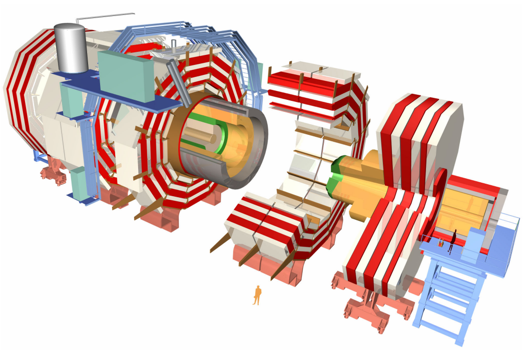
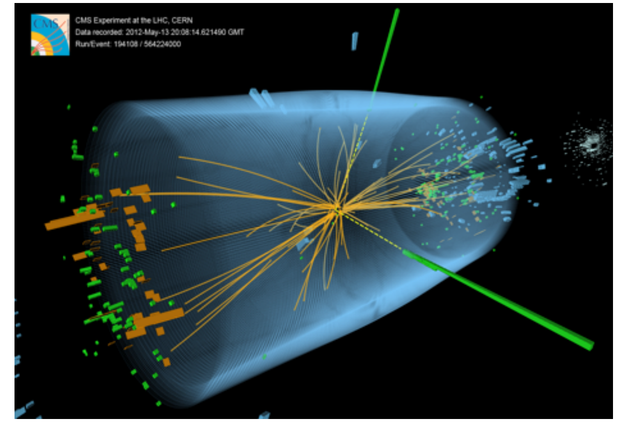




Introduction to CMS

24 October 2014

University of Bristol
Brunel University
Imperial College London
Rutherford Appleton Laboratory

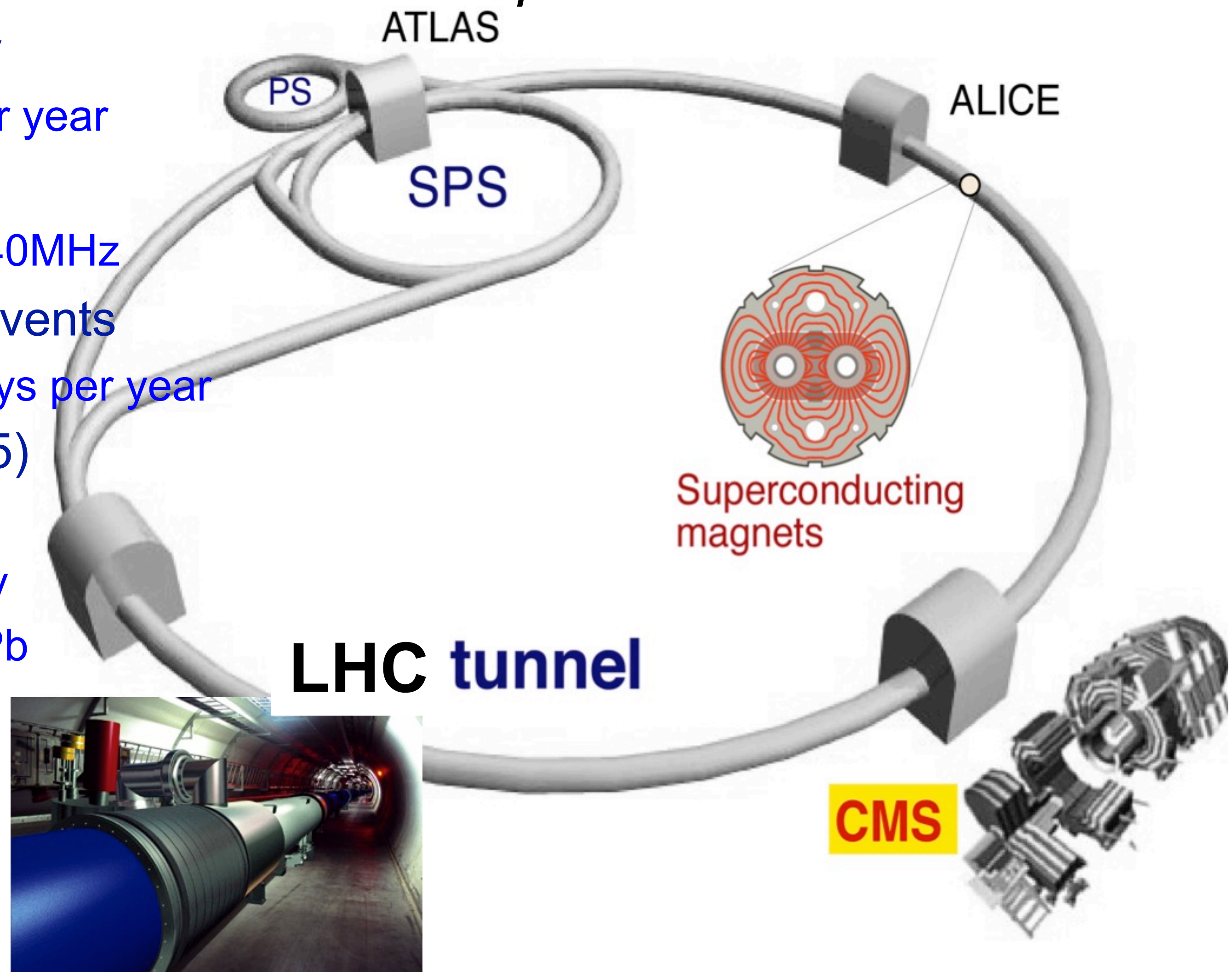
Geoff Hall

Content

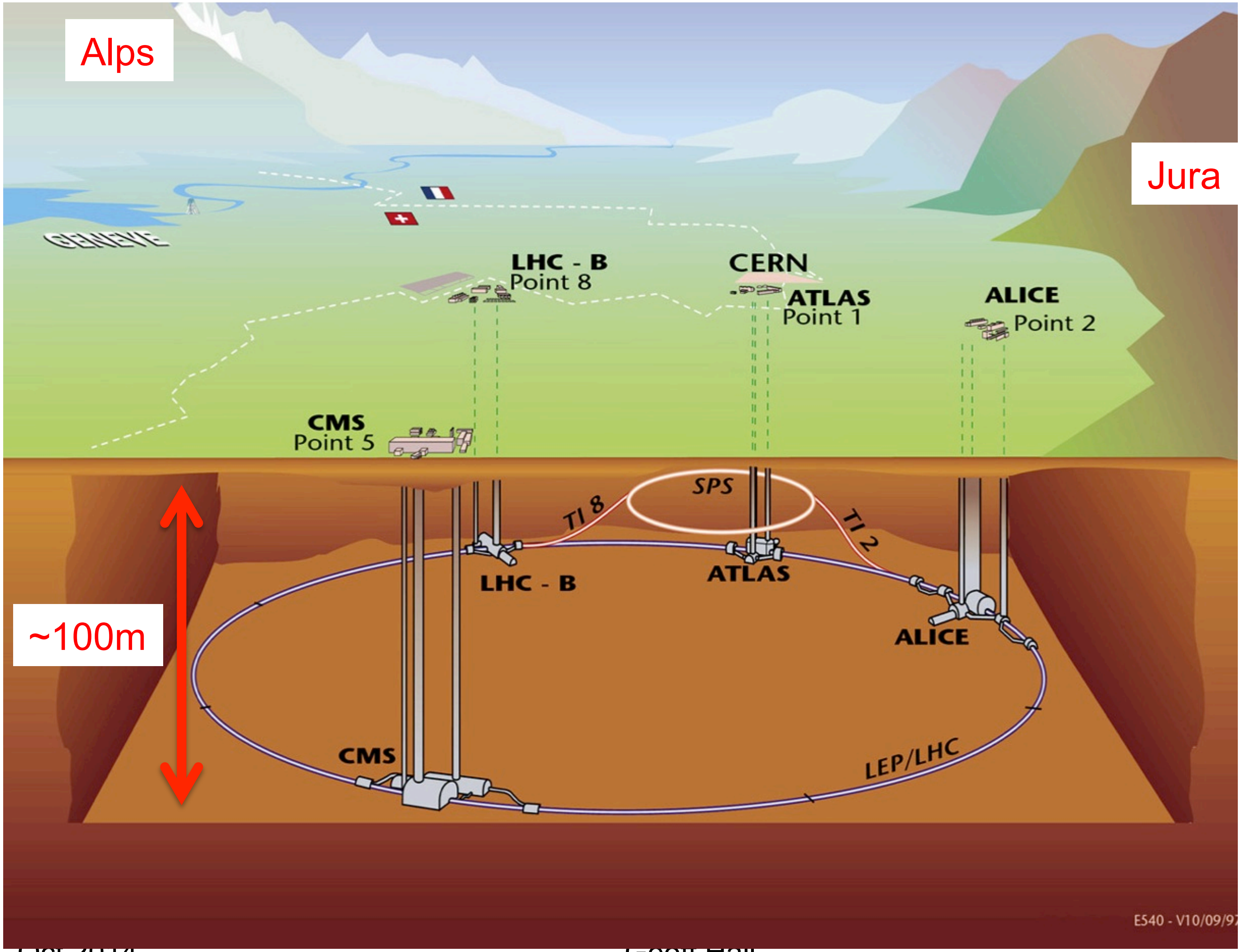
- I know that few in the audience are physicists
  - so I plan to give only an elementary introduction to the experiment
- Main objectives and experimental requirements
  - illustrations of some of the items built
- Brief history of development and construction
- Focus on objects which have been constructed and purchased
  - hope to provide some insight into opportunities for business
- To be supplemented later by a few more details on electronic procurements
  - in a separate session

What is the Large Hadron Collider?

- Latest CERN accelerator *started operation 2010*
  - very high intensity
    - 10^{15} collisions per year
  - very high rate
    - beams cross @ 40MHz
  - few “interesting” events
    - ~100 Higgs decays per year
  - Beams (from 2015)
    - 6.5 TeV protons
    - => 13 TeV energy
      - also ions, eg Pb



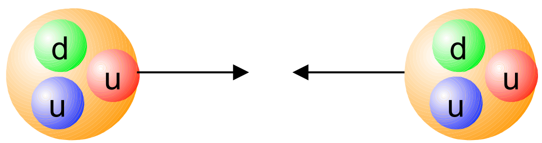
Where is the LHC?



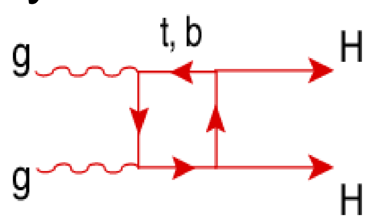
(No more physics after this slide!)

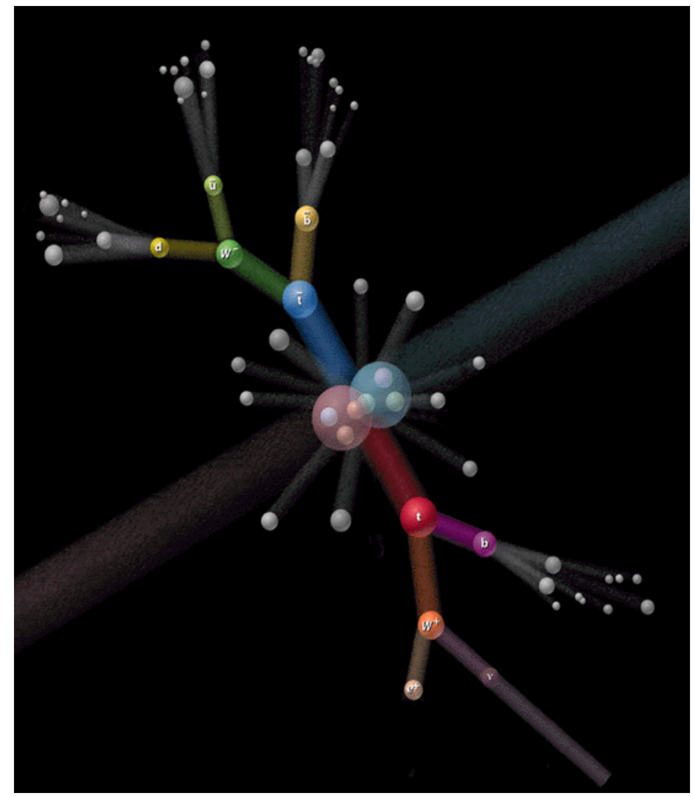
What are we doing at the LHC?

