





Higgs peak at ~125 GeV

Part 2: LHC and CMS Detector

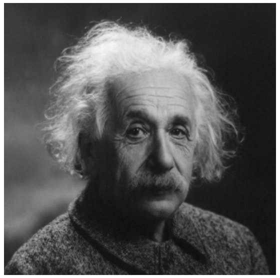
Particle Accelerators

Accelerate particles to high energies and collide them. Higher energies allow us

- To look deeper into matter, $v = \frac{h}{E}$
  ("powerful microscopes")

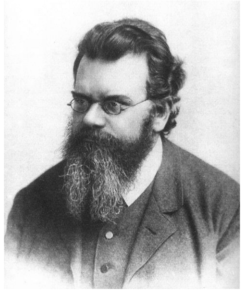
de Broglie

- To discover new heavier particles, $E = mc^2$



Einstein

- To probe conditions of early universe, $E = kT$
  ("powerful telescopes"),



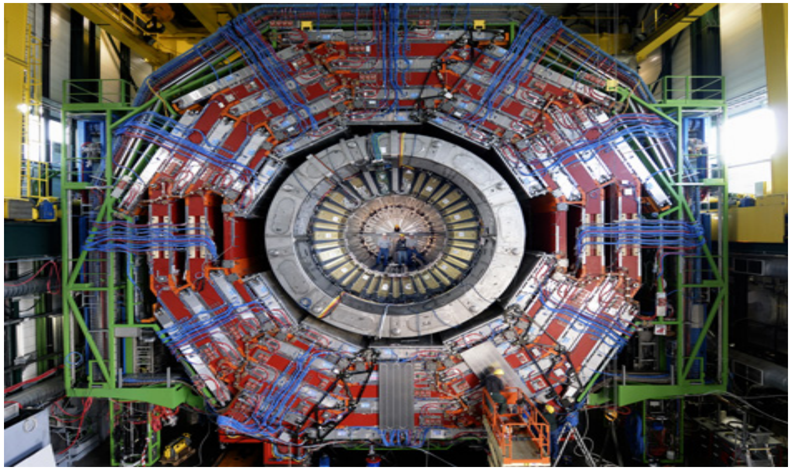
Boltzmann

Revisit the earlier moments of our ancestral universe to observe phenomena and particles normally no longer visible or existing in our time.

All in a controlled way in the laboratory

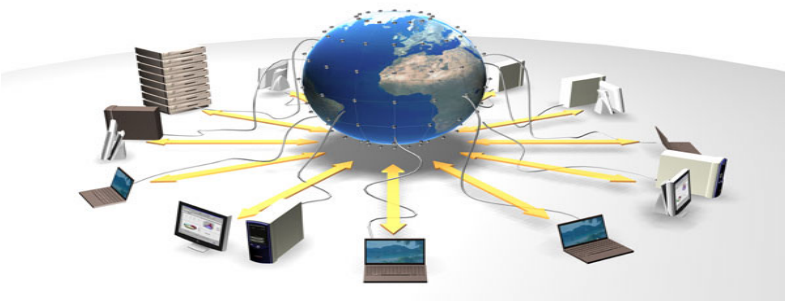
This requires …

1. Accelerators : powerful machines capable of accelerating particles to extremely high energies and bring them into collision with other particles



2. Detectors : gigantic instruments that record the particles as they "stream" out from the point of collision.

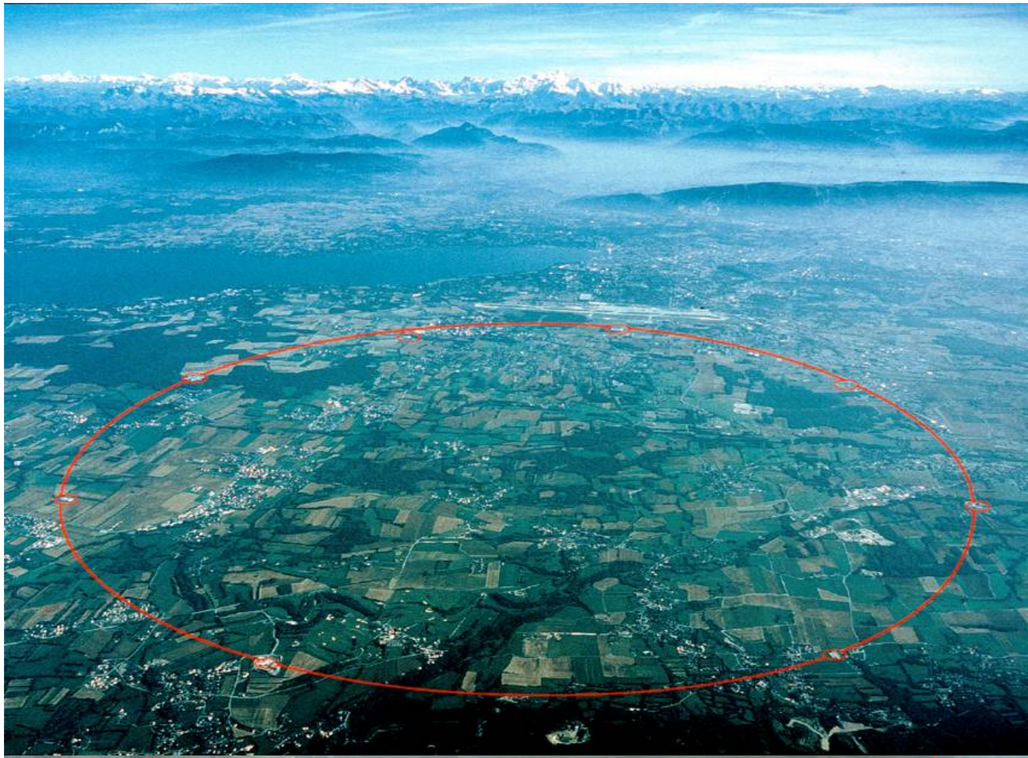
3. Computers : to collect, store, distribute and analyse the vast amount of data produced by the detectors

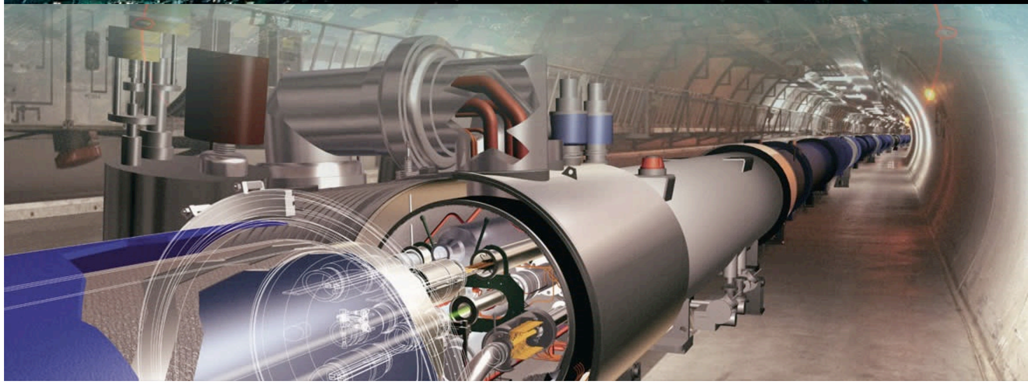


4. People : Only a worldwide collaboration of thousands of scientists, engineers, technicians and support staff can design, build and soon operate such complex "machines"

Large Hadron Collider

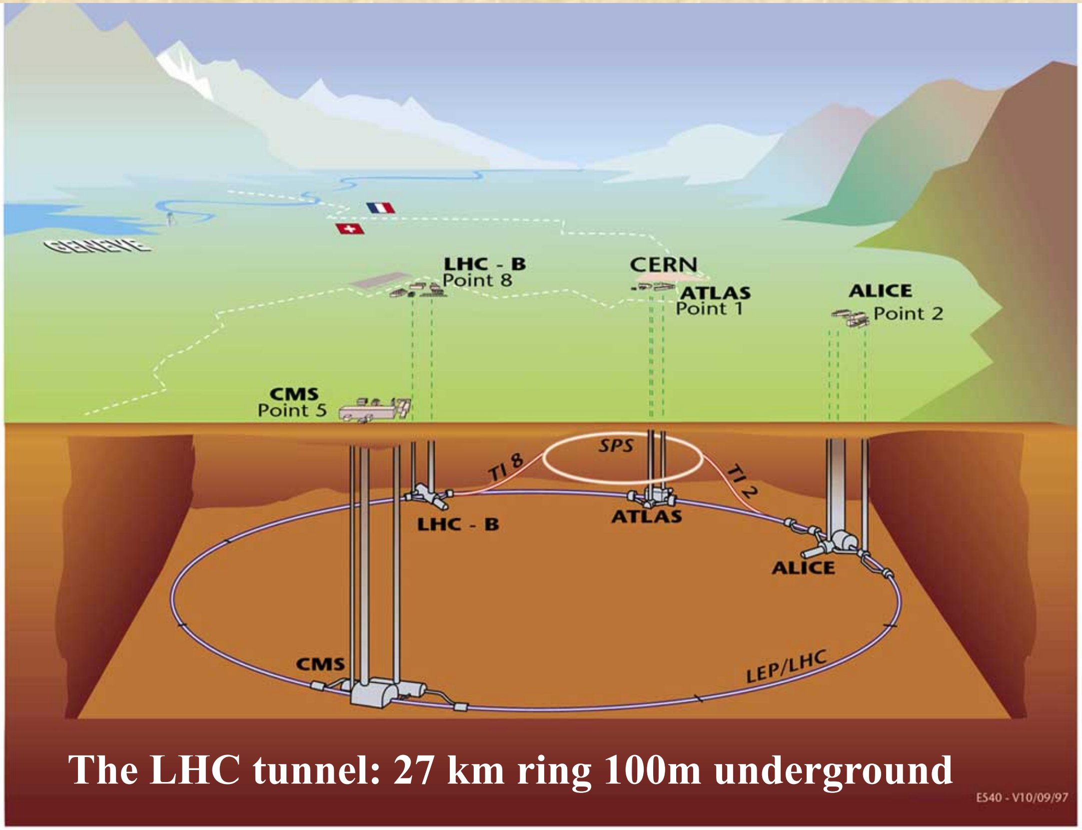
- CERN – European Organization for Nuclear Research.
  - On the boarder of Switzerland and France, near Geneva.
  - Founded in 1954
- Large Hardon Collider
  - Large is an understatement
  - Hadron here refers to protons counter-circulating in a 17 mile tunnel deep underground.
  - Collider: tiny bunches of the protons collide 20 million times per second to create the massive particles.





- First LHC collisions were recorded in late 2009

Large Hadron Collider

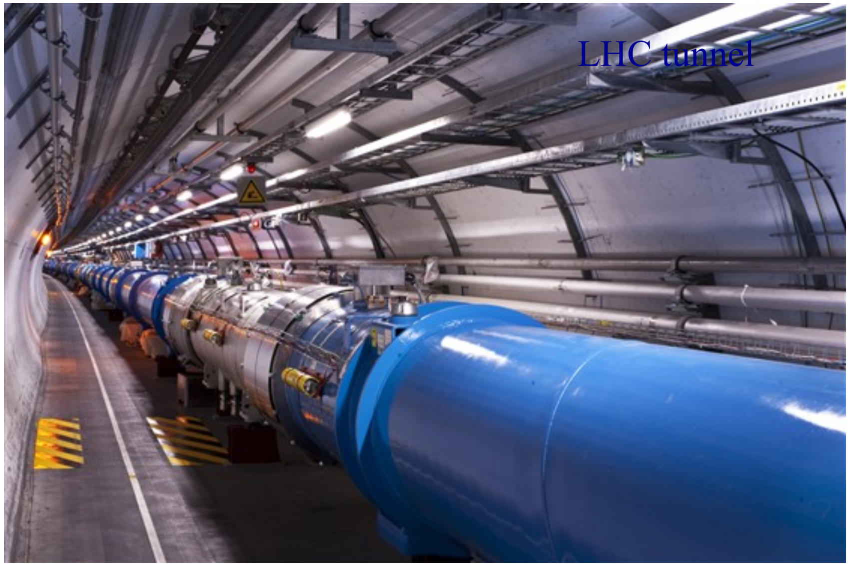


Proton beams are guided around their circular orbits by powerful superconducting dipole magnets operating at 8.3 T (200,000 × Earth's magnetic field) & 1.9 K temperature in superfluid helium. The largest cryogenic system in the world

Large Hadron Collider

One of the largest and most complex scientific project ever attempted

- Conceived in late 1980's. Was built from 1998 to 2008.
- The world's highest energy collider with proton beams of E=6.5 TeV – the same kinetic energy as aircraft carrier at 15 knots!
- Protons move with 99.999999% of the speed of light
- Superconducting magnetic dipoles operate at 1.9 K. The largest cryogenic system in the world – colder and emptier than space.
- LHC cost ~ 4 billion CHF



Timeline of the LHC project

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne

1987 Rubbia "Long-Range Planning Committee" recommends Large Hadron Collider as the right choice for CERN's future

1990 ECFA LHC Workshop, Aachen

1992 General Meeting on LHC Physics and Detectors, Evian les Bains

1993 Letters of Intent (ATLAS and CMS selected by LHCC)

1994 Technical Proposals Approved

1996 Approval to move to Construction (ceiling of 475 MCHF)

1998 Memorandum of Understanding for Construction Signed

1998 Construction Begins (after approval of Technical Design Reports)

2000 CMS assembly begins above ground. LEP closes

2004 CMS Underground Caverns completed

2009 First proton-proton Collisions

First collisions at E_{com}=7 TeV, March 30, 2009

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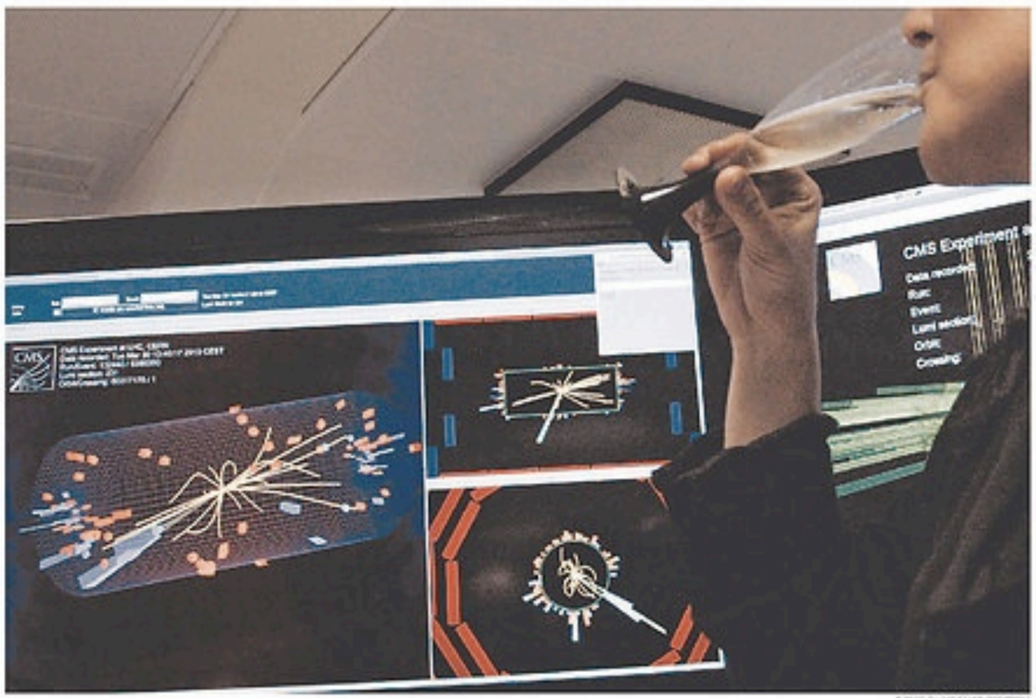
"All the News That's Fit to Print"

The New York Times

Late Edition

Today, morning showers in spots, then clearing, milder, high 60. **Tonight,** clear, low 49. **Tomorrow,** ample sunshine, cooler at the coast, high 69. Weather map, Page A24.

