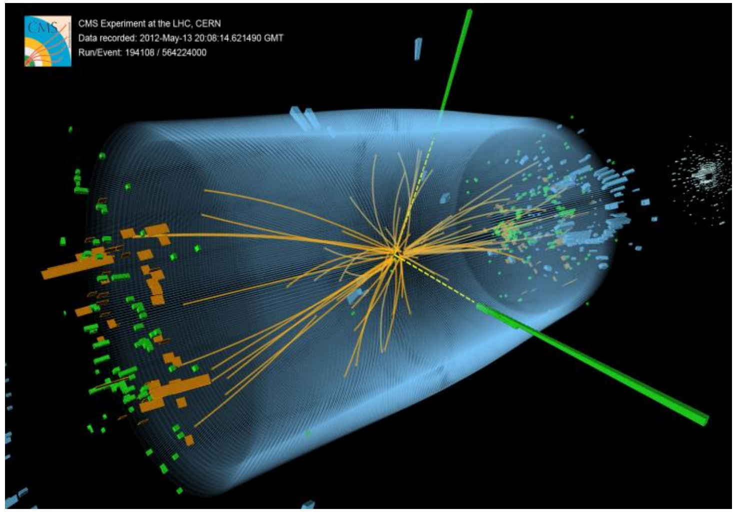
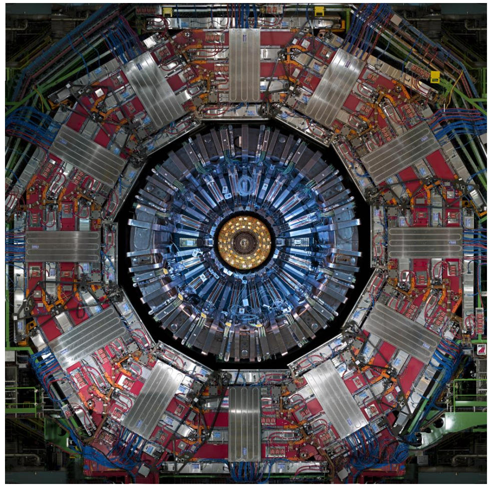
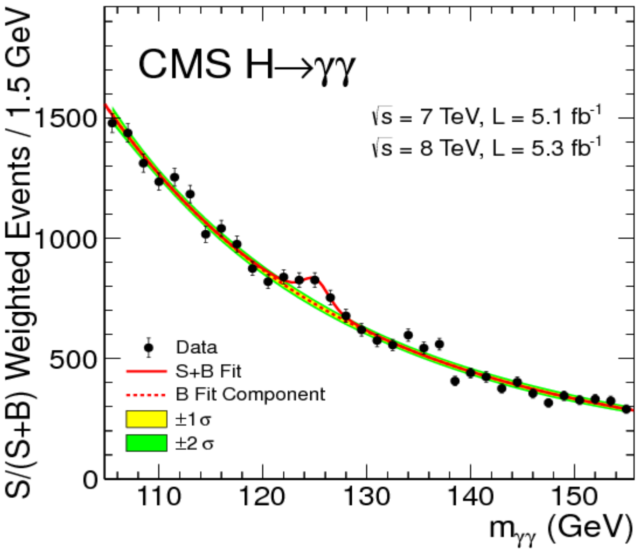
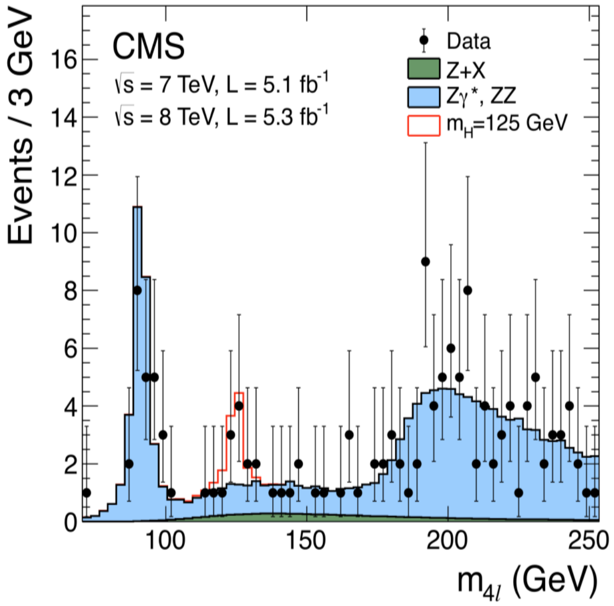
Imperial College London

H@10: Imperial College in the Search









Particle Physics

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

Aims to answer the two following questions:

What are the elementary constituents that make up our universe?

What are the forces that control their behaviour at the most basic level?

Experimentally:

1. **Make particles interact and study the products and properties of the result of the interaction**
2. **Measure the energy, direction and type of the products as accurately as possible**
3. **Reconstruct what happened during the collision**

Particle Accelerators

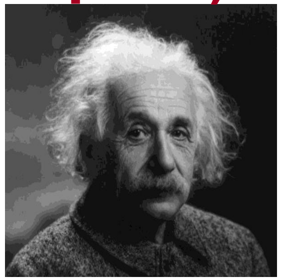
accelerate particles to extremely high energies.

High energies allow us to

i) Study the young universe (E= kT)
Revisit the earlier moments of our ancestral universe
(look further back in time ➔"powerful telescopes")

Boltzmann

ii) Discover new particles with high(er) mass ($E = mc^2$)



Einstein

iii) Look deeper into Nature ($E \alpha$ 1/size),
(look deeper ➔"powerful microscopes")

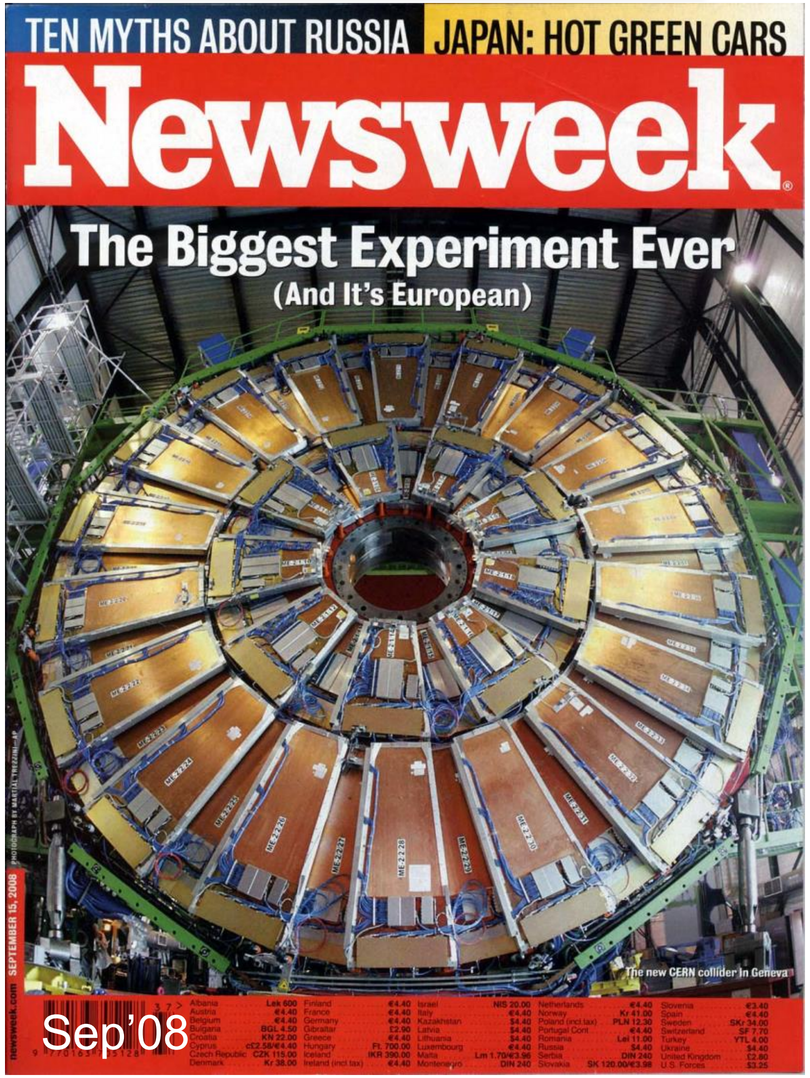
de Broglie

Observe phenomena and particles normally no longer observable in our everyday experience.