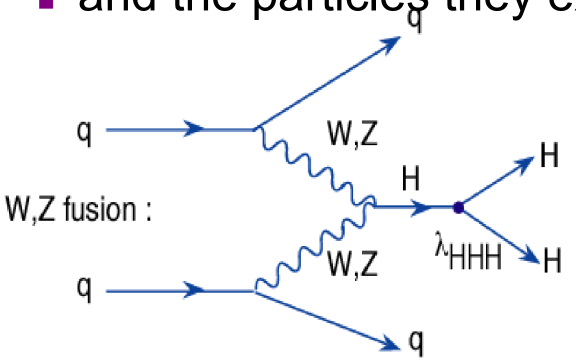
- Colliding beams of protons
  - to maximise the energy available to create new particles

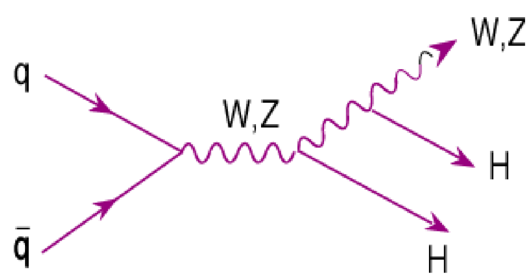
proton  proton

- proton collisions are actually between their constituent parts…
  - $\lambda \sim 1/p \approx 1/E$
- gluons
- quarks (≈ real and virtual)
- and the particles they exchange (Z, W,…)









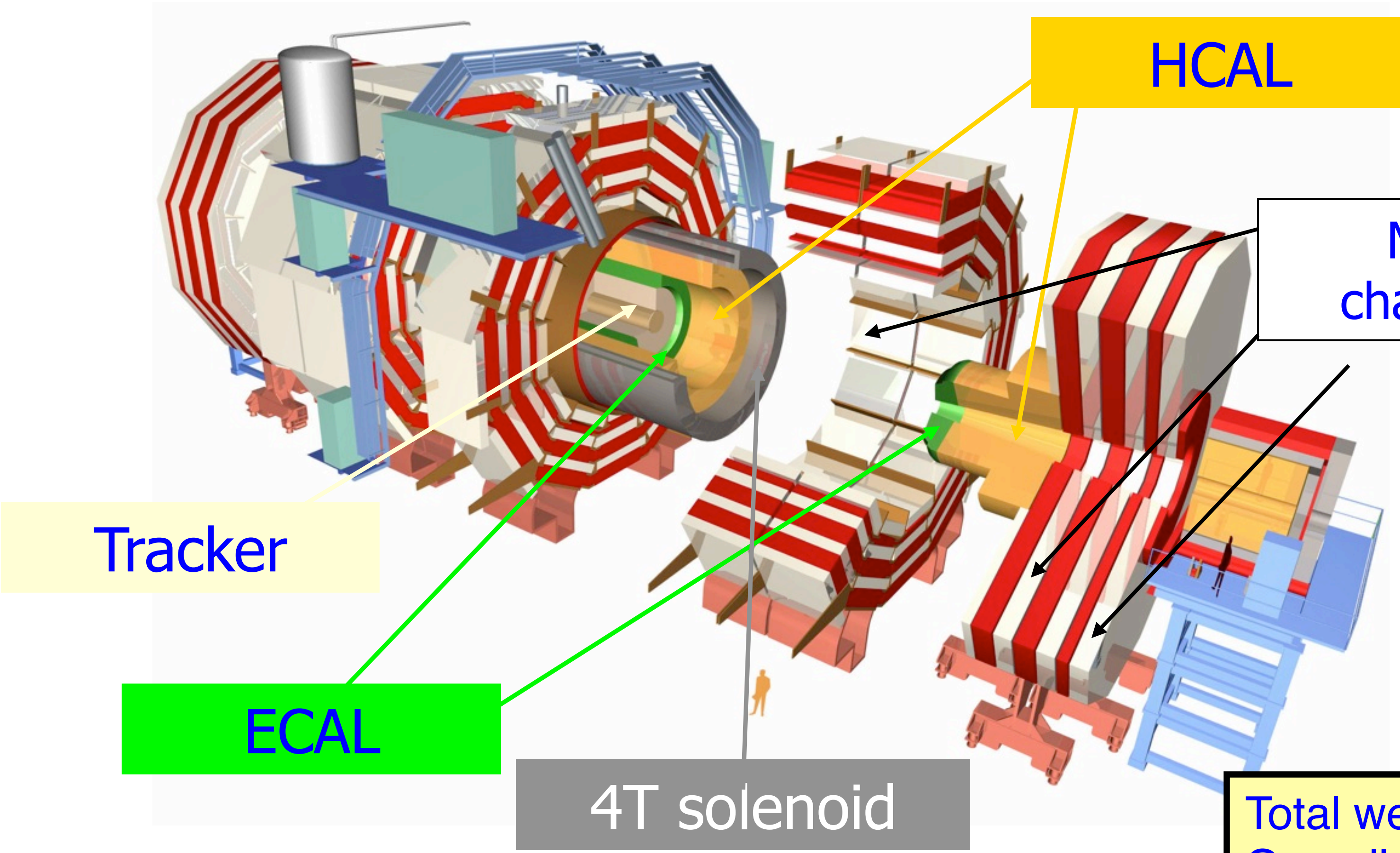
The Compact Muon Solenoid experiment

- a <u>general purpose detector</u> for studying the full range of physics at the CERN Large Hadron Collider
  - designed to operate (nominally) for 10 years
  - high radiation levels throughout the experiment
  - they originate with flux of particles originating from the p-p collisions
    - so highest in centre and endcap regions
  - also operate with heavy ions: ~ 1 month annually

R [cm]	Fast hadron fluence [cm^{-2}]	Dose [kGy]	Dose [Mrad]
4.3	246 10^{13}	830	83
22	16 10^{13}	67	6.7
115	2 10^{13}	2	0.2

Suffice to say, these are very high and comparable with nuclear reactor interiors

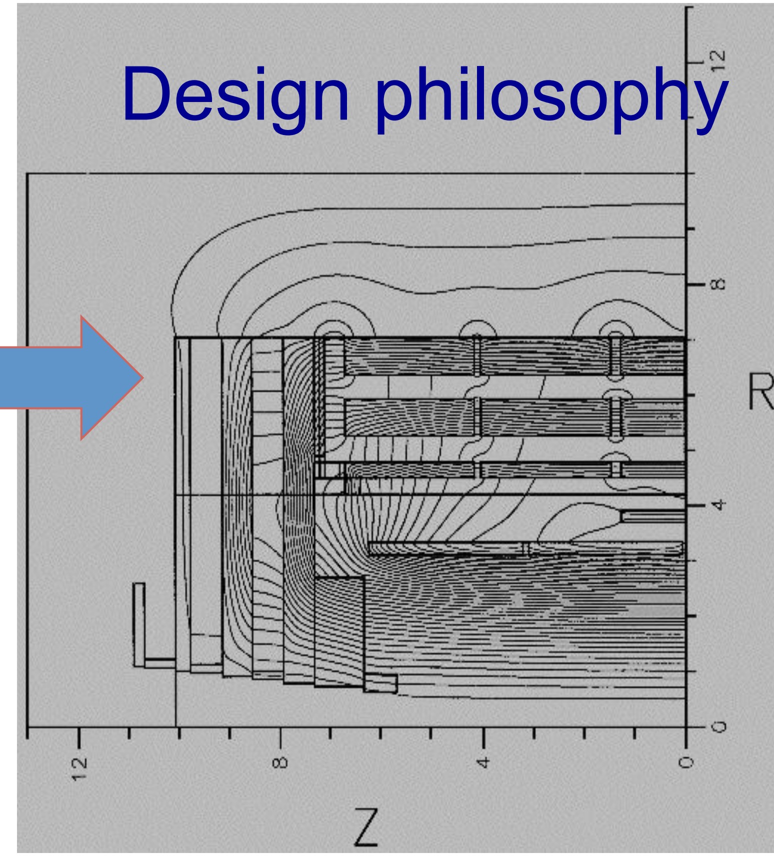
CMS: Compact Muon Solenoid



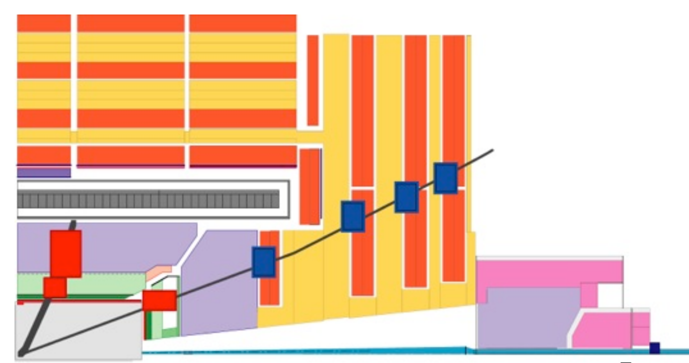
Total weight: 12,500 t
Overall diameter: 15 m
Overall length 21.6 m
Magnetic field 4 T

constructed as a series of layered sub-detectors, each with a specific purpose

Design philosophy

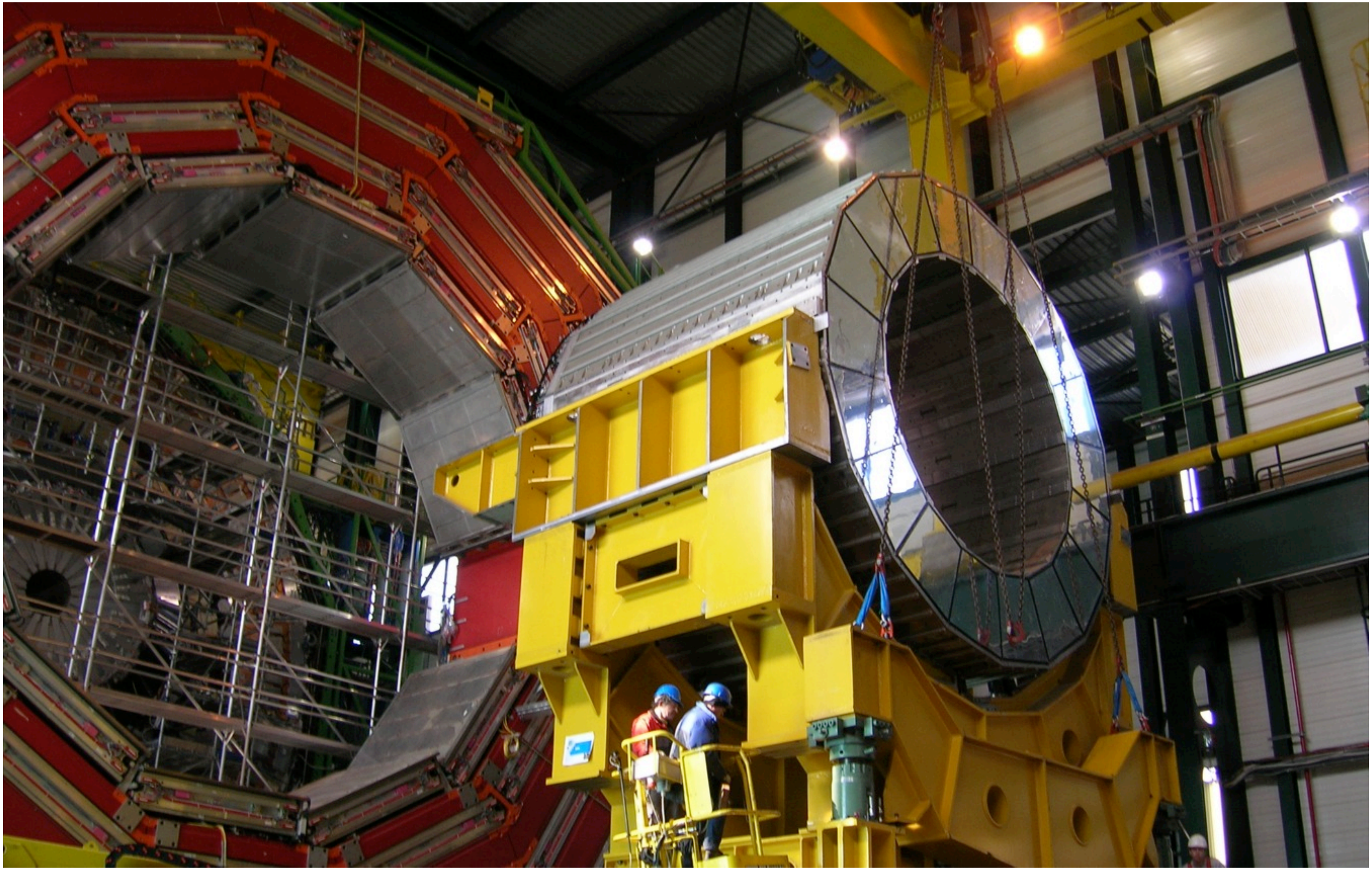


- Large solenoidal (4T) magnet
  - iron yoke - returns B field, absorbs particles
- Muon detection - *penetration*
  - the only particles we can measure which traverse the whole detector
- Calorimeters – *absorb Energy*
  - electromagnetic – electrons and gammas
  - hadronic – all other types of particle
- Tracking system – *bend in B field*
  - momentum measurements of charged particles
  - complex, multi-particle events
  - complement muon & ECAL measurements