VOL. CLIX . . No. 54,996 © 2010 The New York Times NEW YORK, WEDNESDAY, MARCH 31, 2010 $2.00



DENIS BALIBOUSE/REUTERS

Particles Collide, and Champagne Glasses Clink

In a control room, a scientist toasted the start of the Large Hadron Collider outside Geneva on Tuesday. The $10 billion collider is designed to smash subatomic particles together at high energy levels, giving insight into the universe's beginnings. Page A11.

Plan to Widen Use of Statins Has Skeptics

Cholesterol Pills Aimed at Healthy People

By DUFF WILSON

With the government's blessing, a drug giant is about to expand the market for its blockbuster cholesterol medication Crestor to a new category of customers: as a preventive measure for millions of people who do not have cholesterol problems.

Some medical experts question whether this is a healthy move.

They point to mounting concern that cholesterol medications — known as statins and already the most widely prescribed drugs in the United States — may not be as safe a preventive medicine as previously believed for people who are at low risk of heart attacks or strokes.

Statins have been credited with saving thousands of lives every year with relatively few side effects, and some medical experts endorse the drug's broader use. But for healthy people who would take statins largely as prevention — which would be the case for the new category of Crestor patients — other experts suggest the benefits may

OBAMA TO OPEN OFFSHORE AREAS TO OIL DRILLING

SEEKS MAJOR EXPANSION

Atlantic, Eastern Gulf of Mexico and Alaska Are in Plan

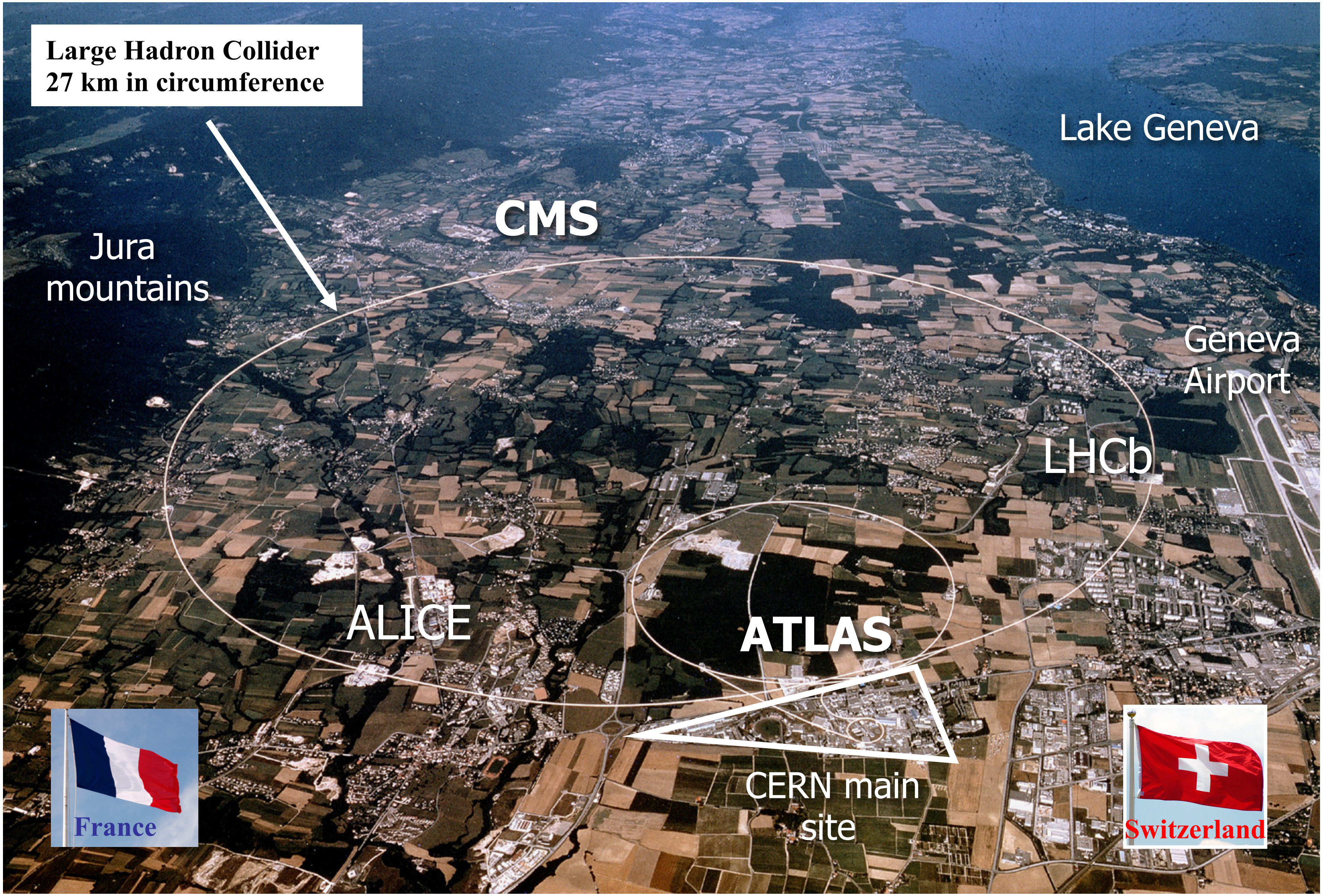
By JOHN M. BRODER

WASHINGTON — The Obama administration is proposing to open vast expanses of water along the Atlantic coastline, the eastern Gulf of Mexico and the north coast of Alaska to oil and natural gas drilling for the first time, officials said Tuesday.

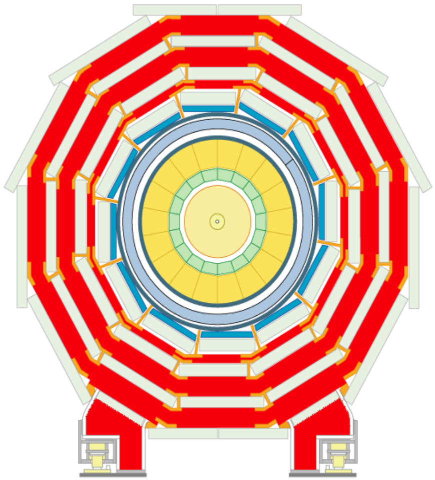
The proposal — a compromise that will please oil companies and domestic drilling advocates but anger some residents of affected states and many environmental organizations — would end a longstanding moratorium on oil exploration along the East Coast from the northern tip of Delaware to the central coast of Florida, covering 167 million acres of ocean.

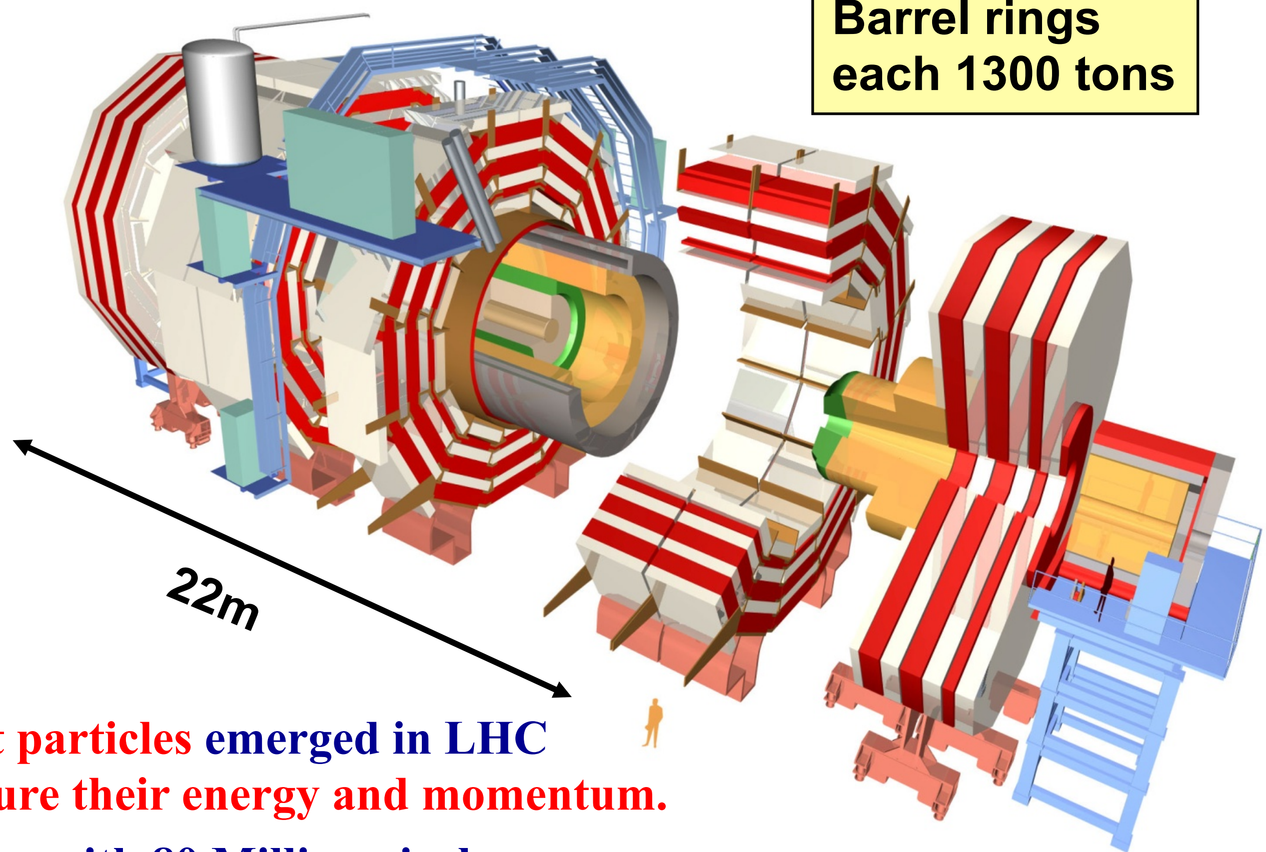
Under the plan, the coastline from New Jersey northward would remain closed to all oil and

