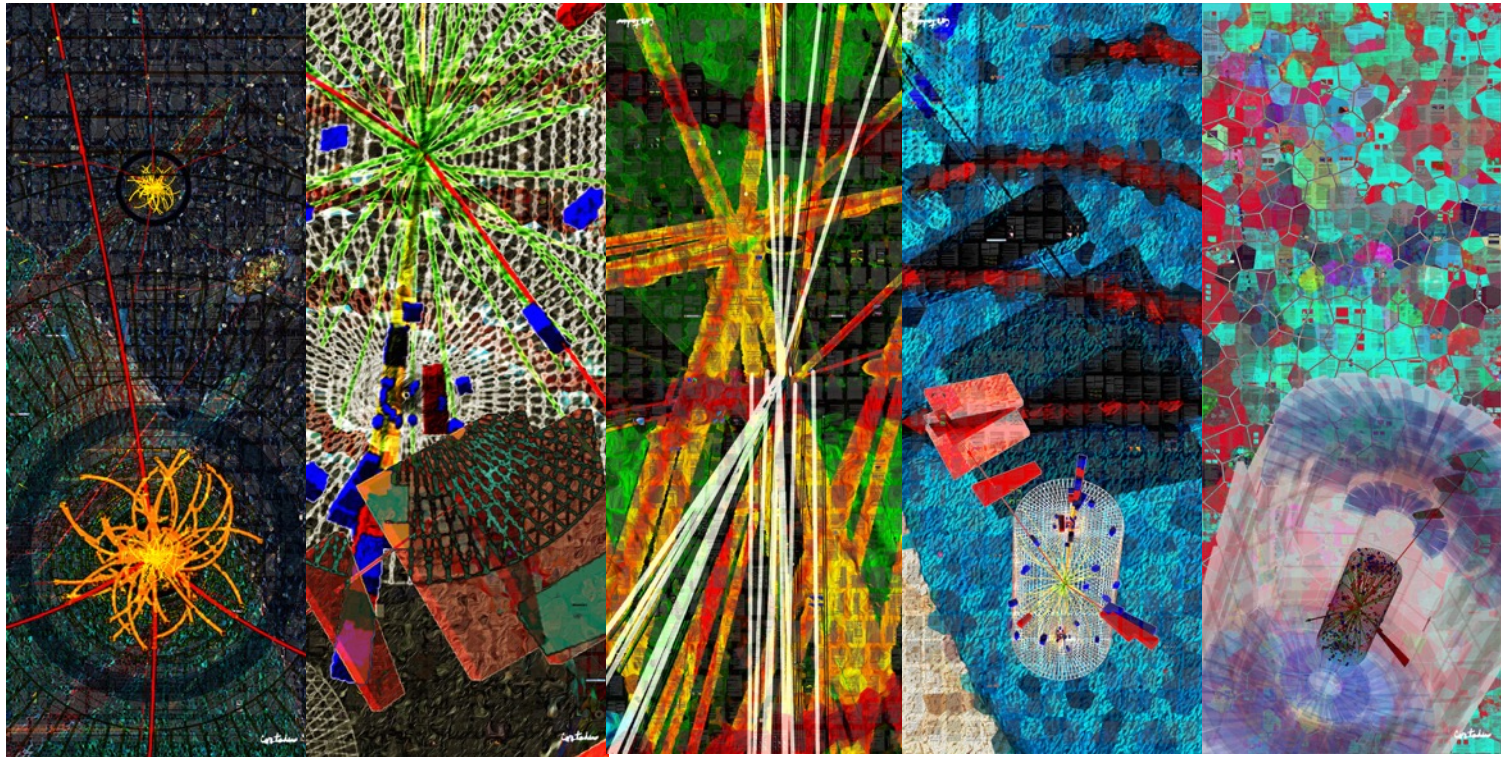
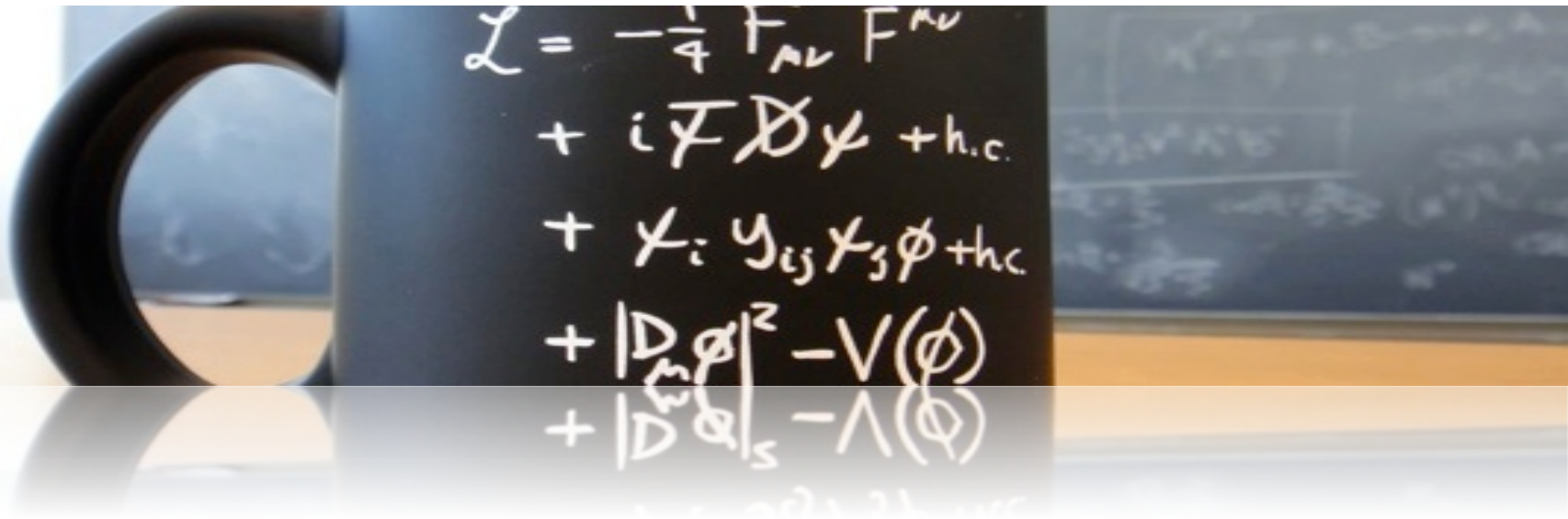


# The LHC experimental program

J. Varela, 14 July 2020

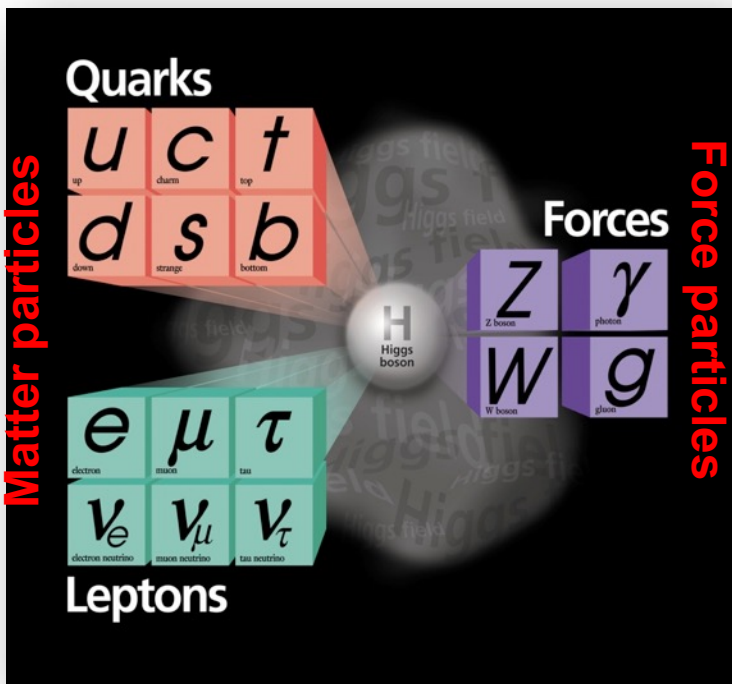


# The LHC physics case

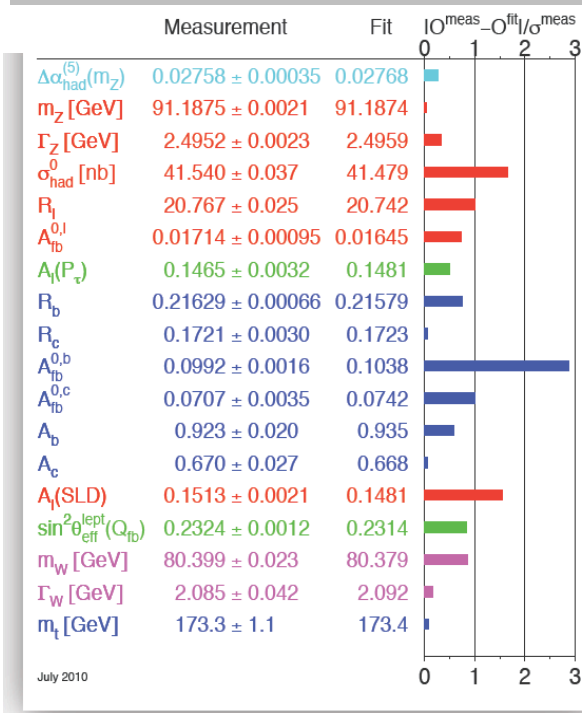


# The Standard Model of Particle Physics

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



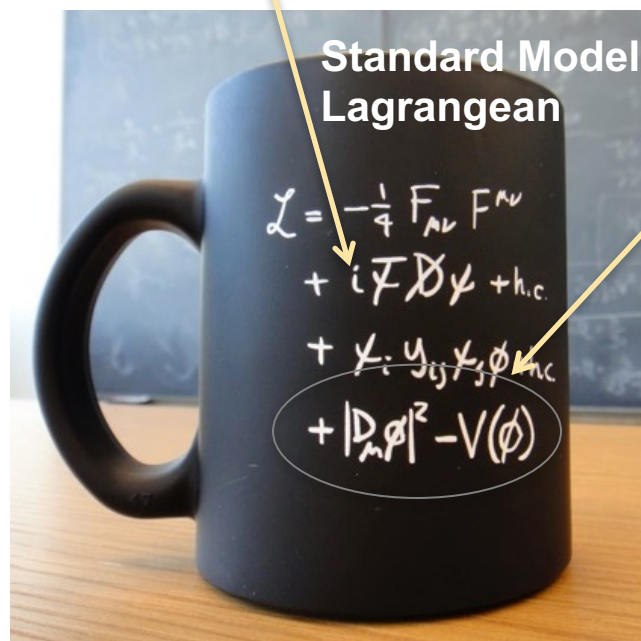
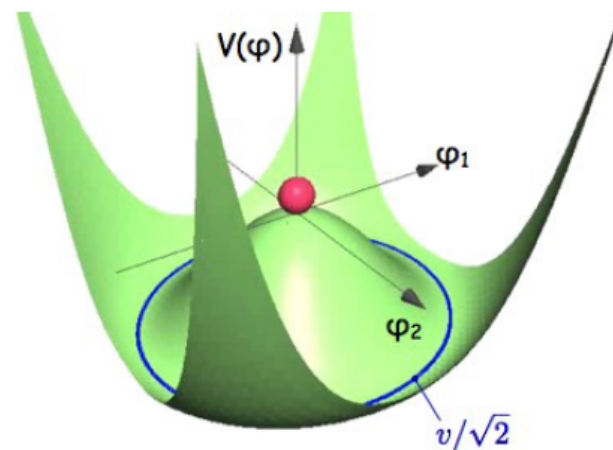
One of the greatest achievements of the 20<sup>th</sup> Century Science



# 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.

Large Hadron Collider

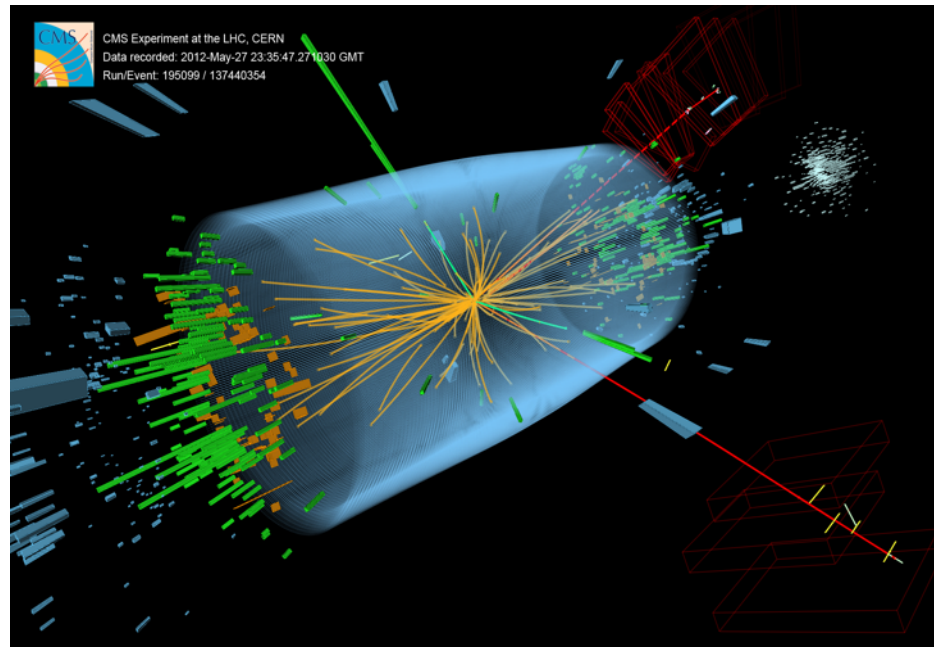
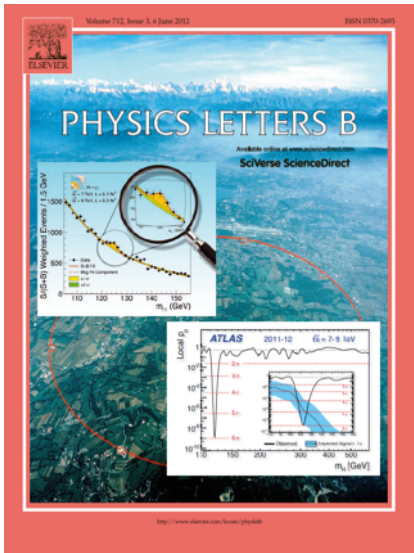


# Higgs boson discovery in 2012

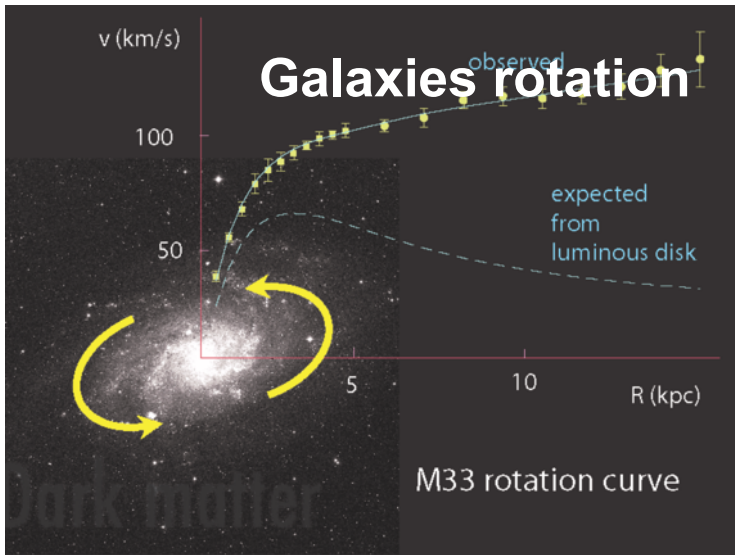
**A major discovery in physics**

**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



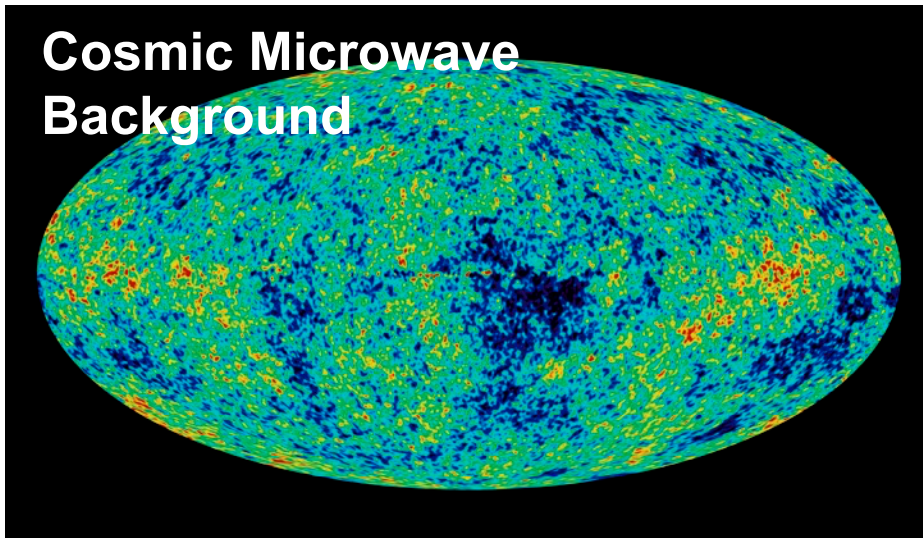
# The dark side of the Universe



**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  $2.7^{\circ}\text{K}$
- 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