All in a controlled way - "in the laboratory"

The Journey: As Seen by the Outside

During Construction



Upon Discovery

Theoretical and Experimental Developments(1960s-1980s)

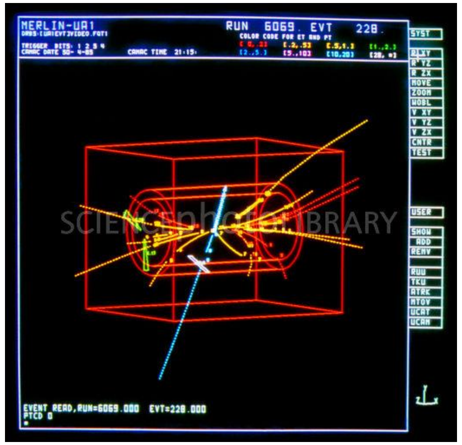
1964: The (4) famous papers on *spontaneous symmetry breaking mechanism* attracted very little attention at the time. The *boson* attracted even less (Imperial College's **Tom Kibble**, 2011)

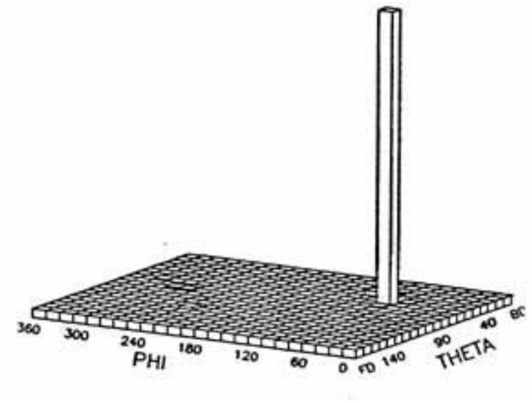
1967: SU(2)XU(1): Unified model of weak and electromagnetic interactions of leptons proposed by Weinberg (1967), and independently by Imperial College's **Abdus Salam** (1968).

1971: Both Salam and Weinberg had speculated that their theory was renormalizable. This was proven by 't Hooft & Veltman.

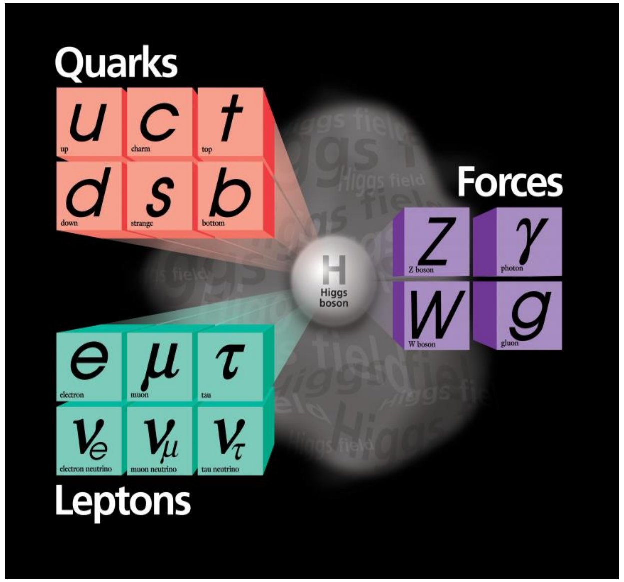
1973: the key prediction of the electroweak theory, the existence of neutral current interactions — those mediated by Z^0 — was confirmed at CERN.

1983: the *W* and *Z* bosons were discovered at CERN (UA1 and UA2)



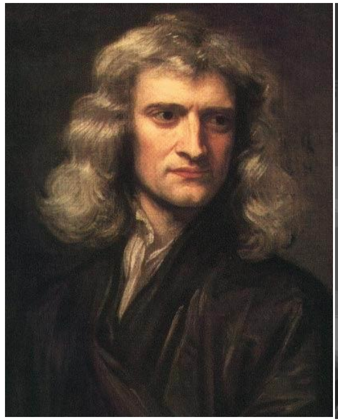


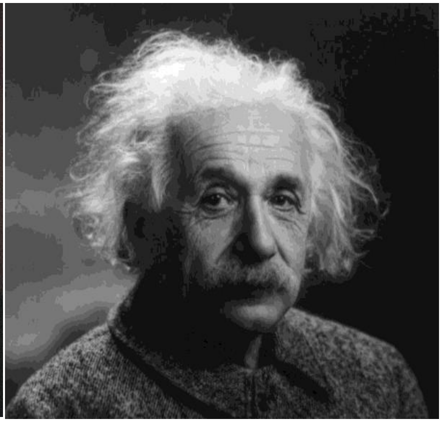
THEN the **Higgs boson** became the last important missing particle (the keystone) of the standard model of particle physics (SM)



What is the Higgs boson? What is Mass?

Mass Gives Our Universe Substance!





To Newton: F= ma, w = mg
To Einstein: $E = mc^2$
Mass curves space-time

All of this is correct.
But how do fundamental objects become massive?
Simplest theory – all fundamental particles are massless !!

A bold intellectual conjecture (1964): a field pervades our entire universe. Particles interacting with this field acquire mass, the stronger the interaction the larger the mass

The field is a quantum field – its quantum is the Higgs boson.
Finding the Higgs boson establishes the existence of this field.

Physics Questions wrt Hadron Colliders

Physics Drives Detector Design

1. Standard Model of Particle Physics contains too many apparently arbitrary features
the hope is that these should become clearer as we make progress towards a unified theory.

✓ **2. Clarify the e-w symmetry breaking sector**
SM has an unproven element: the generation of mass
Higgs mechanism? or other physics ?
Answer will be found at LHC energies

e.g. why $M_\gamma = 0$
M_W, M_Z ~ 100 GeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies
Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!
Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter
Even if the Higgs boson is found all is not completely well with SM alone:
next question is "Why is Higgs boson's mass so low"?
If a new symmetry (Supersymmetry) is the answer, it must show up at O(1TeV)

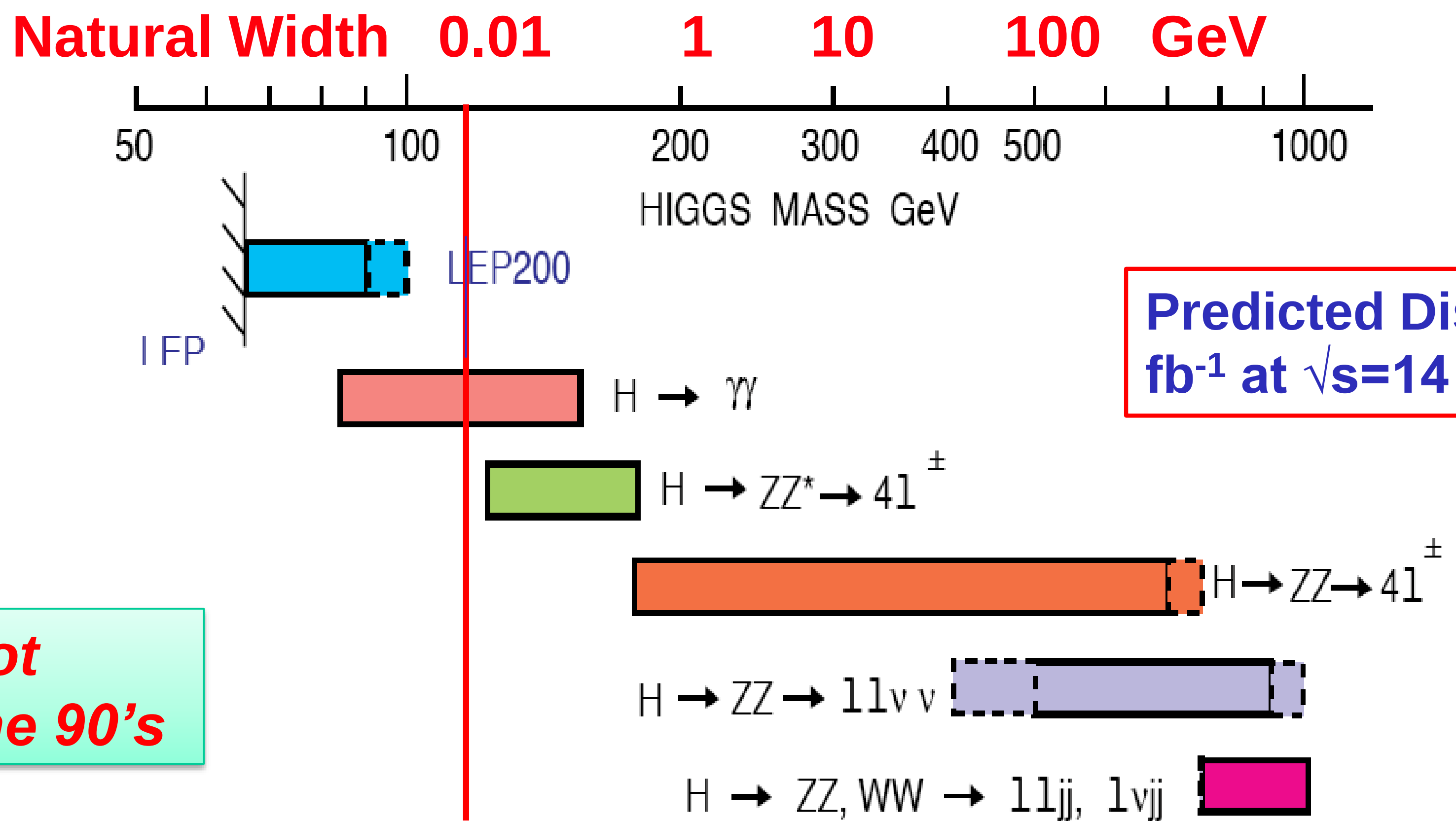
5. Search for new physics at the TeV scale
SM is logically incomplete – does not incorporate gravity
Superstring theory ⇨ dramatic concepts: supersymmetry , extra space-time dimensions ?

