Understanding the Structure of Matter

Outline

- History of particle physics
- Some of the pioneering detectors
  - Emulsion, Cloud chamber, Bubble chamber, …
- Modern day particle detection
- Some outcome

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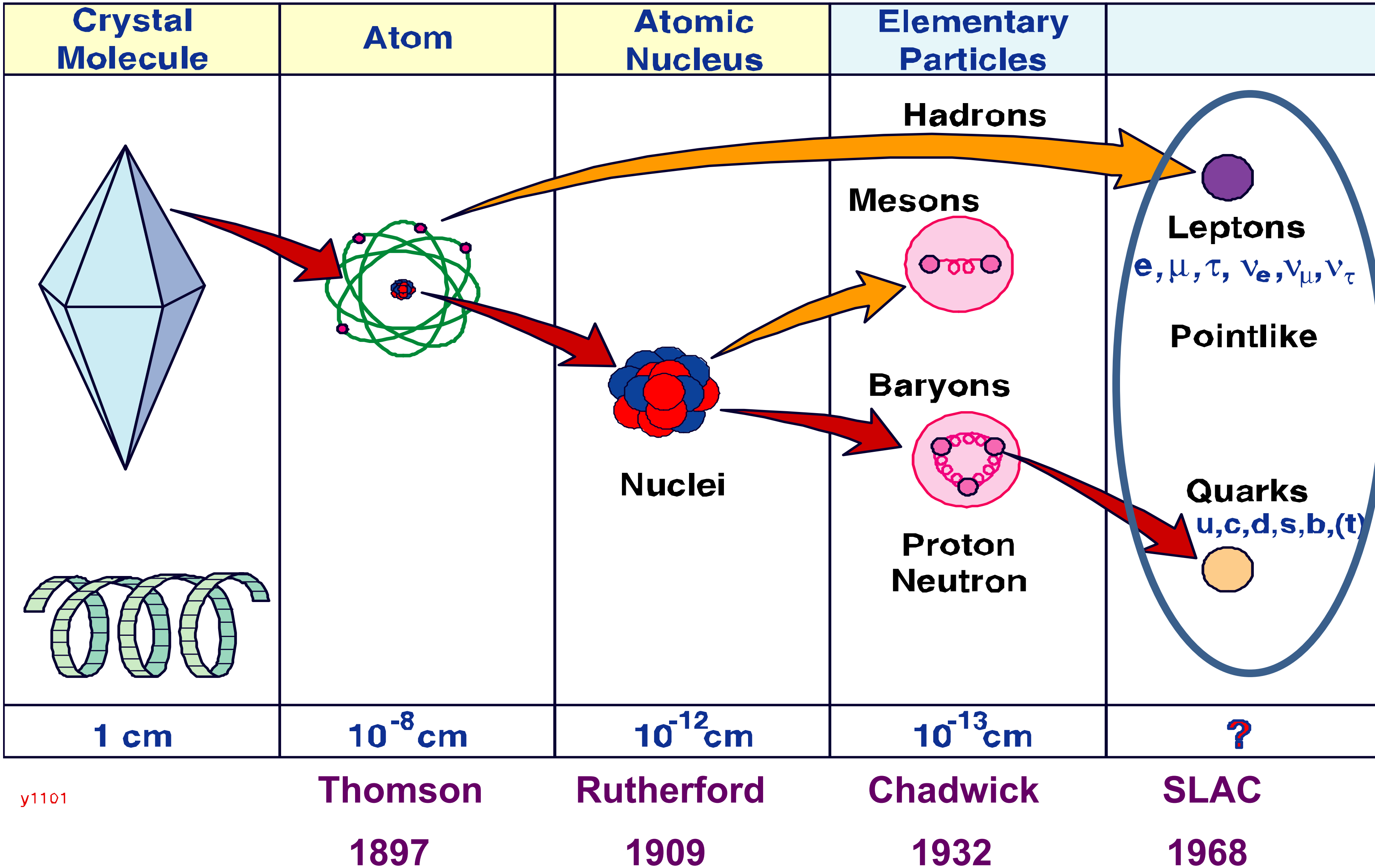
Sunanda Banerjee

Structure

- Study of structure of matter was a part of philosophy in the ancient days
- Early philosophy: everything comes out of four (five) fundamental things
  - Fire, water, earth, air, (space)
- Galileo came with the famous quote: "*I attach more value to finding a fact, even about the slightest thing, than to long disputations about the Greatest Questions that fail to lead to any truth whatsoever*"
  - That was the start of modern science
- So it became a part of Chemistry discipline during 19th and early 20th century
- Modern science showed something else – atoms, sub-atoms, sub-sub-atoms, ….. and from Chemistry came out nuclear physics and then particle physics

Constituents of matter



Evolution of Particle Physics (I)

- Rutherford & Soddy discover β rays (1899)
- Becquerel proves that β rays are electrons (1900)
- Pauli proposes the existence of the neutrino (1930)
- Chadwick discovers the neutron (1932)
- Fermi gives a theory of β decay (1934)
- Yang & Mills invent non-Abelian gauge theory (1954)
- Cowan & Reines discover the neutrino (1955)
- Yang & Lee propose parity violation (1957)
- V-A theory by Feynman/Gell-Mann, Marshak/Sudarshan (1957)
- Schwinger suggests gauge theory of weak interactions (1958)
- Nambu shows how gauge bosons can have mass (1960)
- Large number of strongly interacting particles are observed (50's and 60's)

Evolution of Particle Physics (II)

- Glashow constructs unified electroweak gauge theory (1961)
- Goldstone shows that SSB implies massless scalars (1962)
- Anderson suggests removal of Goldstone bosons (1963)
- Cabibbo introduces flavour-mixing (1963)
- Cronin & Fitch discover CP violation (1964)
- Gell-Mann, Zweig propose quark model (1964)
- Higgs and others introduce Higgs mechanism (1964)
- Kibble works out Higgs mechanism in non-Abelian case (1966)
- Weinberg, Salam construct their electroweak model (1967)
- Friedman, Kendall and Taylor discover quarks in DIS (1969)
- Glashow, Iliopoulos & Maiani predict the charm quark (1970)
- t'Hooft proves the renormalizability of GSW model (1971)

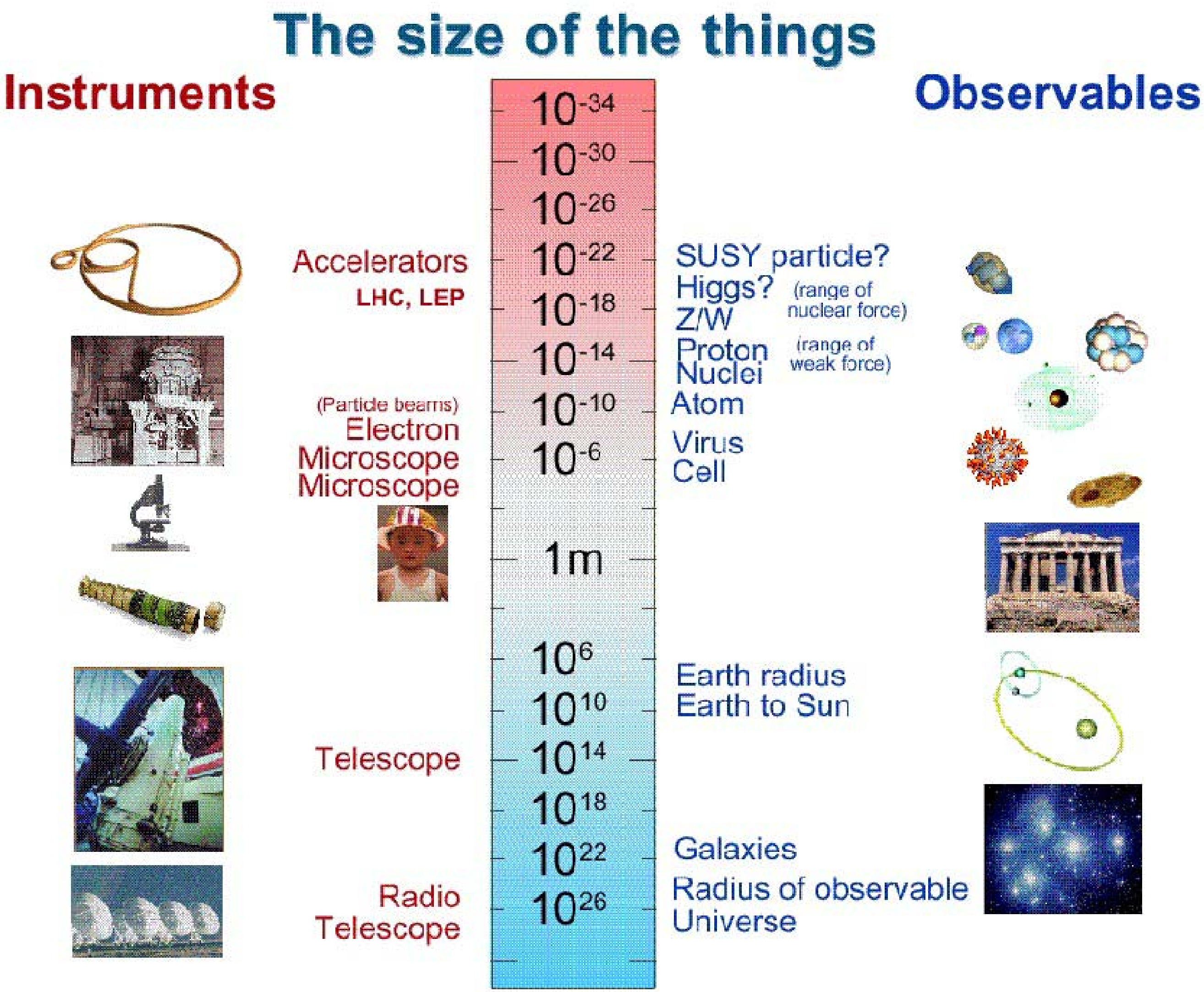
Evolution of Particle Physics (III)

- t'Hooft discovers the hierarchy problem (1972)
- Gell-Mann & Fritzsch construct QCD (1972)
- CERN Gargamelle discovers neutral currents (1973)
- Kobayashi-Maskawa propose the third generation (1973)
- Richter, Ting discover the J/ψ; confirm c quark (1974)
- Pati & Salam propose first GUT; predict proton decay (1974)
- Georgi & Glashow propose SU(5) GUT (1975)
- Perl discovers the tau lepton (1975)
- Fermilab E288 experiment discovers b quark (1977)
- CERN SpS (UA1, UA2) discovers W and Z bosons (1983)
- Technicolor model came as an alternate way for giving particle masses (1981-82)

Evolution of Particle Physics (IV)

- Georgi & Dimopoulos construct the MSSM (1981)
- ARGUS (DESY) discovers B0-B0bar mixing; m_t > 60 GeV (1987)
- LEP finds Only three light neutrino's (1990)
- Oblique parameters at LEP; technicolor under tension (1992)
- CDF & D0 (Fermilab) discovers the top quark (1994)
- Super-K confirms neutrino oscillations (1998)
- Arkani-Hamed & Co revive extra dimensions (1998)
- Third type of neutrino discovered at Fermilab (2000)
- SNO confirms neutrino oscillations through appearance (2001)
- BaBar/BELLE discover CP violation in the B system (2001)
- Higgs boson is seen by ATLAS and CMS (2012)

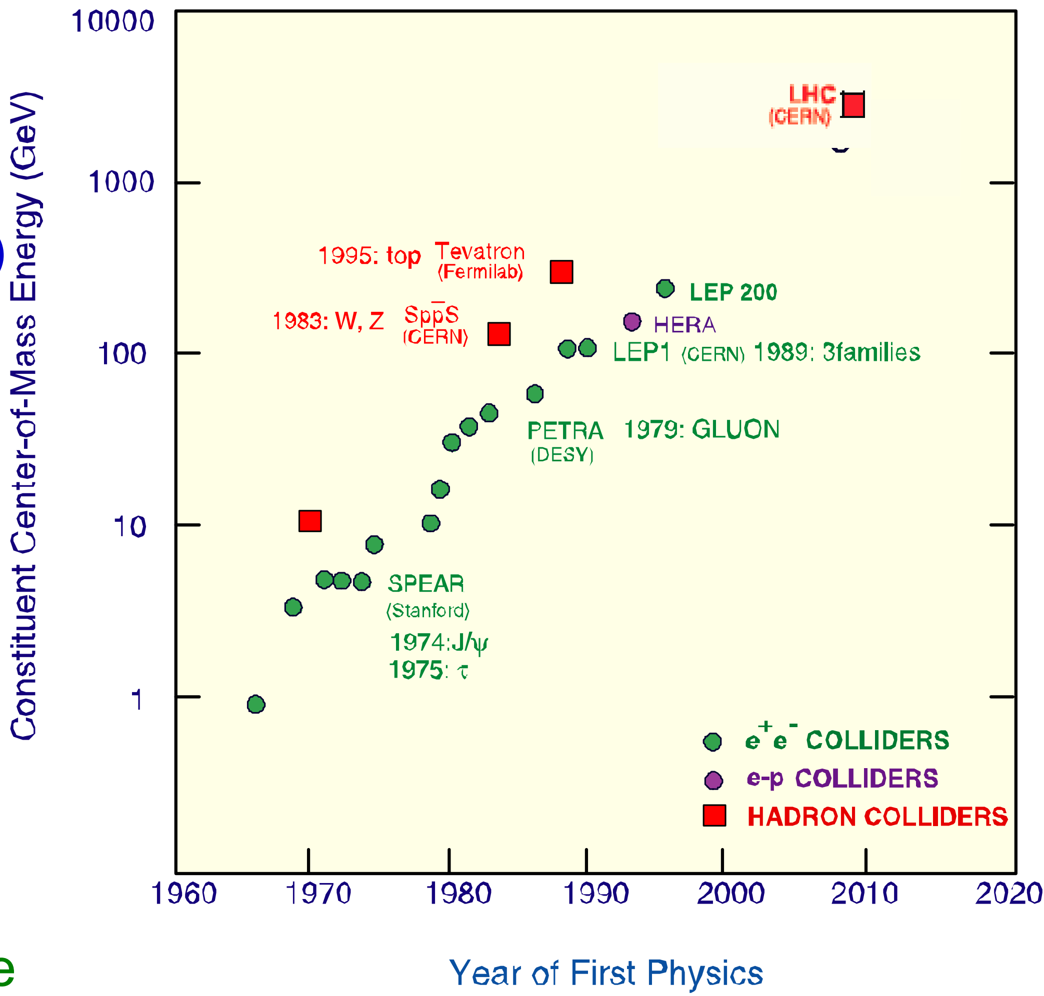
How to probe?



- Study structure of matter by using microscopes with the highest resolving power
- Use very high energy probes - need particle accelerators
- Accelerate stable charged particles by passing them through E-field

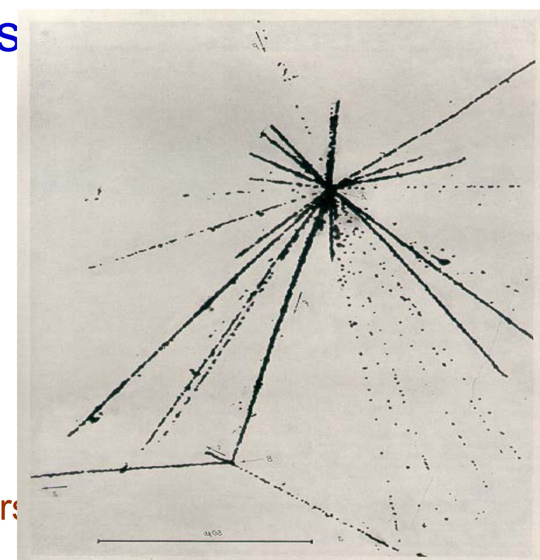
What is behind all this progress?

- Probes used to look into structure:
  - Cathode rays by William Crookes (1870)
  - Radioactivity by Becquerel (1896)
  - Cosmic Rays by Hess (1912)
  - Electrostatic accelerator
    - Cockroft/Walton, Van de Graff, … (1930's onward)
  - Oscillating field particle accelerators
    - Linear accelerators
    - Cyclotron (Lwarence, 1931)
    - Synchrotron (40's)
    - Storage ring (60's)
- Make powerful microscopes to examine what the probes provide



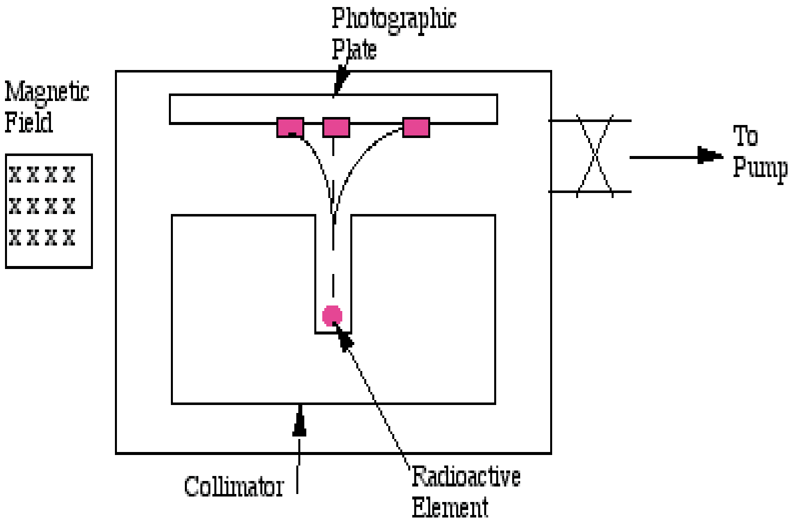
Seeing is believing

- One of the first techniques used in the detection method is the use of nuclear emulsions
  - It has been used in the early generation of experiments
  - It is still used as one of the highest precision detectors
- Nuclear emulsion as particle detectors:
  - It is a photographic plate and is used to record the tracks of charged particles
  - It consists of a large number of small crystals of silver halide, mostly bromide
  - The sensitivity to light has allowed silver halides to become the basis of modern photographic materials



Use of Nuclear Emulsion (I)

- The first notable the use of the photographic emulsion (plates) is the discovery of radioactivity by Henri Becquerel in 1896.
- The radiation emitted by uranium shared certain characteristics with X-rays but, unlike X-rays, could be deflected by a magnetic field and therefore must consist of charged particles. For his discovery of radioactivity, He was awarded the 1903 Nobel Prize for physics.



Henri Becquerel

Use of Nuclear Emulsion (II)

- The Emulsion technique was greatly improved during 30’s and 40’s thanks to the group of the Bristol University lead by Powell
- Developing of electron sensitive Nuclear Emulsions (produced by ILFORD and KODAK)
- In parallel, dedicated microscopes were developed
- From the Cosmic-Rays pion was detected through its decay into muon.
- Powell was awarded the Nobel Prize for physics in 1950 for his discovery using nuclear emulsion

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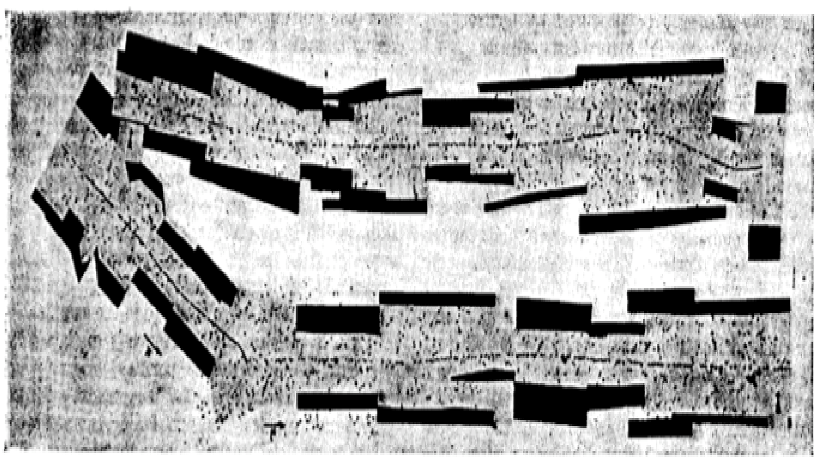
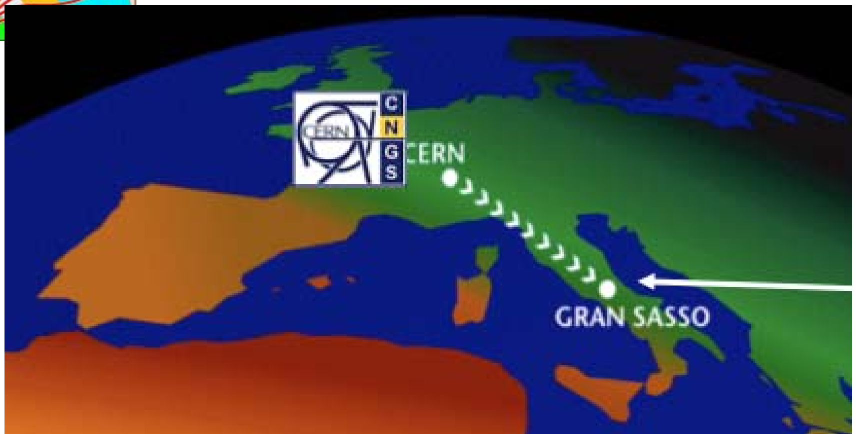
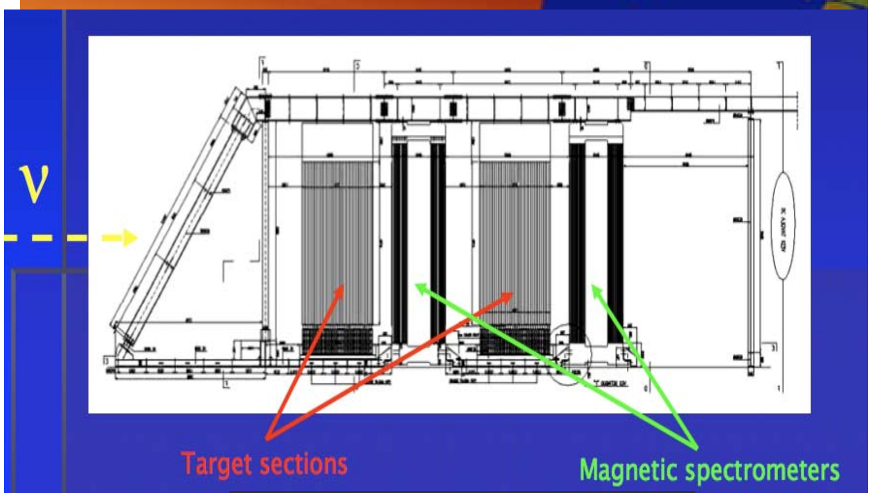
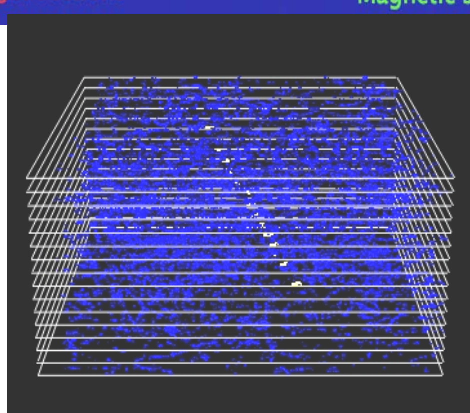


