Course on Physics at the LHC

LIP Lisbon, March - June 2014

The standard model of particle physics	Prof. João Varela (LIP, IST)	10, 13 March
Detector physics and experimental methods	Dr. Michele Gallinaro (LIP), Pedro Silva (LIP/CERN)	20, 24 March
Top quark and heavy flavor physics	Dr. Michele Gallinaro (LIP), Prof. António Onofre (LIP, UM)	31 March, 7, 14 April
Statistical methods in data analysis	Dr. Pedrame Bargassa (LIP)	28 April
Standard model Higgs and beyond	Dr. Pedro Silva (LIP/CERN), Dr. André David (CERN), Dr. Patricia Muino (LIP), Dr. Ricardo Gonçalo (LIP)	5, 12, 19, 26 May
Supersymmetry	Dr. Pedrame Bargassa (LIP)	2, 9 June
B physics and rare decays	Dr. Nuno Leonardo (LIP/CERN)	16 June
Matter at high density and temperature	Prof. João Seixas (LIP, IST), Dr. Pietro Faccioli (LIP)	23, 30 June

The lectures will take place on Mondays, between 17:00 and 18:30 at LIP,
Av. Elias Garcia, 14 r/c, 1000 Lisbon - Portugal

More info at
http://idpasc.lip.pt/LIP/events/2014_lhc_physics

Course coordinator: Prof. João Varela (LIP, IST)
Dr. Michele Gallinaro (LIP)

Introduction

Specialized course on the Physics at the Large Hadron Collider organized by LIP in the framework of IDPASC.

The objective of the Course is to introduce the physics, analysis methods and results on the physics of the LHC experiments.

Emphasis is placed on the search for new physics, in particular phenomena at the basis of the electroweak symmetry breaking.

Benchmark channels in proton-proton collisions will be discussed in detail:

- identification of the objects involved
- signal and background properties
- background estimation and S/B discriminants
- estimation of systematical errors
- extraction and interpretation of the final results

Program

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Required background

The course is intended for under-graduate or graduate students having basic training in Particle Physics:

Basic concepts
Elementary constituents of matter and interactions. Quantum numbers and conservation rules. Spin and symmetry groups. Relativistic kinematics. Cross-section. Natural units. Mass and lifetime. Resonances.

Structure of matter
Elastic scattering and form factors. Inelastic scattering experiments. Nucleon structure functions. Scale invariance. Quark model. Parton distribution functions. Introduction to QCD.

Fundamental interactions
Introduction to QED. Fermi interaction. Parity violation. Currents V-A and weak doblets. W and Z bosons. Cabibbo angle. Neutral currents. Electroweak interaction. Gauge symmetries. The Higgs mechanism. Weinberg-Salam model. CP violation.

Background bibliography

F. Halzen and A.D.Martin, ' Quarks and Leptons ', John Wiley and Sons (1984)

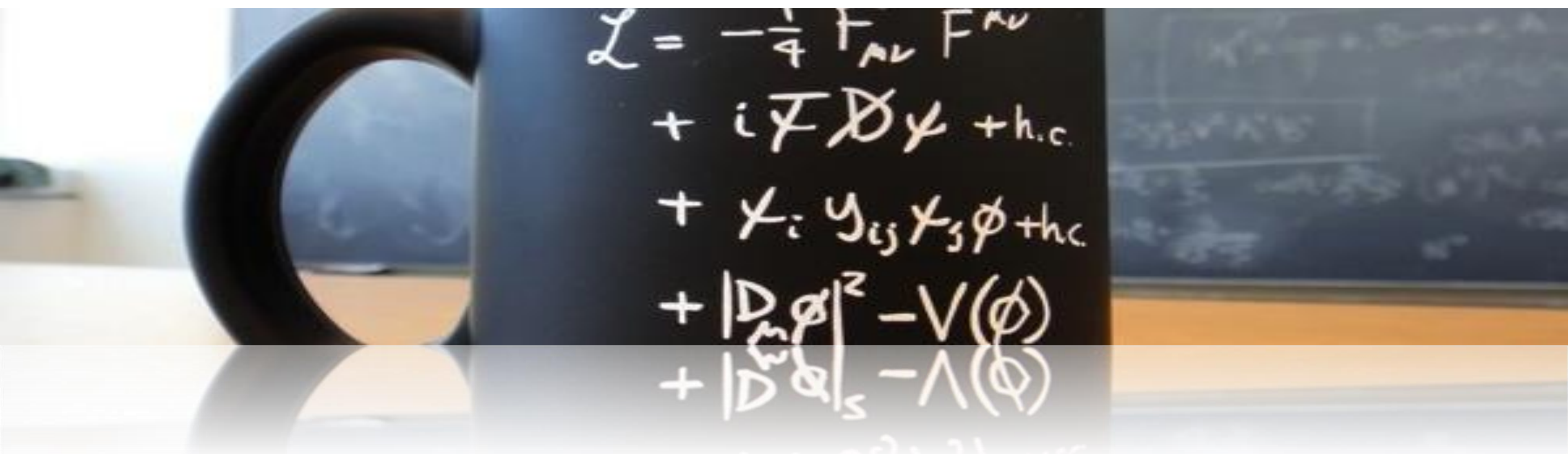
D. Griffiths, ' Introduction to Elementary Particles ', John Wiley and Sons (1987)

B.R.Martin, G. Shaw, ' Particle Physics ', John Wiley and Sons (1999)

1. The LHC physics case

1. The LHC experimental program

The LHC physics case



Particle Physics

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

Edward Witten

Aims to answer the two following questions:

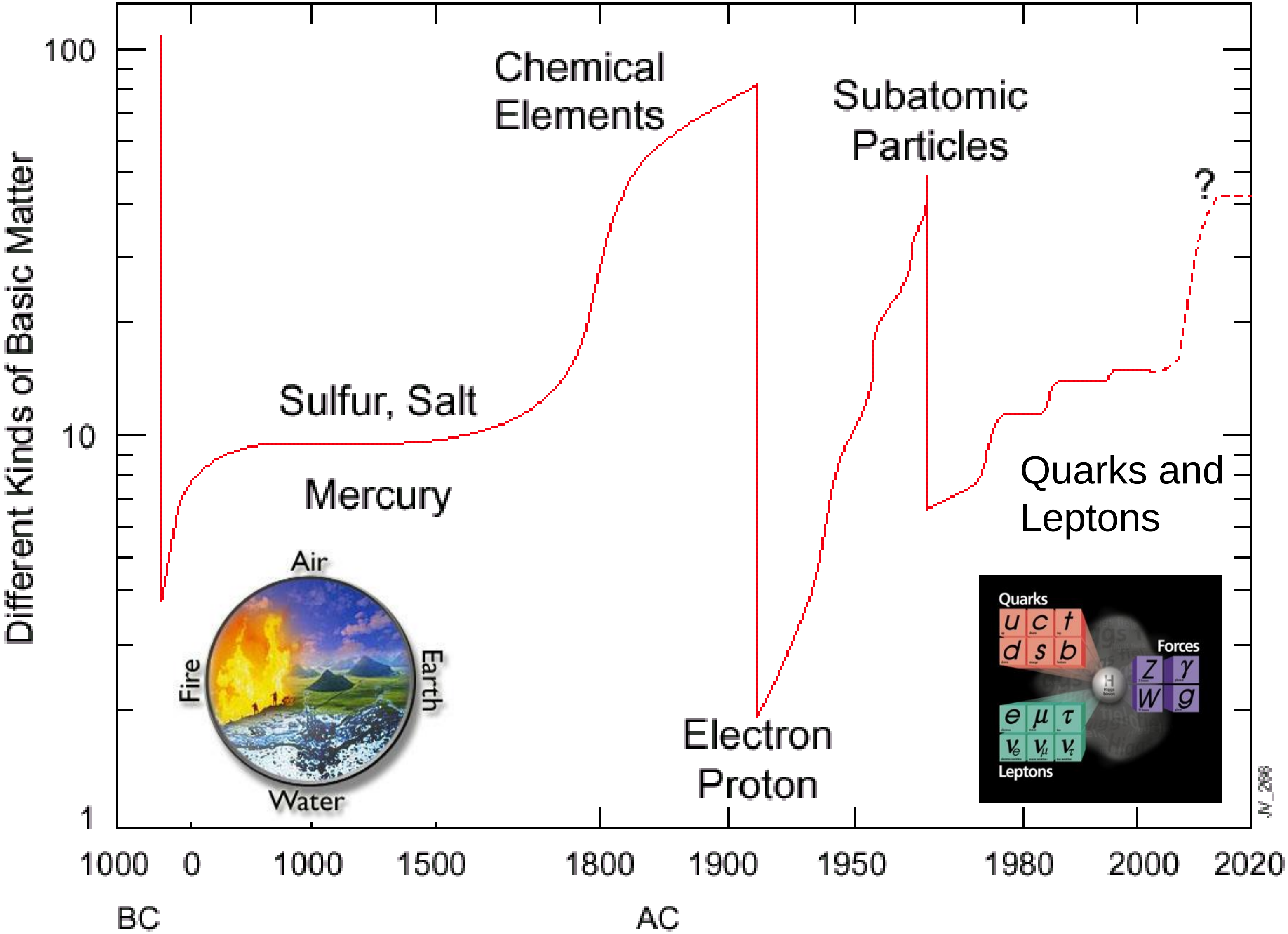
What are the elementary constituents of matter ?

What are the forces that determine their behavior?

Experimentally

Get particles to interact and study what happens

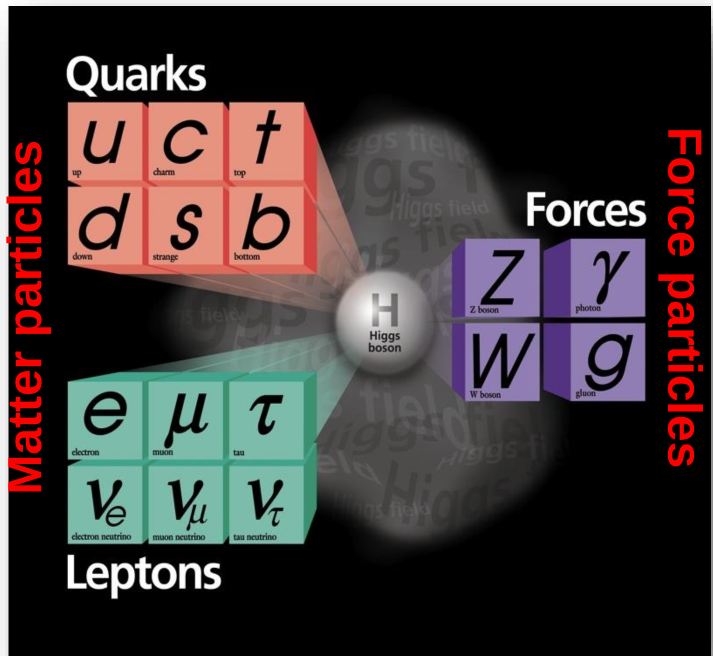
Constituents of matter along History



The Standard Model

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

- The Standard Model of Particle Physics
  - With a new "Periodic Table" of fundamental elements



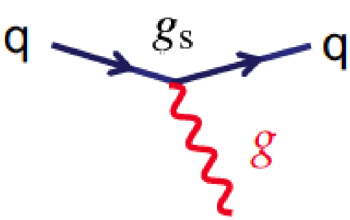
One of the greatest achievements of 20th Century Science

$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q')H$$

Standard model interactions

The interaction of gauge bosons with fermions is described by the Standard Model

STRONG



Only quarks

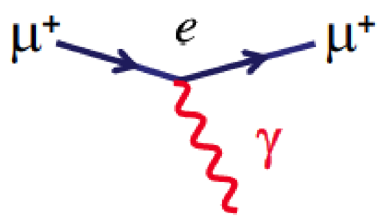
Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM



All charged fermions

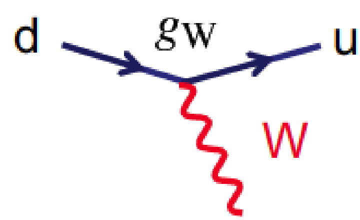
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

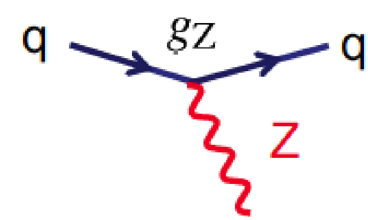
WEAK CC



All fermions

<u>Always</u> changes flavour

WEAK NC



All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

W+, W-

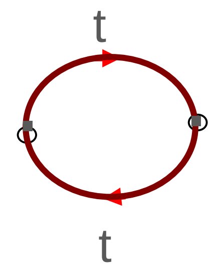
very massive

Z^0

very massive

Quantum field theory

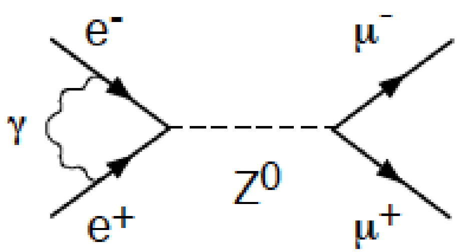
A particle-antiparticle pair can pop out of empty space ("the vacuum") and then vanish back into it

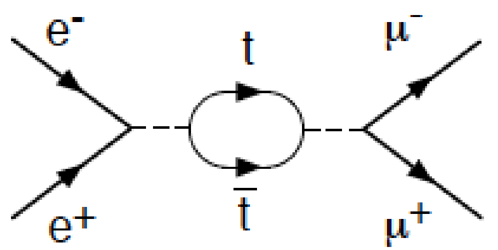


Vacuum Fluctuation
Involving top quarks

These are *Virtual* particles.

Other examples of Virtual particles:



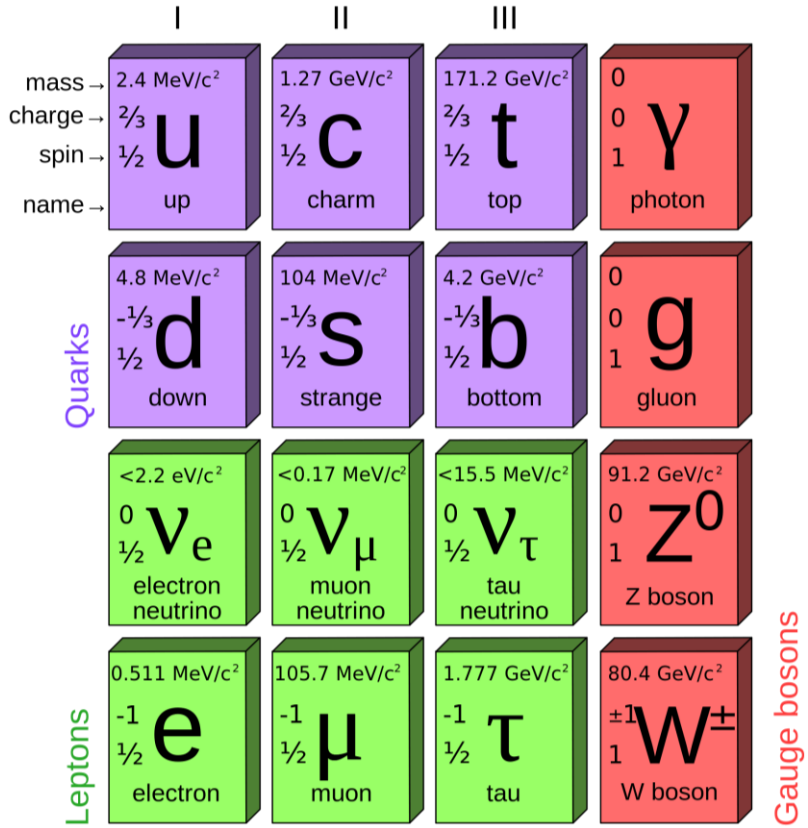


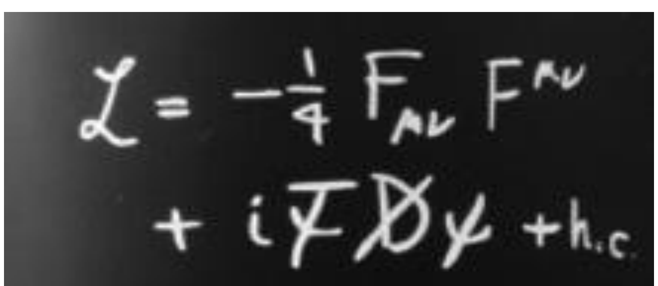
This has far-reaching consequences

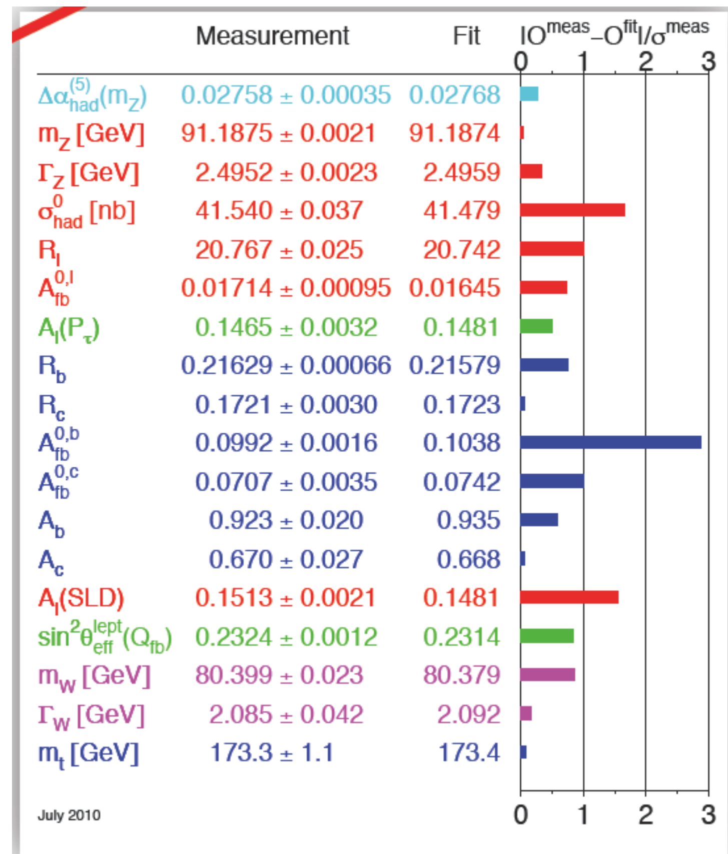
- The structure of the universe depends on particles that ***don't exist in the usual sense***
- We do not see these particles in everyday life
- We must recreate the state of the early hot universe to make them

SM confirmed by data

STANDARD MODEL OF ELEMENTARY PARTICLES







	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^0 [nb]	41.540 ± 0.037	41.479	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.379	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.3 ± 1.1	173.4	

Confirmed at sub 1% level!

What’s missing?

A “funny” thing happened on the way to the modern theory of quarks, leptons, force fields, and their quanta:

The equations only made sense if all the bosons, and all the quarks and leptons, had no mass and moved at the speed of light!

The Higgs

In the simplest model the interactions are symmetrical and particles do not have mass

The symmetry between the electromagnetic and the week interactions is broken:

- Photon do not have mass
- W, Z do have a mass ~ 80-90 GeV

Higgs mechanism:

mass of W and Z results from the interactions with the Higgs field

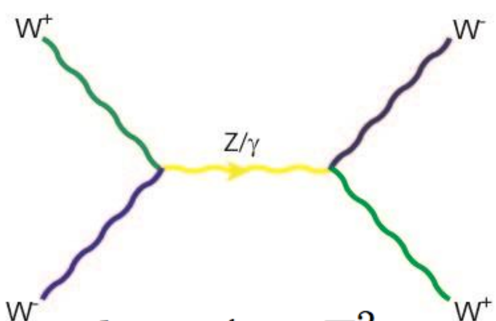
Added bonus

Non-zero average value of the Higgs field can also give masses to the quarks, electrons and muons – to all point-like particles.

Old theoretical problem affecting the quantum theory of the weak force :

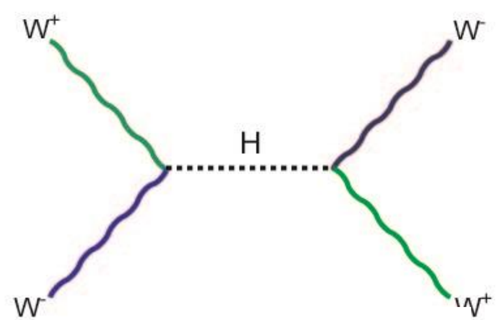
> the probability of two W's interacting becomes larger than 1 at high energies (> 1 TeV).

This is solved by the Higgs field!



$$\lim_{E\to\infty} \mathcal{A} \propto E^2$$

+



$$\lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

Beyond the standard model

The Standard Model answers many of the questions about the structure of matter. But the Standard Model is not complete; there are still many unanswered questions.

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

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

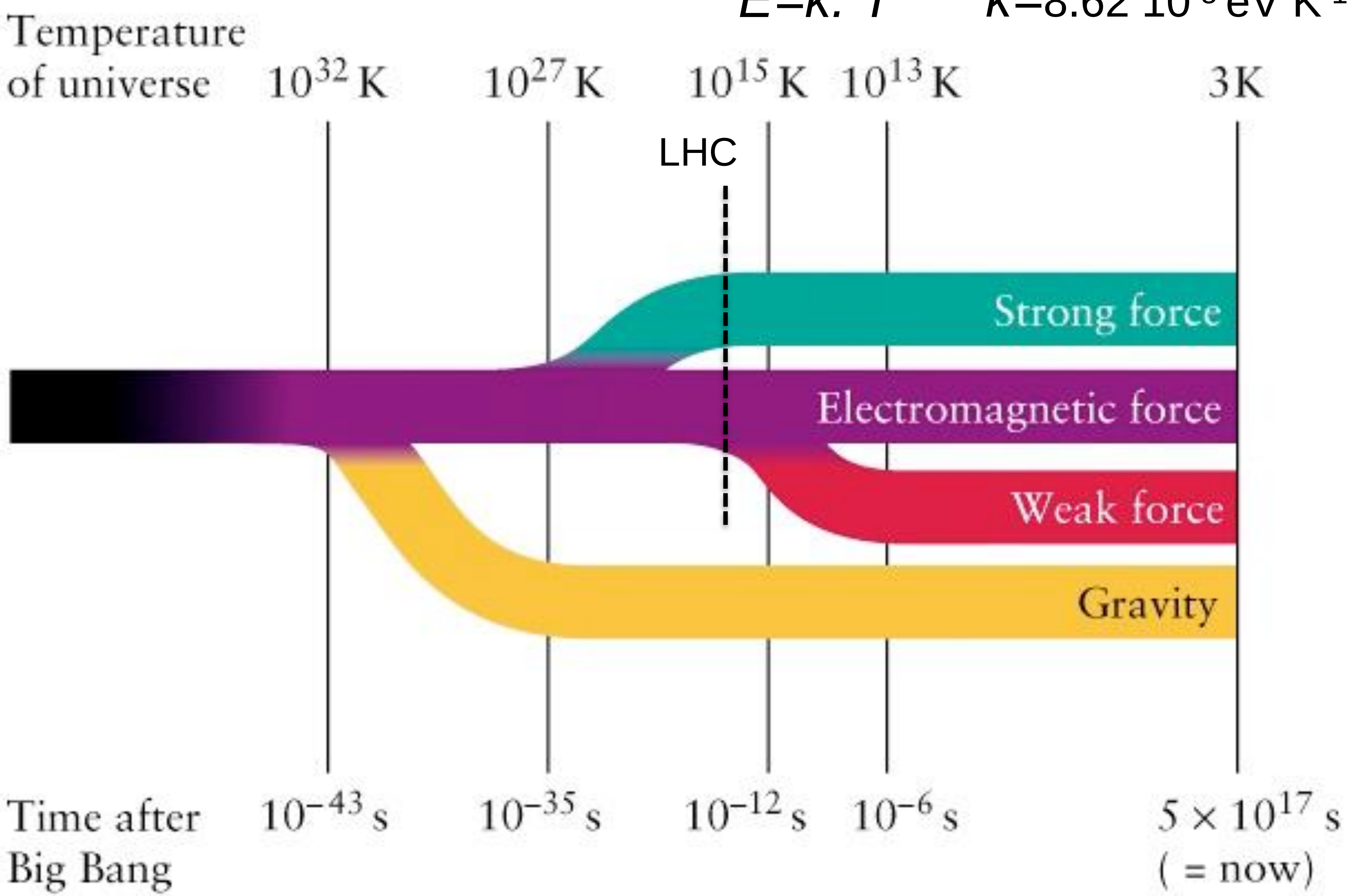
Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

Forces and expansion of the Universe

$E = k.\ T \qquad k = 8.62\ 10^{-5}\ \mathrm{eV\ K^{-1}}$

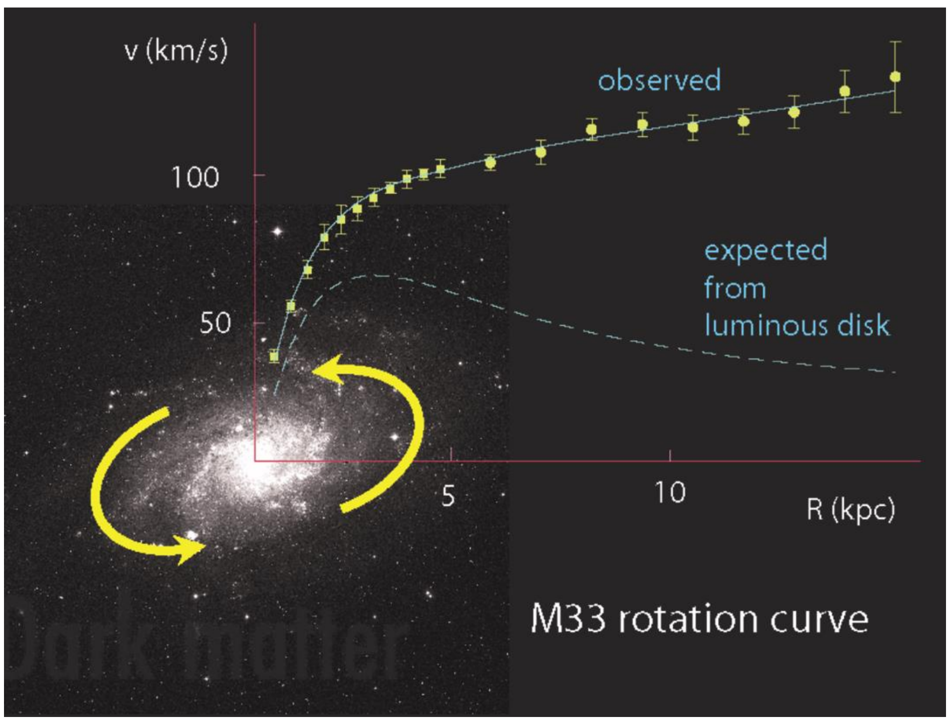


The dark side of the Universe

Long standing problem:

We know that ordinary matter is only ~4% of the matter-energy in the Universe.

What is the remaining 96%?

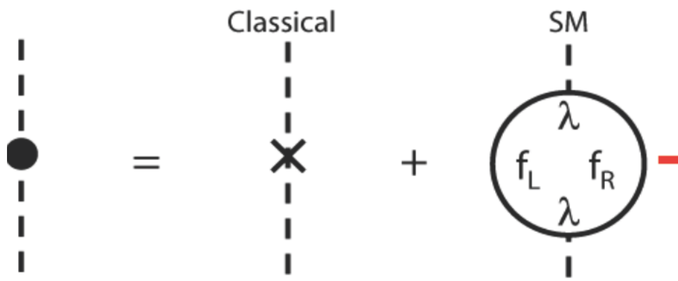


The LHC may help to solve this problem, discovering **dark matter**

Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

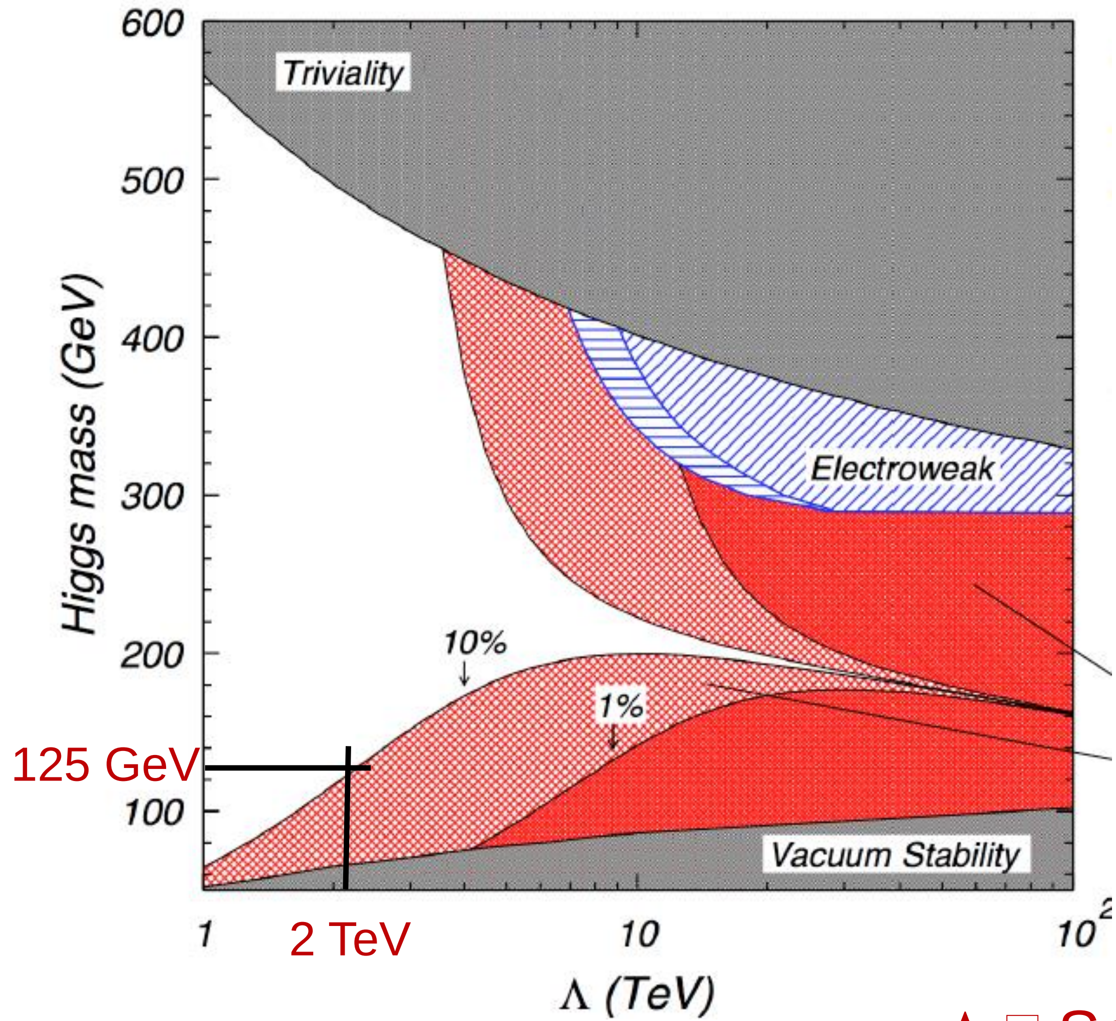
- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale of validity of the SM)
- Λ could be huge – e.g. the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

This is known as the hierarchy problem

New physics at a few TeV?



Naturalness implies Supersymmetry or another ‘New Physics’ below ~ 2 TeV

Excluded to avoid fine-tuning

Λ □ Scale of New Physics

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
- Technicolour
- Compositeness

Any of this could still be found at the LHC

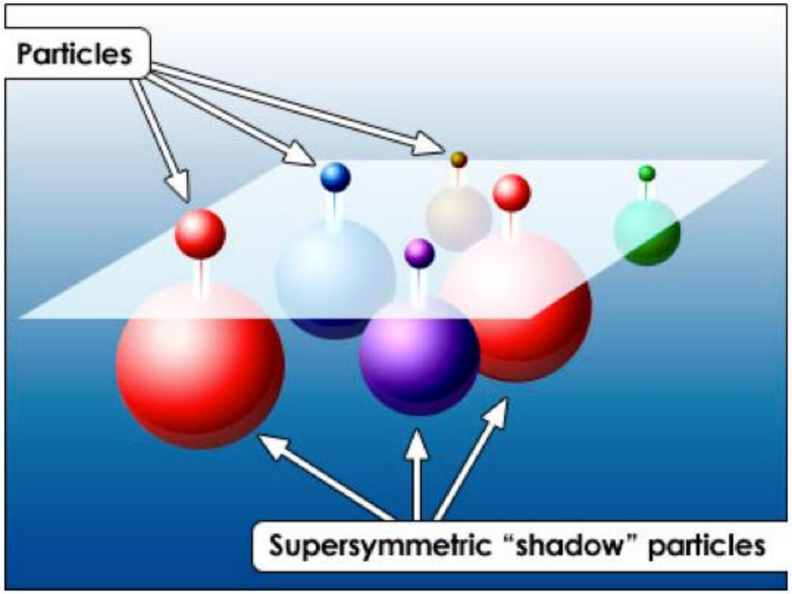
Supersymmetry

Some physicists attempting to unify gravity with the other fundamental forces have proposed a new fundamental symmetry:

- Every fermion should have a massive "shadow" boson
- and boson should have a massive "shadow" fermion.

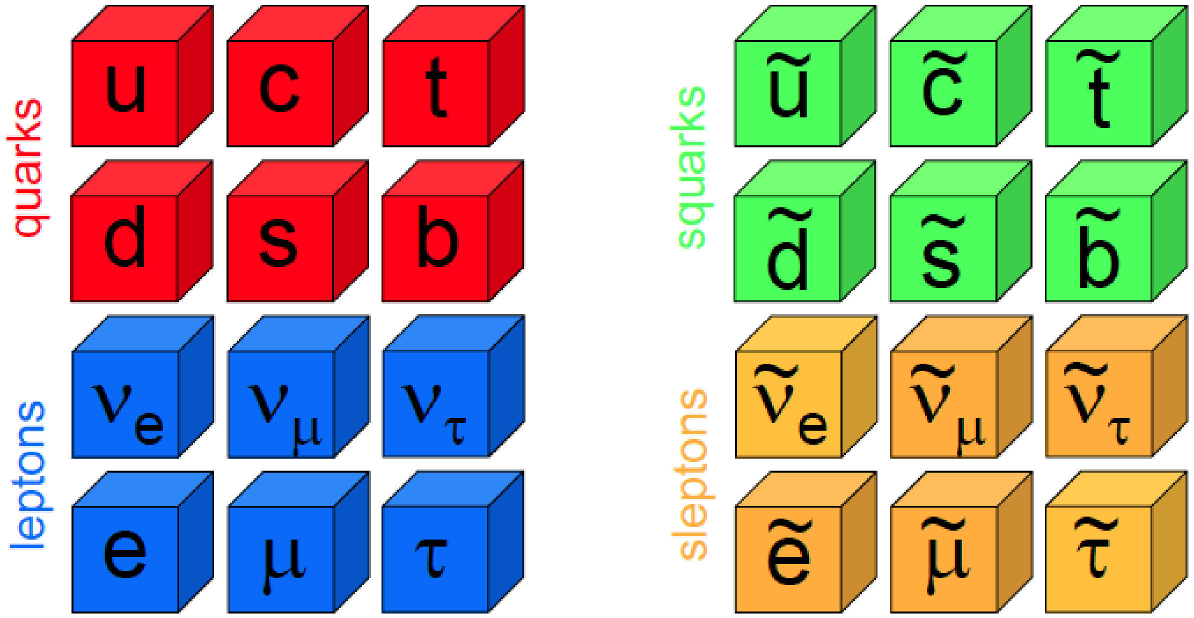
This relationship between fermions and bosons is called supersymmetry (SUSY)

No supersymmetric particle has yet been found, but experiments are underway at CERN to detect supersymmetric partner particles.



Supersymmetry

Double the whole table with a new type of matter?



Heavy versions of every quark and lepton
Supersymmetry is broken

Could DM be SUSY particles?

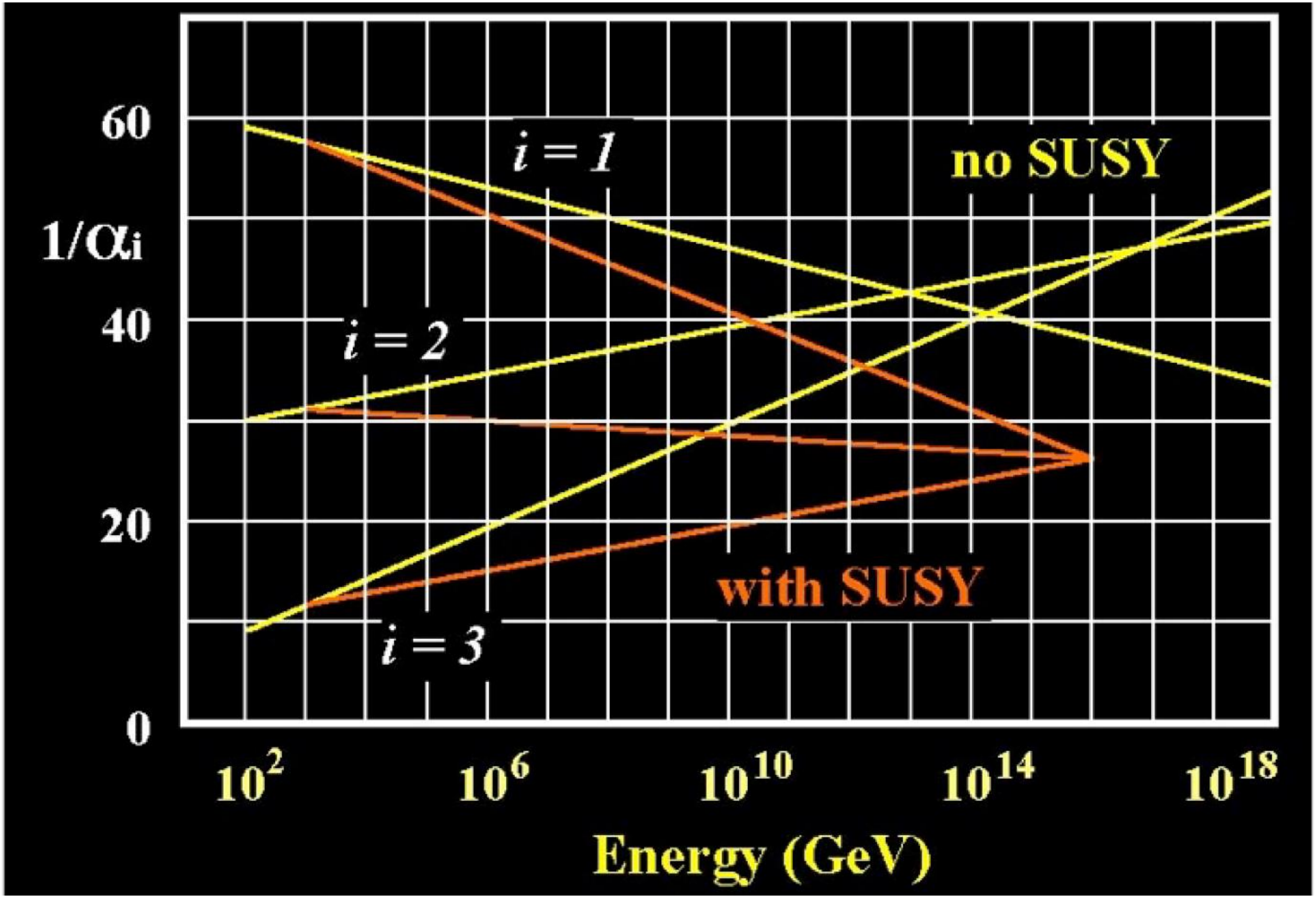
For every “normal” force quanta (boson), there are supersymmetric partners:

photon	photino
W, Z bosons	Wino, Zino
gluon	gluino
Higgs boson	higgsino

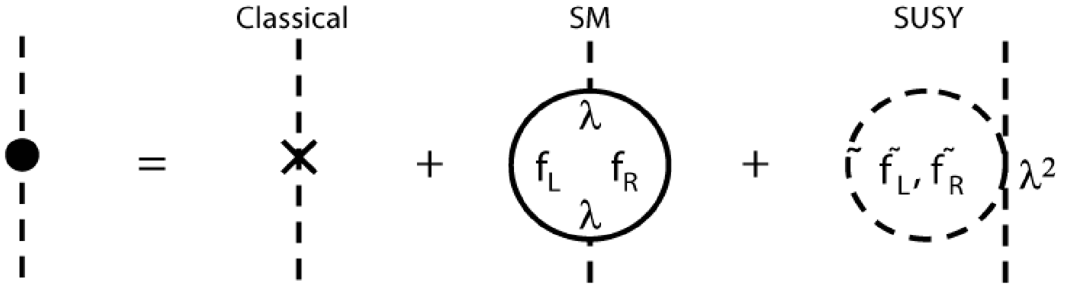
These “…inos” are prime suspects to be the galactic dark matter!

Relics from the Big Bang!

The temptation unification



SUSY and the Higgs mass



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

Cancellation

Higgs mass:

- correction has quadratic divergence!
  - Λ a cut-off scale – e.g. Planck scale

$$\begin{aligned} m_h^2 &= (m_h^2)_0 \boxed{- \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2} + \ldots \\ &\approx (m_h^2)_0 + \boxed{\frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}})} , \end{aligned}$$

Superpartners fix this:

- Need superpartners at mass ~1-2 TeV
  - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.

Extra dimensions

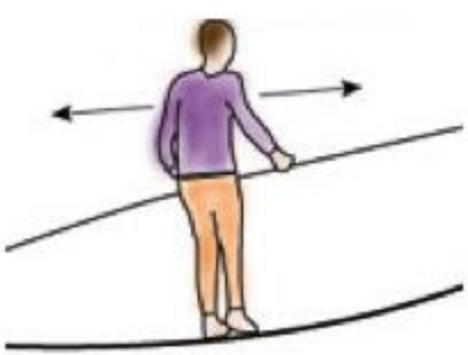
Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

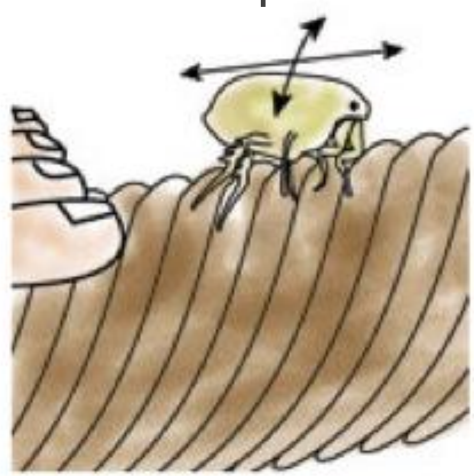
How can there be extra, smaller dimensions?

