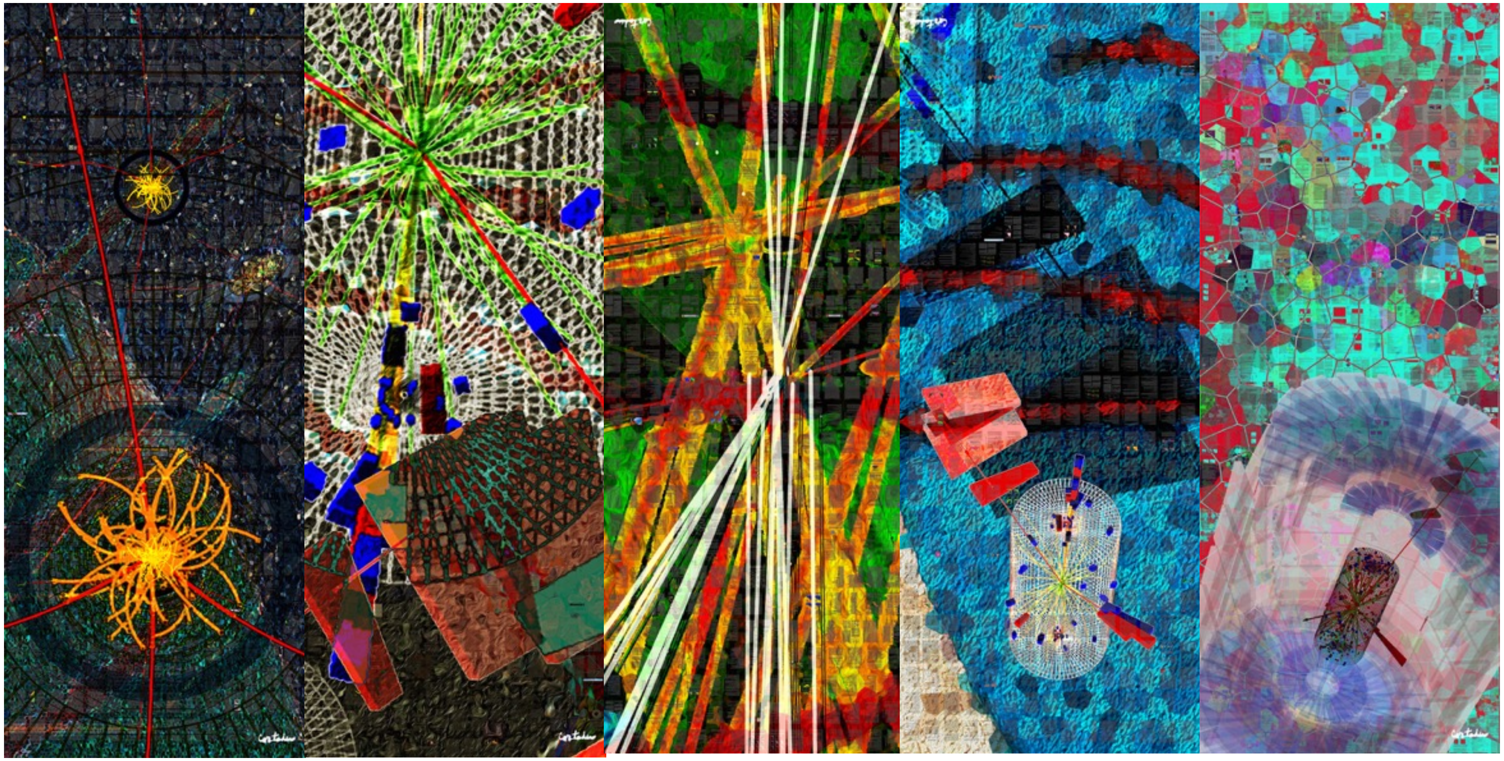
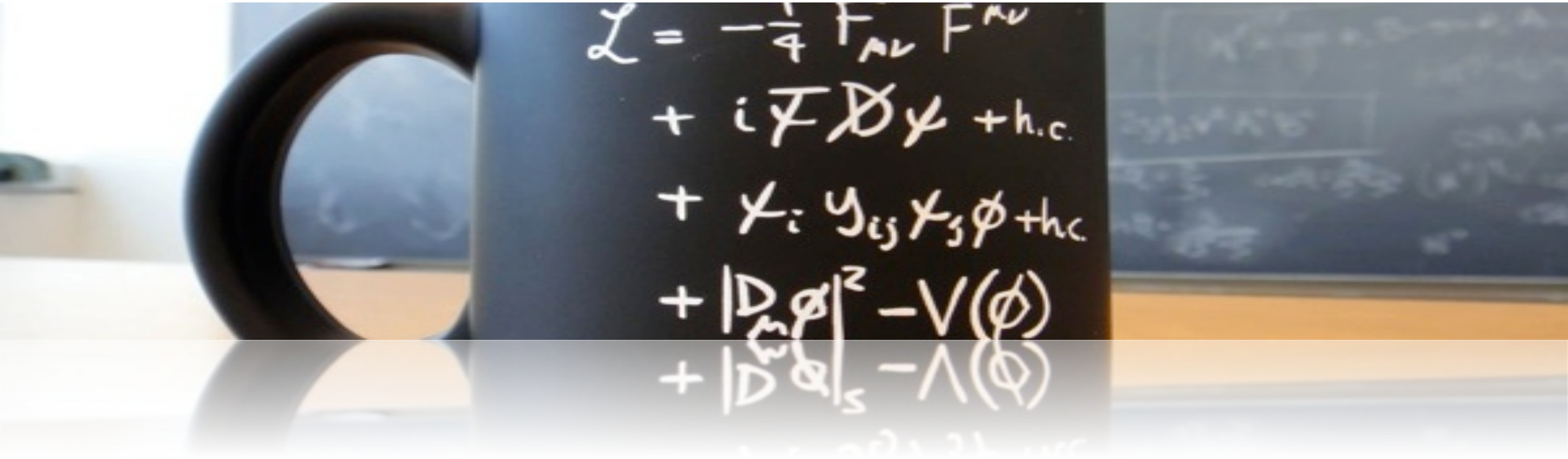
The LHC experimental program

J. Varela, 14 July 2020

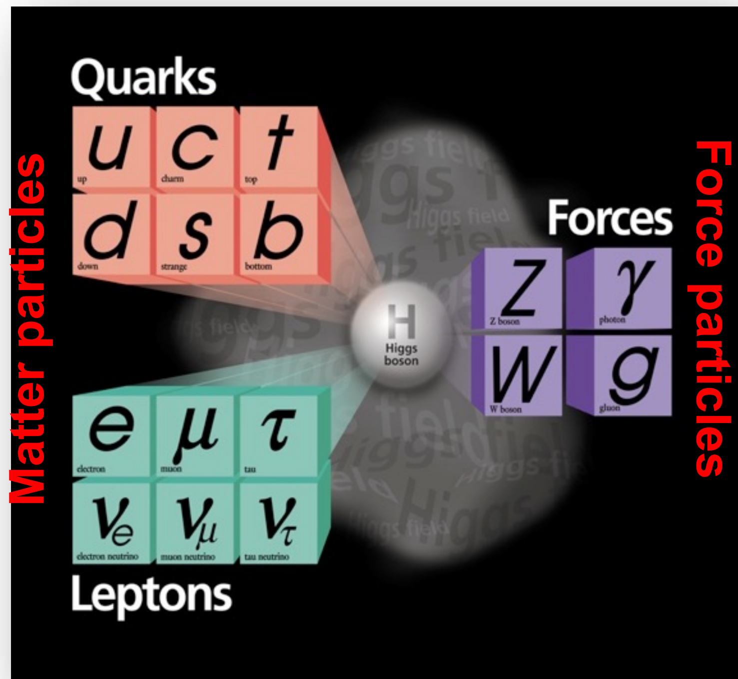


The LHC physics case

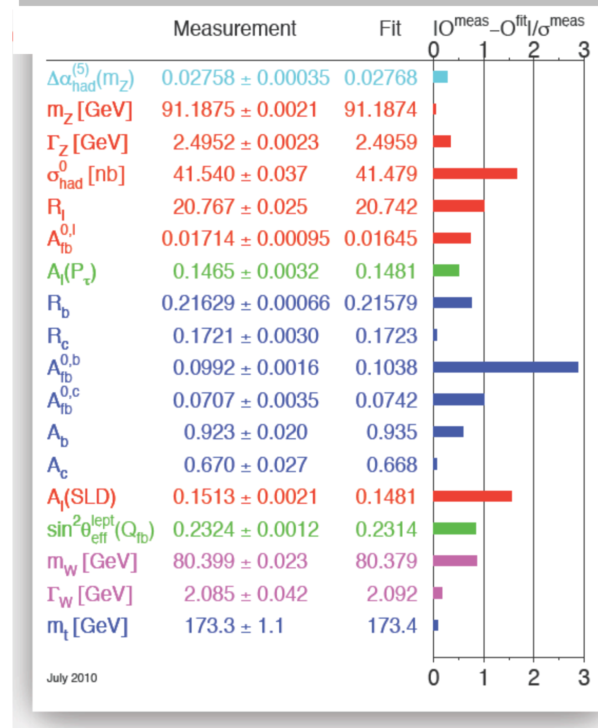


The Standard Model of Particle Physics

Over the last ~100 years: The combination of Quantum Field Theory and the discovery of many particles has led to the Standard Model of Particle Physics



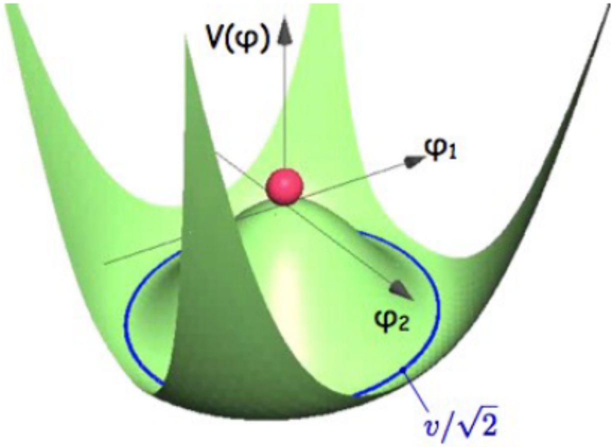
Confirmed at sub 1% level



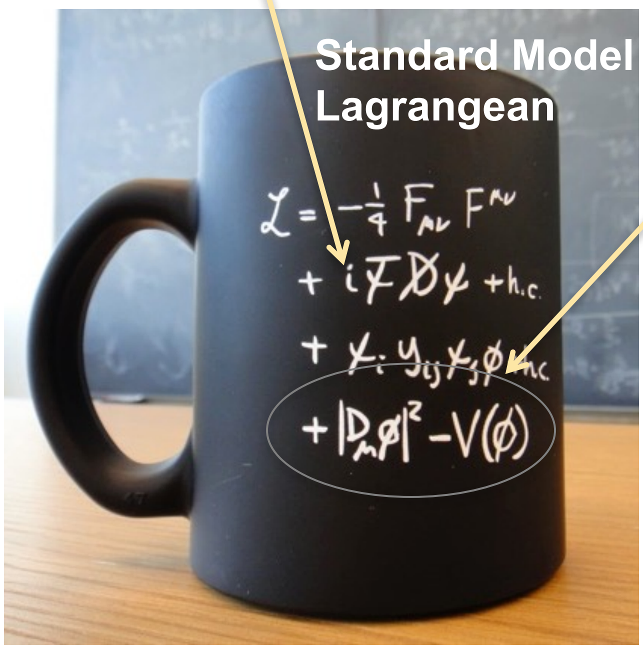
One of the greatest achievements of the 20th Century Science

The Higgs field

- In the Standard Model the interactions are derived from an **underlying symmetry principle**. All particles would have zero mass and would travel at the speed of light.



What breaks the symmetry, allowing the Universe as we observe it?



Higgs field:
(Englert-Brout, Higgs, Guralnik-Hagen-Kibble)

- The Higgs field permeates the space of the whole Universe;
- The field has a non-zero value in the energy minimum;
- Particles get mass through the interaction with the Higgs field.

The Terascale and the LHC

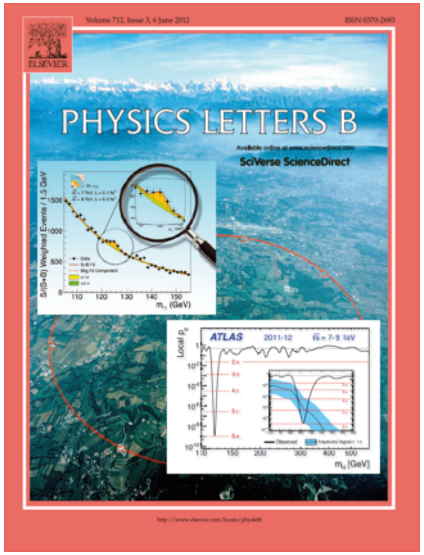
The Standard Model would fail at high energy without the Higgs particle or other 'new physics'.

It was expected that the **'new physics'** would manifest at an energy around

1 Tera-electronVolt (TeV) = 10^{12} electronVolt (eV)

accessible at the LHC for the first time.

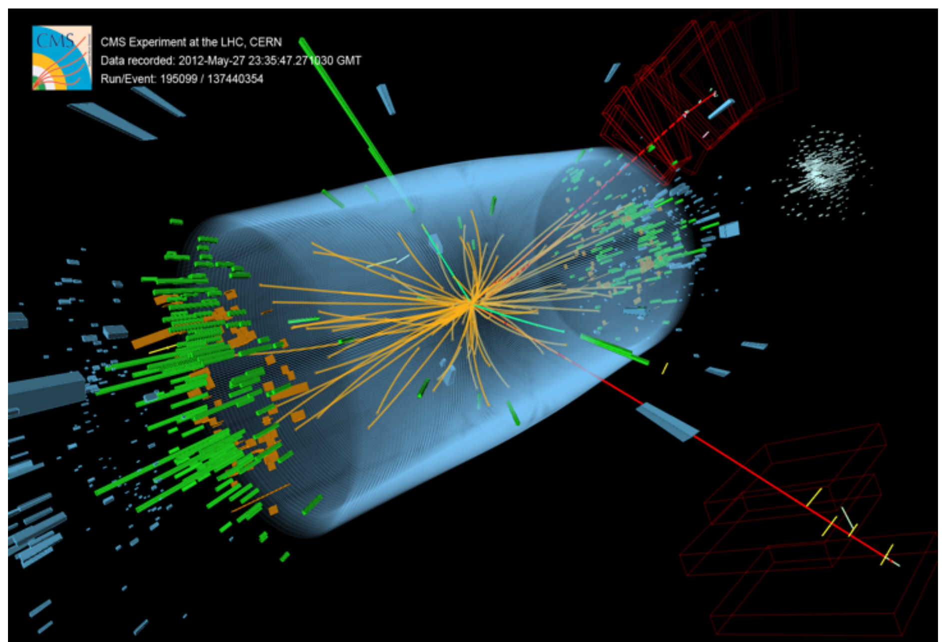
Higgs boson discovery in 2012



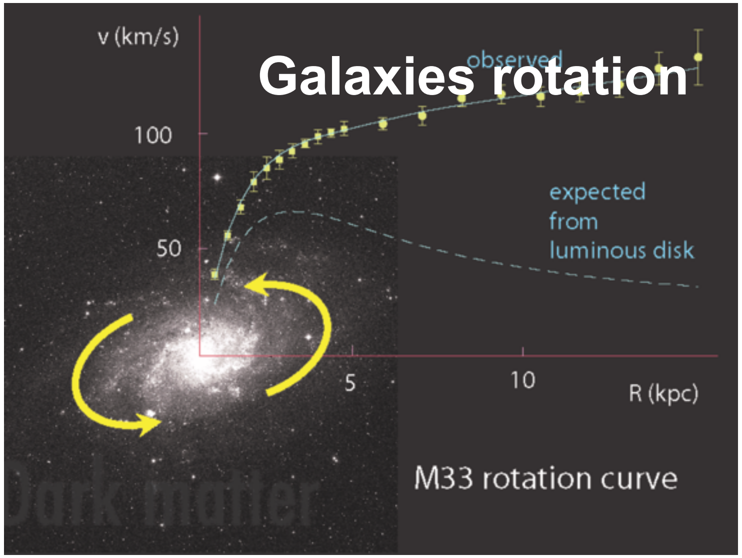
A major discovery in physics

A new paradigm: the space in the whole Universe is filled with the Higgs field

The study of the nature and properties of the Higgs boson is a scientific imperative for the next decades



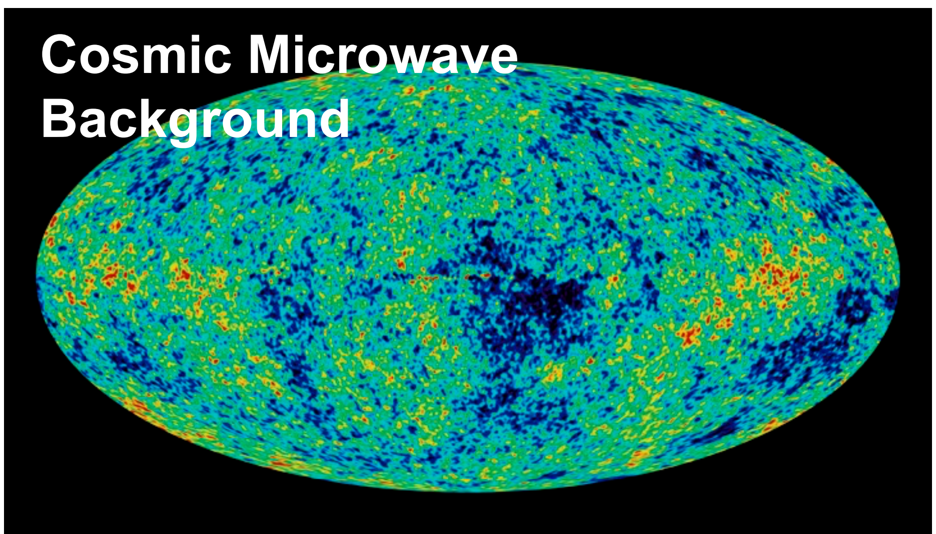
The dark side of the Universe



Precision cosmology measurements give strong motivations for new physics:

What is Dark Matter?
What is Dark Energy?