Fig. 1. OBSERVATION BY MRS. I. POWELL. COOKE × 95 ACHROMATIC OBJECTIVE; C2 ILFORD NUCLEAR RESEARCH EMULSION LOADED WITH BORON. THE TRACK OF THE μ-MESON IS GIVEN IN TWO PARTS, THE POINT OF JUNCTION BEING INDICATED BY *a* AND AN ARROW

Use of Nuclear Emulsion (III)



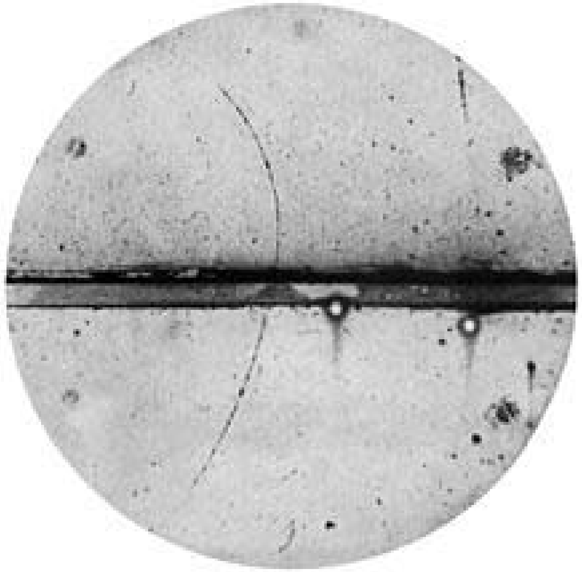




- OPERA is designed for the direct search of ν_τ appearance in the pure ν_μ CNGS beam from CERN to Gran Sasso(732km)
- It uses nuclear emulsion films acting as very high precision tracking detectors, and are interleaved with plates of lead
- The brick, is made of 57 emulsion films interleaved with 56 lead foils of 1 mm thickness.
- There is a magnetic spectrometer: μ ID, charge and momentum.Target tracker: Trigger and localiza ν interactions
- It has observed evidence of the appearance of ν_τ from ν_μ beam

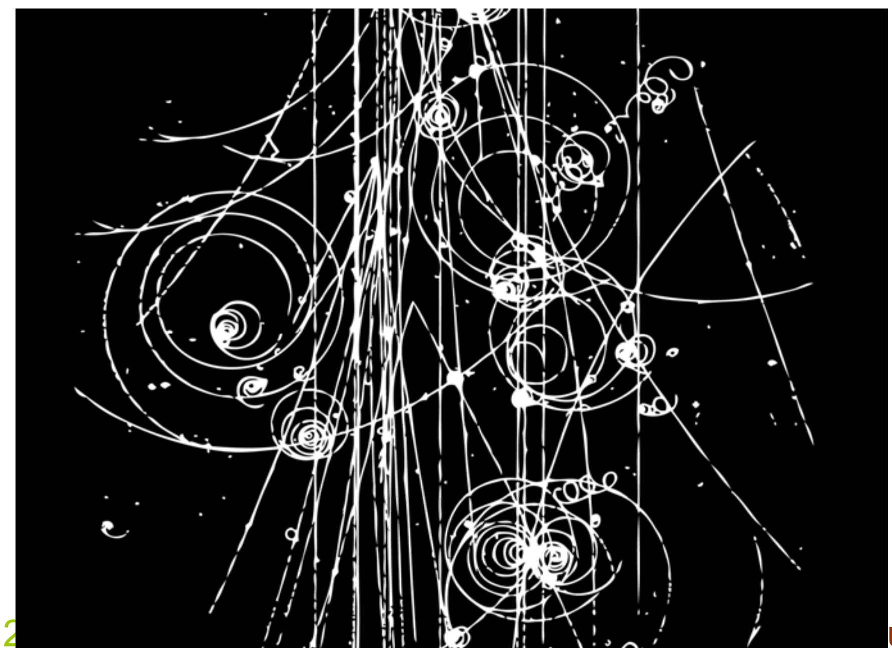
Cloud Chamber

- Cloud chamber is a sealed envelop containing supersaturated vapour. A charged particle while traversing the medium ionizes it and there will be condensation around the ions
- Can be operated in pulse mode and cine films are used to photograph the chamber
- Discovered in 1911 by C.T.R.Wilson and awarded Nobel prize in 1927
- It is used to discover positron by Anderson in 1932
- V-particles are also first observed in cloud chamber experiment by Rochester and Butler in 1947



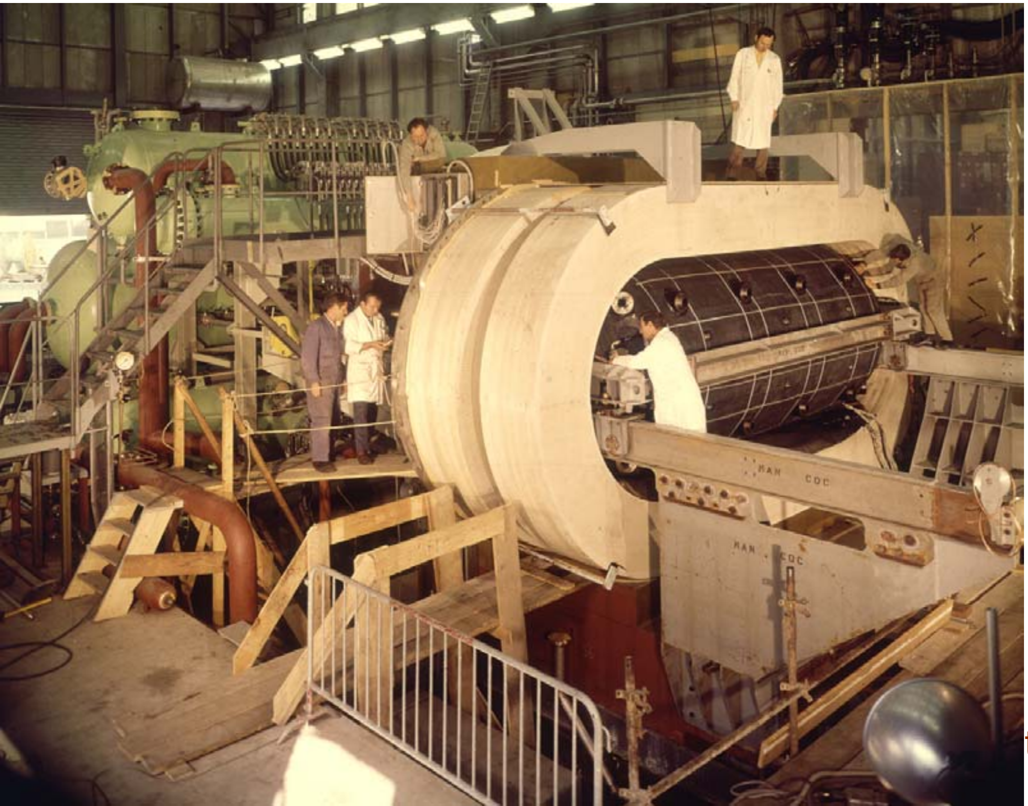
Bubble Chamber

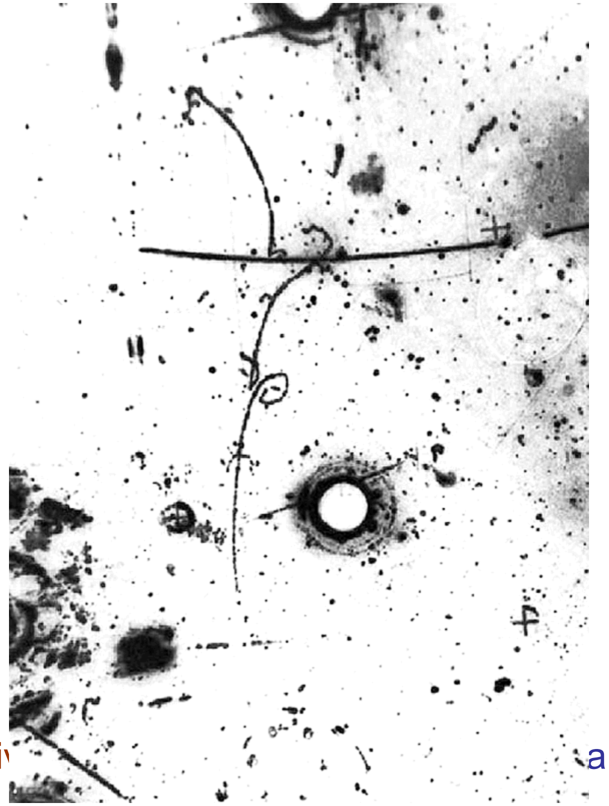
- Use superheated liquids in a closed vessel. Charged particles traversing the liquid will cause centres for boiling. Once bubbles reach critical size, they are photographed.
- It was invented in 1952 by Glaser for which he was awarded Nobel prize in 1960.
- It led to the discovery of many hadrons (called resonances) and led Gellmann-Zweig to quark model. These discoveries also gave Luis Alvarez a Nobel in 1968



Missed Nobel

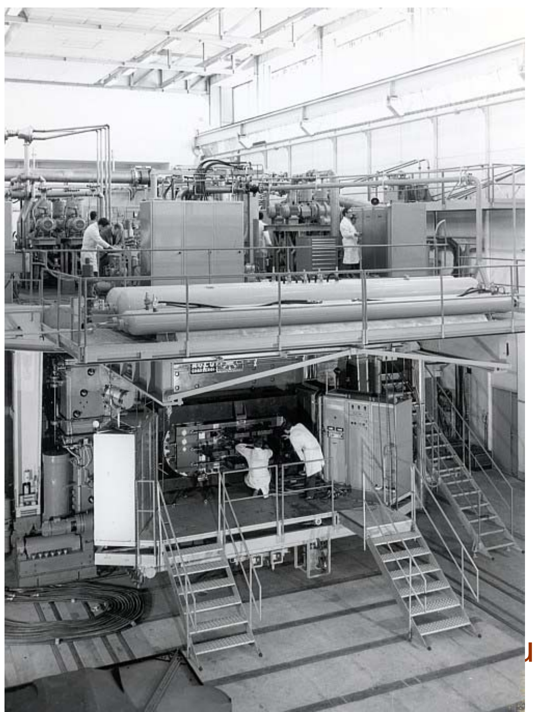
- A heavy liquid (freon) bubble chamber (Gargamelle) was constructed under the leadership of Andre Lagarique and put into neutrino beam of PS in early 70's
- They observed evidence of neutral current in both hadronic and pure leptonic channel
- This led Nobel committee to award Weinberg-Salam-Glashow the prize but poor experimentalists miss out any recognition





Personal Memoirs

- Several bubble chambers were constructed at a number of laboratories all over the world. They were used
  - To discover hundred of baryons and mesons which led to the belief that protons, neutrons, pions, … are not fundamental
  - To study neutrino interactions which led to discovery of neutral currents and also charm quark (people did not realize it then)
- Idea of sophisticated analysis started from the challenge of geometrical reconstruction of 3D events from 2D images



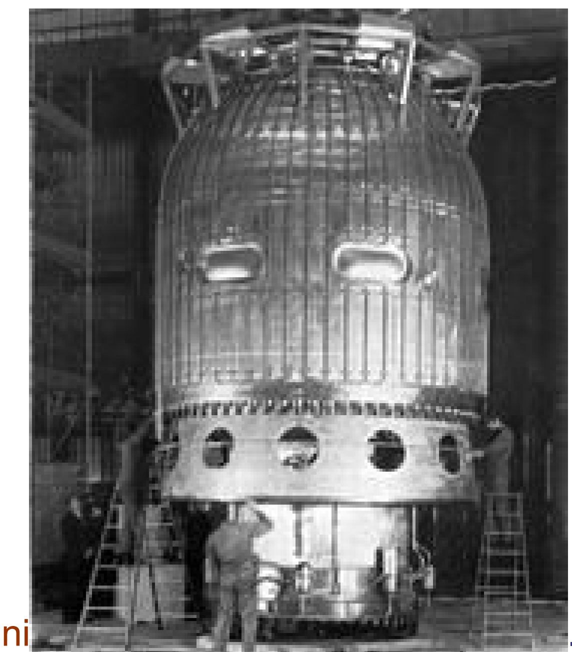


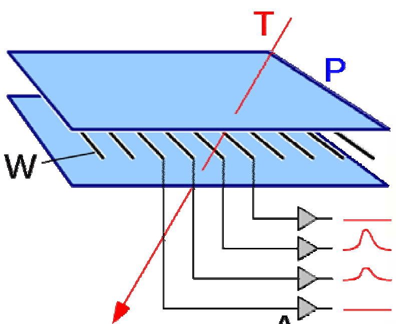
Photo: CERN

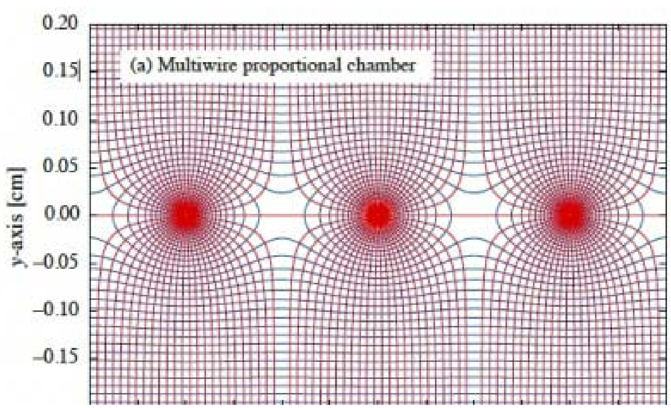
Modern Methods

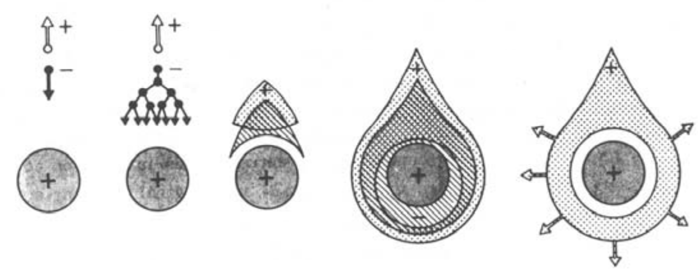
- Probing at short distances means particles at very high energies and they are detected through their interaction with matter
  - Charged particles lose energy through ionization and excitation. If they pass through a gaseous volume, the atomic electrons released through ionization can be collected by applying voltage → ionization chambers or a derivative of that
  - The excited atoms may de-excite and give rise to radiation → fluorescence, scintillation
  - Charged particles traversing at a speed higher than the speed of light in a medium gives rise to Cerenkov radiation
  - Charged particles crossing the boundary of two media having different dielectric constant emit transition radiation
  - Convert neutral particle to charged particle through some interaction and then use charged particle detection technique → calorimeters (totally destroy the particle and sample # of shower particles)

Multiwire Proportional Chamber

- For fast detection of many particles, Charpak developed this novel device in 1968 and was duly rewarded with Nobel prize in 1992
- It is an extension of proportional counter – with all wires behaving as independent detectors. It has very good relative time resolution, good positional accuracy and has very fast recovery
- Electrons multiply through acceleration process and measurable signals are produced
- Various extension of this device is made for modern days experiments: drift chamer, time expansion chamber, drift chamber
- Also same idea is used in non-gaseous detectors: liquid argon detector, silicon strip detector, etc.

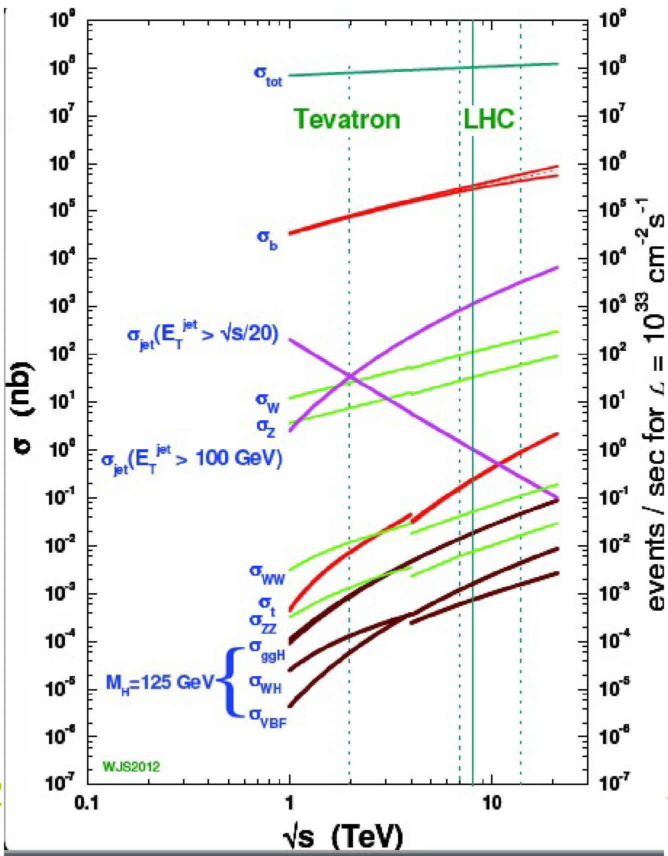


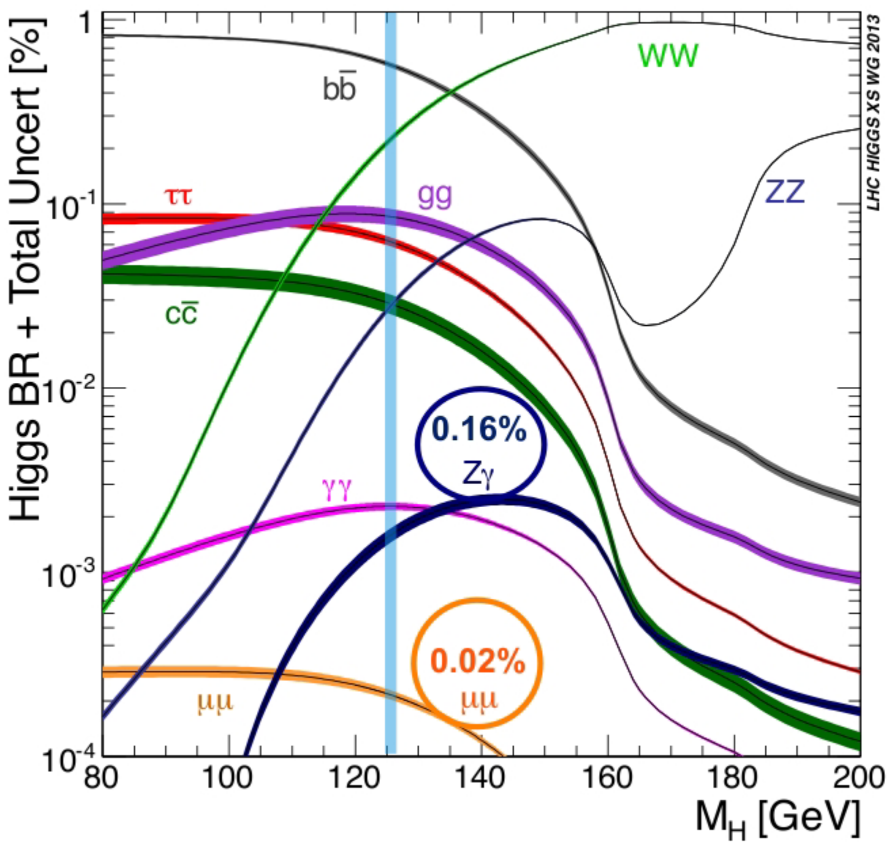




A Modern Day Experiment

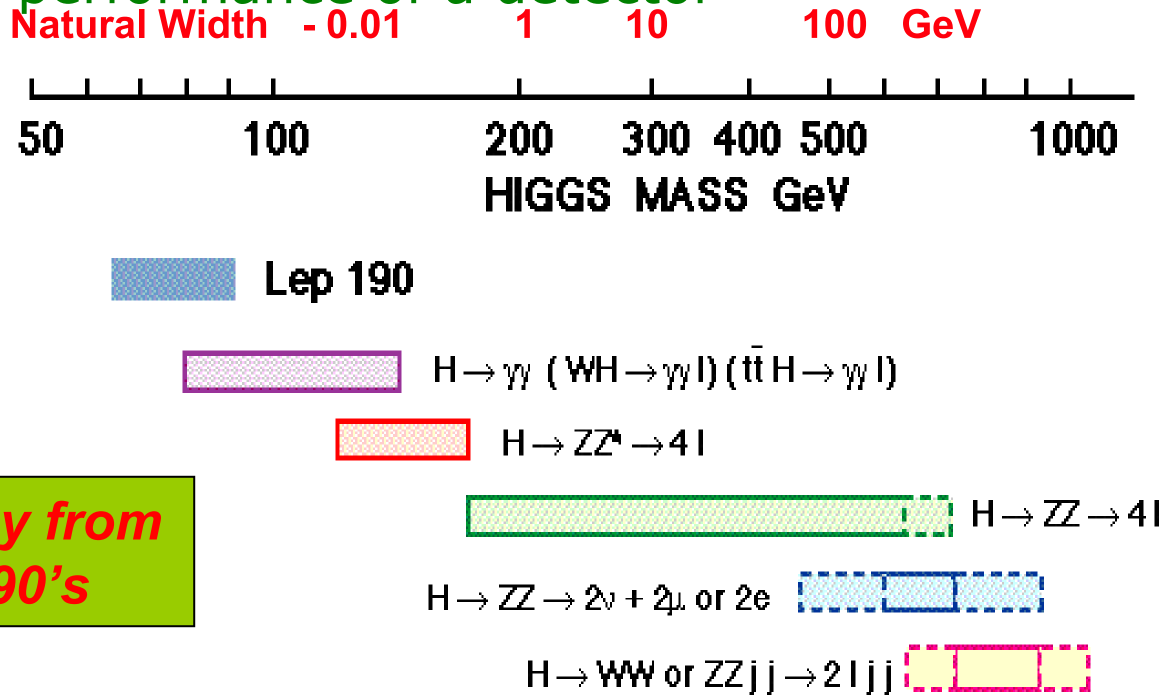
- Use the existing techniques to design a modern day experiment: look for Higgs boson
  - Know the mass could be between 100 GeV and 1000 GeV
  - Use high energy (7-8 TeV) pp collisions
  - Need a large number of collisions