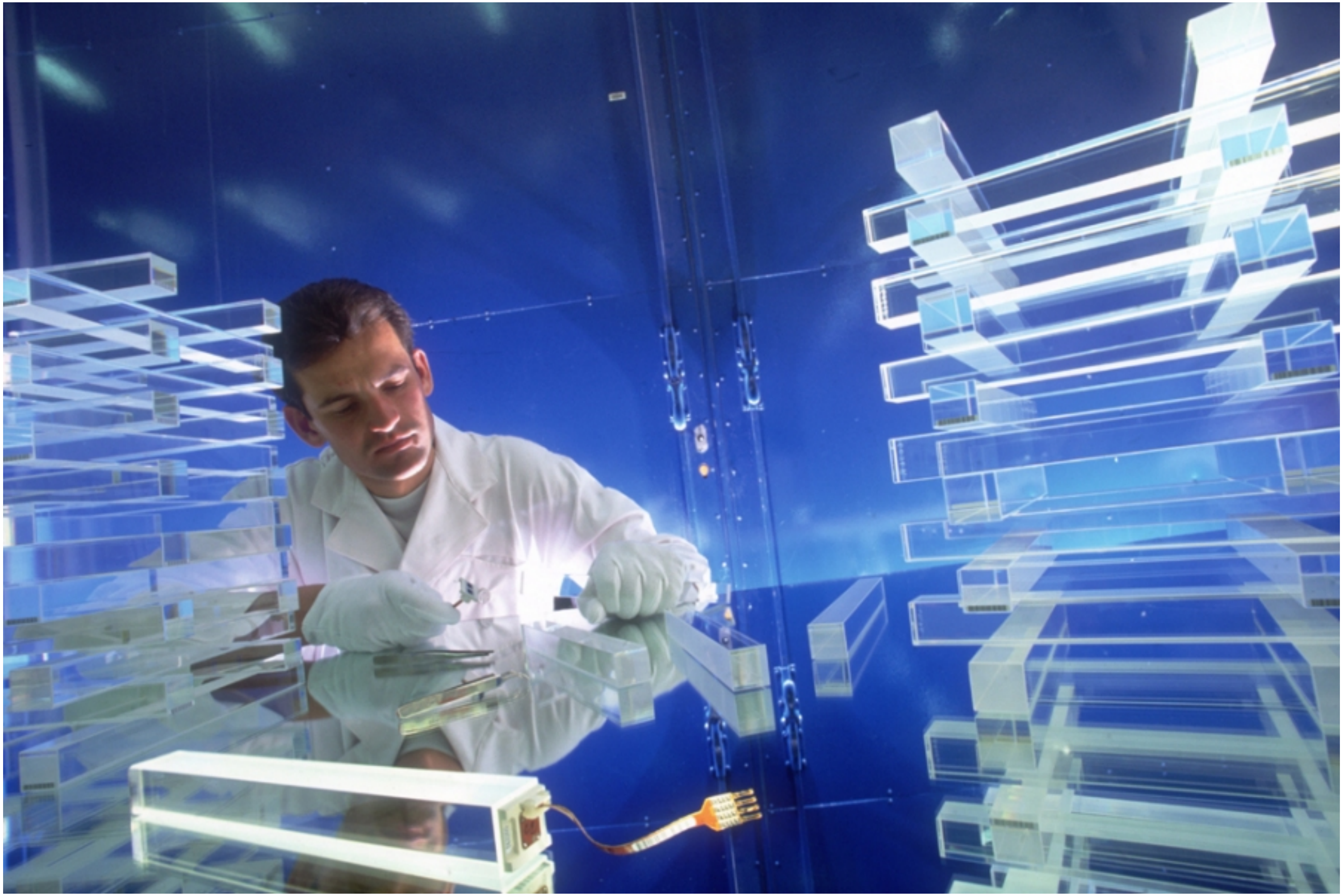


From a hole in the ground

Assembly on the surface

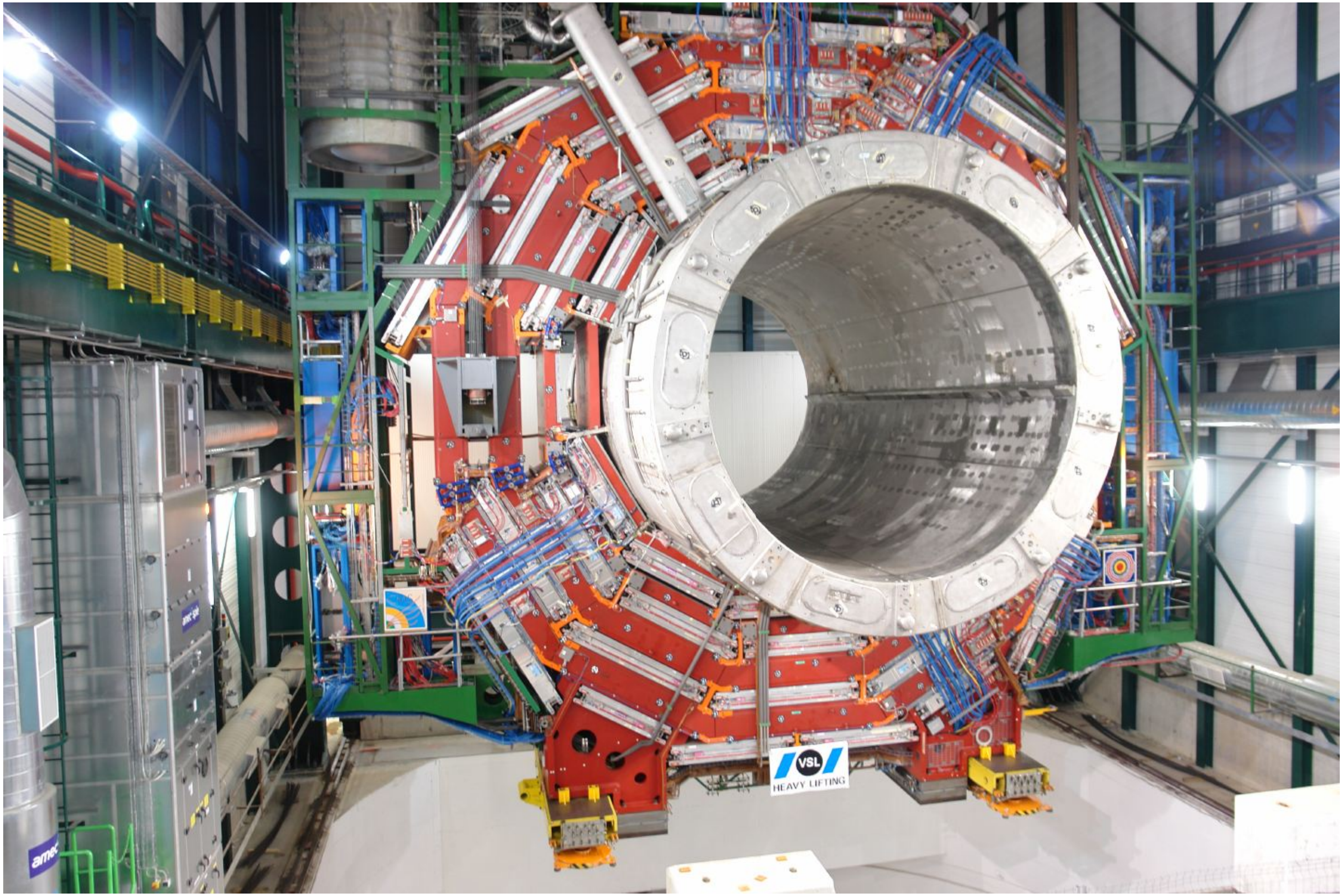


ECAL crystal scintillators

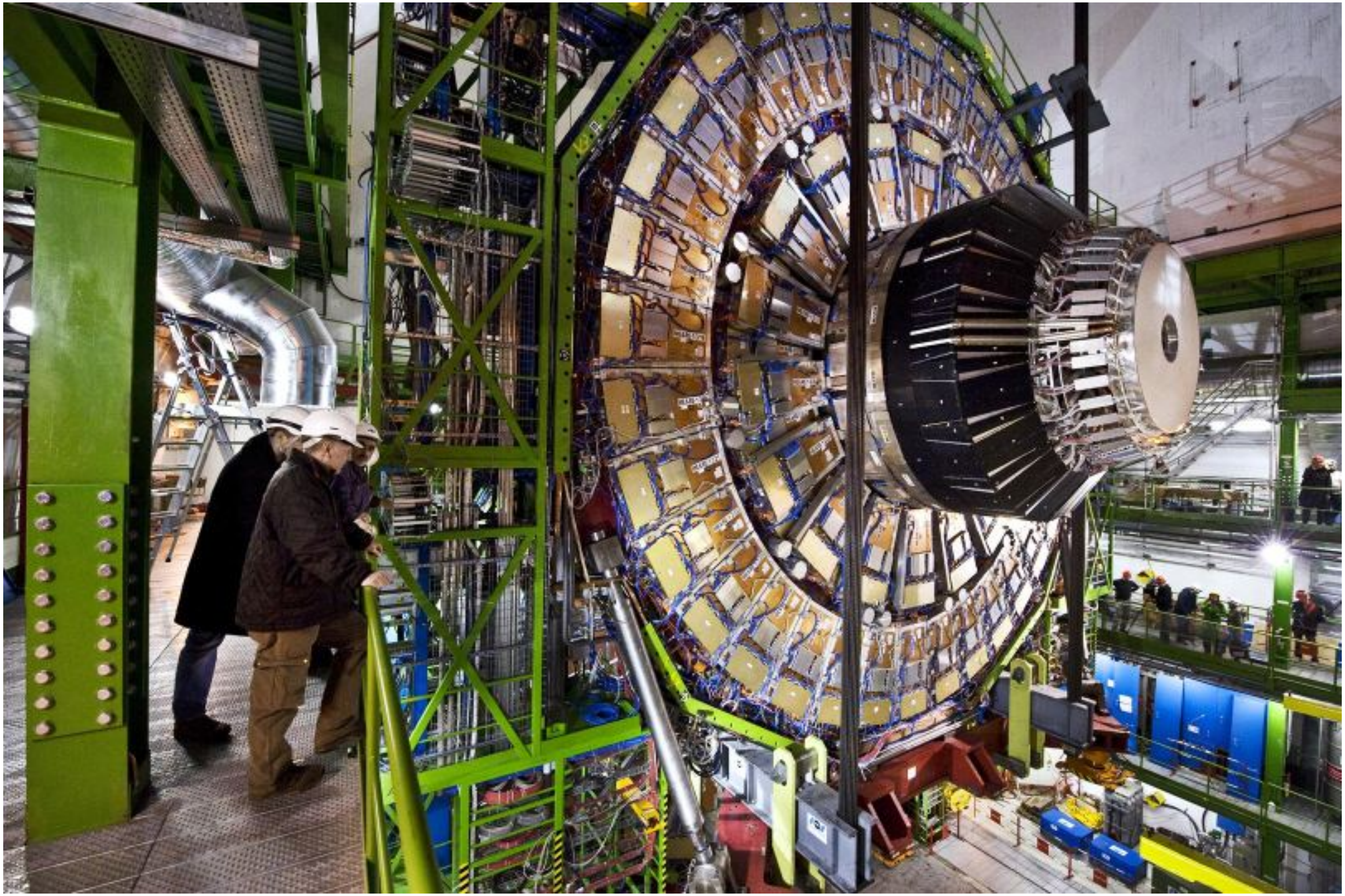


Lowering endcap YE+3 Nov 2006

Lowering magnet and central YB0 Feb 2007

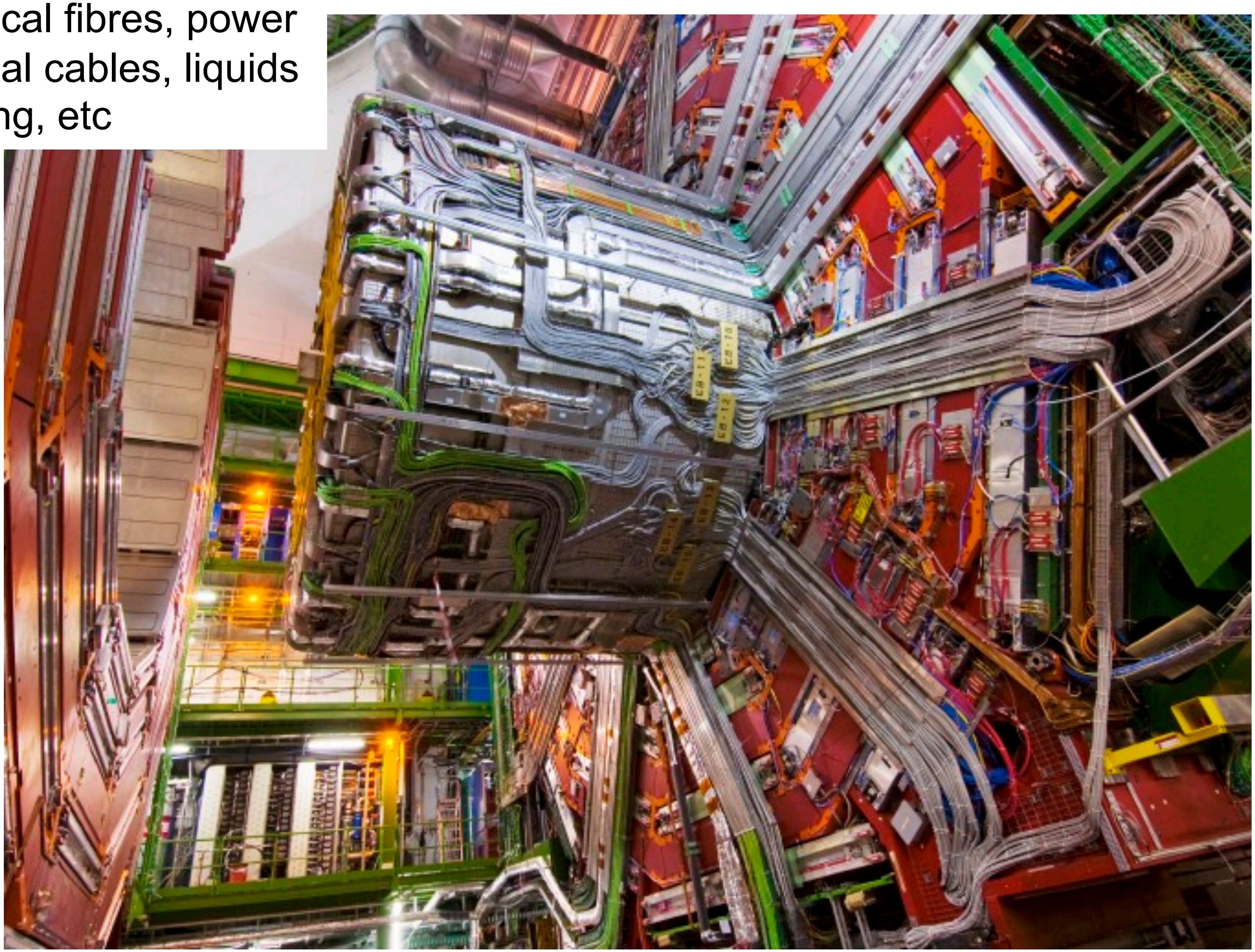


Endcap muon/forward calorimetry YE-1 Jan 2008



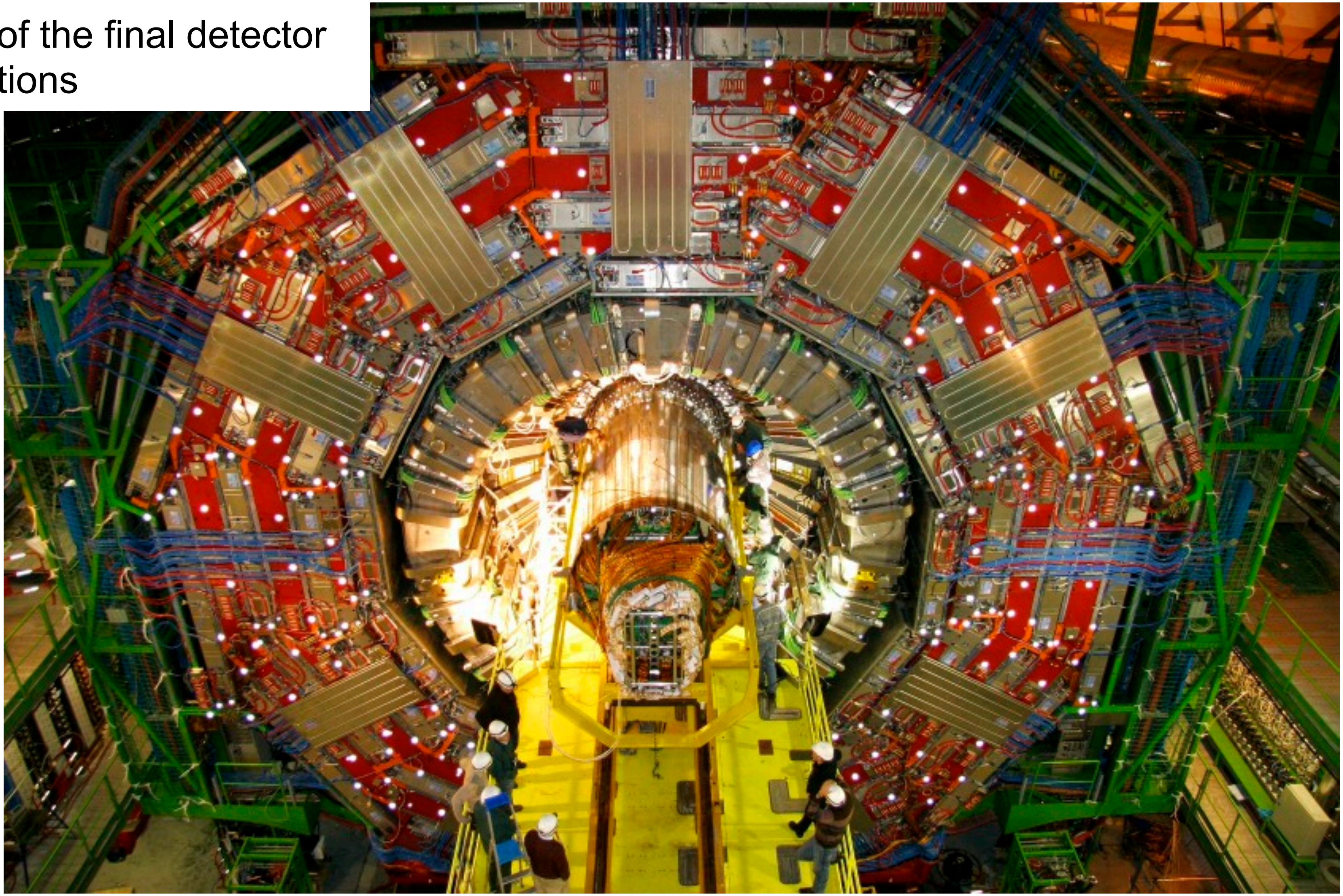
Vacuum tank December 2007

Services =
gas, optical fibres, power and signal cables, liquids for cooling, etc



Tracker installation Dec 2007

One of the final detector insertions



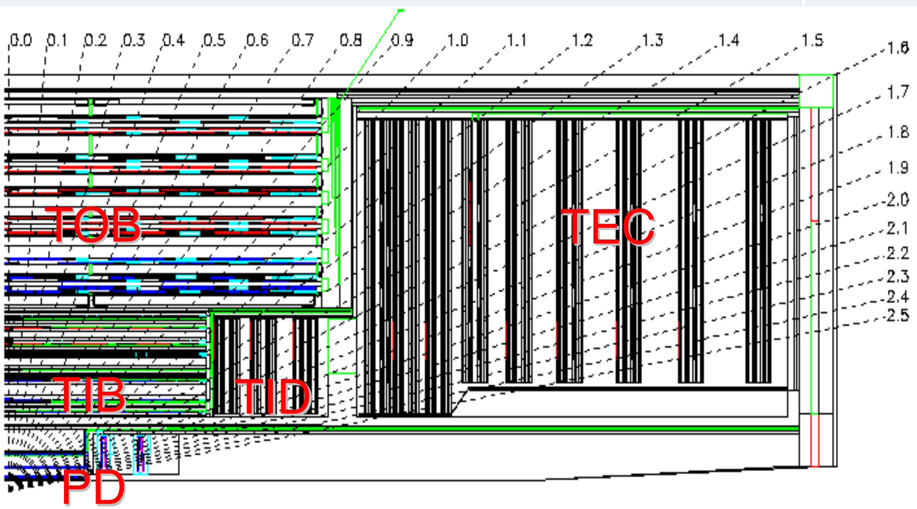
The detectors

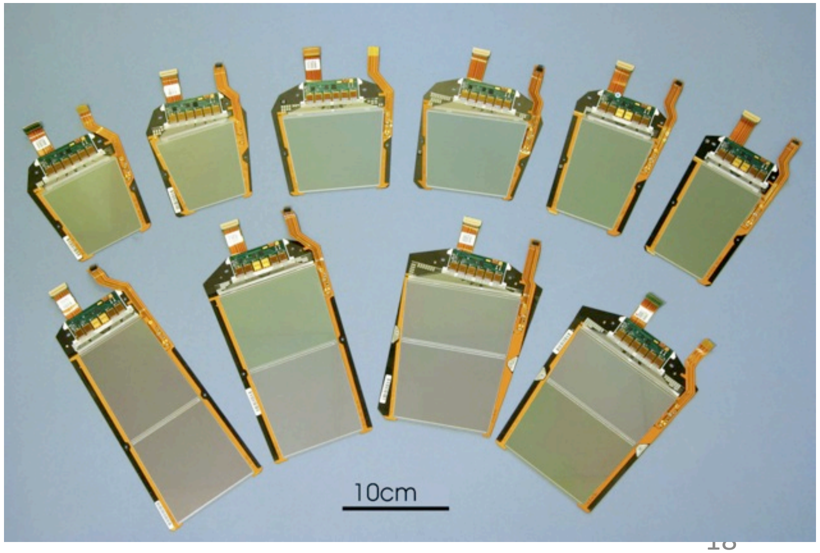
- Would not exist without commercial procurements
- For illustration, I have chosen a couple of examples where there has been a strong UK involvement. Our detector activities have included
  - Custom integrated circuit electronics
  - Board-based digital electronics
  - Silicon sensors
  - Vacuum photodiodes
  - Scintillating crystals
  - Semi-custom optical links
  - Mechanical assemblies – some very large
  - Data acquisition and software development
  - …
