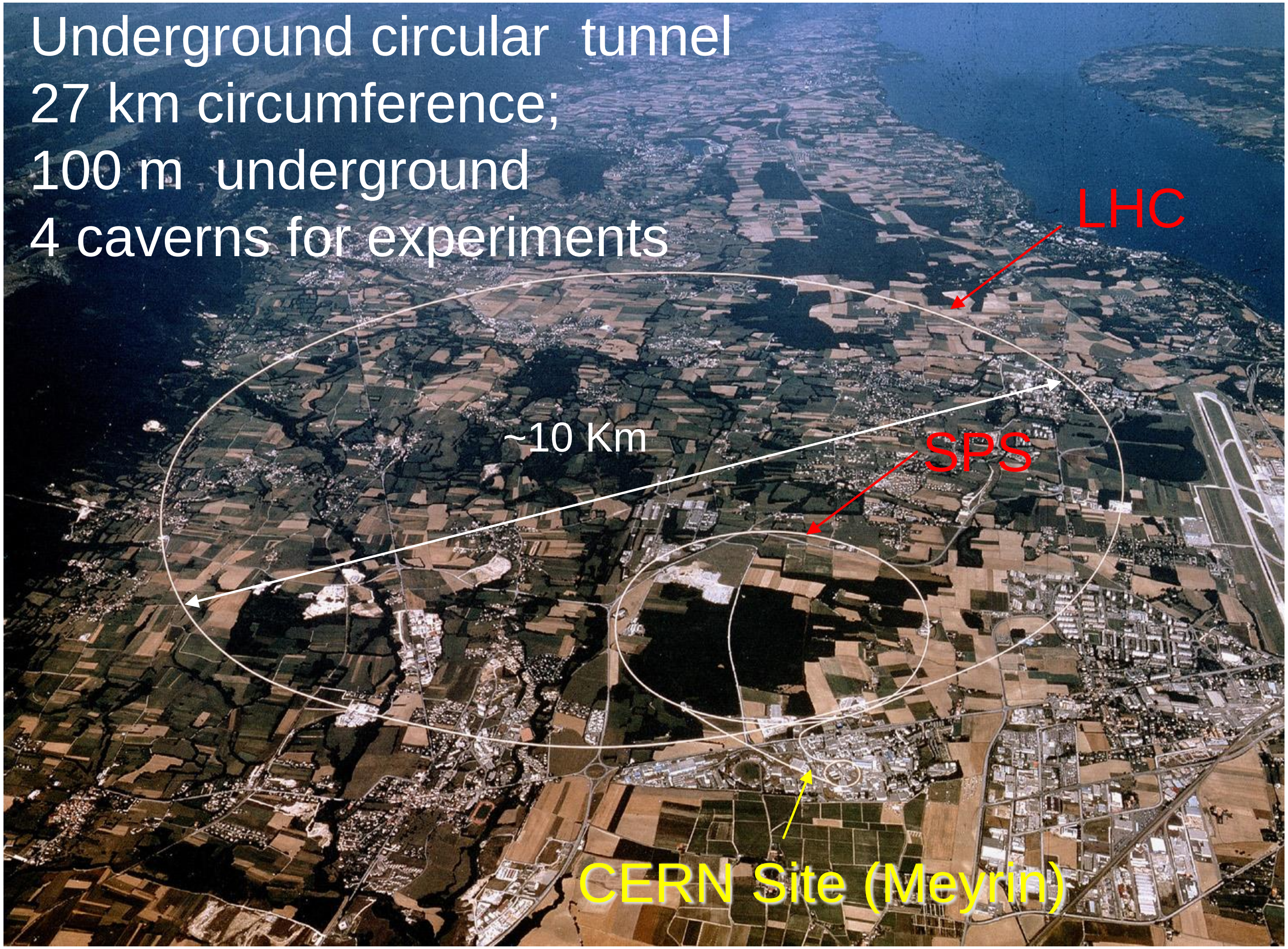
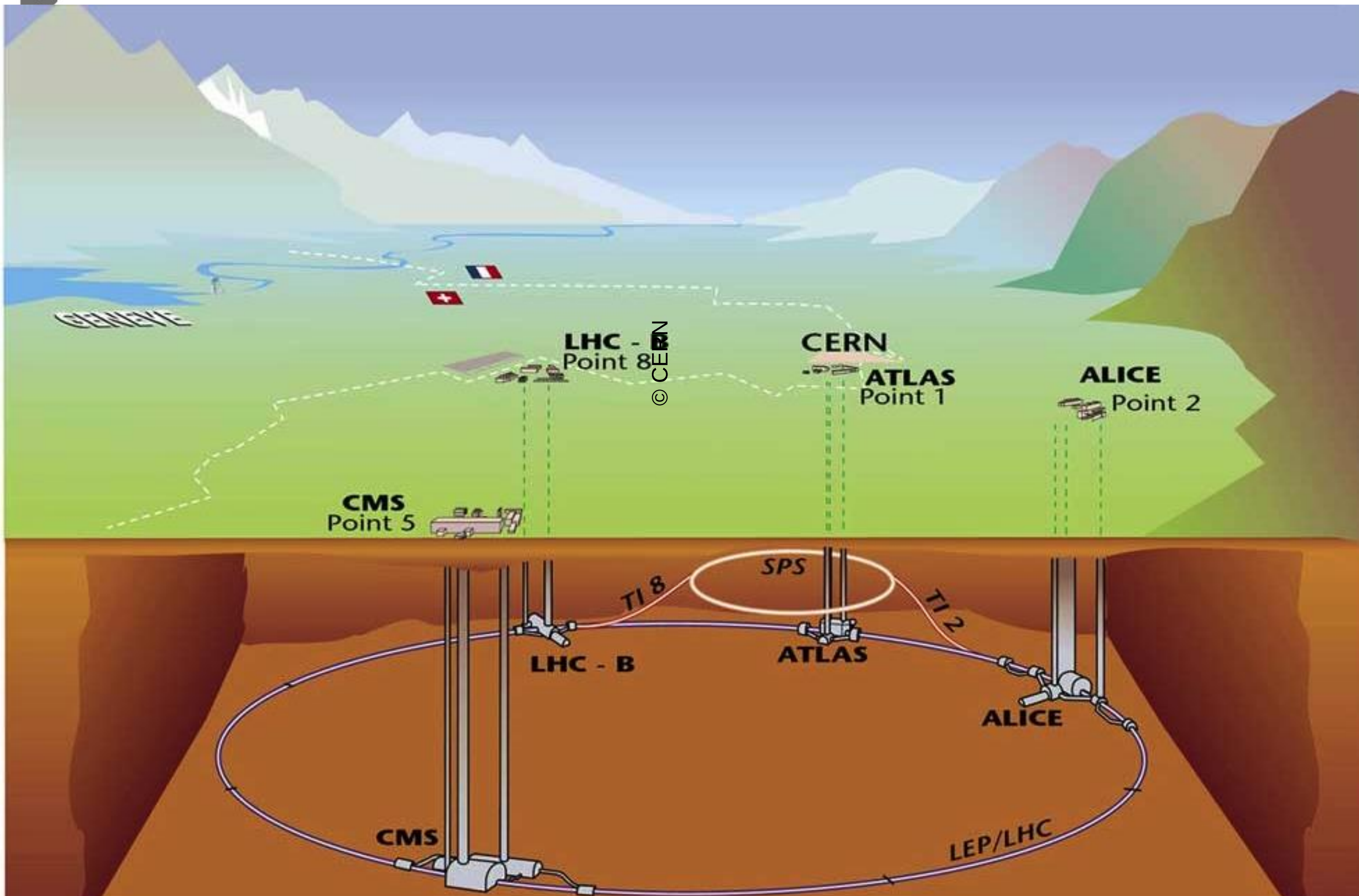
The LHC proton collider

Accelerator and Experiments

Underground circular tunnel
27 km circumference;
100 m underground
4 caverns for experiments



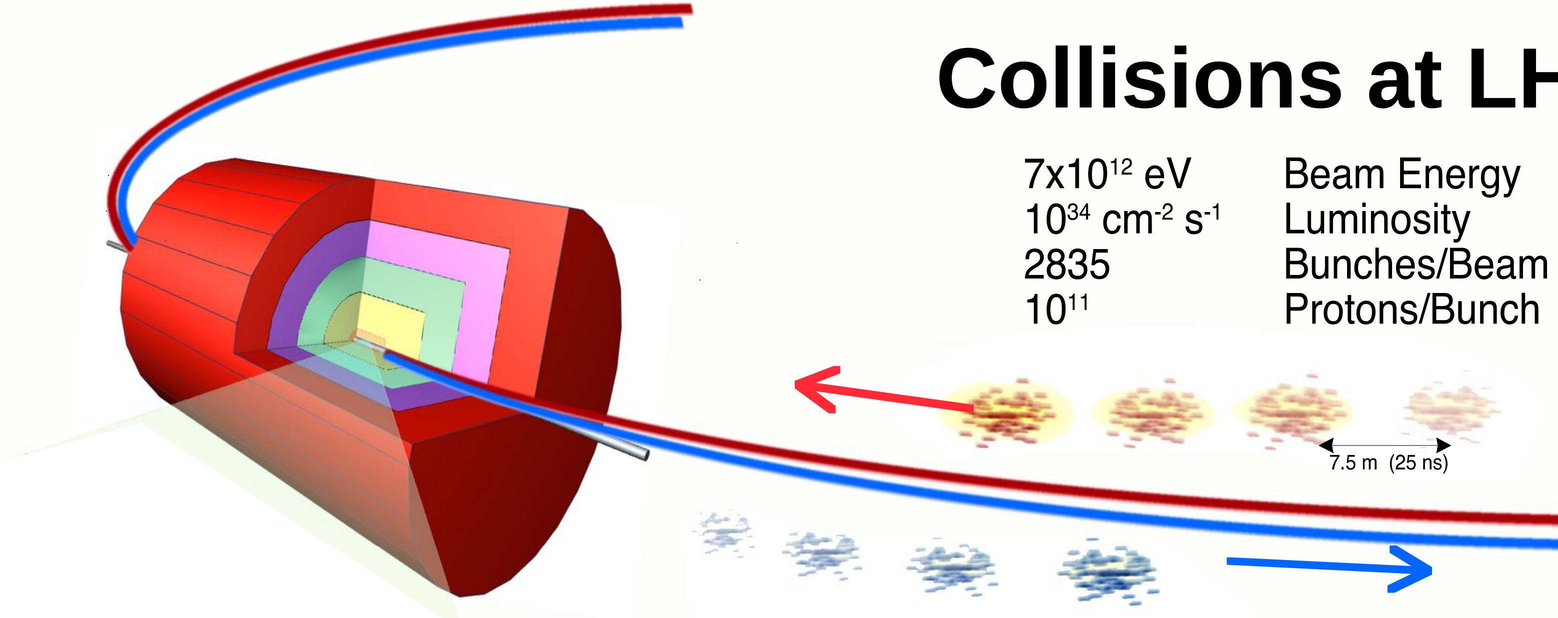
Accelerator and experiments layout



Tiny bunches of counter-circulating protons.
Colliding head-on 40 million times each second.

Collisions at LHC

$7x10^{12}$ eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch



7 TeV Proton Proton
colliding beams

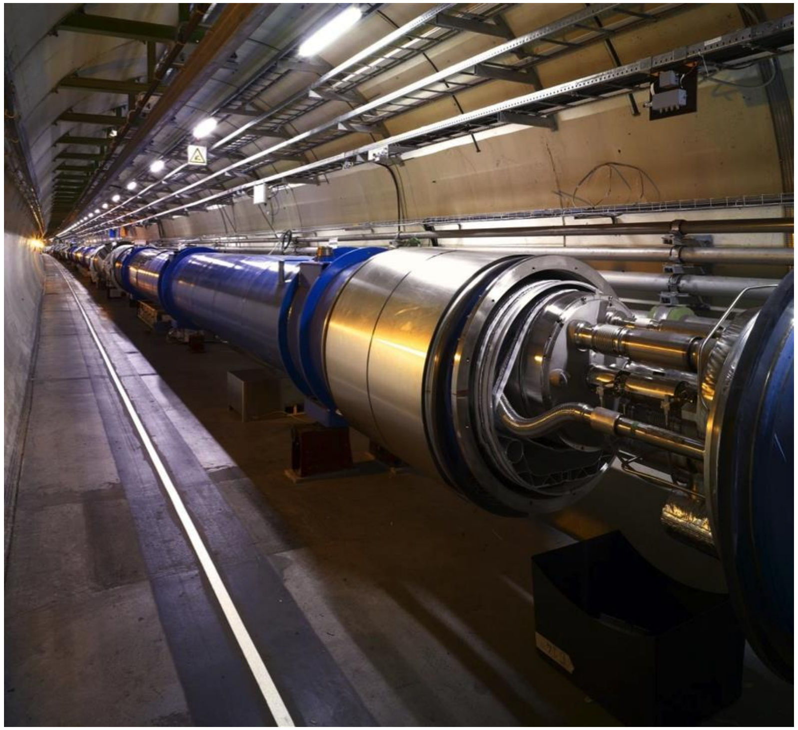
Accelerator challenges

Relative to Tevatron (Fermilab, USA)

Energy (14 TeV) x 7

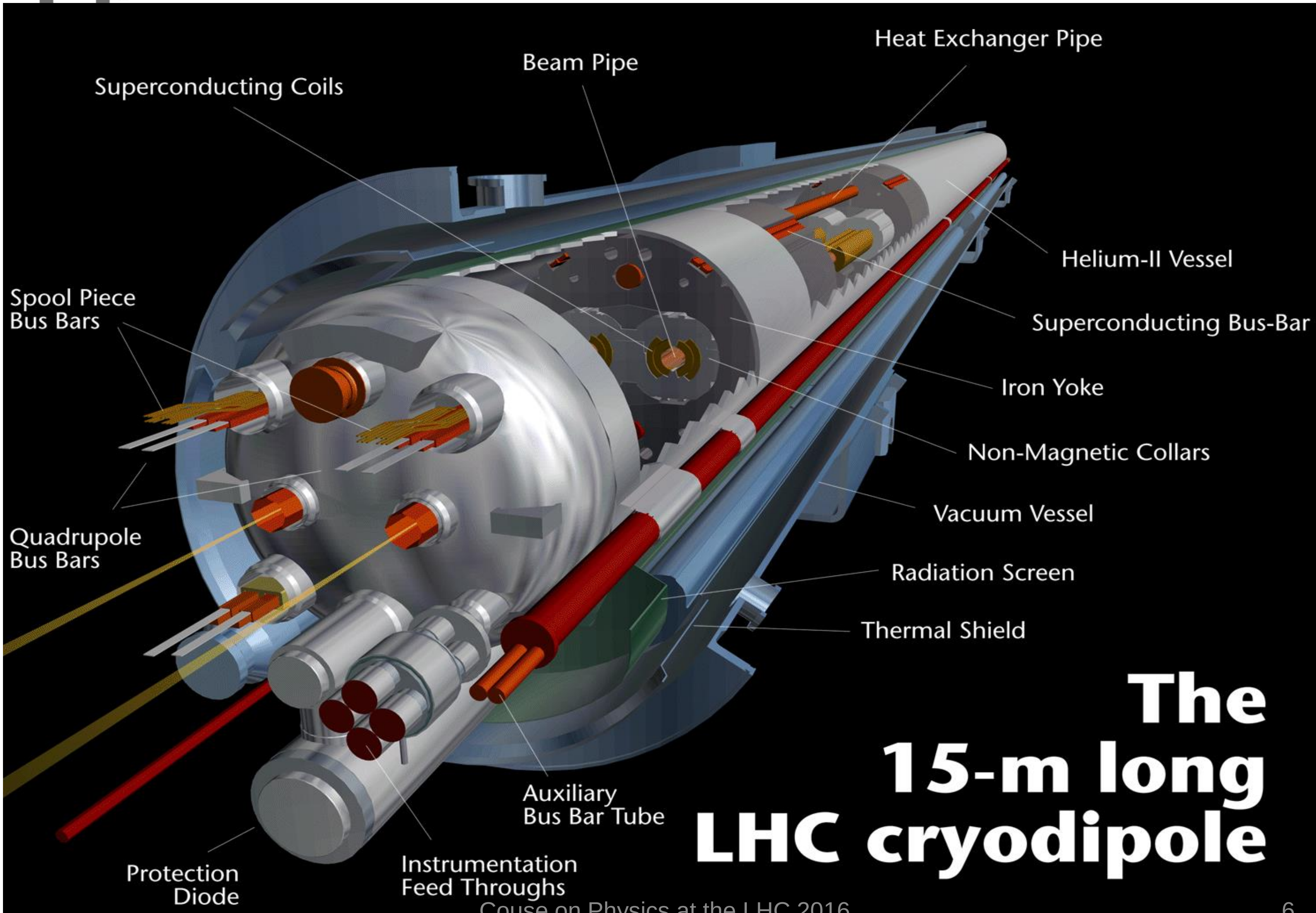
Luminosity ($10^{34}cm^{-2}s^{-1}$) x 30

- Superconducting dipoles 8.3 Tesla
- Operating temperature 1.9K (-271 C)
- Stored energy per beam 350 M Joule
  - energy of a train of 400 tons at 150 Km/h