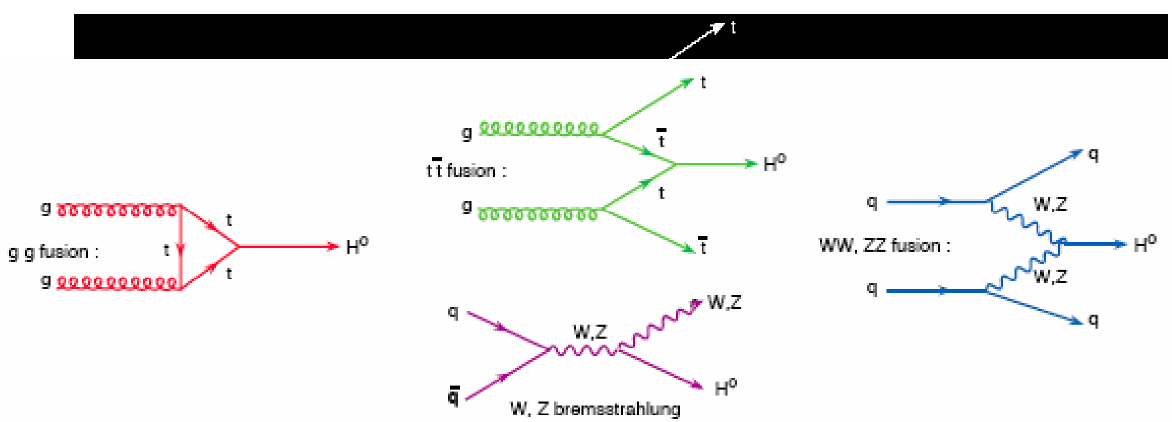


The Benchmark Reaction: SM Higgs

At the LHC the SM Higgs provides a good benchmark to test the performance of a detector



Transparency from the early 90's



CMS Design Criteria

Very good muon identification and momentum measurement

Trigger efficiently and measure sign of TeV muons dp/p < 10%

High energy resolution electromagnetic calorimetry

~ 0.5% @ E_T ~ 50 GeV

Powerful inner tracking systems

Momentum resolution a factor 10 better than at LEP

Hermetic calorimetry

Good missing E_T resolution

(Affordable detector)

Experimental Challenge

This detector is radically different from the ones from the previous generations

High Interaction Rate

pp interaction rate **1 billion interactions/s**
Data can be recorded for only ~10^2 out of 40 million crossings/sec
Level-1 trigger decision takes ~2-3 μs
⇨ **electronics need to store data locally (pipelining)**

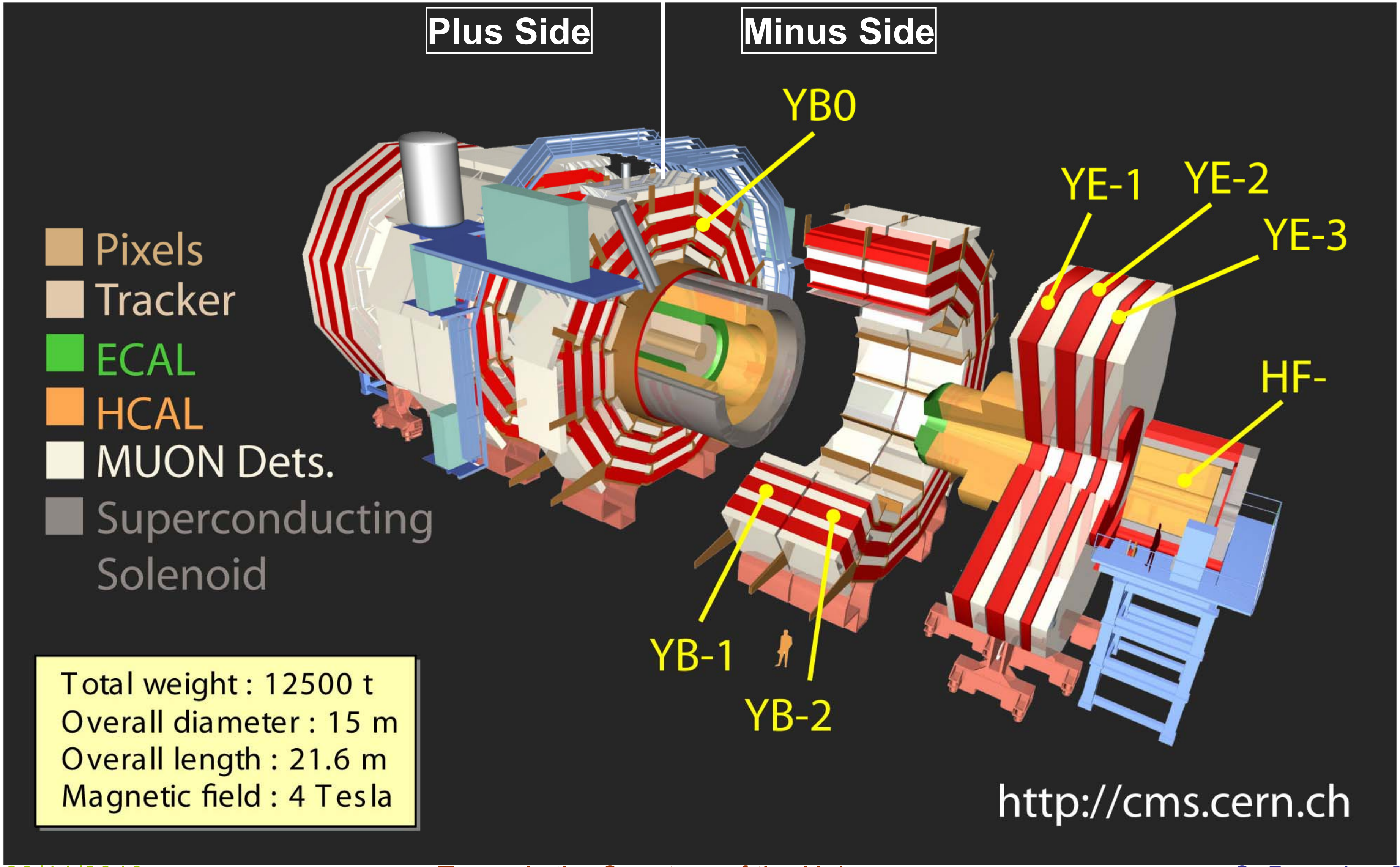
Large Particle Multiplicity

~ <20> superposed events in each crossing
~ 1000 tracks stream into the detector every 25 ns
need highly granular detectors with good time resolution for low occupancy
⇨ **large number of channels (~ 100 M ch)**

High Radiation Levels

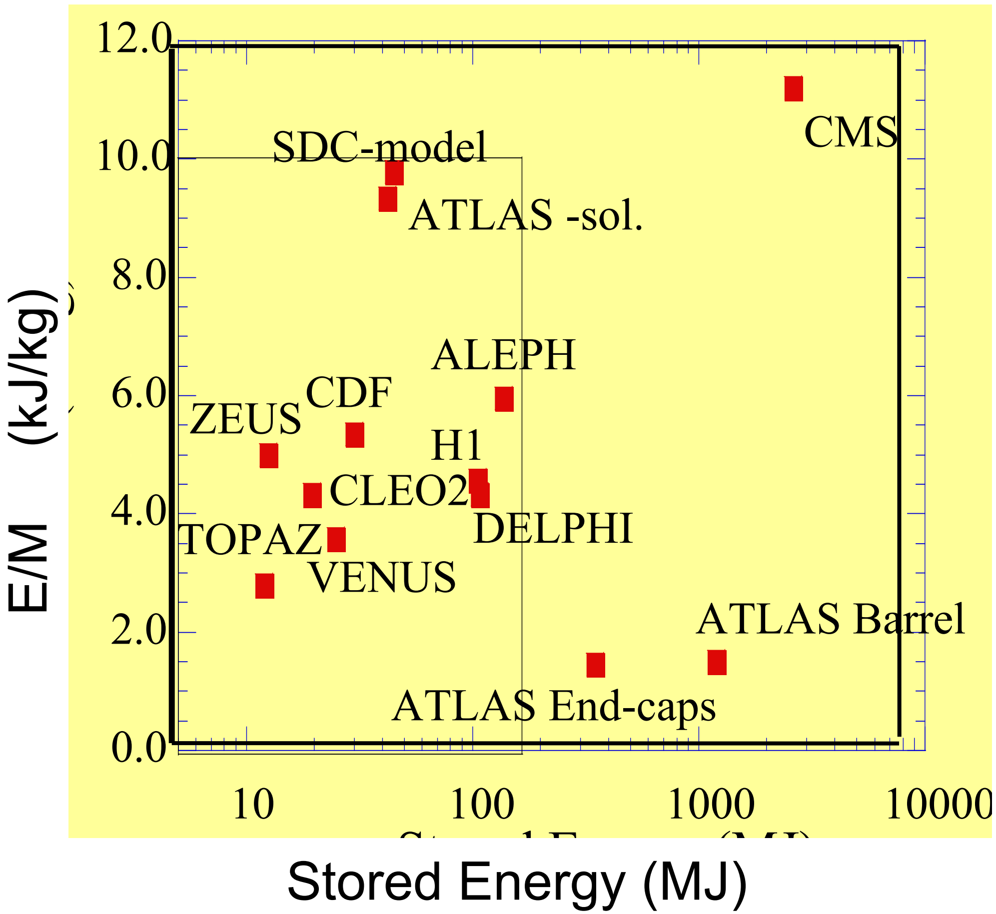
⇨ **radiation hard (tolerant) detectors and electronics**

Exploded View of CMS



CMS Superconducting Solenoid

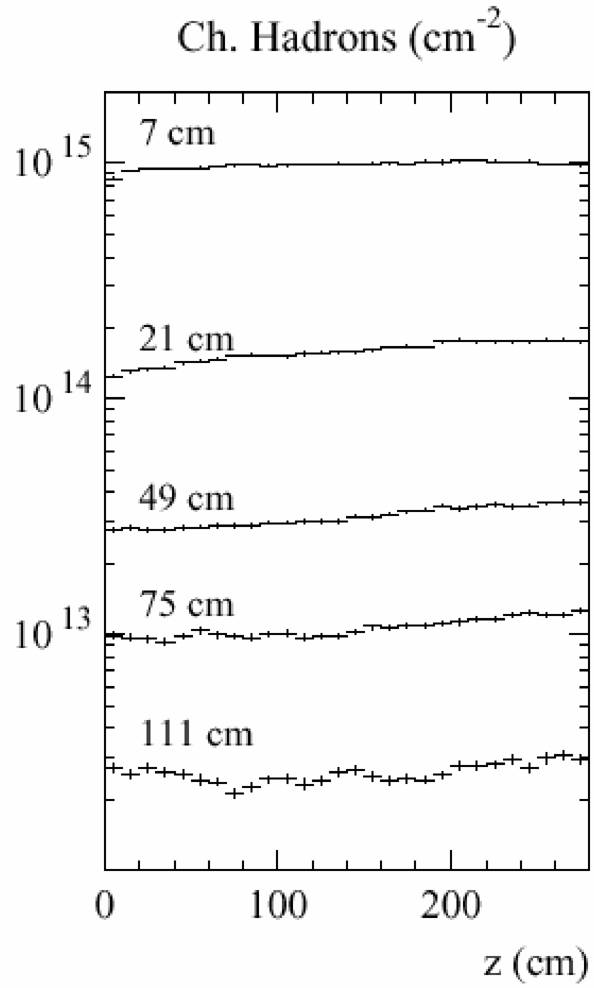
Design Goal: Measure 1 TeV/c muons with < 10% resolution



Tracking at LHC

Need factor 10 better momentum resolution than at LEP
1000 particles emerging every crossing (25ns)

Fluence over 10 years of LHC Operation



$\leq 4.10^7$ $h^\pm/cm^2/s$
pixels ($\approx 10^4$ μm^2)
occupancy $\approx 10^{-4}$

$\leq 4.10^6$ $h^\pm/cm^2/s$
Si μ-strip det.
($\approx$10 mm^2)
occupancy $\approx$ 1%

$\leq 4.10^5$ $h^\pm/cm^2/s$
Si or Gas detectors.
($\approx$1 cm^2)
occupancy $\approx$ 1%

Si Microstrips For Inner Tracking

Technologies Considered

Scintillating fibres, MSGCs, Si Pixels, Si Microstrips

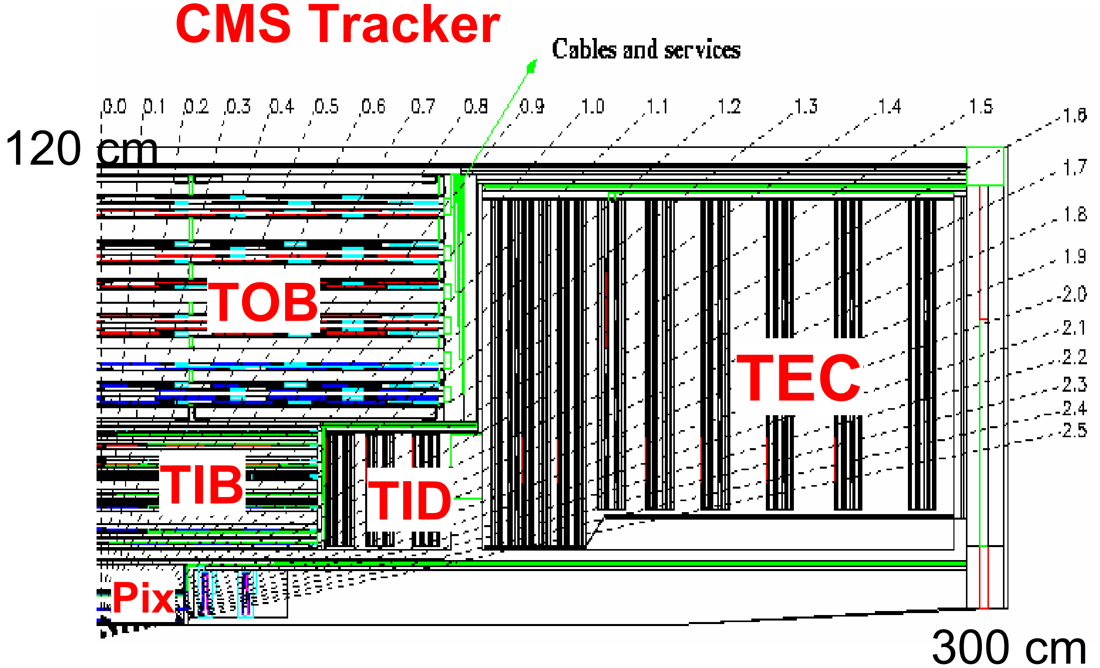
Silicon technology (ideally) suited to LHC environment

Four key developments for Si microstrip detectors

- ❑ Sensor fabrication on 6-inch instead of 4-inch wafers
- ❑ Implementation of front-end read-out chip in industry standard deep sub-micron technology
- ❑ Automation of module assembly and use of high throughput wire bonding machines
- ❑ Downwards evolution of price per unit area

Layout of CMS Tracking

CMS Tracker

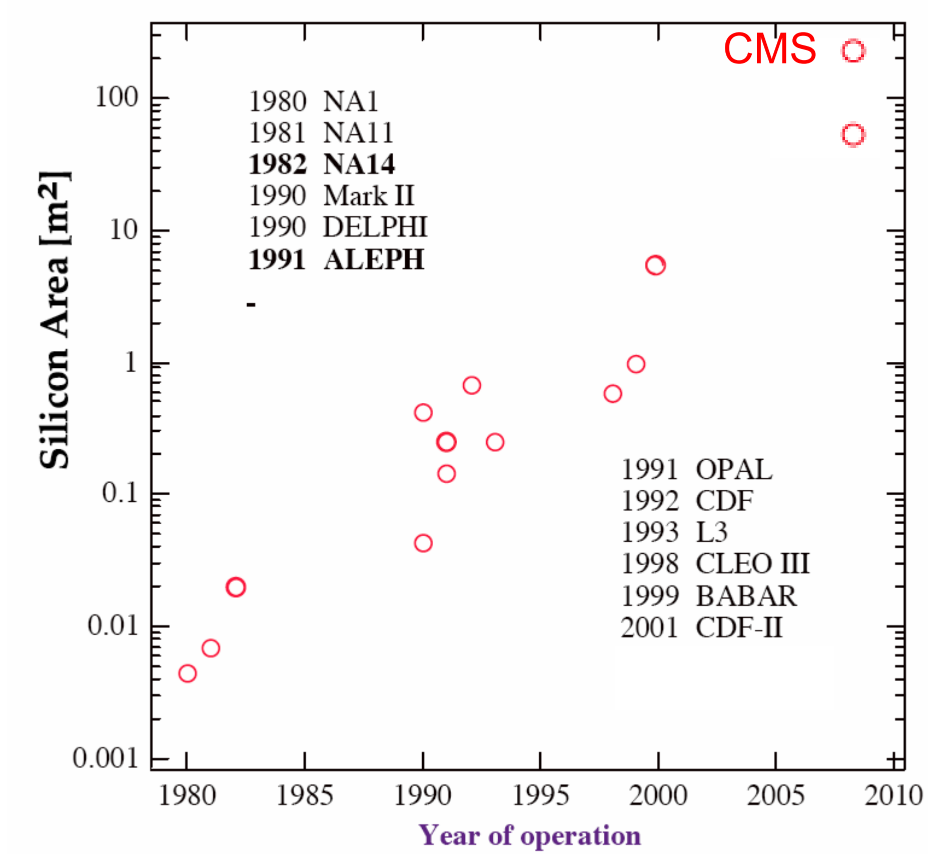


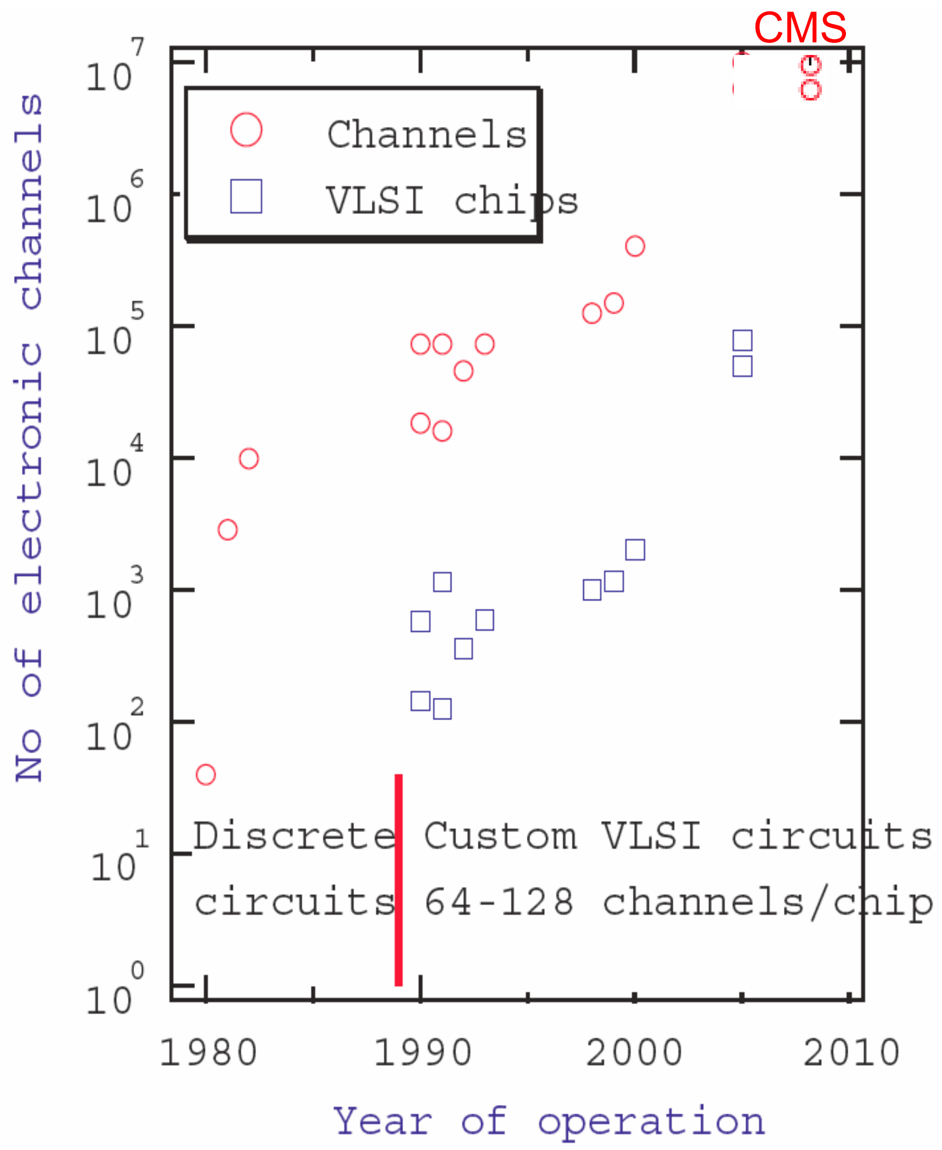
Si pixels surrounded by Si strip detectors

Pixels: ~ 1 m^2 of silicon sensors, 65 M pixels, 100x150 μm^2 , r = 4, 7, 11 cm

Si μstrips : 223 m^2 of silicon sensors, 10 M strips, 10 pts, r = 20 – 120 cm

Evolution in Silicon & Electronics in High Energy Physics



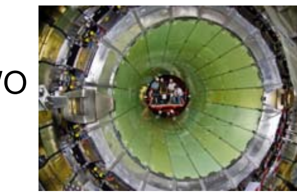


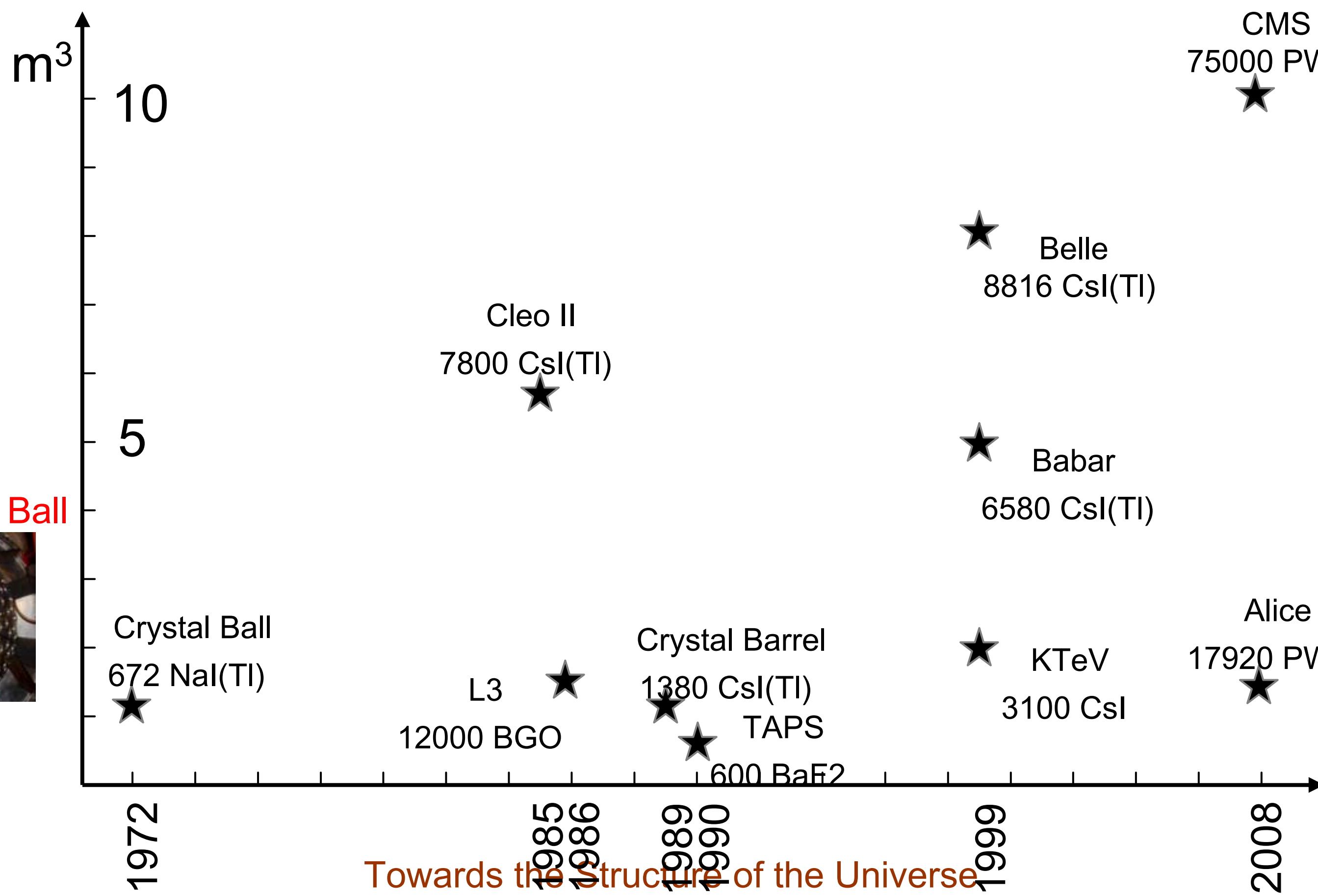
Lead Tungstate ECAL

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

CMS chose scintillating crystals

CMS





From Crystal Ball

Timeline for $PbWO_4$ Crystals ECAL

Idea (1993 – few yellowish cm^3 samples)