95% of the Universe is unknown



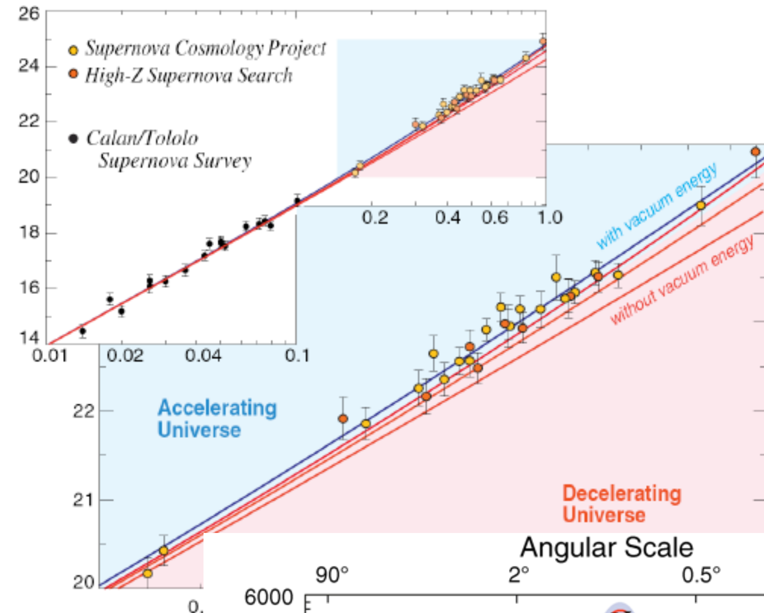
- Thermalized e.m. radiation at average temperature of 2.7^{0}K
- Left over of the epoch of matter-radiation decoupling
  - ~ 300'000 years after the Big-Bang
- Measurement of CMB fluctuations (at the level of 10^{-5}) allow precise assessment of dark matter and energy.

Dark matter and energy

In 1998, the observation of distant **Supernovae** allowed to measure the expansion rate of the universe.

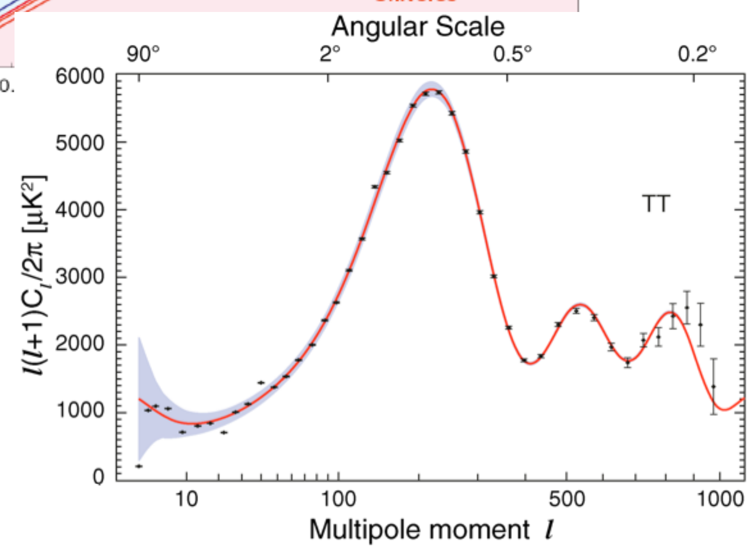
The result is that the **expansion of the Universe is accelerating**

Some form of **dark energy** fills the whole space creating negative pressure



From CMB measurements:

- 5% ordinary matter
- 26% dark matter
- 69% dark energy



Beyond the Standard Model

Why do we **observe matter and almost no antimatter** if we believe that there is a symmetry between the two in the universe?

What is the **"dark matter"** and **”dark energy”**?

What is the **nature of the Higgs field?**

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there **three generations of quarks and leptons**?

What is the explanation for the observed **pattern for particle masses**?

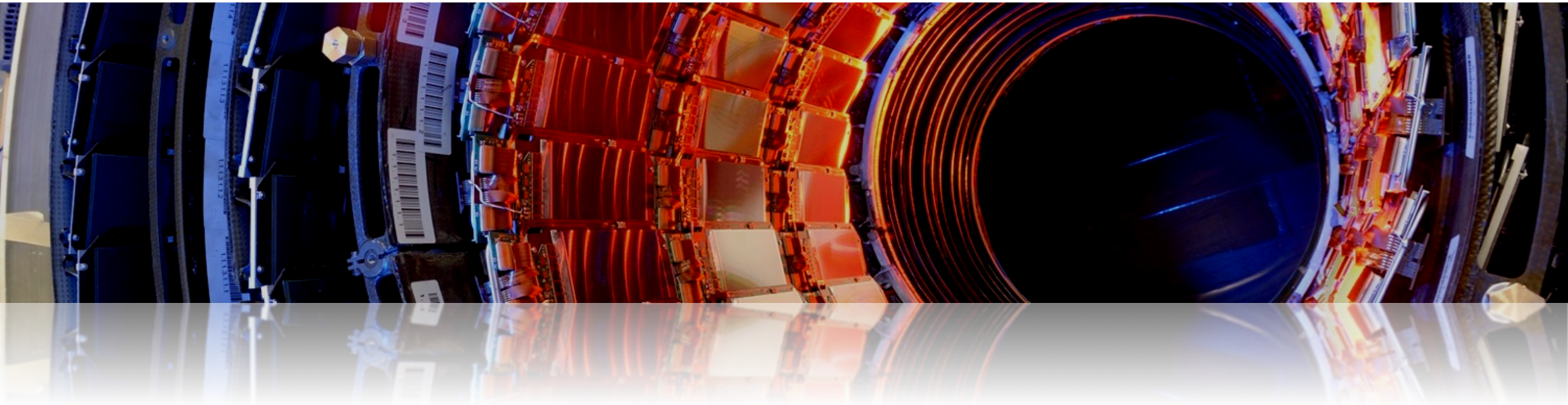
Many possible theories

There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Compositeness

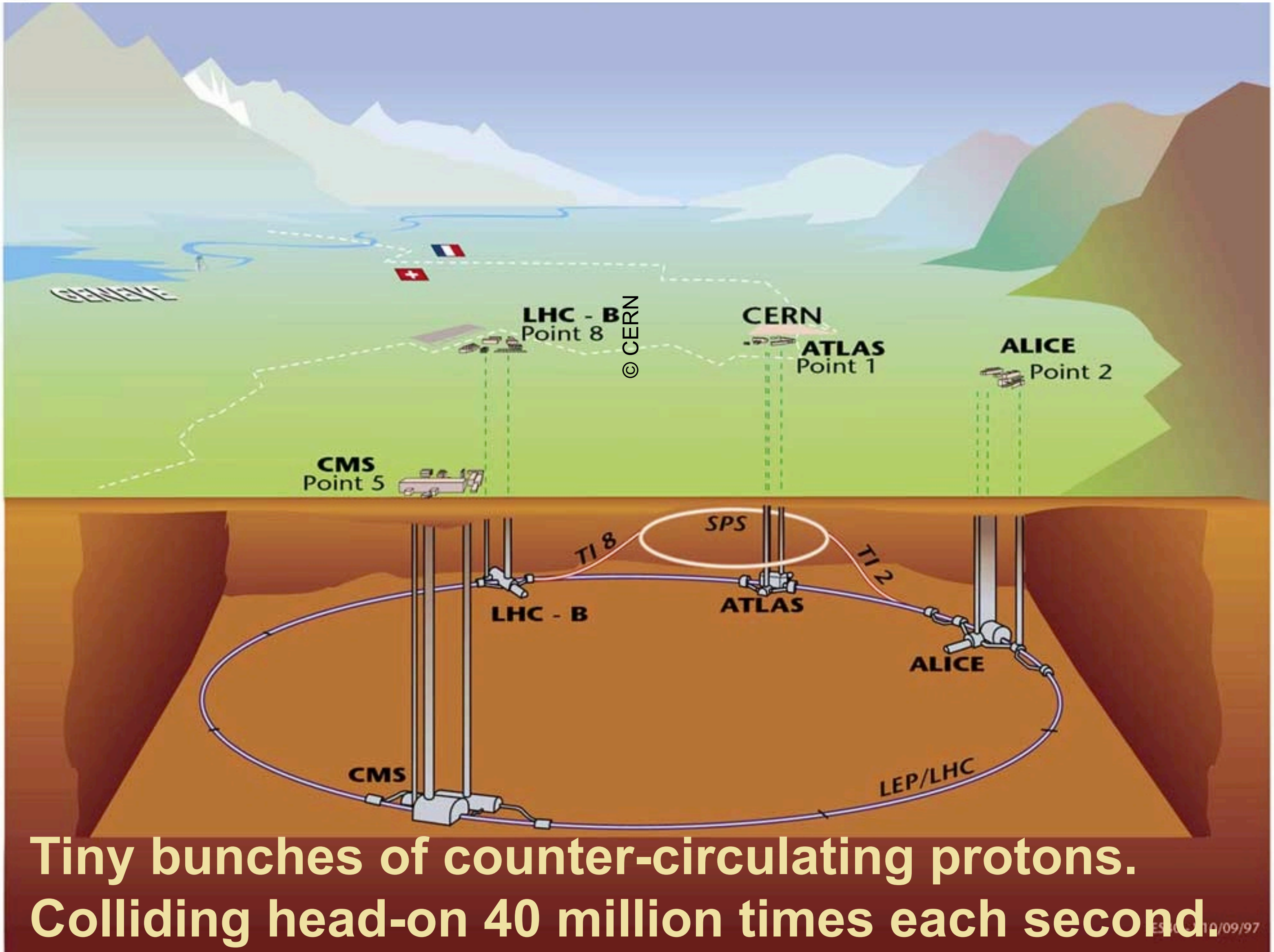
Any of this could still be found at the LHC