The main problems of the SM show up in the Higgs sector.

Physics Drivers 1

Search for the SM Higgs Boson and LHC Experiment Design

Detection of the SM Higgs boson over the wide mass range, and its diverse manifestations, played a central role in the conceptual design of the ATLAS and CMS experiments.



Natural width
Γ ~ h/τ

Predicted Discovery (5σ) with 100 fb^{-1} at $\sqrt{s}$=14 TeV !

Plot from the 90's

Search for a low mass Higgs boson (e.g. H→γγ, H→ZZ→4*l*) placed stringent performance requirements on ATLAS and CMS detectors (especially Tracker momentum and ECAL energy resolution).

LHC Project Timeline

1984 **Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne**

1987 **“Rubbia Committee” recommends LHC as the right choice for CERN’s future**

1990 **ECFA LHC Workshop, Aachen**

1992 **General Meeting on LHC Physics and Detectors, Evian les Bains**

1993 **From three Letters of Intent, ATLAS and CMS selected by LHCC**

1994 **ATLAS and CMS Technical Proposals Approved**

1996 **Approval to move to Construction (materials cost of <475 MCHF**$_{1996}$**)**

1998 **Memorandum of Understanding for Construction Signed**

1998 **Construction Begins (after approval of Technical Design Reports)**

2000 **Assembly begins of ATLAS and CMS (above ground). LEP closes**

2008 **ATLAS & CMS ready for First LHC Beams**

2009 **First proton-proton collisions**

2012 **A new heavy boson discovered with mass ~130 × mass of proton**

2015 **Launch of HL-LHC** (to collect 10 times more data than originally foreseen)

2029-2040 **High Luminosity (HL-LHC) Data Taking**

Imperial College London

1990 Aachen Workshop

Photon decay modes of the intermediate mass Higgs

ECFA Higgs working group

C.Seez and T. Virdee

L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

A report is given of studies of:
(a) H -> γγ (work done by C. Seez and T. Virdee)
(b) W H -> γγ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range ($90 < m_H < 150$ GeV/c^2).
The study of the two photon decay mode is described in detail.

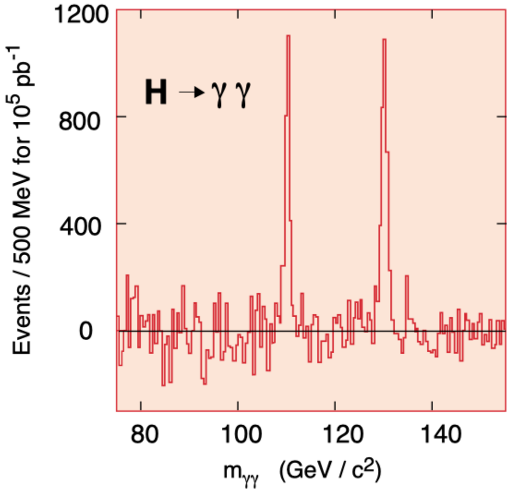
Aachen: Tower of St. Foillan and the Cathedral

Aachen 1990

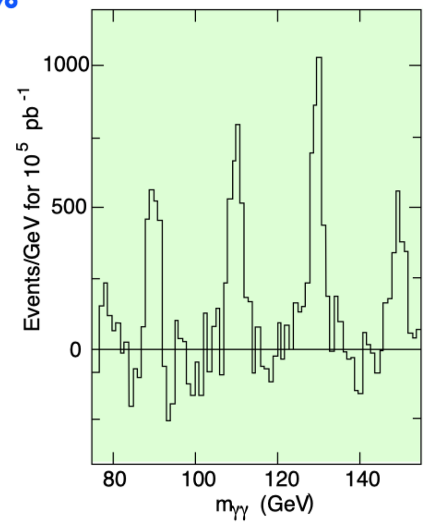
(a) H→γγ (work done by C. Seez and T. Virdee Imperial College)

"As the decay width of the Higgs is about 5.5 MeV at m_H=100 GeV/c^2, and 8.3 MeV at 150 GeV/c^2, the width of the reconstructed mass distribution, and hence the signal/background ratio, will be limited by instrumental mass resolution, in particular by the energy resolution of the electromagnetic calorimeter.

$\sigma/E = 2\%/\sqrt{E} \oplus 0.15/E \oplus 0.5\%$



$\sigma/E = 9\%/\sqrt{E} \oplus 0.3/E \oplus 1\%$



Experimental and Technological Challenges

at a high luminosity hadron collider

In 1980's: "we think we know how to build a high energy, high luminosity hadron collider – we don't have the technology to build a detector for it"

- **1 billion proton-proton interactions per second**

Bunches of 100 billion protons, cross 32 million times a second in the centre of each experiment.
At HL-LHC event rate will increase by a factor > 5.

- **Large Particle Fluxes**

~ thousands of particles stream into the detector every 25 ns
⇨ large number of channels (~ 100 M ch) to keep occupancy low ~ 1 MB/25ns i.e. 40 TB/s
At HL-LHC this will increase to > 200 TB/s

- **High Radiation Levels**

Radiation hard (tolerant) detectors and electronics, especially in the endcaps

Extreme requirements in several domains (also at HL-LHC)

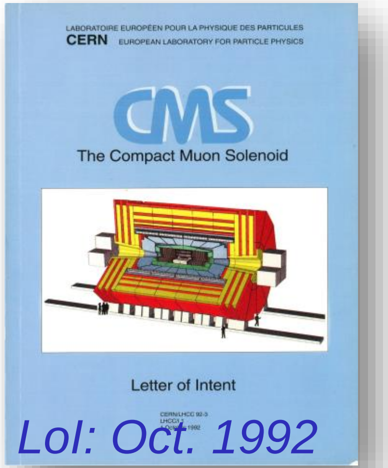
Limited budgets!

Looked at what existed, innovated and automated to drive costs down

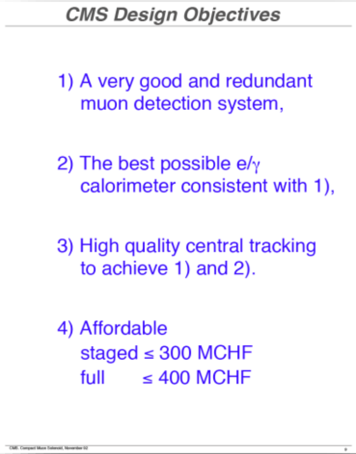
The CMS Experiment: The Concept

Physics Goals to Design Objectives

Into reality16 years later in 2008



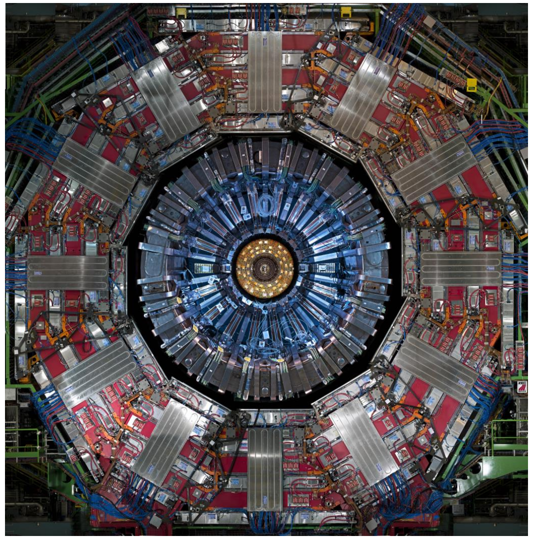
LoI: Oct. 1992



CMS Design Objectives

1) A very good and redundant muon detection system,
2) The best possible e/γ calorimeter consistent with 1),
3) High quality central tracking to achieve 1) and 2).
4) Affordable
   staged ≤ 300 MCHF
   full ≤ 400 MCHF