CERN and LHC Site



CMS detector



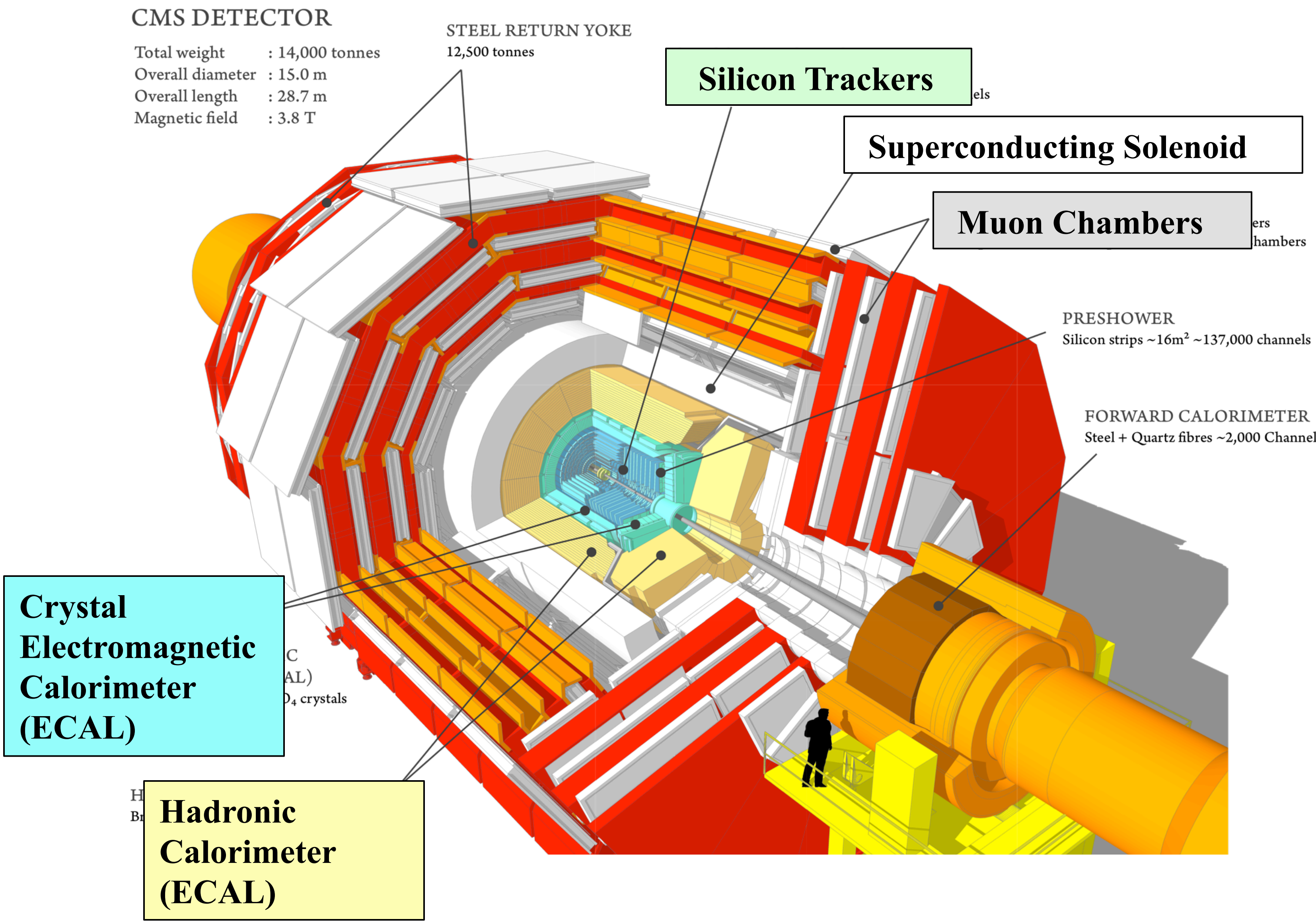


Barrel rings each 1300 tons

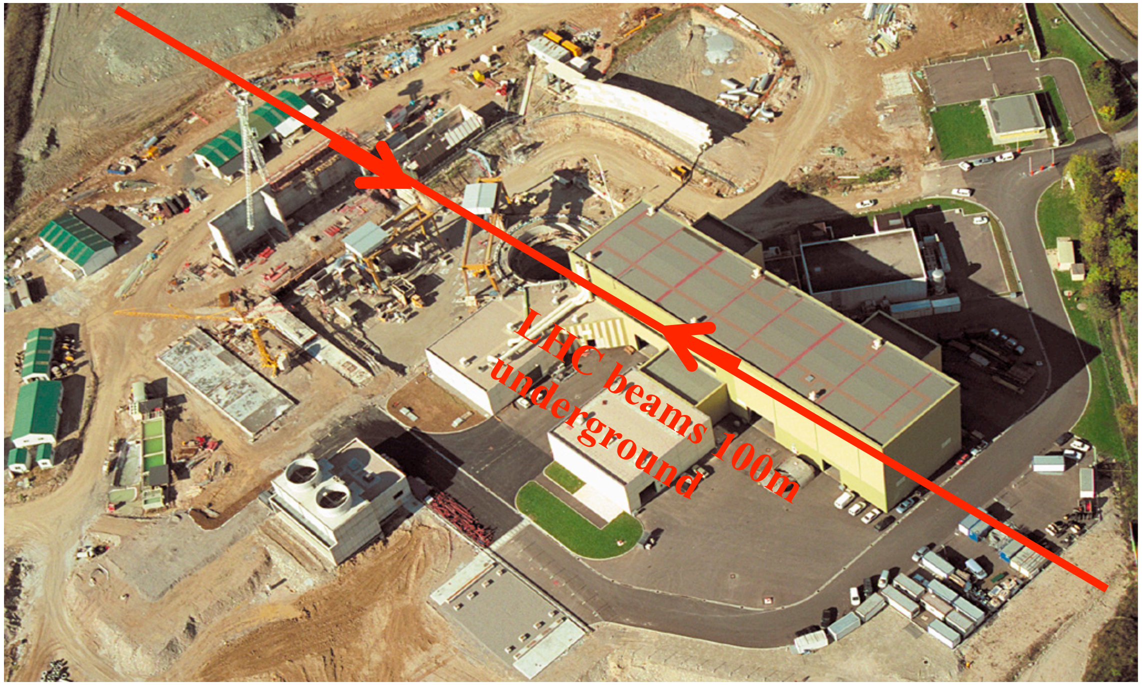
Endcap disks

- **Apparatus to detect particles emerged in LHC collisions and measure their energy and momentum.**
- **CMS is like a camera with 80 Million pixels**
- **But it's obviously no ordinary camera**
  - **It can take up to 40 million pictures per second**
  - **The pictures are 3 dimensional**
  - **And at 31 million pounds, it's not very portable**

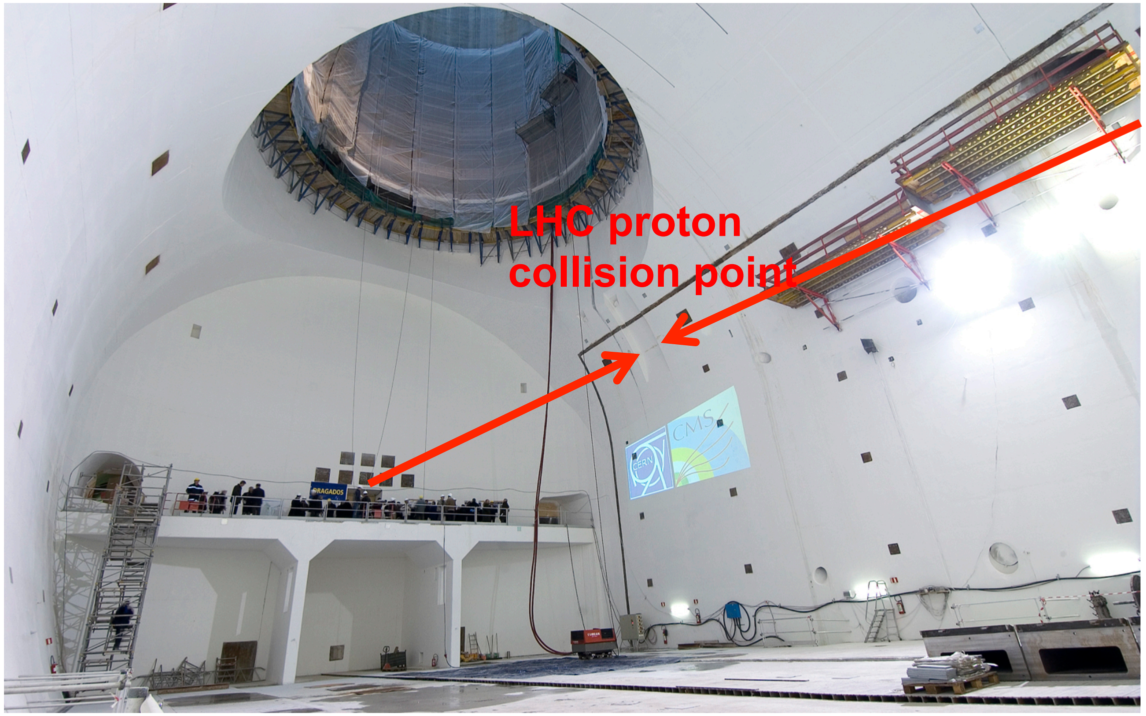
CMS detector



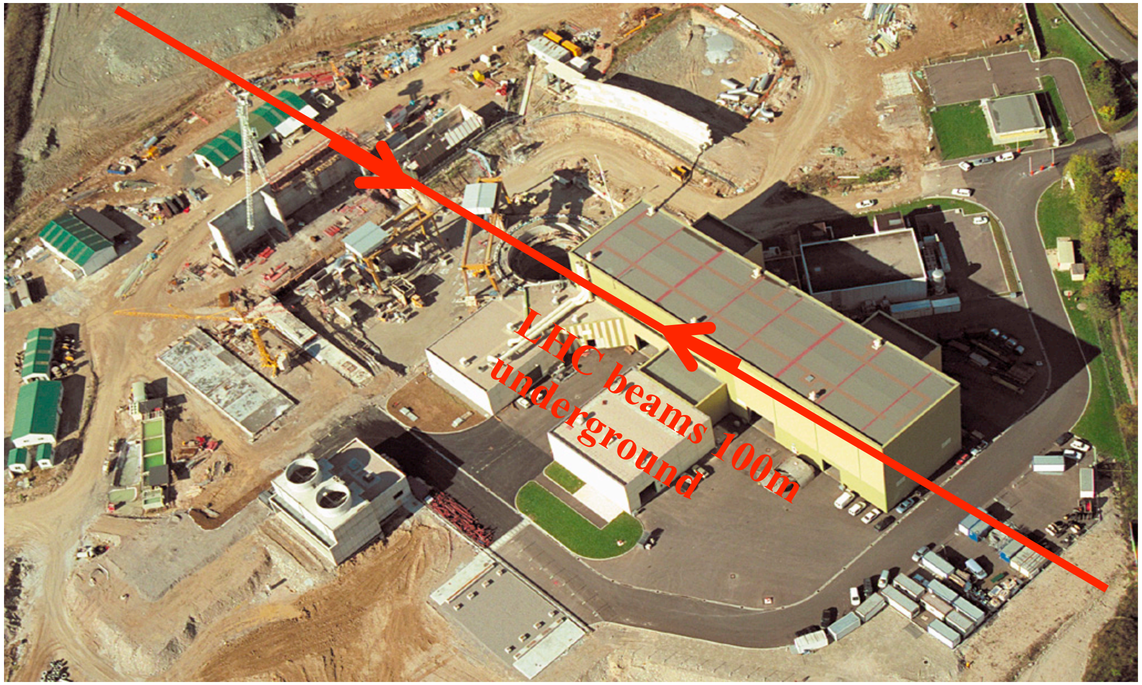
The surface building for the pre-assembly of CMS and the LHC access shafts



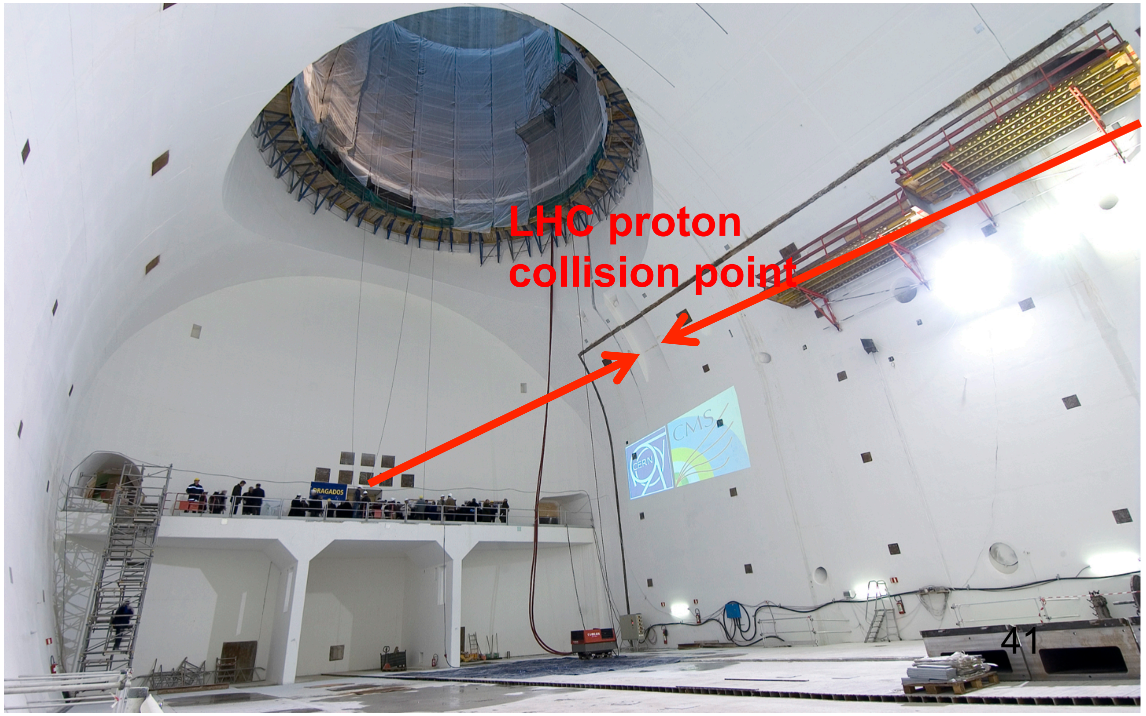
The CMS Underground cavern



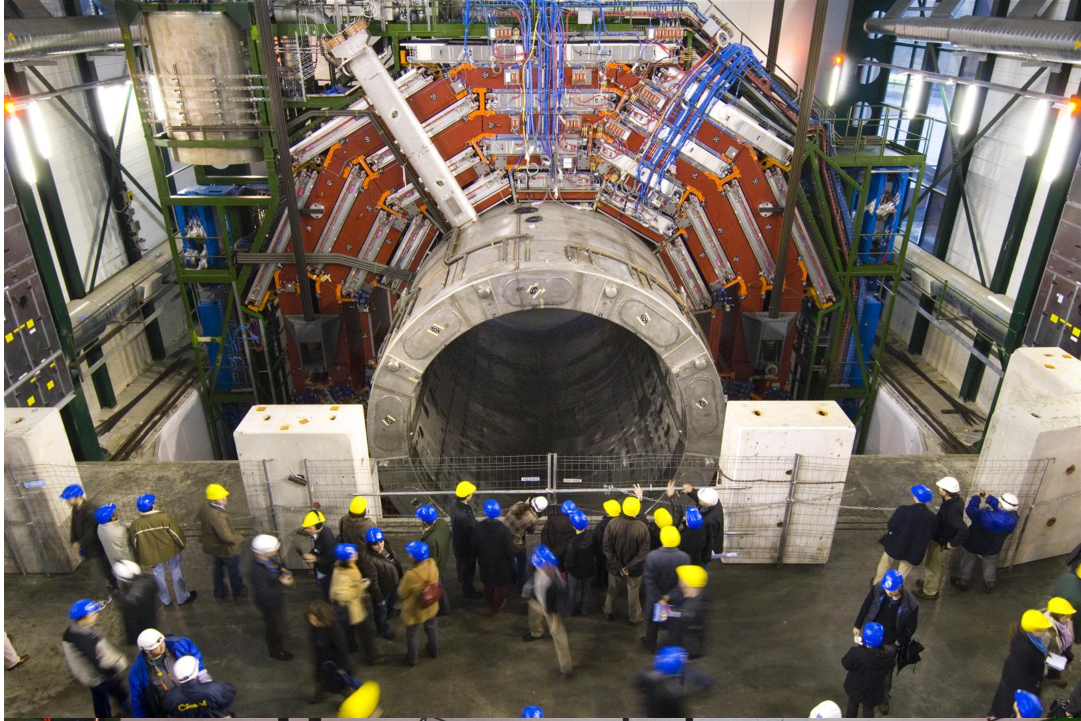
The surface building for the pre-assembly of CMS and the LHC access shafts