The LHC proton collider and the experiments



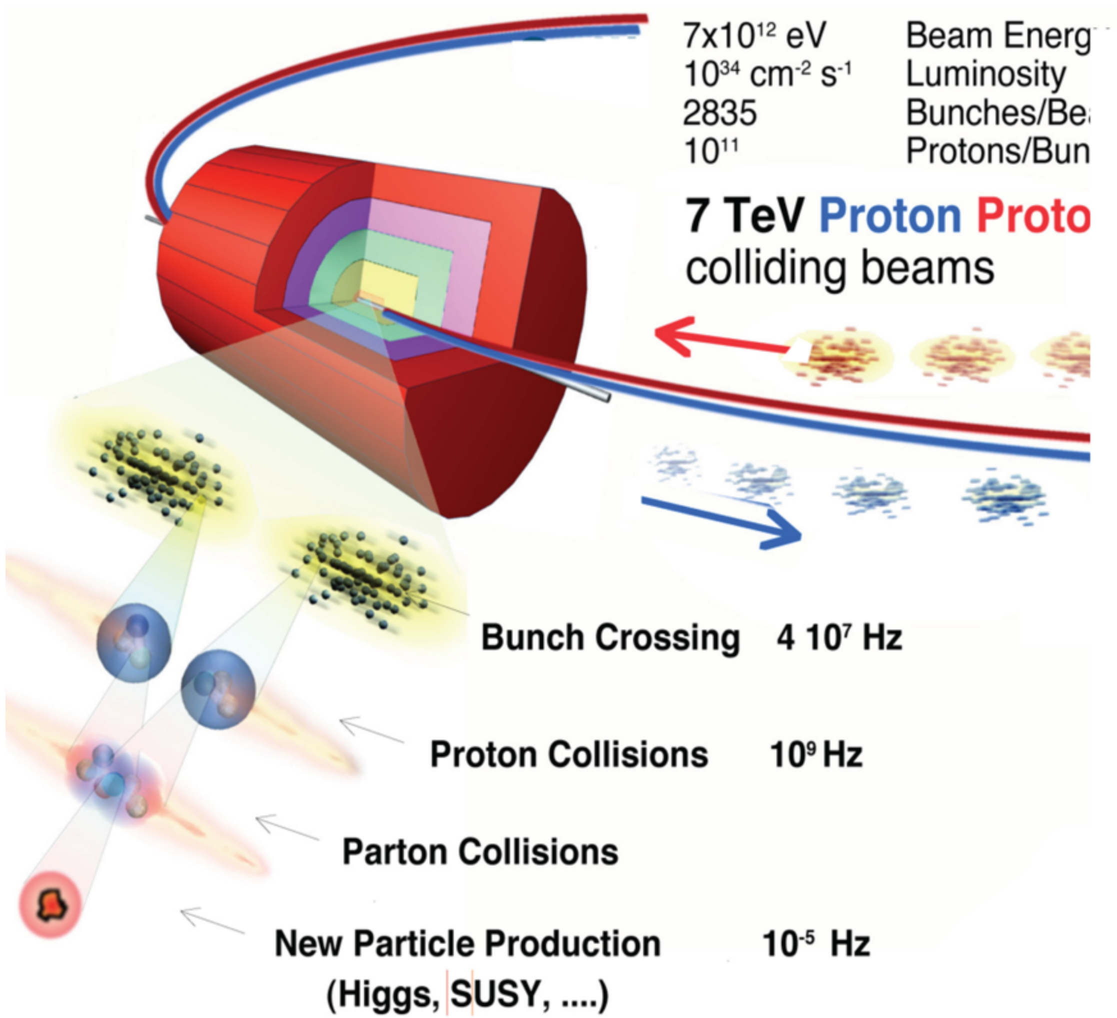
Accelerator and Experiments

Accelerator and experiments layout



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

Collisions at LHC



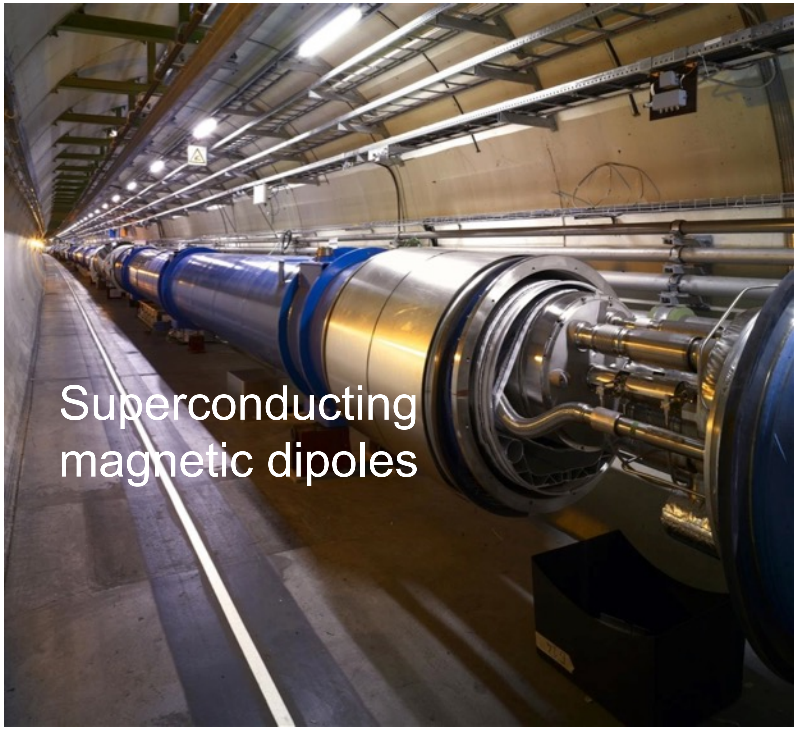
LHC accelerator challenges

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

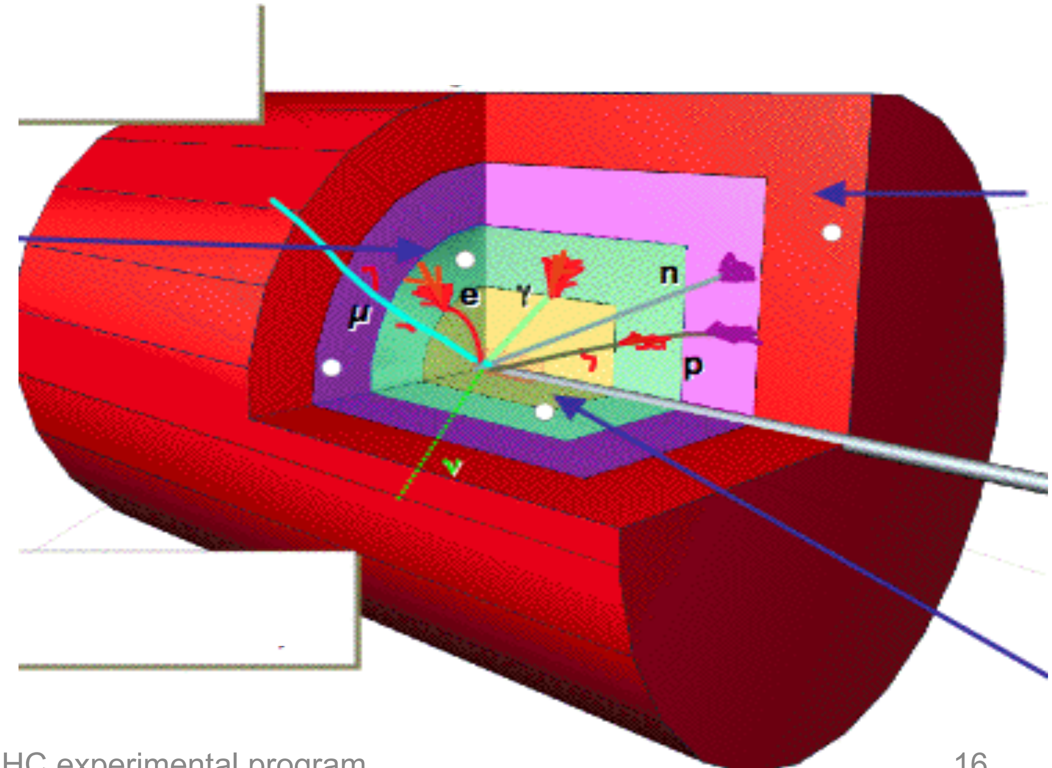


General purpose LHC experiments

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)

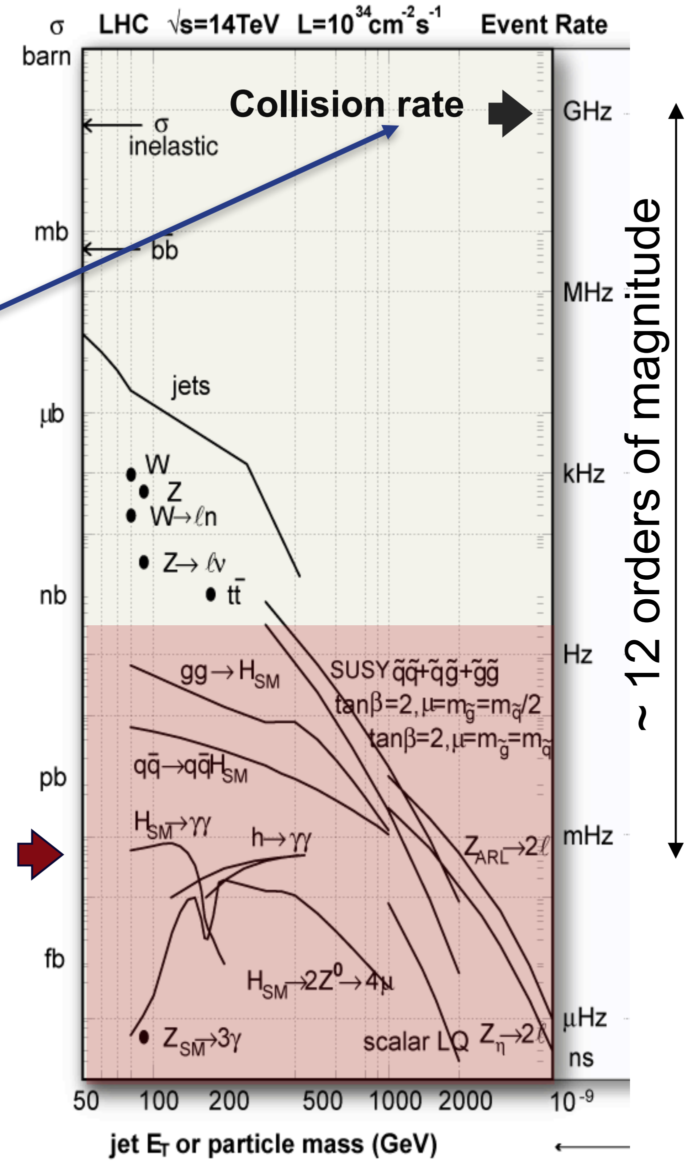


High collision rate

Search for rare physics processes requires very high collision rate

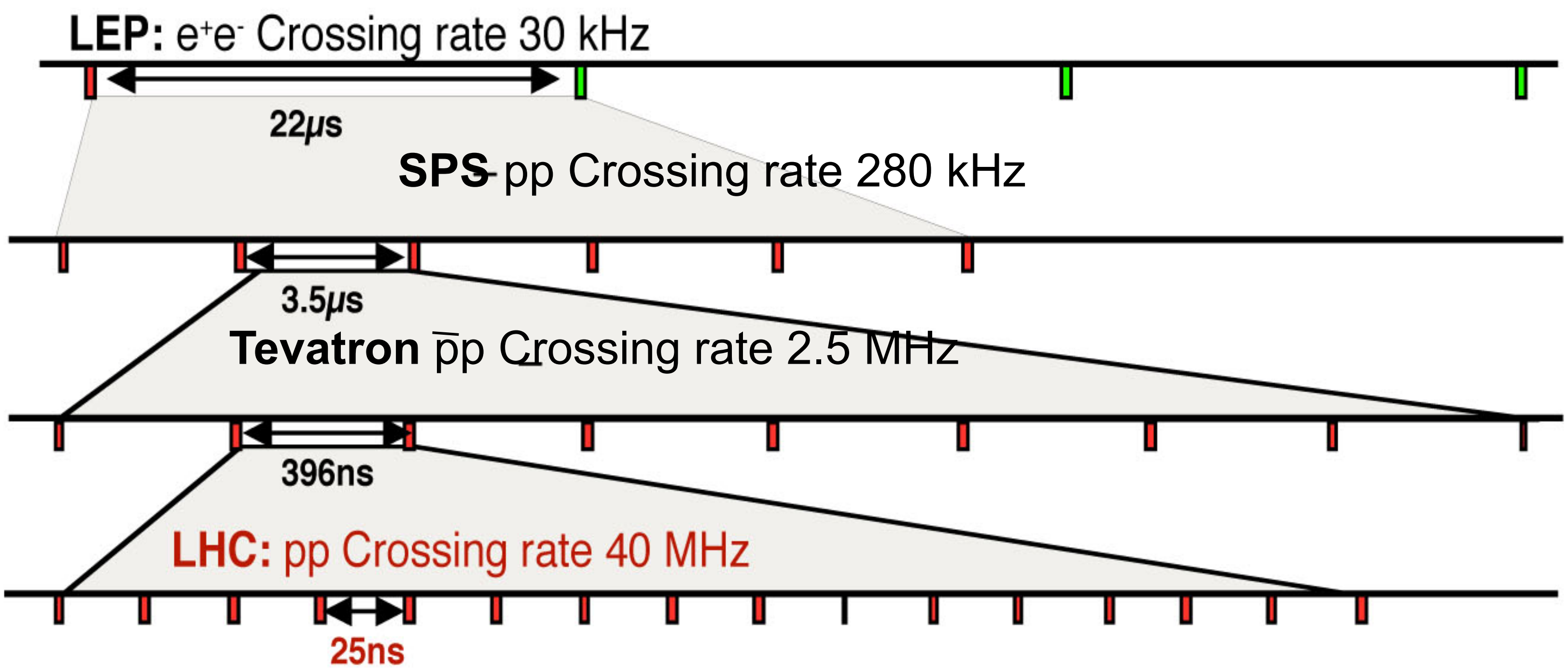
- **LHC Luminosity** is 2.10^{34} $cm^{-1}s^{-1}$
- Proton-proton collision rate is 2.10^{9} events/s
- Higgs decaying in two photons: 10^{-3} events/s

At the LHC, high luminosity is as important as high energy!



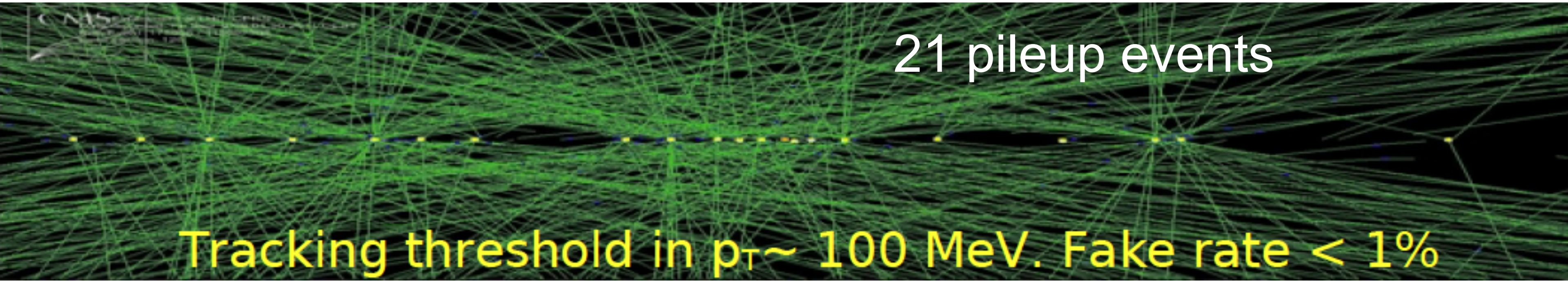
Bunch crossing frequency

- LHC has 2800 proton bunches
- Crossing rate is 40 MHz
- Distance between bunches in time: 25ns (corresponds to 7.5 m)
- Bunch size: cross-section 20x20 μm ; length 20 cm



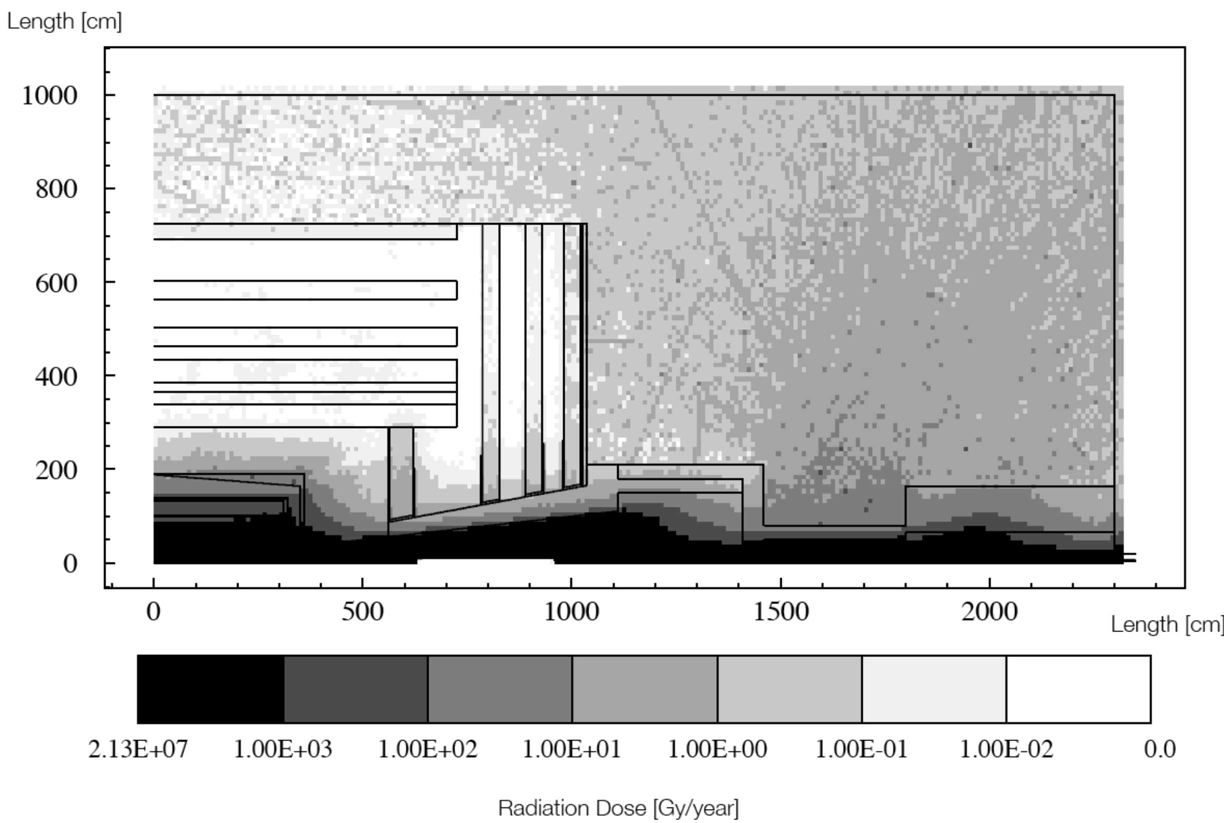
Event pileup

- Each bunch has 1.5 10^{11} protons
- At each crossing of bunches, about 50 collision occur
- The particles produced (~1500 charged particles) are “seen” by the detector as a single image (event)