The acrobat can move forward and backward along the rope: **one dimension**

The flea can move forward and backward as well as side to side: **two dimensions**

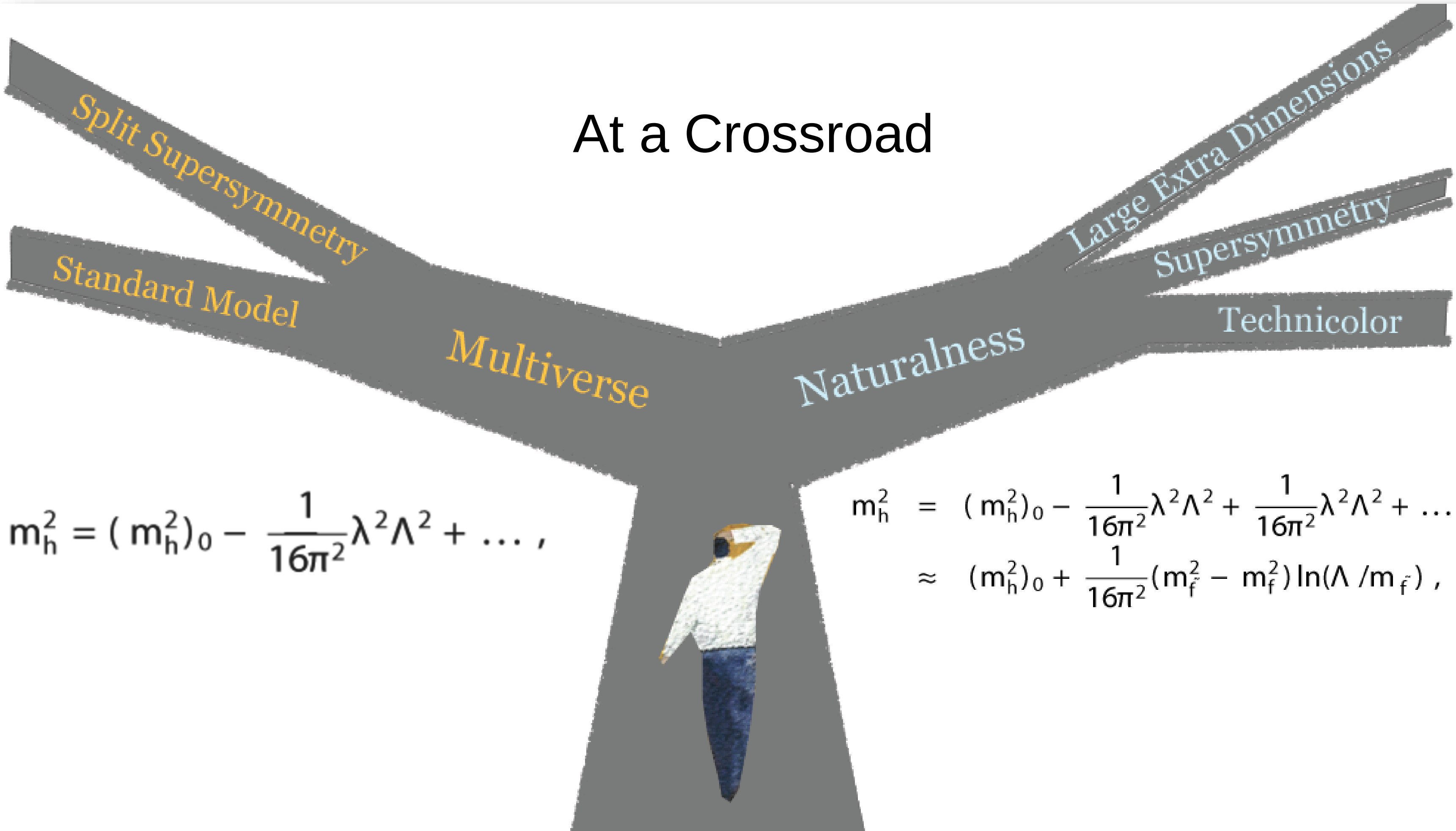
But one of these dimensions is a small closed loop.





Naturalness

At a Crossroad

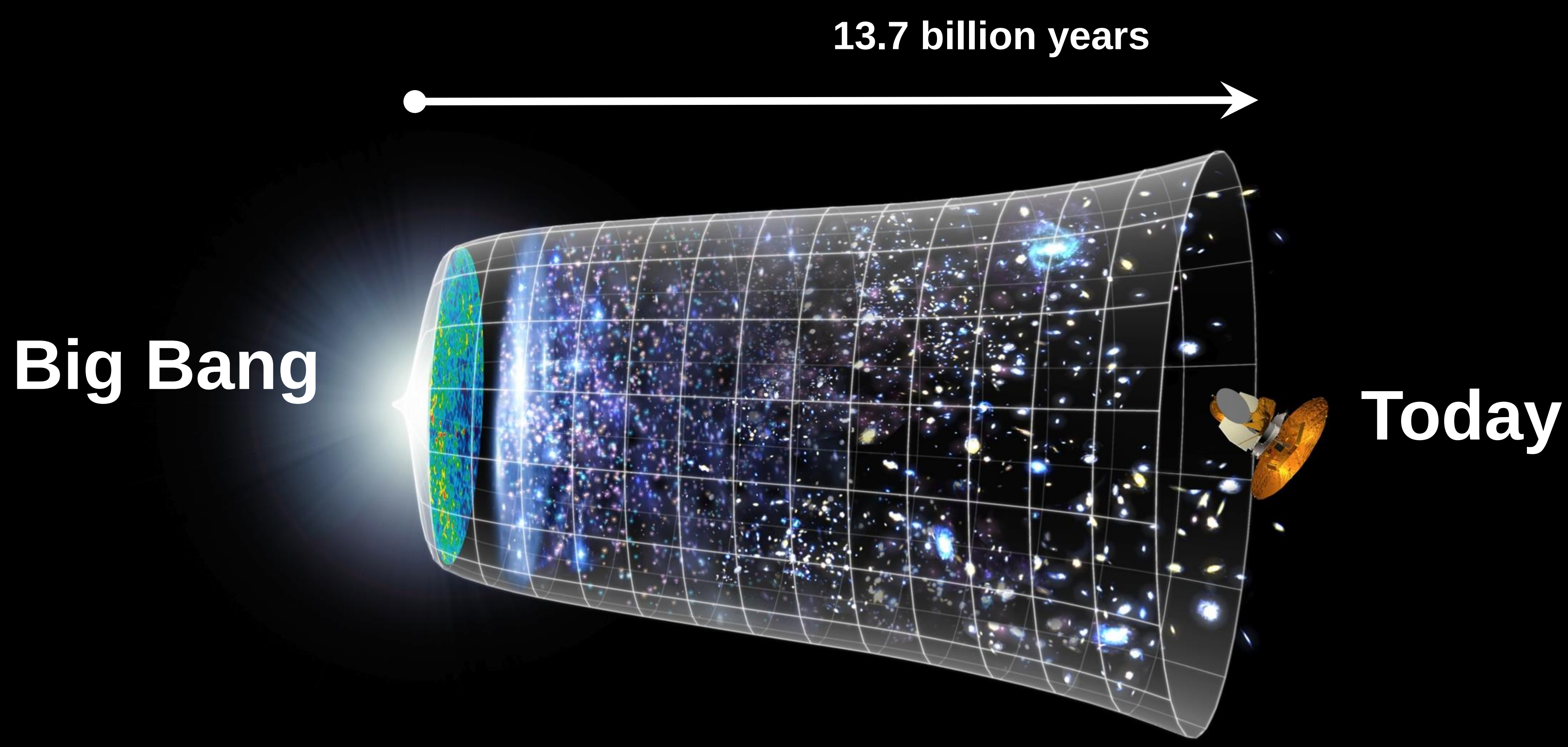


$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

$$\begin{aligned} m_h^2 &= (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots \\ &\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}}) , \end{aligned}$$

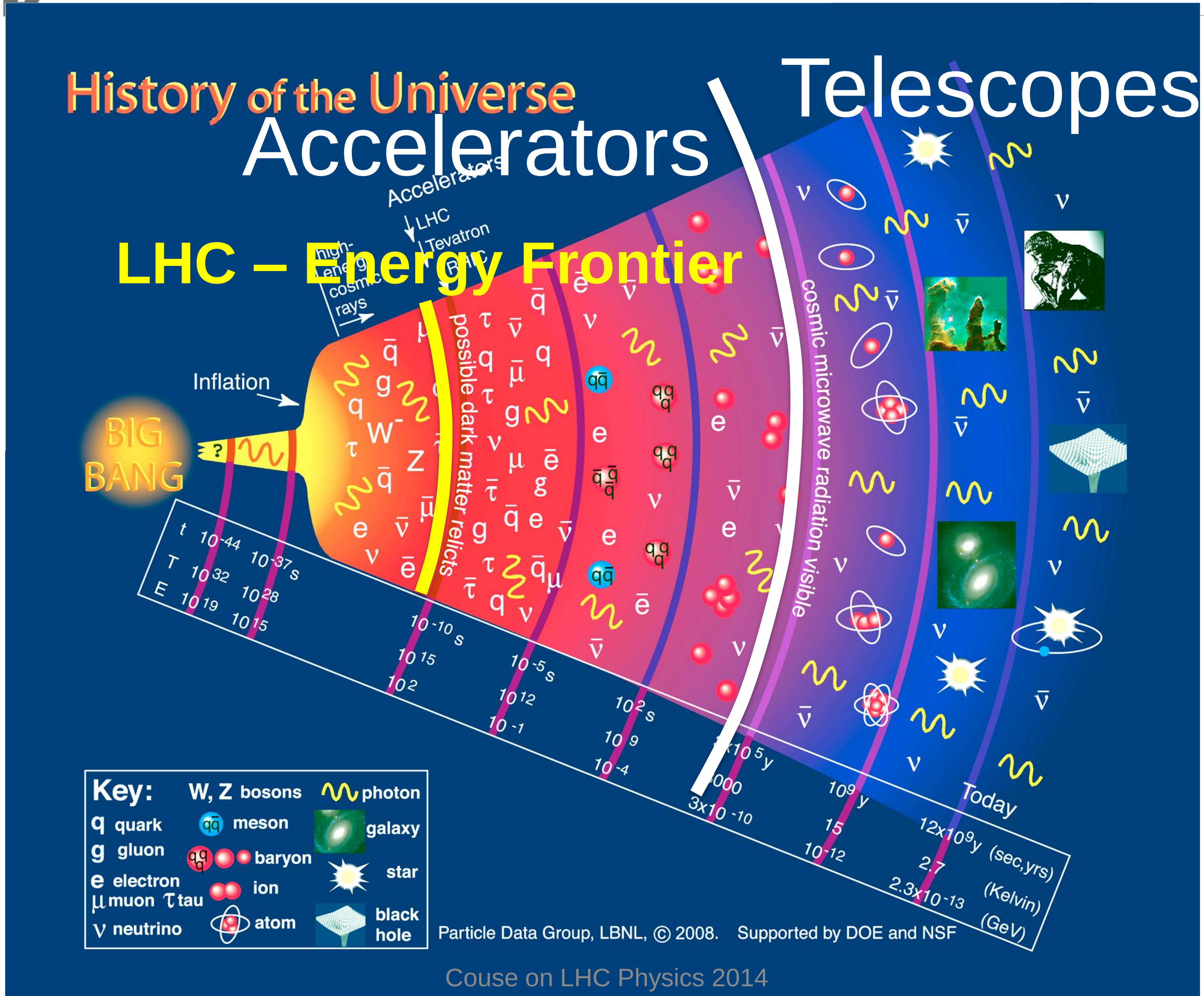
Savas Dimopoulos, CERN Colloquium, Sep 20, 2012

Timeline of the Universe



LHC recreates the conditions one billionth of a second after Big Bang

Understanding the Universe

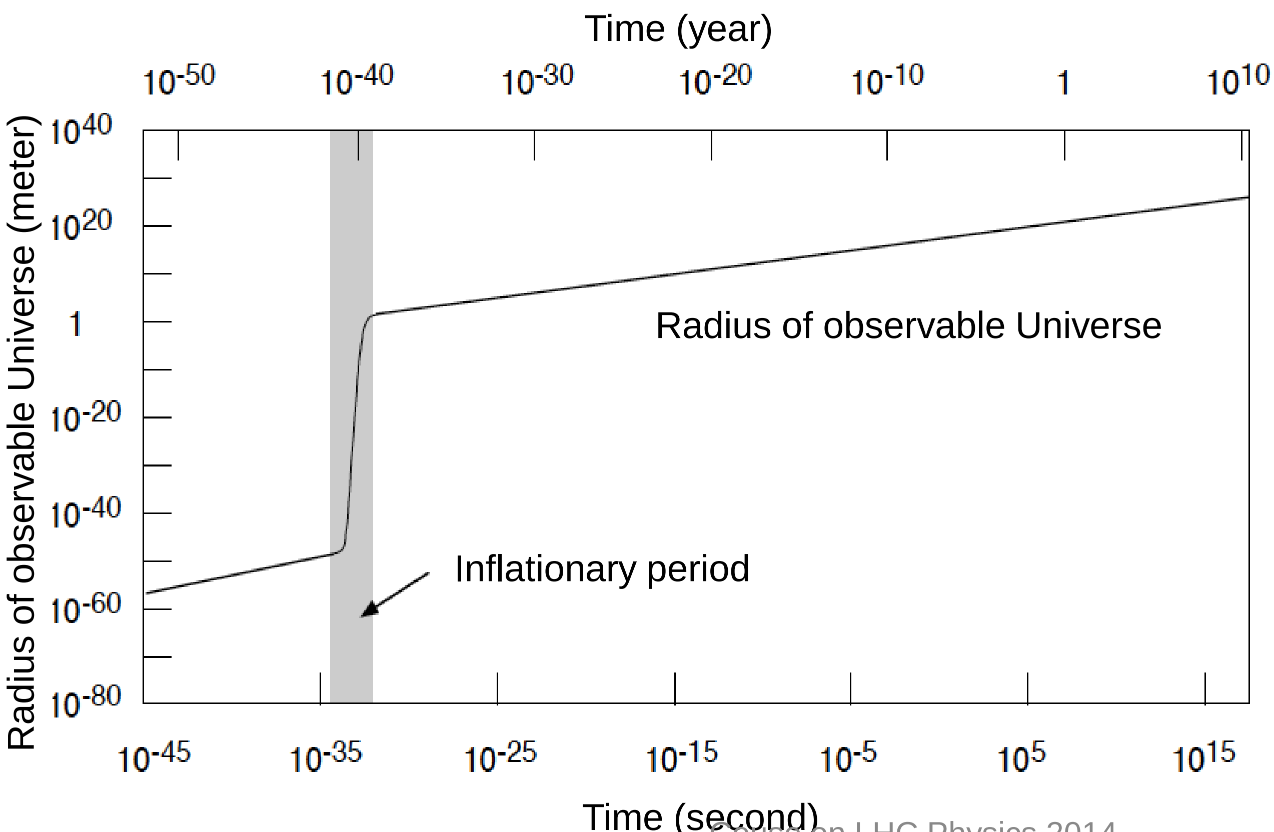


Cosmological inflation

In the very early universe, the physical vacuum undergoes a transition from a high energy state to a low energy state.

The resulting energy shift drives a dramatic exponential expansion.

Explains why the Universe has a uniform Temperature (3 K)

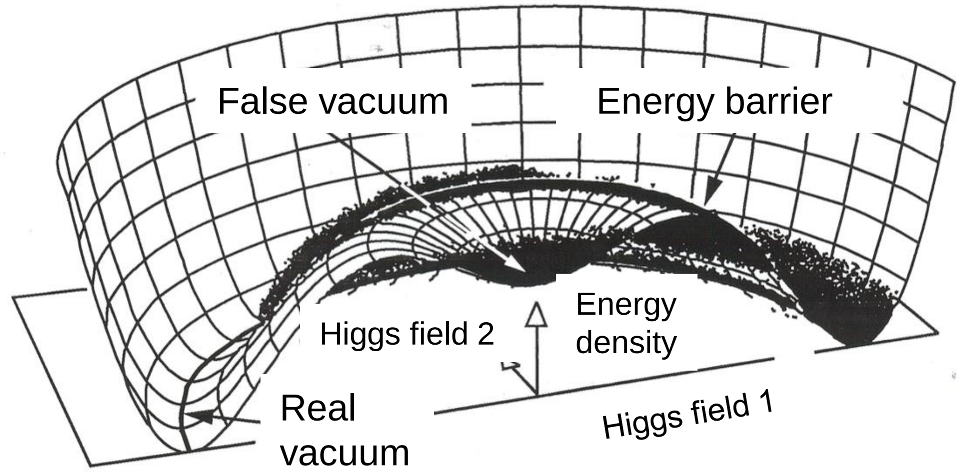


The inflation theory was developed independently in the late 1970's by Alan Guth, Alexey Starobinsky, and others

Higgs like field and inflation

Before the inflation (10^{-34} s), the Higgs-like field is trapped is a state of false vacuum.

The Universe undergoes a super-cooling transition: the temperature decreases below the phase transition point but the Higgs field stays in the false vacuum state.



While the energy density of the Higgs field is positive, the Universe expands at accelerated rate (inflation) and the energy stored in the Higgs field increases.

Inflation stops when the Higgs field decays to the real vacuum.

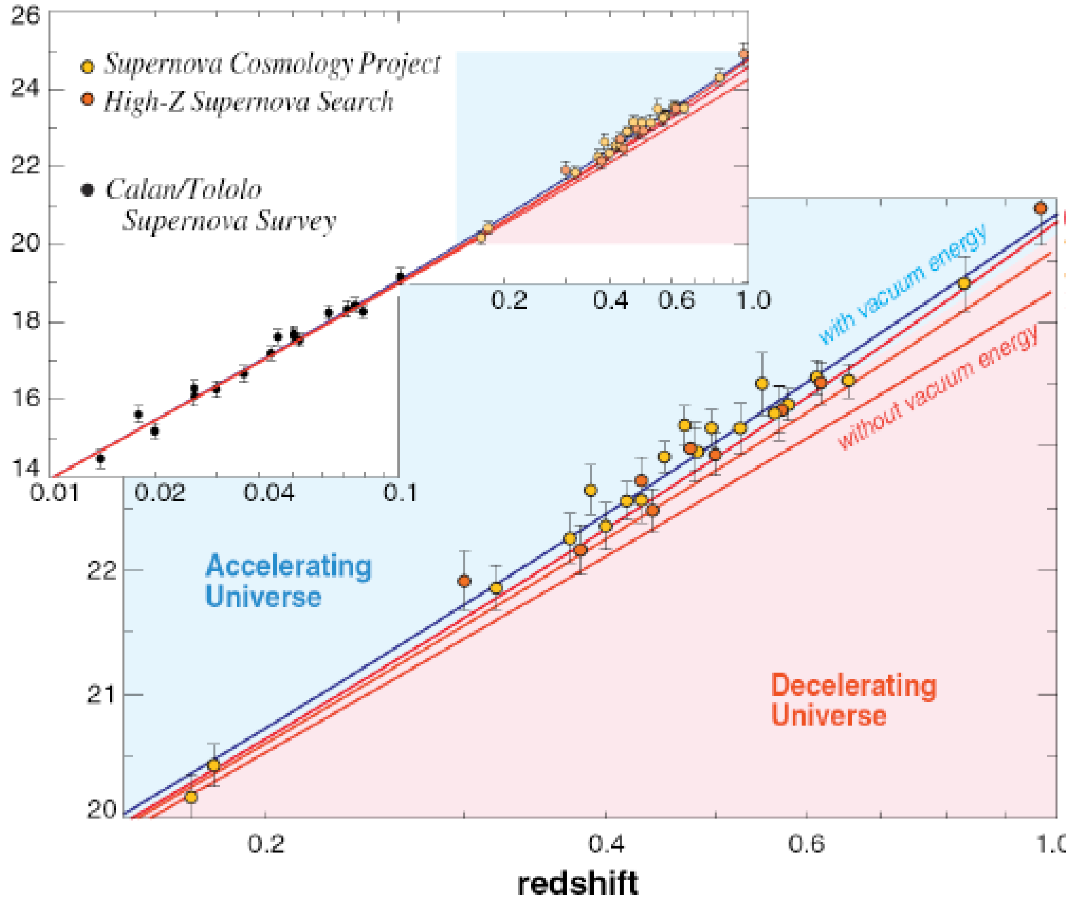
The energy released by the Higgs field is converted into matter particles.

The Universe expansion is accelerating

In 1998, two groups used distant Supernovae to measure the expansion rate of the universe: Perlmutter et al. (Supernova Cosmology Project), and Schmidt et al. (High-z Supernova Team)

They got the same result:
The Universe expansion is accelerating

Some form of energy (dark energy) fills space



Vacuum energy density

Dark energy responsible for acceleration of expansion is very small

From particle physics we know that Vacuum has energy:

- potential energy of scalar fields
- energy of quantum fluctuations as predicted by quantum mechanics

This vacuum energy is 100 orders of magnitude larger than dark energy!

This huge discrepancy is known as the vacuum catastrophe.

The Terascale

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

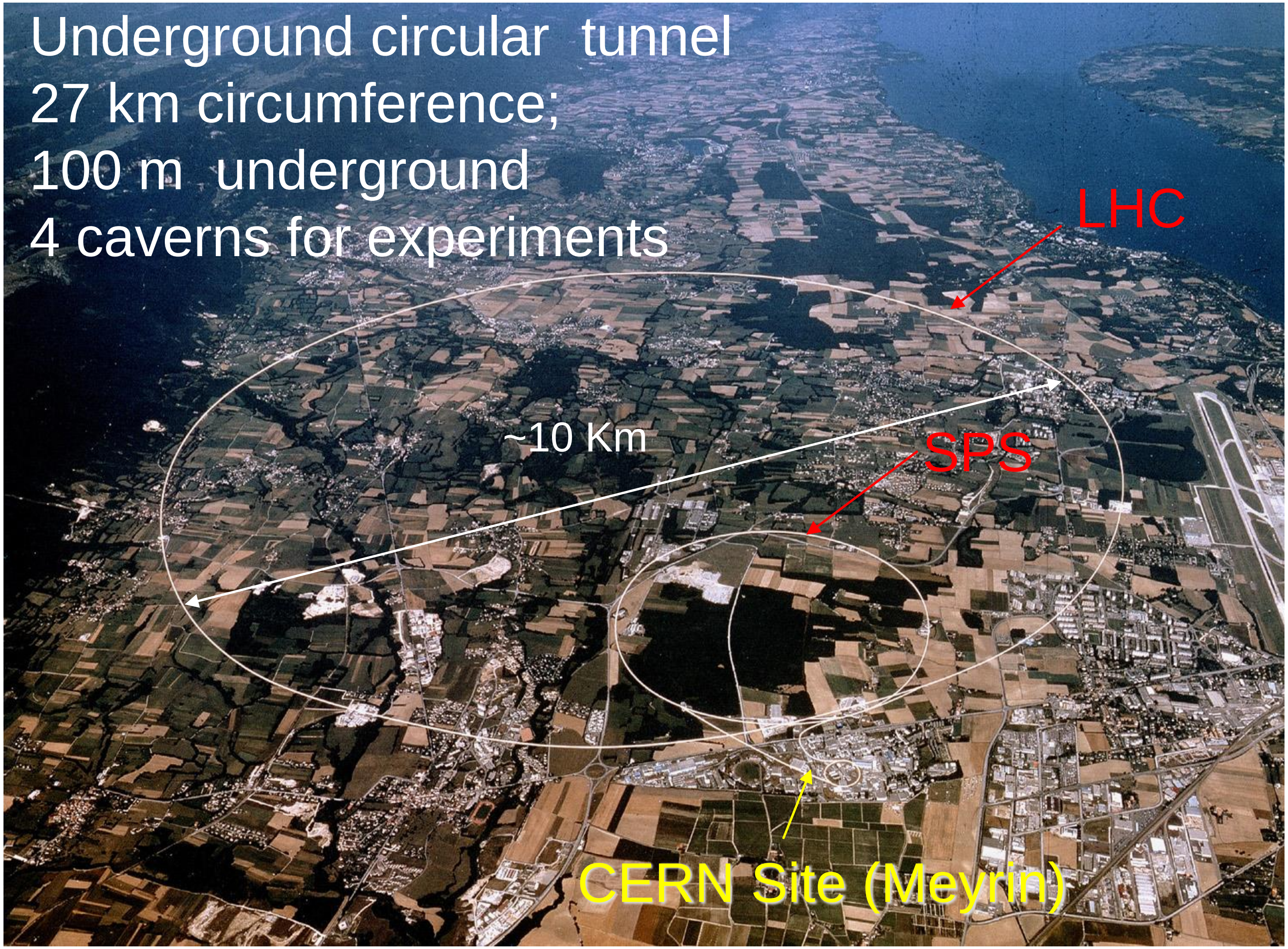
Based on the available data and on quite general theoretical insights it was expected that the **‘new physics’** would manifest at an energy around

1 Tera-electronVolt = 10^{12} electronVolt

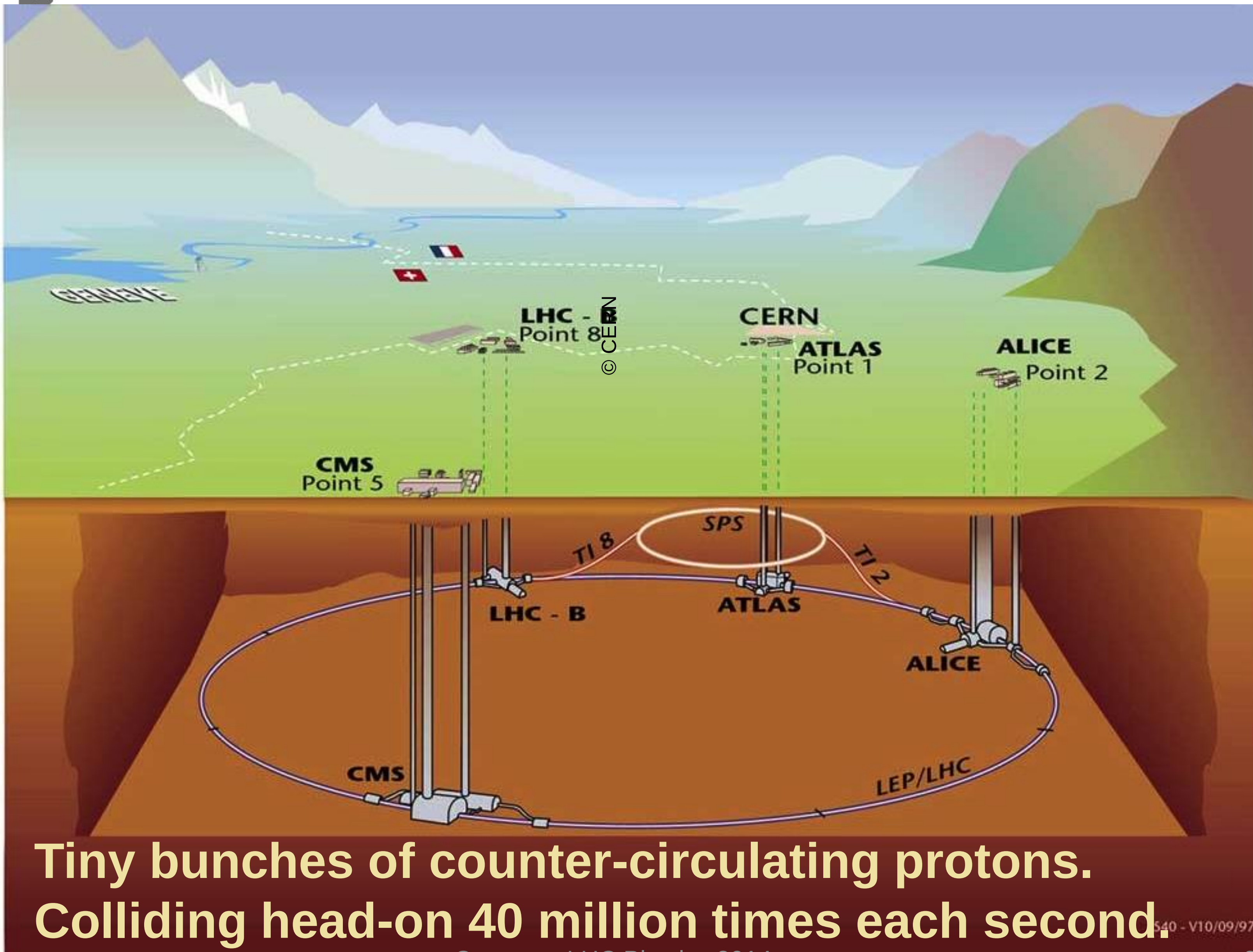
accessible at the LHC for the first time

The LHC proton collider

Accelerator and Experiments



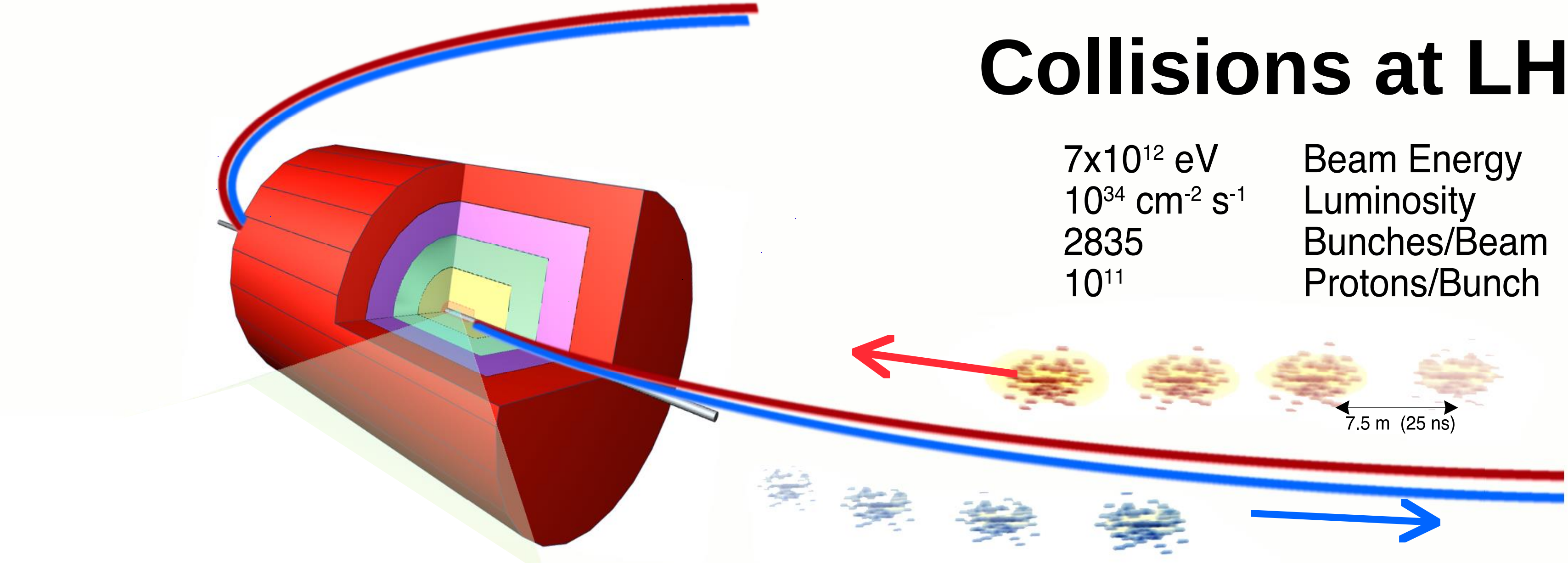
Accelerator and experiments layout



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

Collisions at LHC

7×10^{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

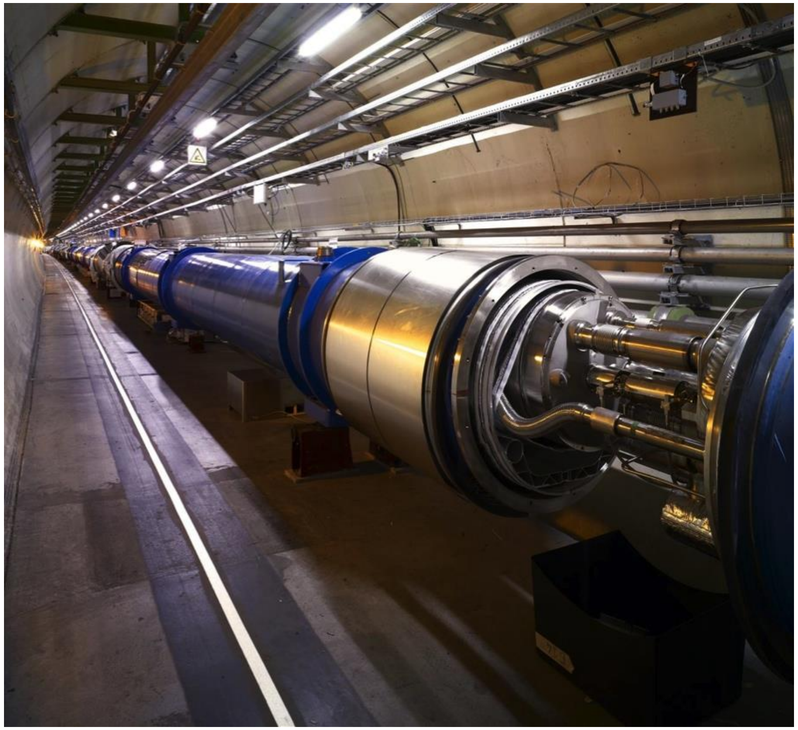
Relative to Tevatron (Fermilab, USA)

Energy (14 TeV) x 7

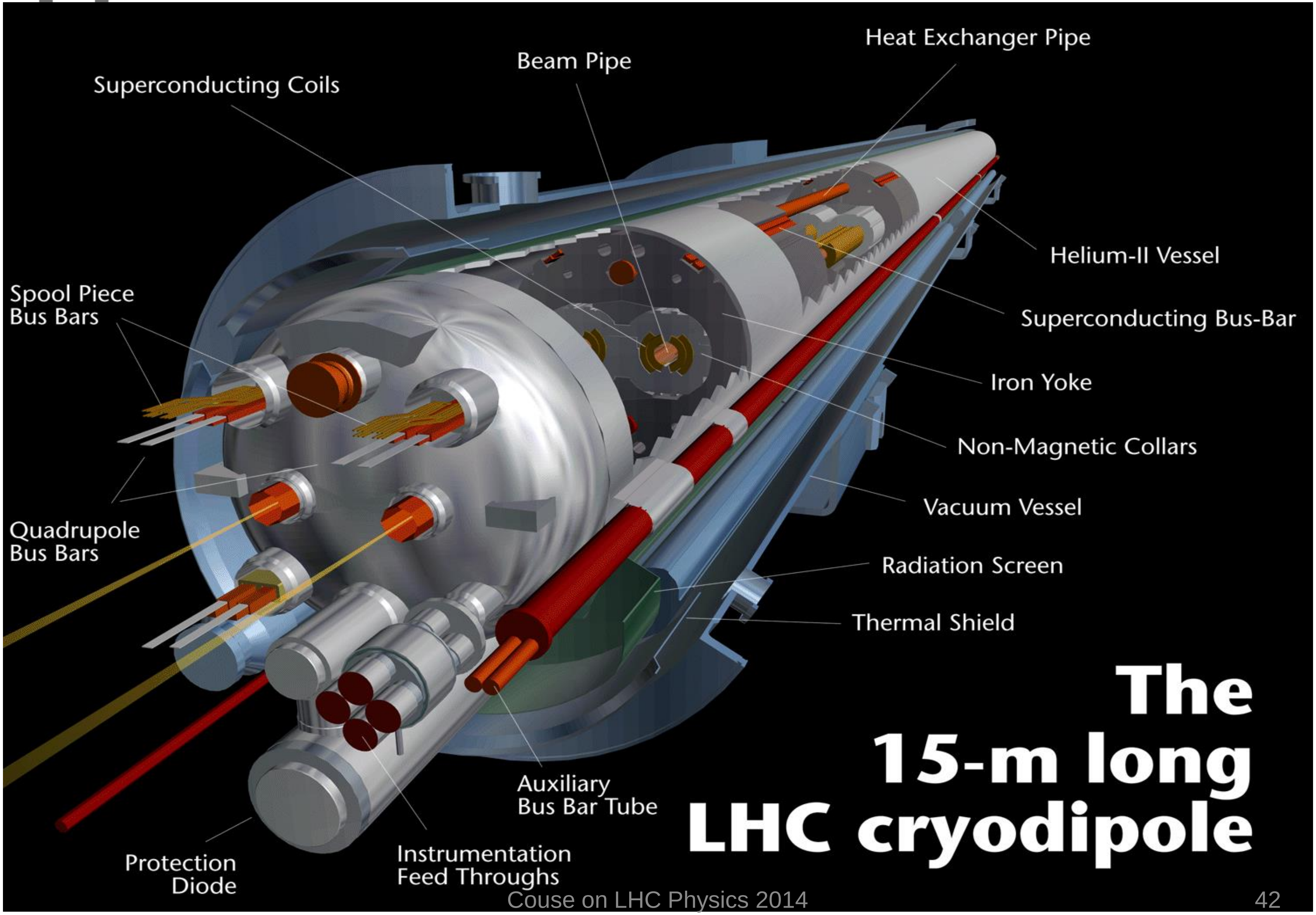
Luminosity ($10^{34}cm^{-2}s^{-1}$) x 30

- 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

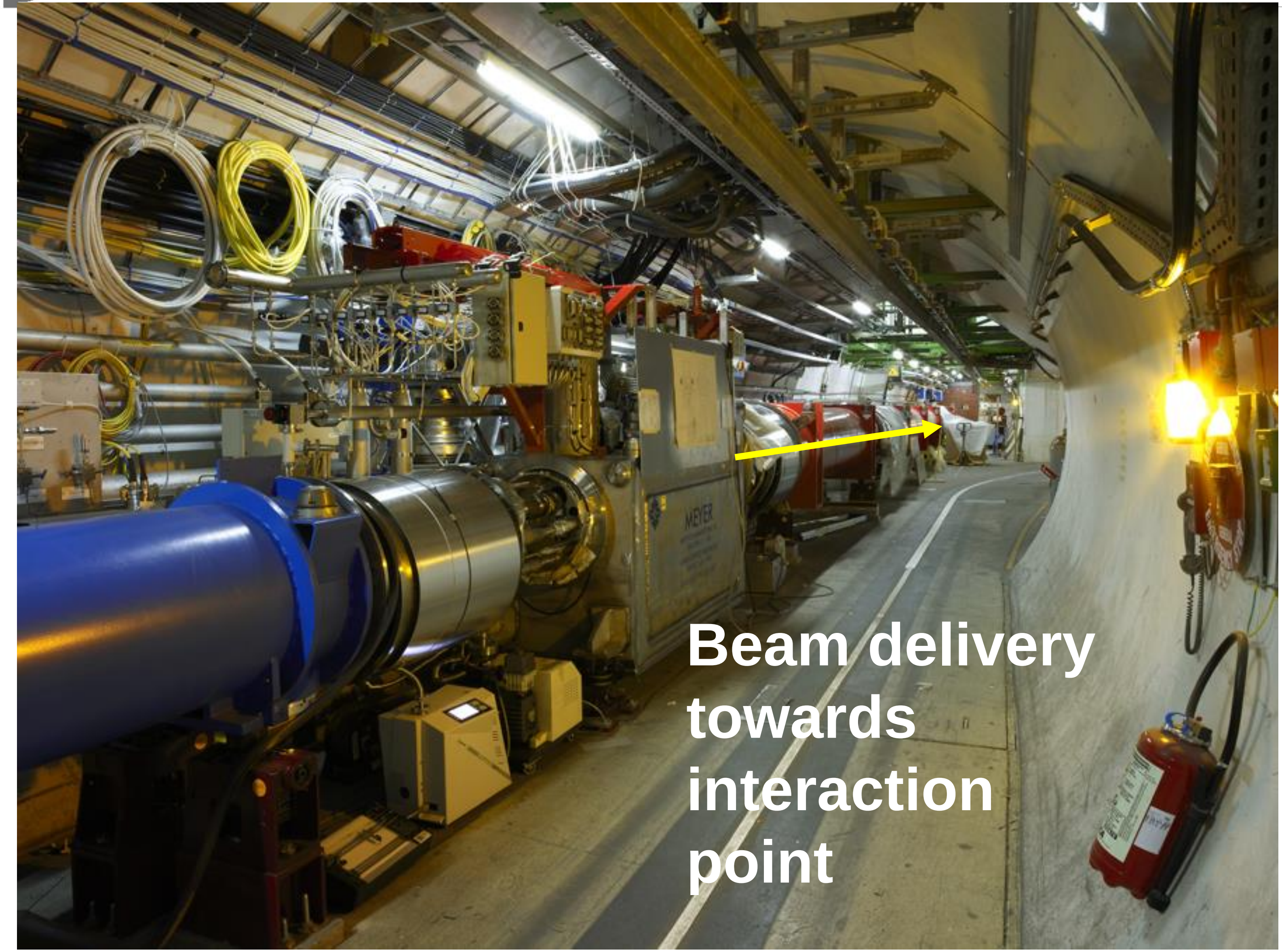
- More than 2000 dipoles
- 100 ton liquid helium
- LHC power consumption 120 MW



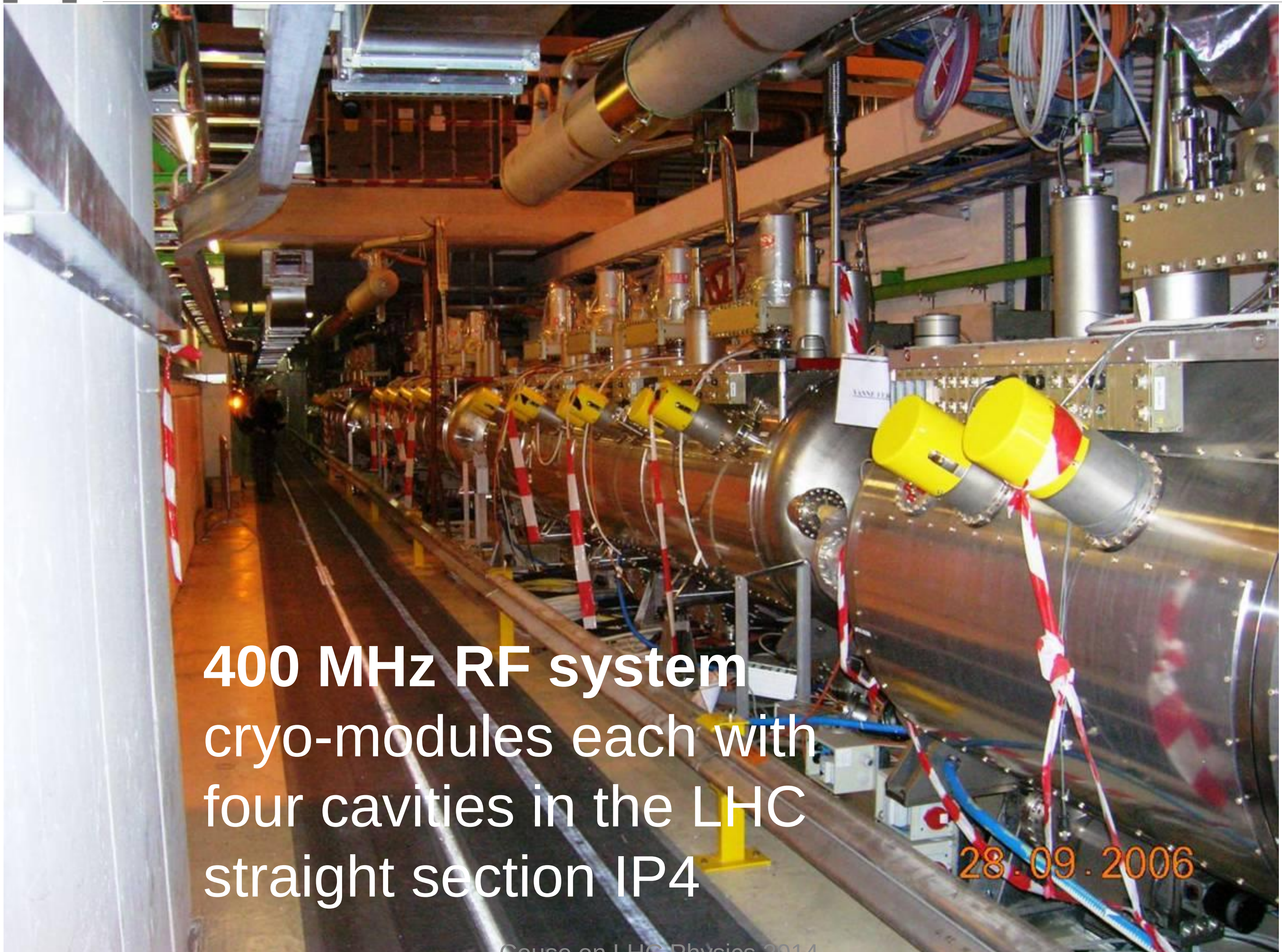
Superconducting magnetic dipole



In the tunnel



In the tunnel

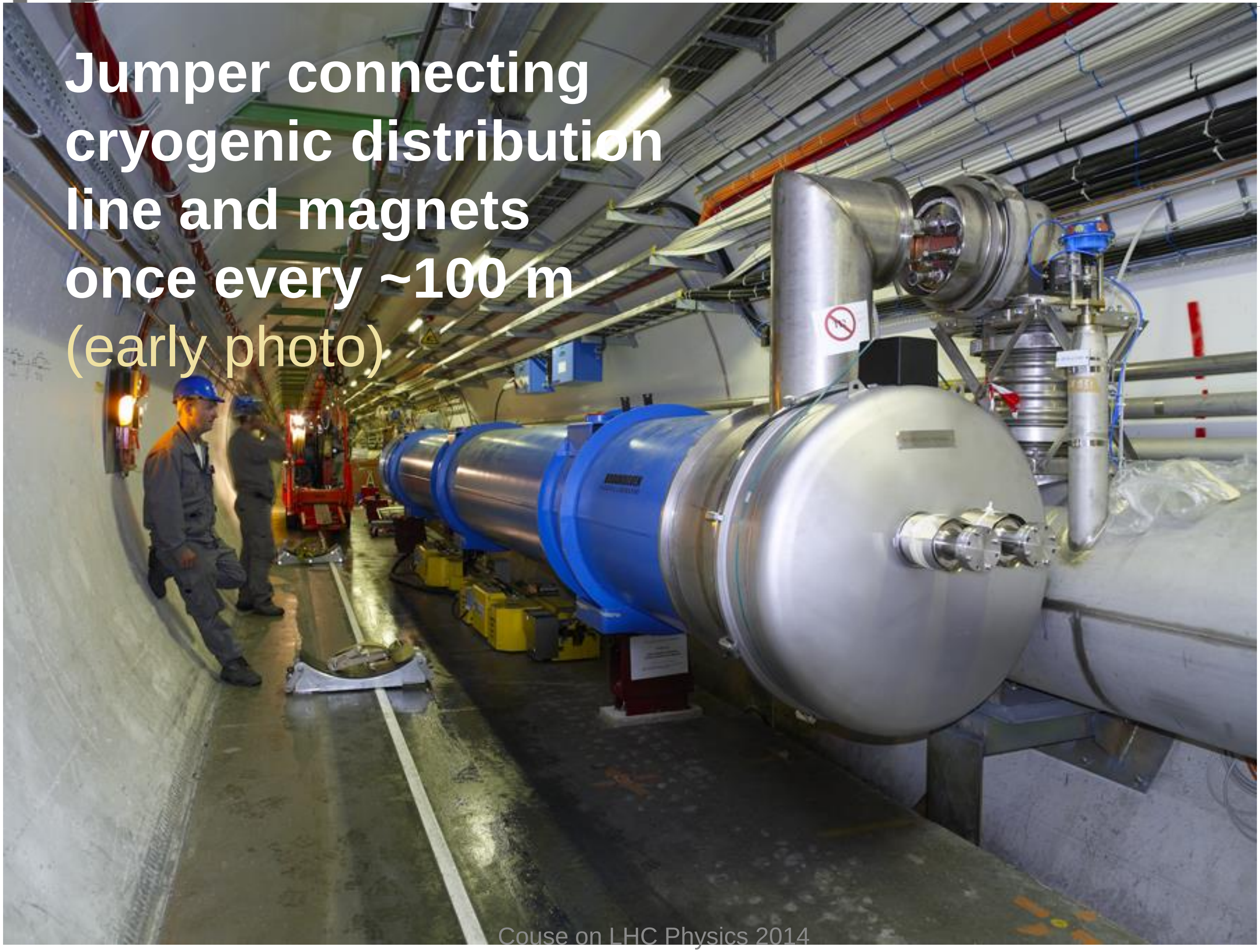


400 MHz RF system
cryo-modules each with four cavities in the LHC straight section IP4

In the tunnel

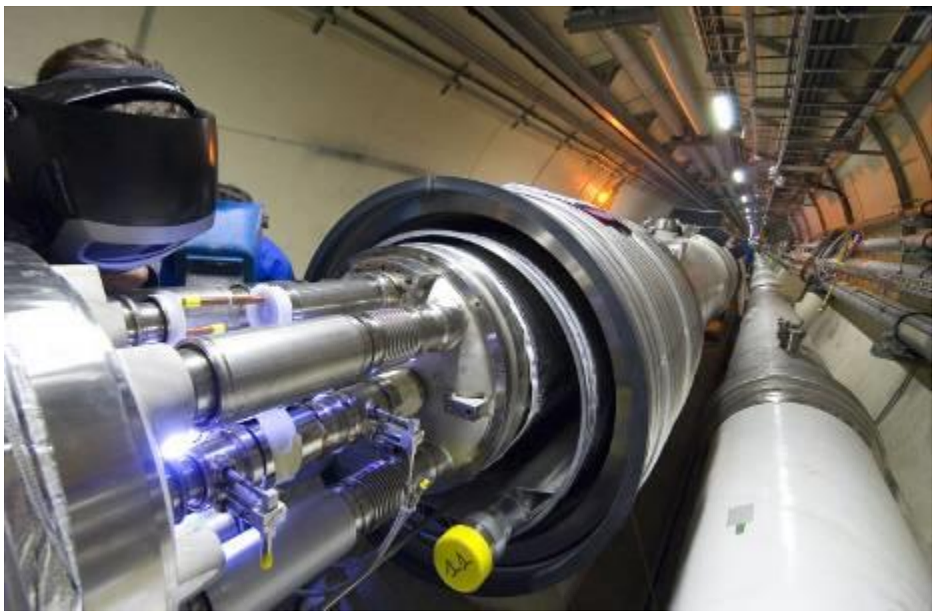
Jumper connecting cryogenic distribution line and magnets once every ~100 m

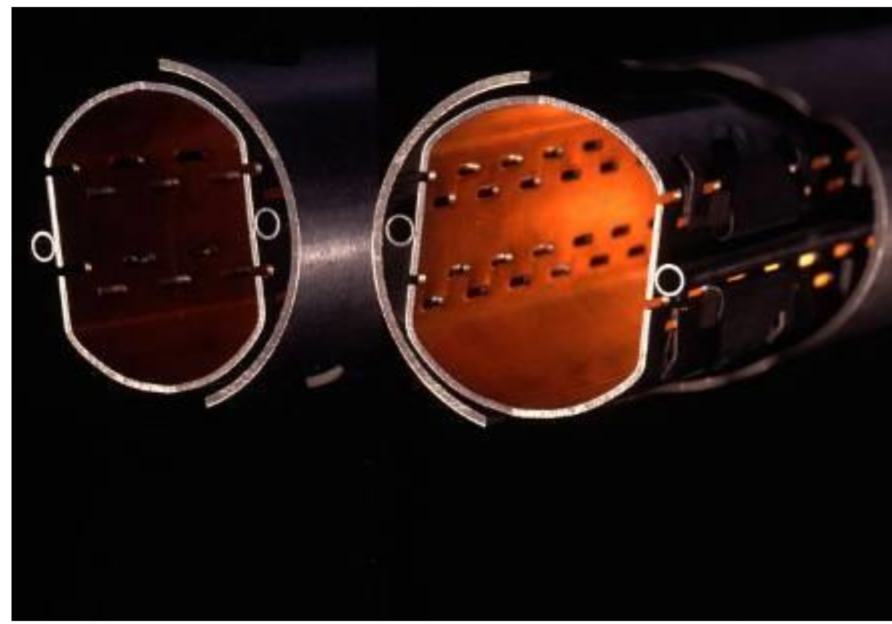
(early photo)



It’s empty!

