SCIENTIFIC AMERICAN Travel BRIGHT HORIZONS 16

The Big Bang Factory

Story of the World's Largest Machine

February 24, 2013

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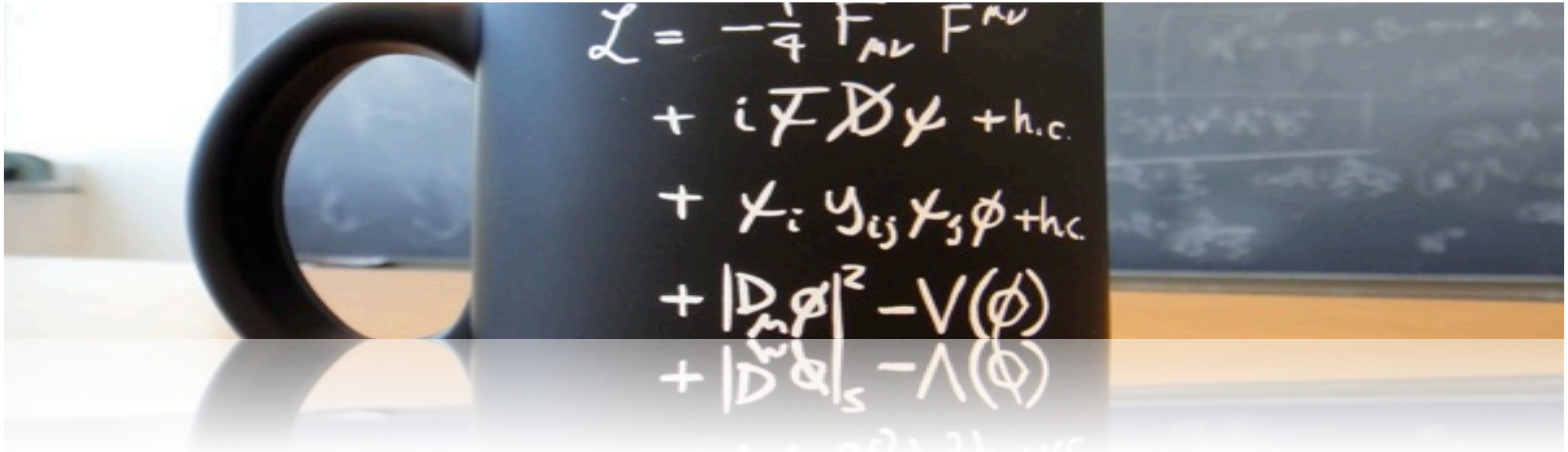
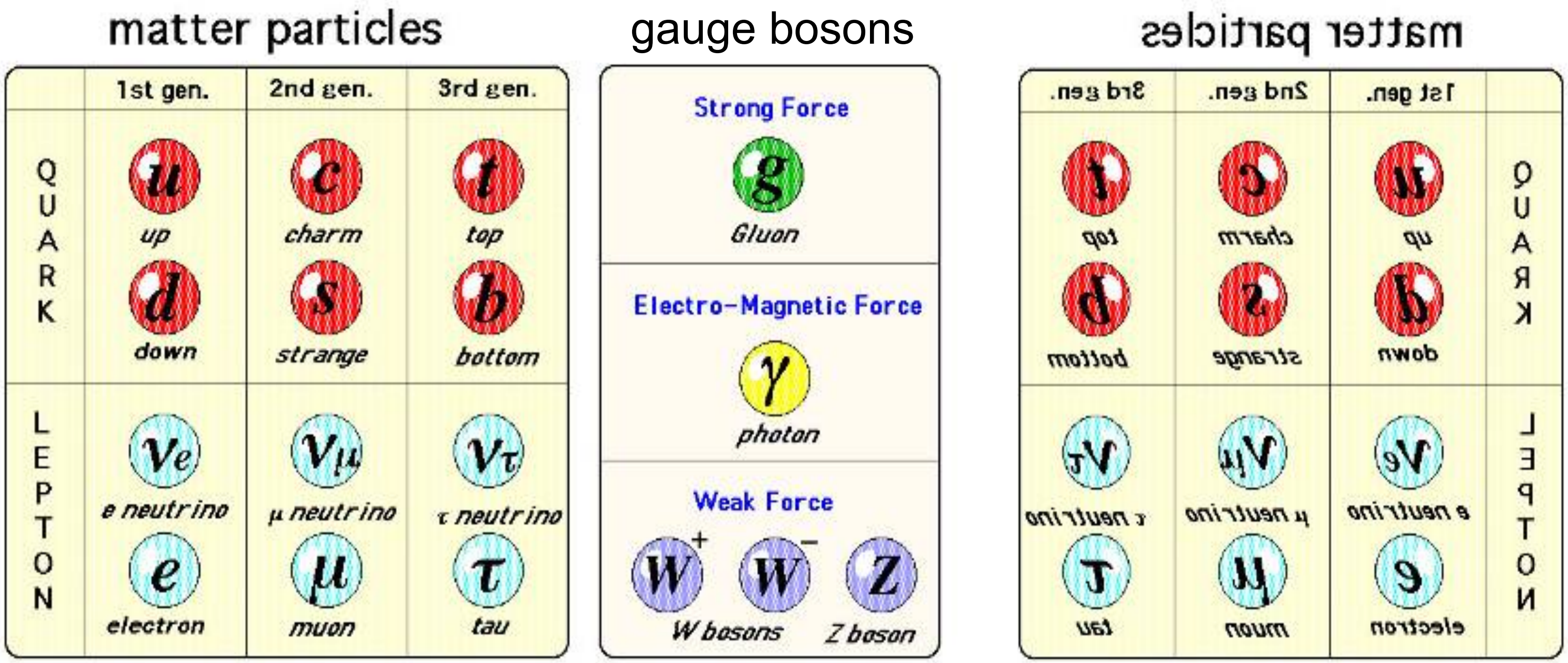
Outline of lecture 2

- The LHC physics case
- The LHC proton collider
- The experiments
- Experimental challenges
- The machine start-up

The LHC physics case
(1980-90)

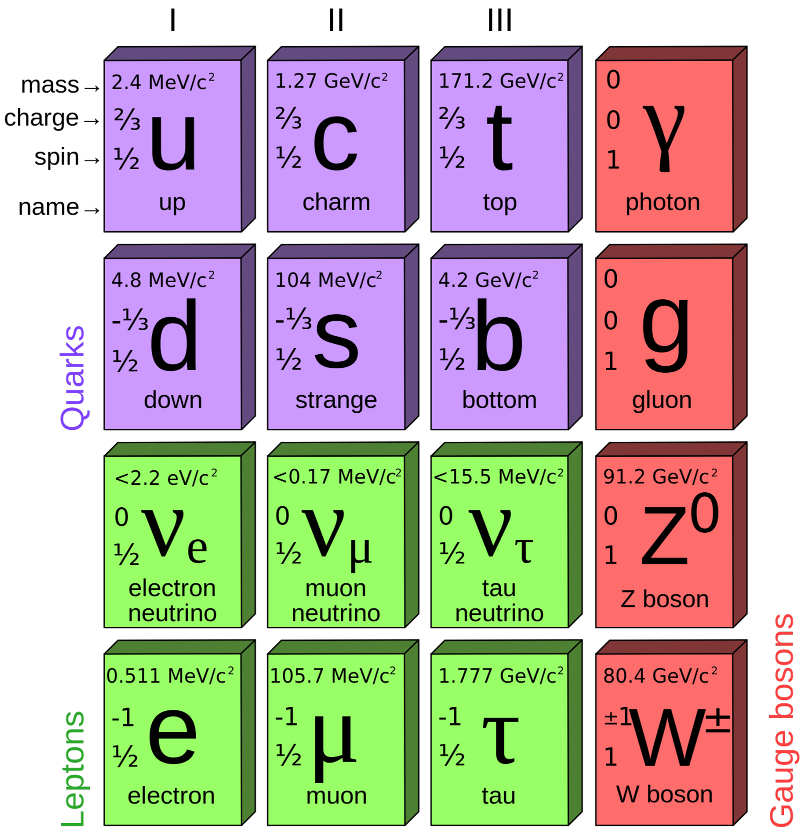


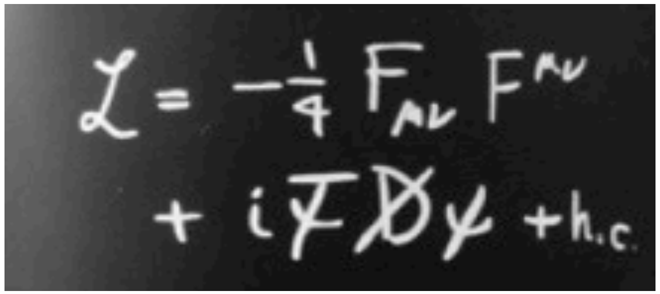
The Standard Model



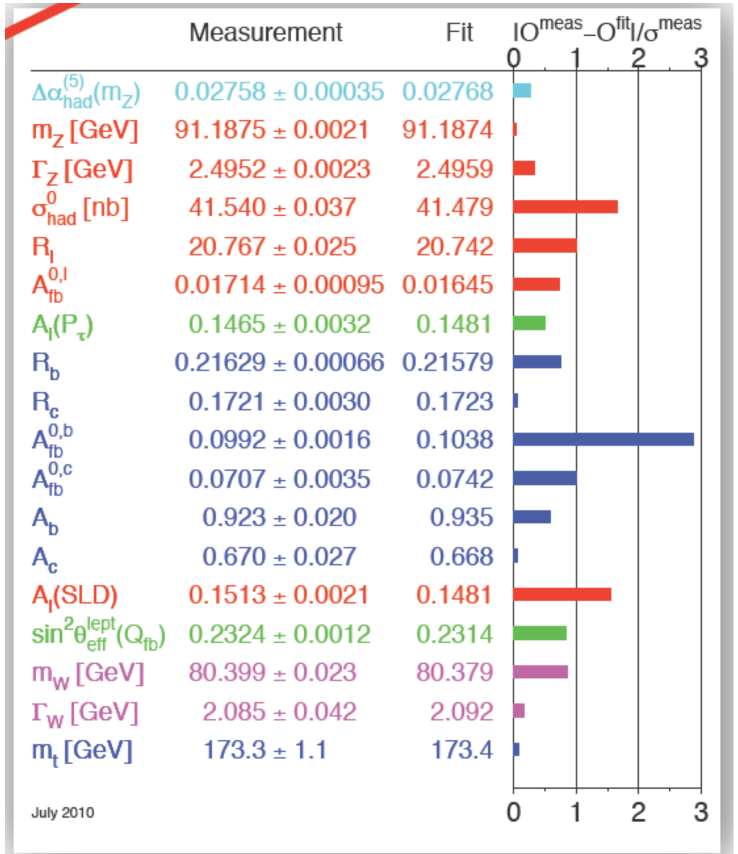
$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q')H$$

SM confirmed by data





STANDARD MODEL OF ELEMENTARY PARTICLES



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!

Mass results from the interaction of particles with the Higgs field

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

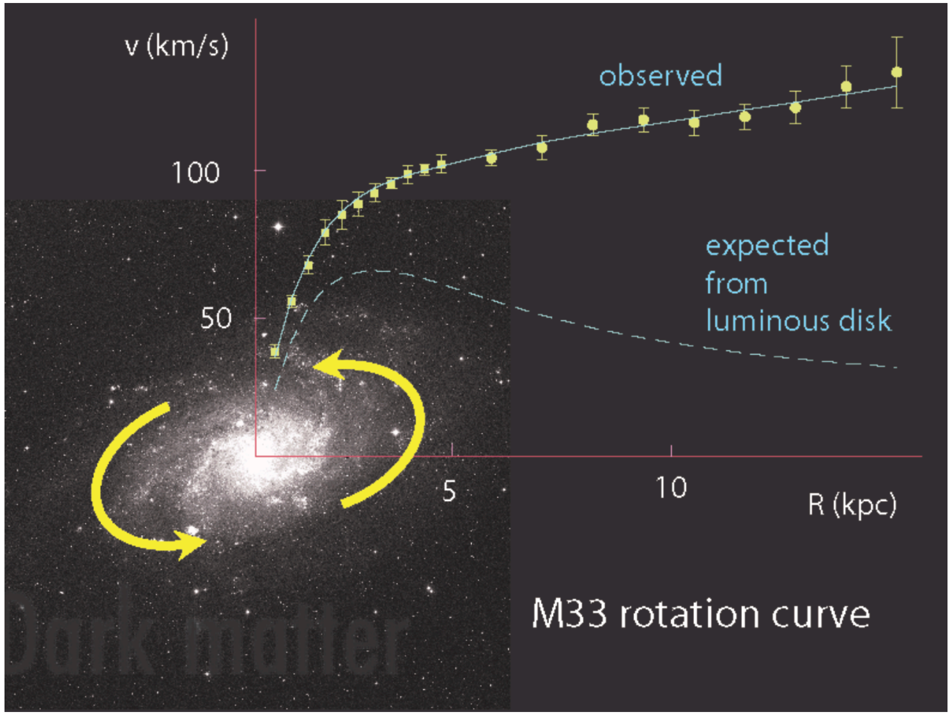
accessible at the LHC for the first time

The 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%?

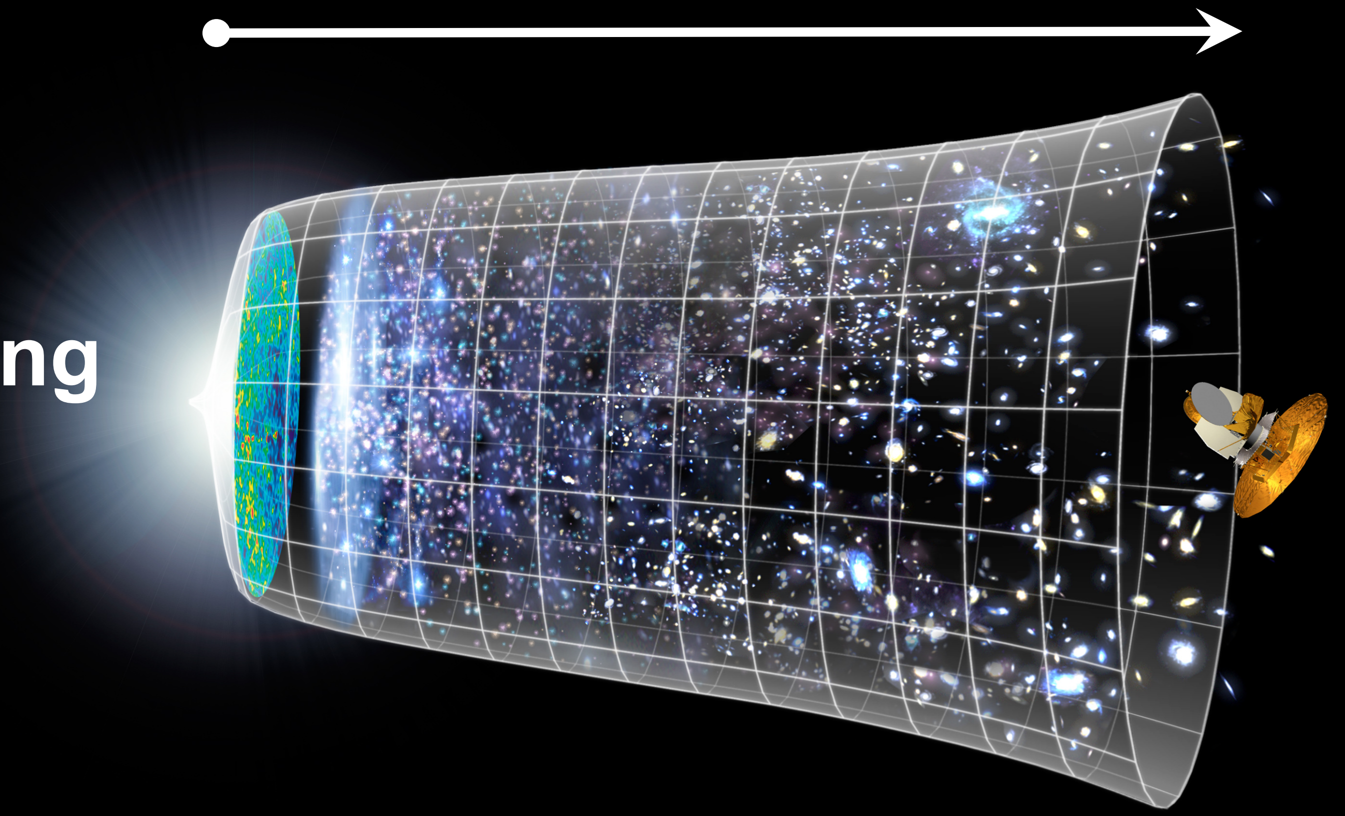


The LHC may help to solve this problem, discovering **dark matter**

Timeline of the Universe

13.7 billion years

Big Bang



Today

NASA/WMAP Science Team

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

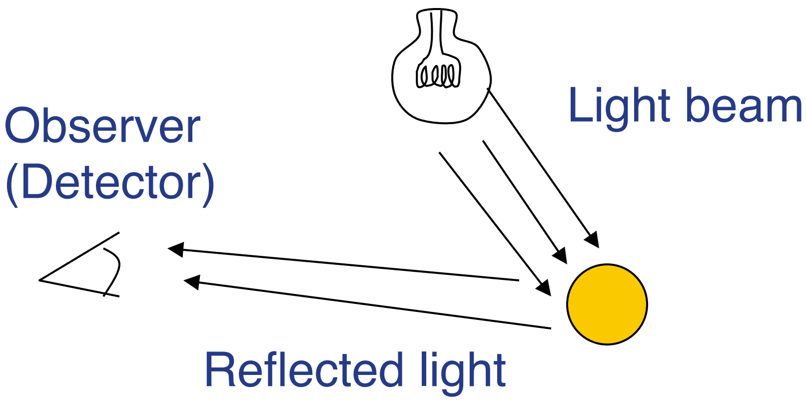
Why accelerators?

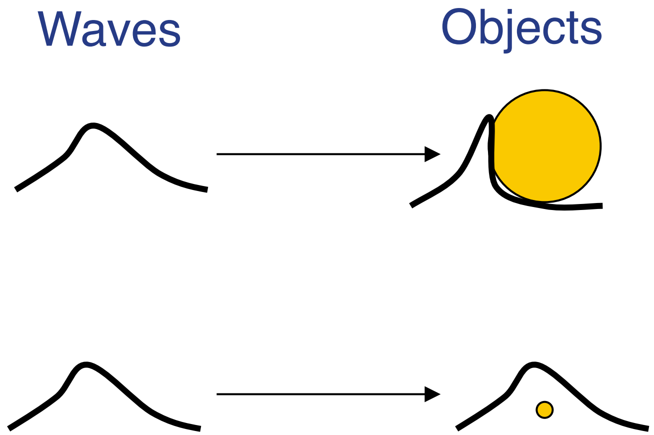
Let there be light

How do we see an object

Light is reflected by objects and detected in the eyes. An image is reconstructed in the brain.

Light is not reflected by objects smaller than the wave length





Wave length of visible light is ~ 0.5 micron
The energy of the photons is 2.5 eV $(p=1/\lambda)$

(1 micrometer – 1 μm - is one millionth of a meter)

Particles and waves

Elementary particles have a mysterious behavior

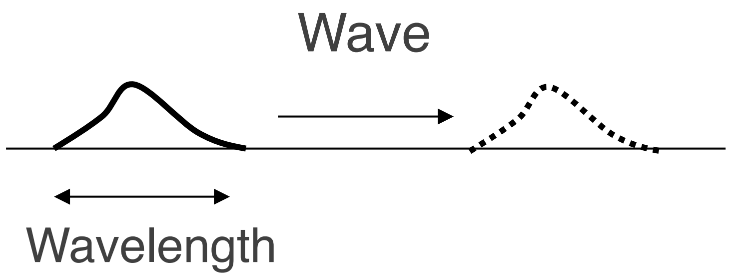
In some situations particles behave like waves

QUANTUM MECHANICS

DeBroglie (1920):

$$\lambda = 1 / p$$

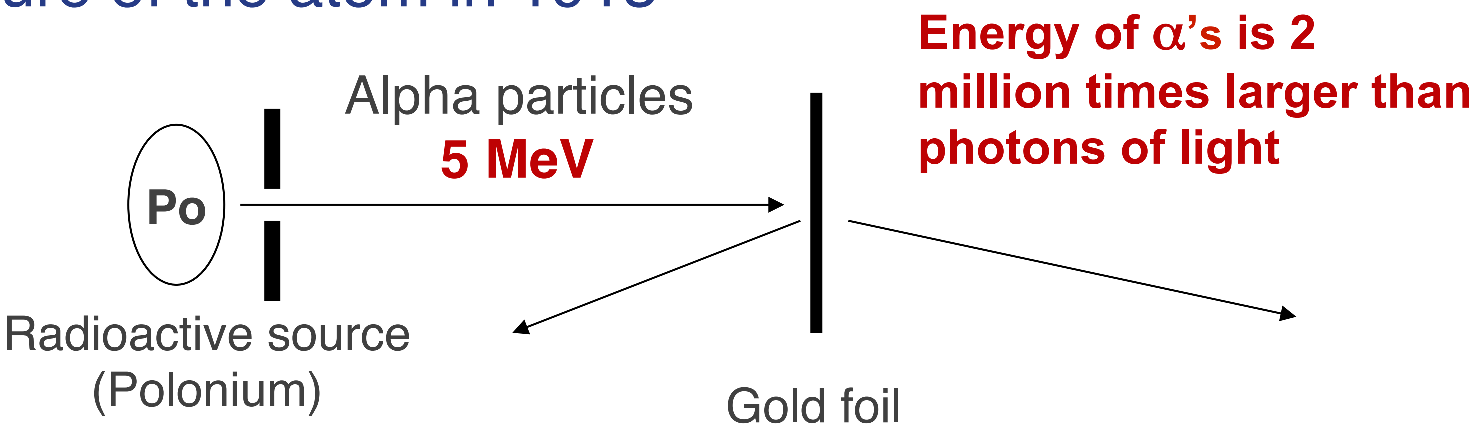
Wavelength — Momentum (mass times speed)

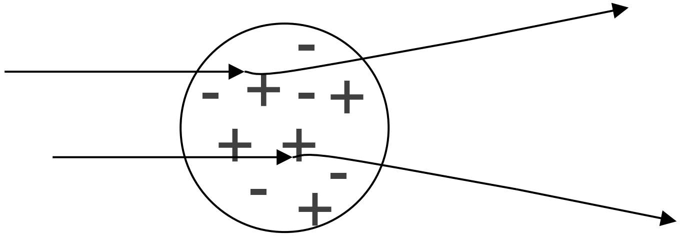


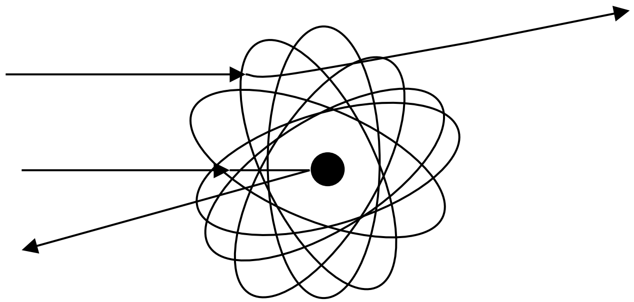
The larger is the energy (momentum) the smaller is the wavelength

Particle beam to 'see' the atom

Remember the Rutherford experiment and the discovery of the structure of the atom in 1913







Atomic model incompatible with the experimental results

The experiment revealed a very small and high density nucleus inside the atom

The most powerful microscope

The LHC allows to see objects with 10^{-20} m

Light	Atom	Proton	Quarks	?
10^{-7} m	10^{-10} m	10^{-15} m	$< 10^{-18}$ m	10^{-20} m

1 / 1000   1 / 100,000   1 / 1000   1 /100

Optical microscope
1 eV

LHC
10^{13} eV

10 000 000 000 000

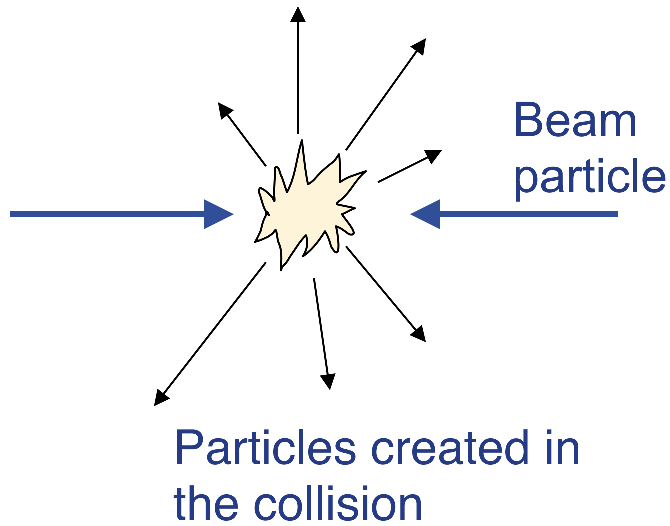
Ten million million times more resolution power

$E=m.c^2$

Mass is transformed in energy at power nuclear reactors

Energy is transformed in mass at accelerators

The kinetic energy of the beam particles is transformed in the mass of other particles created in the collision

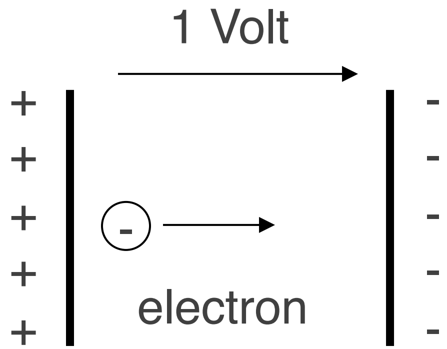


The mass of particles is equal to energy necessary to produce them

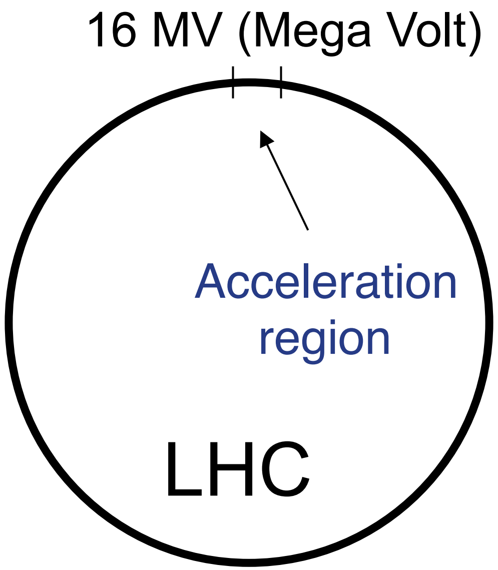
Heavy particles need very high energy accelerators to be created

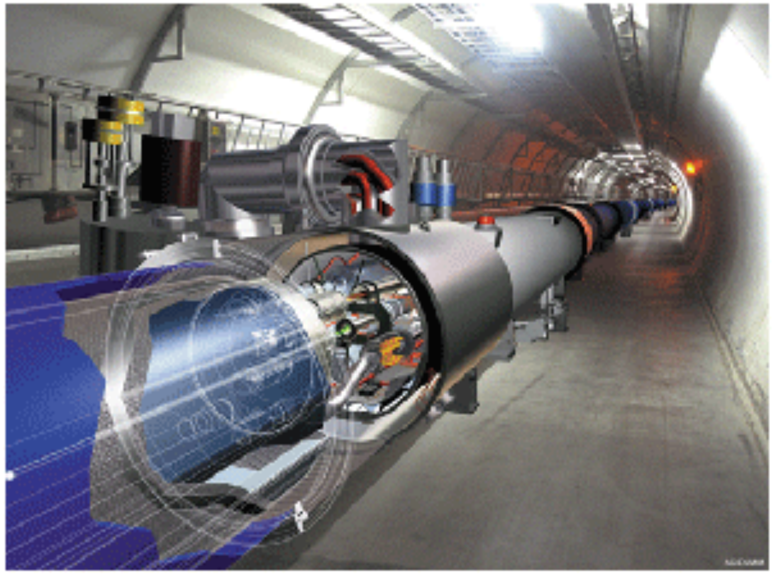
Accelerators

Elementary particles are accelerated in electric fields



The electron gets an energy of 1 electron-volt (eV)





LHC - Large Hadron Collider

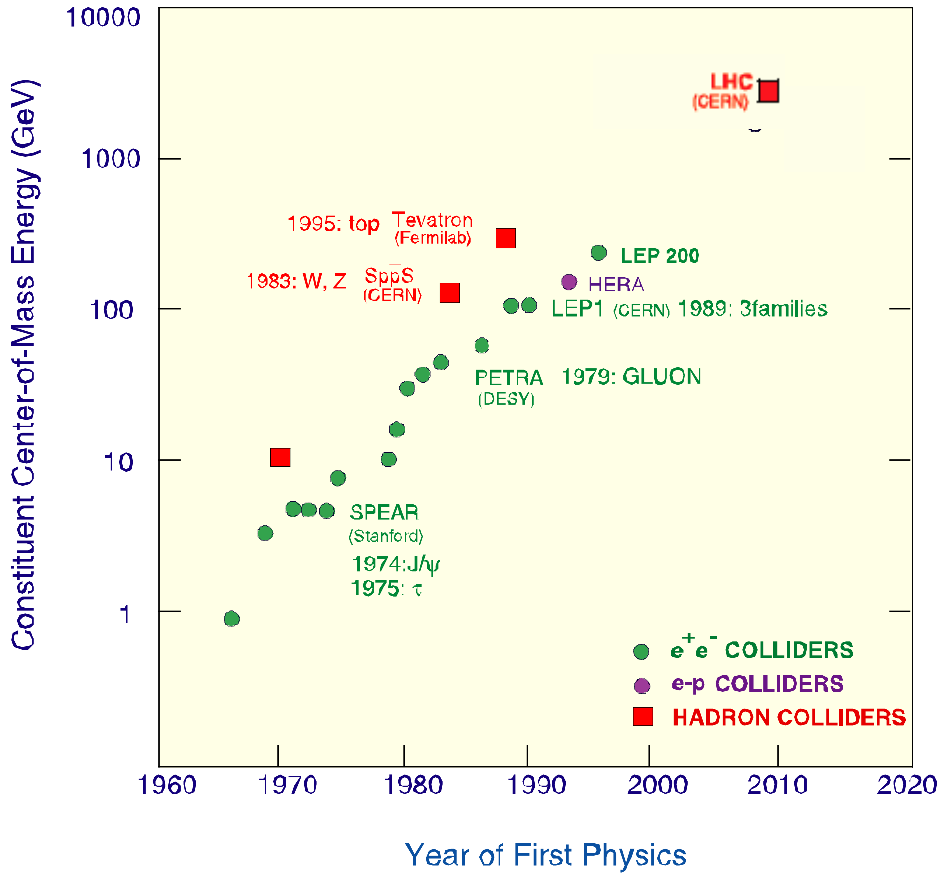
Protons get an energy of 7 TeV

7.10^{12} eV =

7 000 000 000 000 eV =

7 million million eV

What type of accelerator ?



Proton-proton collider

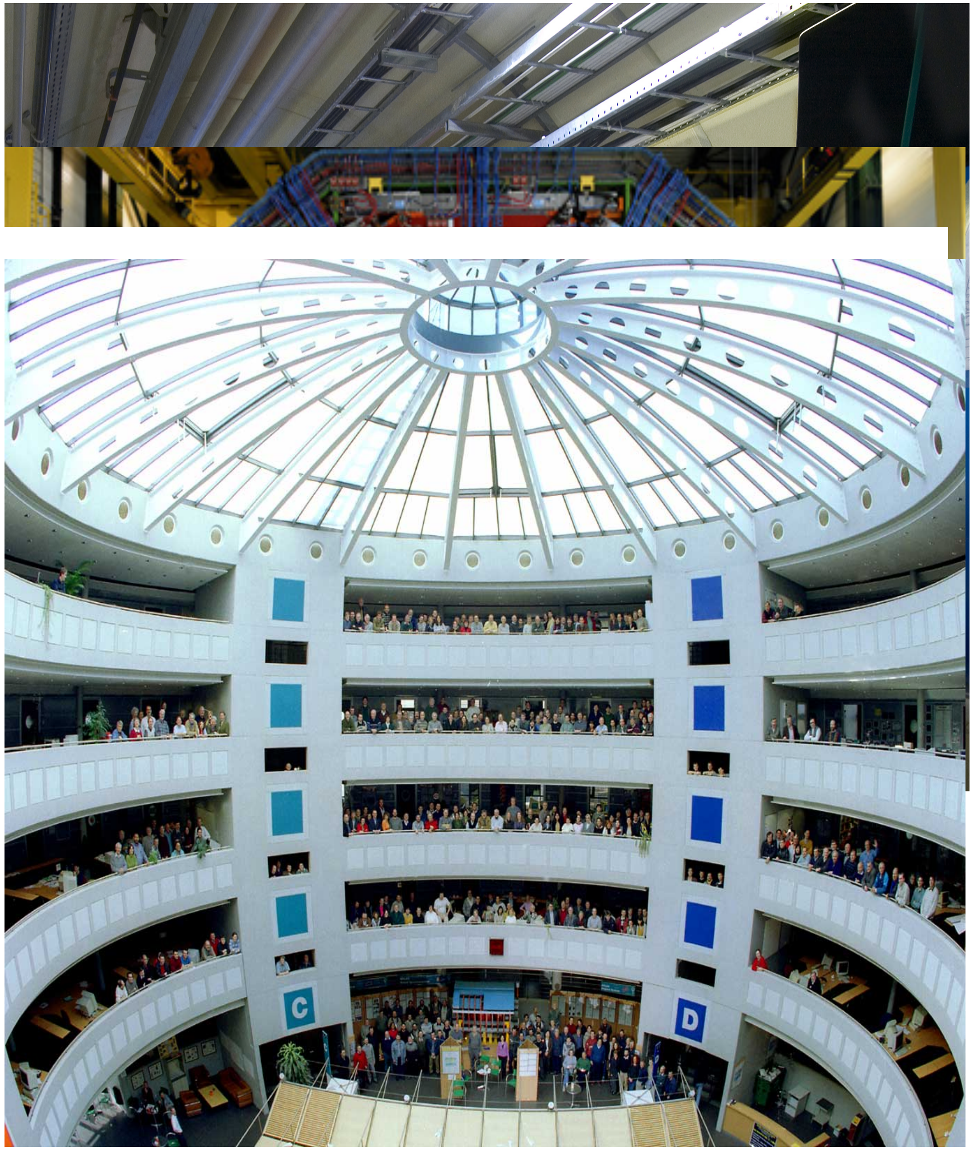
The easiest path to explore a new energy domain

Search for the unexpected at ~ 1 TeV

Largest possible luminosity

In about one hundred years the energy of accelerators was increased by a factor one million

This research requires…….



1. Accelerators : powerful machines capable of accelerating particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the particles as they "stream" out from the point of collision.

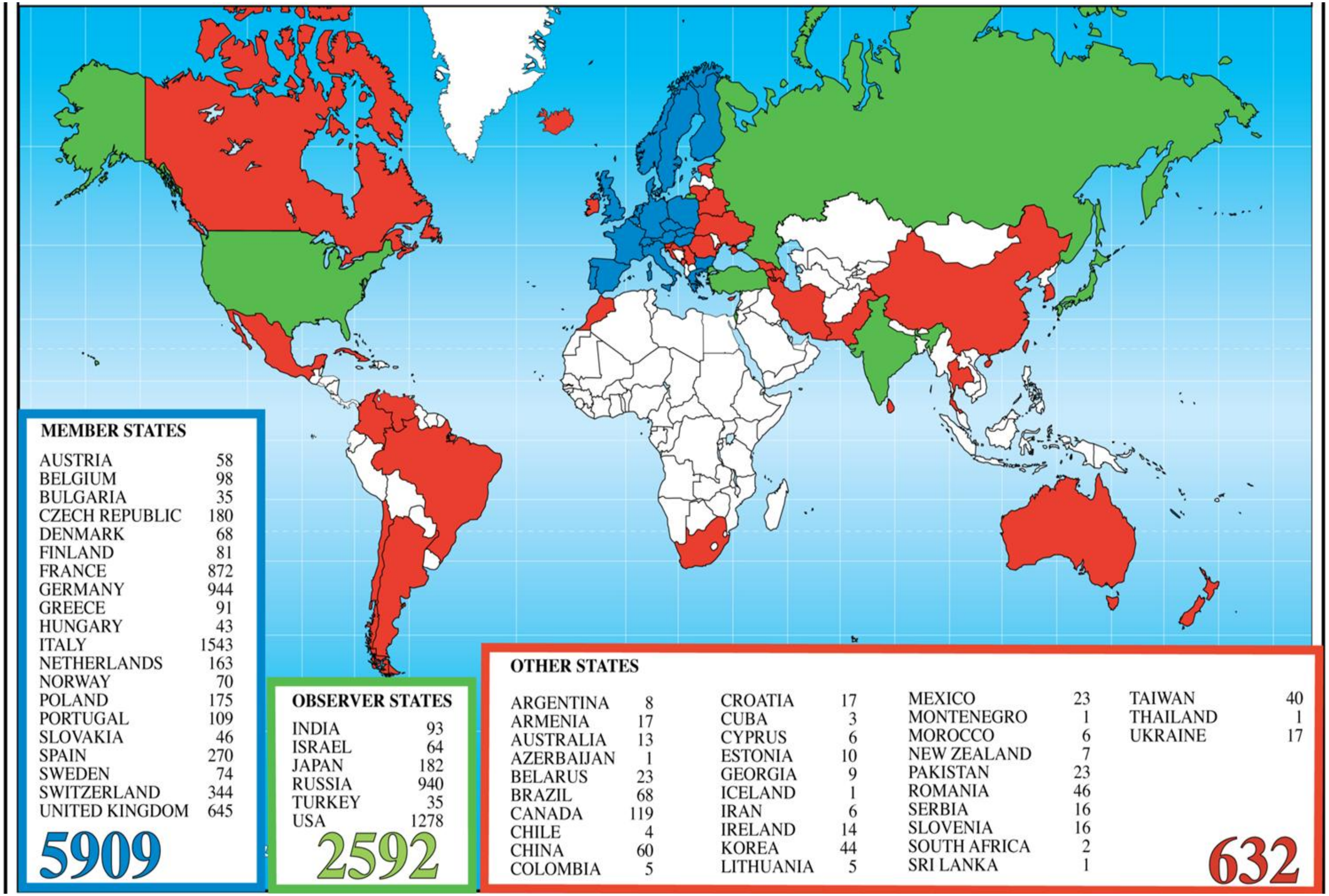
3. Computers : to collect, store, distribute and analyse the vast amount of data produced by the detectors

4. People : Only a worldwide collaboration of thousands of scientists, engineers, technicians and support staff can design, build and operate such complex "machines"

In 1995 the CERN Council approved the construction of the LHC accelerator two large detectors (CMS and ATLAS) and two smaller ones (ALICE, LHCb)

Cost ~ 6 Billion CHF

The User Community of CERN



MEMBER STATES

AUSTRIA	58
BELGIUM	98
BULGARIA	35
CZECH REPUBLIC	180
DENMARK	68
FINLAND	81
FRANCE	872
GERMANY	944
GREECE	91
HUNGARY	43
ITALY	1543
NETHERLANDS	163
NORWAY	70
POLAND	175
PORTUGAL	109
SLOVAKIA	46
SPAIN	270
SWEDEN	74
SWITZERLAND	344
UNITED KINGDOM	645

5909

OBSERVER STATES

INDIA	93
ISRAEL	64
JAPAN	182
RUSSIA	940
TURKEY	35
USA	1278

2592

OTHER STATES

ARGENTINA	8	CROATIA	17	MEXICO	23	TAIWAN	40
ARMENIA	17	CUBA	3	MONTENEGRO	1	THAILAND	1
AUSTRALIA	13	CYPRUS	6	MOROCCO	6	UKRAINE	17
AZERBAIJAN	1	ESTONIA	10	NEW ZEALAND	7		
BELARUS	23	GEORGIA	9	PAKISTAN	23		
BRAZIL	68	ICELAND	1	ROMANIA	46		
CANADA	119	IRAN	6	SERBIA	16		
CHILE	4	IRELAND	14	SLOVENIA	16		
CHINA	60	KOREA	44	SOUTH AFRICA	2		
COLOMBIA	5	LITHUANIA	5	SRI LANKA	1		

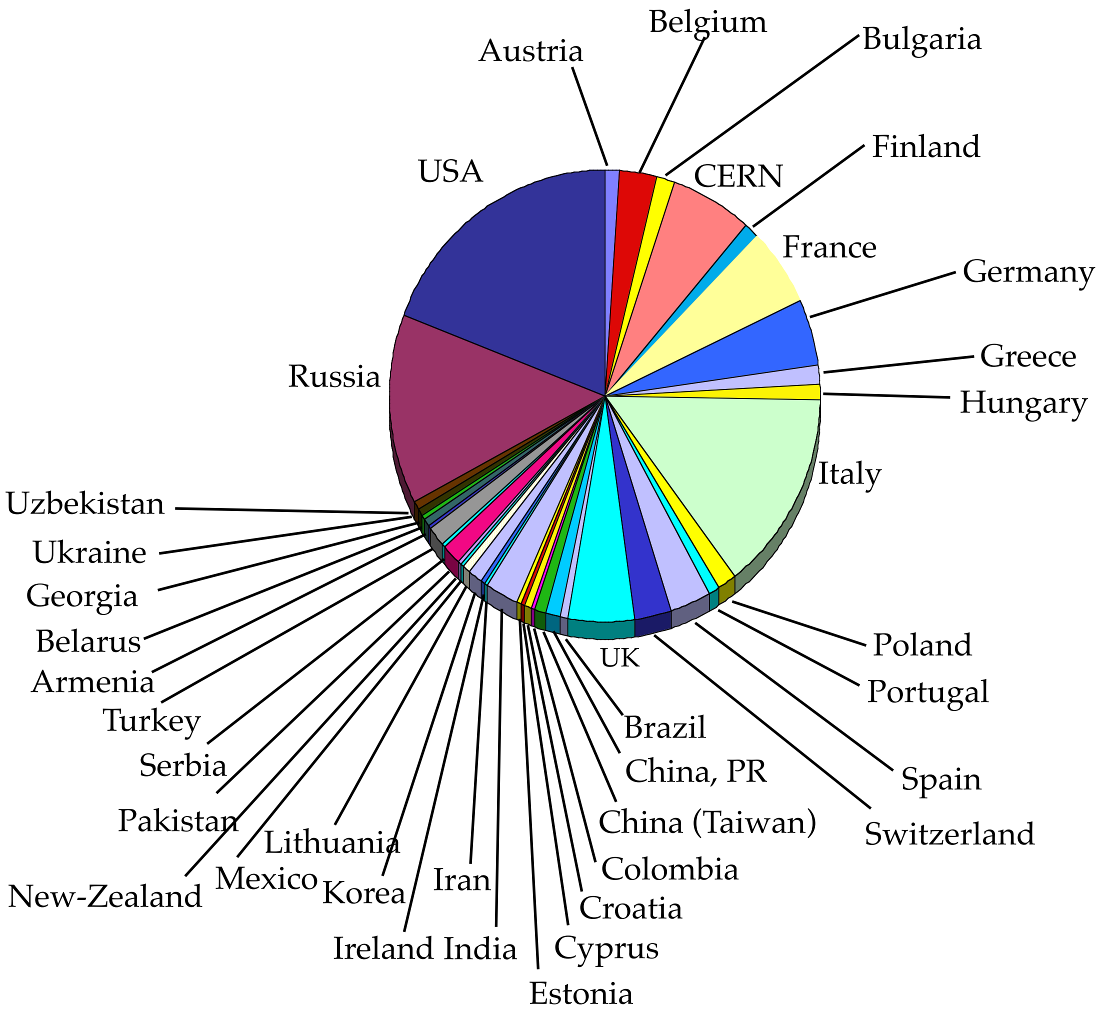
632

The CMS Collaboration

	Number of Laboratories
Member States	59
Non-Member States	67
USA	49
Total	175

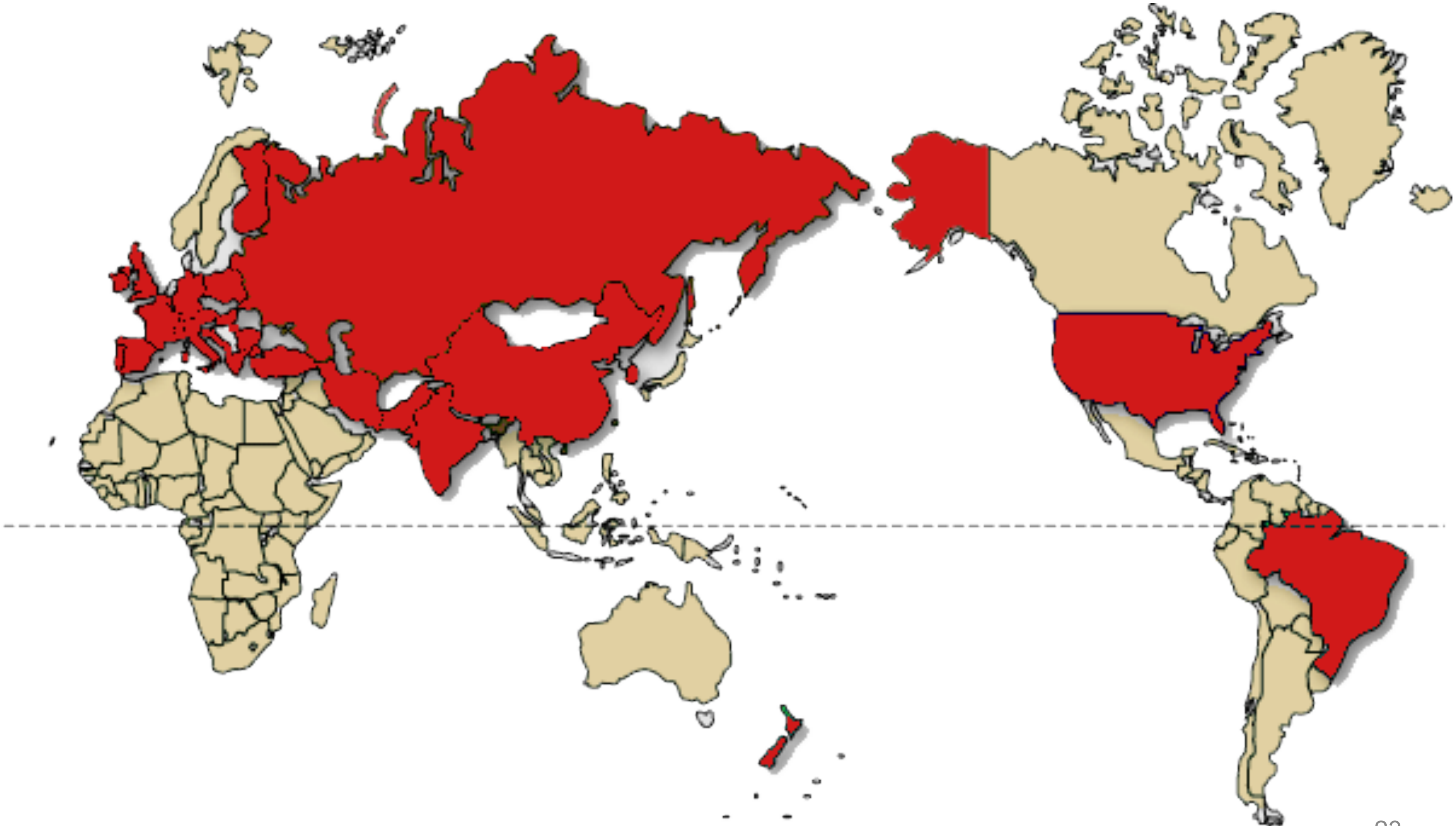
	# Scientific Authors
Member States	1084
Non-Member States	503
USA	723
Total	2310

Associated Institutes	
Number of Scientists	62
Number of Laboratories	9



2310 Scientific Authors
38 Countries
175 Institutions

The CMS collaboration

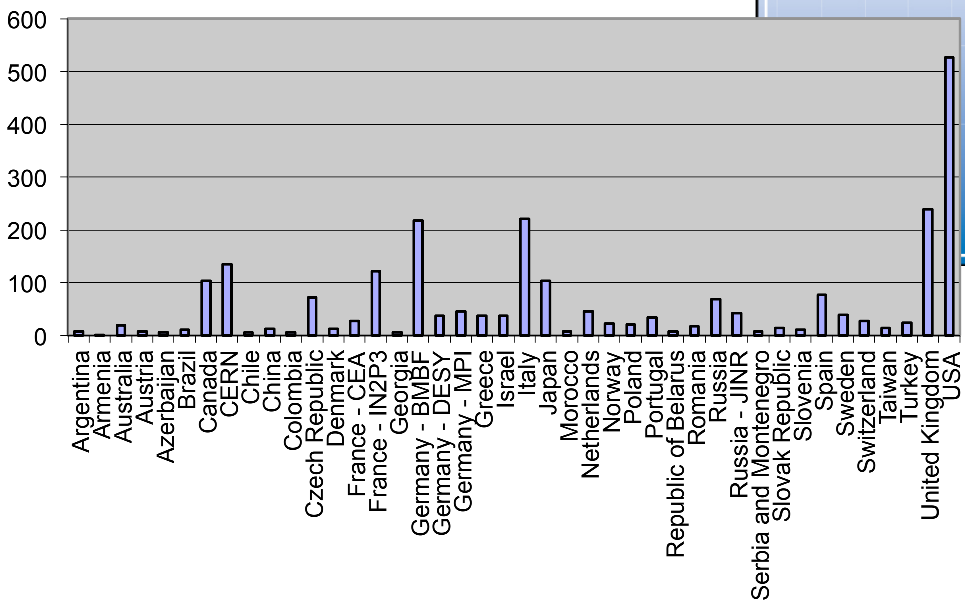


The ATLAS Collaboration

ATLAS

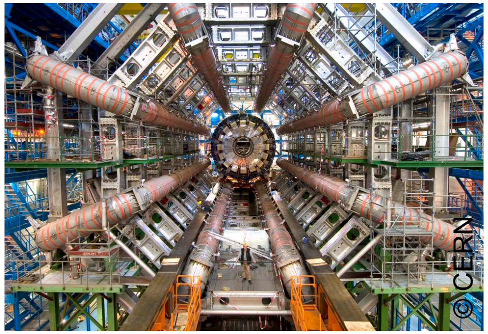
37 Countries
169 Institutions
2500 Scientific Authors

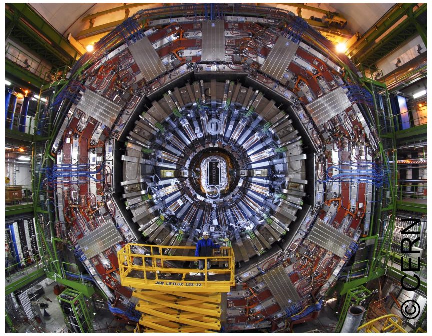
ATLAS Members per Funding Agency



The LHC proton collider

Huge instruments now in place in Switzerland and France outside Geneva:





The Large Hadron Collider

Large is an understatement!
Hadrons referred to here are protons.
Collide is what it does.