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

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

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

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

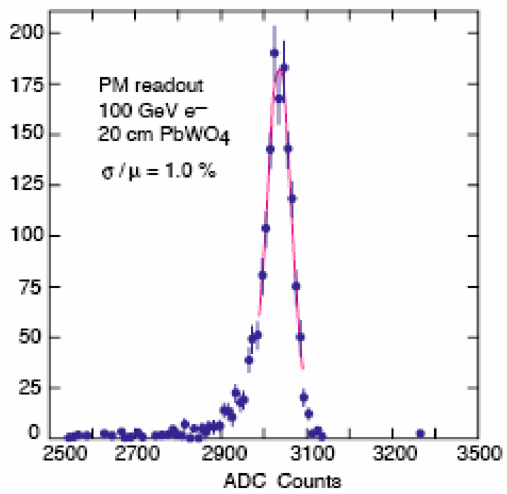
→ **Installation and Commissioning** (2007-2008)

→ **Data Taking** (2008 onwards)

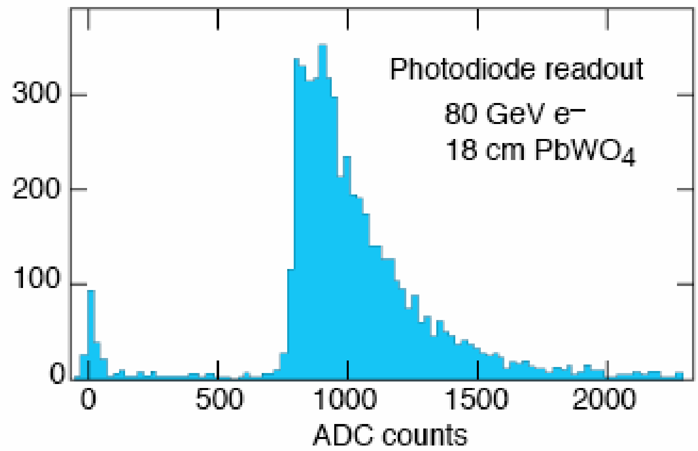
$\Delta t \sim 15$ years !!!

Choice of the Photodetector

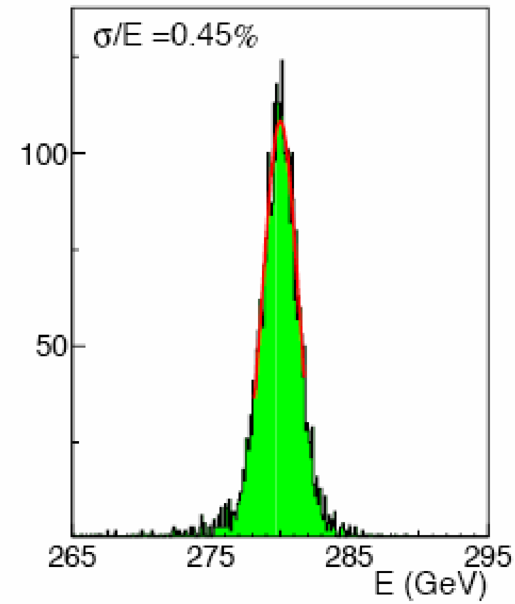
Photomultiplier Readout



Si Photodiode Readout

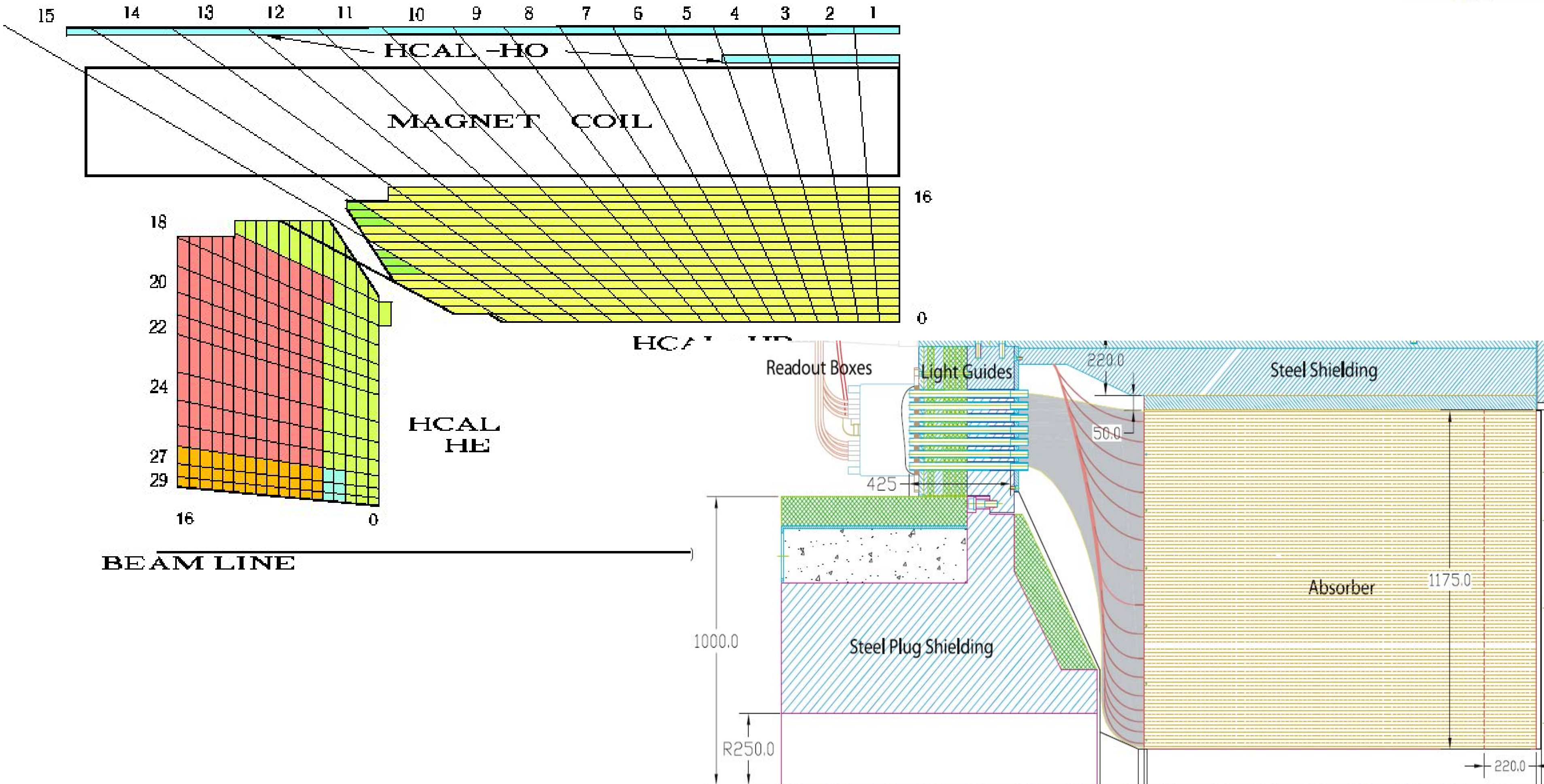


Avalanche Photodiode Readout



Transparency from 1993

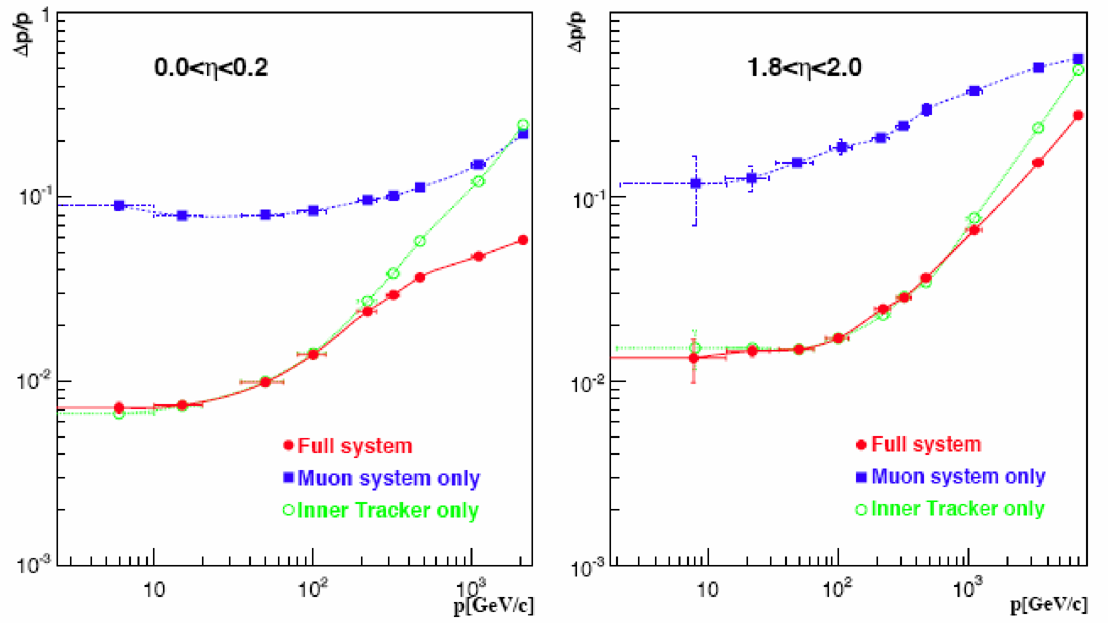
Hadron Calorimeter



- ❑ Central hadron calorimeter consists of plastic scintillator layers interleaved with brass plate absorbers
- ❑ Forward hadron calorimeter is still absorber with quartz fibres

Muon Detector

- Divide the detector into two parts
  - central (barrel) with low rates and background
  - Endcaps with higher rate and possible neutron induced background
- Barrel Muon detectors are 4 stations of drift tube chambers measuring φ and z coordinates
- Endcap Muon detectors are 3(4) stations of cathode strip detectors
- Complement the triggering by adding layers of resistive plate chambers in barrel/endcap for triggers



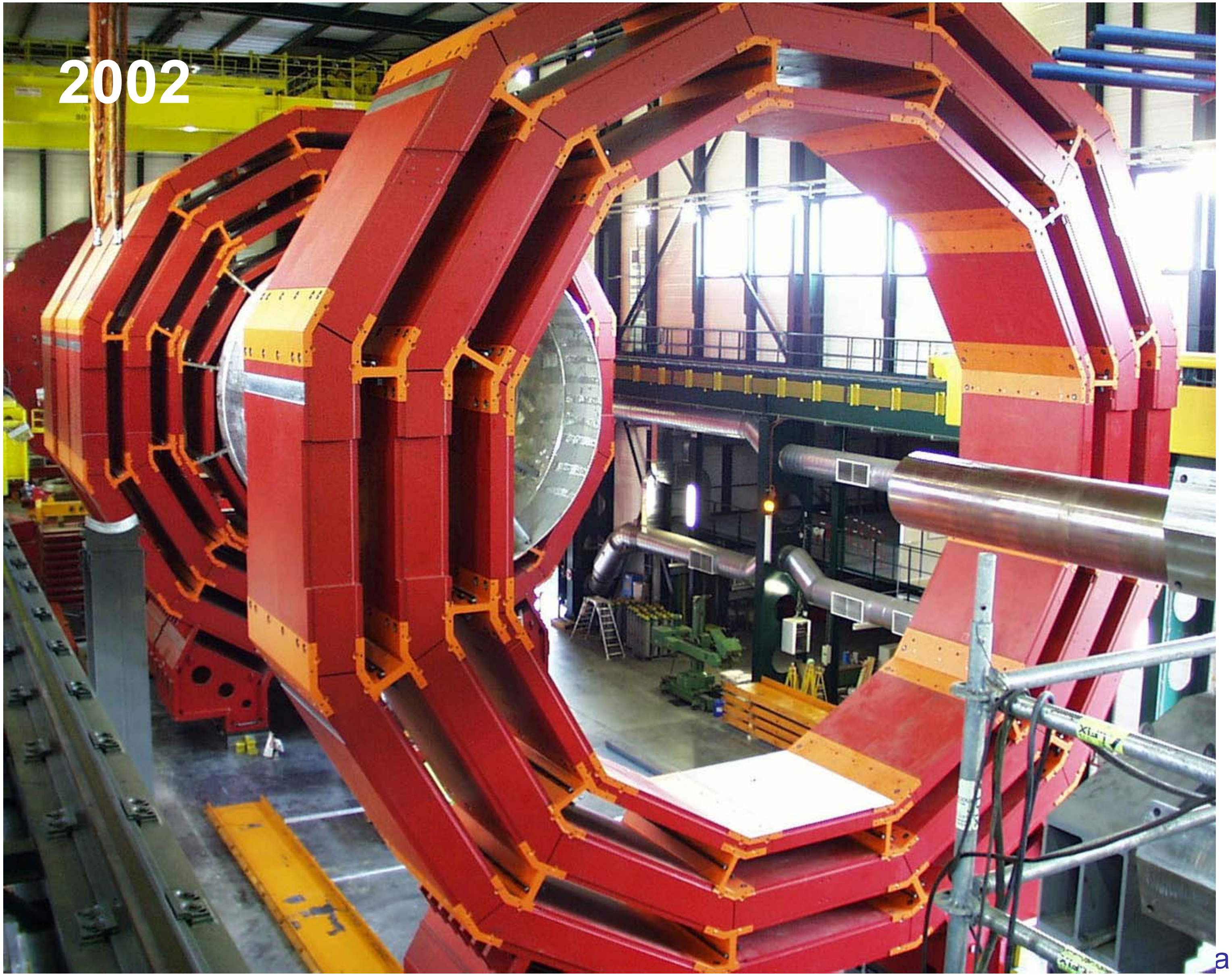
CMS Site at Point 5 (Cessy) in 2000

Magnet

- Coil: 230 tons
- Outer vacuum tank:

  13 m long SS tube, ϕ=7.6 m
- Return yoke is divided in 5 rings in the barrel region and 3 caps on either side
- Tested to design current (4T). But will be operated at 3.8T.