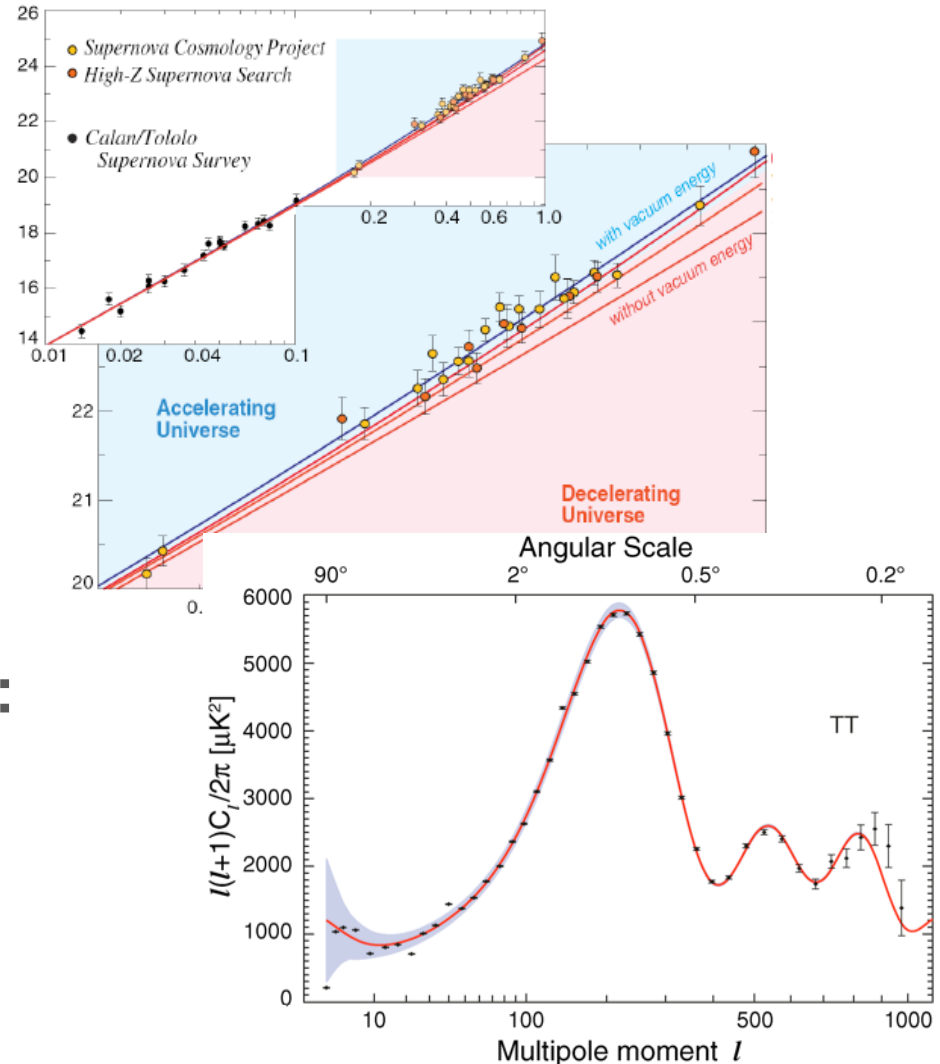
In 1998, the observation of distant **Supernovae** allowed to measure the expansion rate of the universe.

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

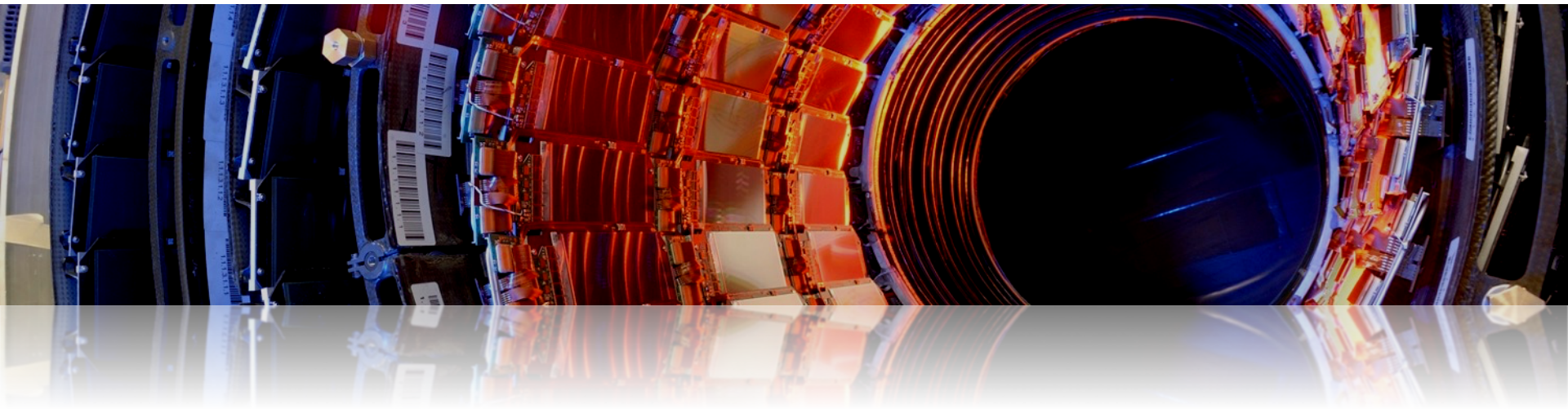
There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- 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**

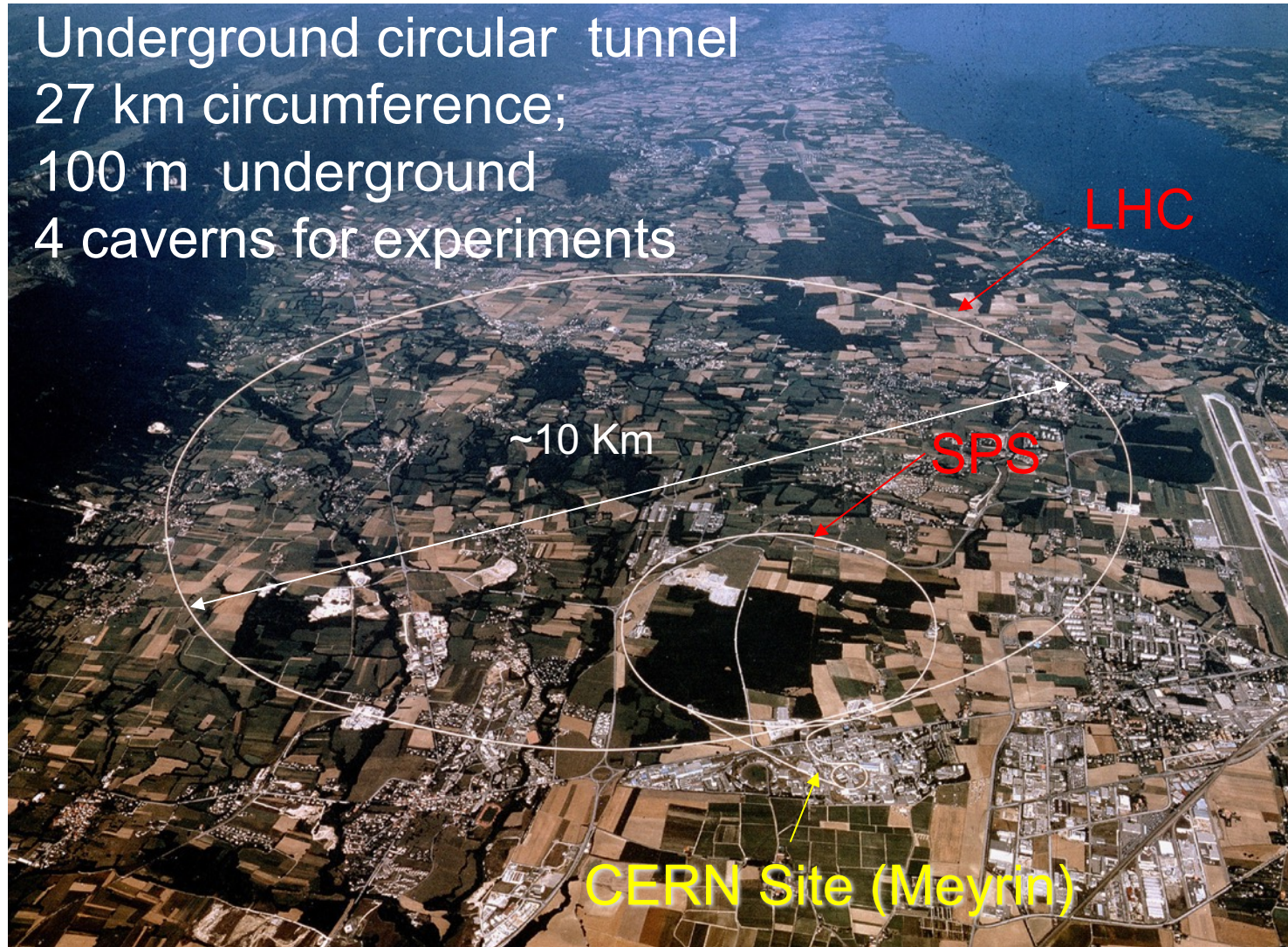


# The LHC proton collider and the experiments



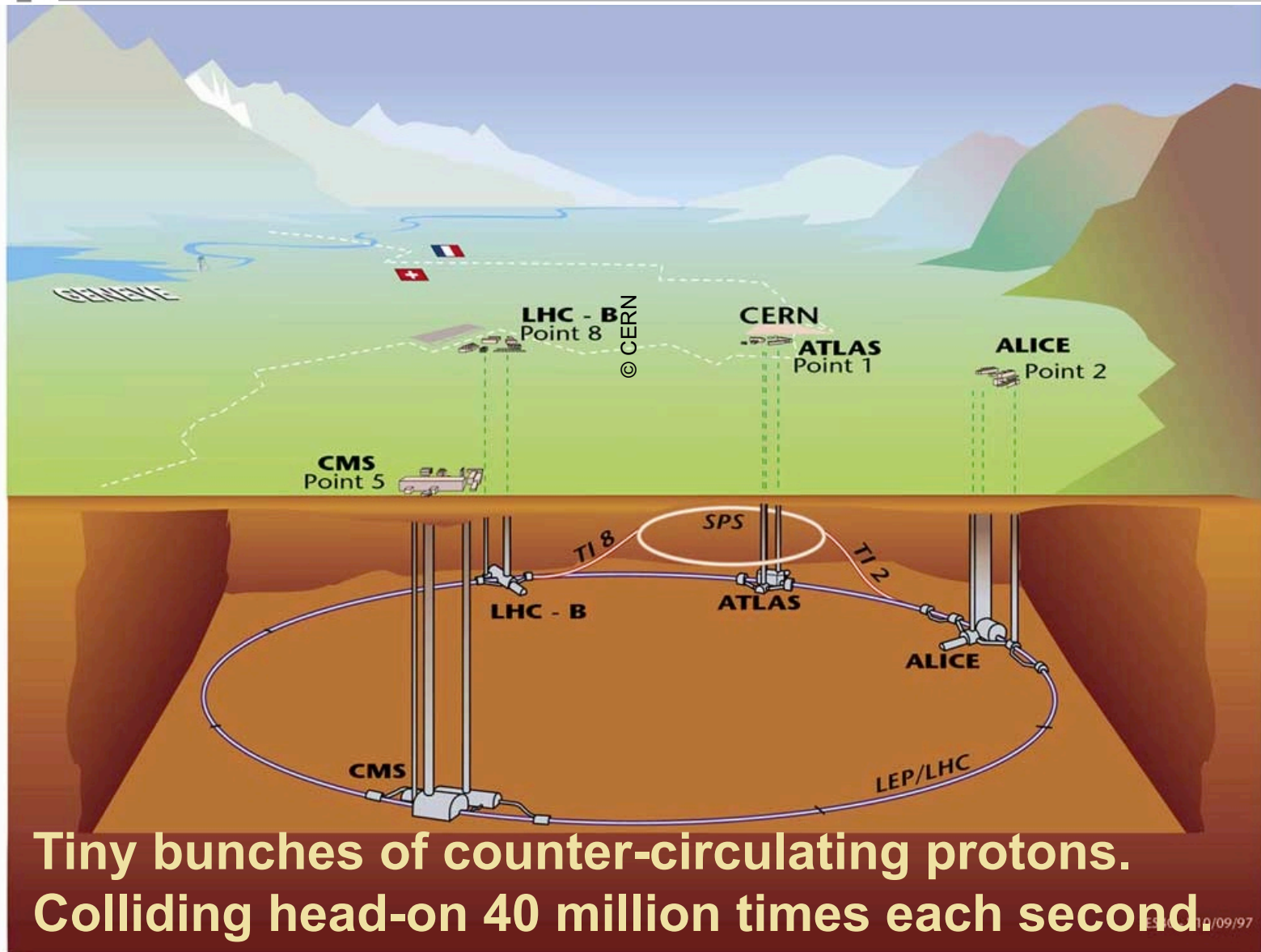
# Accelerator and Experiments

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



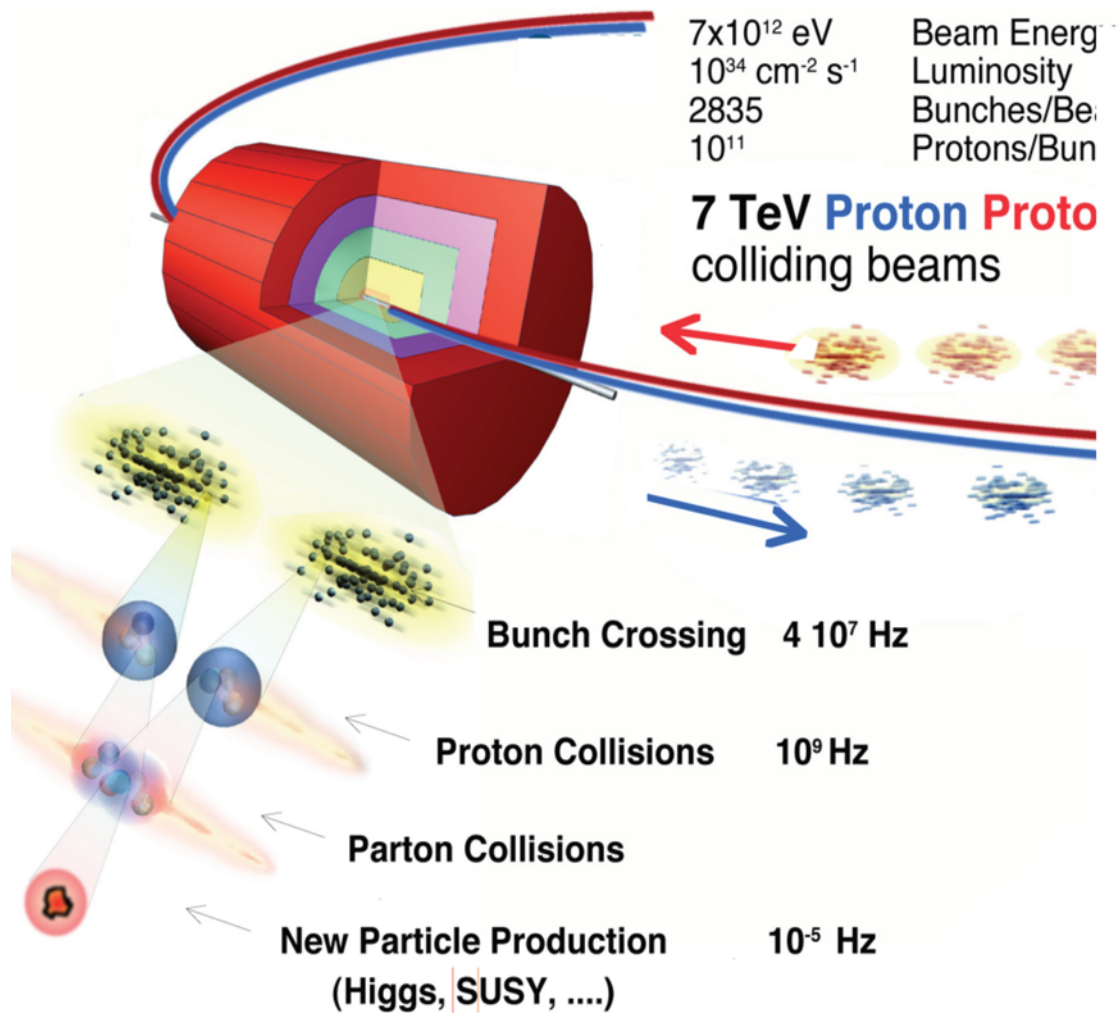


# Accelerator and experiments layout





# Collisions at LHC



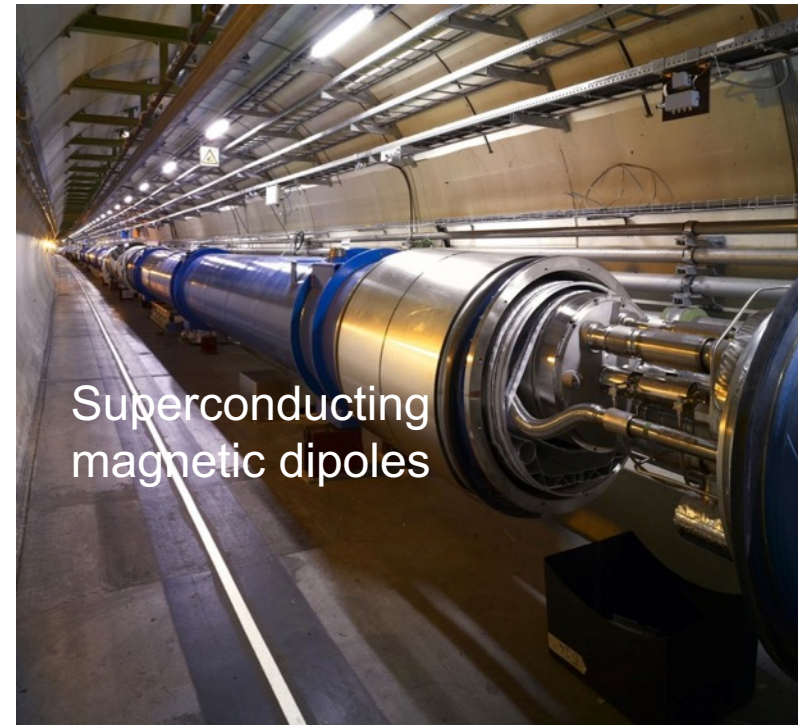
# LHC accelerator challenges

## Relative to Tevatron (Fermilab, USA)

Energy (14 TeV) x 7

Luminosity ( $10^{34}\text{cm}^{-2}\text{s}^{-1}$ ) 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