The LHC Accelerator

J. Varela, The Big Bang factory, 2013

Protons are accelerated by powerful electric fields

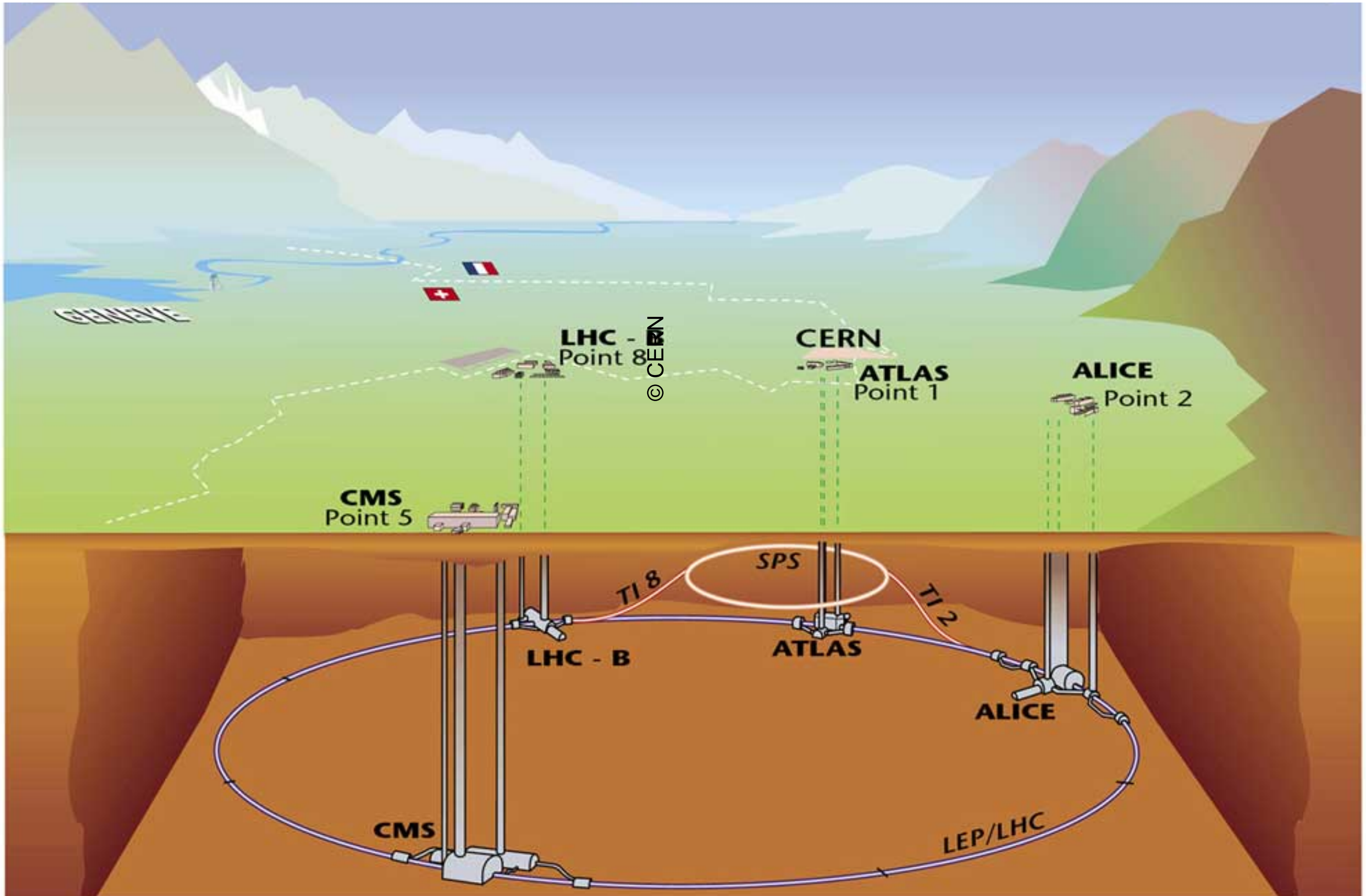
and are guided around their circular orbits by powerful superconducting dipole magnets

Relative to Tevatron (Fermilab, USA)

Energy (14 TeV)	x 7
Luminosity ($10^{34} cm^{-2} s^{-1}$)	x 30

Accelerator and Experiments

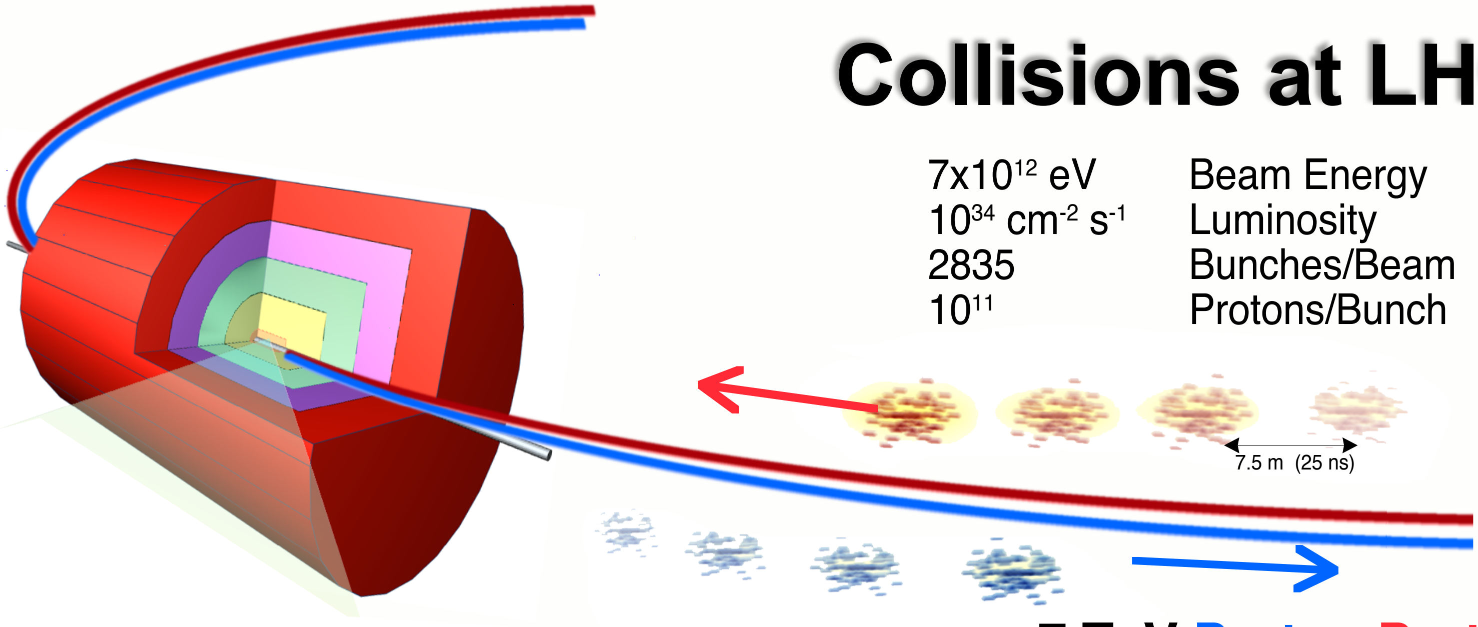
Accelerator and experiments layout



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

Collisions at LHC

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

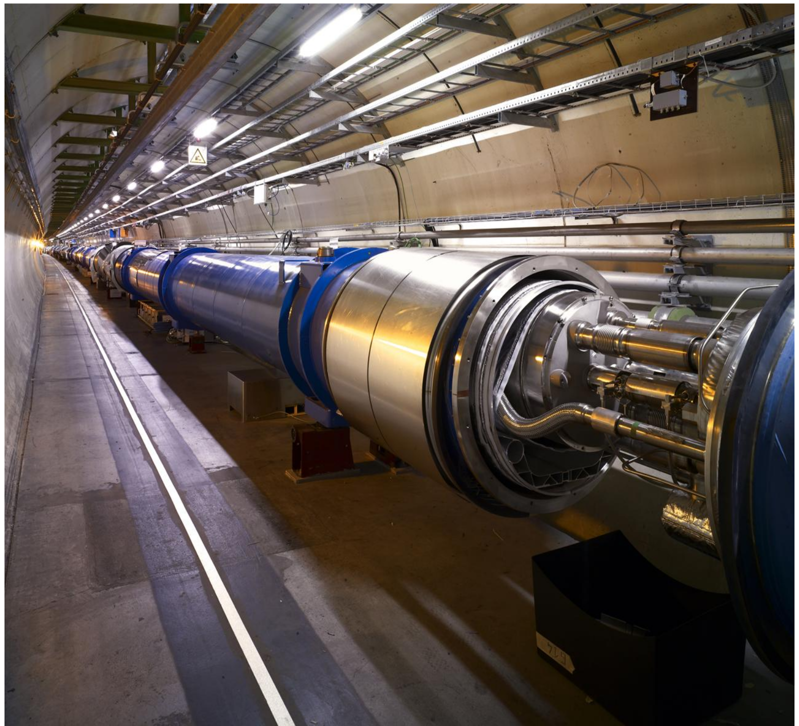


7 TeV Proton Proton
colliding beams

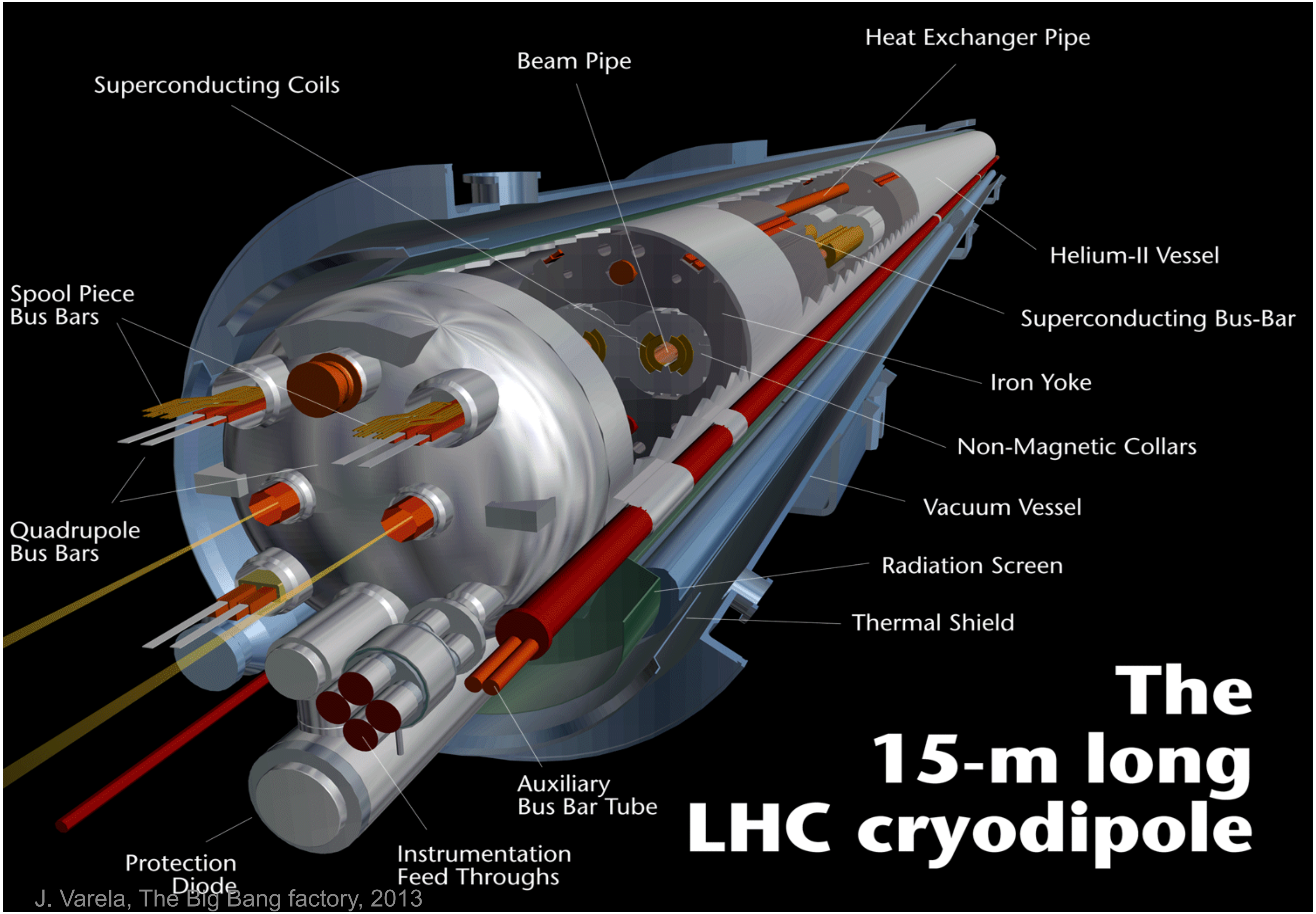
Accelerator challenges

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

- Machine with huge size
  - Tunnel 27 Km
  - More than 2000 dipoles
  - More than 33,000 tonnes of 'cold mass'
  - 27 km of cryogenic distribution line (100 ton liquid helium)
- LHC power consumption 120 MW
  - the same as the Geneva canton



Superconducting magnetic dipole



J. Varela, The Big Bang factory, 2013

Superconducting magnetic dipole

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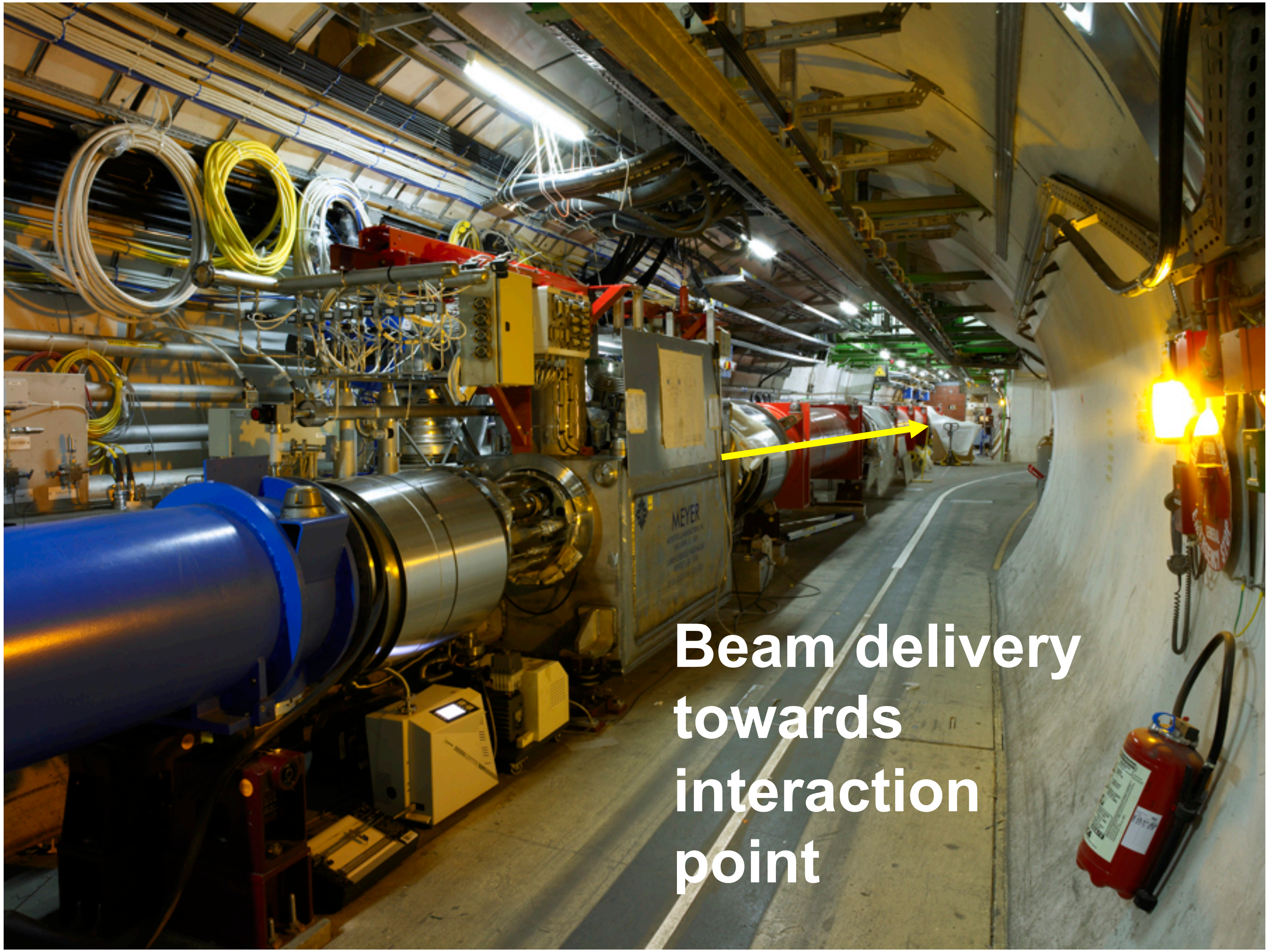
Cryogenics

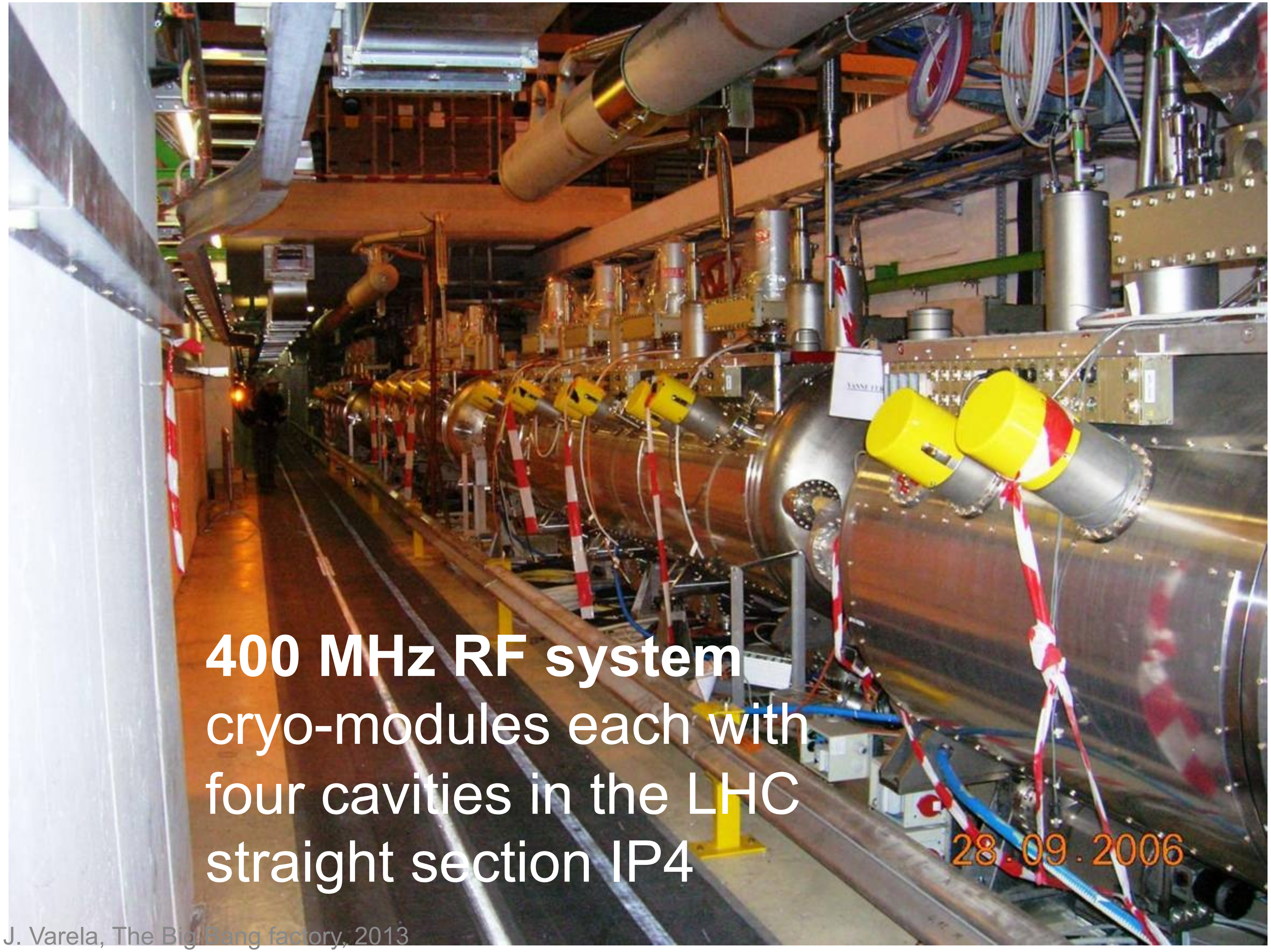
About 100 years ago, in 1908, Kamerlingh Onnes first liquefied Helium (60 ml in 1 hour)

LHC today: 32000 liters of He liquefied per hour by eight big cryogenic plants

In the tunnel

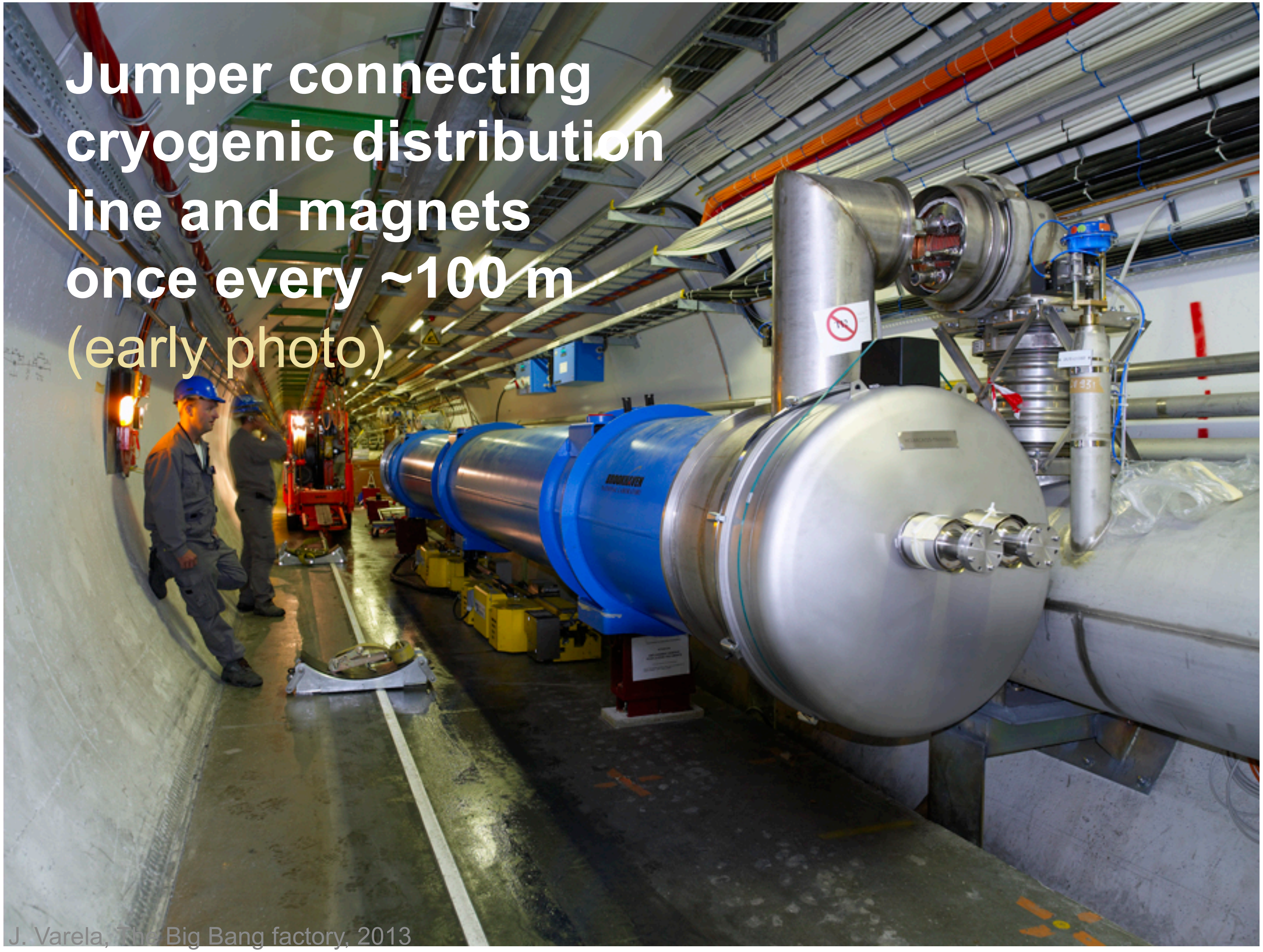


In the tunnel



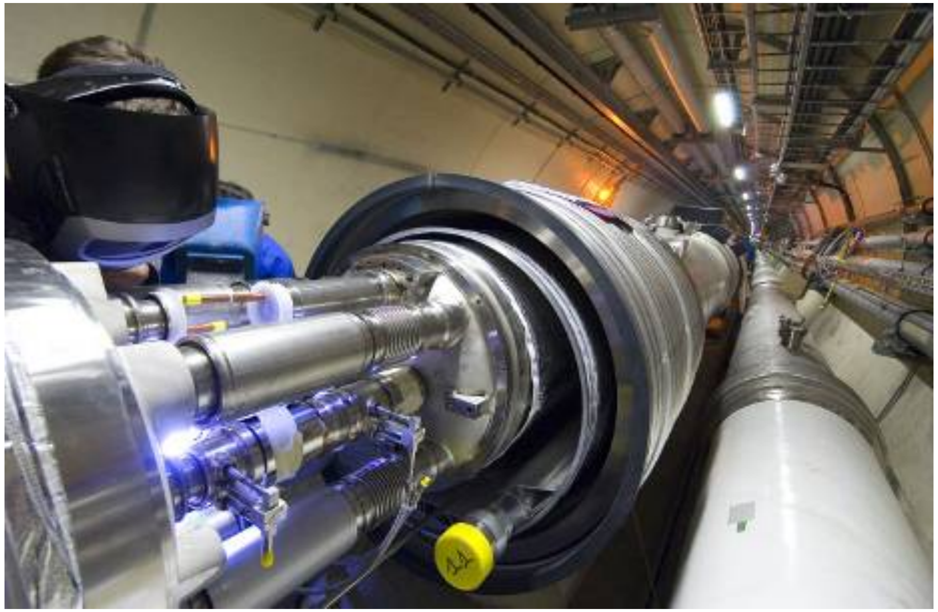
400 MHz RF system
cryo-modules each with four cavities in the LHC straight section IP4

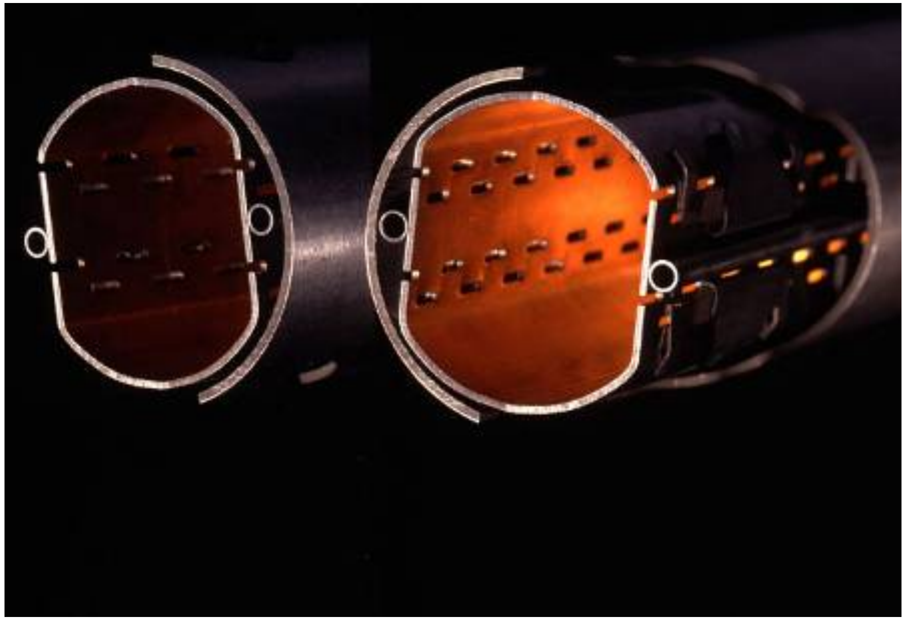
In the tunnel



It's empty!

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



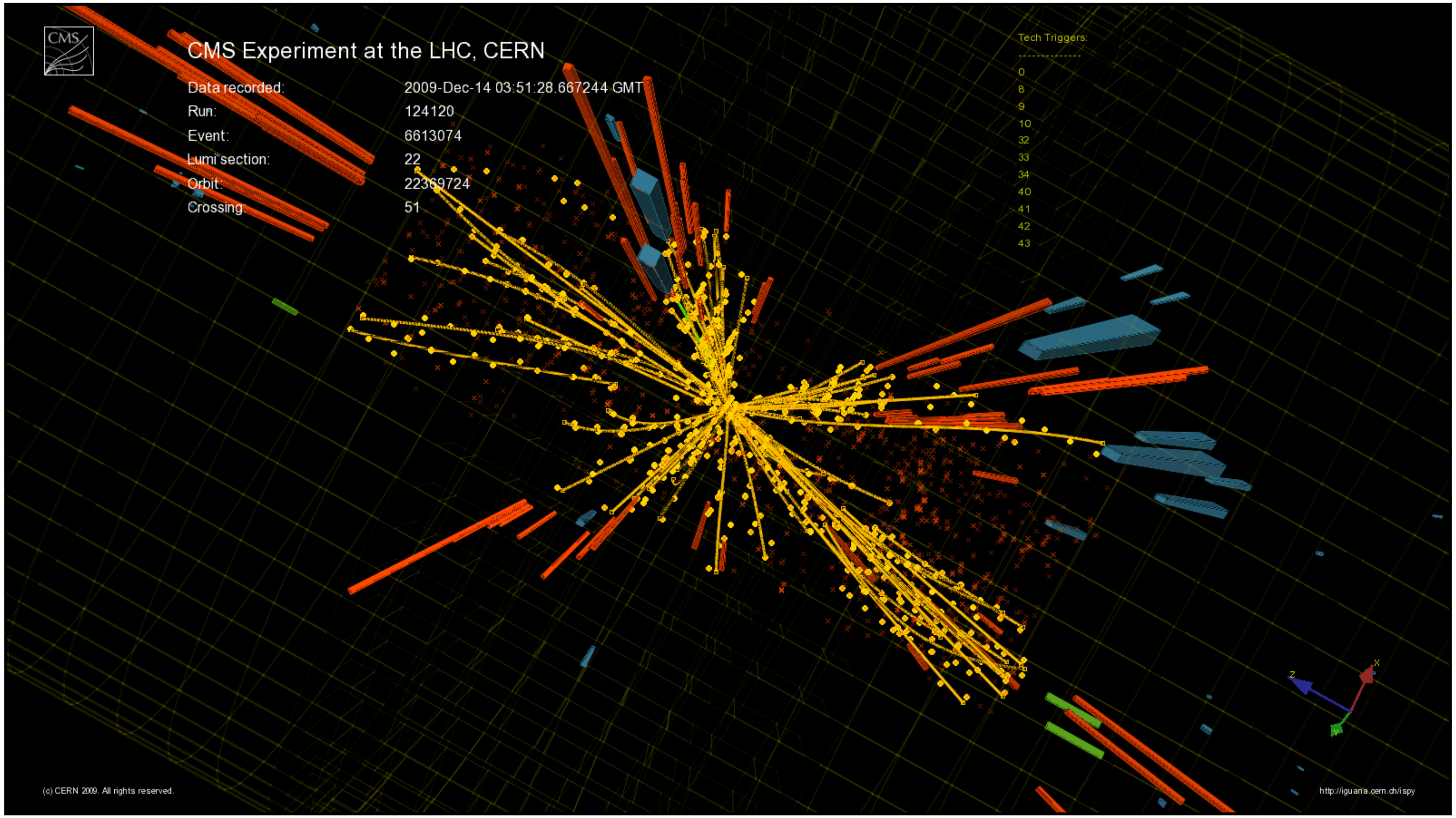


It’s cold!

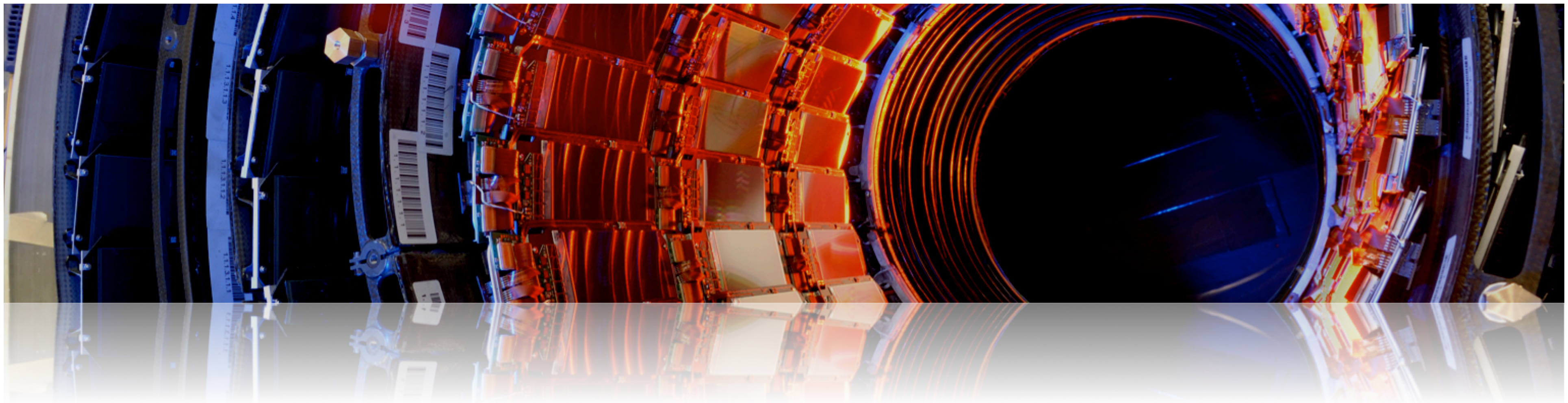
27 Km of magnets are kept at 1.9 ^{o}K, colder than outer space, using over 100 tons of liquid helium.

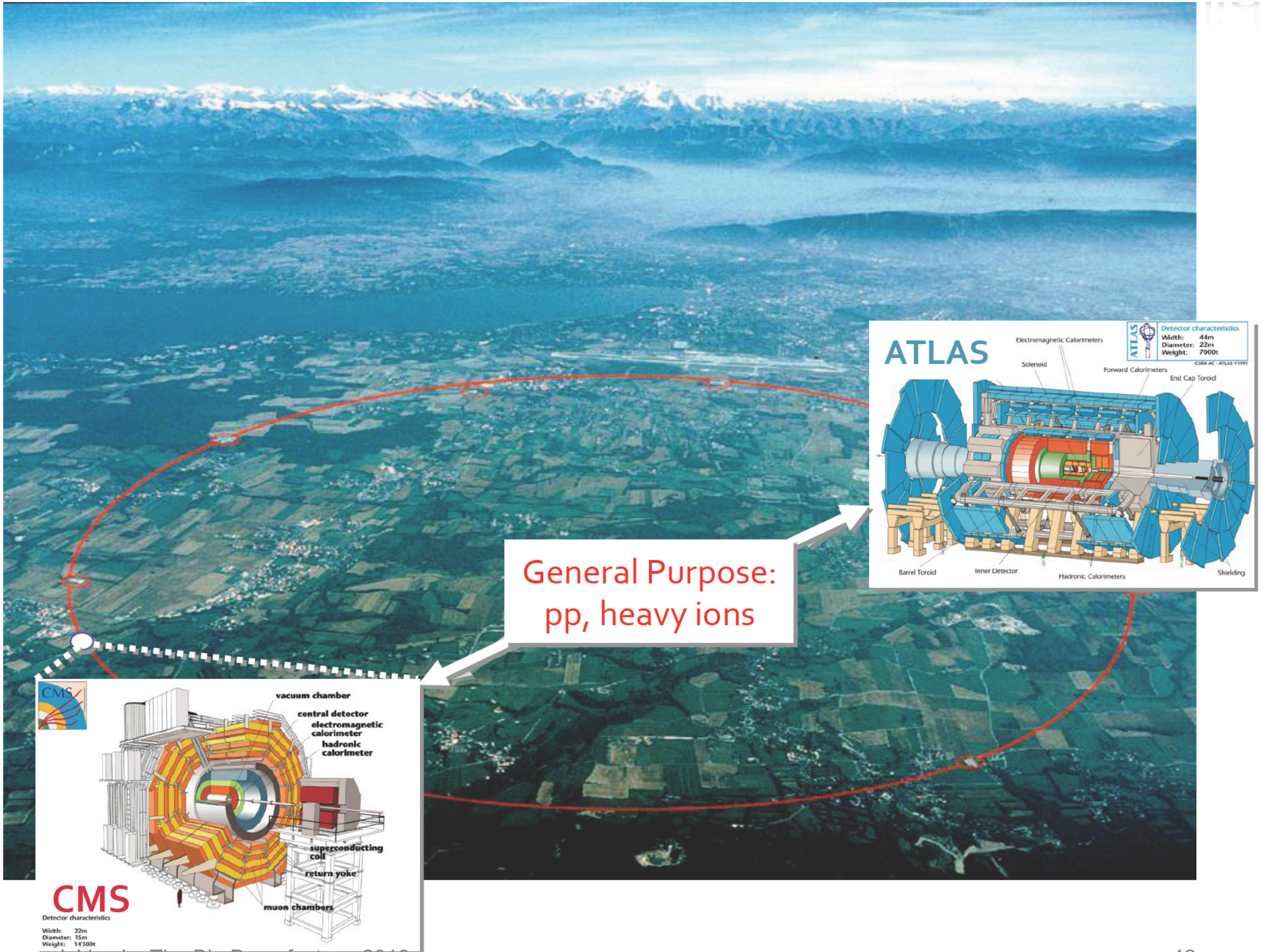
It's Hot!

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



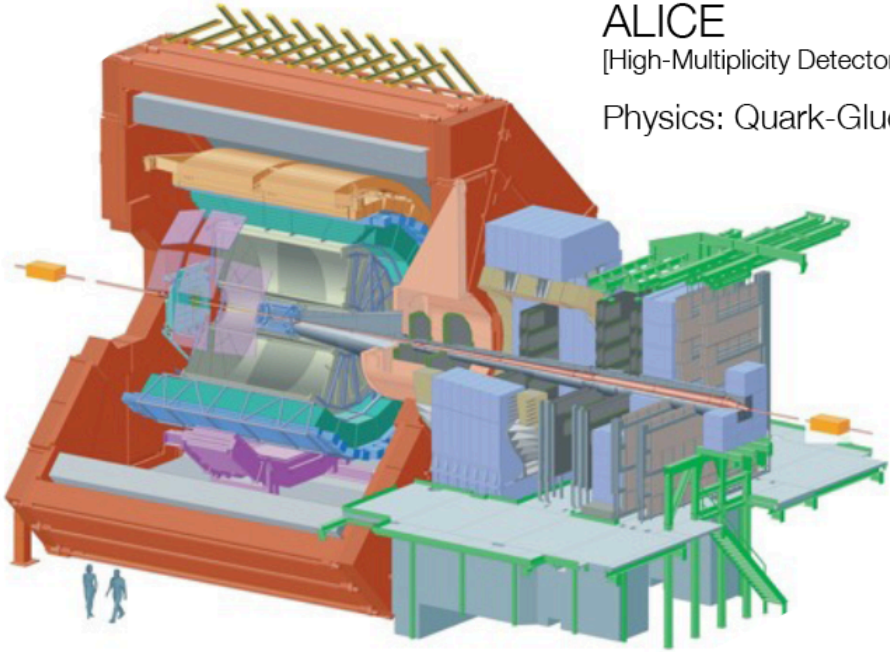
The Experiments





General Purpose:
pp, heavy ions

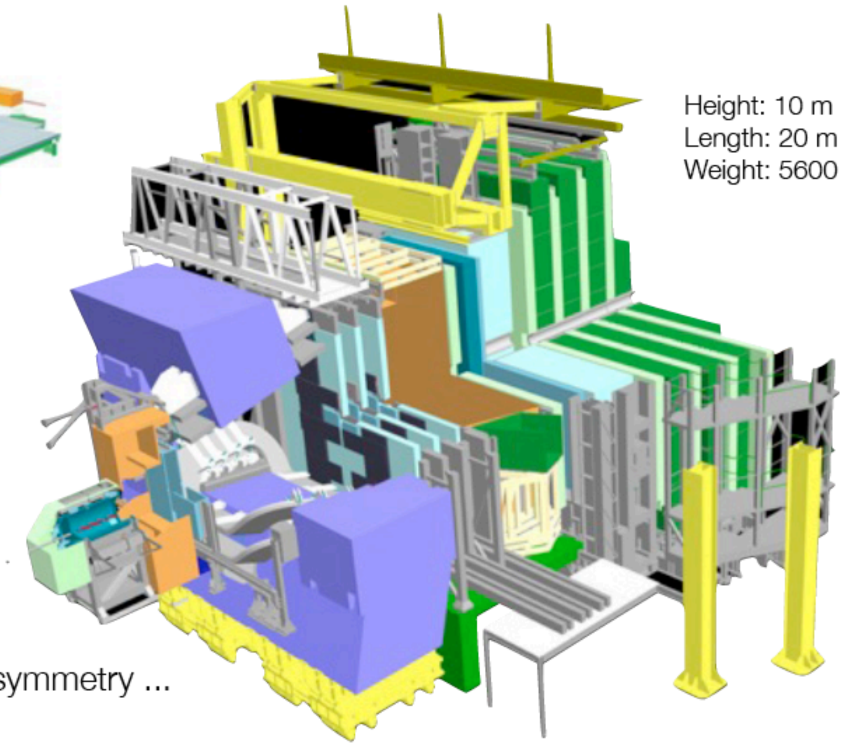
ALICE & LHCb



ALICE
[High-Multiplicity Detector]

Physics: Quark-Gluon Plasma ...