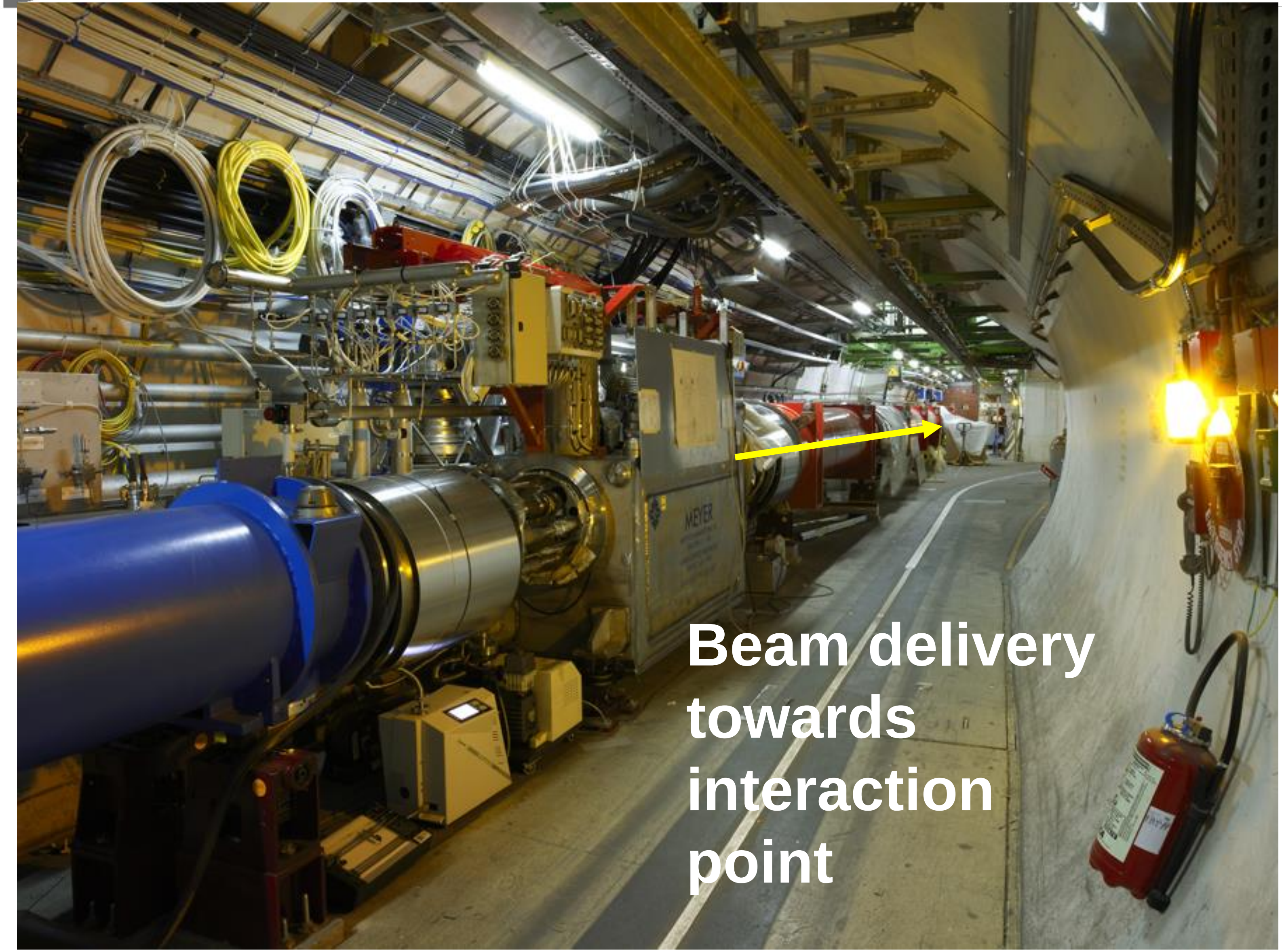


- More than 2000 dipoles
- 100 ton liquid helium
- LHC power consumption 120 MW

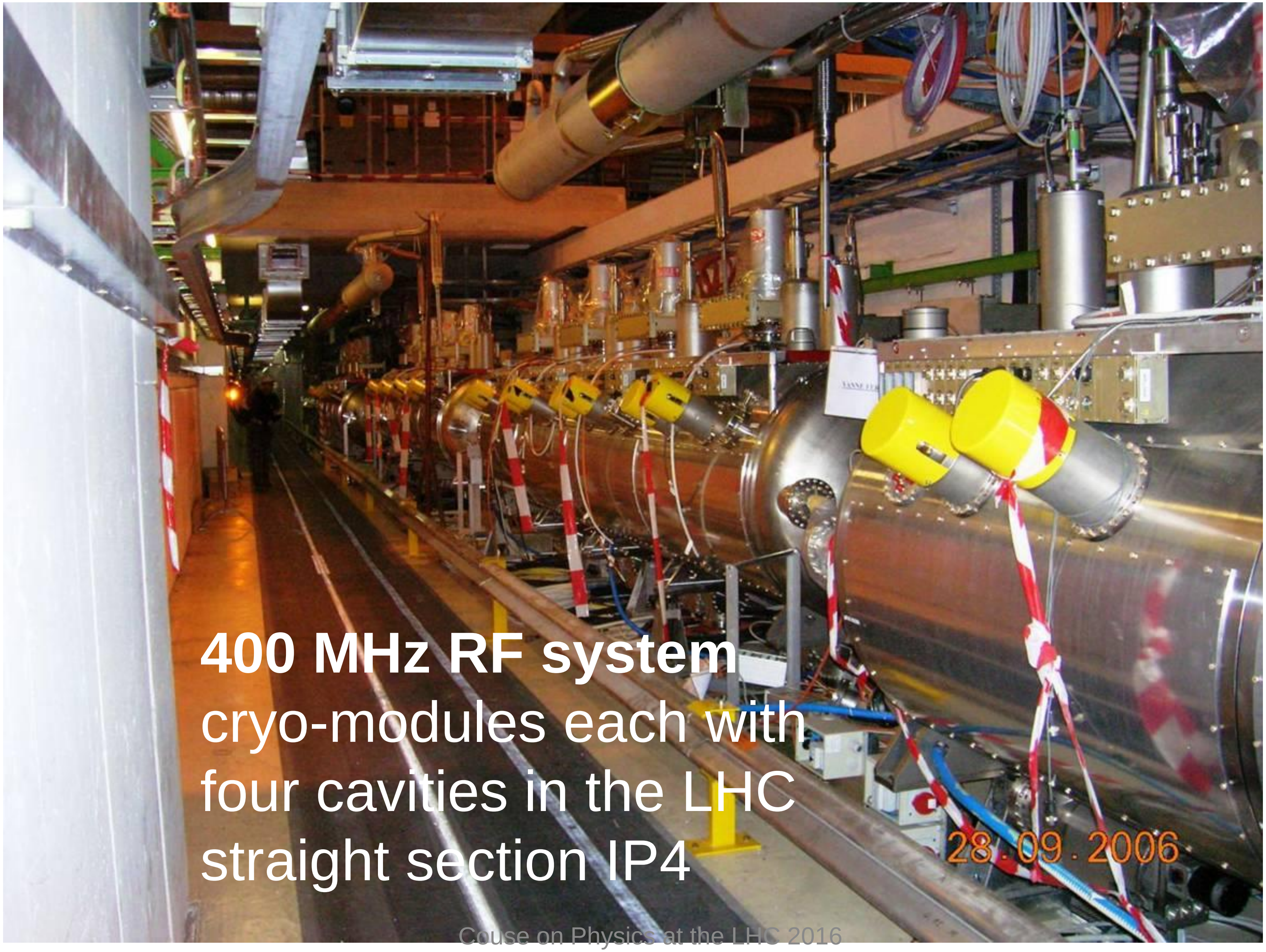
Superconducting magnetic dipole



In the tunnel



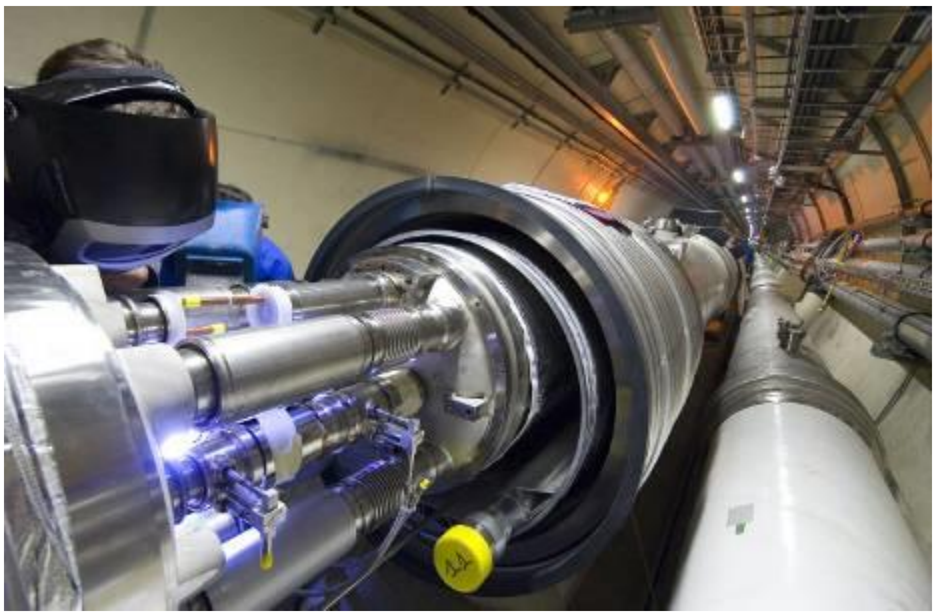
In the tunnel

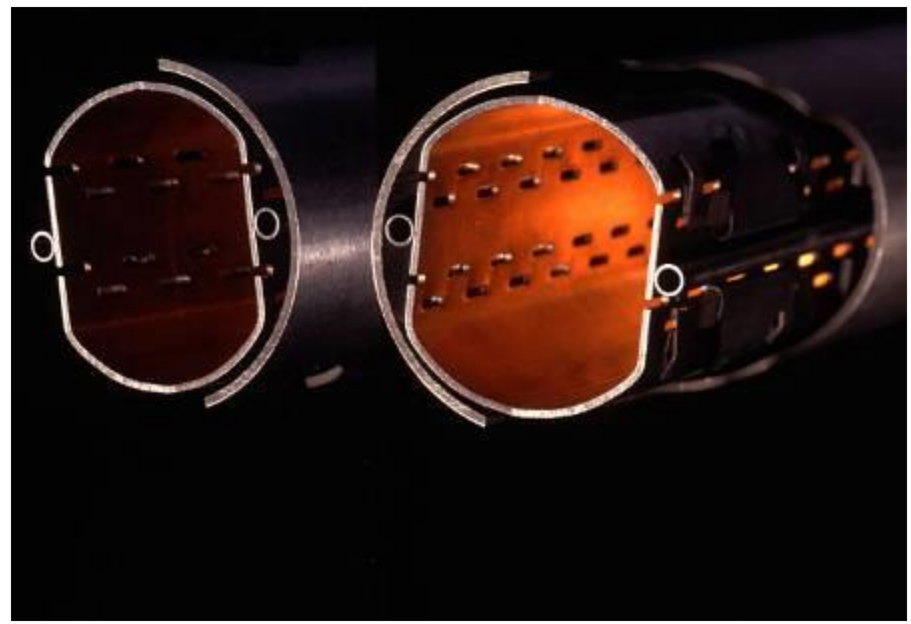


400 MHz RF system
cryo-modules each with four cavities in the LHC straight section IP4

It’s empty!

Air pressure inside the two 27Km-long vacuum pipes (10^{-13} atm) is lower than on the moon.



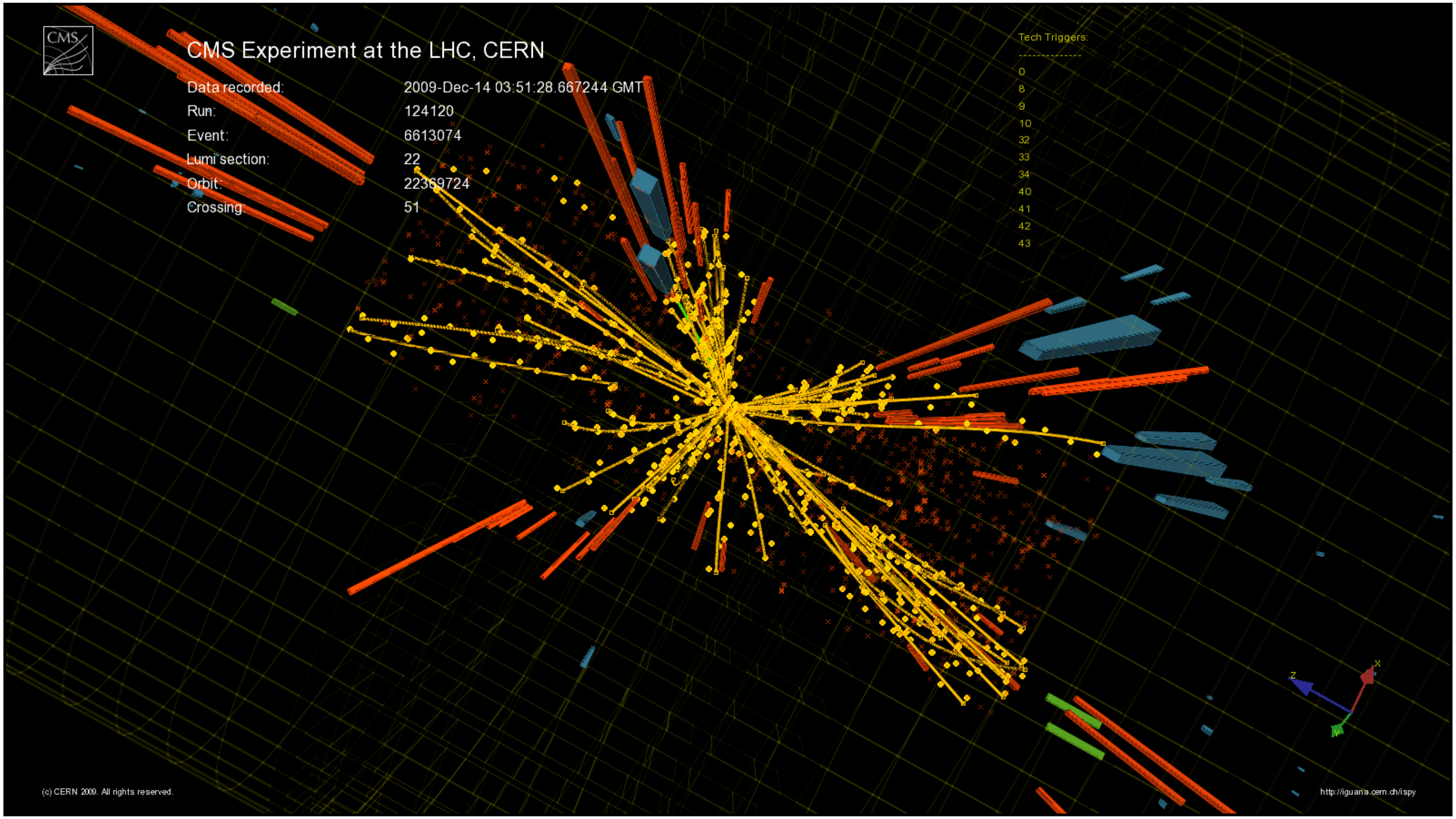


It’s cold!

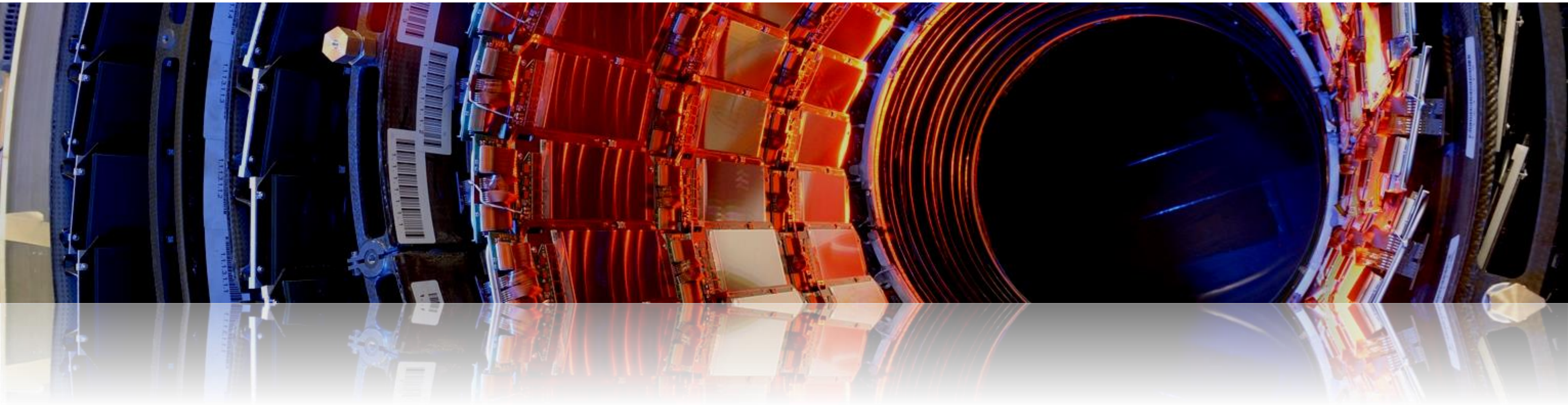
27 Km of magnets are kept at 1.9 ^{o}K, colder than outer space, using over 100 tons of liquid helium.

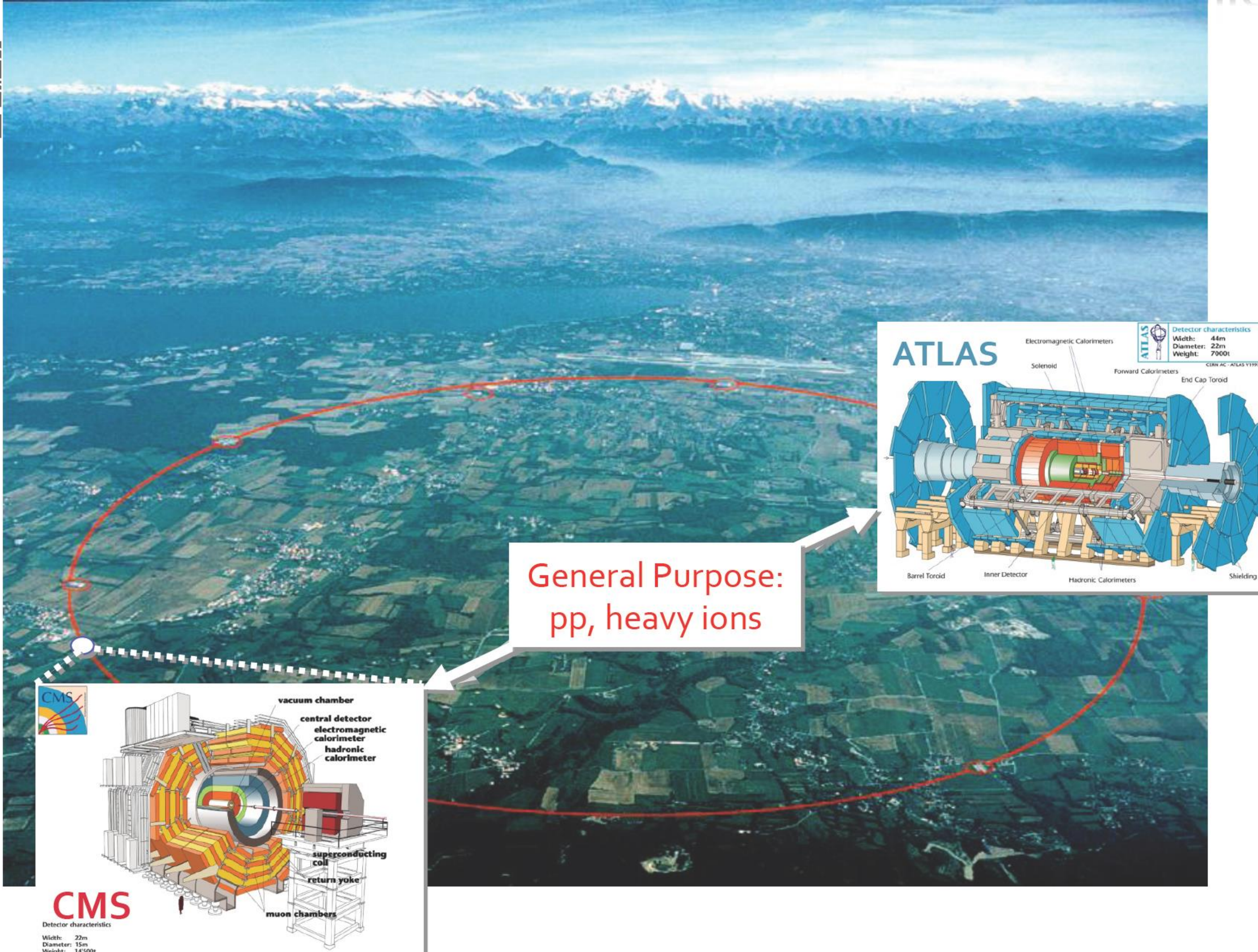
It’s Hot!

In a *tiny* volume, temperatures one billion times hotter than the center of the sun.



The Experiments

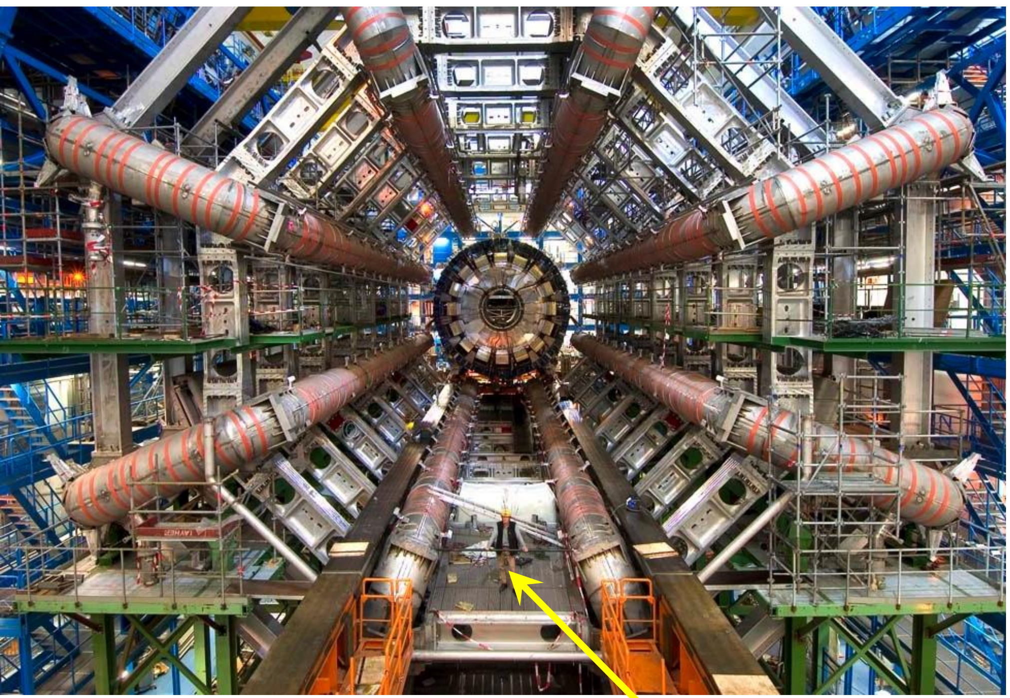


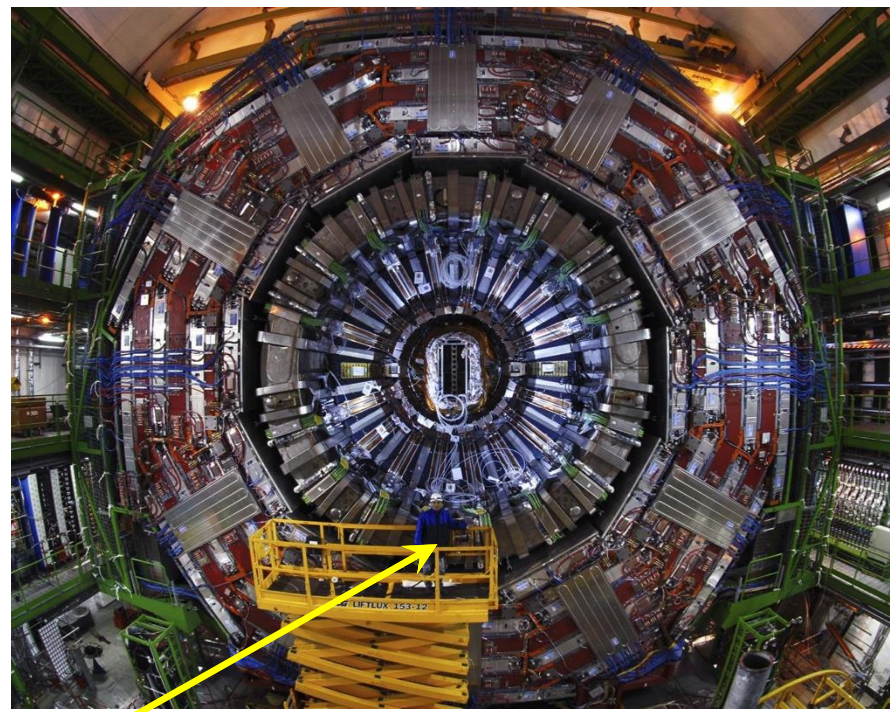

General Purpose:
pp, heavy ions
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t

It’s huge!

Largest, most complex detectors ever built

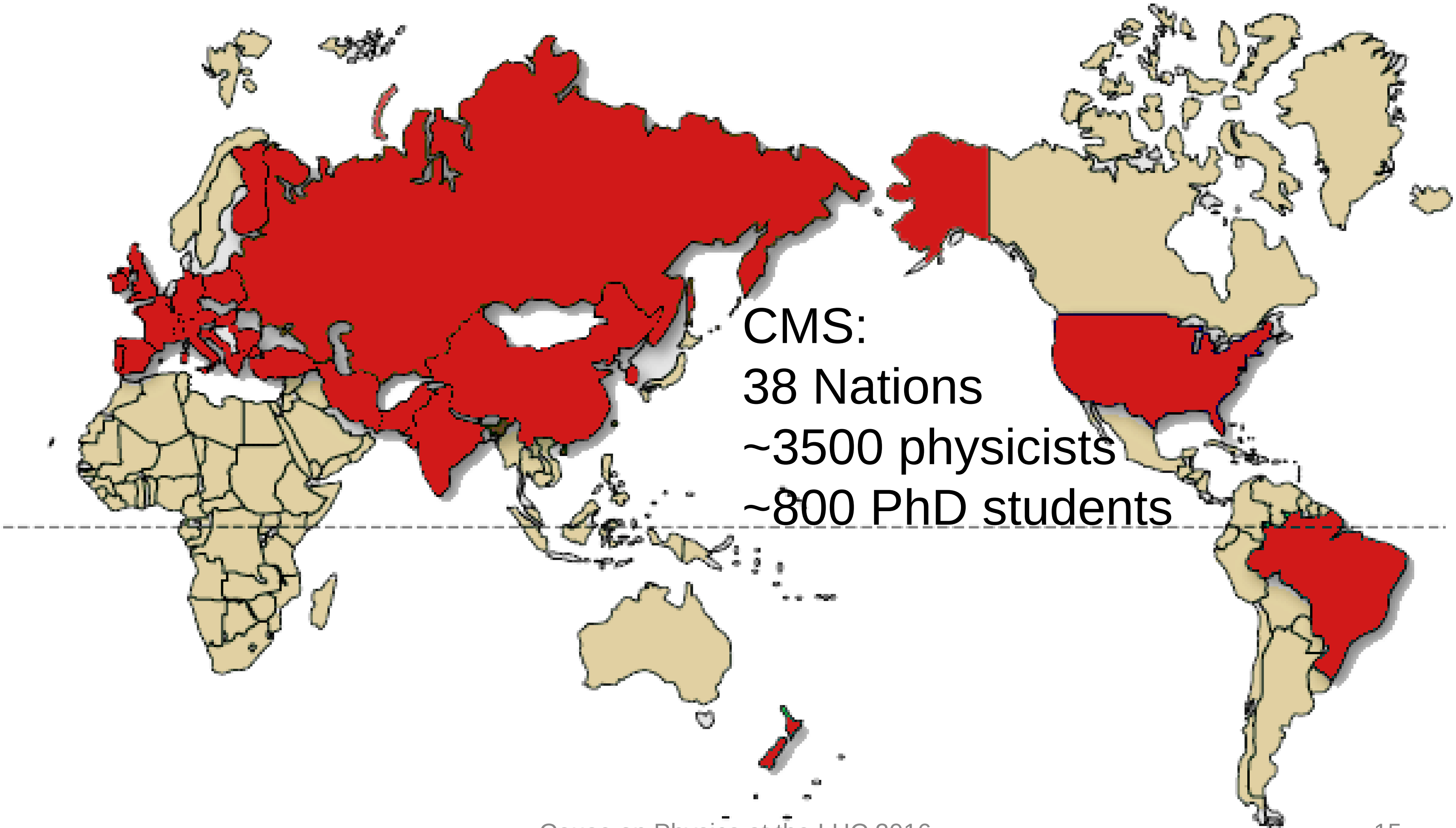
Study tiniest particles with incredible precision





(people)

World-wide collaborations



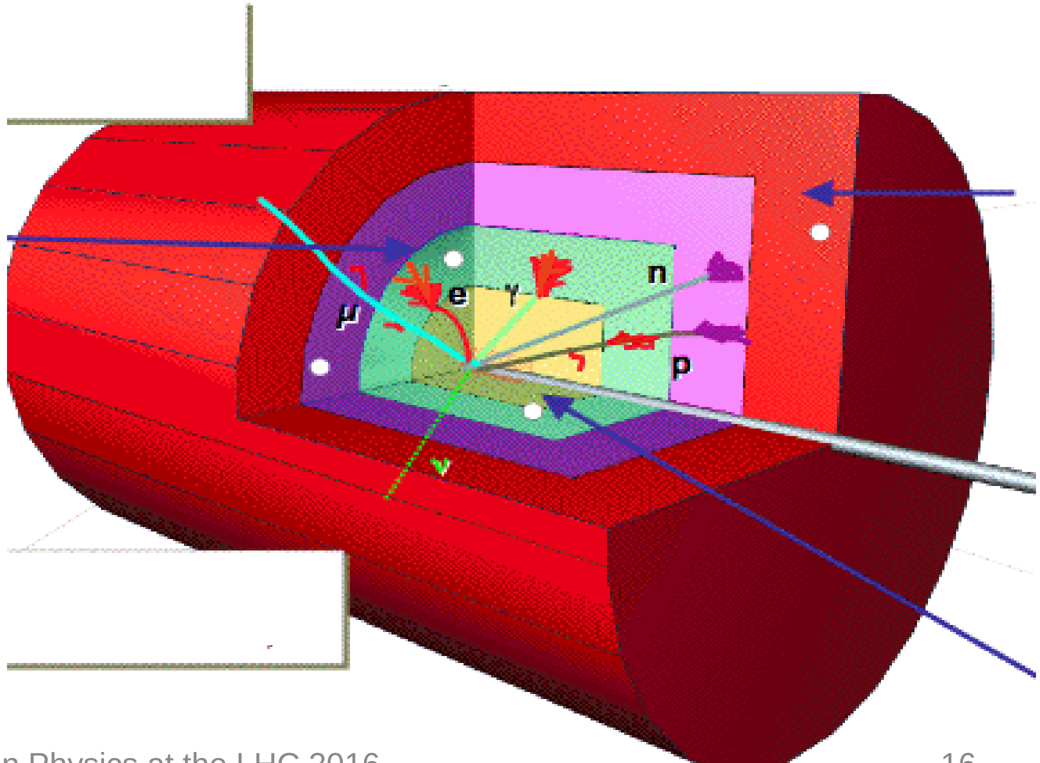
CMS:
38 Nations
~3500 physicists
~800 PhD students

General purpose LHC experiments

Advanced detectors comprising many layers, each designed to perform a specific task.