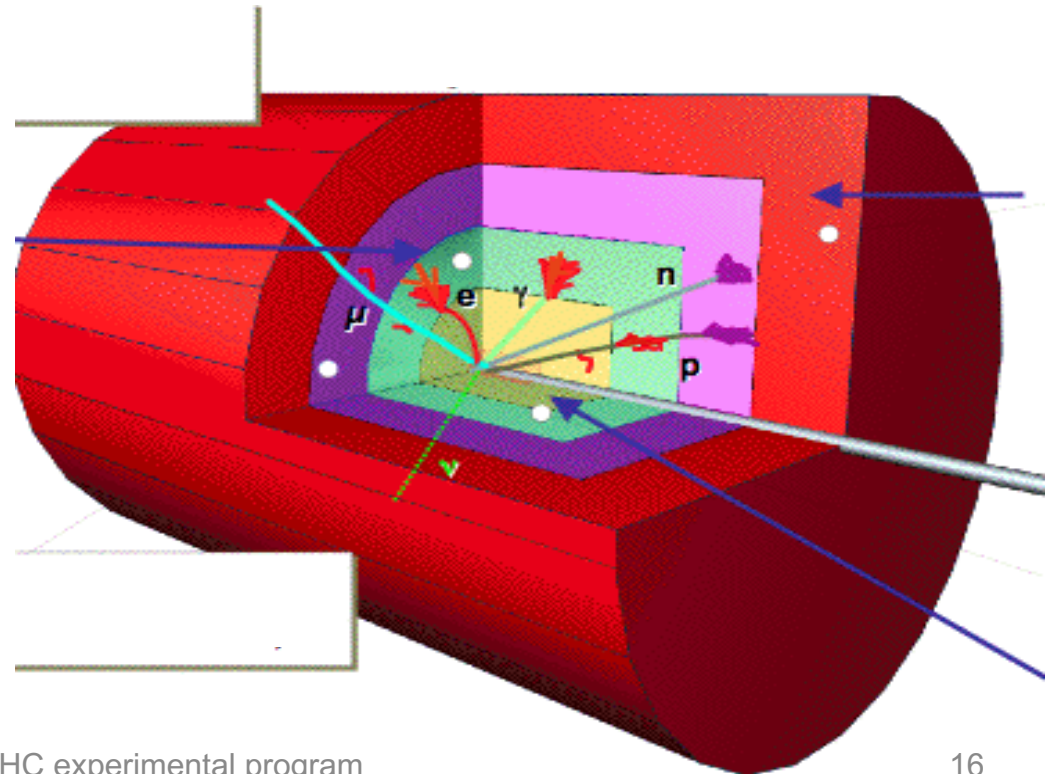


# General purpose LHC experiments

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)

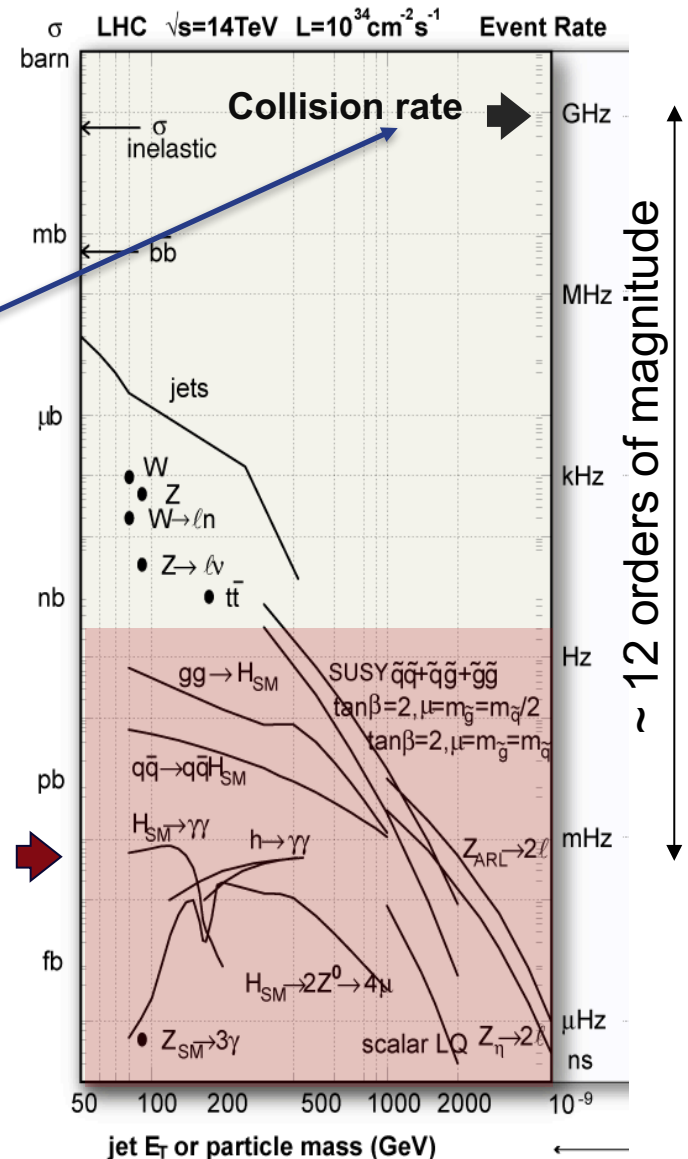




## Search for rare physics processes requires very high collision rate

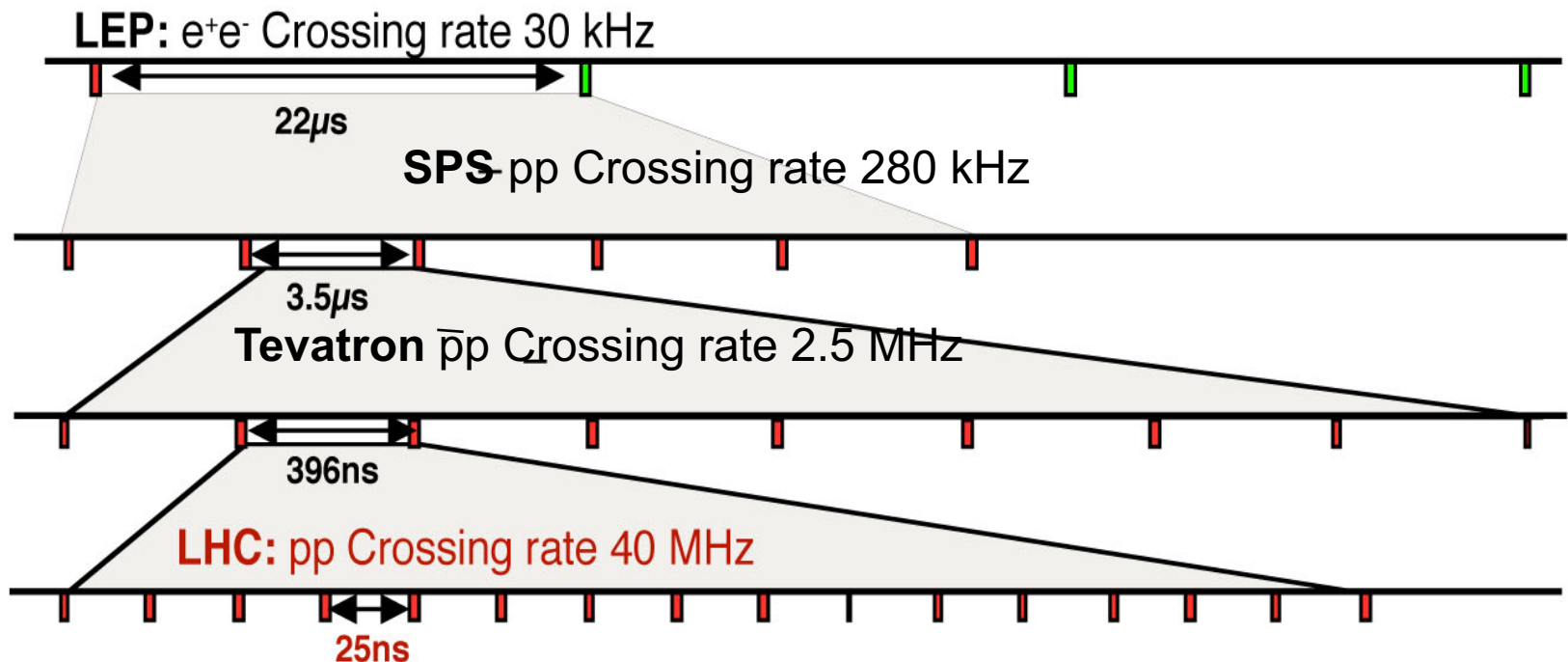
- LHC Luminosity is  $2 \cdot 10^{34} \text{ cm}^{-1}\text{s}^{-1}$
- Proton-proton collision rate is  $2 \cdot 10^9 \text{ events/s}$
- Higgs decaying in two photons:  $10^{-3} \text{ events/s}$

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

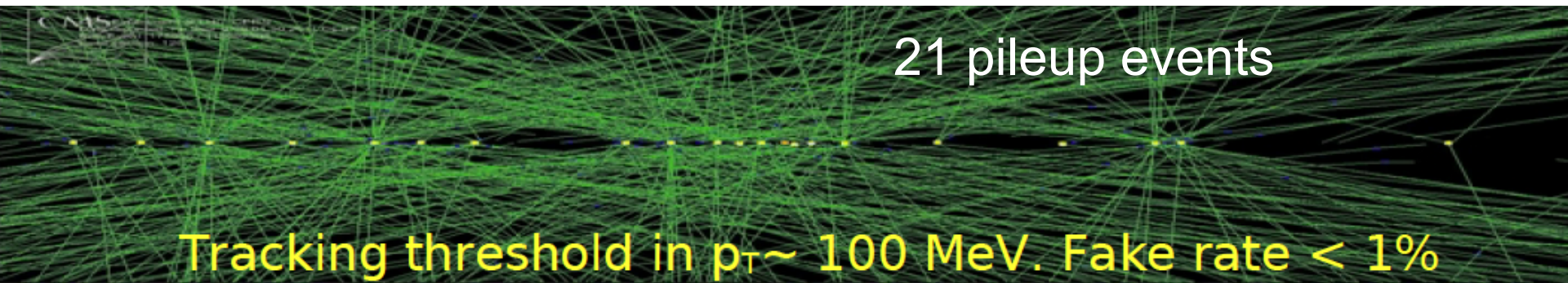


# Bunch crossing frequency

- 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  $\mu\text{m}$  ; length 20 cm

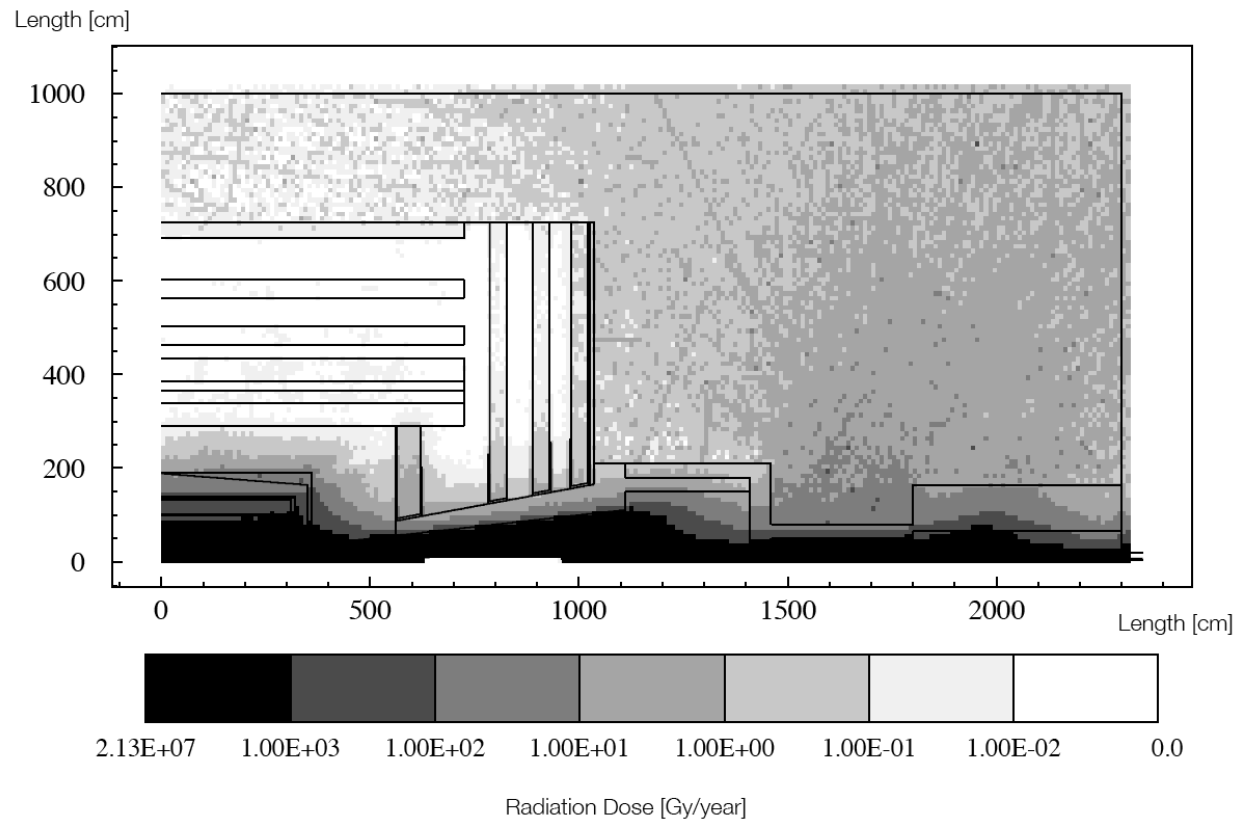


- Each bunch has  $1.5 \cdot 10^{11}$  protons
- At each crossing of bunches, about 50 collisions occur
- The particles produced ( $\sim 1500$  charged particles) are “seen” by the detector as a single image (event)



# High radiation levels

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



# CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS

Pixel (100x150  $\mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
Microstrips (80x180  $\mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