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



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

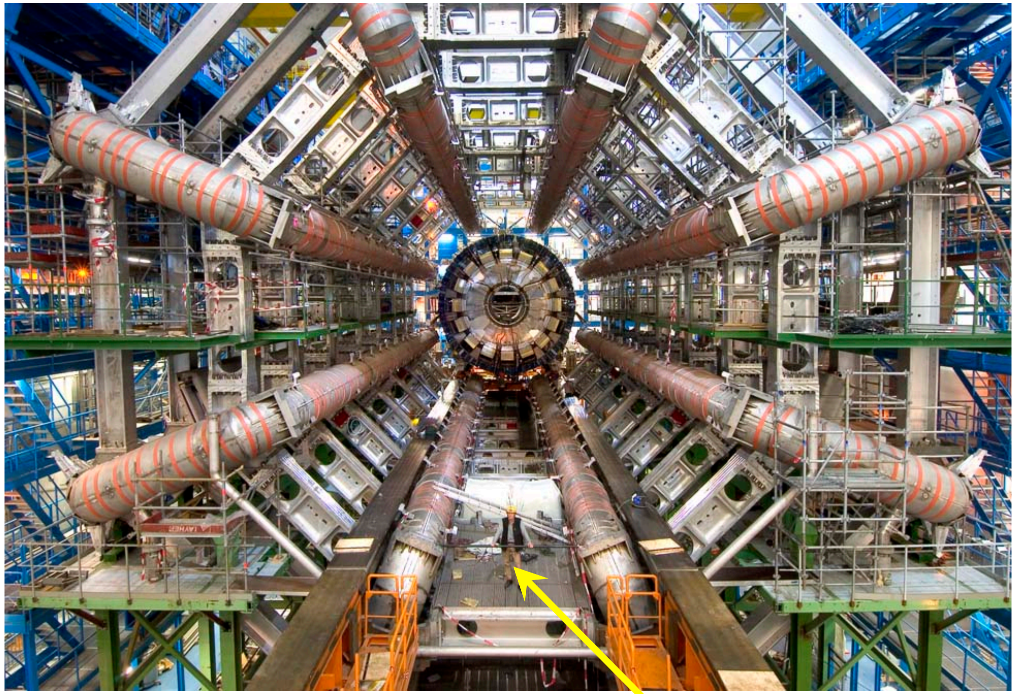
LHCb
[Forward Spectrometer]

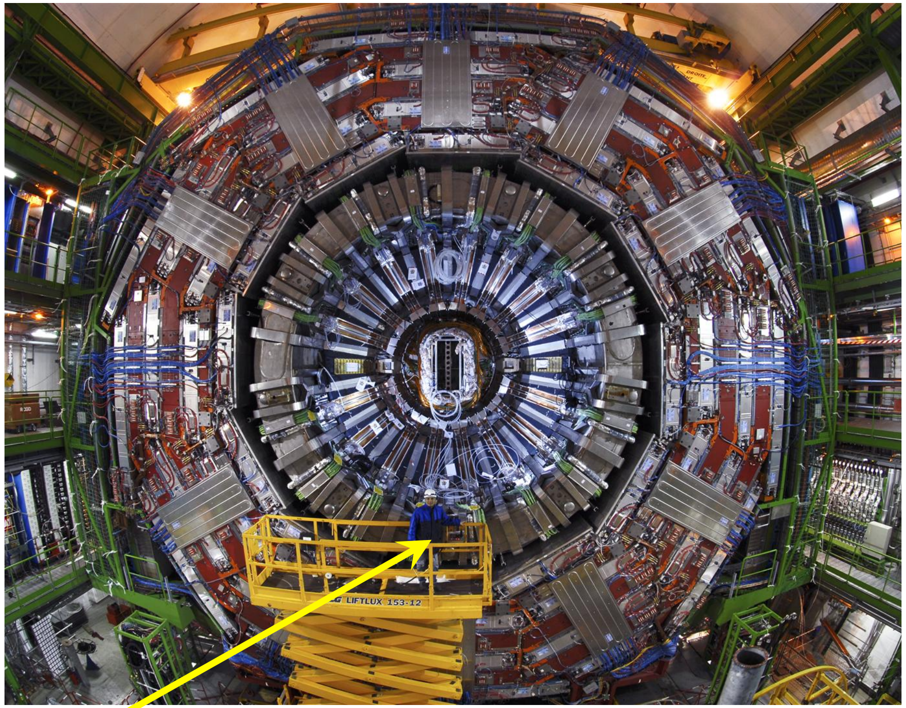
Physics: Matter/Antimatter-Asymmetry ...

It’s huge!

Largest, most complex detectors ever built

Study tiniest particles with incredible precision





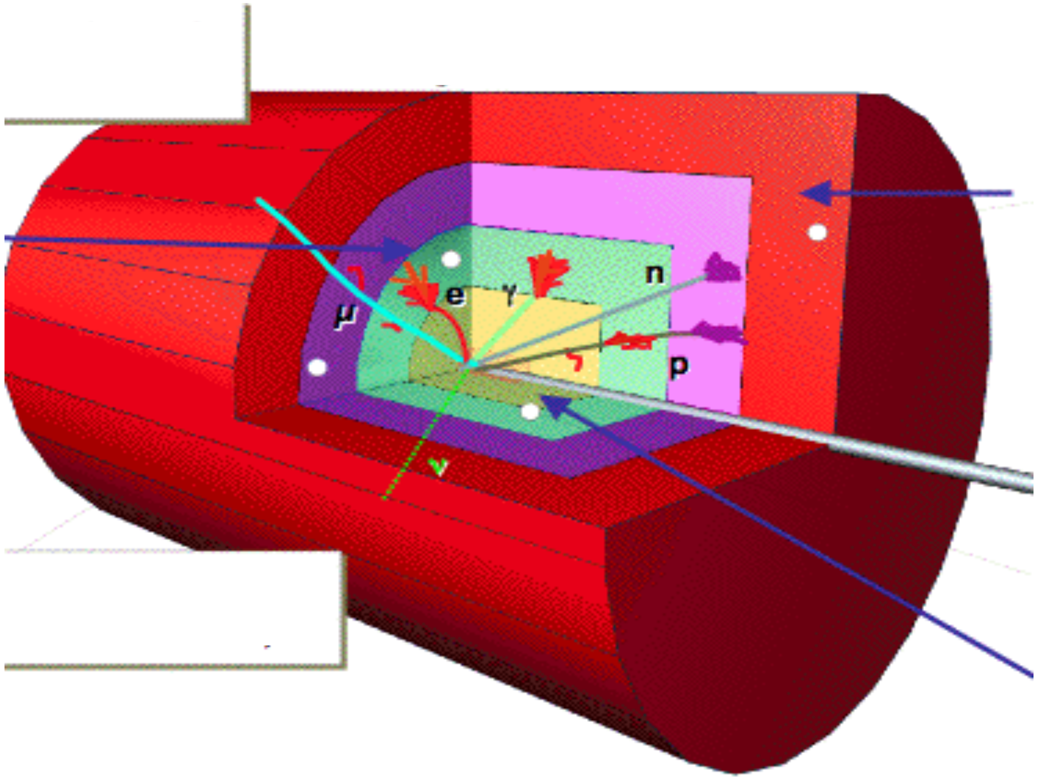
(people)

General purpose LHC experiments

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

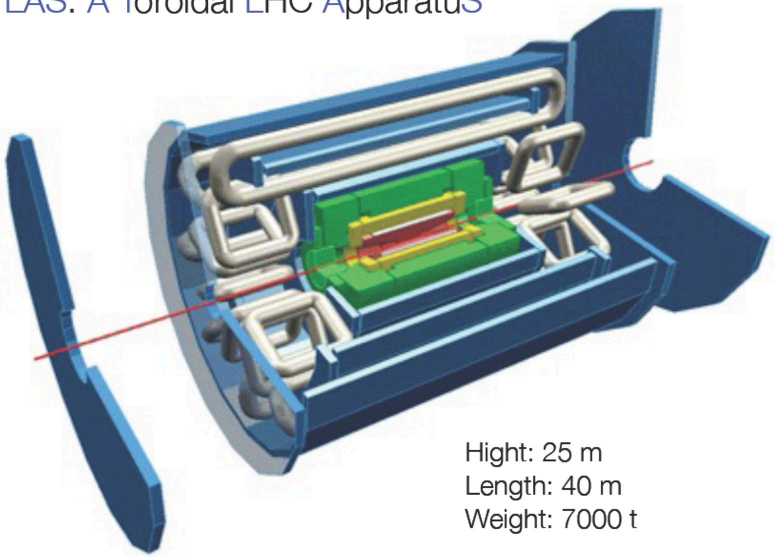
Together these layers allow to identify and precisely measure the energies of all stable particles produced in collisions.

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



Two concepts

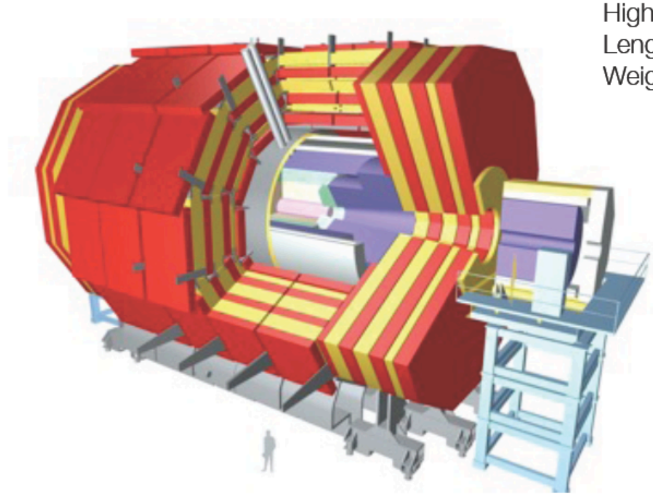
ATLAS: A Toroidal LHC ApparatuS

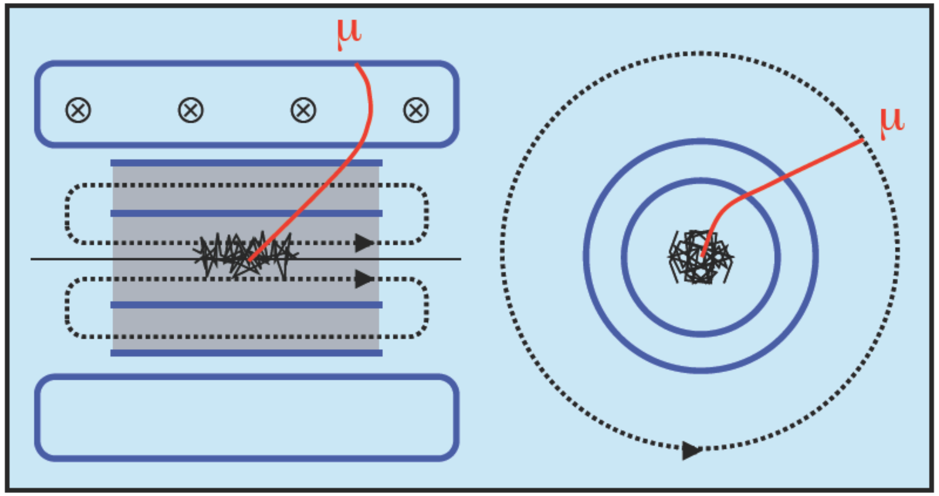


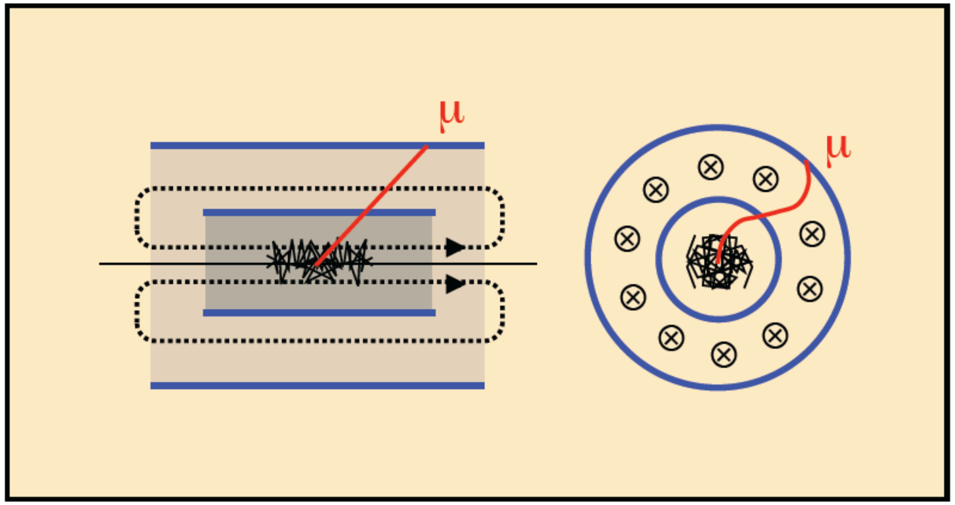
Hight: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid

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

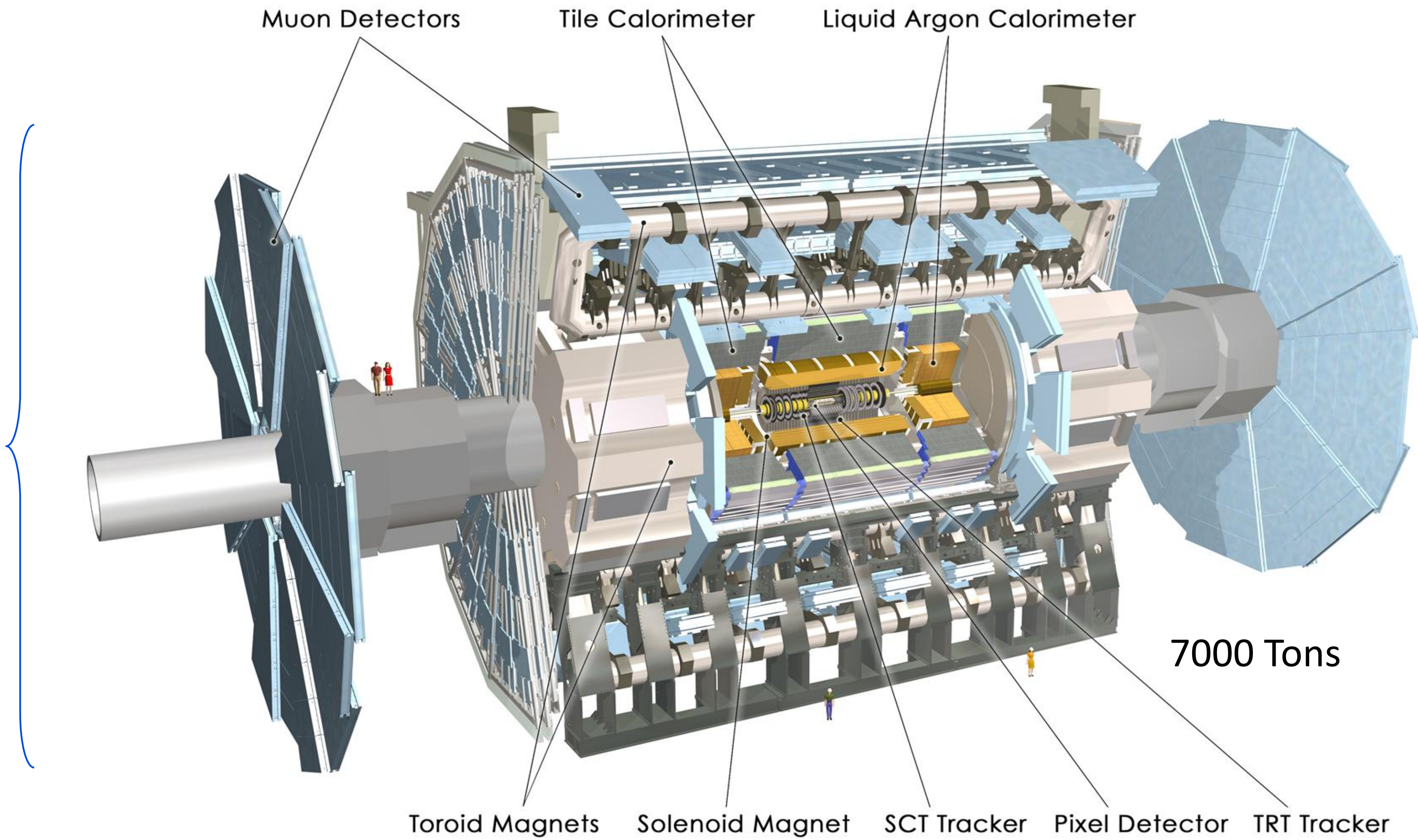


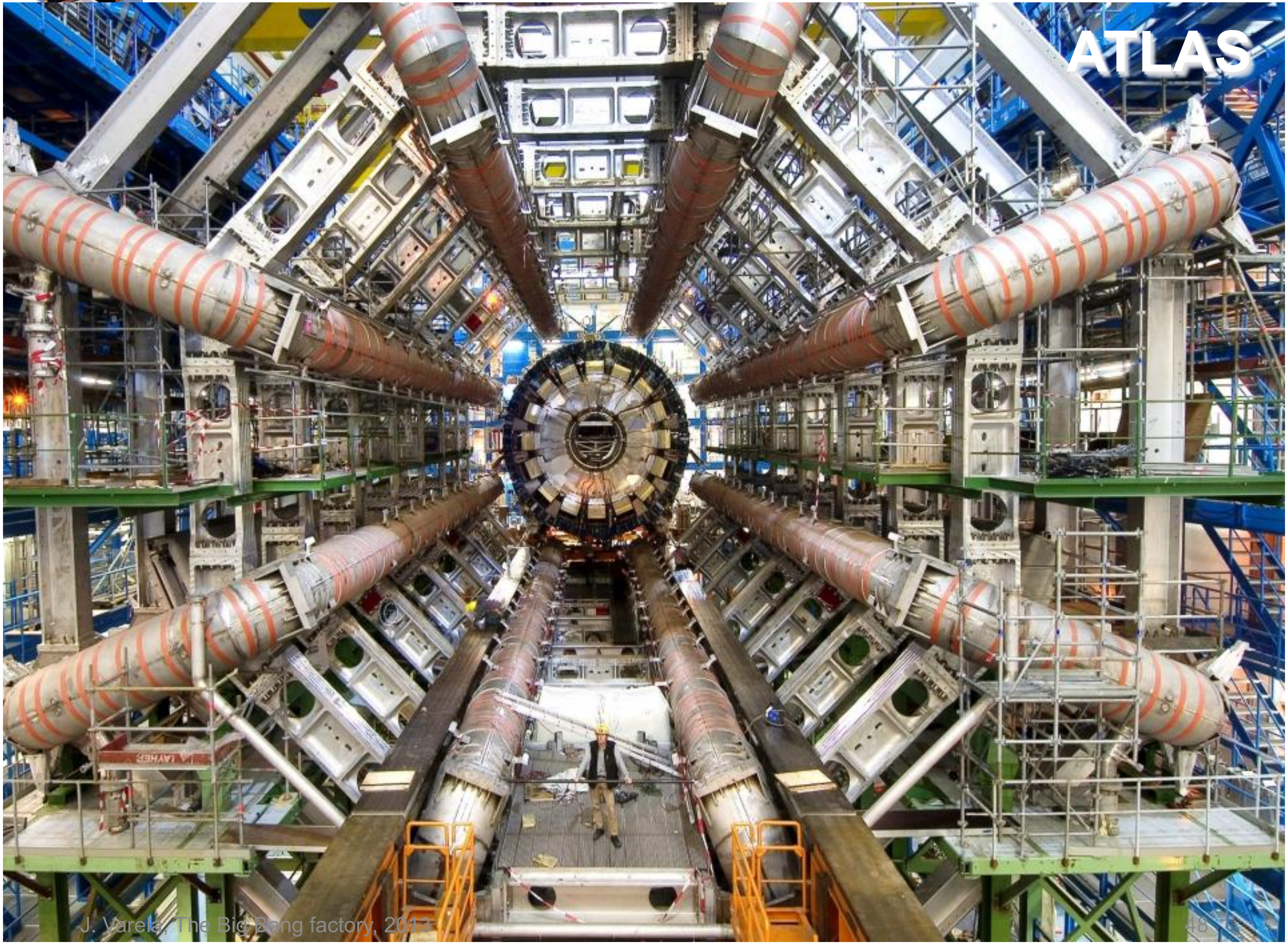




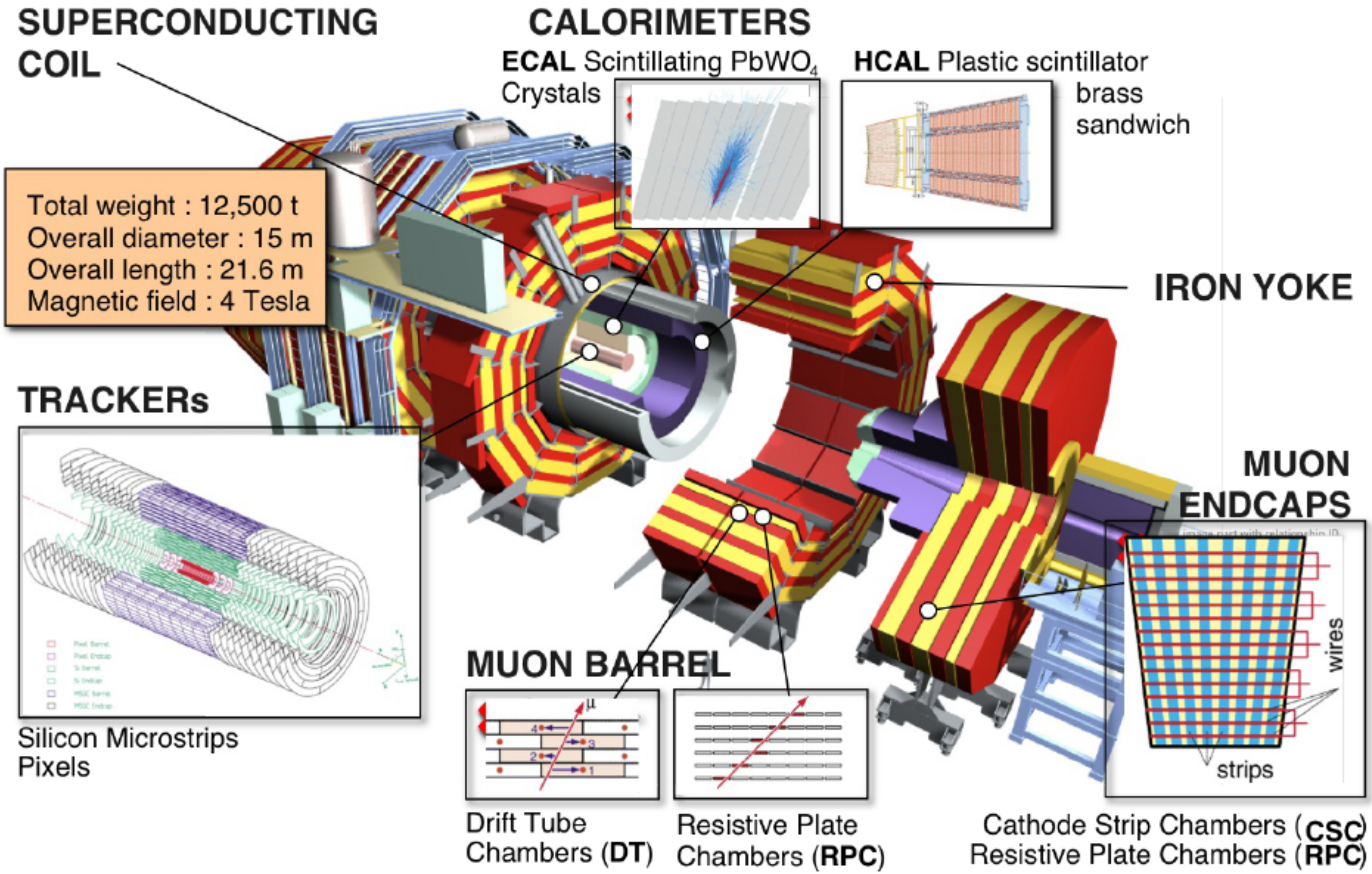
ATLAS detectors

24 m

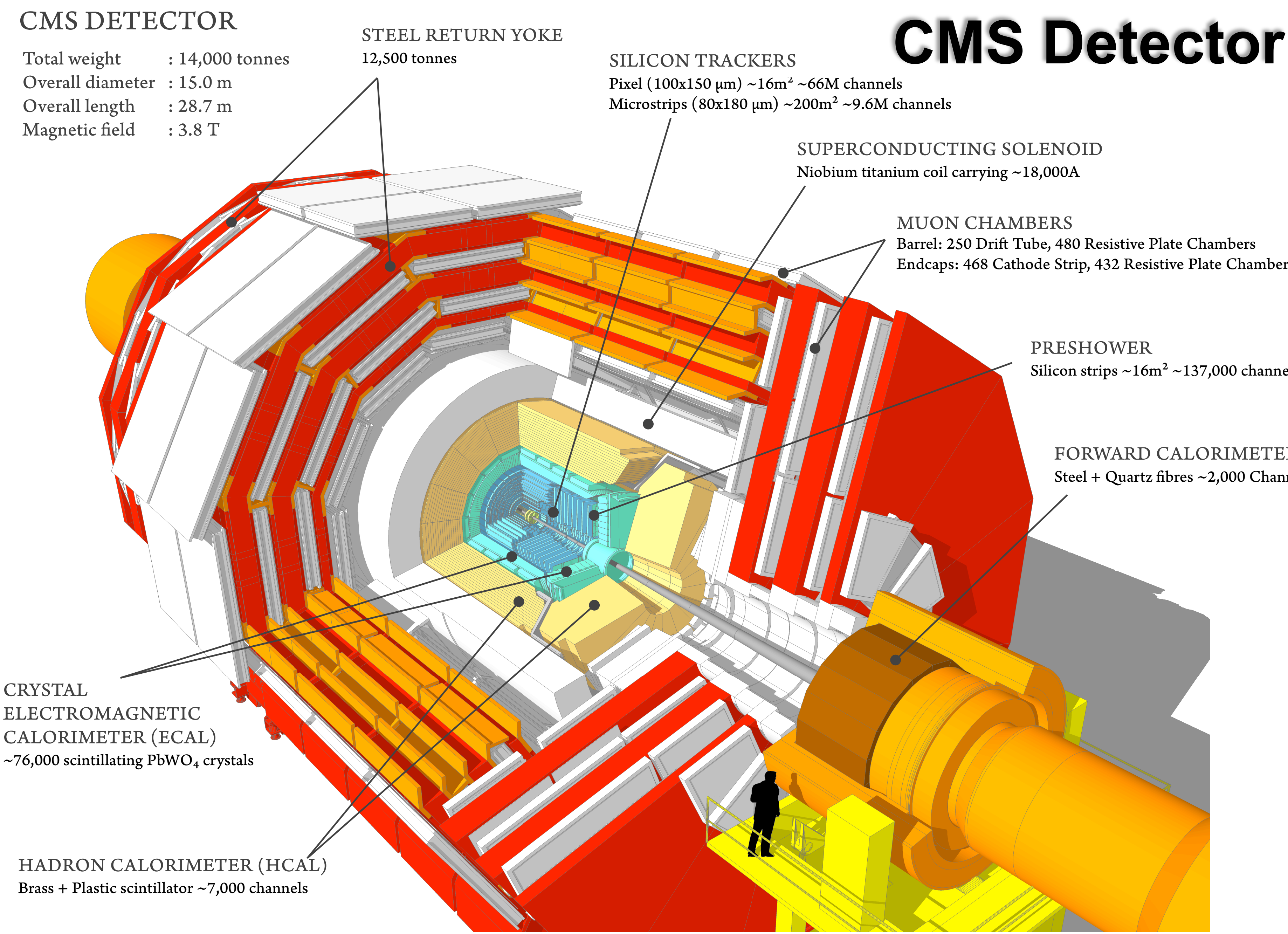


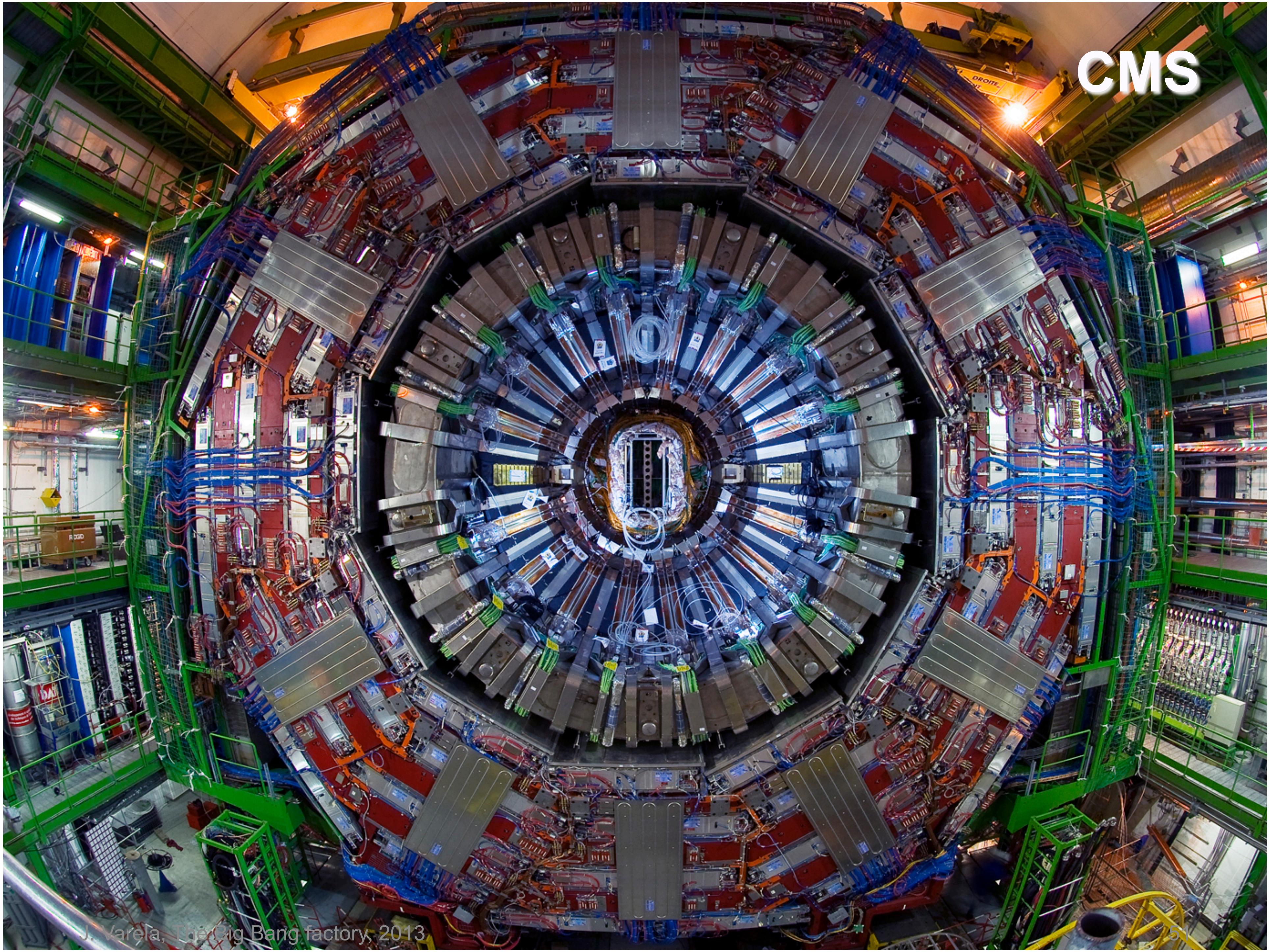

ATLAS

Exploded view of the CMS detectors

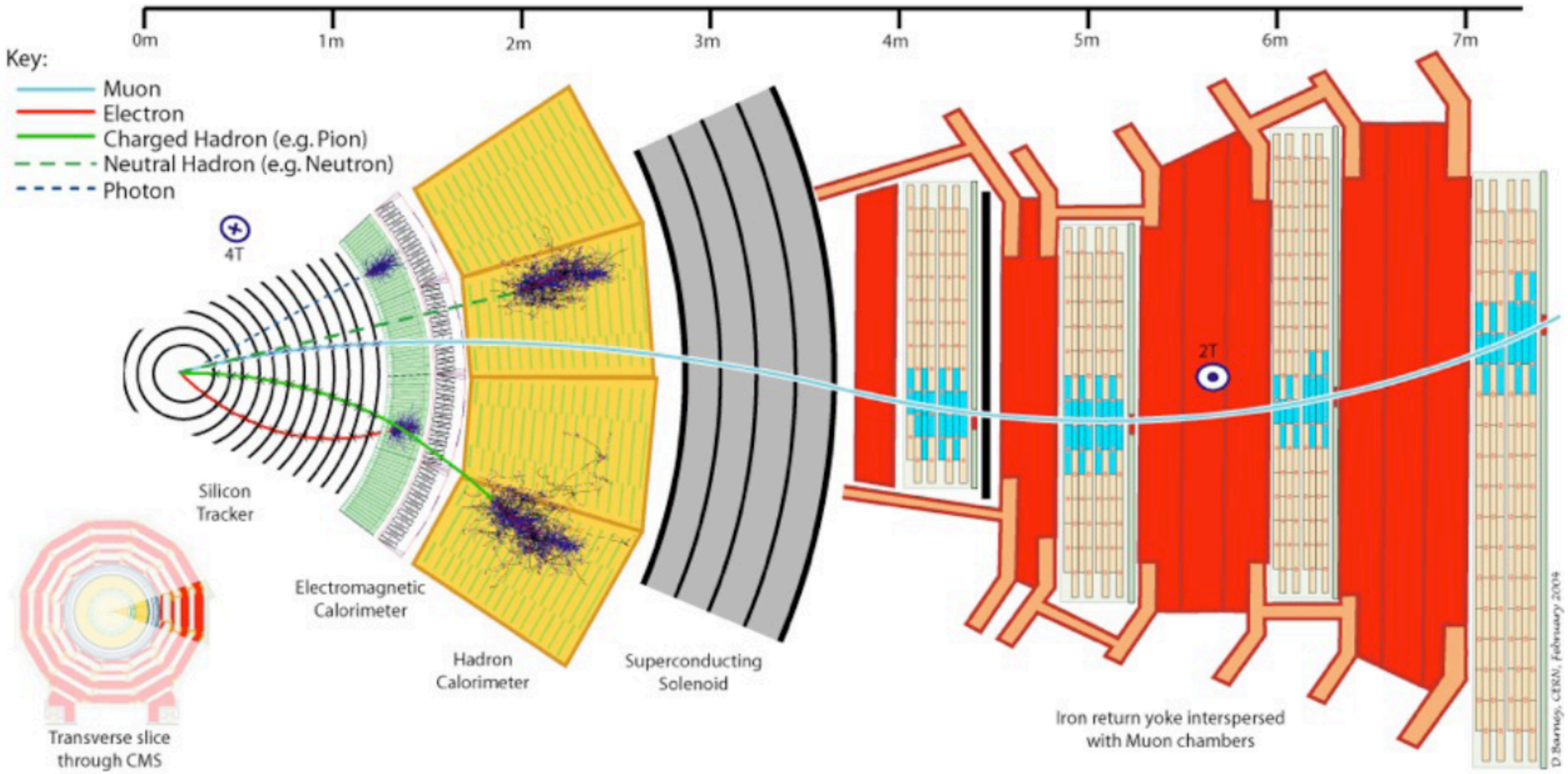


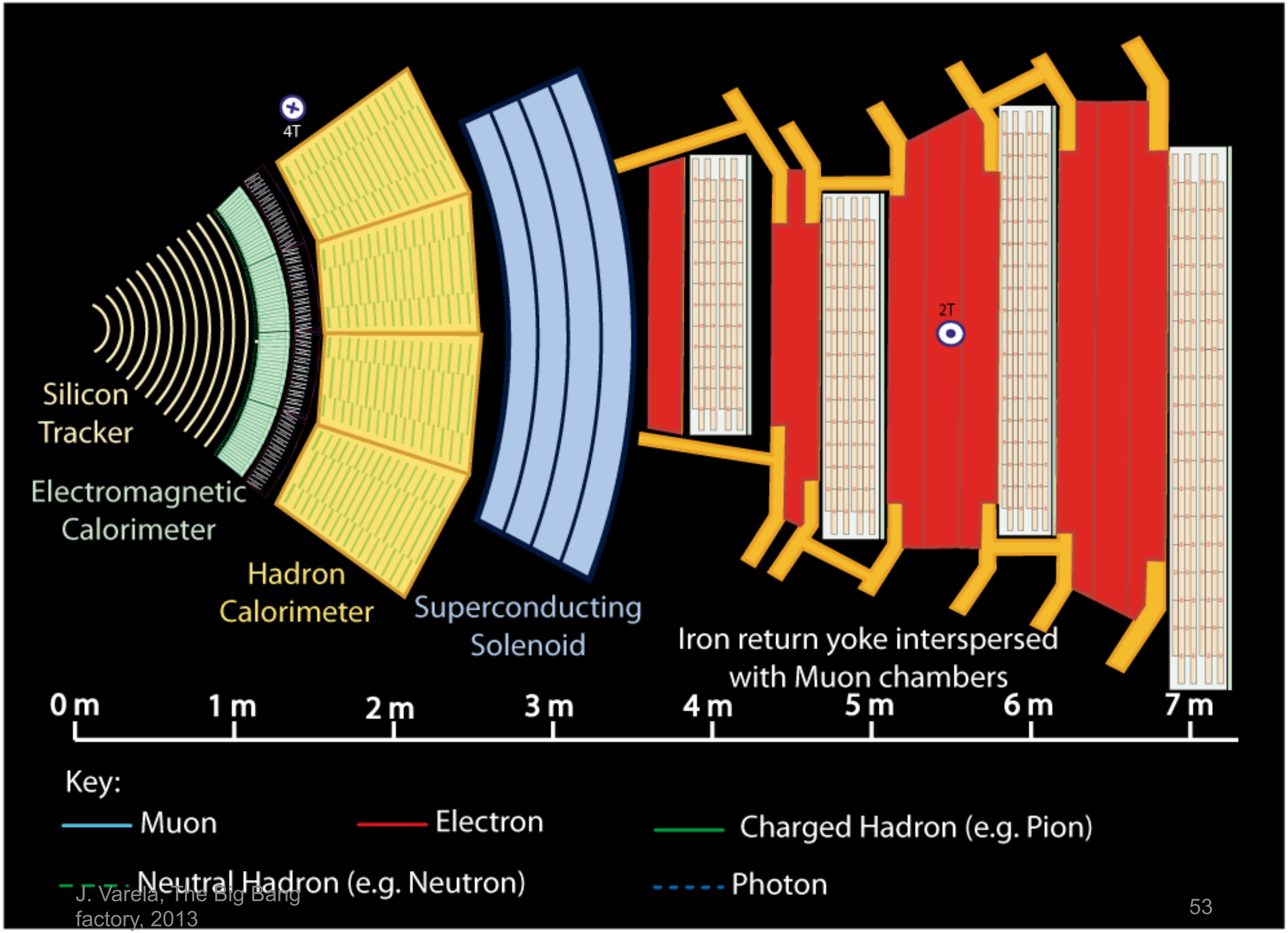
CMS Detector




CMS
J. Varela, The Big Bang factory, 2013

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





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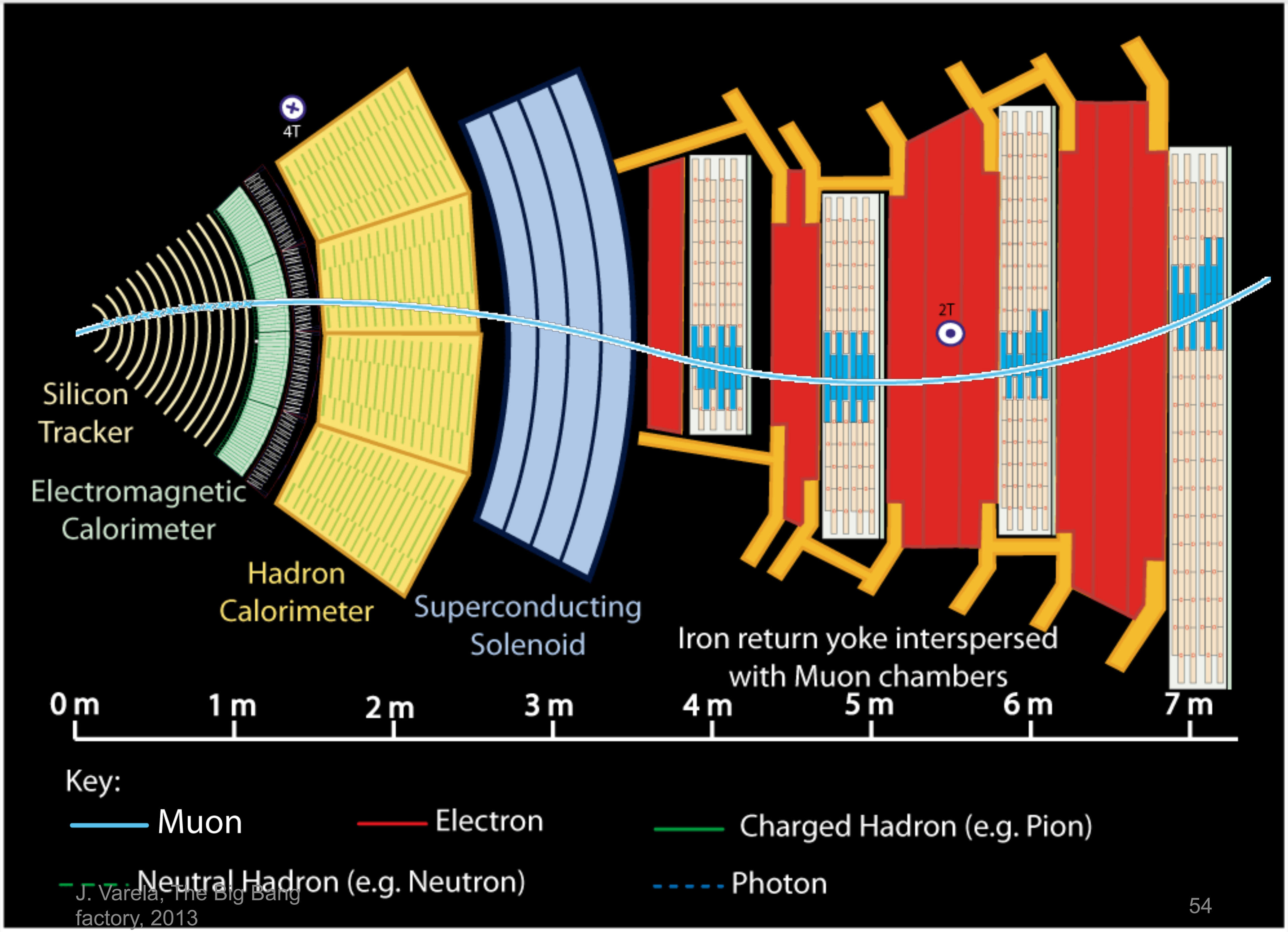
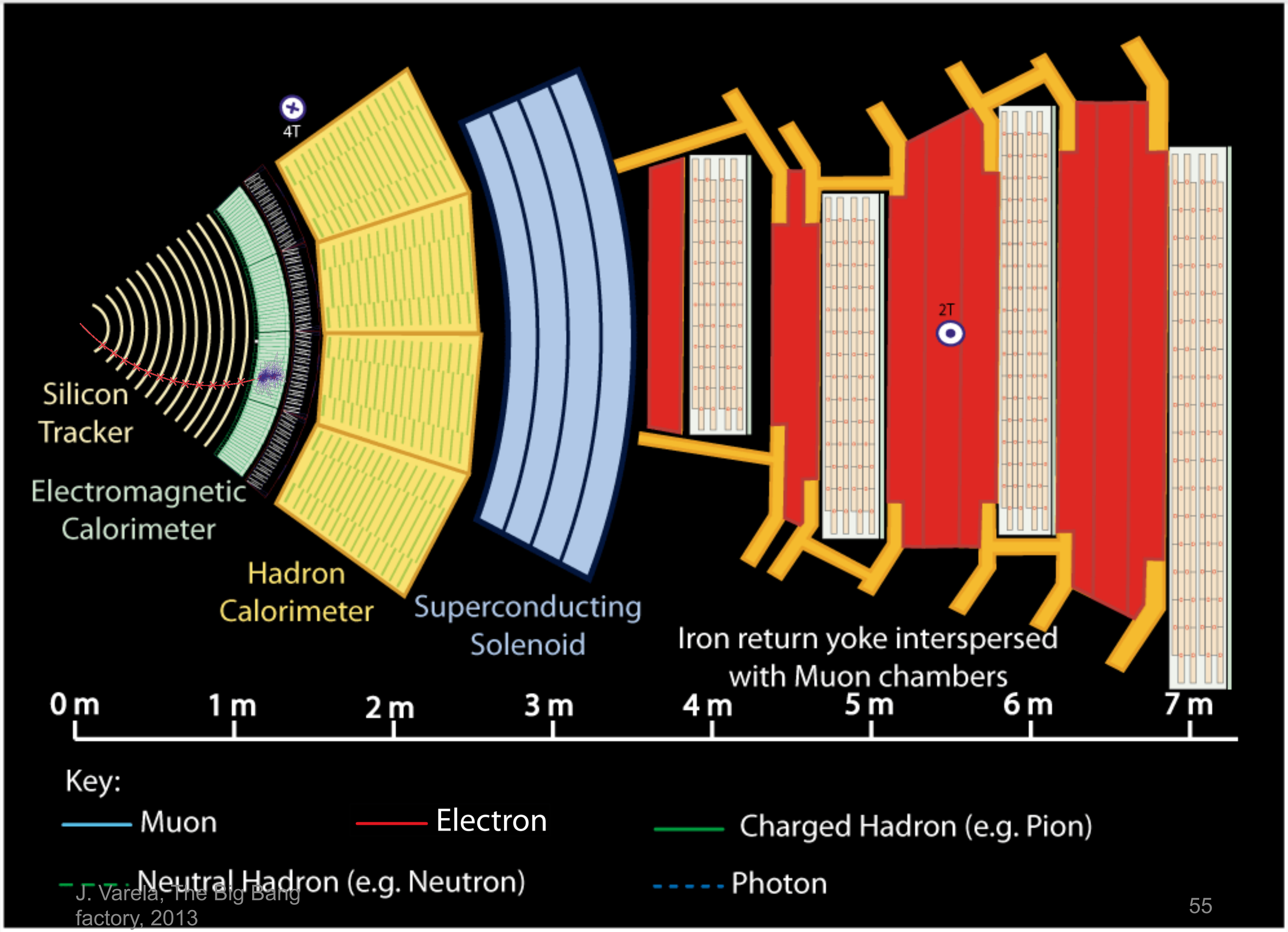
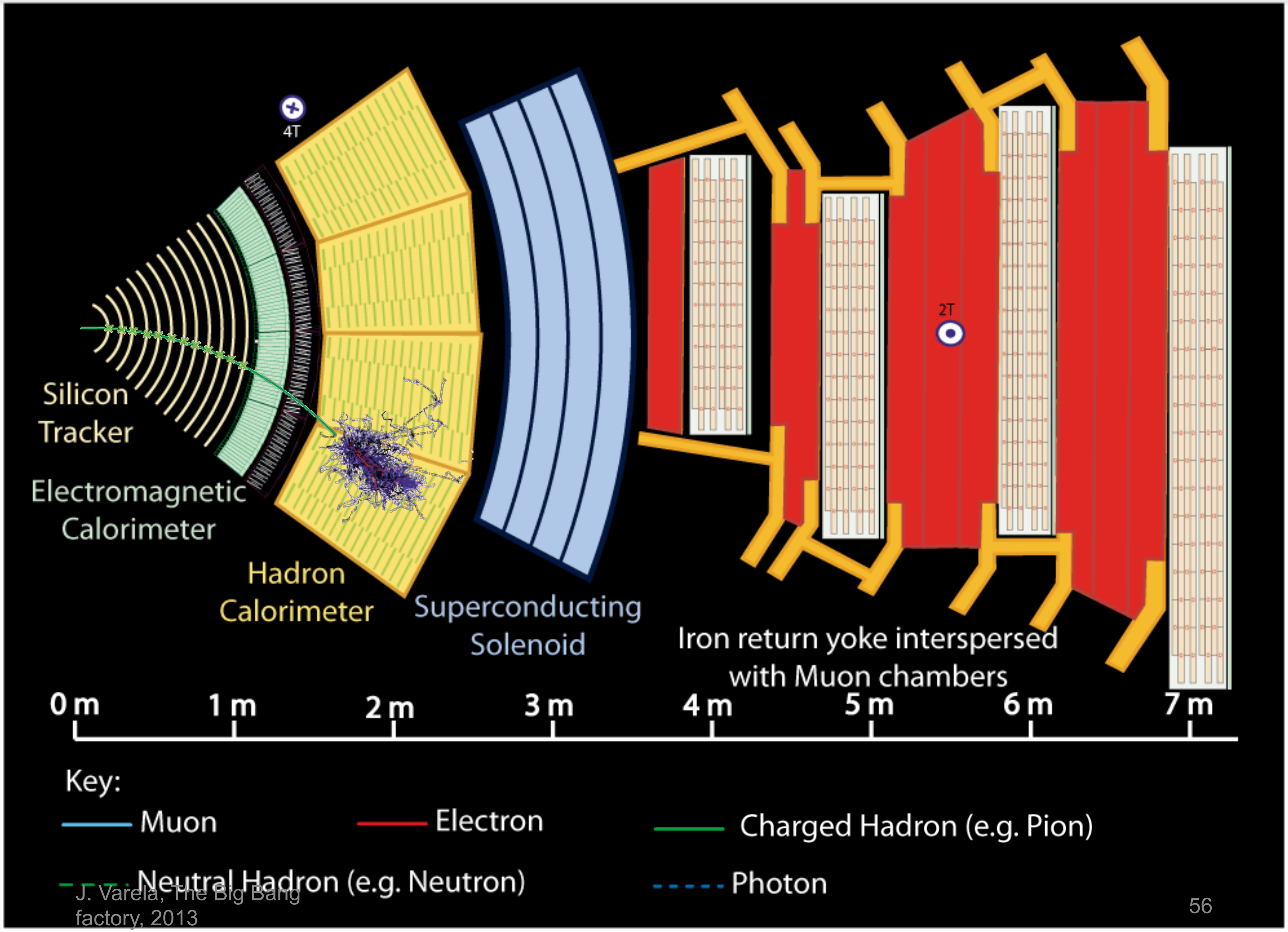
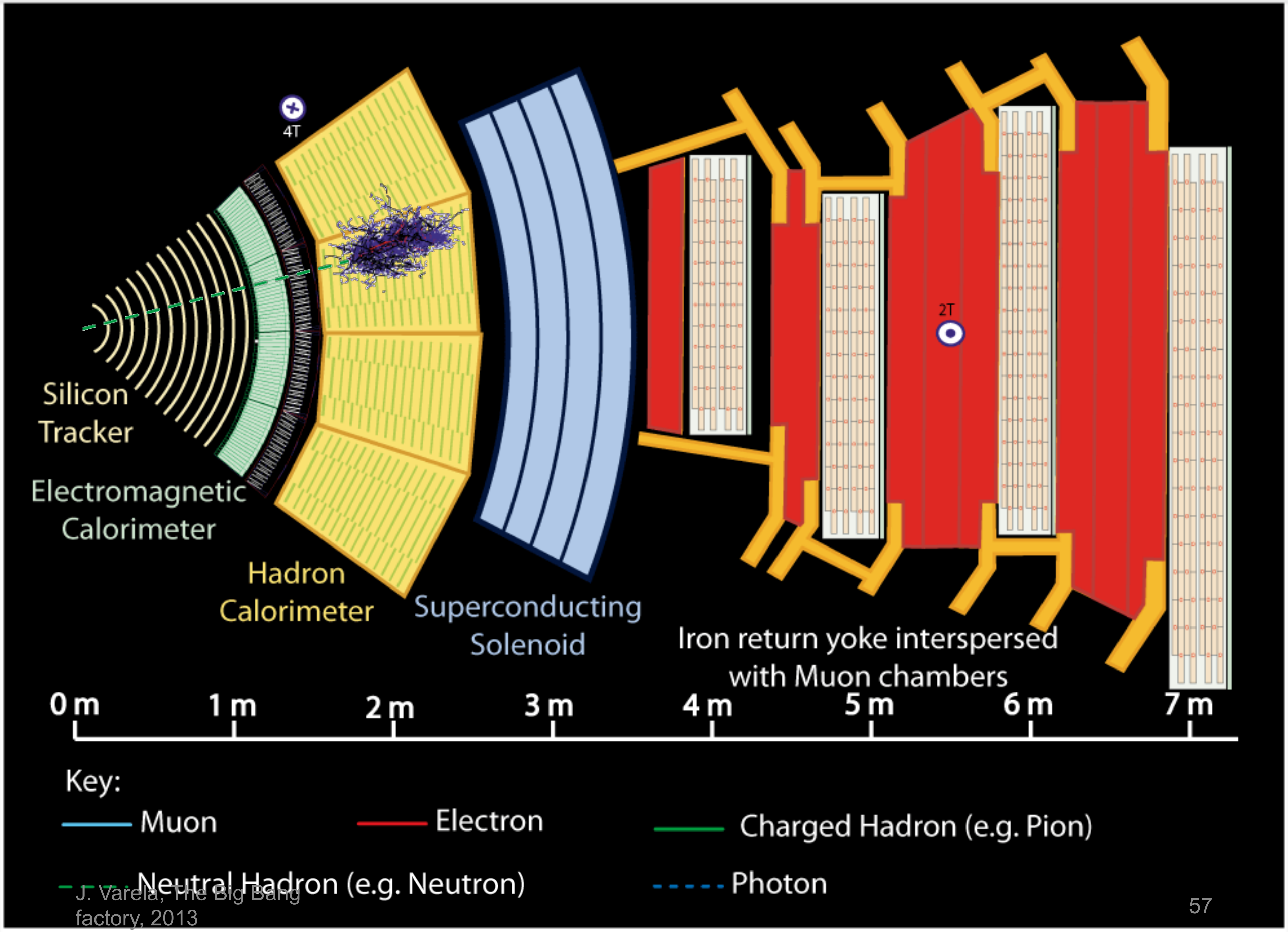


