



# CMS (Compact Muon Solenoid) Introduction

CMS  
(Cessy)

LHCb  
(Ferney)

ATLAS  
(Meyrin)

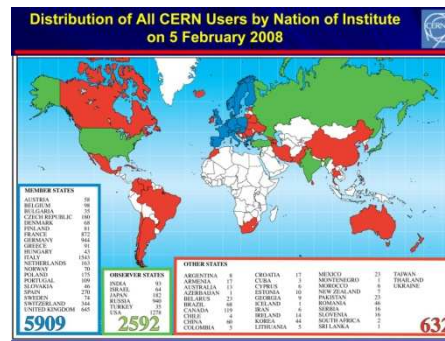
ALICE  
(St. Genis)

SangEun Lee  
Kyungpook National University



# CERN (Conseil Européen pour la Recherche Nucléaire (European Council for Nuclear Research))

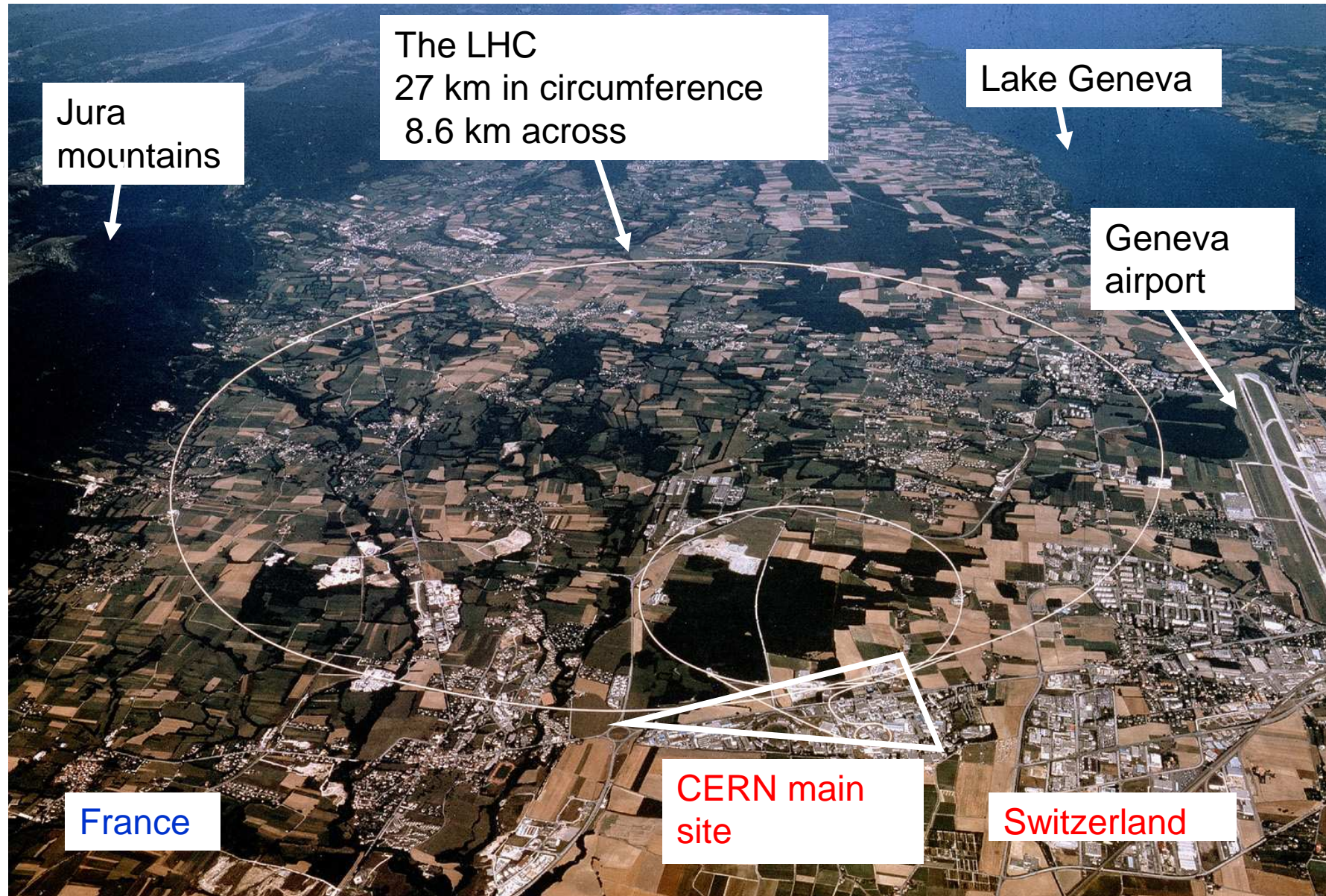
- Now called the European Organization for Nuclear Research - the world's largest particle physics center
- 1949 proposal by Louis de Broglie
- Founded in 1954
- The world's most powerful particle accelerator
- 27 kilometres around, 100 metres underground
- 20 member countries 39 observer and non-member states, 9133 registered users
- More than 9,000 scientists
- Over 100 nationalities







# The Large Hadron Collider (LHC)







# CMS Timeline I

- **1998: An archaeological find: whilst excavating the site engineers unearthed a Roman villa.**
- **1999: Construction of the CMS surface buildings and shafts at Cessy, France.**
- **2000: Digging the shaft whilst CMS assembly begins above ground**
- **2001: Constructing the endcaps**





## CMS Timeline II

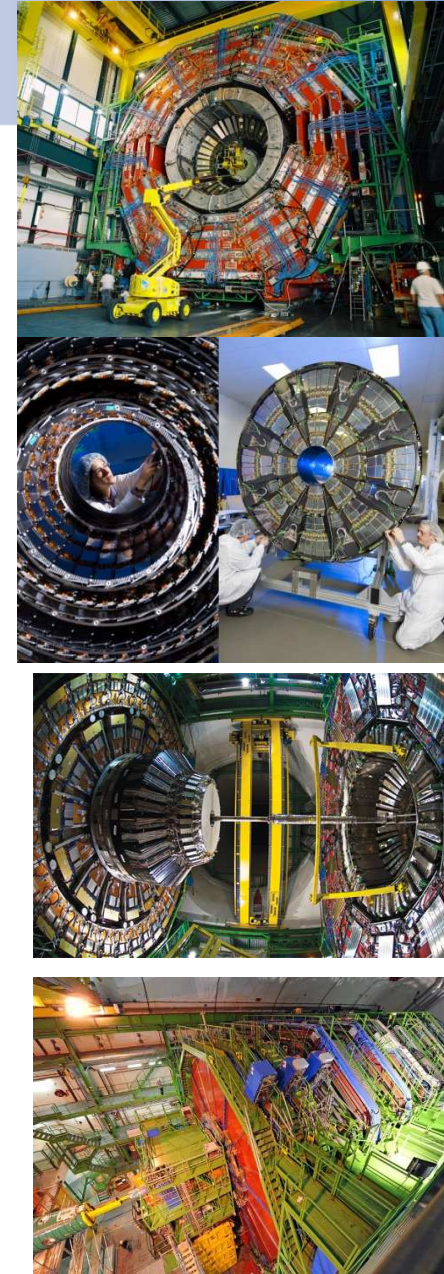
- **2002: Iron yoke rings and the vacuum tank in the surface hall.**
- **2003: Excavation continues in the cavern, 100m underground**
- **2004: Once the last mounds of earth were cleared away, the cavern was finally inaugurated.**
- **2005: Insertion of the inner vacuum tank.**





## CMS Time Line III

- **2006: Preparation for the magnet test cosmic challenge on the surface.**
- **2007: Preparing the barrel and endcap tracker sections offsite.**
- **2008: The installation of the beam pipe.**
- **2009: Total view of the experiment.**

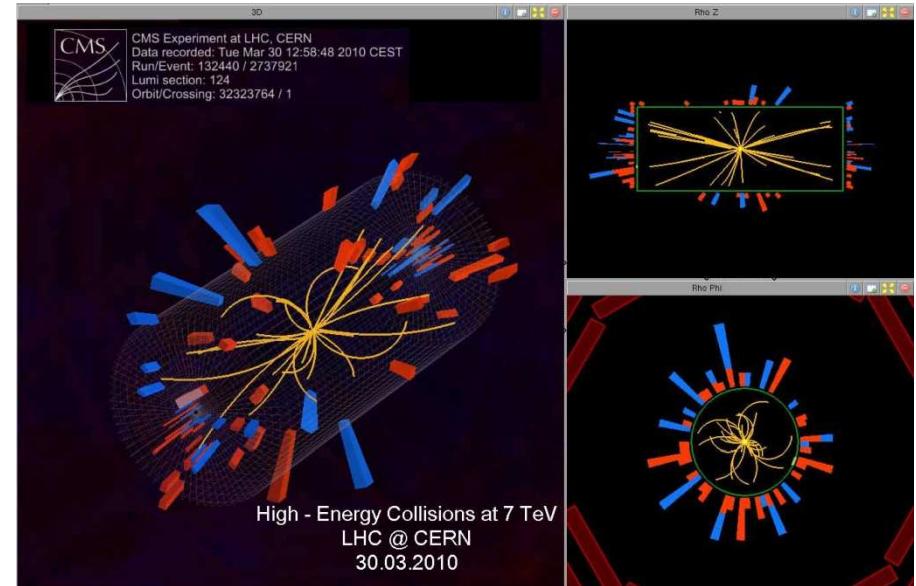






# CMS Time Line IV

- **2010: First 7 TeV proton-proton collisions in CMS on 30th March 2010.**





# 1 TeV Energy

The power of the LHC accelerator is enormous.

Imagine using a car battery of 12V to accelerate a proton. The proton would gain a kinetic energy of

$$E = q \cdot \Delta V = 1 \cdot 12 = 12 \text{ eV}$$

We now need some Greek to put the LHC in context:

$$1 \text{ keV} = 1000 \text{ eV}$$

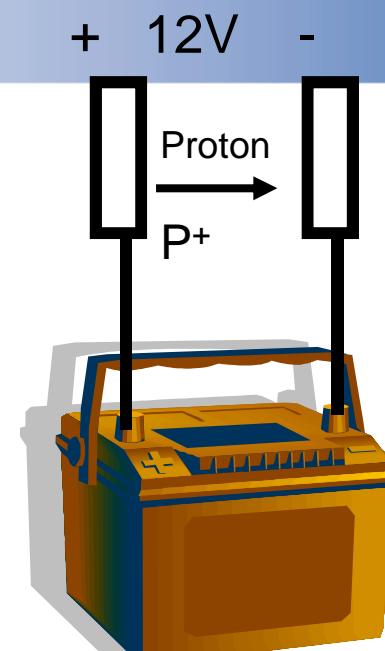
$$1 \text{ MeV} = 10^6 \text{ eV}$$

$$1 \text{ GeV} = 10^9 \text{ eV}$$

$$1 \text{ TeV} = 10^{12} \text{ eV} = 1 \text{ Trillion electron volts}$$

The LHC accelerates protons to 7 TeV

**You would need 1.17 Trillion car batteries to compete!**



1 TeV is about the energy of motion of a flying mosquito.

What makes the LHC so extraordinary is that it squeezes energy into a space about a million million times smaller than a mosquito





# Mass and Energy

And now for a bit of Einstein:

$$E = m c^2$$

If the energy available to make new particles at the accelerator is

$$E = 1 \text{ eV}$$

we can create particles up to a mass of

$$1 \text{ eV}/c^2$$

Electron mass

$$m_e = 0.511 \text{ MeV}/c^2$$

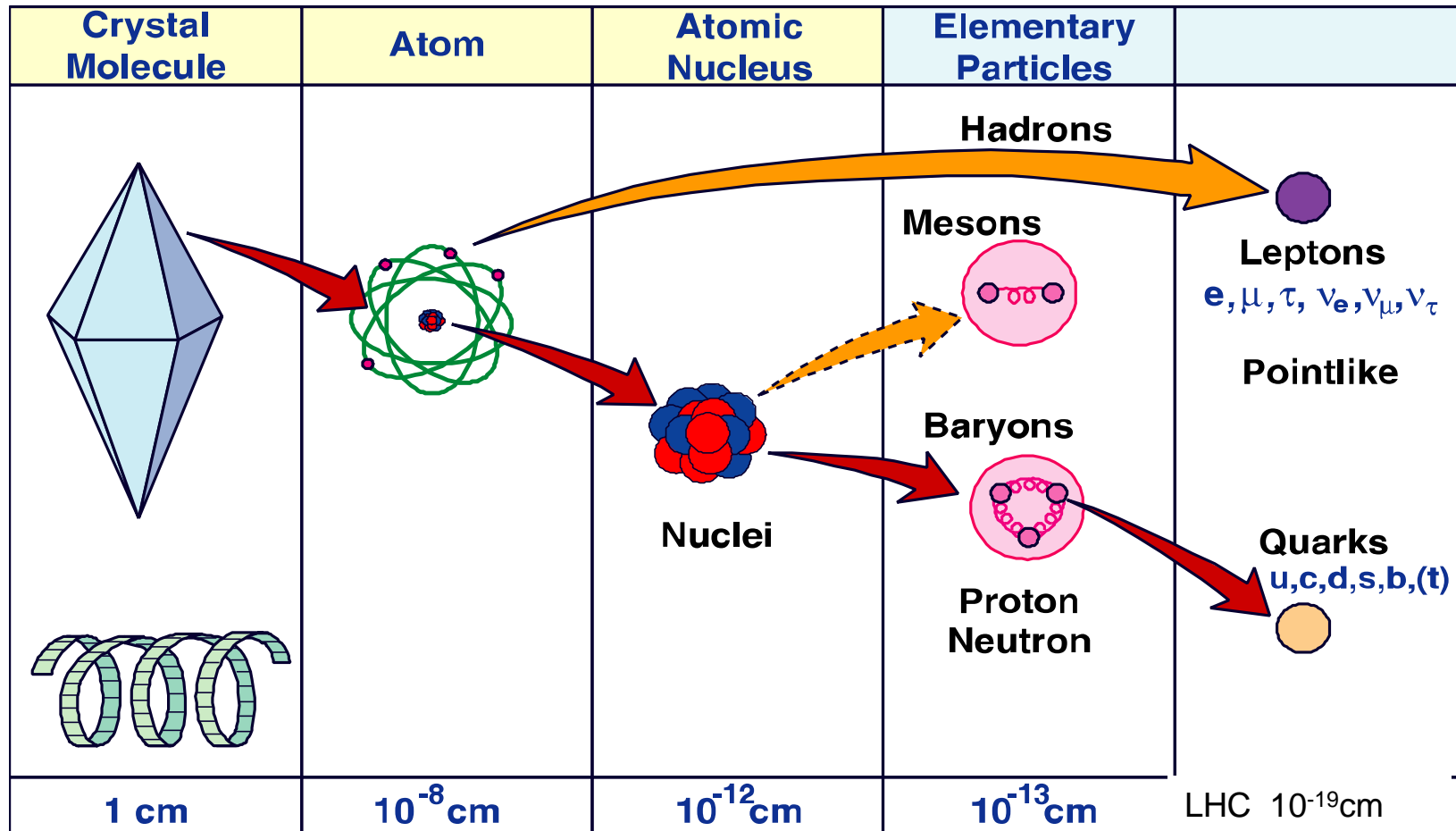
Proton mass

$$m_p = 938 \text{ MeV}/c^2 \sim 1 \text{ GeV}/c^2$$



# A quantum of physics – why the LHC?

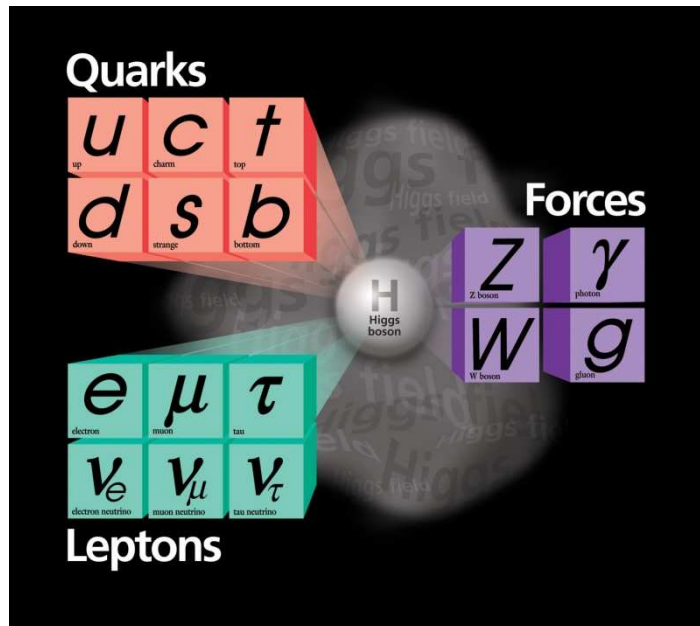
- The 'Standard model' of particle physics has been brilliantly successful but important questions remain







# SM (Standard Model)



The ‘Standard model’ describes

how particles interact  
how different particles behave  
how the forces between particles are manifested

However, the model **cannot** be used to calculate or predict the **Masses of ANY** of the fundamental particles –

not of the electron  
not of the muon  
not of the quarks  
not of the Z and W particles  
and so on .....