# CMS Detector

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying  $\sim 18,000\text{A}$

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER

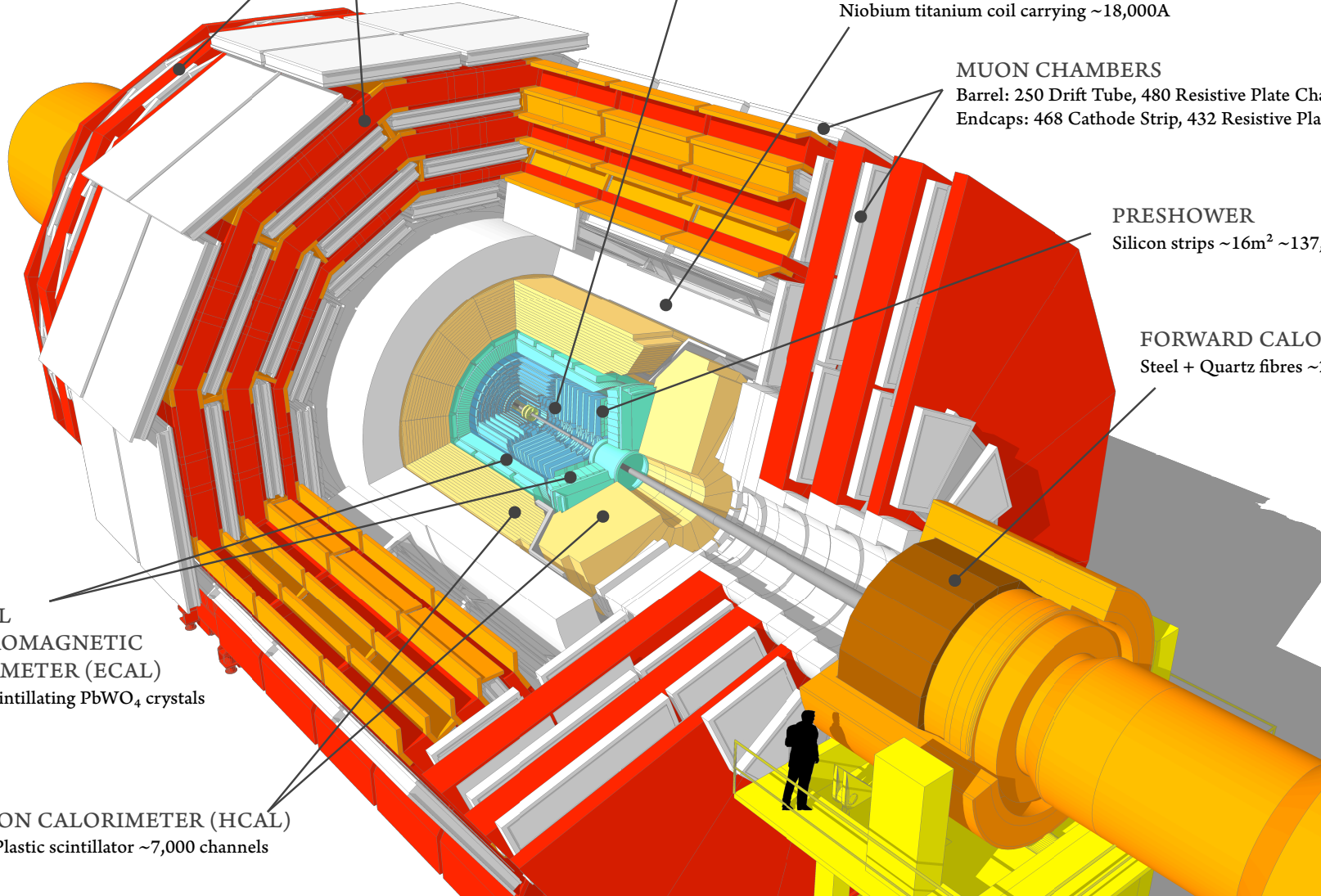
Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER

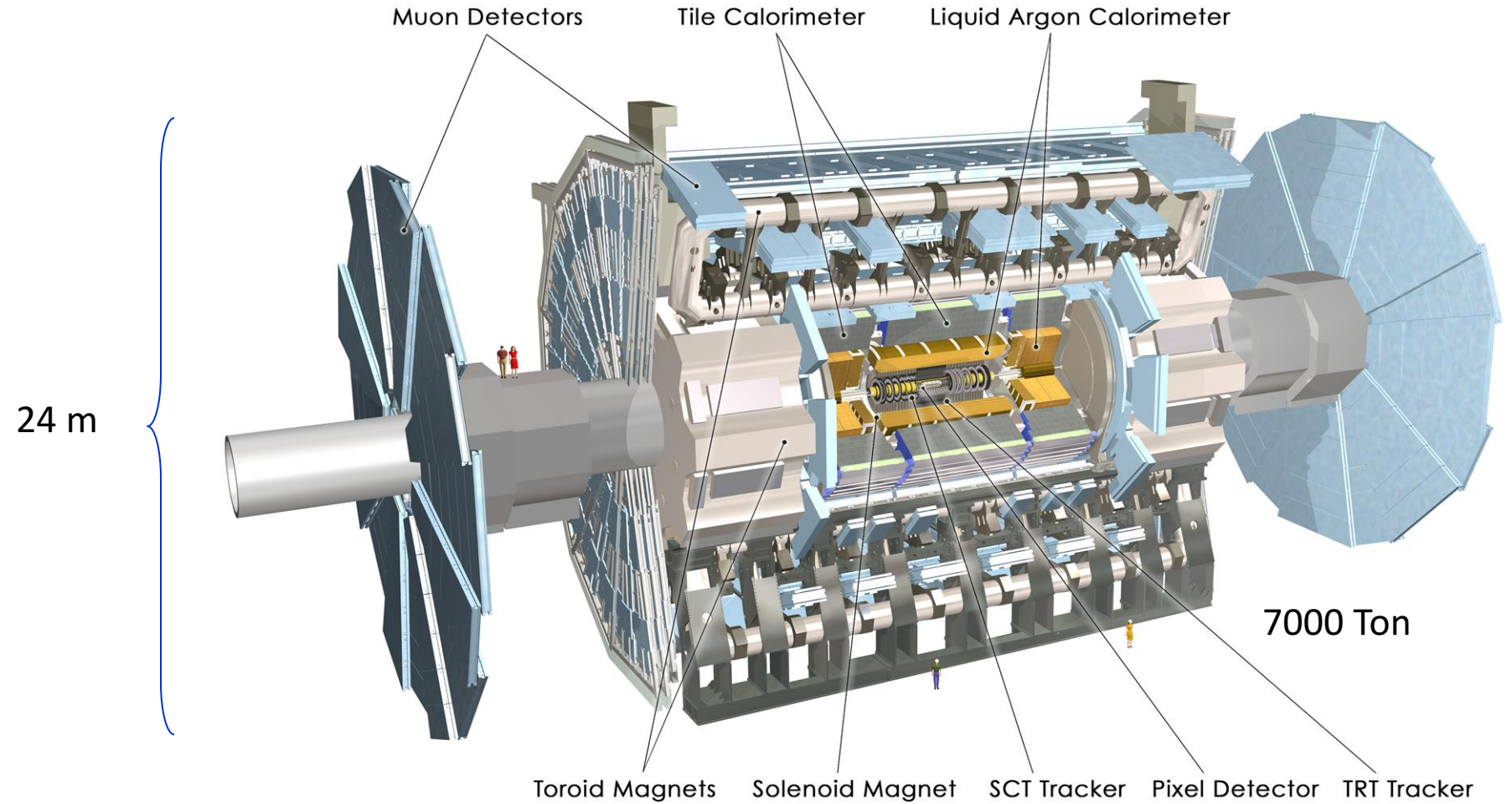
Steel + Quartz fibres  $\sim 2,000$  Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

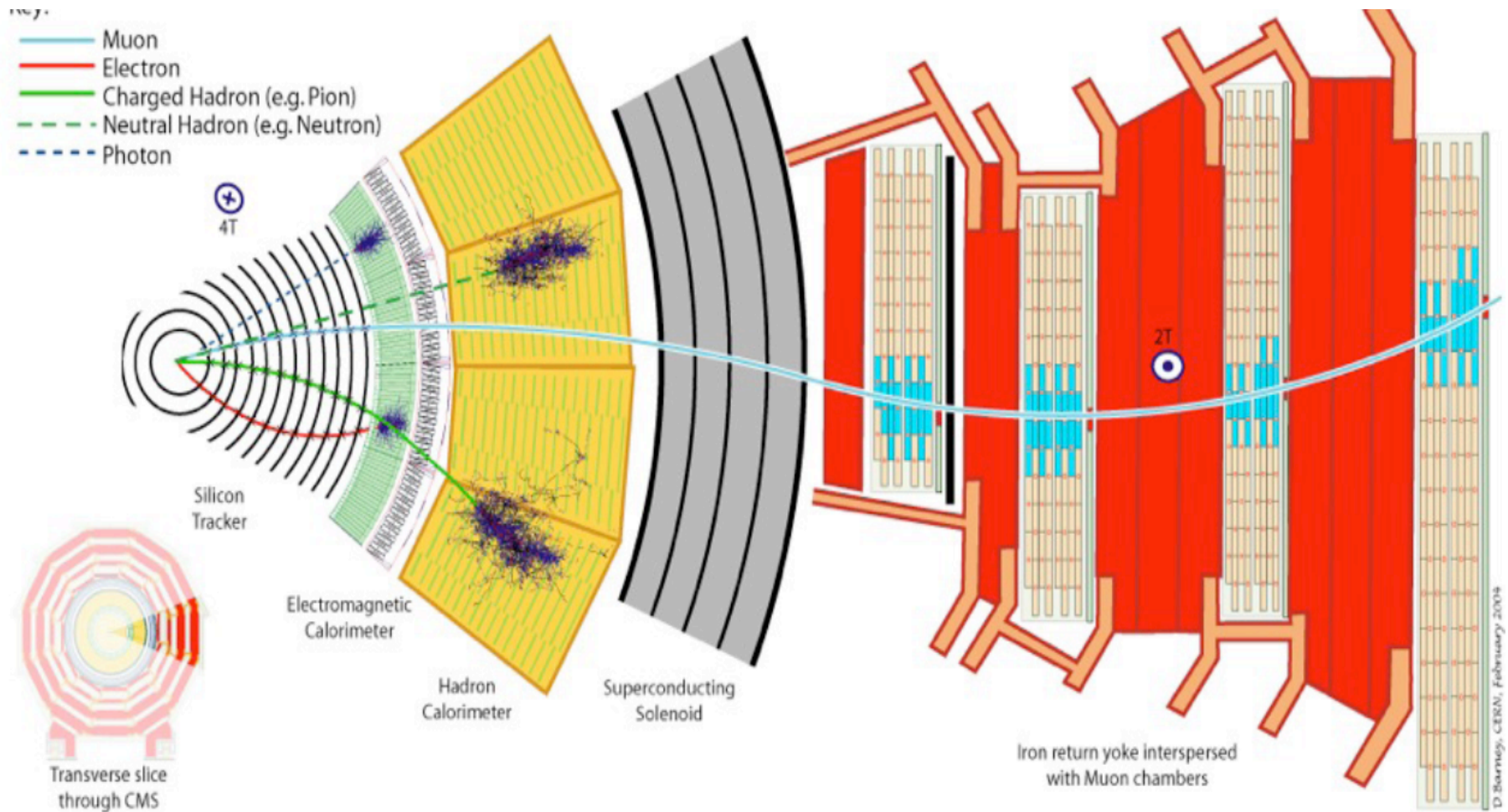
HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels





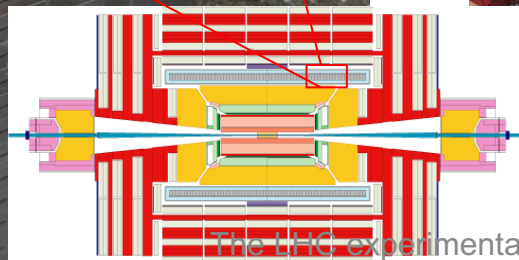


# Detection of hadrons, $e^\pm$ , $\gamma$ and $\mu^\pm$



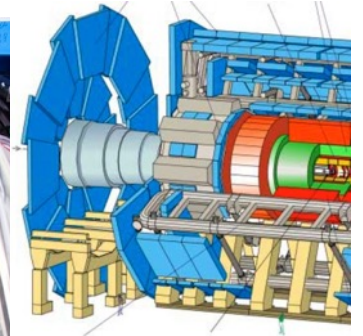
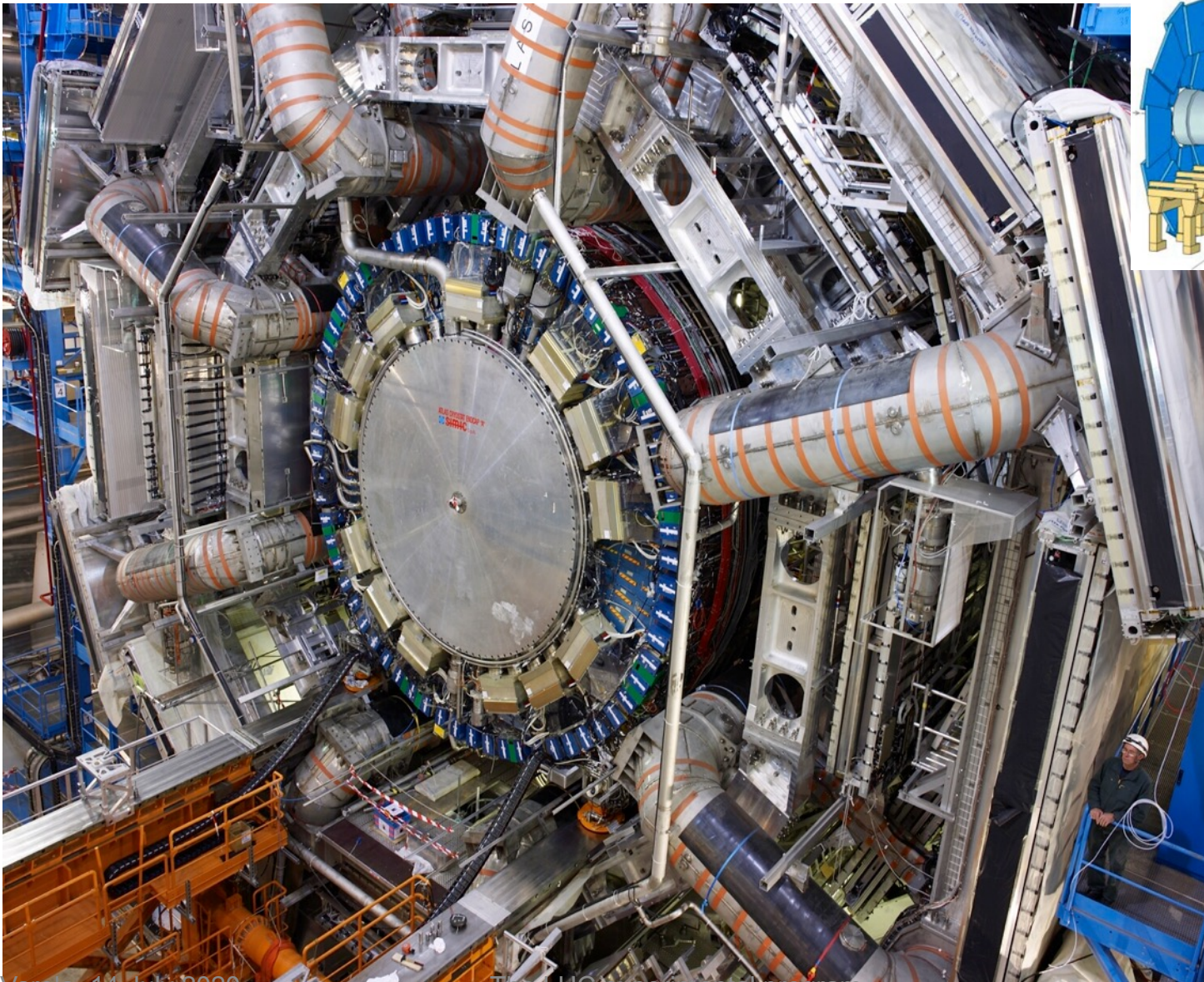