- In most cases in close collaboration with scientists and engineers from other countries

CMS Tracker and its sub-systems

- Two main sub-systems: Silicon Strip Tracker and Pixels
  - pixels quickly removable for beam-pipe bake-out or replacement
  - SST not replaceable in reasonable time

Microstrip tracker	Pixels
~210 m^2 of silicon, 9.3M channels	~1 m^2 of silicon, 66M channels
73k APV25s, 38k optical links, 440 FEDs	16k ROCs, 2k olinks, 40 FEDs
27 module types	8 module types
~34kW	~3.6kW (post-rad)

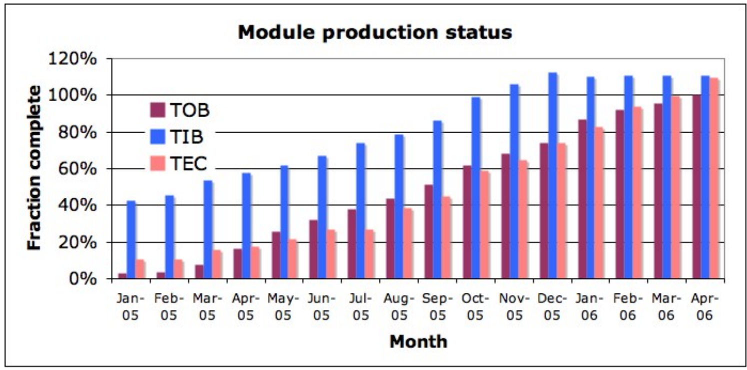




Some milestones of a long project

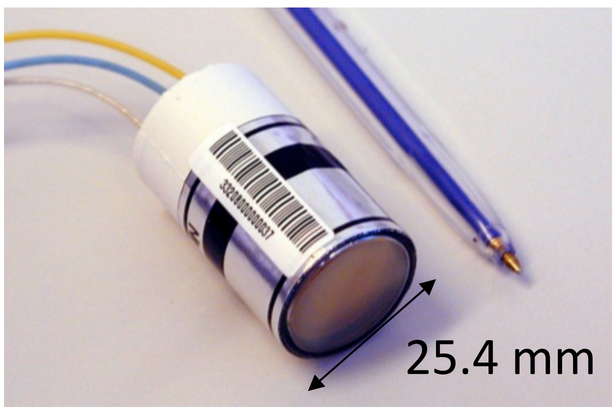
- ~Jan 1990 R&D projects
- Apr 1992 CMS Letter of Intent
- Dec 1994 Technical Proposal
- Apr 1998 Tracker Technical Design Report
- Oct 1999 Front End Readout ASIC in 0.25µm CMOS
- Dec 1999 Decision to construct All Silicon Tracker
- Feb 2000 Tracker Technical Design Report Addendum
- Apr 2006 Module production completed
- Nov 2006 Tracker integration complete
- Dec 2007 Tracker inserted in CMS
- Mar 2008 Tracker connections completed
  - Sep 2008 small interlude
- Nov 2009 Tracker ON with LHC beam
- Mar 2010 Data taking at 7 TeV