The Long Journey



Seminal contributions from G. Hall, C. Seez, T. Virdee

Distinguishing Features of CMS

A single large bore (~ 6m), 13m long, 4T high field superconducting solenoid

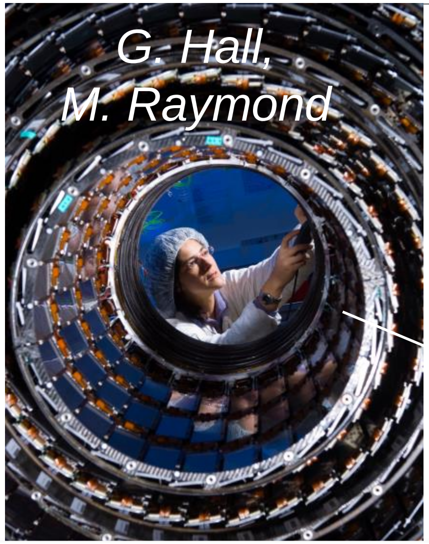
Inner Tracking – all silicon - fewer but higher precision measuring points

EM calorimetry: dense scintillating crystals (lead tungstate)

Muon system: multiple (four) stations, two complementary technologies

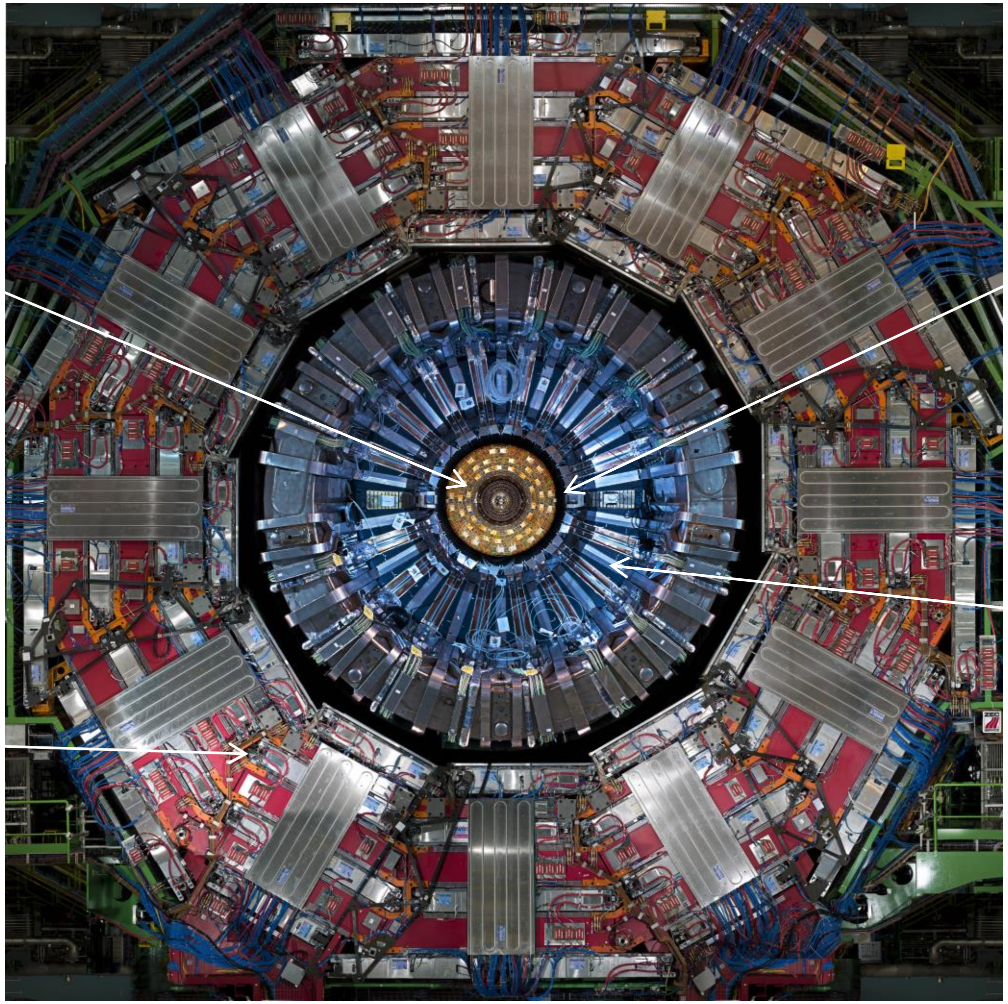
Trigger/DAQ: Only one hardware level of trigger, High-Level Trigger in powerful CPU farm

CMS: Concept to Data Taking took ~ 20 Years!



Silicon Tracker

4000 scientists from >50 countries
1000 Ph. D. Students!



CMS cut in mid-plane

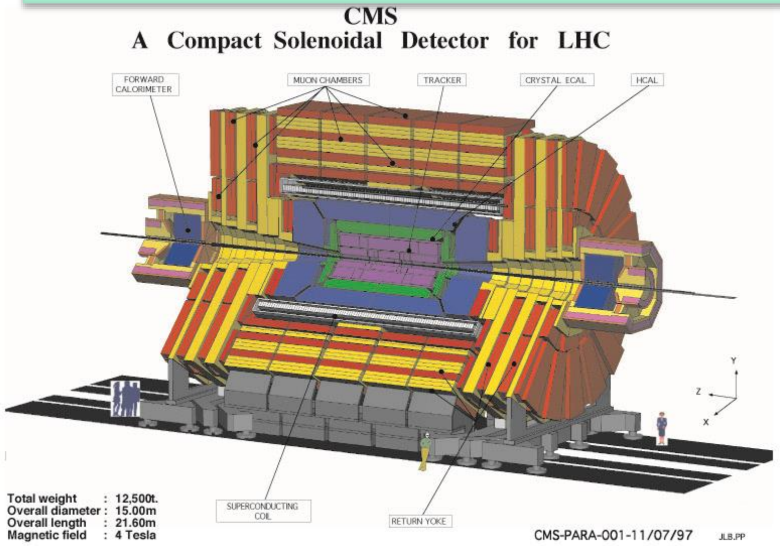
Scintillating Crystals

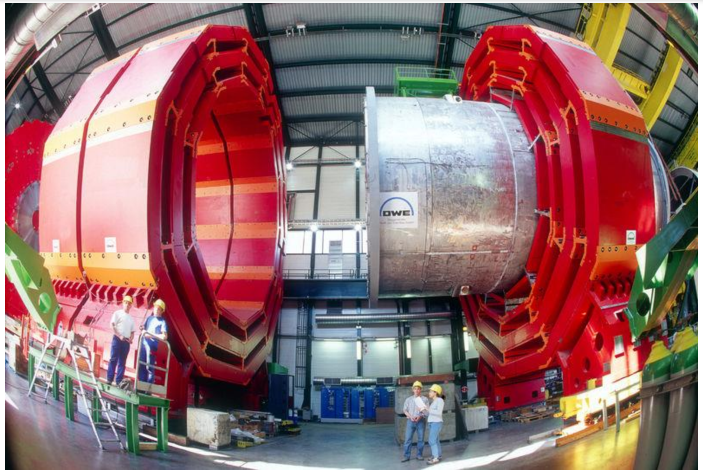
Gas ionization chambers

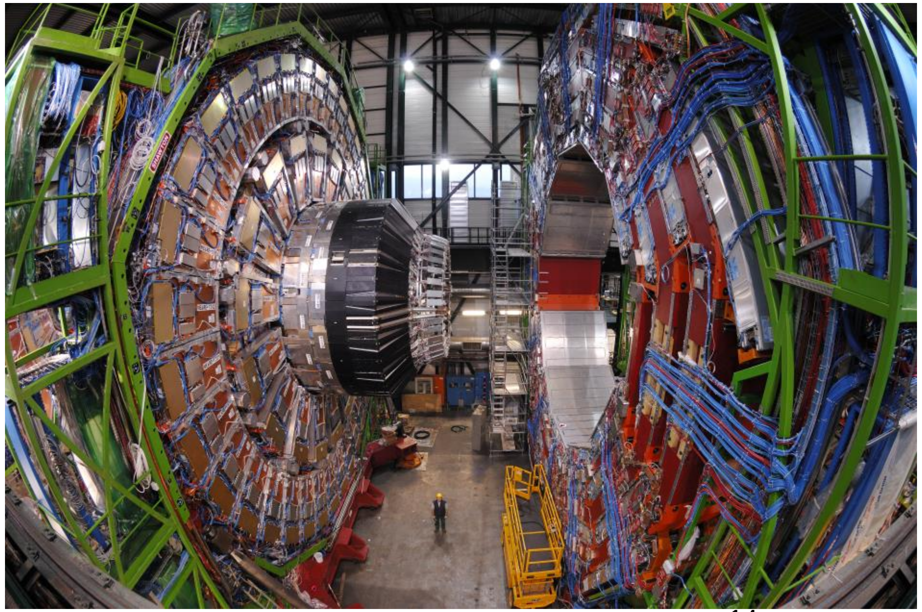
Brass plastic scintillator

Engineering Design

CMS cut in 13 slices; much of the assembly done in surface hall and slices then lowered