Assembly of Iron Yoke



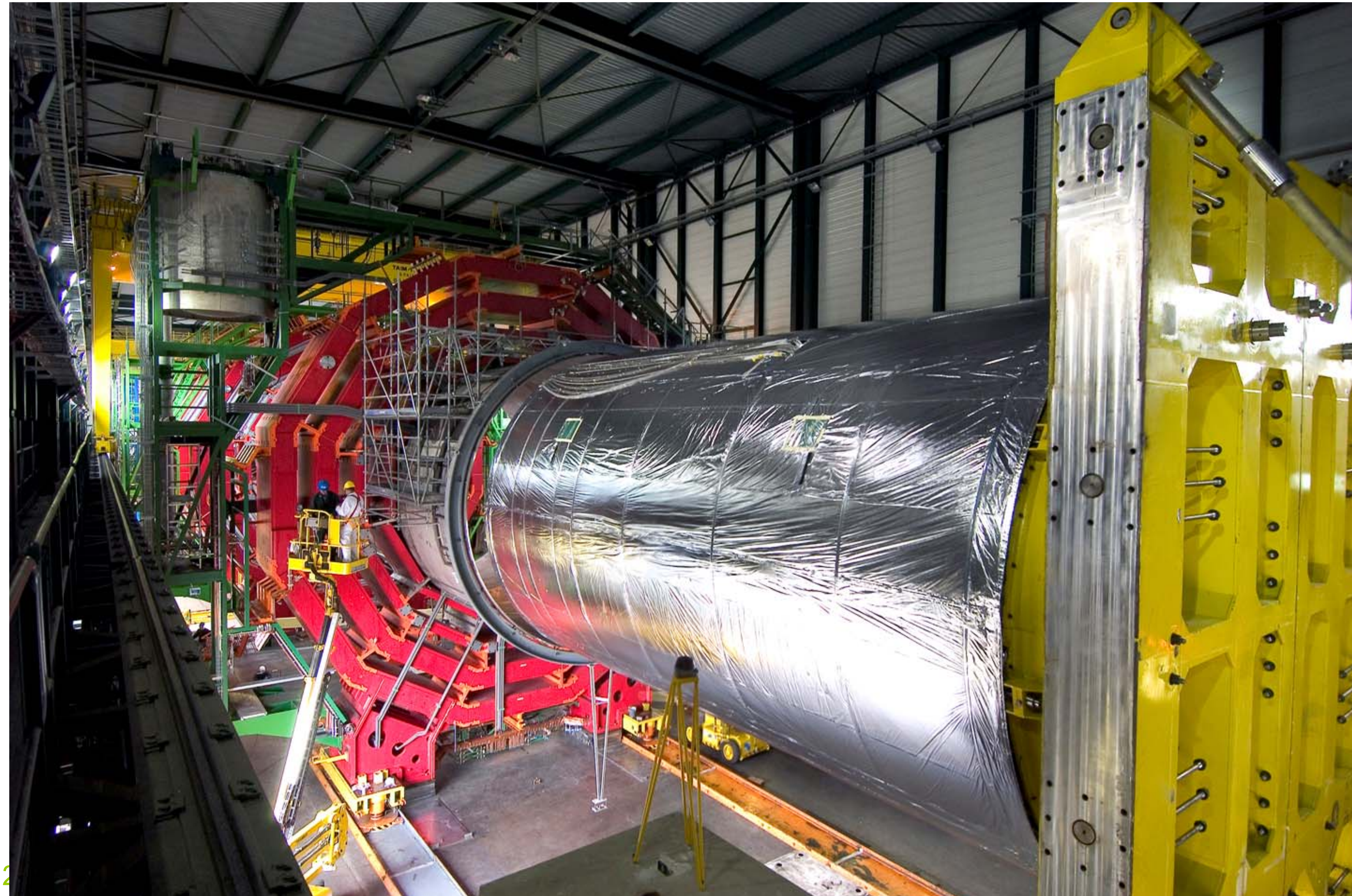
Assembly of Iron Yoke

Assembly of the Coil

Sept 05

Coil: 230 tons
Outer vacuum tank:
13 m long SS tube, ϕ=7.6 m

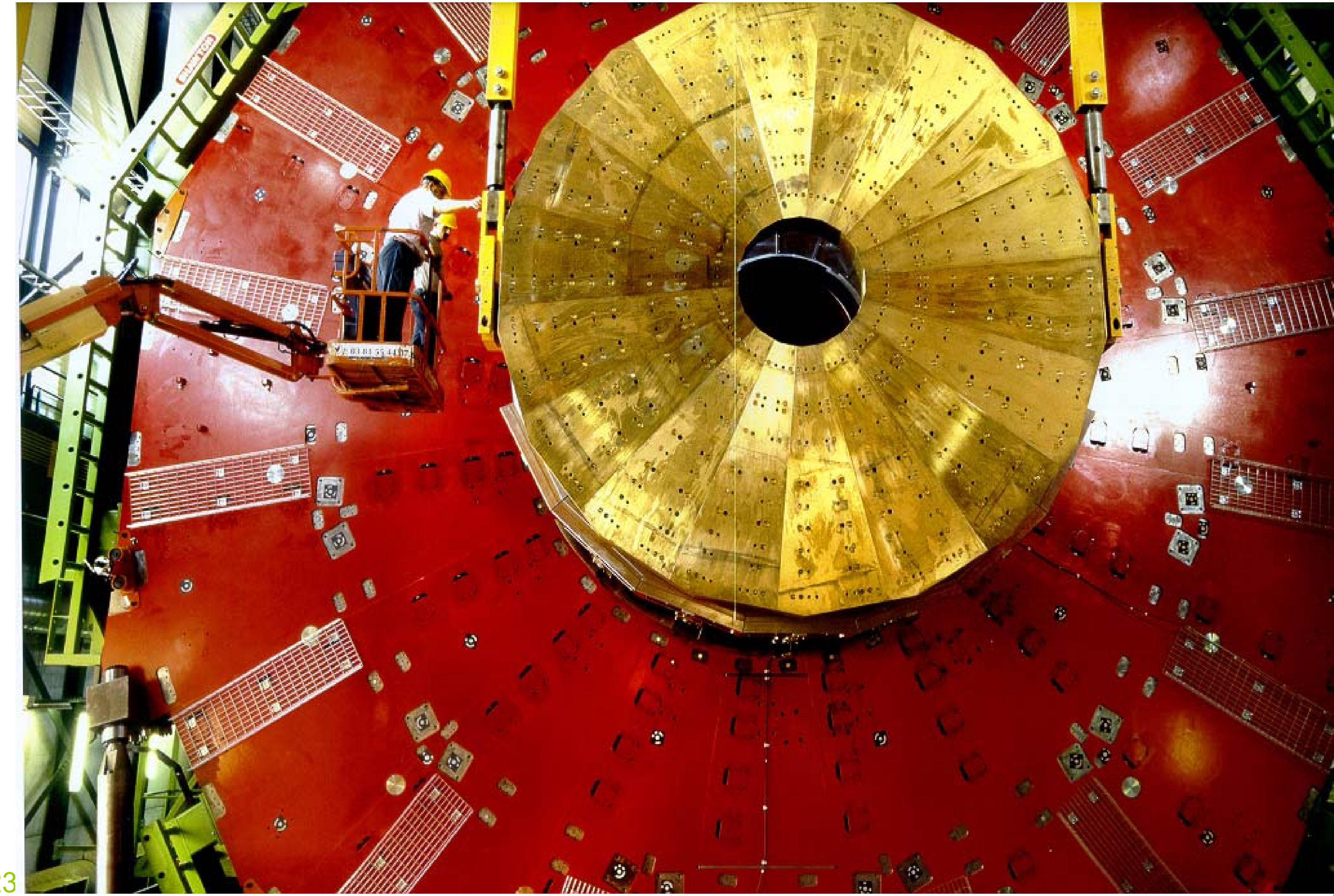
Assembly of the Coil



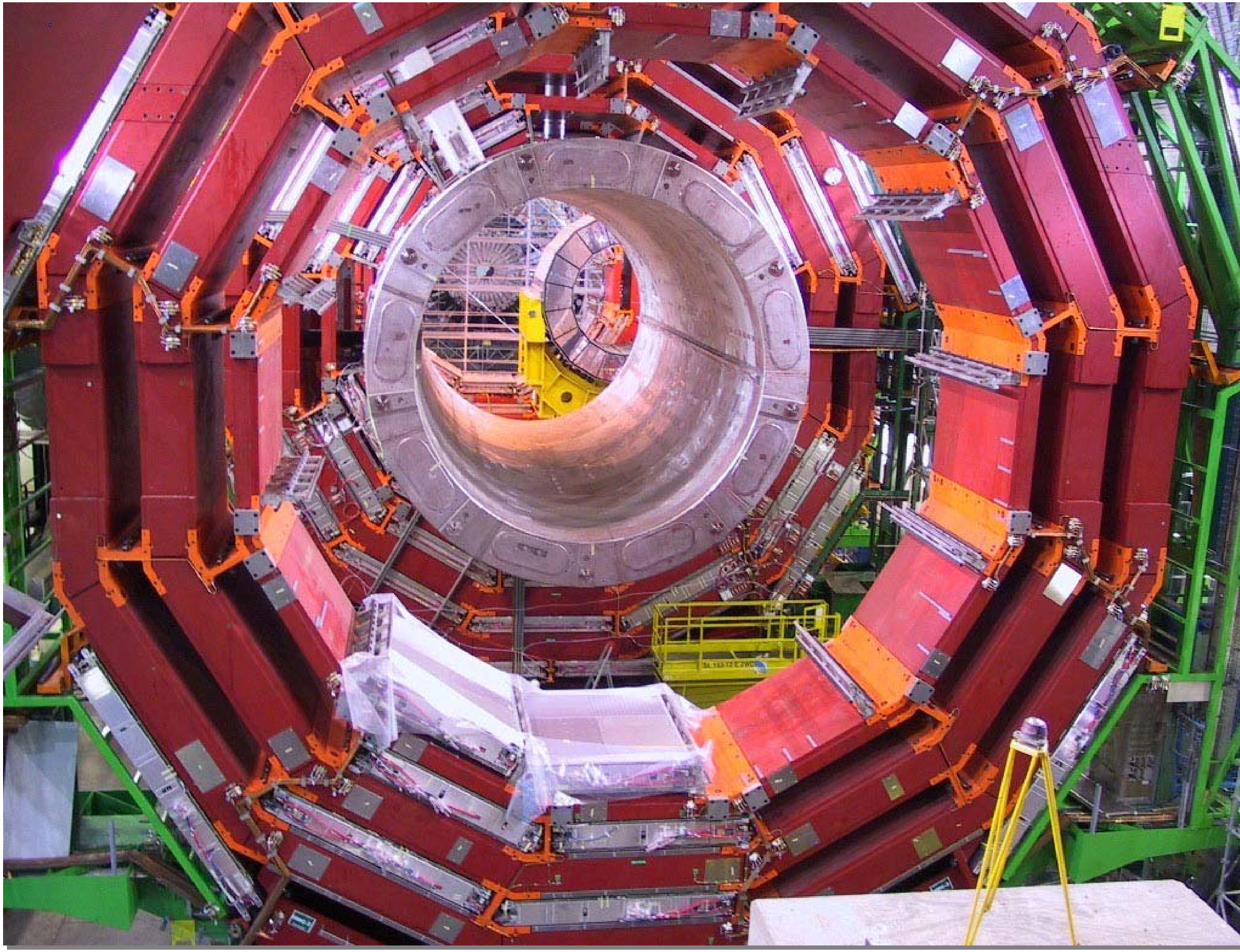
HCAL Endcap- Start of Journey

HCAL Endcap – Midway

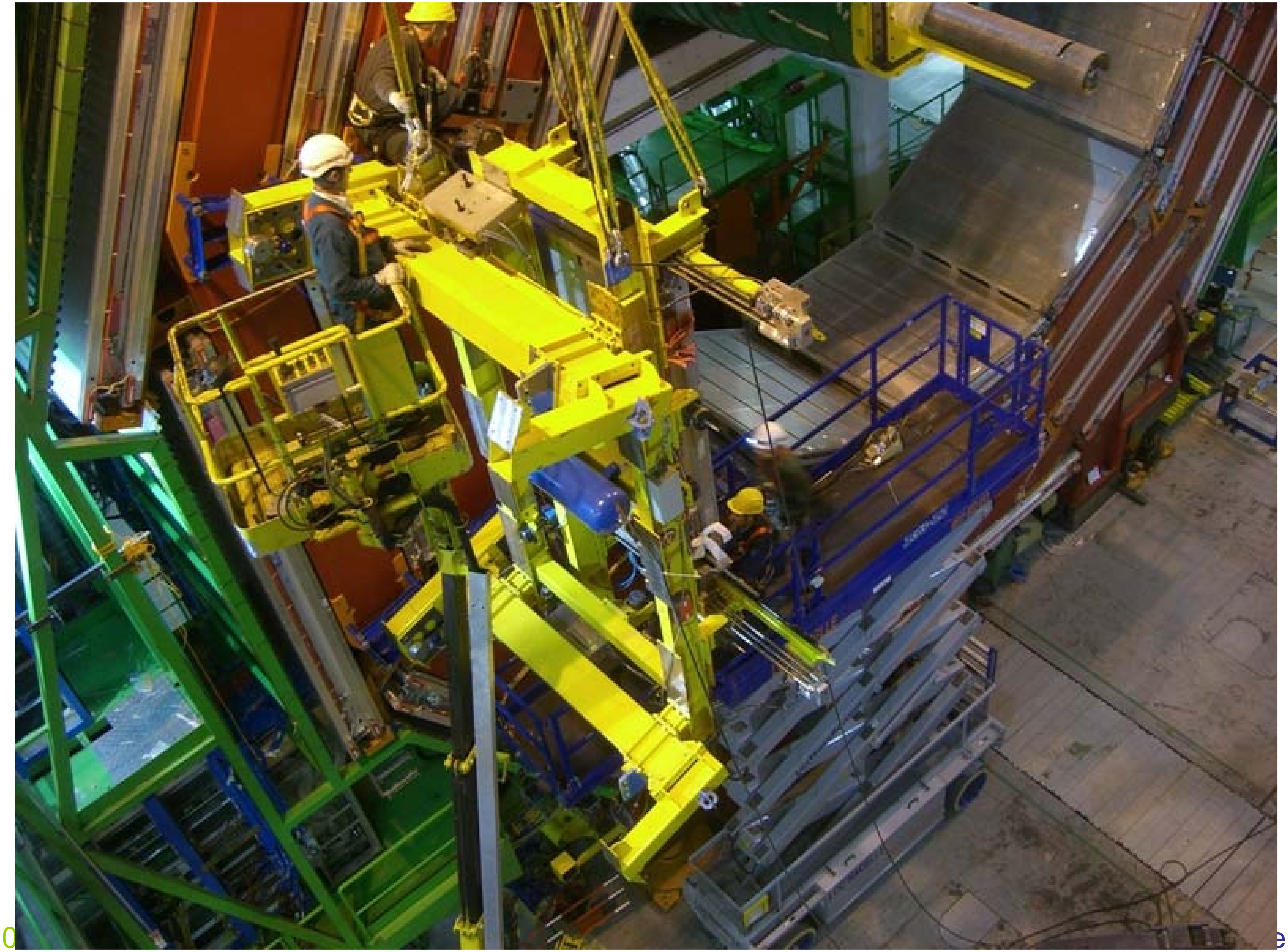
HCAL Endcap – Final Destination



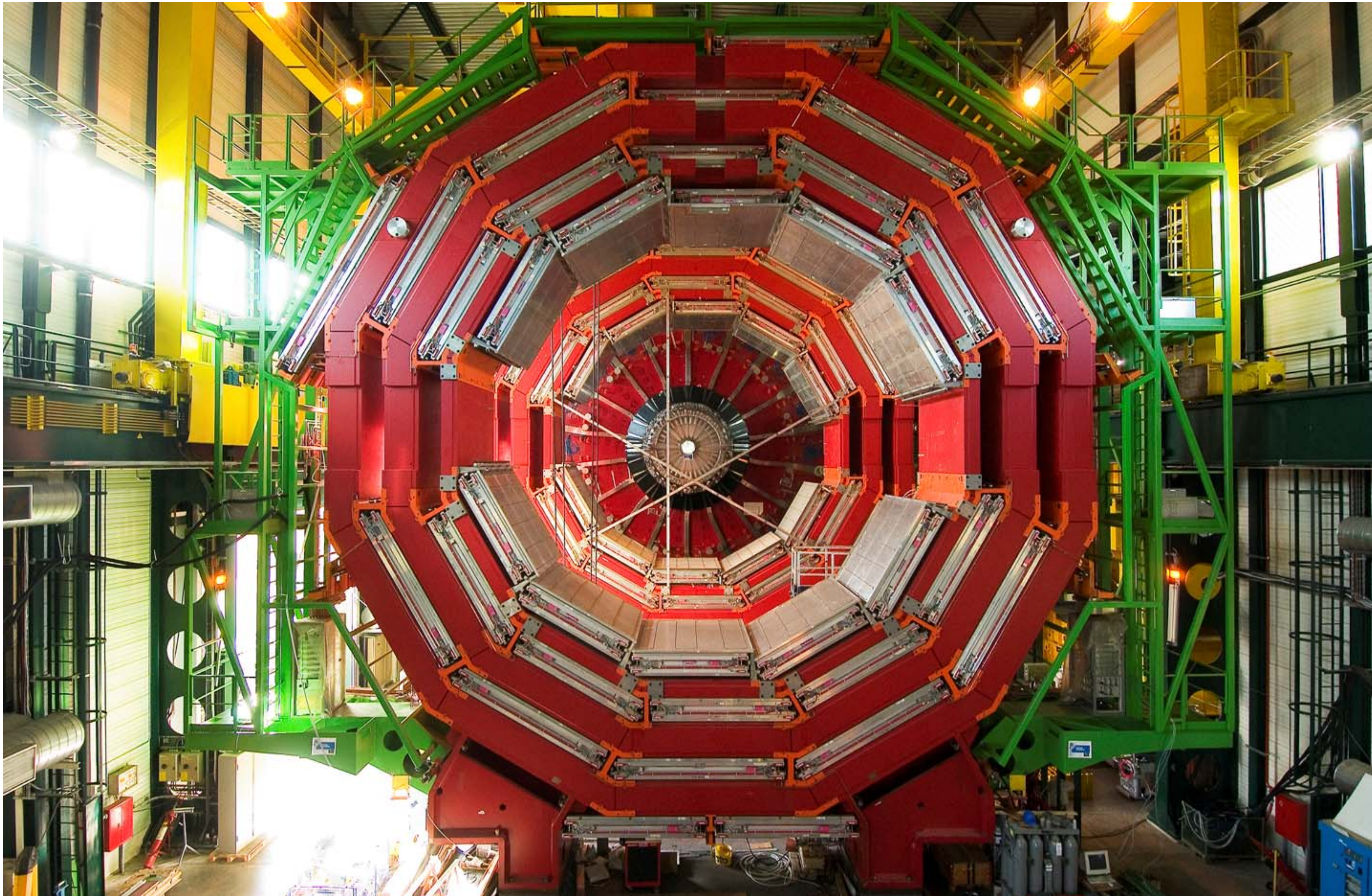
CMS Surface Hall in Feb 2006



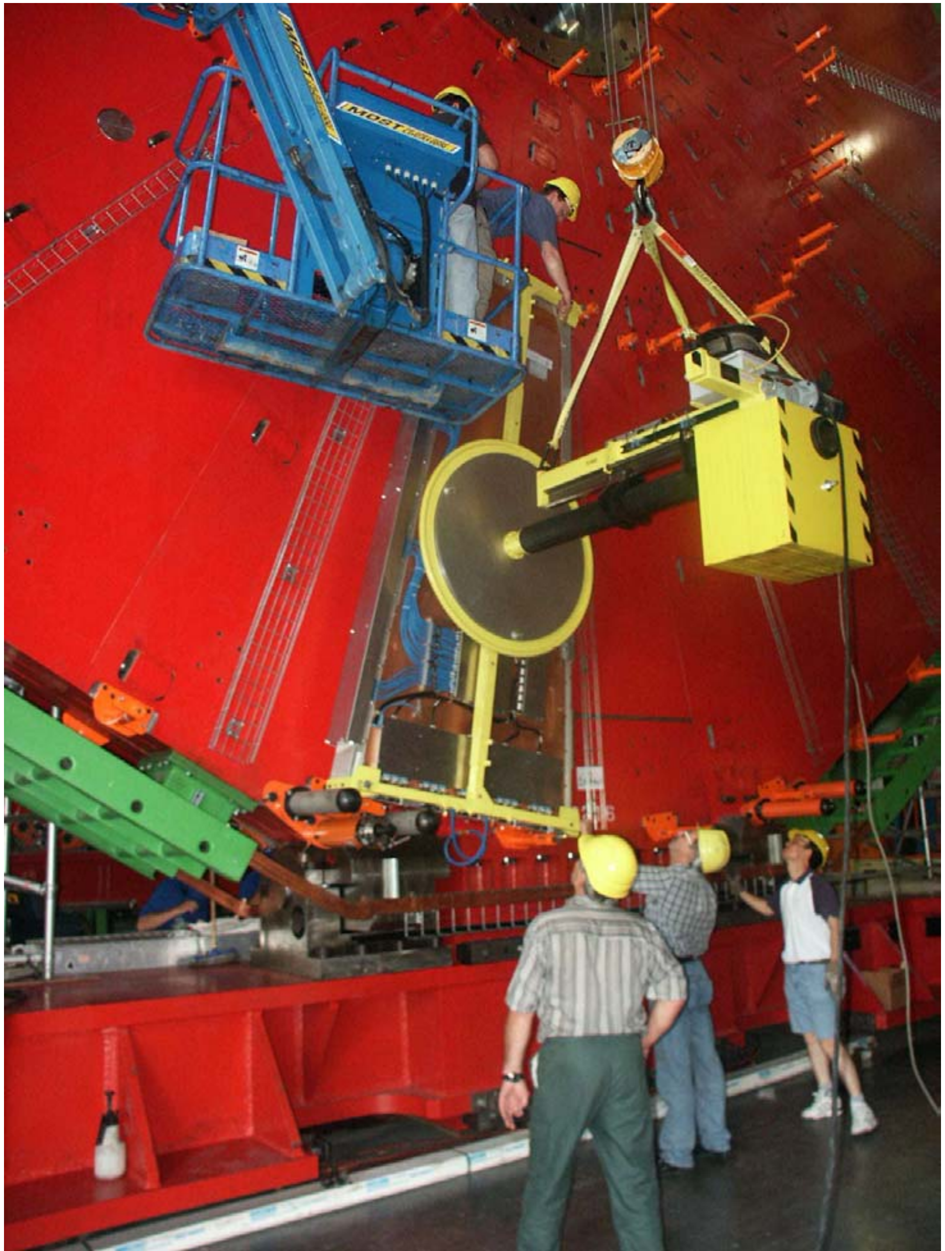
Surface Hall: Barrel Muons



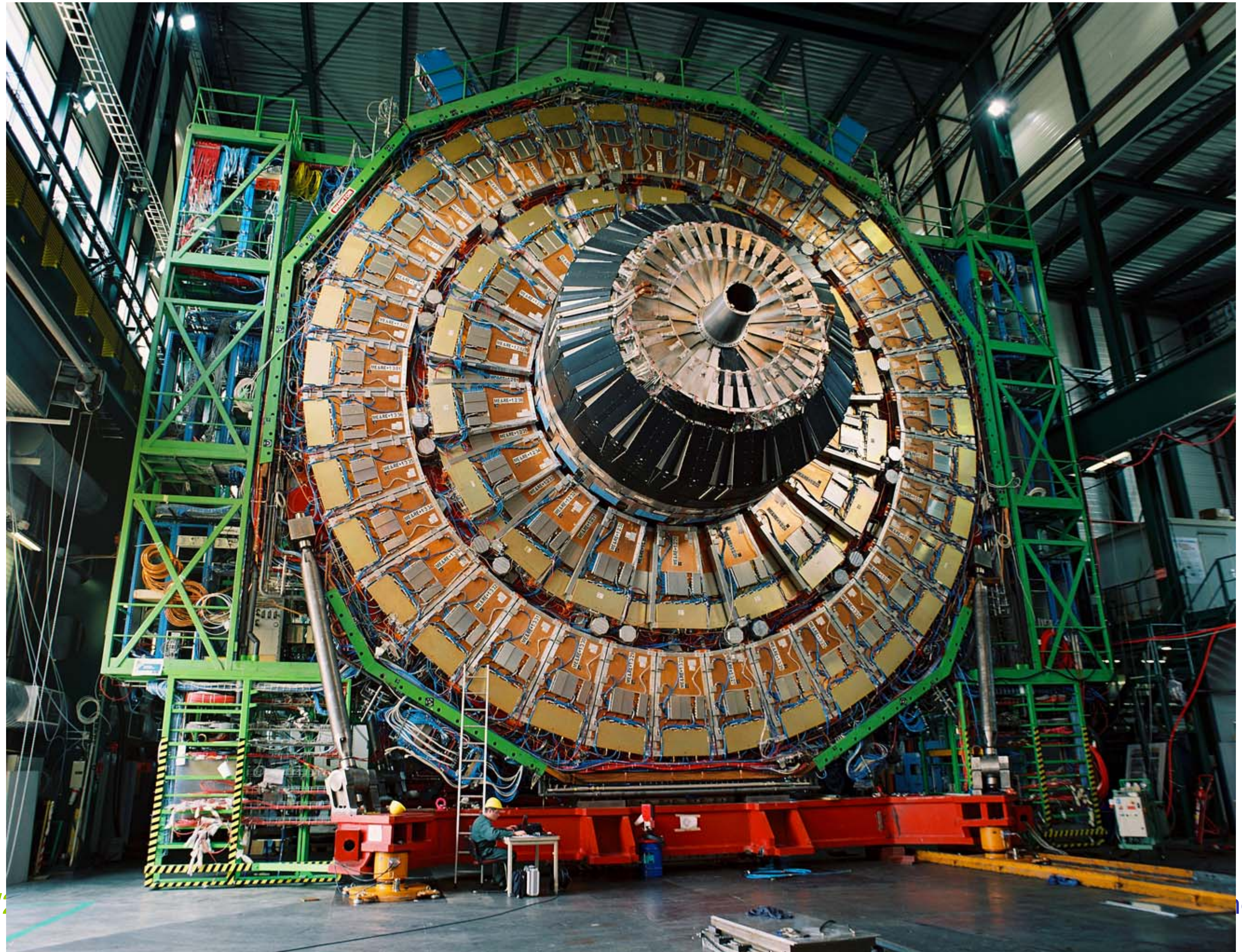
Barrel Muons



Surface Hall: Endcaps



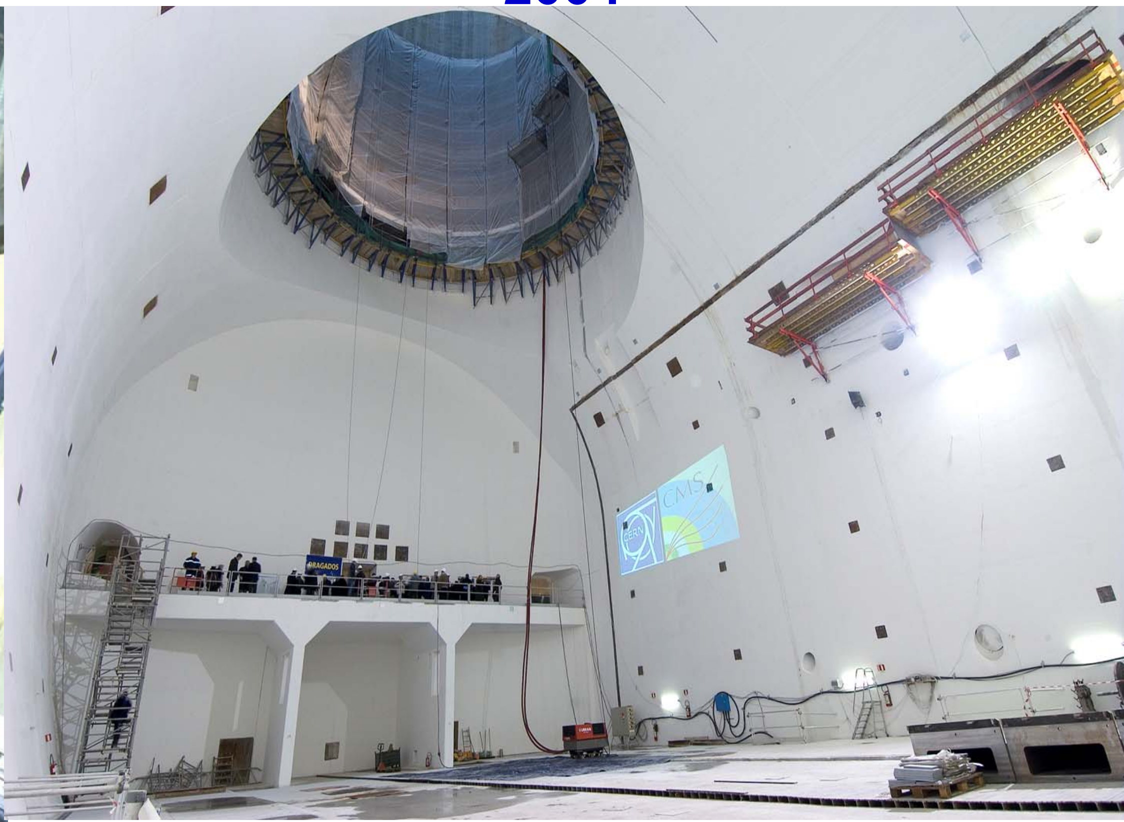