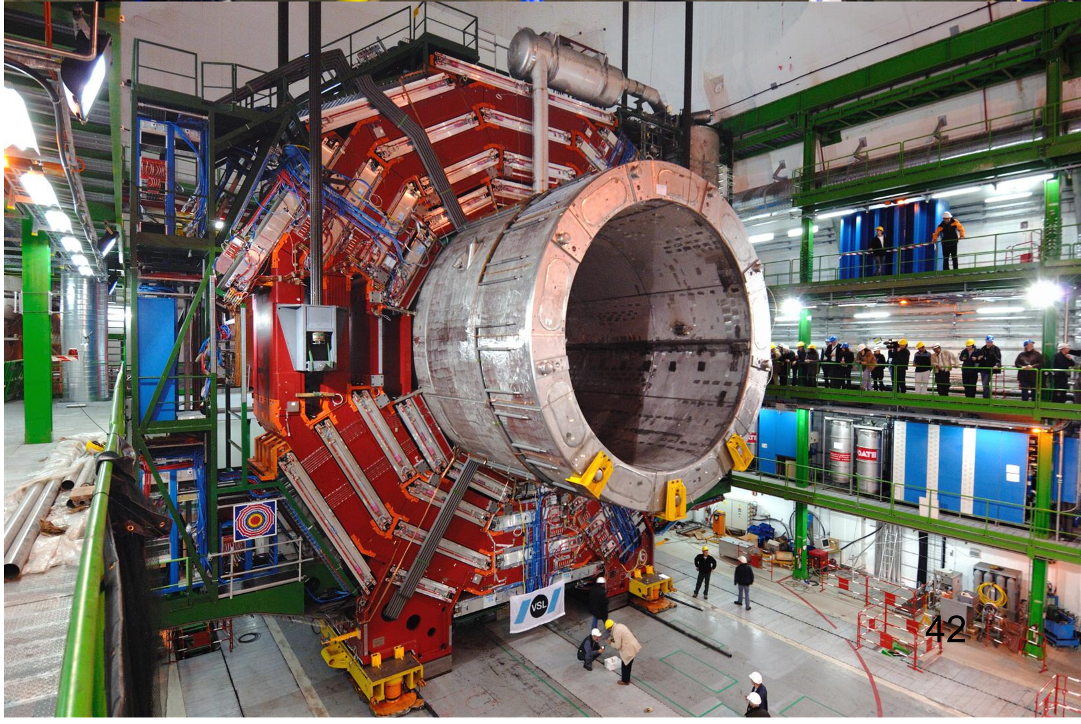
The CMS Underground cavern

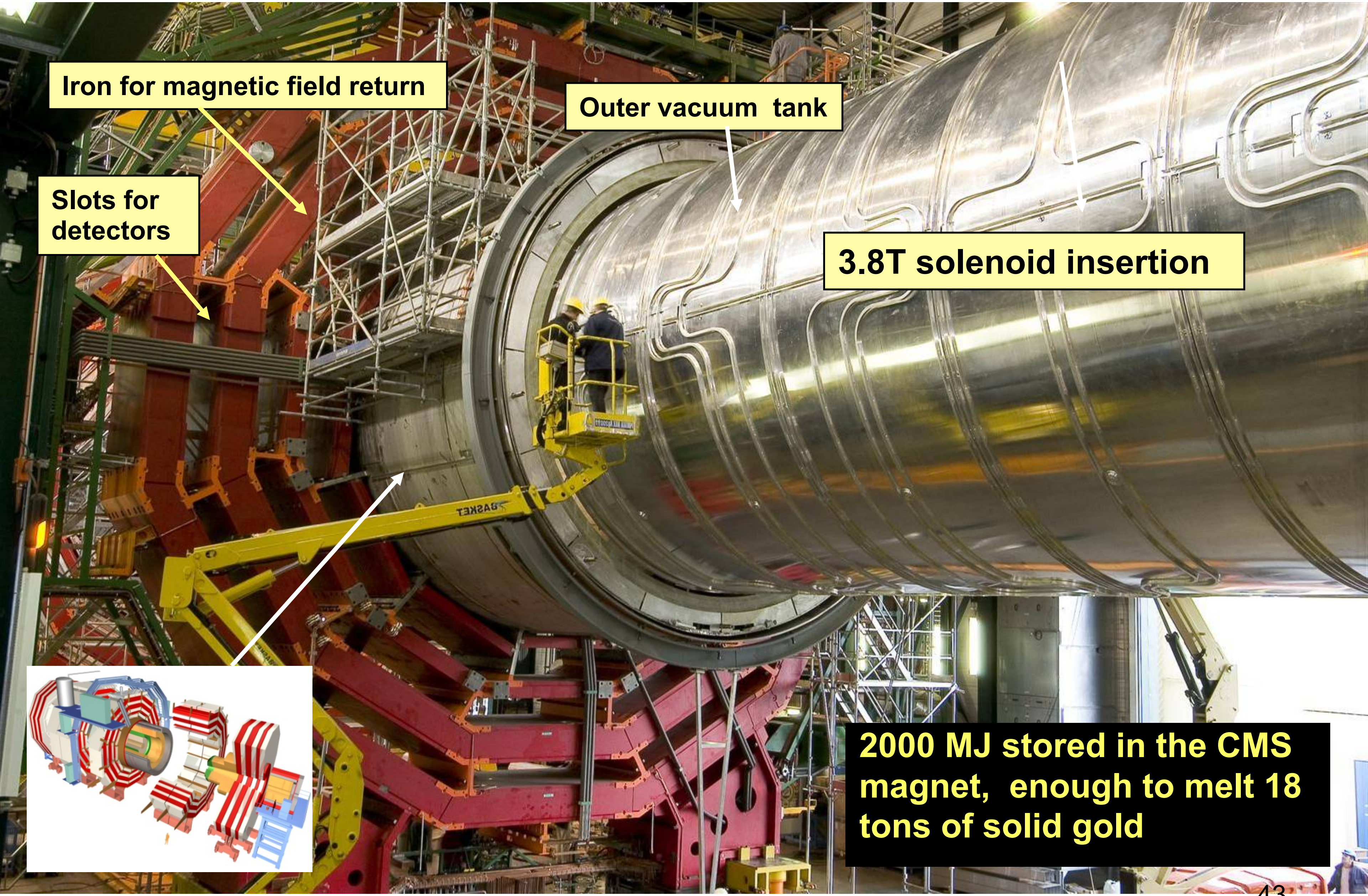


Gentle lowering of $70M of equipment weighing ~2000 tons

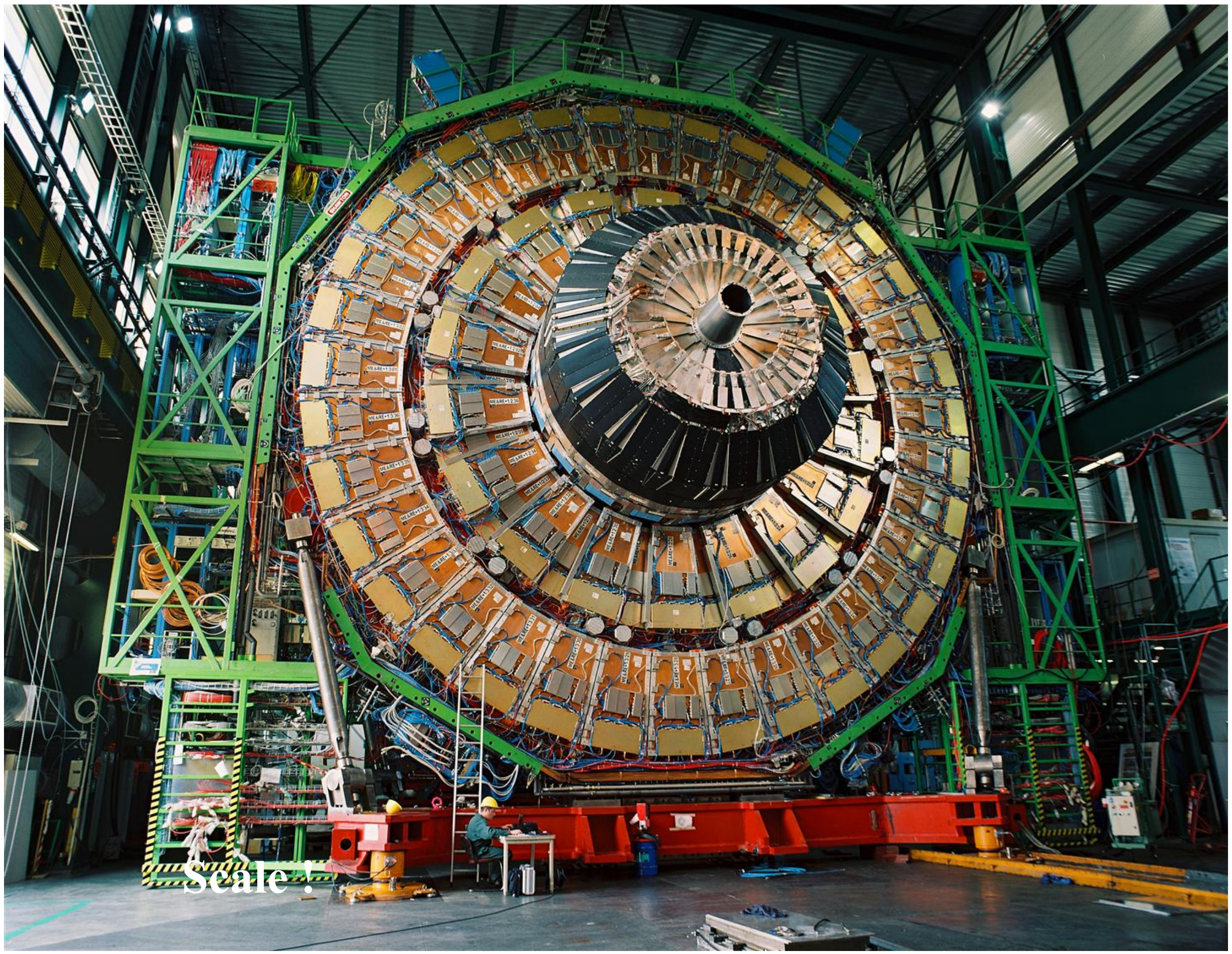


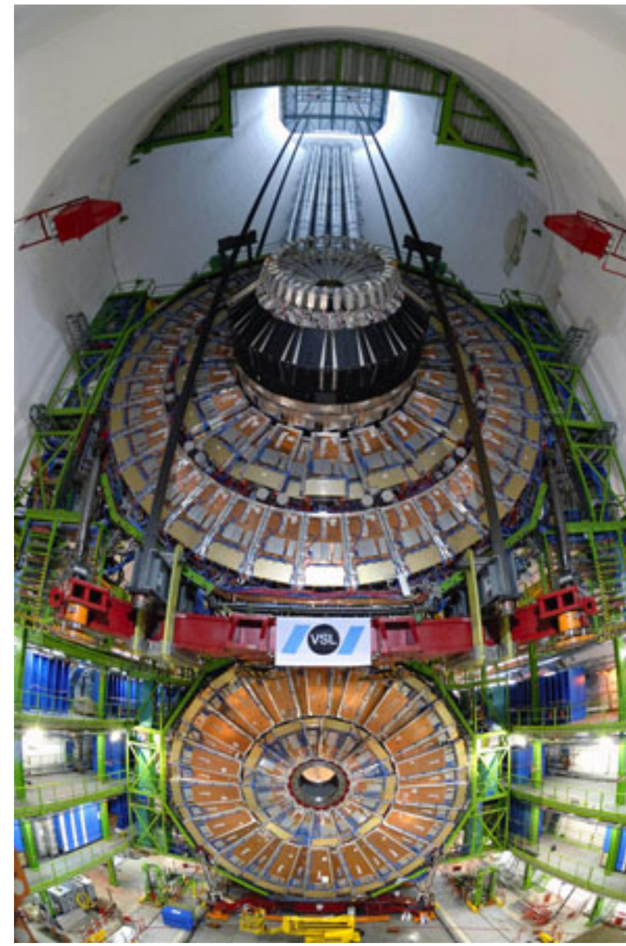
Arrival of the solenoid in the cavern




Iron for magnetic field return
Outer vacuum tank
Slots for detectors
3.8T solenoid insertion
2000 MJ stored in the CMS magnet, enough to melt 18 tons of solid gold