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



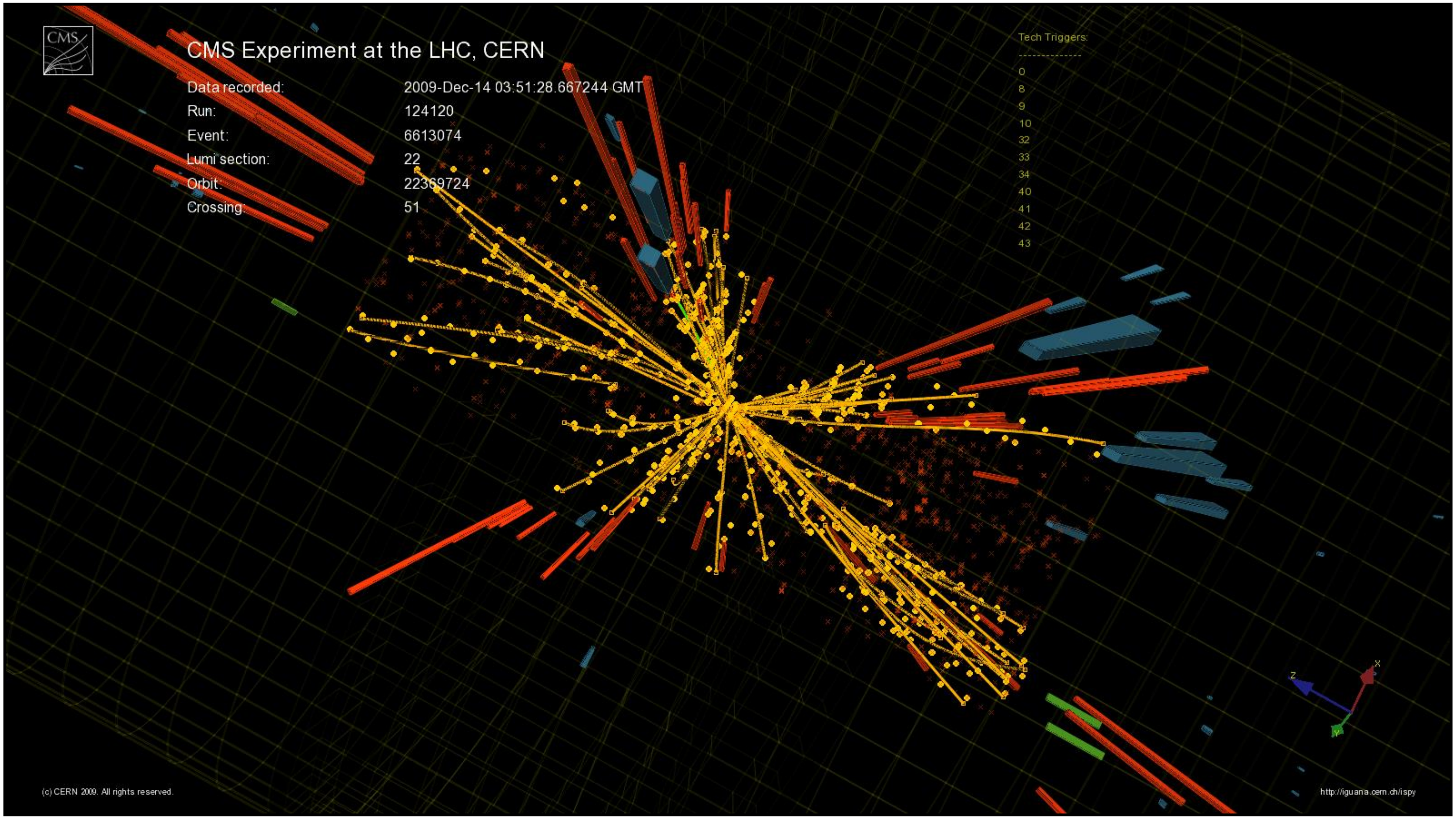


It’s cold!

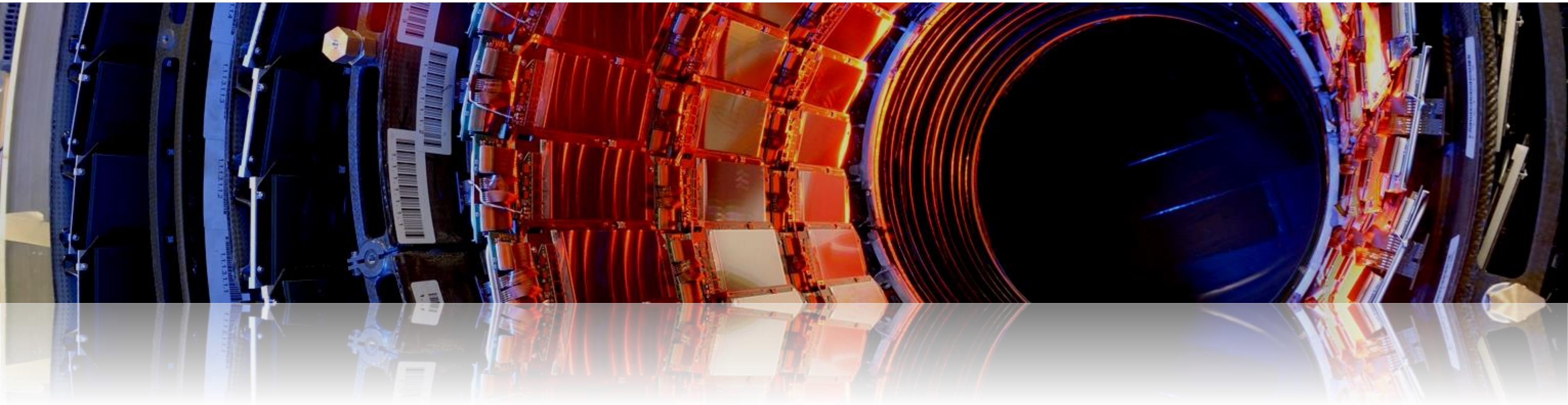
27 Km of magnets are kept at 1.9 ^{o}K, colder than outer space, using over 100 tons of liquid helium.

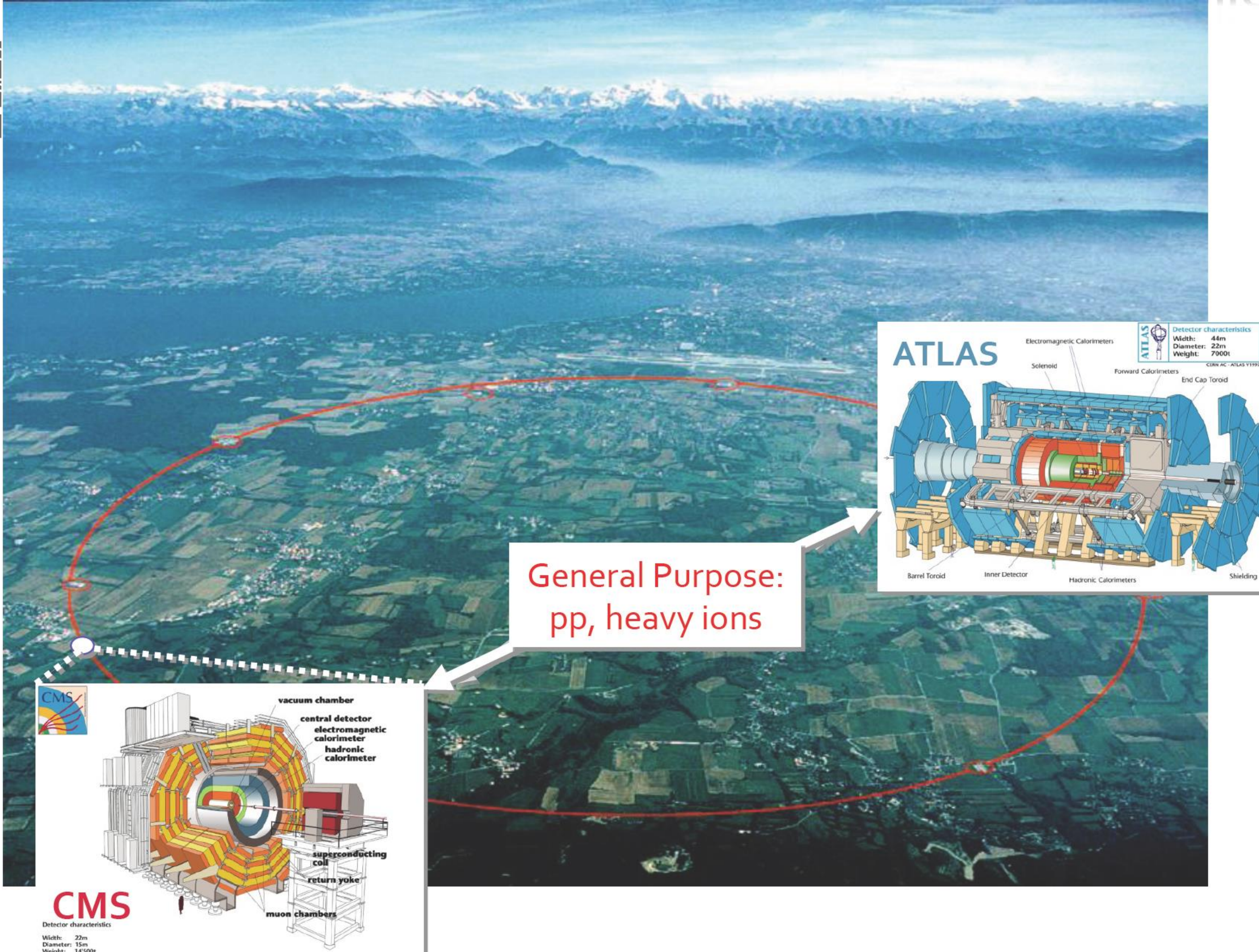
It's Hot!

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



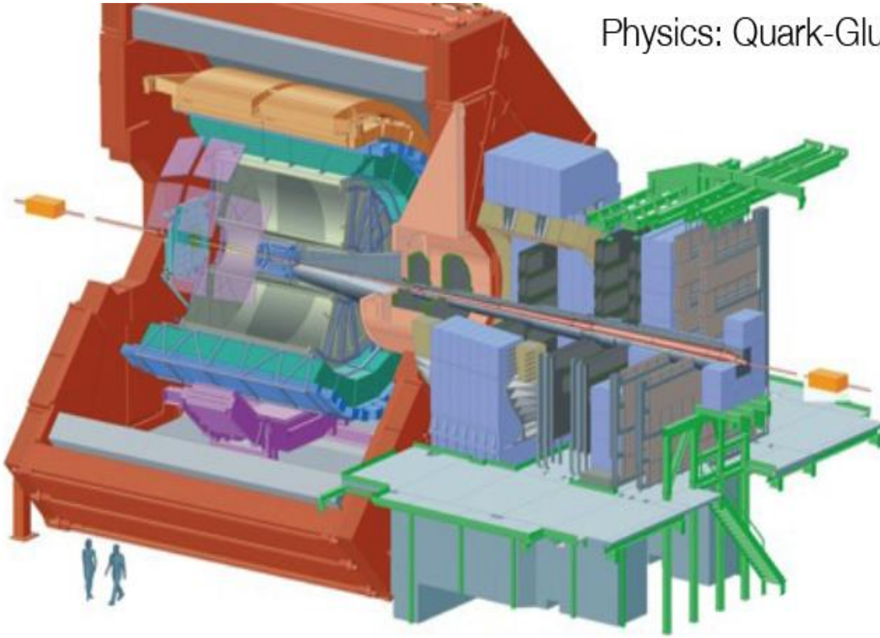
The Experiments



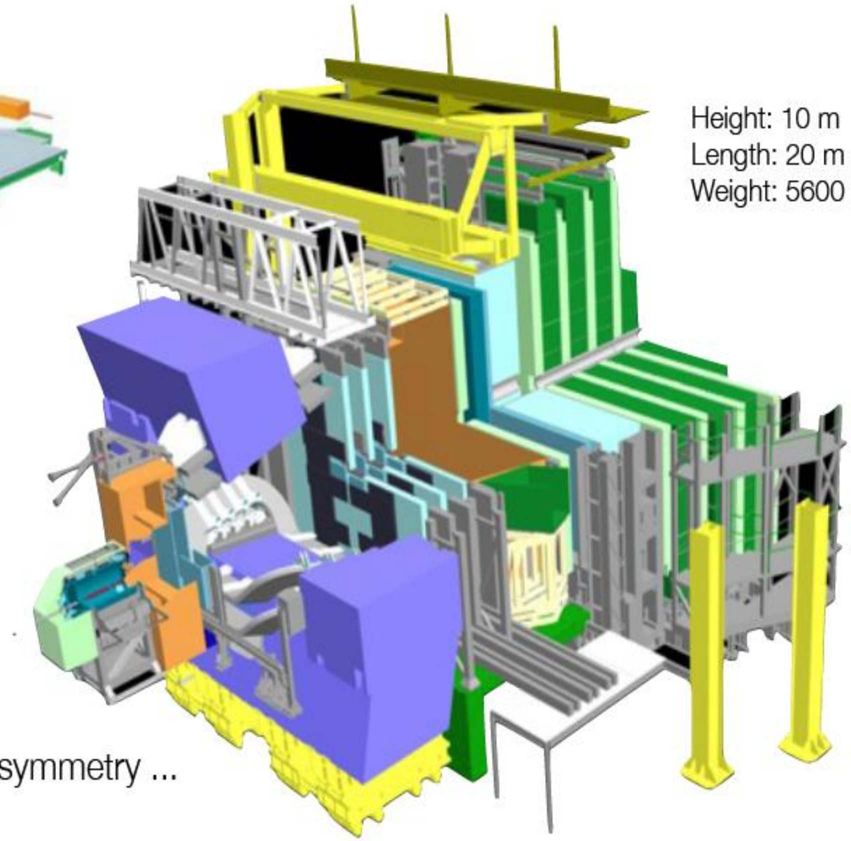

ATLAS
Electromagnetic Calorimeters
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
General Purpose:
pp, heavy ions
vacuum chamber
central detector
electromagnetic calorimeter
hadronic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

ALICE & LHCb

Physics: Quark-Gluon Plasma ...



Height: 16 m
Length: 25 m
Weight: 10000 t



Height: 10 m
Length: 20 m
Weight: 5600 t

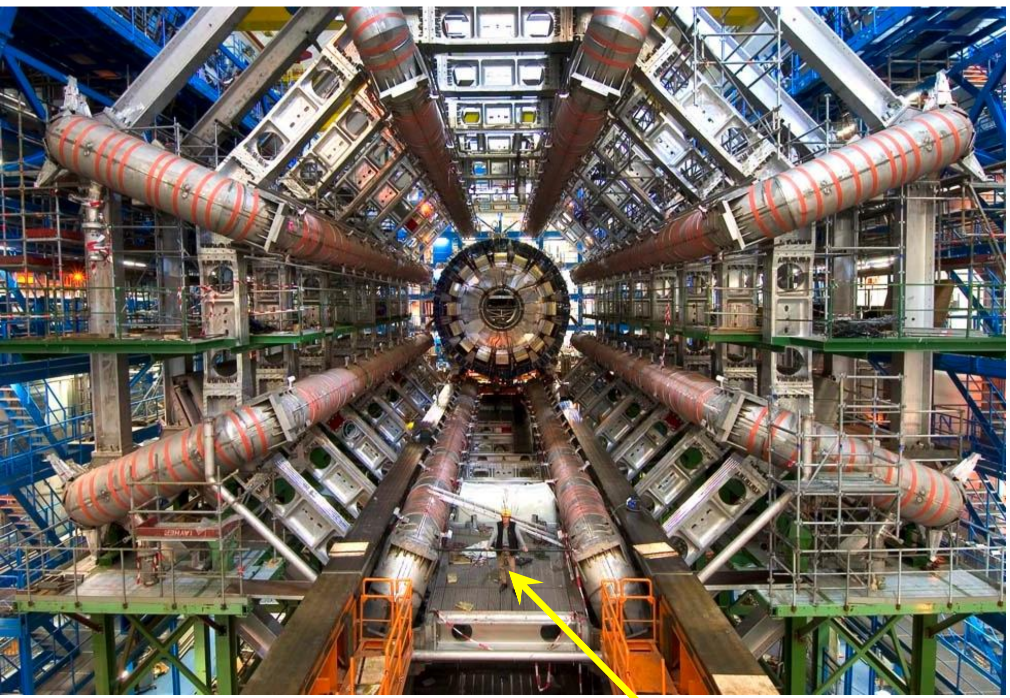
LHCb
[Forward Spectrometer]

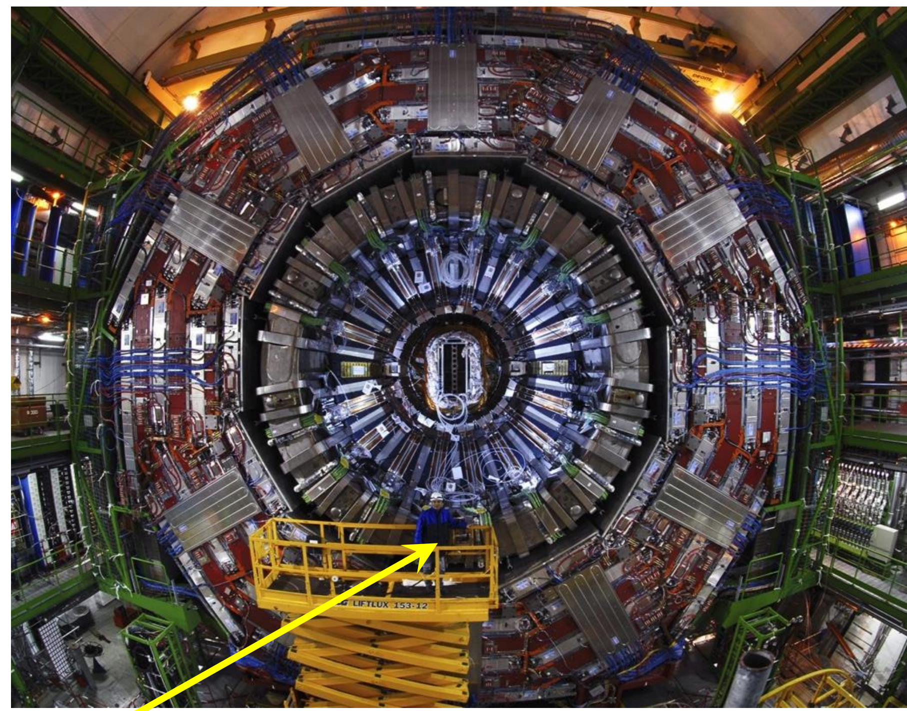
Physics: Matter/Antimatter-Asymmetry ...

It's huge!

Largest, most complex detectors ever built

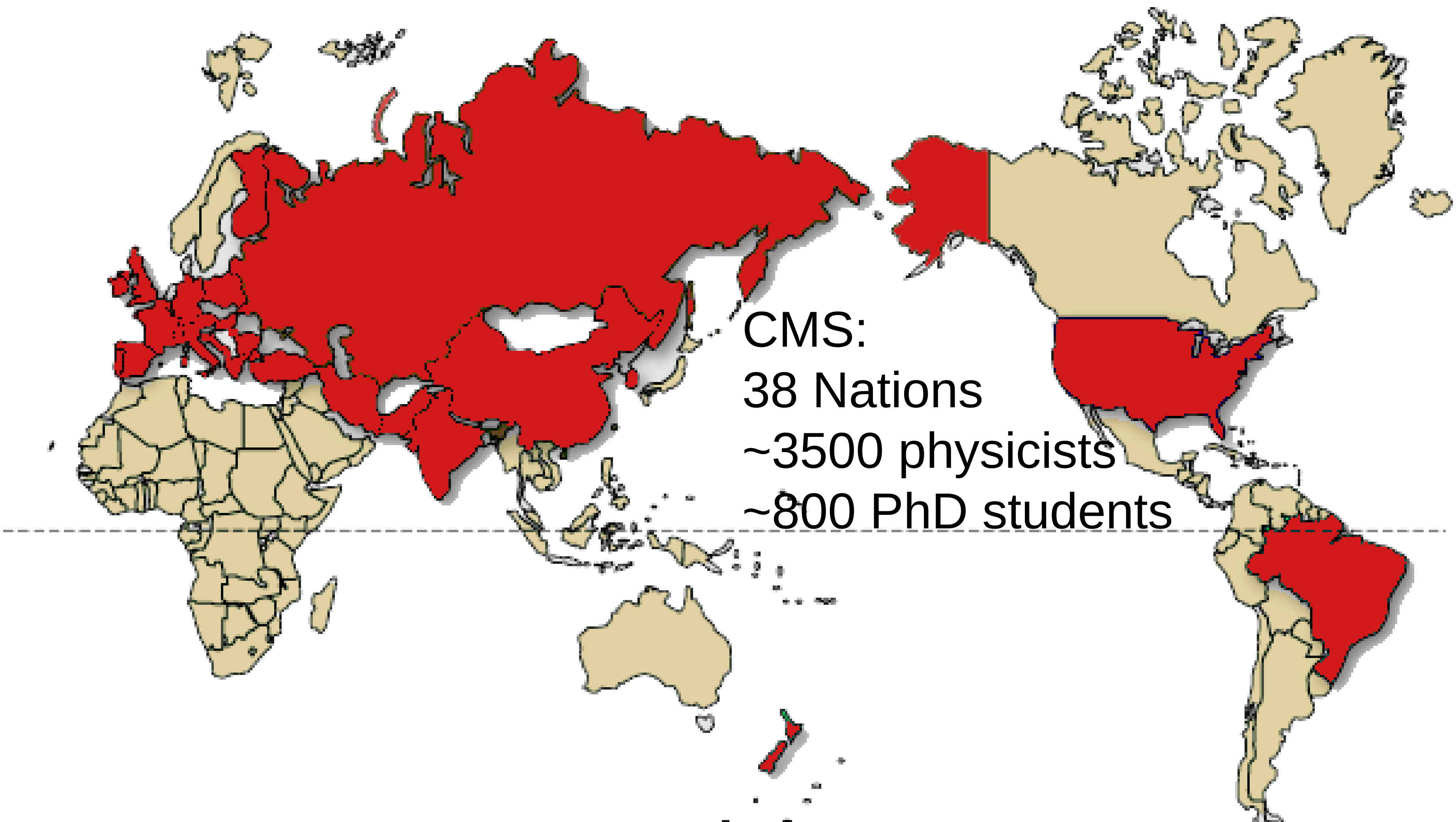
Study tiniest particles with incredible precision





(people)

World-wide collaborations



CMS:
38 Nations
~3500 physicists
~800 PhD students

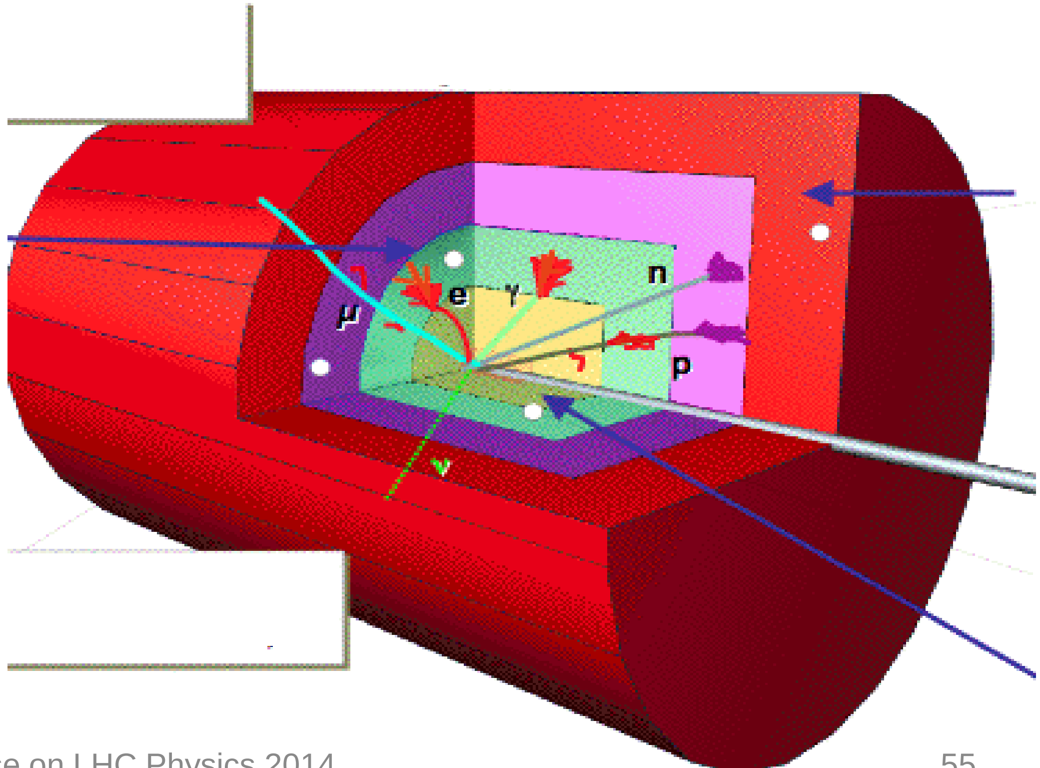
15% of the CMS people

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

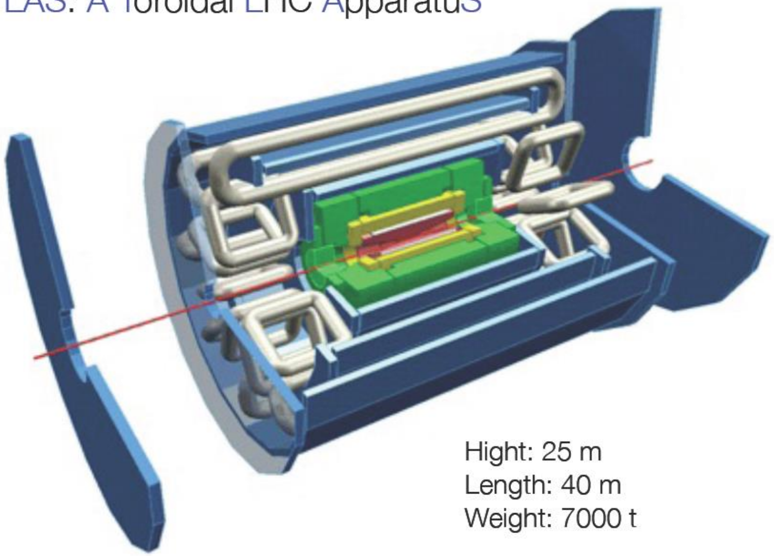
Search and measure the Higgs boson

Search and measure Supersymmetry

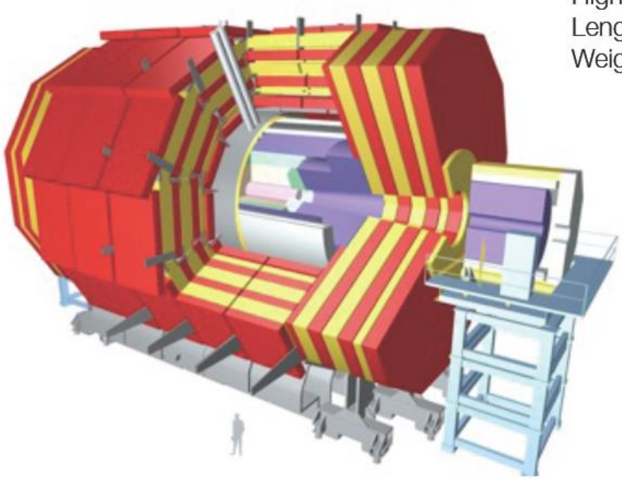
Search for any other new physics at high p_T