Endcap Muons



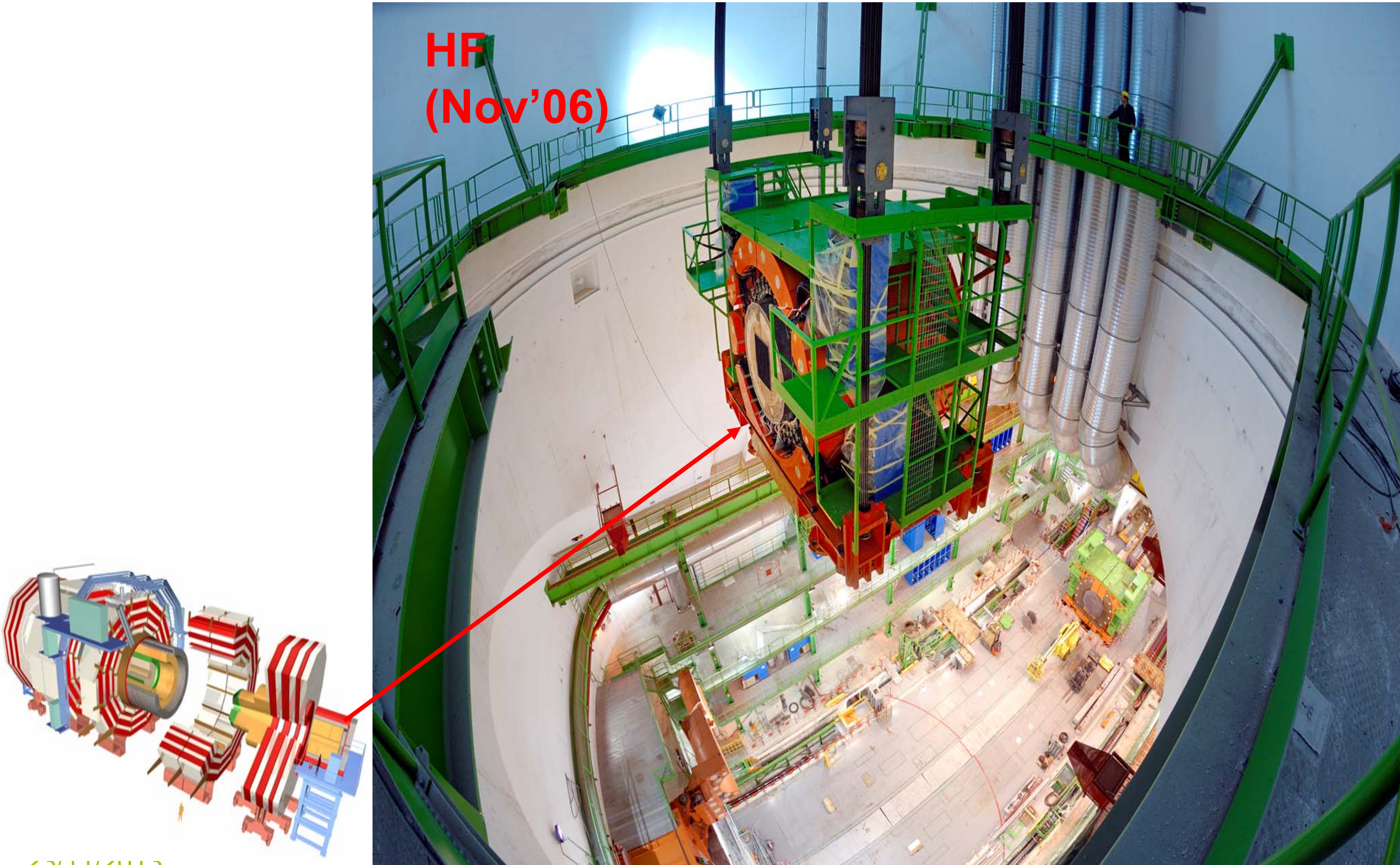
Experiment Cavern

2003

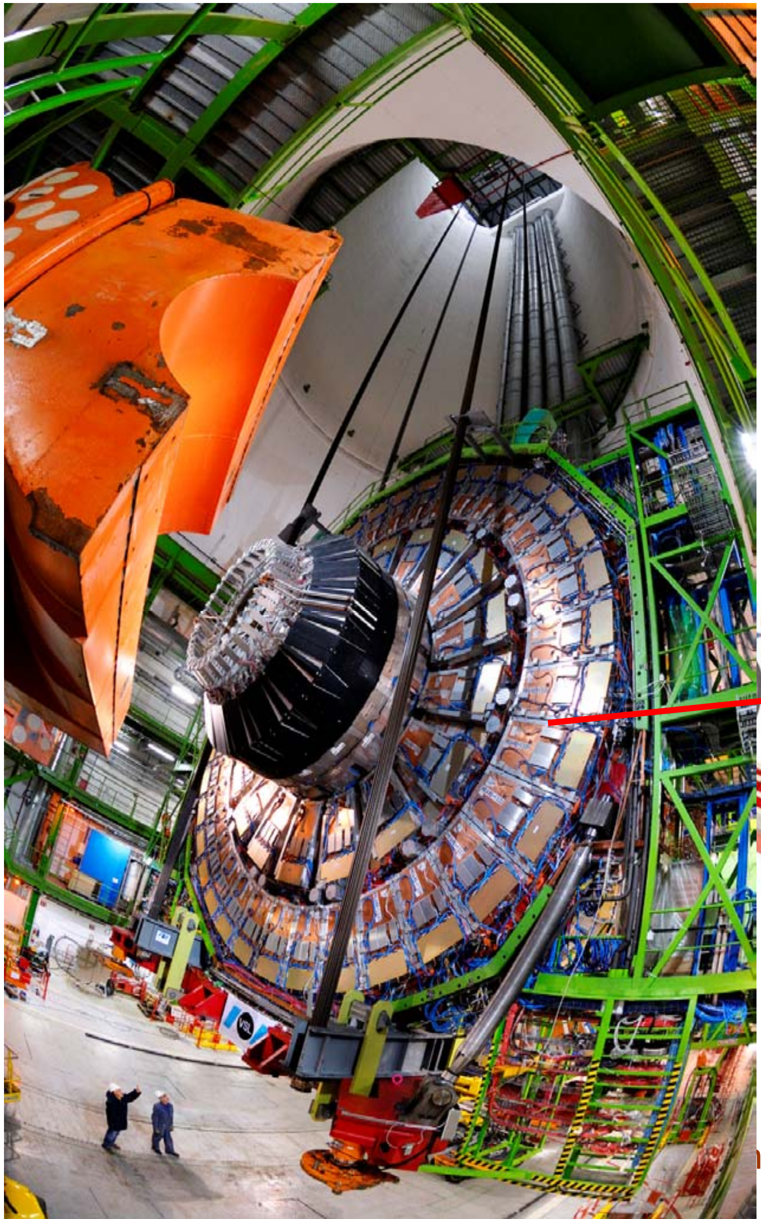
2004

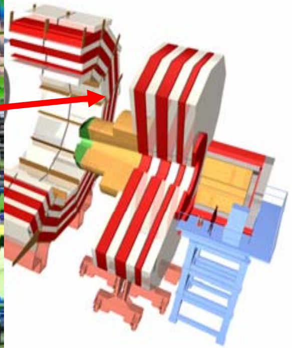


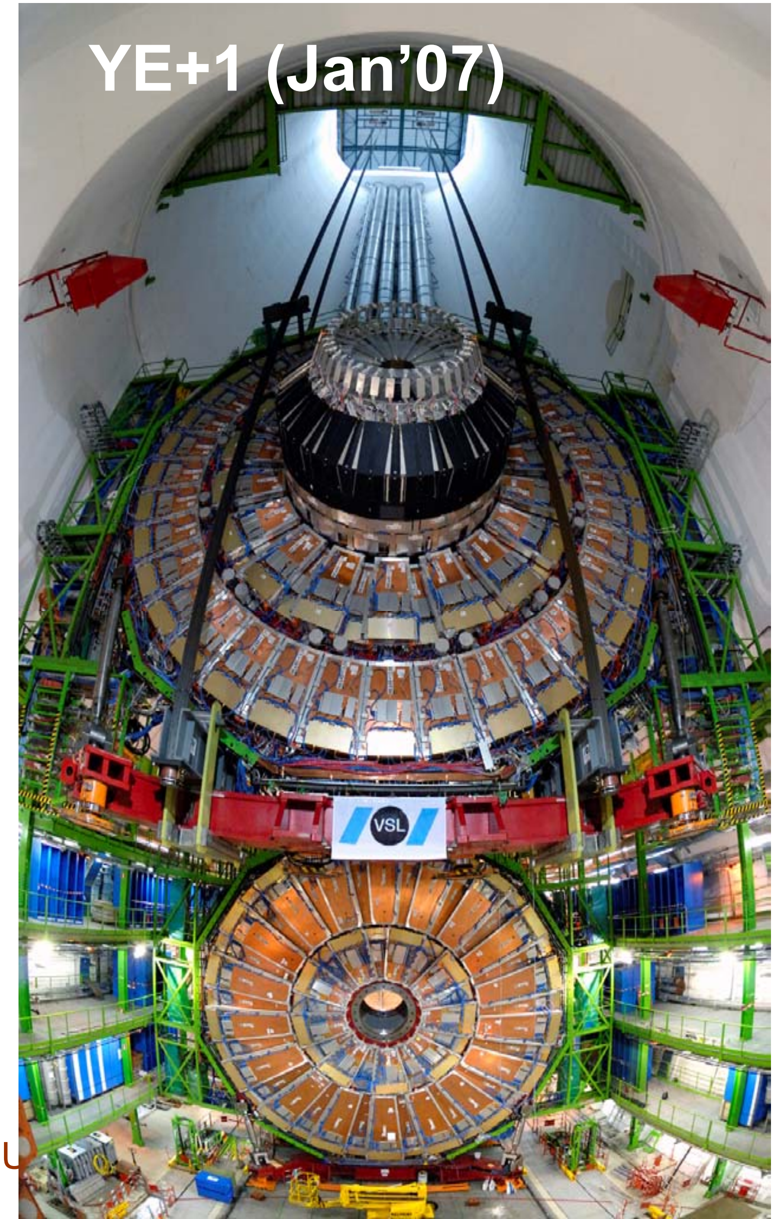
Lowering of the First Element



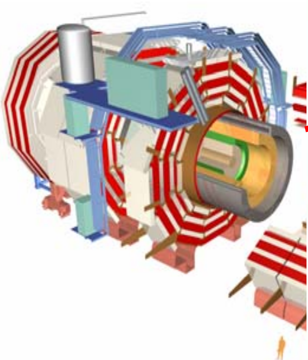
Lowering of Heavy Elements

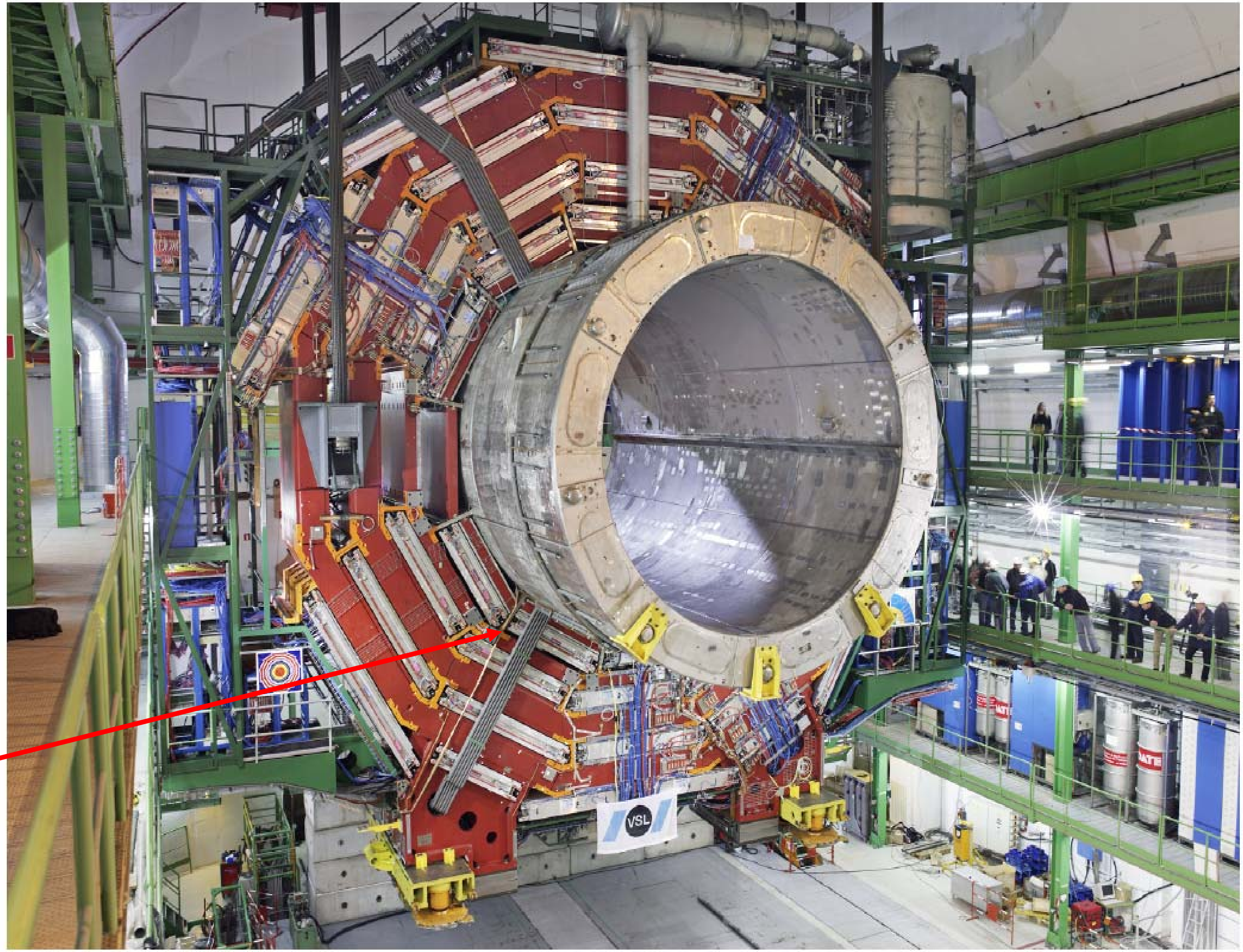






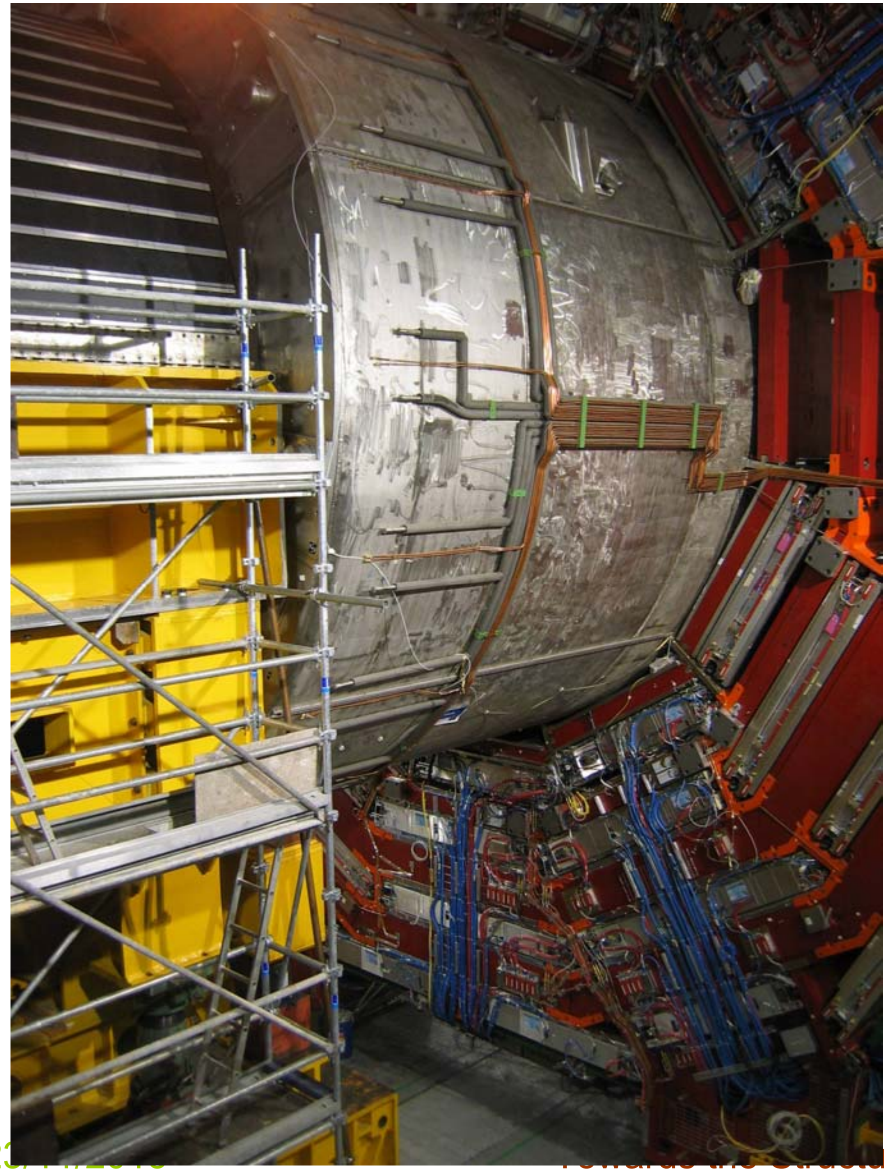
Lowering of Heavy Elements

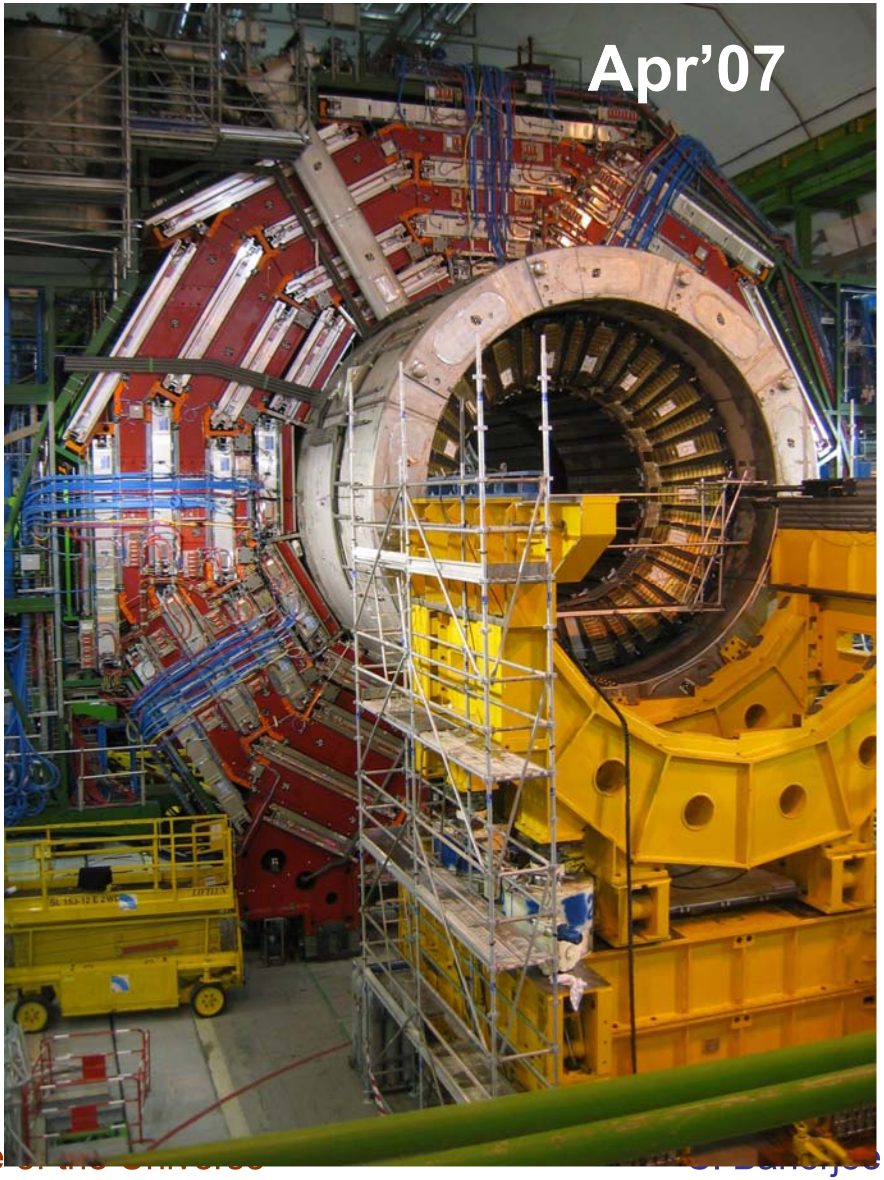




YB0 landing in the CMS experiment hall

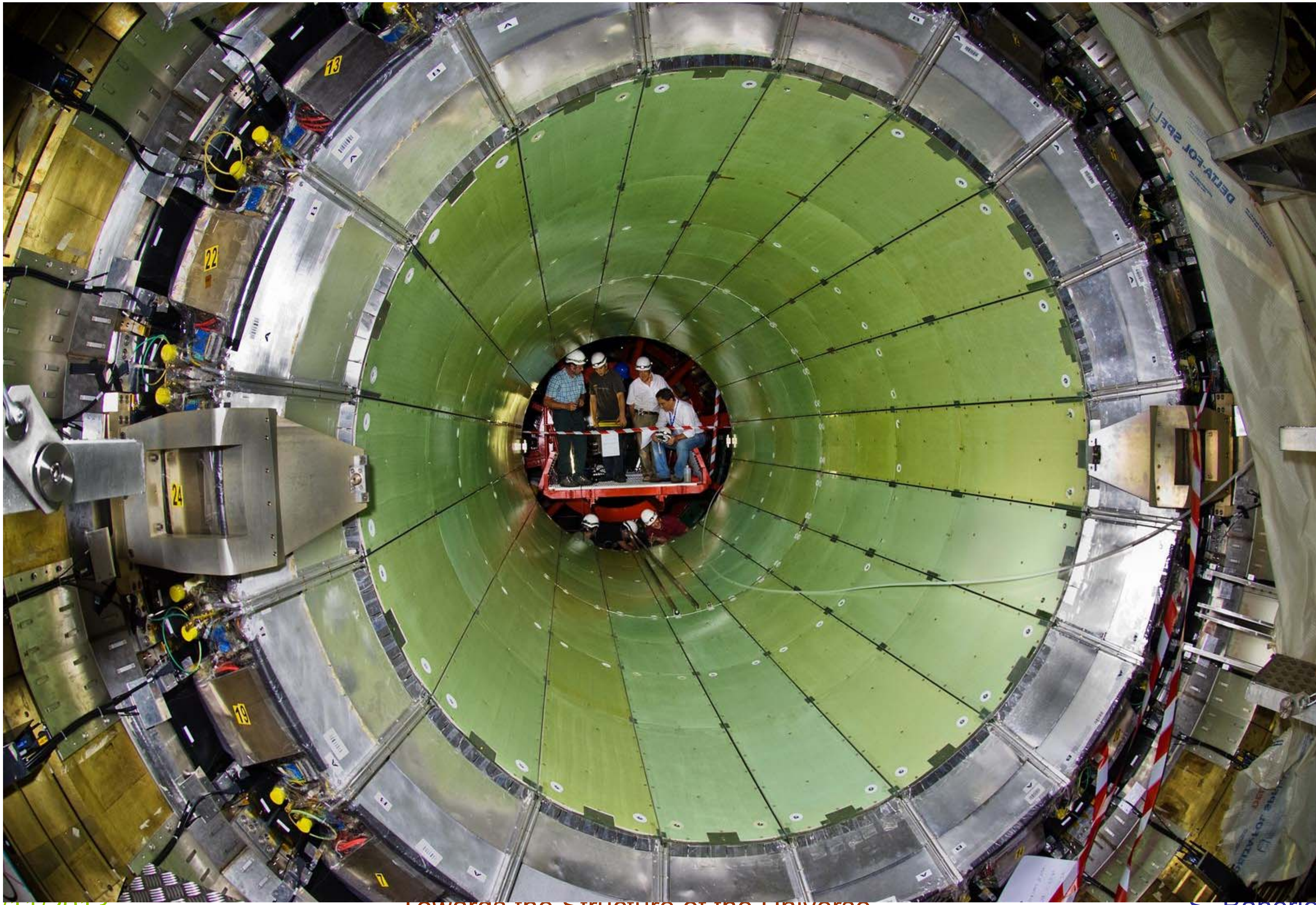
Insertion of HCAL Barrel



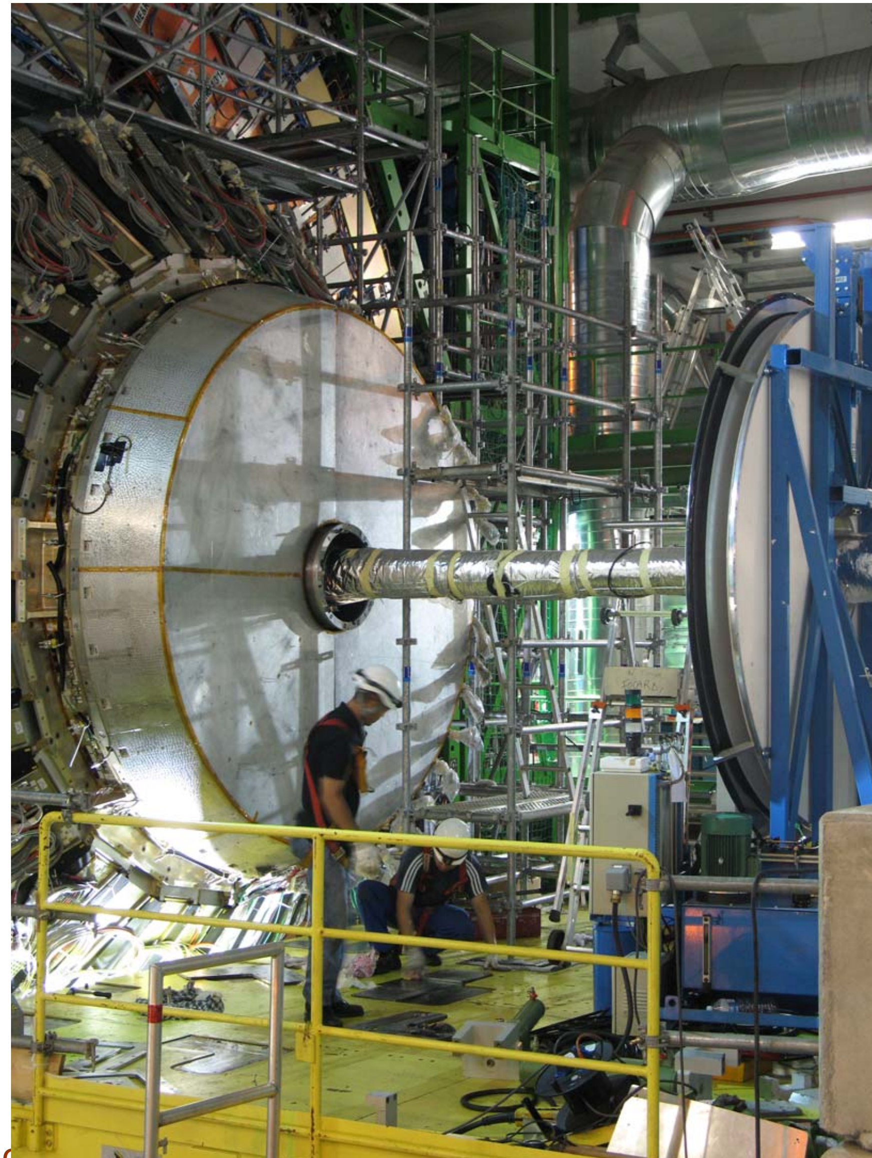


Insertion of Barrel ECAL