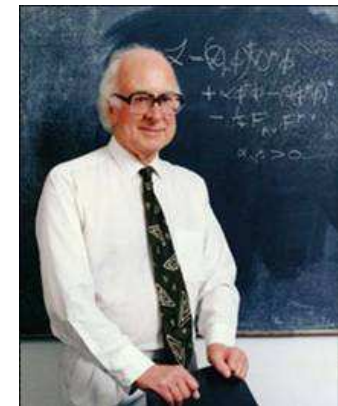
Could the so called “Higgs particle” be the answer?

- The Standard Model is a beautiful theory and
- arguably one that is most precisely tested



# Origin of mass - the Higgs mechanism

- Still Mystery
- Simplest theory – all particles are massless !!
- A field pervades the universe
- **One possibility: Higgs field**
- **Predicted in 1964**
- Particles interacting with this field acquire mass – the stronger the interaction the larger the mass
- The field is a quantum field – the quantum is the Higgs boson
- Finding the **Higgs boson** particle establishes the presence of the field

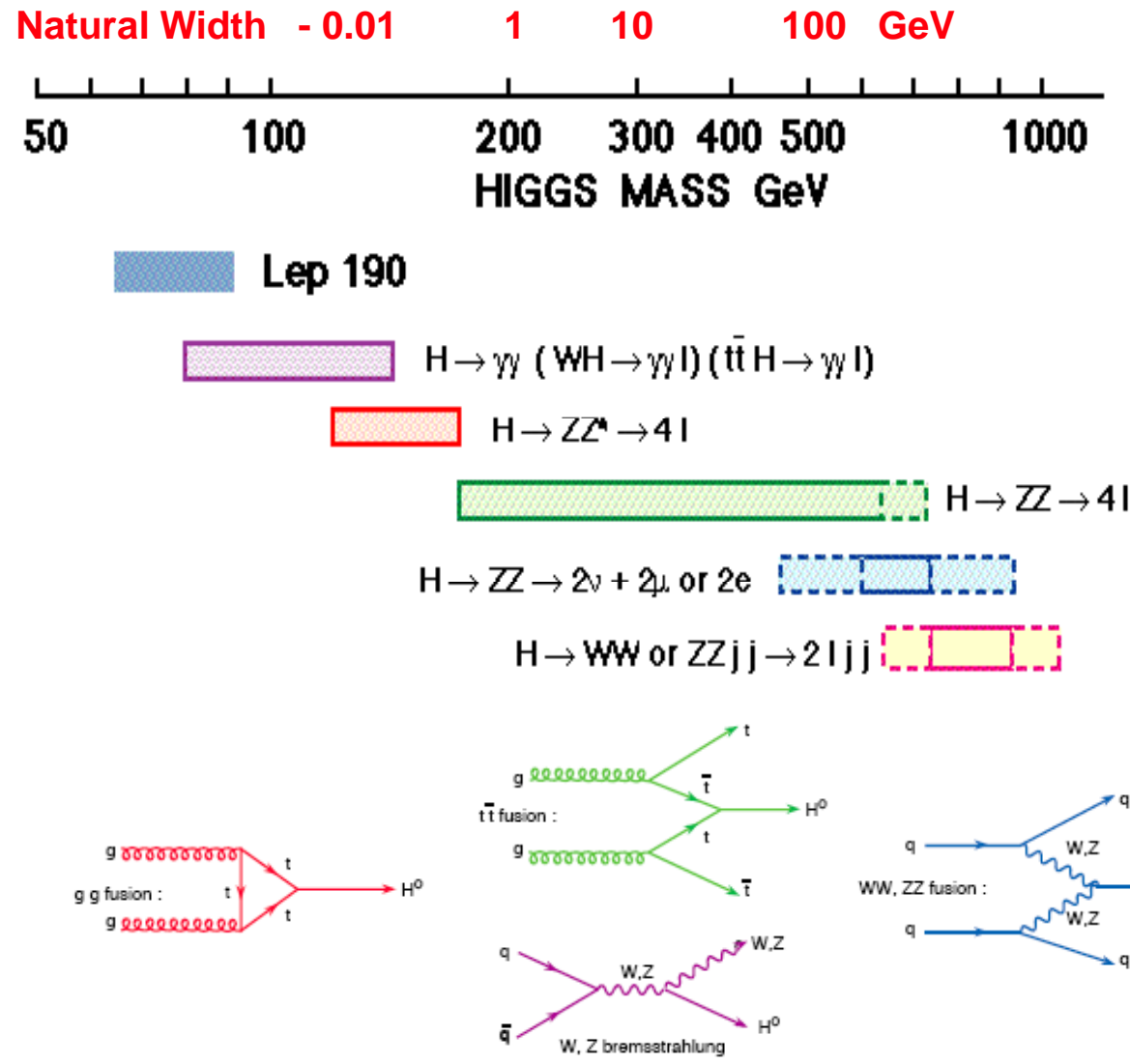






# The Benchmark Reaction: SM Higgs

At the LHC the SM Higgs provides a good benchmark to test the performance of a detector





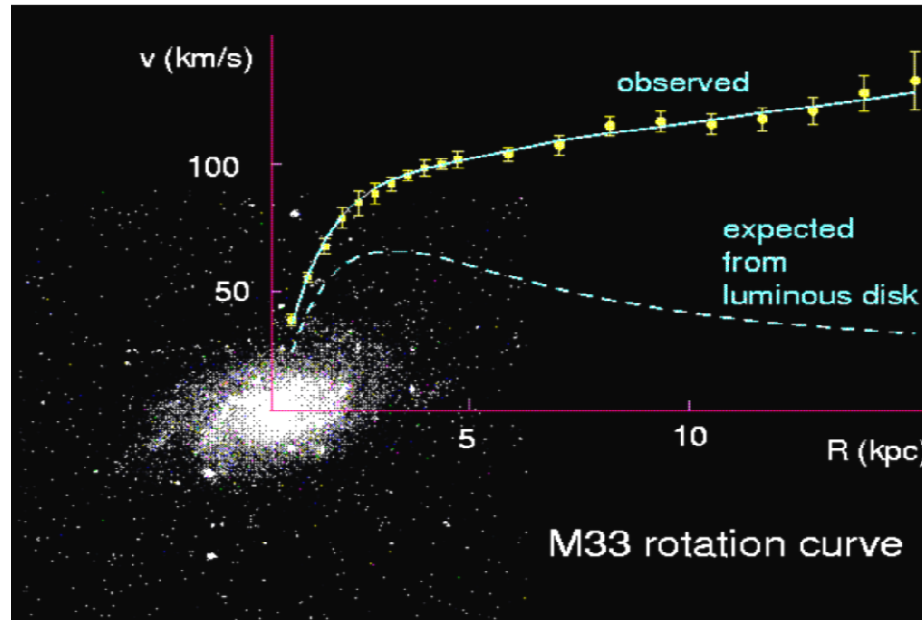
# Matter and Antimatter

- Did the big bang make equal amounts of matter and antimatter?
- If so, where is all the Antimatter?
- Why didn't it annihilate us?
- **Can the LHC find the answers ?**





# Dark matter



Dark  
(invisible)  
matter!

## Dark Matter?

Appears to be a weakly  
interacting massive particle  
**The LHC could be the ideal  
place to find it !**

- the constituents of dark matter are new particles, the CMS Experiment should discover them and elucidate the mystery of dark matter.

### ■ On earth



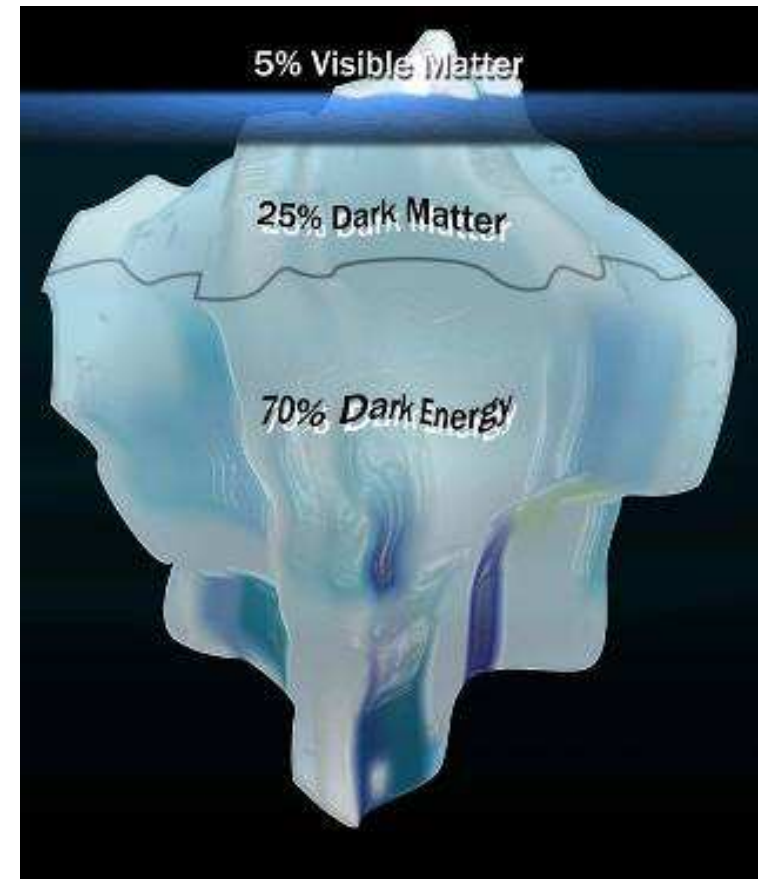
### ■ In Space





# Dark Matter

- Astronomy tells us:
- 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” 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





# Dark Energy

- Fills empty space
- Causes the universe to expand faster and faster
- Being studied on earth and in space
- Still a complete mystery

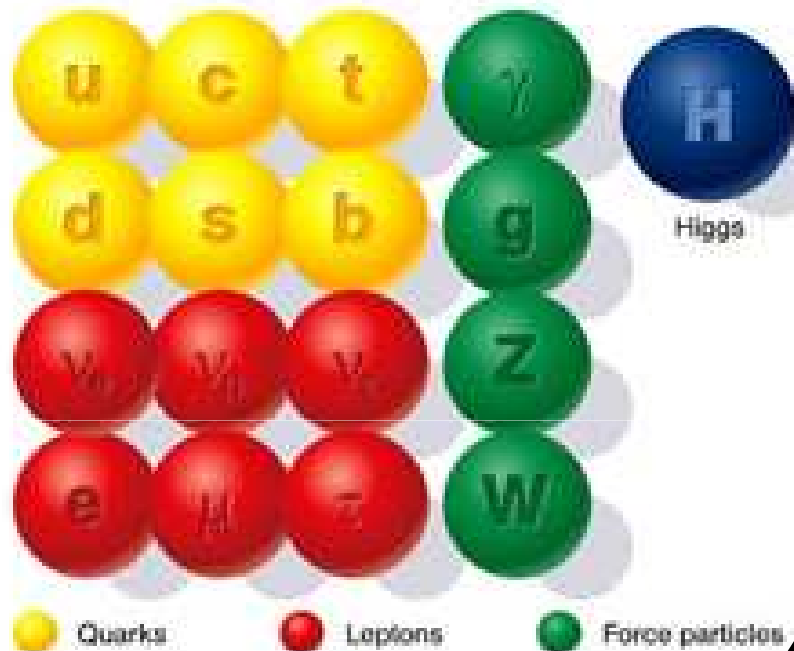






# SUSY (Super Symmetry)

## Standard particles

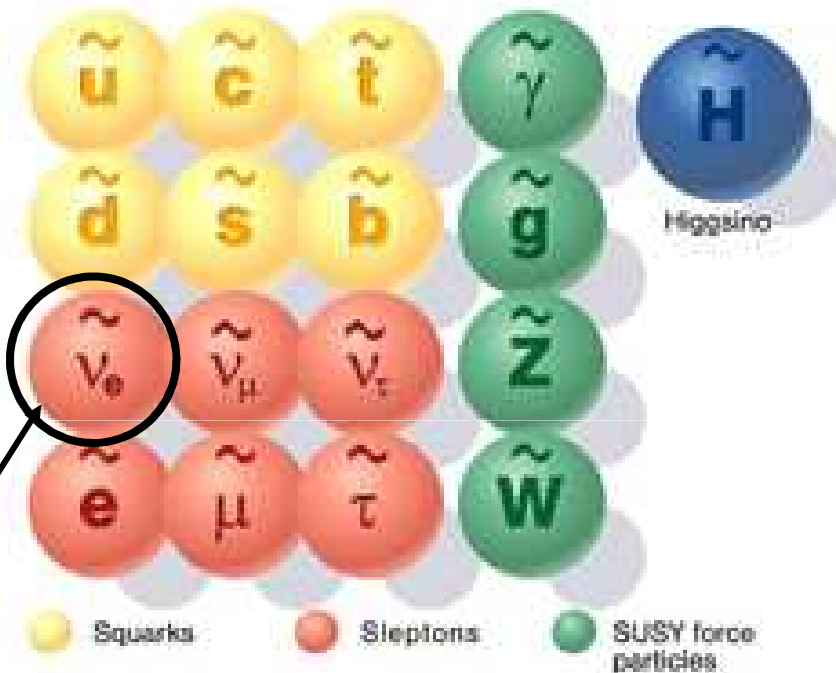


The 'Standard' particles which have been discovered

■ haha

Possible candidate for the dark matter particle

## SUSY particles

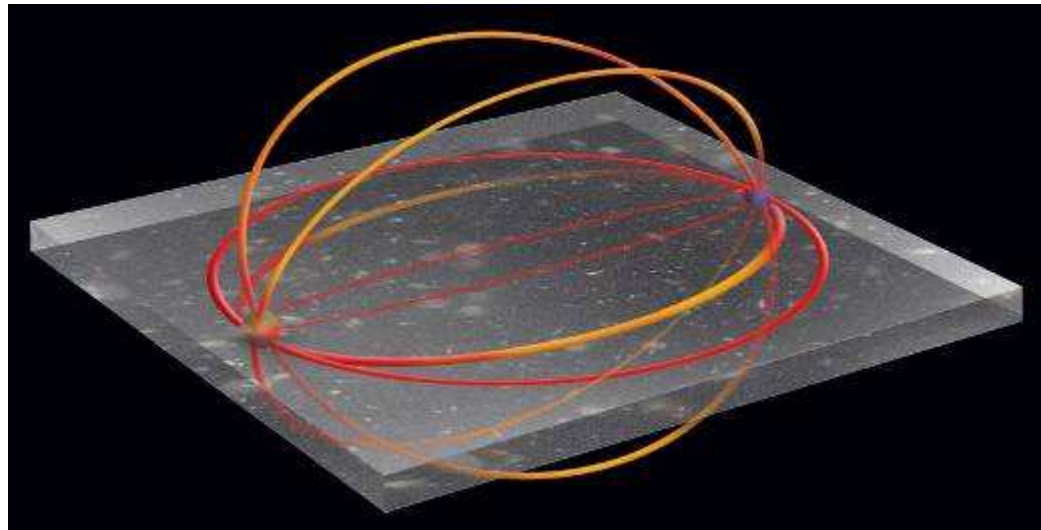


Could LHC be the first accelerator to discover a corresponding world of 'Supersymmetric' particles?