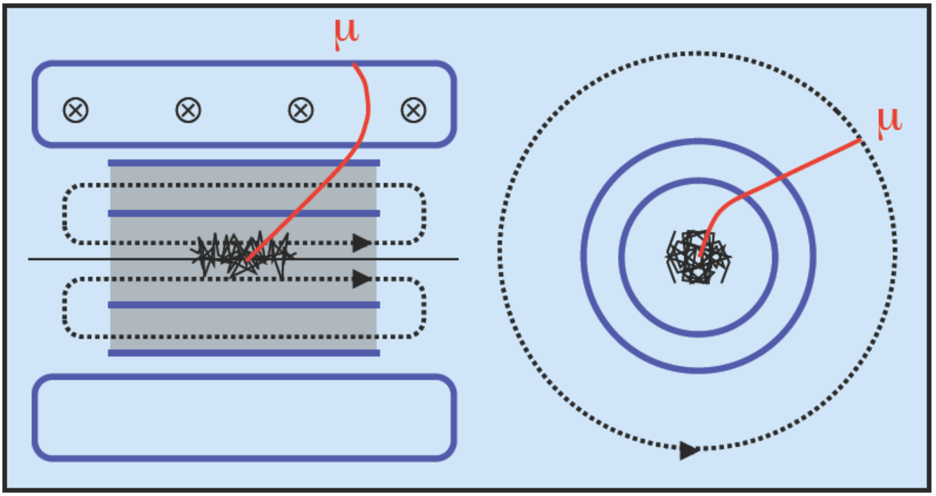
Two concepts

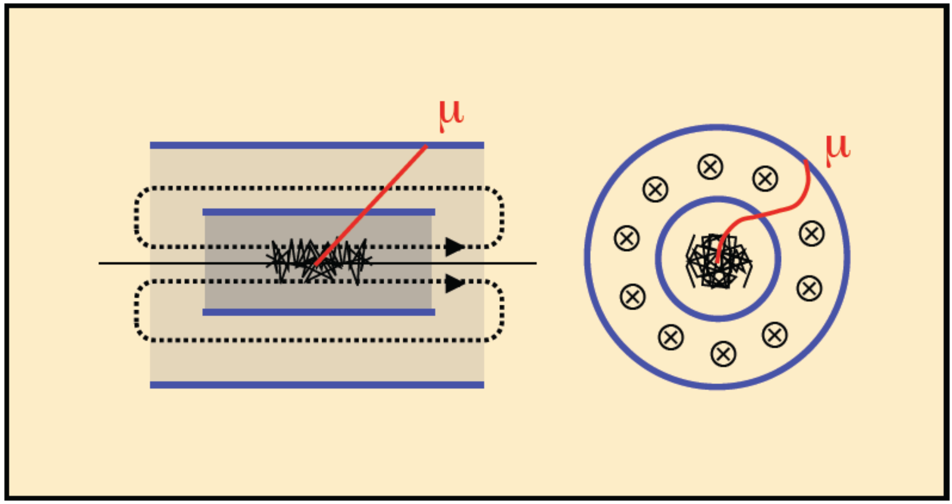
ATLAS: A Toroidal LHC ApparatuS



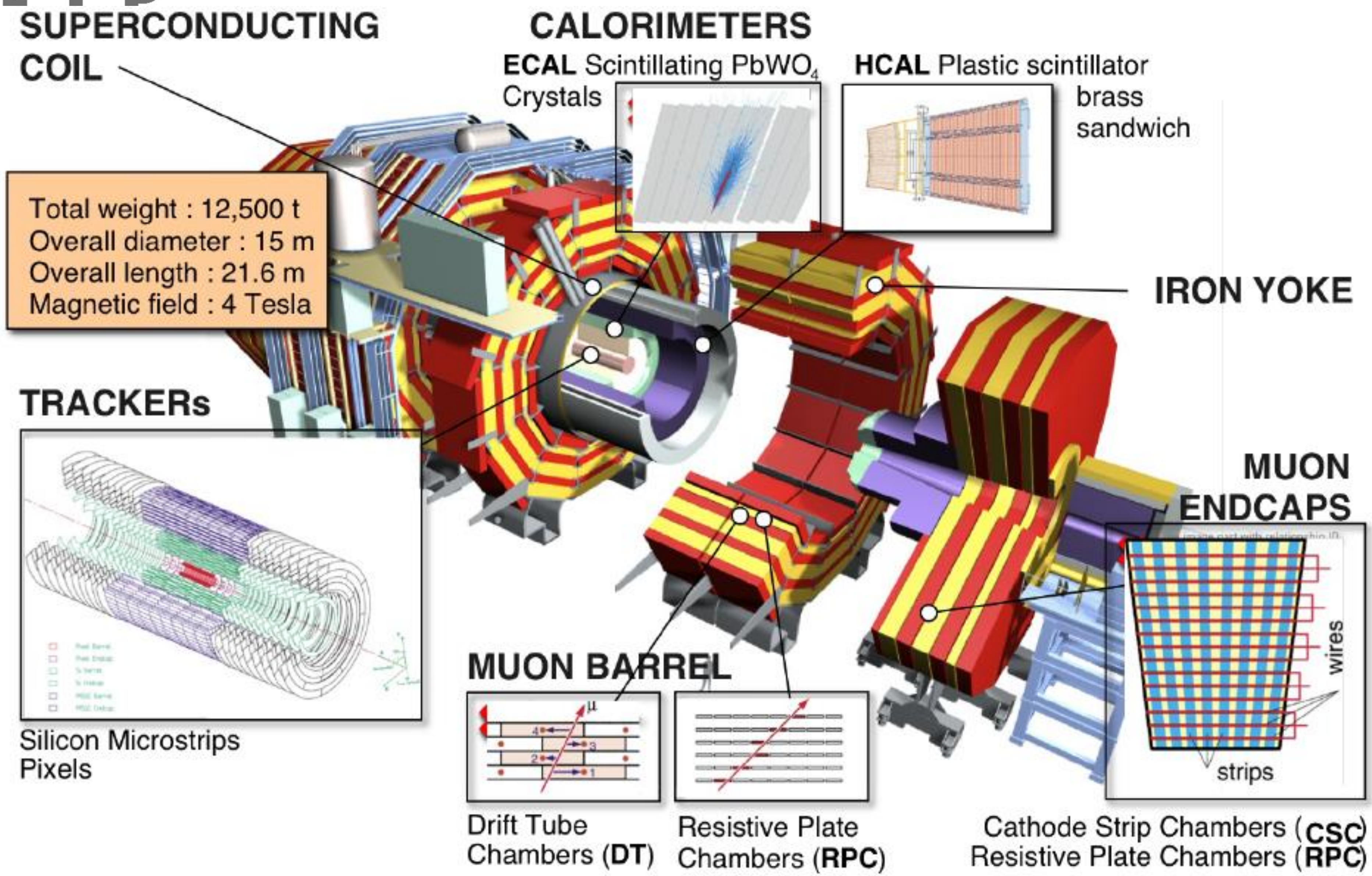
CMS: Compact Muon Solenoid



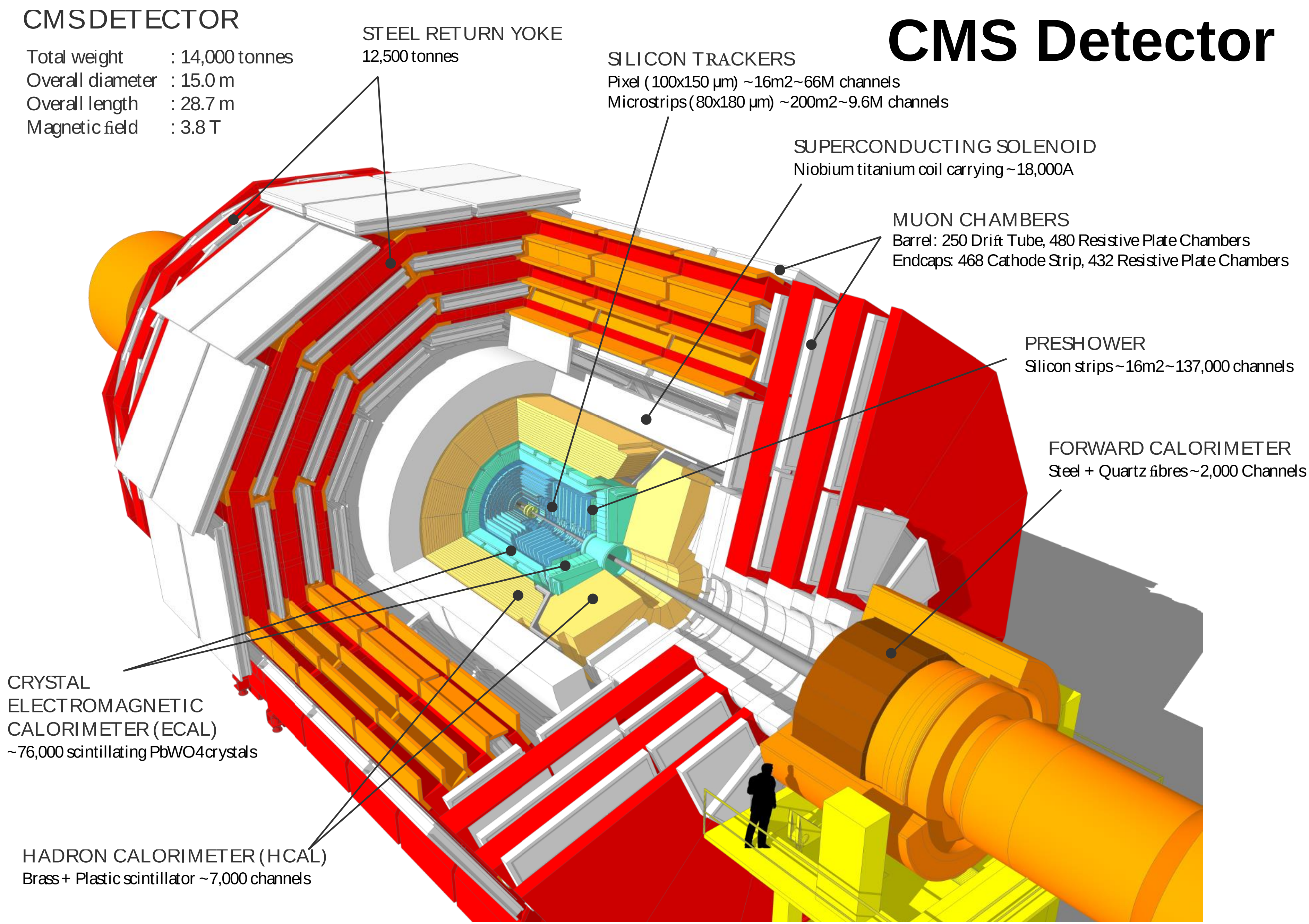




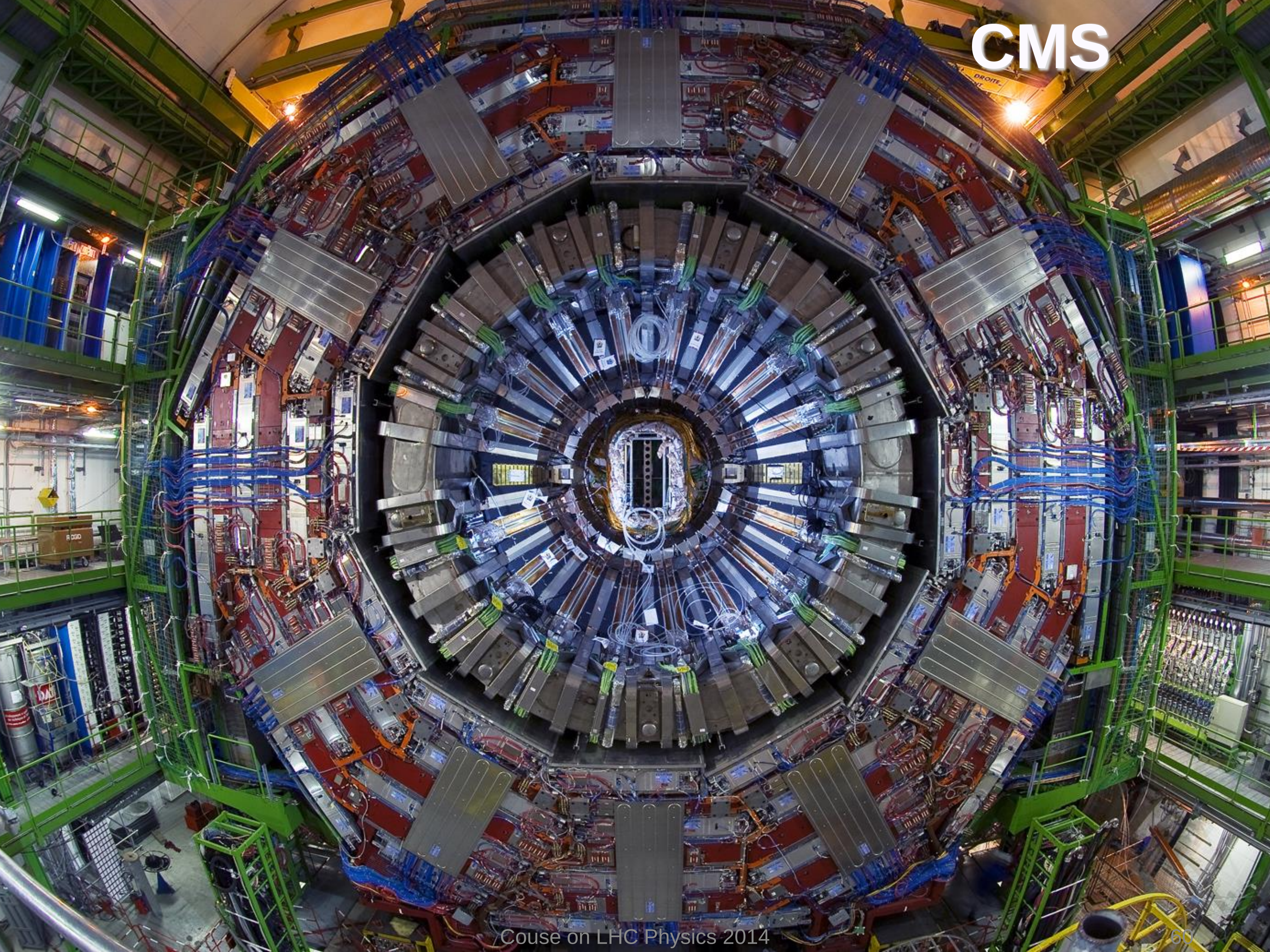
Exploded view of the CMS detectors



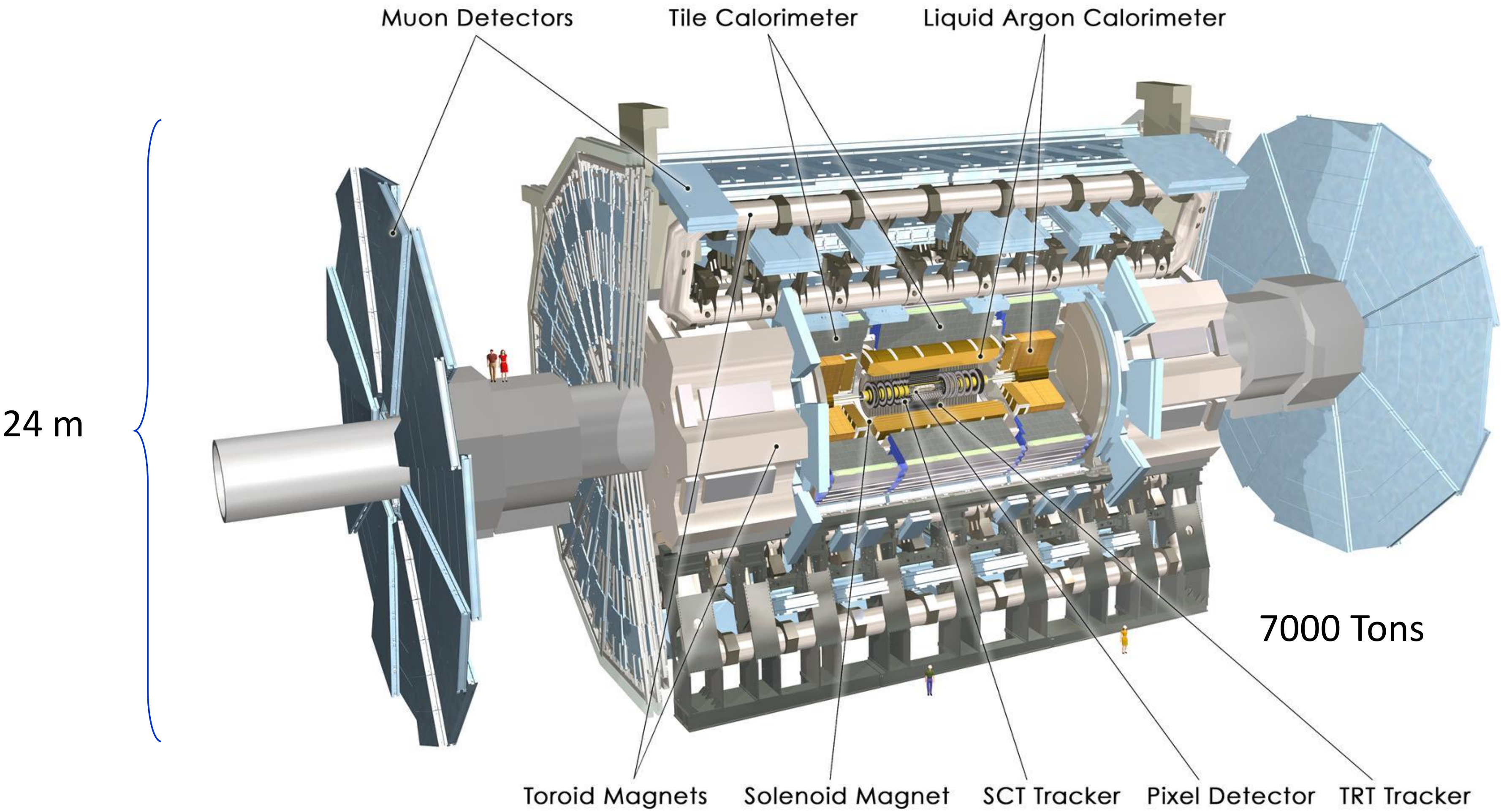
CMS Detector



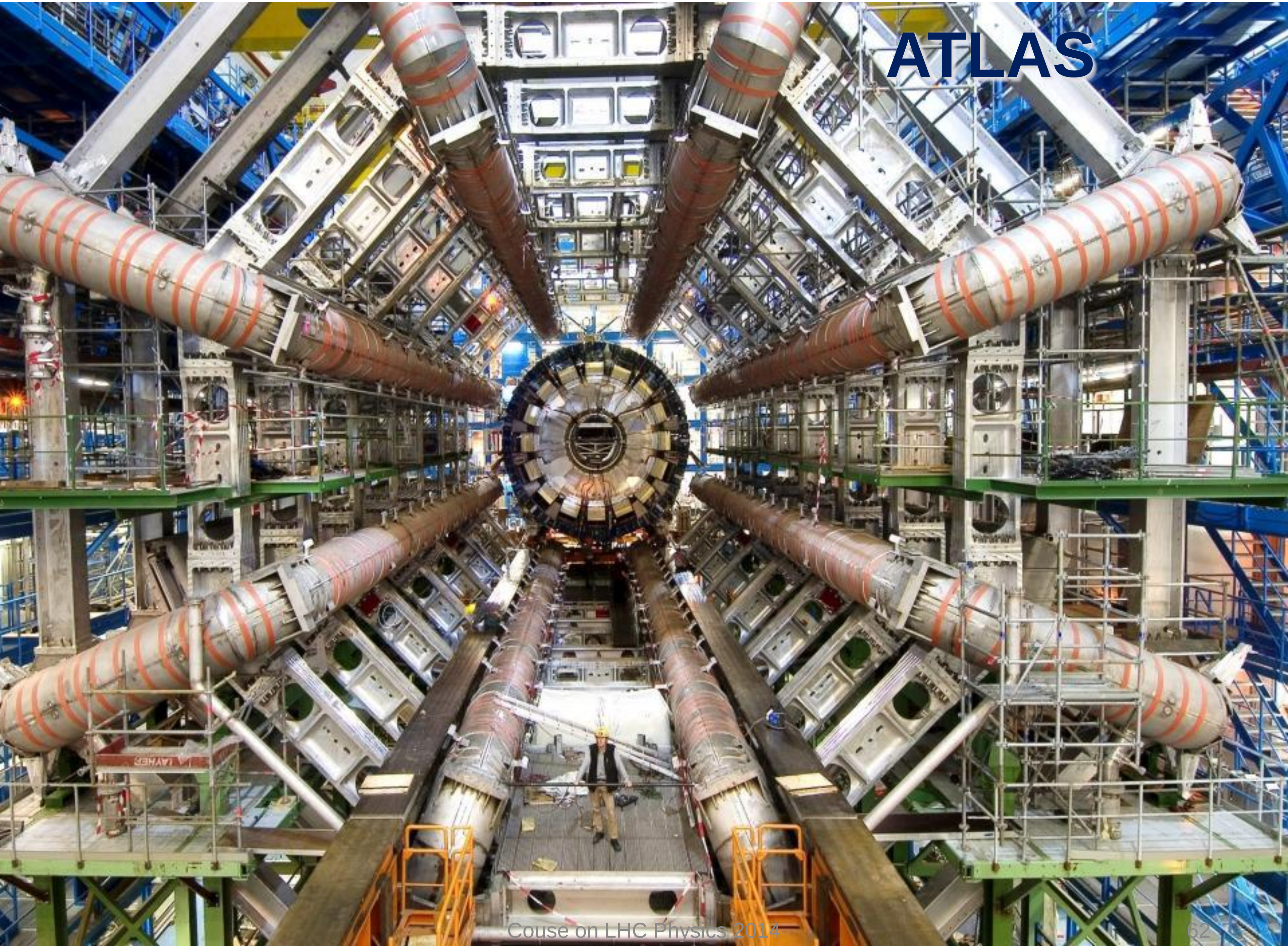
CMS



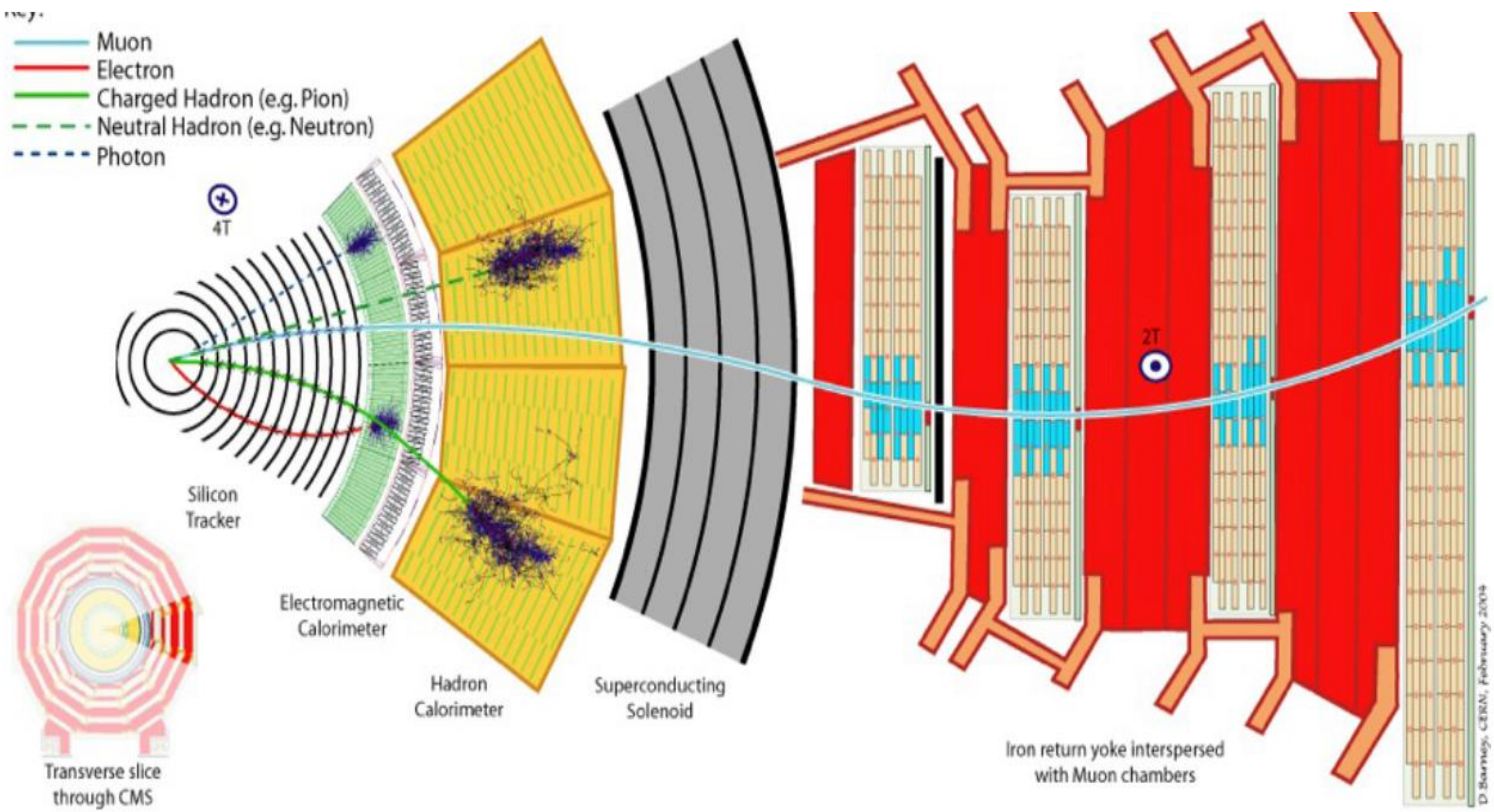
ATLAS detectors



ATLAS



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

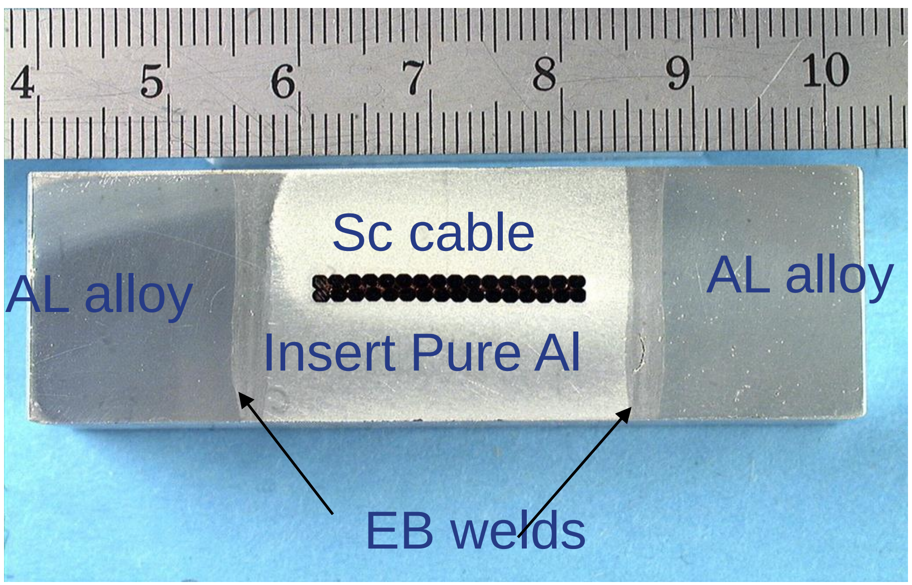


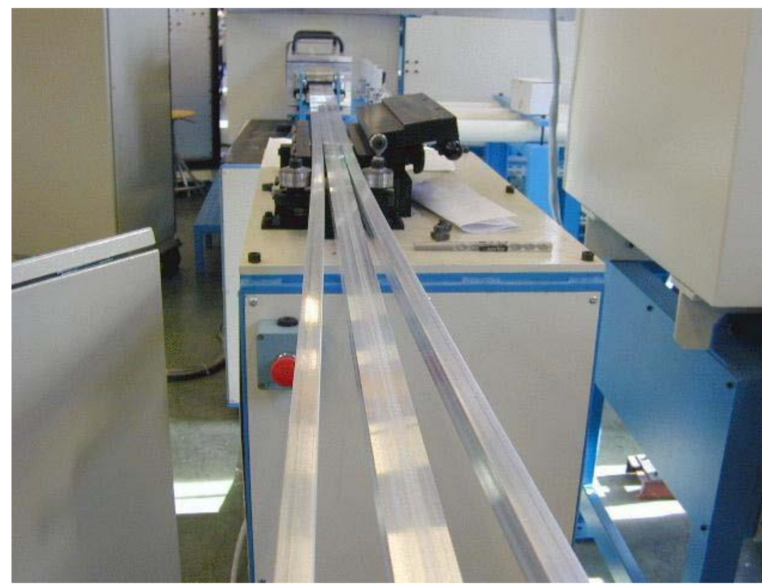
1993-2008: detector R&D and construction

Superconducting cable

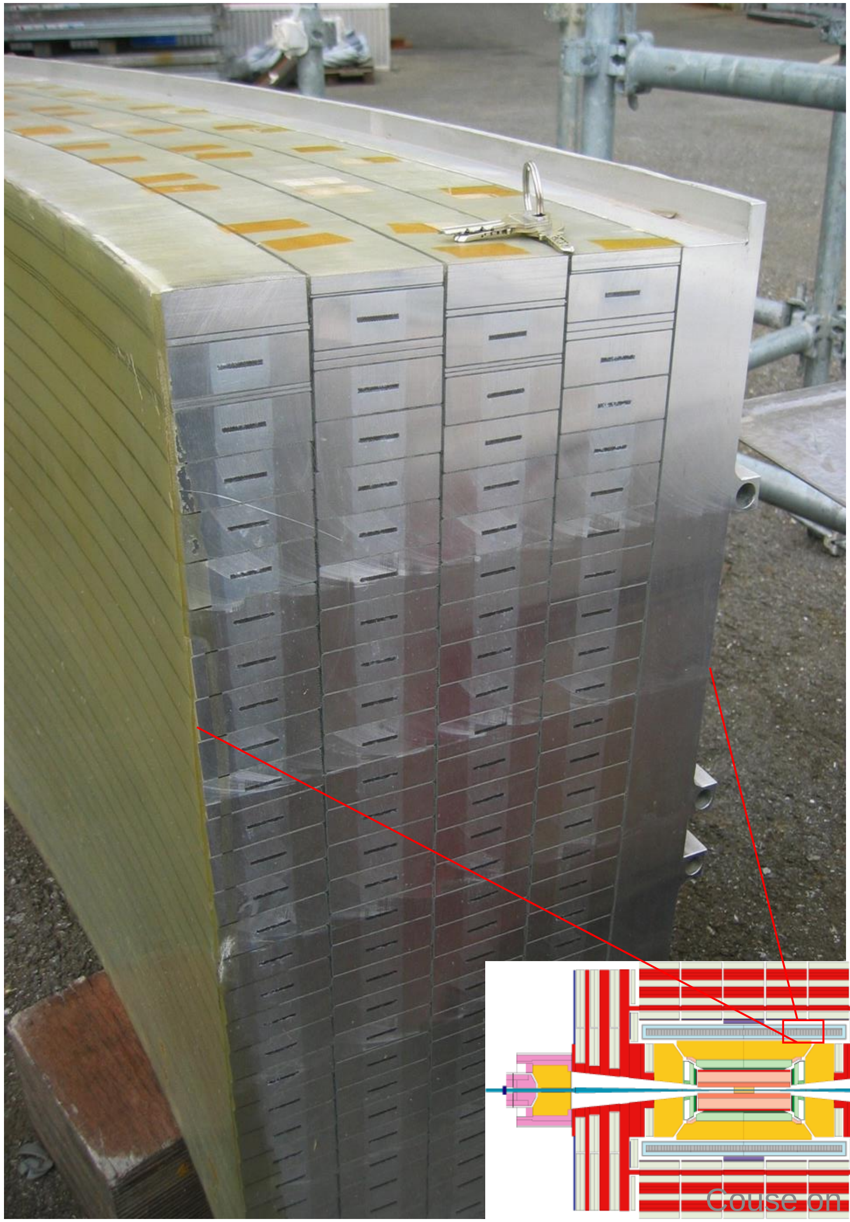
Al stabilized NbTi conductor.

Mechanically reinforced conductor to contain magnetic forces.

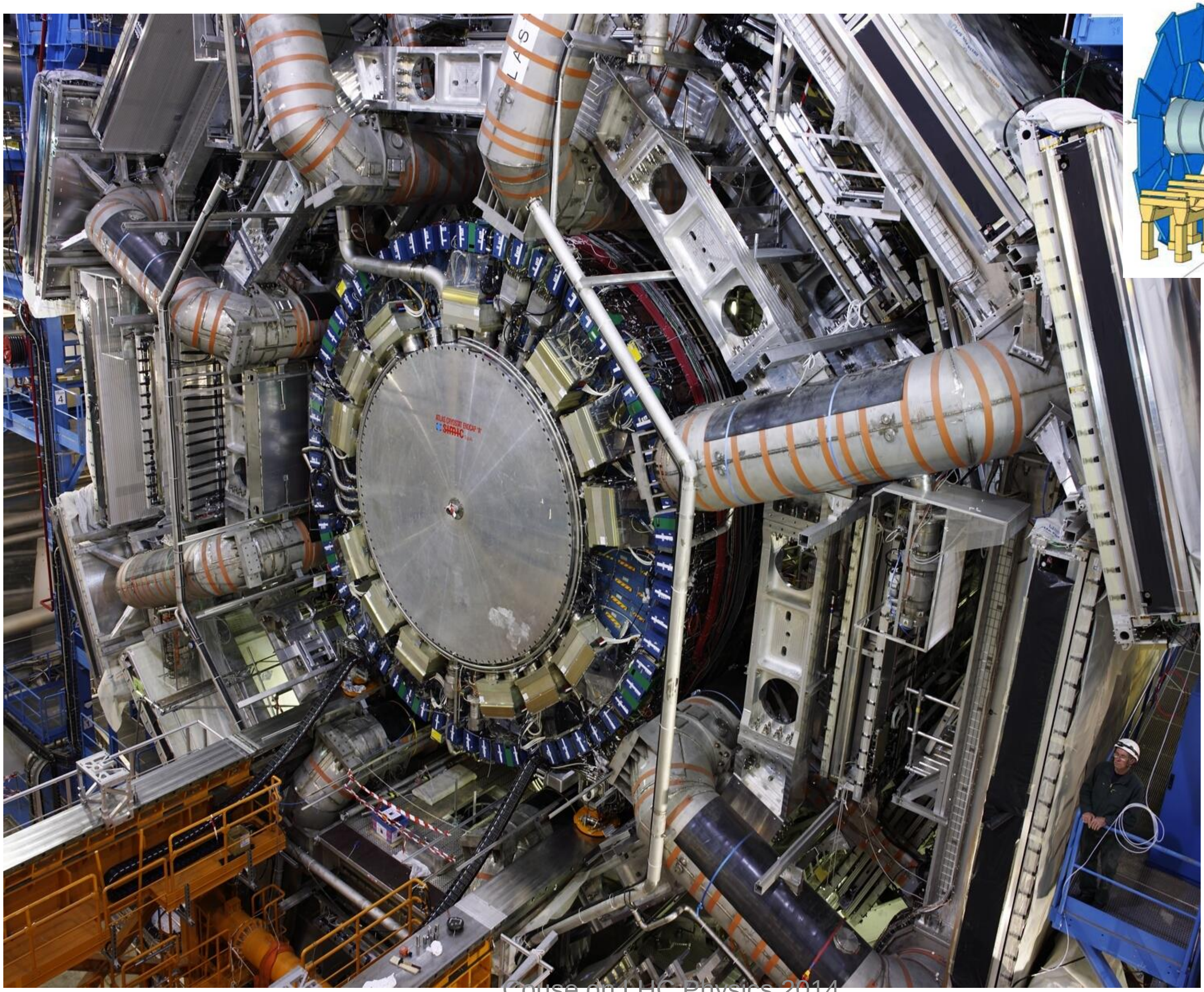


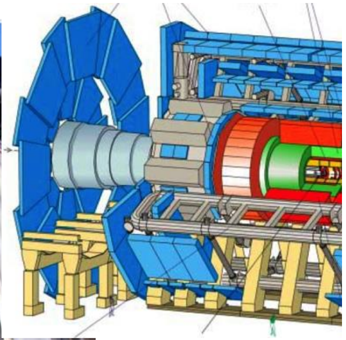


Superconductor solenoid at 3.8 Tesla

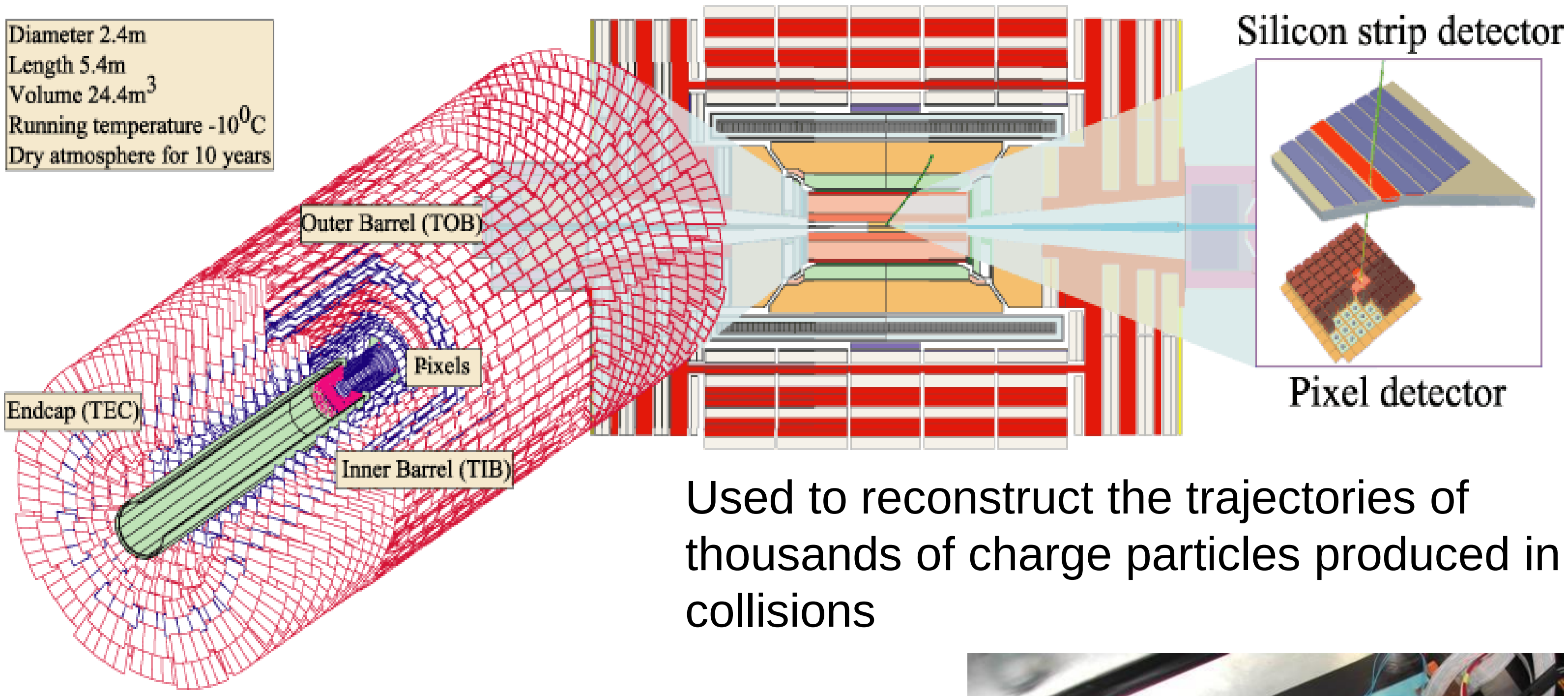


ATLAS Toroidal System



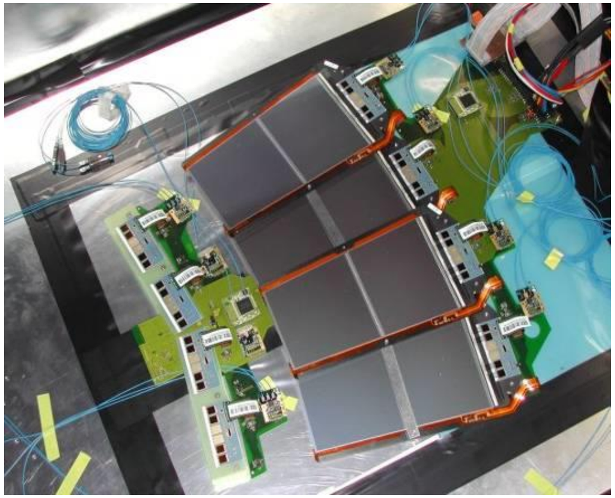


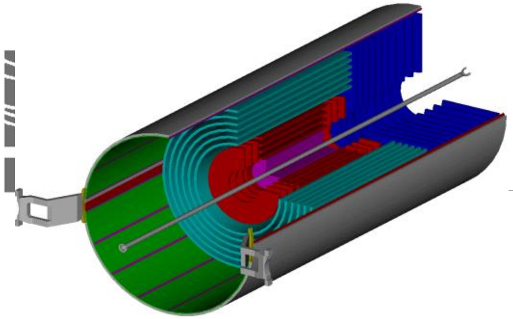
Silicon Tracker



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

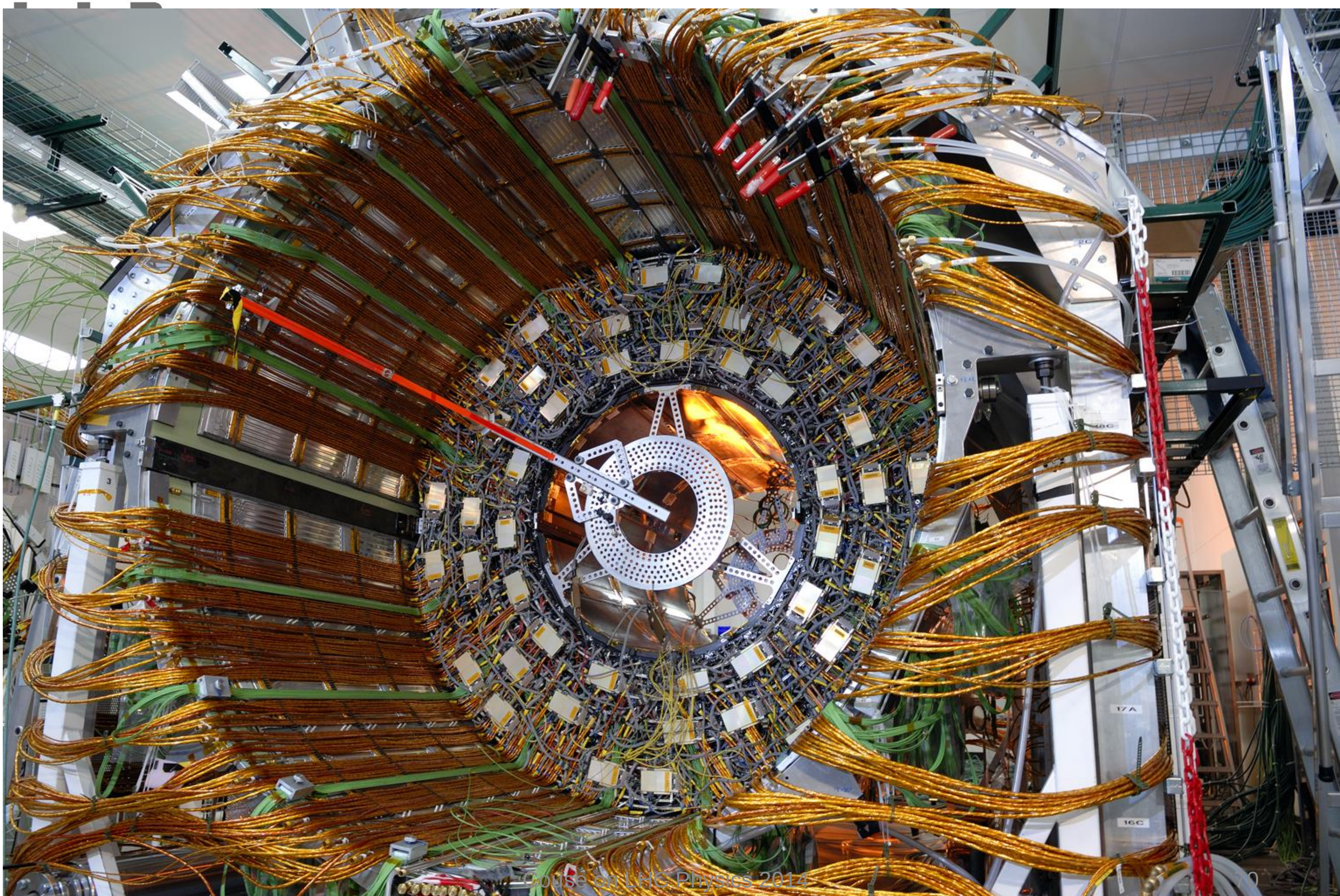




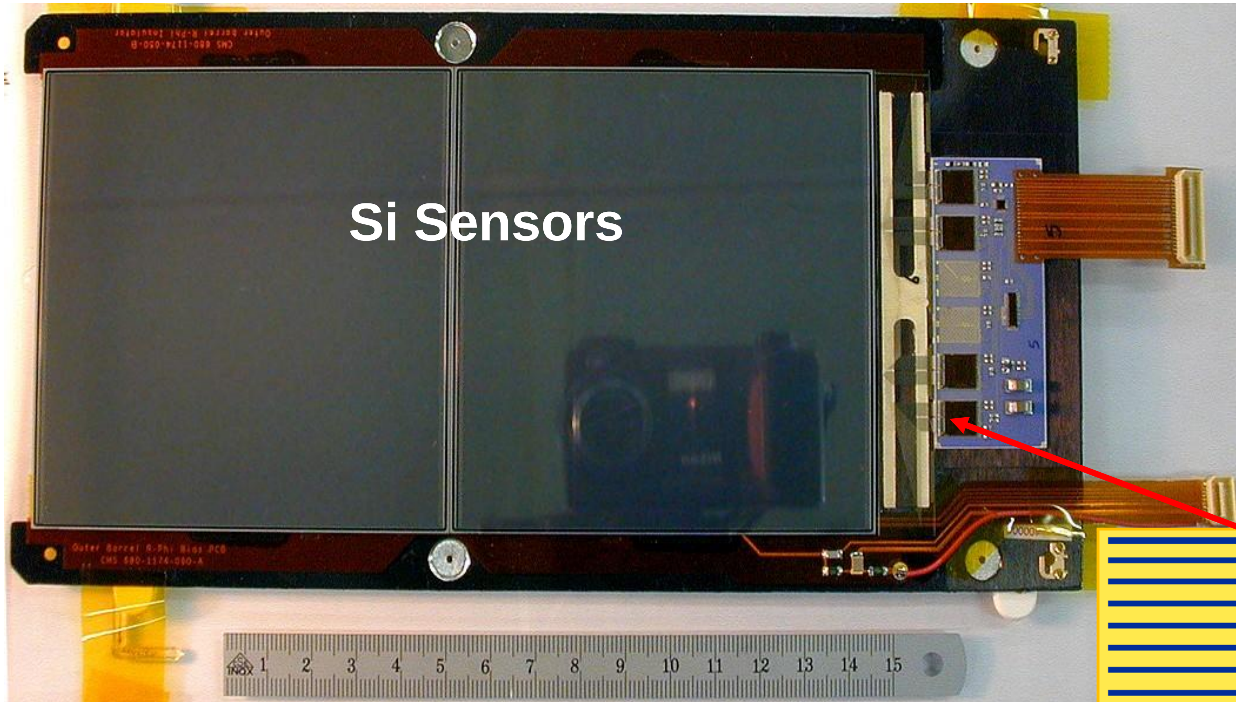
Silicon Tracker

200 square meter of silicon wafers: from cartoon to reality

Silicon Tracker

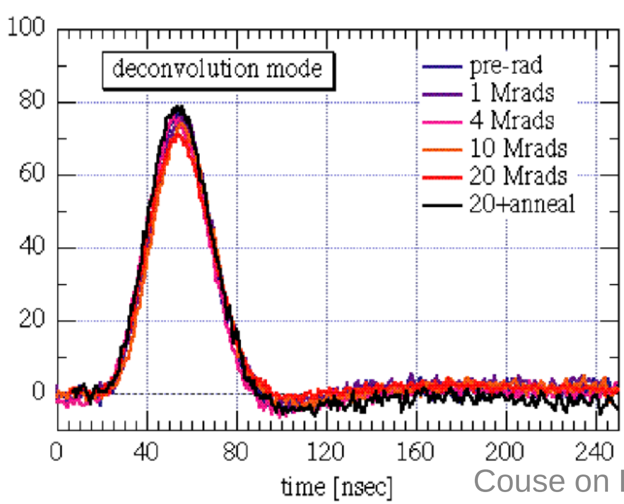


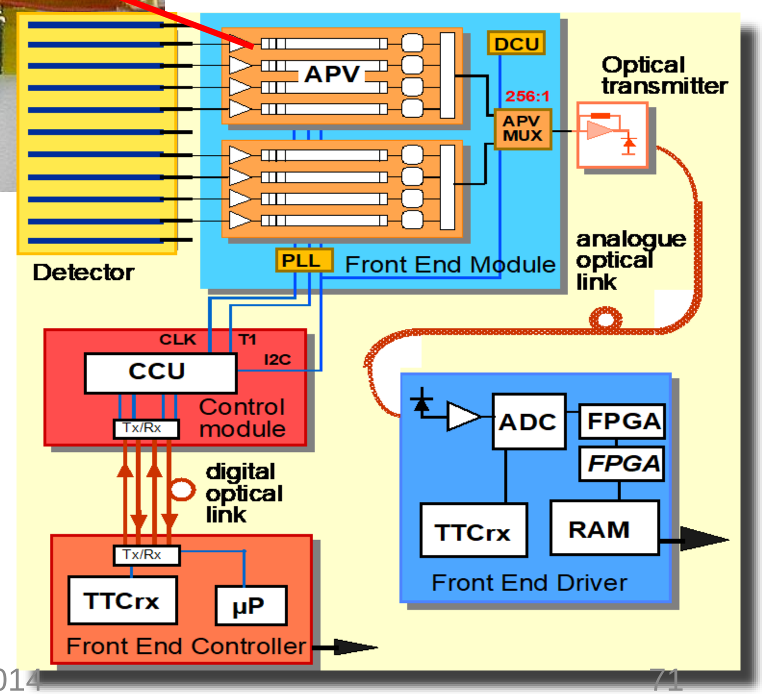
Si sensors and electronics chain



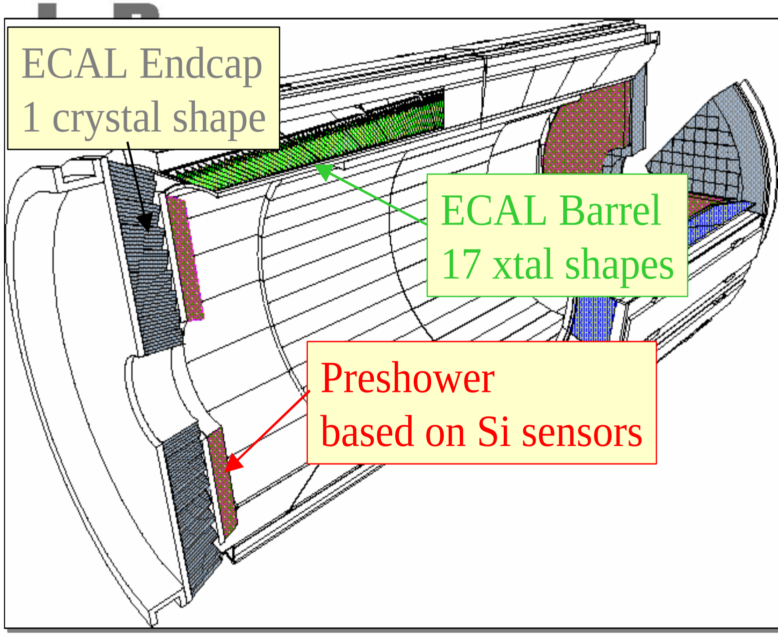
Ride on technology wave

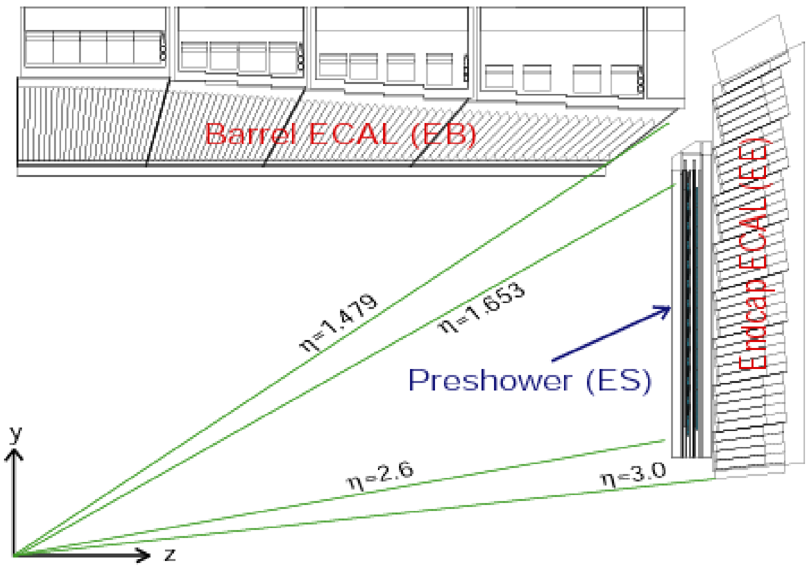
75k chips using 0.25μm technology

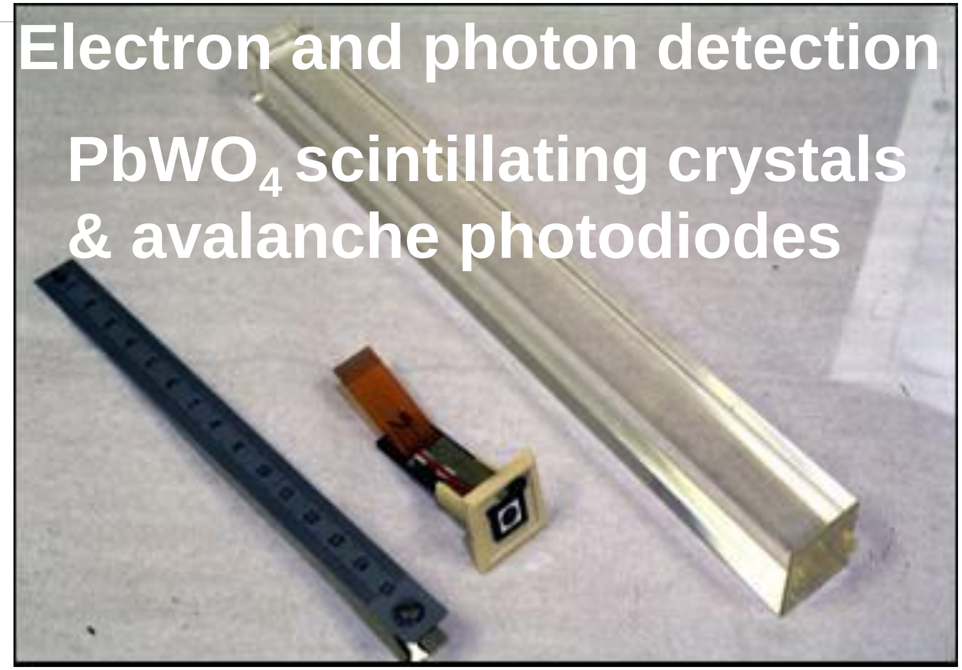




ECAL Electromagnetic Calorimeter



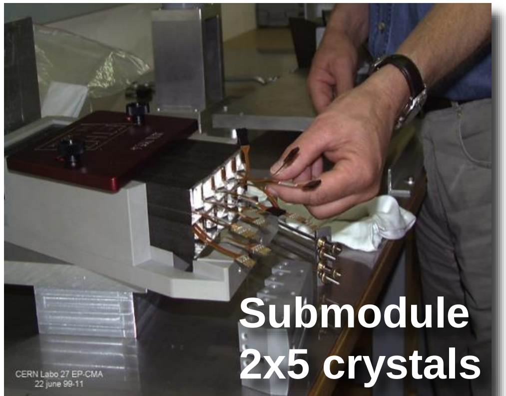


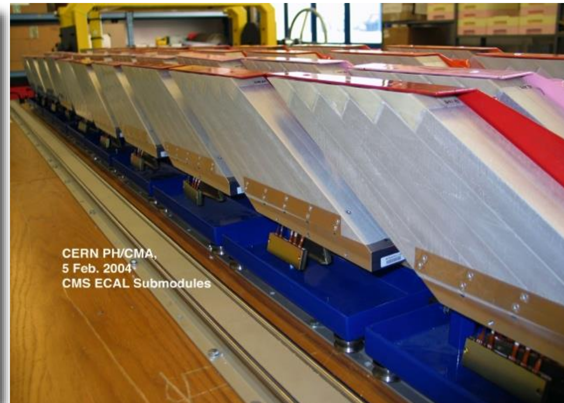


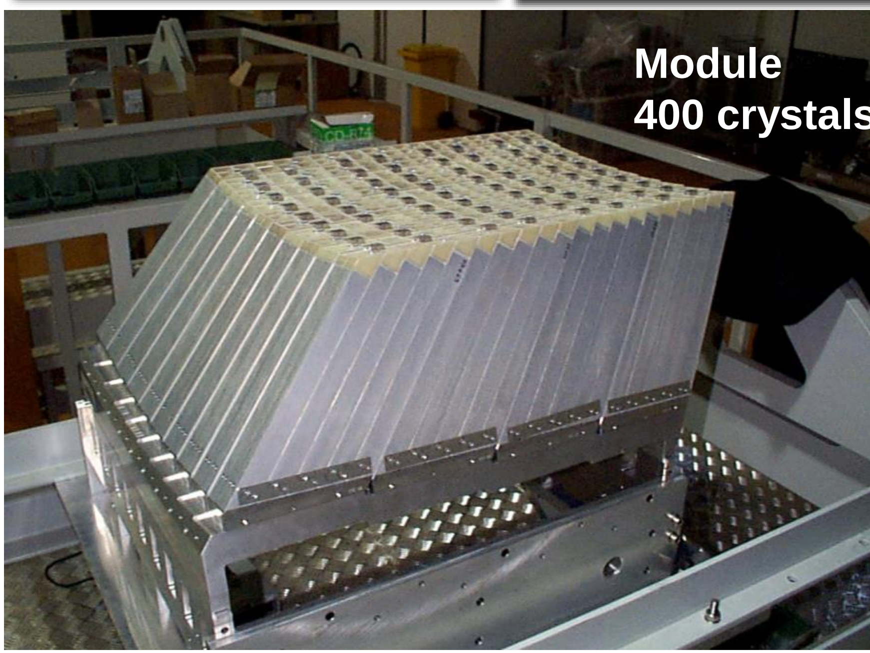
Design Goal: Measure the energies of photons from a decay of the Higgs boson **to precision of ≤ 0.5%**