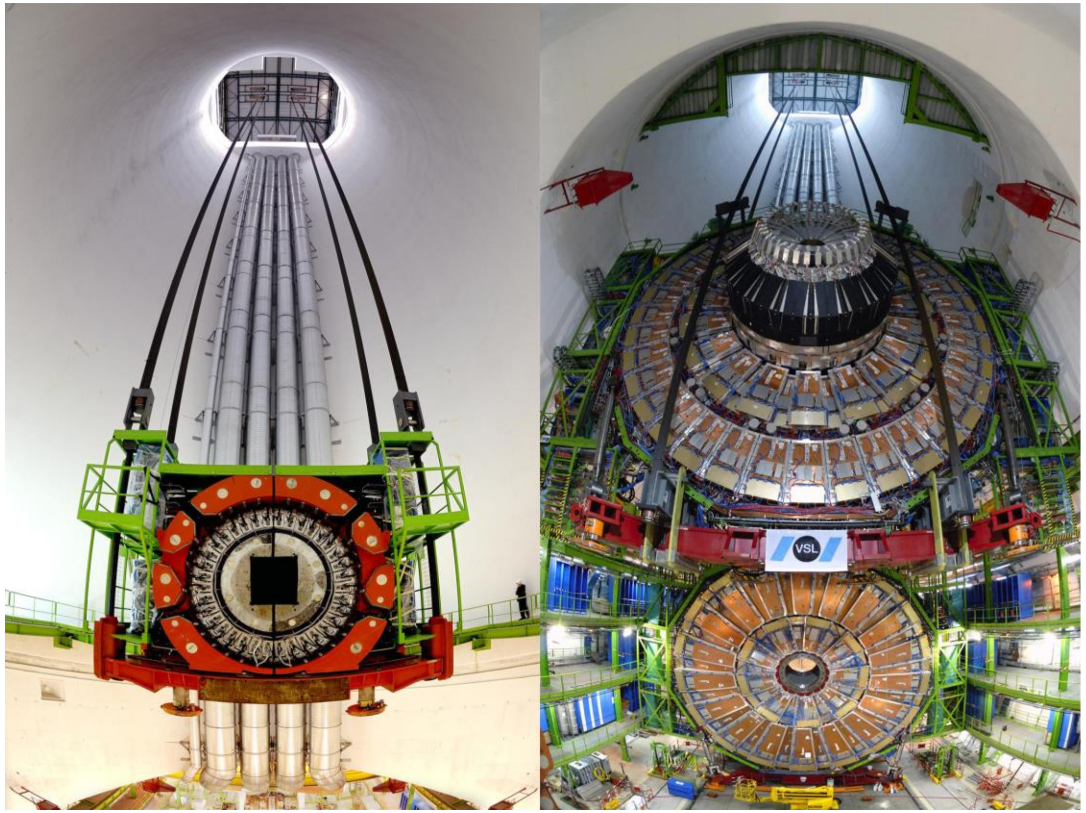


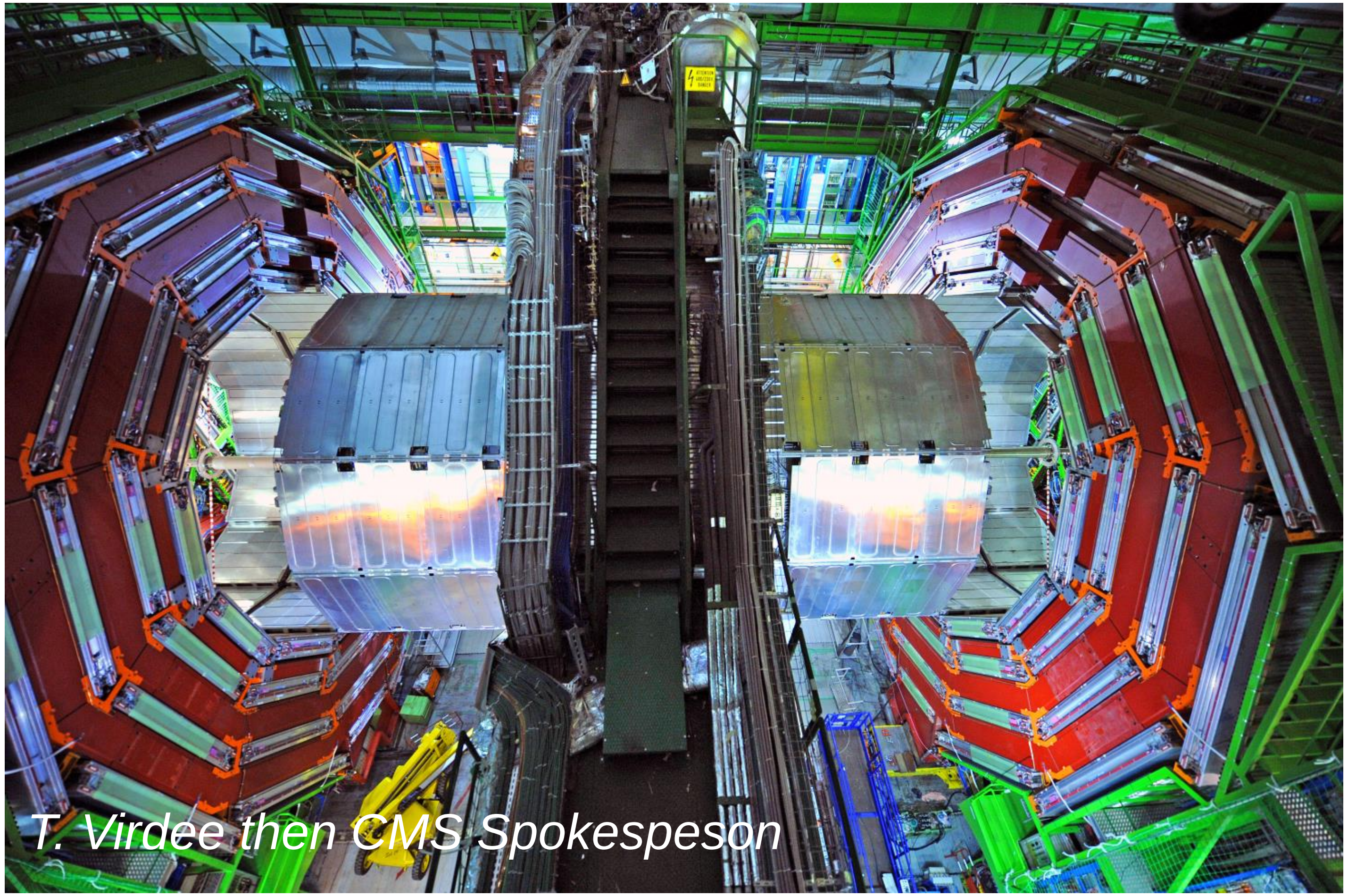




Engineering Design

CMS Cut in 13 slices; much of the assembly done in surface hall and slices then lowered





Some of the Enormous Challenges Faced During Construction of Phase 1 CMS Detector!

- **In addition to the efforts needed to obtain approval (LHCC, CERN, LoI, TP, TDR's, EDR's ….)**

G. Hall, C. Seez, T. Virdee *- conceptual design* ***slide shown at Higgs Hunting 2022, Paris.***

- Engineering design – assembly on surface, construction of the solenoid coil (1997-2006)

- ***Redesign of tracker f.e. electronics in 0.25 μm (1999) (G. Hall, M Raymond, P. Sharp)***
  (severe mid-course correction – thrown back to zero !)