J. Varela, The Big Bang factory, 2013

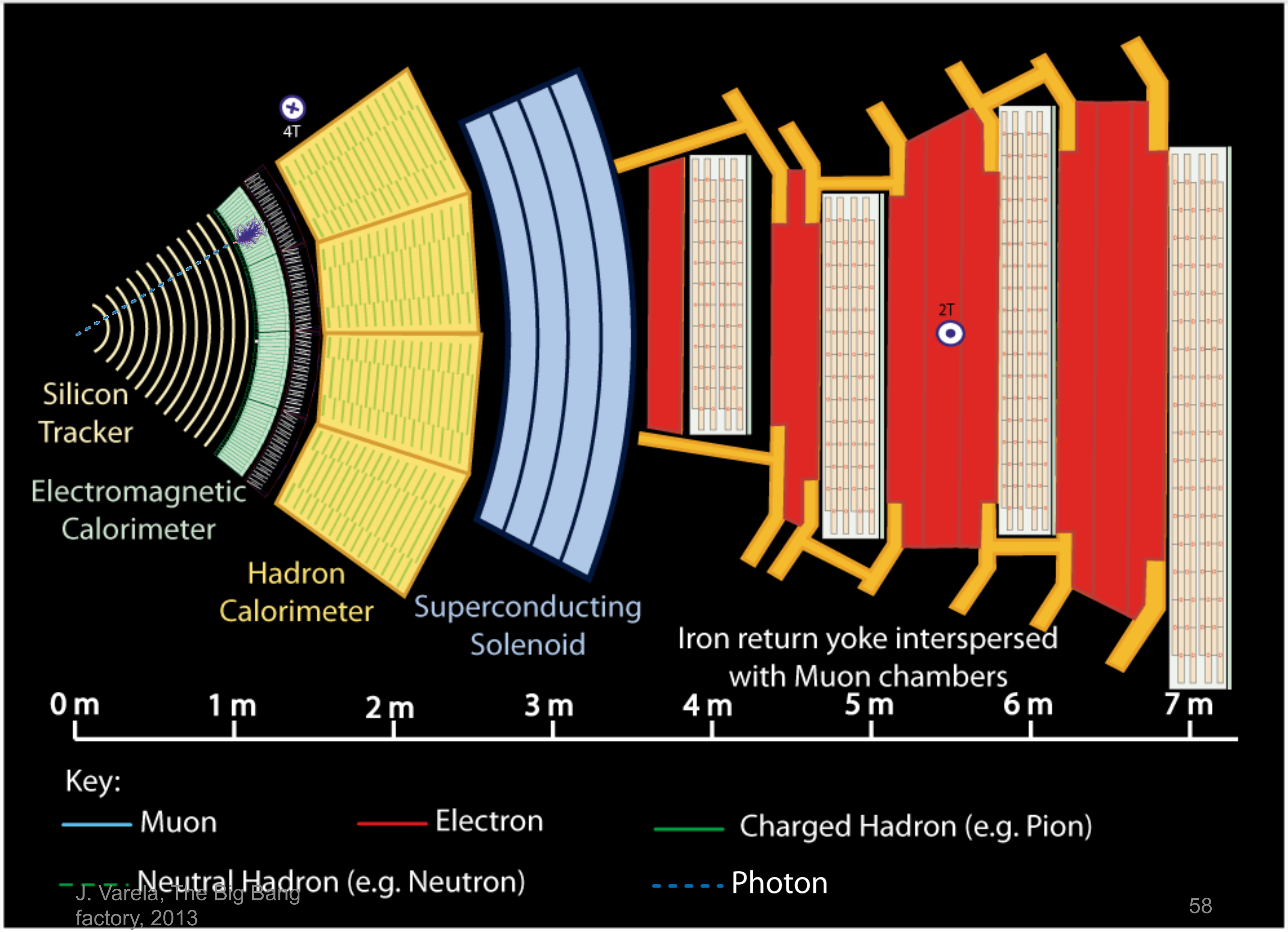


J. Varela, The Big Bang factory, 2013


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



J. Varela, The Big Bang factory, 2013

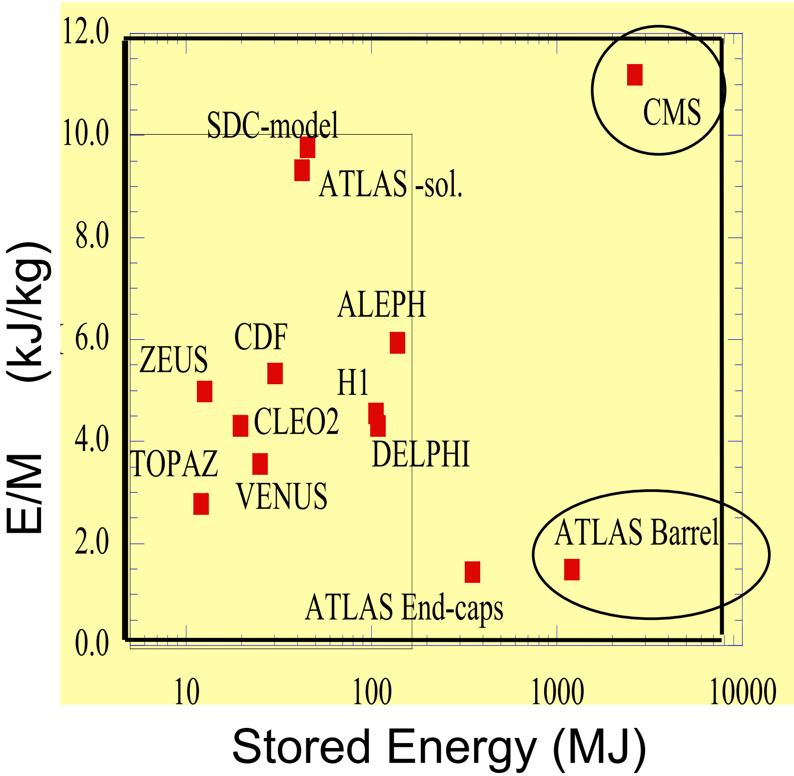


J. Varela, The Big Bang factory, 2013

1993-2008: detector R&D and construction

Superconducting Magnets of ATLAS and CMS

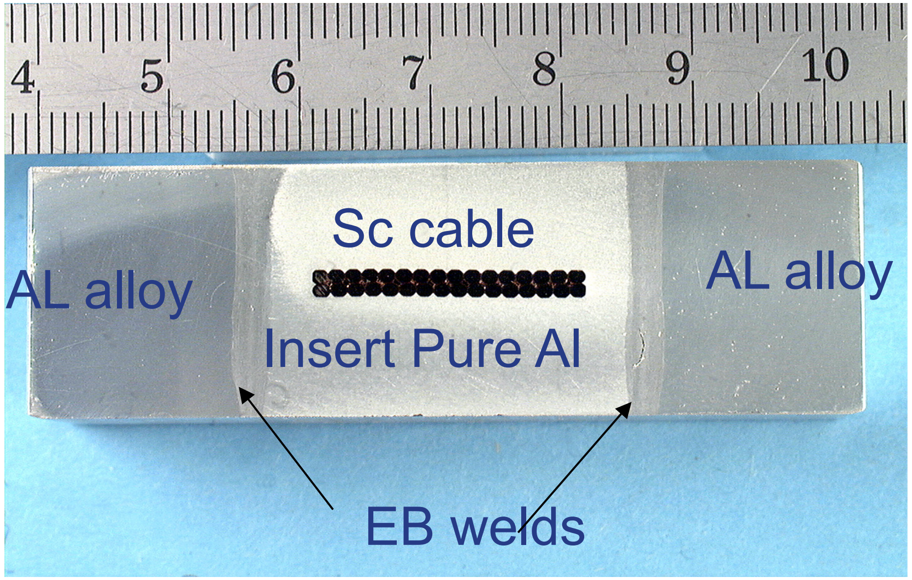
Design Goal: Measure 1 TeV particles with < 10% resolution

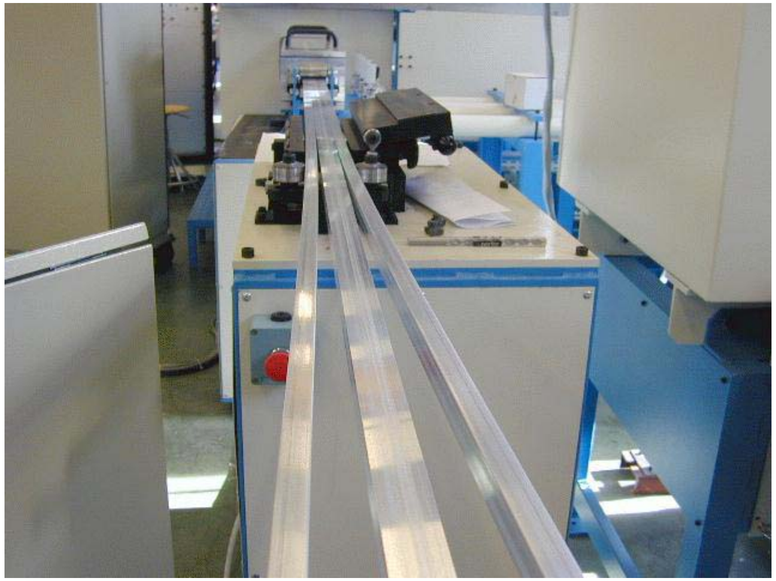


Superconducting cable

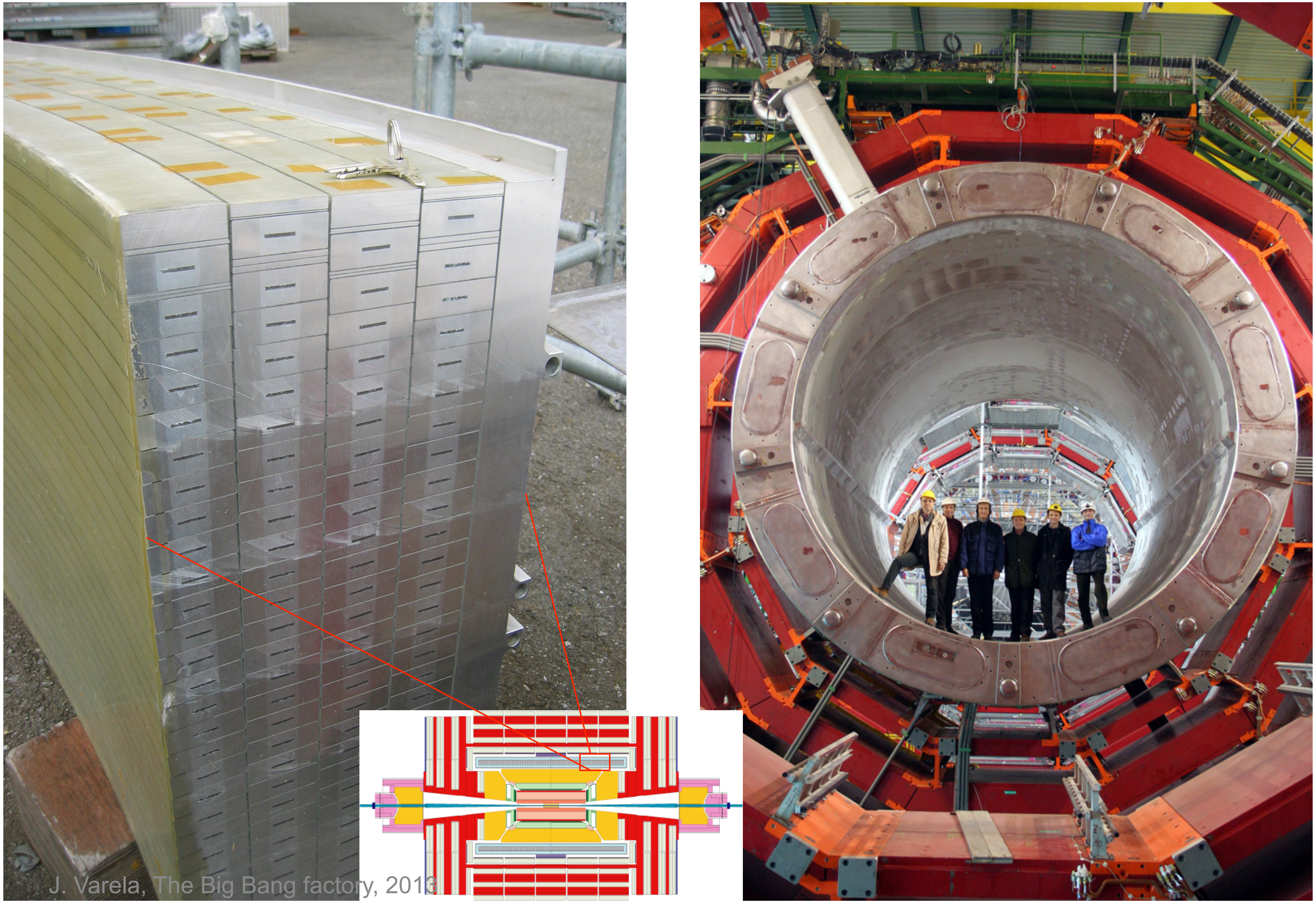
Al stabilized NbTi conductor.

Mechanically reinforced conductor to contain magnetic forces.

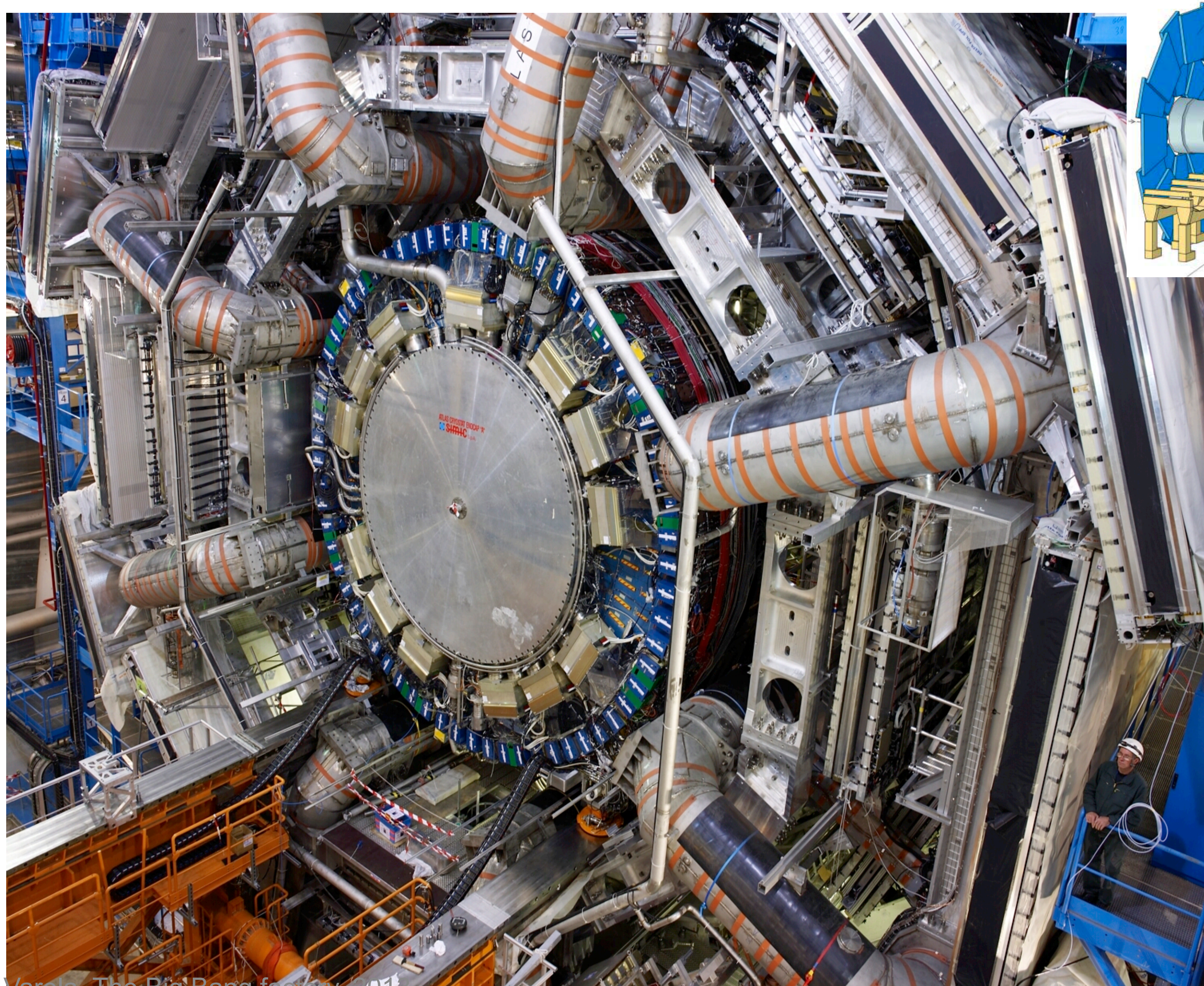


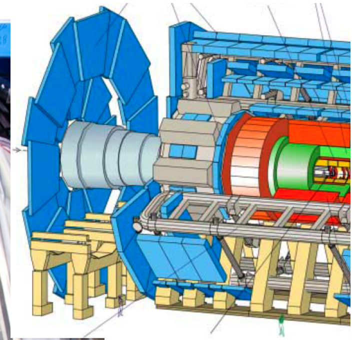


Superconductor solenoid at 3.8 Tesla

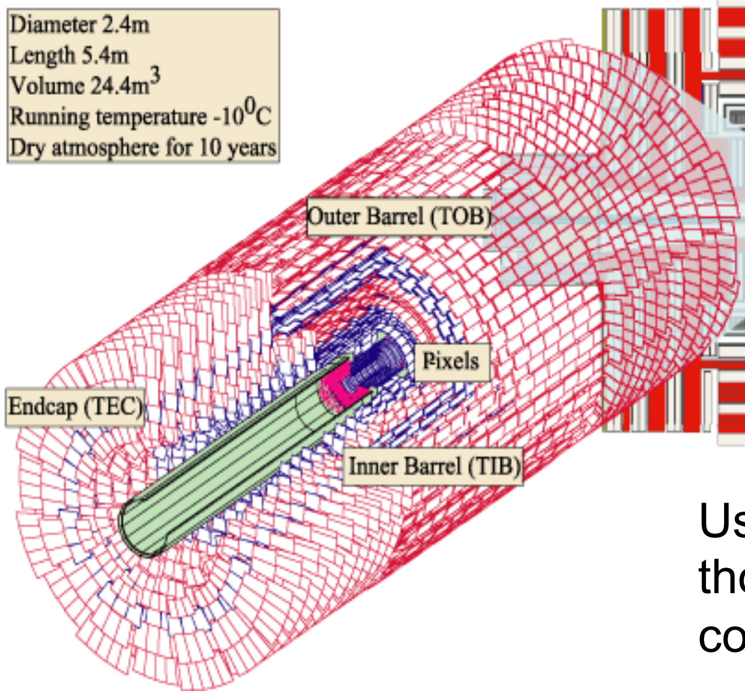


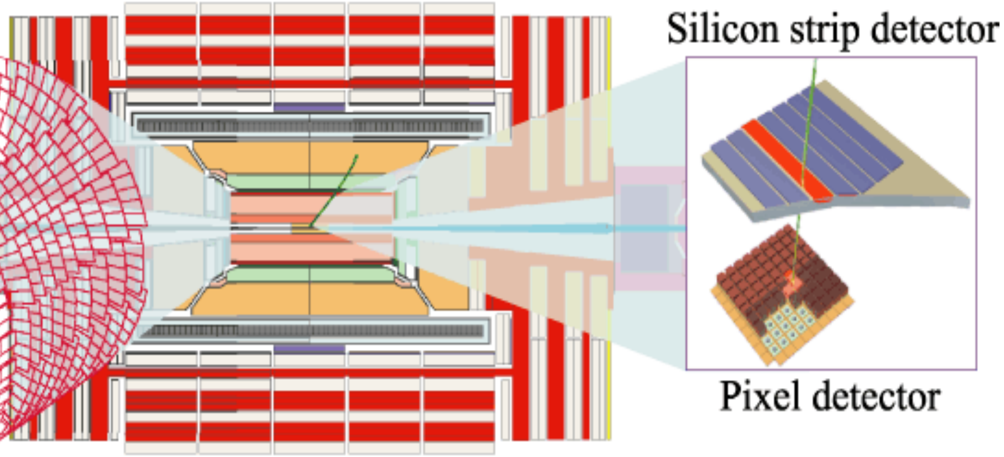
ATLAS Toroidal System





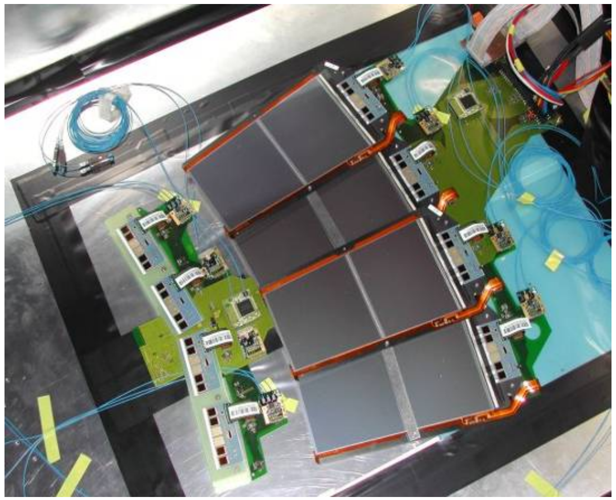
Silicon Tracker

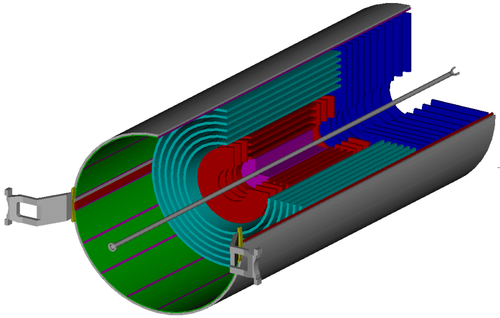




Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

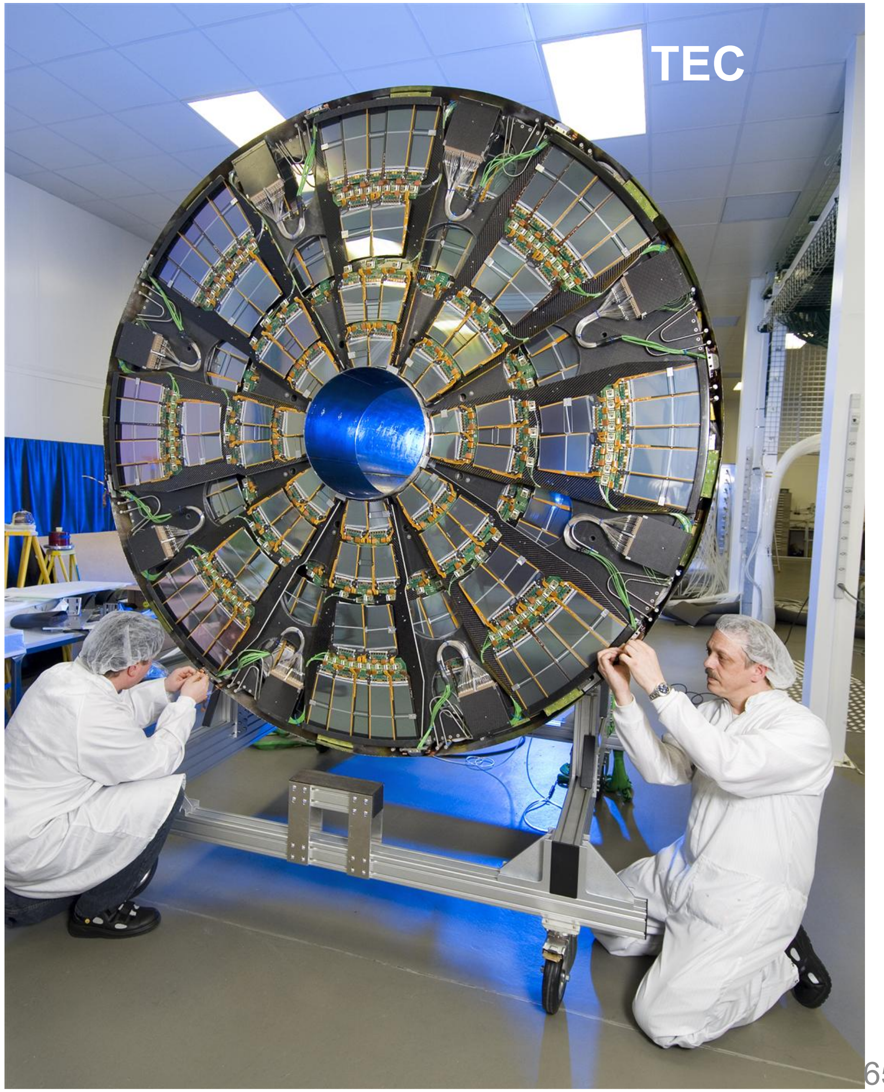
214m^2 silicon sensors
11.4 million silicon strips
65.9 million silicon pixels



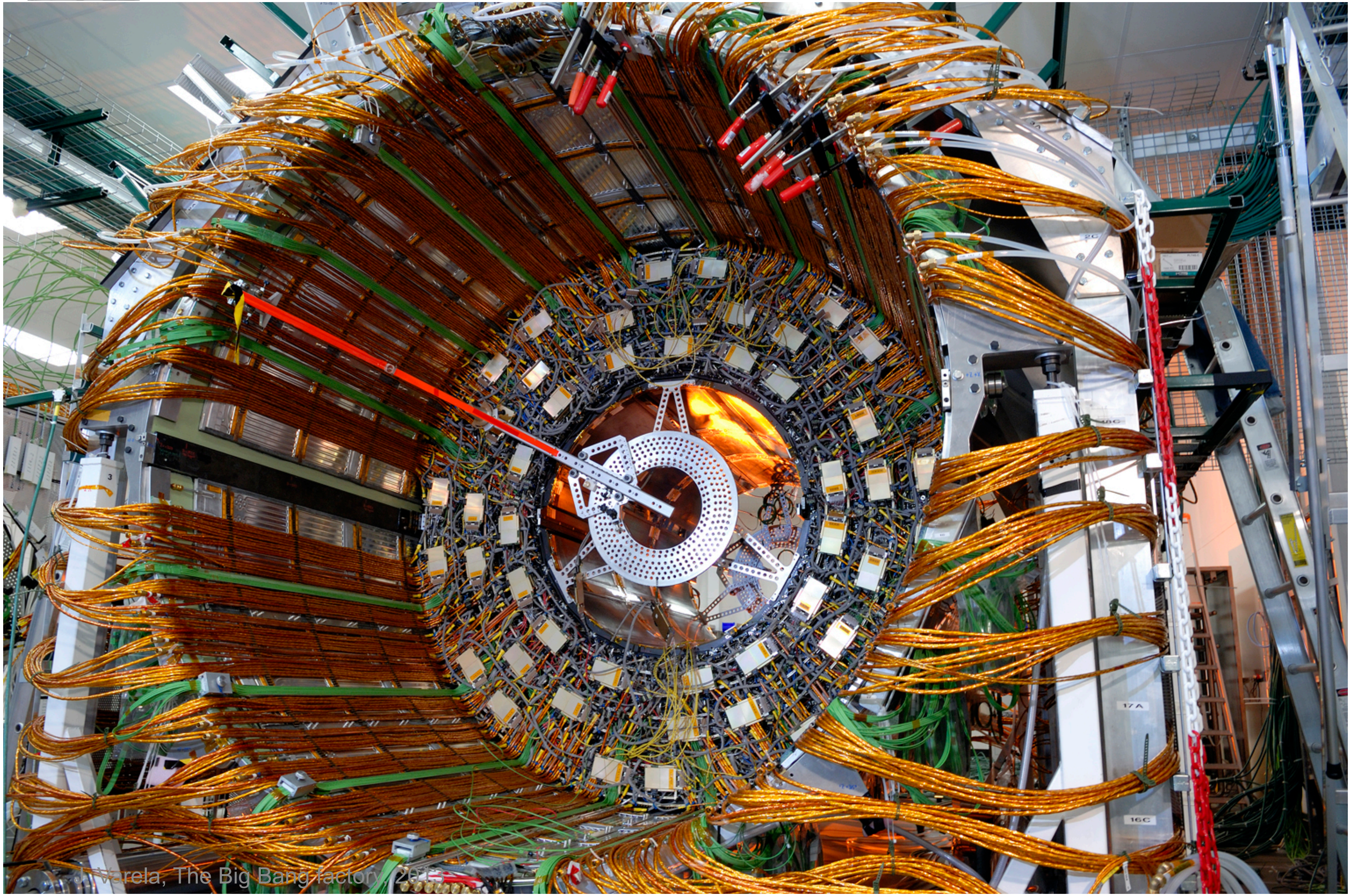


Silicon Tracker

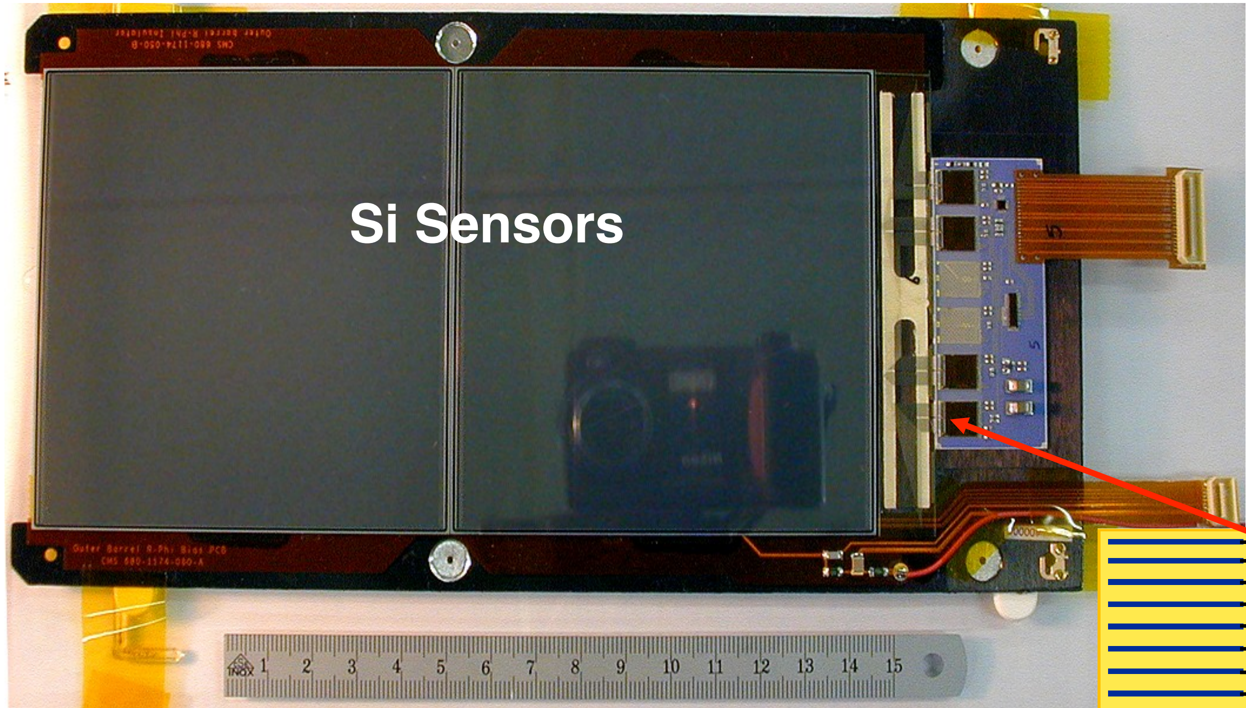
200 square meter of silicon wafers: from cartoon to reality



Silicon Tracker

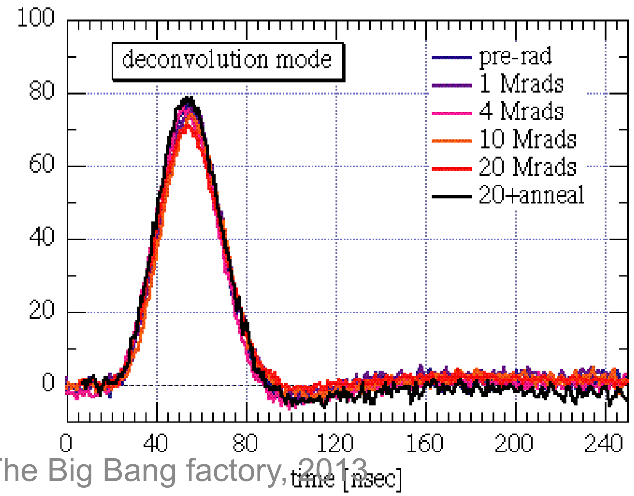


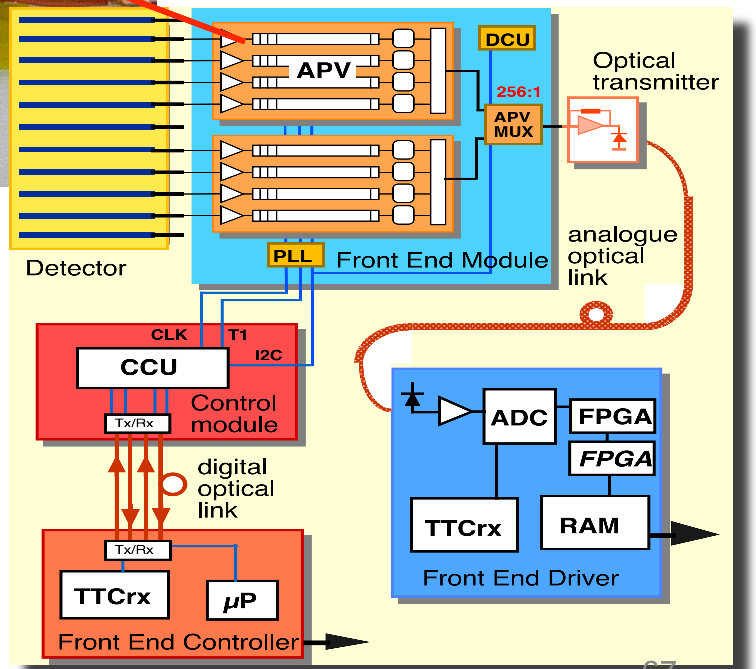
Si sensors and electronics chain



Ride on technology wave

75k chips using 0.25μm technology

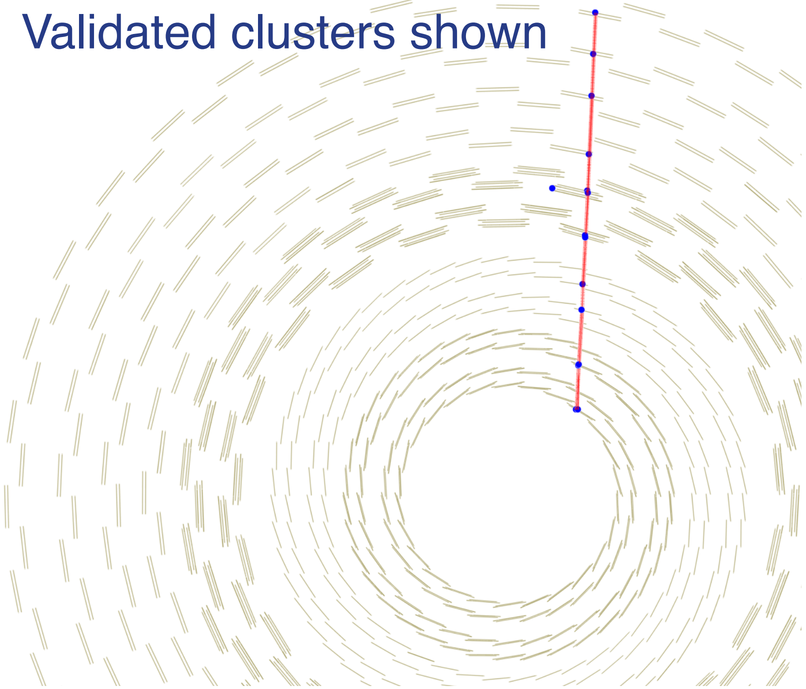




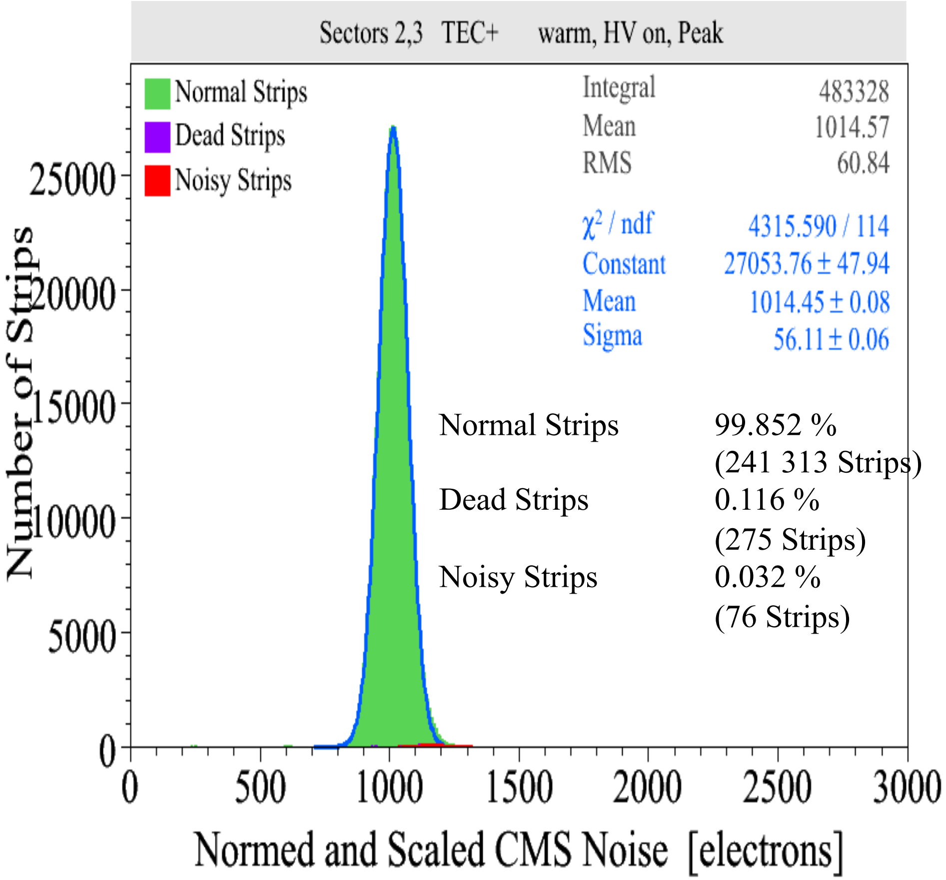
Cosmics in the Tracker

A cosmic muon at -15°C

Validated clusters shown



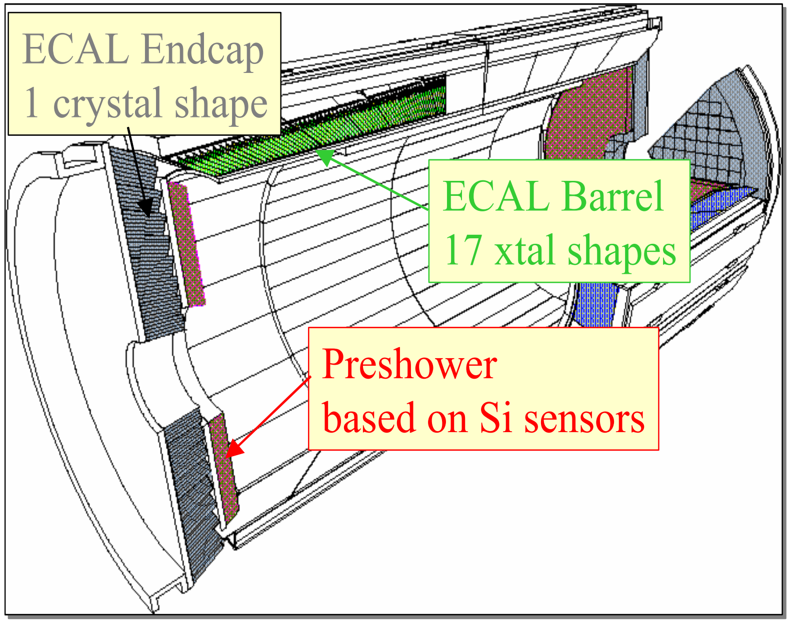
Example of Performance

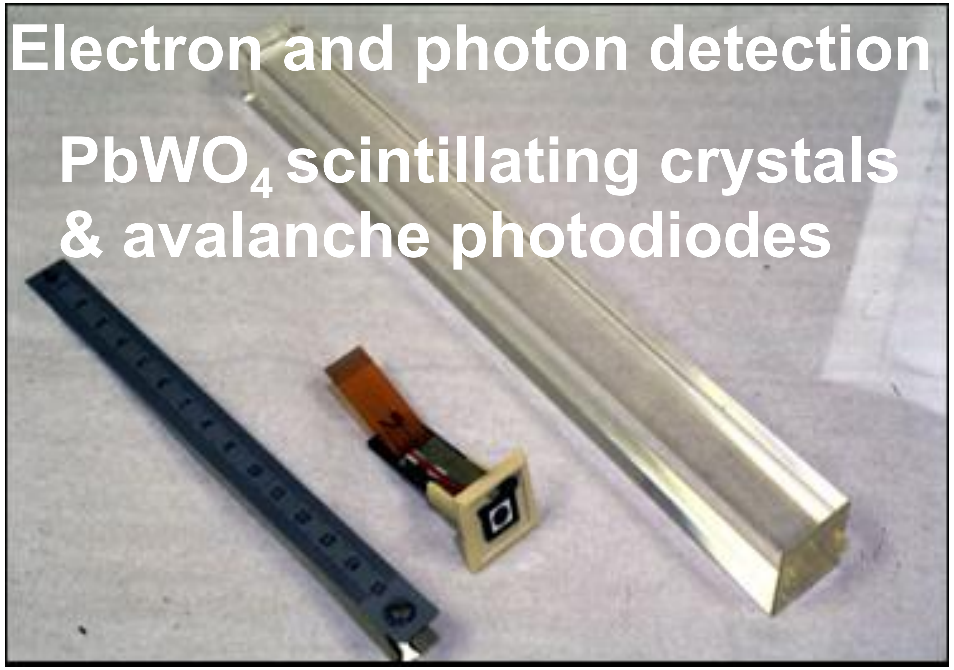


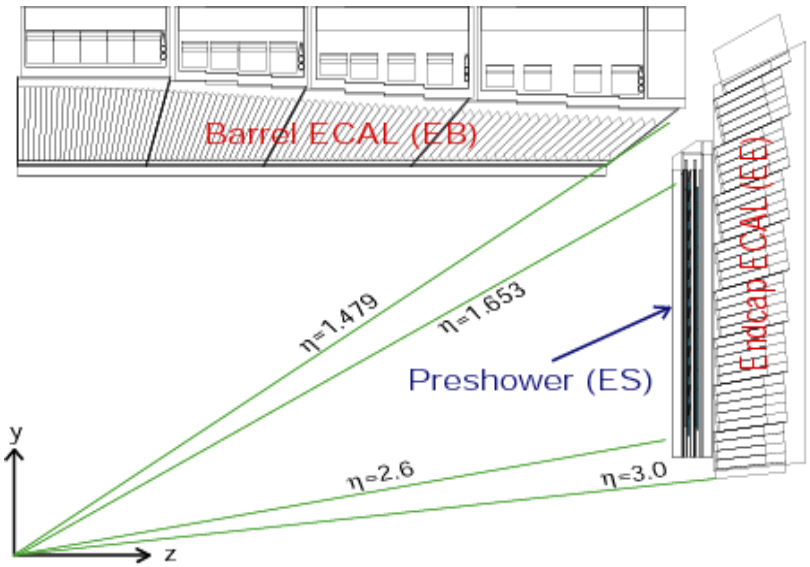
The Quality of the CMS Tracker is Excellent:

- Dead or Noisy Strips < 3 / 1000
- Signal: Noise > 25:1

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	**8.14m³**	**2.7m³**
Xtal mass (t)	**67.4**	**22.0**

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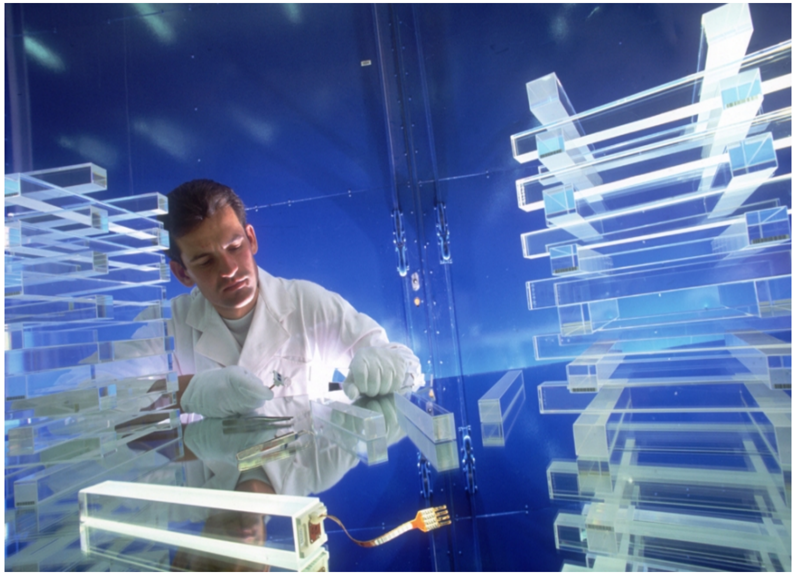
Timeline of the LHC Experiments: a typical example



Development of Lead Tungstate Scintillating Crystals for the CMS Electromagnetic Calorimeter

~ 15 years !!!