# CMS Superconductor Solenoid





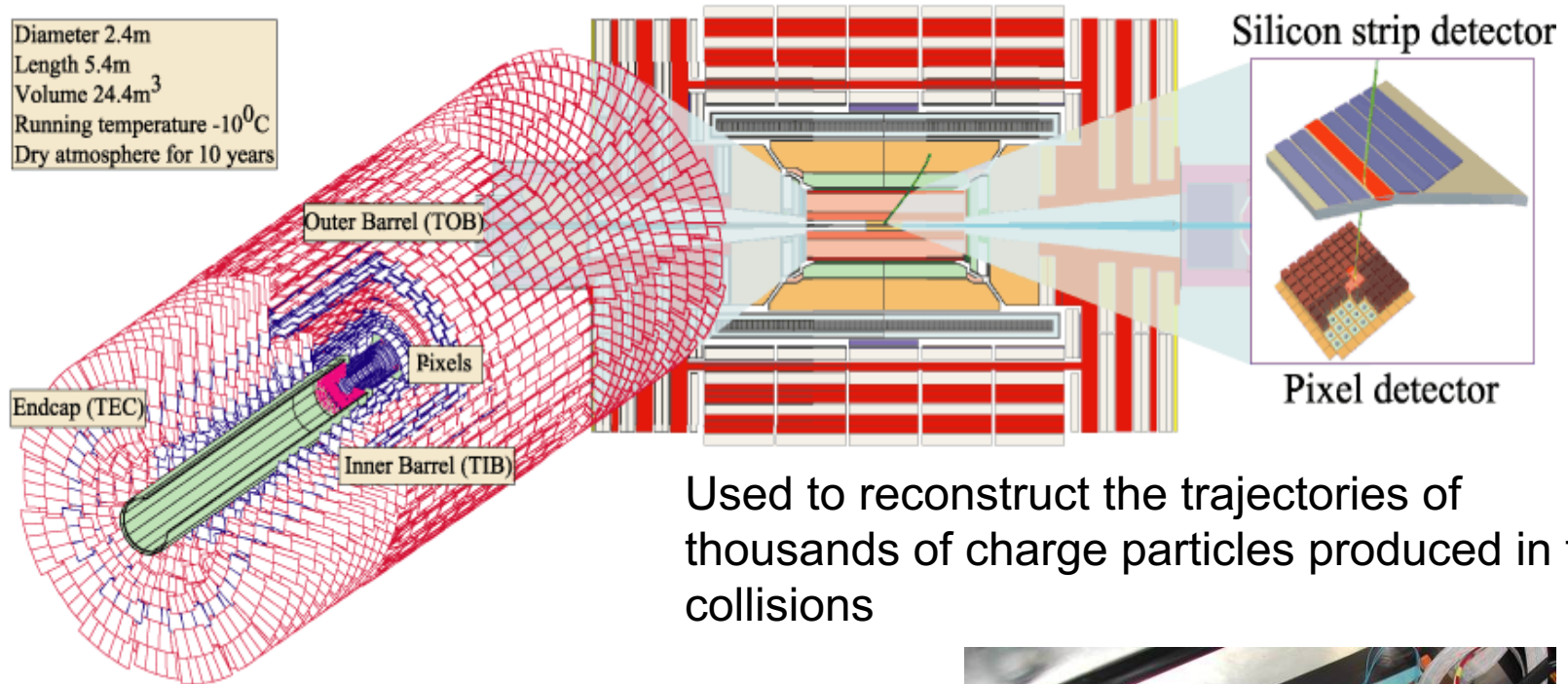
# ATLAS Toroidal System





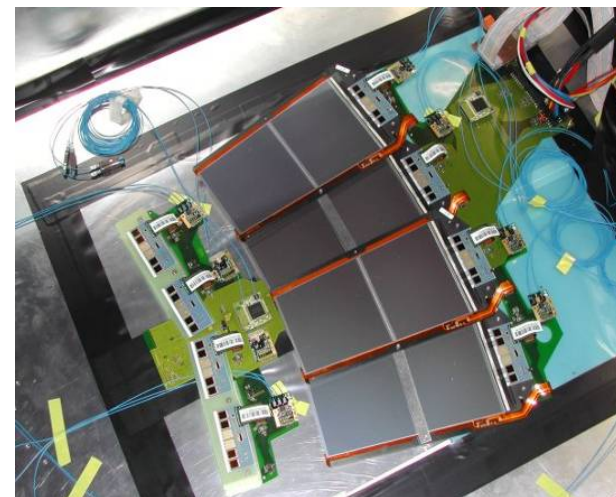
# Silicon Tracker

Diameter 2.4m  
 Length 5.4m  
 Volume 24.4m<sup>3</sup>  
 Running temperature -10<sup>0</sup>C  
 Dry atmosphere for 10 years

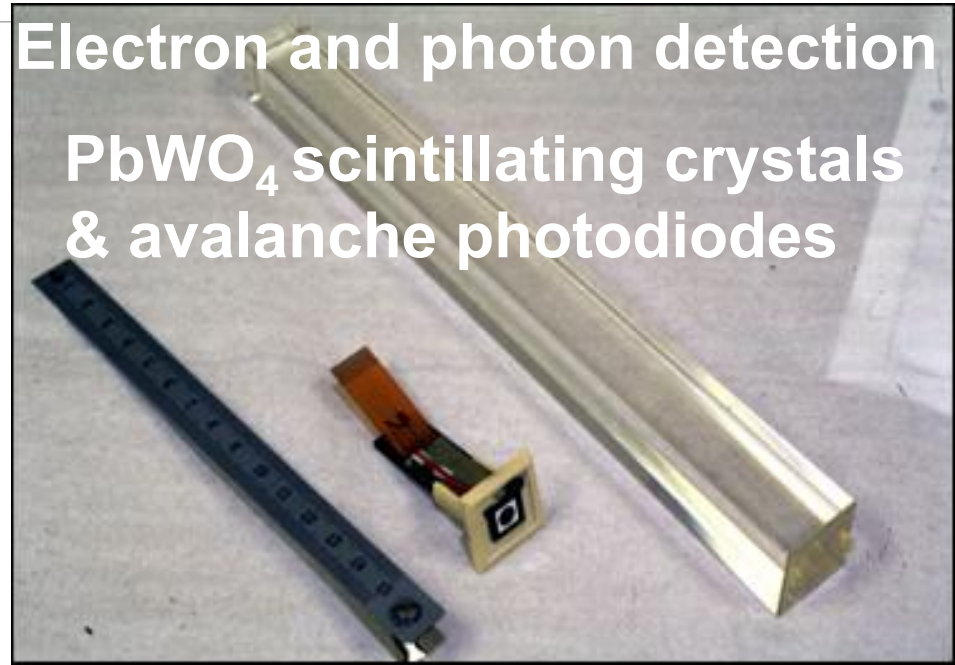
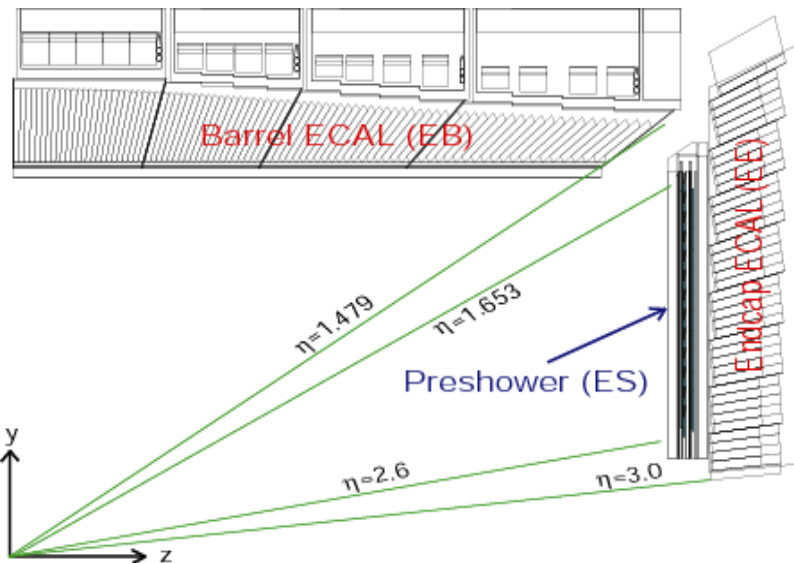
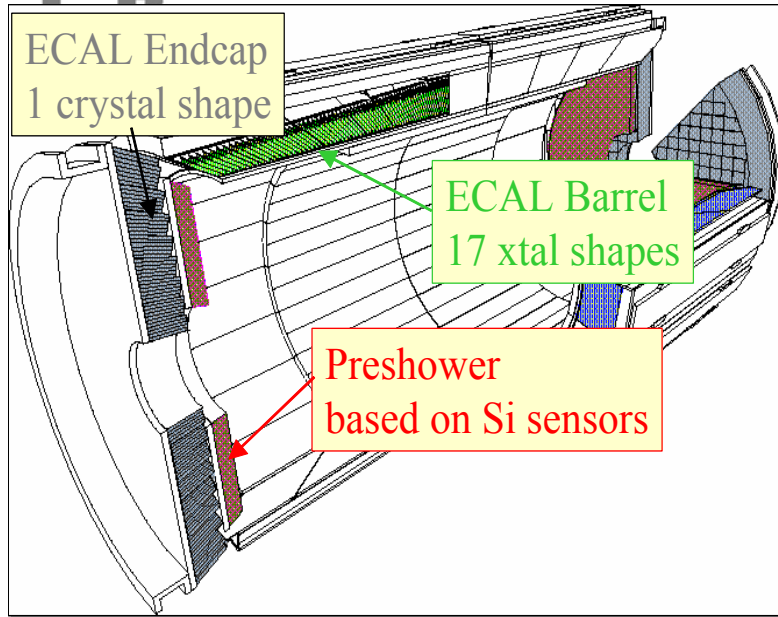


Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

**214m<sup>2</sup> 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  $\leq 0.5\%$

Parameter	Barrel	Endcaps
# of crystals	61200	14648
Volume	8.14m <sup>3</sup>	2.7m <sup>3</sup>
Xtal mass (t)	67.4	22.0

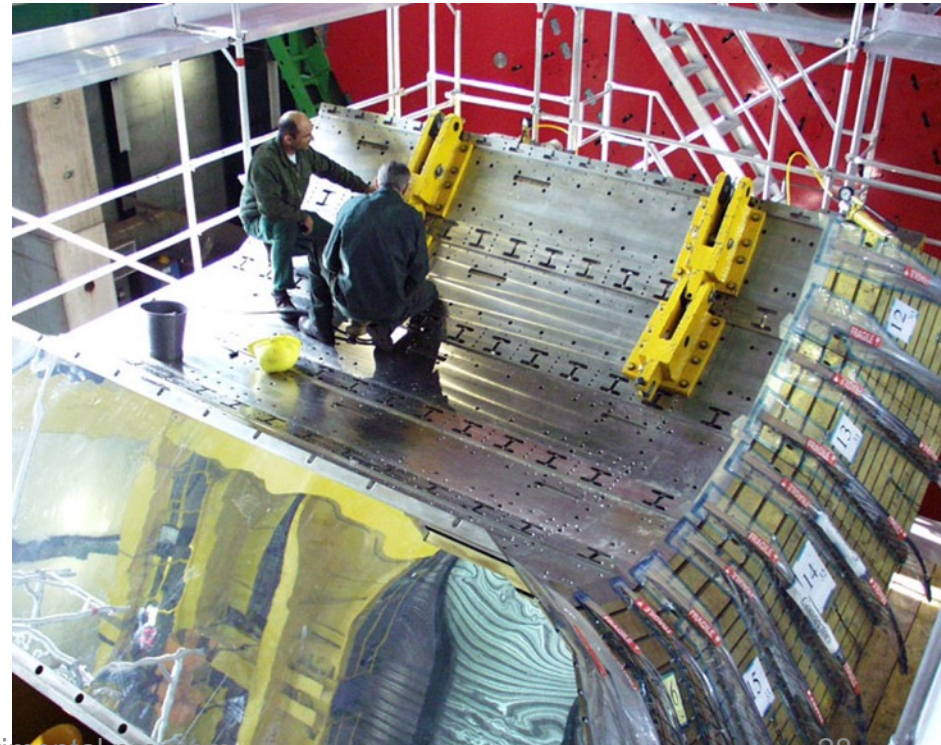
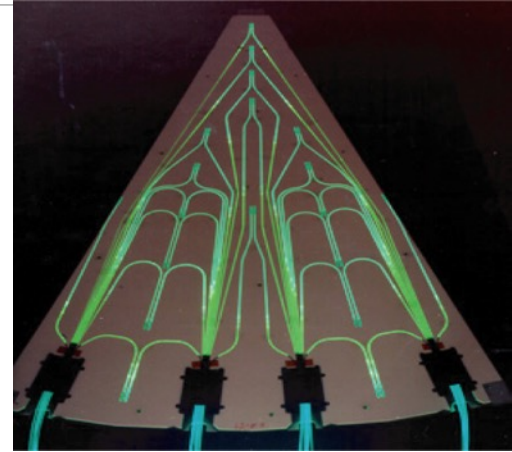


# HCAL Hadronic Calorimeter

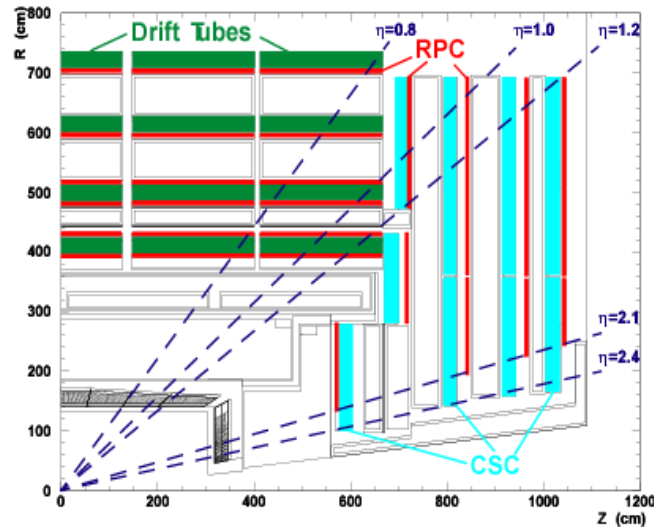
## Detection of hadrons:

- protons, neutrons, pions, etc.

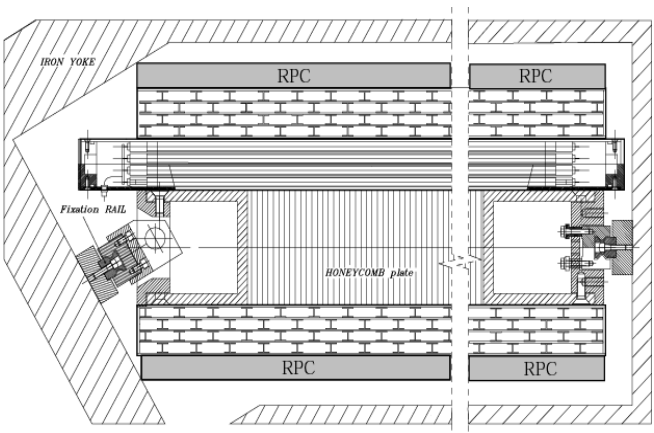
- CMS HCAL has three components:
  - Barrel HCAL (HB)
  - Endcap HCAL (HE)
  - Forward HCAL (HF)
- Plastic scintillator and brass
- Quartz fibers and steel



# Muon detectors



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

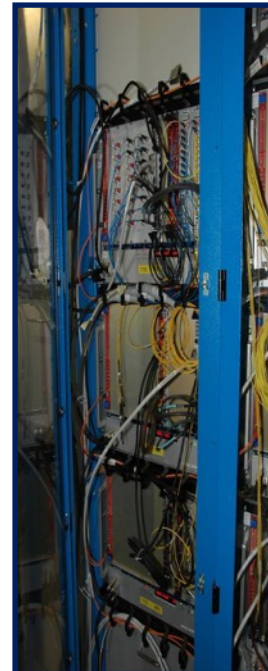
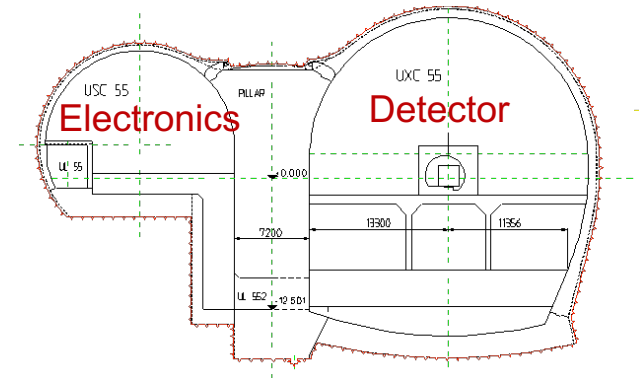