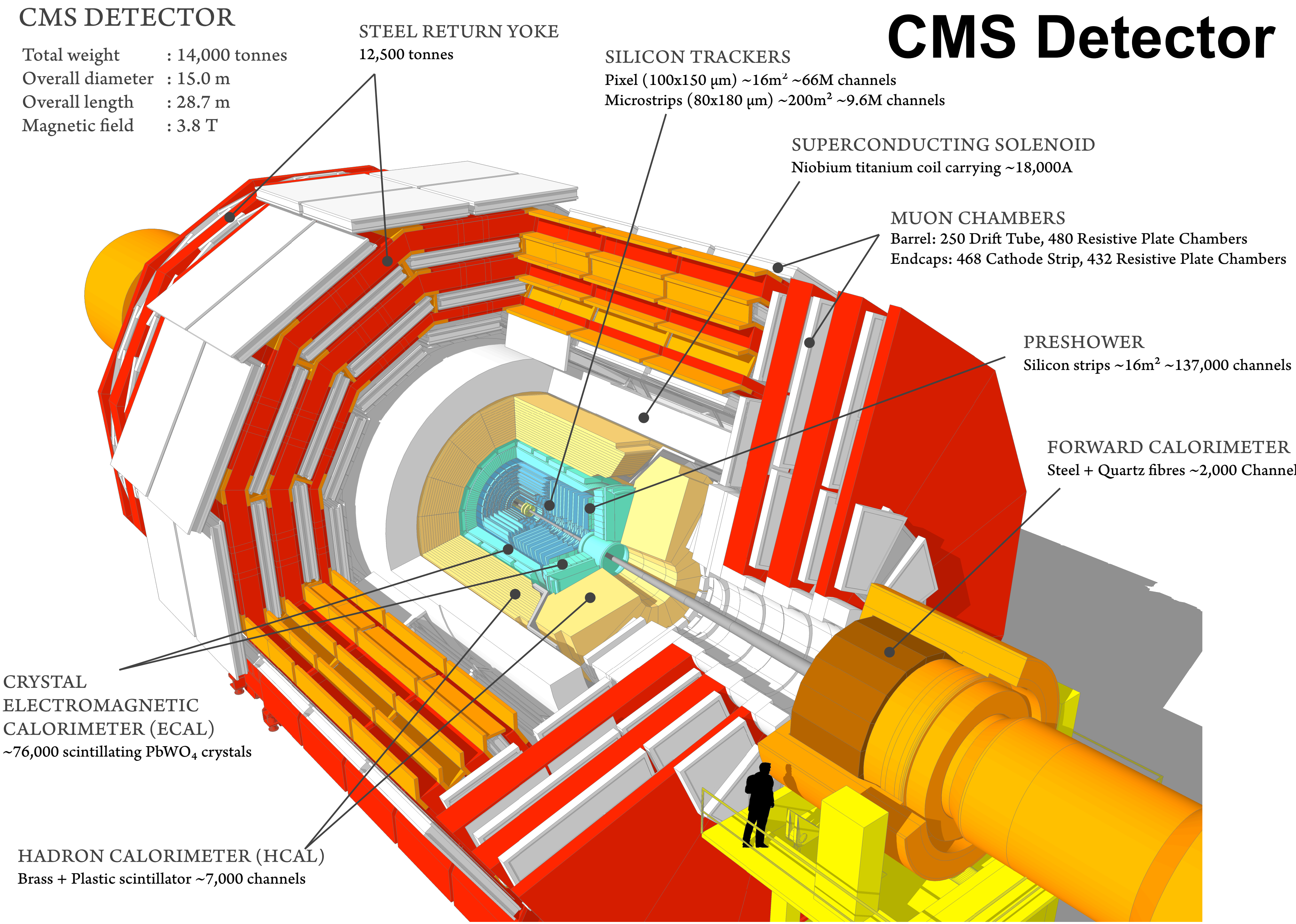


High radiation levels

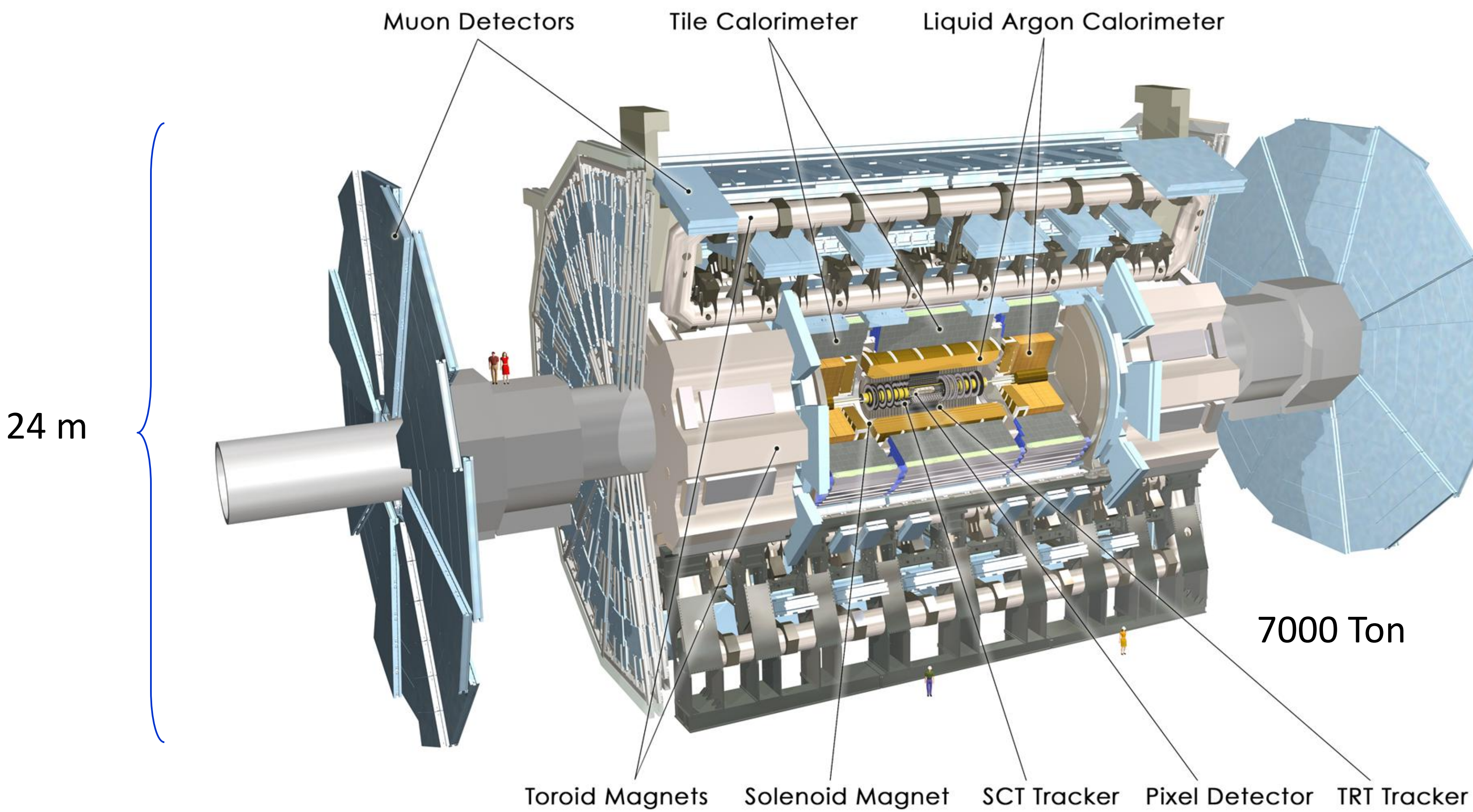
- Detector materials and electronics should survive radiation doses up to ~2 MGy.
- 3 to 4 orders of magnitude larger than radiation doses sustained by satellites in space.



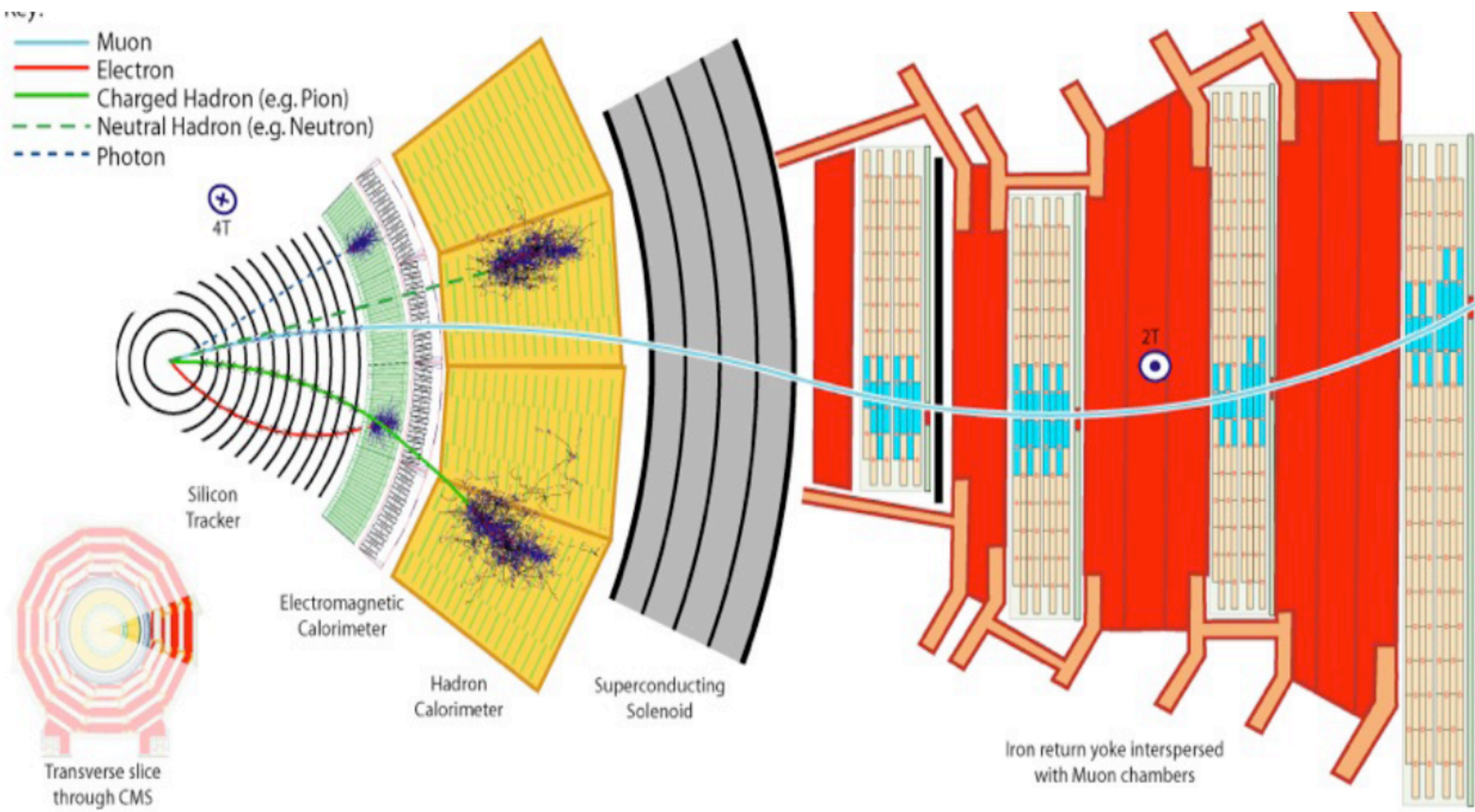
CMS Detector



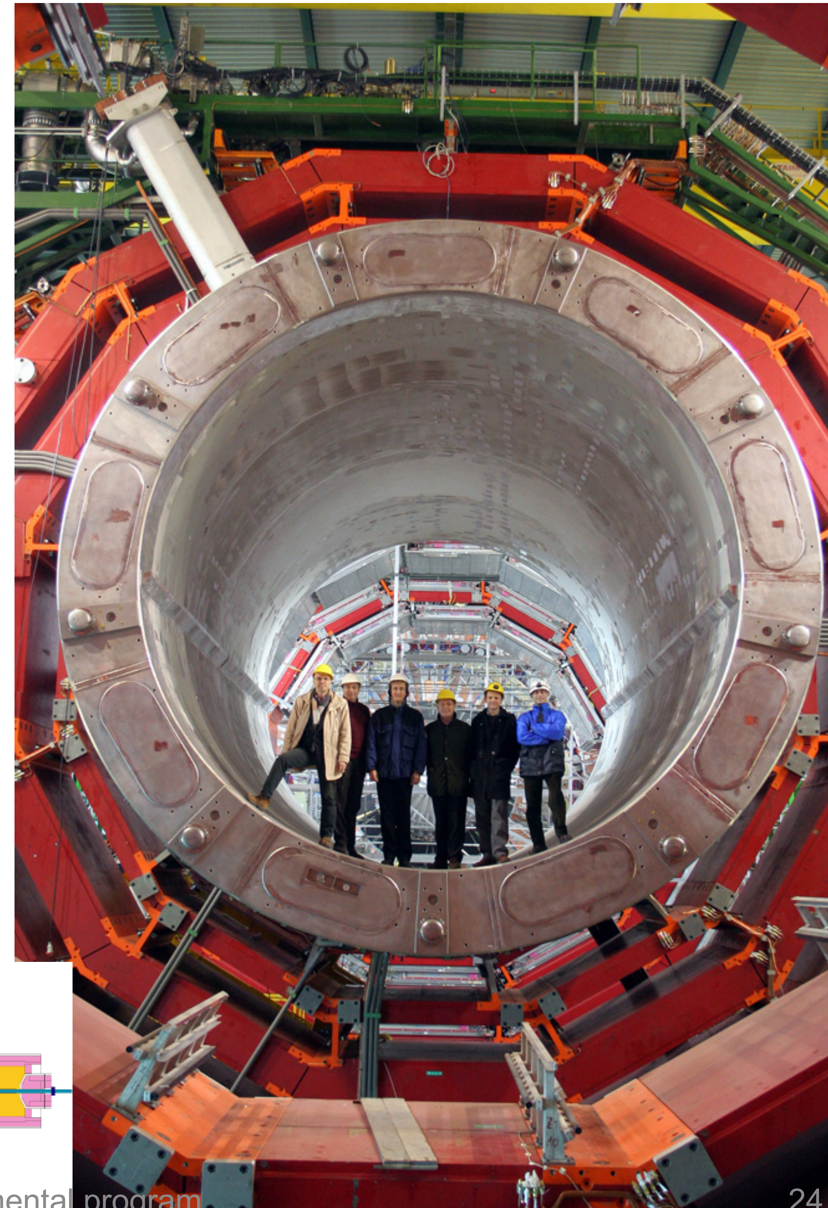
ATLAS detectors



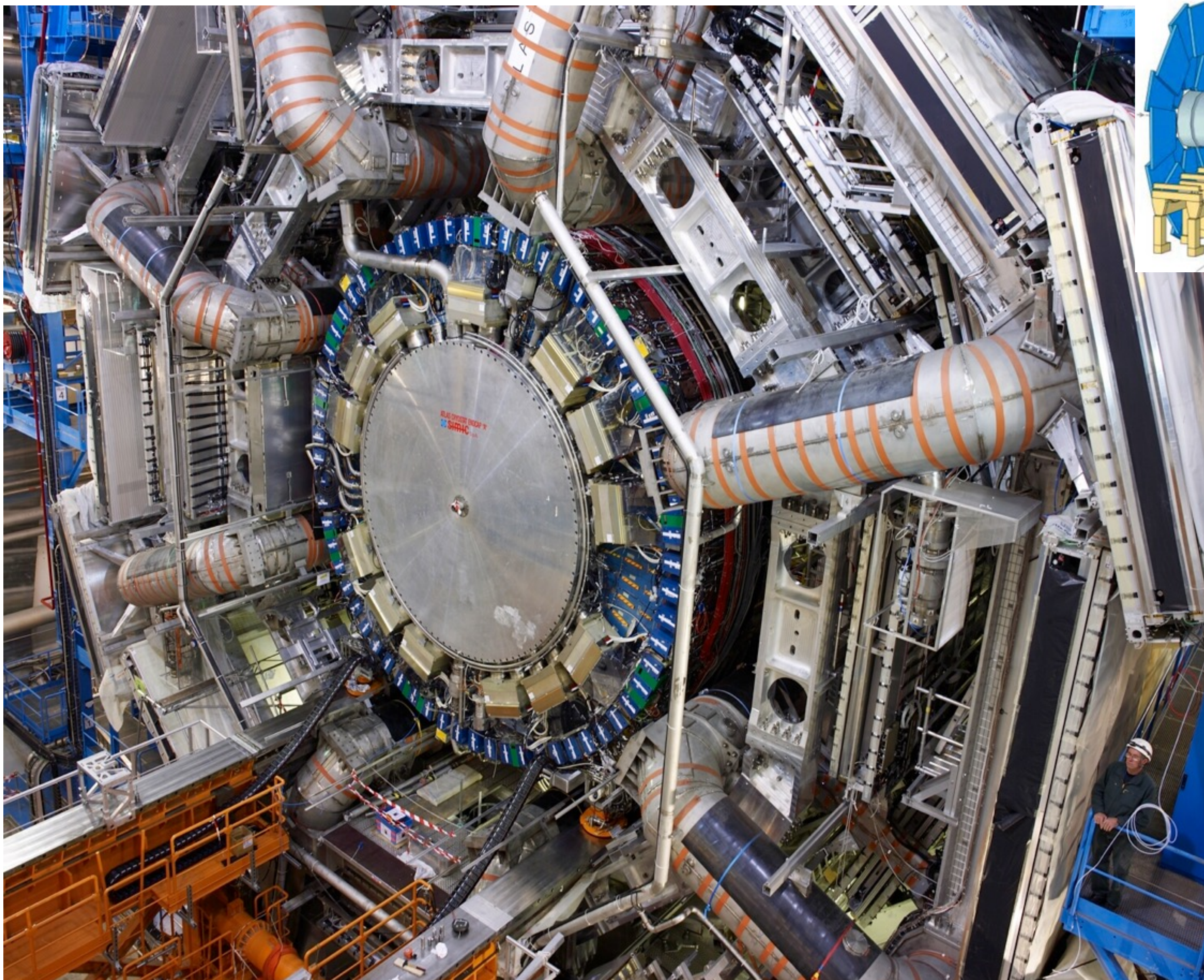
Detection of hadrons, $e^{\pm}$, γ and $\mu^{\pm}$