Idea (1993 – few yellowish cm^3 samples)

→ R&D (1993-1998: improve rad. hardness: purity, stoichiometry, defects)

→ Prototyping (1994-2001: large matrices in test beams, monitoring)

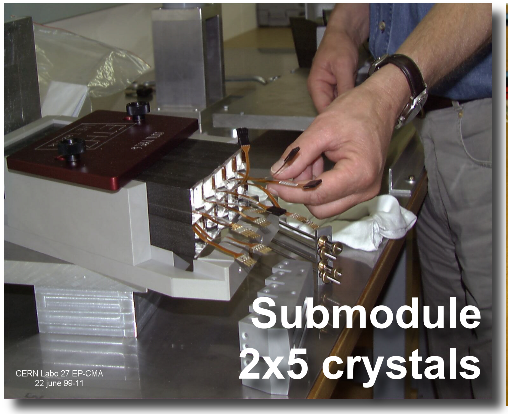
→ Mass manufacture (1997-2008: increase industrial capacity, QC)

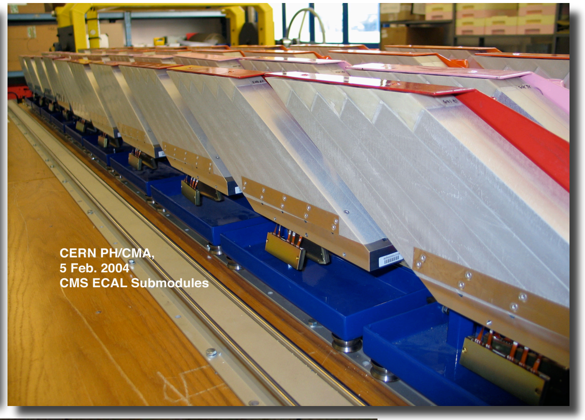
→ Systems Integration (2001-2008: tooling, assembly)

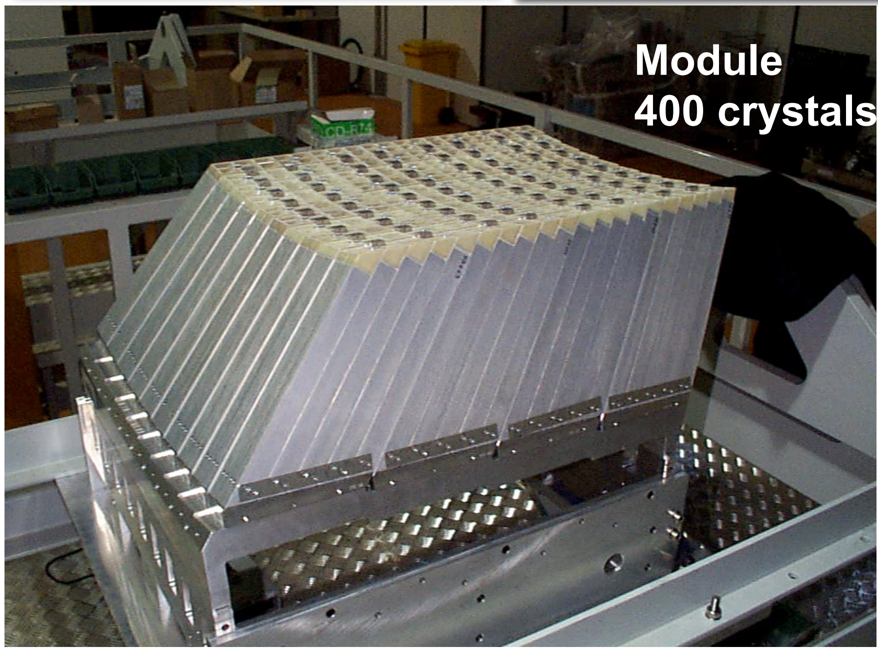
→ Installation and Commissioning (2007-2008)

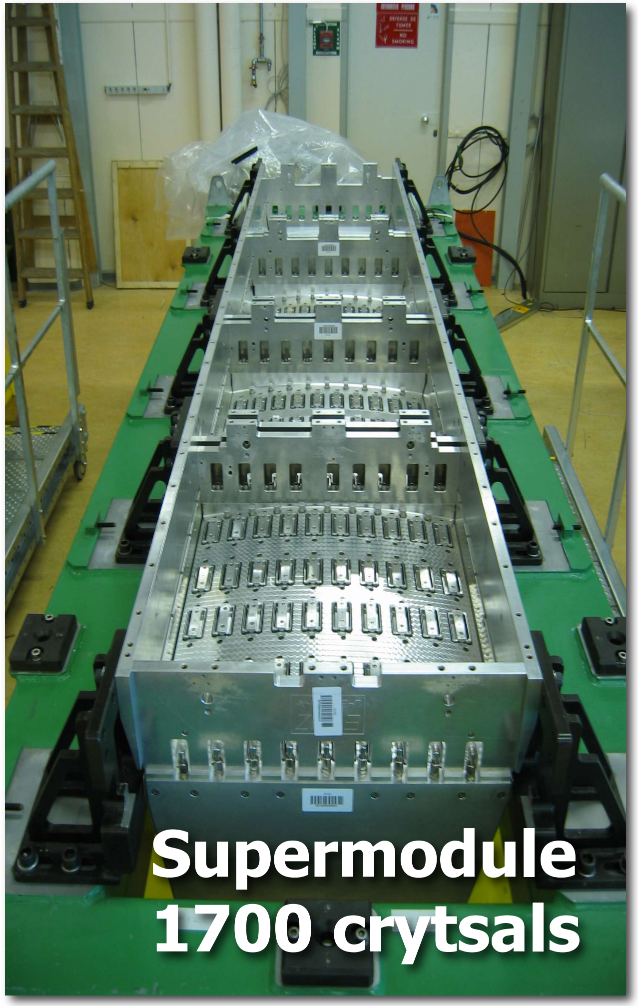
→ Data Taking (2009 onwards)

Assembling the Calorimeter



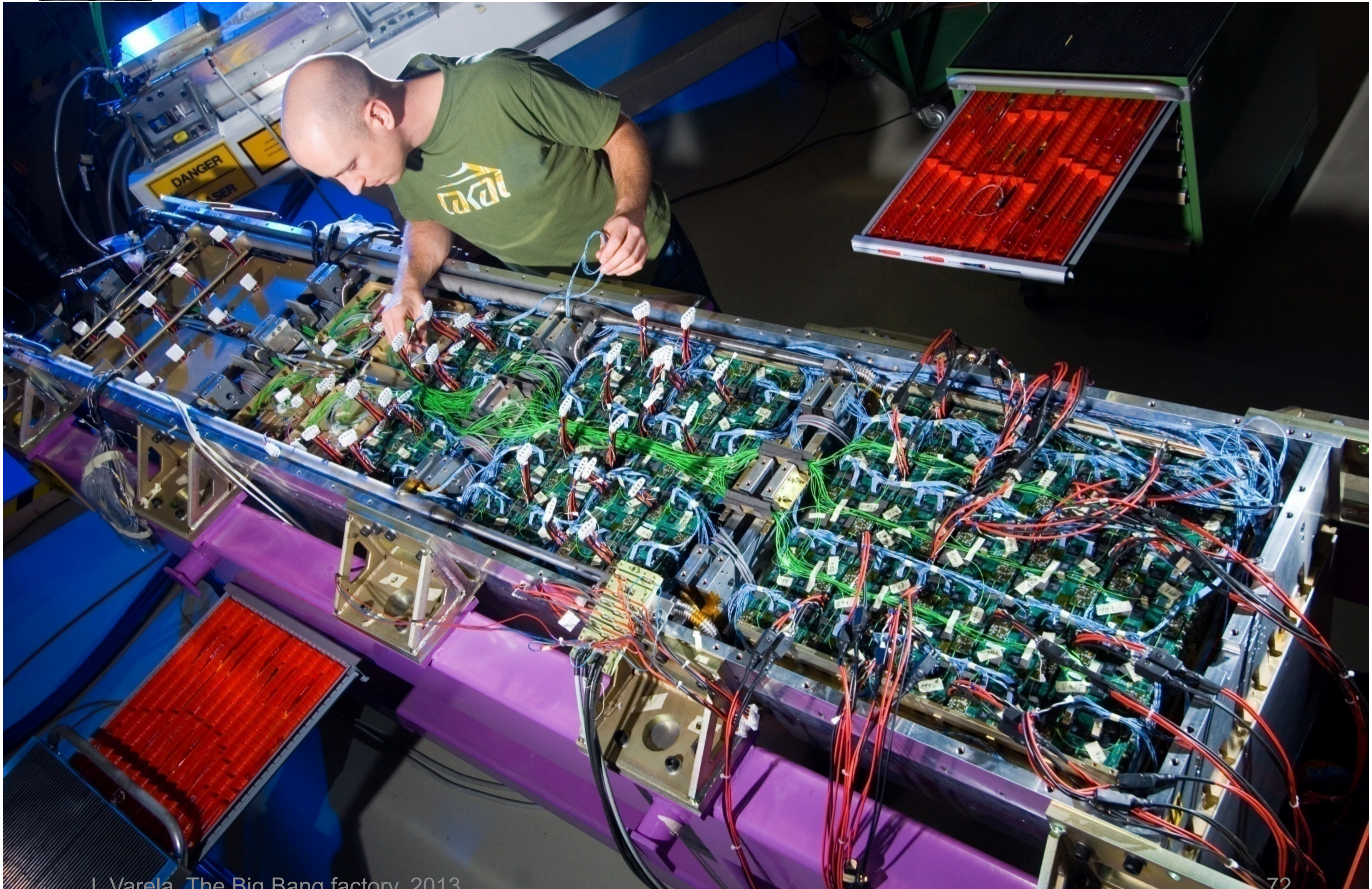






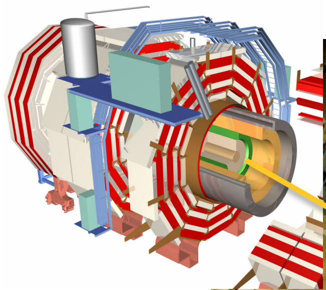
Total 36 Supermodules

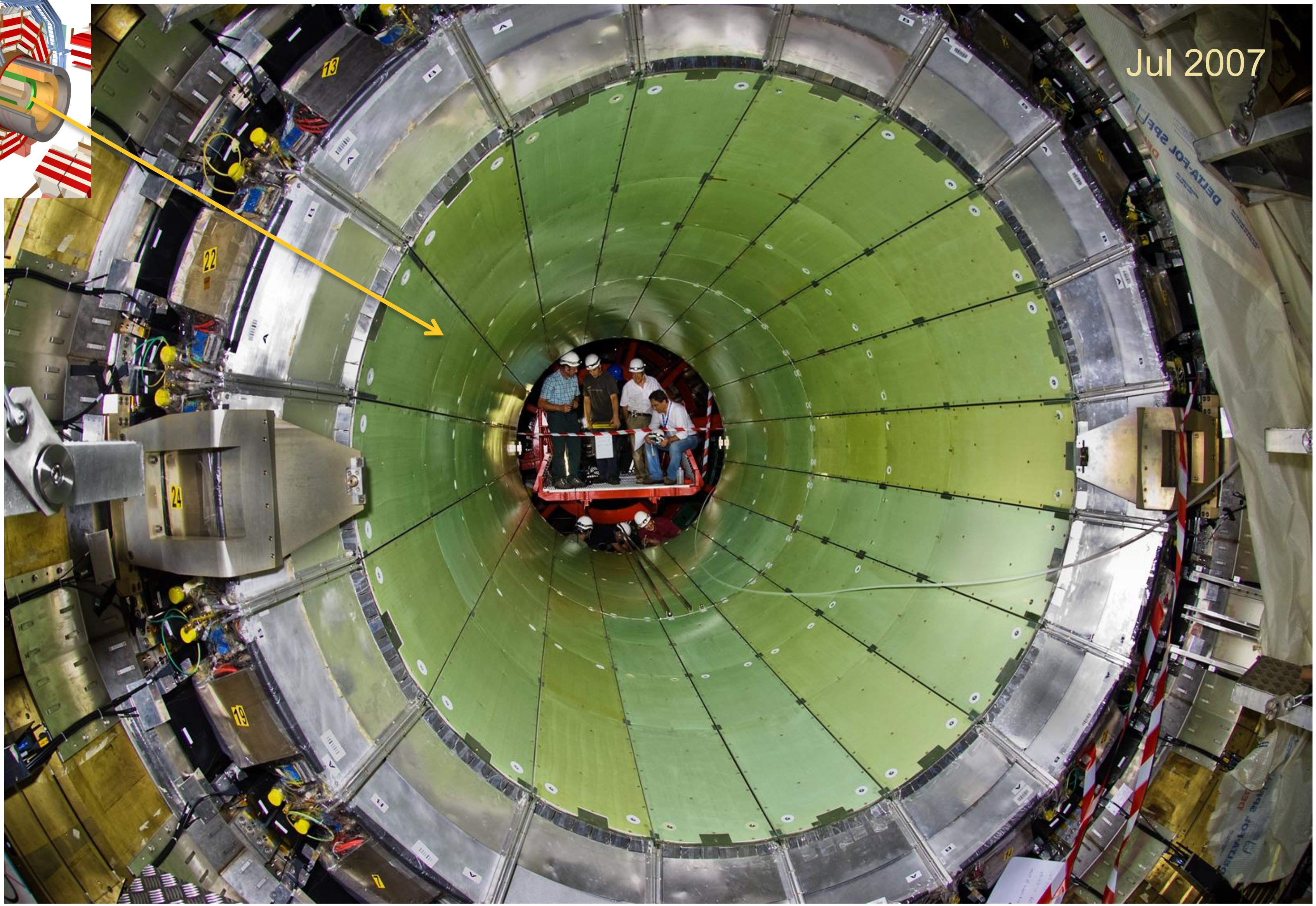
Assembly of front-end electronics



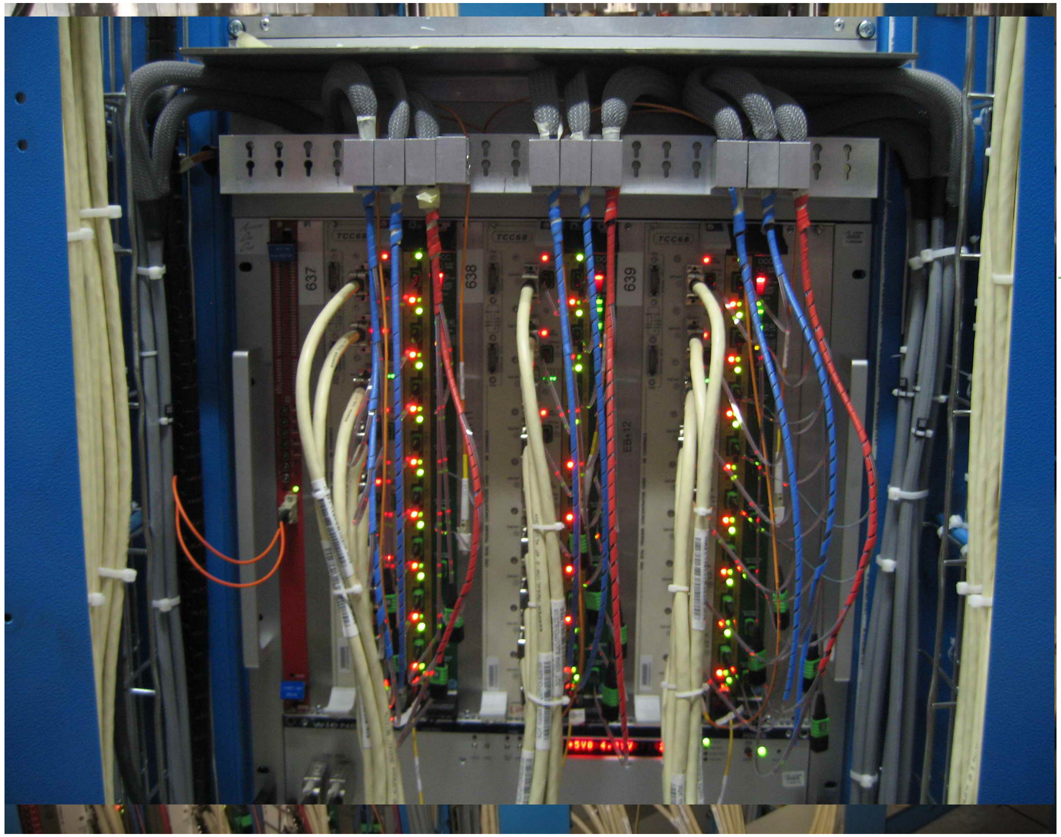
Insertion in the detector

The Calorimeter installed in the Experiment

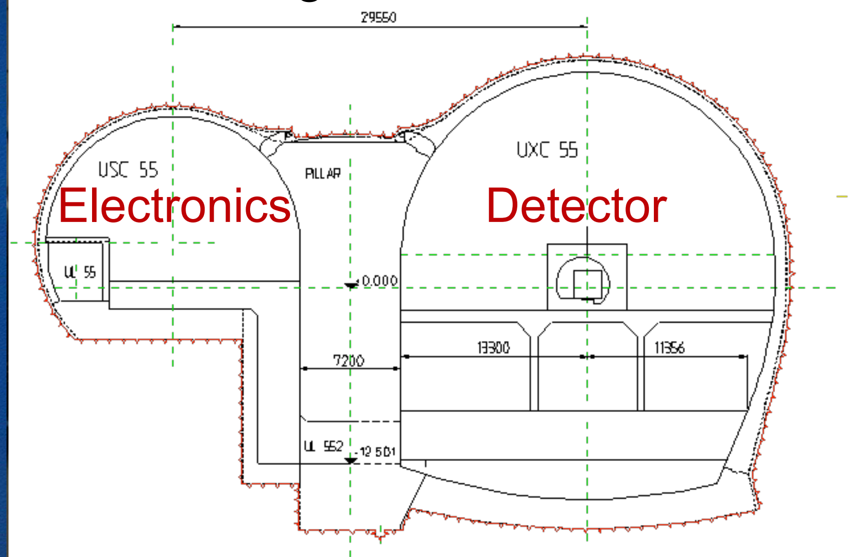


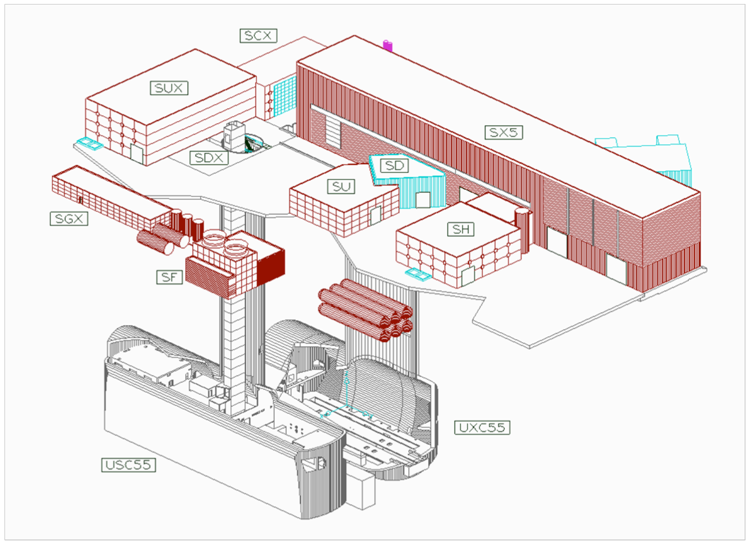


ECAL trigger and readout electronics



Underground caverns

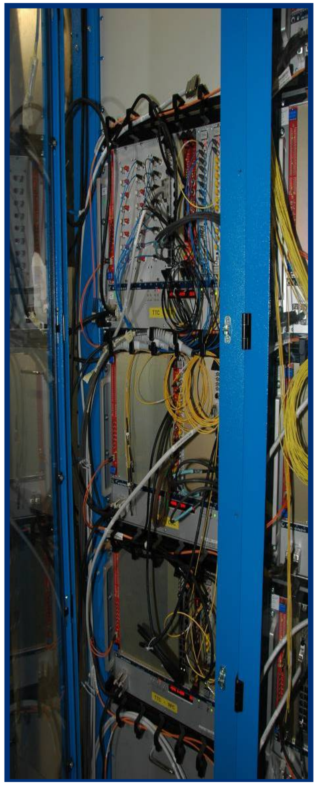


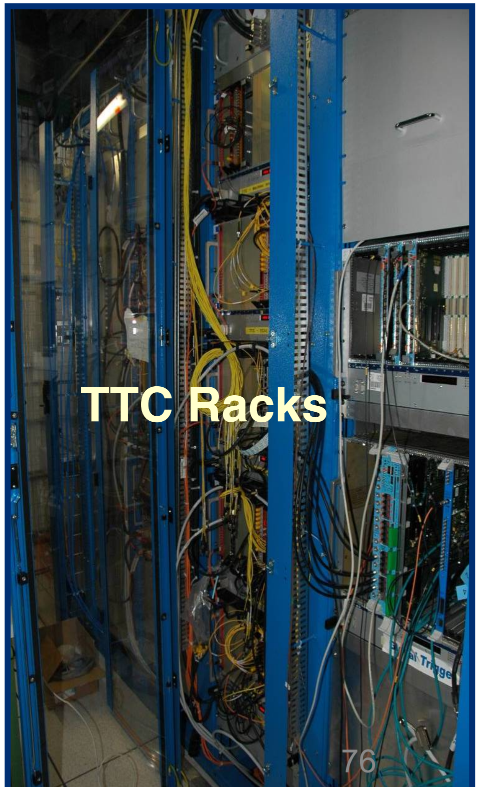


18	Crates
216	Electronic boards
3000	0.8 Gb/s optical links
2500	1.2 Gb/s electrical links

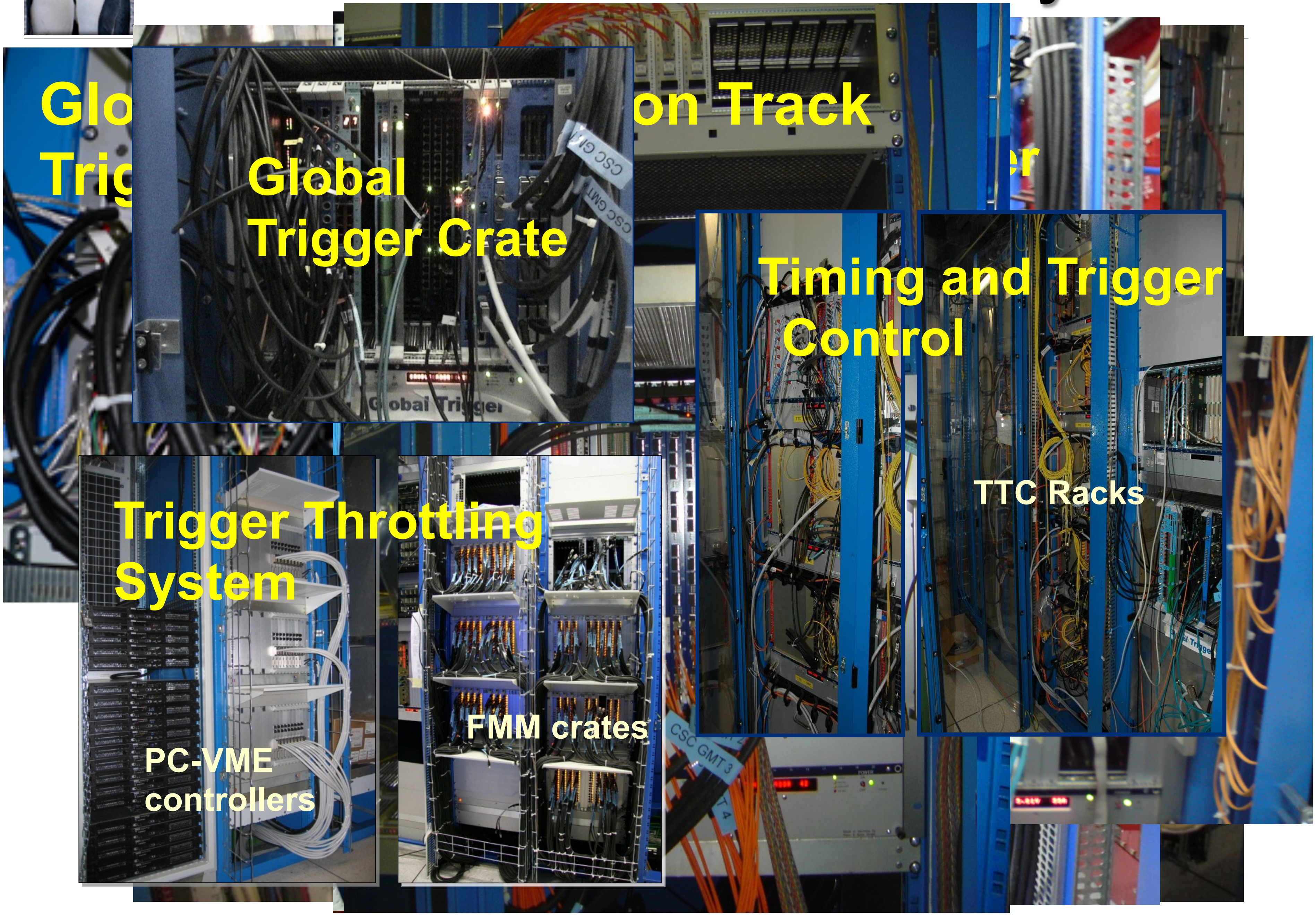
Electronics systems

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



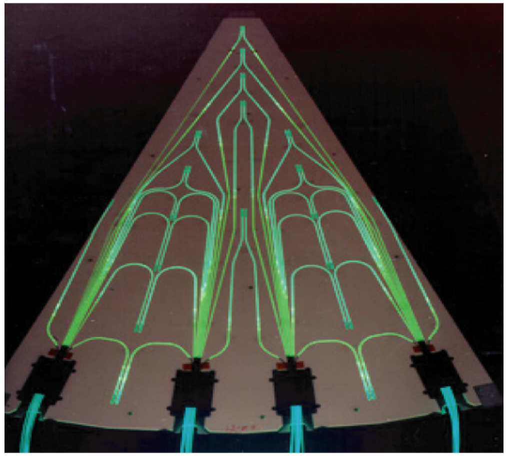


Electronics systems



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

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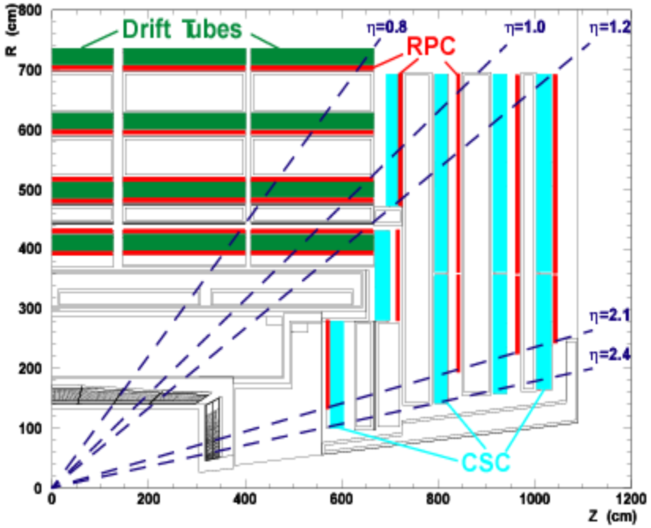
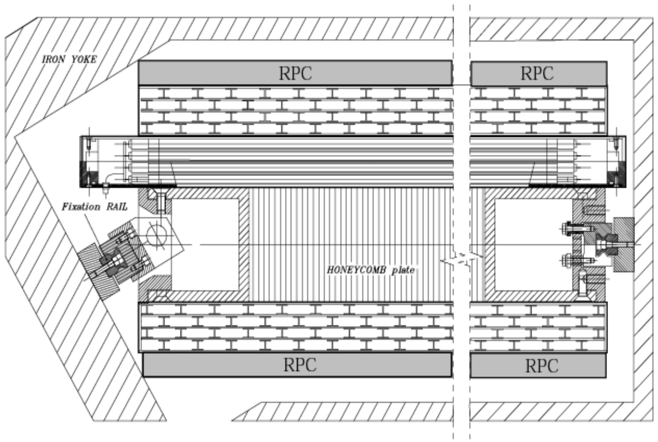
Muon detectors



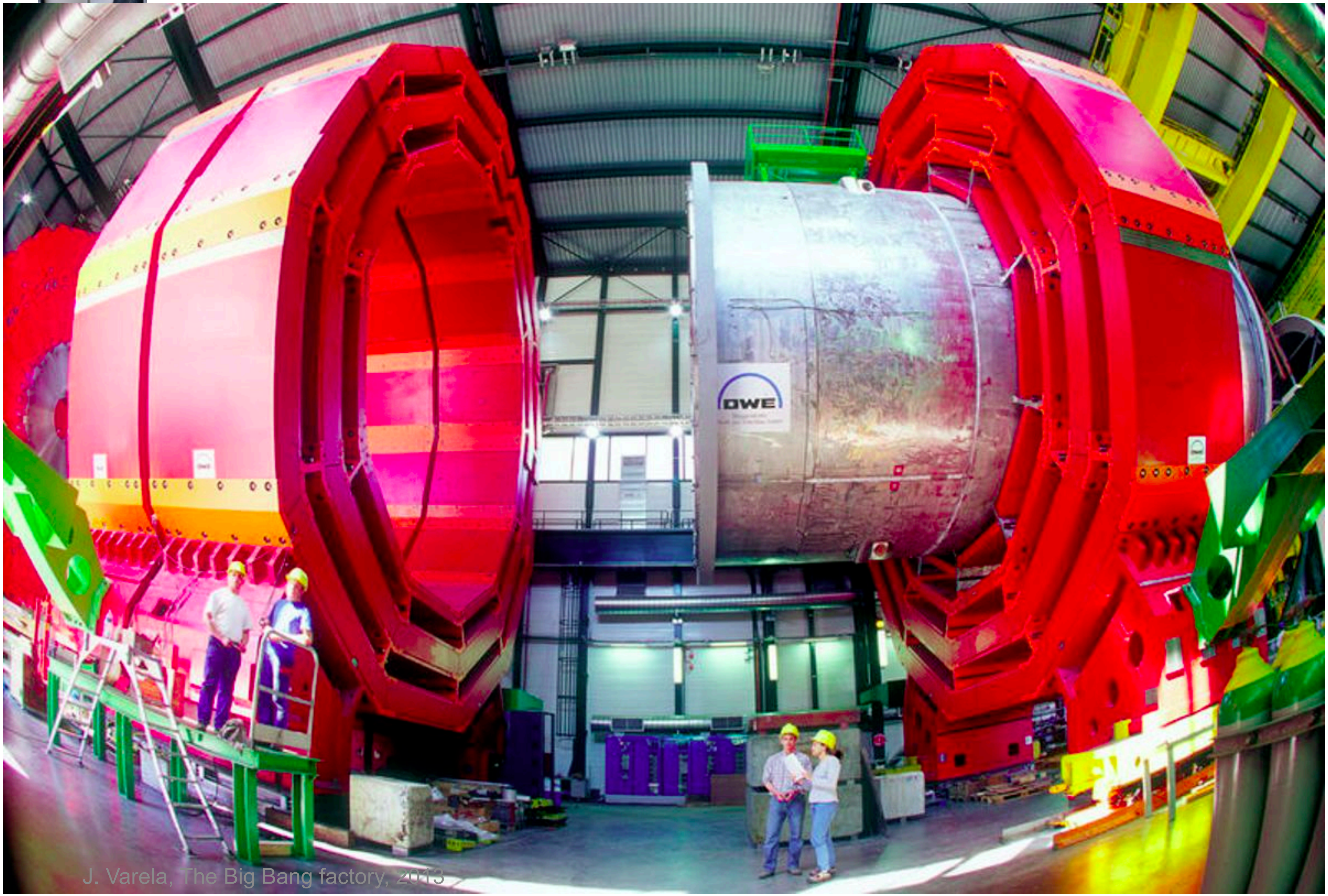
Drift Tubes (DT)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)



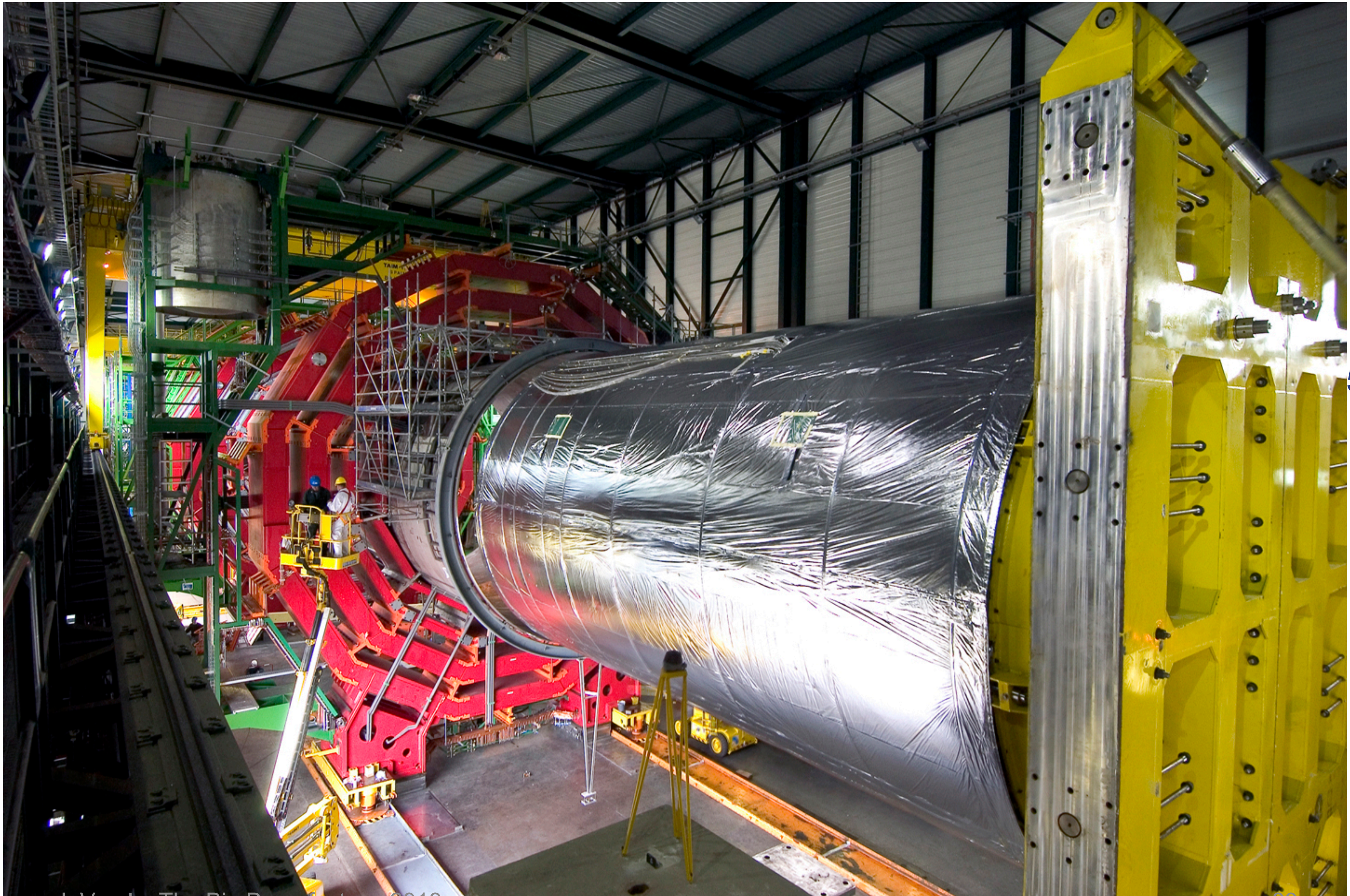
Surface Site in 2000

Civil engineering challenges

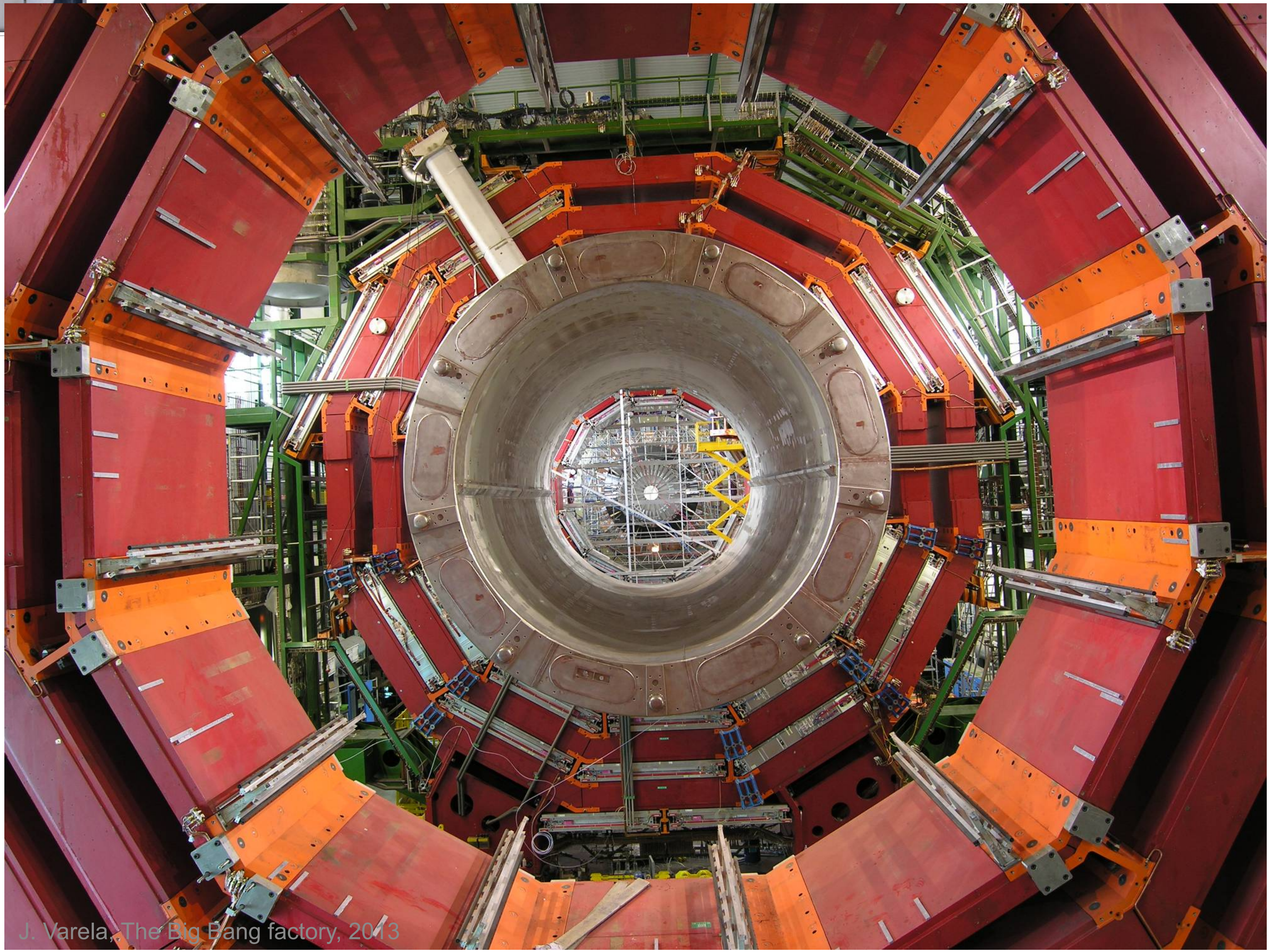
2002: CMS iron yoke assembly in surface hall



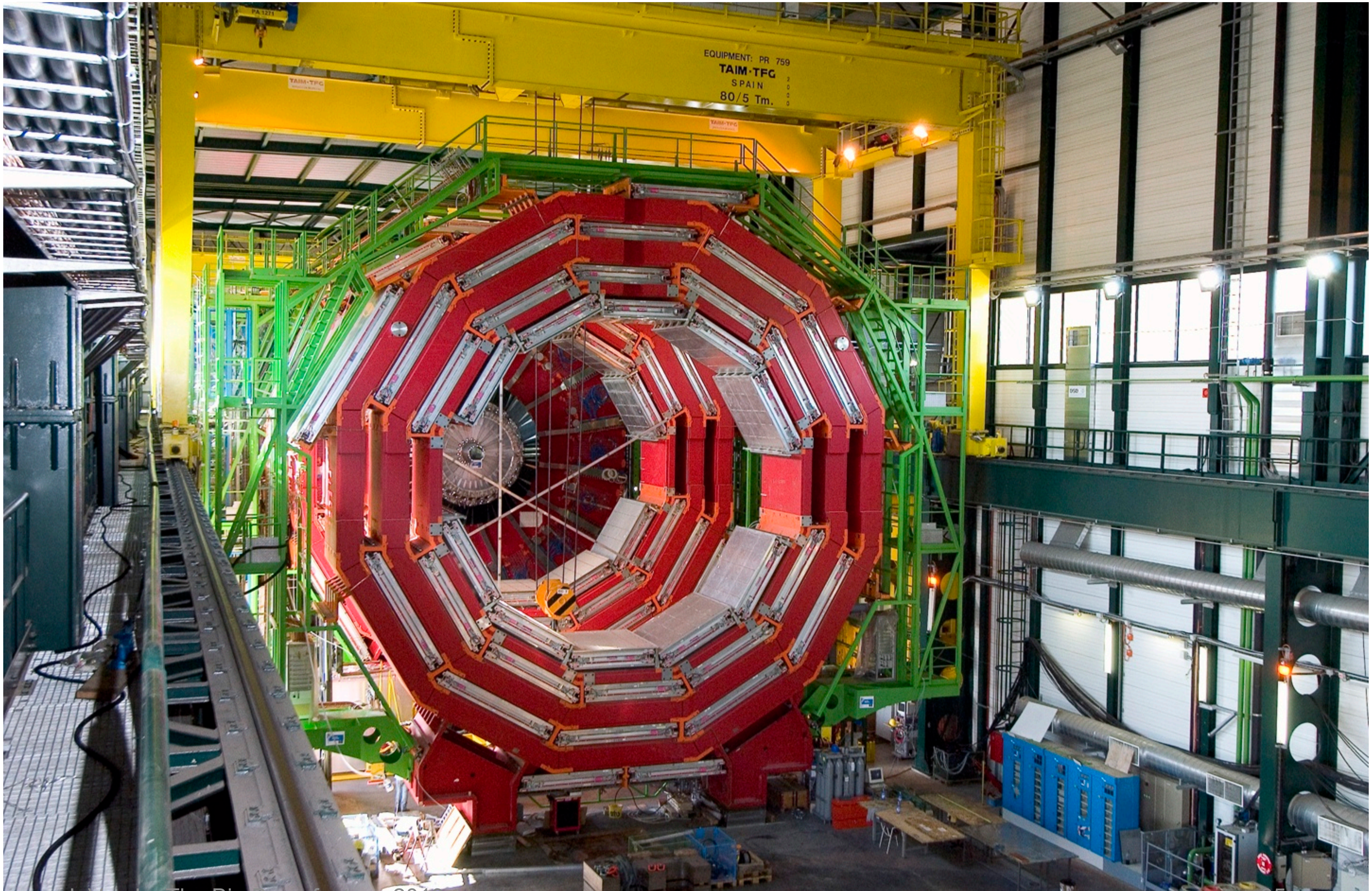
Assembly of the Coil



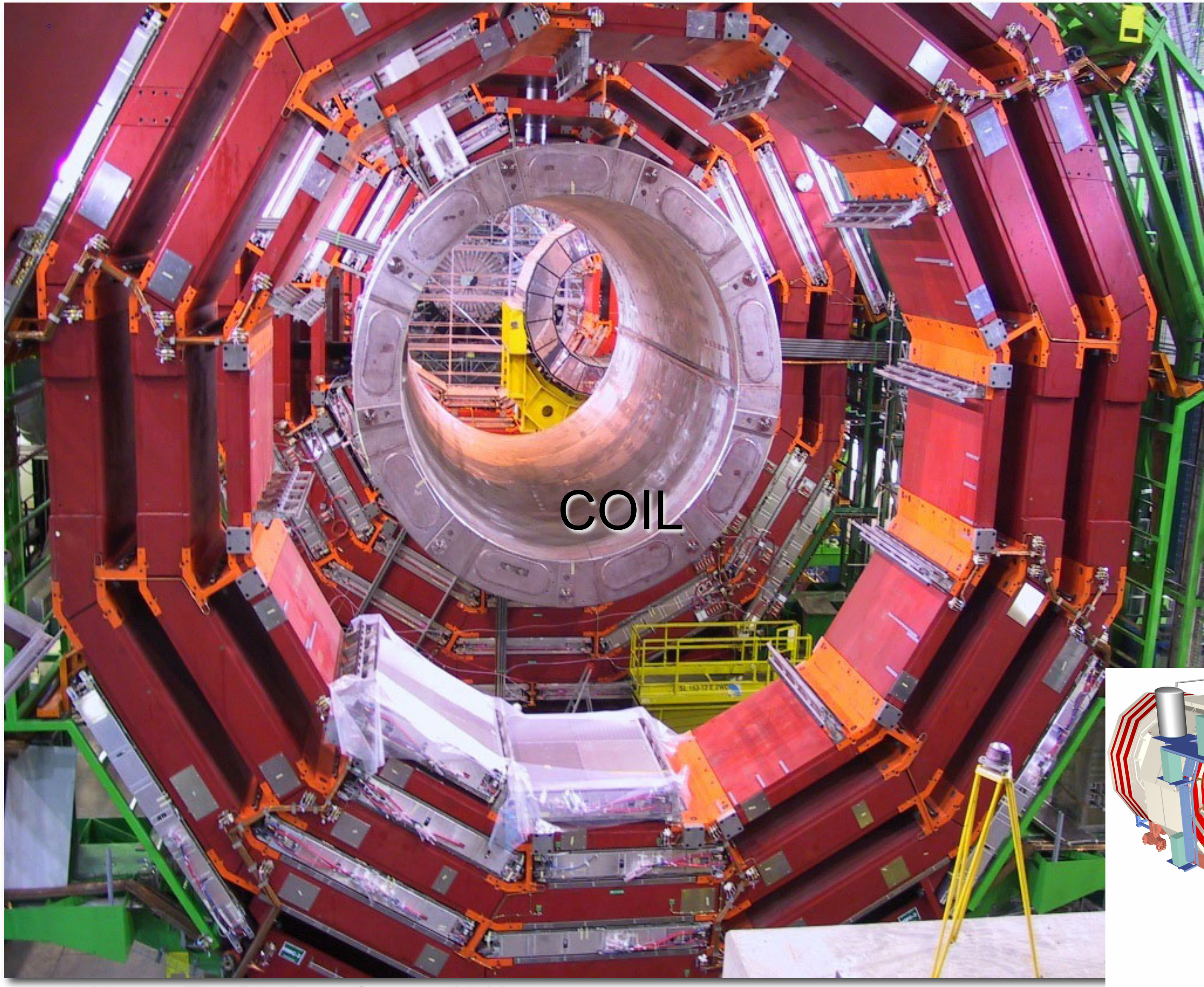
2005: Superconducting solenoid installed