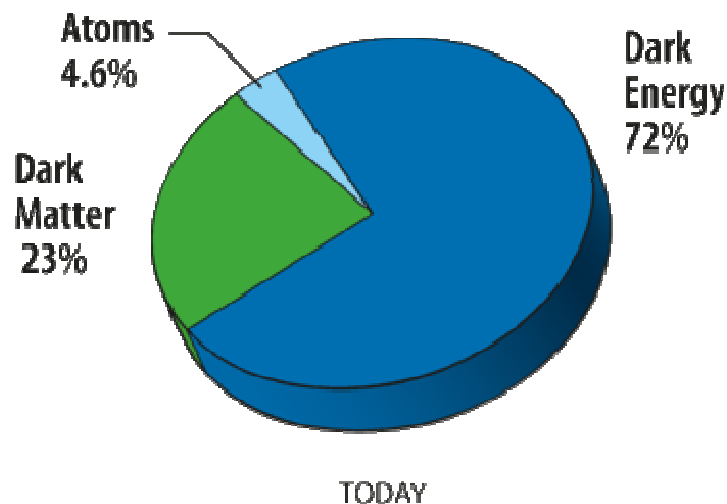
# THE MYSTERY OF GRAVITY

- We feel gravity through planets but the electromagnetic force with even tiny magnets – why is gravity weaker than other forces?
- Maybe gravity sees all dimensions and its force is spread out and weakened





# Physics Issues



The calculated makeup of the Universe  
We only understand 4.6% of it  
after 100s of years of trying !!

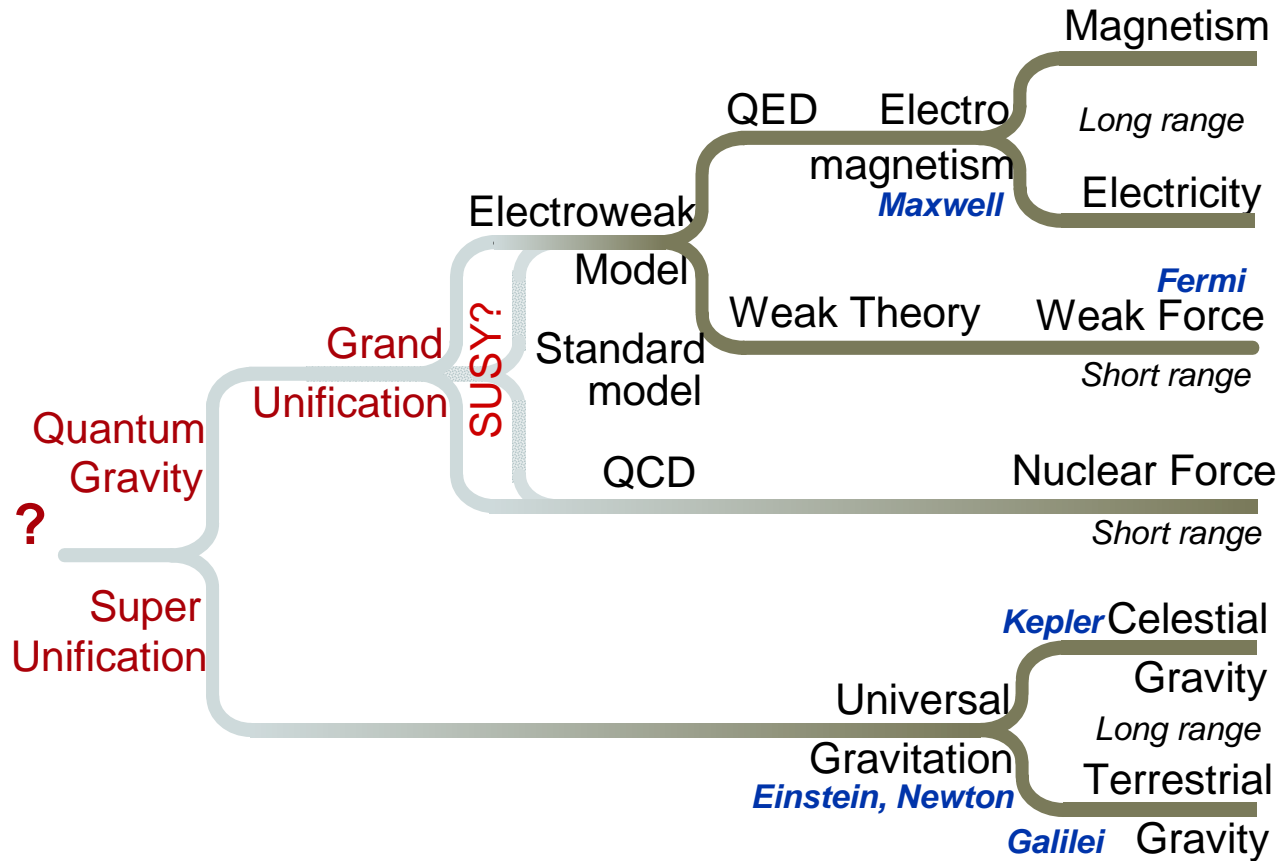
Don't know what Dark Matter is  
Don't know what Dark Energy is  
but SOMETHING is accelerating  
the expansion of our Universe

Supersymmetry ?  
The 'Neutralino' particle at the LHC ?  
A new force field particle, like the Higgs,  
at the LHC ?





# Unification of fundamental forces



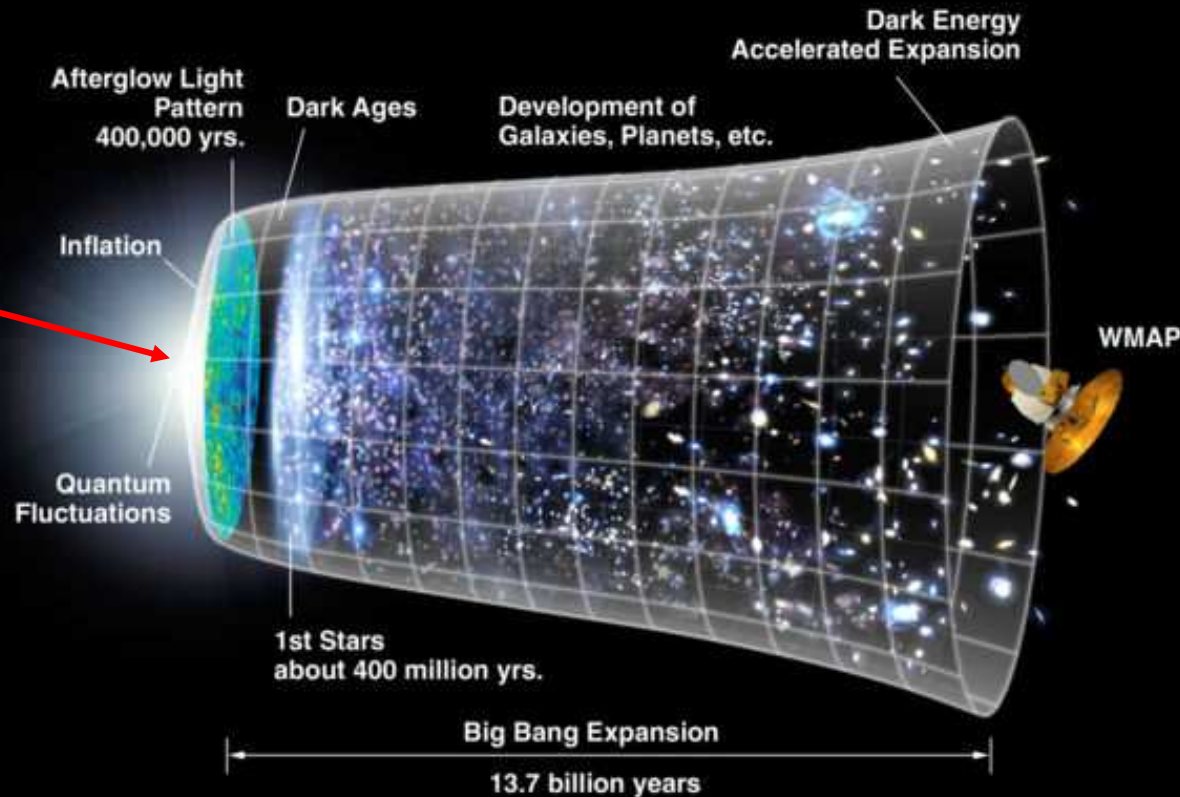
Theories:		
STRINGS?	RELATIVISTIC/QUANTUM	CLASSICAL



# Understanding for the History of Universe

The LHC will recreate the conditions prevailing in the first moments of the Universe after the Big Bang

LHC  
 $\sim 10^{-10}$   
seconds  
after the  
Big Bang



At the LHC the particles will be at an equivalent temperature of  $10^{16}$  K  
= 10 thousand, million, million degrees = hot !!

The sun is only 16 million degrees at its core  
( and only a piddly 6000 degrees on its surface )