## Electronics systems in the Service Cavern.

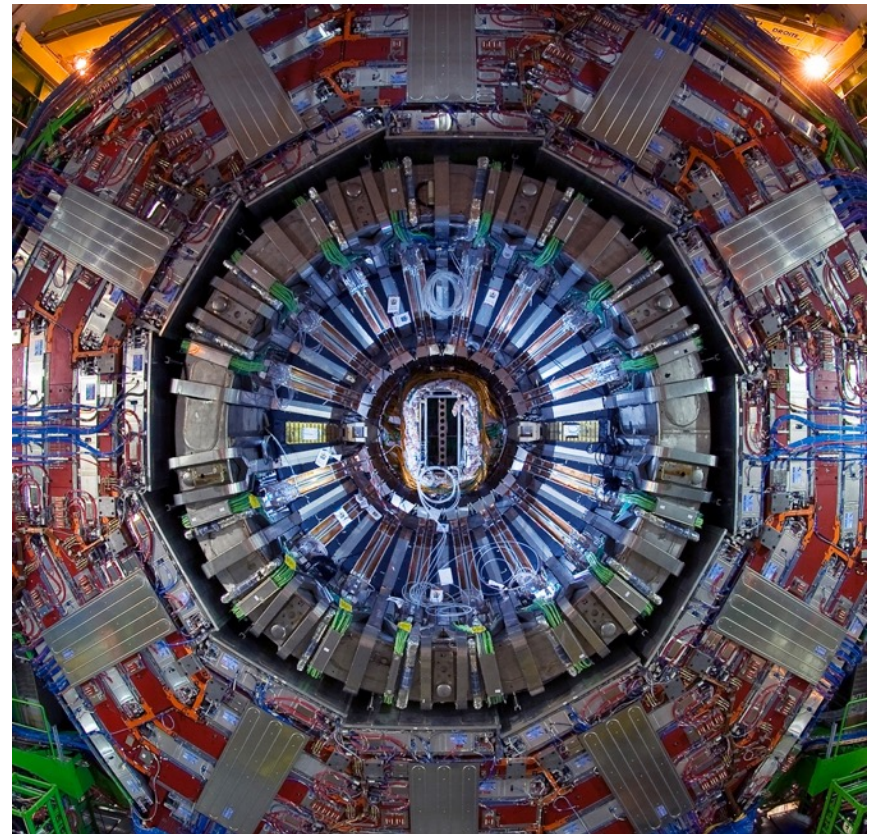
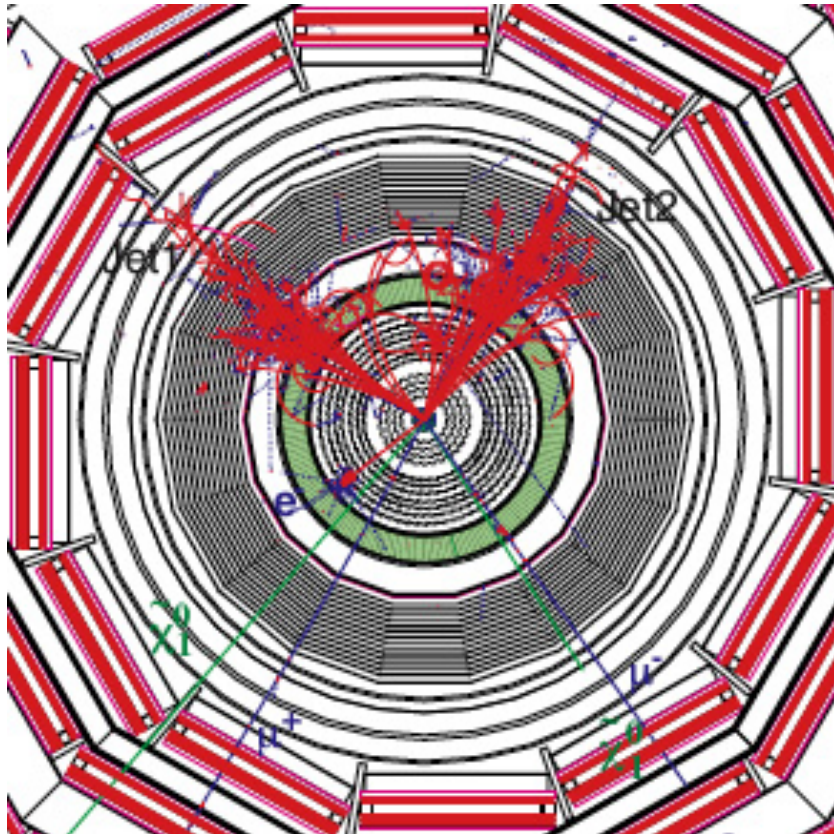
- About 150 racks occupy two floors.
- Most electronics was designed and built specifically for the experiment

## Underground caverns





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

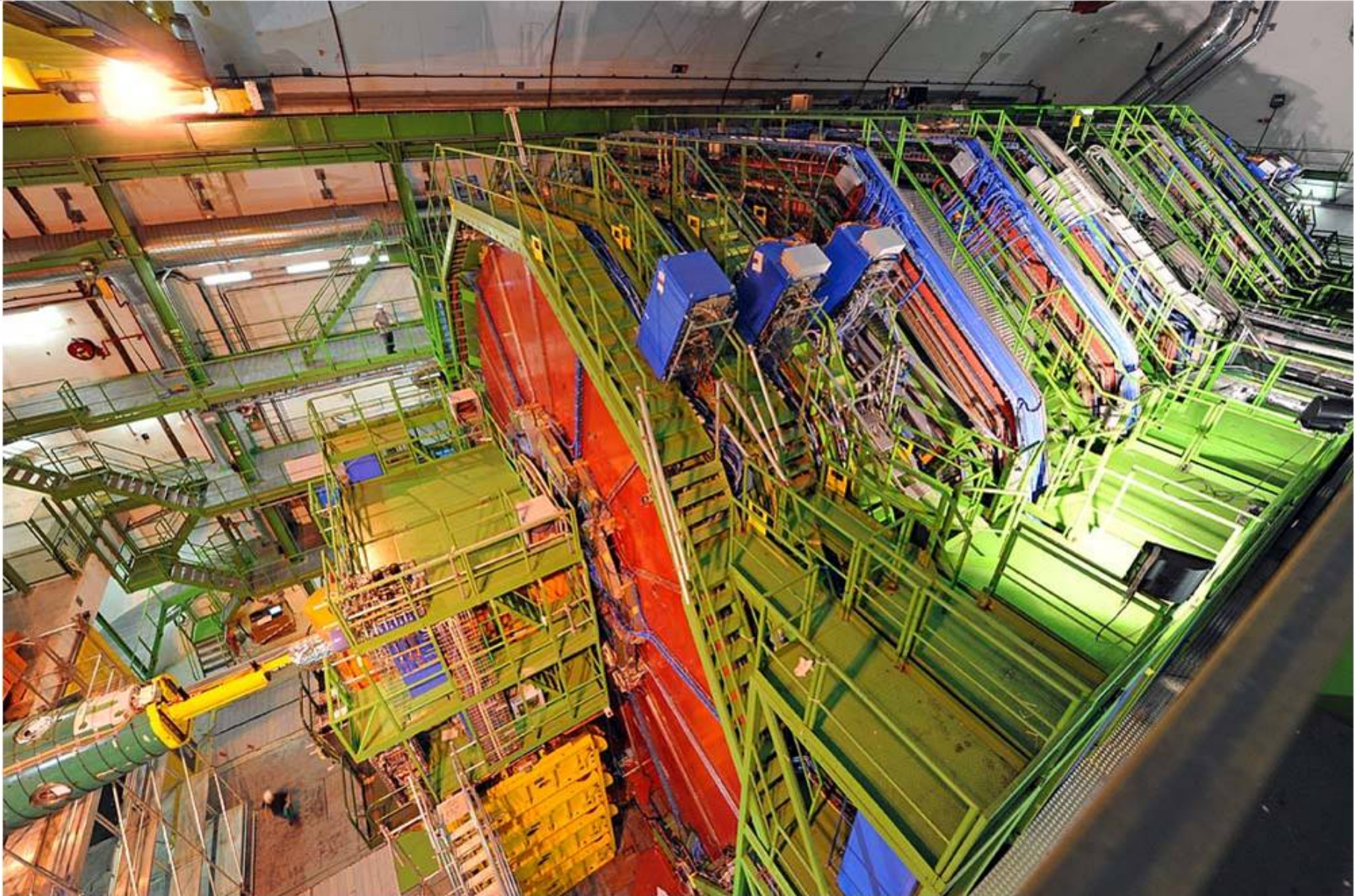
The **Grid** is an infrastructure that provides seamless access to computing power and data storage distributed over the globe





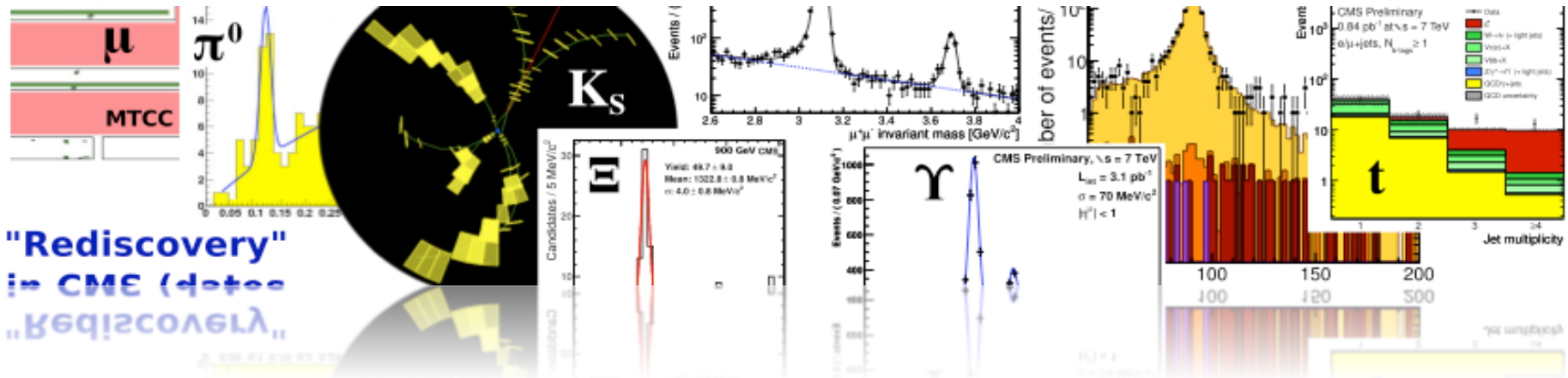


# CMS detector ready for beams

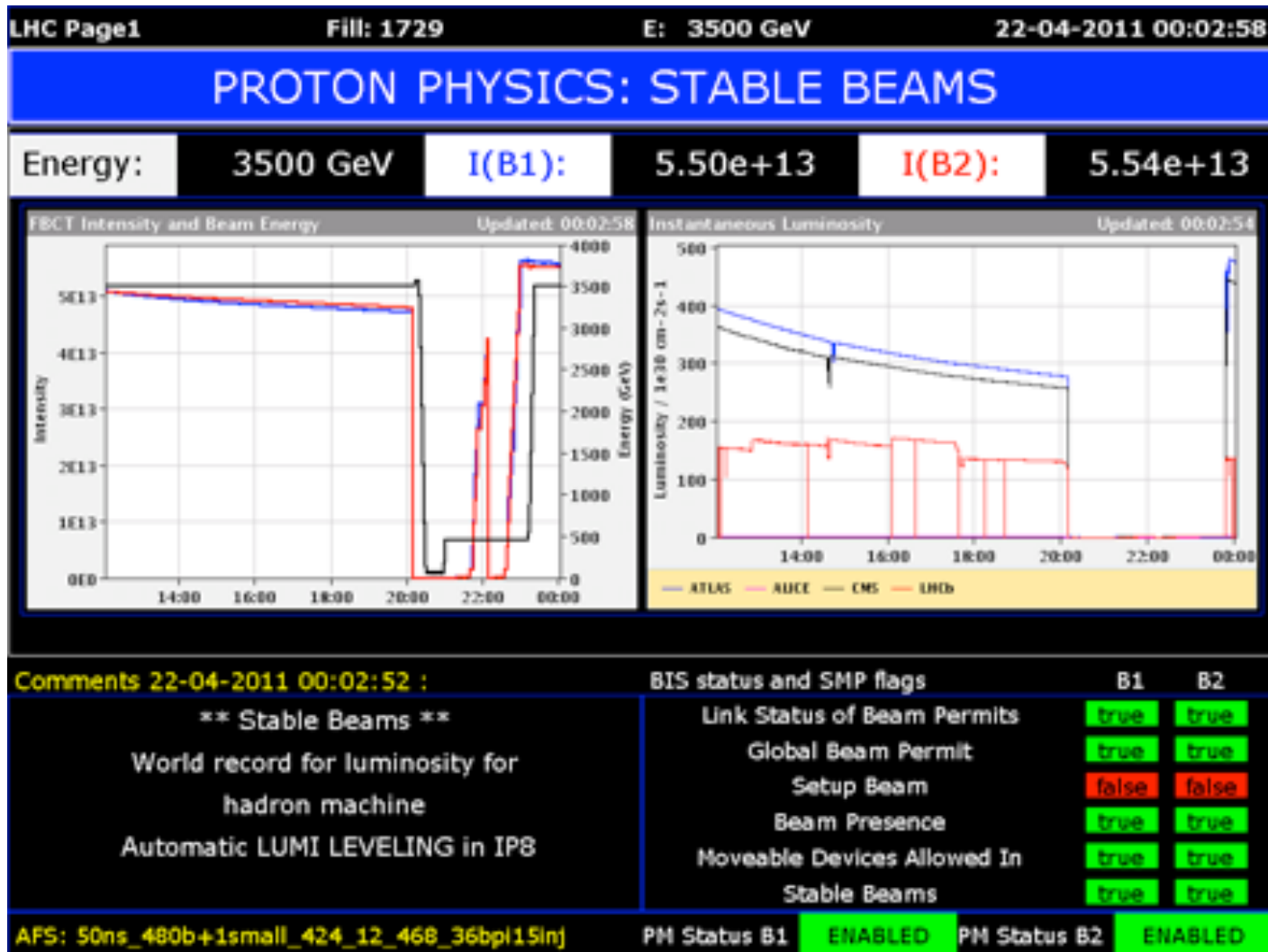




# Detector operation, commissioning and physics production



# LHC Page 1: stable beams





# CMS Page 1: running

30/03/10 Session DAQ state Run Number Lv1 rate Ev. size DeadTime(AB) Acc. Hz(%) <HLT CPU>  
 Tue 13:17:05 126284 Running 132440 1.044 kHz 495.9 kB 0.0% 1043.8(100.0) 1.47%

lhc1

BEAM SETUP: FLAT TOP  
 Energy: 3500 GeV I(B1): 1.88e+10 I(B2): 1.74e+10  
 Comments: 30-03-2010 13:16:51: Preparing for stable beams! Preparing to move collimators IN  
 BIS status and SHIP flags: Link Status of Beam Permits, Global Beam Permits, Setup Beam, Beam Priorities, Movable Devices Allowed In, Stable Beams  
 LHC Operation in CCC: 77600, 70480 PH Status B1: ENABLED PH Status B2: ENABLED

Data to Surface

Sub-System	State	FRL	FED	IN
TRG	Running	3	3	3
CSC	Running	9	9	9
DAQ	Running	0	0	0
DQM	Running	0	0	0
DT	Running	11	11	11
ECAL	Running	54	54	54
ES	Running	40	40	40
HCAL	Running	32	32	32
PIXEL	Running	40	40	40
RPC	Running	3	3	3
SCAL	Running	1	1	1
TRACKER	Running	250	440	438
CASTOR	Running	3	3	3

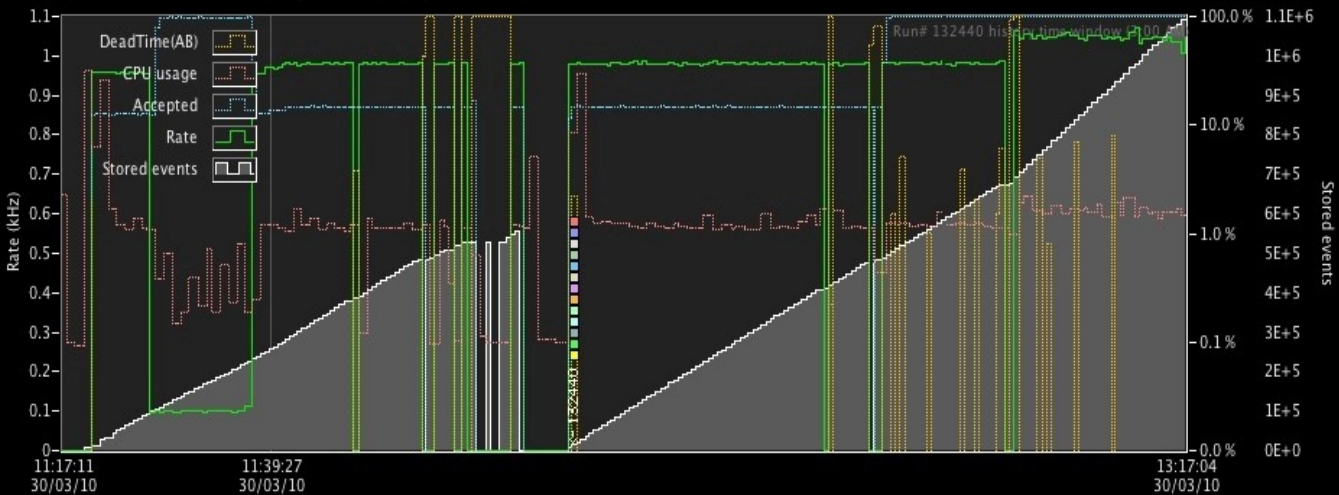
SM streams

Stream	No.Events	Rate (Hz)	BnW (MB/s)
Calibration	379.676E+3	97.52	16.62
EcalCalibrati	379.676E+3	97.56	2.02
A	262.205E+3	112.70	20.95
Express	48.716E+3	37.87	7.55
ALCAPHISYM	7.090E+3	5.53	0.02
HLTMON	3.303E+3	2.02	0.39
ALCAP0	684.000E+0	0.38	0.00
OnlineErrors	26.000E+0	0.03	0.01
RPCMON	15.000E+0	0.00	0.00
Error	0.000E+0	0.00	0.00

Data Flow

#LS 171 LHC\_RAMPING false  
 PHYSICS\_DECLARED true  
 PIX\_HV\_ON true  
 TK\_HV\_ON true  
 CalibCyc ON  
 #Lv1(GT) 3909384  
 Lv1 Rate 1.044 kHz  
 Pending Lv1 114131  
 #Frag. in RU Max 103 Min 42  
 FBI occ. % Max 0 Min 0  
 FBO occ. % Max 0 Min 0  
 BnW (MB/s) 501  
 EvSize (kB) 496.7  
 Events in BU 0  
 <Ev.> 0  
 Pending Req. 15989  
 <#P> 23.8  
 #Running FUs 4704 100.00%  
 Acc.Rate 1043.792 Hz  
 Rceiv.-Disc. 59  
 235 P.M-m  
 167 A.M-m  
 <FU-CPU> 1.47%  
 <SM-CPU> 5.77%  
 Free space TB 229  
 Time to fill disk 2 of srv-c2c07-17 > week  
 Stored 1092490