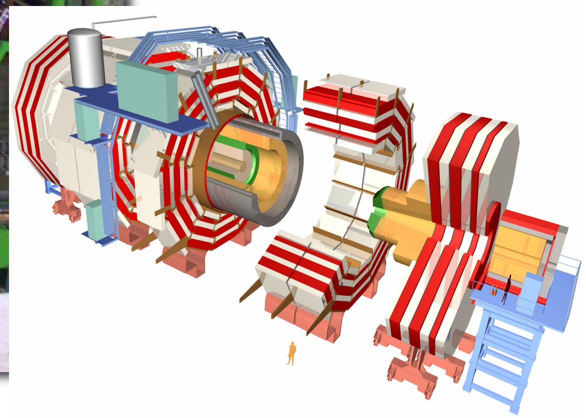


2005-06: Muon chambers inserted in iron yoke



Surface Hall in Feb 2006





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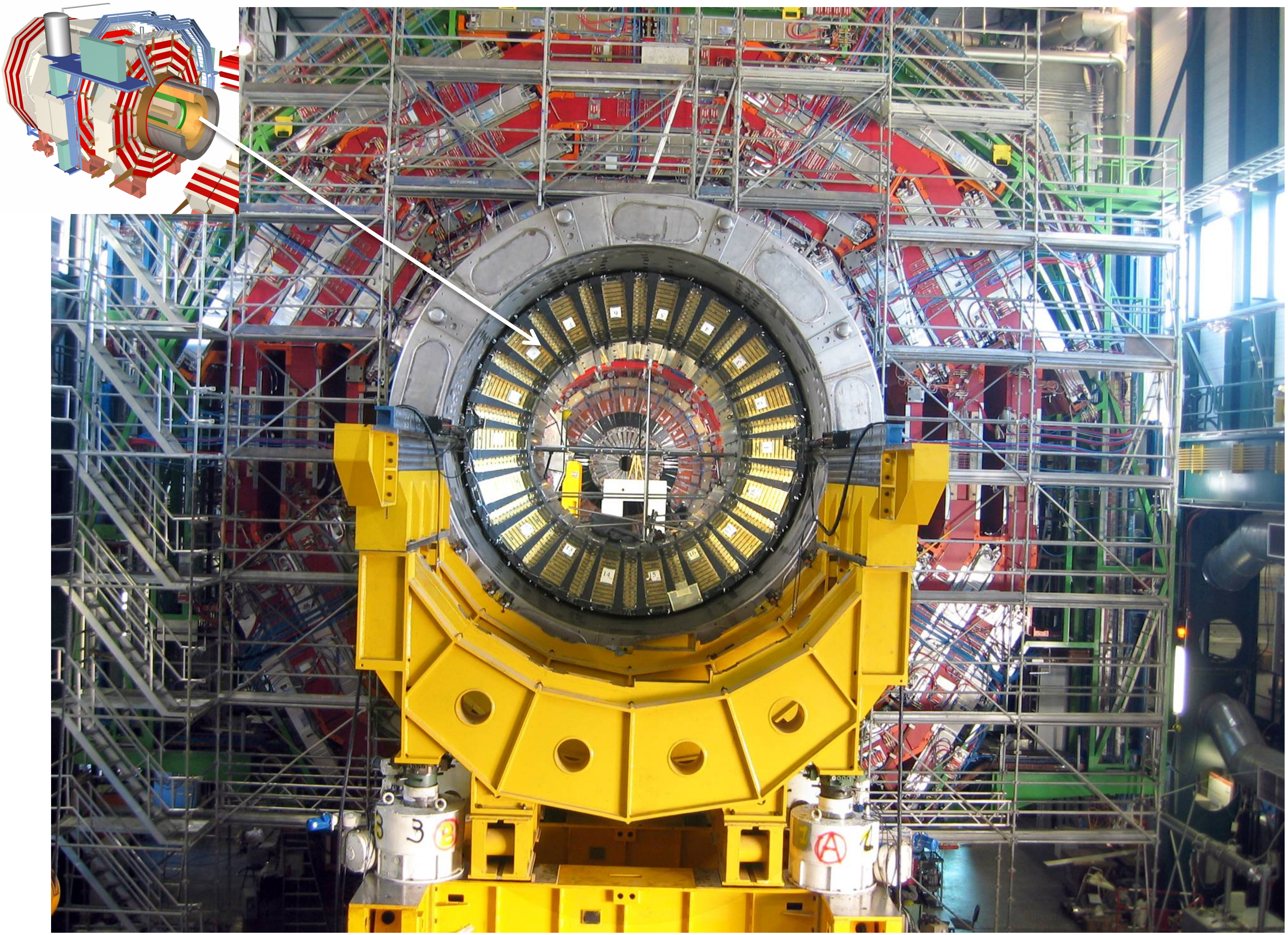
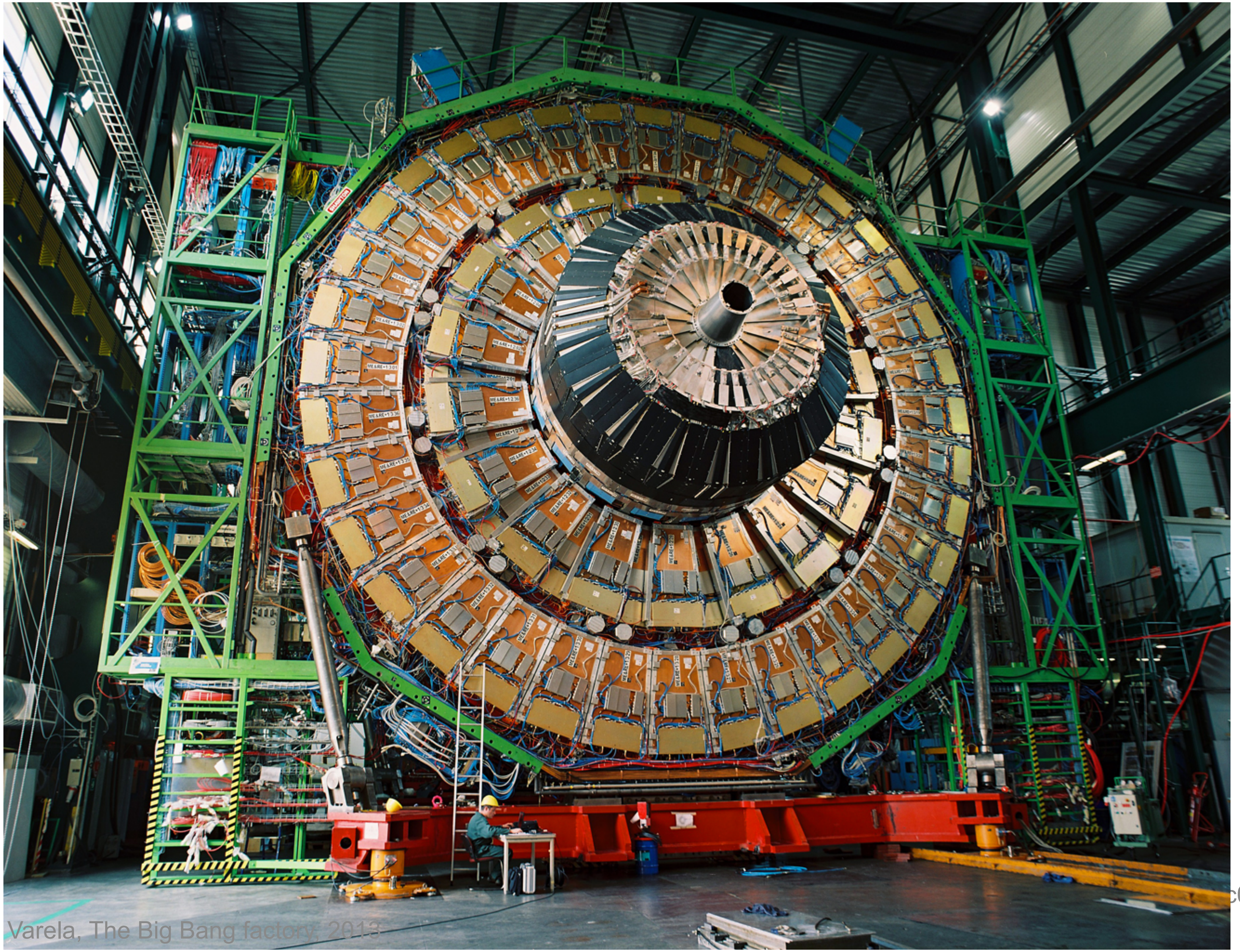
HCAL barrel test assembly



2006: Magnet test on the surface

Surface Hall: Endcaps



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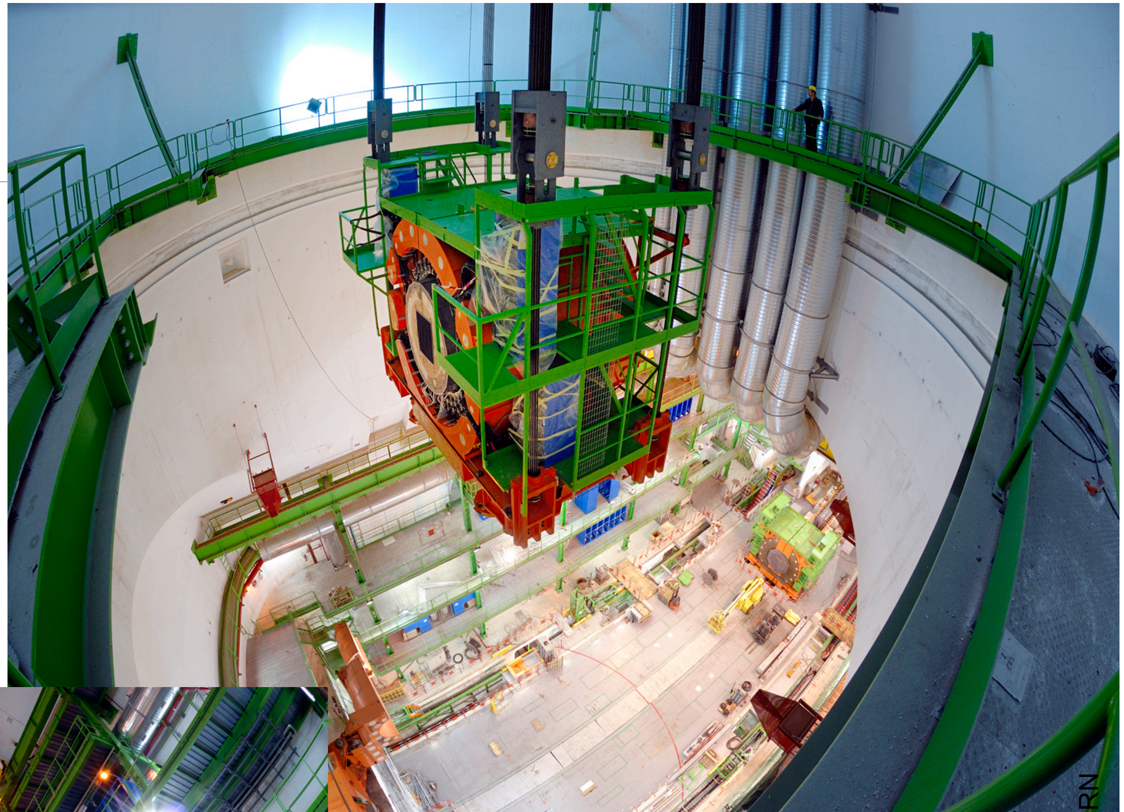
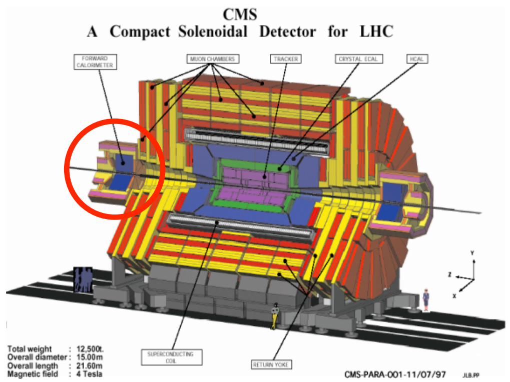
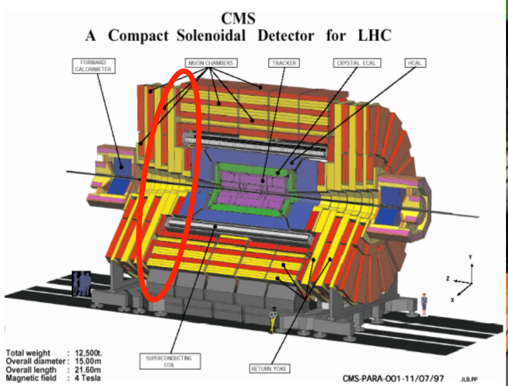
2004: CMS detector cavern

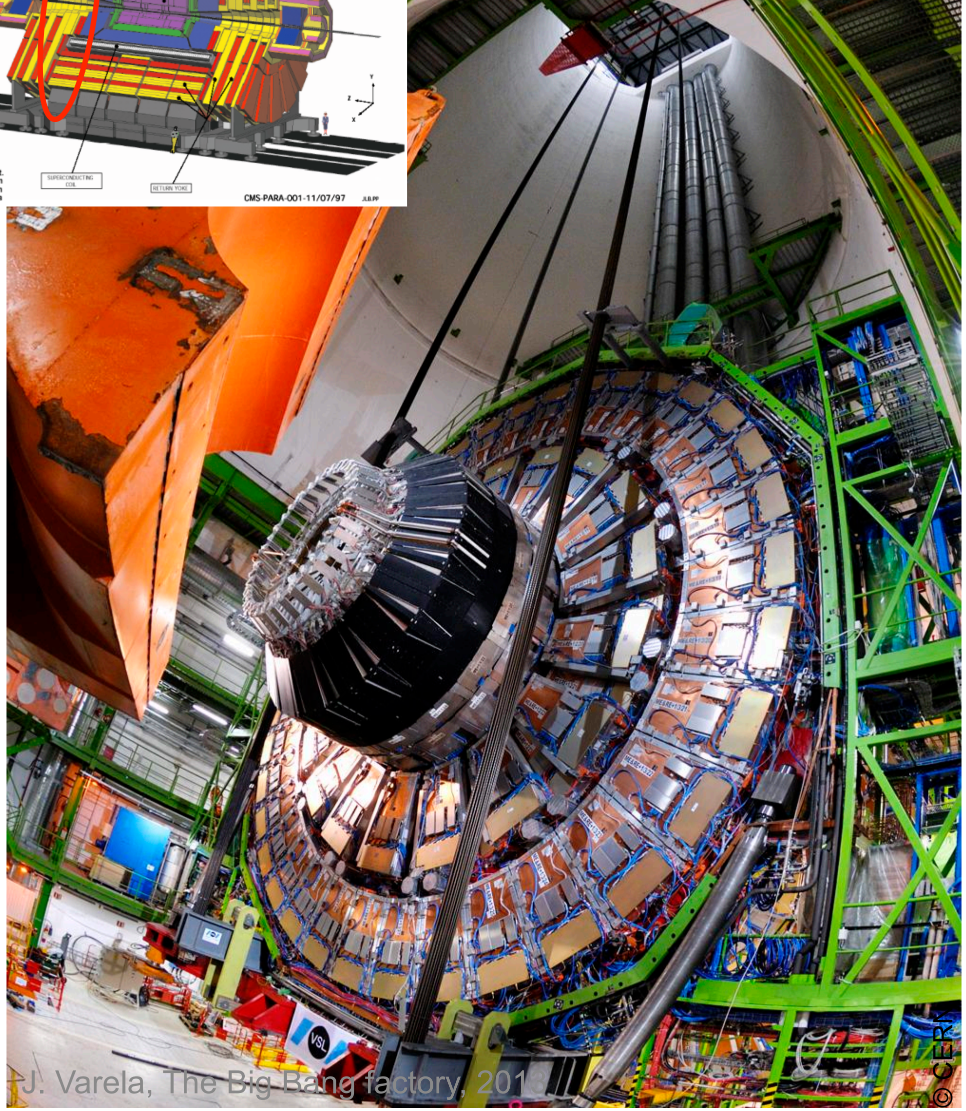
Lowering CMS to the underground cavern begins: November, 2006





2007: Lowering one of six huge disks





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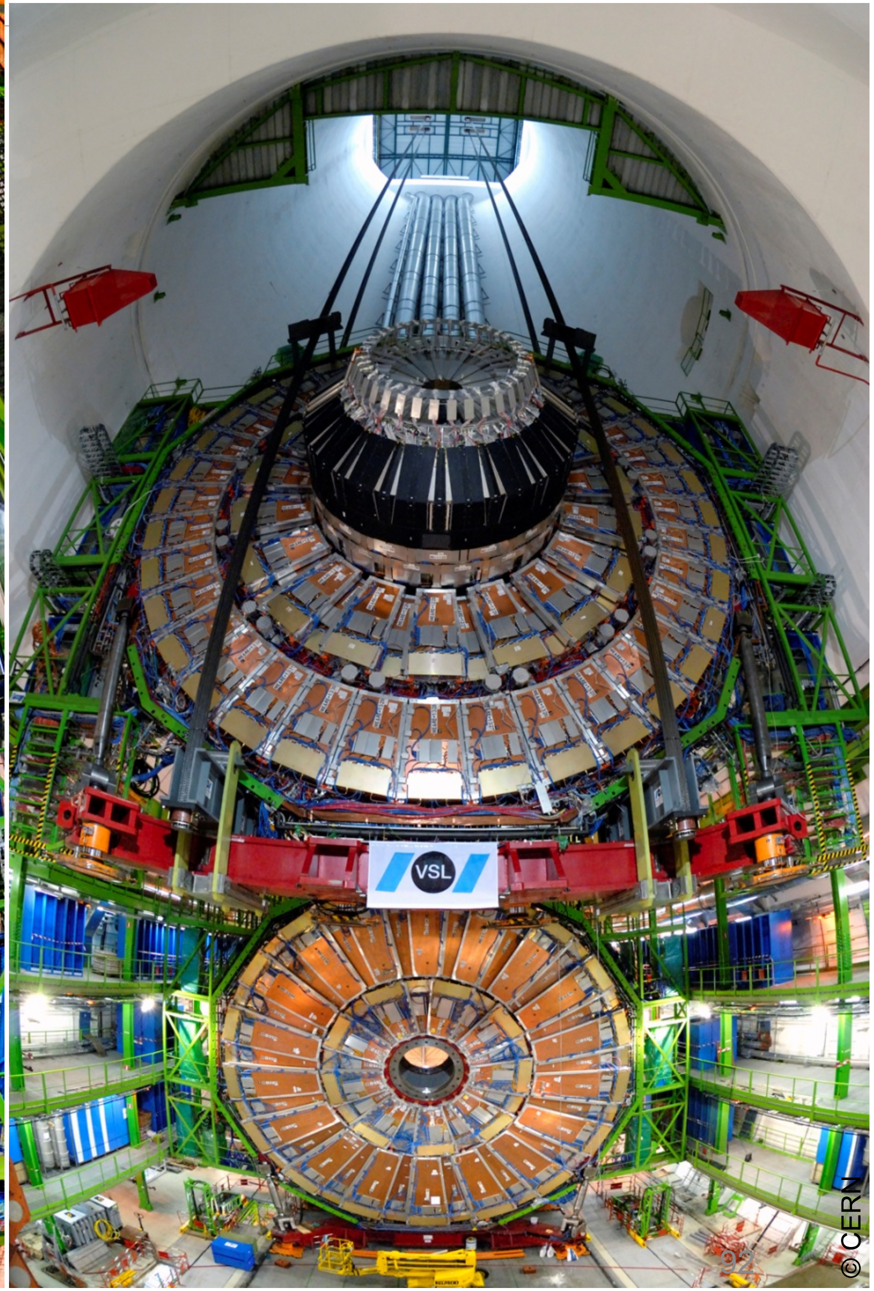
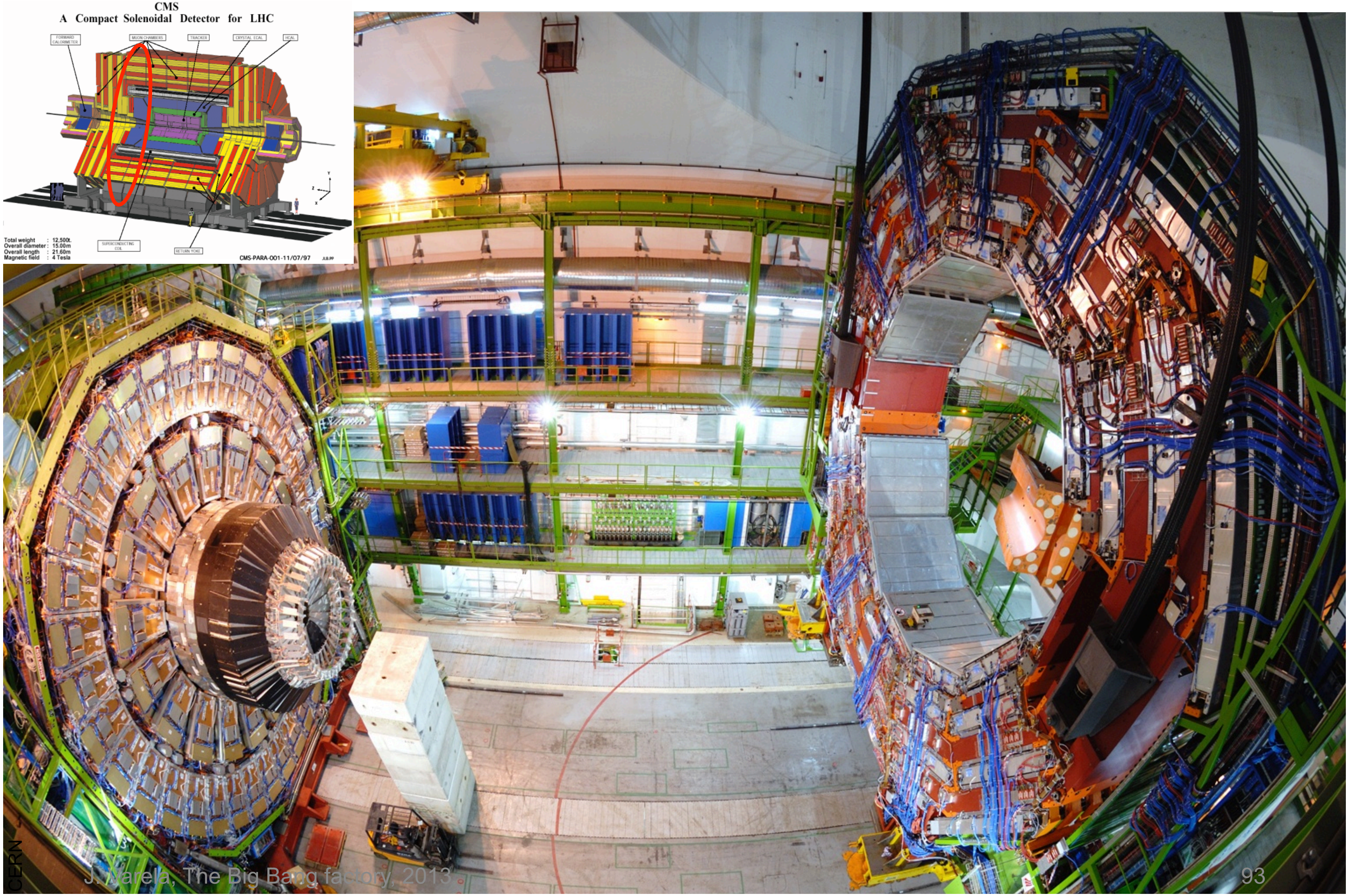
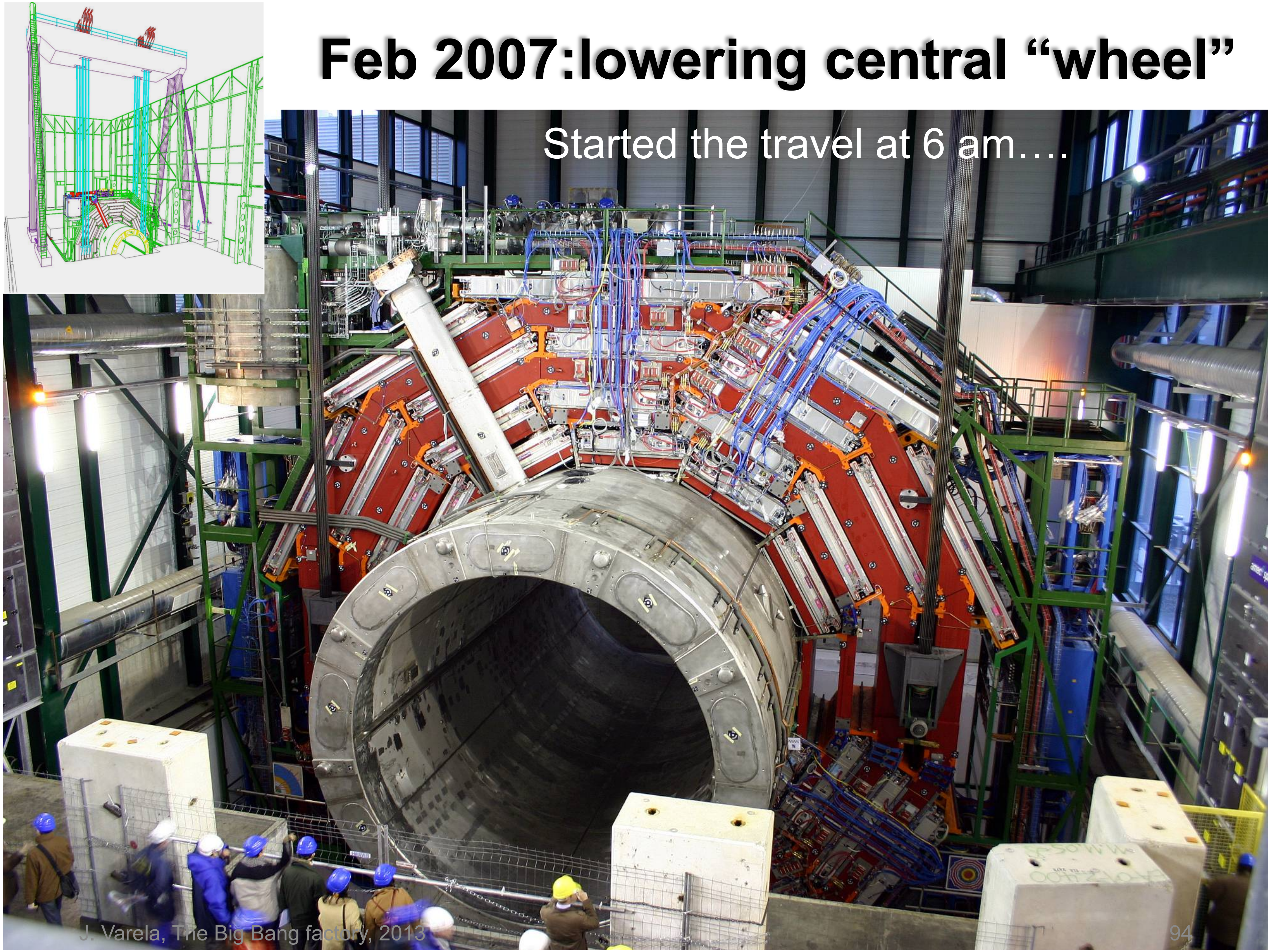


First barrel “wheel”

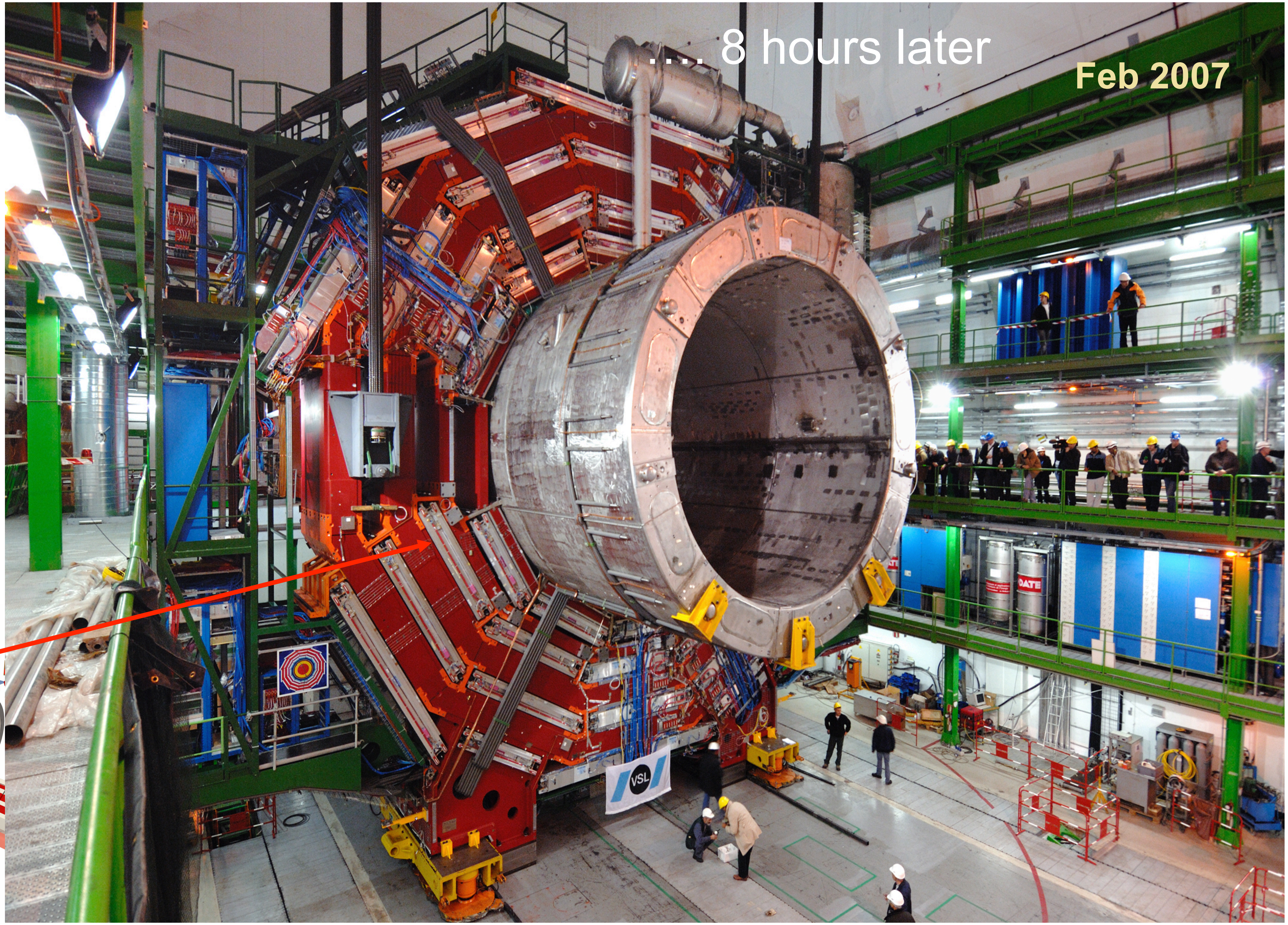


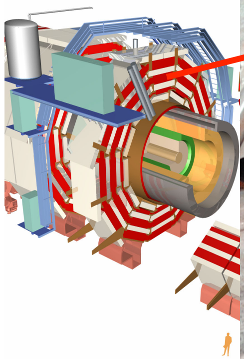
Feb 2007:lowering central “wheel”



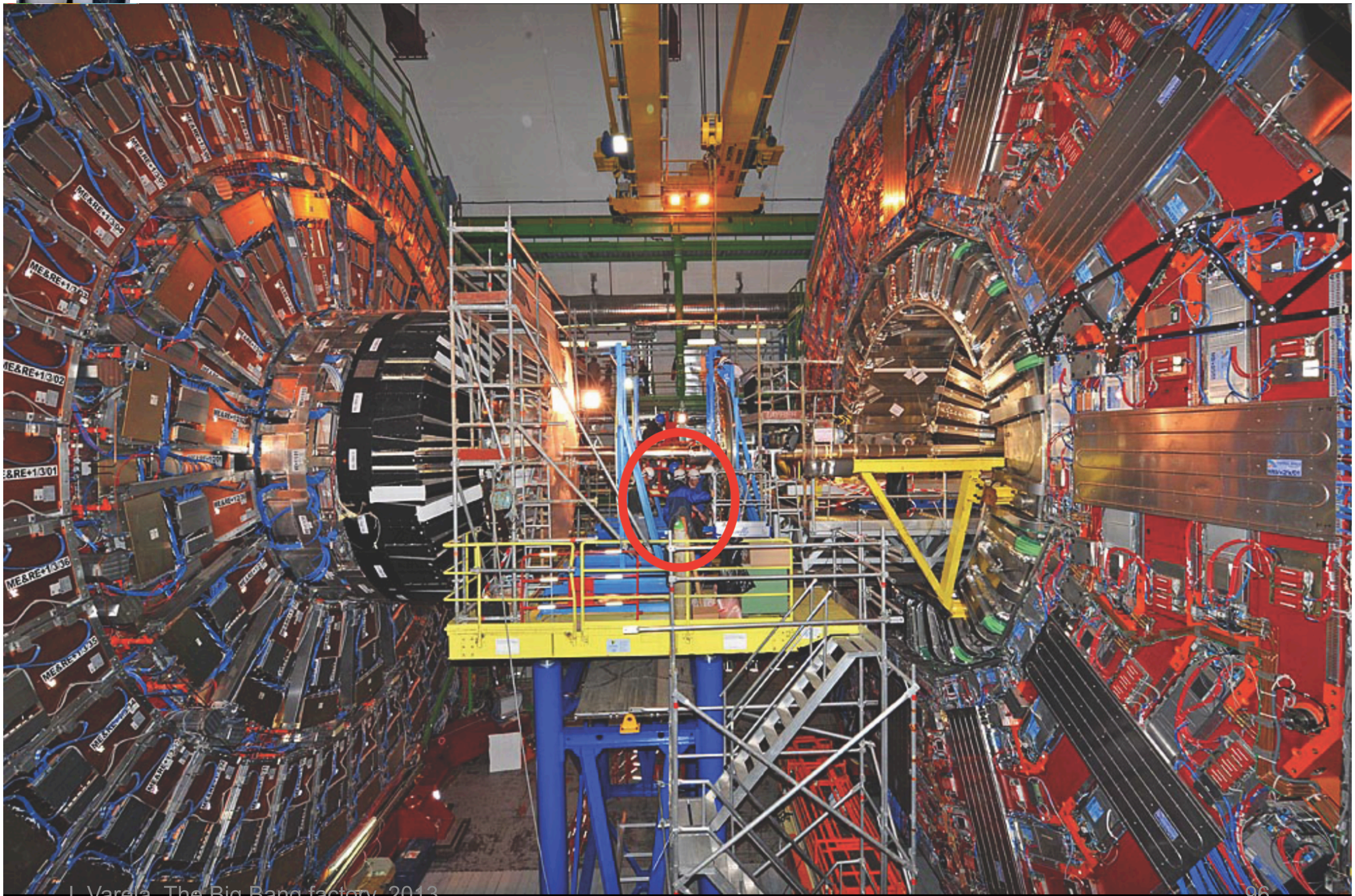
Started the travel at 6 am….