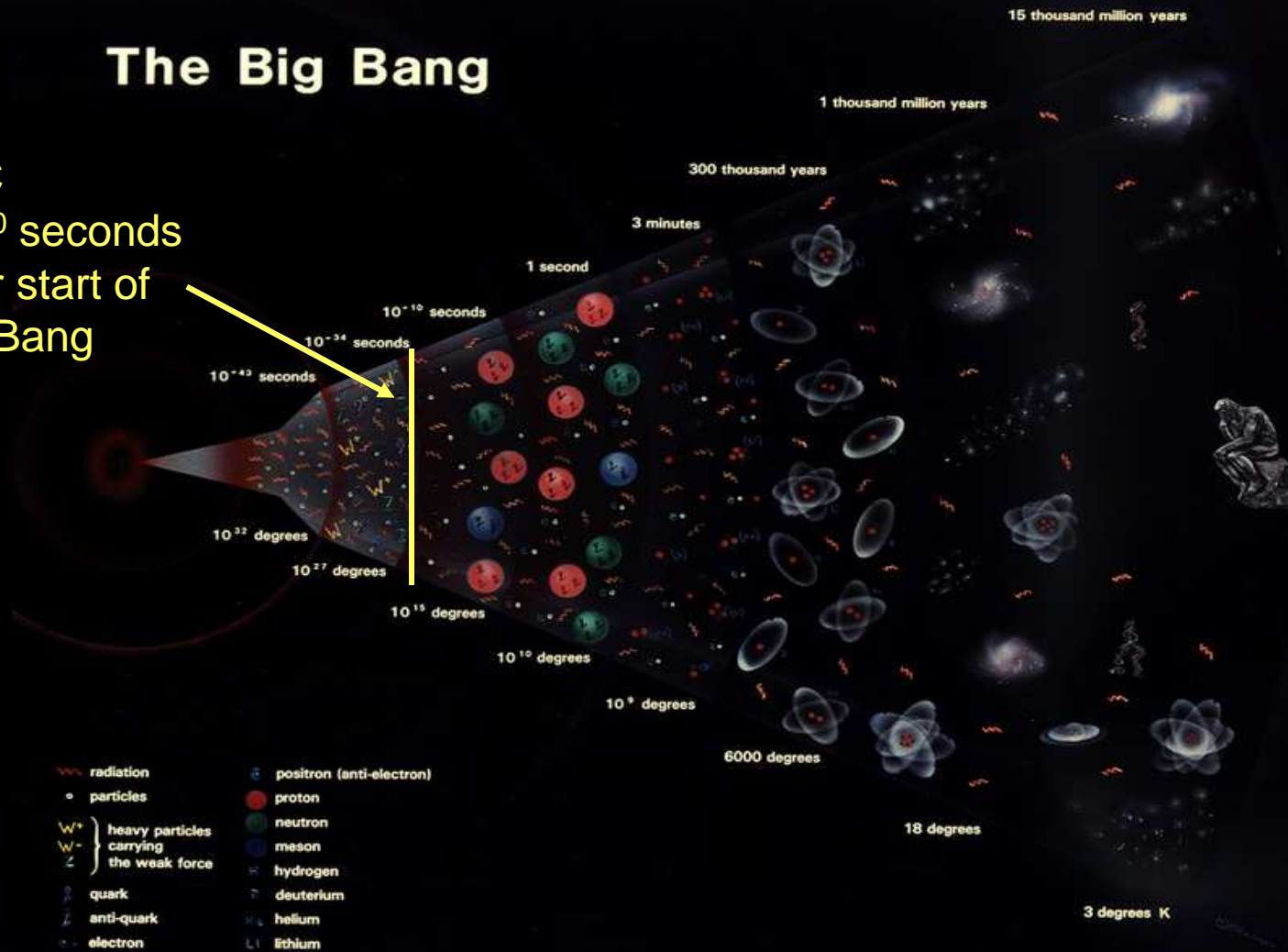
NASA/WMAP Science Team



# Back up 1

LHC  
 $10^{-10}$  seconds  
after start of  
Big Bang

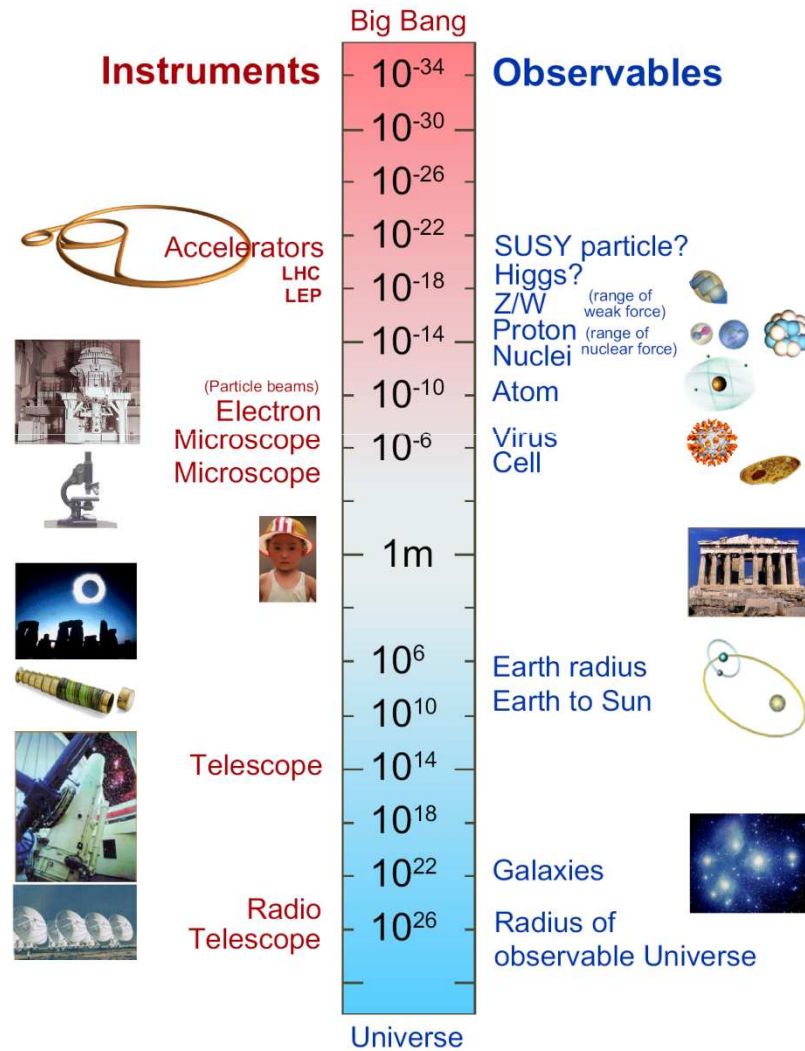
## The Big Bang





# Evolution after the big bang

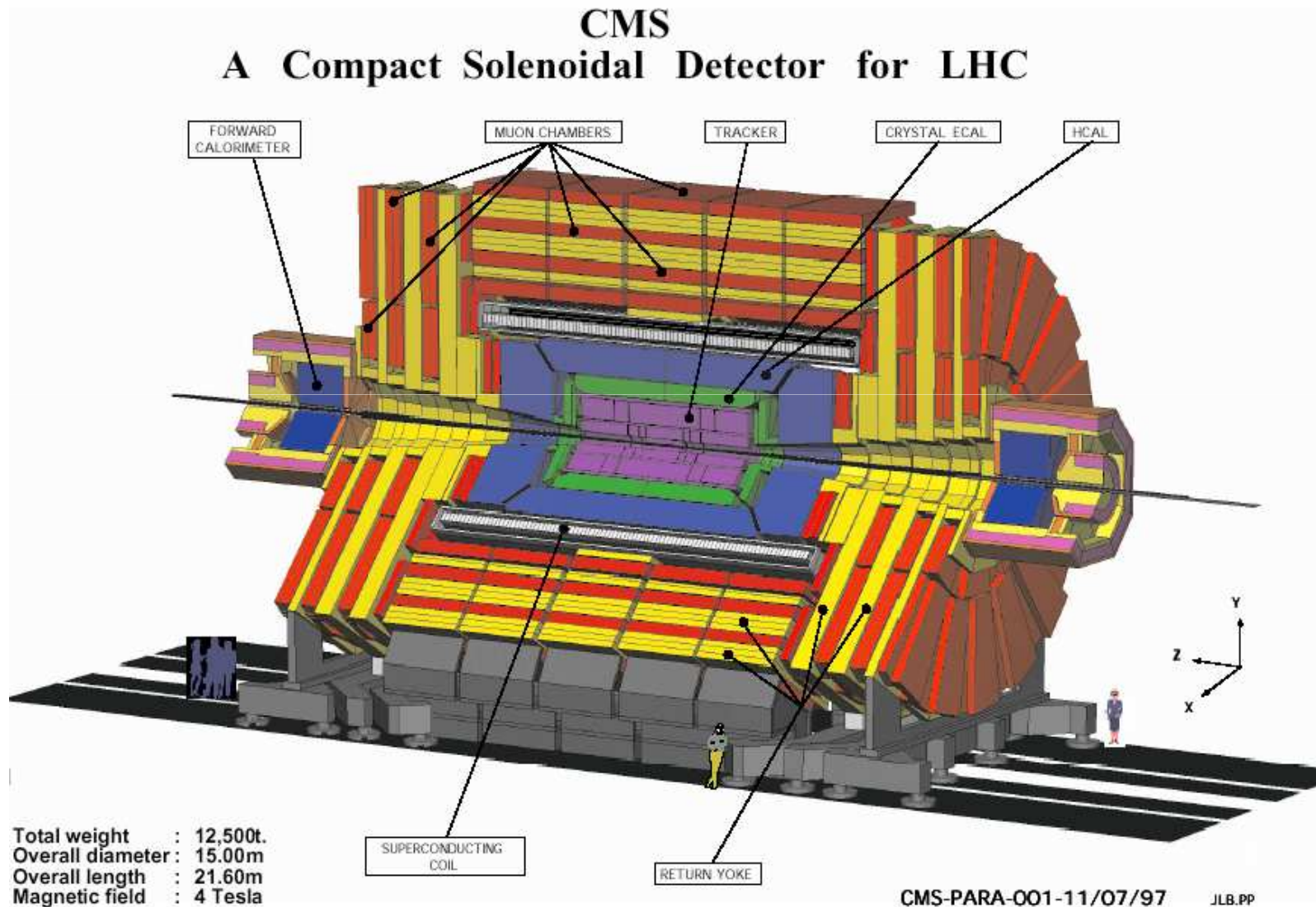
## The size of things







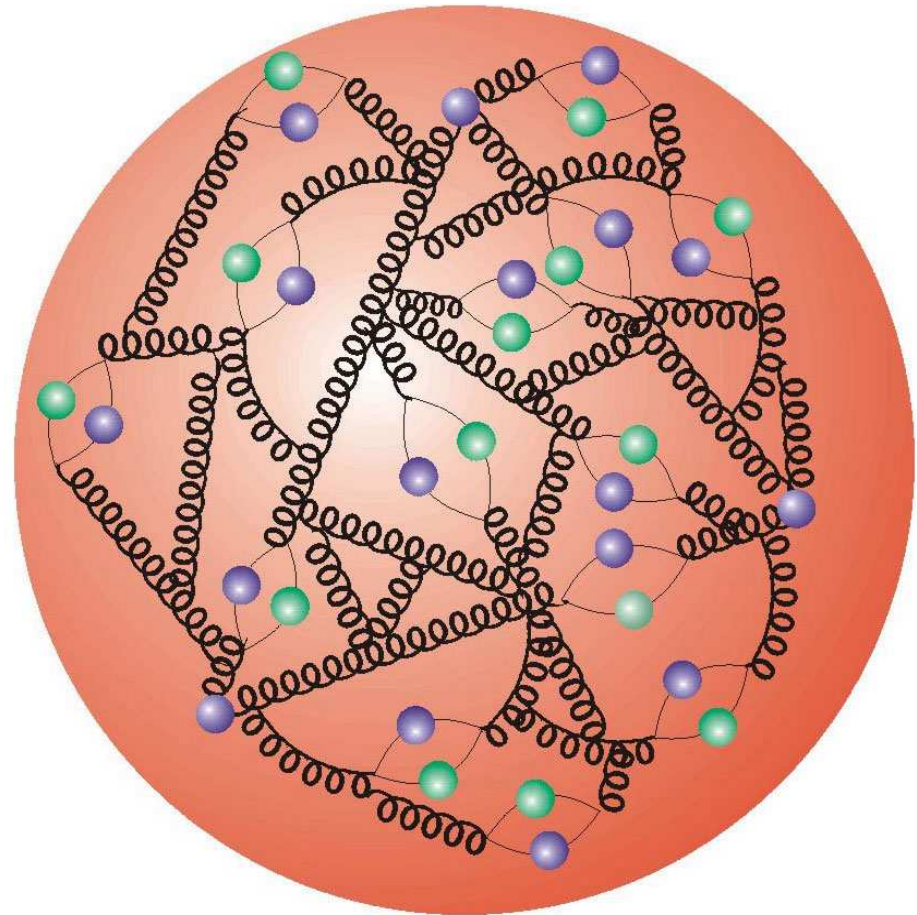
# The CMS Detector



# Proton

A proton is not, in fact, simply made from three quarks (uud)

There are actually 3 "valence" quarks (uud) + a "sea" of gluons and short-lived quark-antiquark pairs





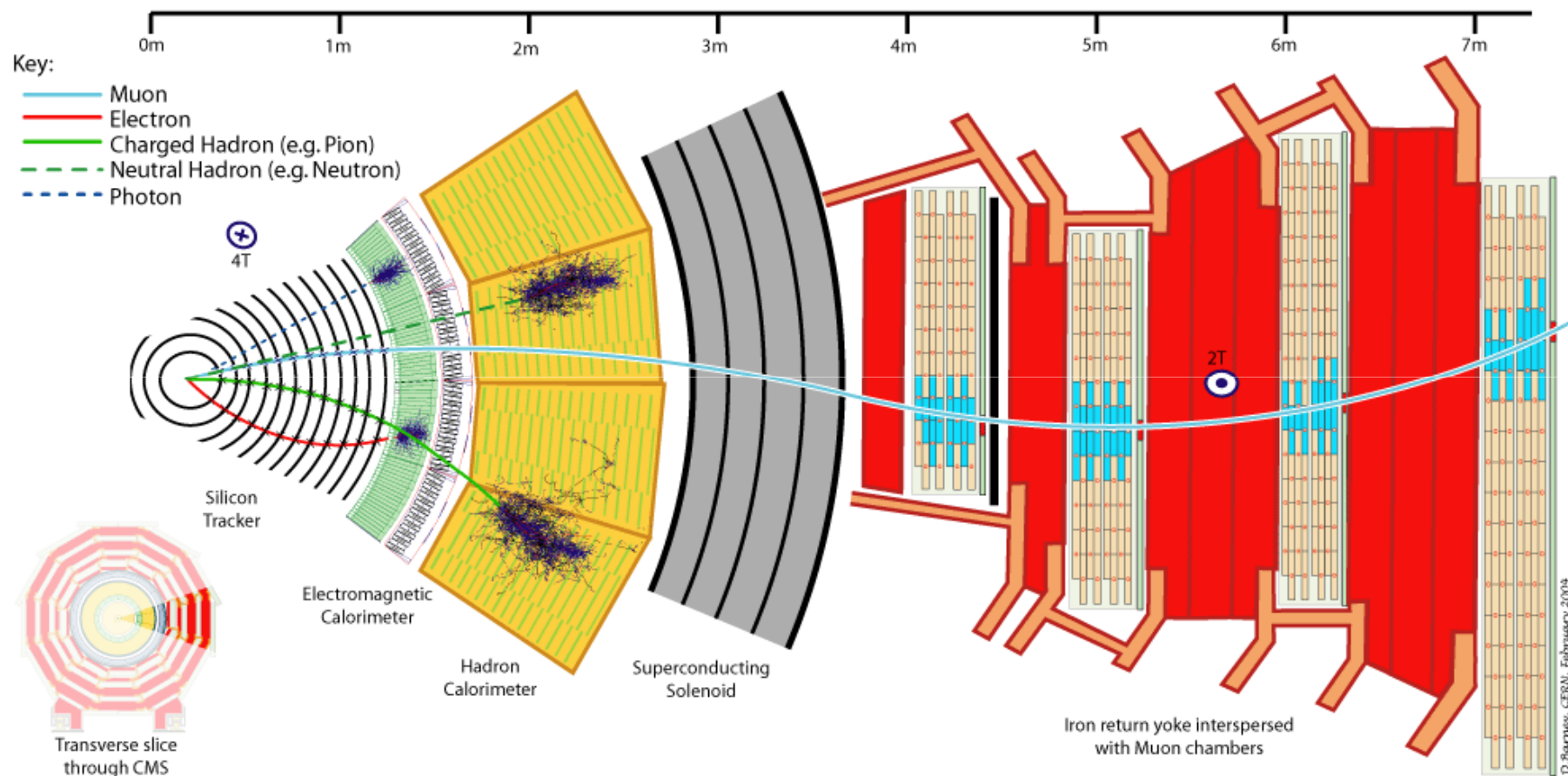
# CMS Characteristics

- Very **good muon identification** and momentum measurement
- Trigger efficiently and measure sign of TeV muons  $dp/p < 10\%$
- High energy resolution **electromagnetic calorimetry**
- $\sim 0.5\%$  @  $E_T \sim 50$  GeV
- Powerful inner **tracking systems**
- Momentum resolution a factor 10 better than at LEP
- Hermetic calorimetry
- Good missing  $E_T$  resolution



# Particle interaction at CMS

■ hahaha

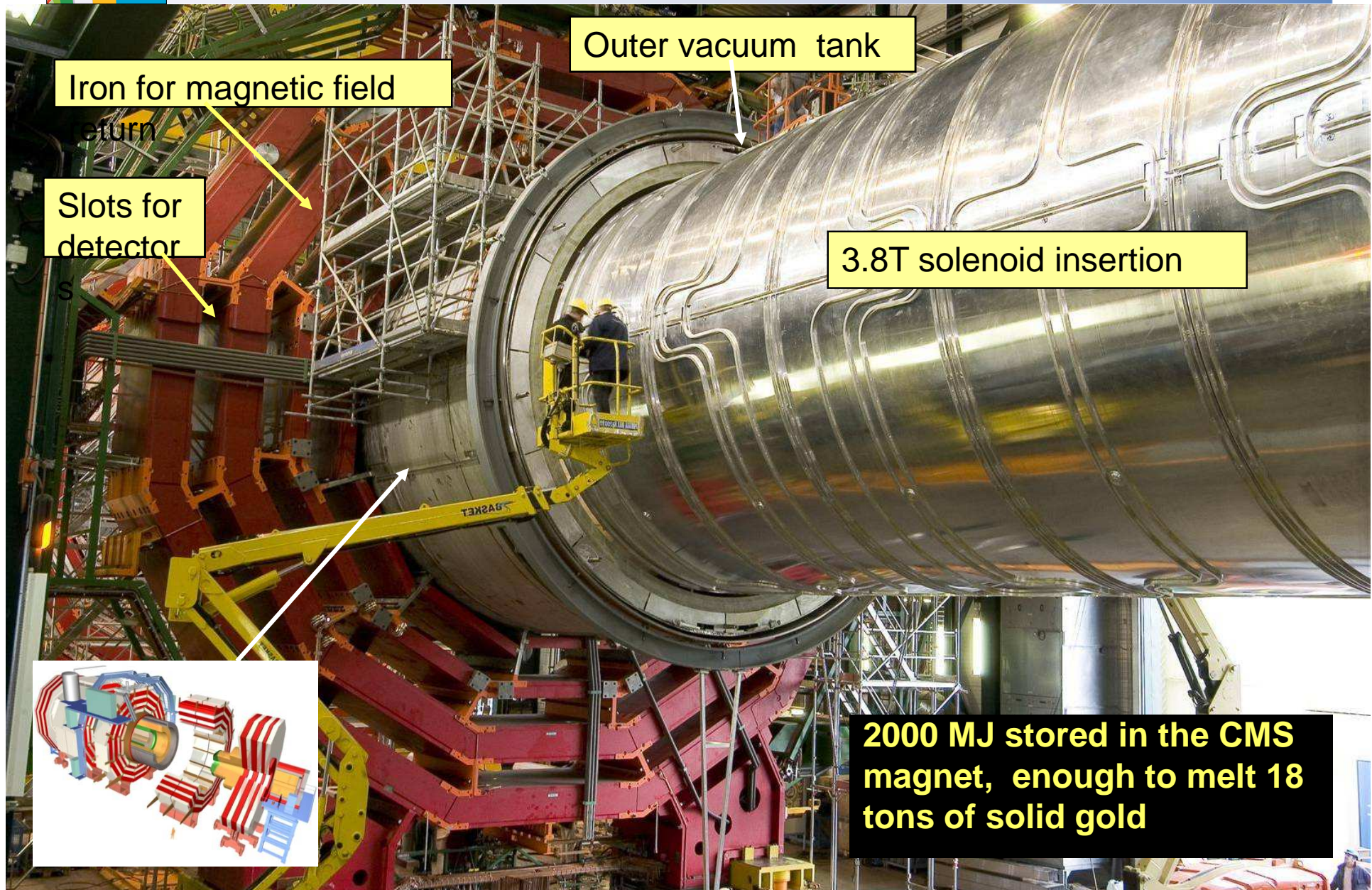


Electrons Photons	Pions Protons Neutrons	3.8T Solenoid	Iron return Muons
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# CMS detector