[Rate(kHz) | Stored | Accepted% | CPU%] / Time



UTC time 30/03/10 11:17:05

Local time: Geneva 13:17, Los Angeles 04:17, Chicago 06:17, Moscow 15:17, Beijing 20:17

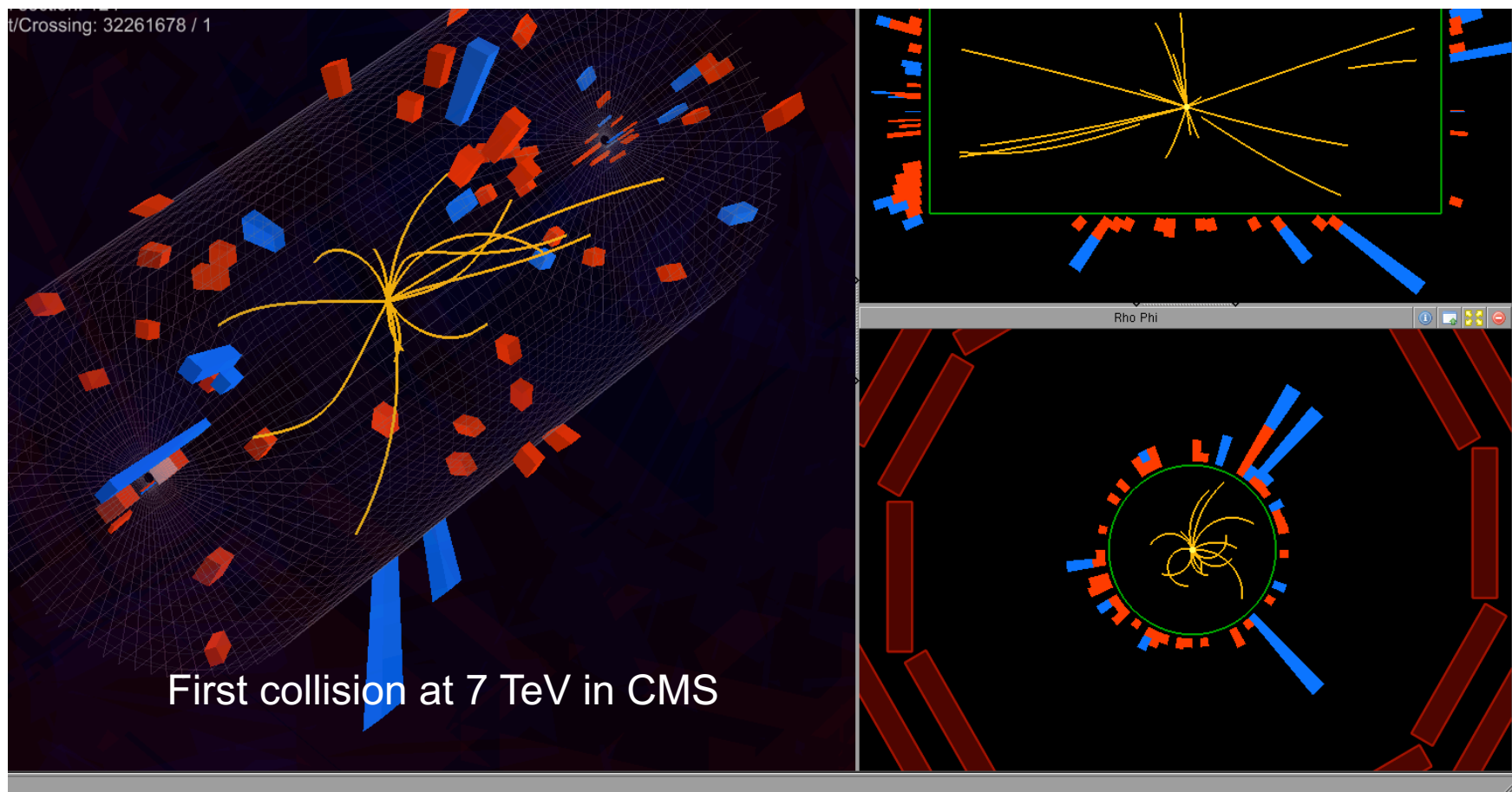


# 2009: First p-p collisions at LHC

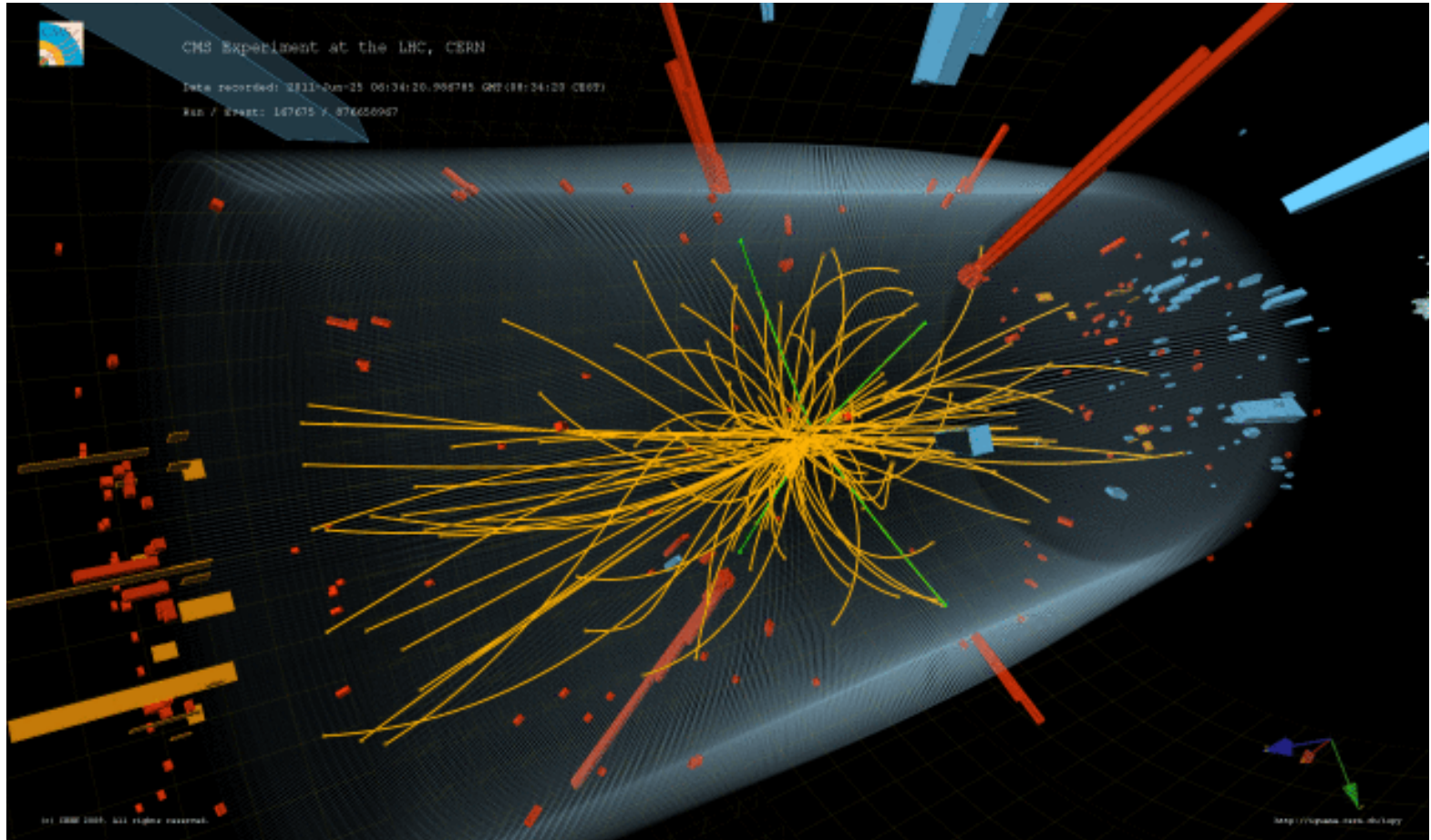
November 23, 2009  
First collisions at 900 GeV

December 14, 2009  
First collisions at 2.36 TeV

March 30, 2010  
First collisions at 7 TeV

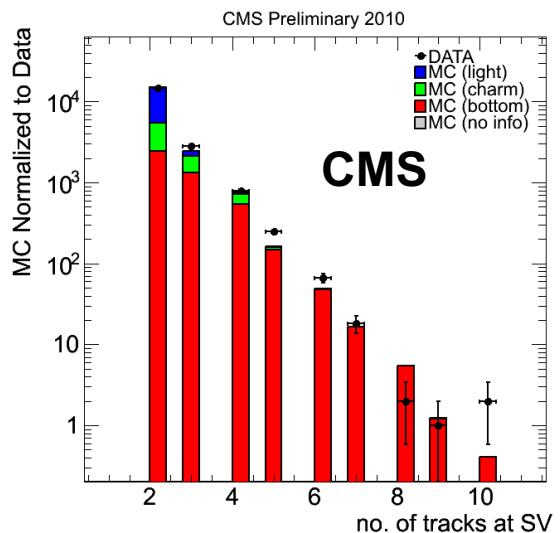
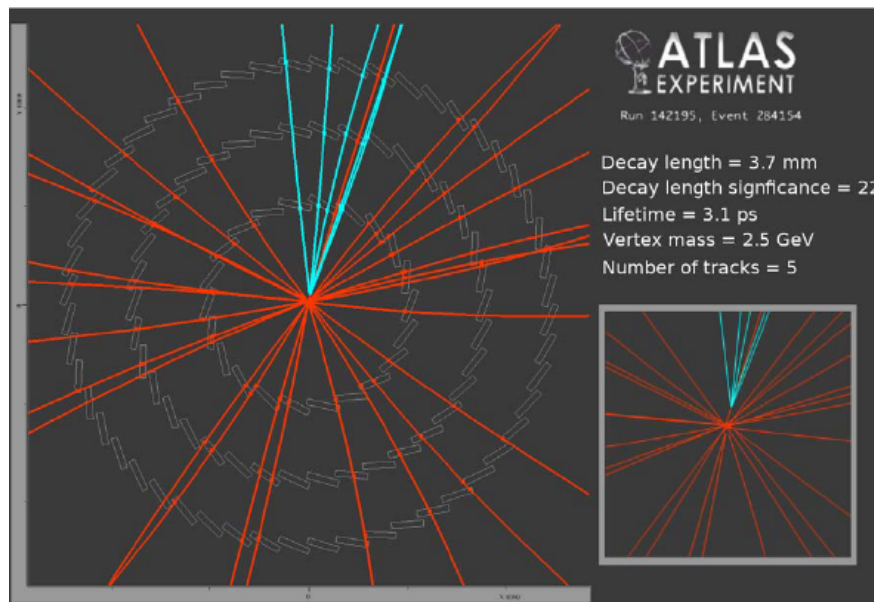
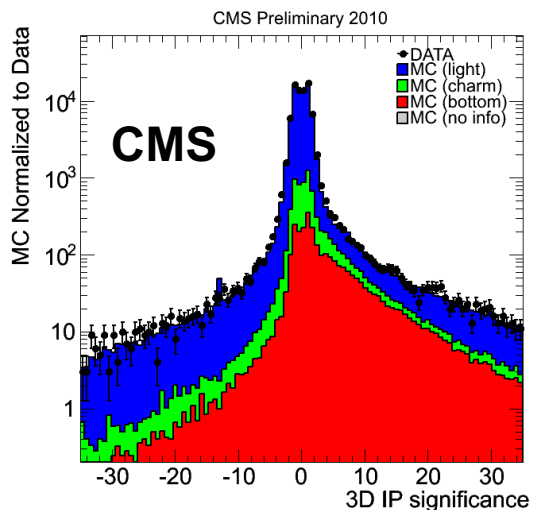


# Higgs decay in 4 electrons



# Tracking: secondary vertices

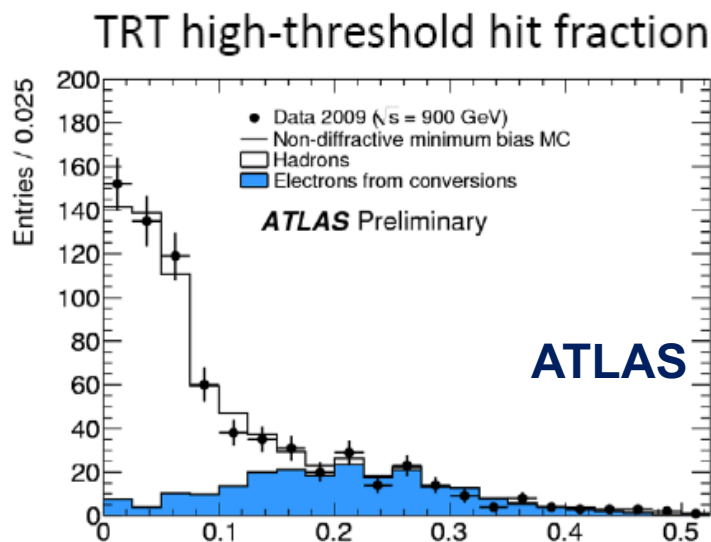
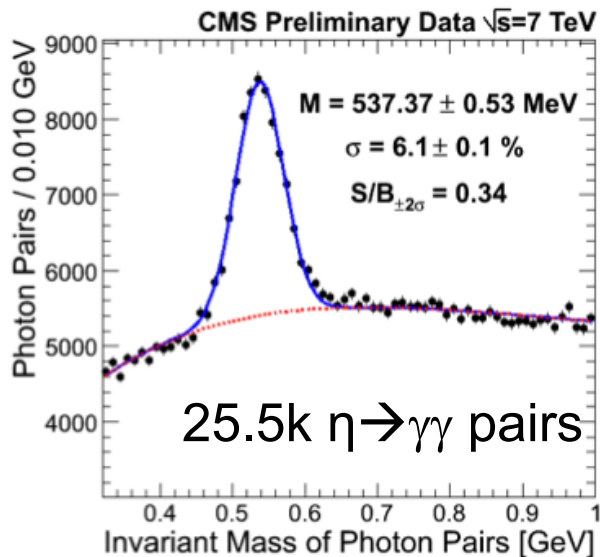
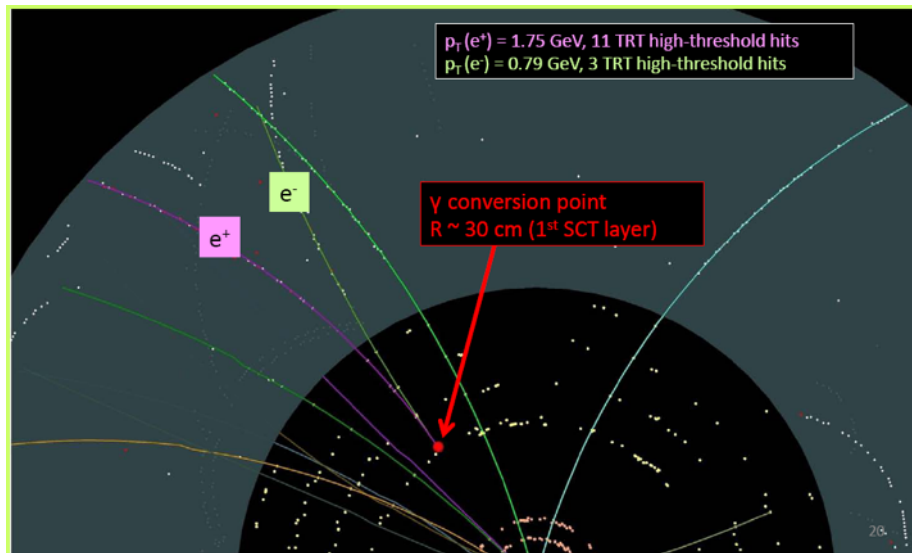
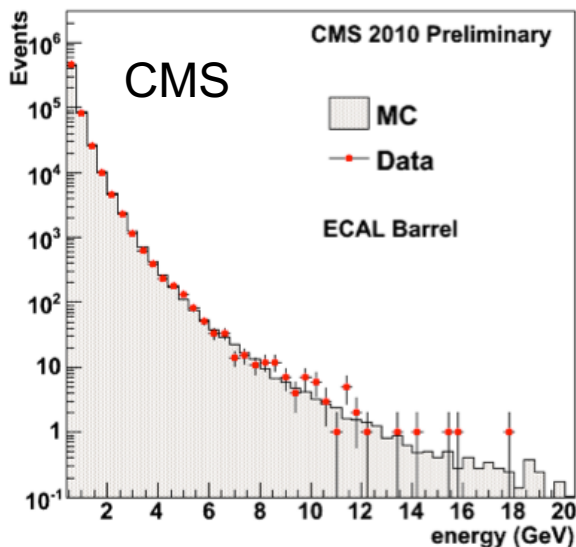
Basic variables relevant for B-tagging are well described by the simulation