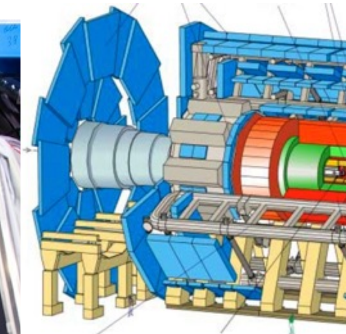


CMS Superconductor Solenoid

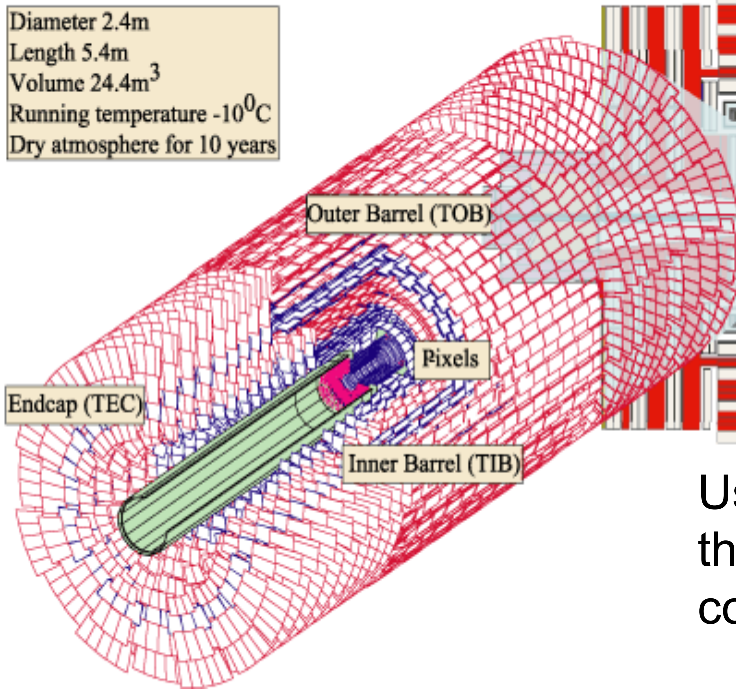


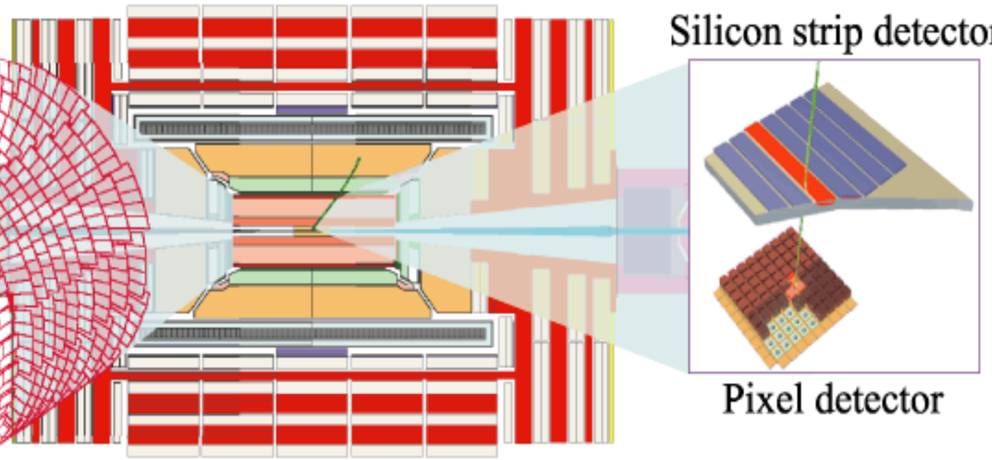
ATLAS Toroidal System





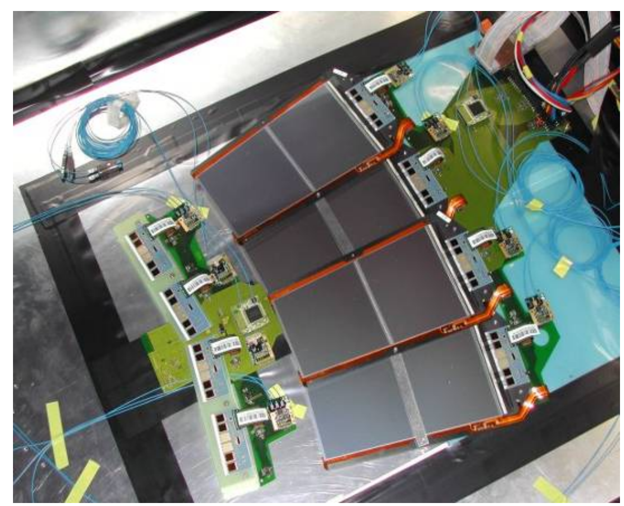
Silicon Tracker



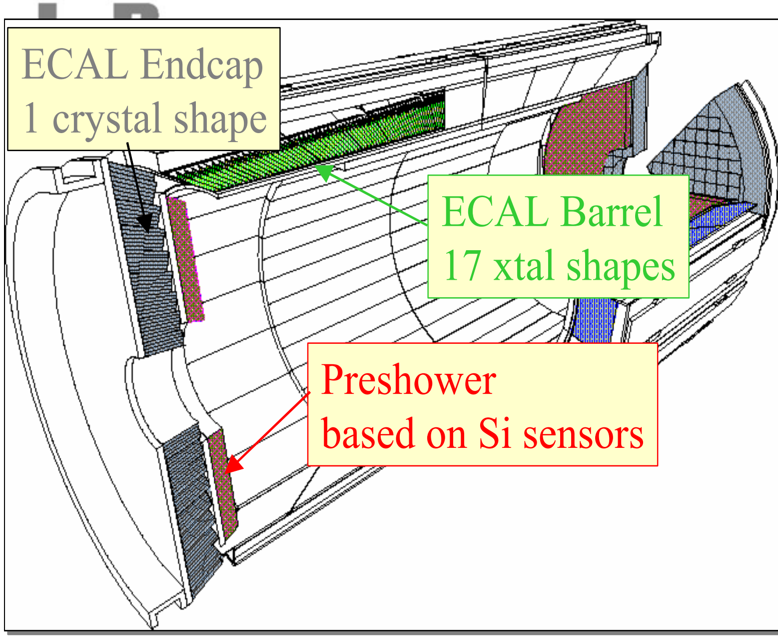


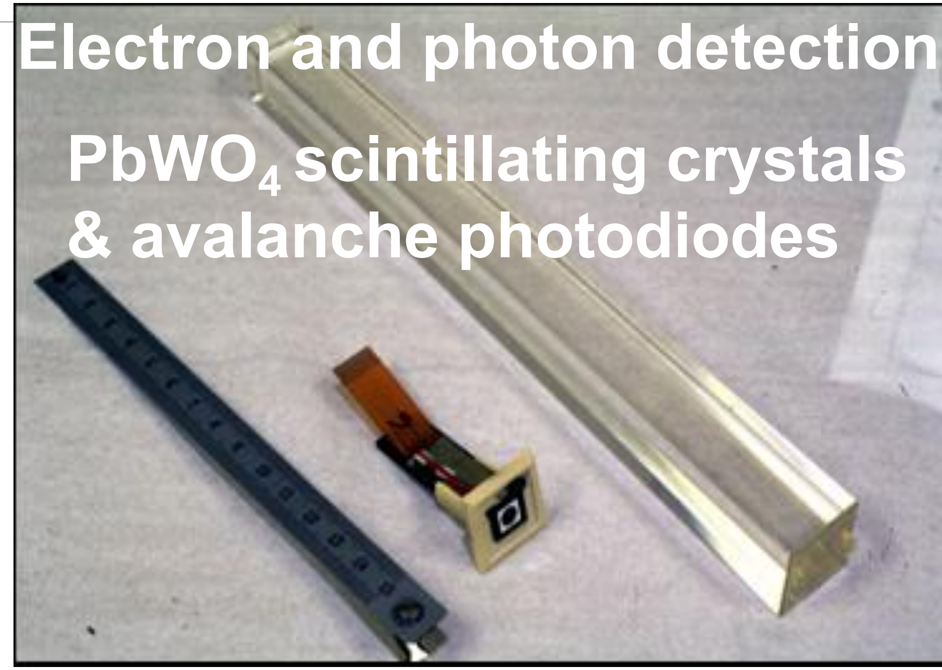
Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

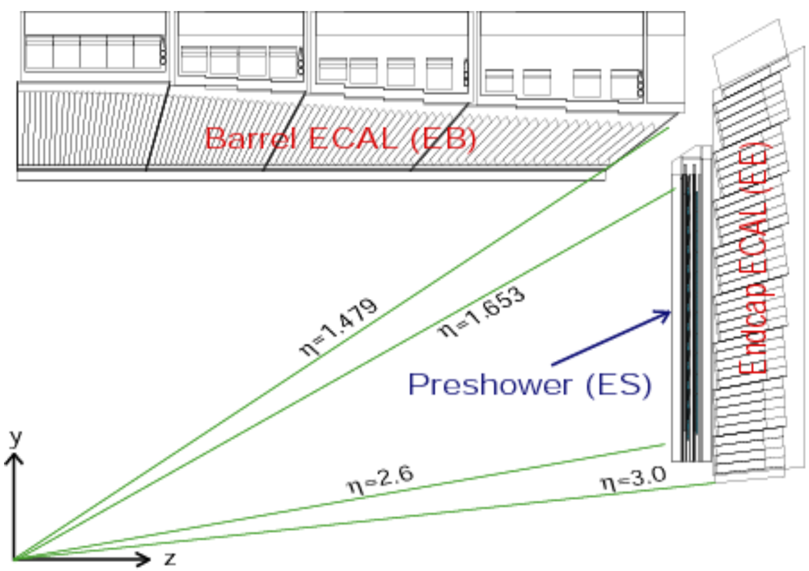
214m^2 silicon sensors
11.4 million silicon strips
65.9 million silicon pixels



ECAL Electromagnetic Calorimeter



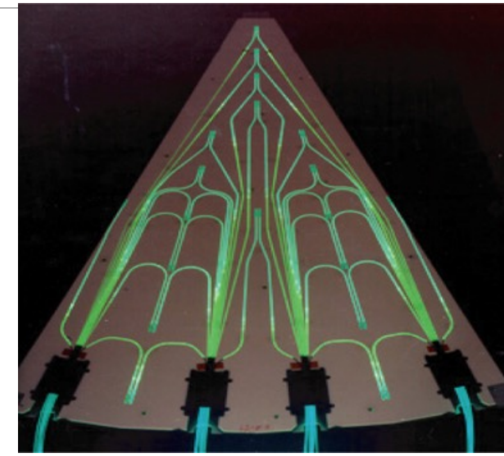




Design Goal: Measure the energies of photons from a decay of the Higgs boson **to precision of ≤ 0.5%**

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

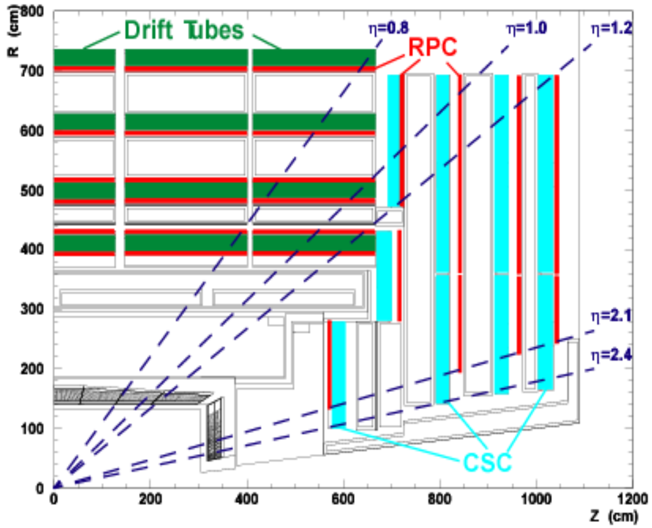
HCAL Hadronic Calorimeter

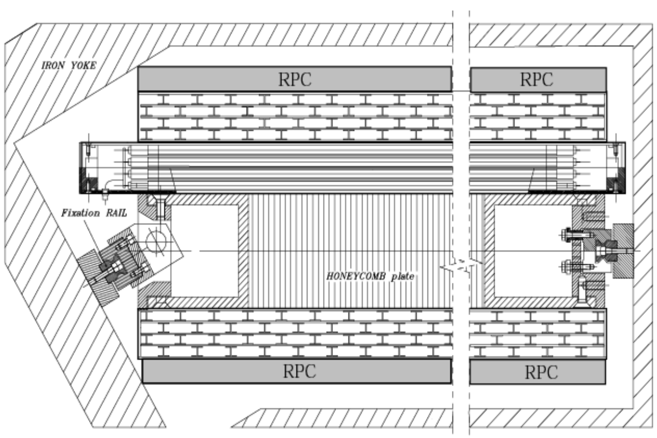


Detection of hadrons:
- protons, neutrons, pions, etc.