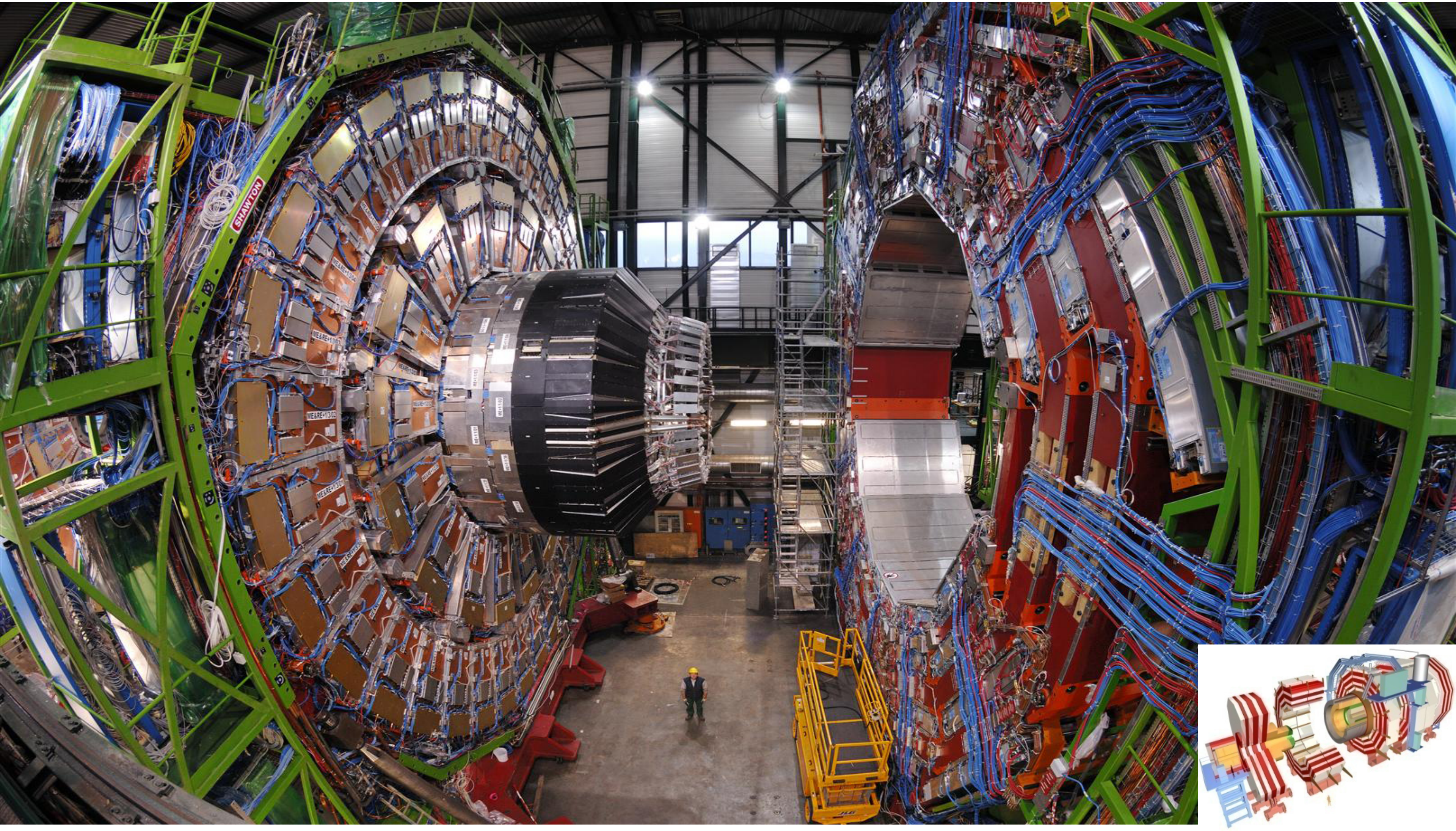
CMS - Compact Muon Spectrometer





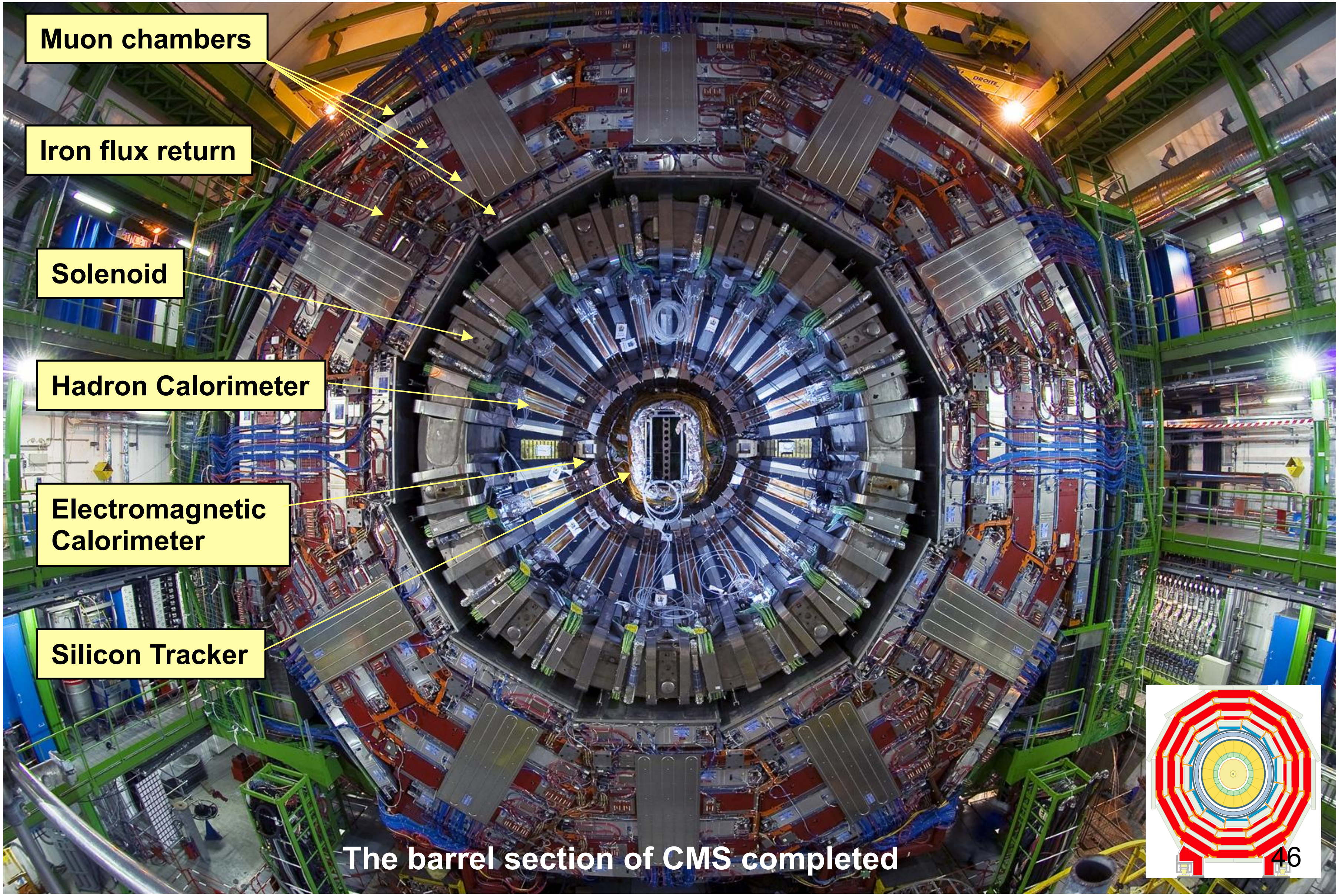
A view of an Endcap disk with its Muon chambers