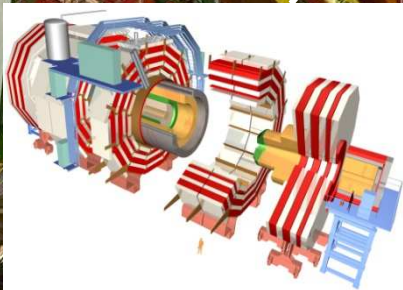
Outer vacuum tank

Iron for magnetic field

return

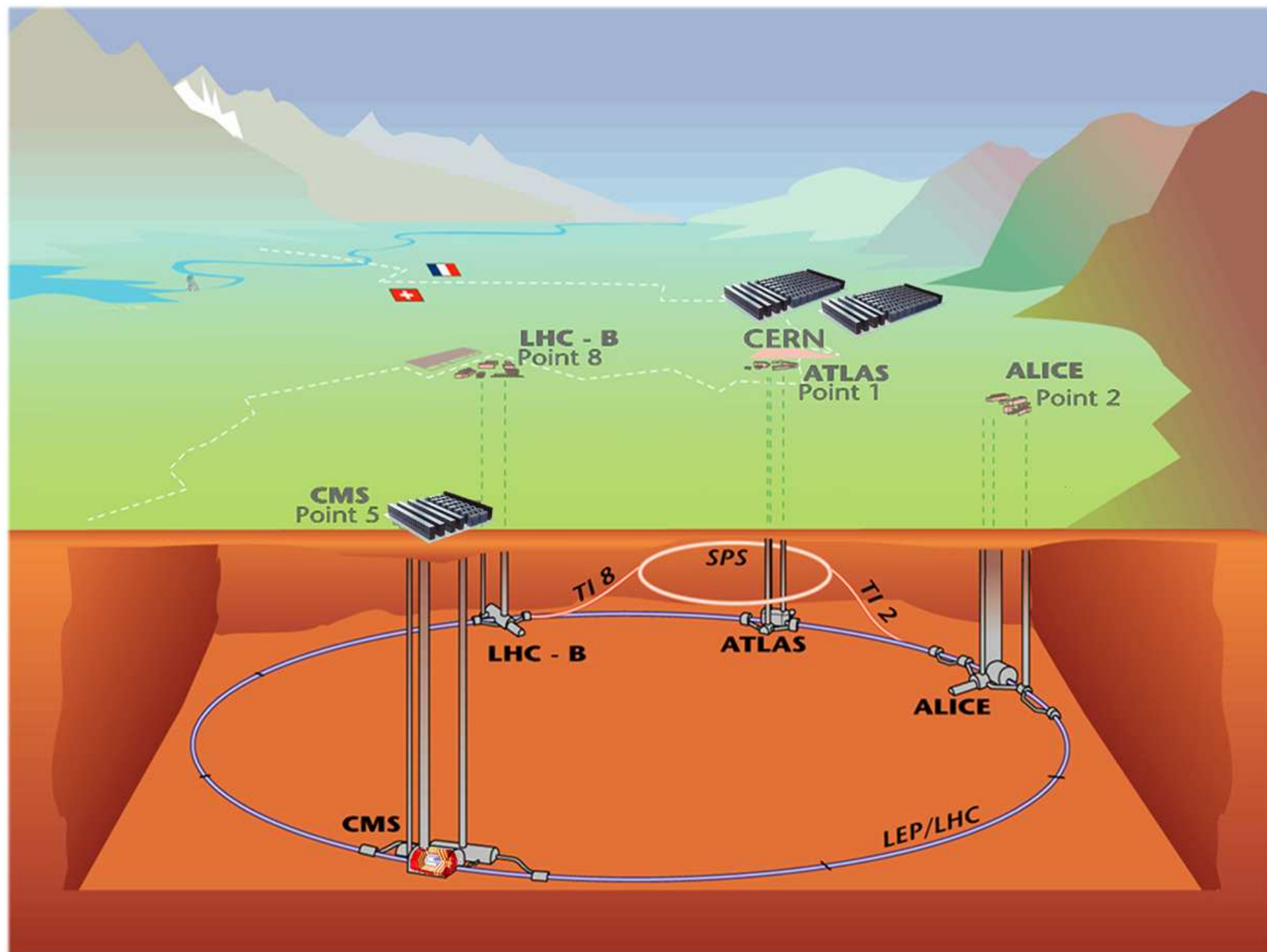
Slots for  
detector

3.8T solenoid insertion



**2000 MJ stored in the CMS  
magnet, enough to melt 18  
tons of solid gold**

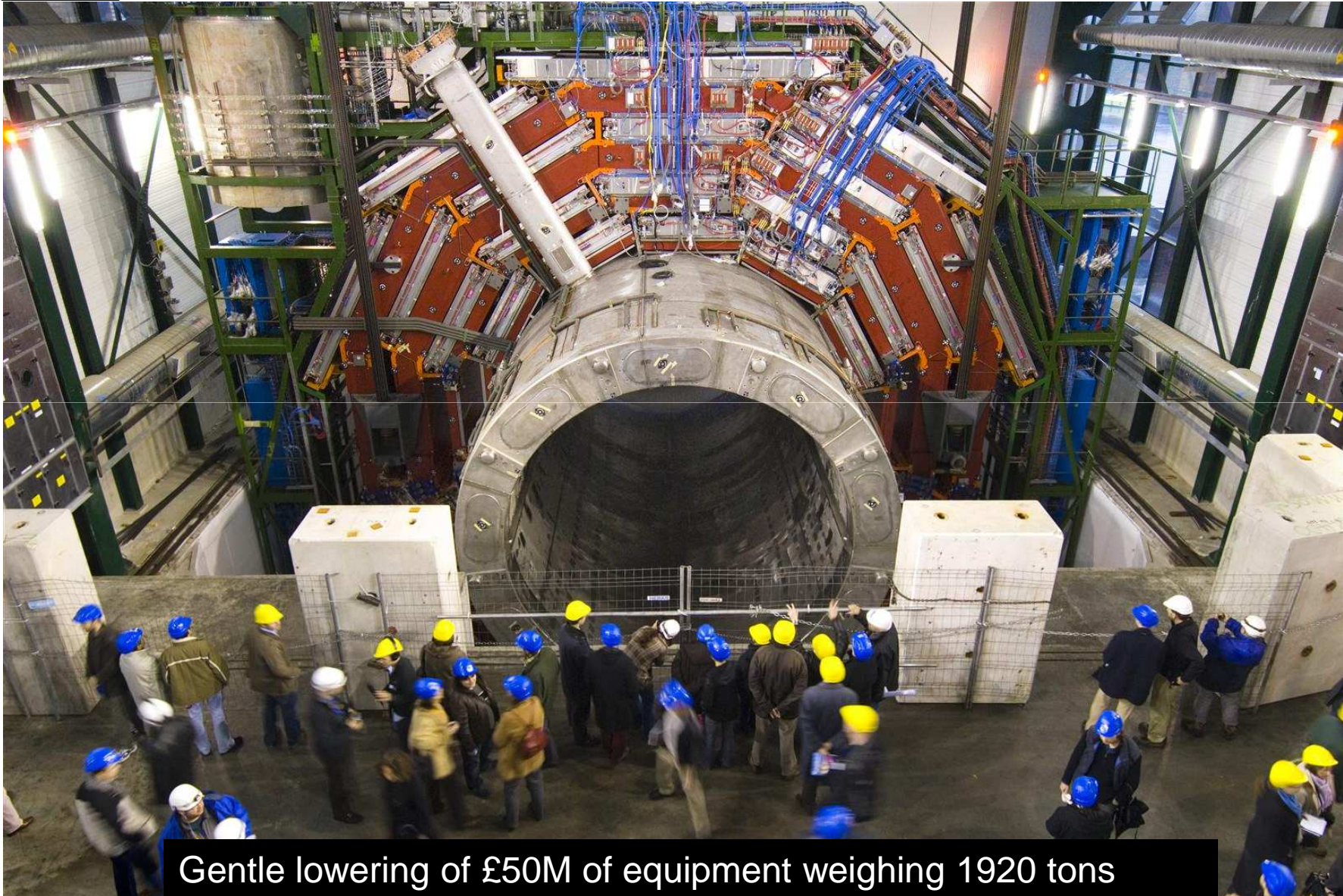








# Lowering CMS Detector

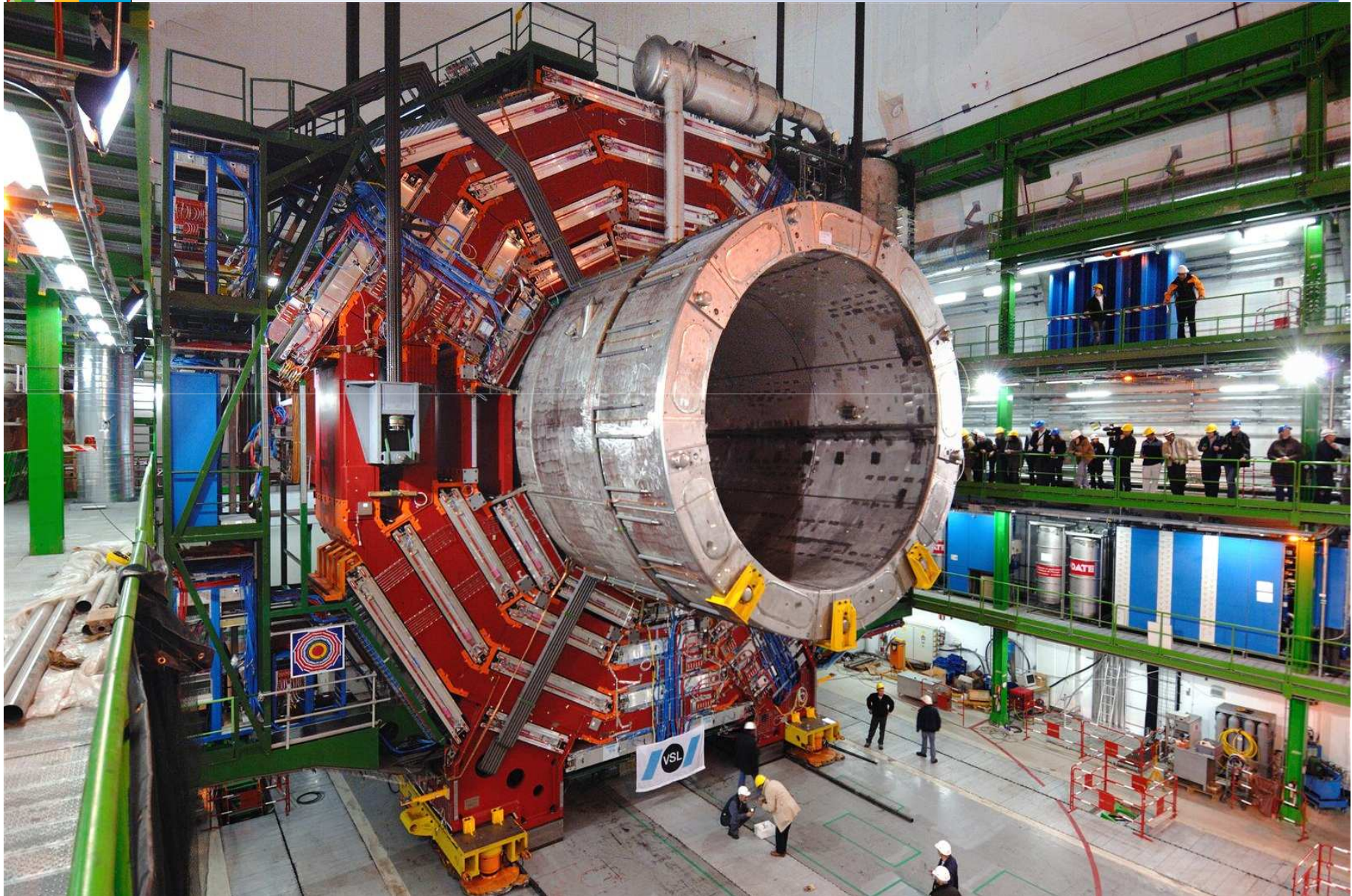


Gentle lowering of £50M of equipment weighing 1920 tons





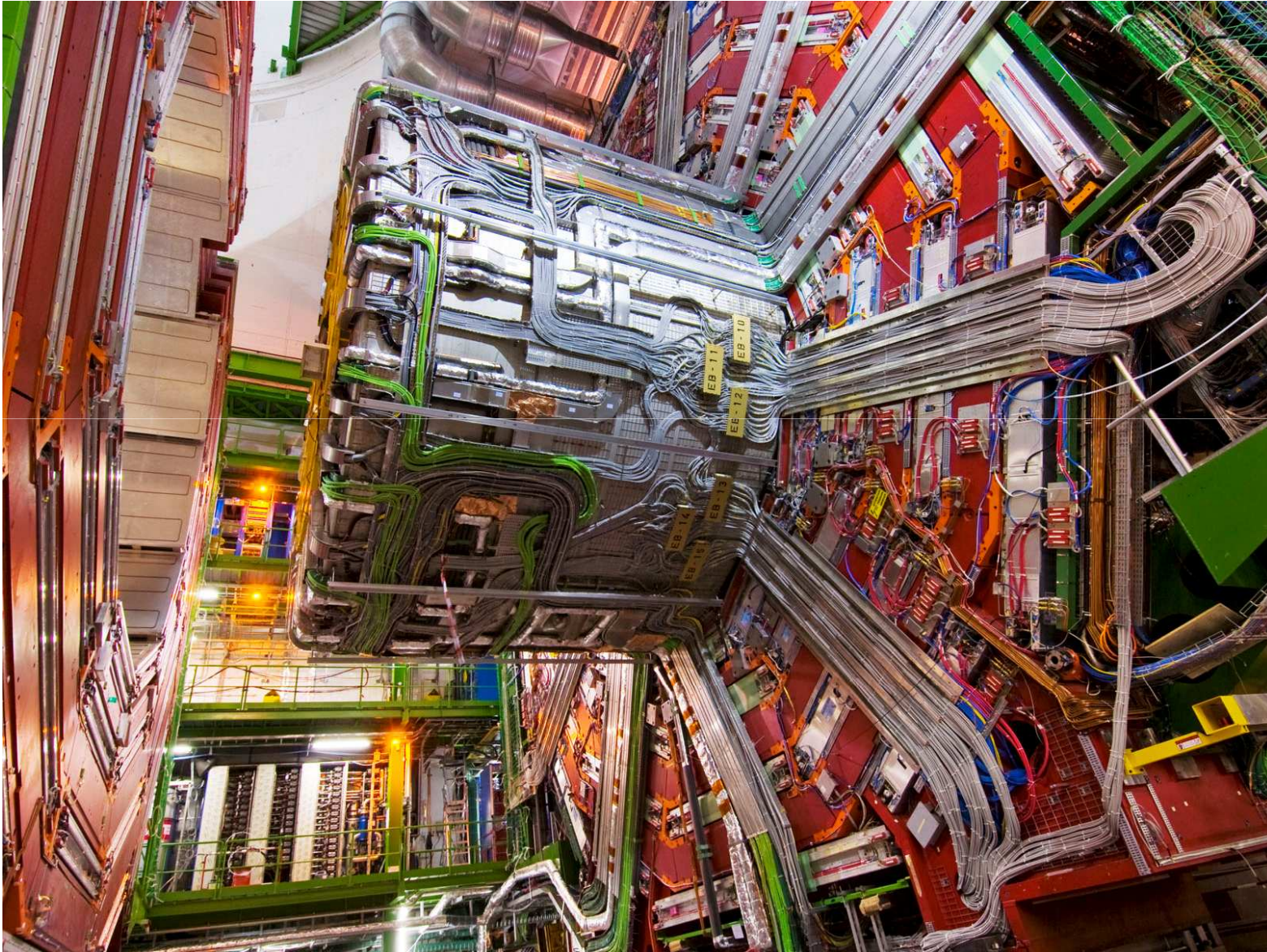
# Arrival of the solenoid in the cavern







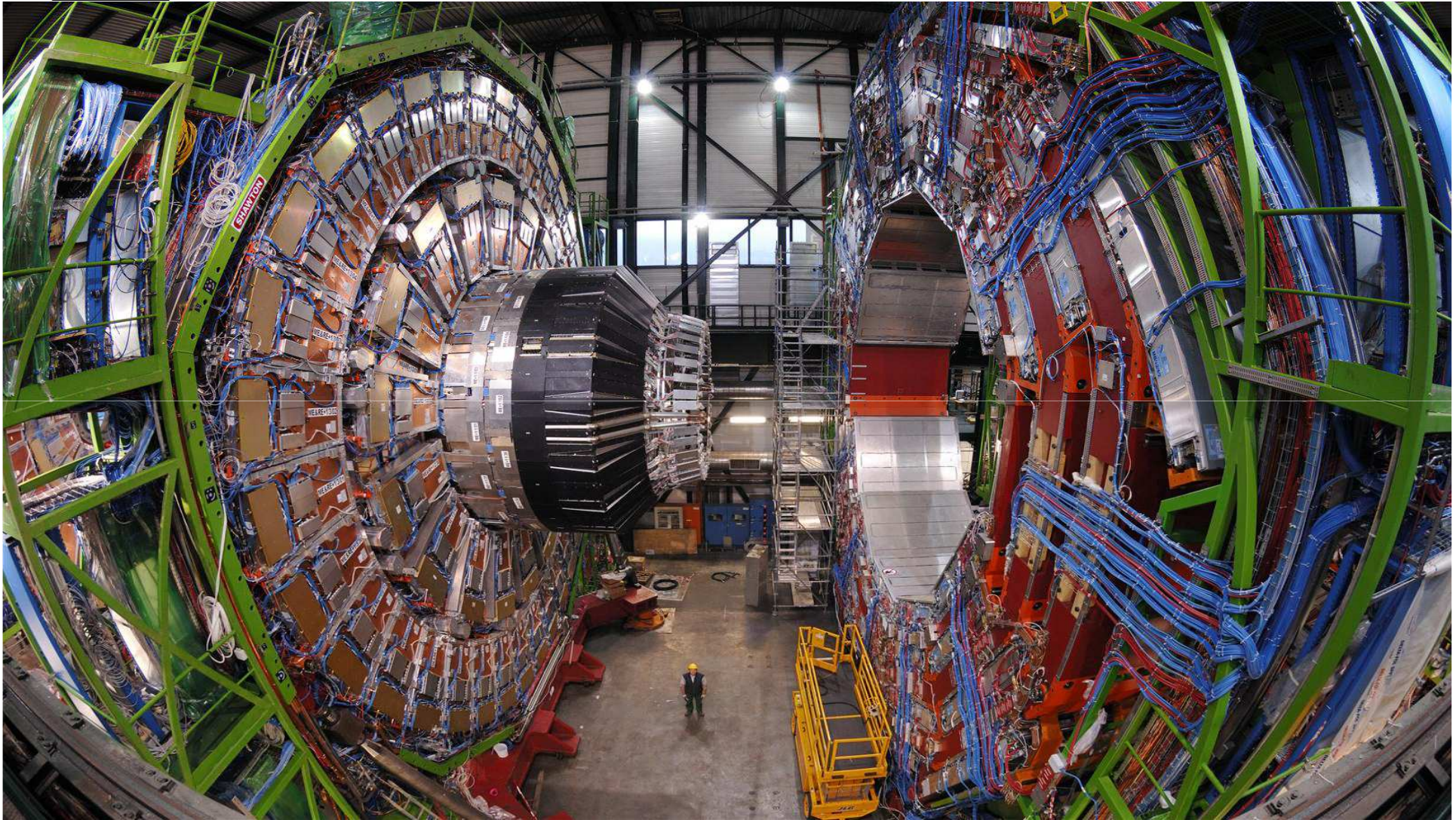
# Cableing







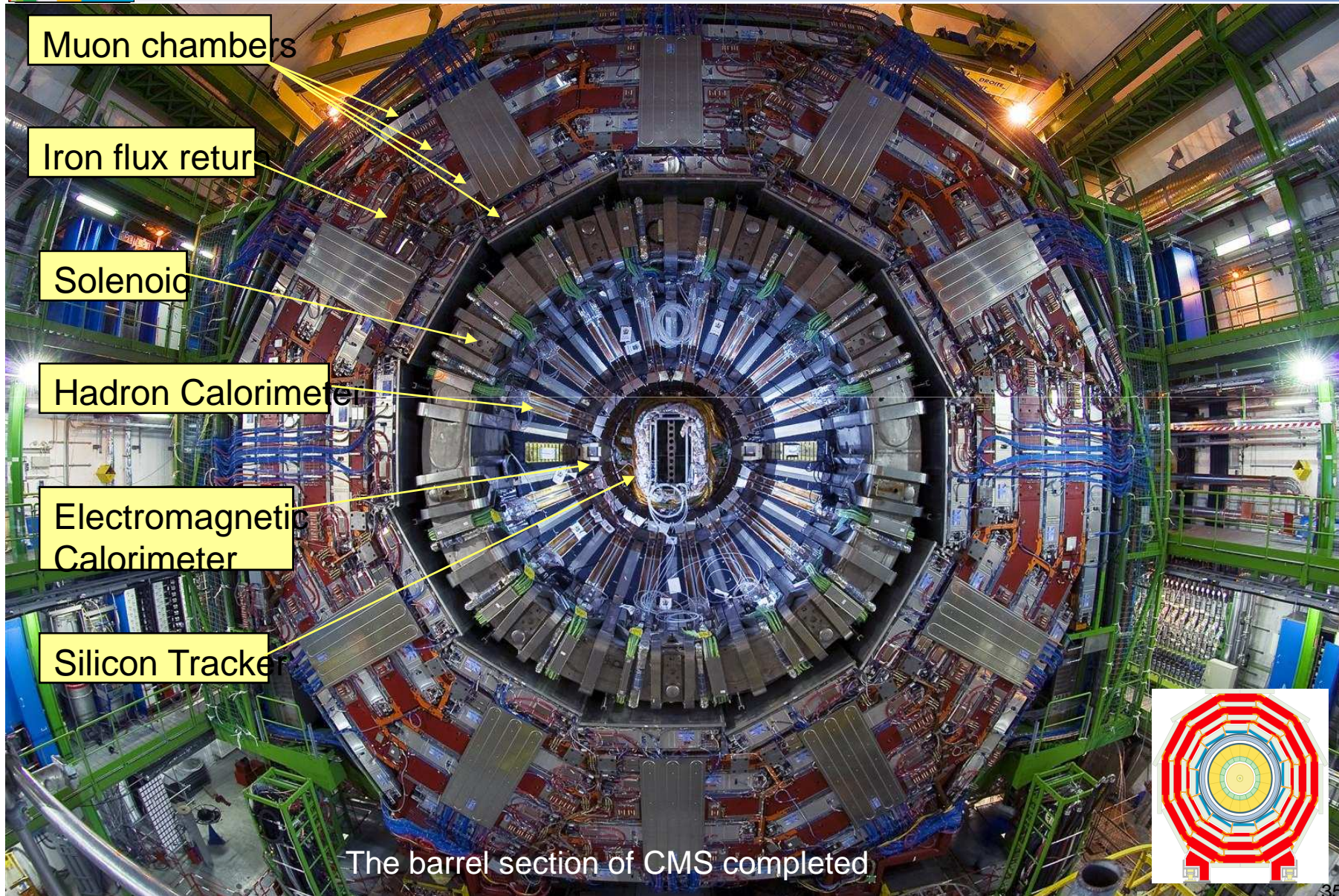
# Nearing completion underground







# CMS - Compact Muon Solenoid

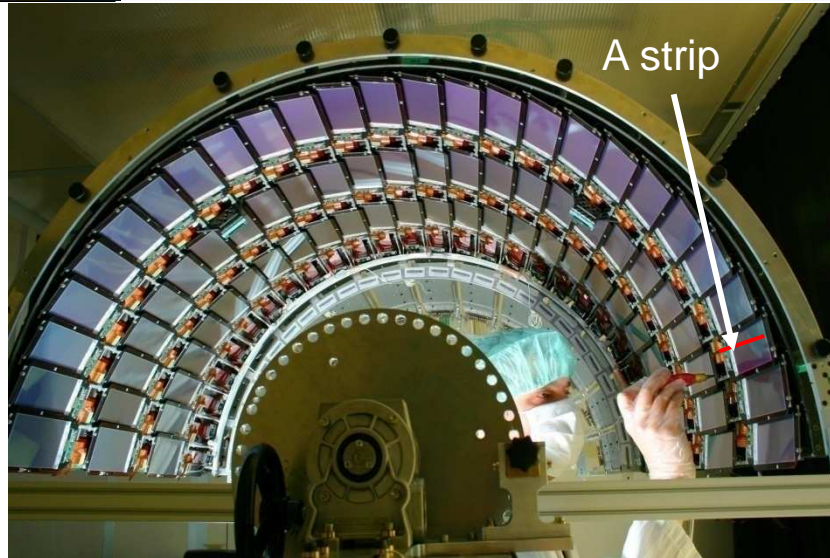


The barrel section of CMS completed

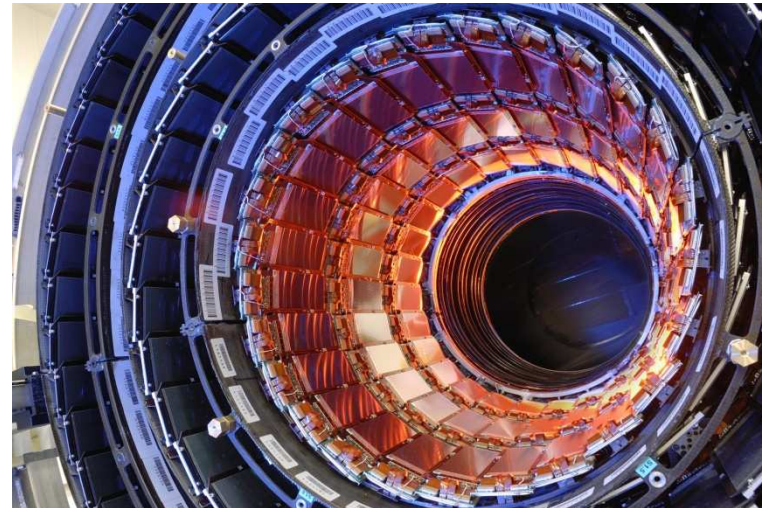




# CMS – data - detecting tracks



The CMS Silicon Tracker  