Together these layers allow to identify and precisely measure the energies of all stable particles produced in collisions.

Photons,
Electrons,
Muons,
Quarks
    (as jets of particles)
Neutrinos
    (as missing energy)



Detector design

Design guided by physics

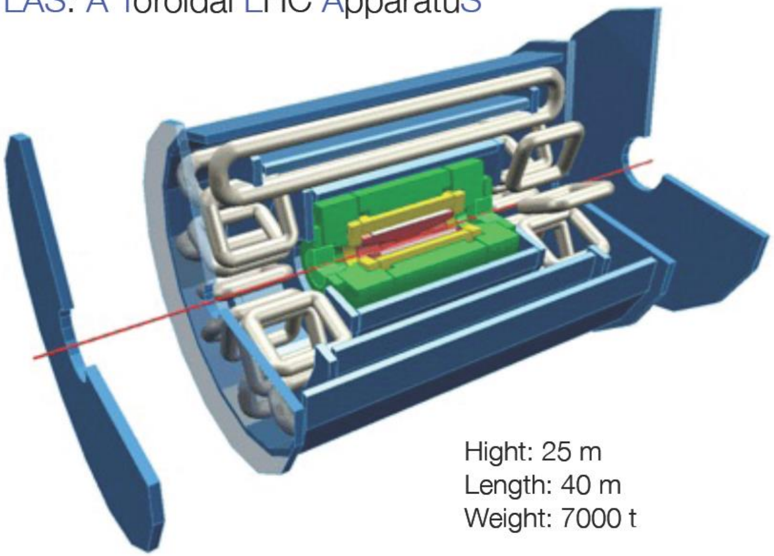
Search and measure the Higgs boson

Search and measure Supersymmetry

Search for any other new physics at high p_T

Two concepts

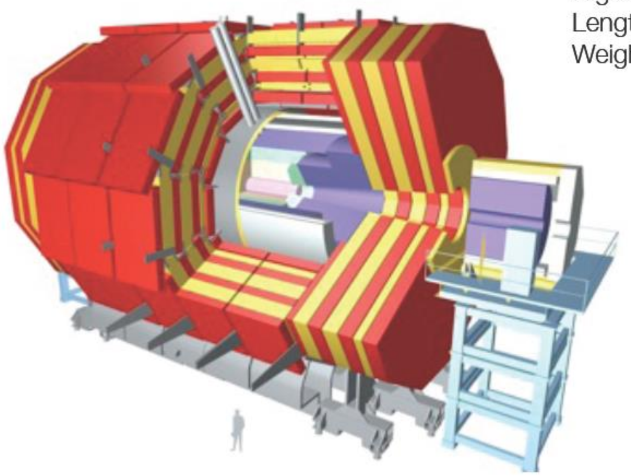
ATLAS: A Toroidal LHC ApparatuS

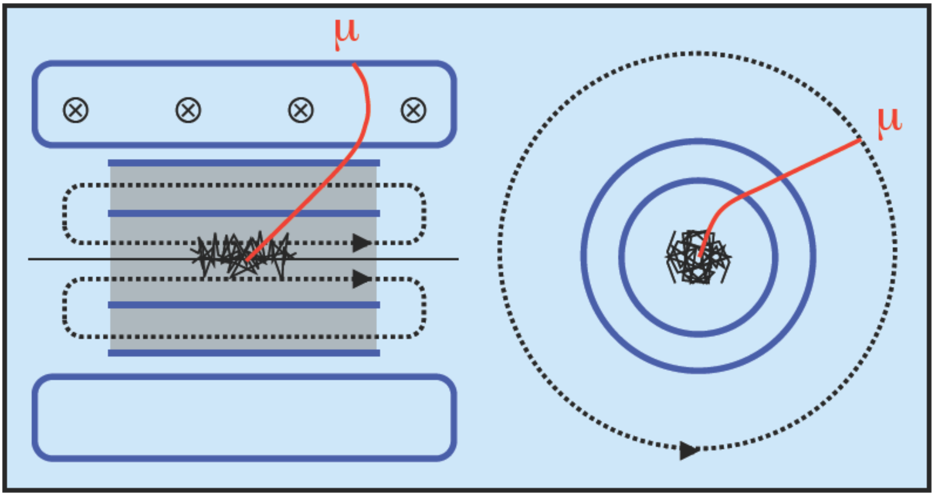


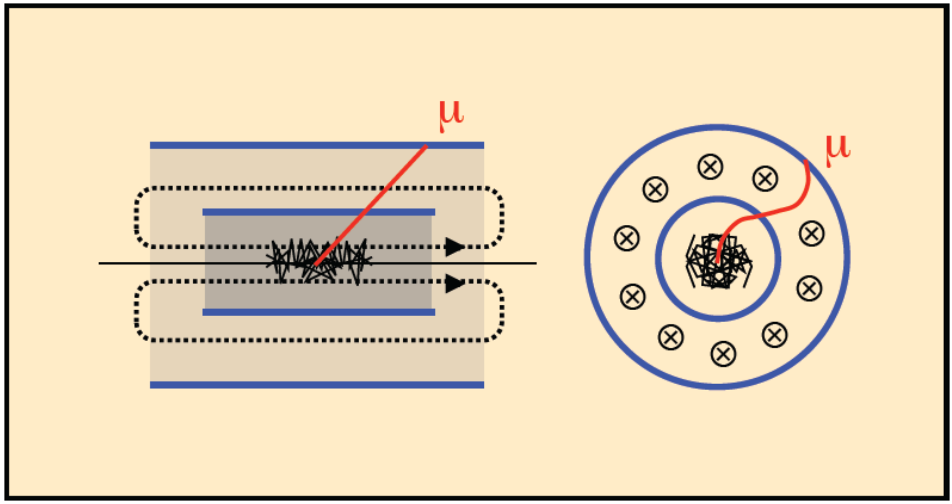
Hight: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid

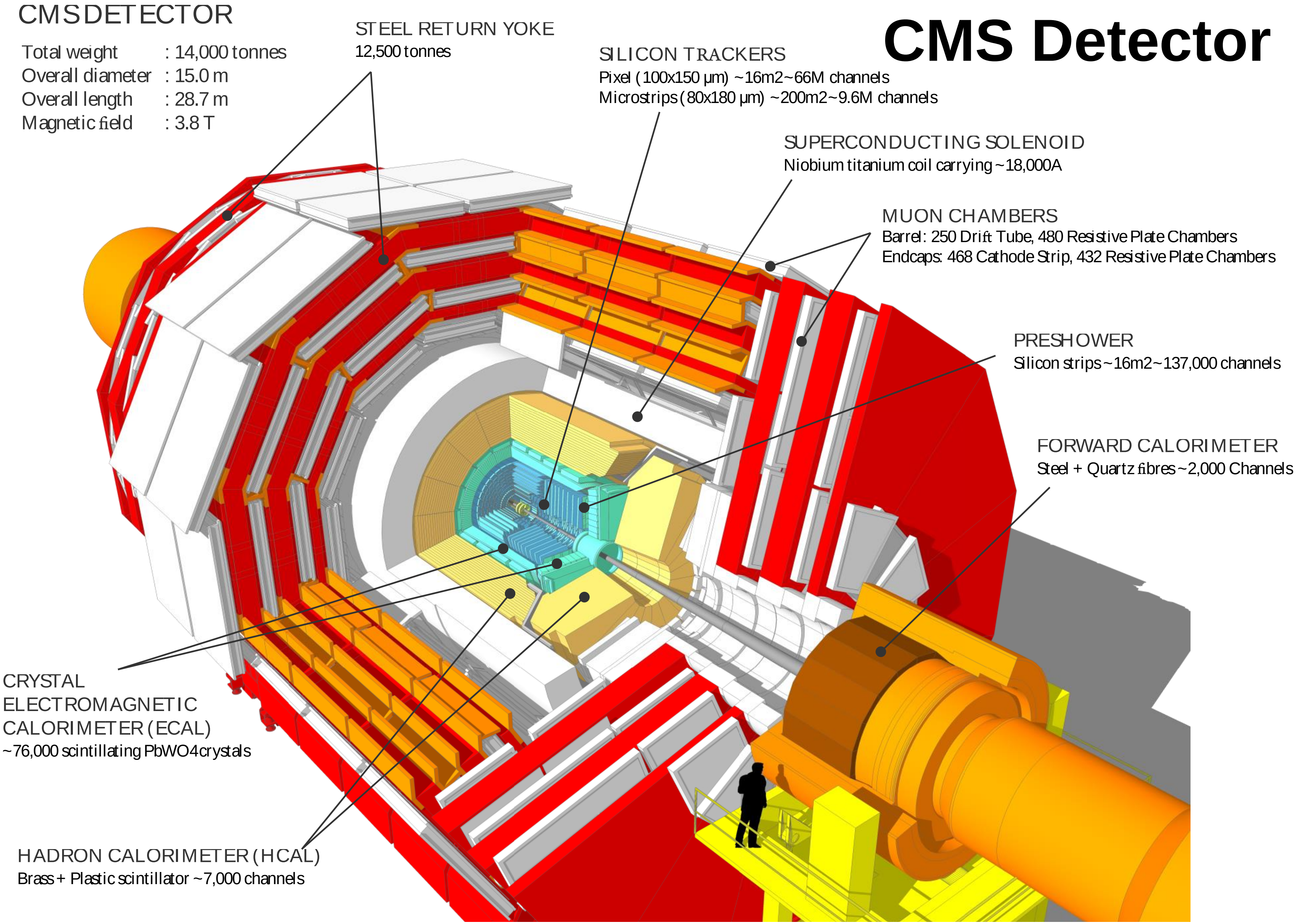
Hight: 15 m
Length: 22 m
Weight: 12500 t