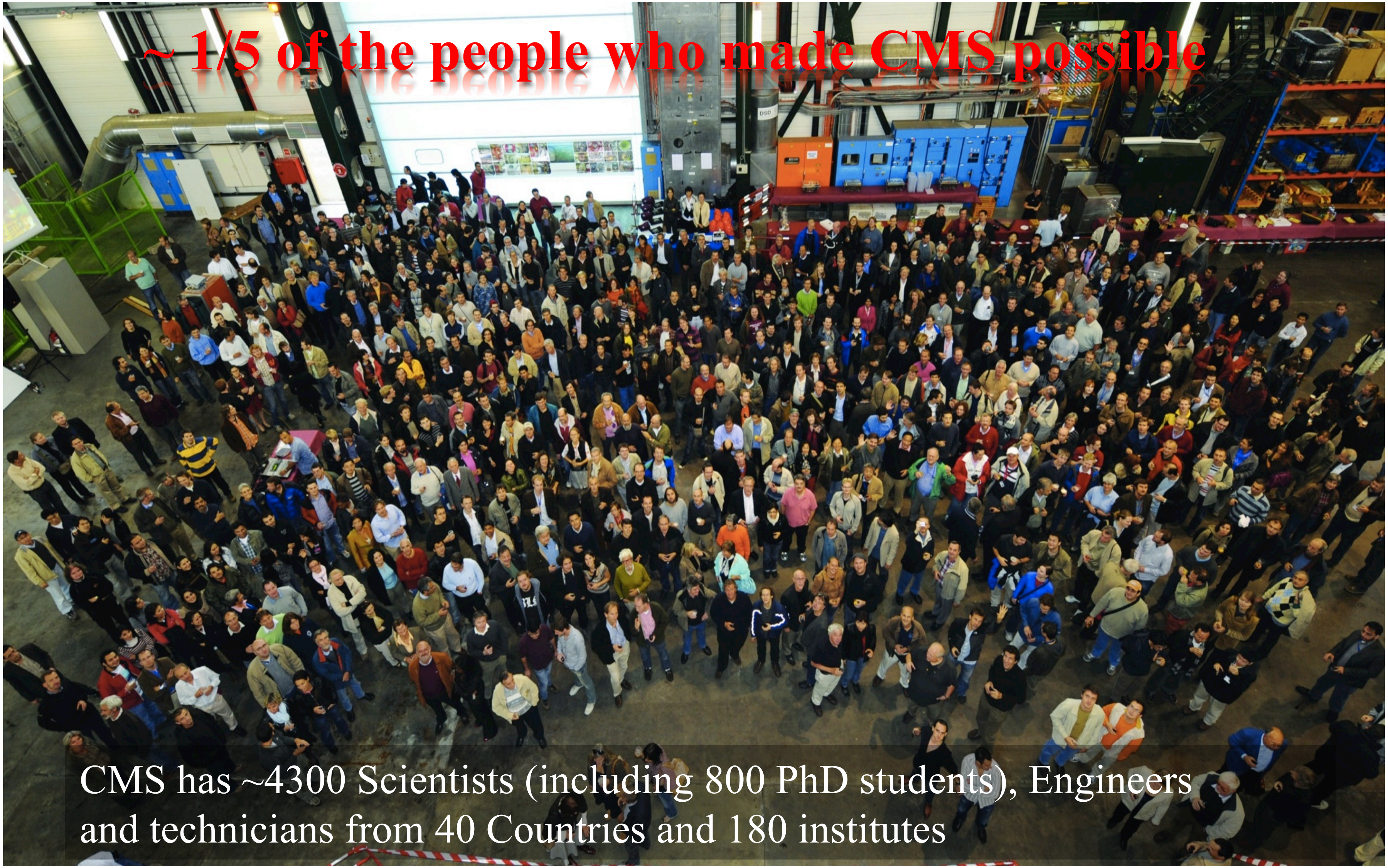
CMS - Compact Muon Spectrometer



Nearing completion underground

CMS - Compact Muon Spectrometer

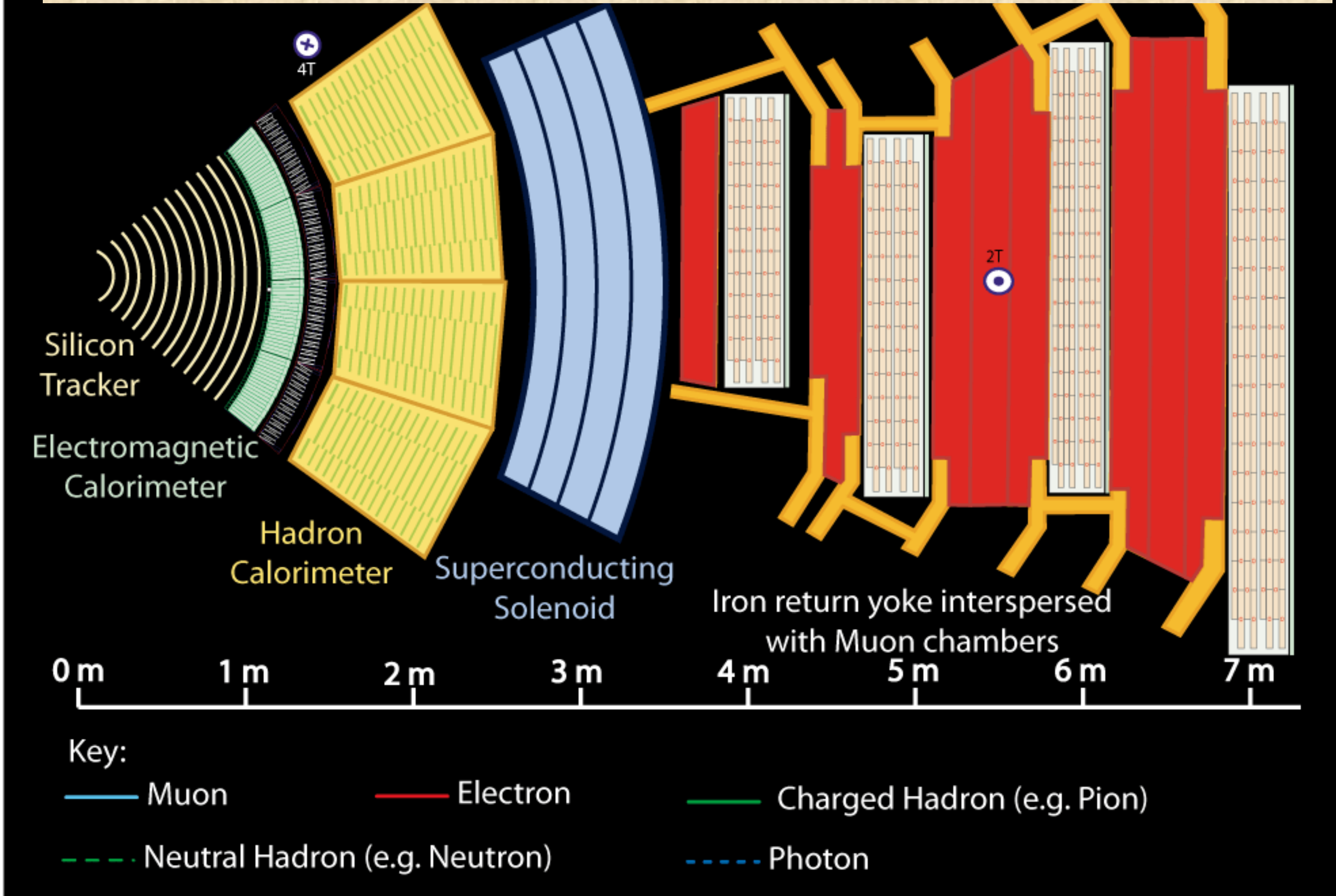




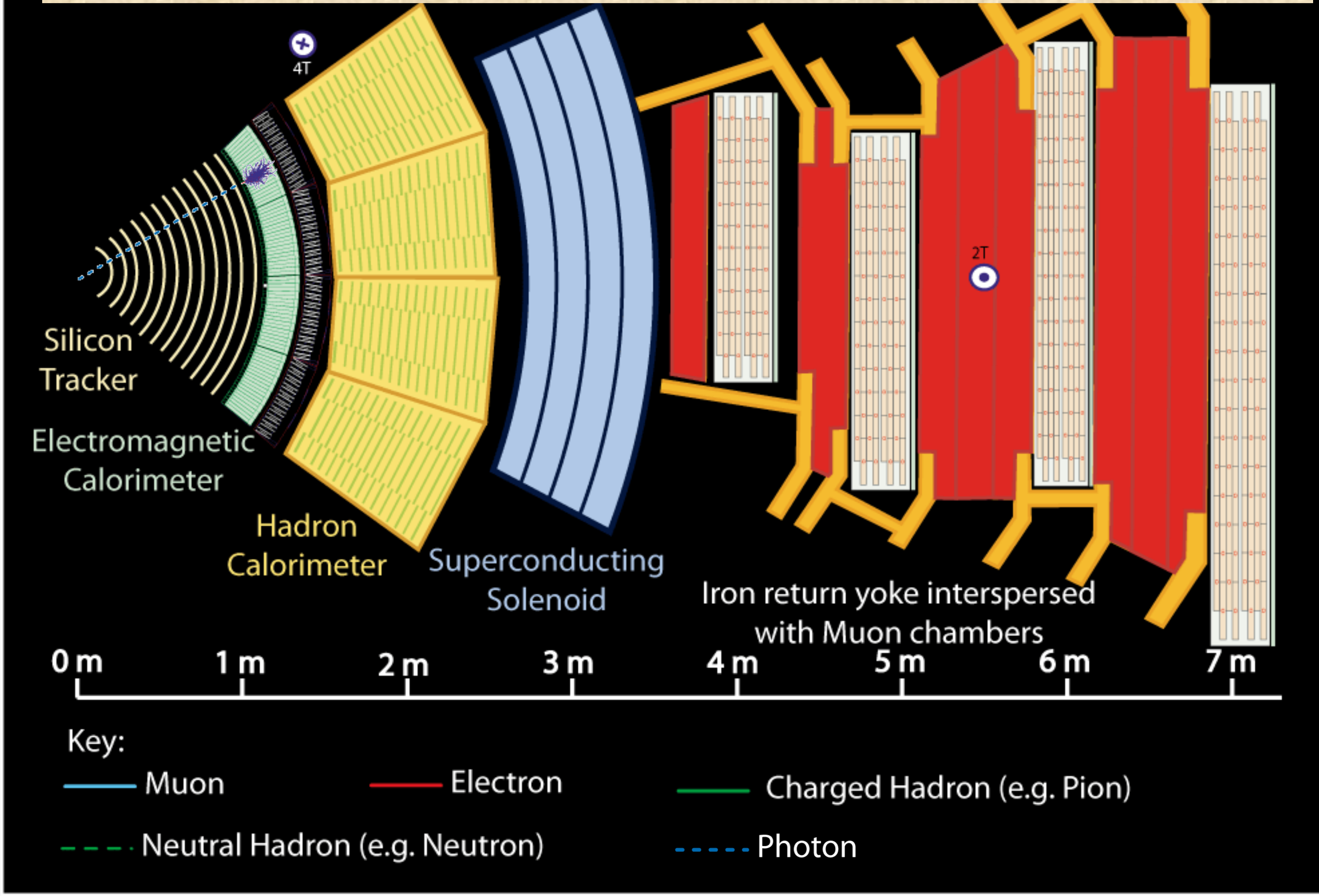
US institution play leading role in CMS. US built ~25% of CMS.