Each Si wafer is 300microns thick  
Can break very easily, like an ultra thin glass window  
Each wafer divided into 32 strips to detect charged particles  
**10 Million strips in total !**



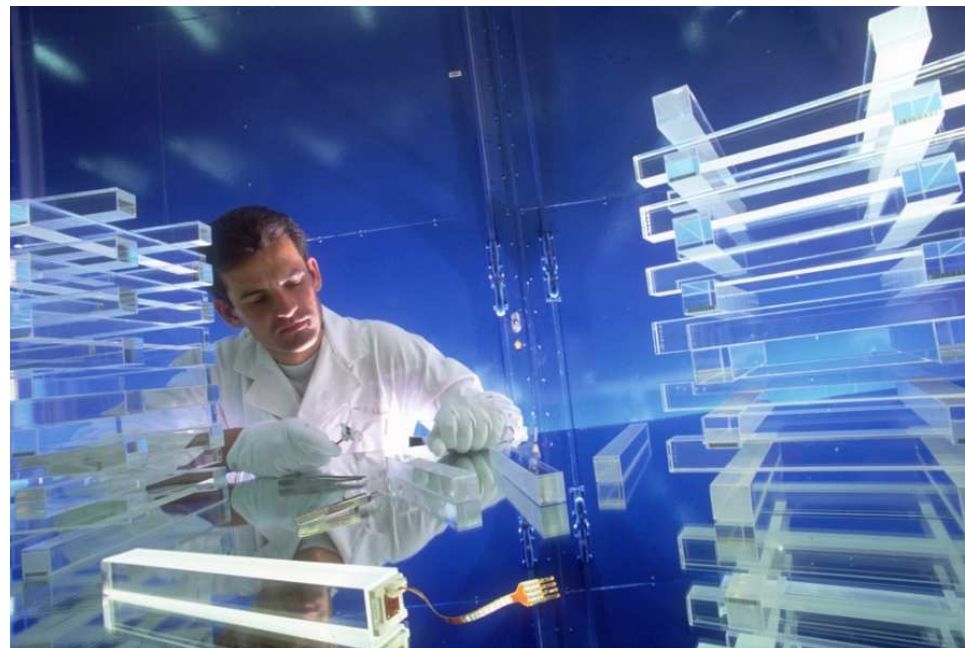




# CMS – detecting electrons and photons



Growing special crystals of lead tungstate ( $\text{PbWO}_4$ )



Preparing the cut crystals for the experiment

Each crystal costs \$1000  
Number of crystals – 75,000 !!

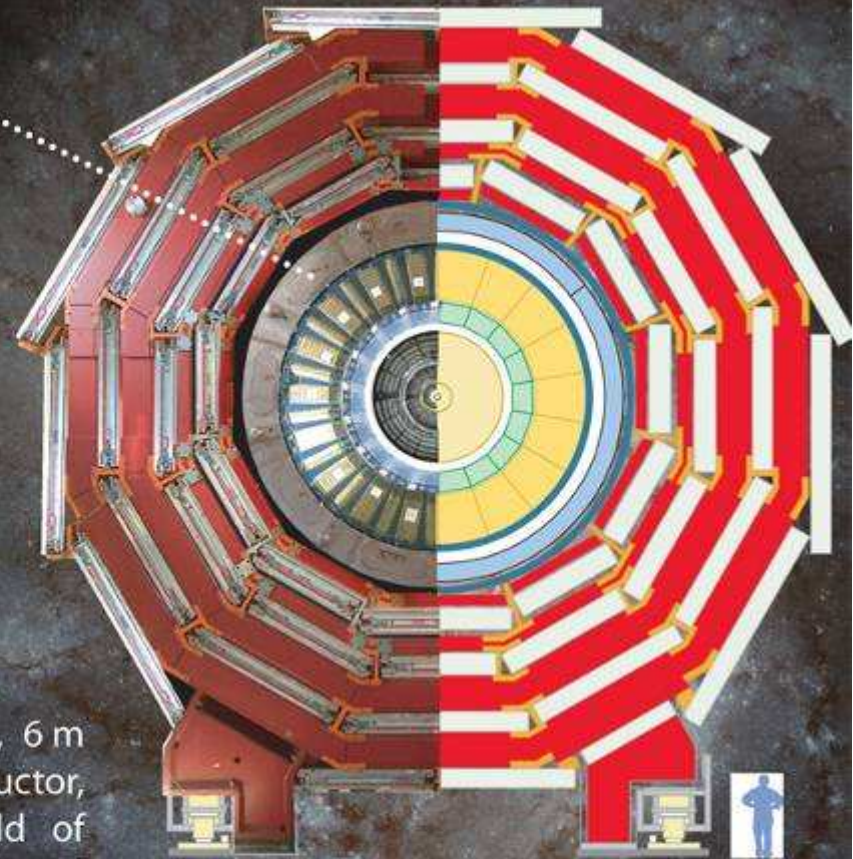


## Components of CMS: the SOLENOID



### Superconducting Solenoid

Passing 20 000 amperes through a 13 m long, 6 m diameter coil of niobium-titanium superconductor, cooled to  $-270^{\circ}\text{C}$ , produces a magnetic field of 4 teslas (about 100 000 times stronger than that of the Earth). This field bends the trajectories of charged particles, allowing their separation and momenta measurements.