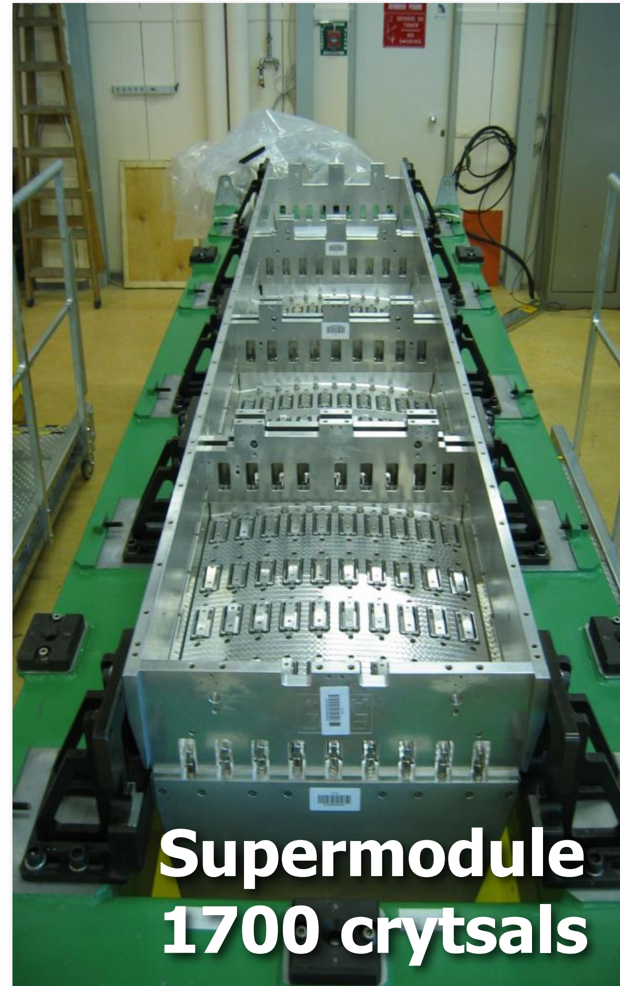
Parameter	Barrel	Endcaps
# of crystals	**61200**	**14648**
Volume	**8.14m^3**	**2.7m^3**
Xtal mass (t)	**67.4**	**22.0**

Assembling the Calorimeter



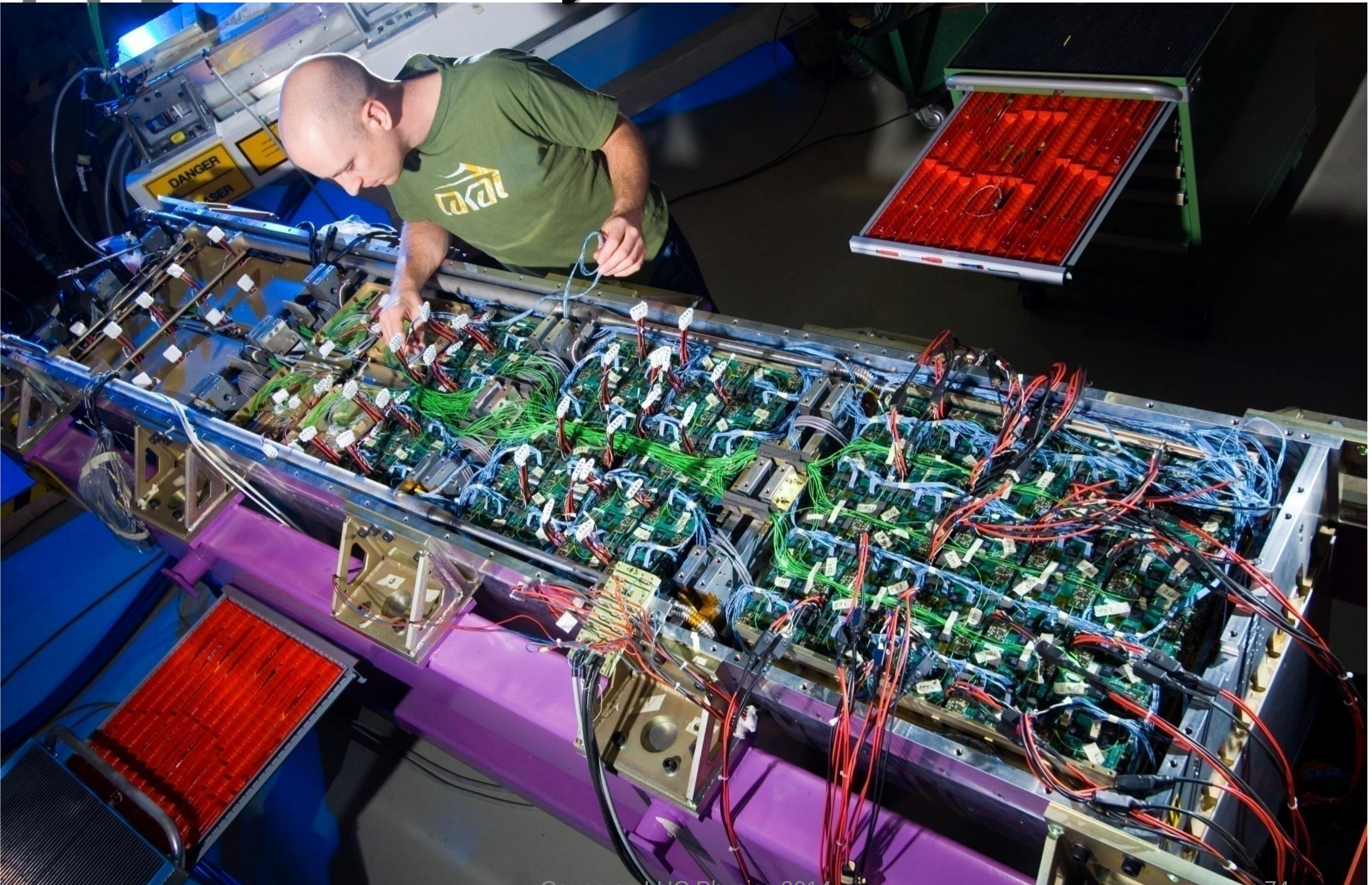






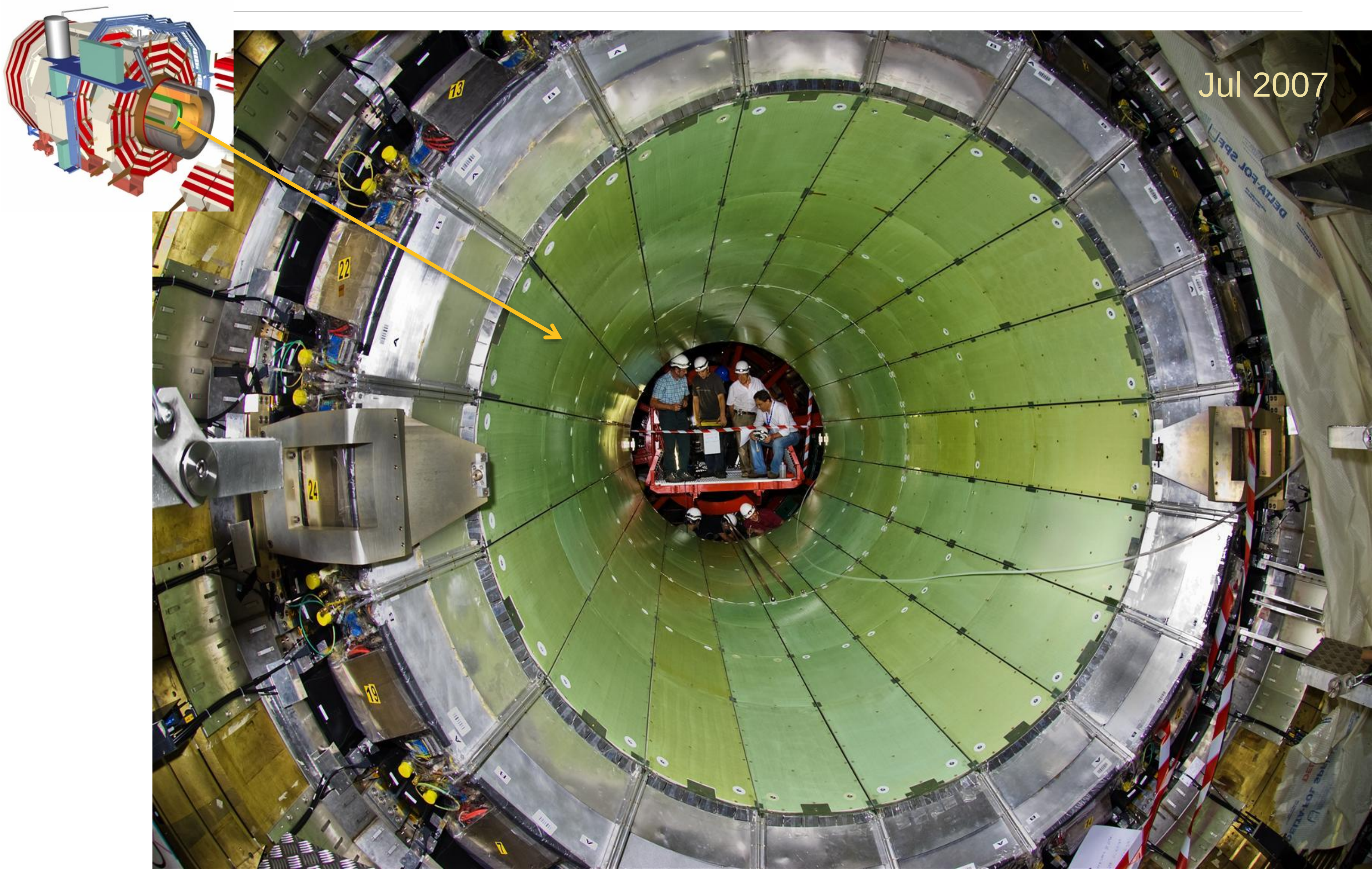
Total 36 Supermodules

Assembly of front-end electronics

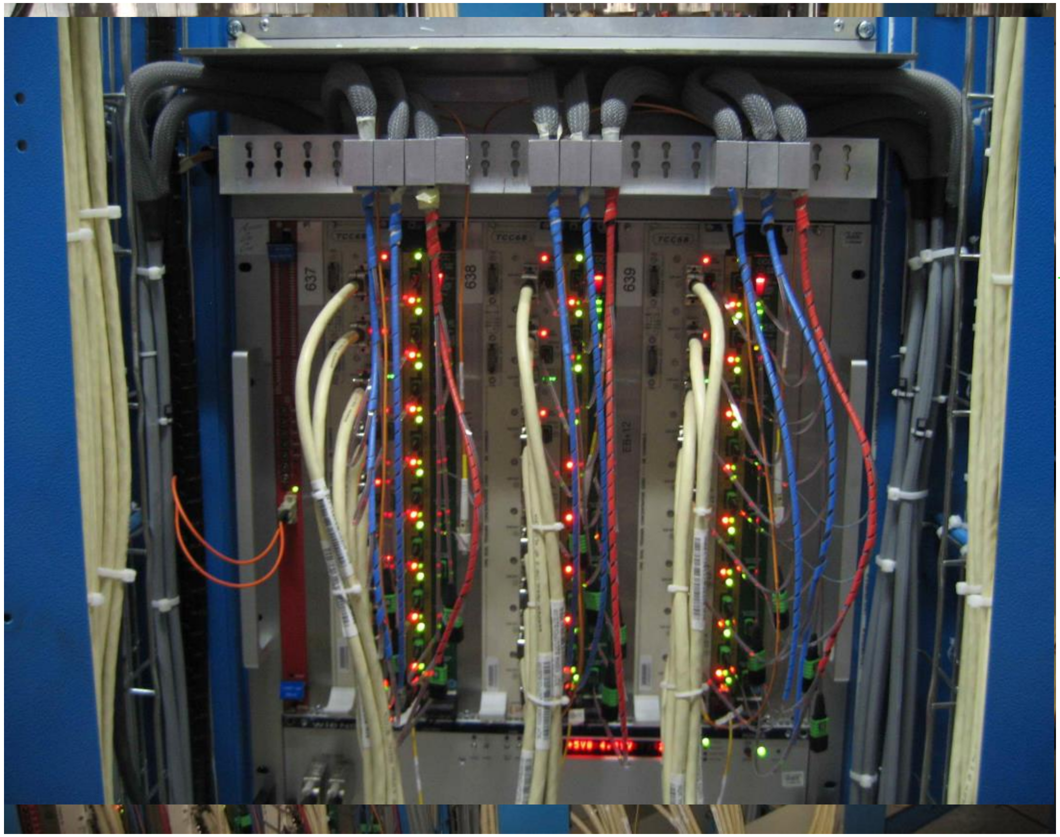


Insertion in the detector

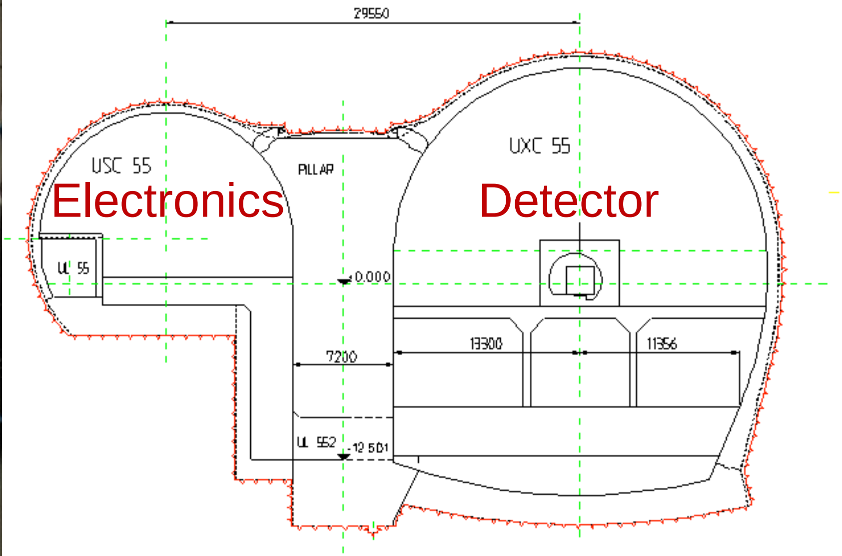
The Calorimeter installed in the Experiment

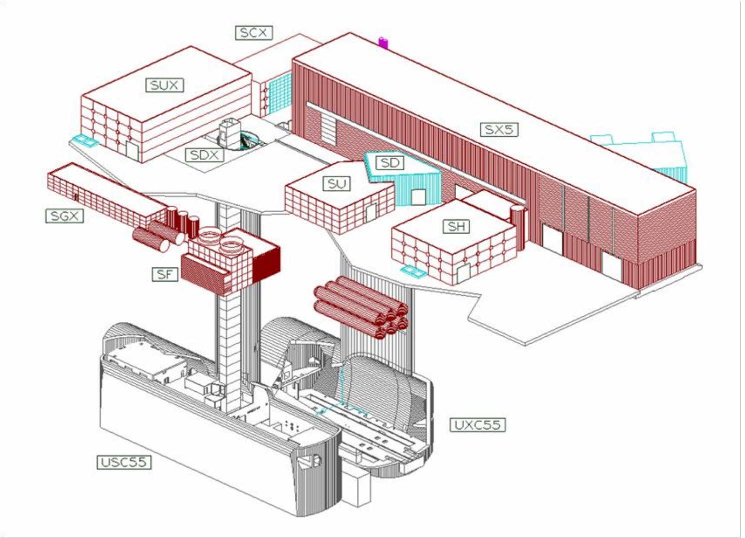


ECAL trigger and readout electronics



Underground caverns

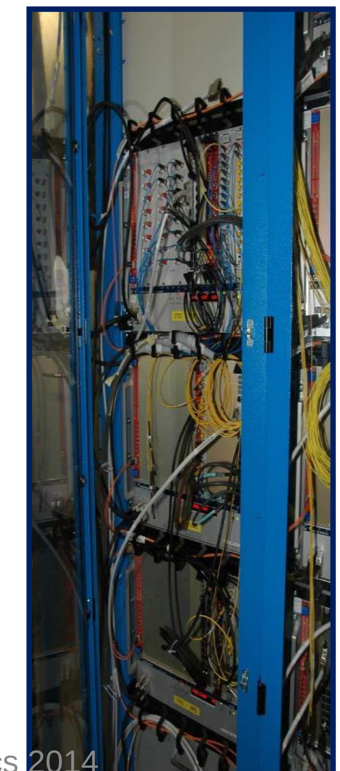


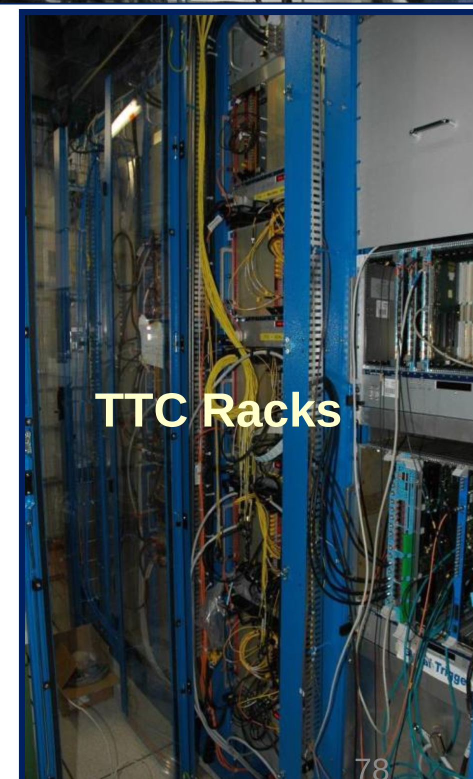


18	Crates
216	Electronic boards
3000	0.8 Gb/s optical links
2500	1.2 Gb/s electrical links

Electronics systems

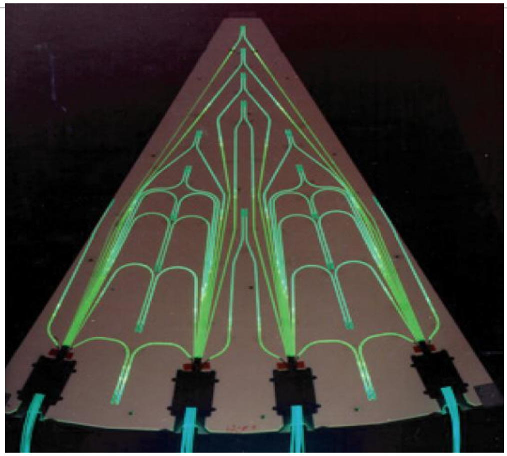
Electronics systems in the Service Cavern.
About 150 racks occupy two floors.
Most electronics was designed and built specifically for the experiment





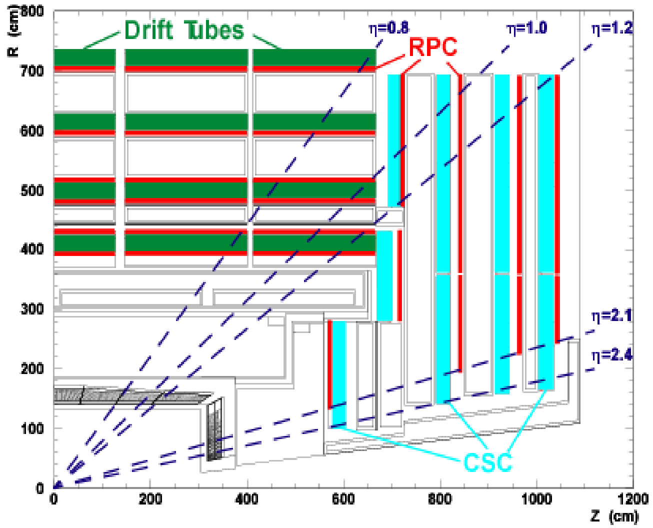
HCAL Hadronic Calorimeter

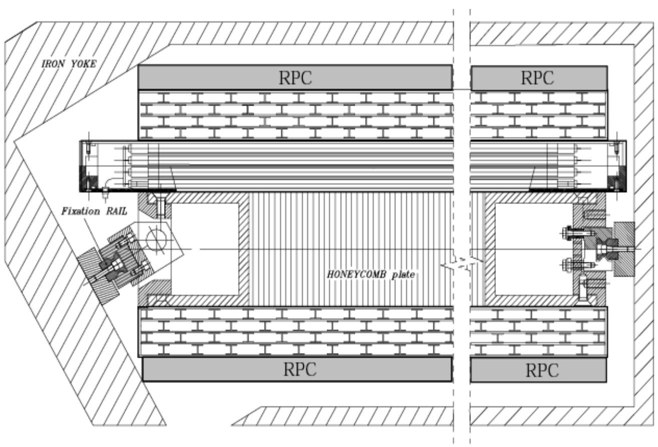
Detection of hadrons:
- protons, neutrons, peons, etc.



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

Muon detectors

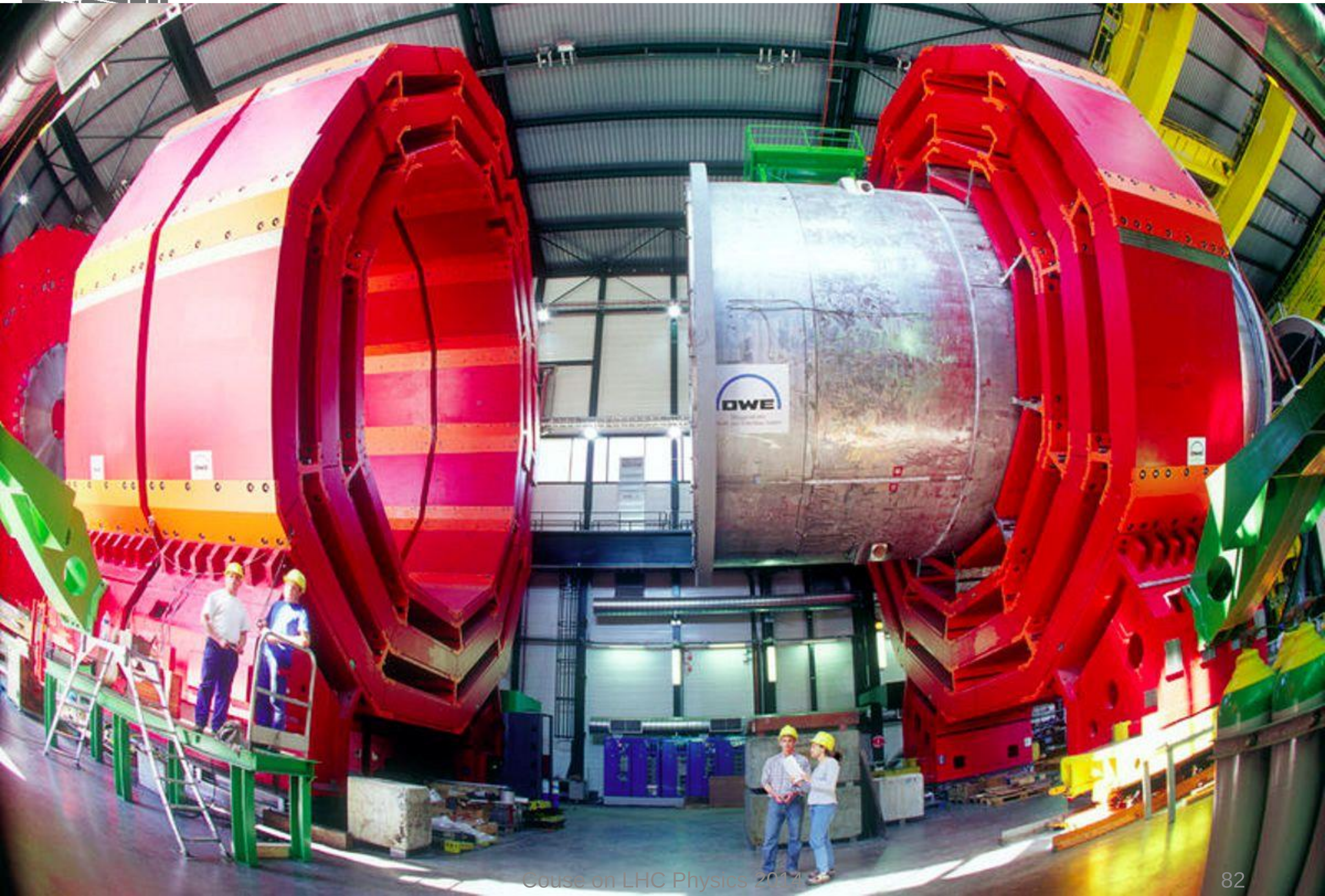




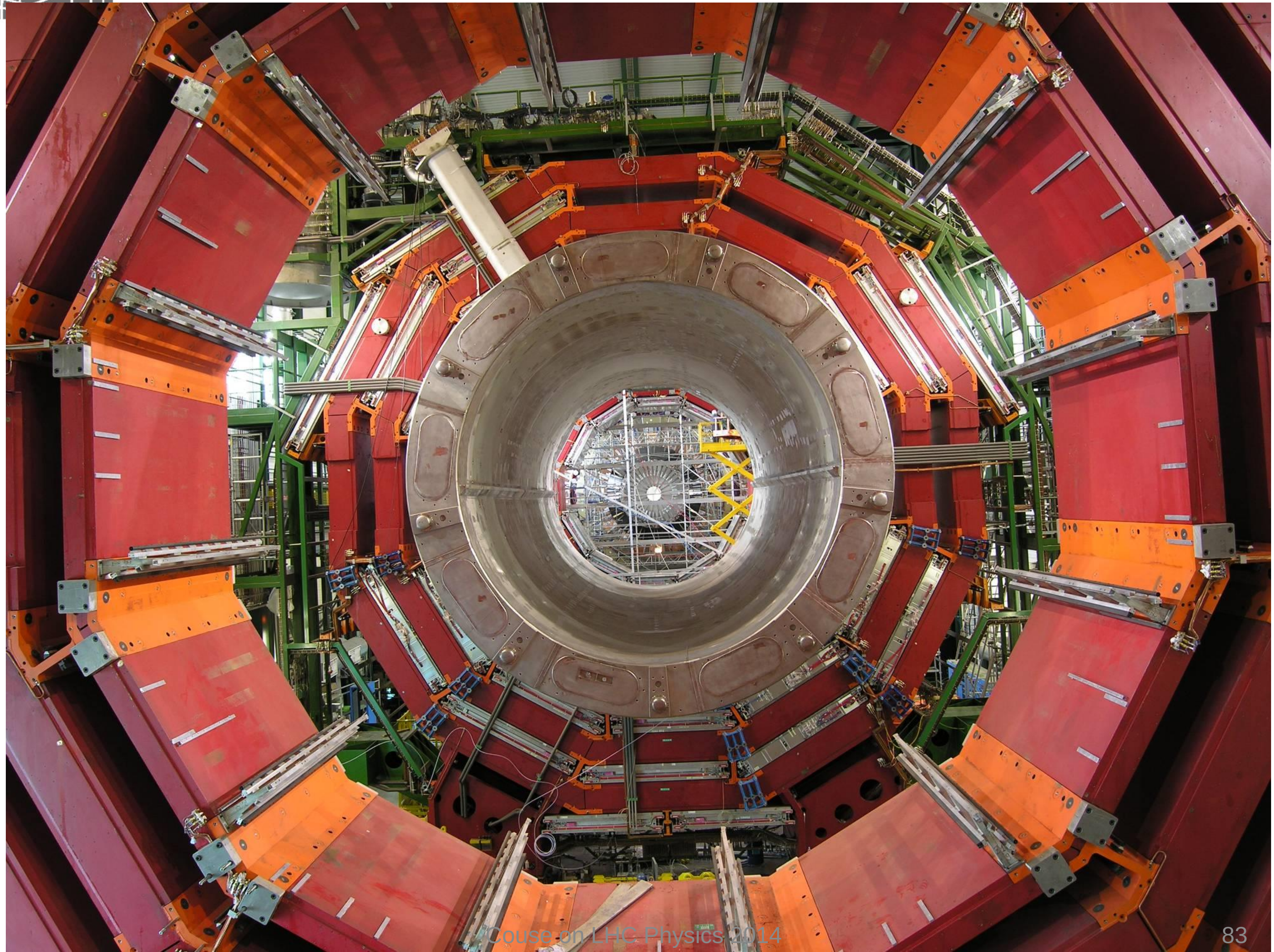
Drift Tubes (DT)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Surface Site in 2000

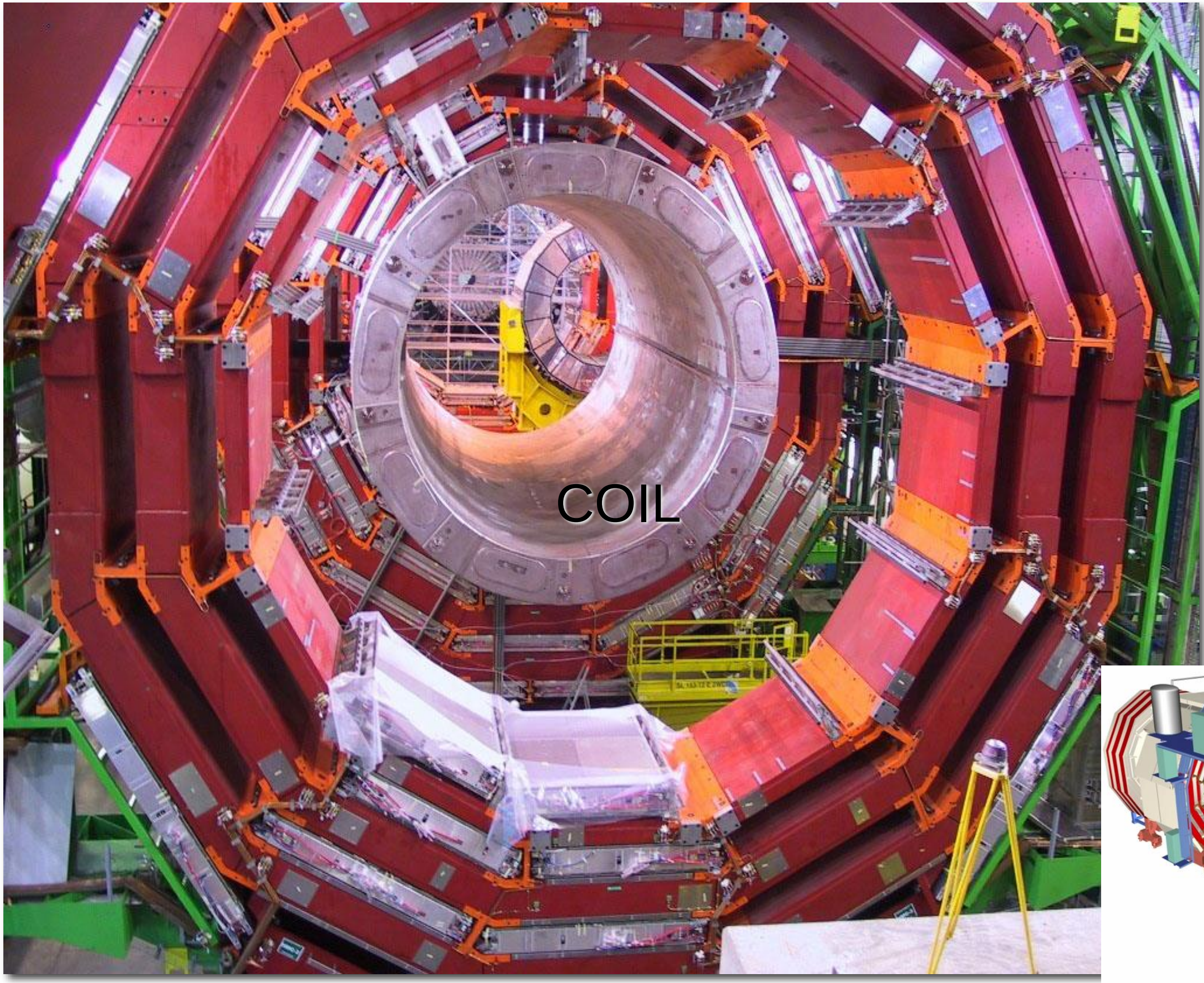
2002: CMS iron yoke assembly in surface hall