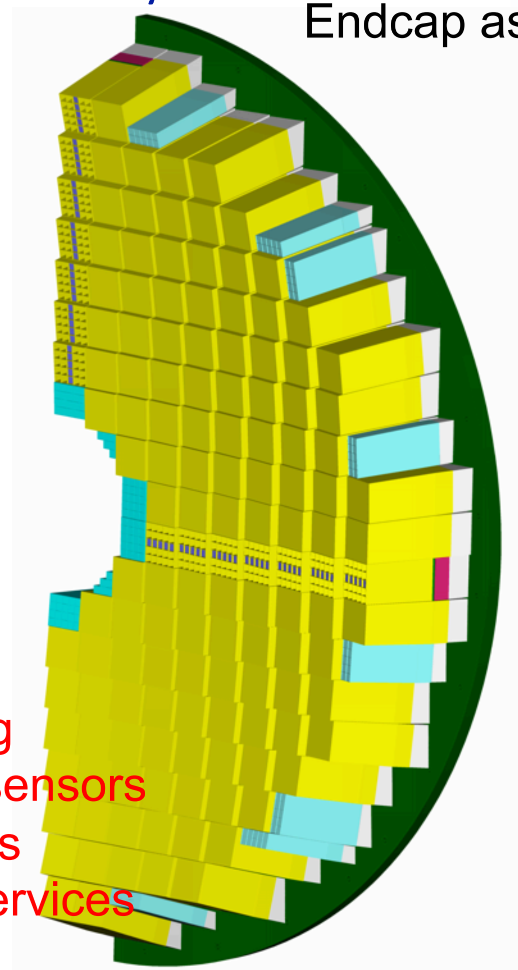
R&D phase

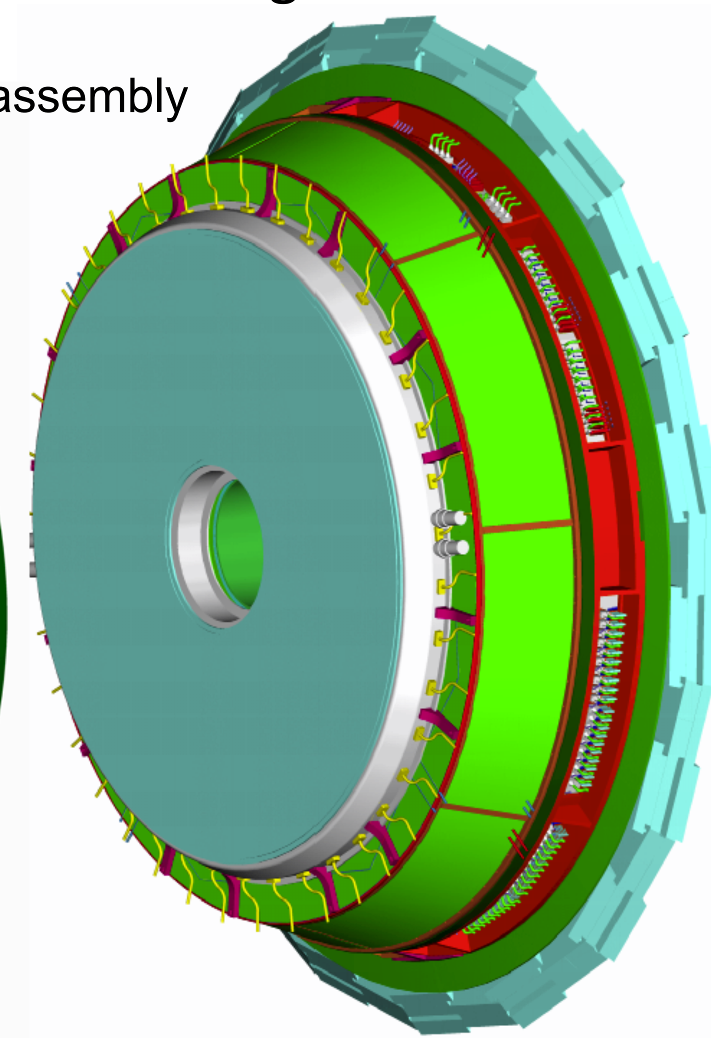


Electromagnetic Calorimeter

- Measures electron and photon locations and energies
  - ~80,000 $PbWO_4$ scintillator crystals
  - Sensors
    - APD (barrel)
    - VPT (end cap)



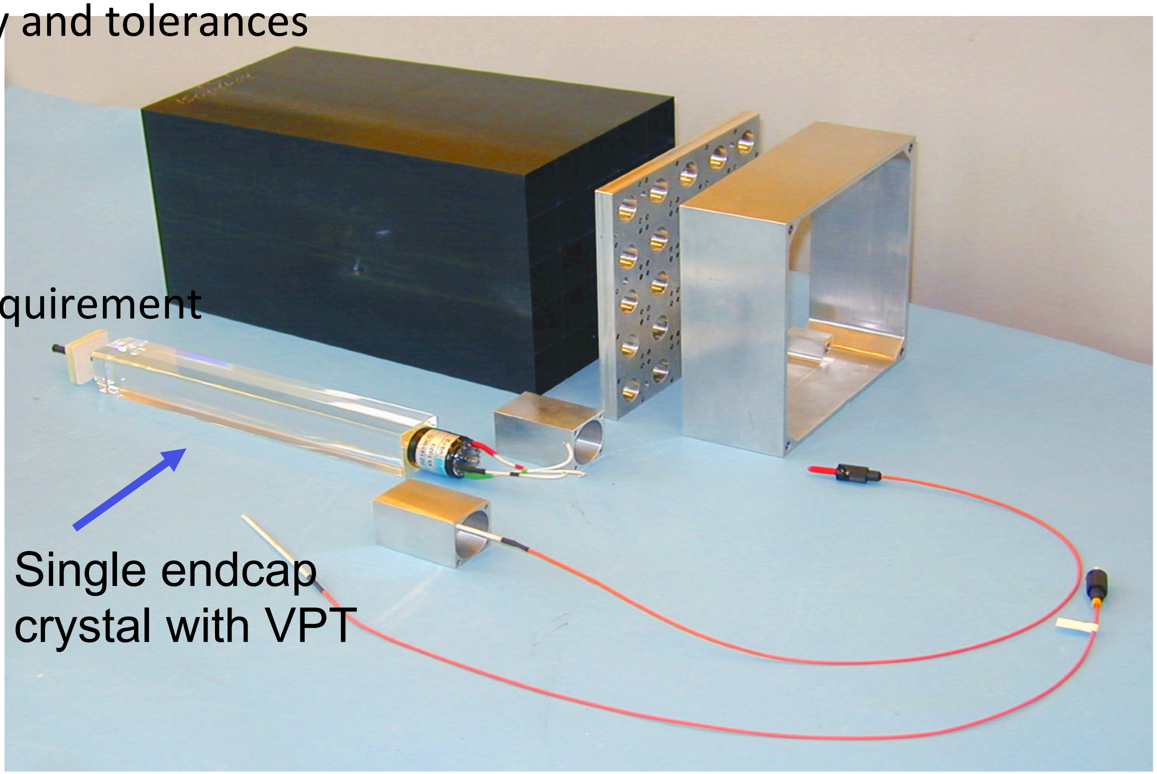




Heavy mechanical engineering
Innovative crystals and photosensors
Demanding modern electronics
Off-detector electronics and services

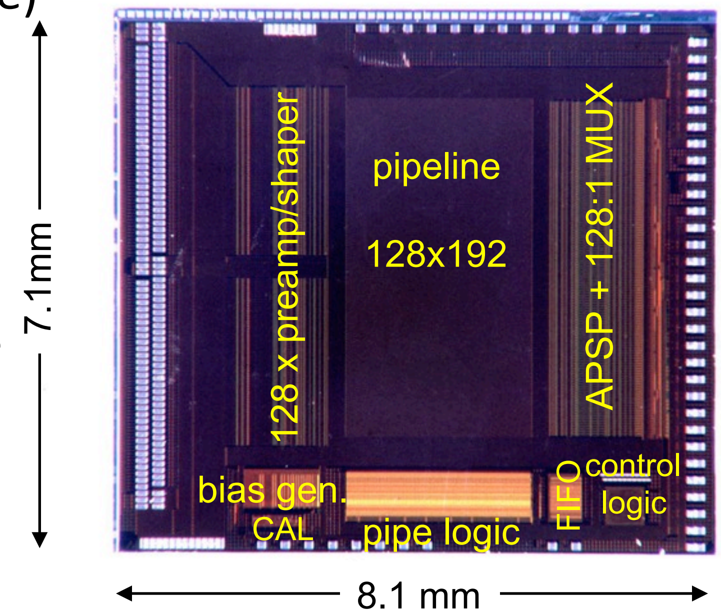
ECAL modules

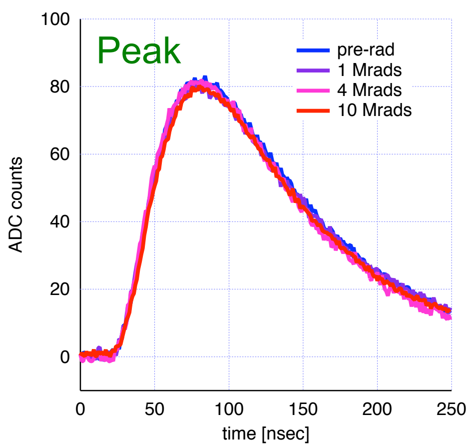
- Main challenges – as well as radiation tolerance
  - CMS ECAL designed for very high energy resolution
    - physics advantages for several specific discoveries
  - very dense crystal material, with demanding specifications
    - precise mechanical assembly and tolerances
    - final object very heavy
  - electronics crucial
    - large signal dynamic range
    - (~16bits) & high precision requirement
    - low noise
    - linearity
    - stability
  - information vital to trigger
    - selects data for readout

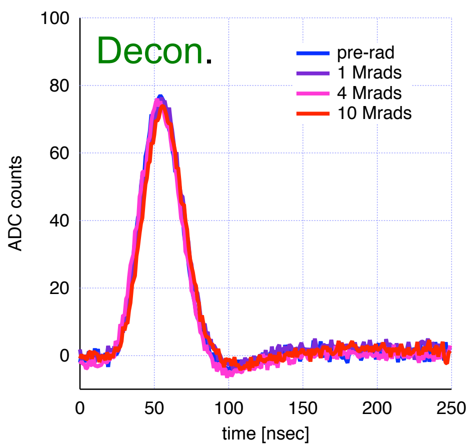


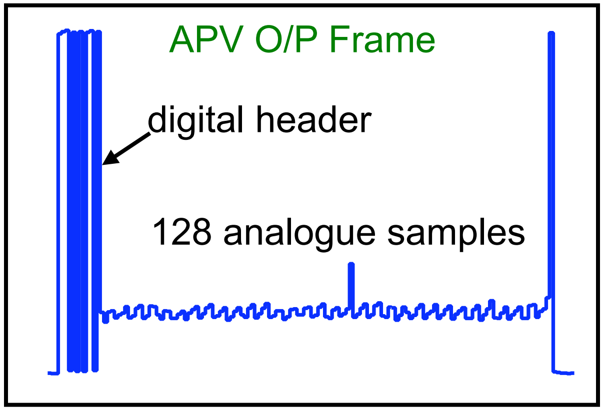
Tracker: APV25 custom integrated circuit

- Main features (many innovative, at the time)
  - Commercial 0.25µm CMOS
  - 128 programmable readout channels
  - amplifiers, memory, controls,…
- Designed and delivered by Imperial College and Rutherford Appleton Lab
  - manufacture via CERN contract