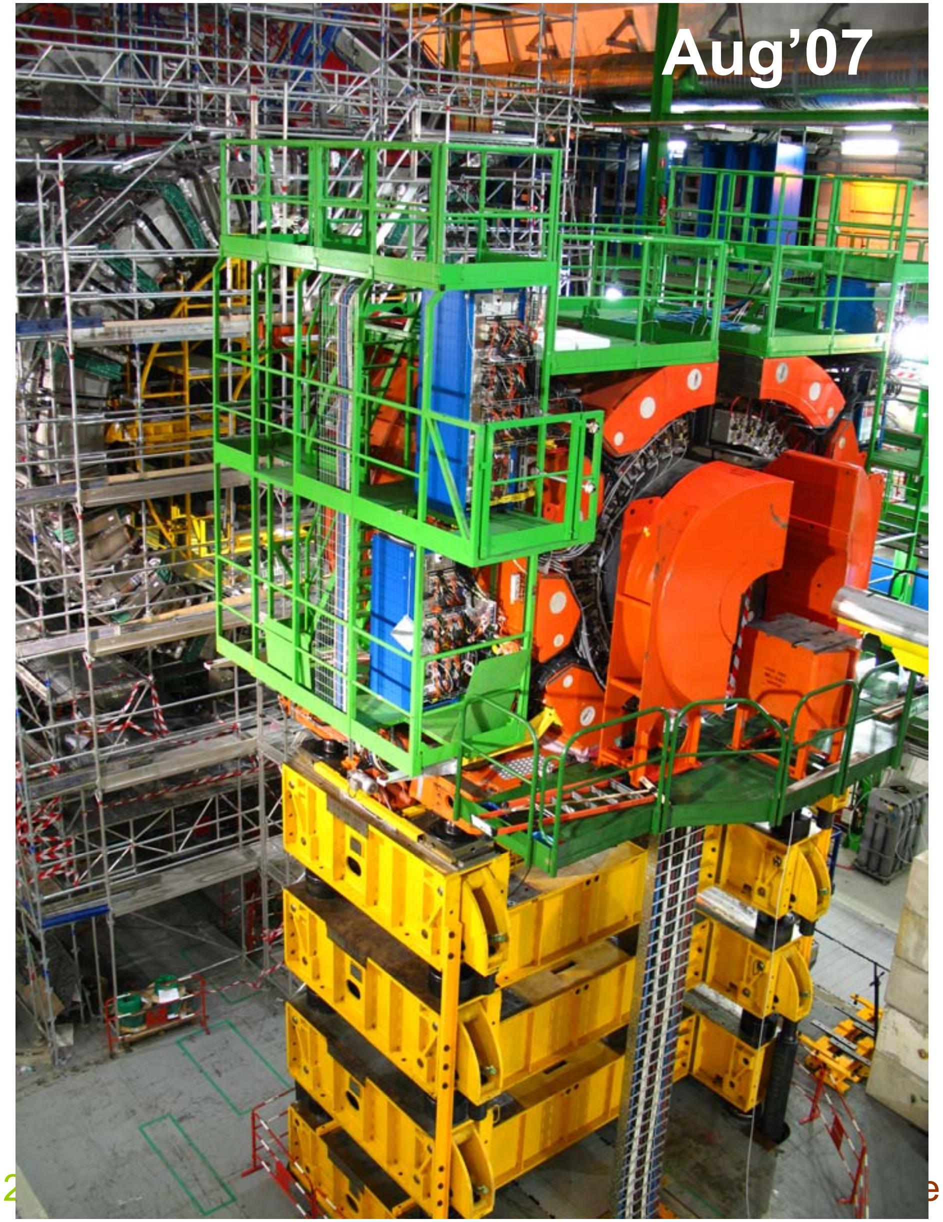
Barrel ECAL

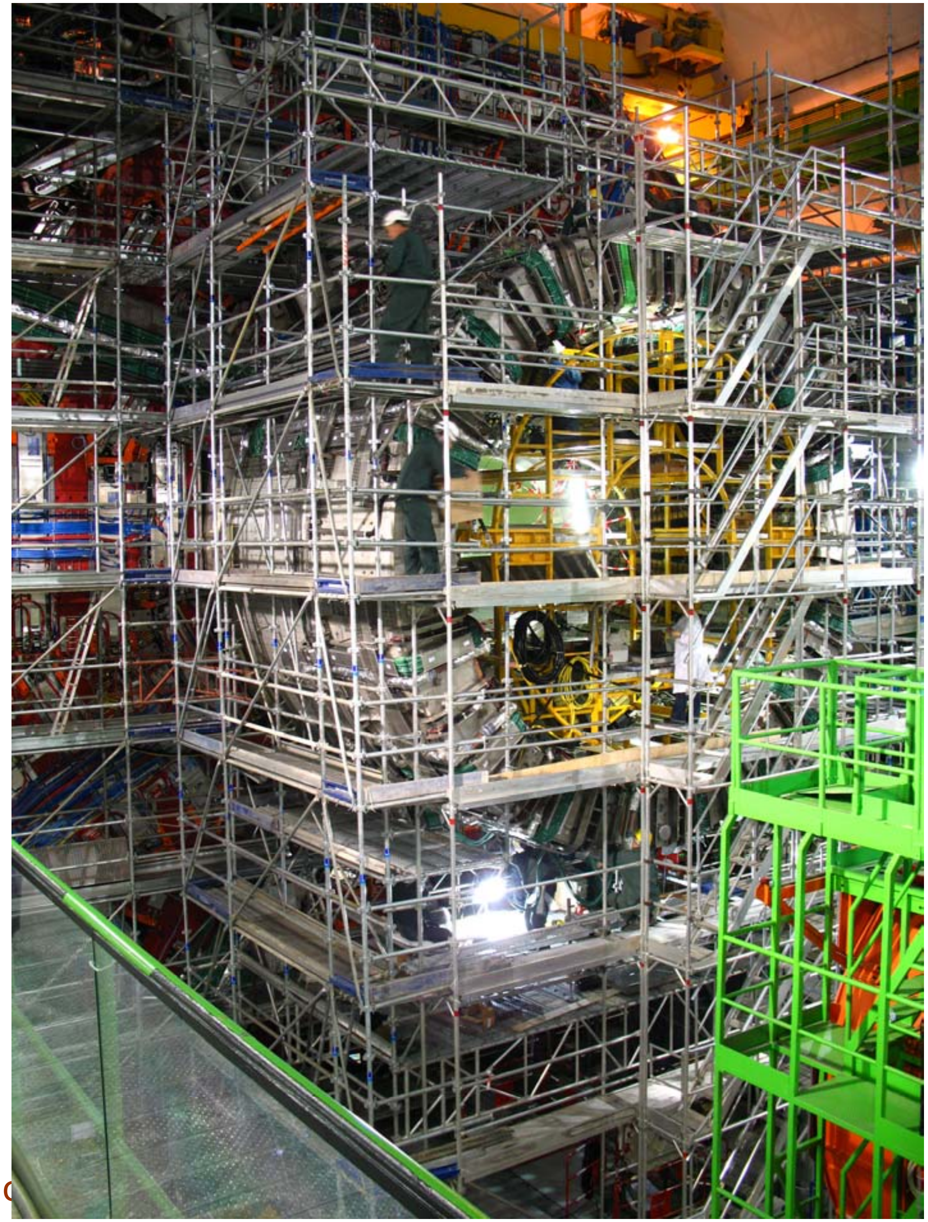


Endcap ECAL



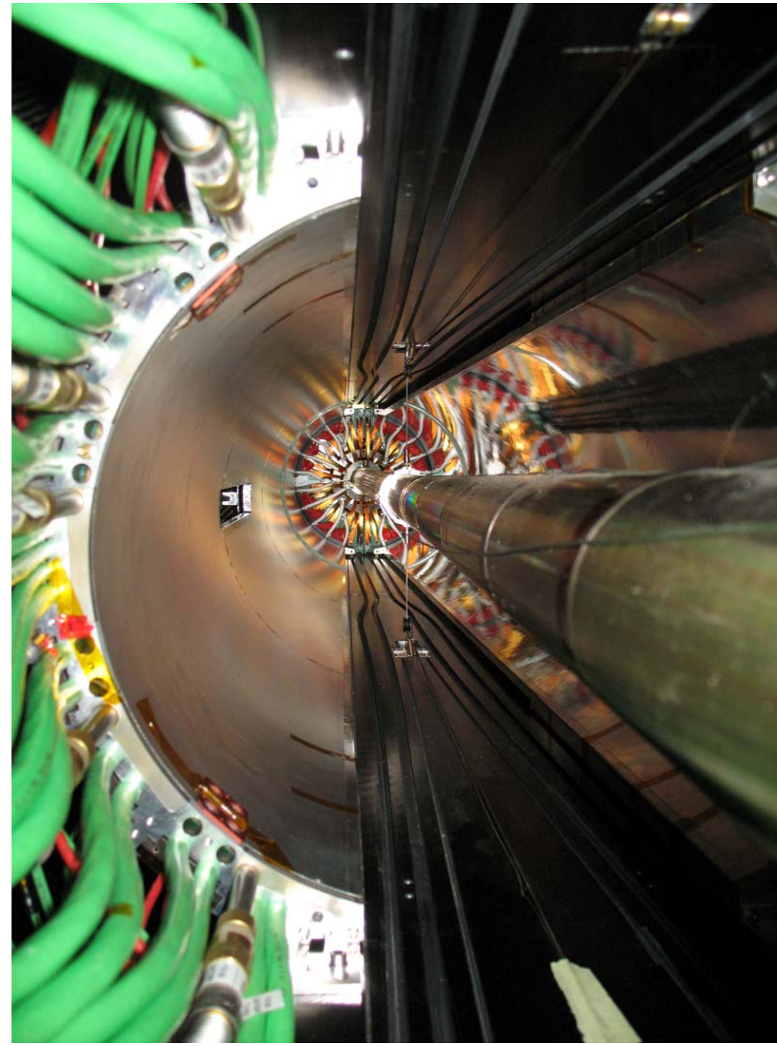
Raising of HF & YB0 Services



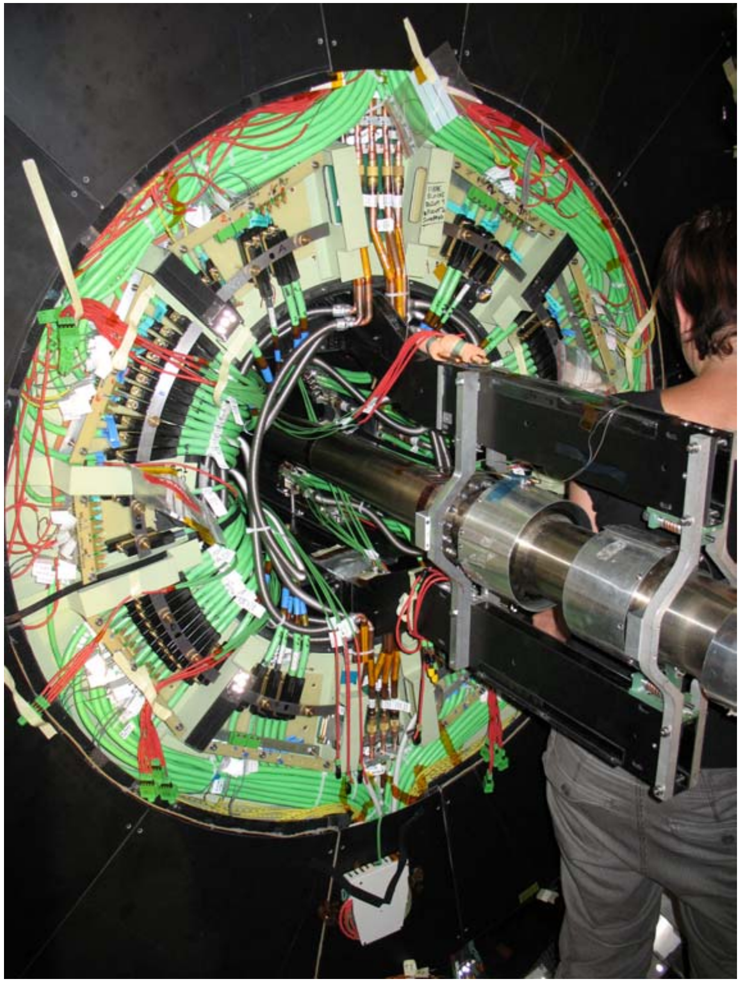


Tracker Delivered to Point 5

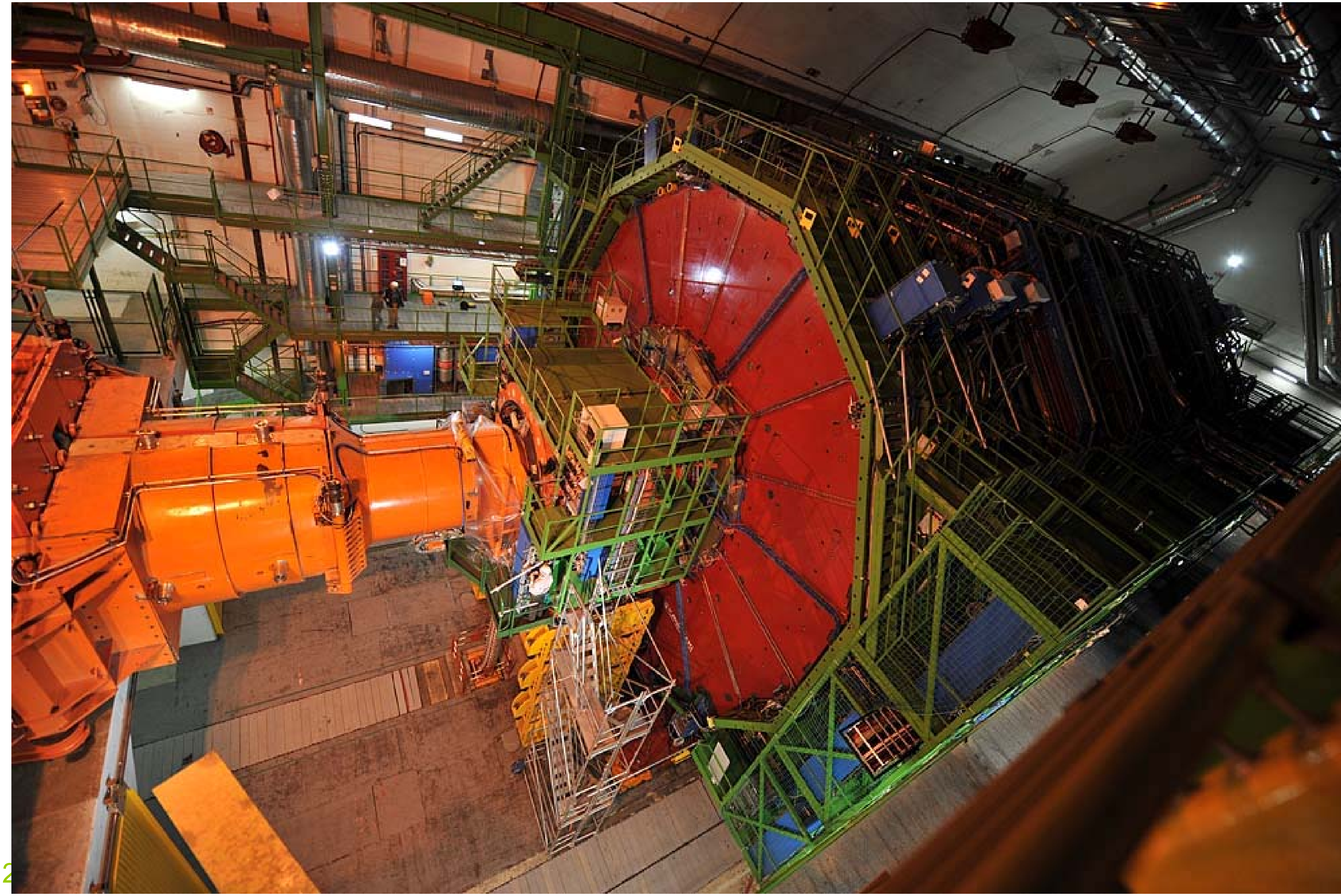
Barrel Pixels



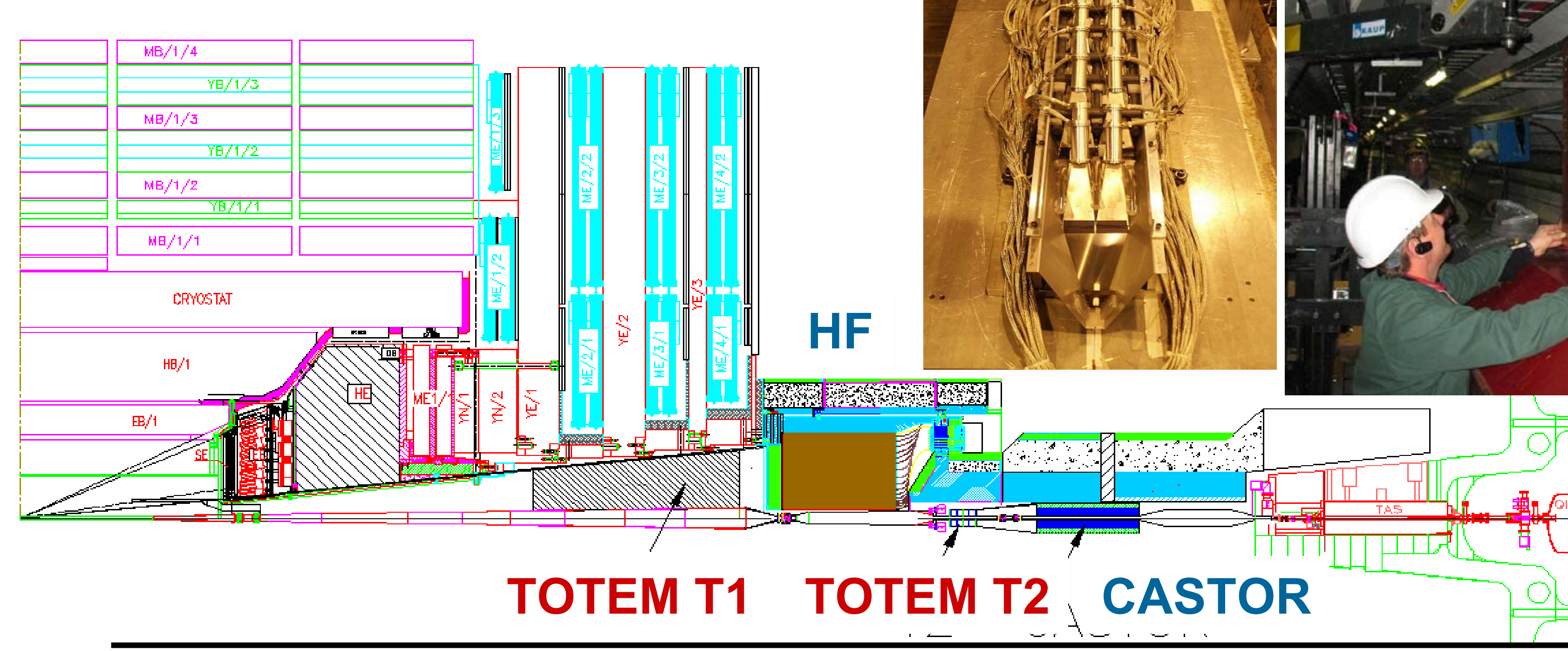
Forward Pixels

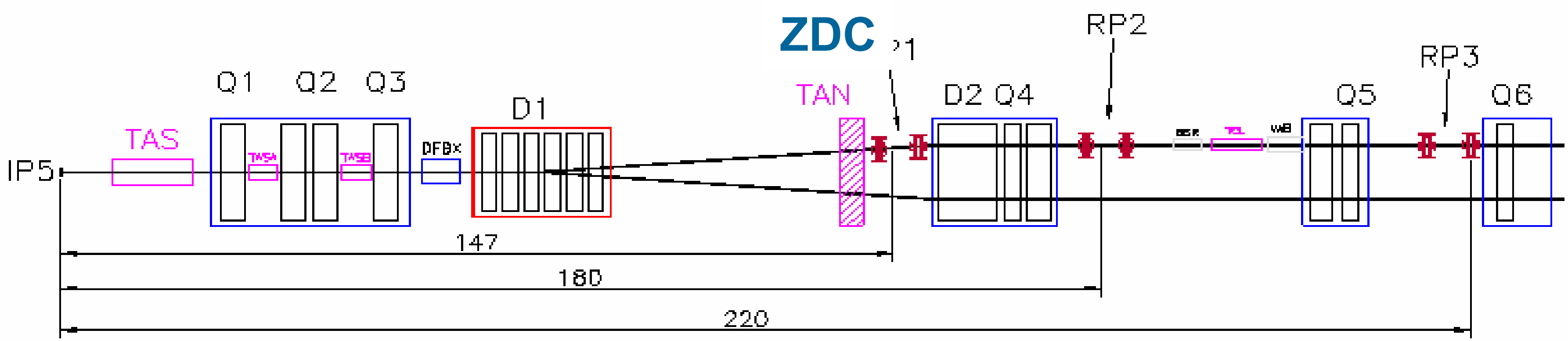


Final Closure



Forward Region + TOTEM

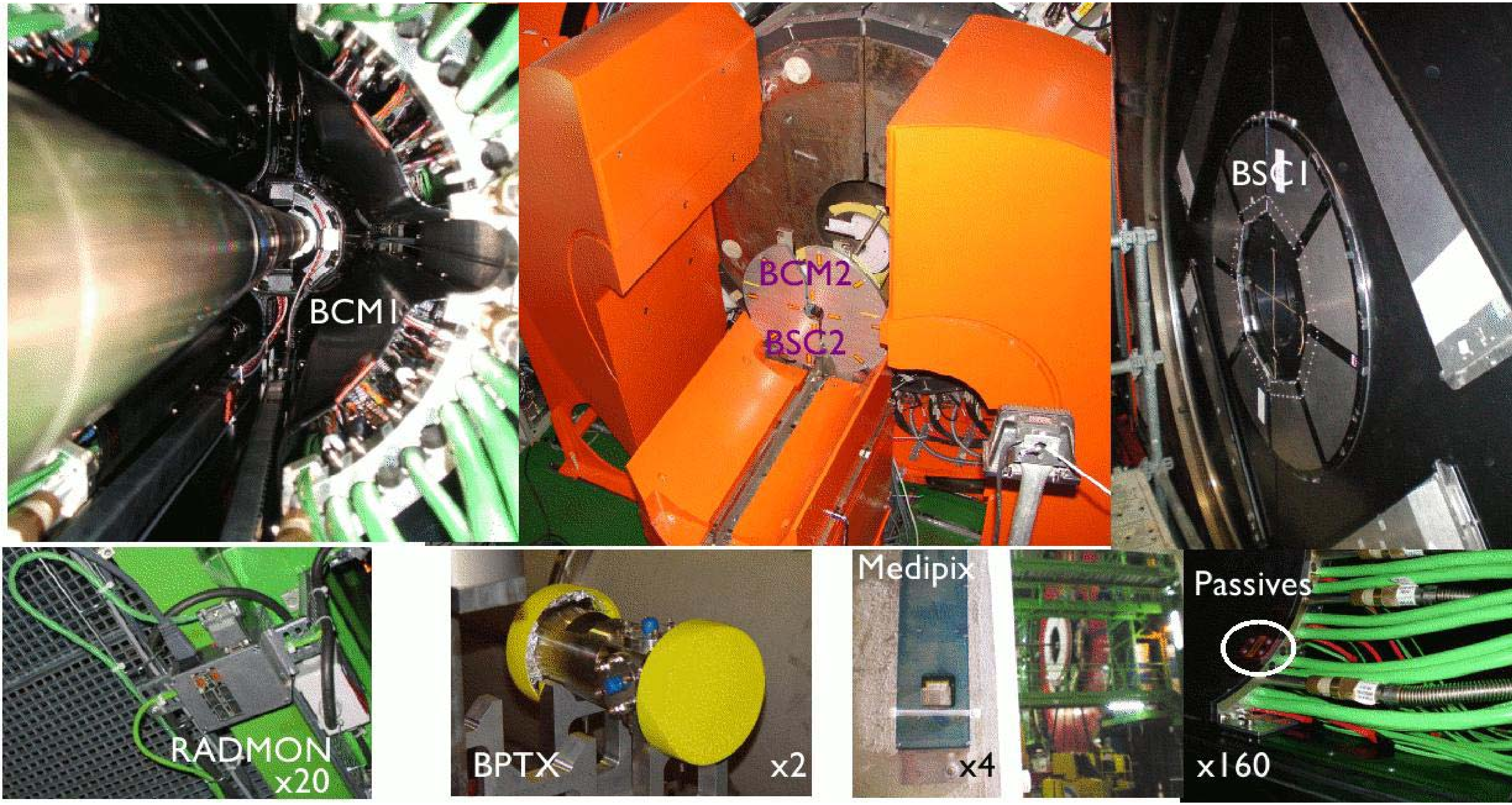




TOTEM ROMAN POT 1 (147 m)

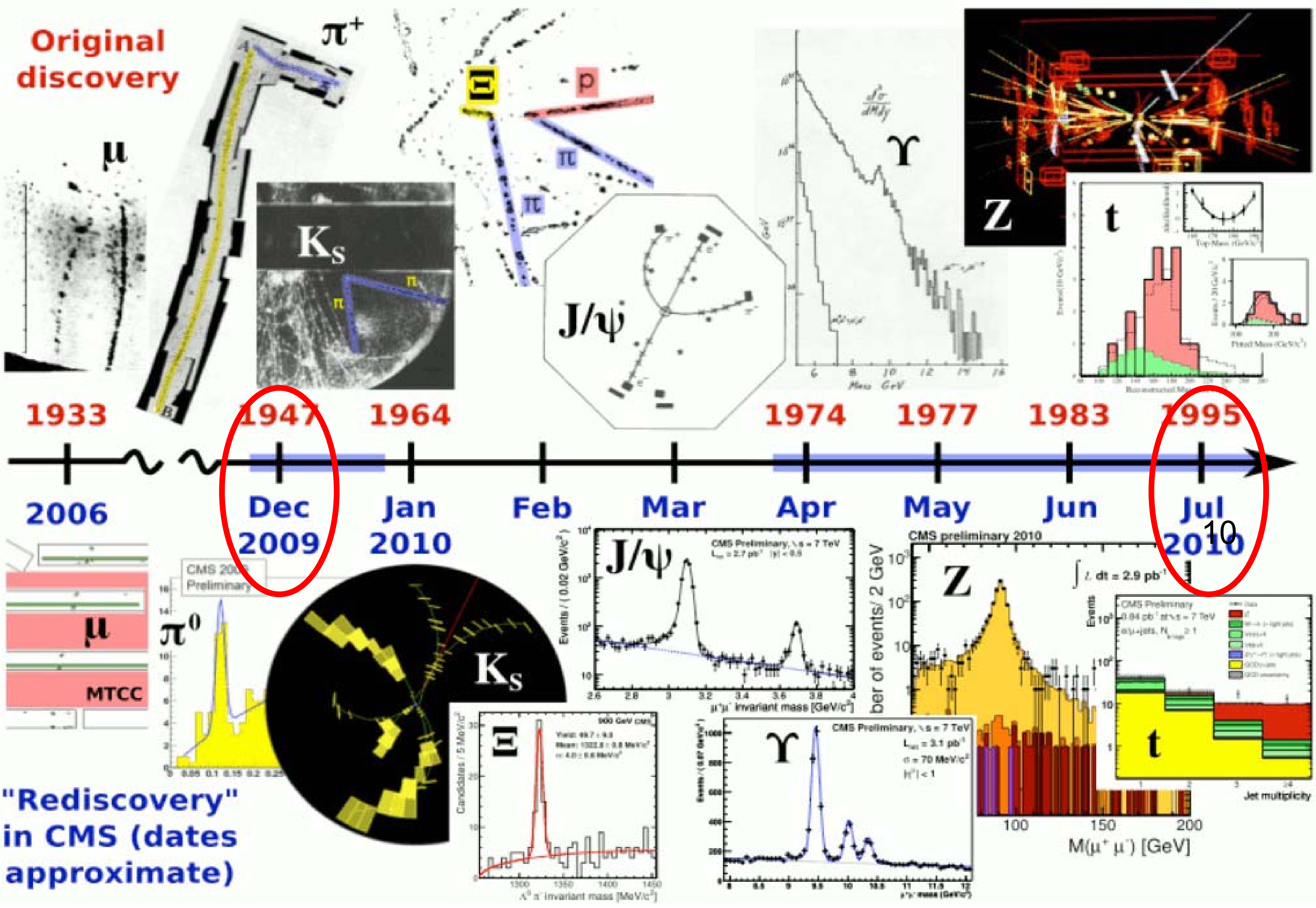
TOTEM ROMAN POT 3 (220 m)

Trigger Counters in Reality

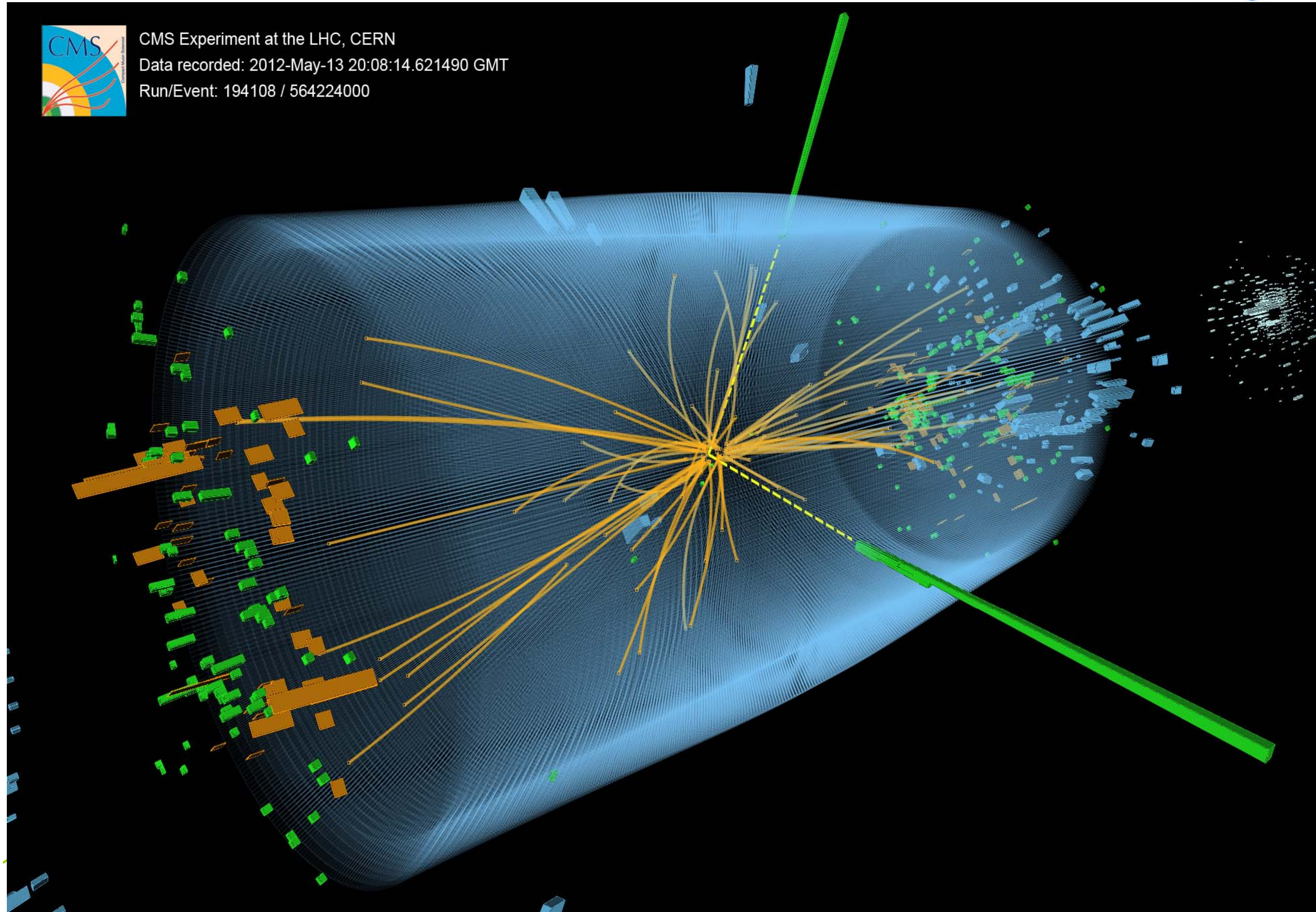