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

Muon detectors

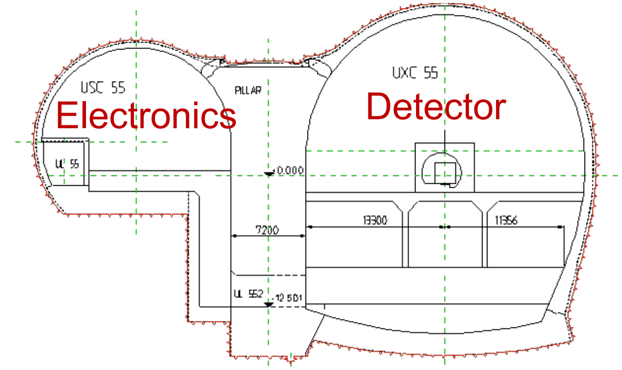




Drift Tubes (DT)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

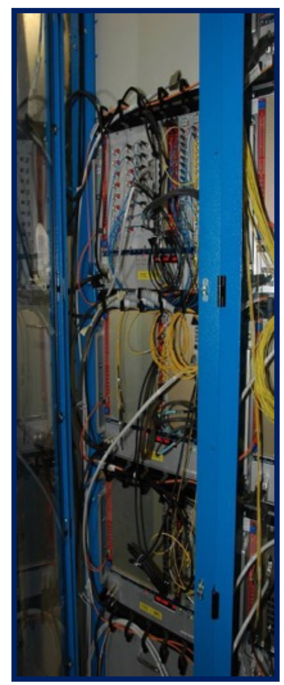
Electronics systems

Underground caverns



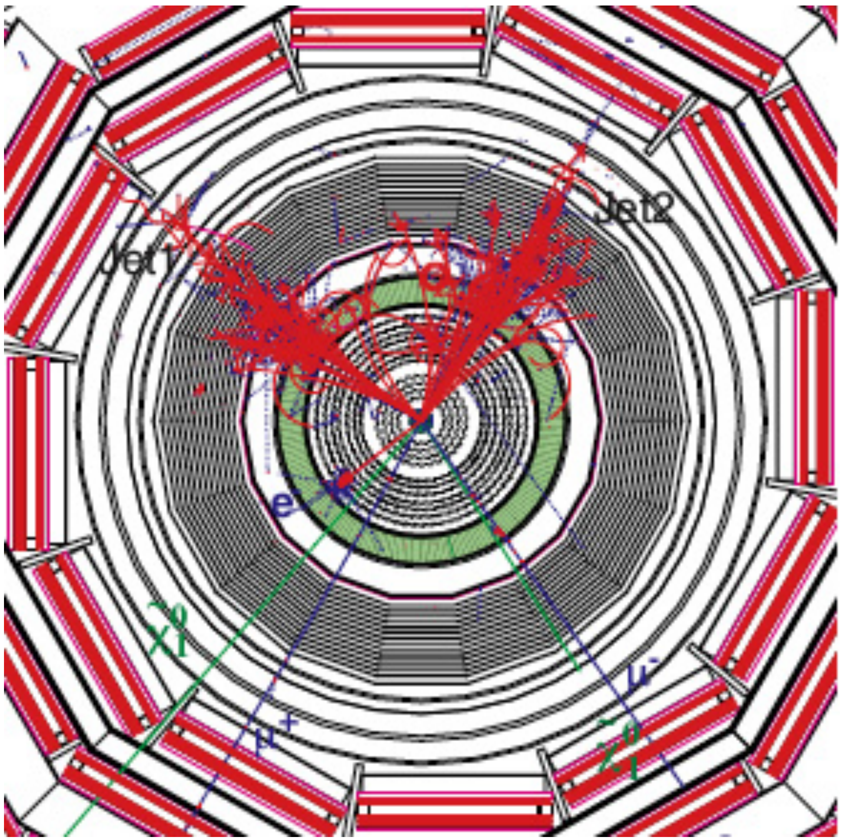
Electronics systems in the Service Cavern.

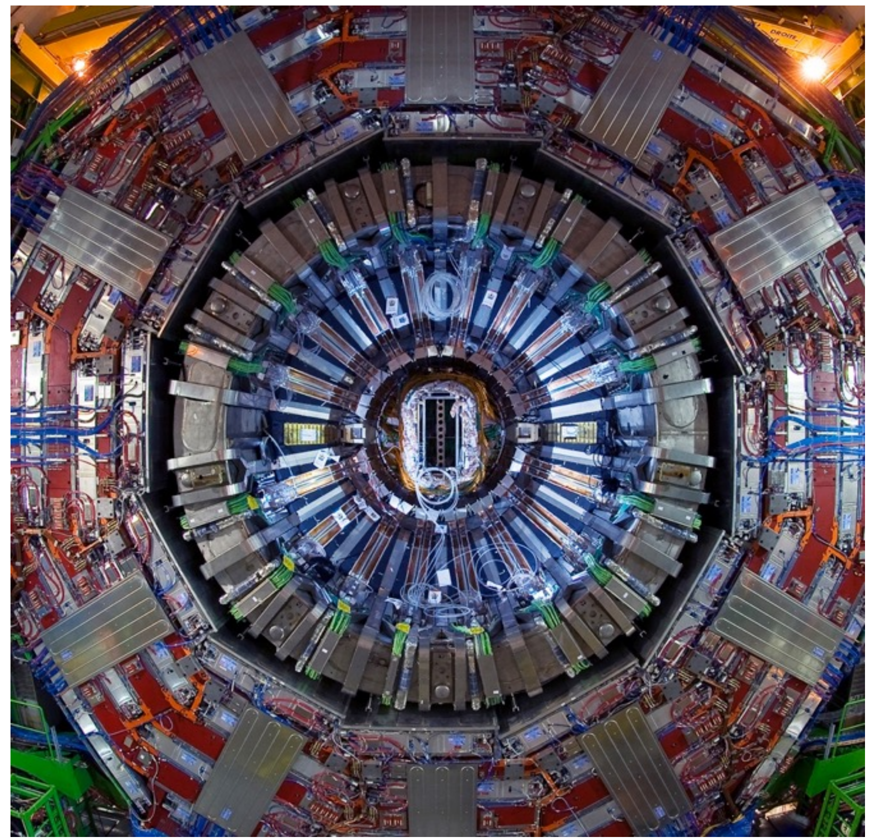
- About 150 racks occupy two floors.
- Most electronics was designed and built specifically for the experiment



Detector simulation

Simulation of proton-proton collision producing dark matter particles



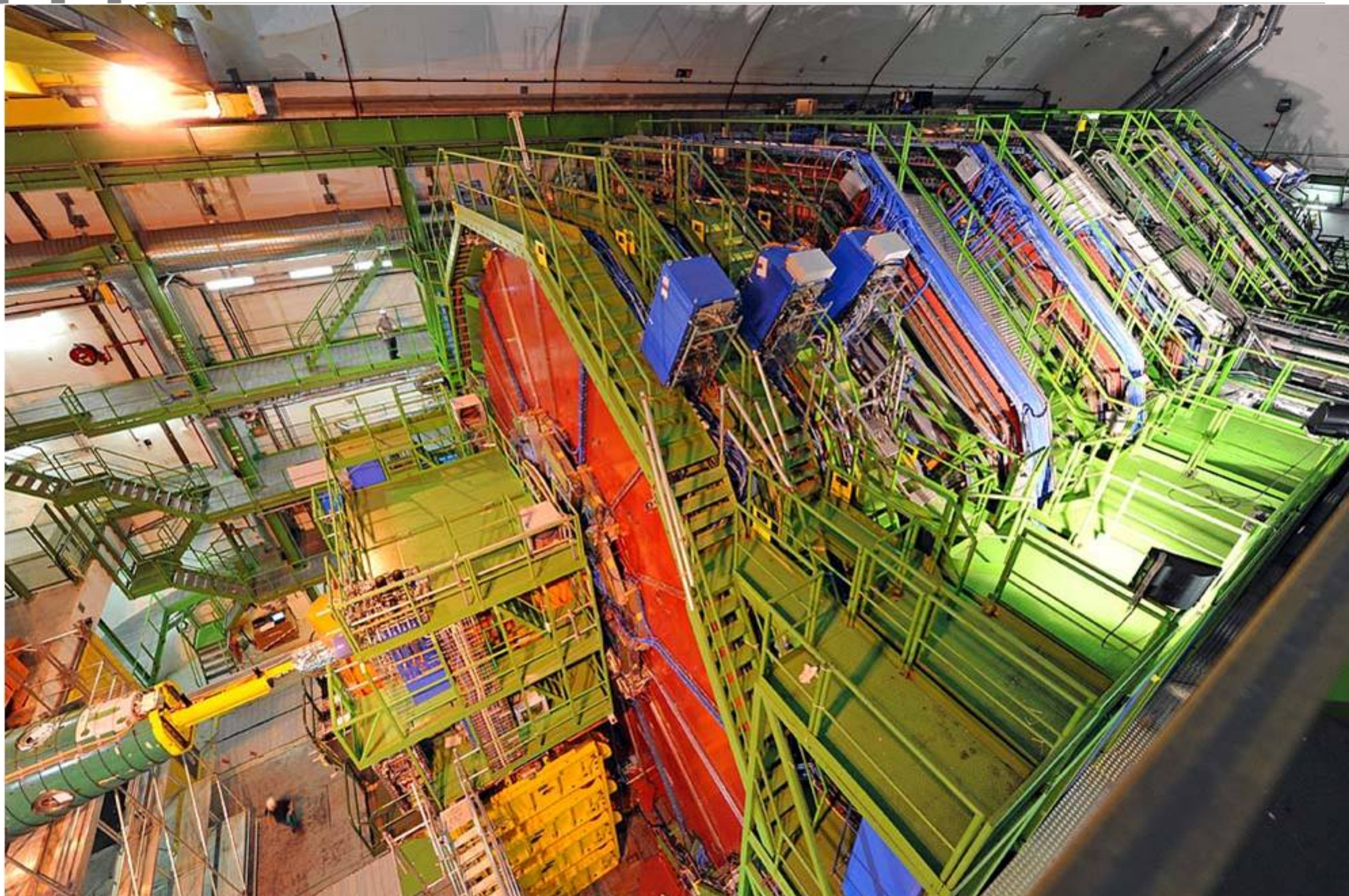


The LHC Computing Grid

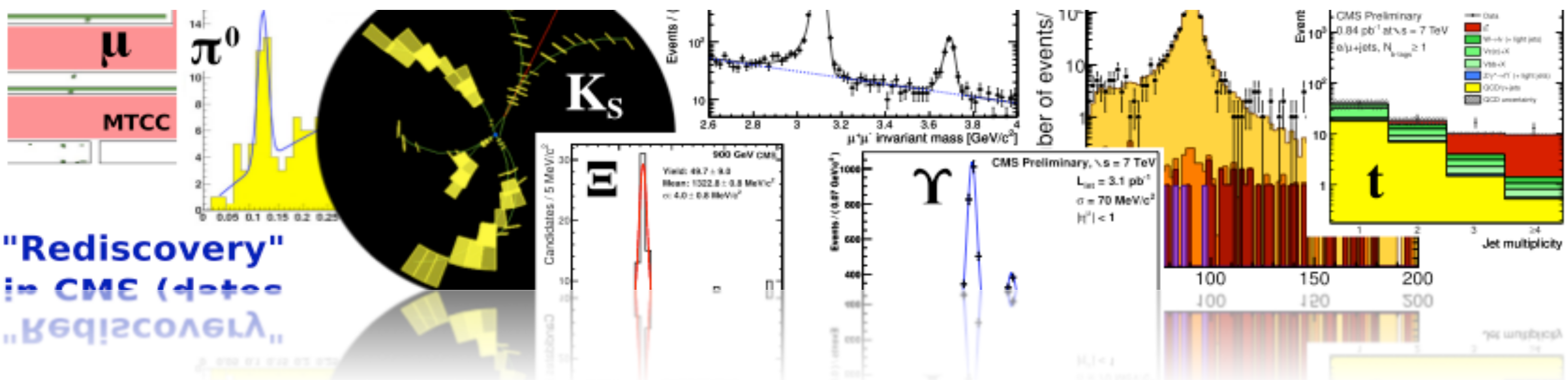
The Grid unites computing resources of particle physics institutions around the world