Magnet coil arrive in the cavern

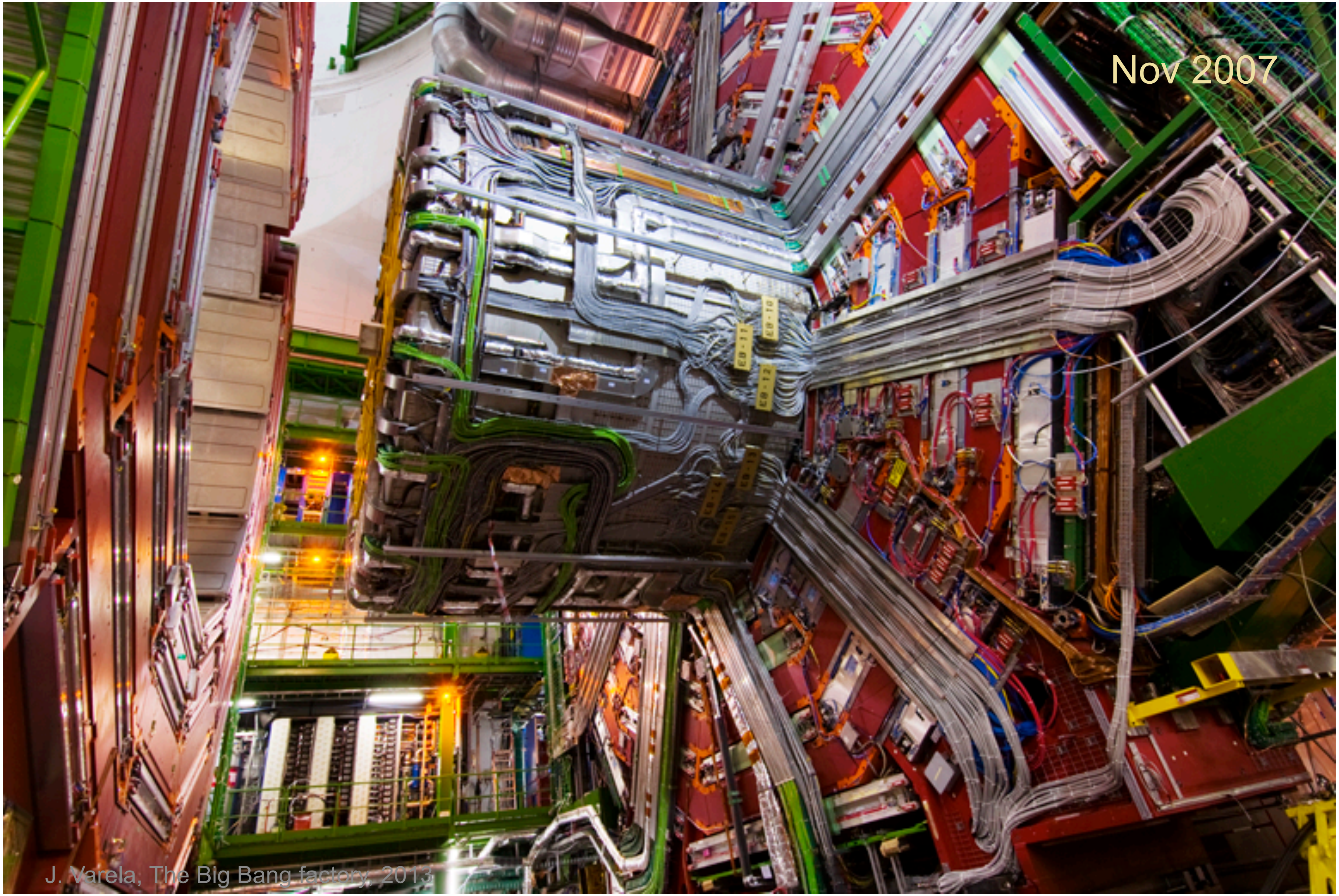




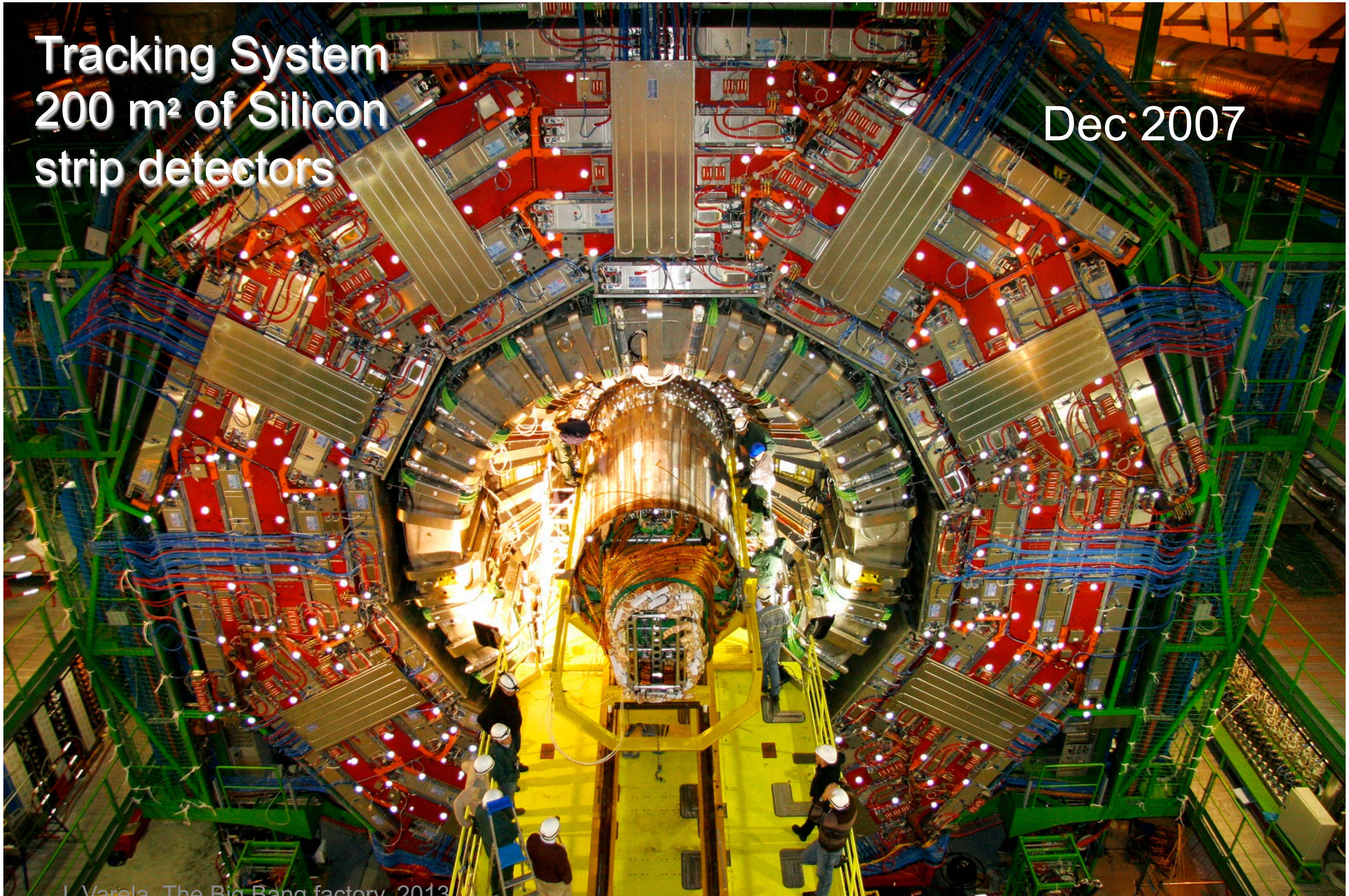
2007-08: Installation in the cavern



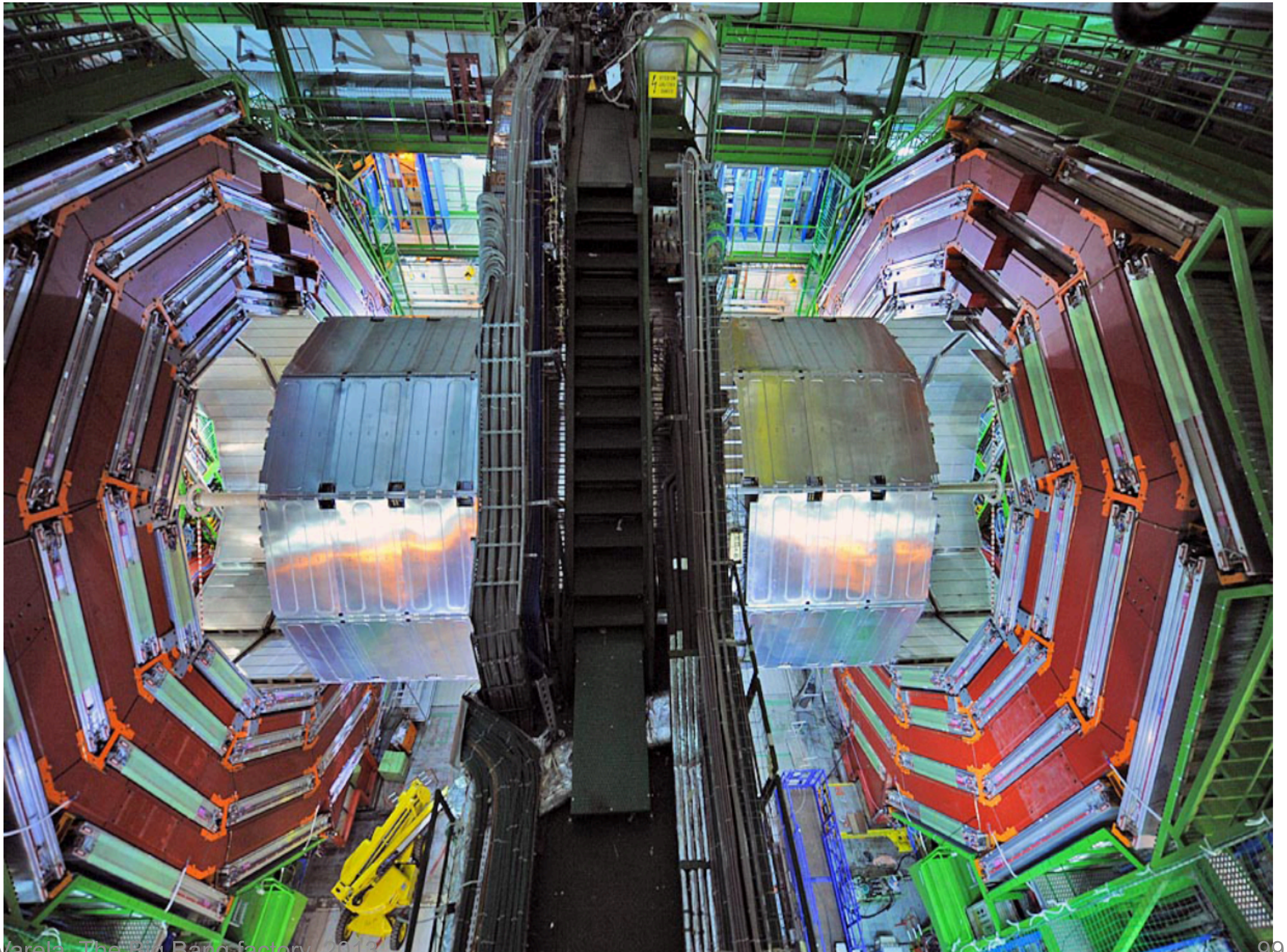
Cables, Pipes and Optical Fibers



Insertion of the Tracker

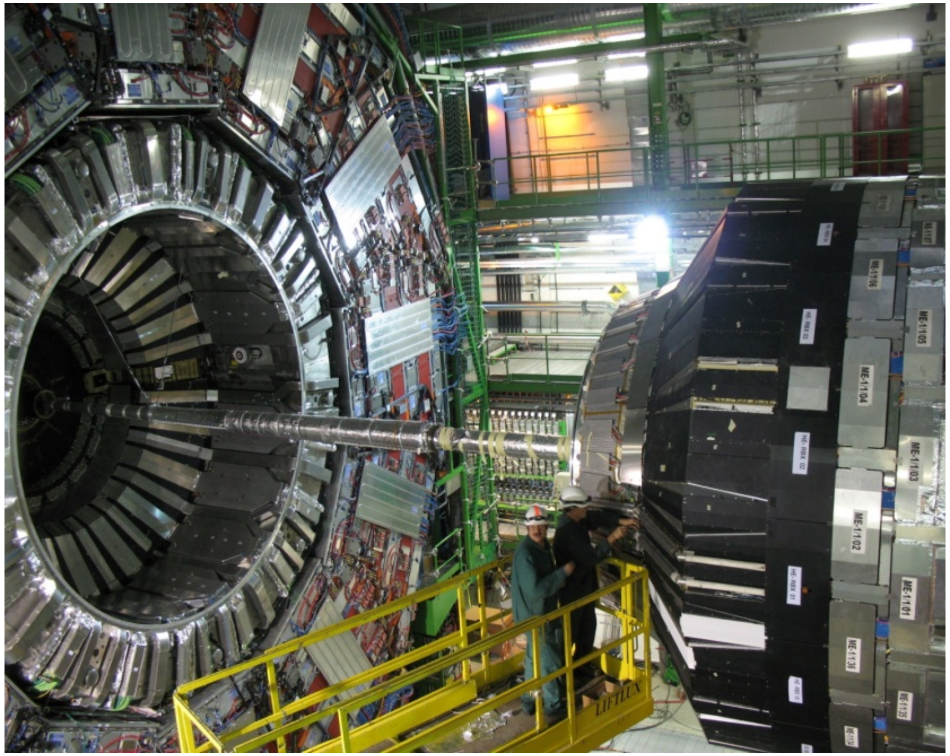


2008: CMS ready to close

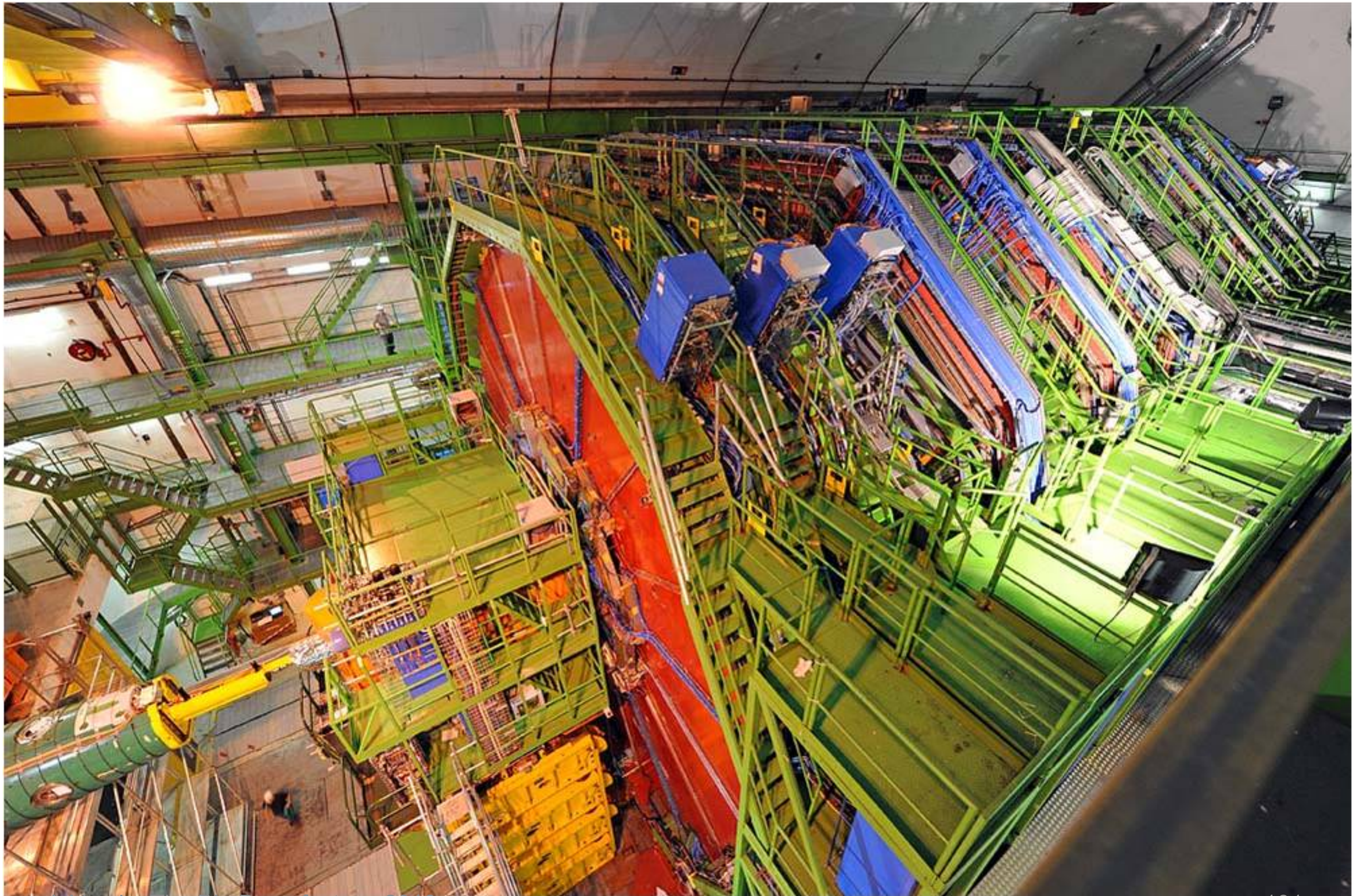


2008: CMS closing up…

CMS closed: August 08

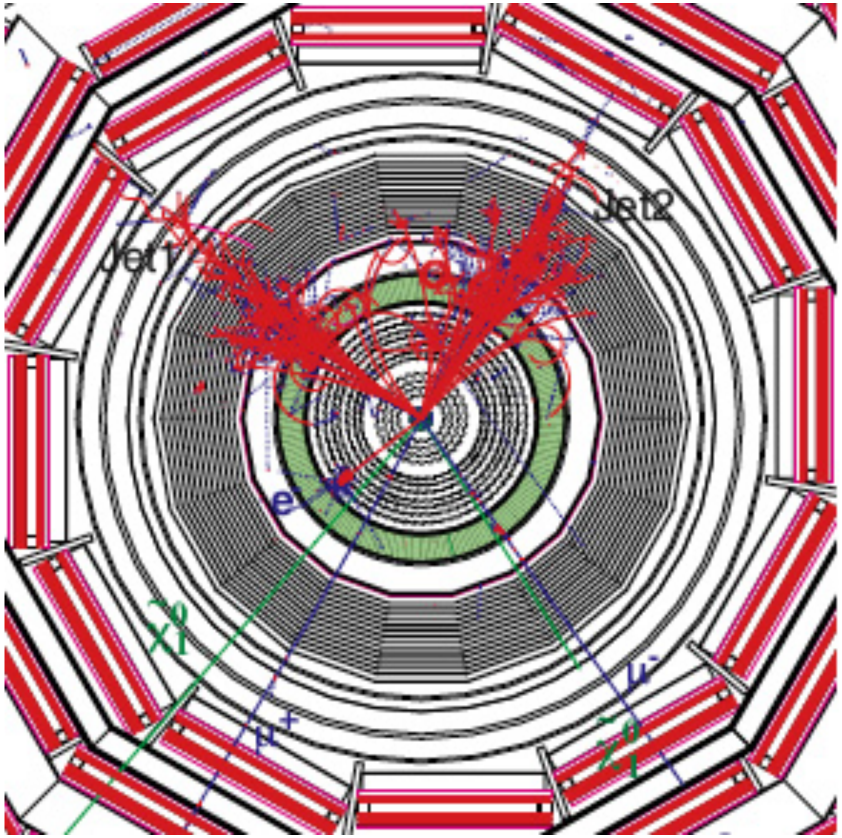


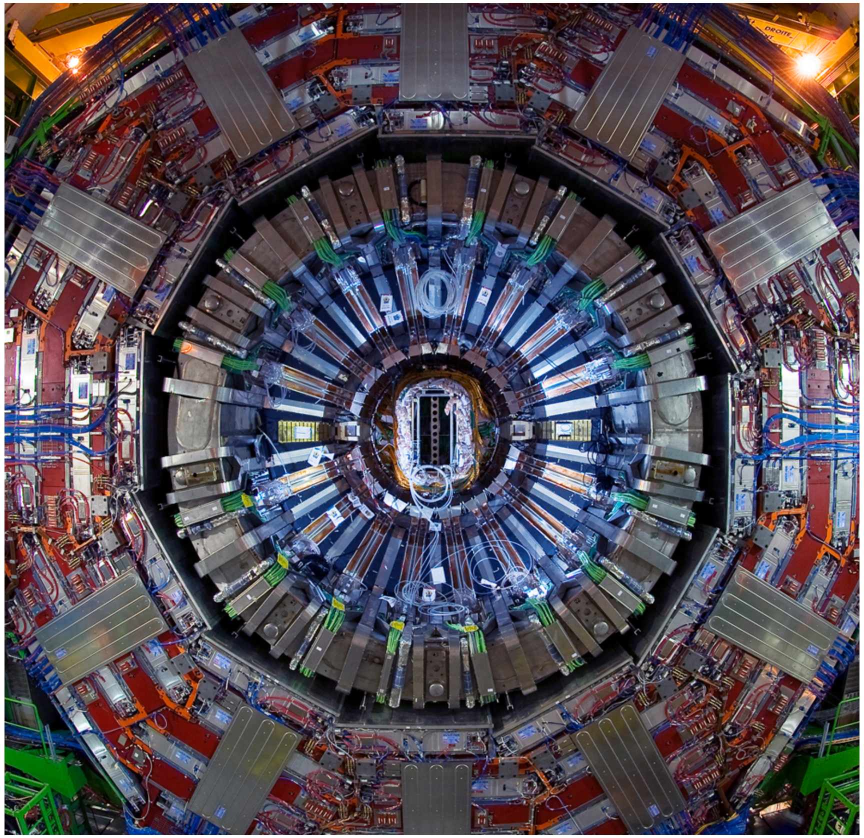
Sep 2008: CMS detector ready for beams



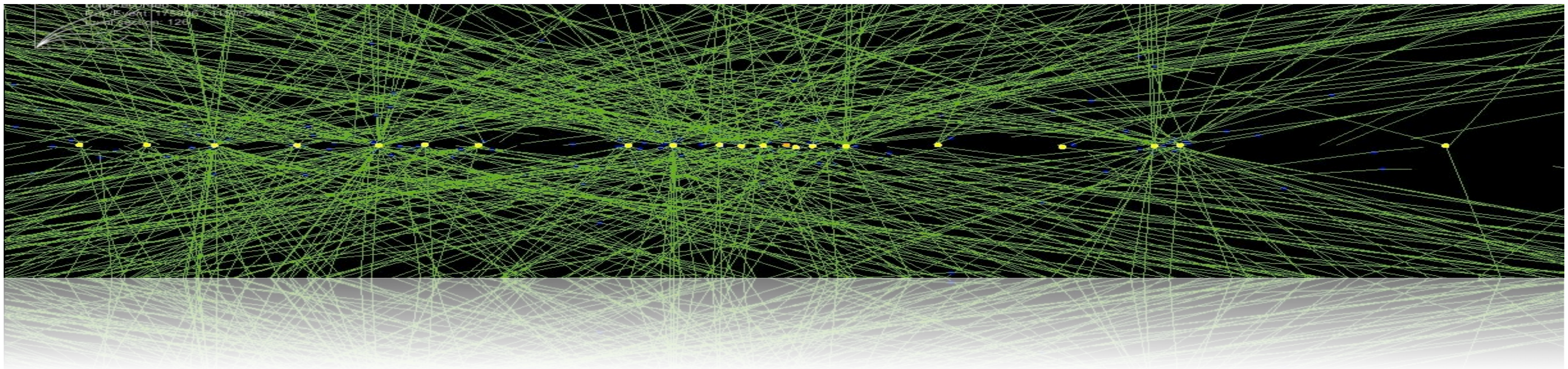
How did we prepare for discoveries?

Simulation of proton-proton collision
making two dark matter particles





Experimental challenges



High collision rate

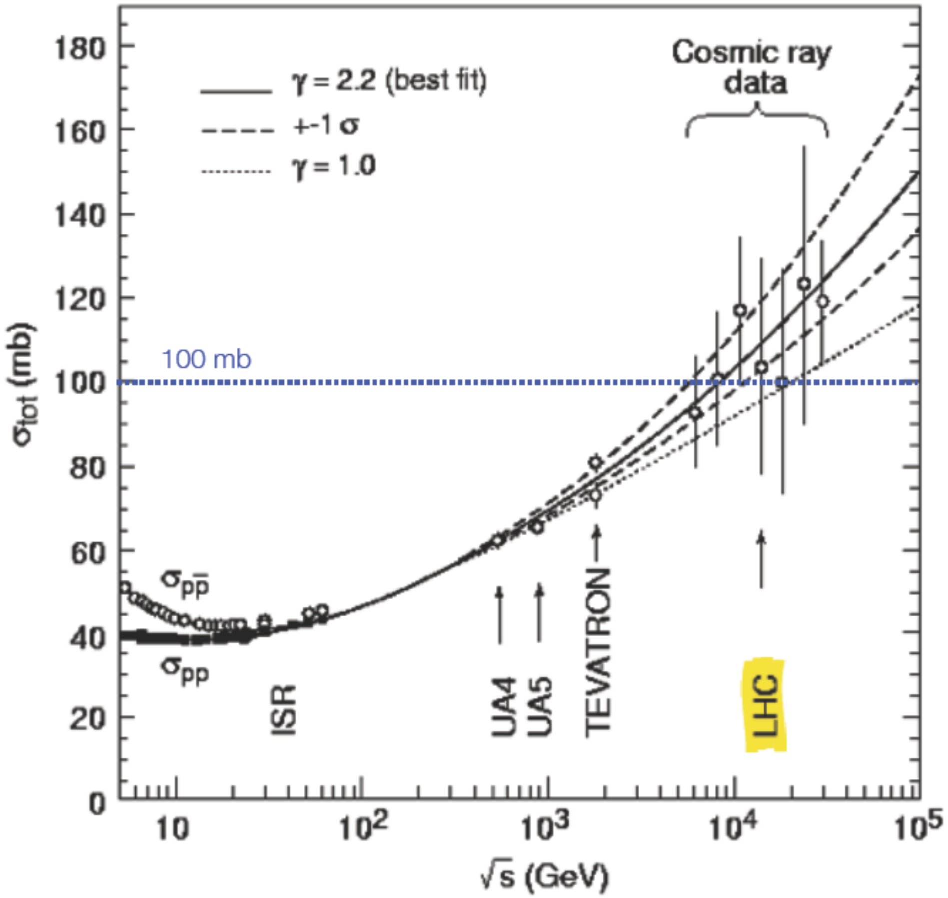
Luminosity:

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

Cross section:

$\sigma \approx 100\ \mathrm{mb}$

➥ $N = L\sigma \approx 1\ \mathrm{GHz}$



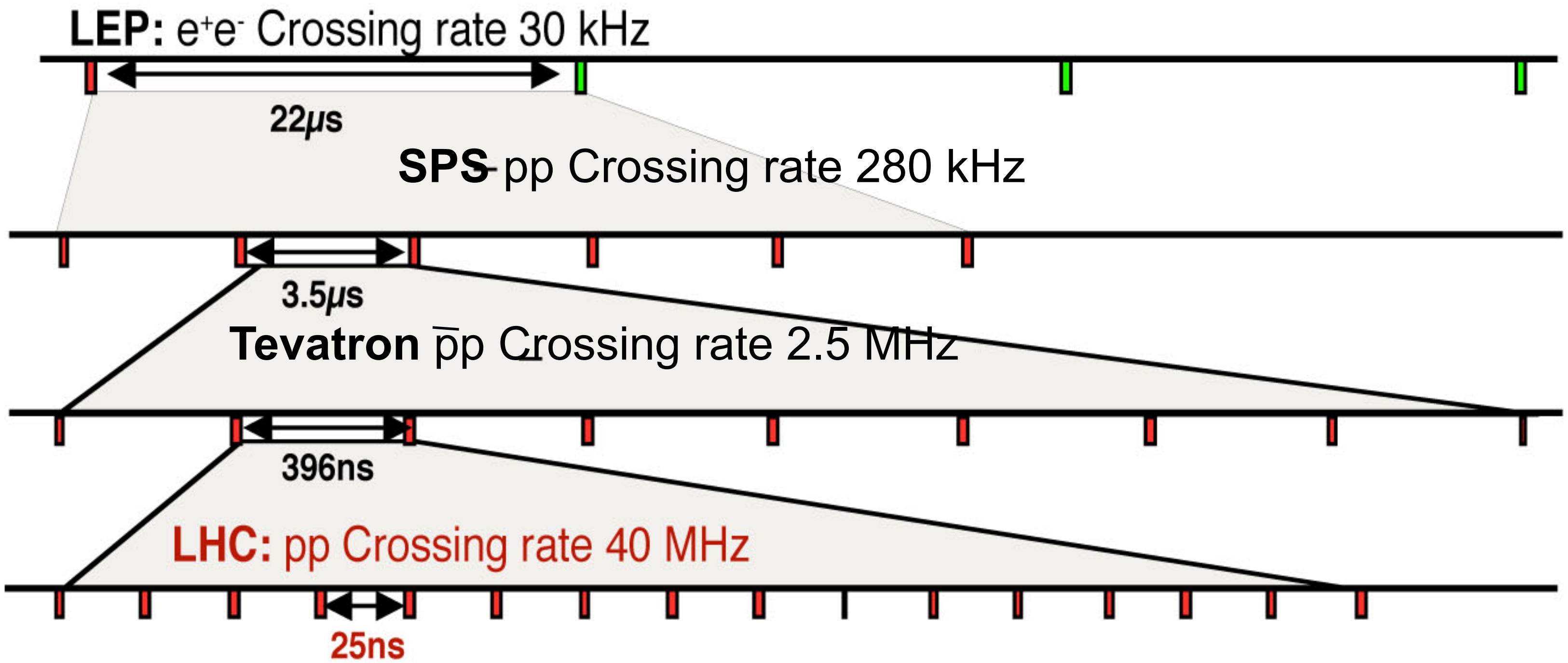
However:

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

This is a real challenge !

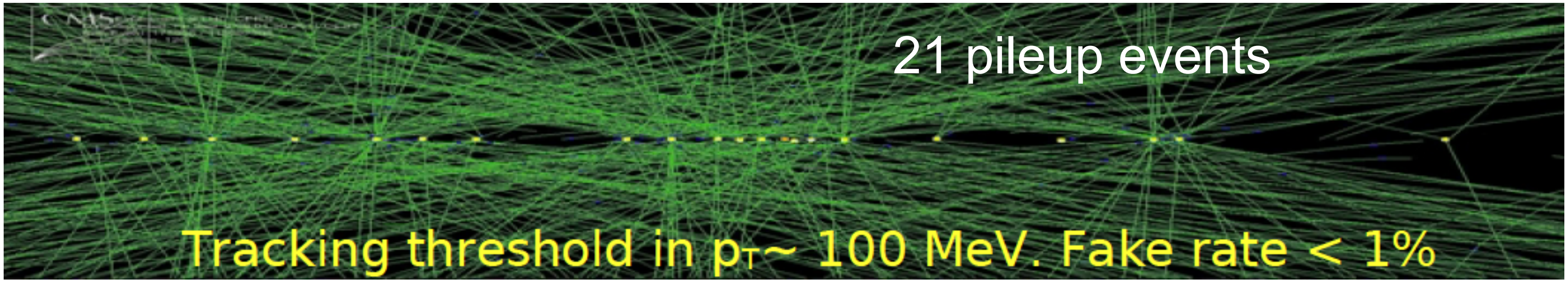
Bunch crossing frequency

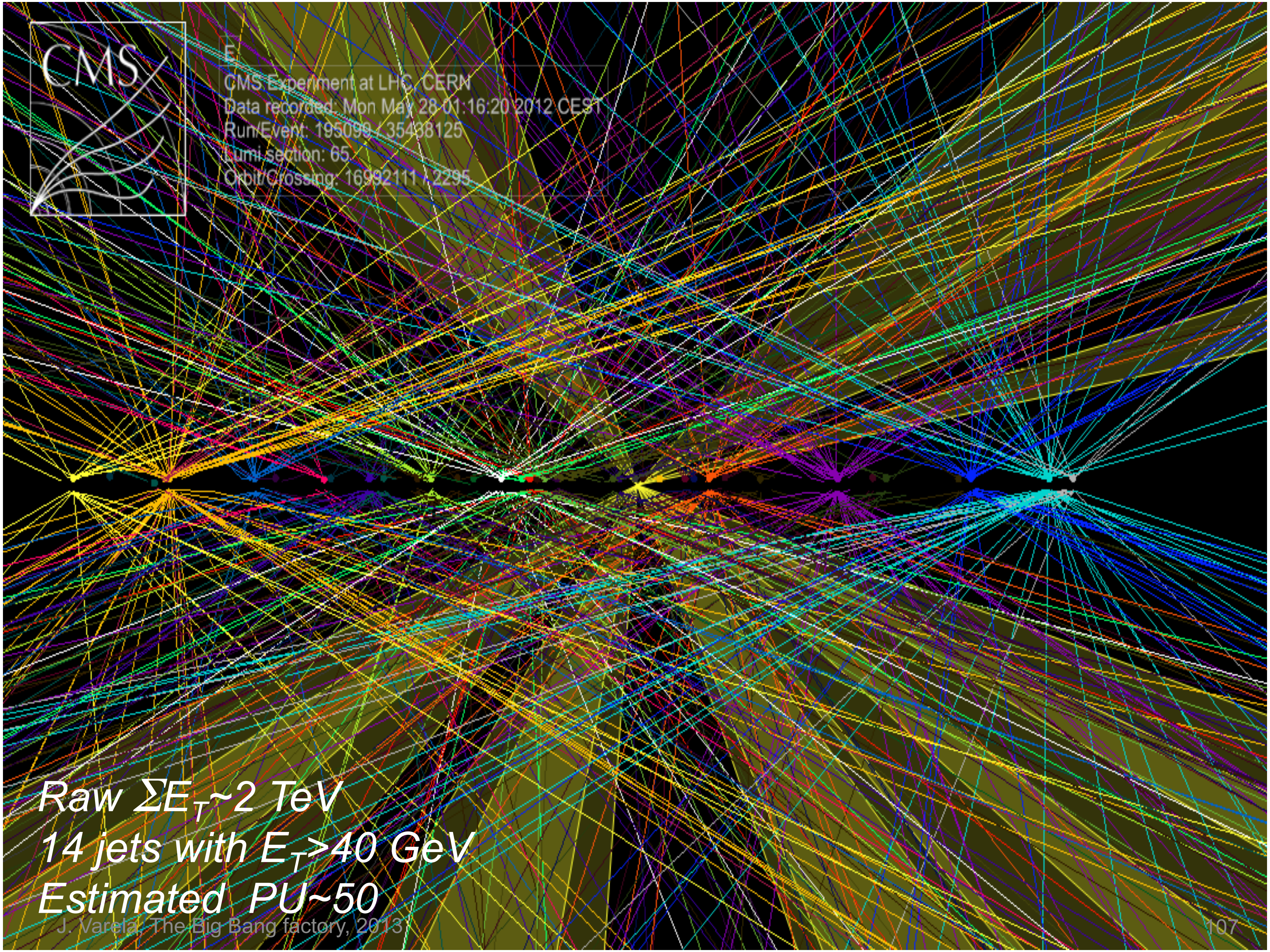
- LHC has 3564 bunches (2835 filled with protons)
- Crossing rate is 40 MHz
- Distance between bunches: 27km / 3600 = 7.5m
- Distance between bunches in time: 7.5m / c = 25ns
- Proton-proton collision per bunch crossing: ~ 25



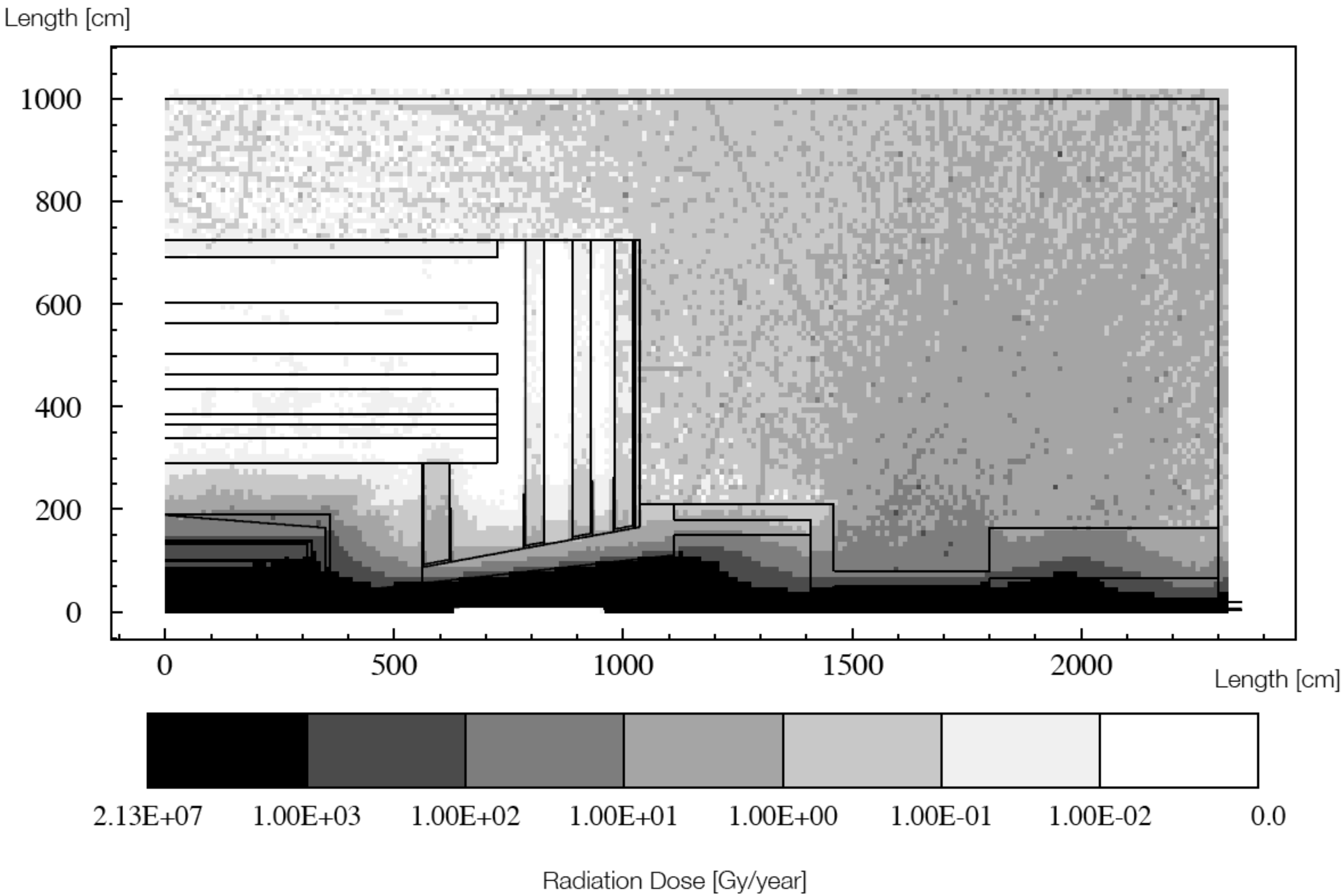
Event pileup

- 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)

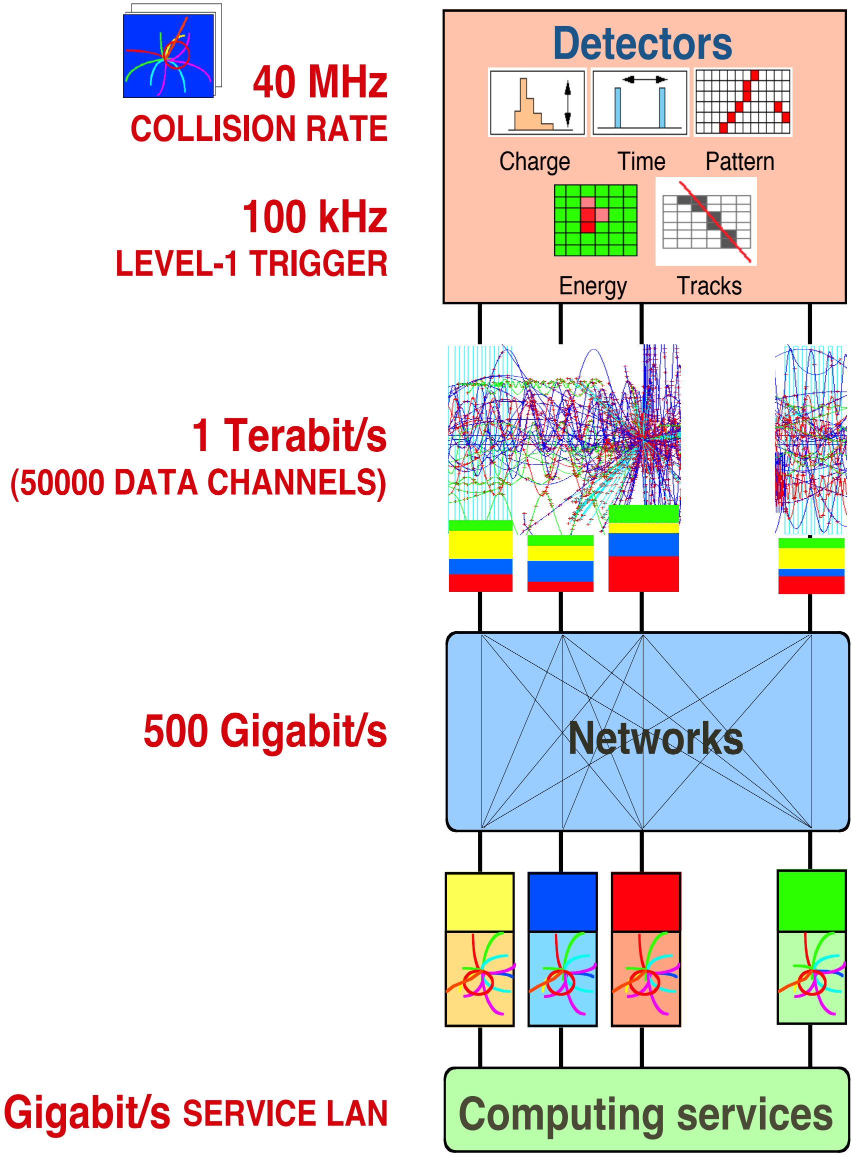



CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
Raw ΣE_T~2 TeV
14 jets with E_T>40 GeV
Estimated PU~50

High radiation levels



Acquiring and recording data of interest



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

40 Million photos/sec

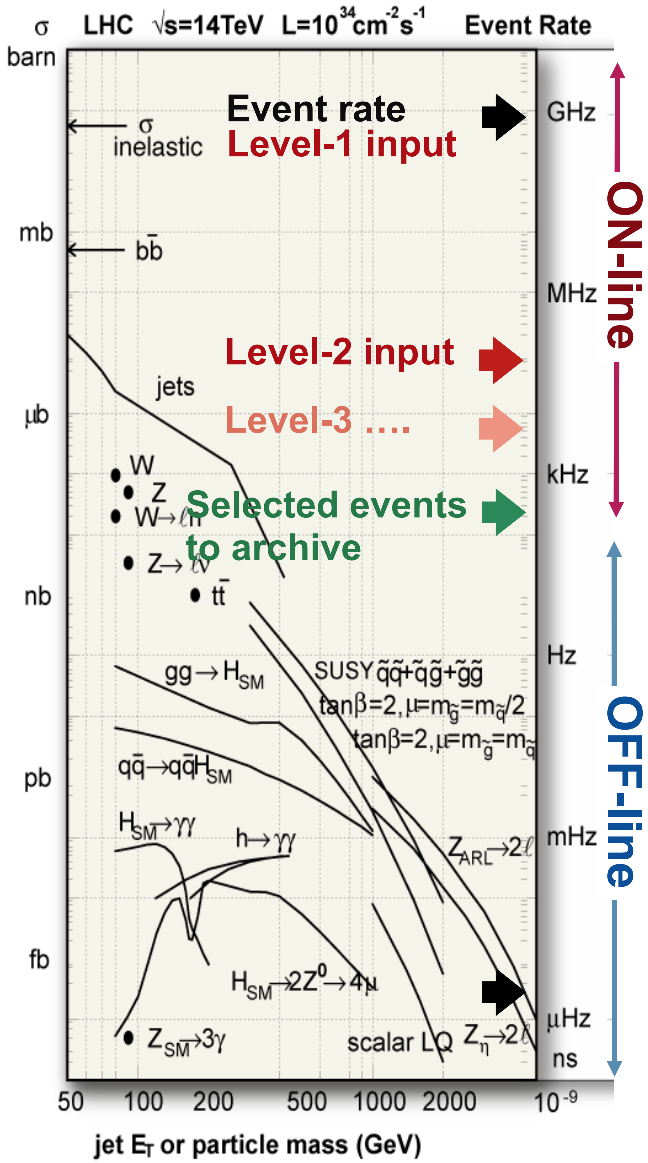
Each photo (~ MB)

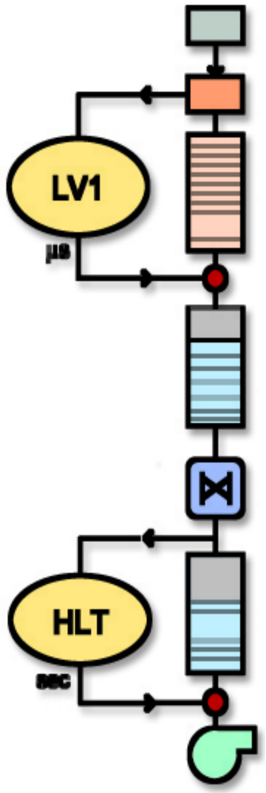
- taken in ~ 500 different parts
- put together using a telecommunications ‘switch’
- analysed in a CPU (in a farm of ~ 50000 cores)

Only a few hundred photos/sec stored on disk.

~ 15 PB/year

Two-level trigger





Trigger system decide if the event is interesting to be recorded

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

- High level: computer farm

Trigger computer farm

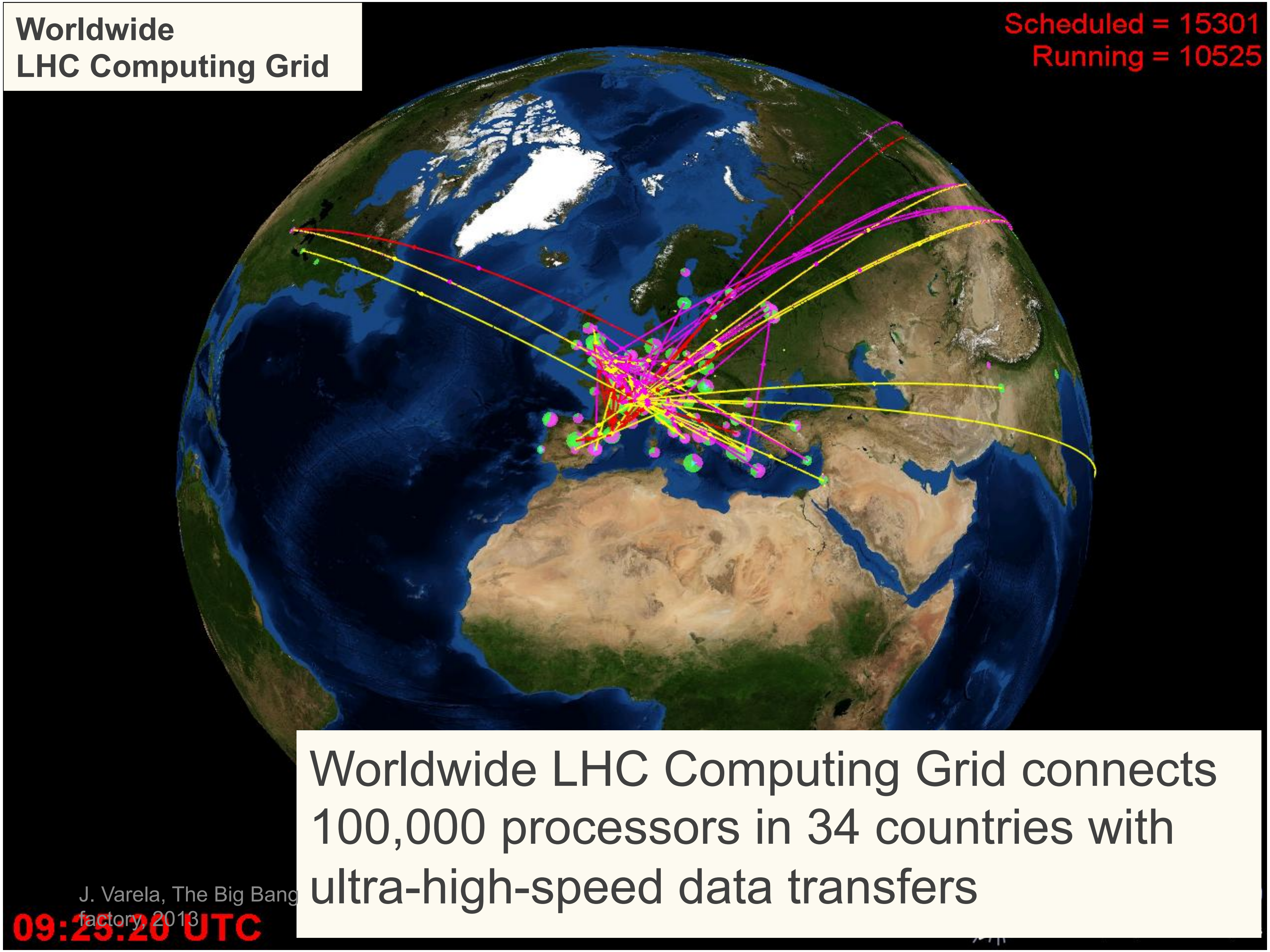
The LHC Computing Grid

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

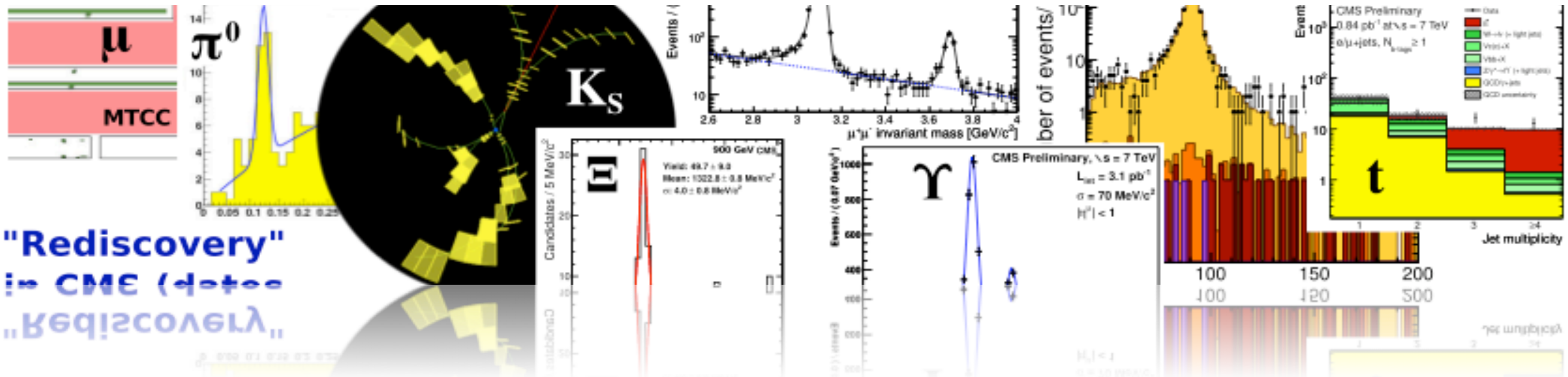
The **Grid** is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe

Worldwide LHC Computing Grid



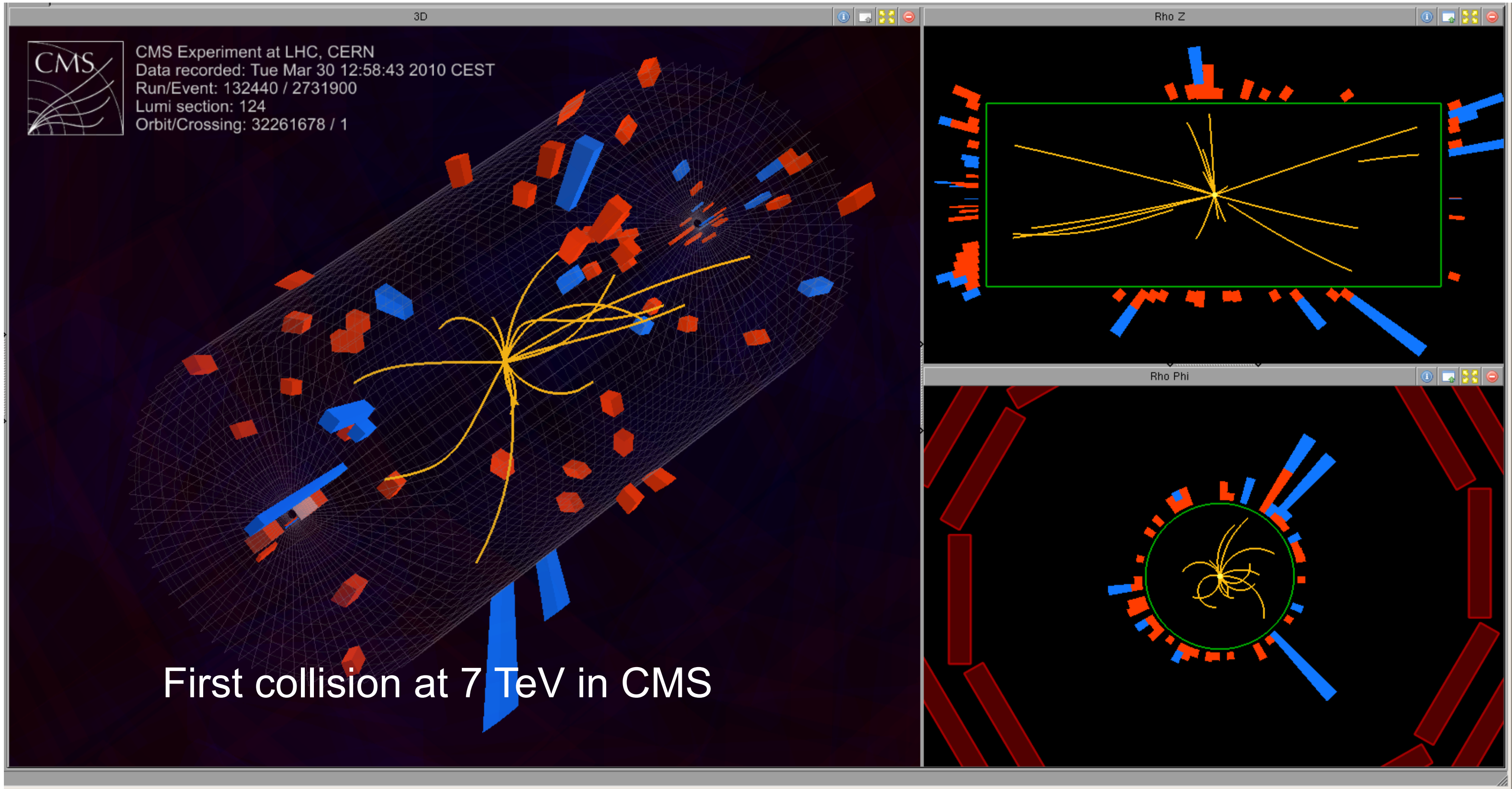
Worldwide LHC Computing Grid connects 100,000 processors in 34 countries with ultra-high-speed data transfers