Secondary vertices compatible with heavy flavor production

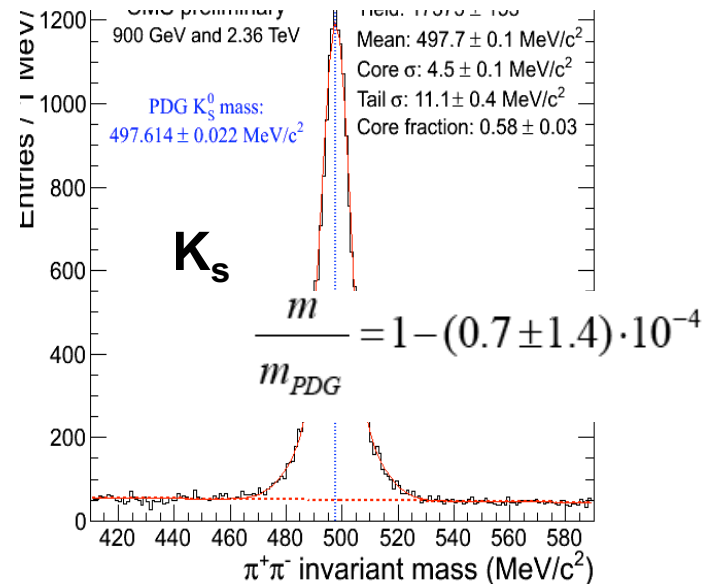
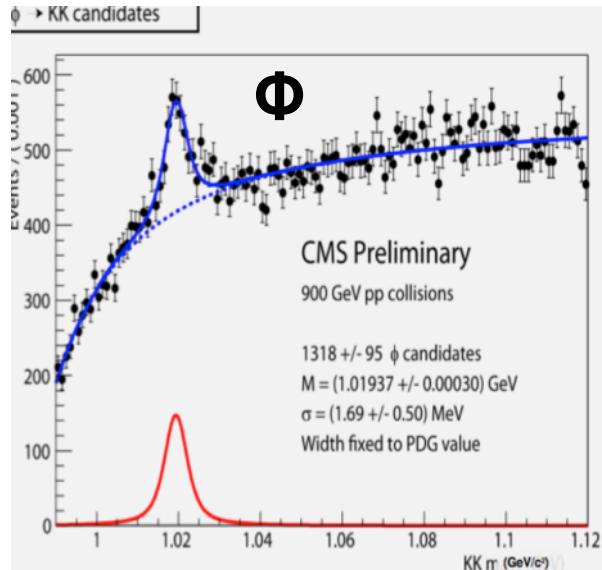
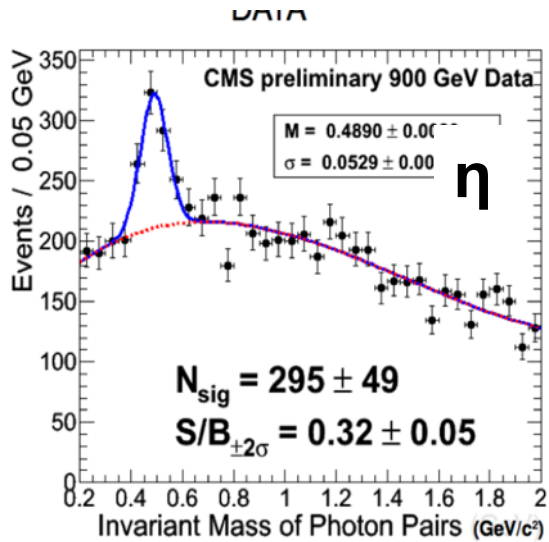
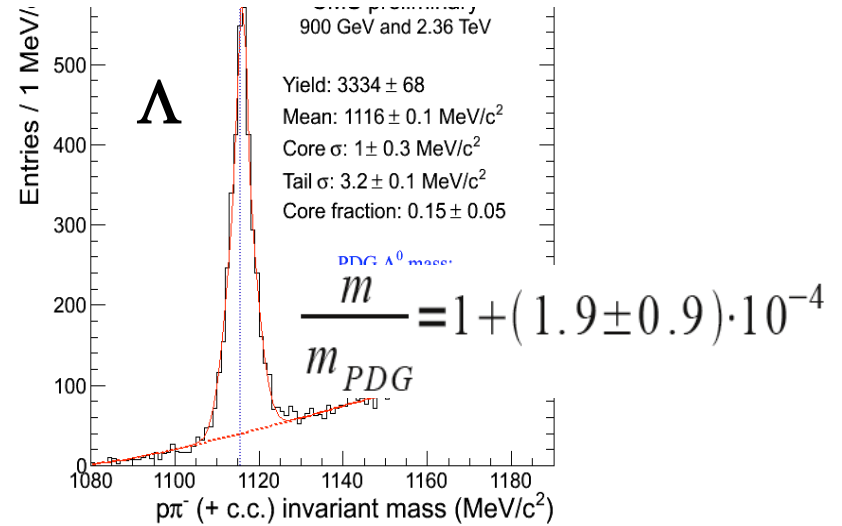
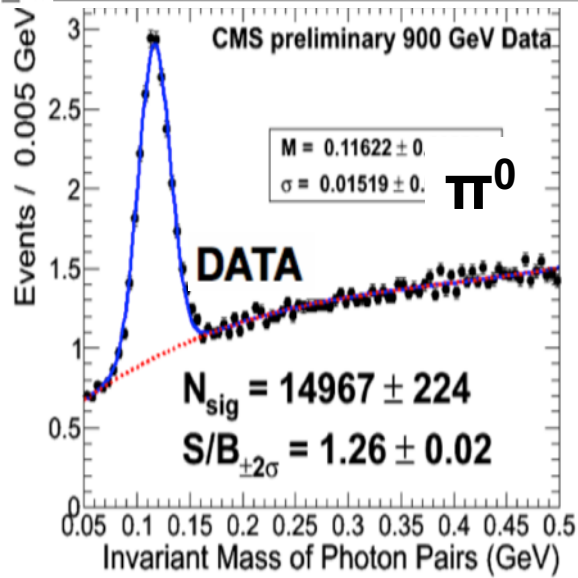


# Photons and electrons

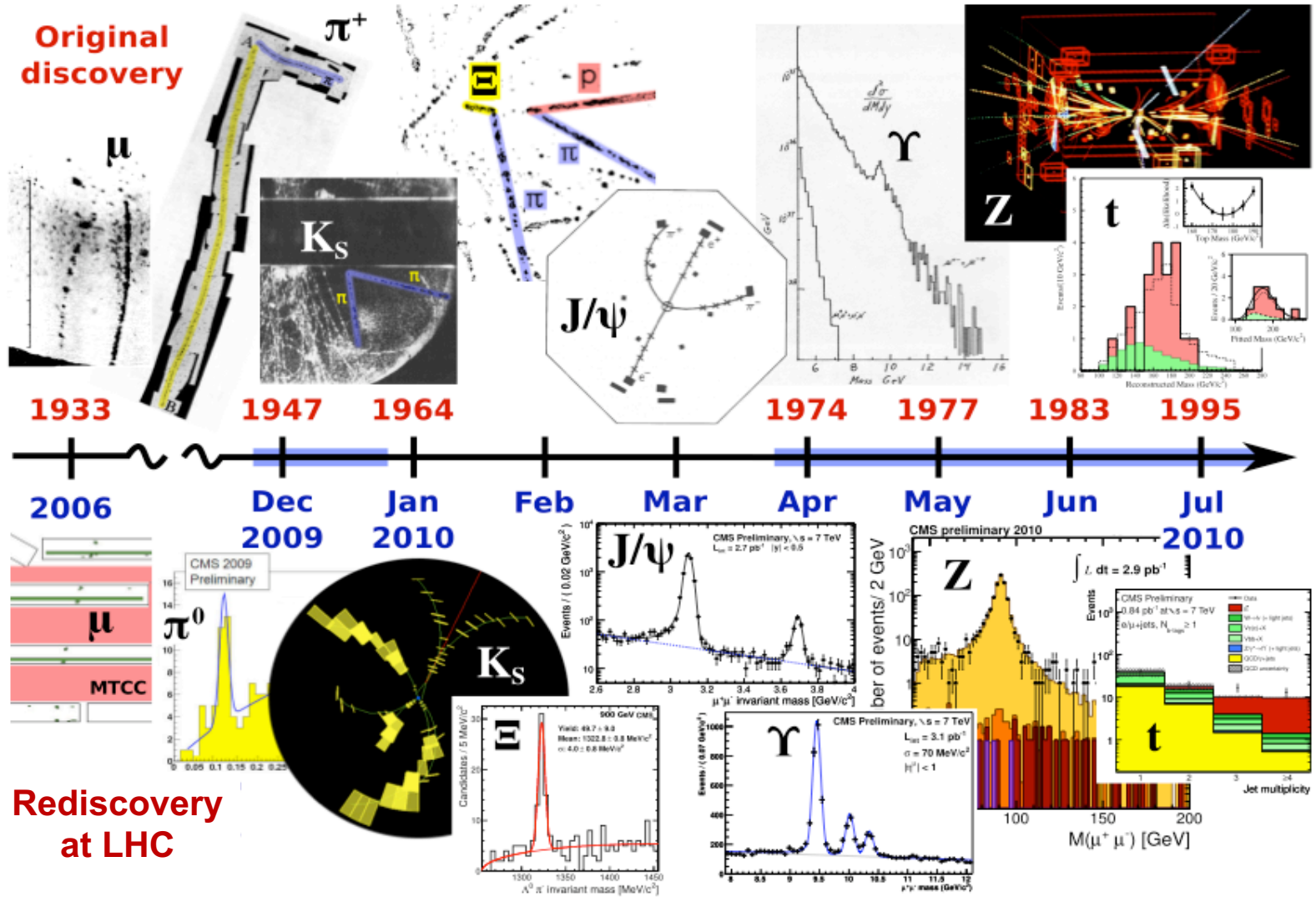




# Rediscovery of resonances



# Rediscovery of the Standard Model



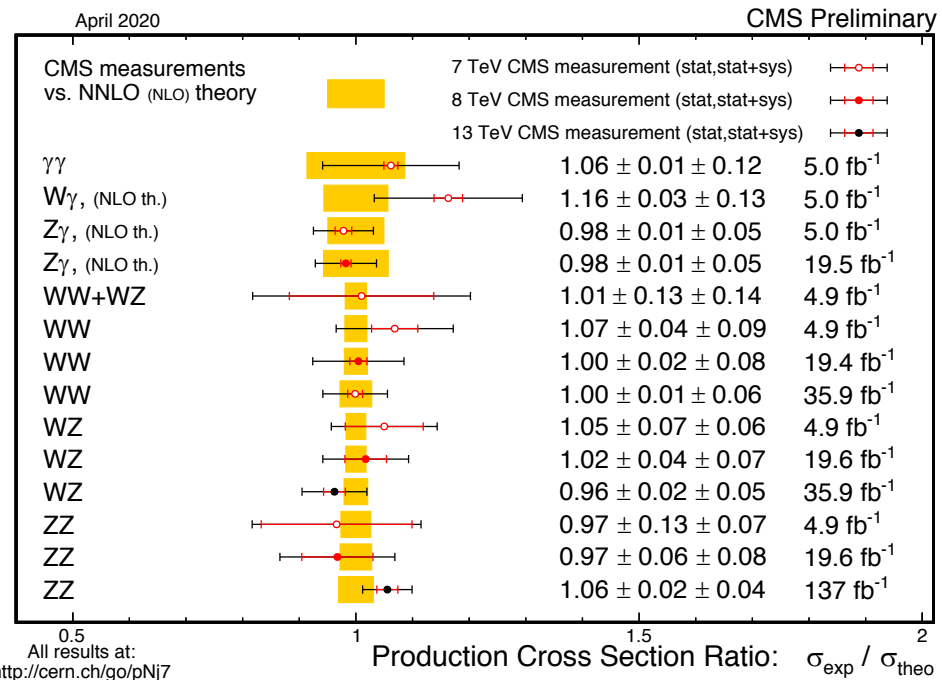
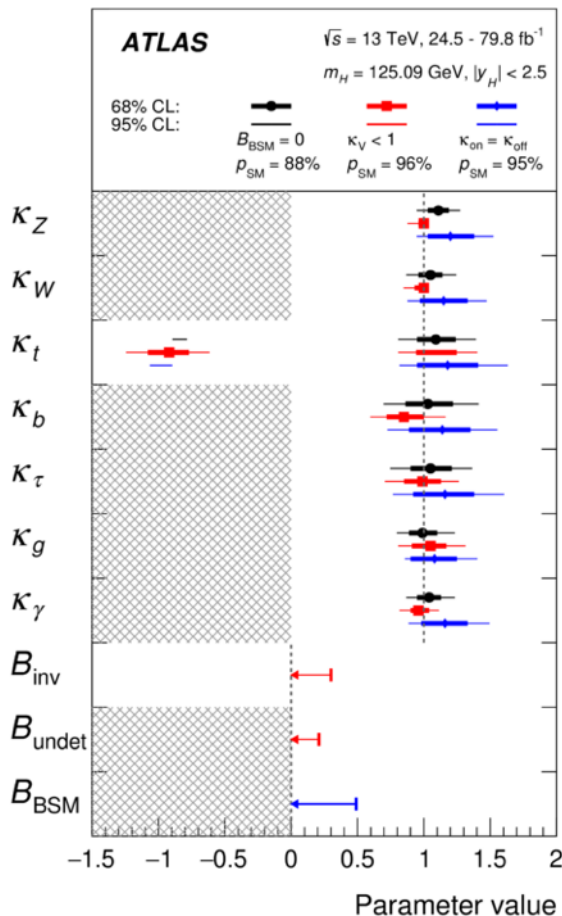


# Search for New Physics

So far the measurements are compatible with the SM predictions

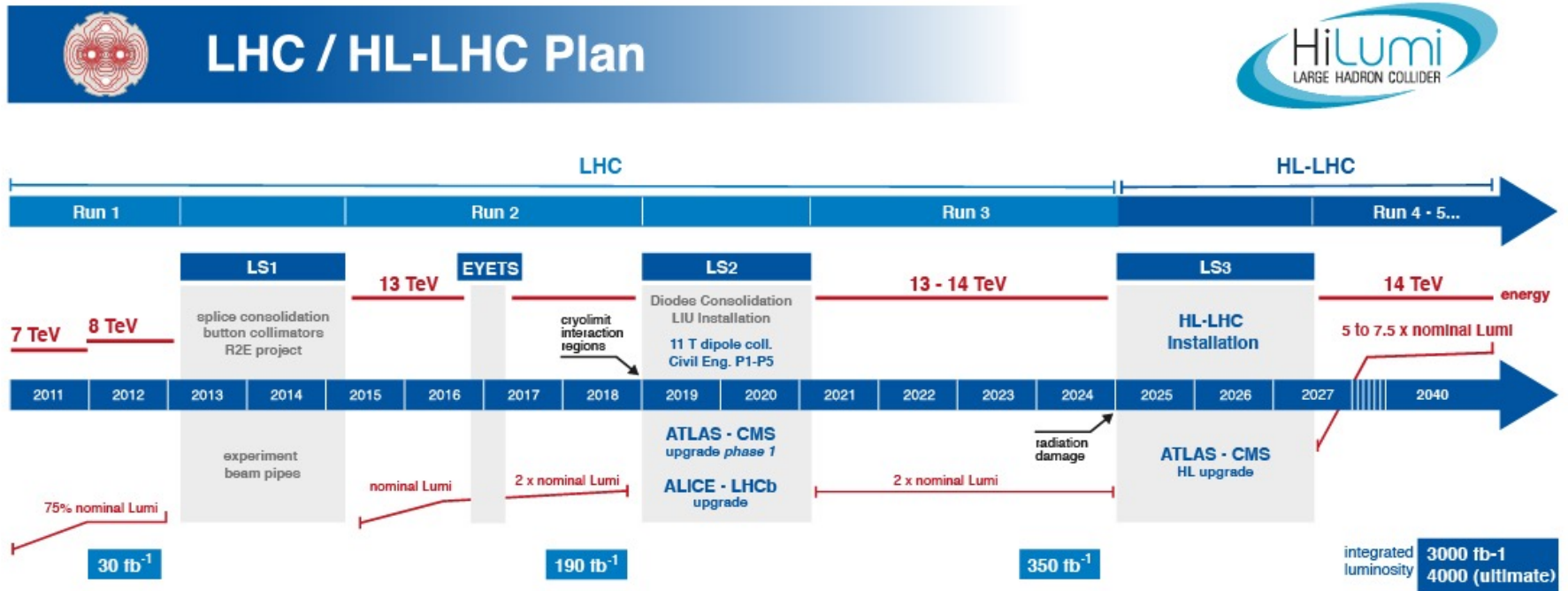
- about ~2500 papers have been published by the LHC collaborations
- few discrepancies observed are not yet conclusive

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 21<sup>st</sup> century

Thank you for your attention