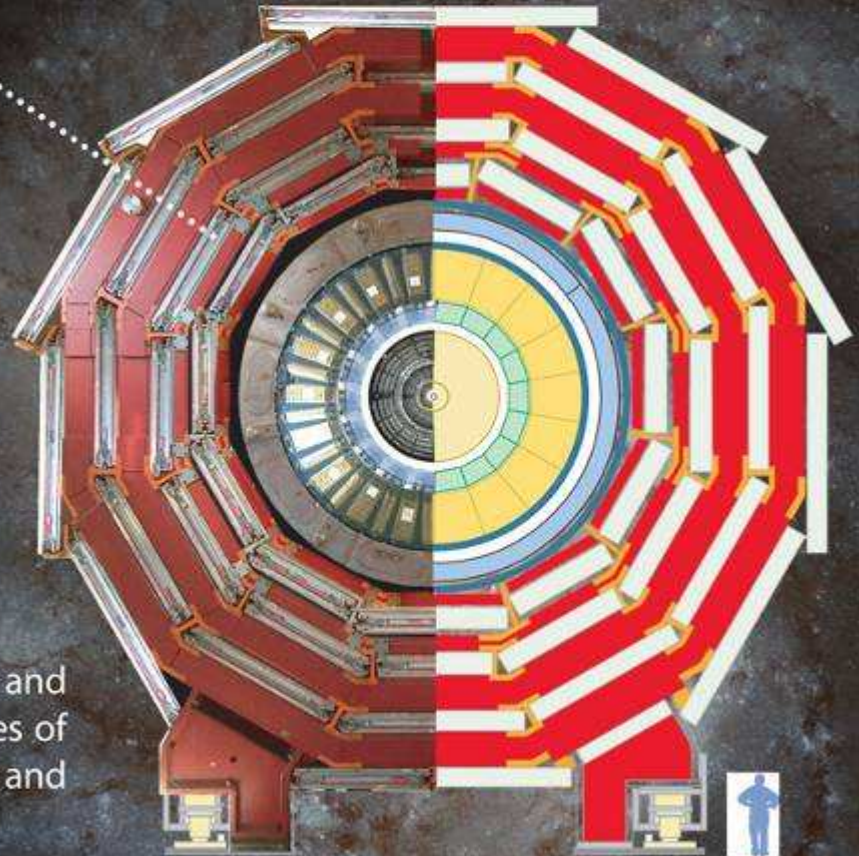


# Components of CMS: the MUON system



## Muon Detectors

To identify muons (essentially heavy electrons) and measure their momenta, CMS uses three types of detector: drift tubes, cathode strip chambers and resistive plate chambers.



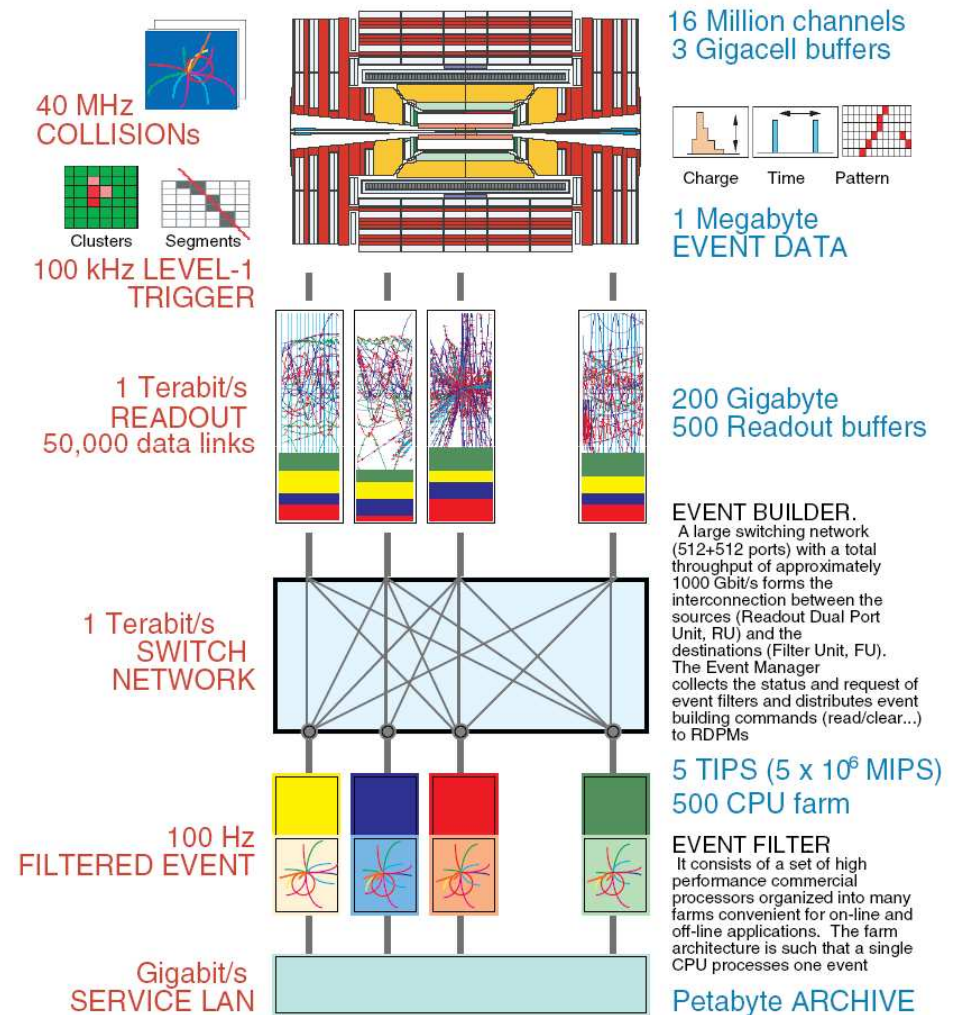


# Storing the data from the collisions

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)

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







# Early Physics Program

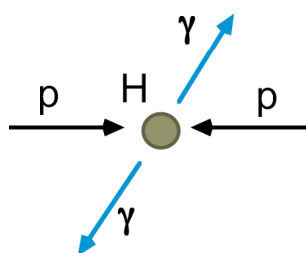
- **Prior to beam: early detector commissioning**
  - Readout & trigger tests, runs with all detectors (cosmics, test beams)
- **Early beam, up to  $10\text{pb}^{-1}$ :**
  - Detector synchronization, alignment with beam-halo events, minimum-bias events. Earliest in-situ alignment and calibration
  - Commission trigger, start “physics commissioning”:
    - Physics objects; measure jet and lepton rates; observe W, Z, top
    - And, first look at possible extraordinary signatures...
- **Physics collisions,  $100\text{pb}^{-1}$ : measure Standard Model, start search**
  - $10^6 W \rightarrow l \nu$  ( $l = e, \mu$ );  $2 \times 10^5 Z \rightarrow ll$  ( $l = e, \mu$ );  $10^4 t\bar{t} \rightarrow \mu + X$ 
    - Improved understanding of physics objects; jet energy scale from  $W \rightarrow j j'$ ; extensive use (and understanding) of b-tagging
    - Measure/understand backgrounds to SUSY and Higgs searches
  - Initial MSSM (and some SM) Higgs sensitivity
  - Early look for excesses from SUSY &  $Z'/jj$  resonances. SUSY hints (?)
- **Physics collisions,  $1000\text{pb}^{-1}$ : entering Higgs discovery era**
  - Also: explore large part of SUSY and resonances at  $\sim$  few TeV



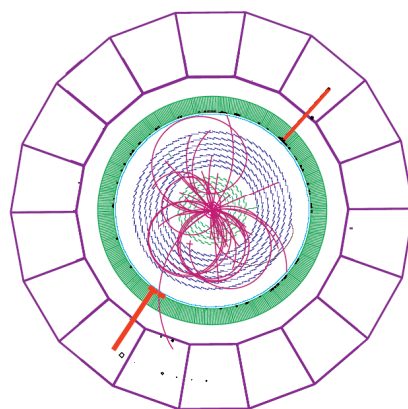


# Seeing the Higgs

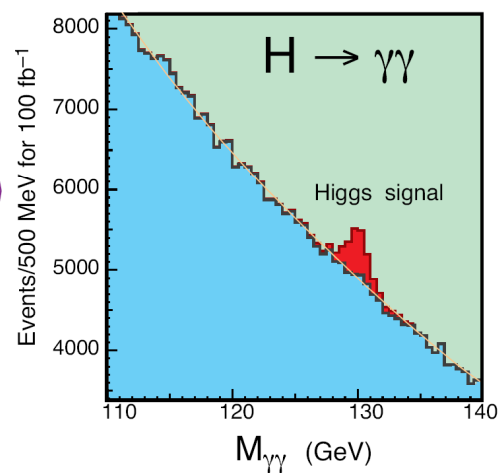
## Higgs to 2 photons ( $M_H < 140$ GeV)



$H^0 \rightarrow \gamma\gamma$  is the most promising channel if  $M_H$  is in the range 80 – 140 GeV. The high performance  $\text{PbWO}_4$  crystal electromagnetic calorimeter in CMS has been optimized for this search. The  $\gamma\gamma$  mass resolution at  $M_{\gamma\gamma} \sim 100$  GeV is better than 1%, resulting in a S/B of  $\approx 1/20$



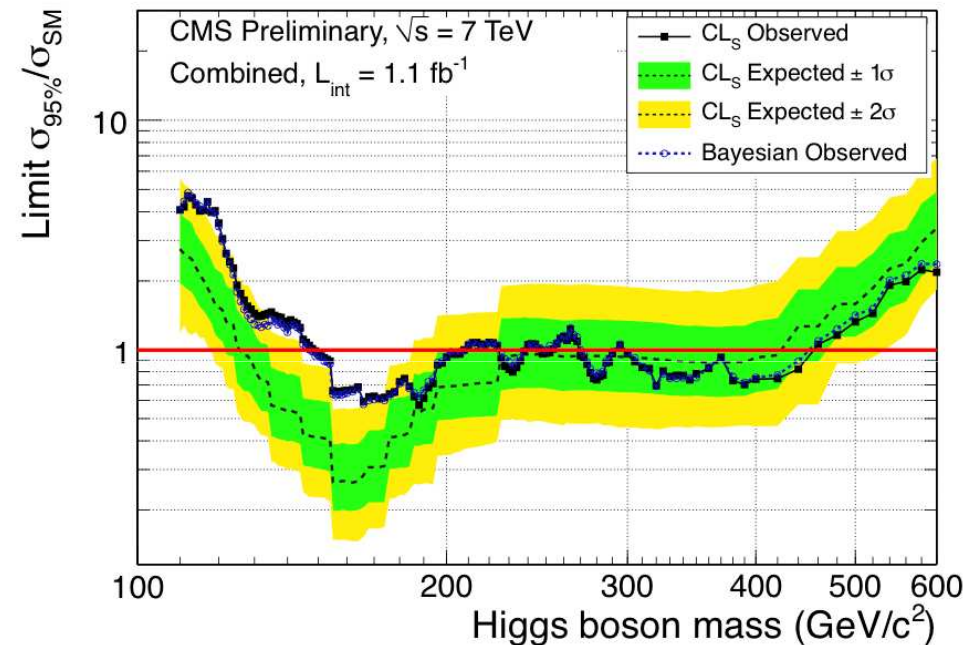
$M_{\text{Higgs}} = 100$  GeV





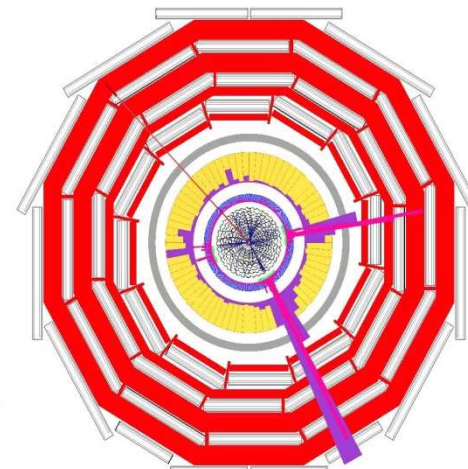
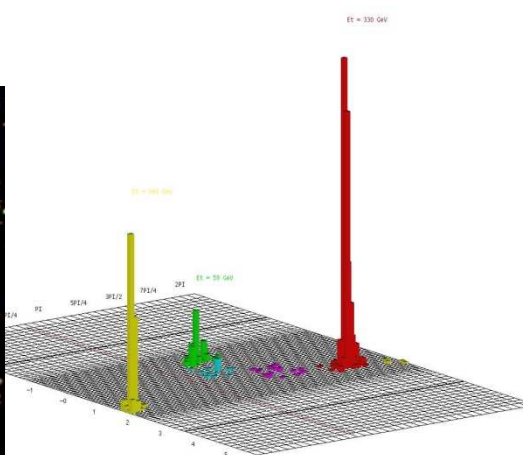
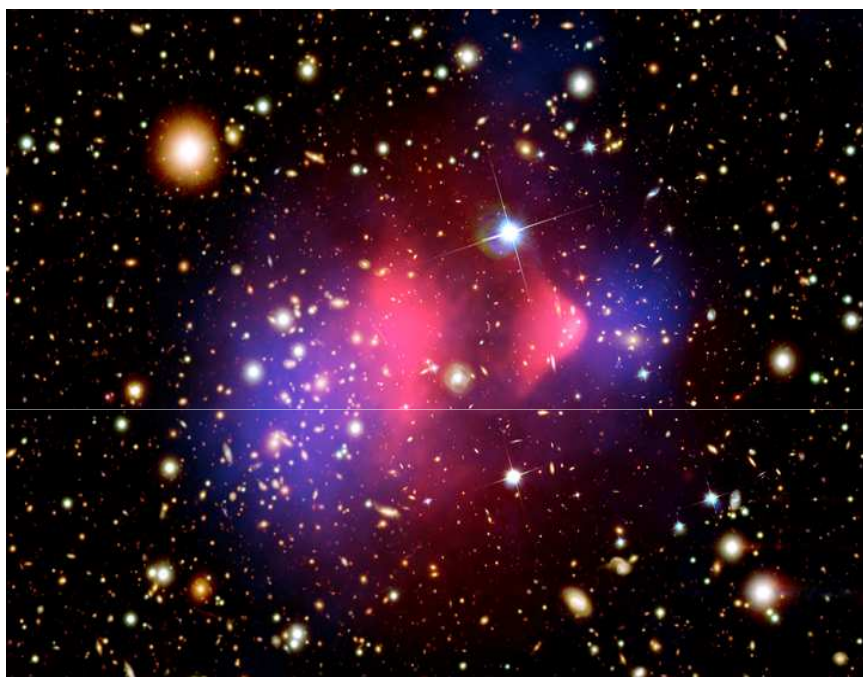
# Higgs Search II

- CMS observes no convincing excesses of events in the explored mass<sup>[2]</sup> range of 120-600 GeV (for full details see [[HIG-11-011](#)]). The analysis excludes, with a confidence level of 95%<sup>[3]</sup>, the existence of a Higgs boson in two broad Higgs mass ranges, 149-206 GeV and 300-440 GeV, as well as several narrower intervals in between (see Figure below). At a lower confidence level of 90%, the existence of a Higgs boson is excluded for the range 145-480 GeV. Re-interpreting the results in the context of the Standard Model with a fourth generation of fermions in addition to the known three generations (SM4), allows us to exclude the SM4 Higgs boson with a mass in the range 120-600 GeV with a confidence level of 95%.
- It should be noted that a modest excess of events is observed for Higgs boson masses below 145 GeV. With the data we will collect in the next few months we will be able to distinguish between the possible interpretations: the production of a Higgs boson or a statistical fluctuation of the backgrounds. During the ongoing LHC proton-proton run CMS will record substantially more data that should be sensitive to observing a Higgs boson, if it exists, over the full range of possible masses.