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

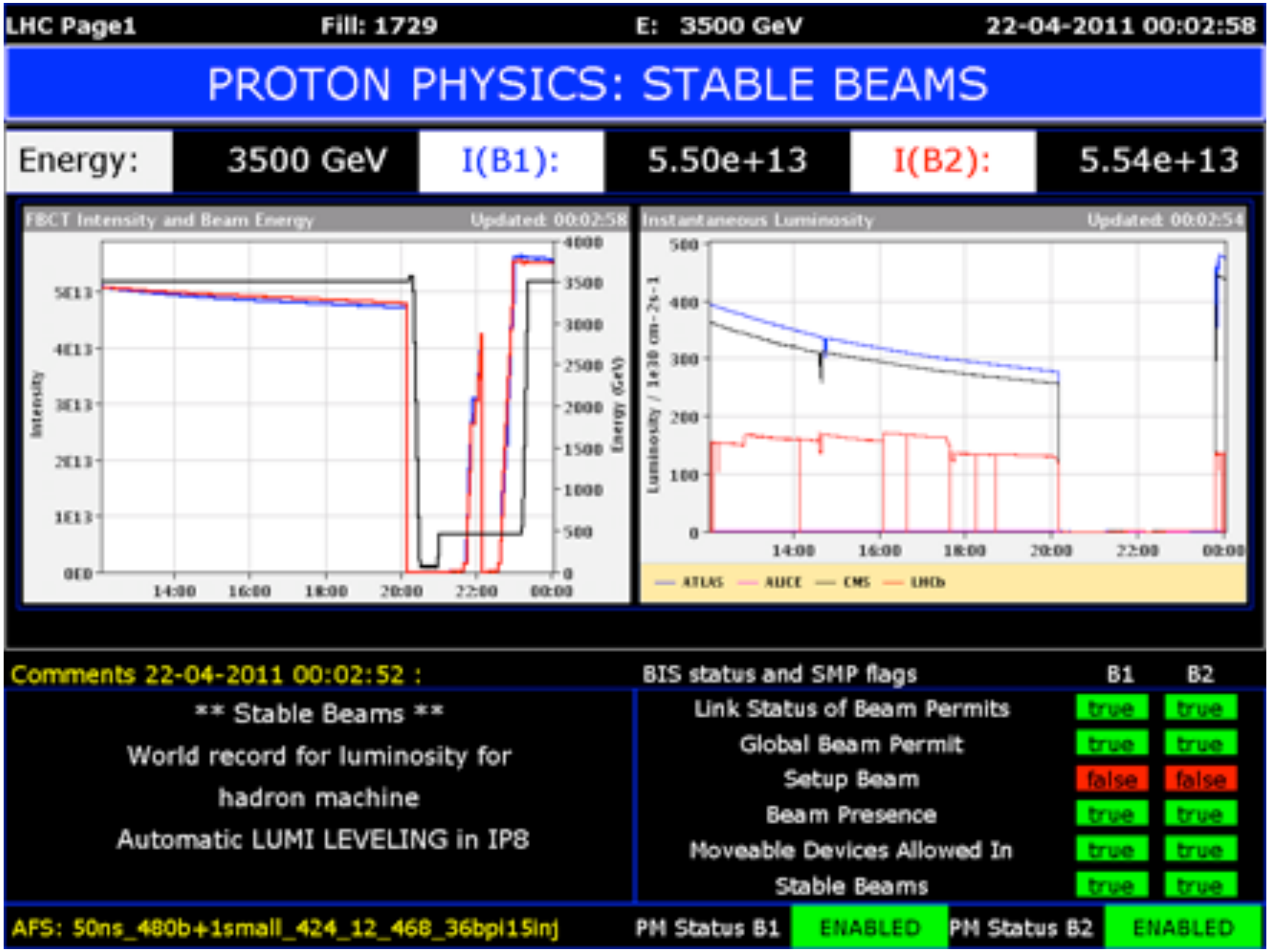
CMS detector ready for beams



Detector operation, commissioning and physics production



LHC Page 1: stable beams



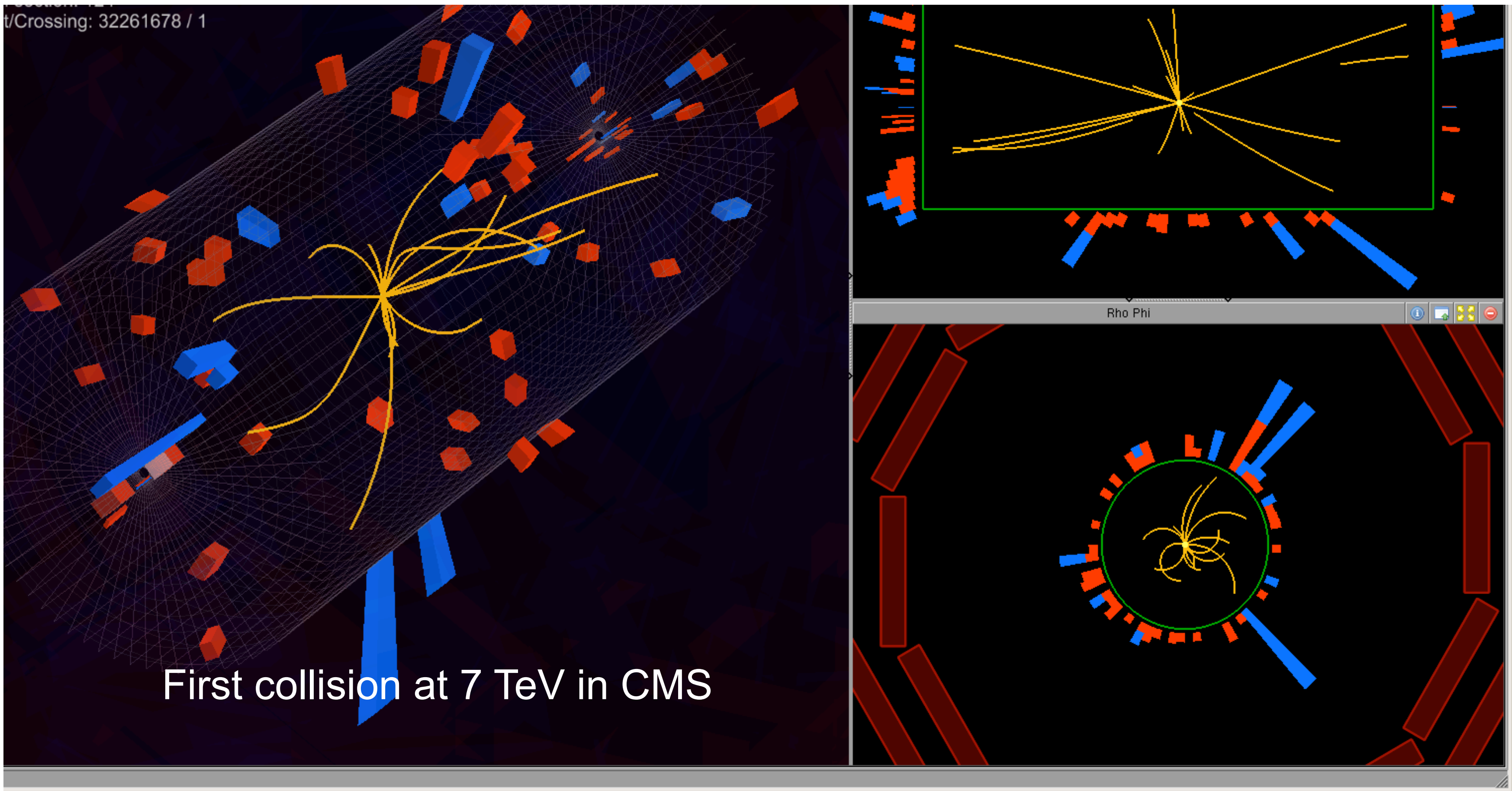
CMS Page 1: running

2009: First p-p collisions at LHC

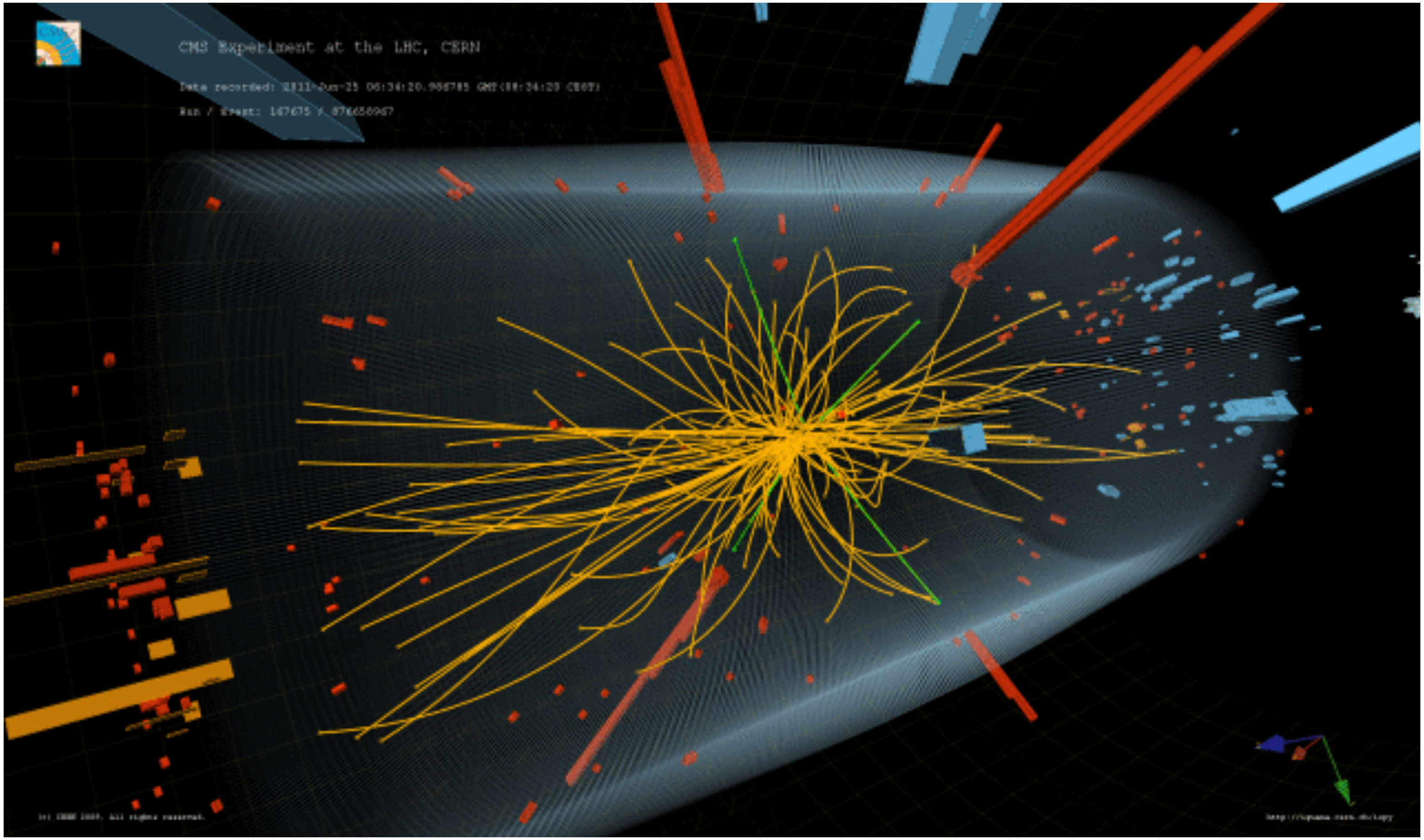
November 23, 2009
First collisions at 900 GeV