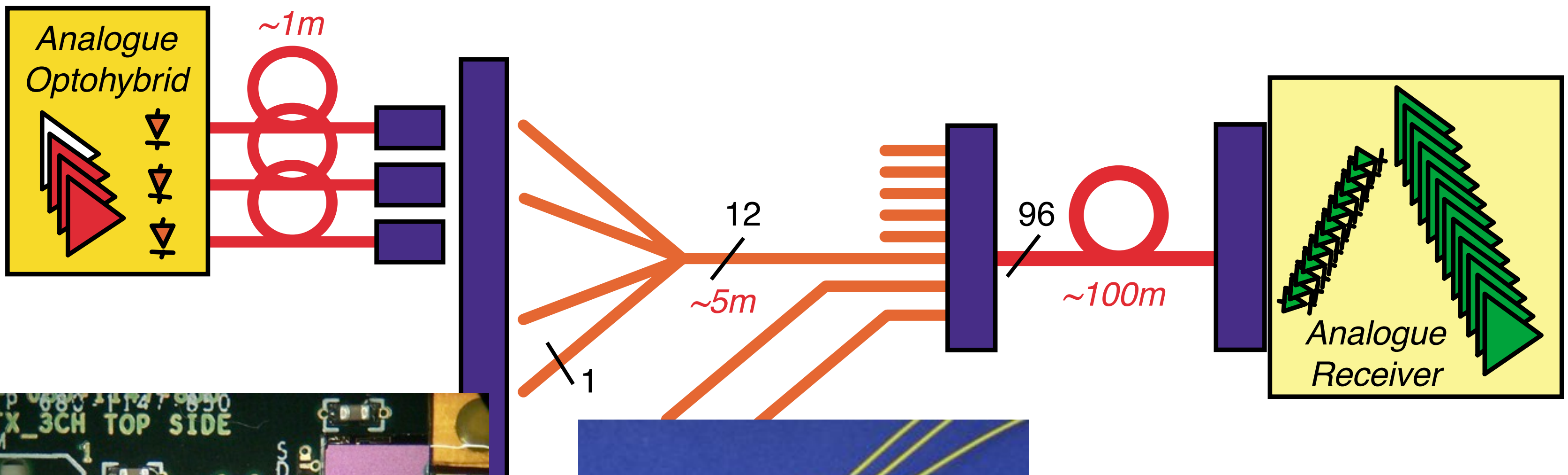


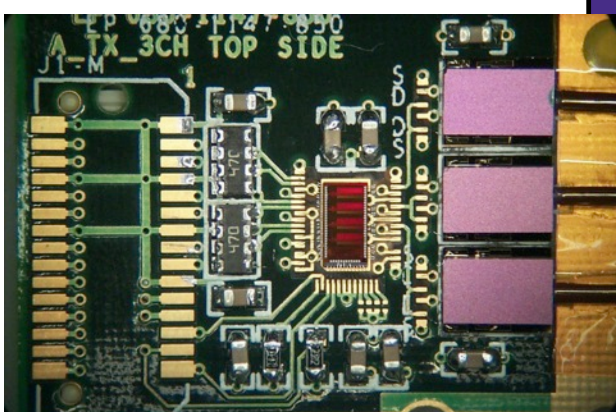


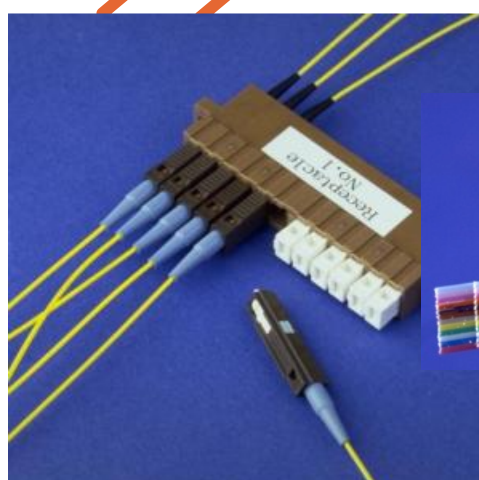


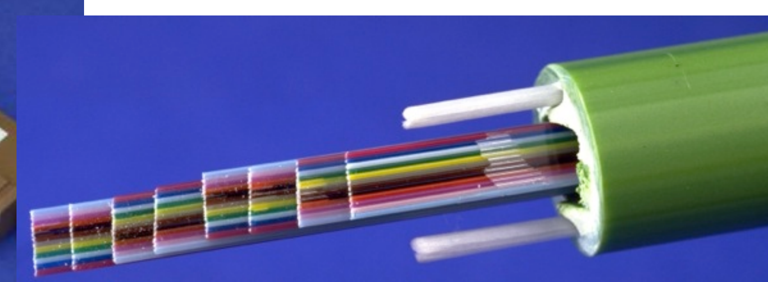
Optical links

- System developed for CMS Tracker mainly by CERN with industrial partners – later used for calorimeter, and other detectors
  - 1.3µm single mode FP laser transmitters, III-V semiconductor Tx & Rx
    - good linearity over wide range, good radiation & B-field tolerance



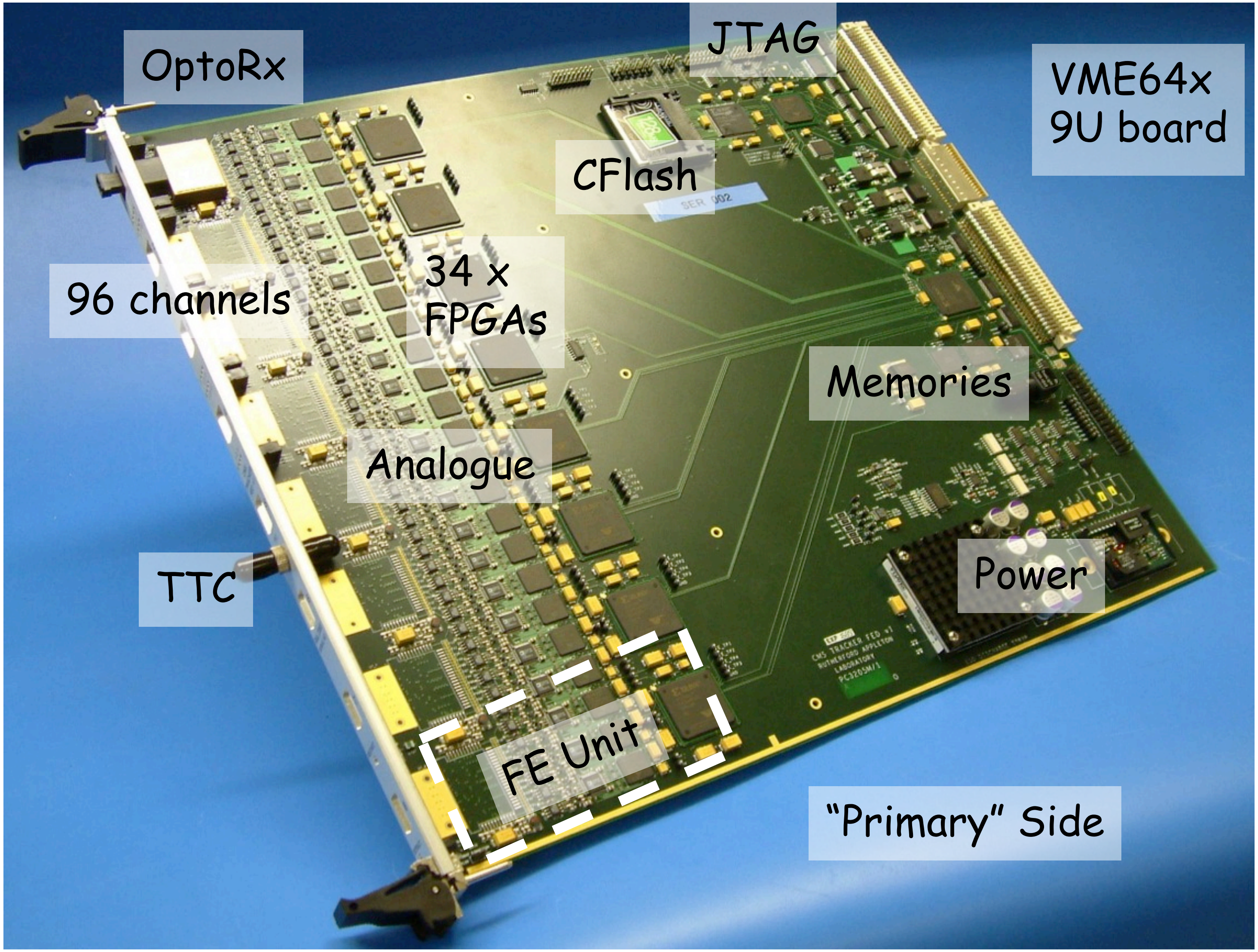






Tracker - Front End Driver

- Monolithic assembly (density/cost)
- ~ year 2005
- in UK with high yield
- opto-electric conversion
- data processing
- data transfer
- VME control and slow readout
- typical of many other CMS modules



TRACKER CONSTRUCTION
by worldwide effort

Austria, Belgium, Finland, France, Germany, Italy, CERN, Switzerland, UK, USA –*62 institutes*

much movement of components and assemblies

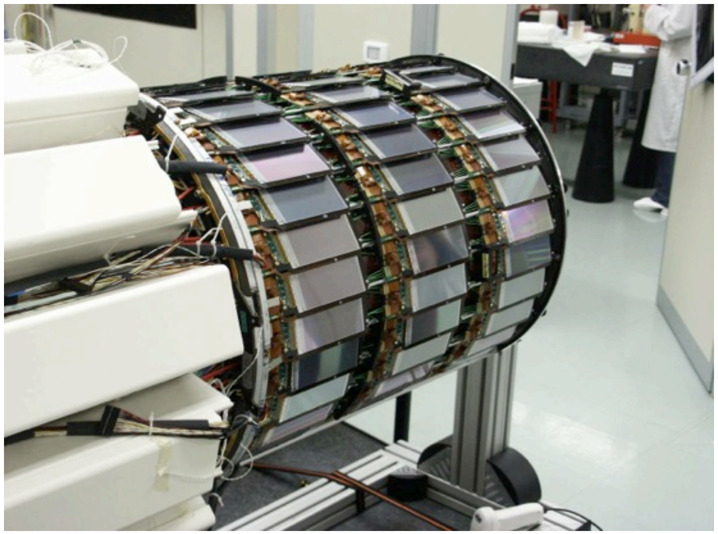
Sensors, ASICs, hybrids procured and tested

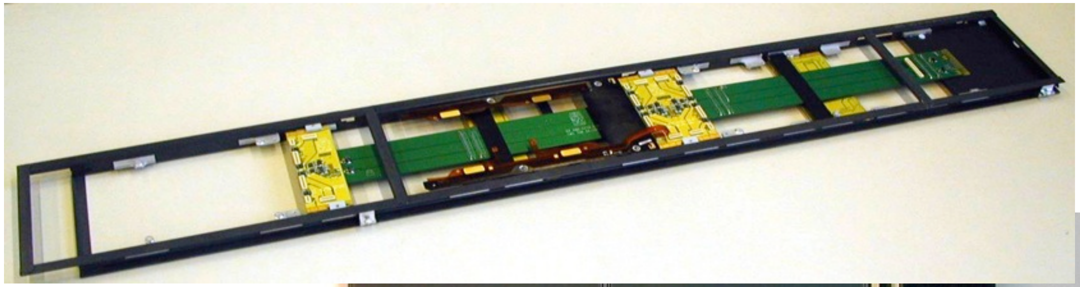
some parts commercially: e.g. hybrids

Modules constructed in our dedicated centres, using automated assembly methods…

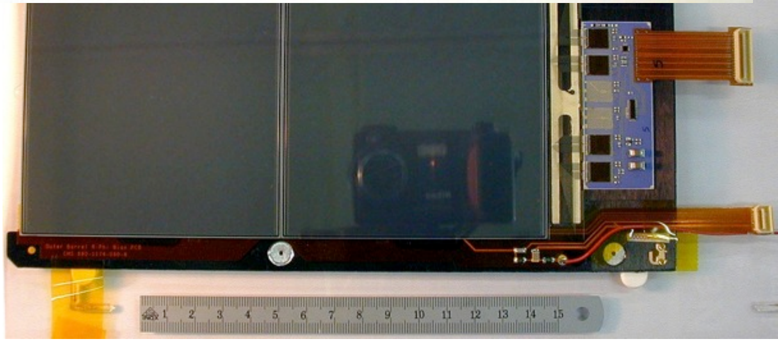
Modules and sub-system assembly

Inner barrel shells (Italy)