- **Change to all-silicon tracker (1999)** ***(G. Hall, P. Sharp, T. Virdee)***

- **Redesign ECAL f.e. electronics in 0.25 μm technology (2001)- (severe mid-course correction – thrown back to zero !)** ***(G. Hall, M. Raymond, P. Sharp, T. Virdee)***

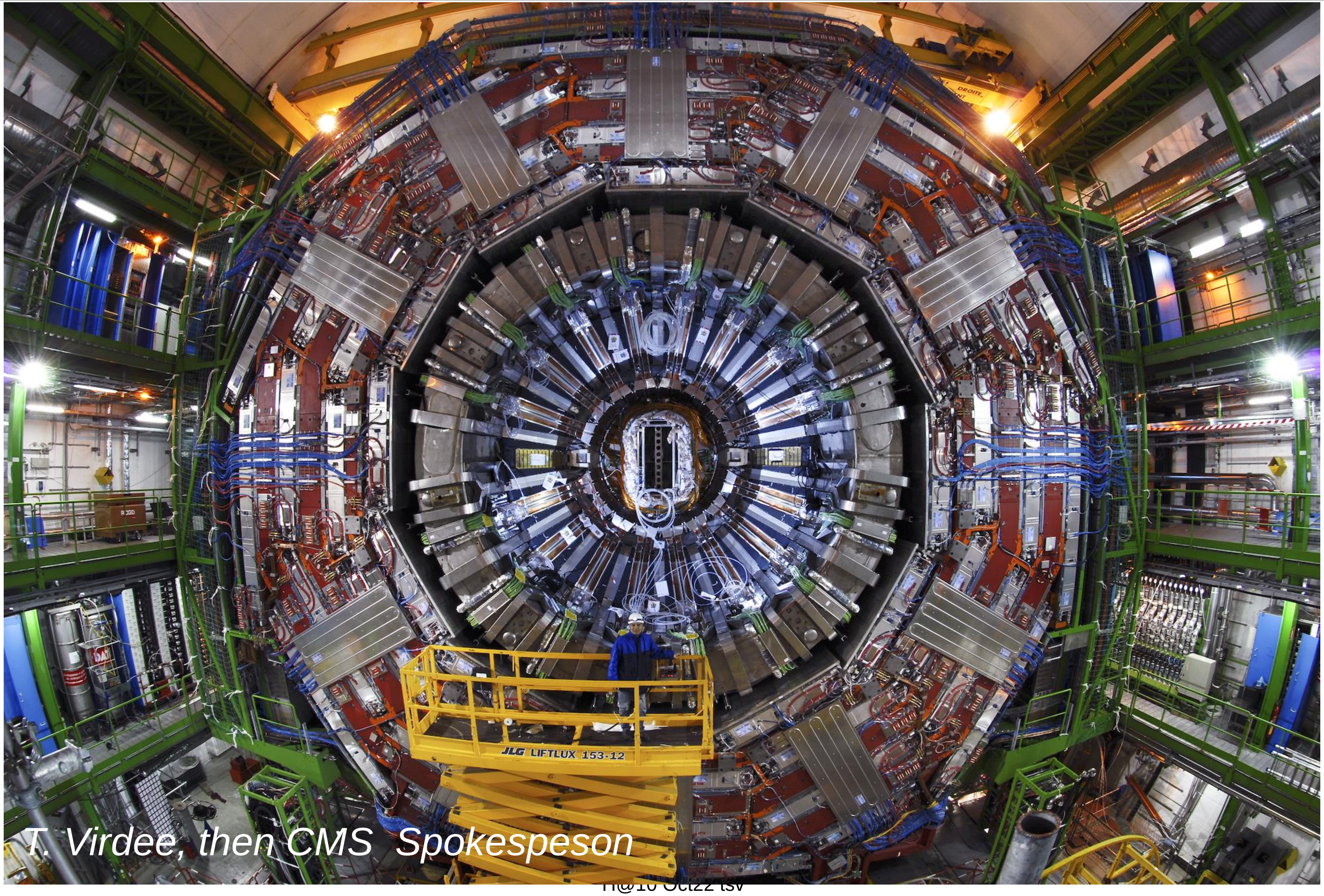
- Detector construction (revamping the Tracker and ECAL projects, production issues e.g. at a late stage all silicon sensors production shifted to HPK, ***crystals production (sizeable price increase) (T. Virdee)***, muon chambers factories...)

- Integration and installation (e.g. lowering of the experiment, installation of services on the coil e.g. limited space for lagging of cooling pipes for the tracker …) ***P. Sharp***

- **"Re-engineering" of reconstruction software (2005) & prepare CMS (SW/people) for physics extraction, *P. Sphicas*** *(our colloquium speaker)*

- ***Particle Flow reconstruction (2009)***

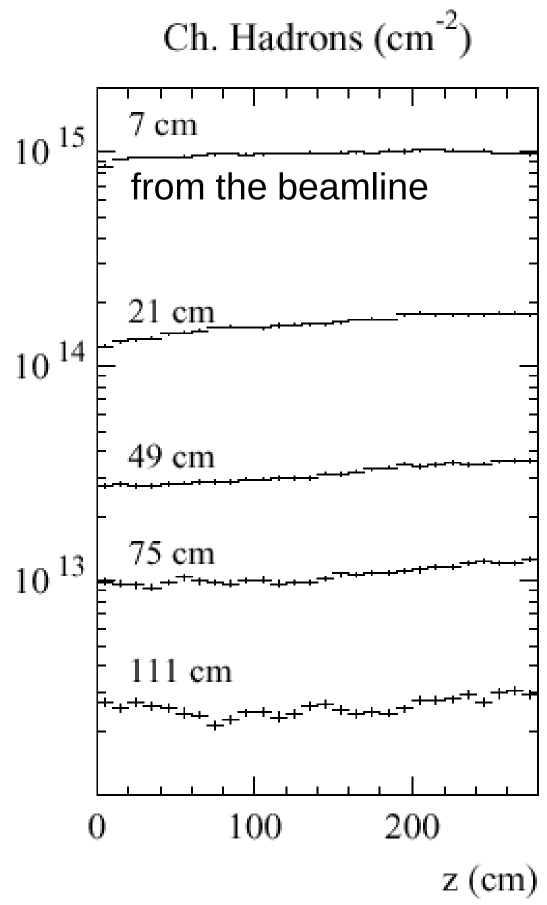
Early 2008: Almost Ready to Go!



T. Virdee, then CMS Spokespeson

Design of Inner Tracker

Fluence over 10 years

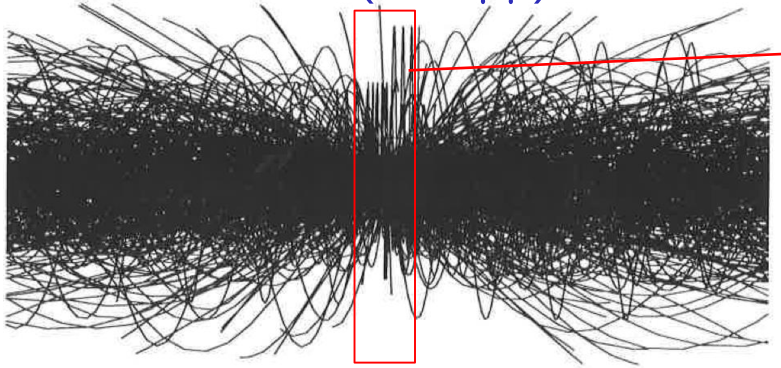


$\leq 4.10^7$ h$^\pm$/cm^2/s
pixels ($\approx 10^4$ μm^2)
occupancy $\approx 10^{-4}$

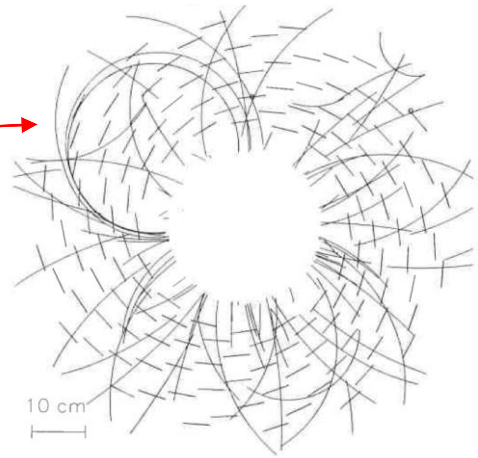
$\leq 4.10^6$ h$^\pm$/cm^2/s
Si μ-strip det.
($\approx$10 mm^2)
occupancy $\approx$ 1%