- These counters trigger if beam goes through and there is some activity in the interaction region

Understand the Detector



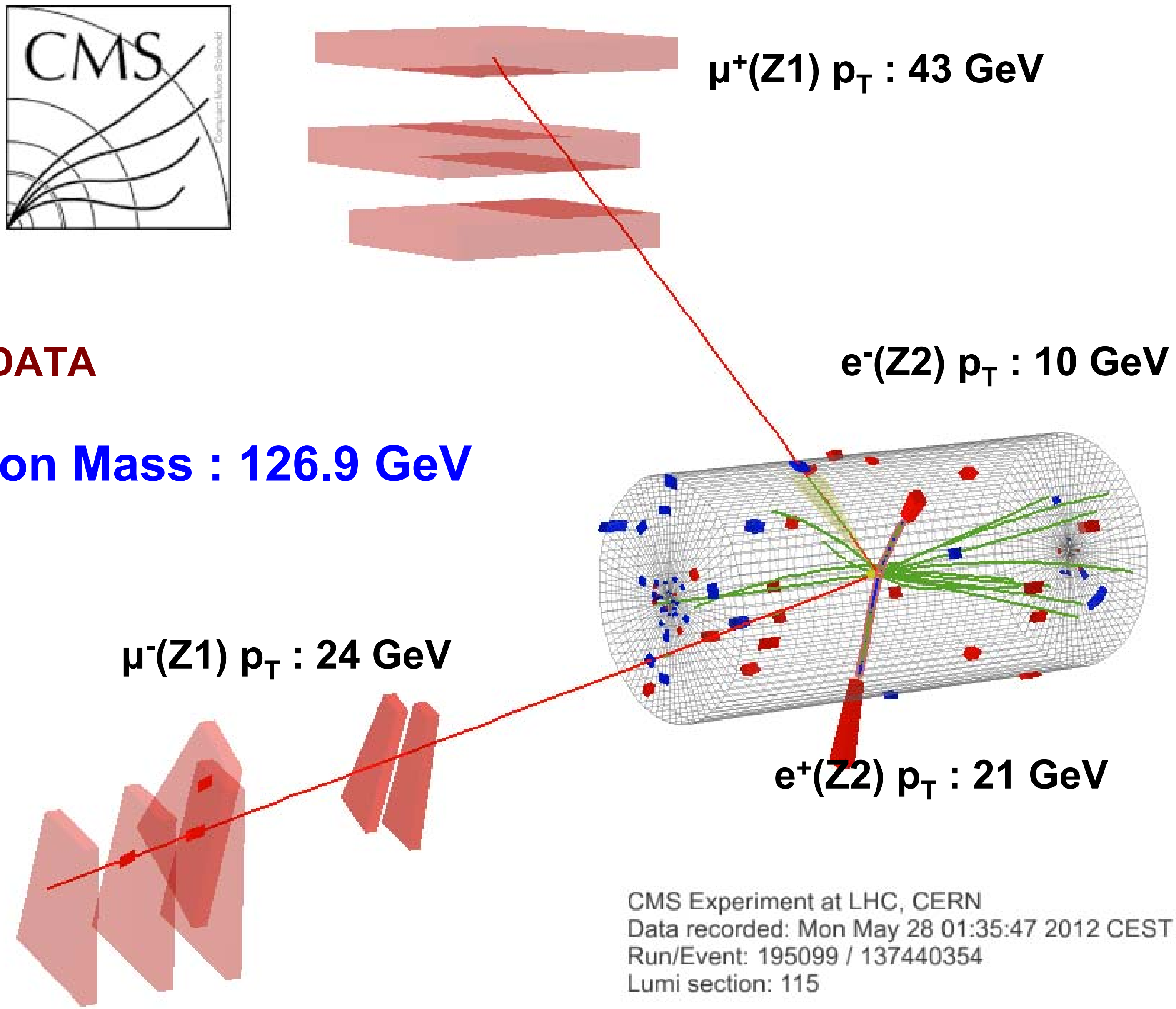
Candidate event (H→γγ)



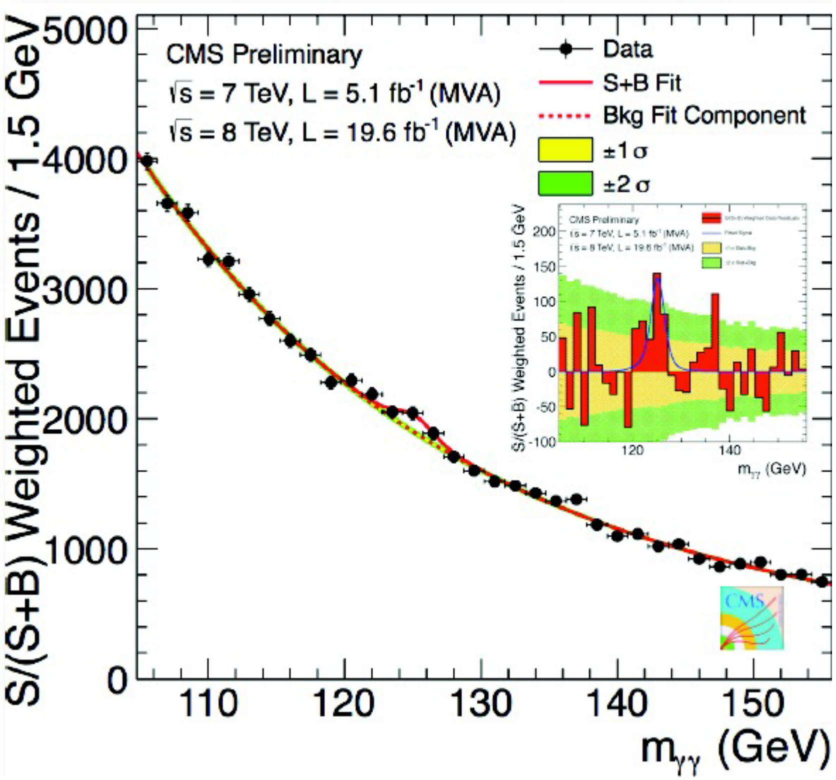
Candidate event ($H \rightarrow ZZ^{(*)} \rightarrow 2e+2\mu$)

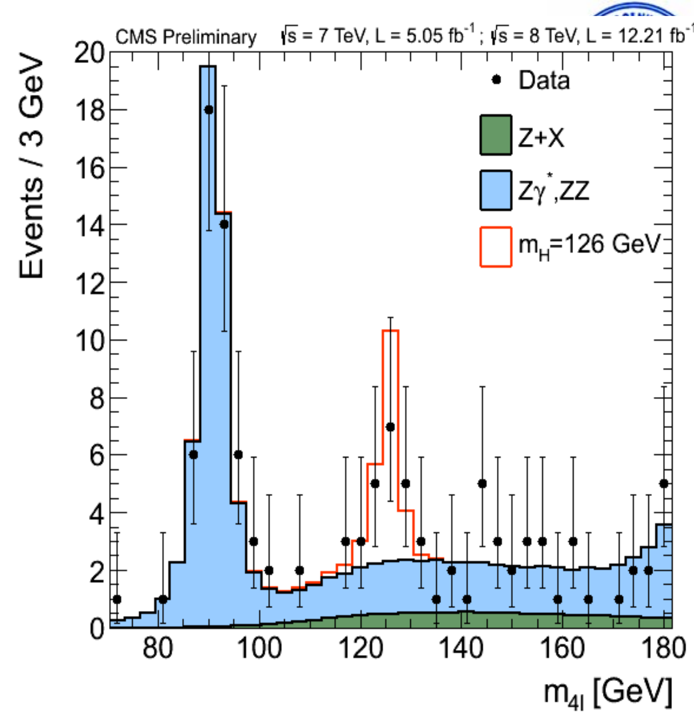
8 TeV DATA

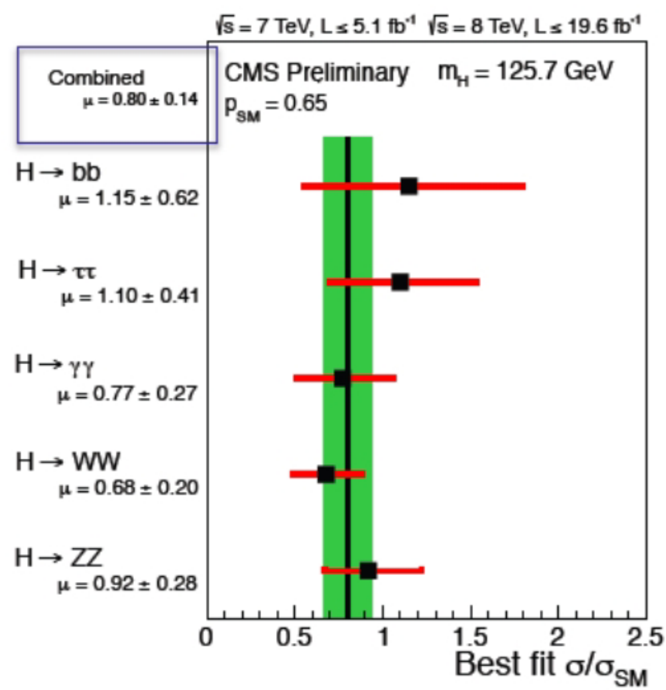
4-lepton Mass : 126.9 GeV



Results







- CMS observes in July 2012:
  - Excess in 4 different channels at 125.3 GeV
  - Level of fluctuation at 5.0-5.1 σ CL (3×10^{-7})
- By end of 2012 it could establish:
  - It is a scalar boson
  - Compatible to Higgs boson in SM