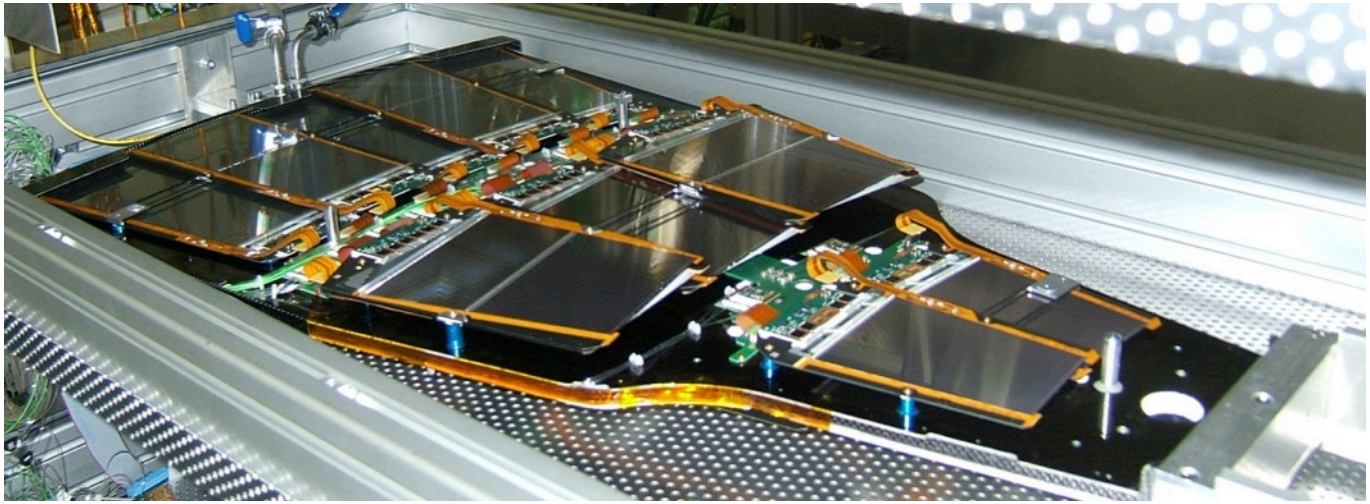




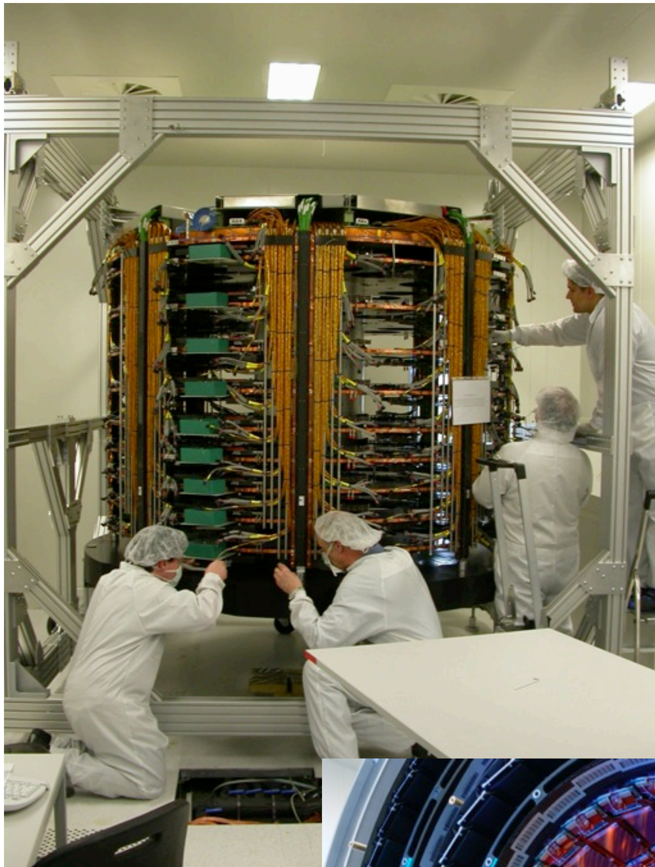
TOB modules and Rods (US, CERN) Hybrids (industry)

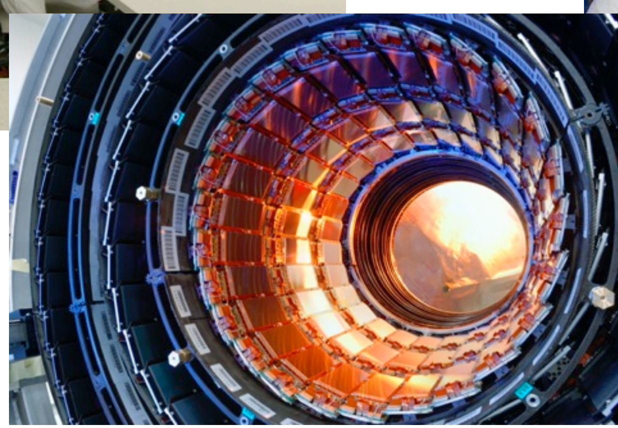


Endcap petals (Au, Ge, Be, Fr)



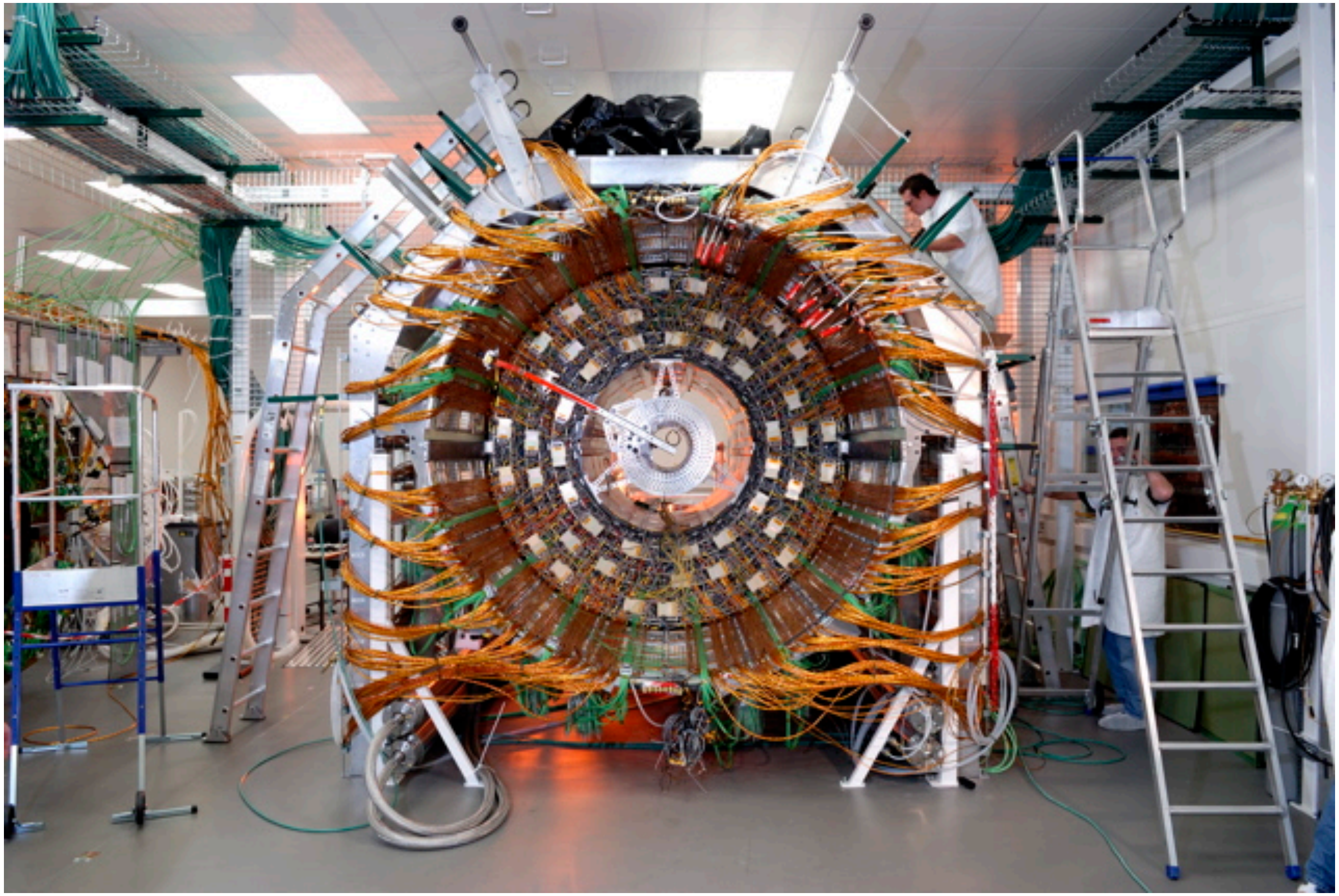
Sub-system integration





Integration at Tracker Integration Facility

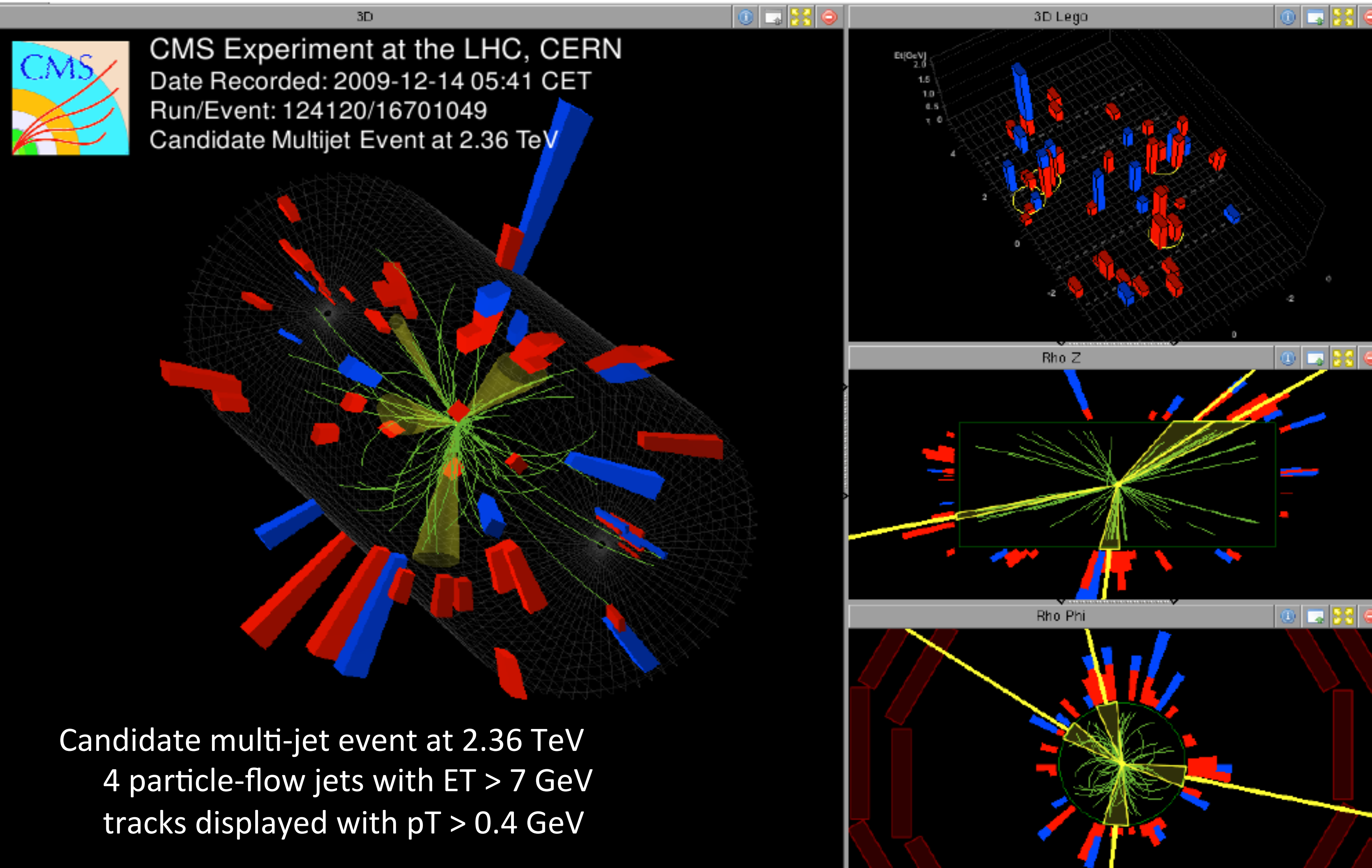
- Dedicated clean room laboratory in CERN
  - assembled sub-systems, then added external cables, cooling, …



Some of the challenges overcome

- Sensors: two major contracts with very different production quality
- Hybrids: flexible kapton-metal layer structure
  - subtle problems in through-via manufacture identified at late stage
- ASIC yield: variations after initial very good beginning
  - worked with company to understand and solve
- Cooling plant performance: manufacture weakness
  - failures in plant and components
- Many, many other issues
  - early attention to minor details is crucial to avoiding costly delays
  - most items are highly specialised with few, or no, second sources