The key US federal agencies are U.S. DEPARTMENT OF ENERGY NSF

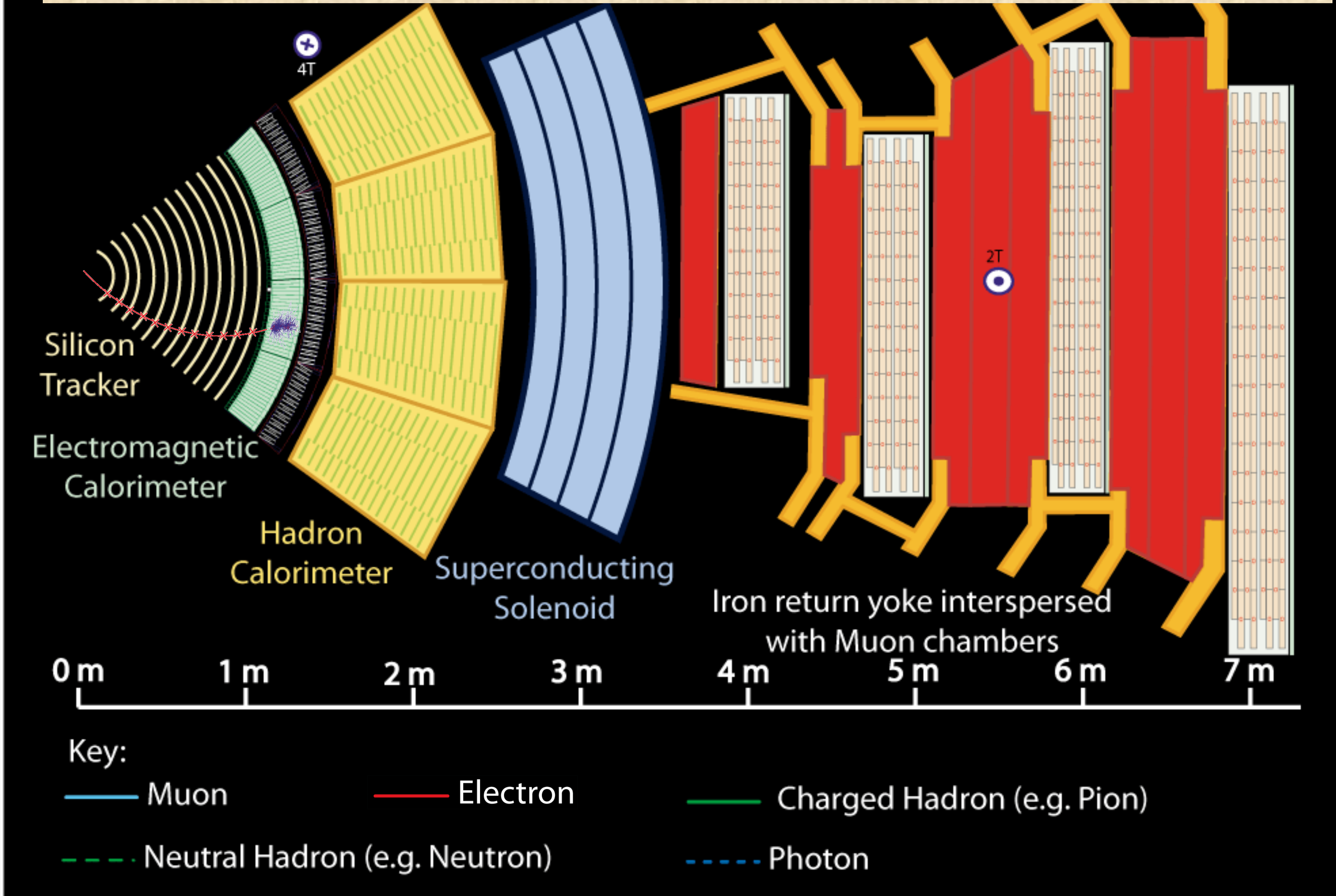
CMS detector: cross-sectional pie slice



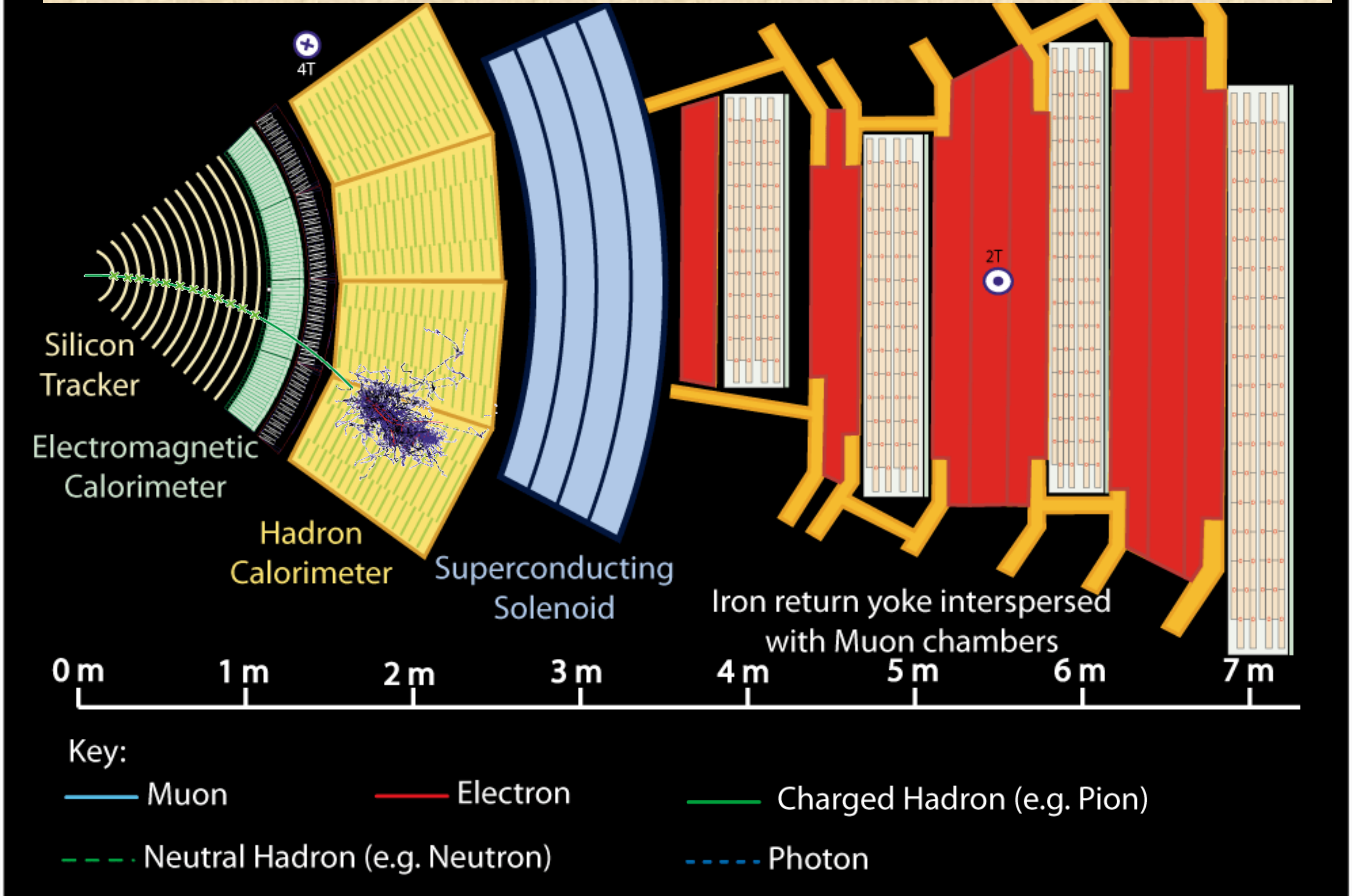
Detecting photon



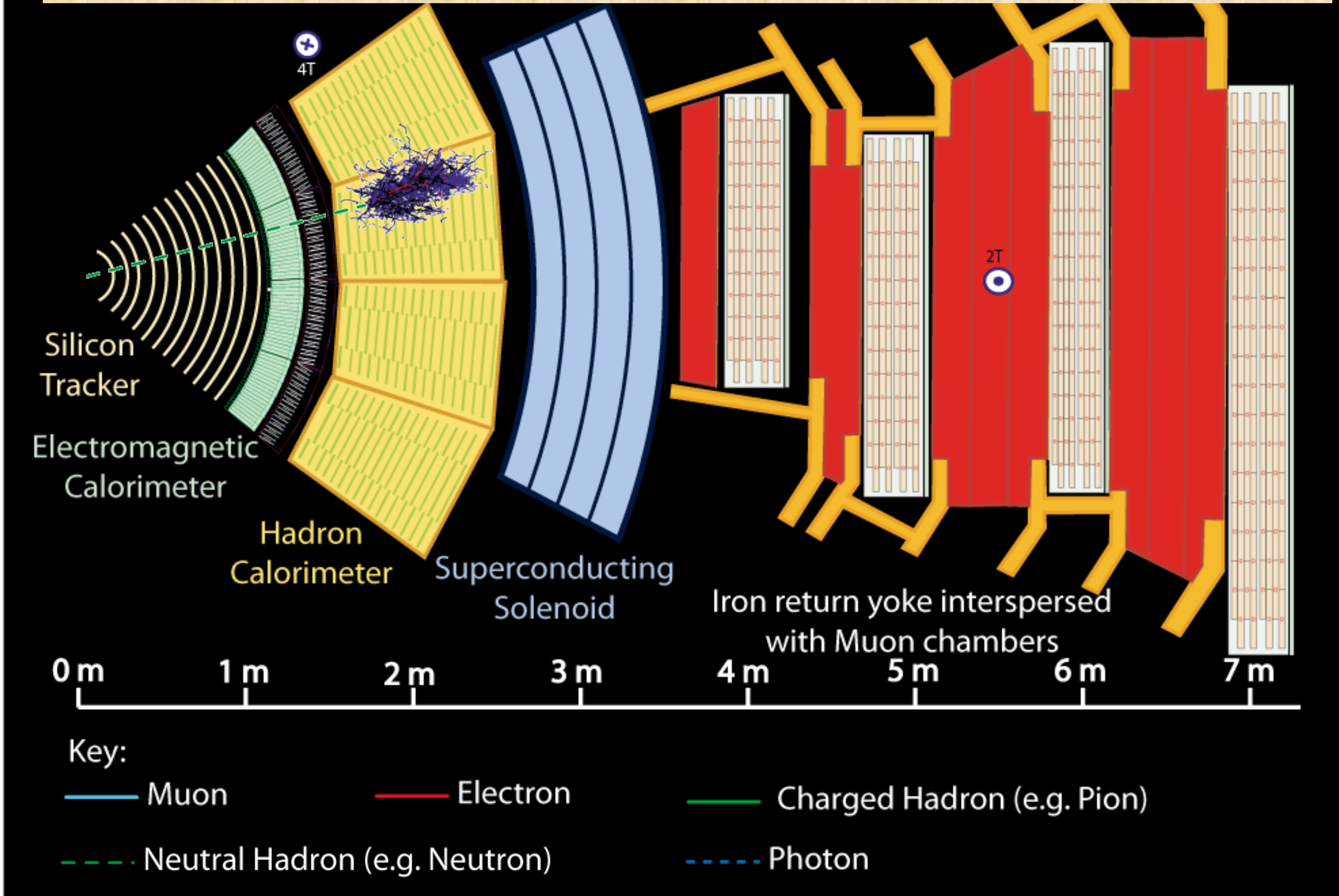
Detecting electron



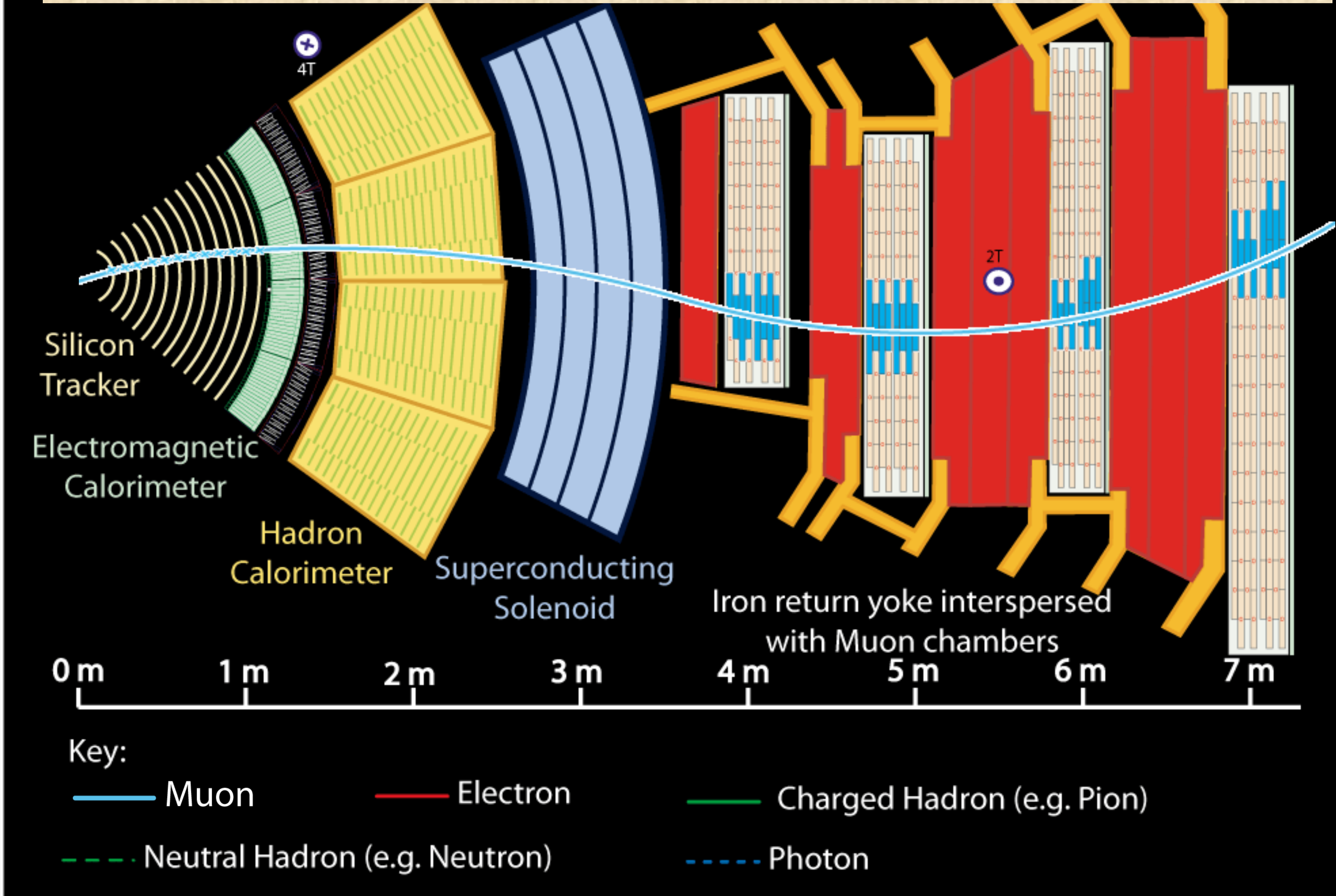
Detecting Charged Hadron



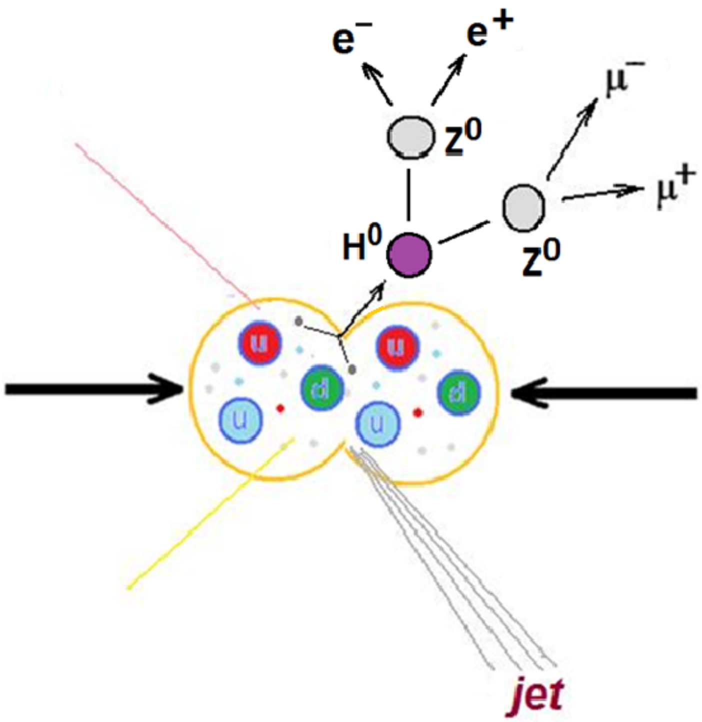
Detecting Neutral Hadron

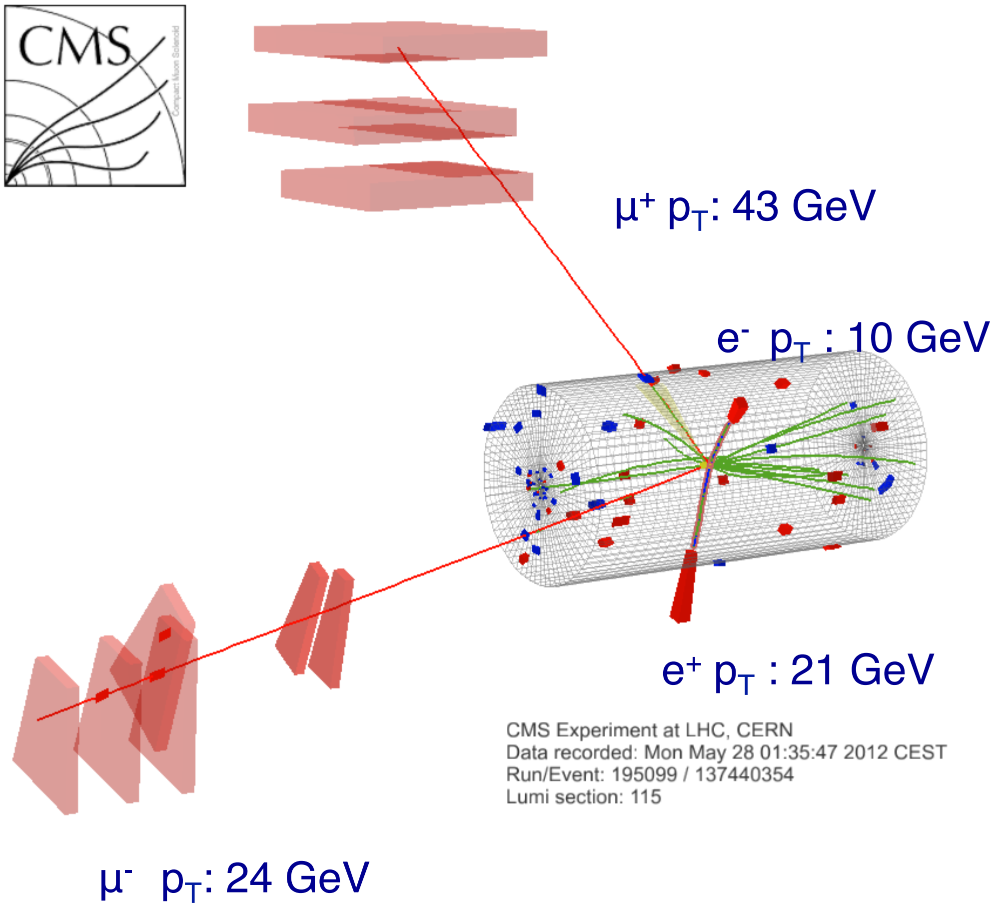


Detecting muon

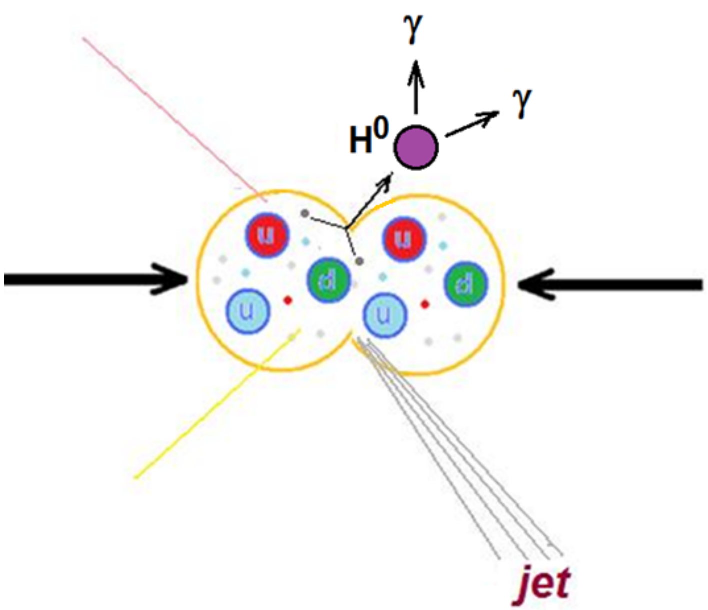


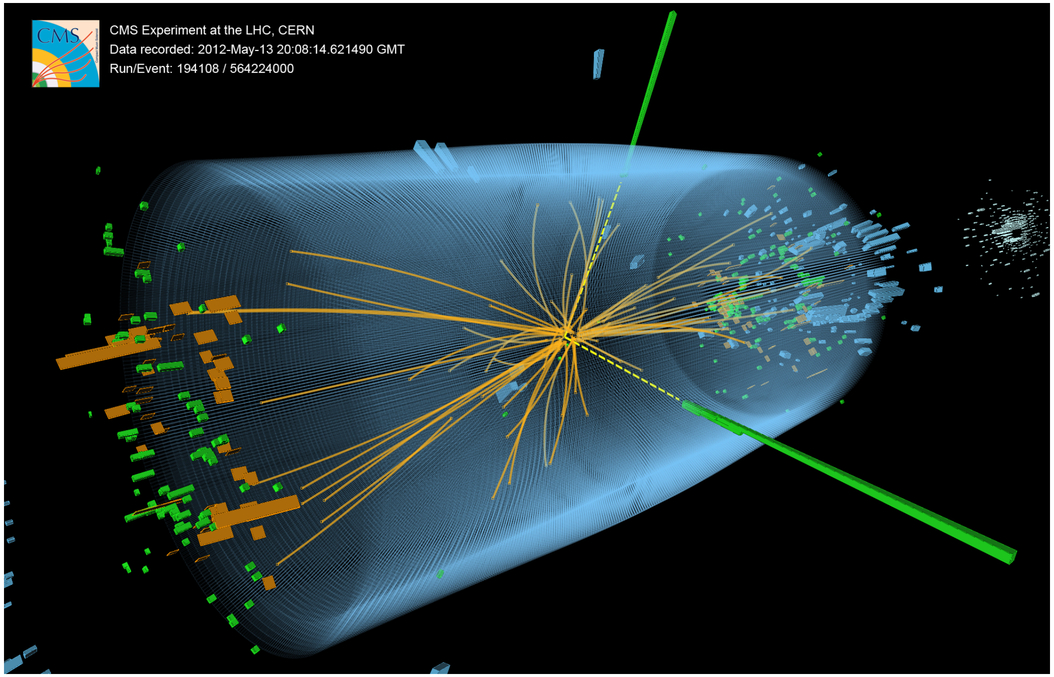
Observing Higgs decays $H \rightarrow ZZ \rightarrow 4\ell$