Detector commissioning and rediscovery of the SM

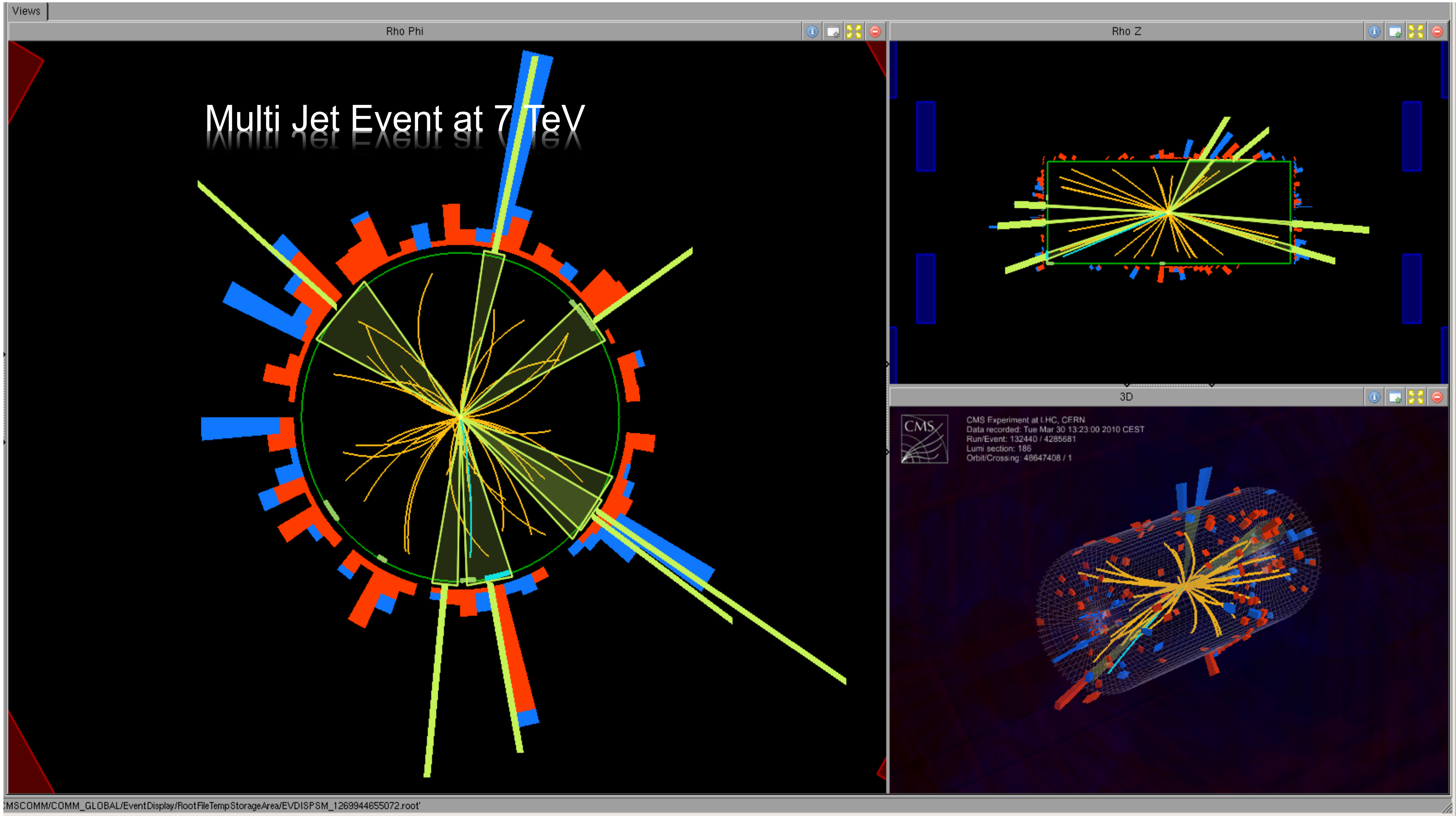


2009: First p-p collisions at LHC

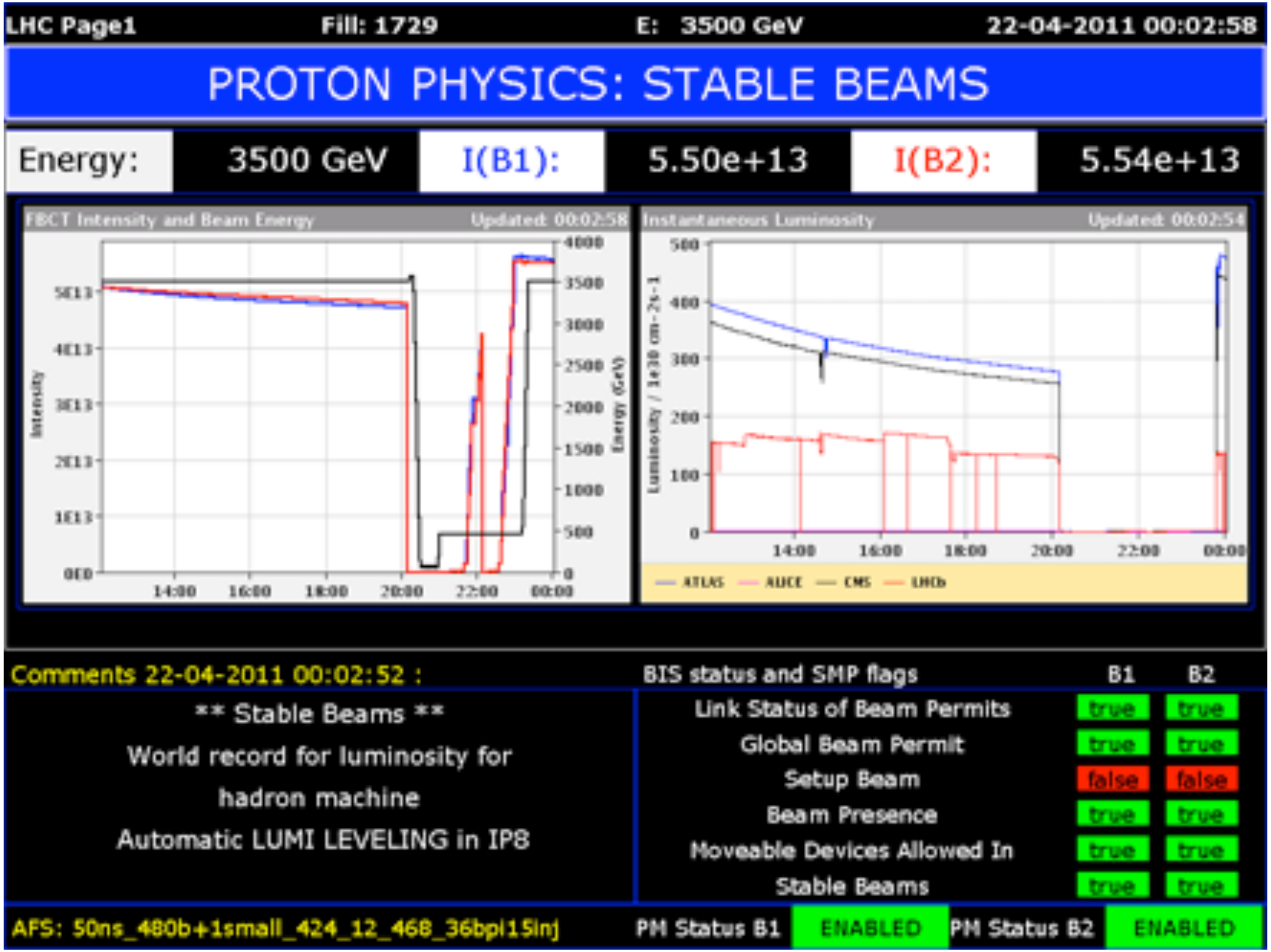
November 23, 2009	December 14, 2009	March 30, 2010
First collisions at 900 GeV	First collisions at 2.36 TeV	First collisions at 7 TeV



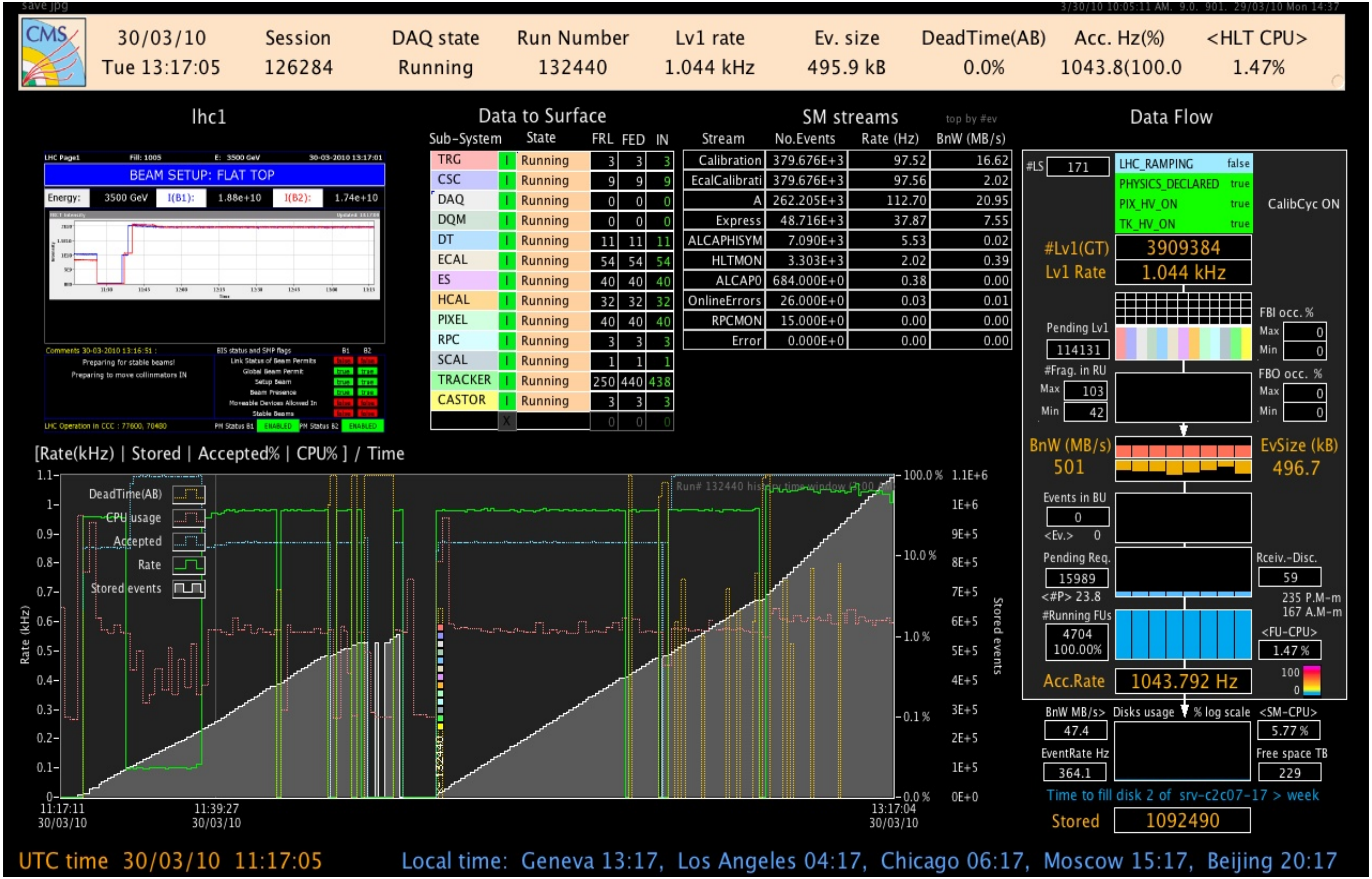
Jet event in CMS



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

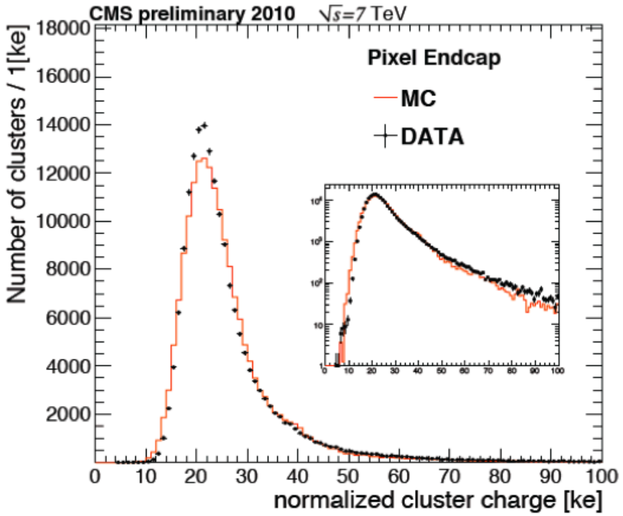
CMS Experiment

...unforgettable moments

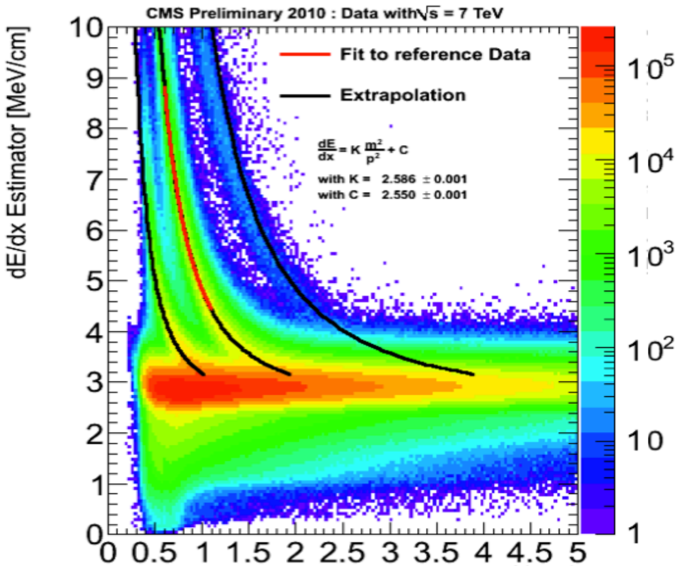
… and happy in the end!

Tracking performance

Pixel cluster charge

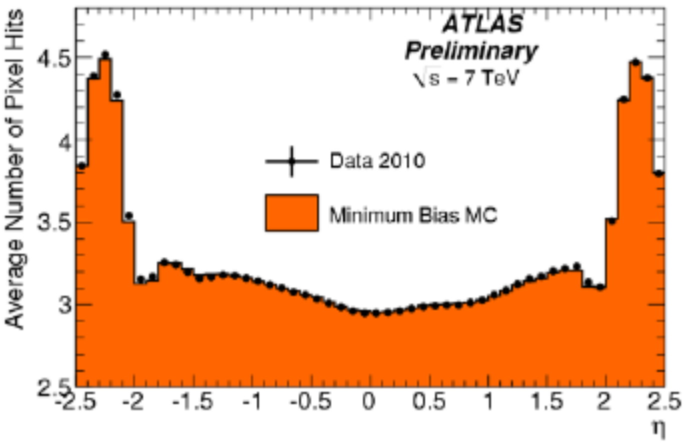


de/dx in the strips



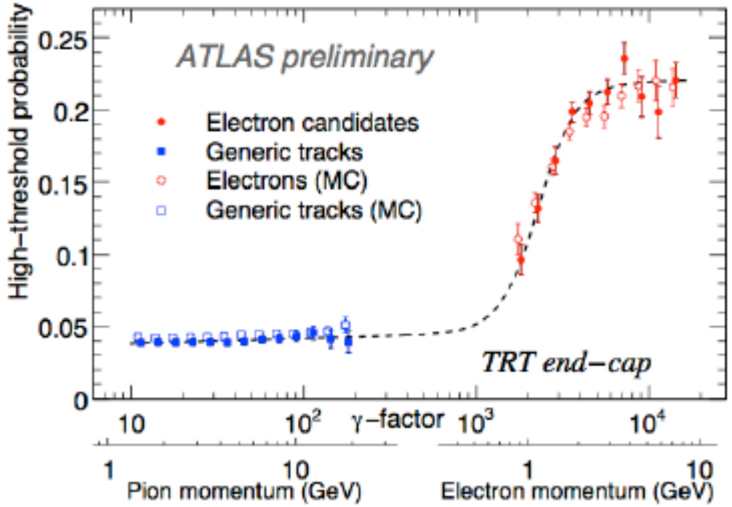
CMS

Pixel Det.



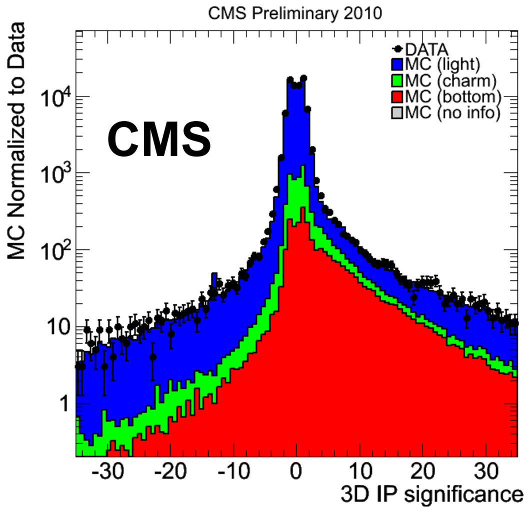
ATLAS

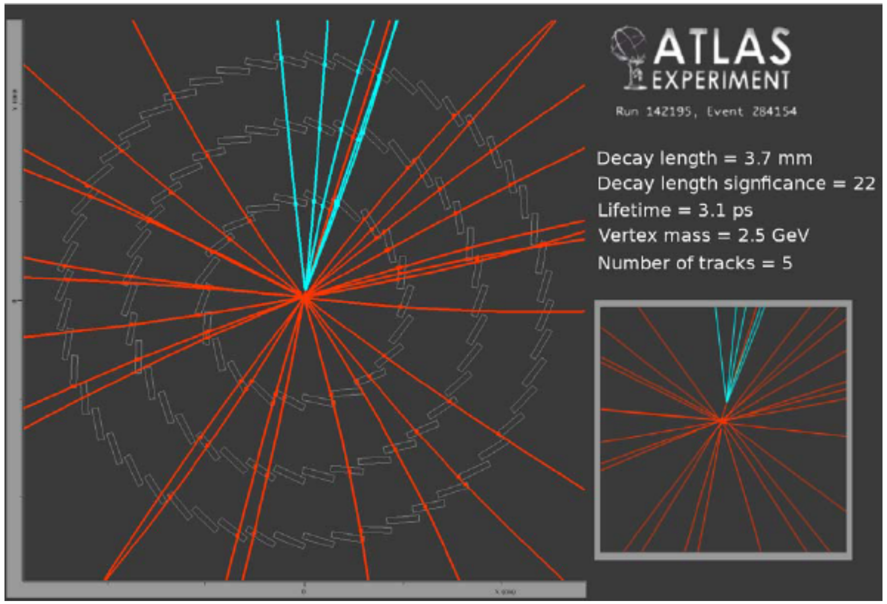
TRT Det.

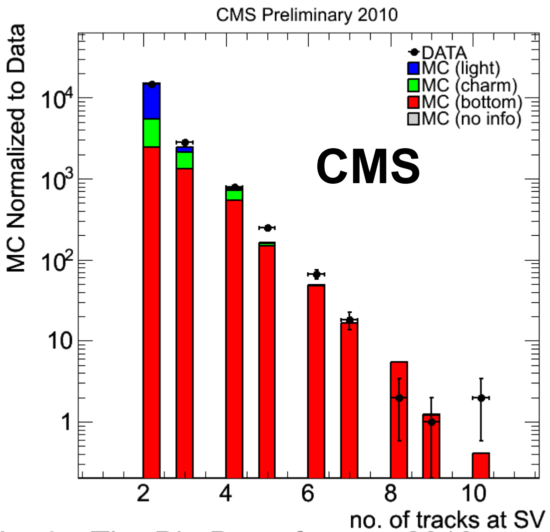


Tracking: secondary vertices

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



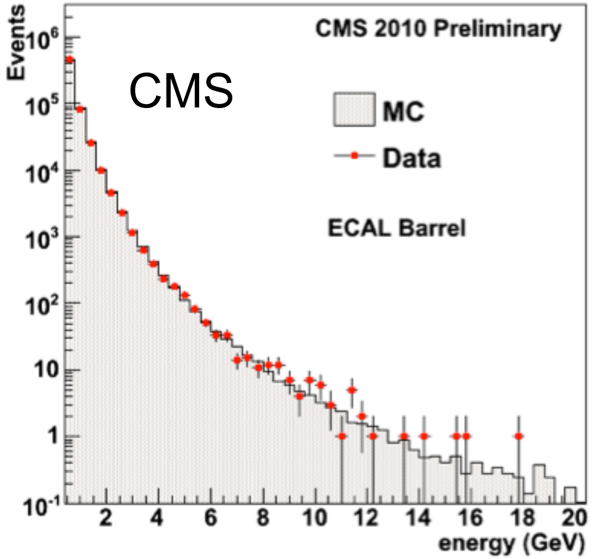


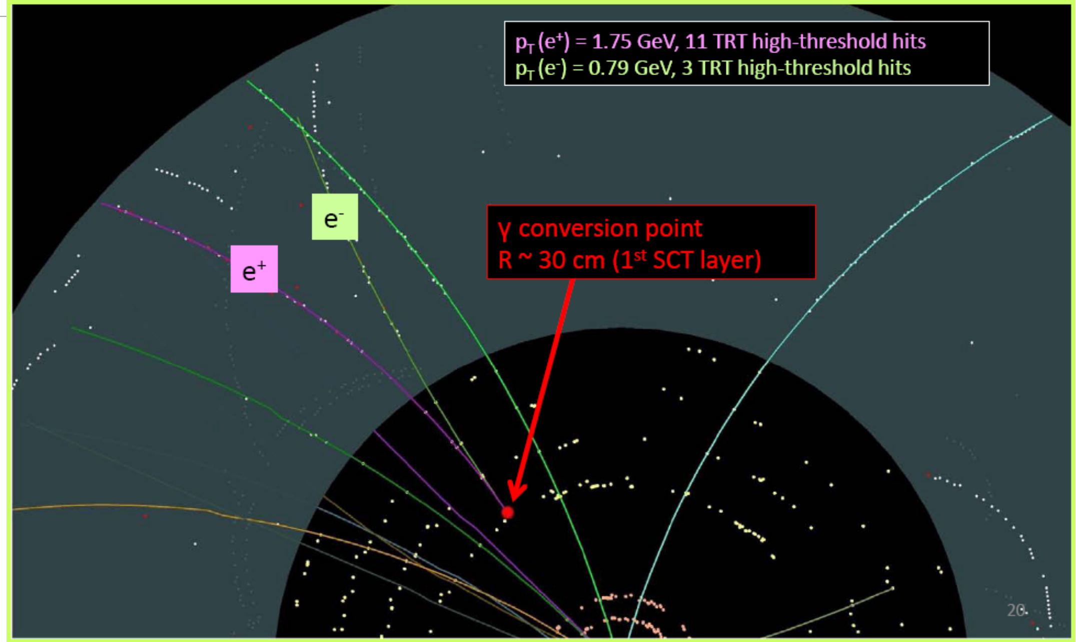


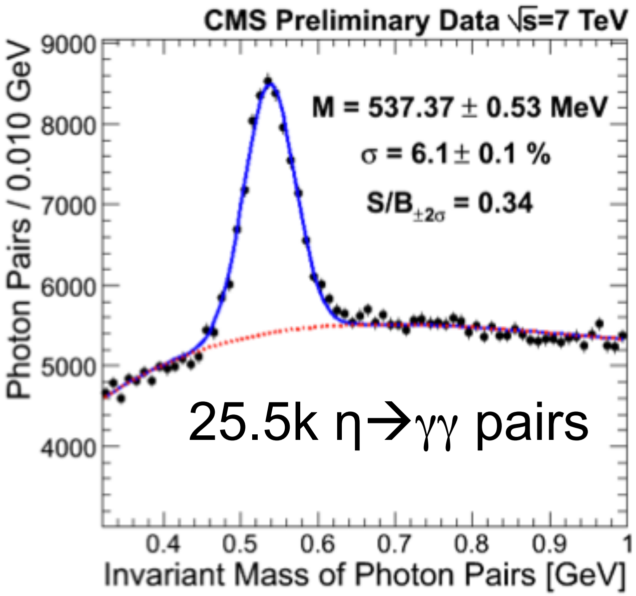
Secondary vertices compatible with heavy flavor production

Photons and electrons

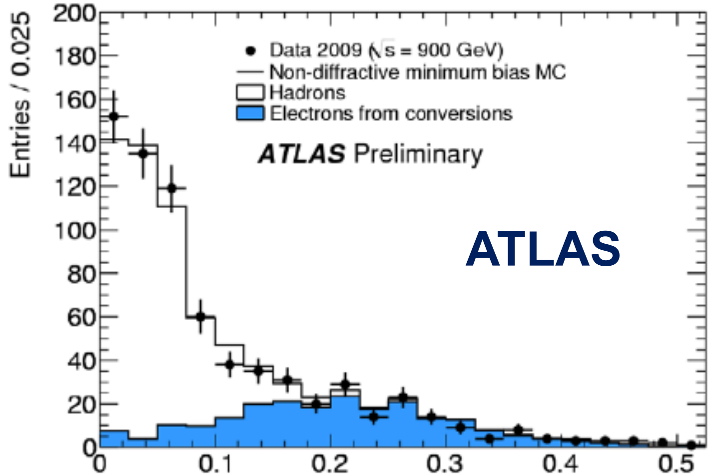
EM cluster energy



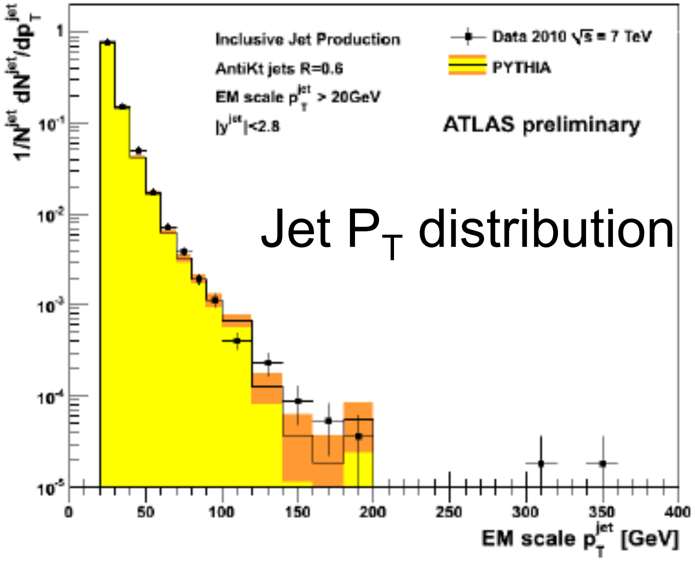




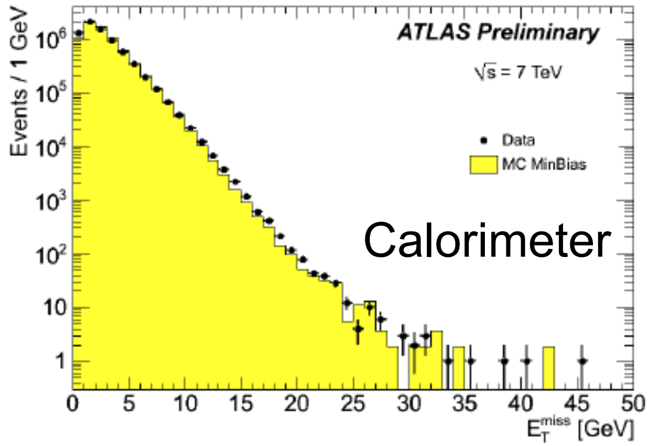
TRT high-threshold hit fraction



Jets and missing energy

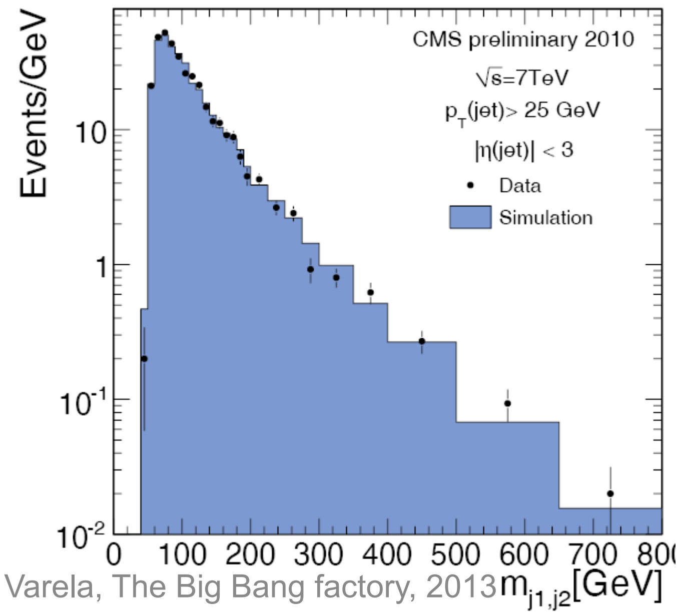


Missing Transverse Energy

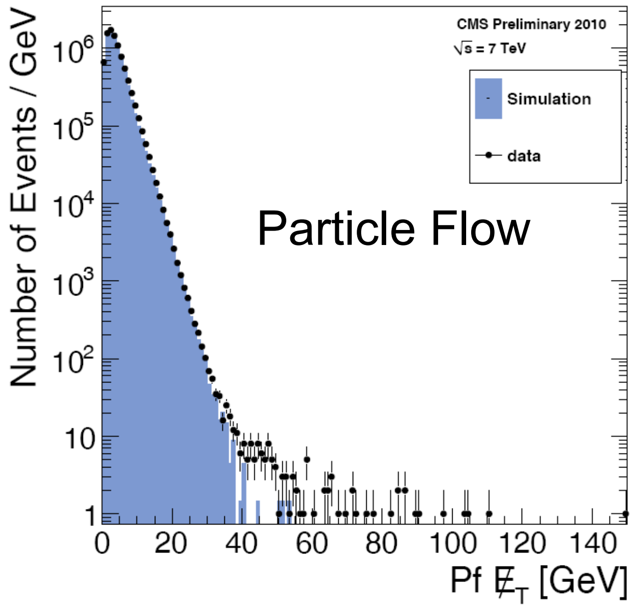


ATLAS

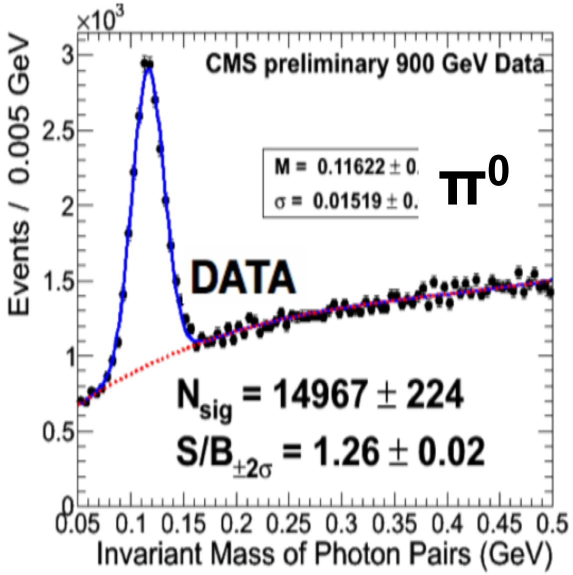
Di-jet mass

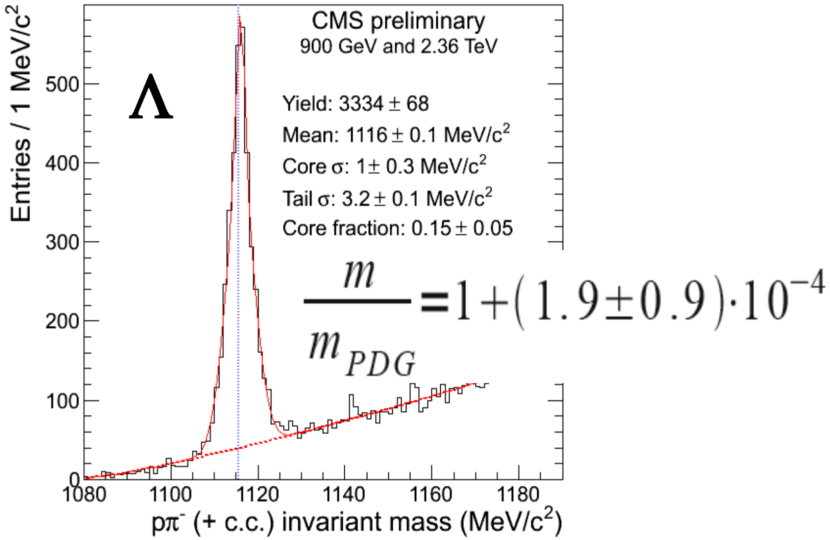


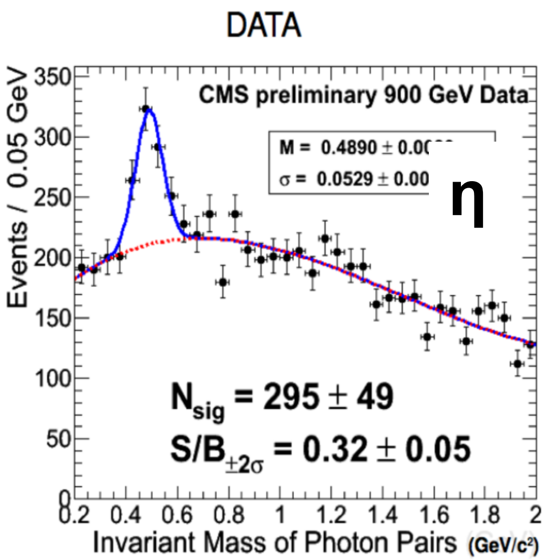
CMS

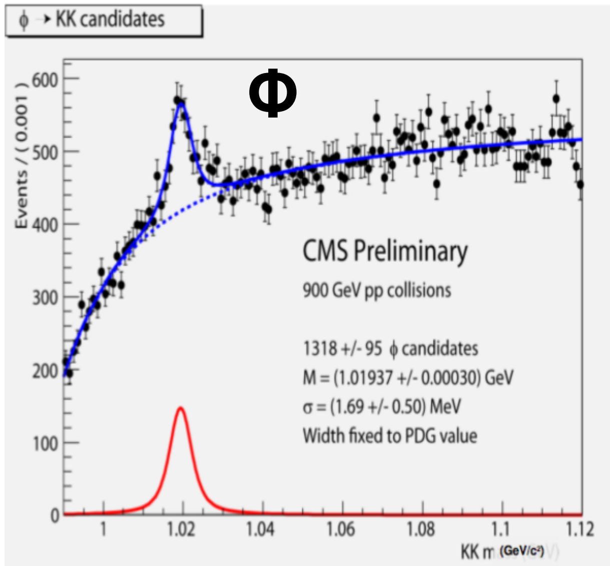


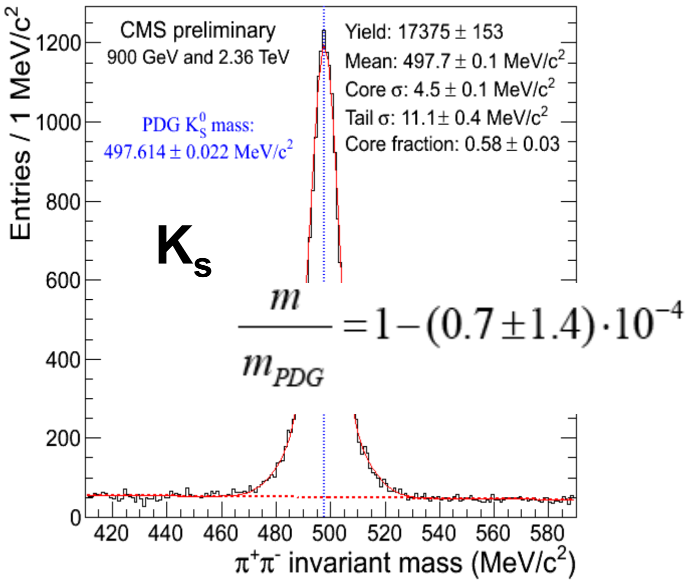
Rediscovery of resonances



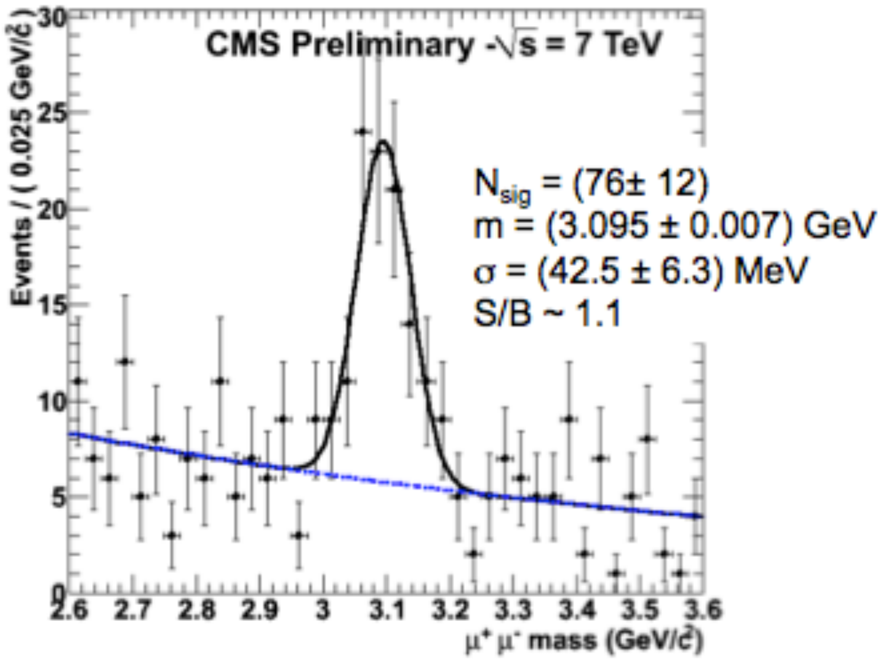








J/ψ' s decaying into muons

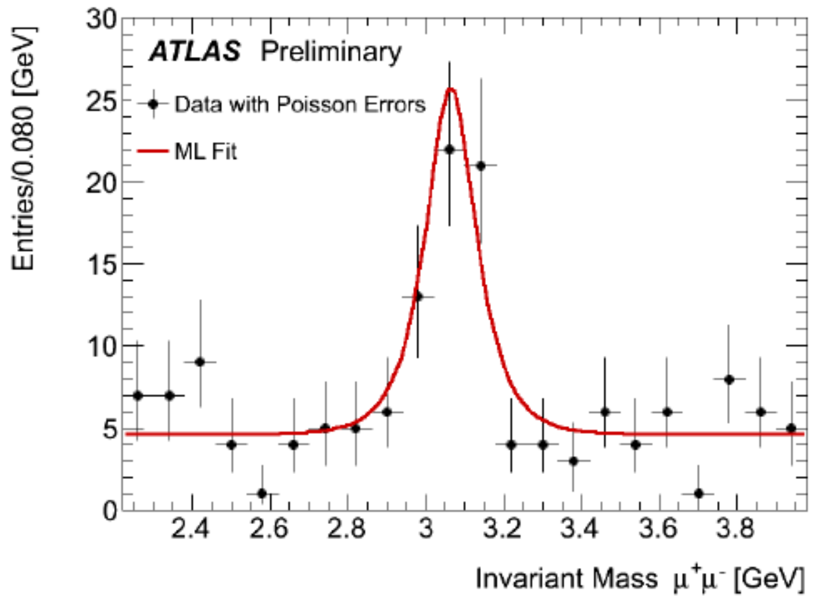


CMS

Gaussian-mean mass: 3.06±0.02 GeV

Resolution: 0.08±0.02 GeV

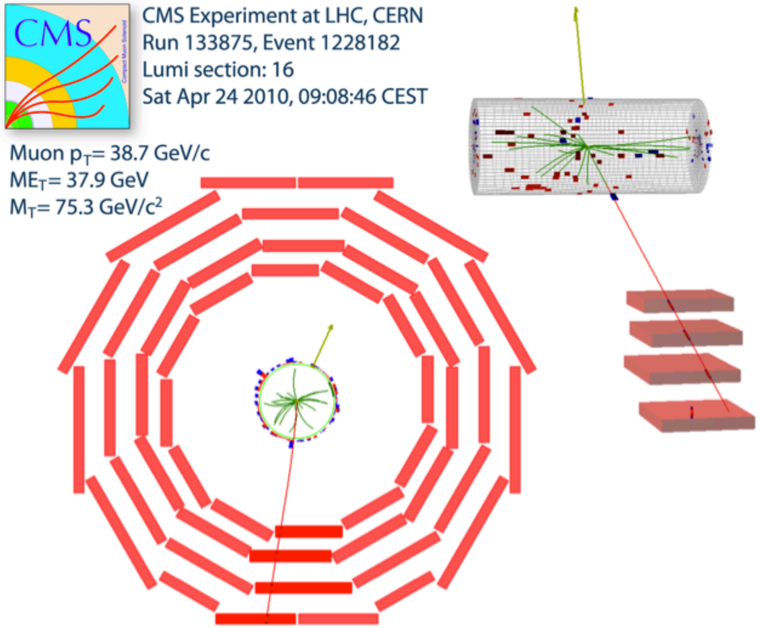
Number of signal events: 49±12



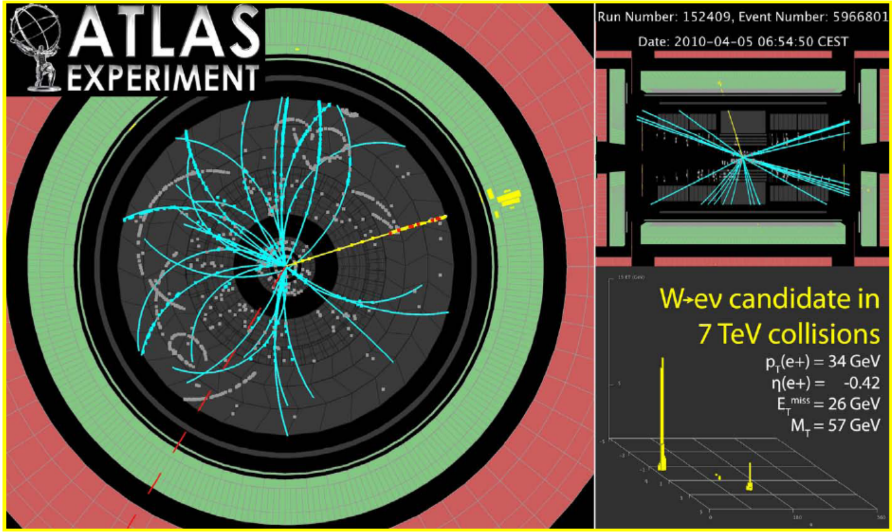
ATLAS

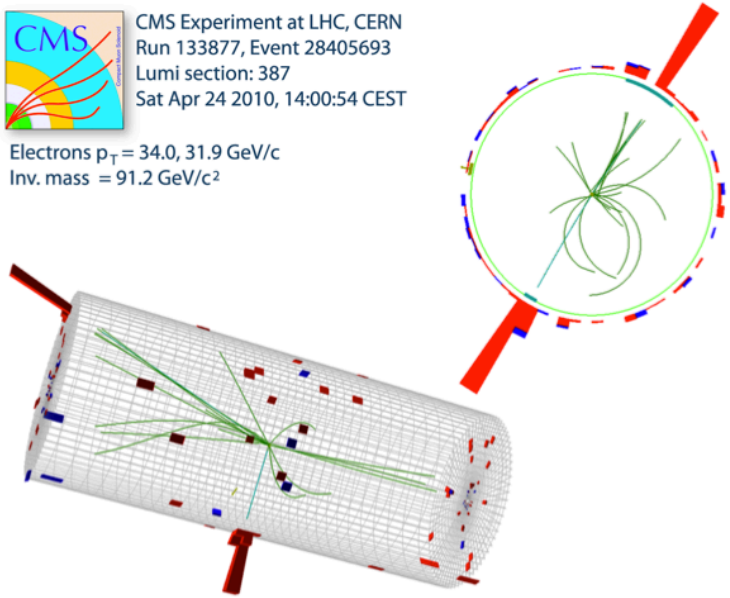
W and Z bosons

W→μν



W→eν

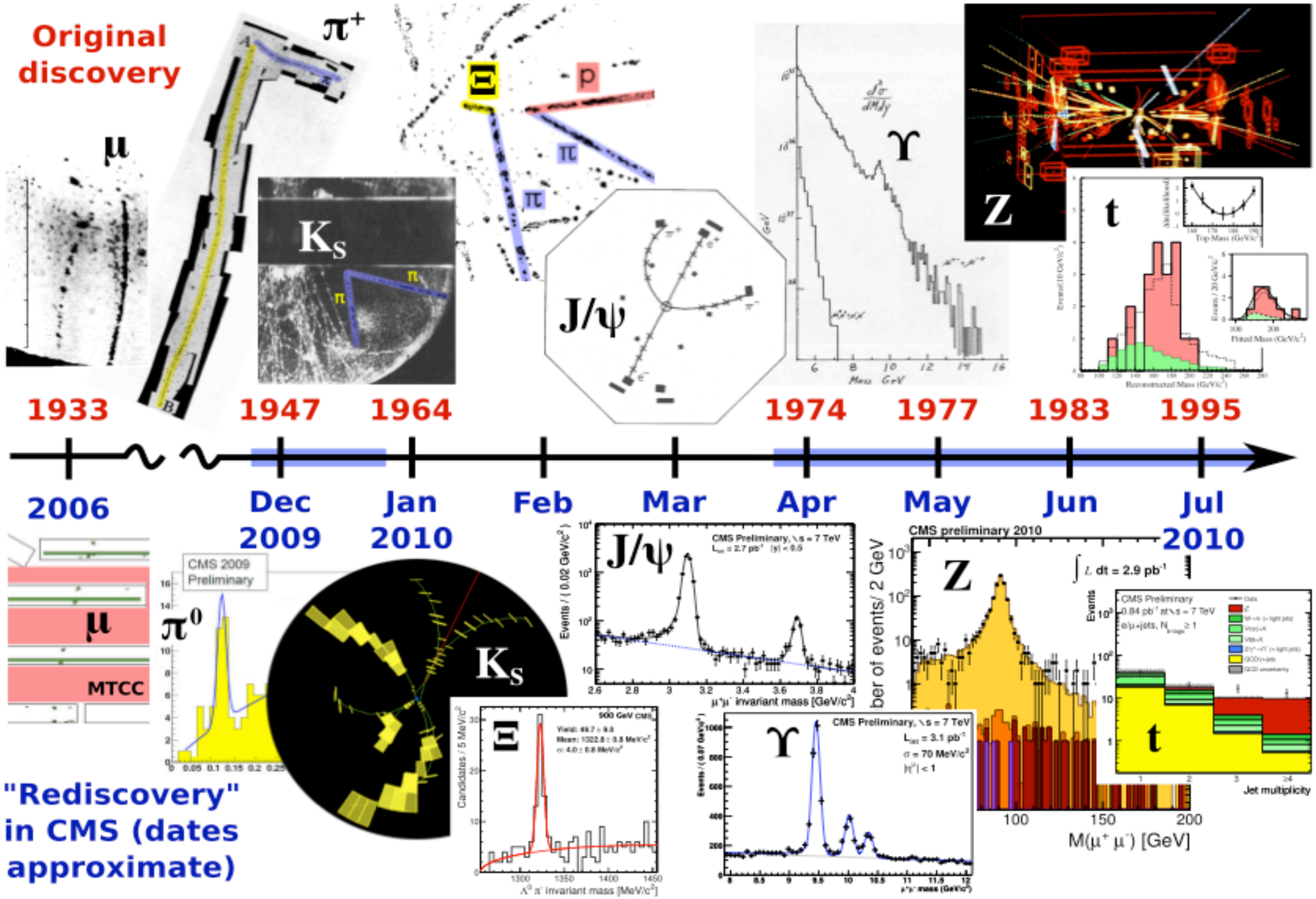




Z→ee:

Mass= 91.2 GeV/c2

Rediscovery of the Standard Model



End of Lecture 2