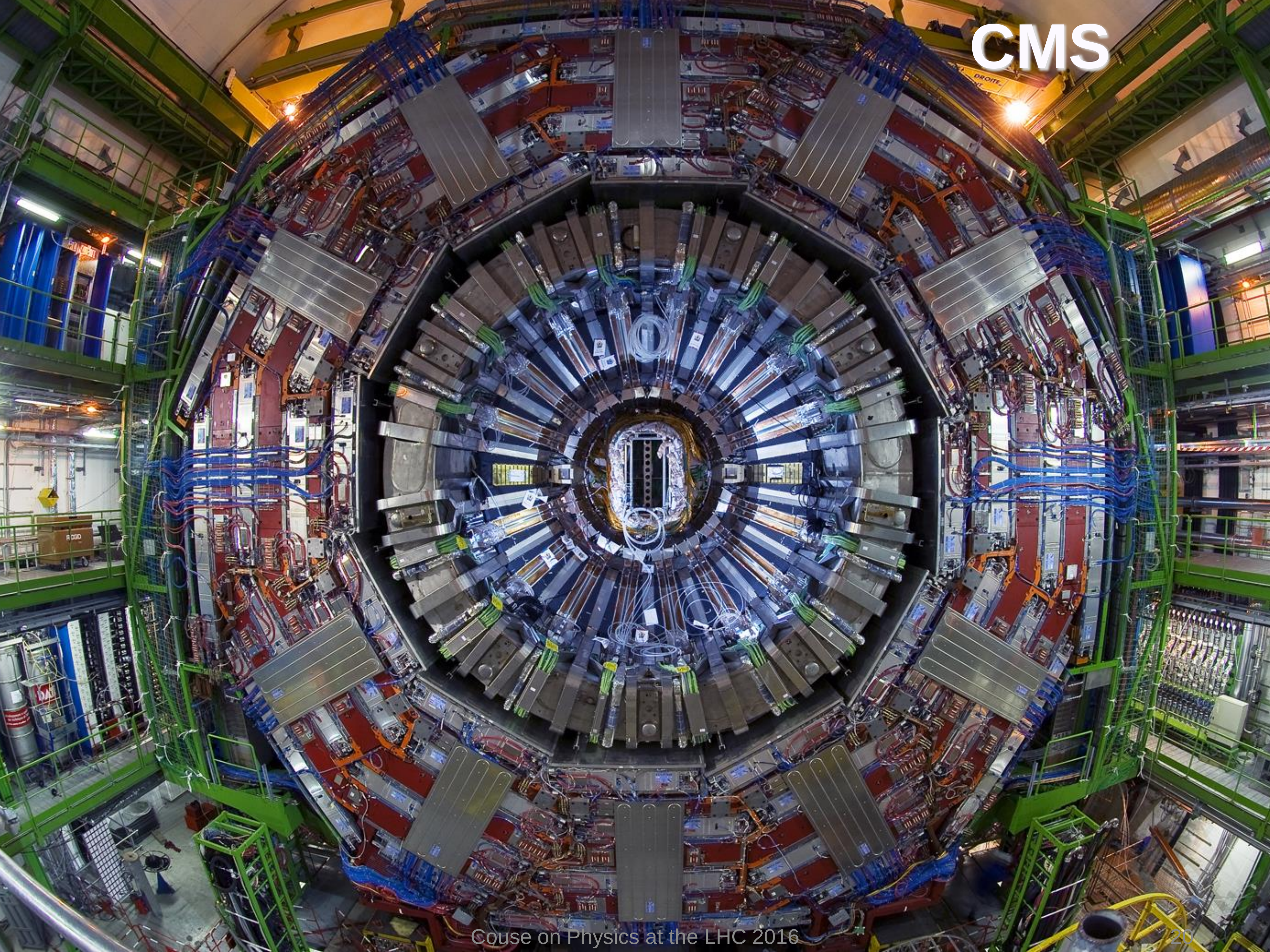




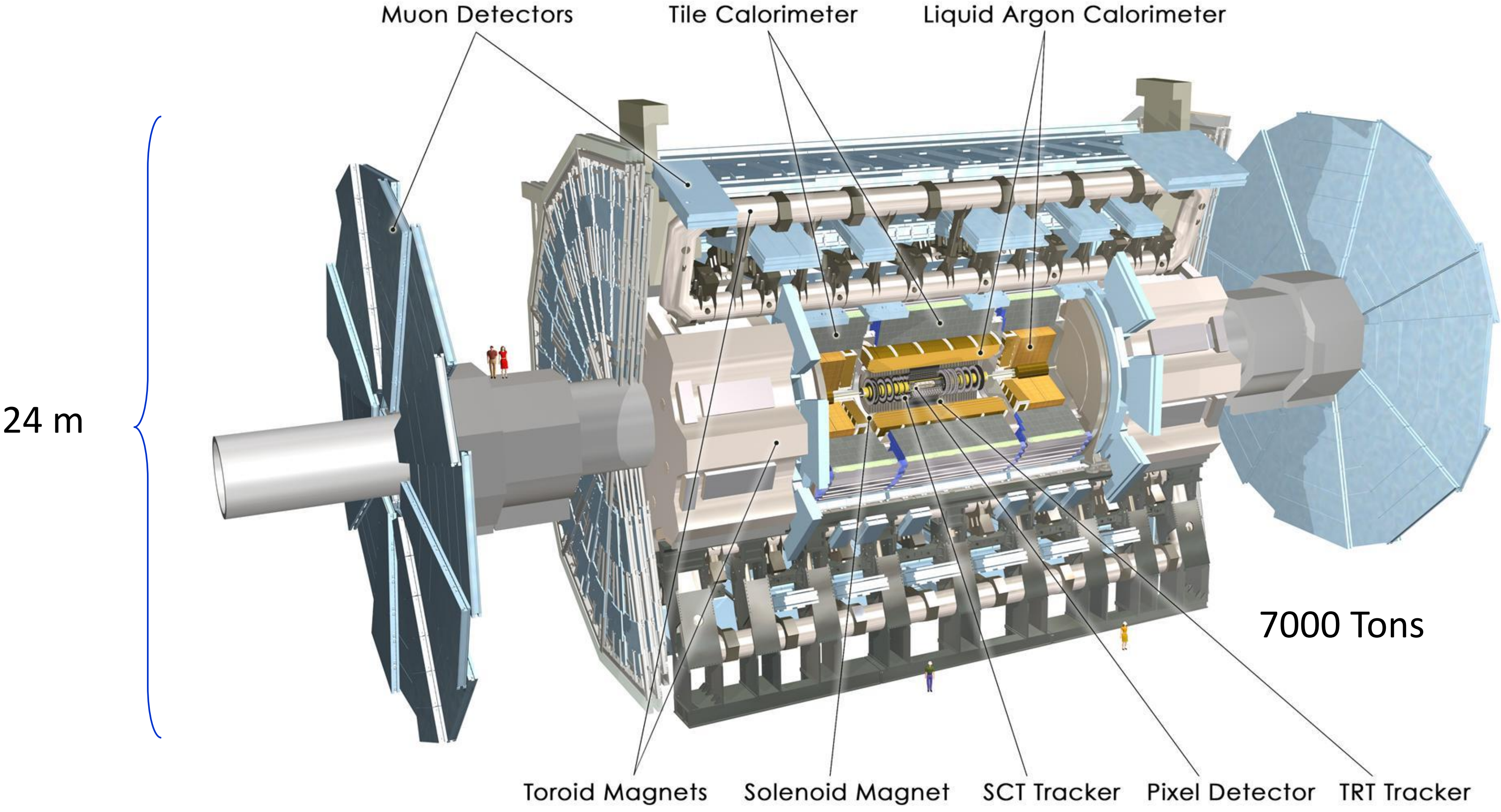


CMS Detector

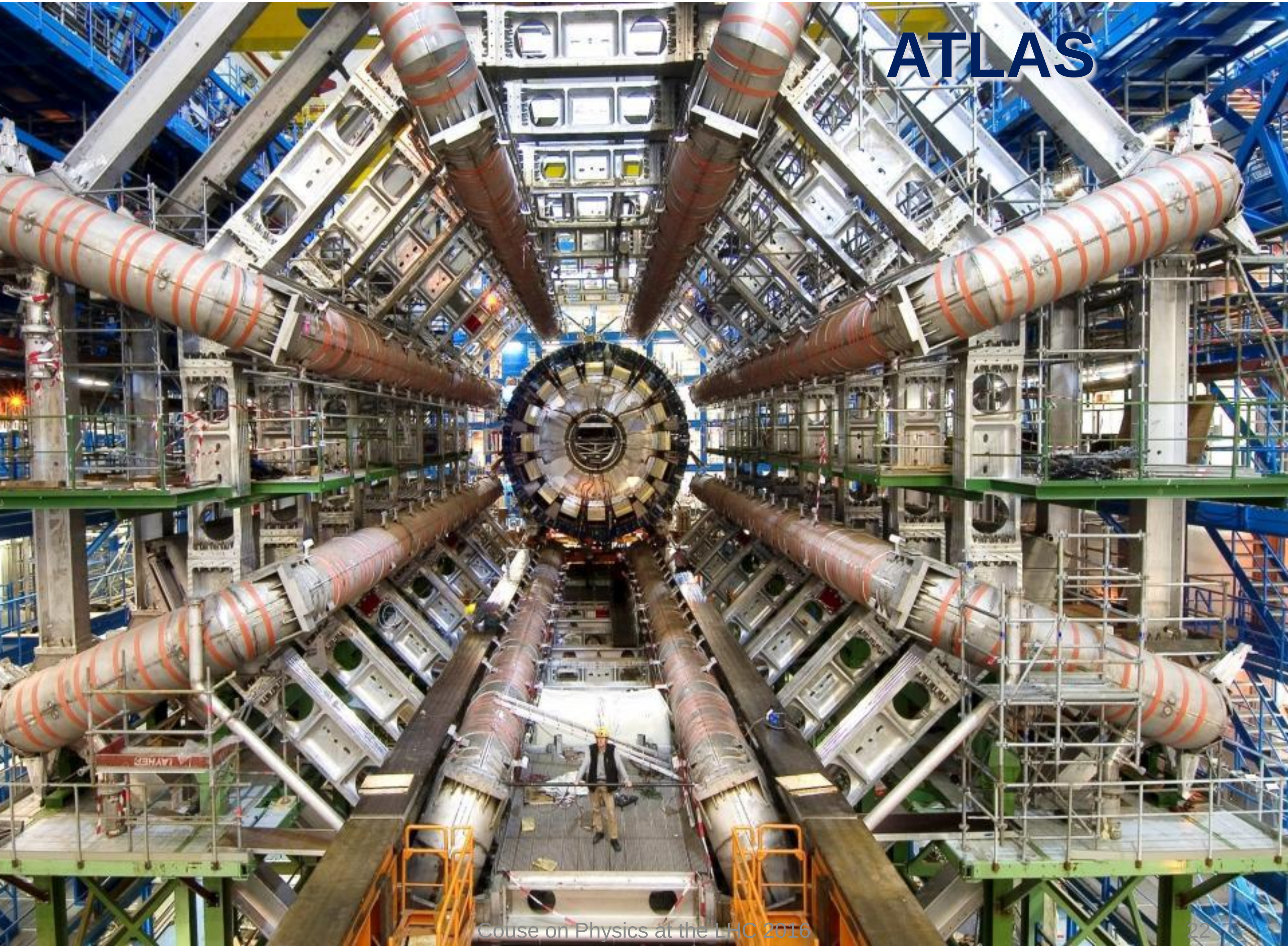



CMS

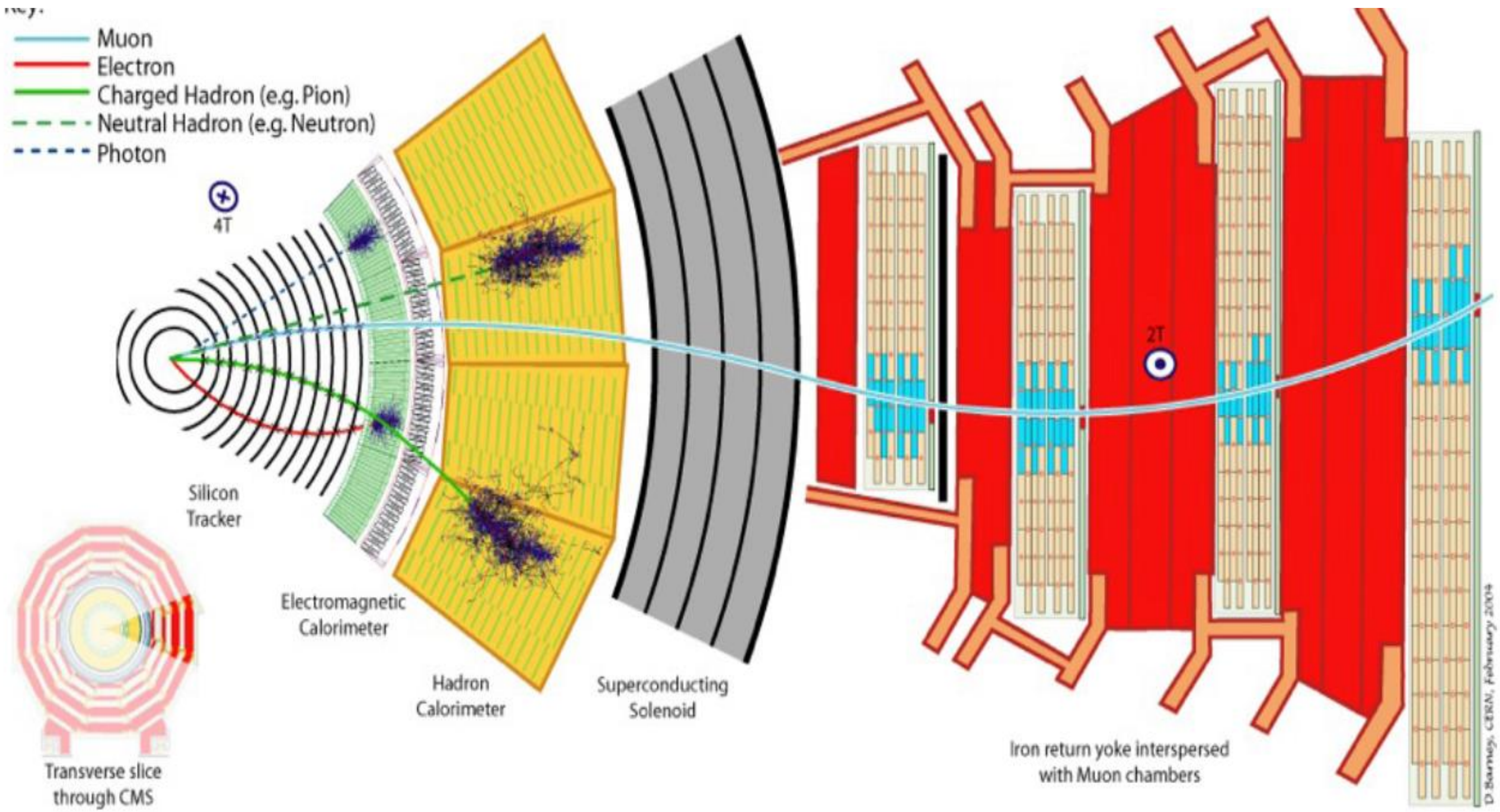
ATLAS detectors



ATLAS



Detection of hadrons, e$^{\pm}$, γ and $\mu^{\pm}$

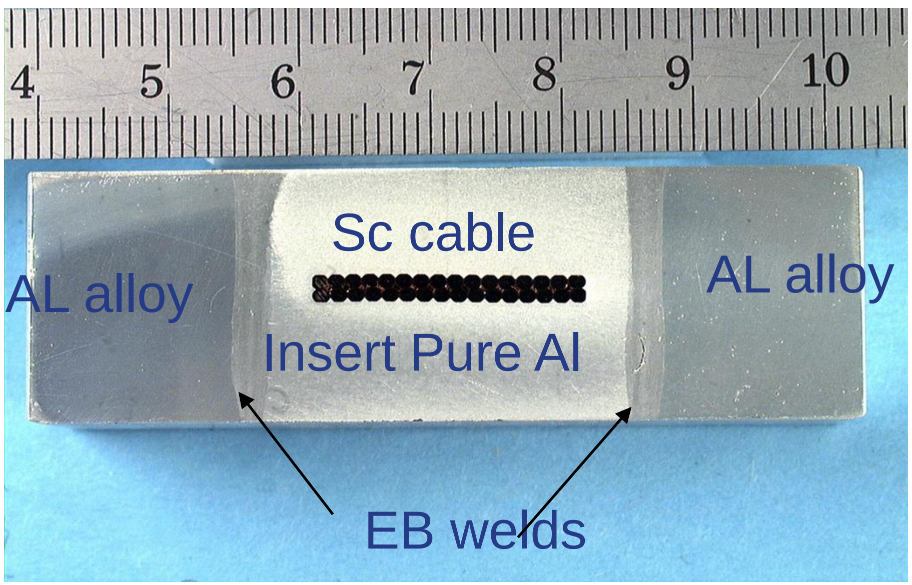


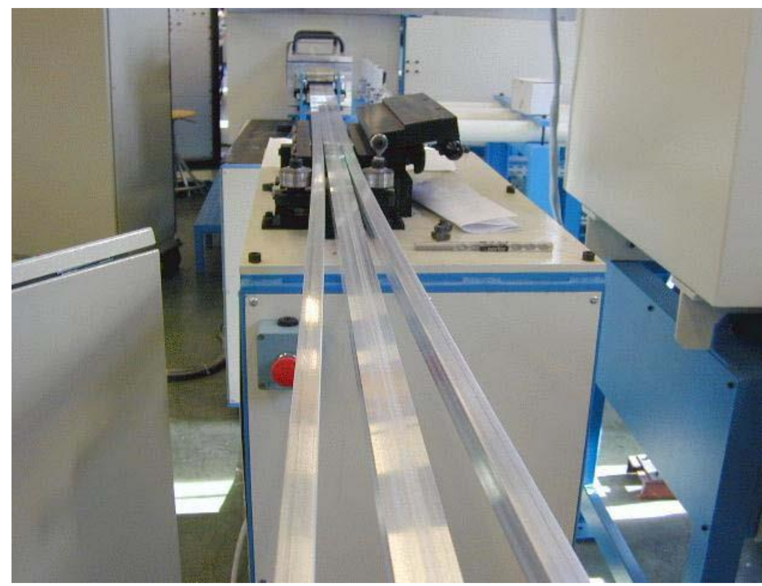
1993-2008: detector R&D and construction

Superconducting cable

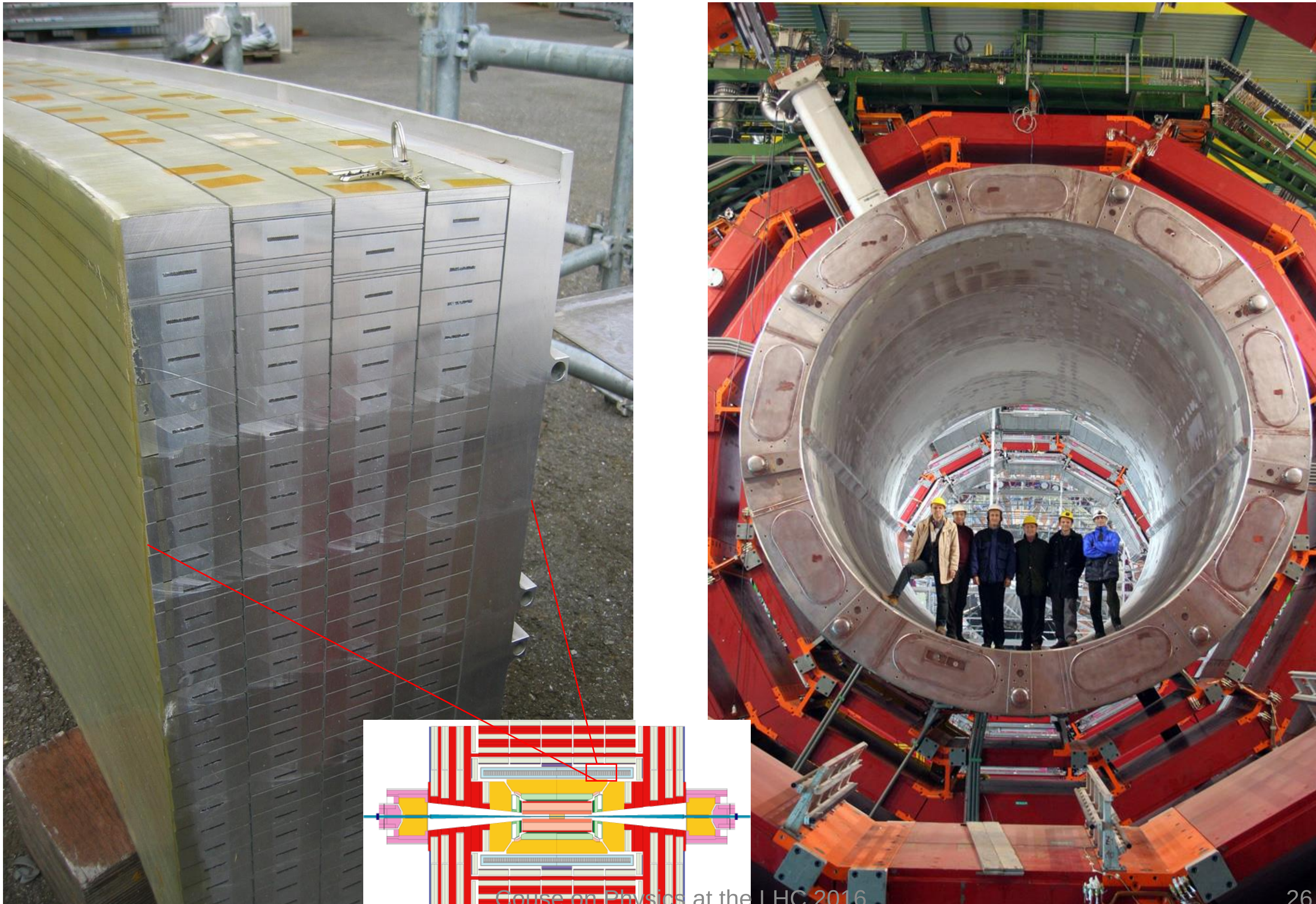
Al stabilized NbTi conductor.

Mechanically reinforced conductor to contain magnetic forces.

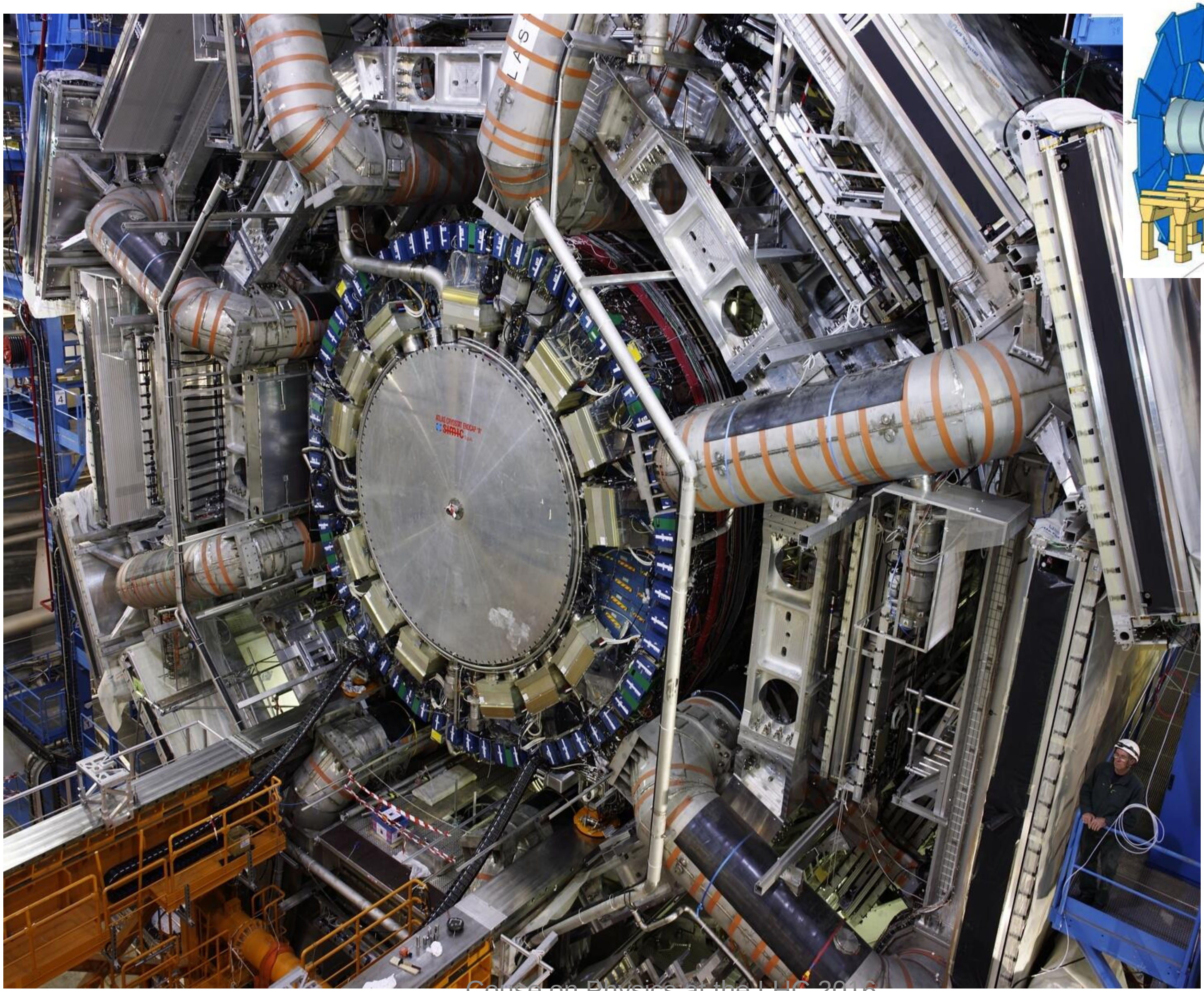


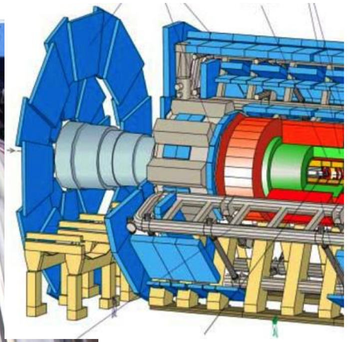


Superconductor solenoid at 3.8 Tesla

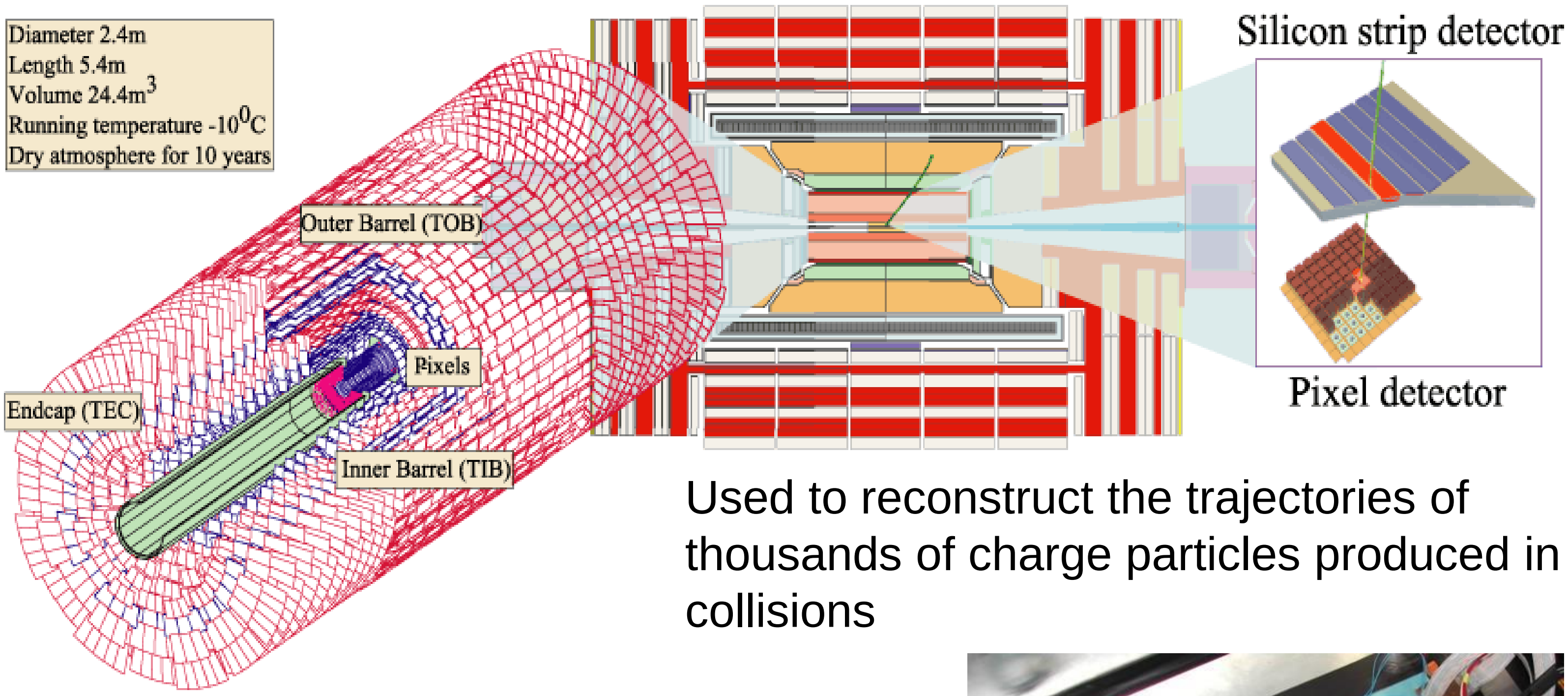


ATLAS Toroidal System



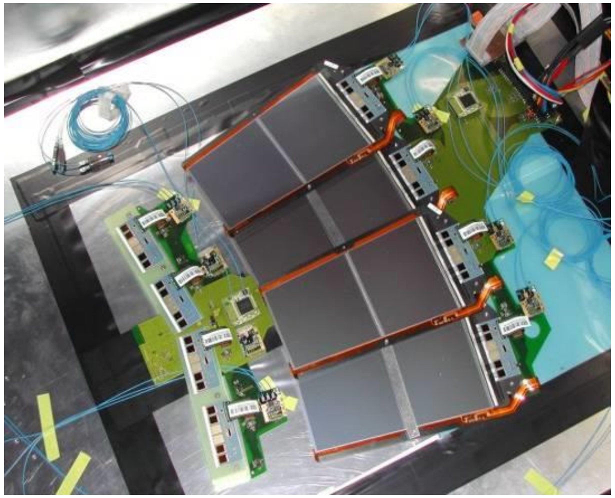


Silicon Tracker

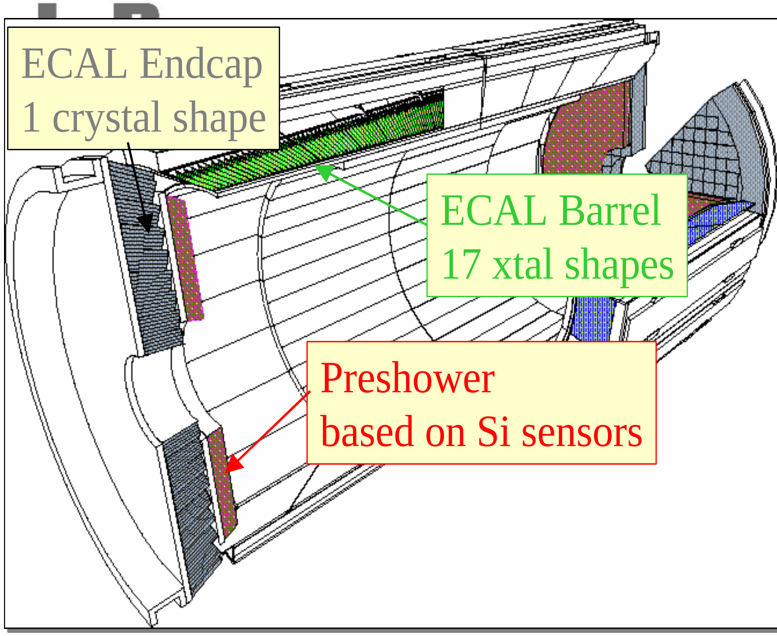


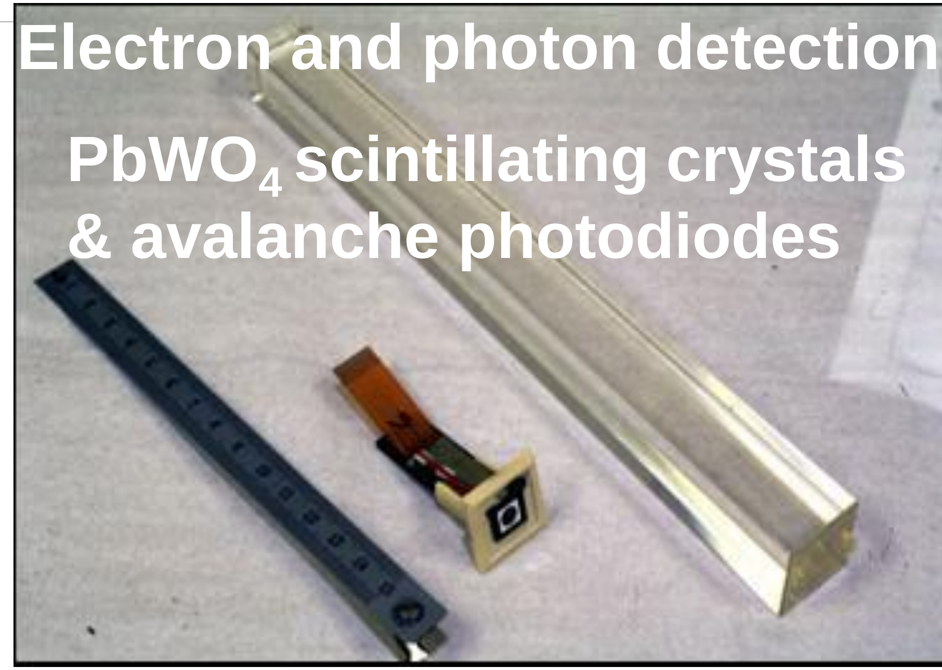
Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

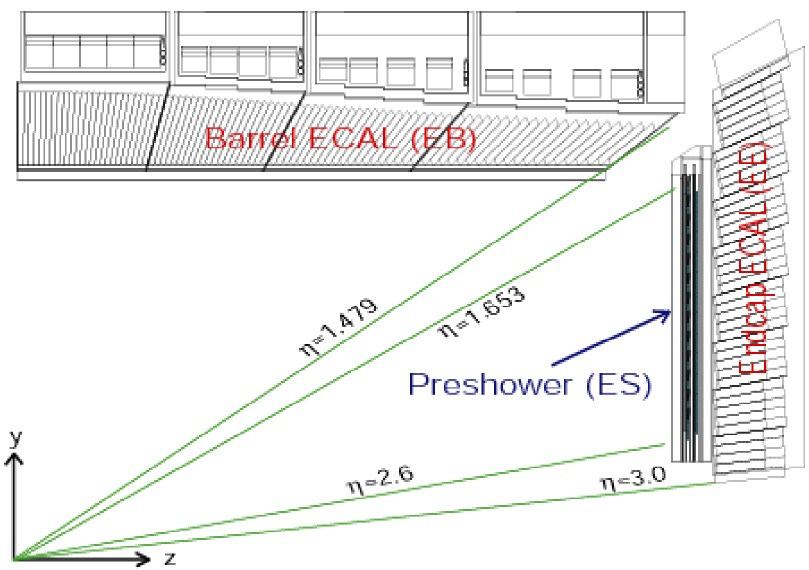
$214m^2$ silicon sensors
11.4 million silicon strips
65.9 million silicon pixels



ECAL Electromagnetic Calorimeter







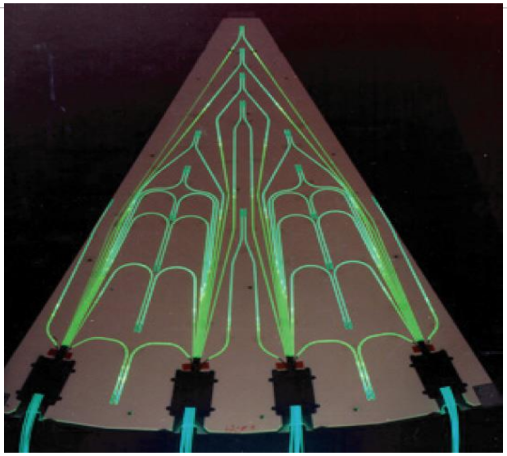
Design Goal: Measure the energies of photons from a decay of the Higgs boson **to precision of ≤ 0.5%**

Parameter	Barrel	Endcaps
# of crystals	**61200**	**14648**
Volume	**8.14m^3**	**2.7m^3**
Xtal mass (t)	**67.4**	**22.0**

HCAL Hadronic Calorimeter

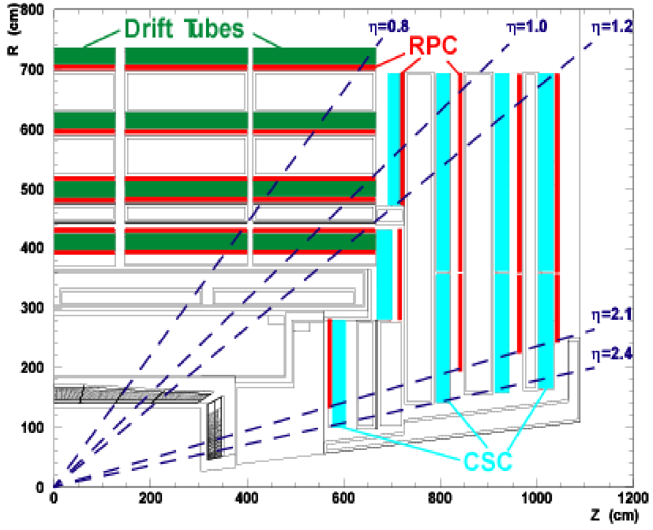
Detection of hadrons:

- protons, neutrons, peons, etc.