Observing Higgs decays: $H \to \gamma\gamma$



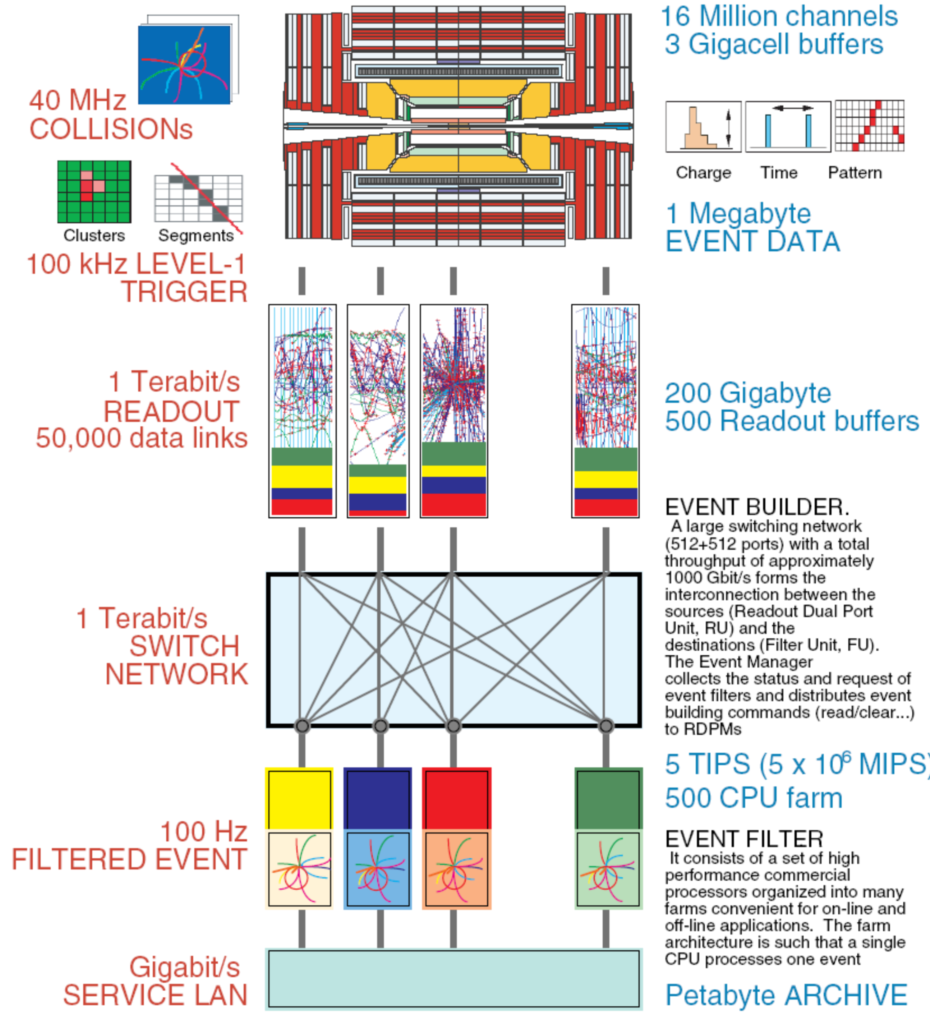


Storing data from collisions

During one second of CMS running, a data volume equivalent to 10,000 Encyclopaedia Britannicas is recorded

The data rate handled by the CMS event builder (~500 Gbit/s) is equivalent to the amount of data currently exchanged by the world's Telecom networks

The total number of processors in the CMS event filter equals the 4000 workstations at CERN today

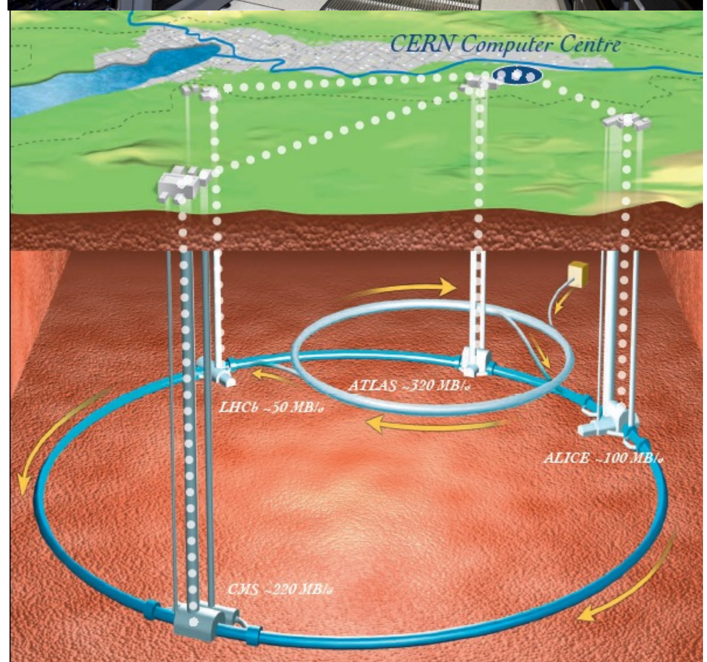


Storing data from collisions

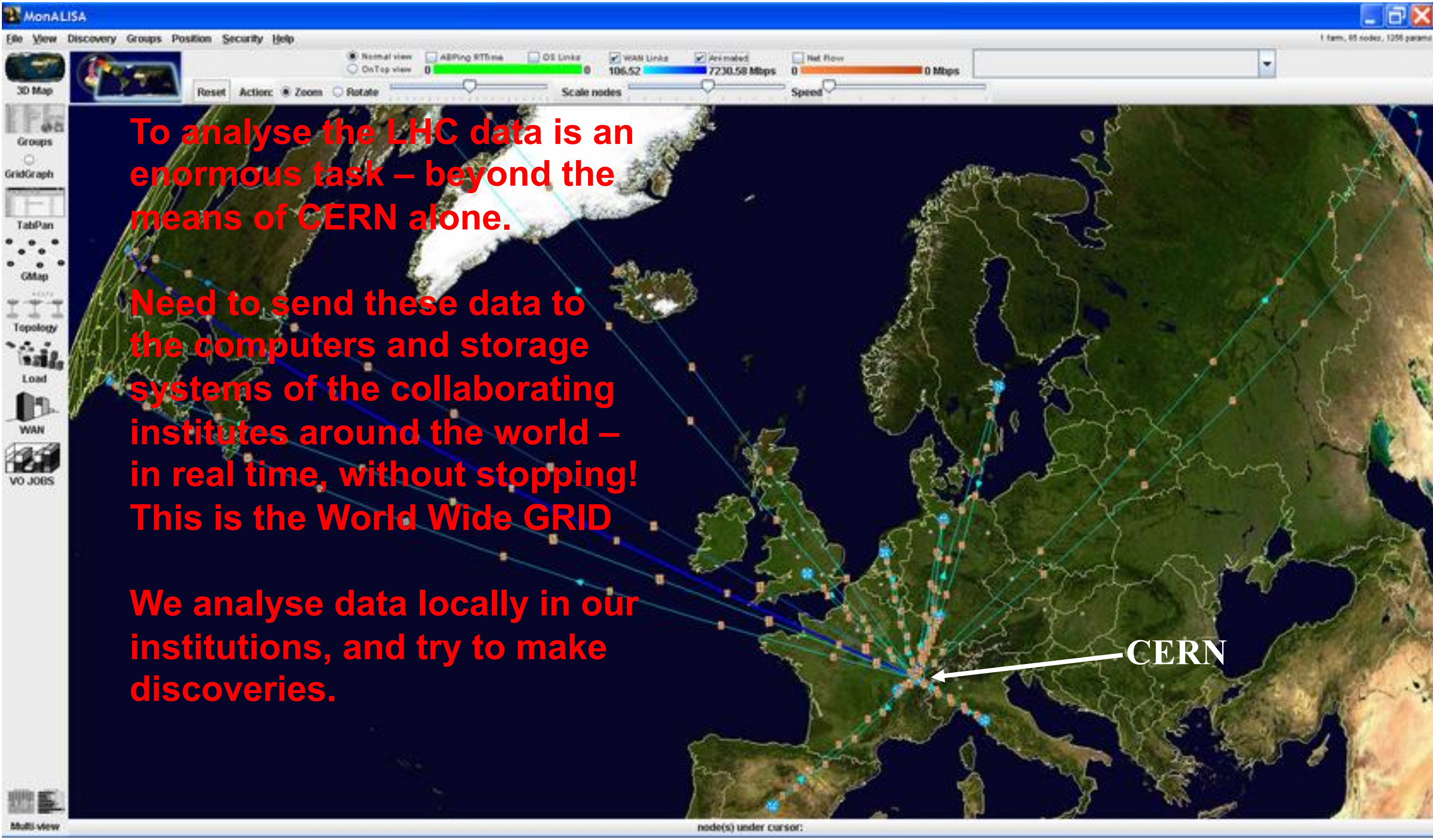
All 4 experiments at the LHC send their data continuously to the CERN computer centre for storage and processing

The data are shipped from the experimental underground caverns to computers on the surface

From the surface, the data are sent overland by high speed links to the CERN computer centre



Analyzing data from LHC collisions



To analyse the LHC data is an enormous task – beyond the means of CERN alone.

Need to send these data to the computers and storage systems of the collaborating institutes around the world – in real time, without stopping! This is the World Wide GRID

We analyse data locally in our institutions, and try to make discoveries.

Open questions of High Energy Physics

This is the dawn of an exciting age of new discoveries at LHC. The theoretical framework of the fundamental nature of matter, the Standard Model, explains much, but much remains unclear:

- **What is dark matter?**
- **What happened to antimatter?**
- **Are there extra dimensions of spacetime?**
- **Are there new symmetries of Nature?**
- **Are there new, as yet unobserved forces?**
- **What are neutrinos telling us?**
- **What is dark energy?**
- **How did the universe come to be?**
- **Why are there so many kinds of particles?**
- **New principles, new physical laws?**

Backups

Collisions at LHC

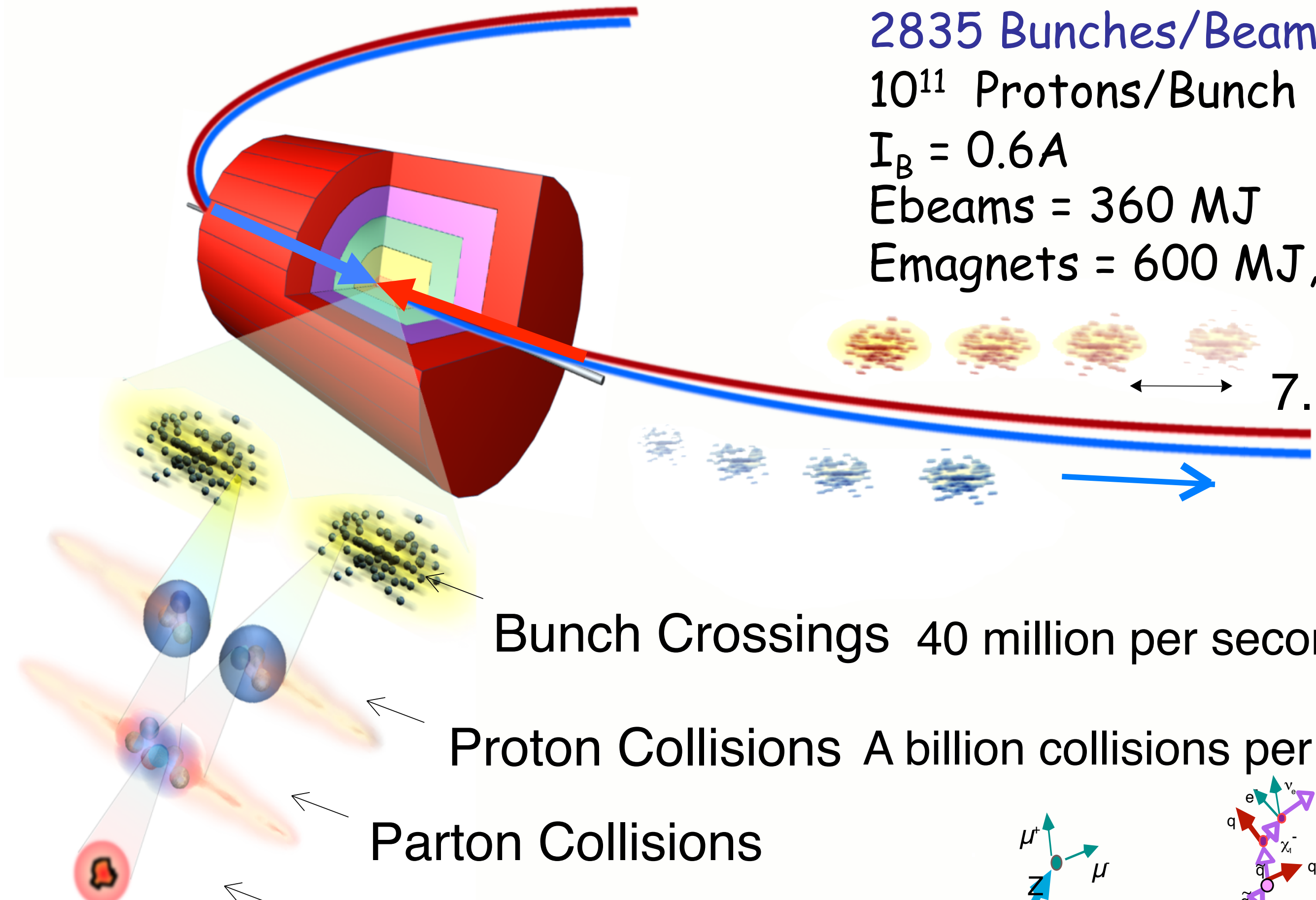
2835 Bunches/Beam

10^{11} Protons/Bunch

I_B = 0.6A

Ebeams = 360 MJ

Emagnets = 600 MJ, Total 1 GJ !!



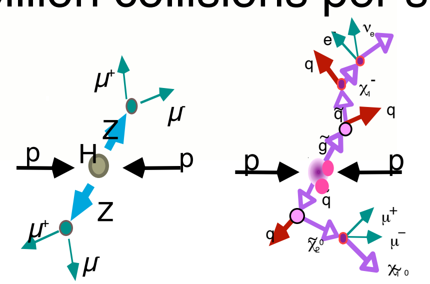
7.5 m (25 ns)

Bunch Crossings 40 million per second

Proton Collisions A billion collisions per second

Parton Collisions

New Particle Production (Higgs, SUSY, ...)



One new particle 'perhaps' each hour ??

High Energy Physics: Technology Transfers

- **The World Wide Web**

1990:Tim Berners-Lee, a CERN computer scientist invented the World Wide Web.

The "Web" as it is affectionately called, was originally conceived and developed for the large high-energy physics collaborations which have a demand for instantaneous information sharing between physicists working in different universities and institutes all over the world. Now it has millions of academic and commercial users.

- **Sound Reproduction**
- **Grid Computing**
- **X-Ray Detector**
- **Ultrasound Gas Analysis**
- **Emergency Personnel Location**
- **Industrial Image Processing**