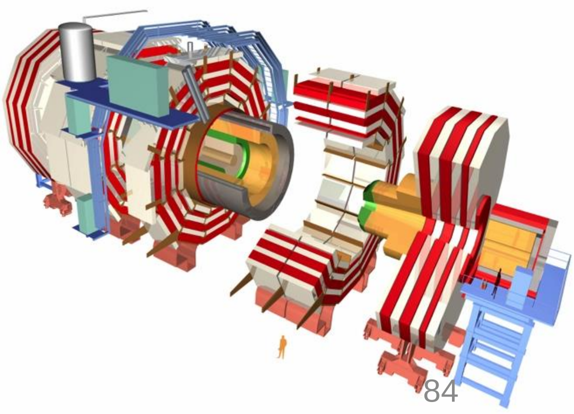


2005: Superconducting solenoid installed

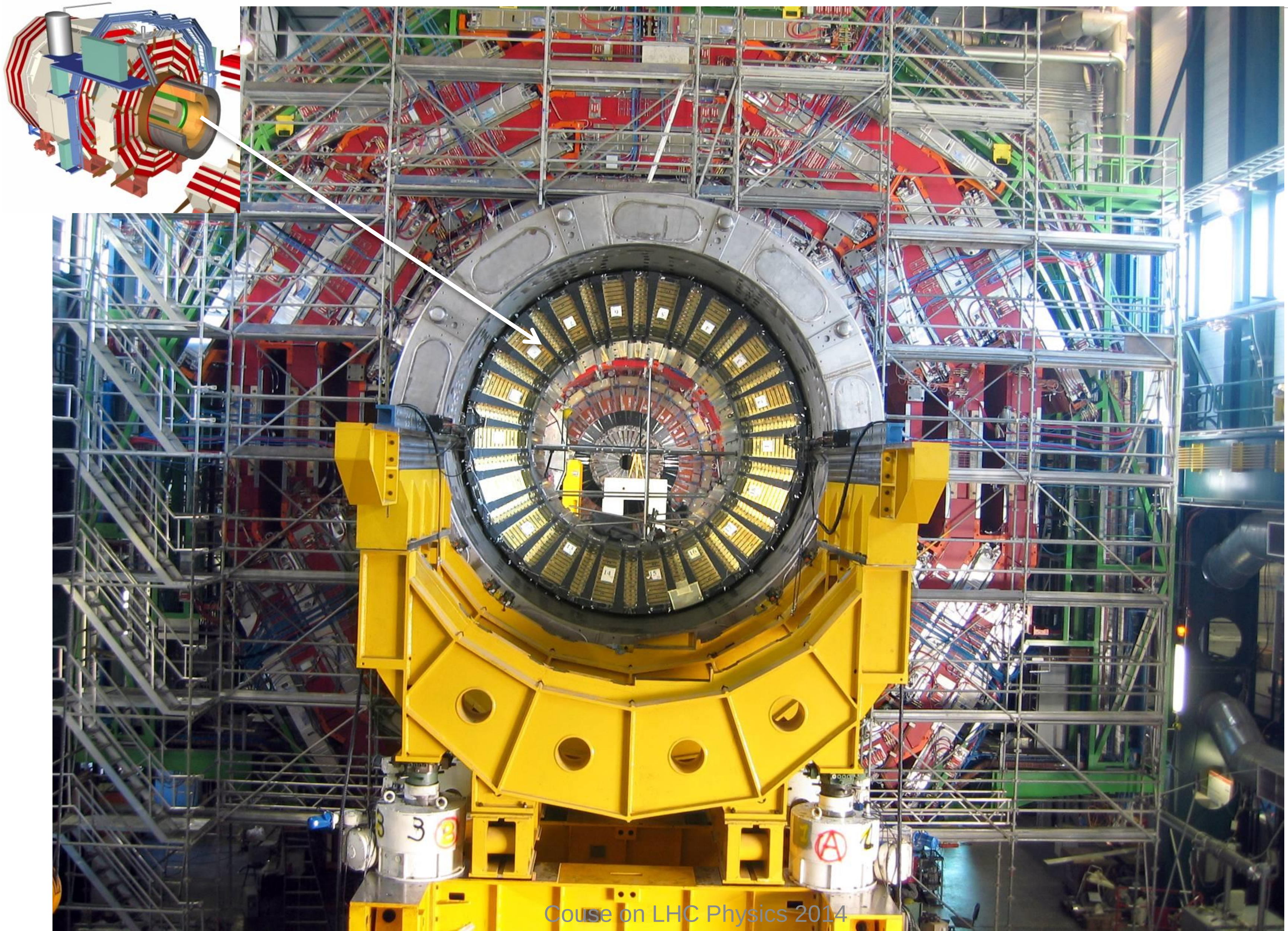


Surface Hall in Feb 2006

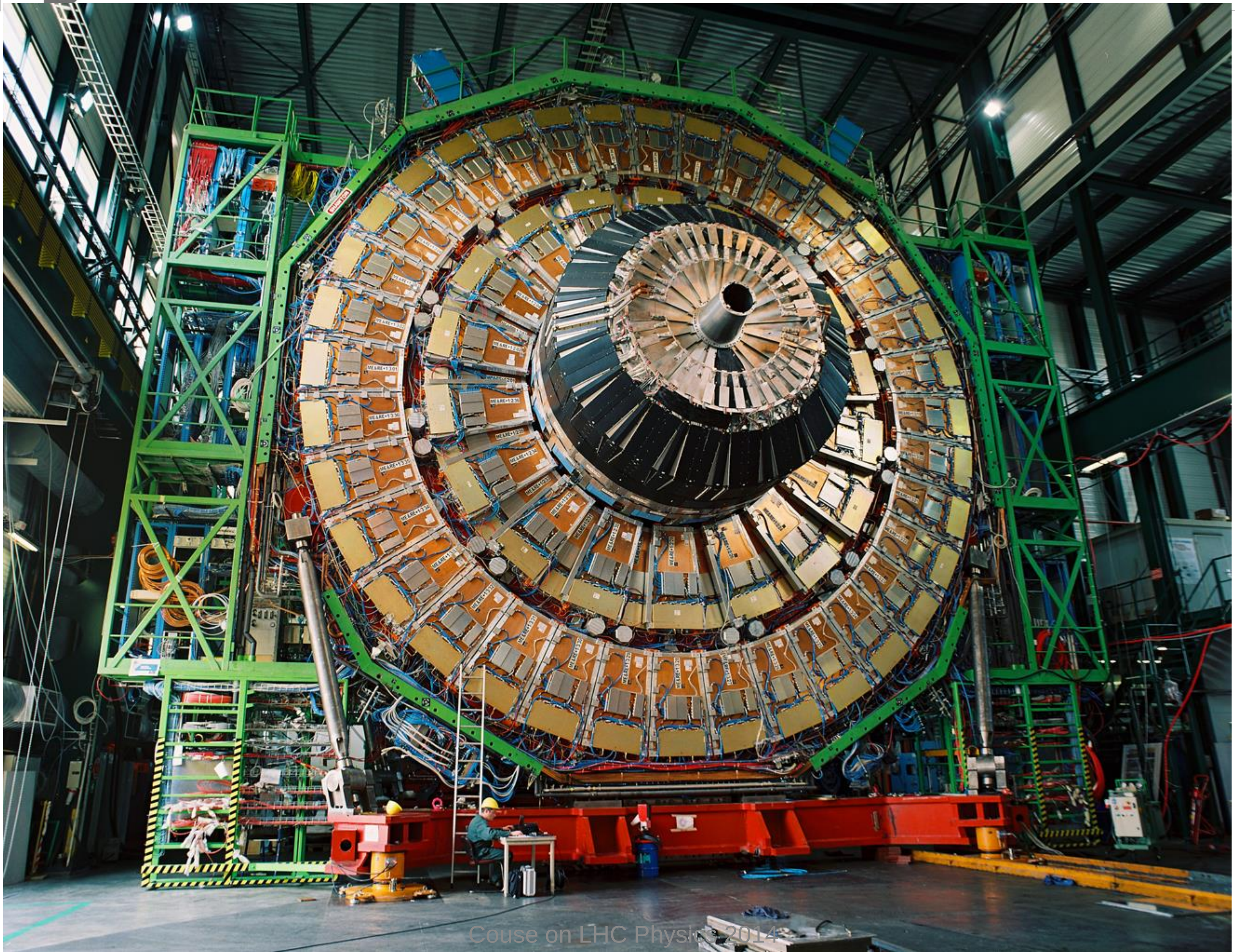




HCAL barrel test assembly

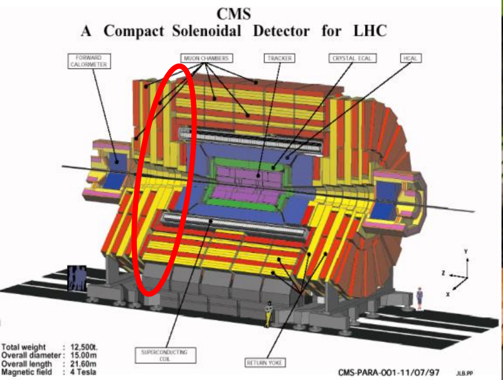


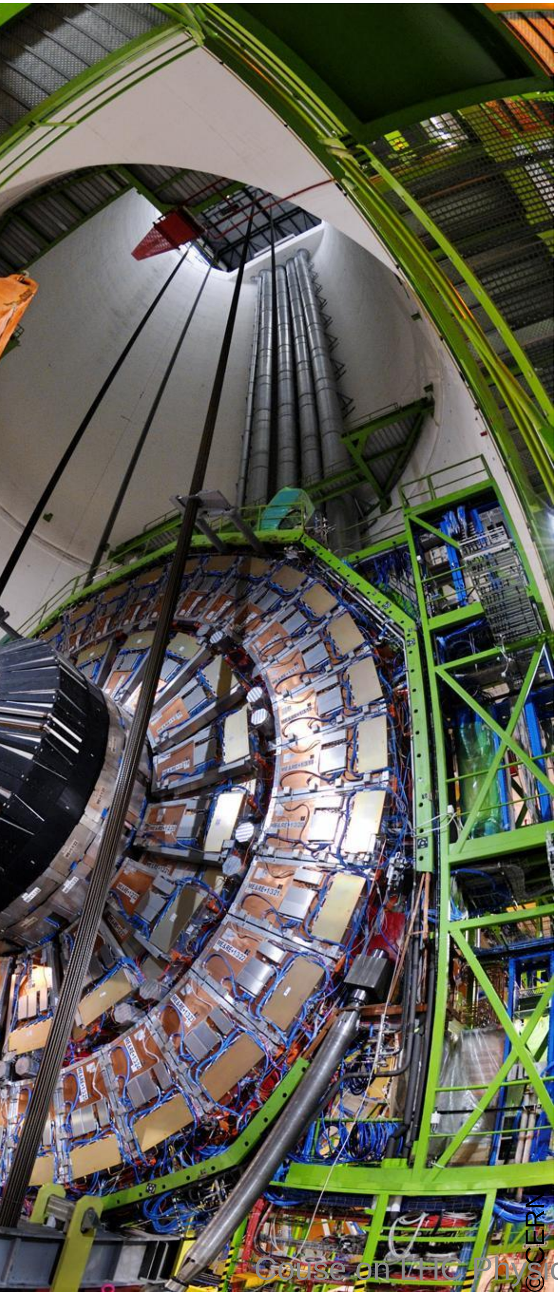
Surface Hall: Endcaps

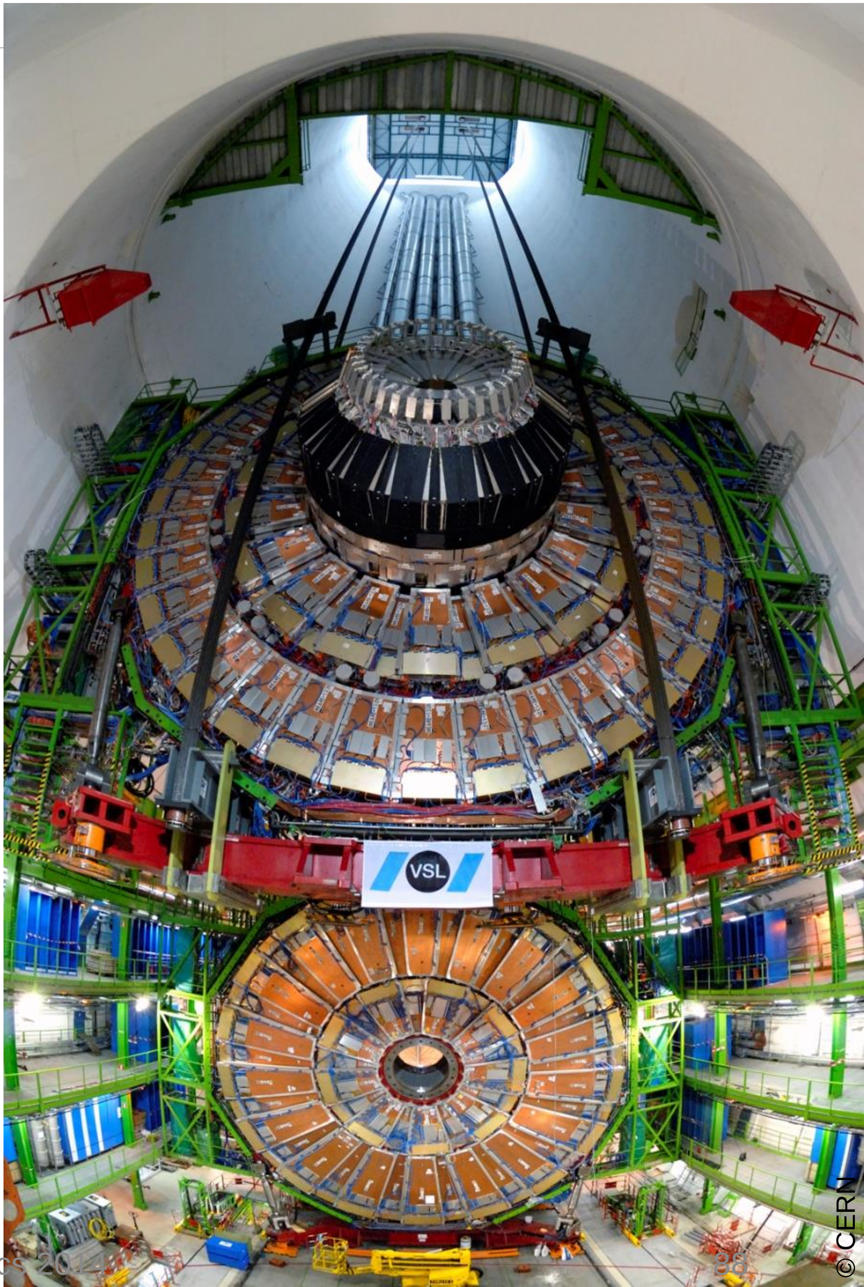


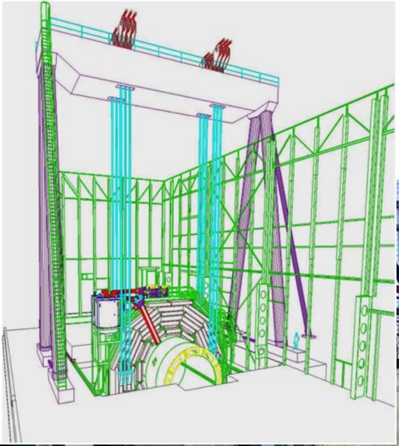
2004: CMS detector cavern

2007: Lowering one of six huge disks

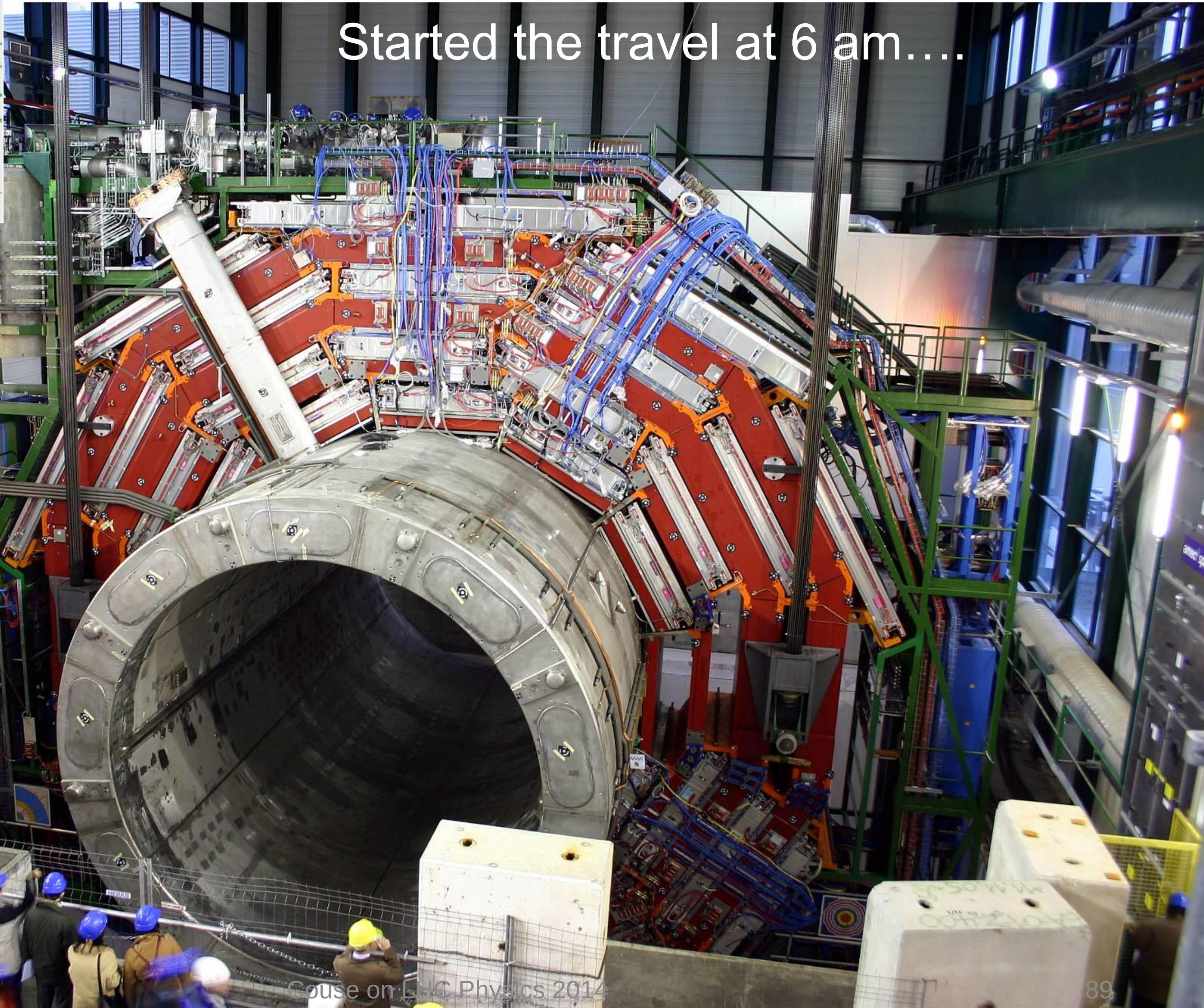




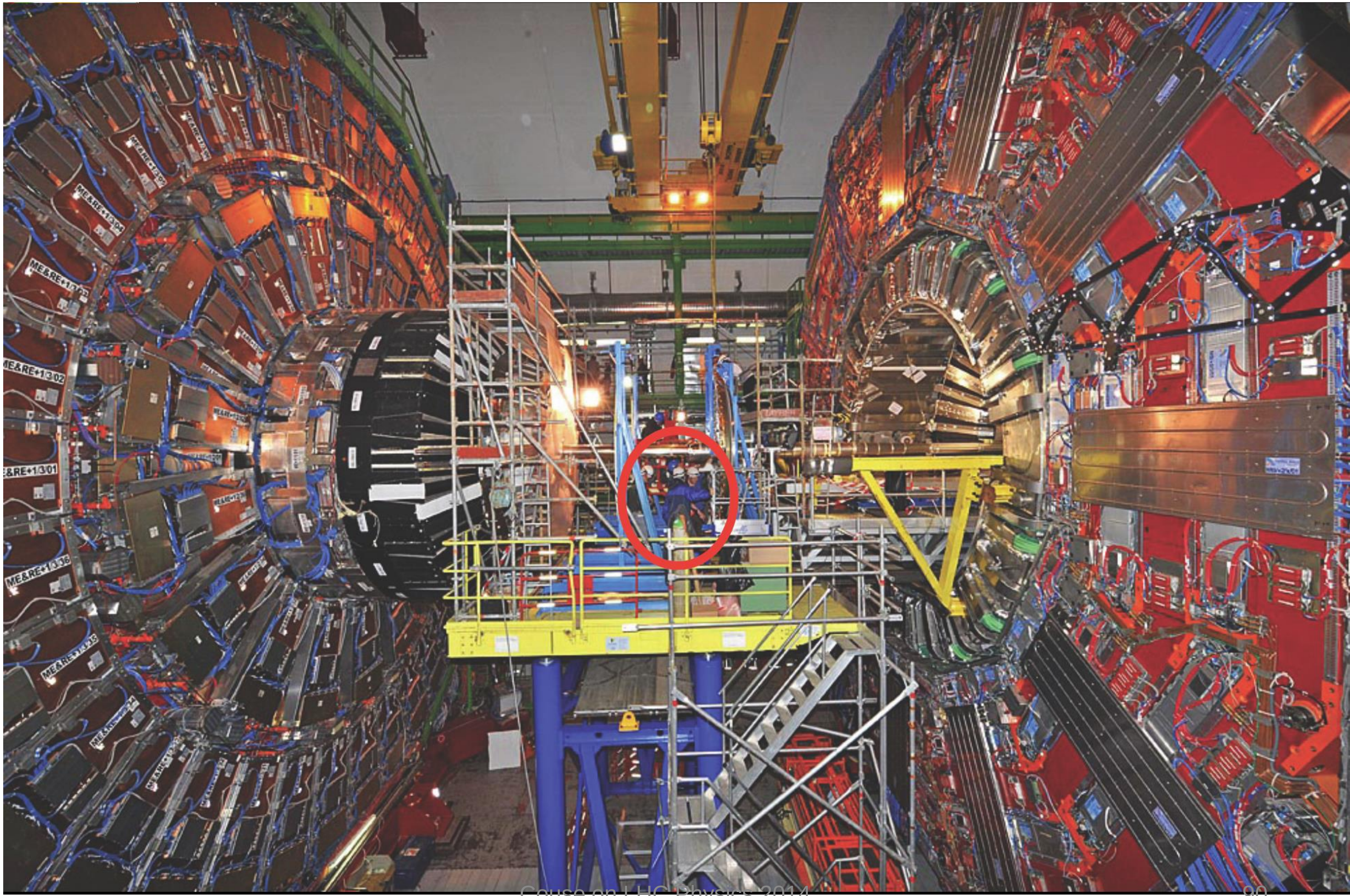




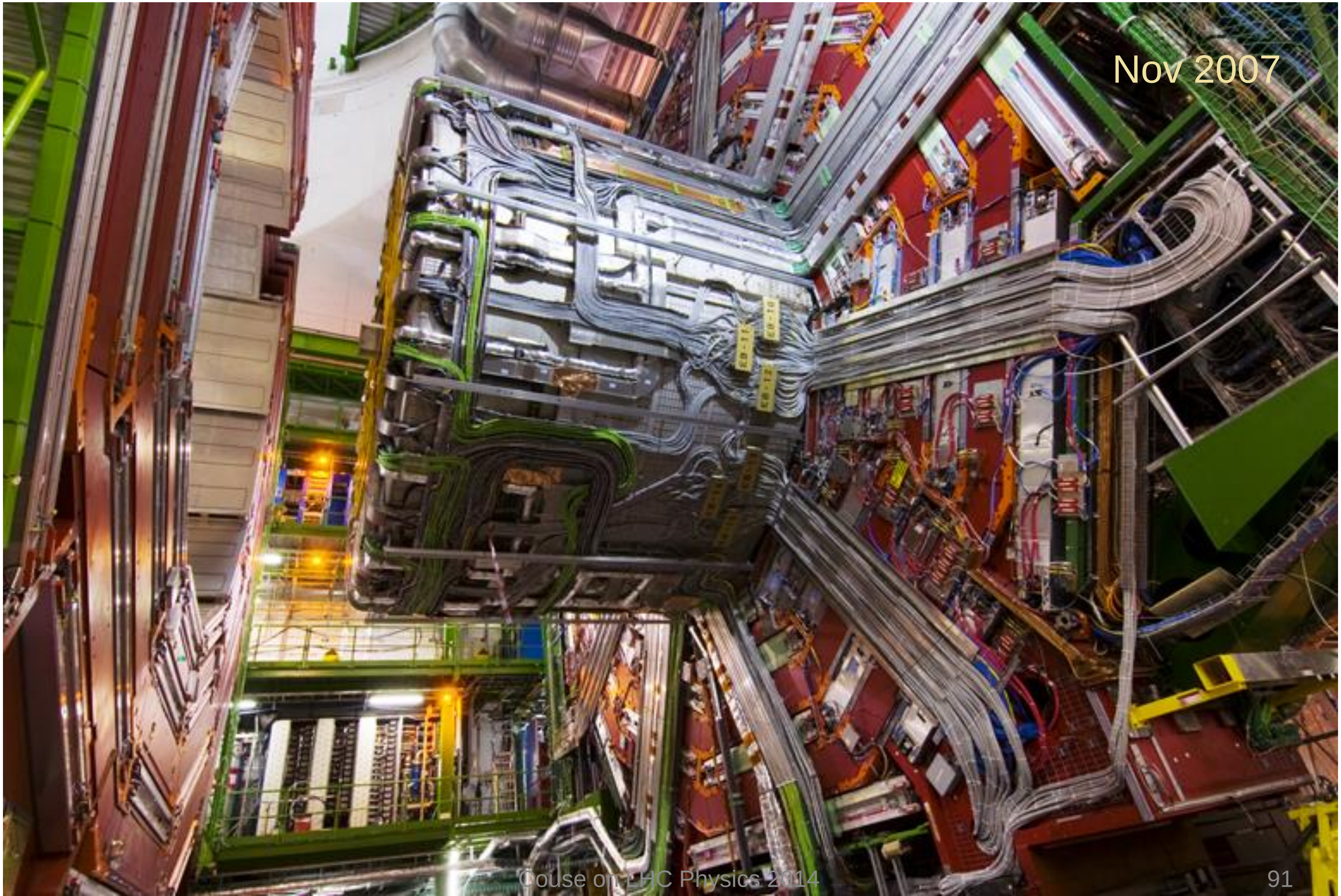
Feb 2007:lowering central “wheel”



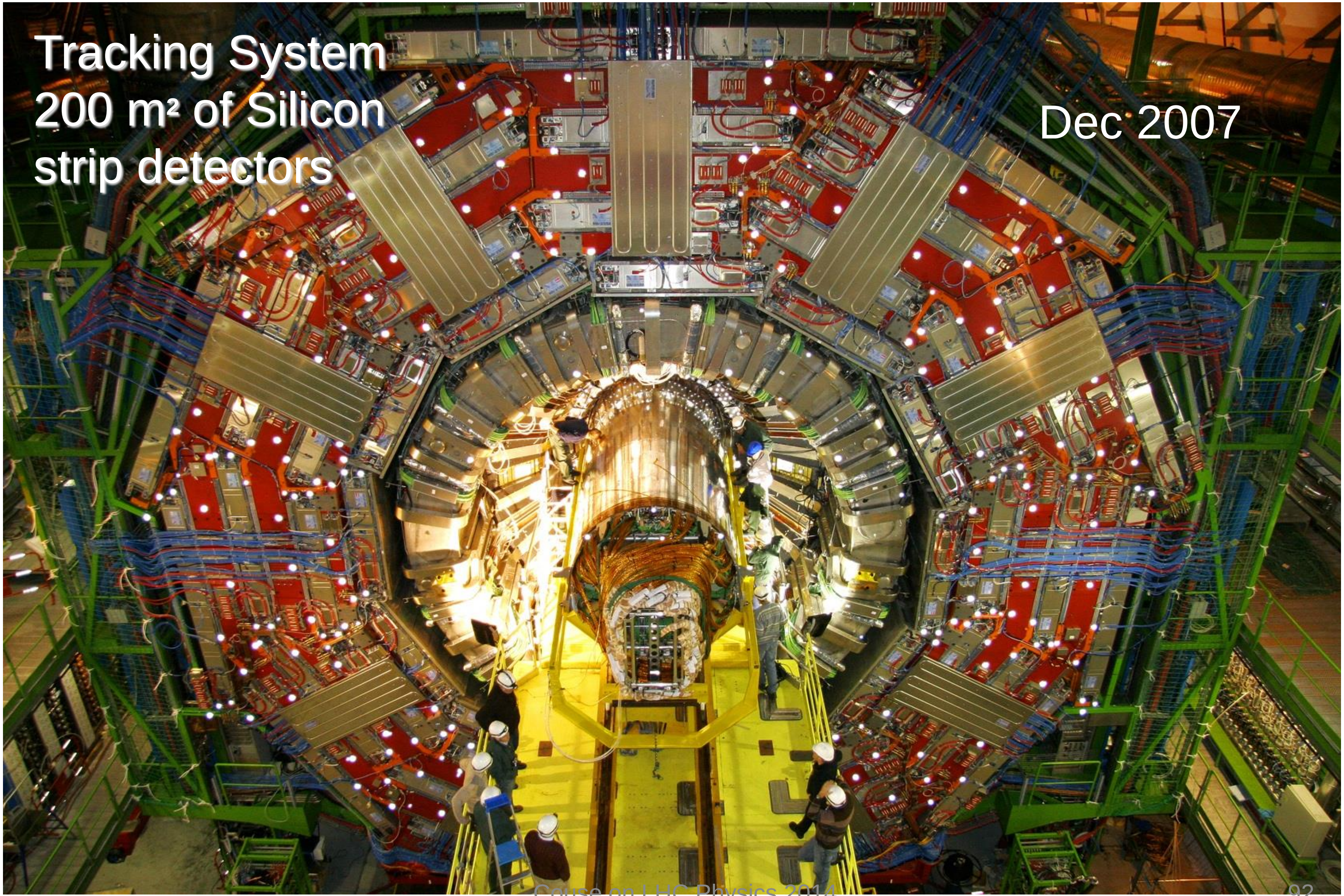
2007-08: Installation in the cavern



Cables, Pipes and Optical Fibers



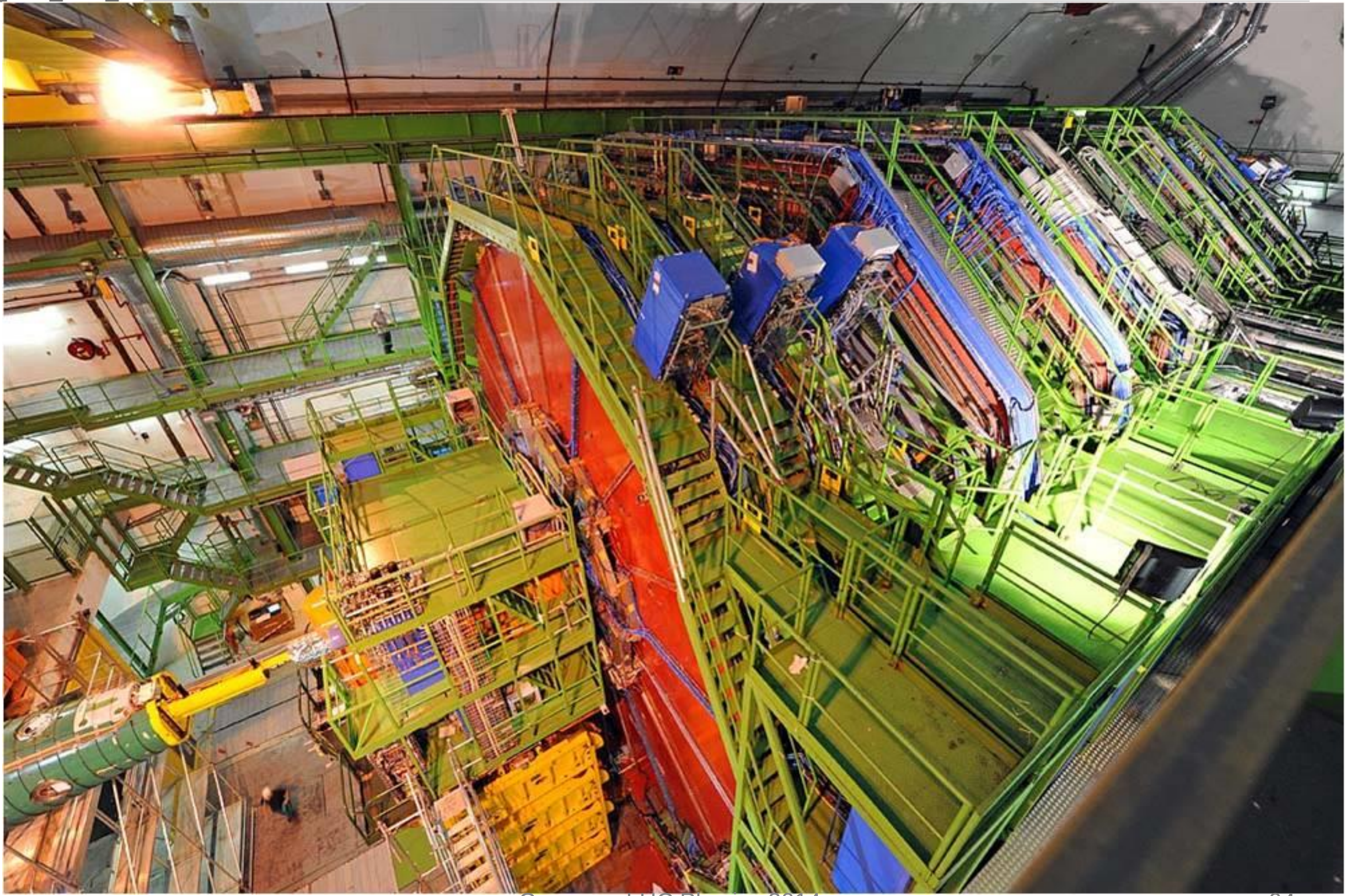
Insertion of the Tracker



2008: CMS closing up…

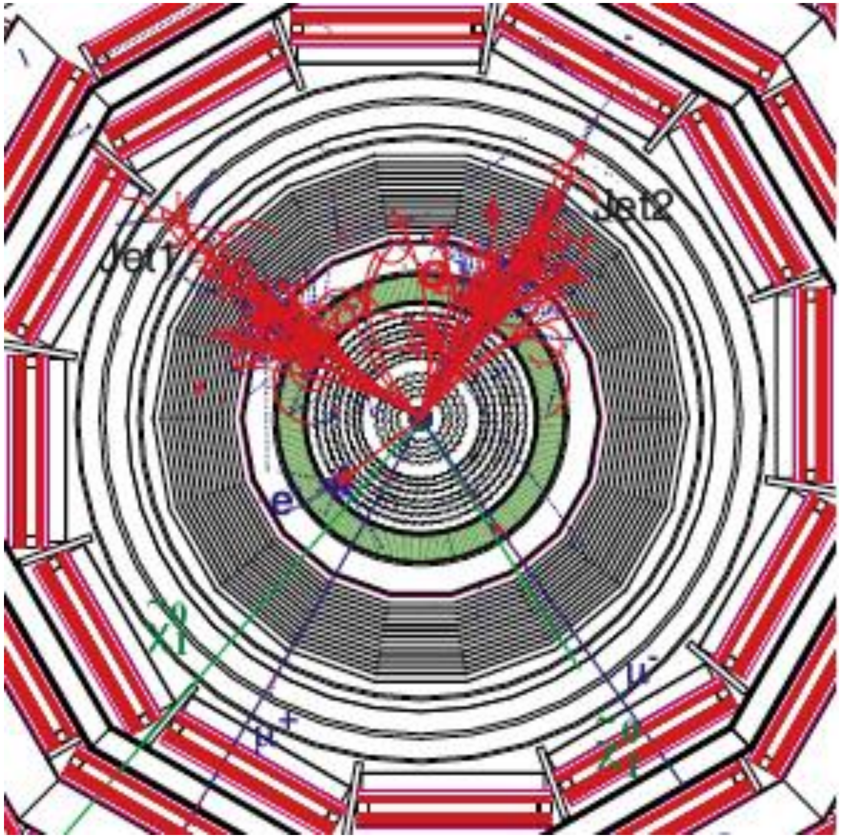
CMS closed: August 08

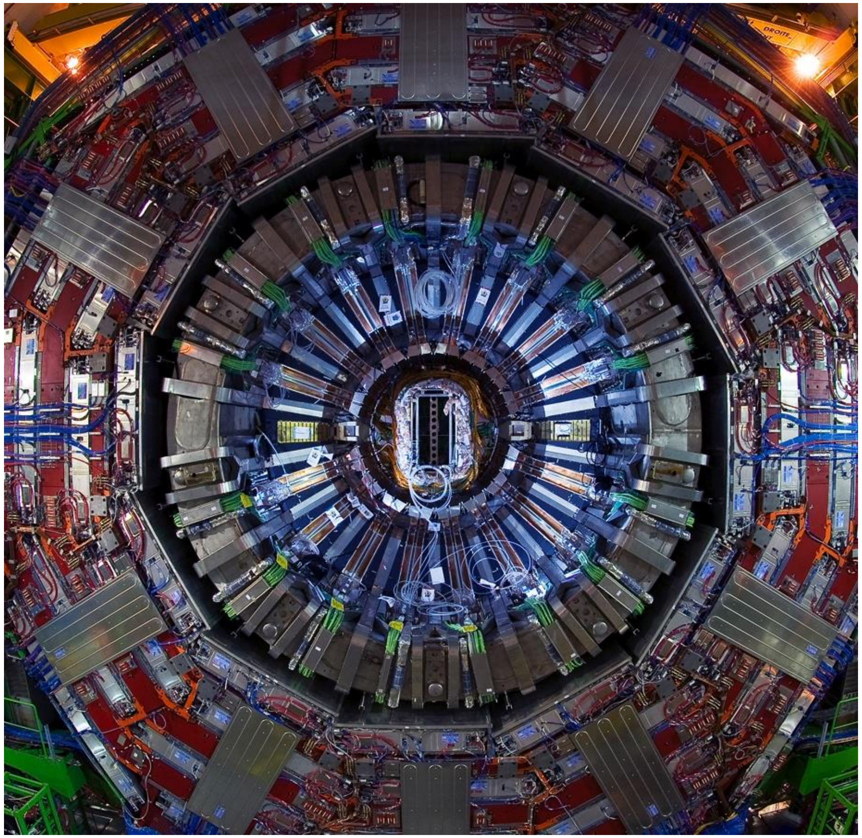
Sep 2008: CMS detector ready for beams



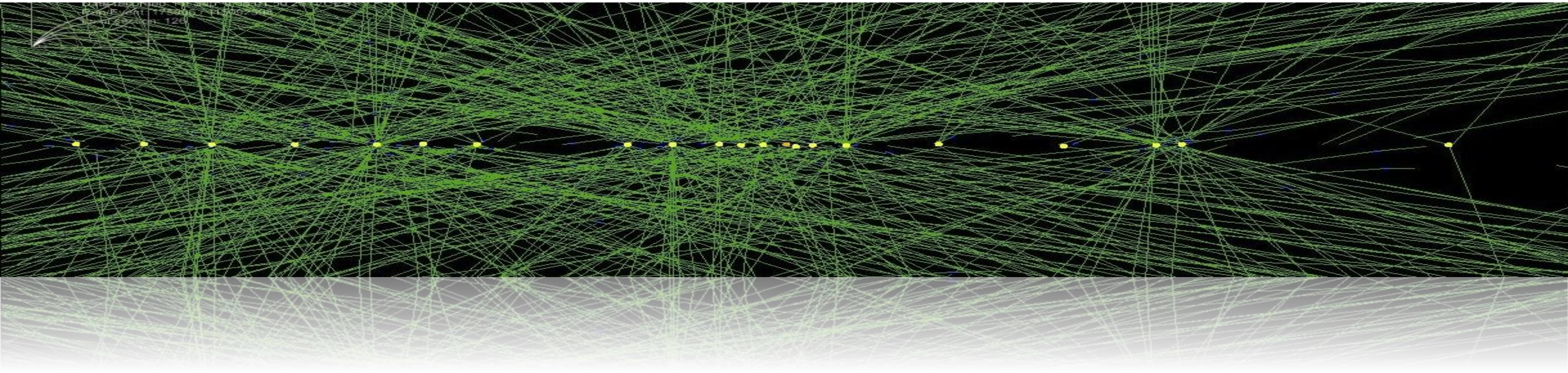
How did we prepare for discoveries?

Simulation of proton-proton collision
making two dark matter particles





Experimental challenges



High collision rate

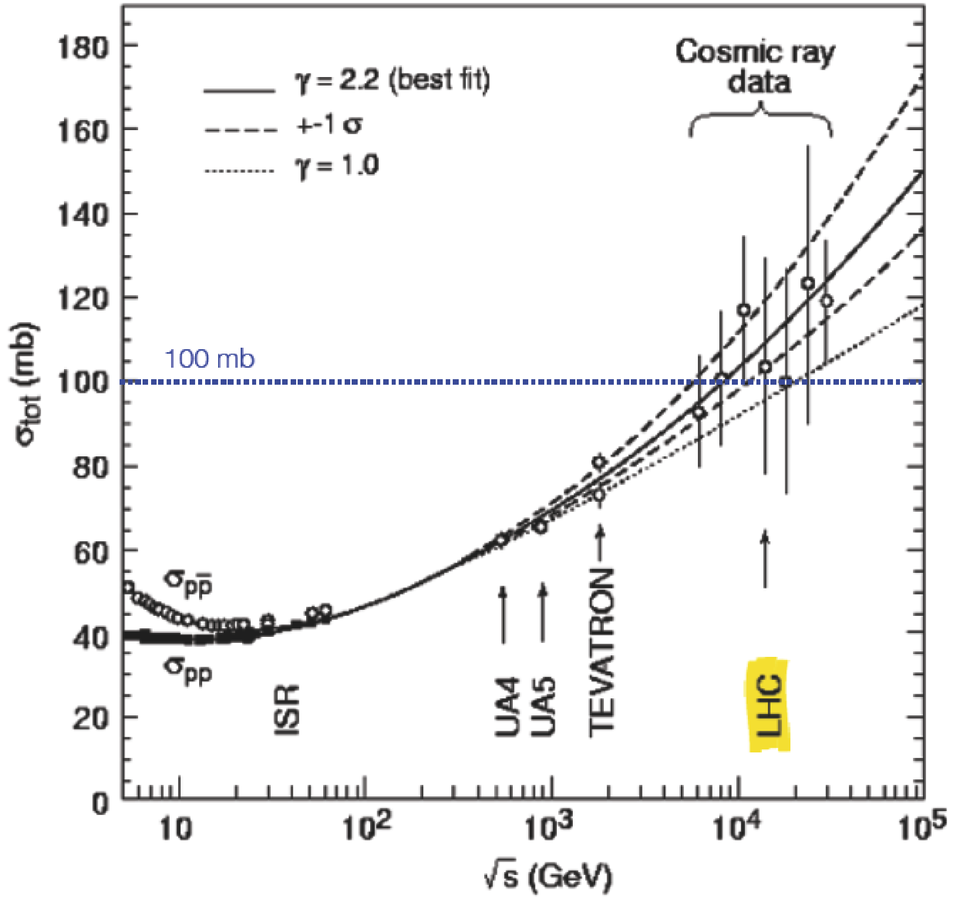
Luminosity:

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

Cross section:

$\sigma \approx 100$ mb

➡ $N = L\sigma \approx 1$ GHz



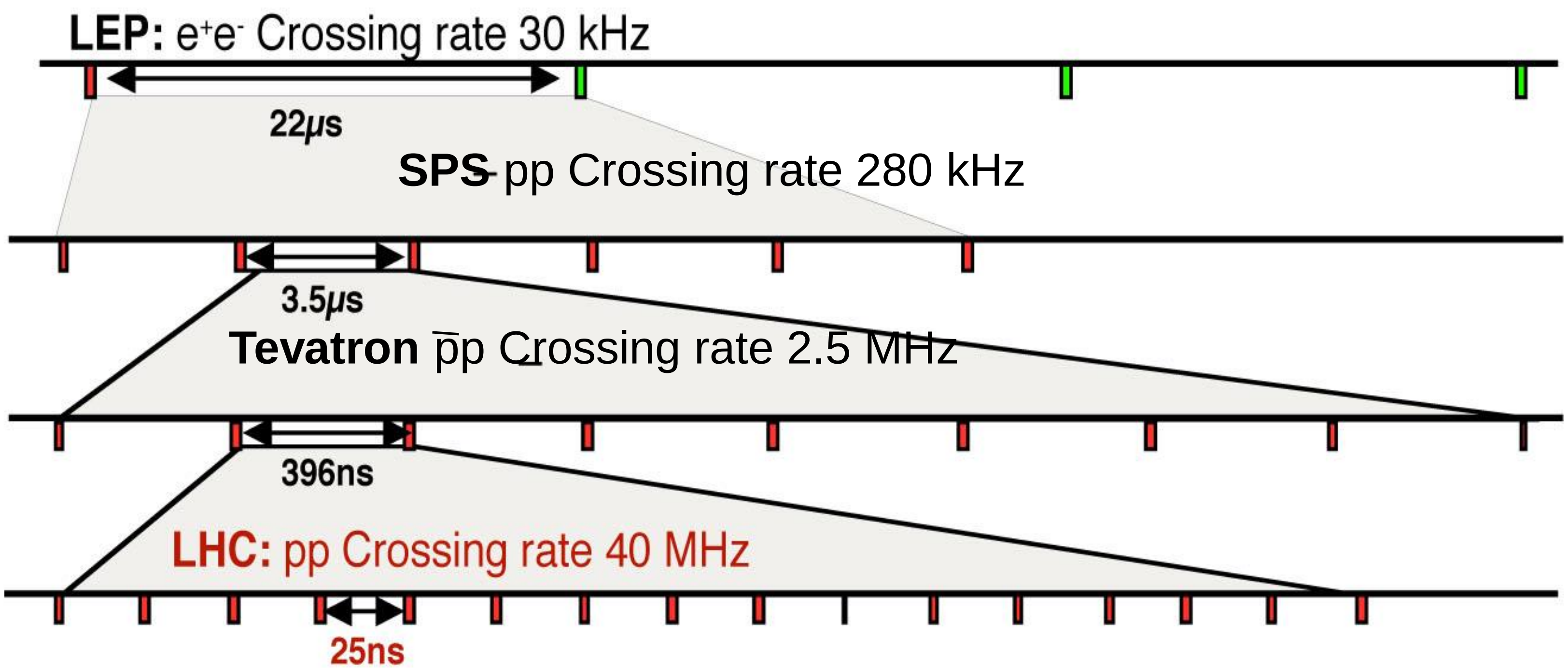
However:

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

This is a real challenge !