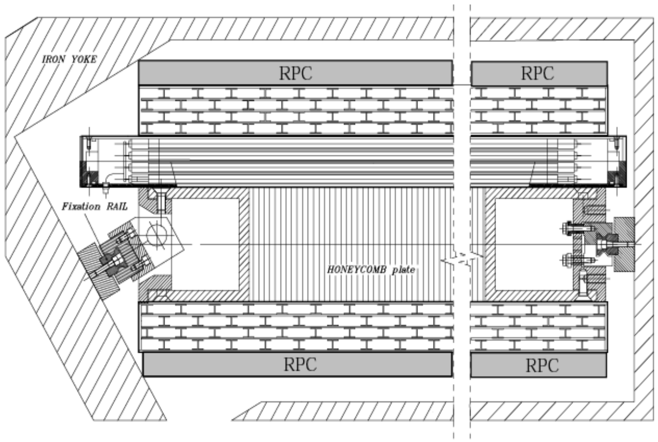


- CMS HCAL has three components:
  - Barrel HCAL (HB)
  - Endcap HCAL (HE)
  - Forward HCAL (HF)
- Plastic scintillator and brass
- Quartz fibers and steel

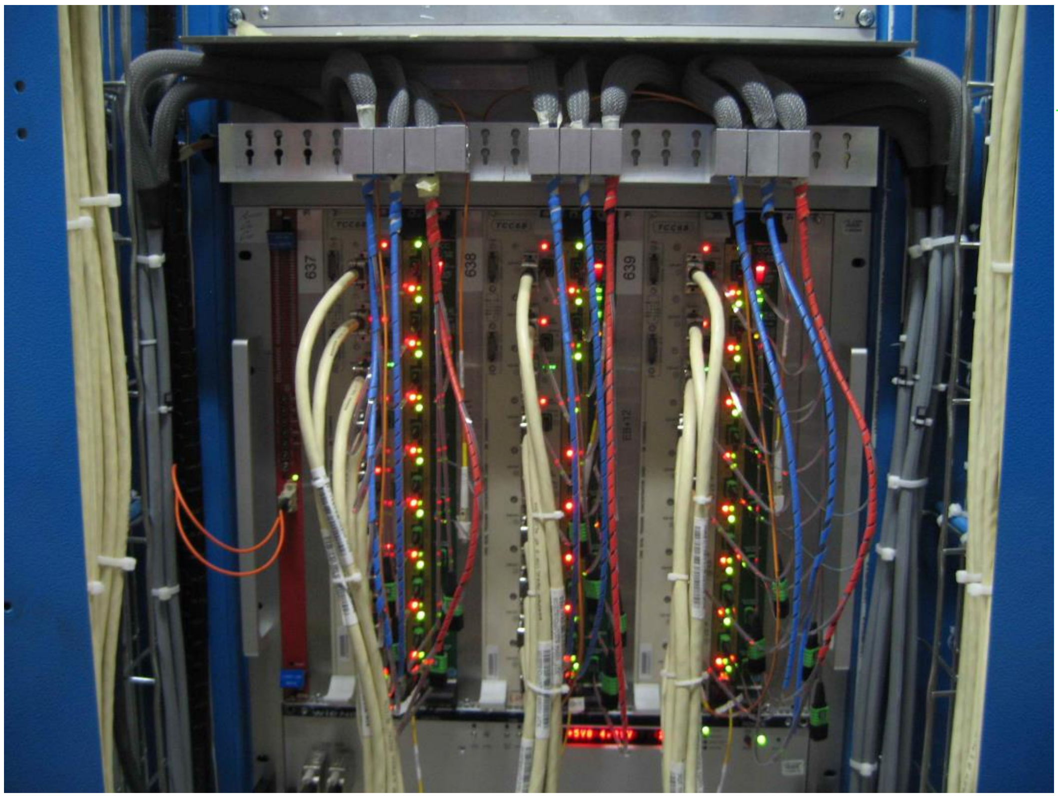
Muon detectors



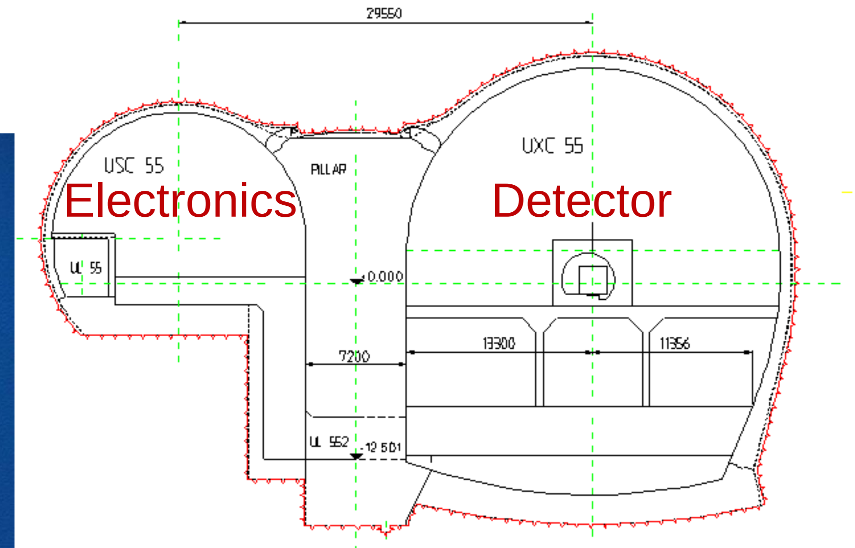
Drift Tubes (DT)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

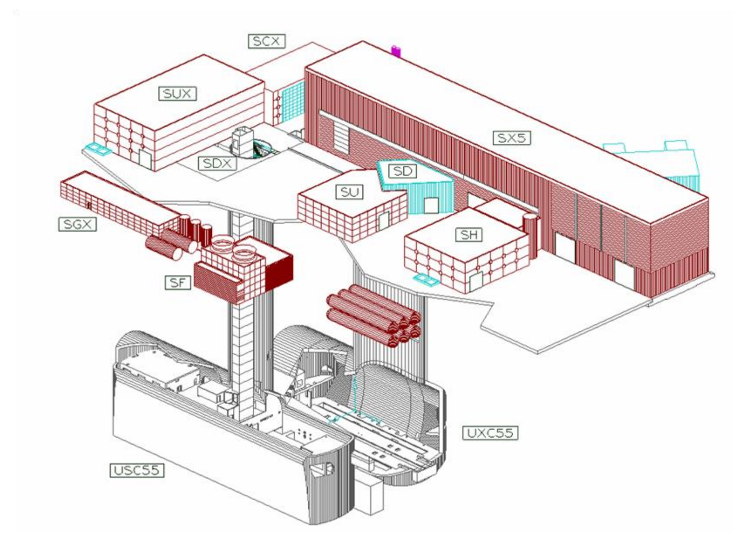


Trigger and readout electronics



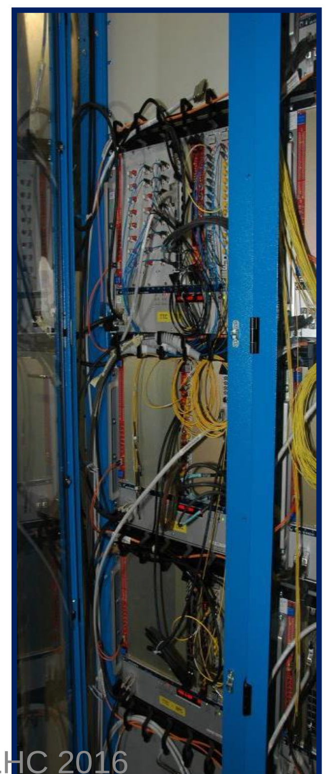
Underground caverns





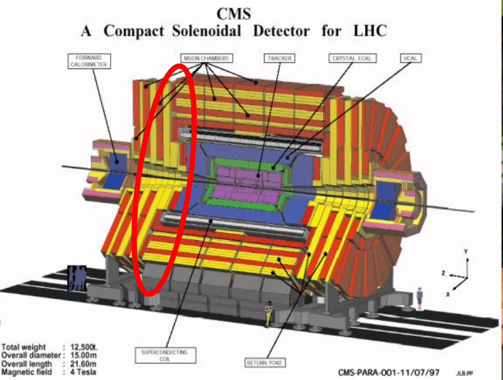
Electronics systems

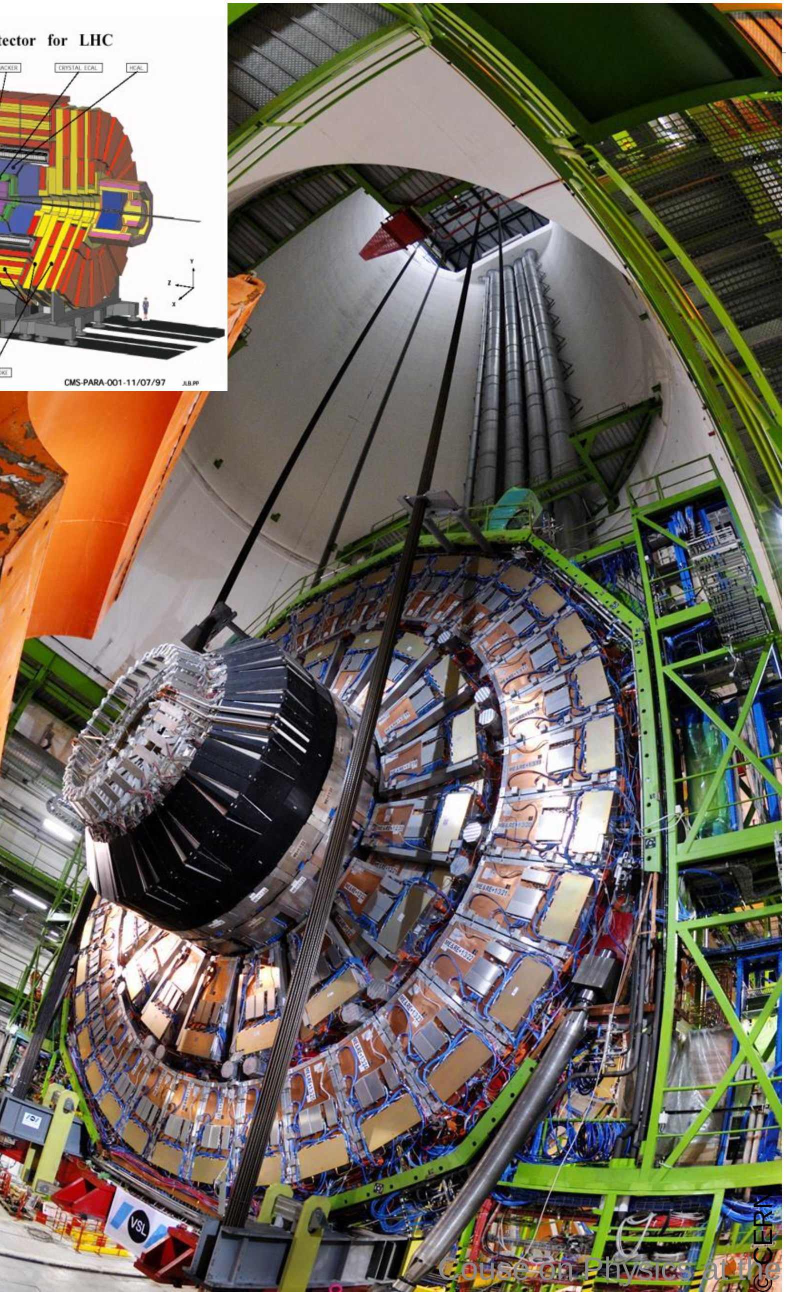
Electronics systems in the Service Cavern.
About 150 racks occupy two floors.
Most electronics was designed and built specifically for the experiment

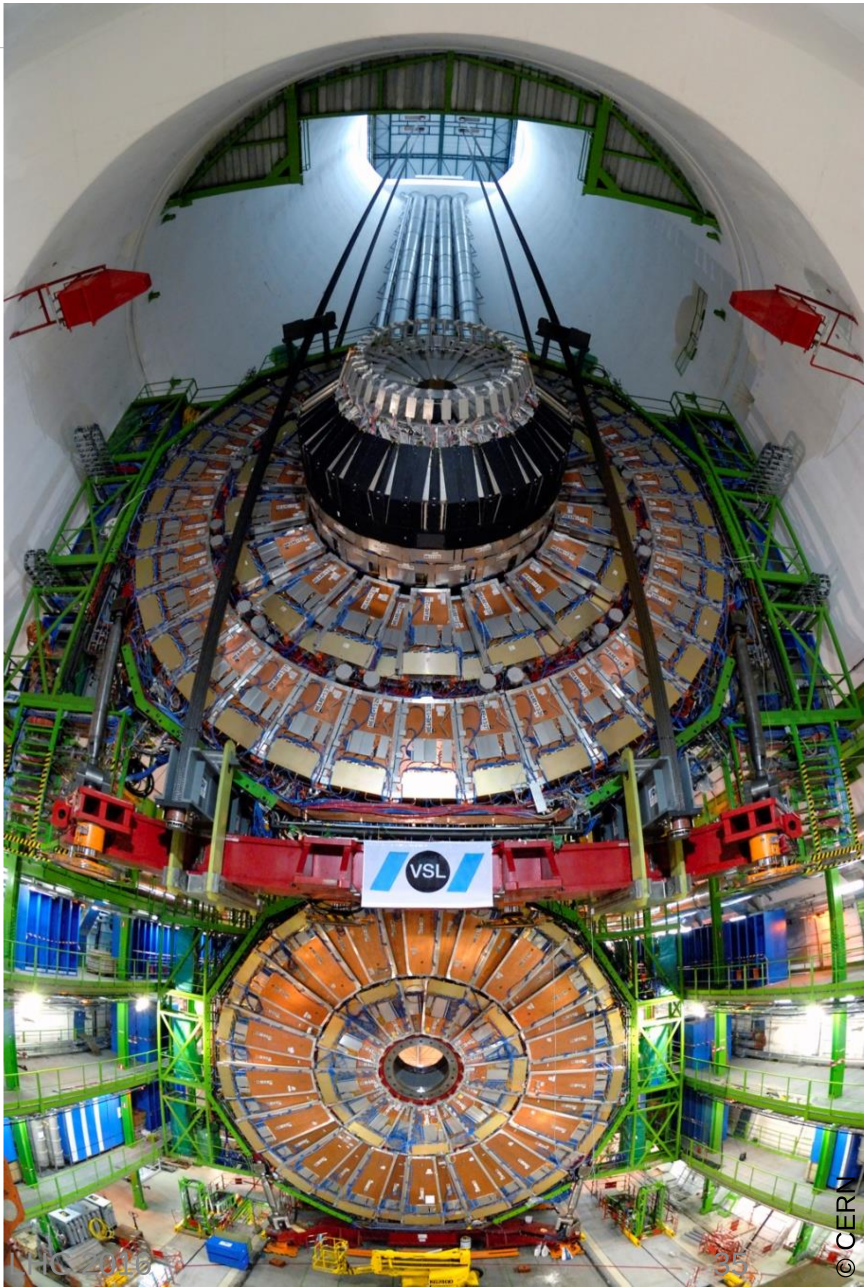


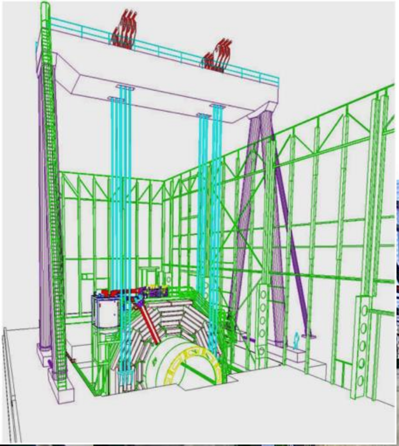
2004: CMS detector cavern

2007: Lowering one of six huge disks

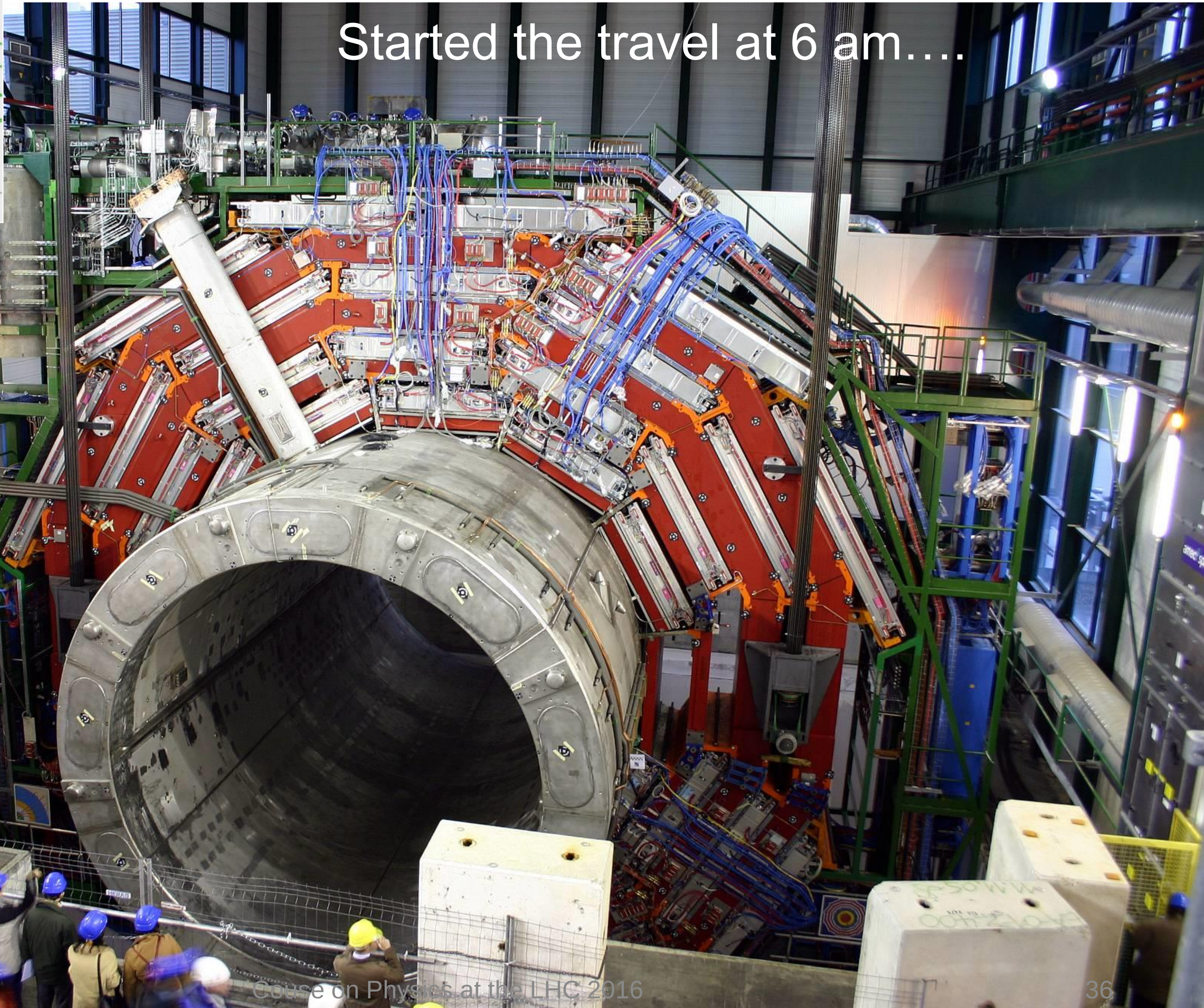






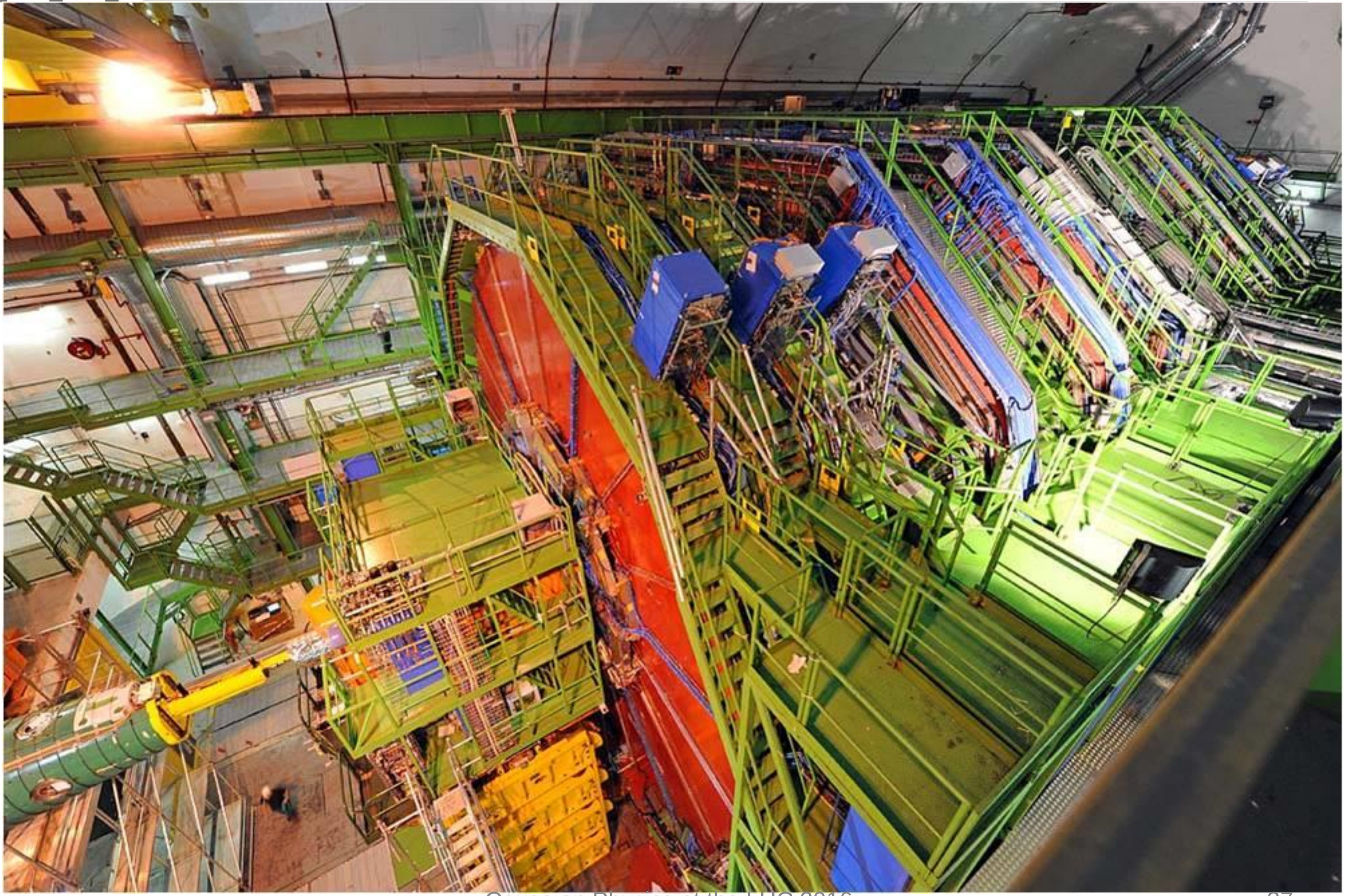


Feb 2007:lowering central “wheel”



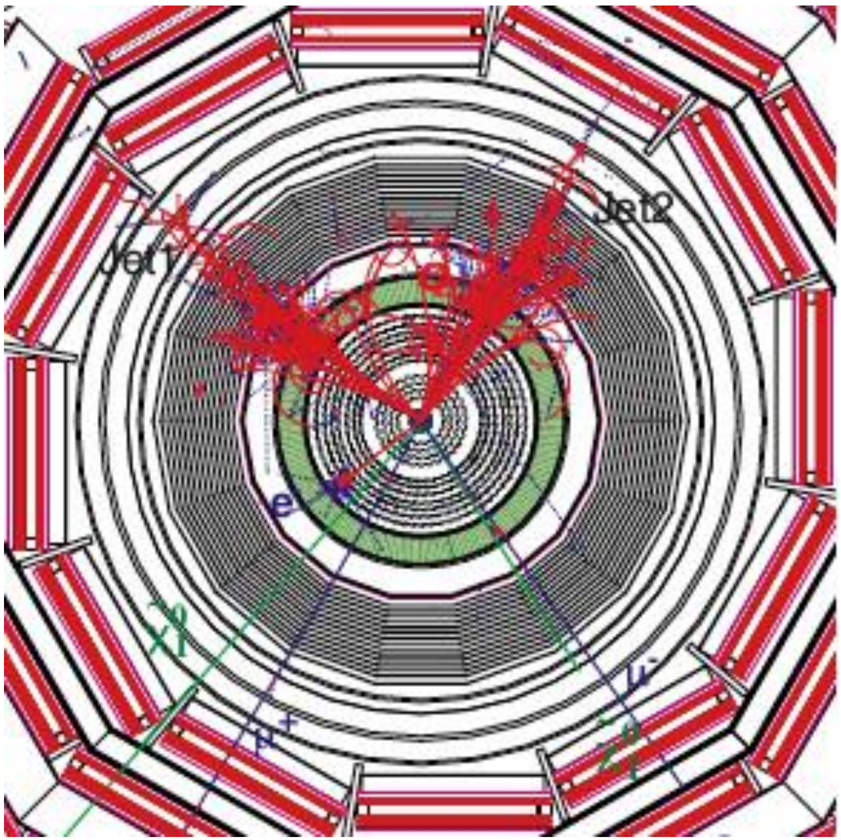
Started the travel at 6 am….