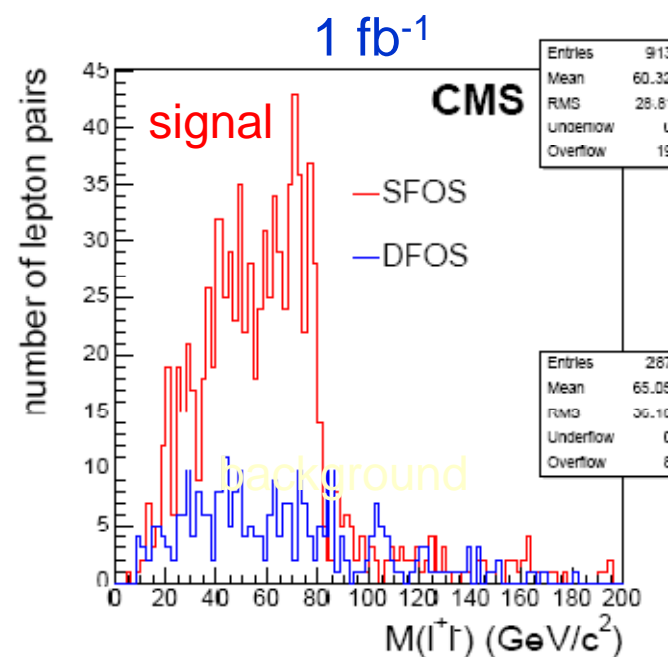
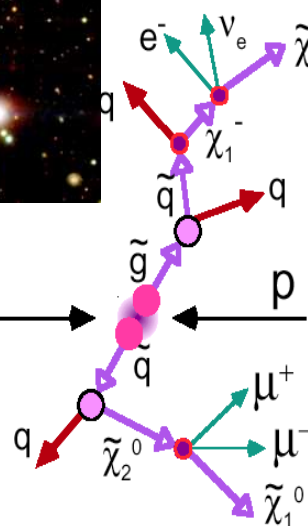




# Seeking “SUSY”



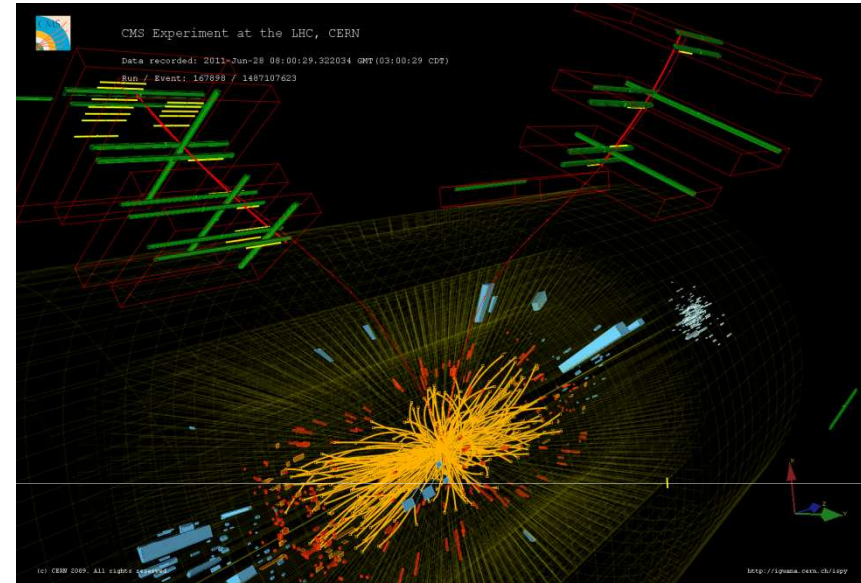
- Lightest SUSY particle would be a prime candidate for Dark Matter





# Search for rare decays of $B_s$

- CMS has searched for the decays of  $B_s$  (and  $B^0$  particles, comprising a 'bottom' and a 'down' quark) to muon pairs using proton-proton collision data collected up to June 2011. A challenging aspect of this search is reducing the large backgrounds from other B-hadron decays or particles misidentified as muons.
- The number of candidate decays observed in the available data sample is consistent with the Standard Model expectations for signal and background (see Figure). Given the absence of a significant excess, CMS has excluded (at 95% confidence level) branching fractions larger than  $1.9 \times 10^{-8}$  and  $4.6 \times 10^{-9}$  for the decay of  $B_s$  and  $B^0$  particles, respectively.
- This result constitutes one of the most stringent exclusion limits achieved until now. The data CMS will collect in the remainder of 2011 and in 2012 will be sensitive to smaller branching fractions, at the level of SM expectations, and may lead to the observation of an enhanced decay rate which **could be indicative of a non-Standard-Model physics process.**

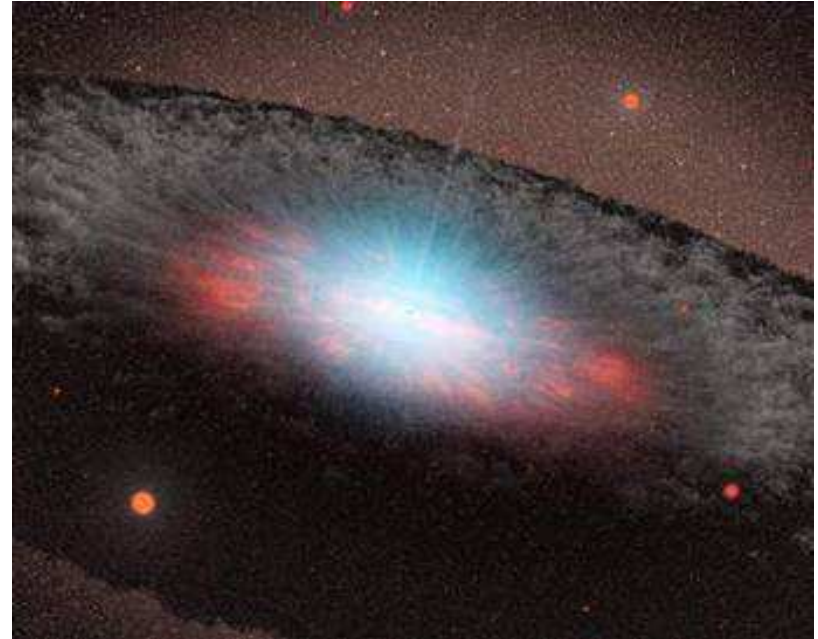


Candidate dimuon event in the  $B_s \rightarrow \mu\mu$  mass window. The muons are drawn as red lines extending outwards from the central collision, leaving green hits in the muon chambers (large, pale red boxes). The yellow lines show the tracks left by other particles in the collision. The solid red and pale blue boxes indicate energy deposits in the calorimeters.





# Black holes at the LHC ?



Black holes at the LHC would be nothing like these artists impressions of the super-massive (100,000 suns) black holes in outer space  
The black holes at the LHC would be tiny in comparison and decay very quickly

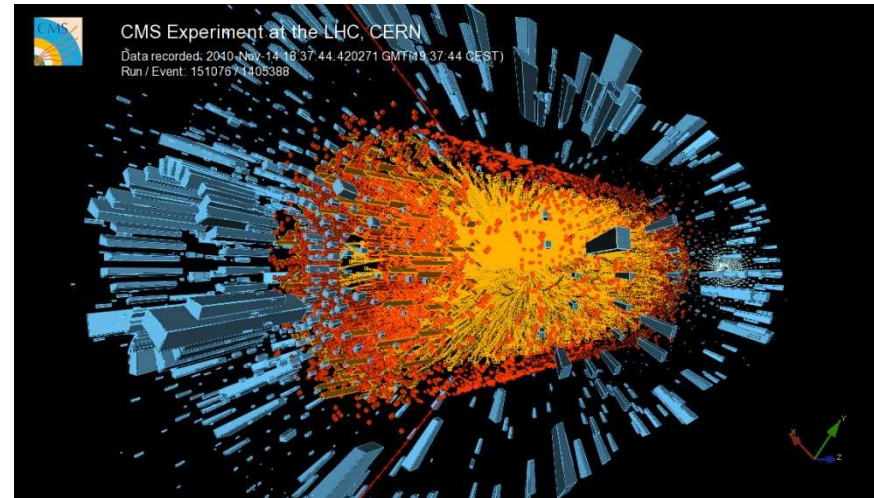
To create black holes the protons need to collide absolutely head on  
Finding black holes could also indicate extra dimensions exist





# Heavy ion collisions

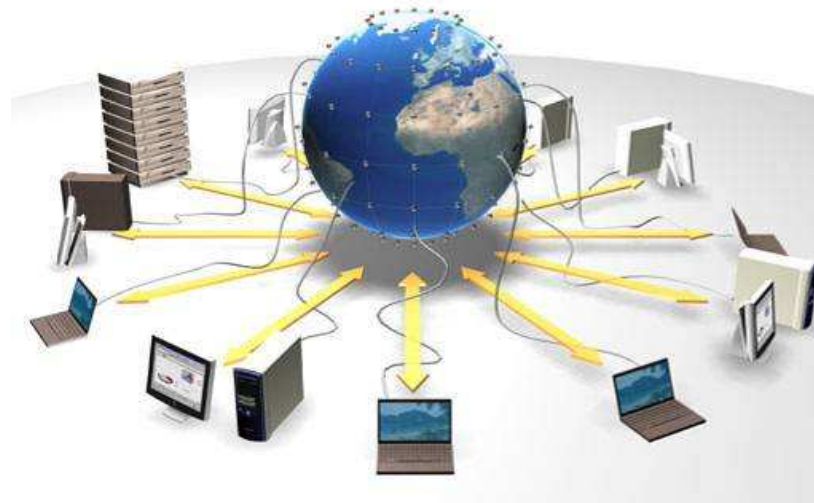
- The CMS collaboration is presenting its latest results this week at the annual Quark Matter conference, held this year in Annecy, France. The results are based on analyses of data collected during the LHC's heavy-ion run in the last two weeks of 2010 and early proton runs in 2011, both of which were conducted at an energy of 2.76 TeV per nucleon pair.





# Accelerator and life

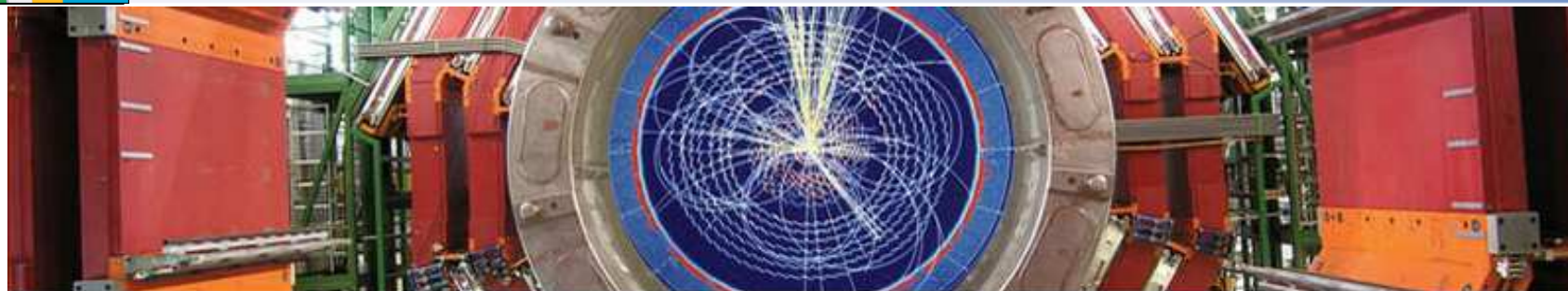
- Around 9000 of the 17000 accelerators operating in the World today are used for medicine.
- PET (Positron Emission Tomography) uses antimatter (positrons).
- Other spinoffs include... **WWW** - 20 years old!







# Summary



# CMS

An experiment at the LHC

**Colliding** Protons and heavy ions at unprecedented energies

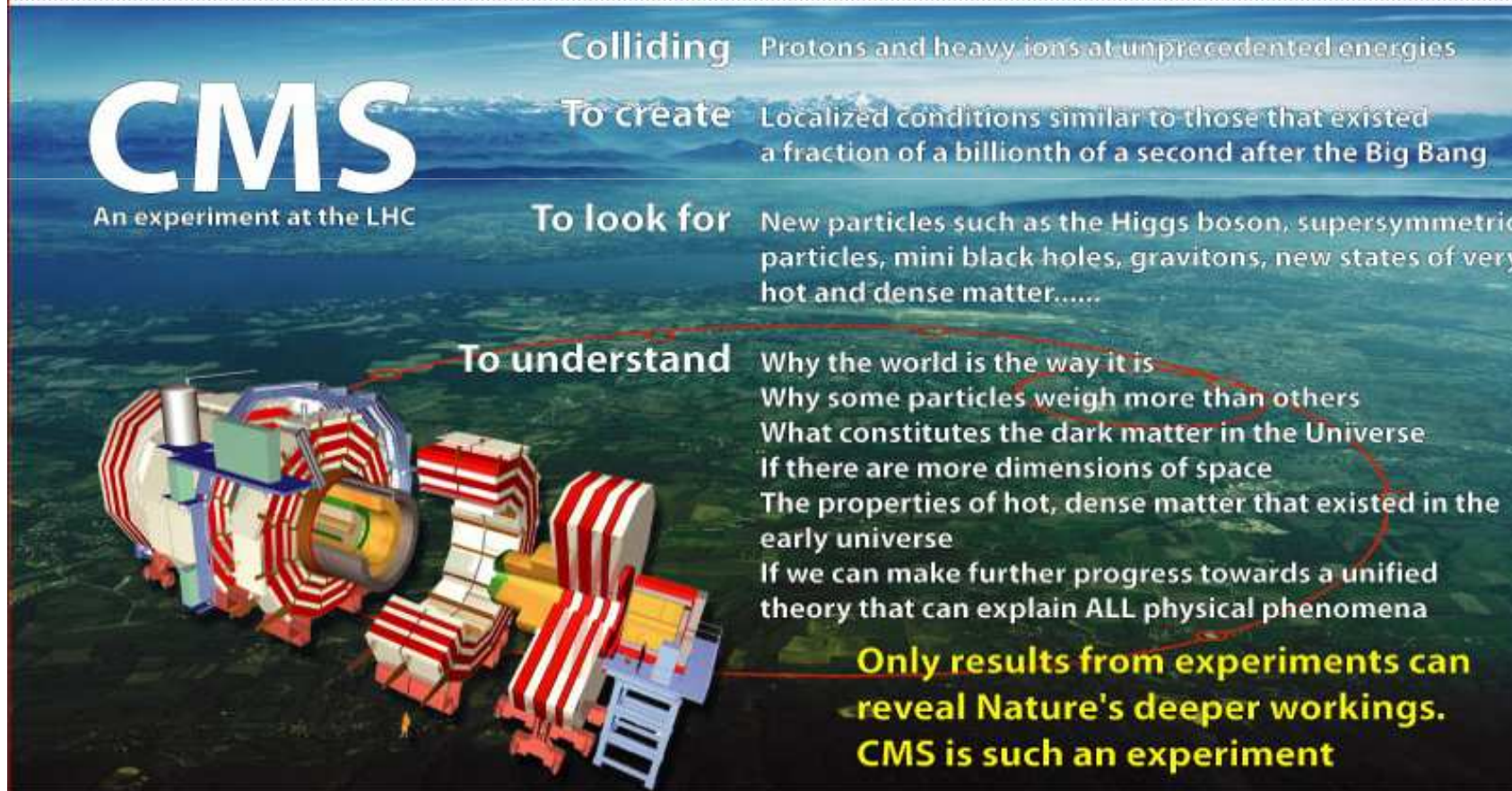
**To create** Localized conditions similar to those that existed a fraction of a billionth of a second after the Big Bang

**To look for** New particles such as the Higgs boson, supersymmetric particles, mini black holes, gravitons, new states of very hot and dense matter.....

**To understand**

- Why the world is the way it is
- Why some particles weigh more than others
- What constitutes the dark matter in the Universe
- If there are more dimensions of space
- The properties of hot, dense matter that existed in the early universe
- If we can make further progress towards a unified theory that can explain ALL physical phenomena

**Only results from experiments can reveal Nature's deeper workings.  
CMS is such an experiment**







## Some Q & A

- ***How many people are involved in building CMS ? Do they work 24 hours a day ? Do they work over Christmas ? How many man-years of effort are required to build it ?***
- **See <http://cmsdoc.cern.ch/peoplestat.html>**
- **At the moment there are about 2700 scientists and engineers from 184 institutes in 39 countries**
- **Also huge effort from industry**
- **Started construction about 1998, but design etc. started nearly 20 years ago!**



## Some Q & A

- ***How much power does it consume ?***
- See the CMS Times this week!
- About 10 MegaWatts required during operation
  - ◆ Equivalent to about **3000 average houses**
- About **1200 m<sup>3</sup> of water per hour** for cooling
  - ◆ The jet d'eau in Geneva pumps **1800 m<sup>3</sup> per hour!**



## Q & A

- ***Why do we have CMS and ATLAS? i.e. why 2 experiments to do the same thing?***
- An important part of the “scientific method” is **validation**. We do not know the “answer” in advance. So having two detectors (built and optimized in different ways) can provide independent verification (or denial!) of discoveries