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

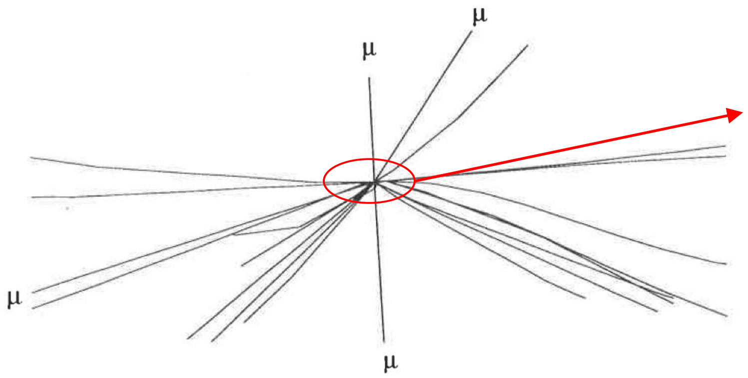
4T Field
30 min bias events +
H$\rightarrow$ZZ (Z $\rightarrow$ $\mu\mu$)

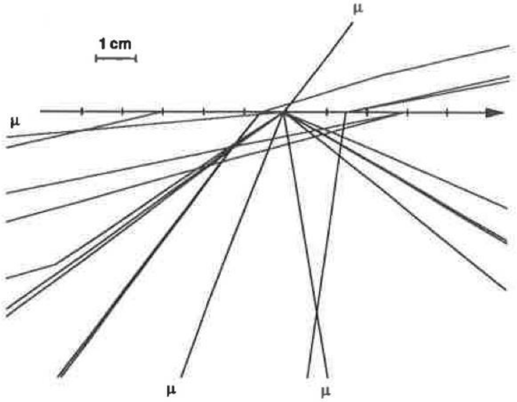


10 cm slice (in z)



All charged tracks within $|\eta| < 2.5$





Reconstructed p_T > 2GeV

CMS: Inner Tracking

Parameter	ATLAS	CMS
Dimensions (cm)		
-radius of outermost measurement	101–107	107–110
-radius of innermost measurement	5.0	4.4
-total active length	560	540
Silicon microstrip detectors		
-number of hits per track	8	14
-radius of innermost meas. (cm)	30	20
-total active area of silicon (m^2)	60	200
-wafer thickness (microns)	280	320/500
-total number of channels	6.2×10^6	9.6×10^6

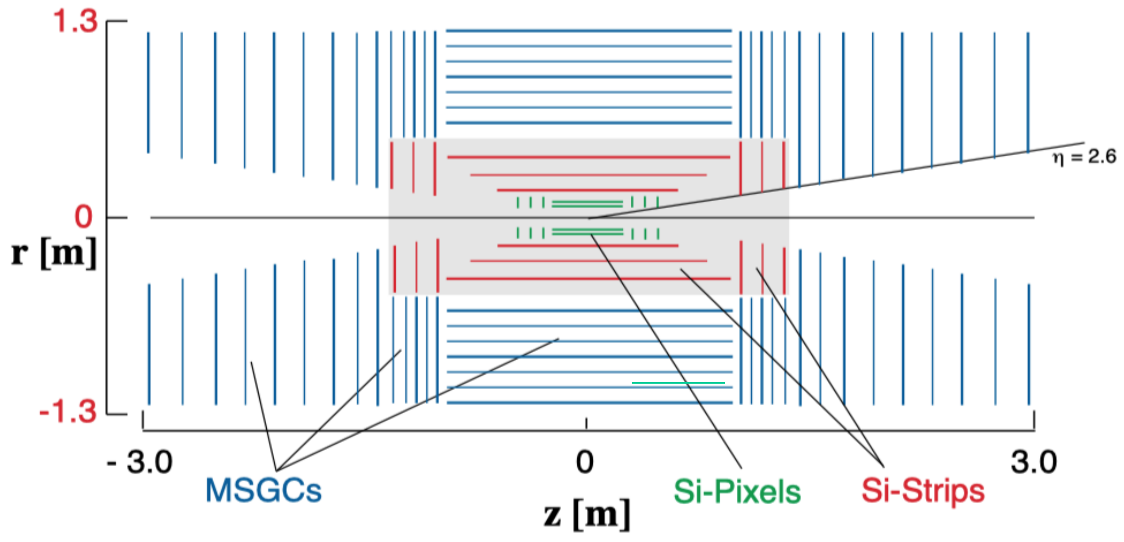
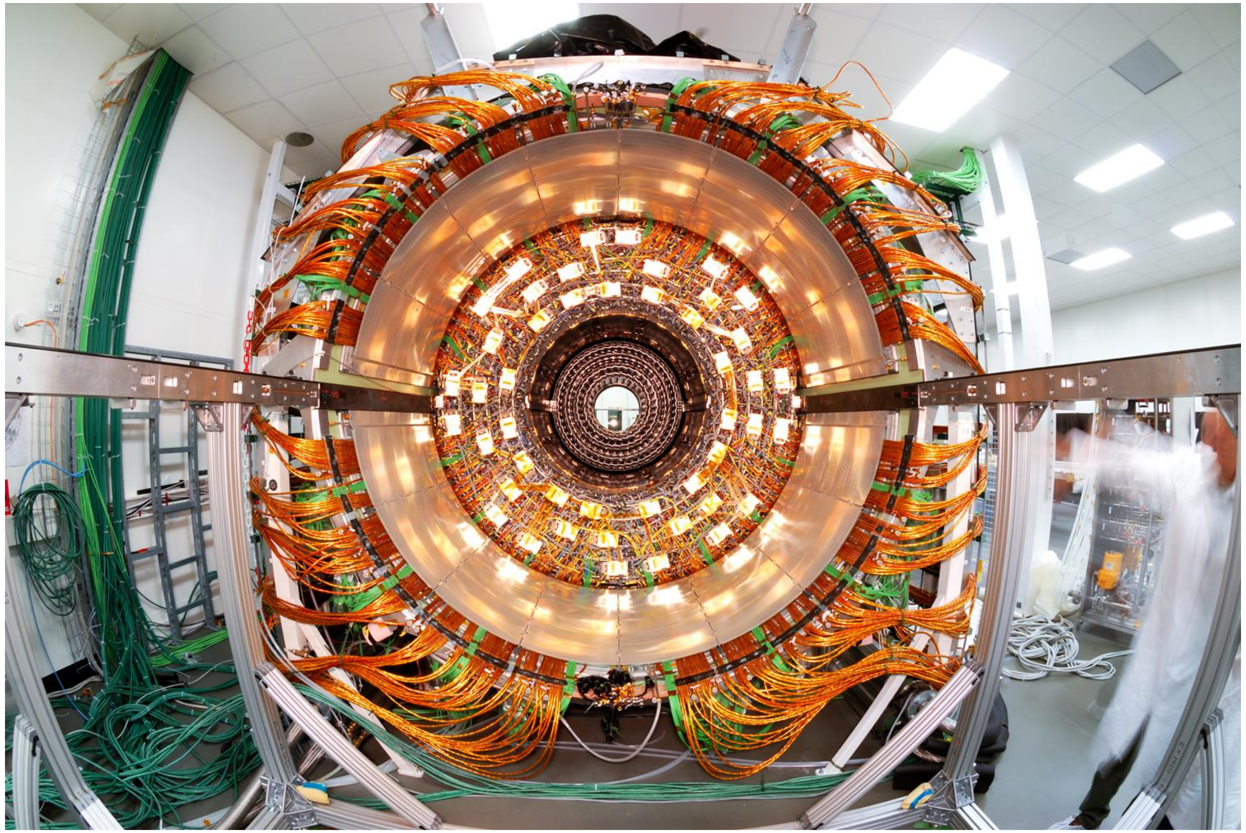
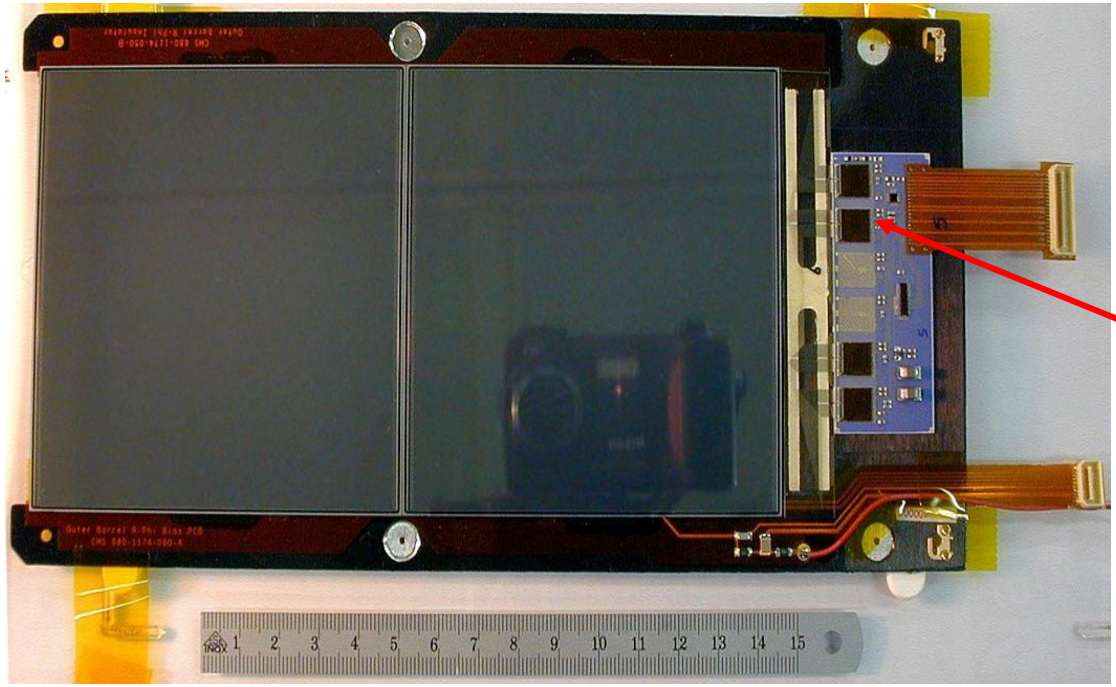
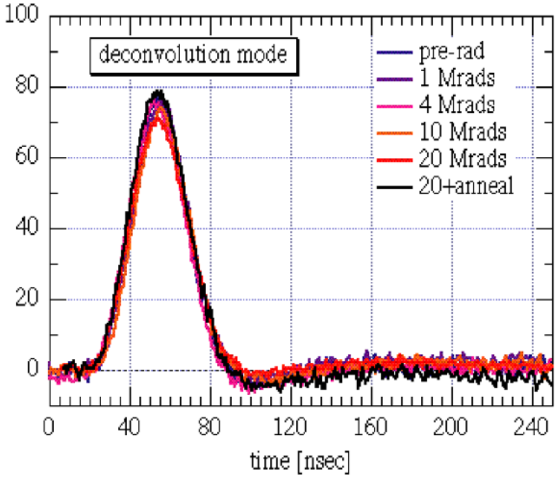