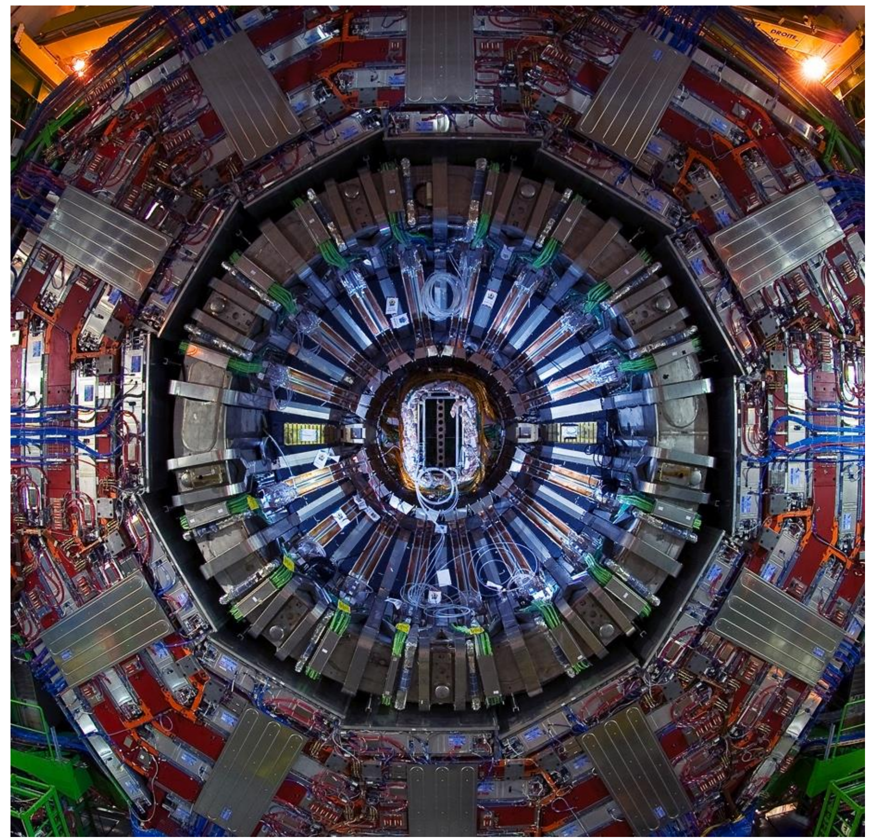
Sep 2008: CMS detector ready for beams



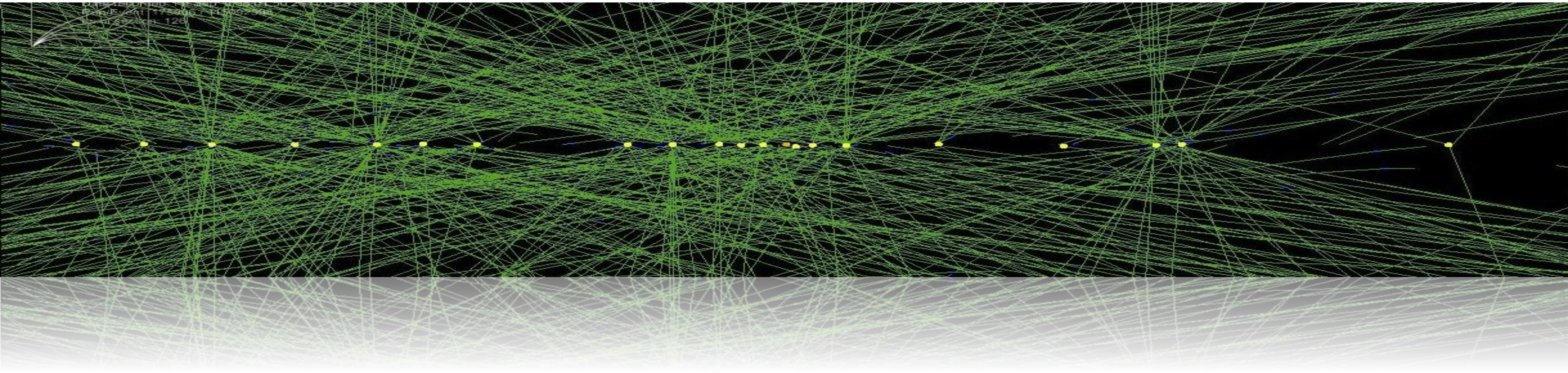
How did we prepare for discoveries?

Simulation of proton-proton collision
making two dark matter particles





Experimental challenges



High collision rate

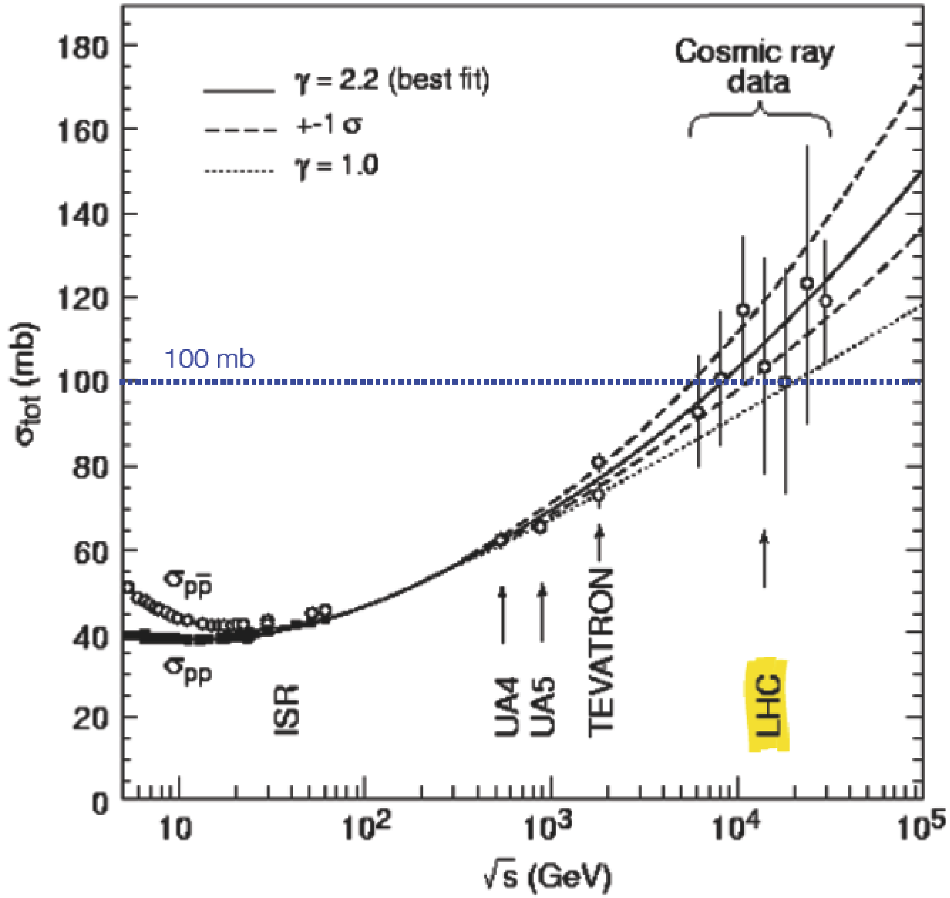
Luminosity:

$L = 10^{34}\ cm^{-2}s^{-1}$
$= 10^{7}$ Hz/mb

Cross section:

$\sigma \approx 100$ mb

➡ $N = L\sigma \approx 1$ GHz



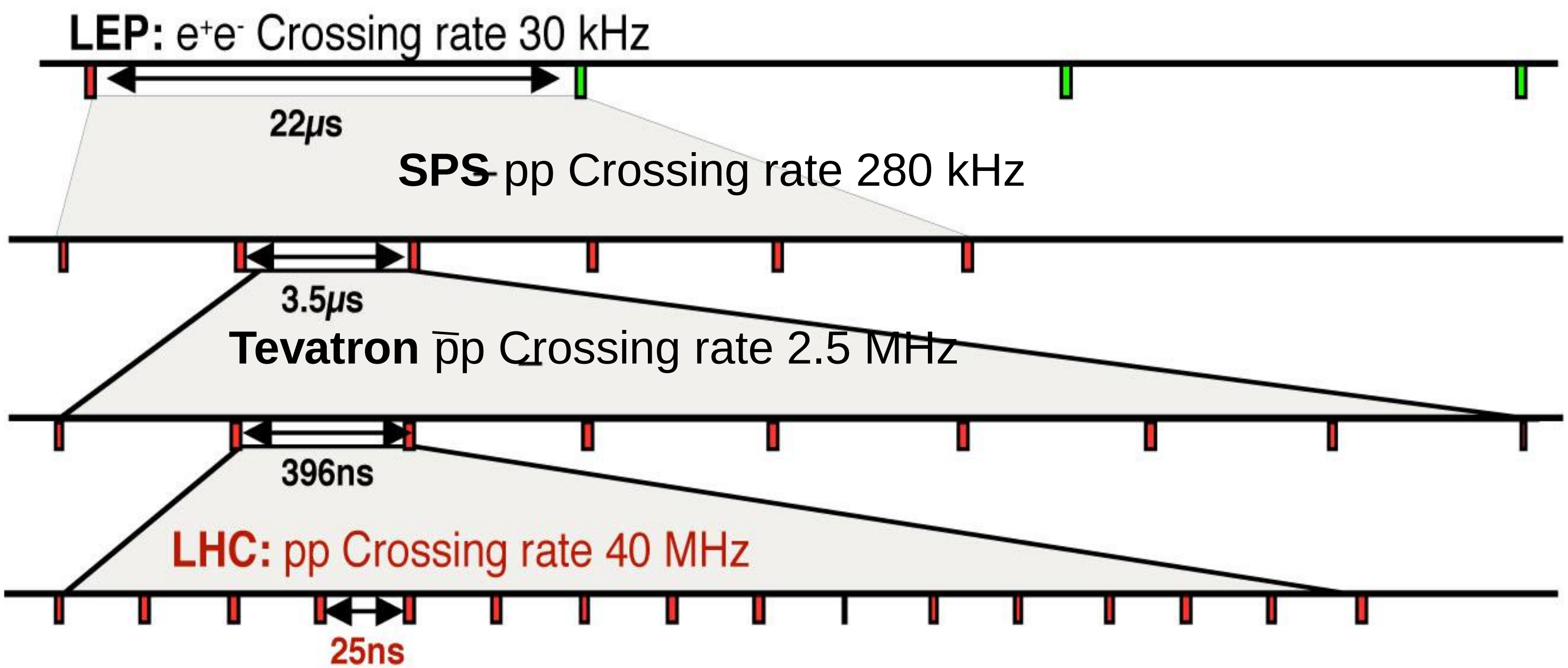
However:

Bunch crossing rate: 40 MHz
∴ Interactions/crossing ~ 25

This is a
real challenge !

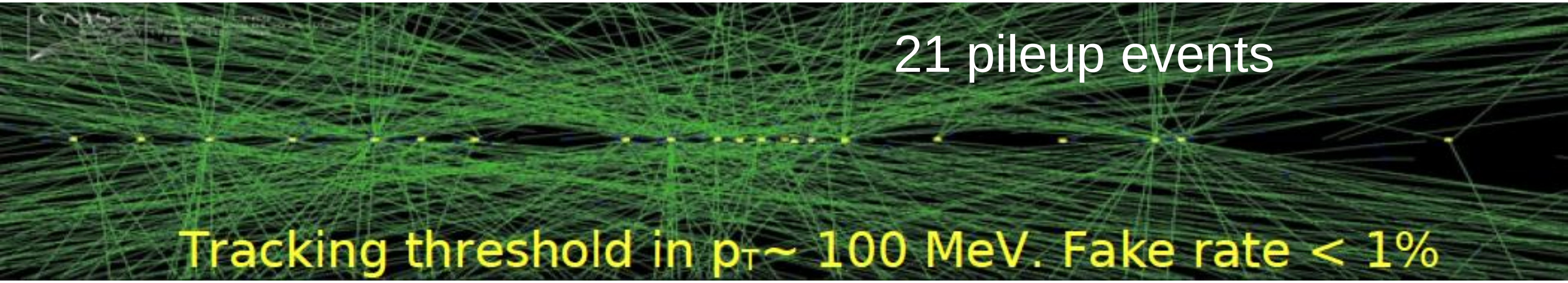
Bunch crossing frequency

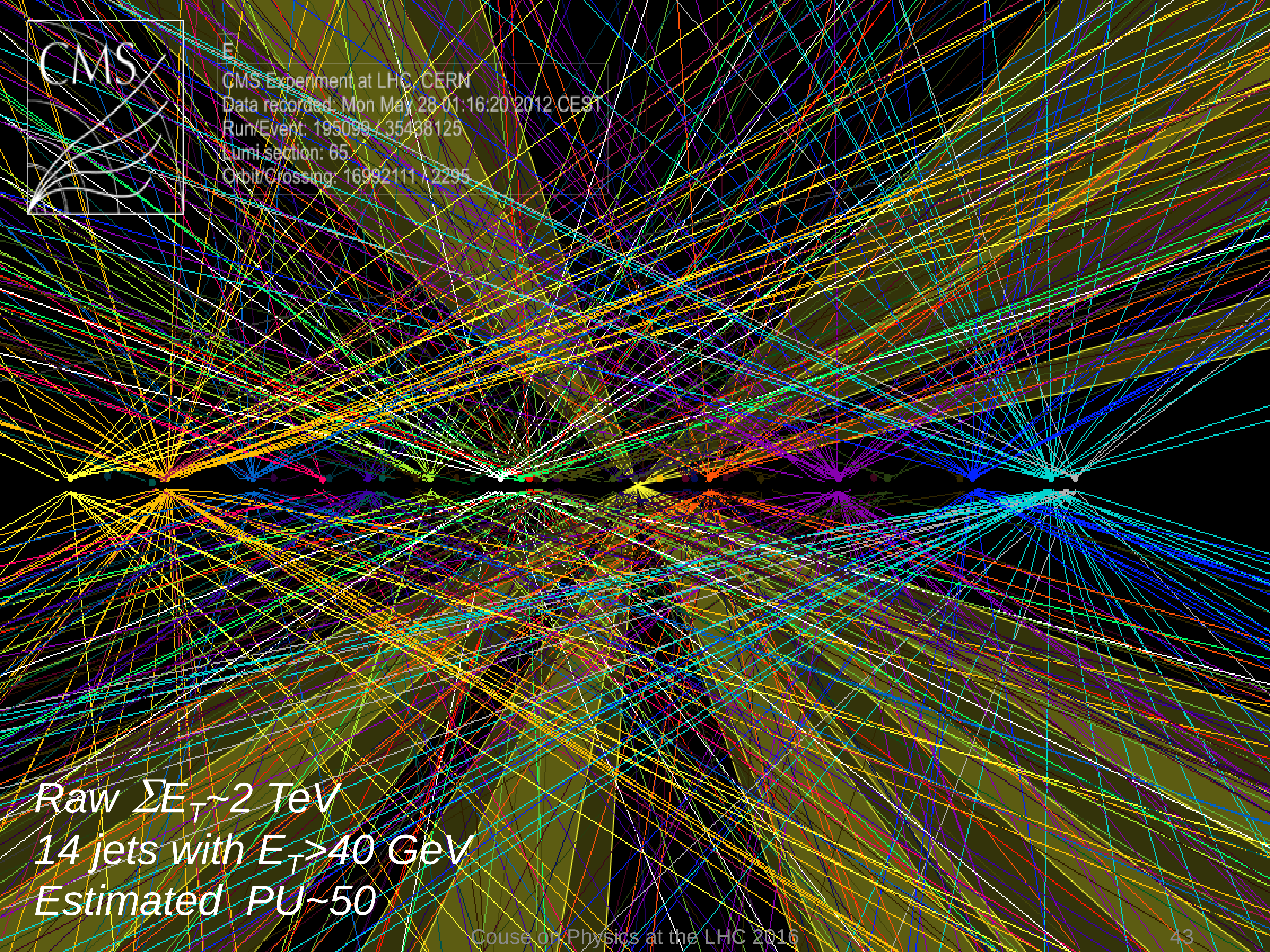
- LHC has 3564 bunches (2835 filled with protons)
- Crossing rate is 40 MHz
- Distance between bunches: 27km / 3600 = 7.5m
- Distance between bunches in time: 7.5m / c = 25ns
- Proton-proton collision per bunch crossing: ~ 25



Event pileup

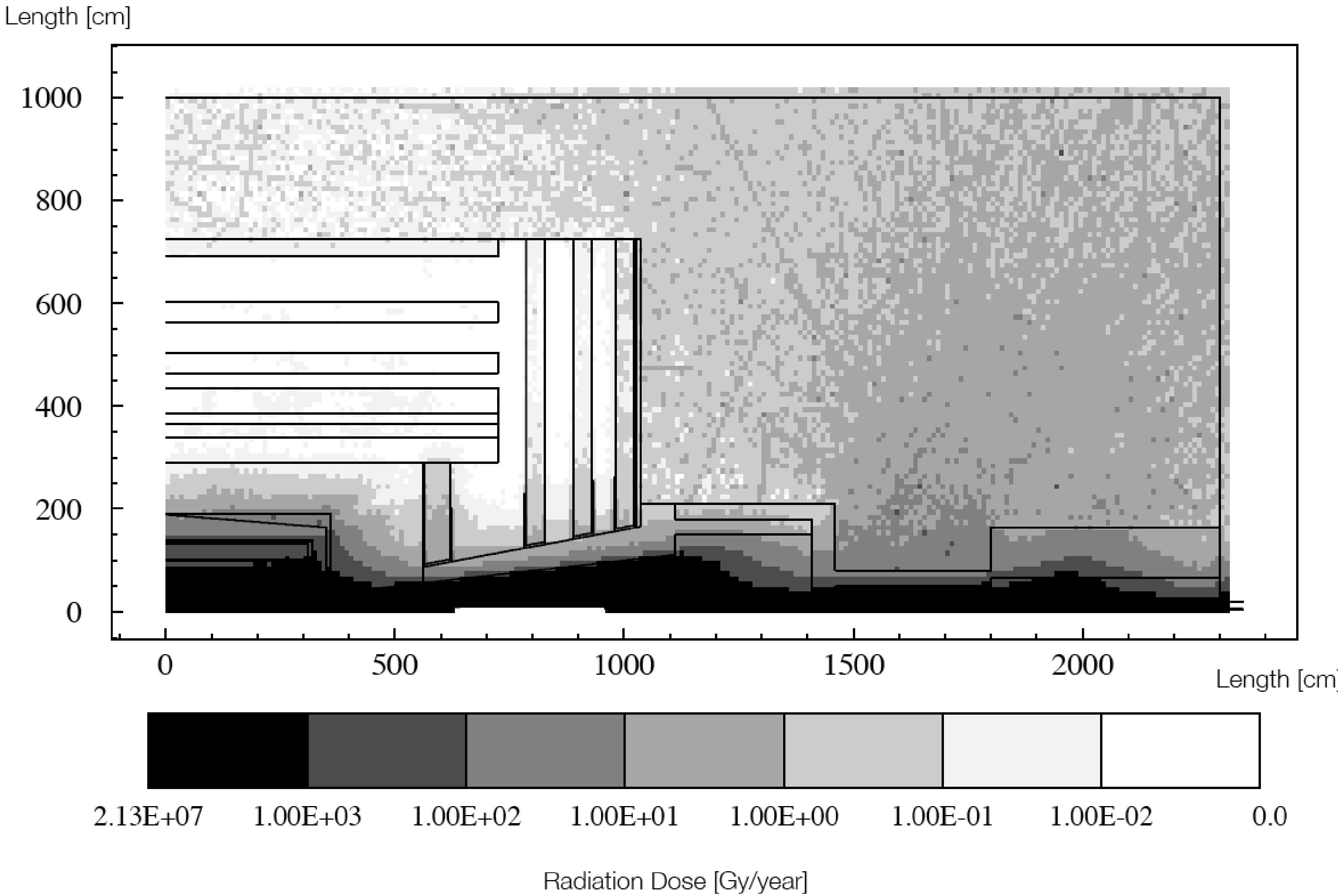
- Proton bunches have a cigar shape, about 5 cm long and 20 microns diameter
- Each bunch has 1.5 10^{11} protons
- At each crossing of bunches, about 25 collision occur
- The particles produced (30x25 = 750 charged particles) are “seen” by the detector as a single image (event)