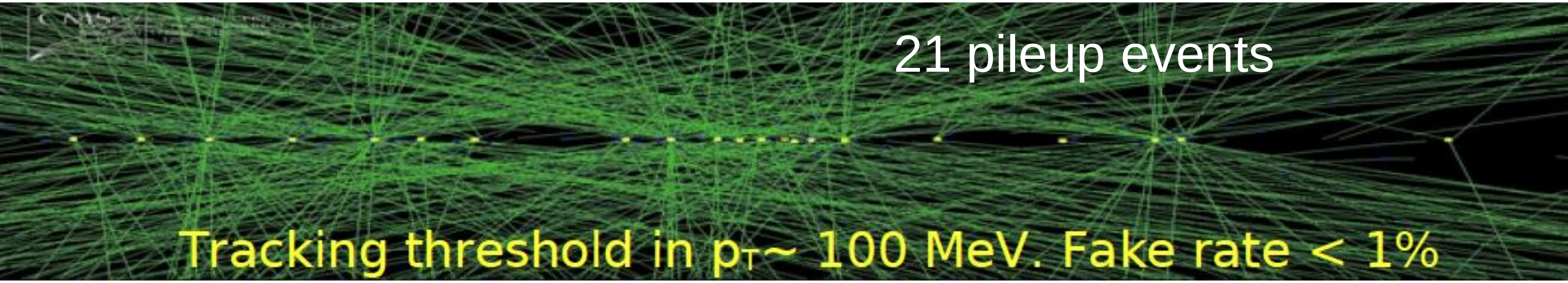
Bunch crossing frequency

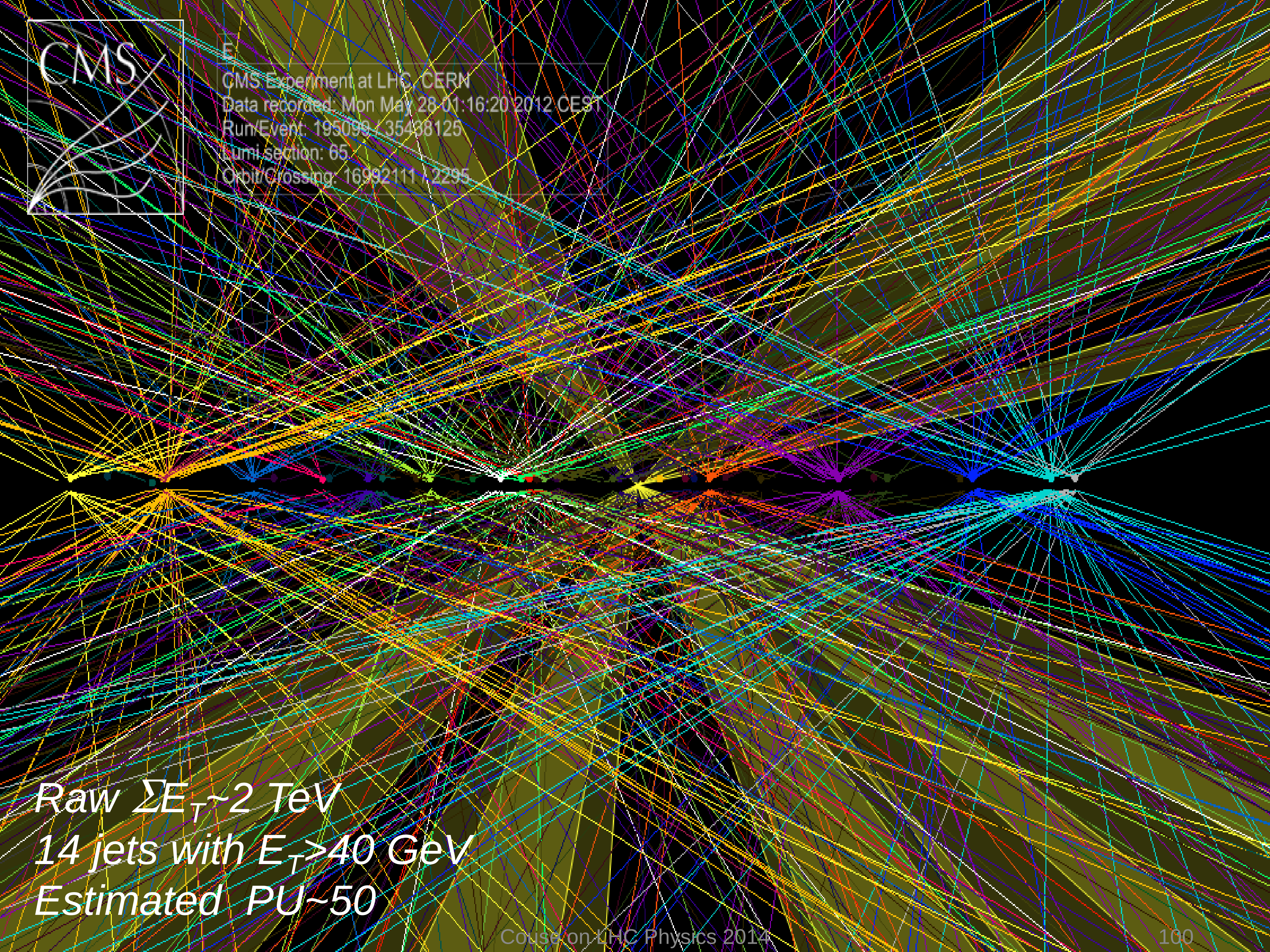
- LHC has 3564 bunches (2835 filled with protons)
- Crossing rate is 40 MHz
- Distance between bunches: 27km / 3600 = 7.5m
- Distance between bunches in time: 7.5m / c = 25ns
- Proton-proton collision per bunch crossing: ~ 25



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)



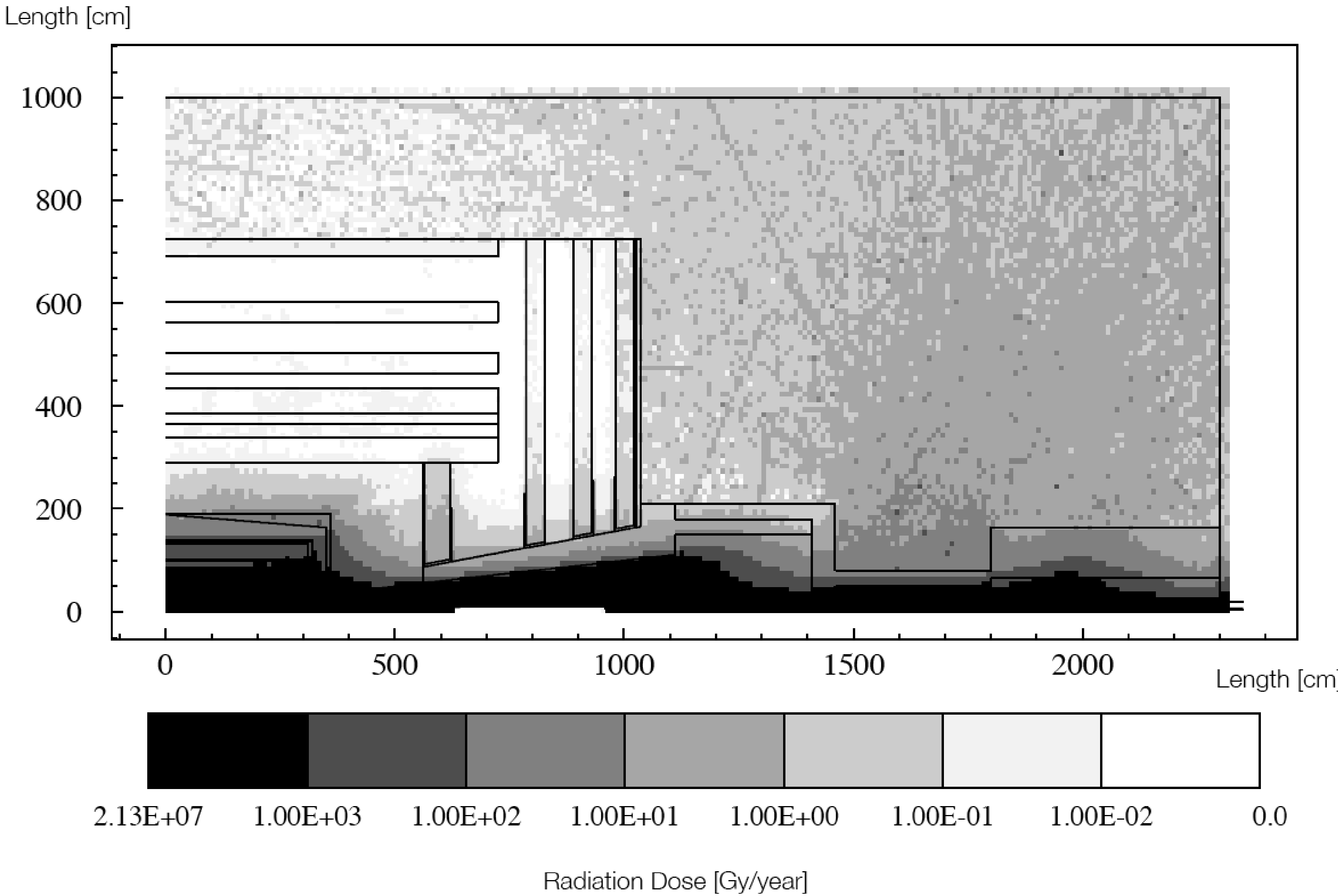


Raw ΣE_T~2 TeV

14 jets with E_T>40 GeV

Estimated PU~50

High radiation levels



Acquiring and recording data of interest

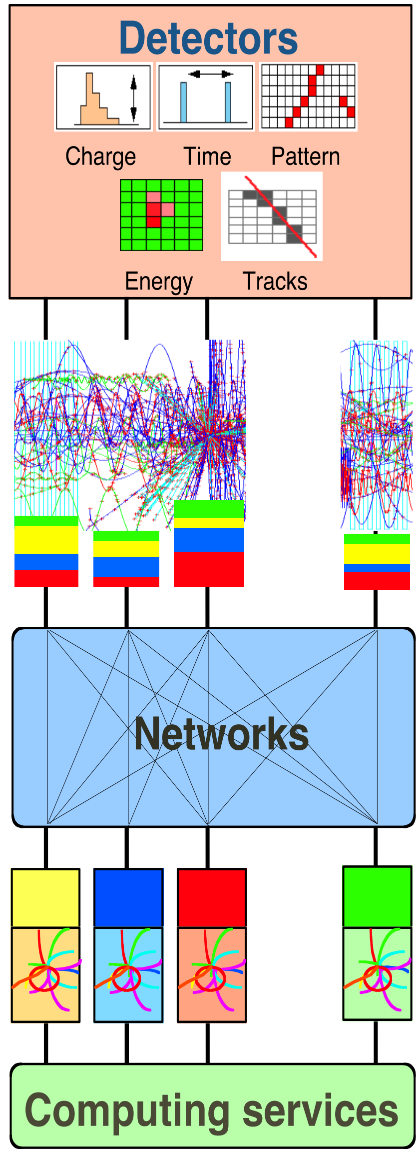
40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



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

40 Million photos/sec

Each photo (~ MB)

- taken in ~ 500 different parts

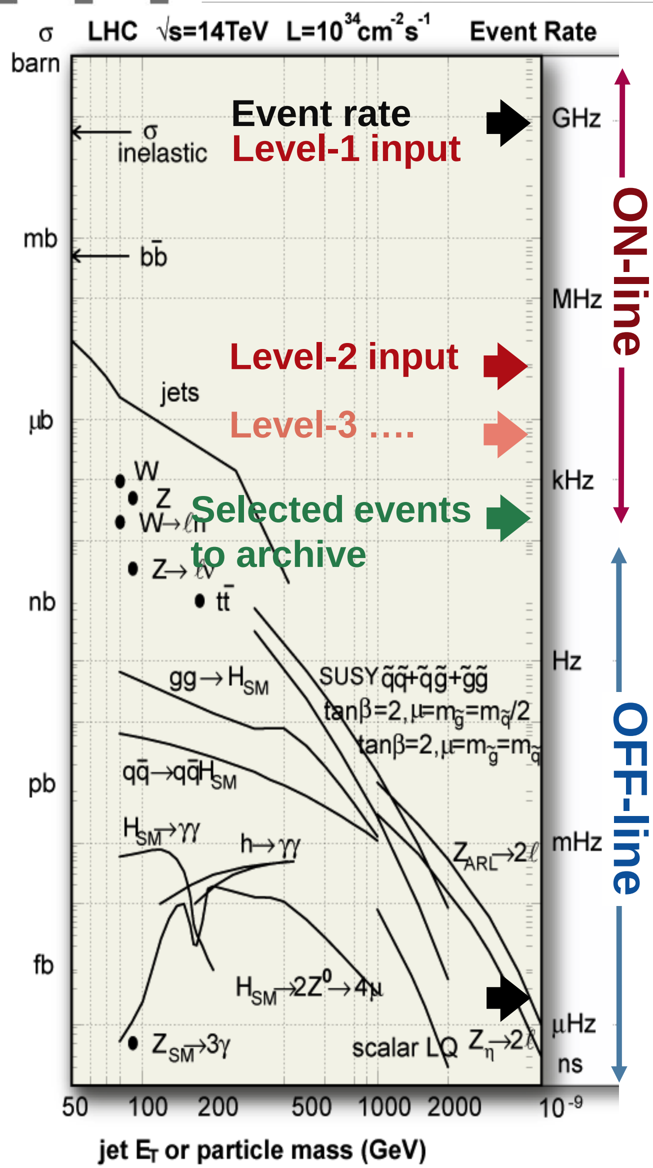
- put together using a telecommunications ‘switch’

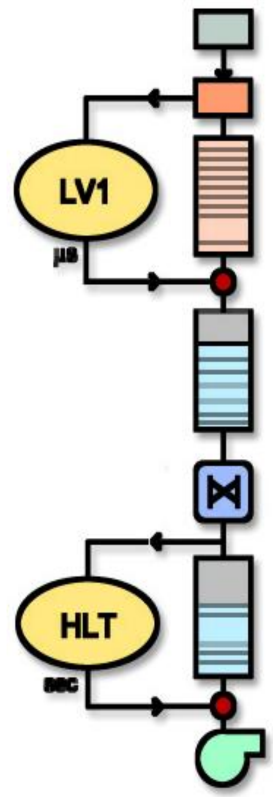
- analysed in a CPU (in a farm of ~ 50000 cores)

Only a few hundred photos/sec stored on disk.

~ 15 PB/year

Two-level trigger



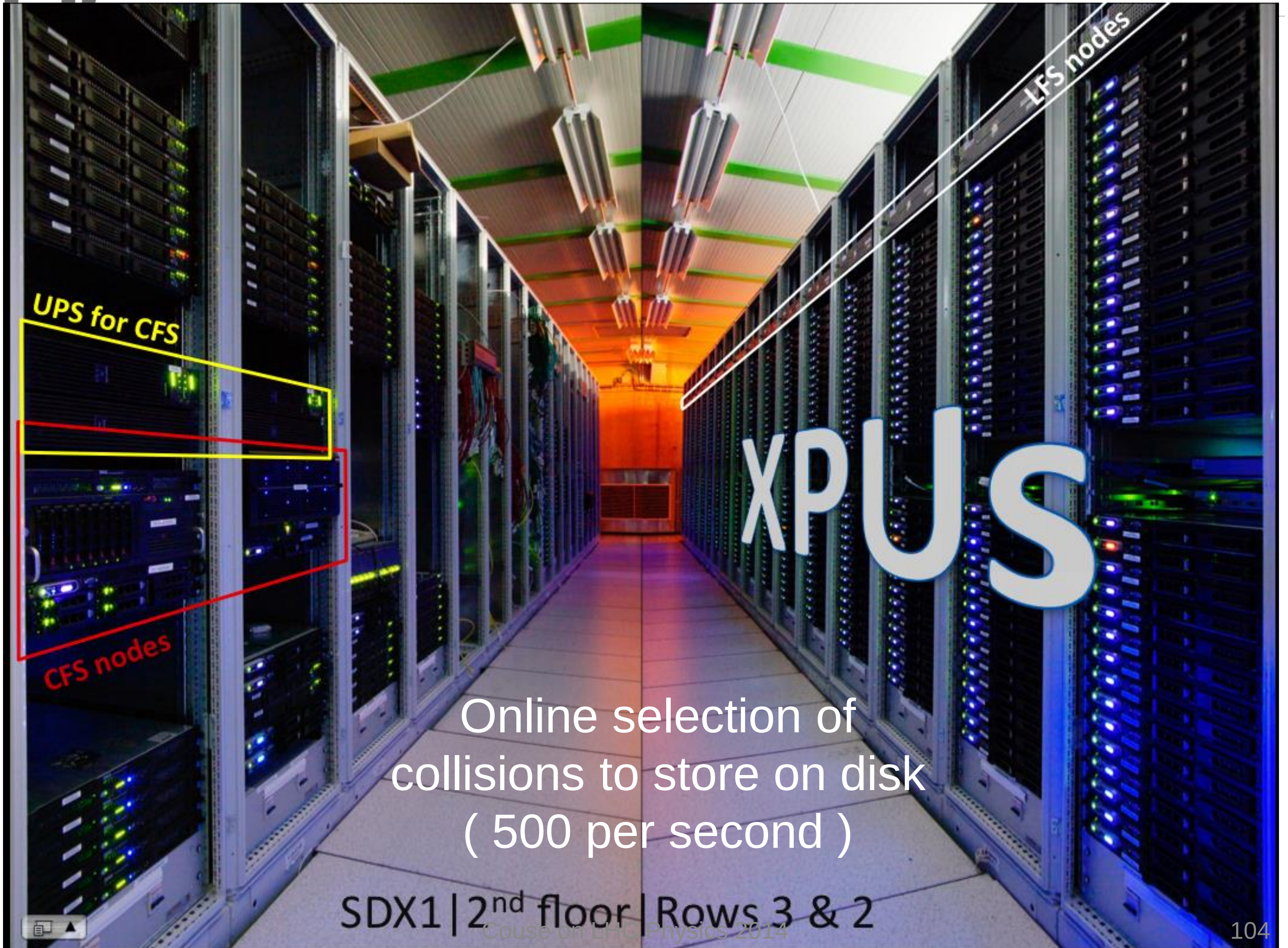


Trigger system decide if the event is interesting to be recorded

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 $5.\mathrm{x}10^{33}$ $cm^{-2}s^{-1}$
  - 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

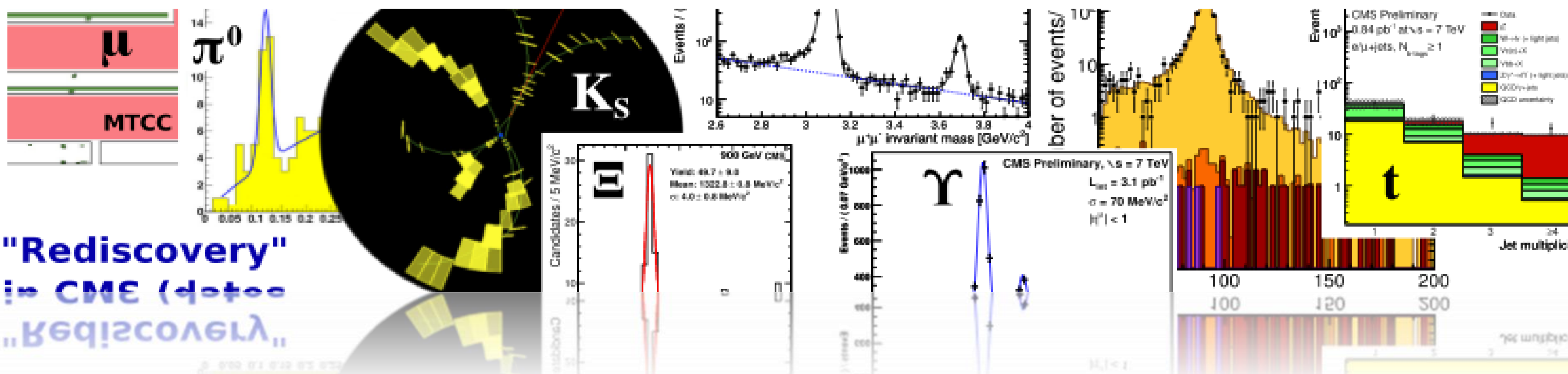
The LHC Computing Grid

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

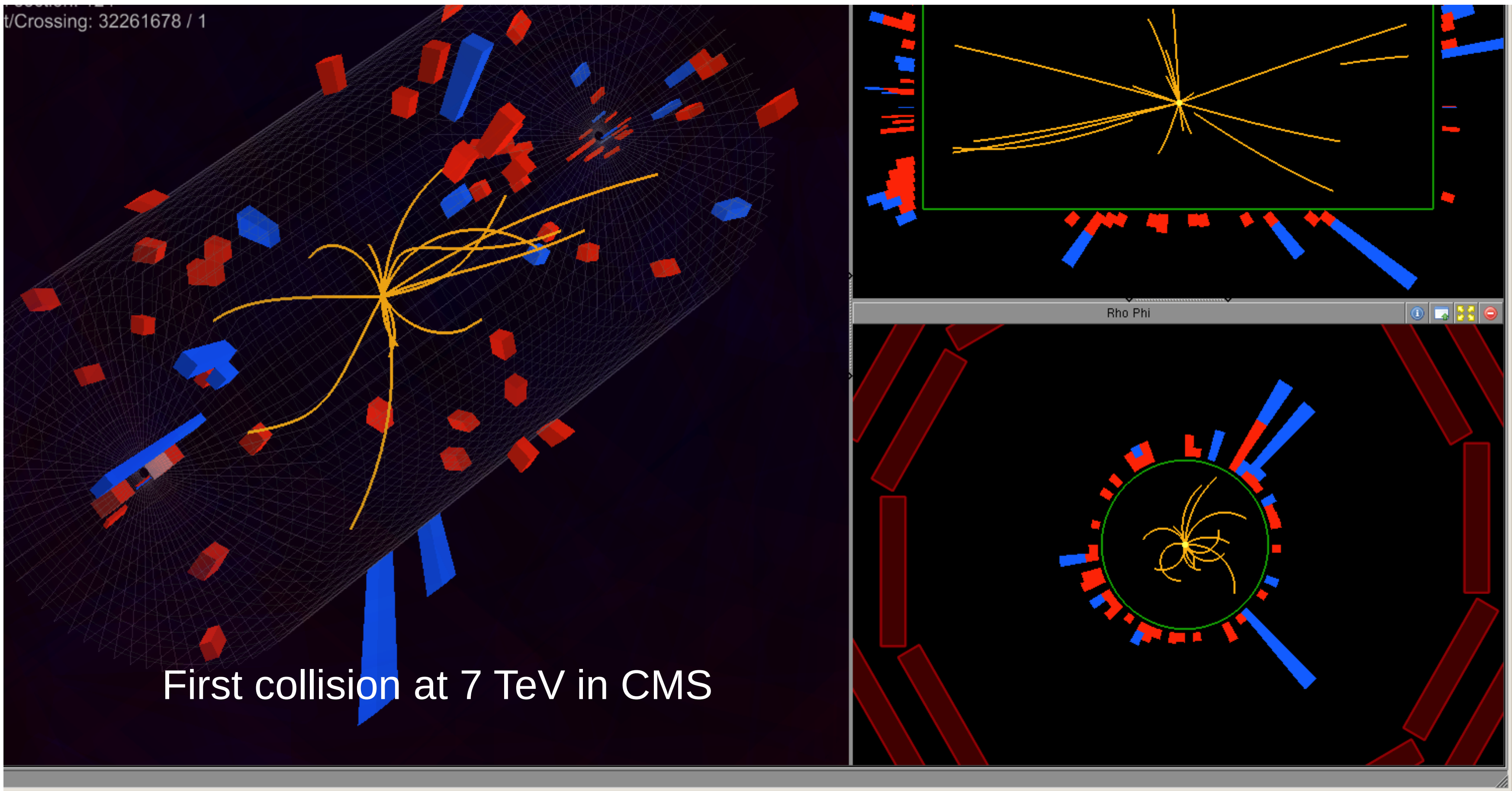


2009: First p-p collisions at LHC

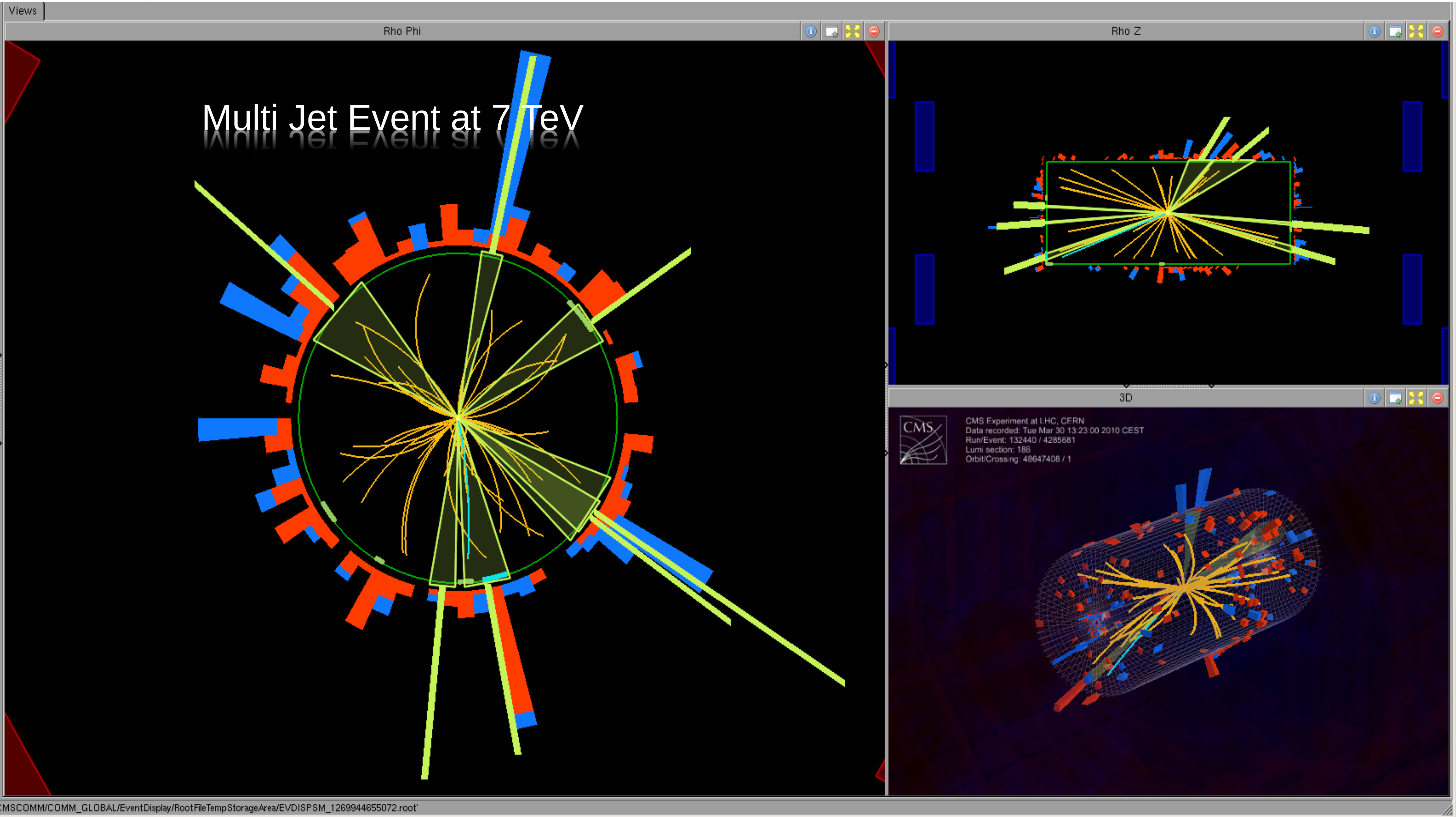
November 23, 2009
First collisions at 900 GeV

December 14, 2009
First collisions at 2.36 TeV

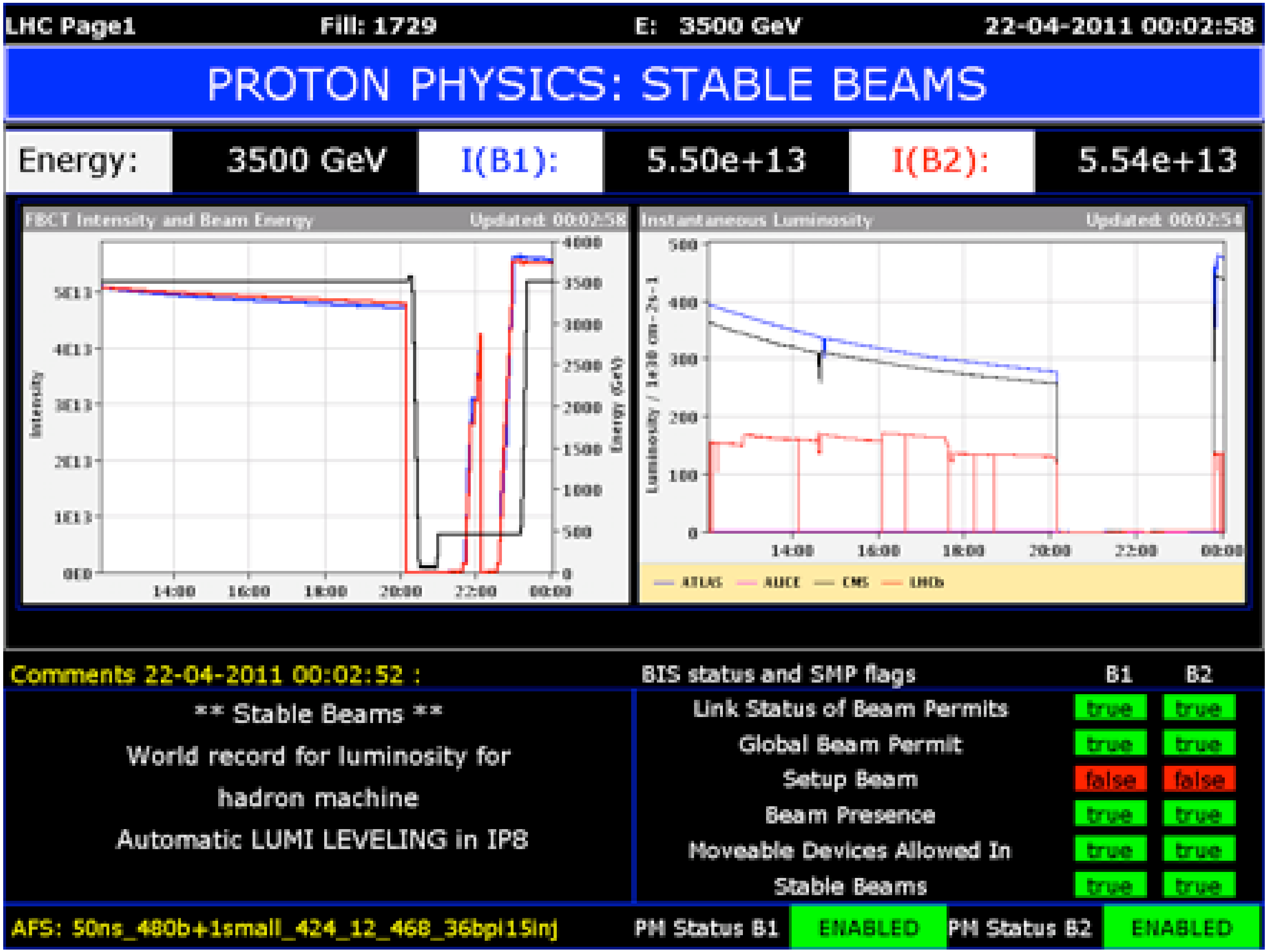
March 30, 2010
First collisions at 7 TeV



Jet event in CMS



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

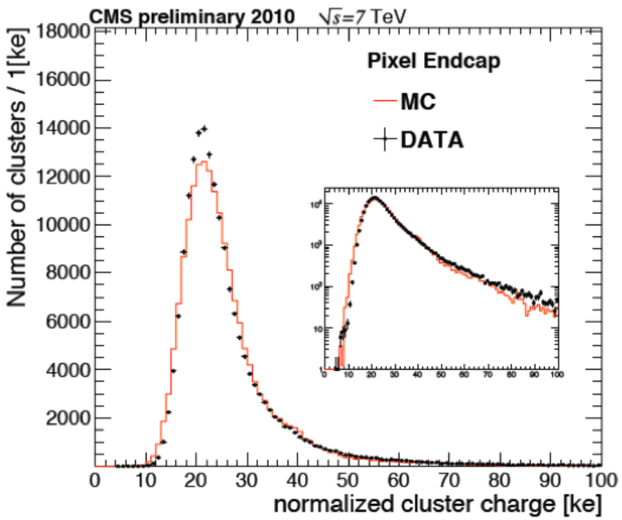
Any Internet access

CMS Experiment

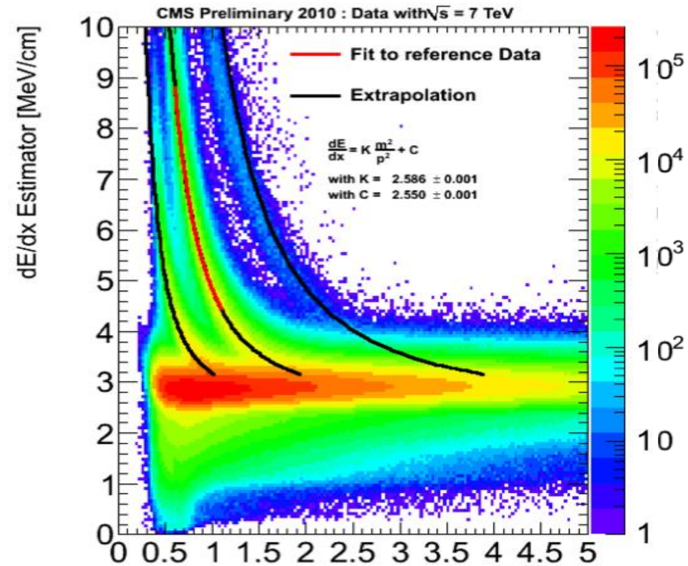
...unforgettable moments

Tracking performance

Pixel cluster charge

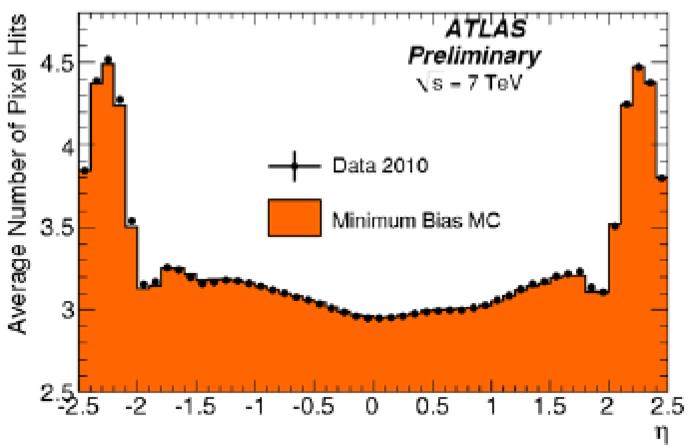


de/dx in the strips



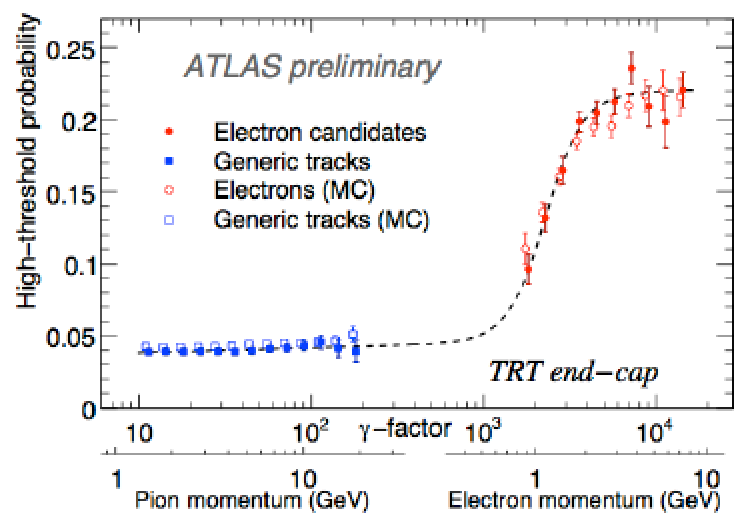
CMS

Pixel Det.



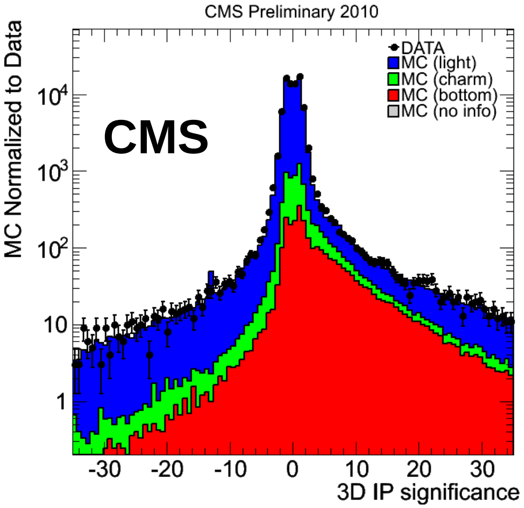
ATLAS

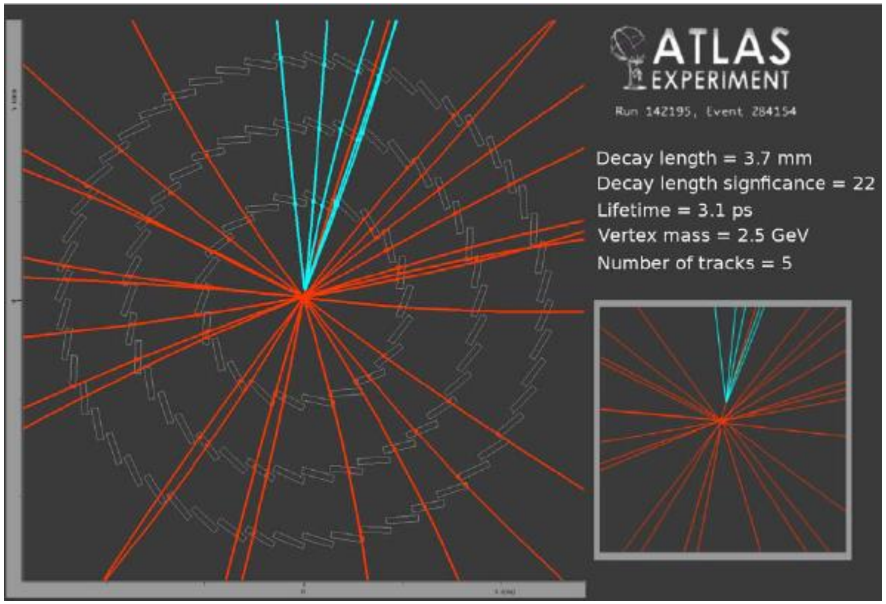
TRT Det.

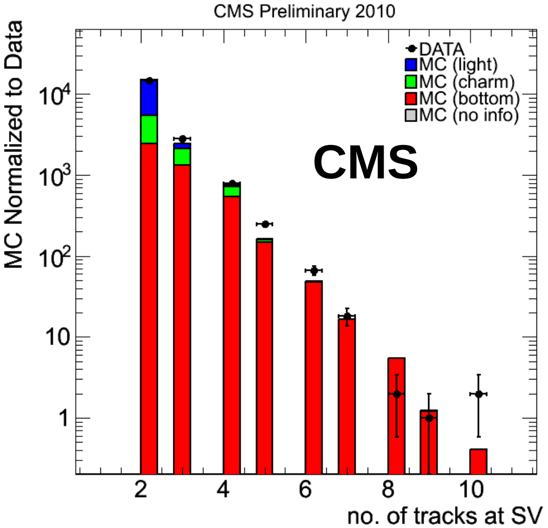


Tracking: secondary vertices

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



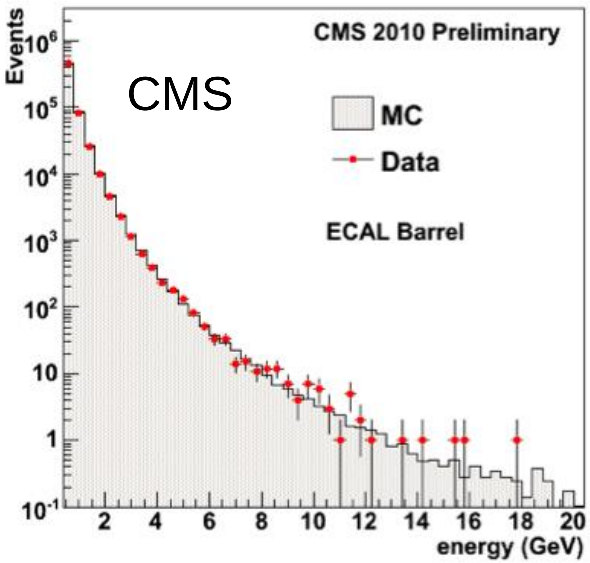


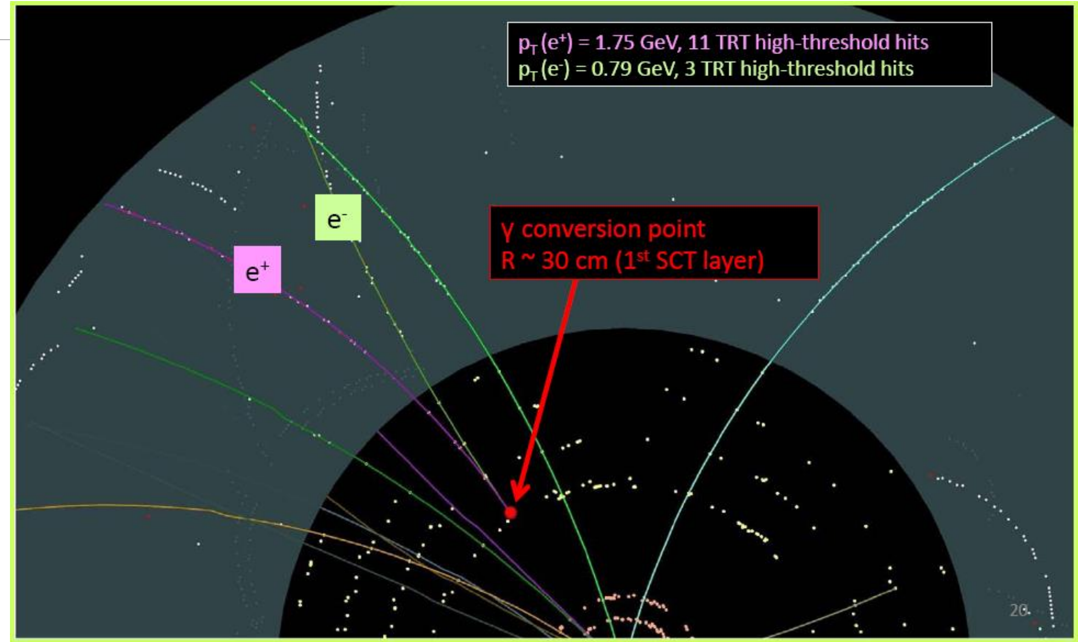


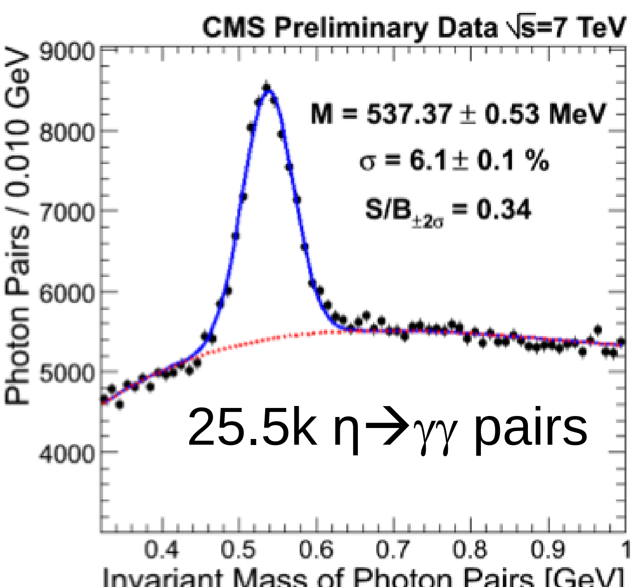
Secondary vertices compatible with heavy flavor production