Collision tracks: December 2009

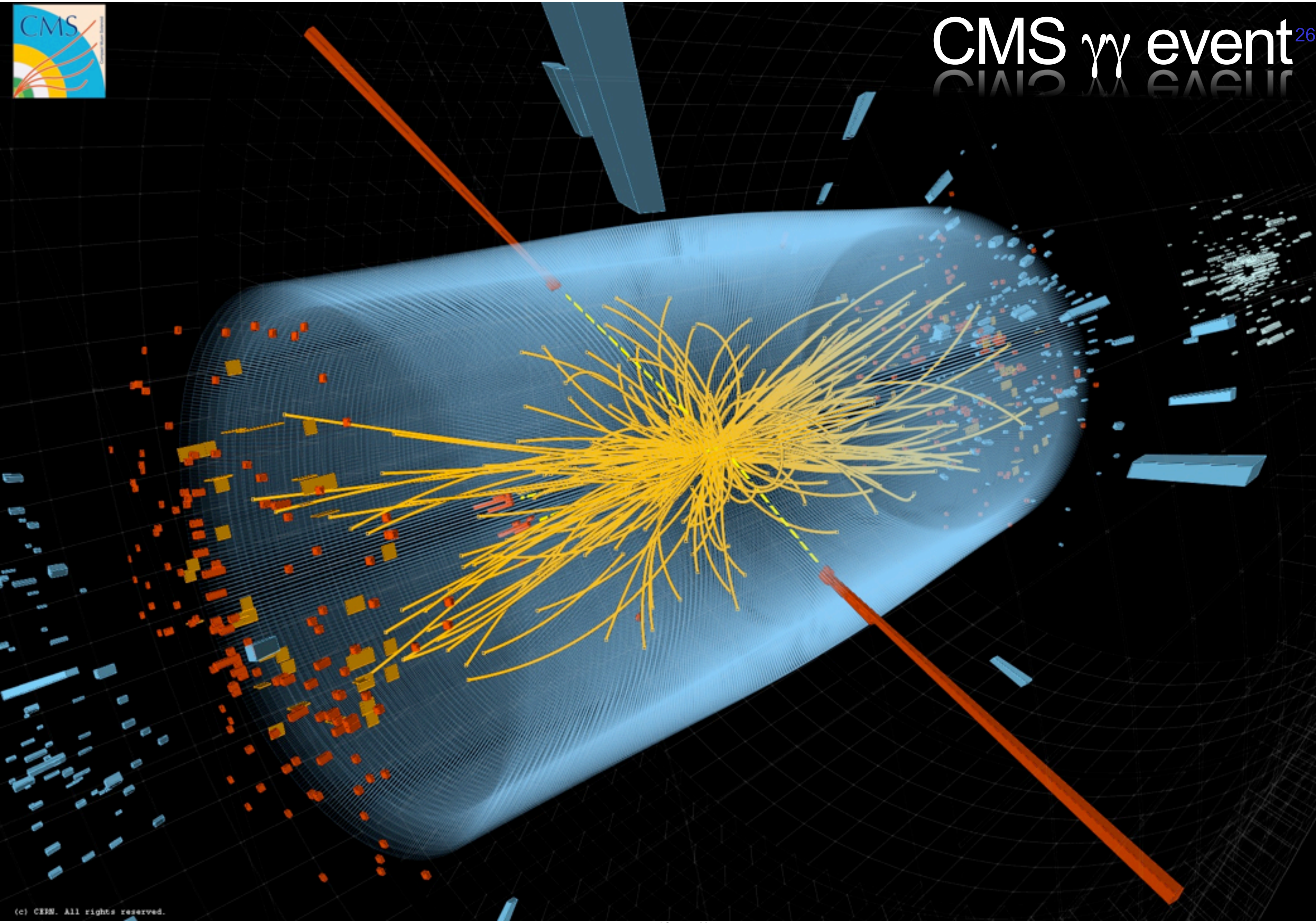


Candidate multi-jet event at 2.36 TeV

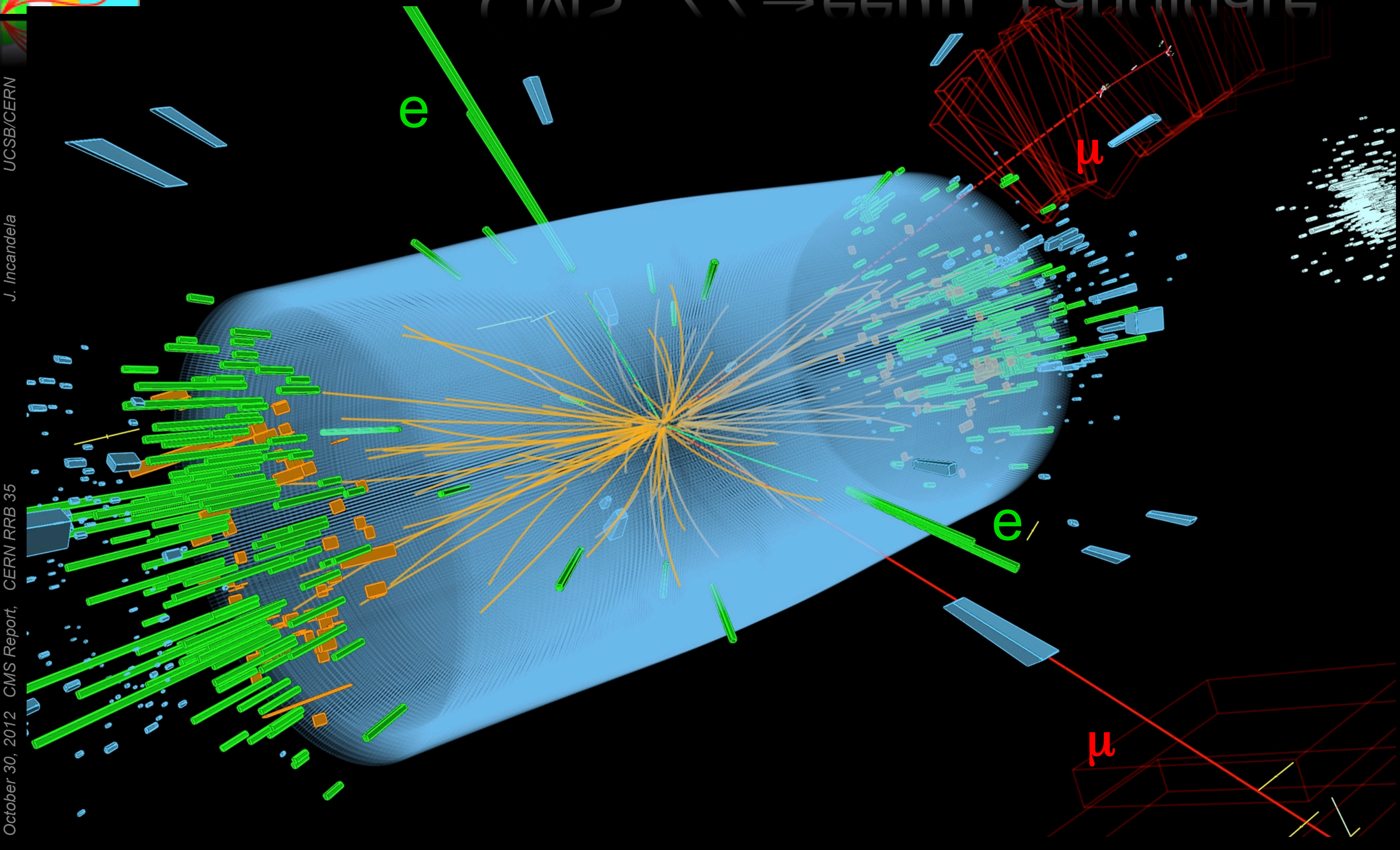
4 particle-flow jets with ET > 7 GeV

tracks displayed with pT > 0.4 GeV

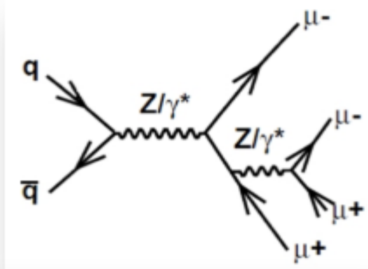
CMS γγ event[26]

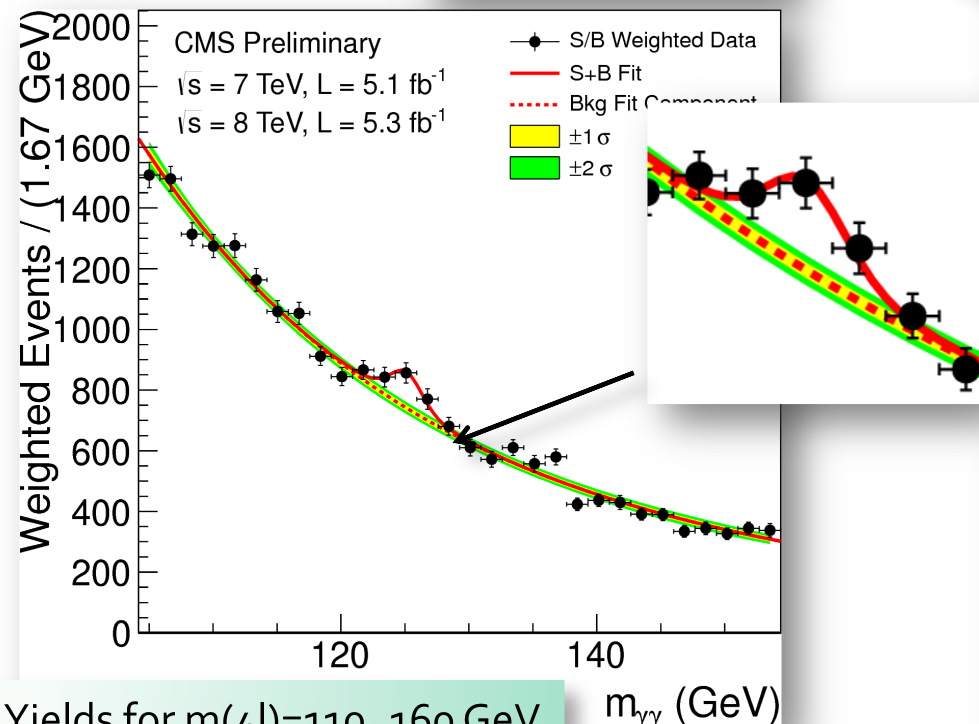


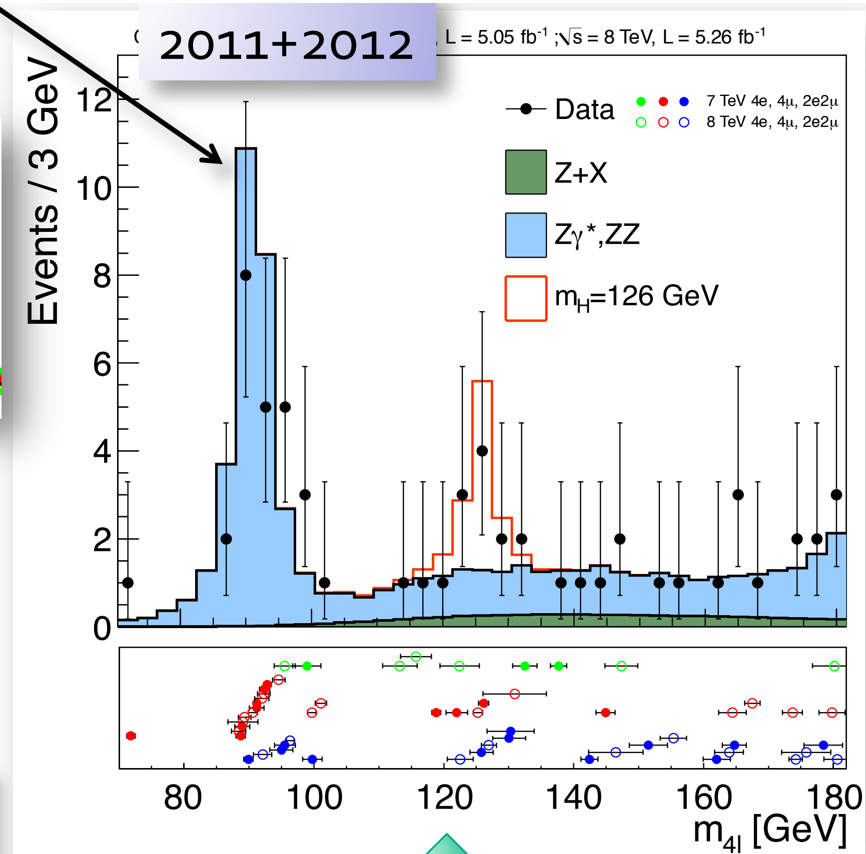
CMS ZZ→eeμμ candidate



Discovery!







Yields for m(4l)=110..160 GeV

Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
m_H = 126 GeV	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18

164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

Event-by-event errors

October 30, 2012 CMS Report, CERN RRB 35 J. Incandela UCSB/CERN

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The future

- The experiments were demanding to design and build
  - the accelerator too…
  - but we succeeded in overcoming unprecedented challenges
  - a huge effort by many people and institutes, over many years

- Now we have set ourselves an even more difficult problem
  - upgrade the experiments to take data for a further 10-15 years
  - under even more demanding conditions
  - radiation tolerance, data volumes, reliability,..
  - while maintaining, or even improving, performance
- Replacing several major sub-detectors
  - and many other improvements
  - currently at R&D stage, prototyping, then construction from 2018?