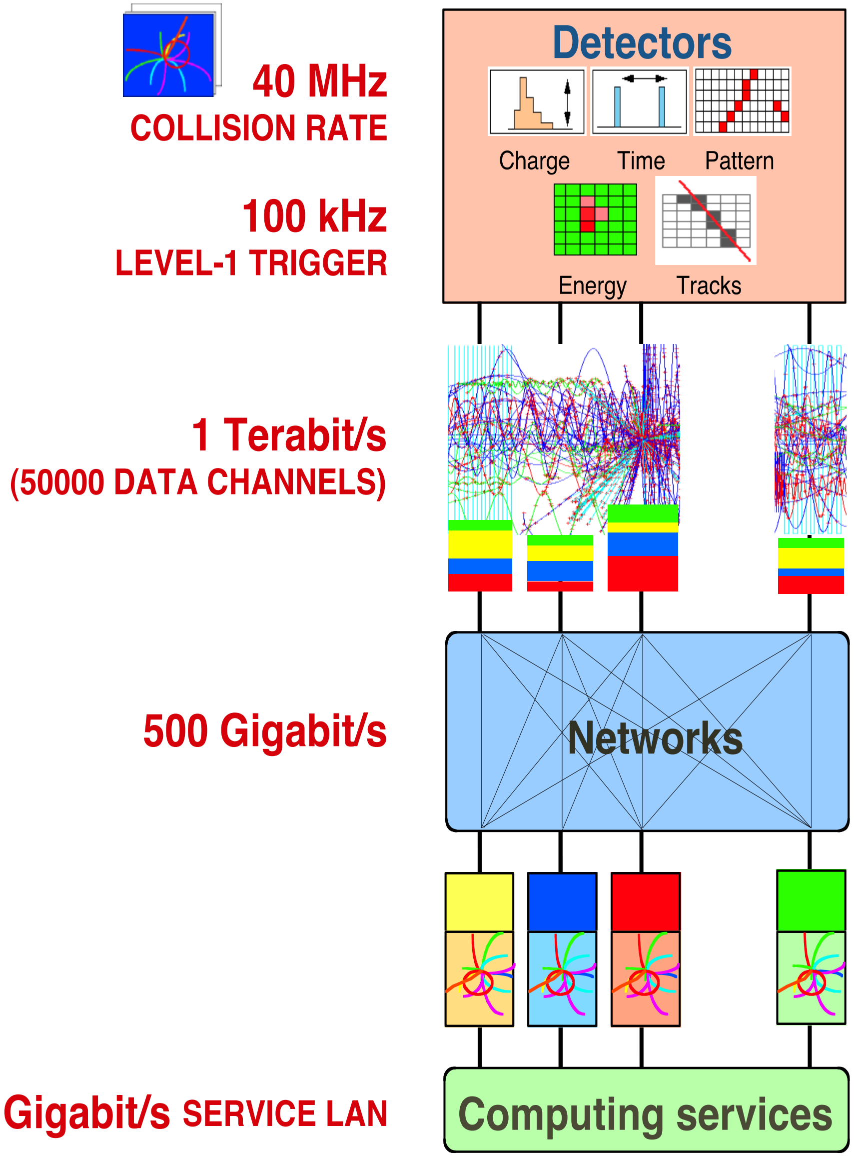


Raw ΣE_T~2 TeV
14 jets with E_T>40 GeV
Estimated PU~50

High radiation levels



Acquiring and recording data of interest



Analogy with a 100 M pixel 3-D digital camera:

40 Million photos/sec

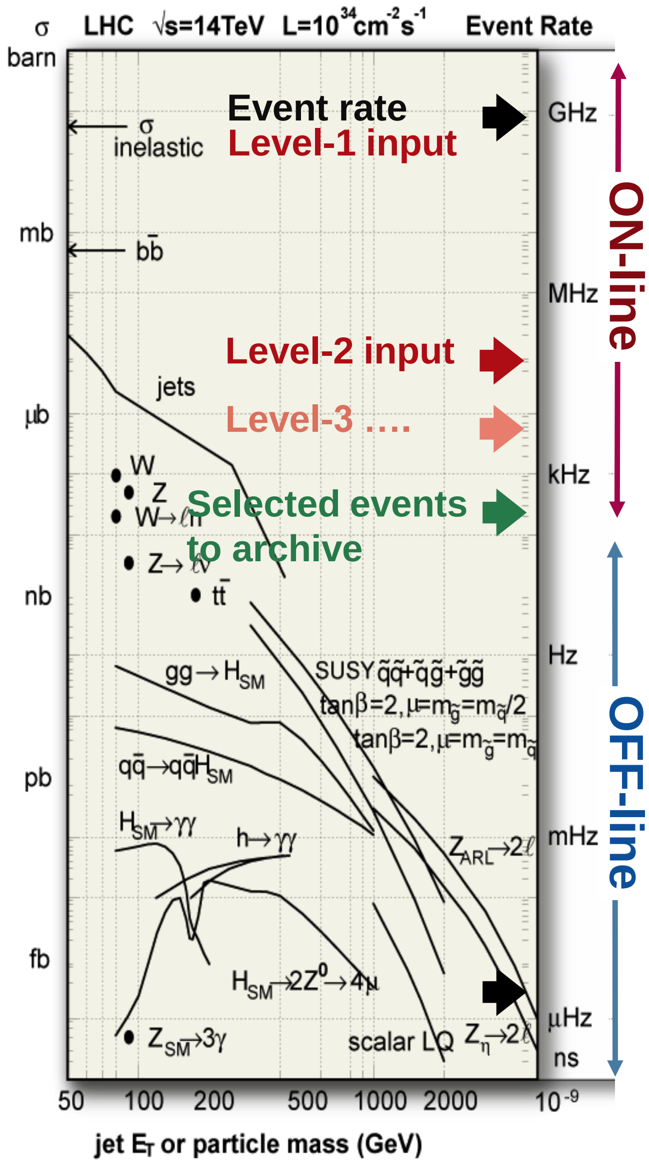
Each photo (~ MB)

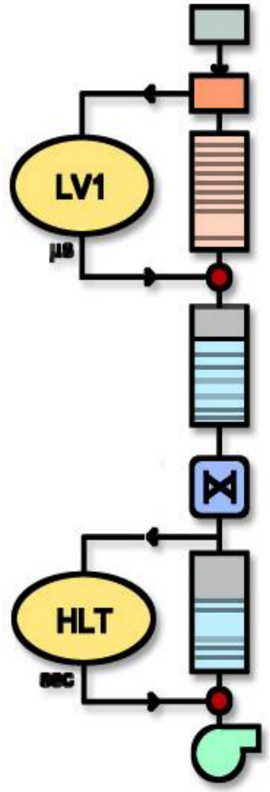
- taken in ~ 500 different parts
- put together using a telecommunications ‘switch’
- analysed in a CPU (in a farm of ~ 50000 cores)

Only a few hundred photos/sec stored on disk.

~ 15 PB/year

Two-level trigger



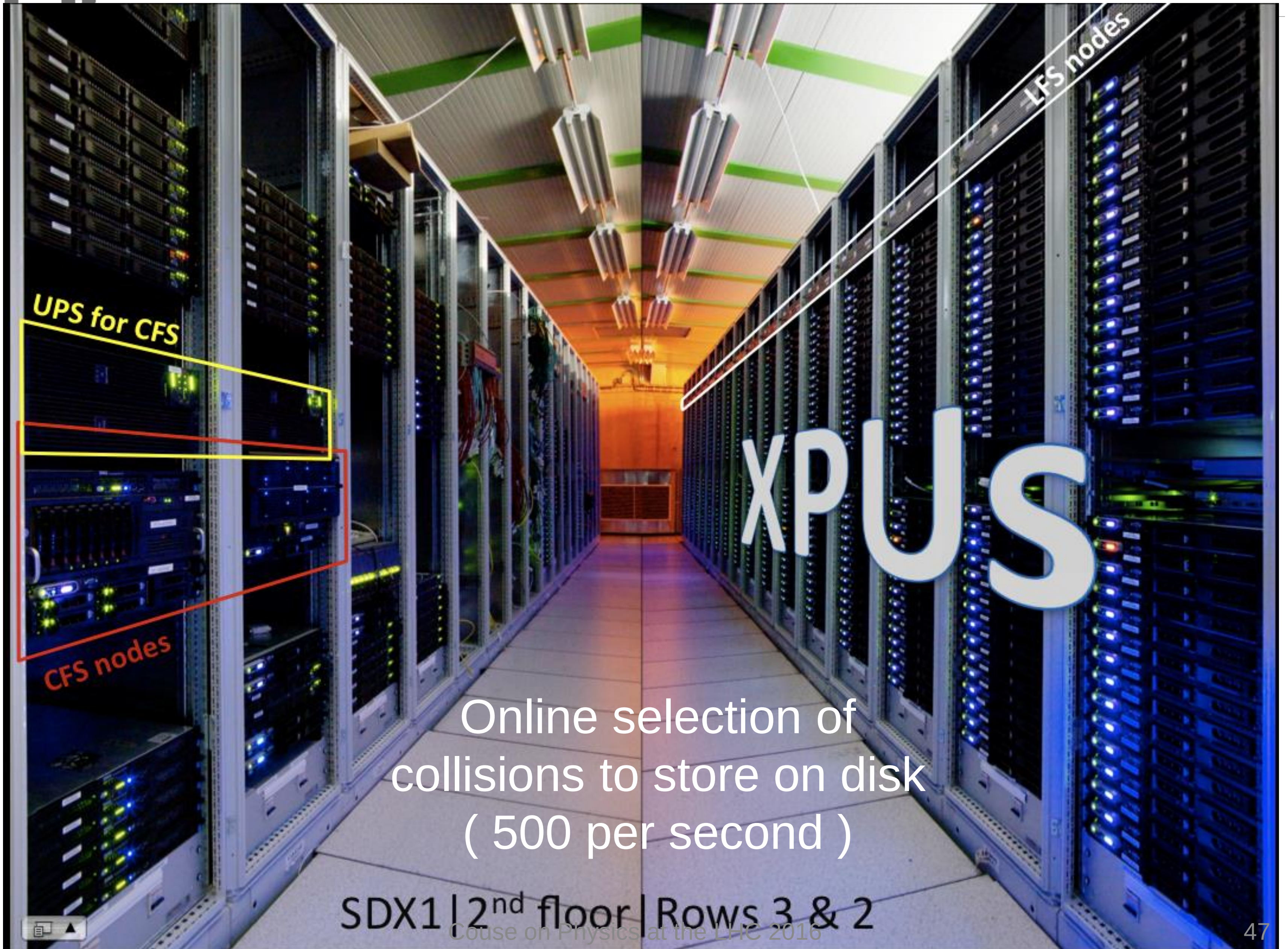


Trigger system decide if the event is interesting to be recorded

Two-step process:
- Level 1: dedicated hardware processors

- High level: computer farm

Trigger computer farm



Online selection of collisions to store on disk (500 per second)

Triggers and event selection

- Select processes that produce particles with high transverse energy
- Examples at $5.x10^{33}$ $cm^{-2}s^{-1}$
  - Single lepton and photon triggers (P_T ~ 30 GeV)
  - Multiple lepton and photon triggers (P_T ~ 15 GeV)
  - Missing transverse energy (P_T ~ 50-100 GeV)
  - Multiple jet triggers (P_T ~ 50-100 GeV)
- About 100 trigger conditions in L1 trigger table
- About 400 trigger conditions in HLT trigger table

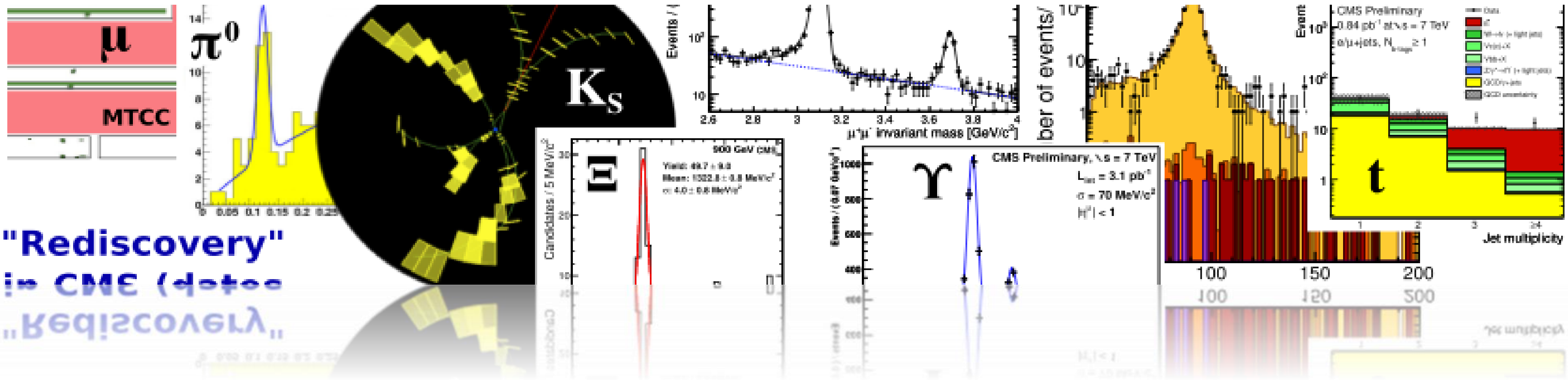
The LHC Computing Grid

The Grid unites computing resources of particle physics institutions around the world

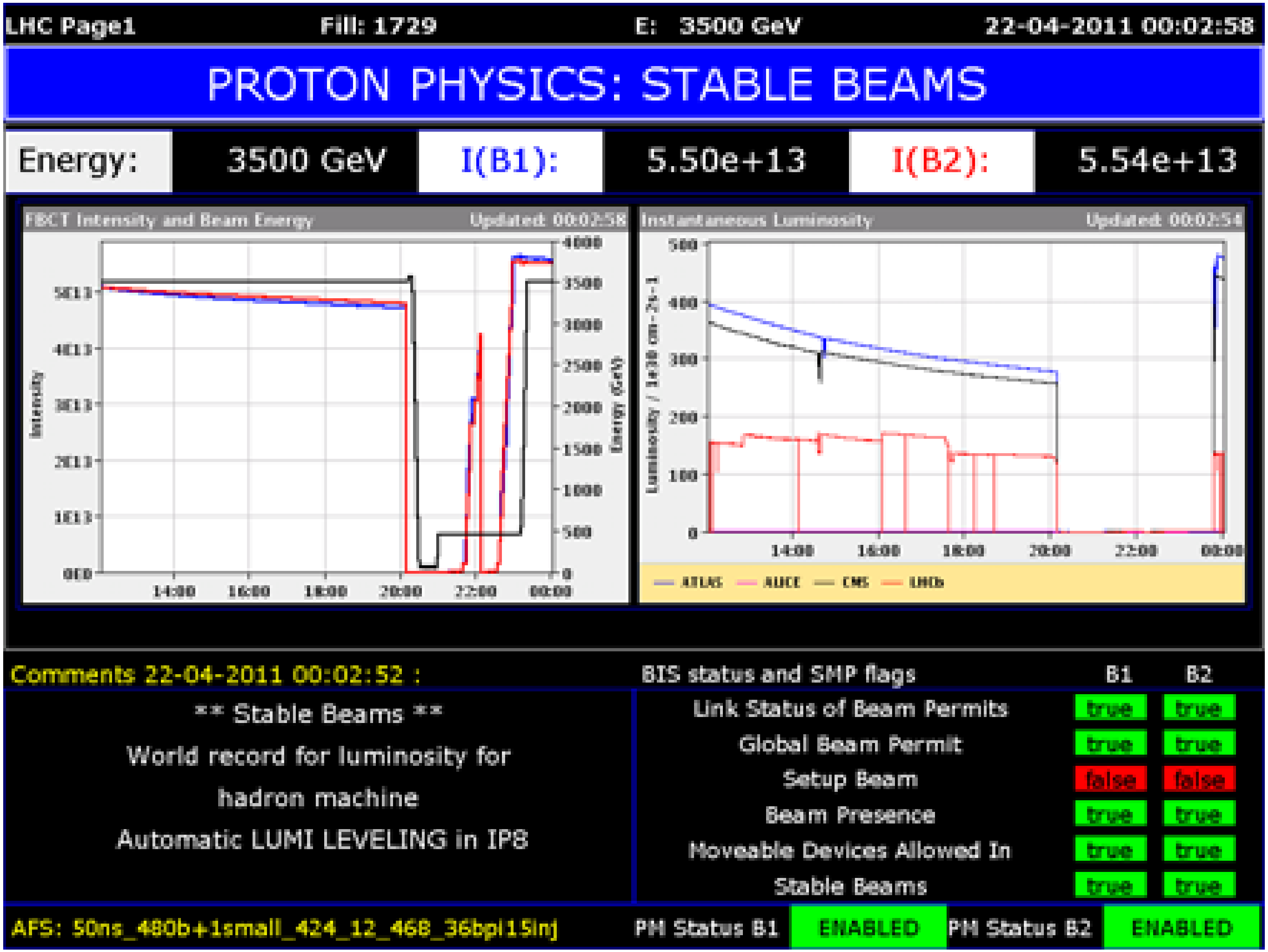
The **World Wide Web** (invented at CERN) provides seamless access to information that is stored in many millions of different geographical locations

The **Grid** is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe

Detector commissioning



LHC Page 1: stable beams



March 30, 2010: CMS Page 1

Experiment control rooms

Cessy: Master Control Room

Fermilab: Remote Operations Center

Meyrin: CMS Data Quality Monitoring Center

Any Internet access

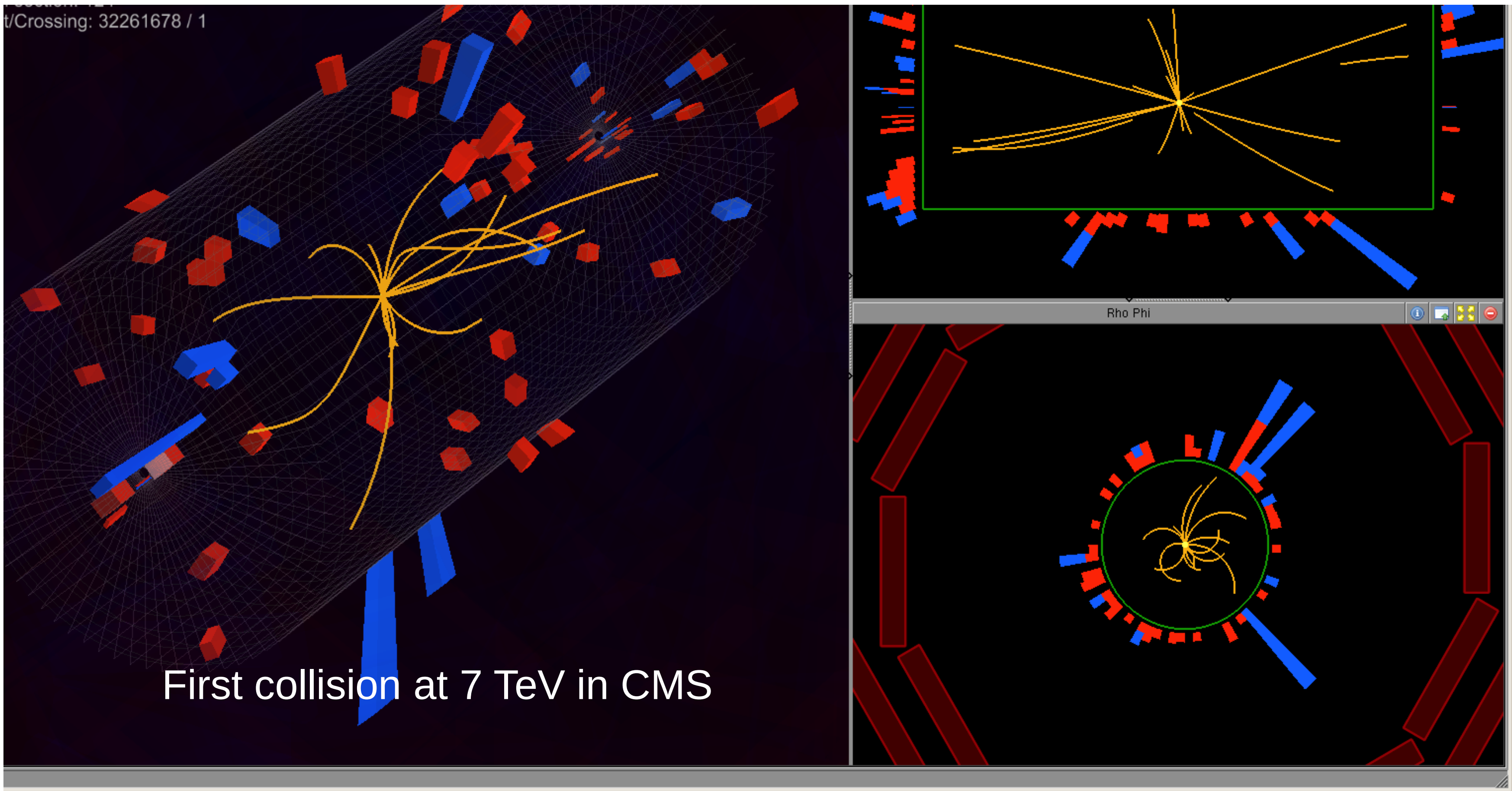
CMS Experiment

2009: First p-p collisions at LHC

November 23, 2009
First collisions at 900 GeV

December 14, 2009
First collisions at 2.36 TeV

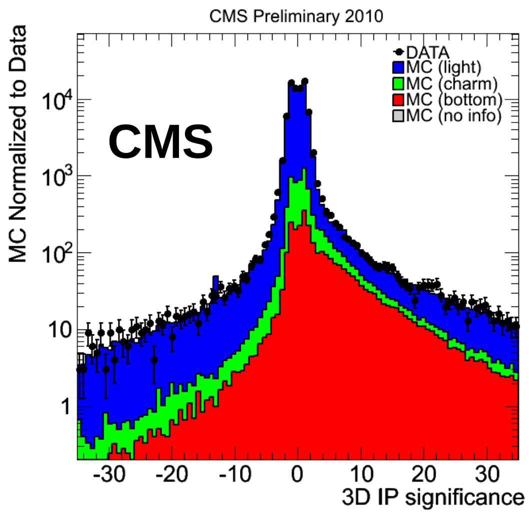
March 30, 2010
First collisions at 7 TeV