Photons and electrons

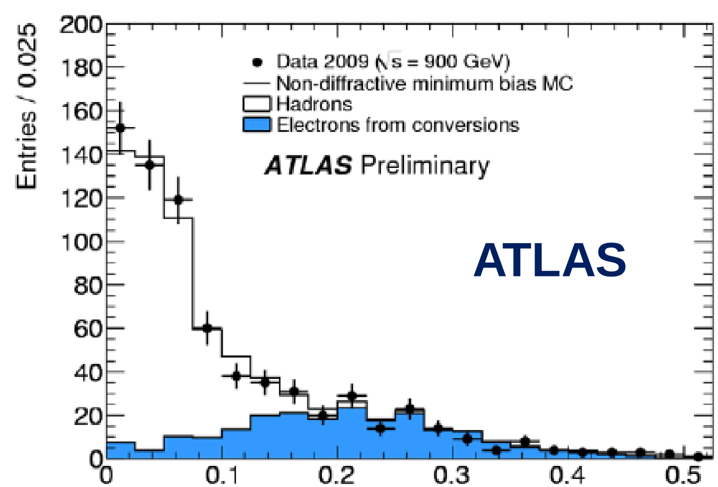
EM cluster energy



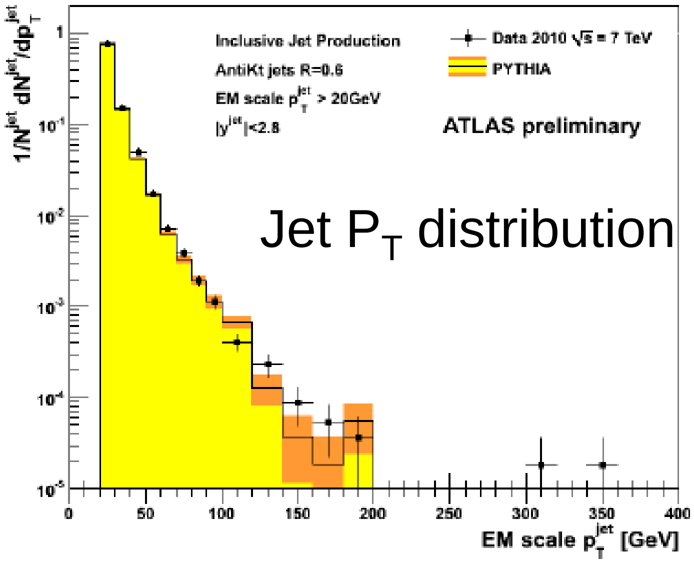




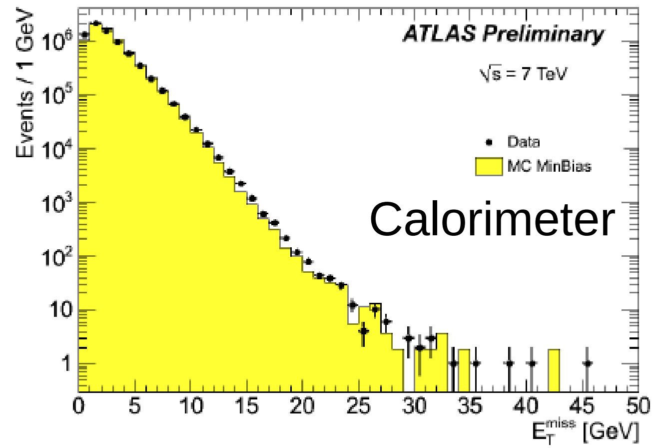
TRT high-threshold hit fraction



Jets and missing energy

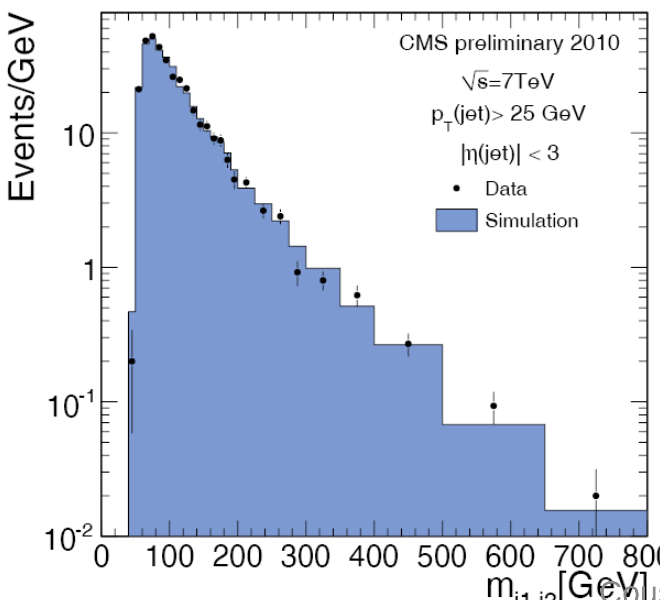


Missing Transverse Energy

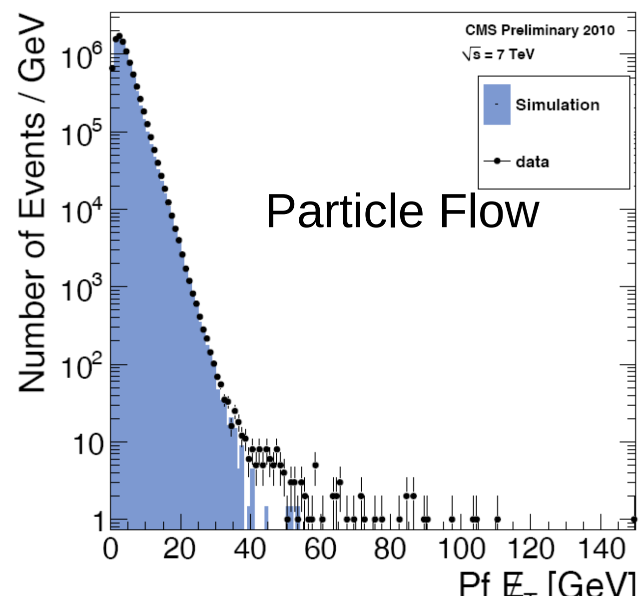


ATLAS

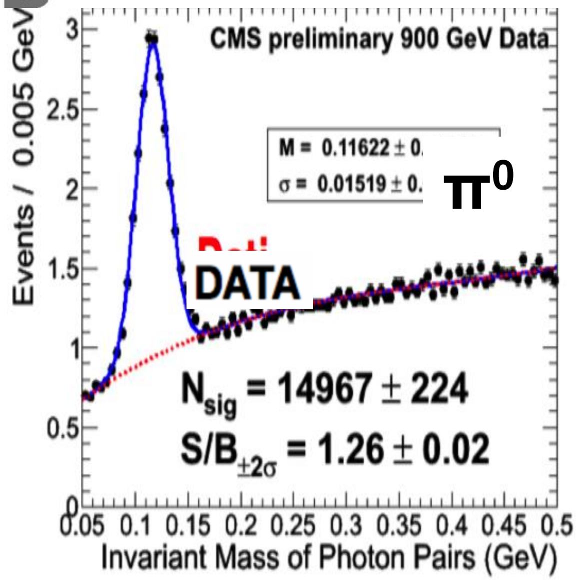
Di-jet mass

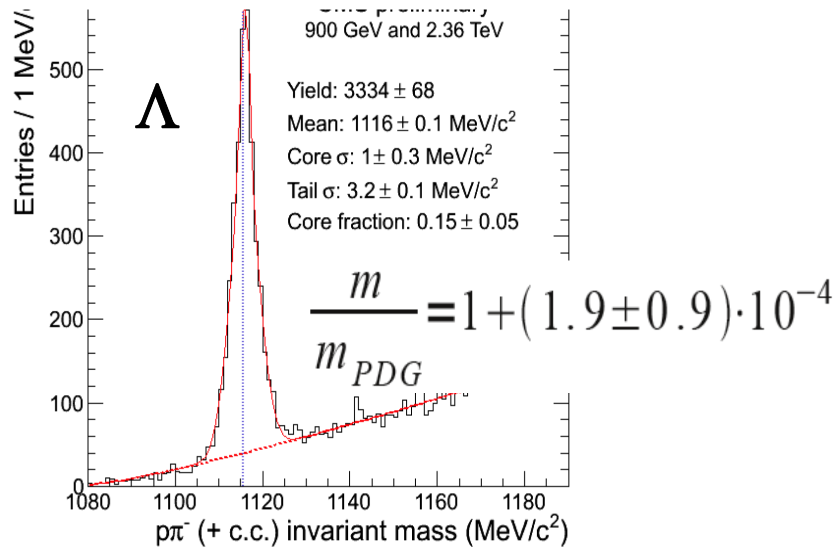


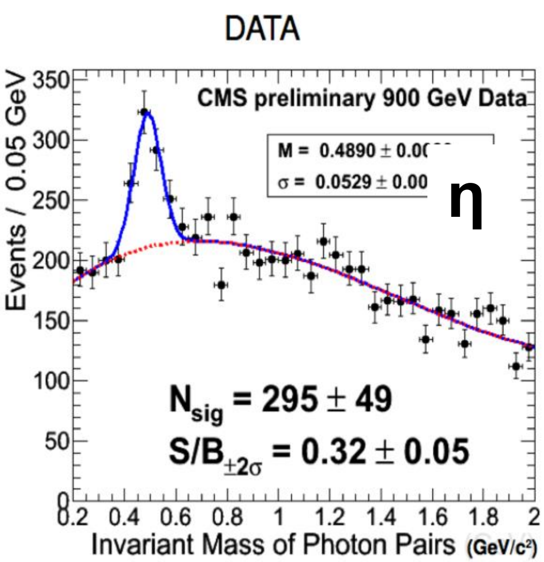
CMS

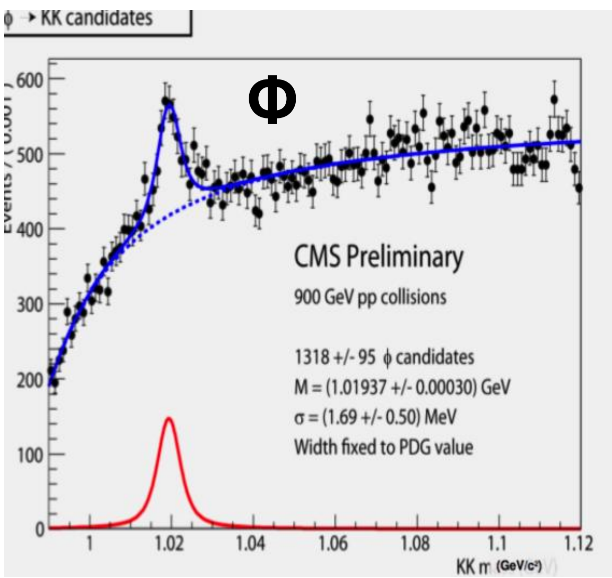


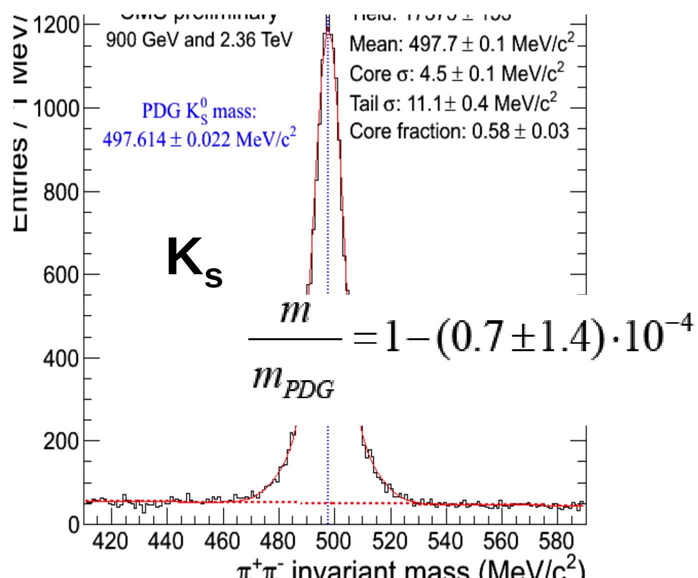
Rediscovery of resonances



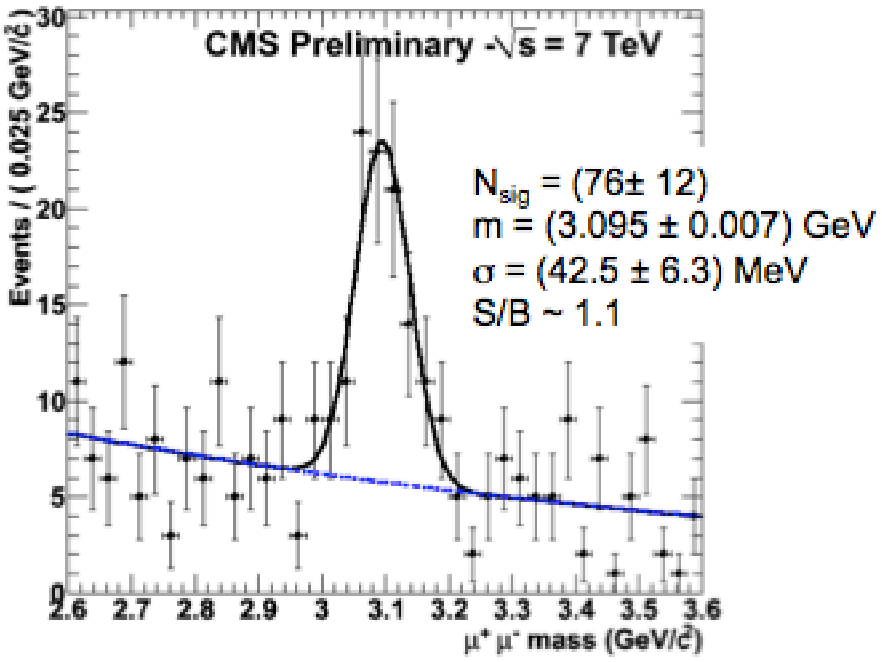








J/ψ' s decaying into muons

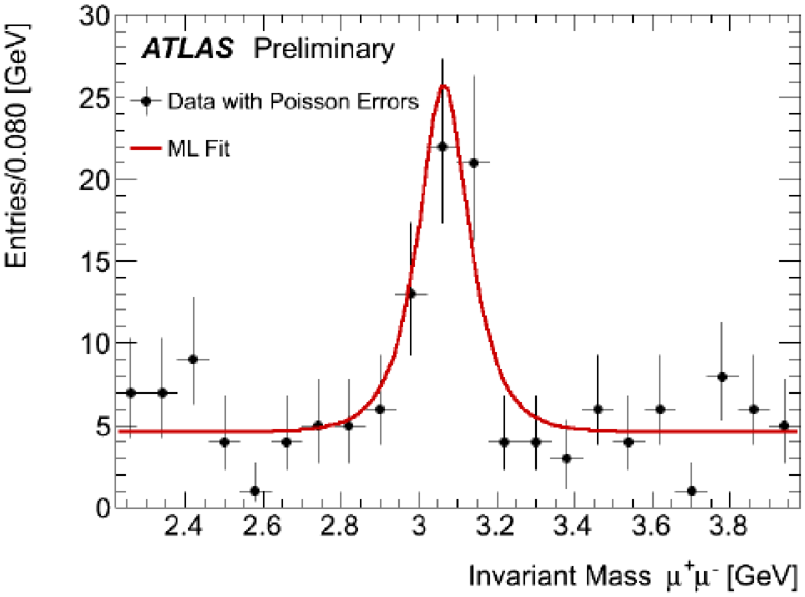


CMS

Gaussian-mean mass: 3.06±0.02 GeV

Resolution: 0.08±0.02 GeV

Number of signal events: 49±12

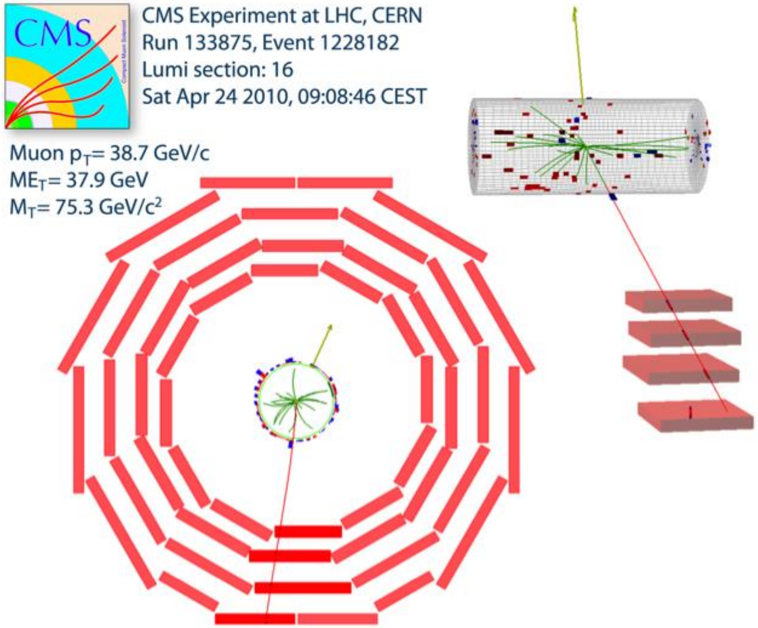


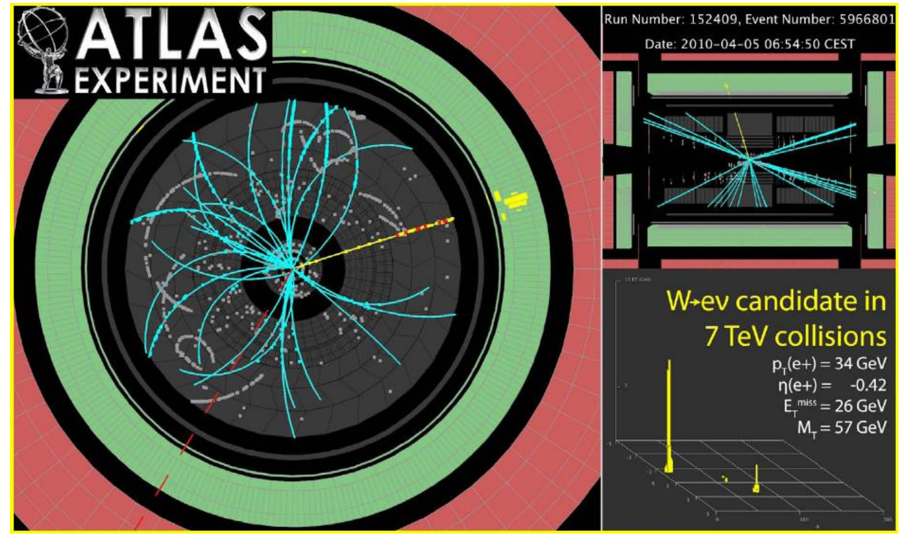
ATLAS

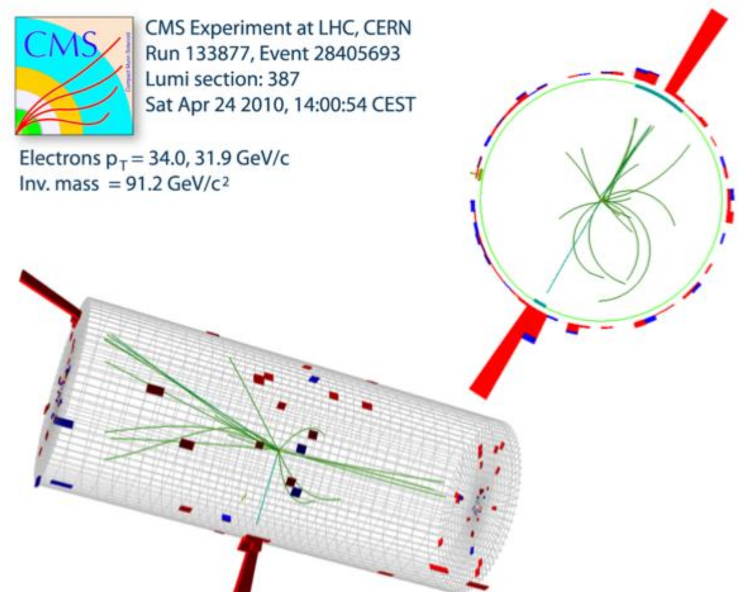
W and Z bosons

W→eν

W→μν



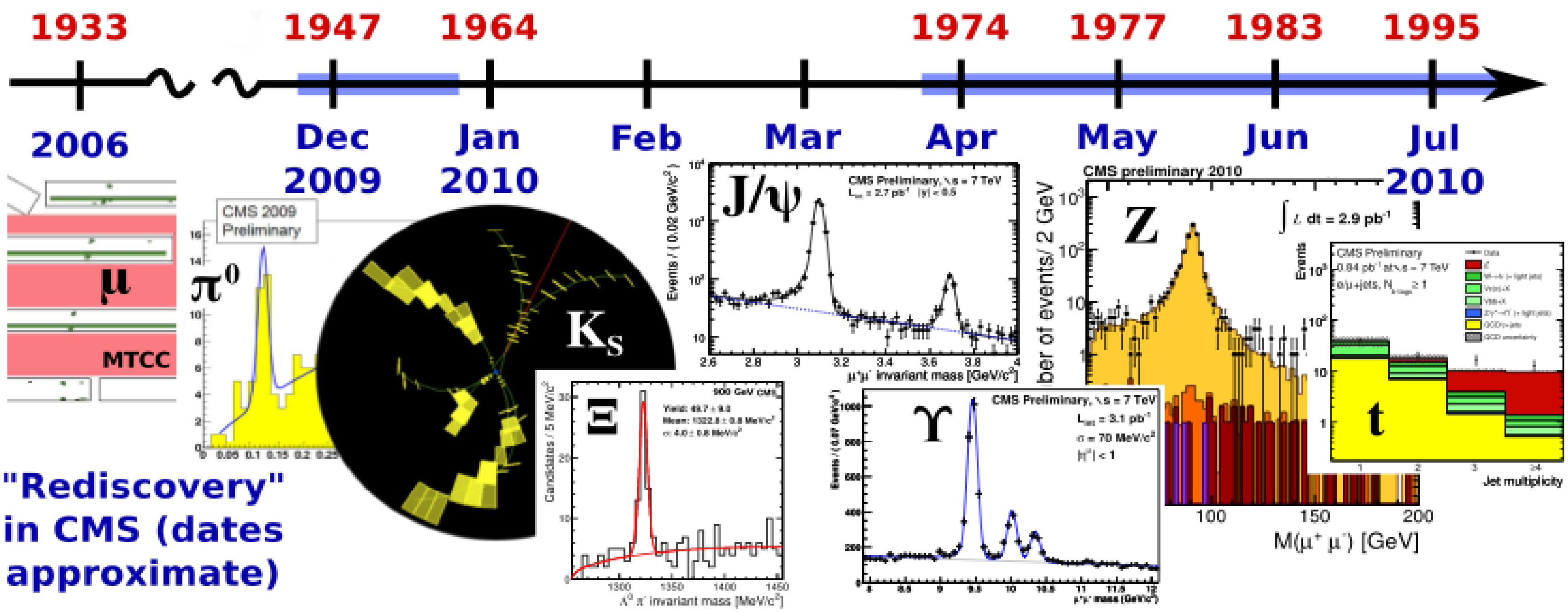




Z→ee:

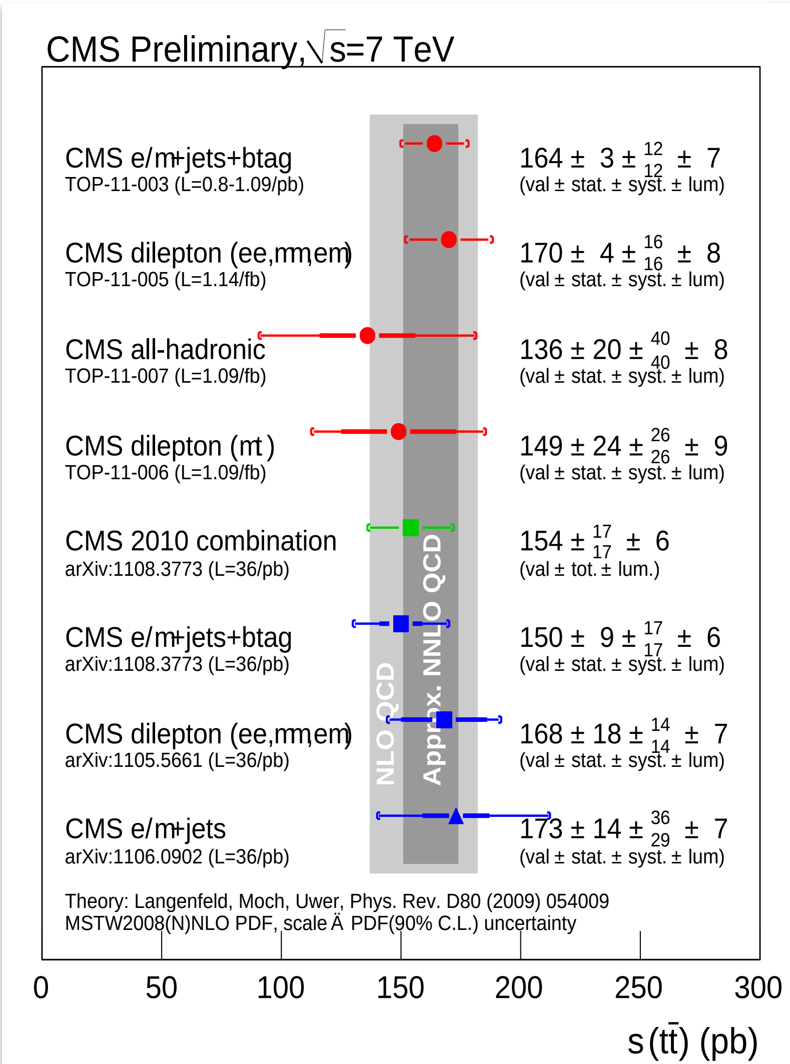
Mass= 91.2 GeV/c2

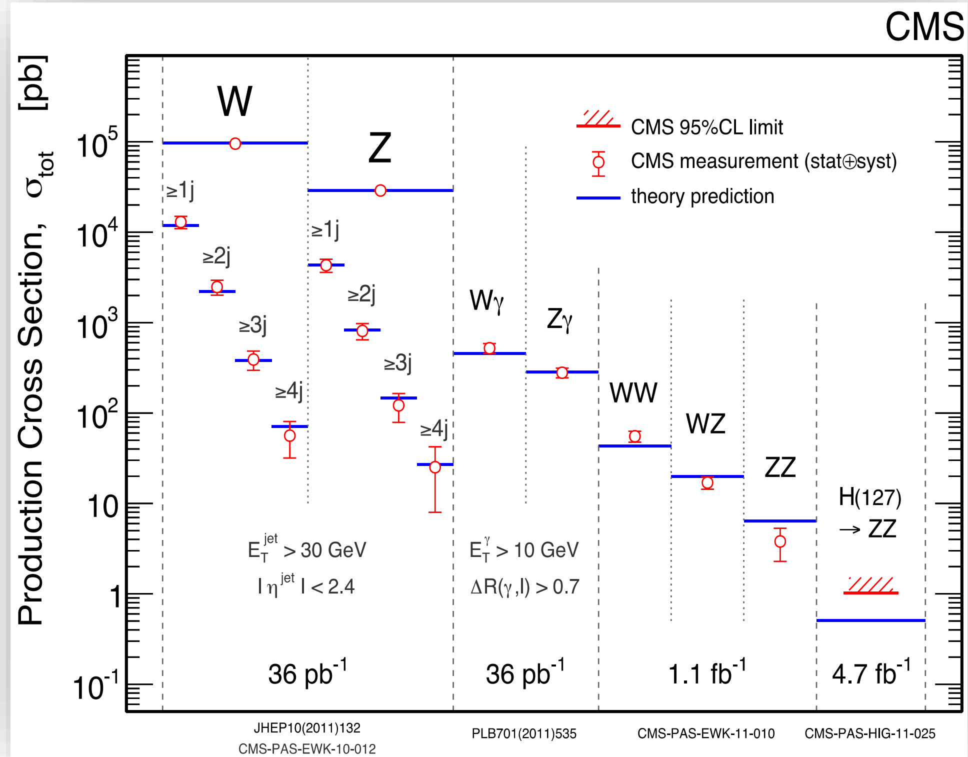
Rediscovery of the Standard Model at LHC



"Rediscovery" in CMS (dates approximate)

Standard Model at 7 TeV (2010-2011)

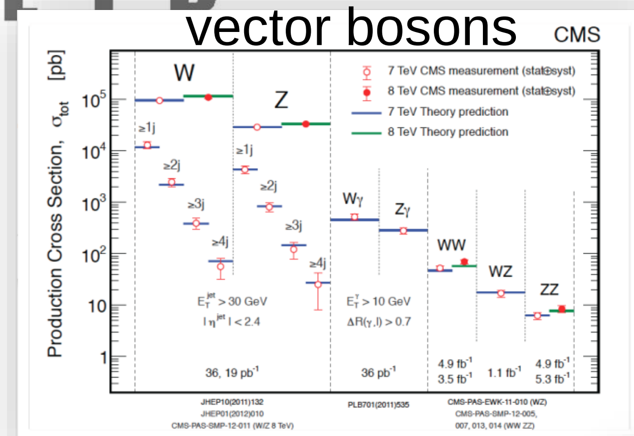


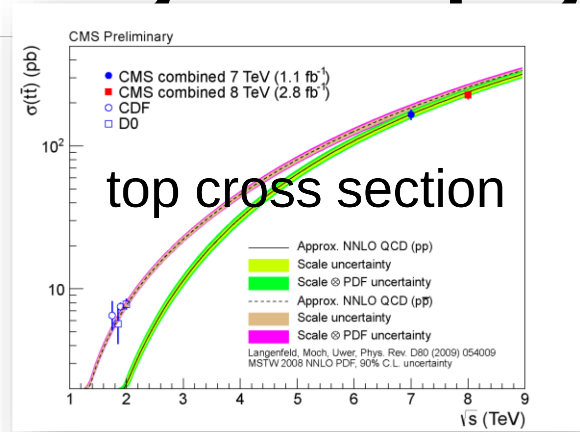


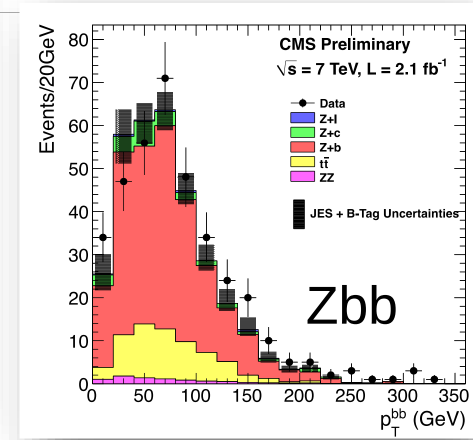
- **Fabulous agreement**
- **Lots of data**

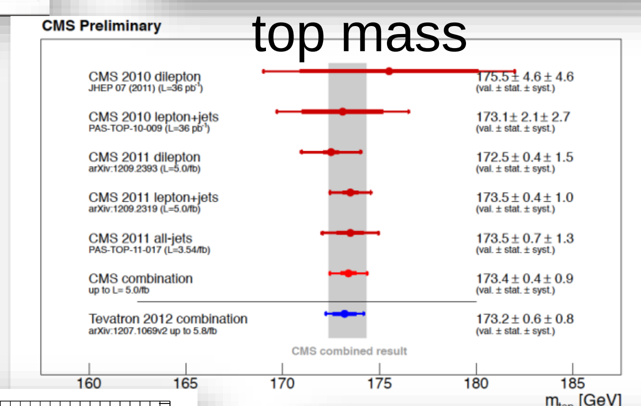
… on to the Higgs…

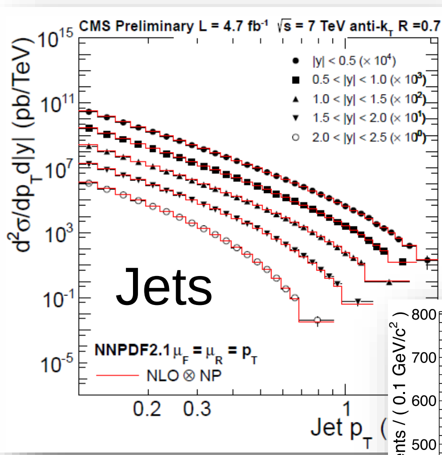
…and many more physics results

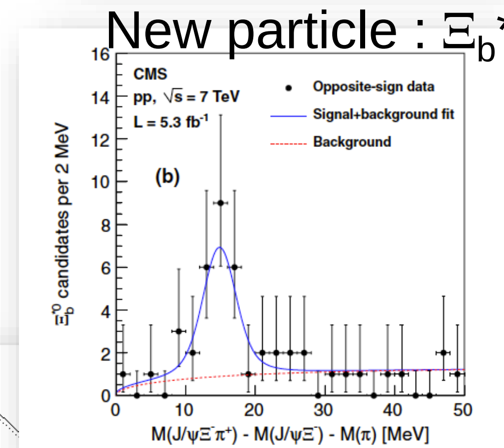


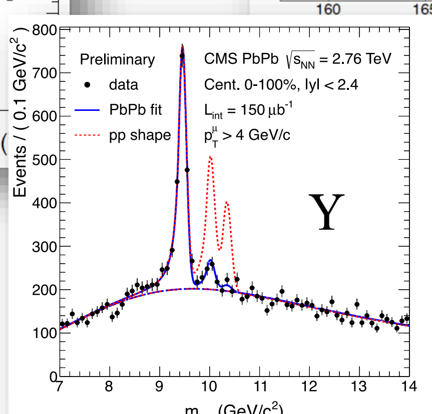


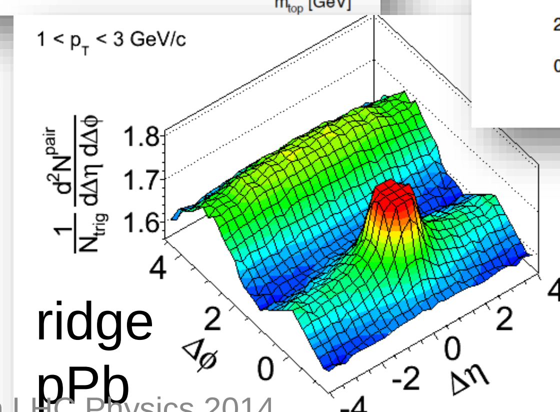








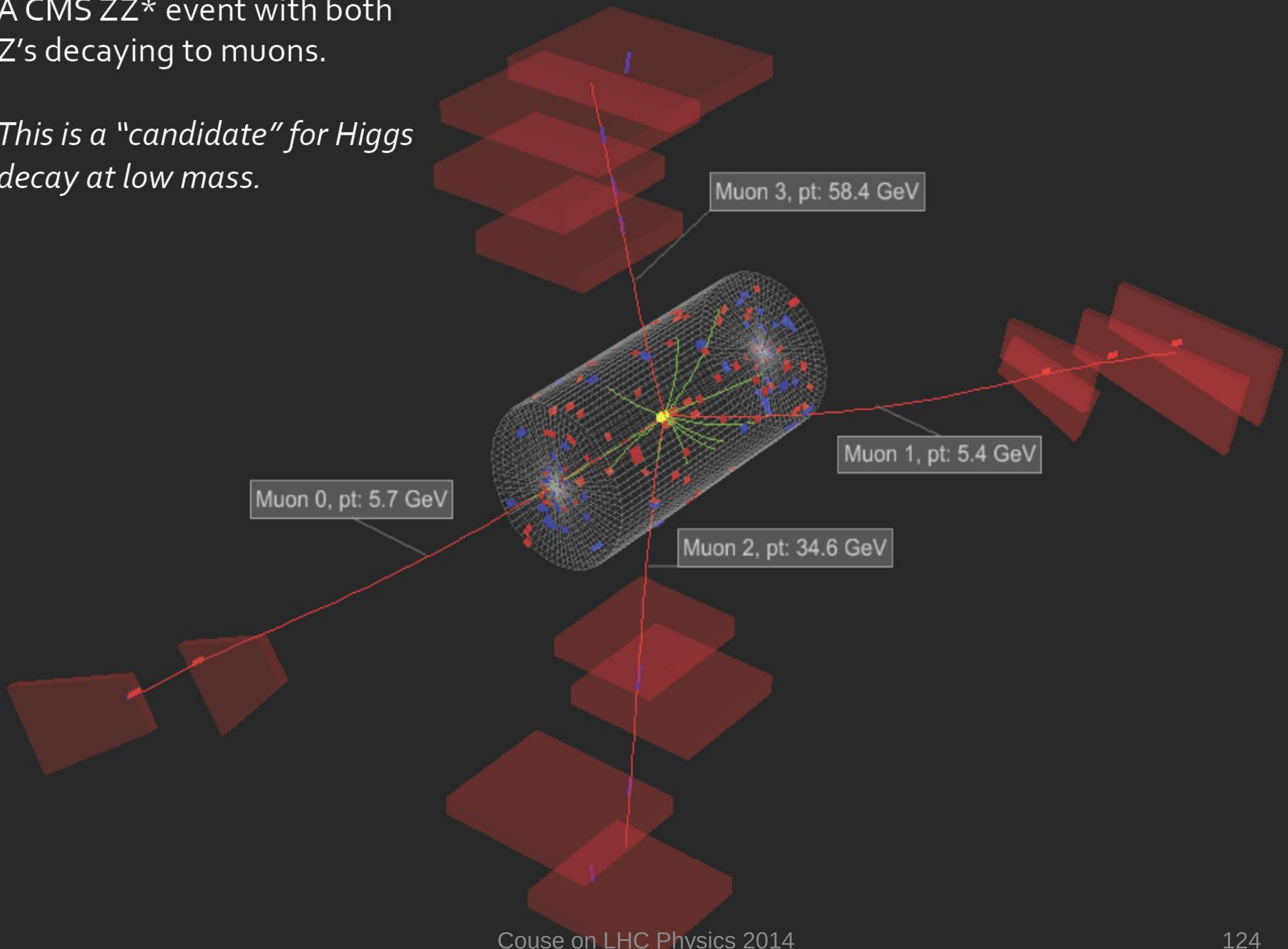


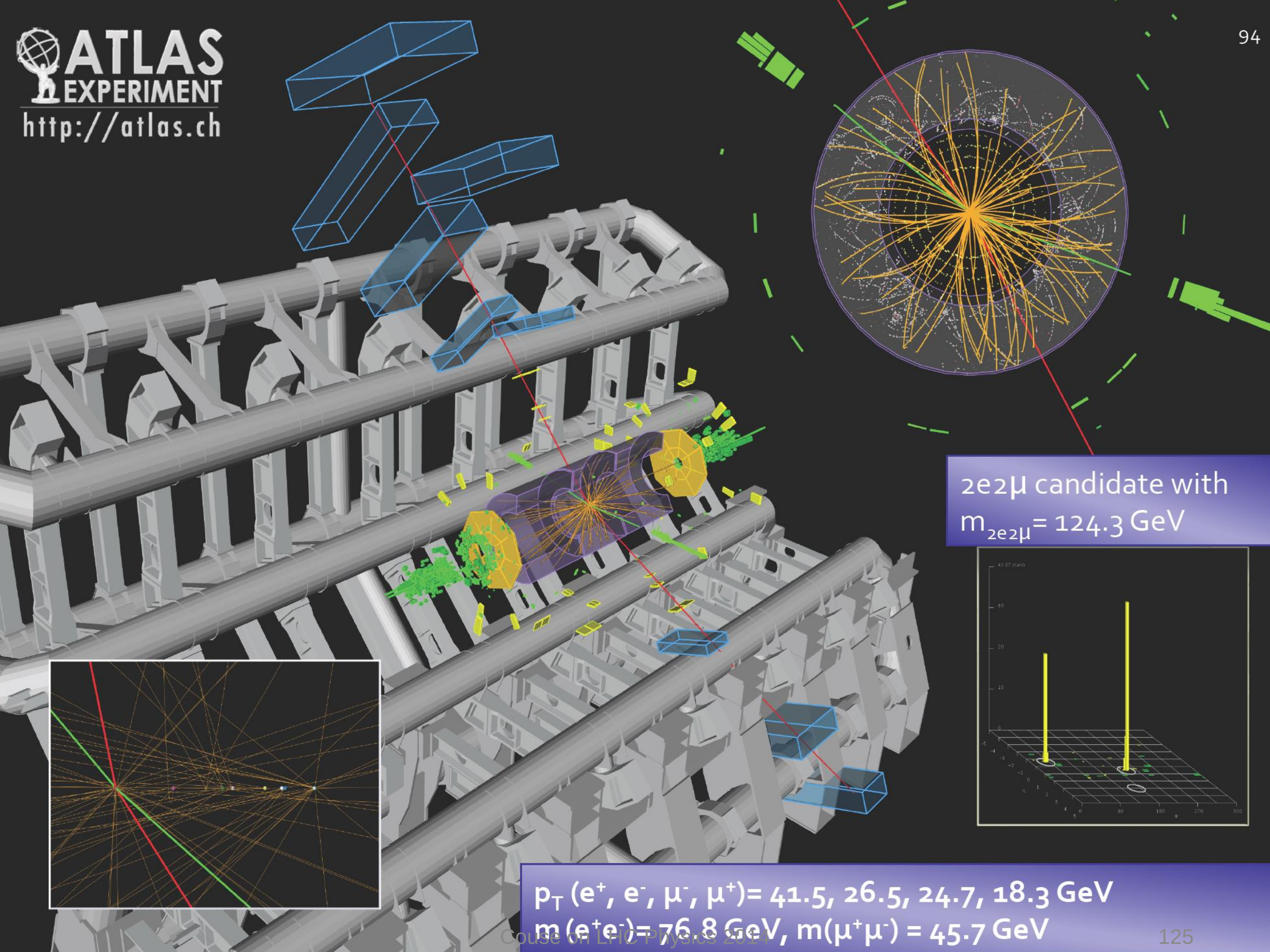


More than 500 papers from LHC

A CMS ZZ* event with both Z's decaying to muons.

This is a "candidate" for Higgs decay at low mass.



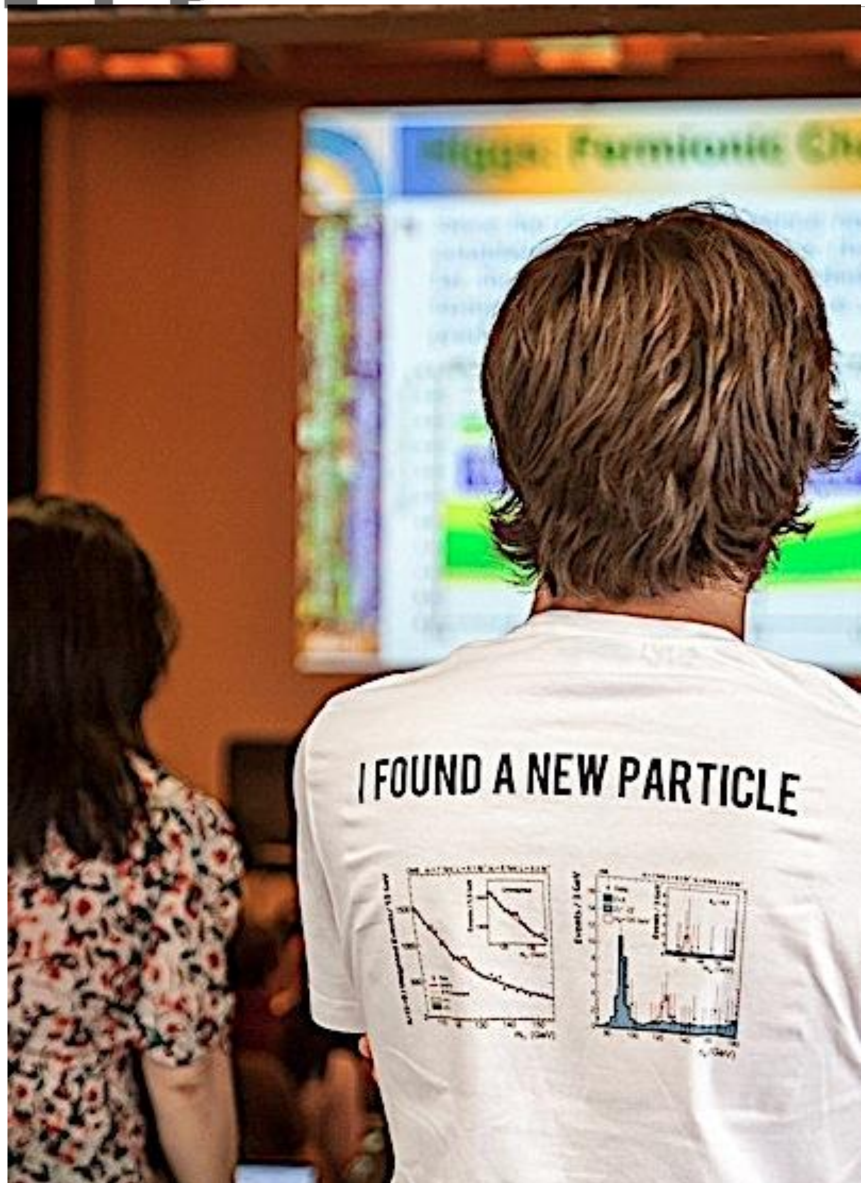


2e2μ candidate with $m_{2e2\mu}$ = 124.3 GeV

p_T (e^+, e^-, μ^-, μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m(e^+e^-)= 76.8 GeV, m($\mu^+\mu^-$) = 45.7 GeV

Both LHC experiments have observed a new boson with a mass near **125 GeV** at significance above **5 σ** !

A new boson was discovered



A major discovery in physics

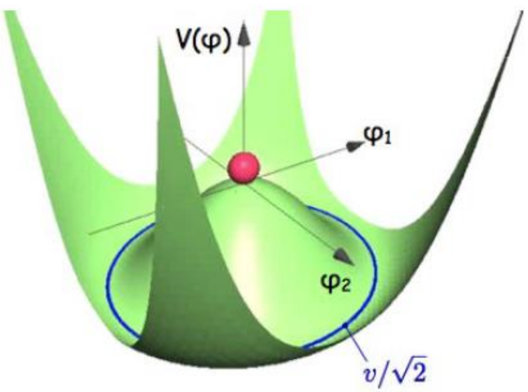
The **new boson** is either the SM Higgs or a Higgs-like particle

Electroweak symmetry breaking is very likely due to some kind of Higgs field

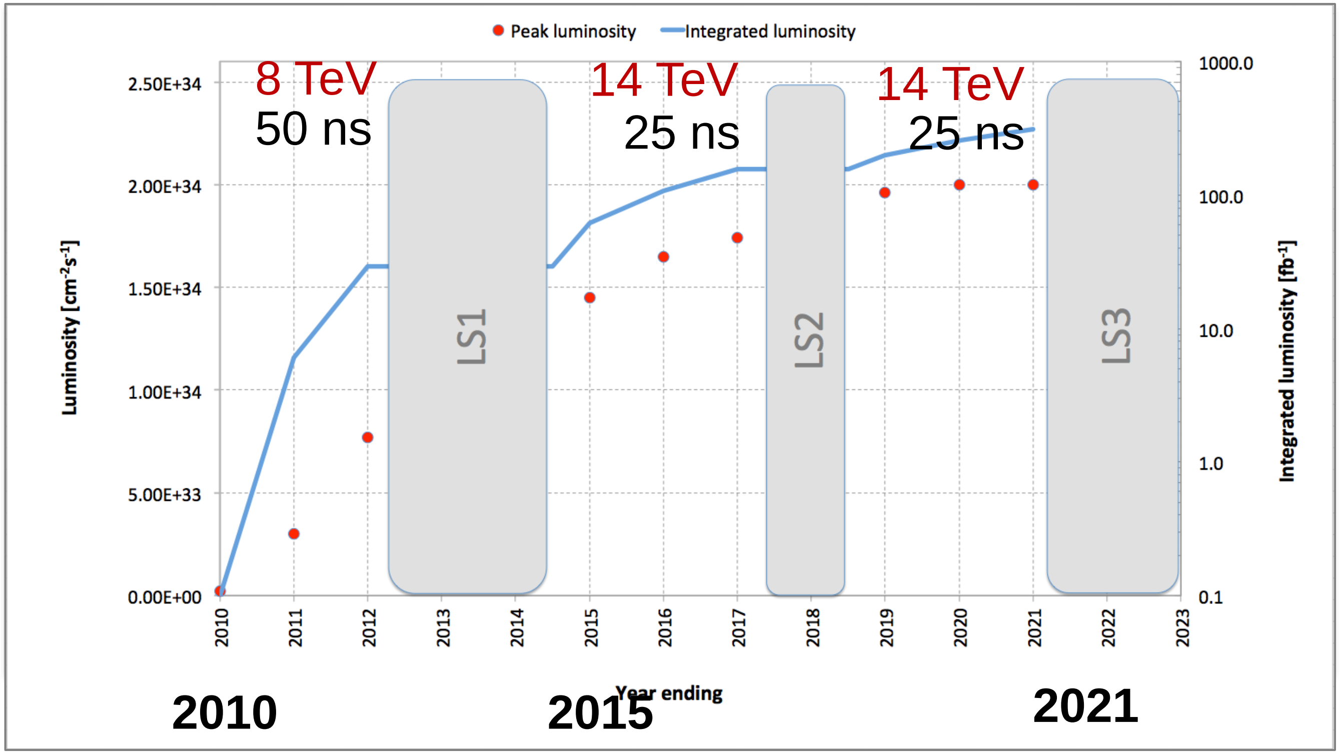
The hypothesis that the **space is filled with a Higgs field** since the origin of the Universe is a plausible assumption.

A new framework to understand the Universe. Cosmological models become more plausible:

- The Universe inflation after the big-bang
- Energy of a Higgs-like field as the source of all matter in the Universe



LHC projections



14 TeV

HL-LHC

Luminosity-leveled at $5x10^{34}$ Hz/cm^2

2023

30 fb^{-1} **300 fb^{-1}** **3000 fb^{-1}**

CMS Detector Upgrades:

Phase 1 Upgrade

Phase 2 Upgrade

End of Lecture 1