December 14, 2009
First collisions at 2.36 TeV

March 30, 2010
First collisions at 7 TeV

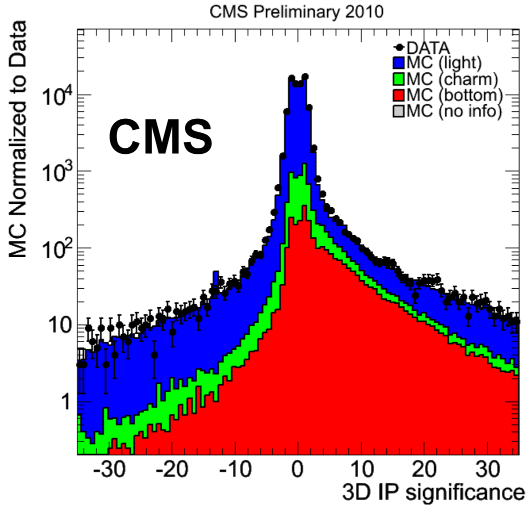


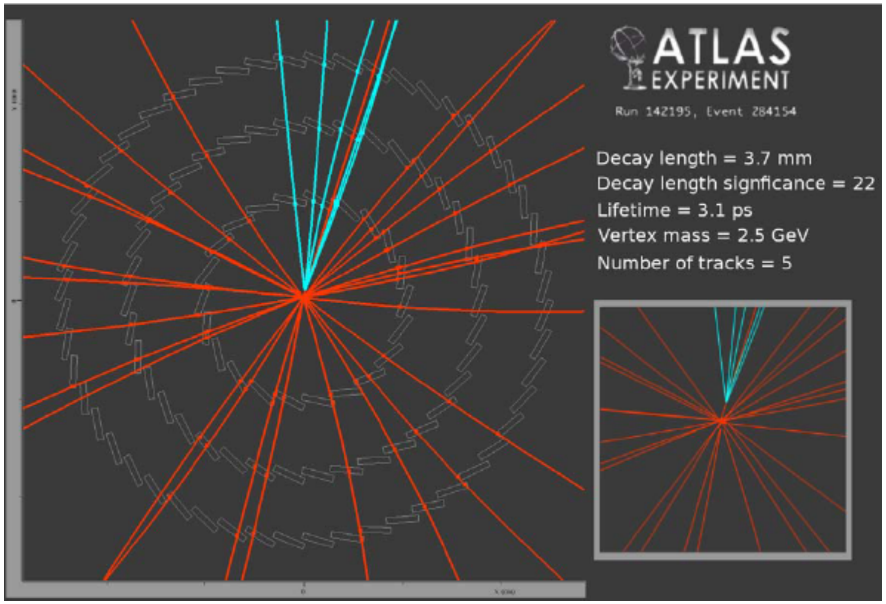
Higgs decay in 4 electrons

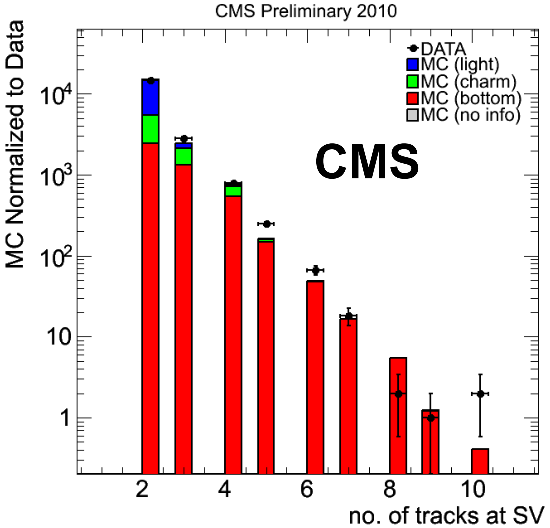


Tracking: secondary vertices

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

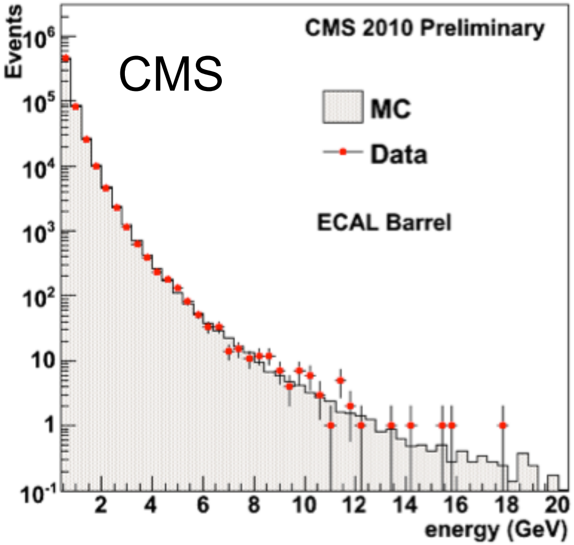


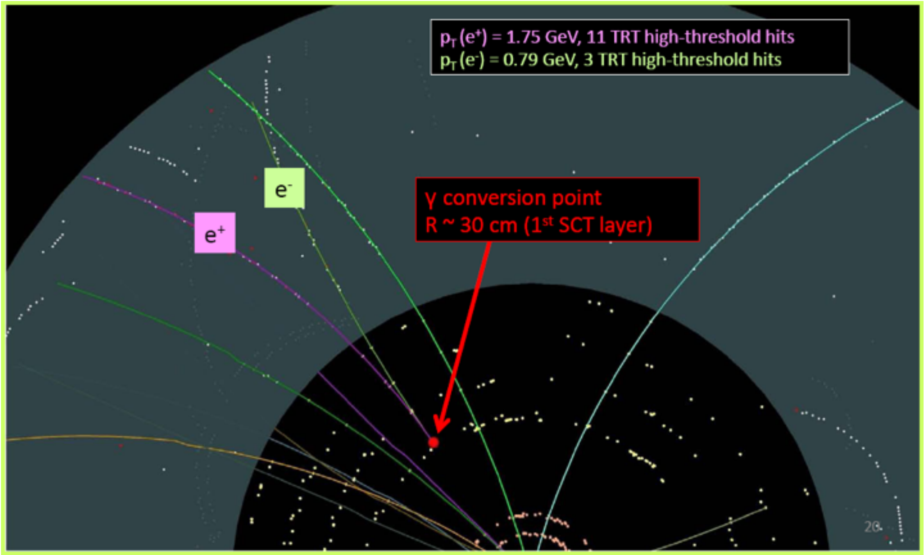


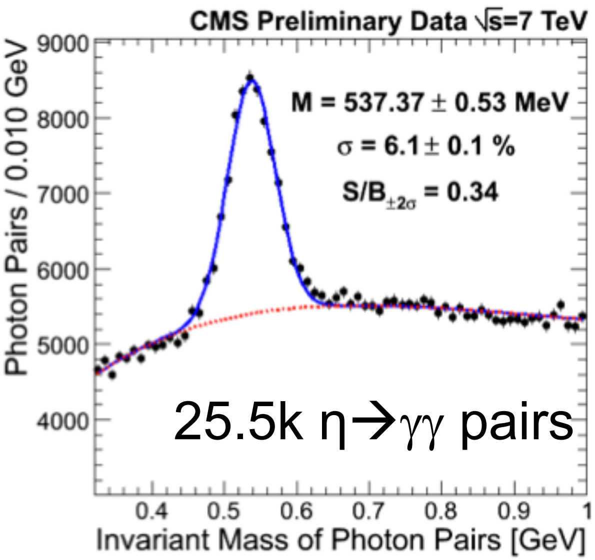


Secondary vertices compatible with heavy flavor production

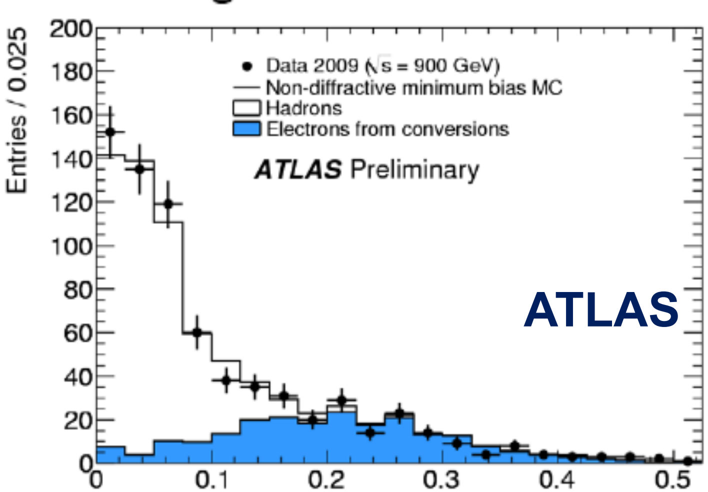
Photons and electrons



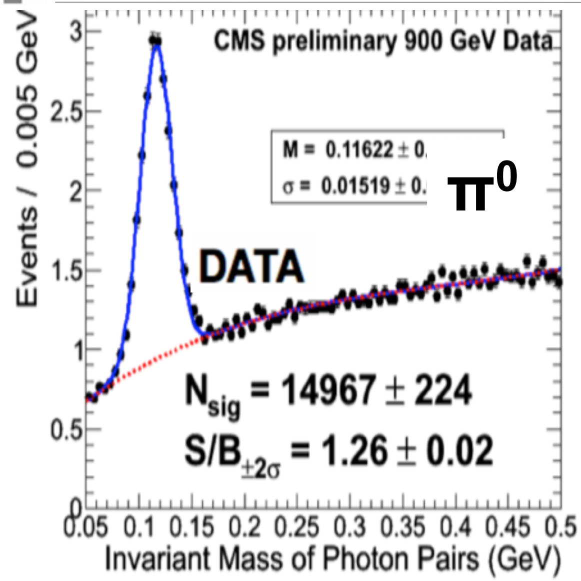


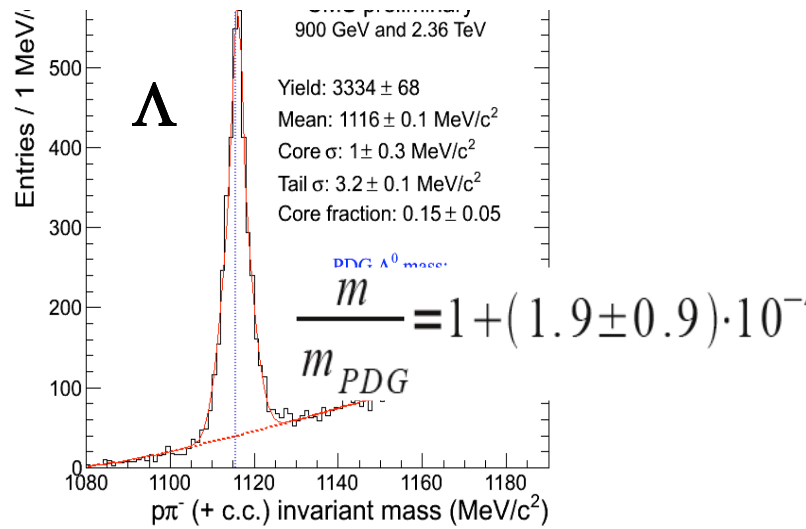


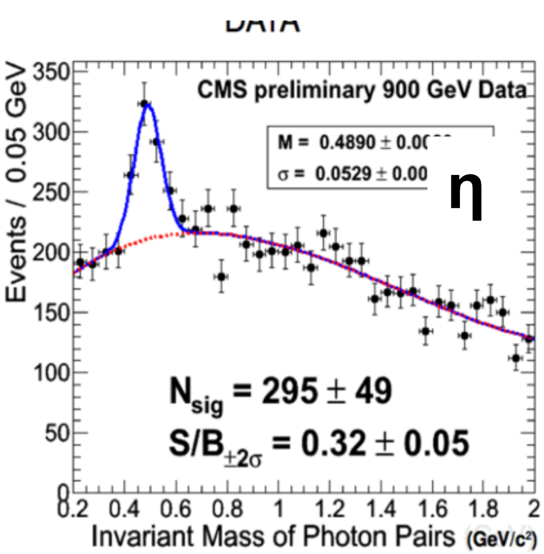
TRT high-threshold hit fraction

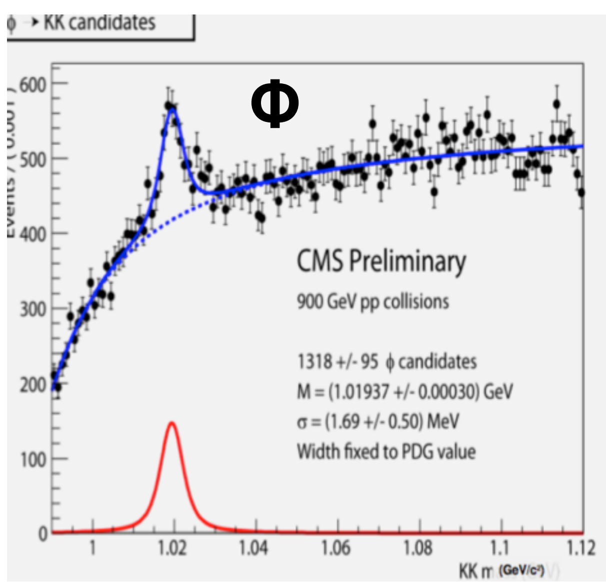


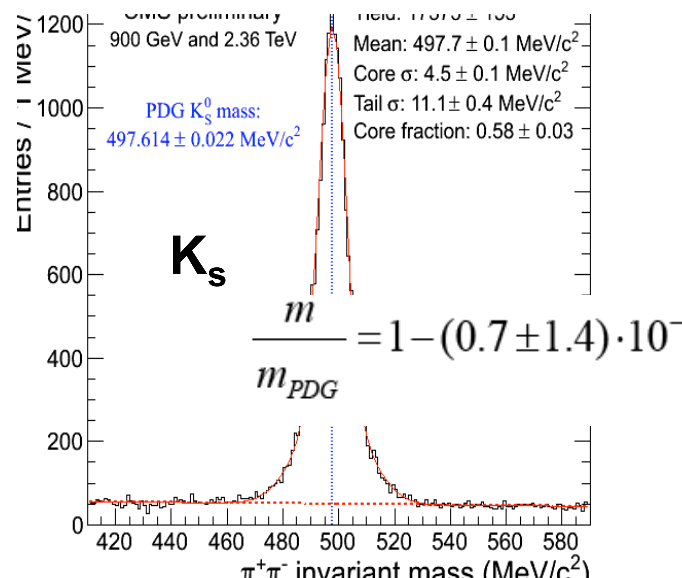
Rediscovery of resonances



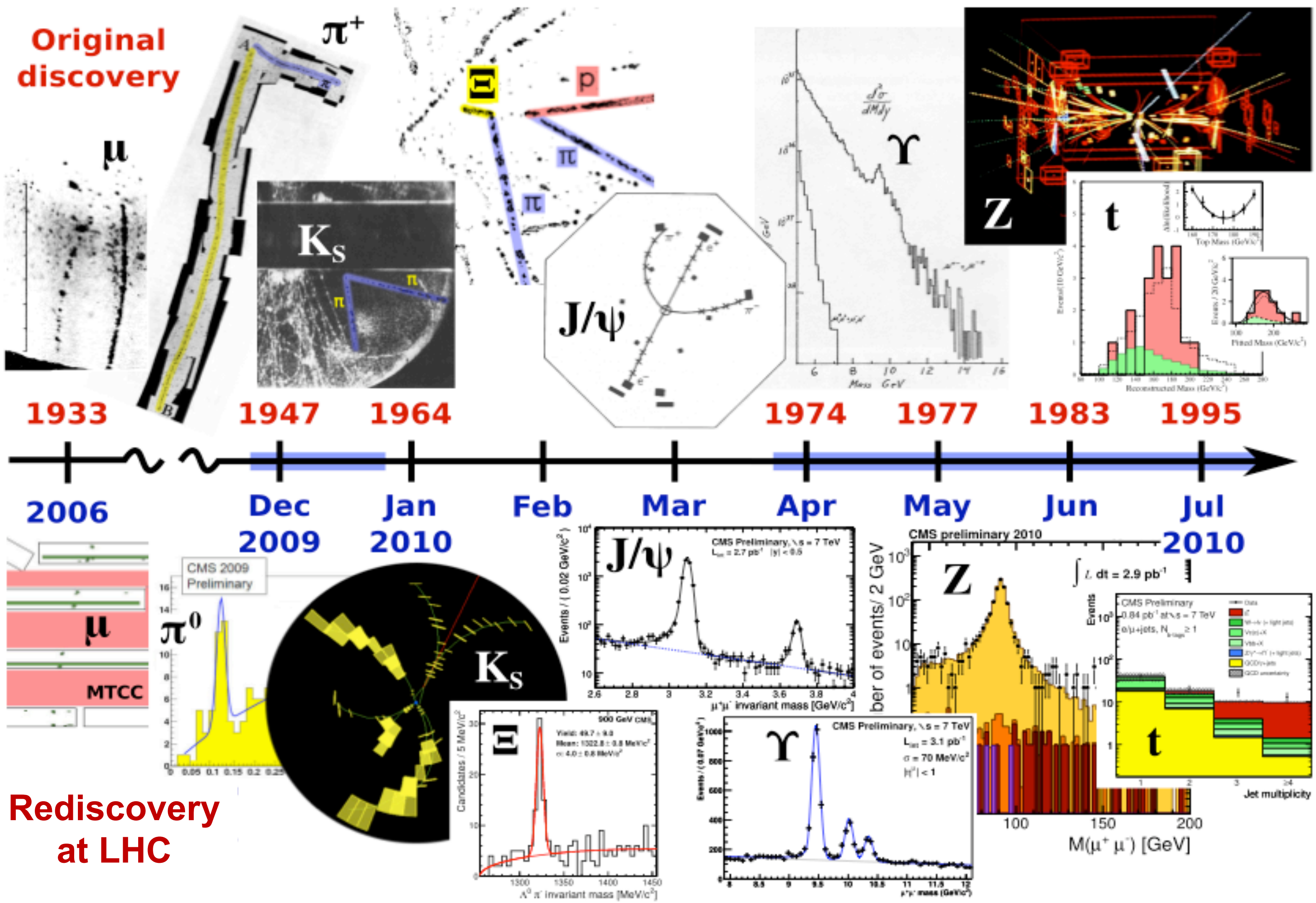








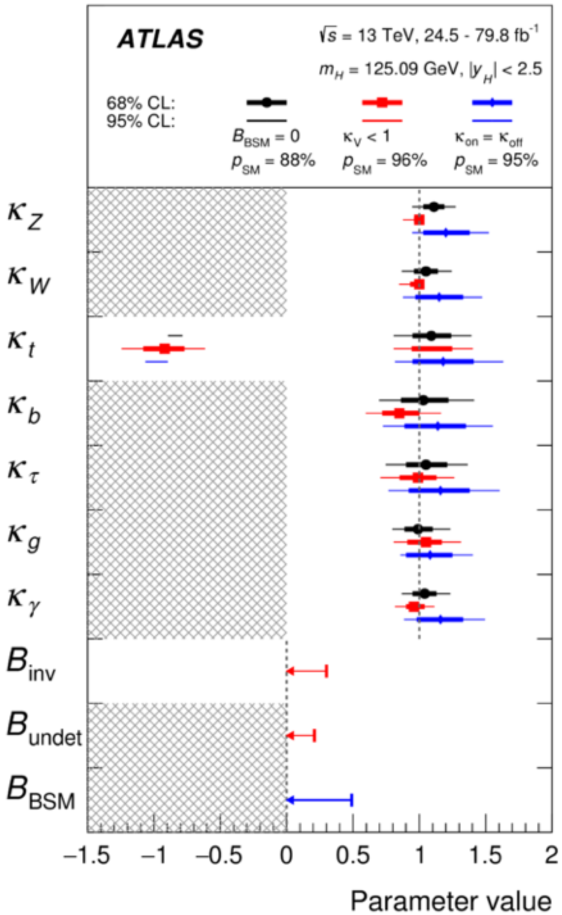
Rediscovery of the Standard Model



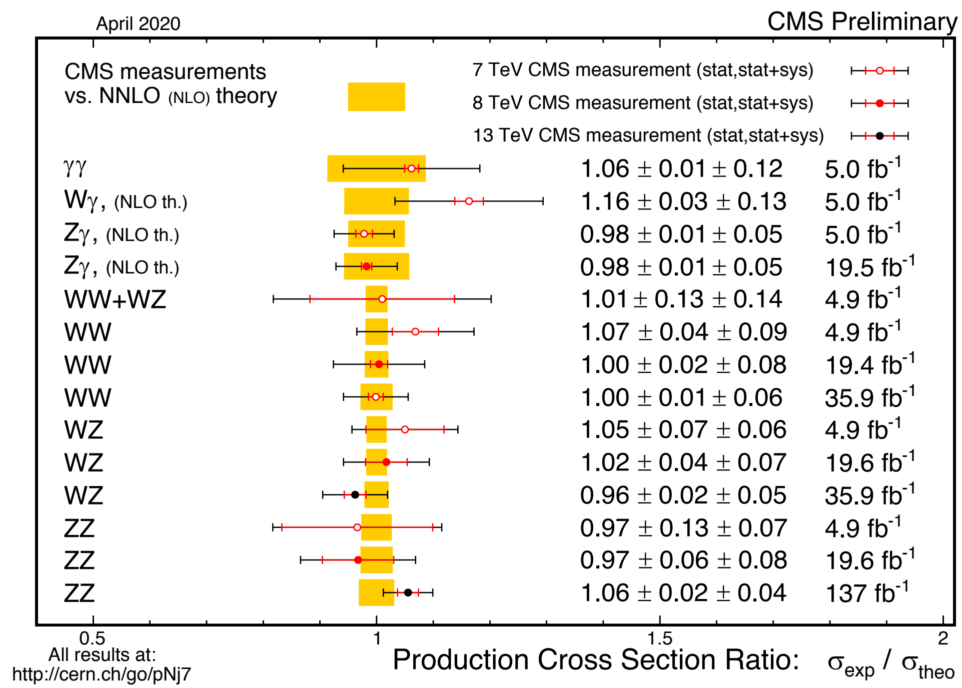
Search for New Physics

So far the measurements are compatible with the SM predictions

- about ~2500 papers have been published by the LHC collaborations
- few discrepancies observed are not yet conclusive

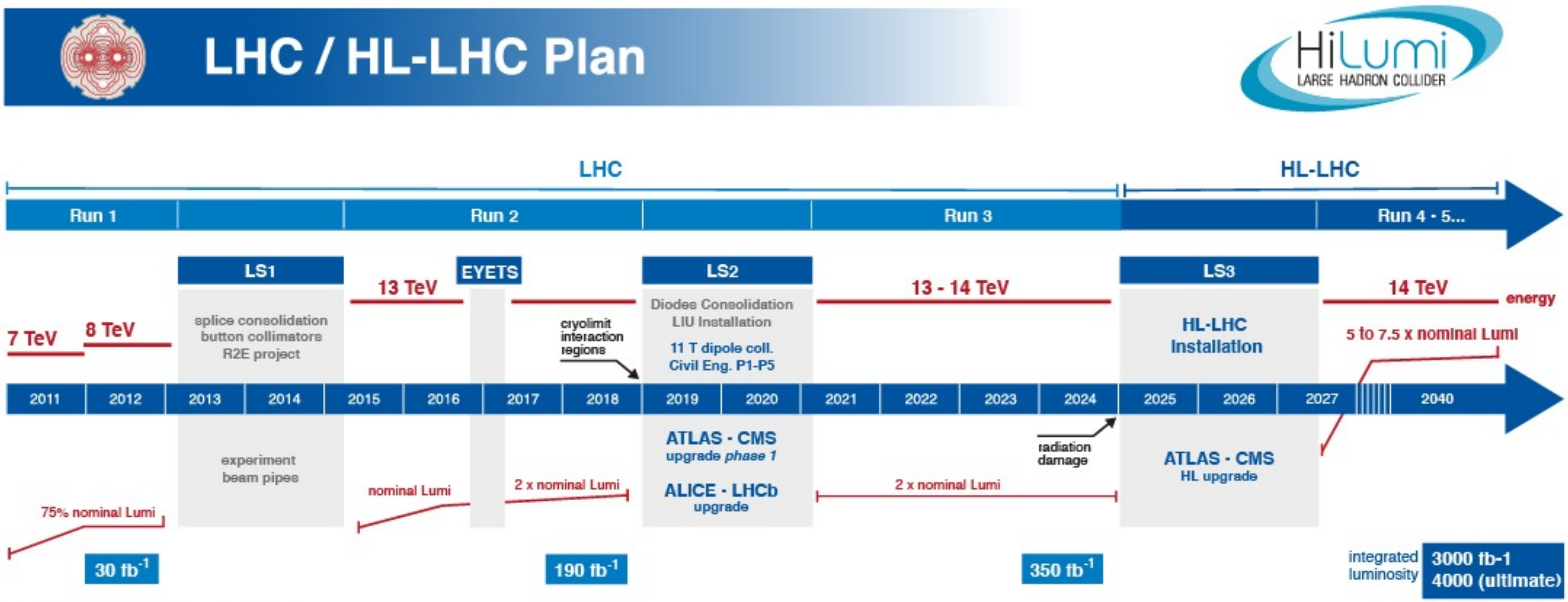


More data is needed to achieve measurements at 1% precision or below



The future: High-Luminosity LHC

HL-LHC will provide 20 times more data than available today!



Bound to be one of the greatest endeavors of science in the 21st century

Thank you for your attention