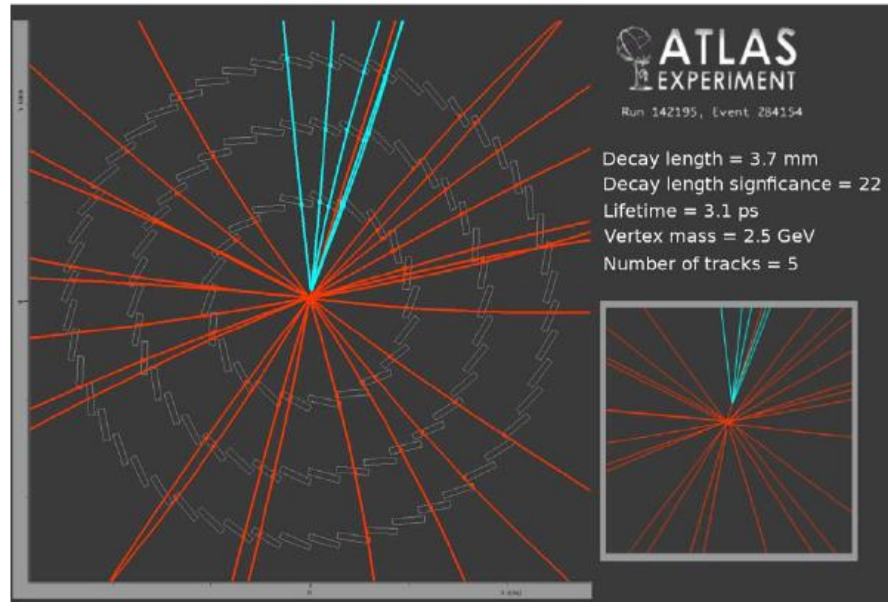


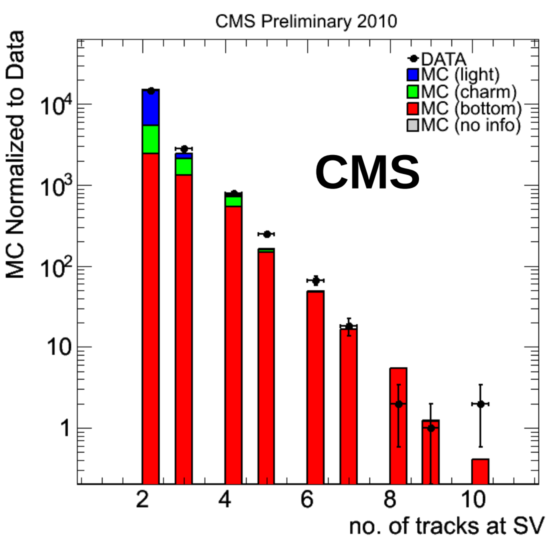
...unforgettable moments

Tracking: secondary vertices

Basic variables relevant for B-tagging are well described by the simulation



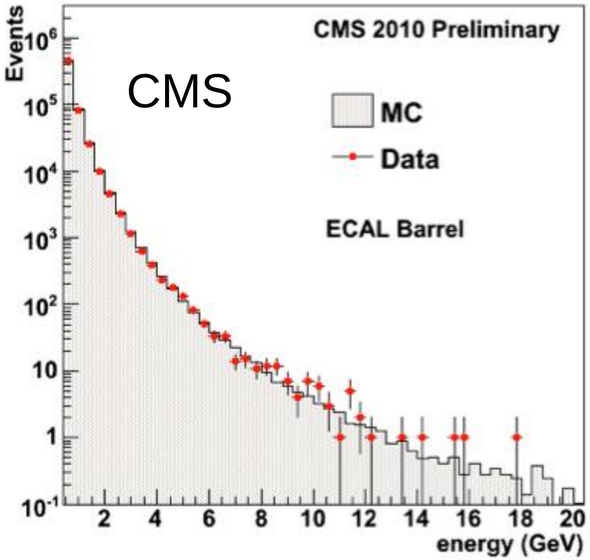


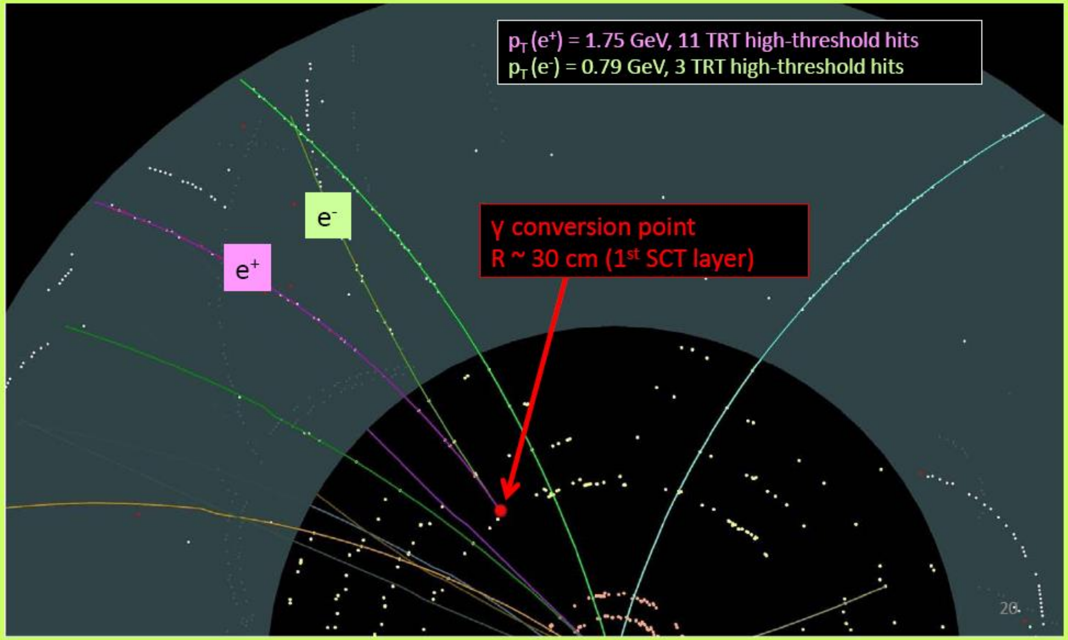


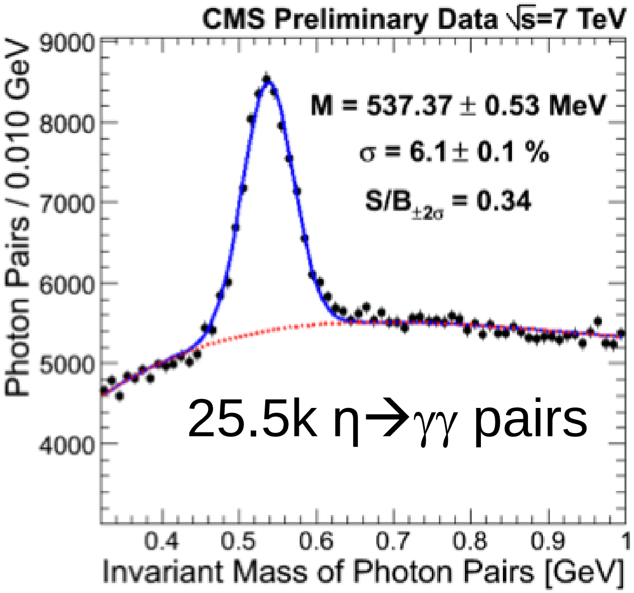
Secondary vertices compatible with heavy flavor production

Photons and electrons

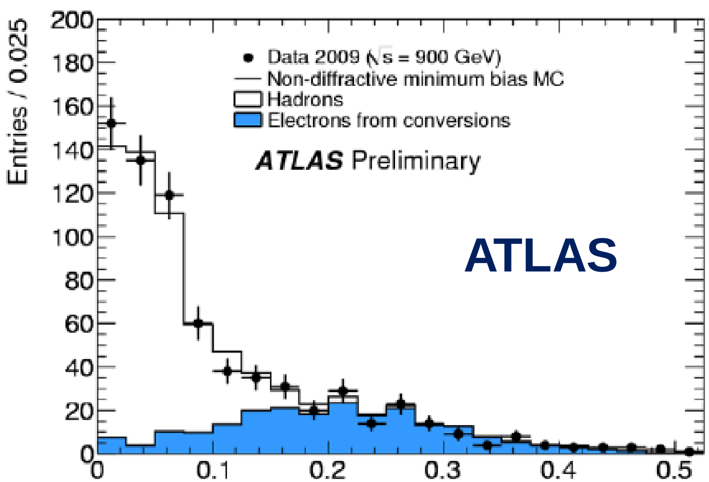
EM cluster energy





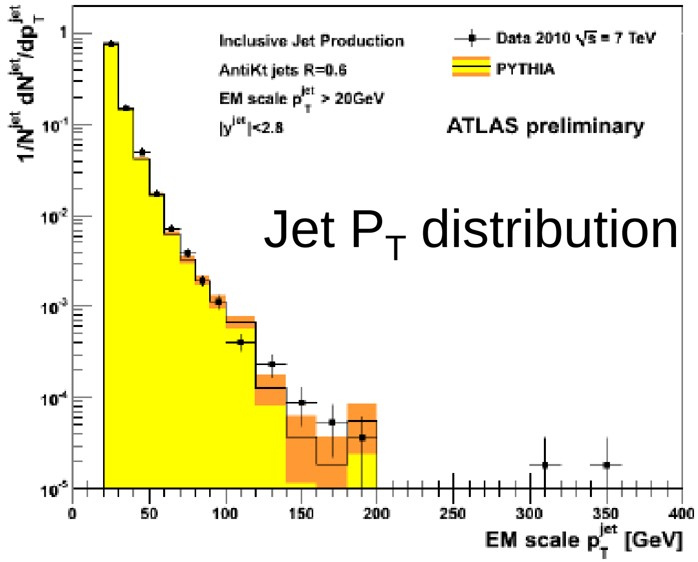


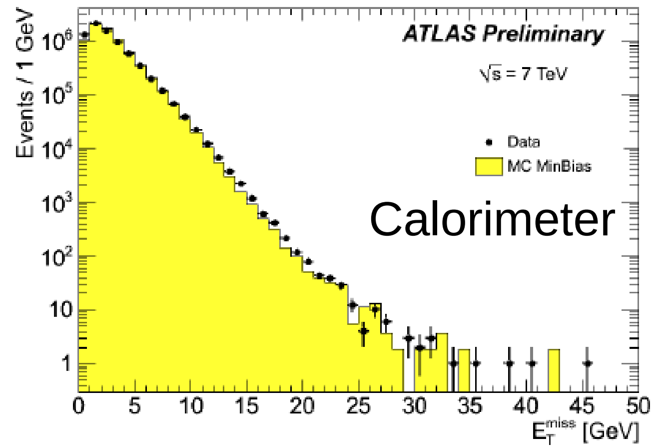
TRT high-threshold hit fraction



Jets and missing energy

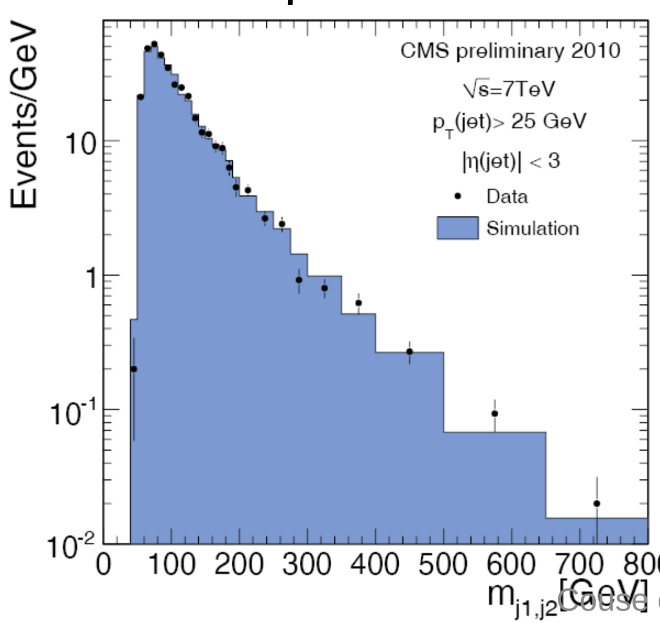
Missing Transverse Energy



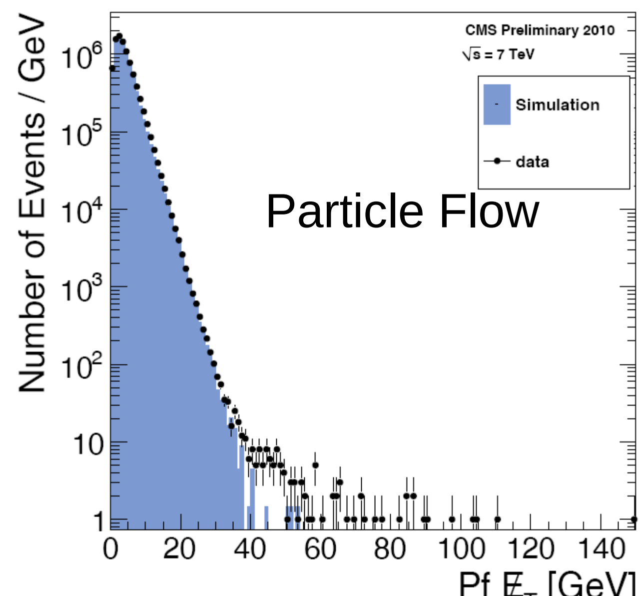


ATLAS

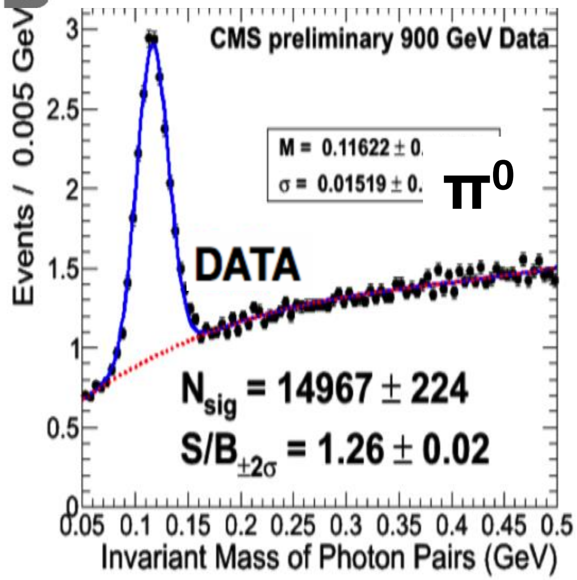
Di-jet mass

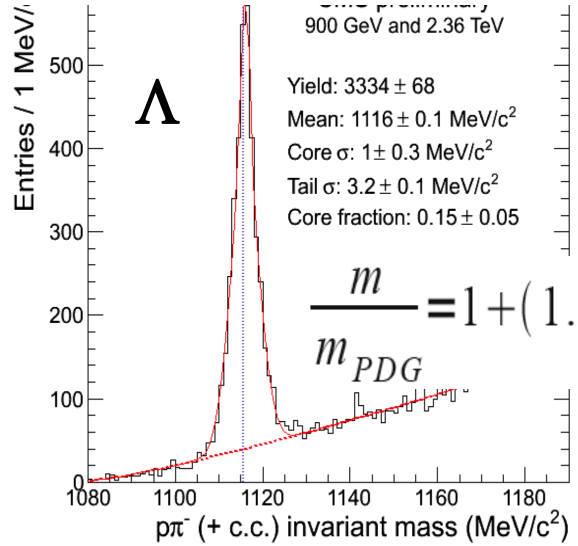


CMS

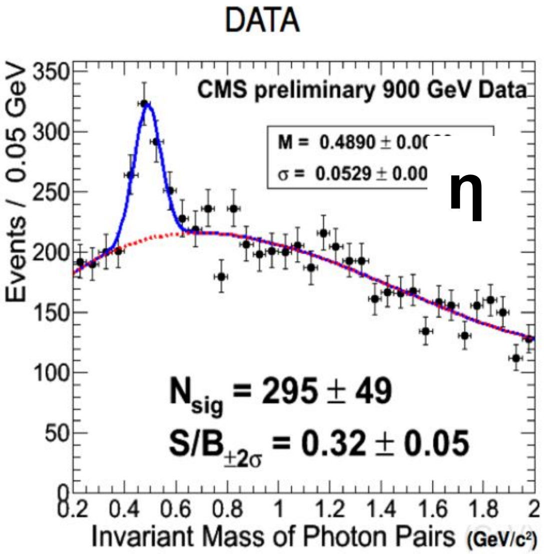


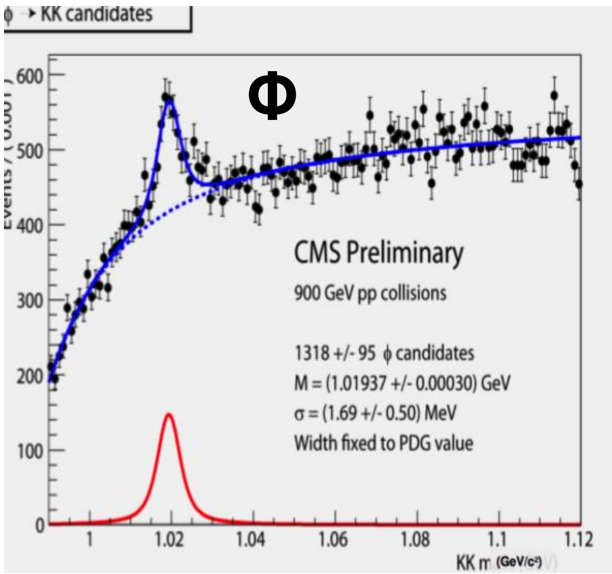
Rediscovery of resonances

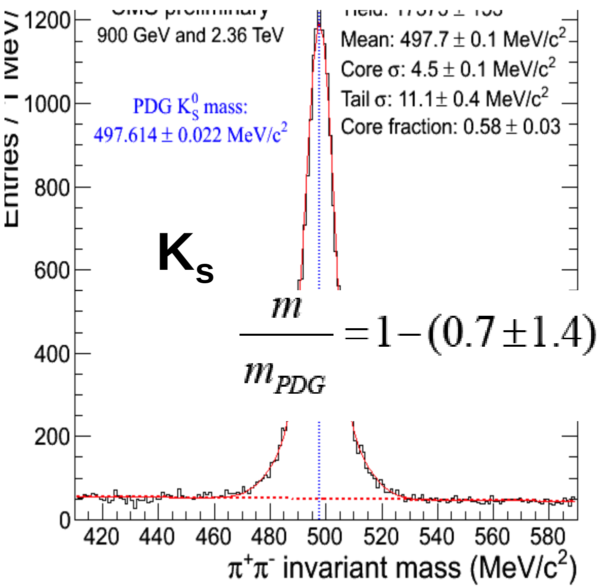




$$\frac{m}{m_{PDG}} = 1 + (1.9 \pm 0.9) \cdot 10^{-4}$$

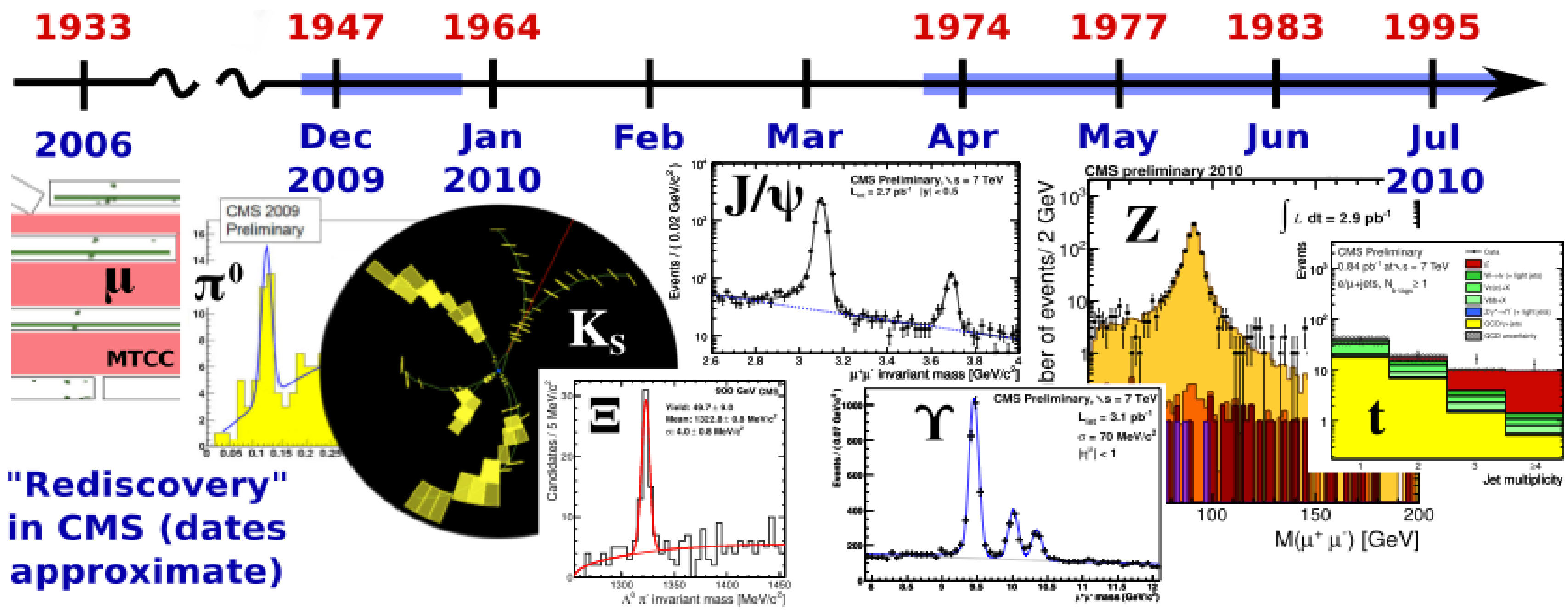




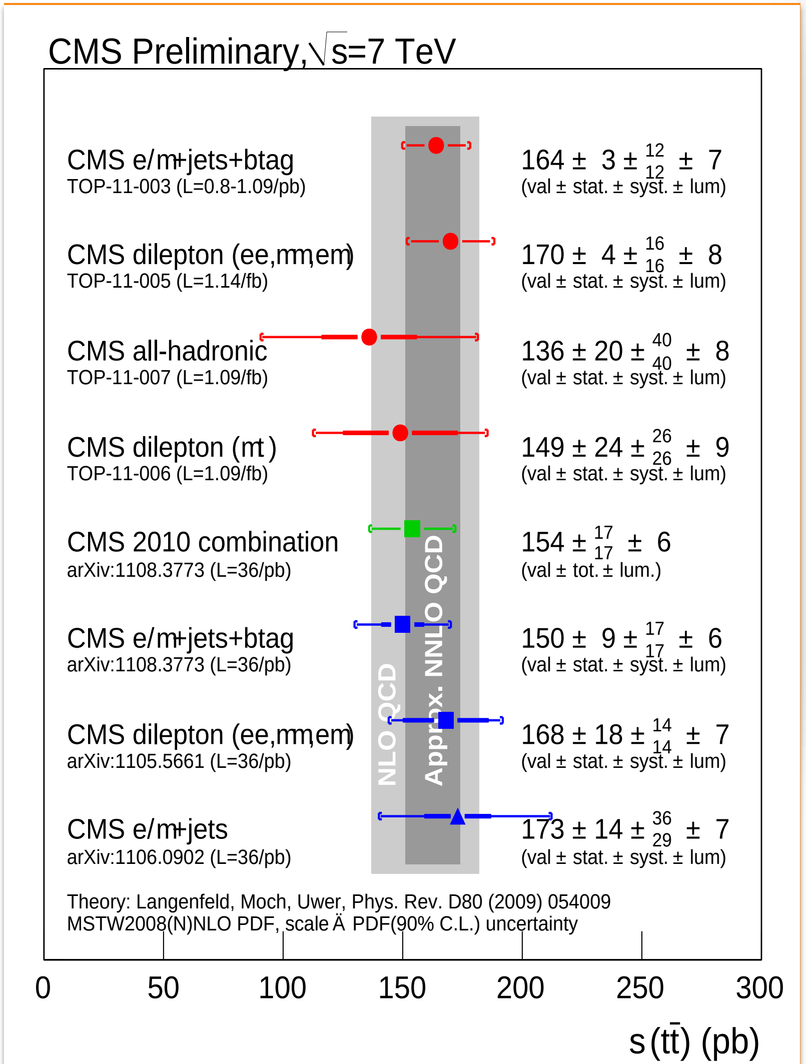


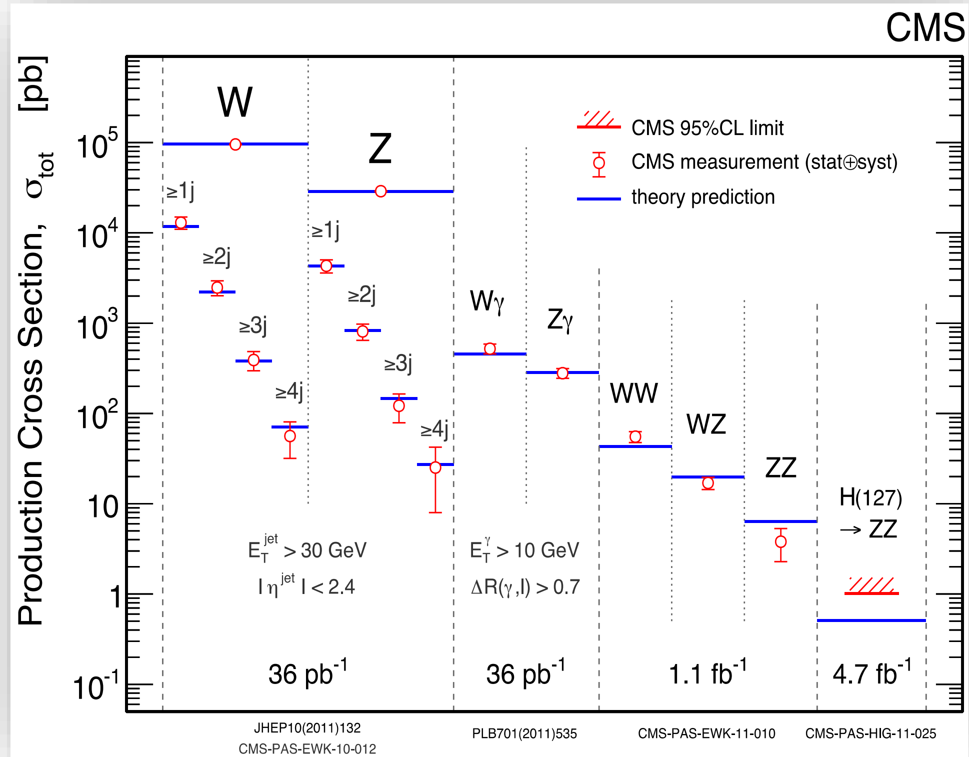
$$\frac{m}{m_{PDG}} = 1 - (0.7 \pm 1.4) \cdot 10^{-4}$$

Rediscovery of the Standard Model at LHC



Standard Model at 7 TeV (2010-2011)





- **Fabulous agreement**
- **Lots of data**

… on to the Higgs…

End of Lecture 2