Fig. 3.1: Schematic of inner tracker. Thick lines denote double-sided readout.



Si Modules and Electronics Chain

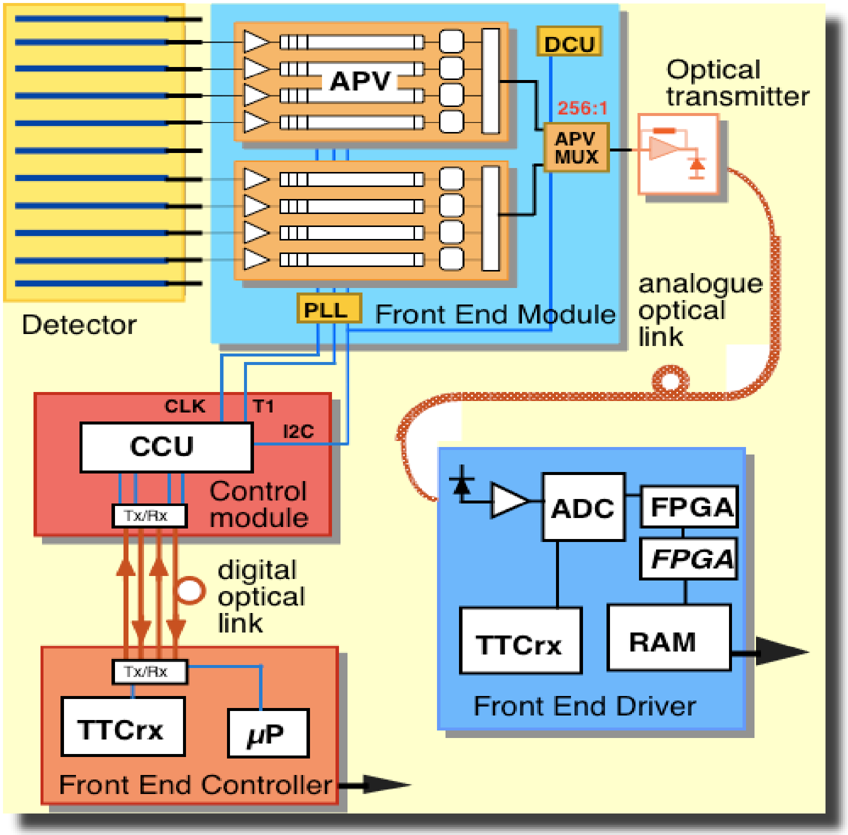




Riding the technology wave

G. Hall, M. Raymond, P. Sharp

75k chips using
0.25μm technology



Tracker fe -ASIC: a mid-course correction

CMS – deep sub-micron technology

- **1997 – front-end chip (APV) for Si microstrip tracker had been finalized and radiation tested, and was ready to go into production**
- **Vendor decided to produce the chip in a new foundry (a commercial decision)**
- **Radiation hardness was no longer sufficient for chips produced in the new foundry**

- Some far-sighted engineers advocated use of a new 0.25μm technology (many advantages: commercial technology, faster turnaround time, higher yield, lower cost)
    - A CERN staff member had gone on a sabbatical to IBM New York – to study trends in industry
    - With some design tricks this technology was shown to be rad-hard
    - CERN (A. Marchioro), RAL (M. French, P. Sharp) and Imperial (G. Hall, M. Raymond) developed/prototyped ASICs in this new technology
- After much internal discussion, decision made to proceed - 100k chips manufactured (2000-2004)

Many technical advantages followed such as lower costs, faster turnaround between design iterations, lower intrinsic noise levels and lower power consumption. **Riding this technology wave allowed costs to be contained in an area that otherwise carried a very high risk.**

2005 IOP Duddell Medal

Geoff Hall, Imperial College London; Alessandro Marchioro, Cern; Peter Sharp, RAL/Cern, for their development of "radiation hard" analogue electronics for silicon detectors, enabling their use as a means of precision detection and measurement of charged particle production at the Large Hadron Collider.

Another example of Challenging Technologies:
ECAL: Development of Lead Tungstate Crystals

Physics Driving the Design
Measure the energies of photons from a decay of the Higgs boson to a precision of ≤ 0.5%.

Idea (1993 – few yellowish cm^3 samples)

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

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

→ **Mass manufacture (1997-2008: increase production capacity, introduce QA/QC)**

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

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

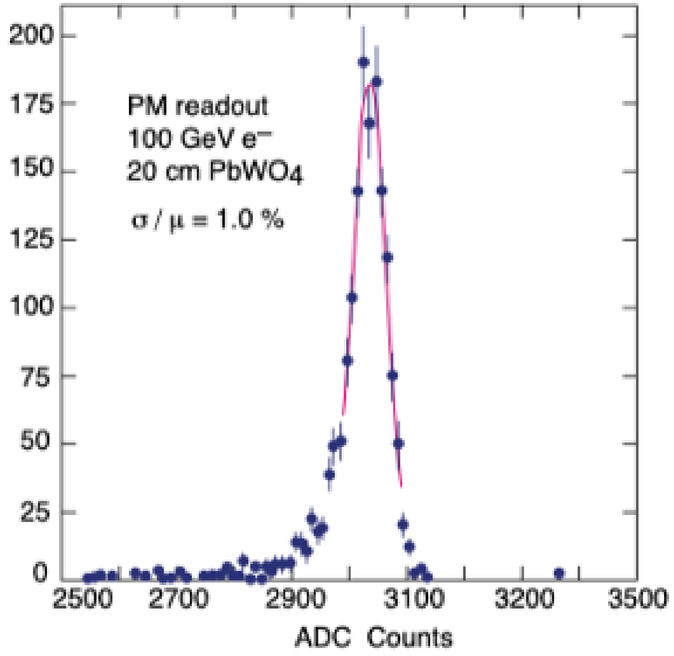
→ **Collision Data Taking (2009 onwards)**

→ **Discovery of a new heavy boson (2012)**

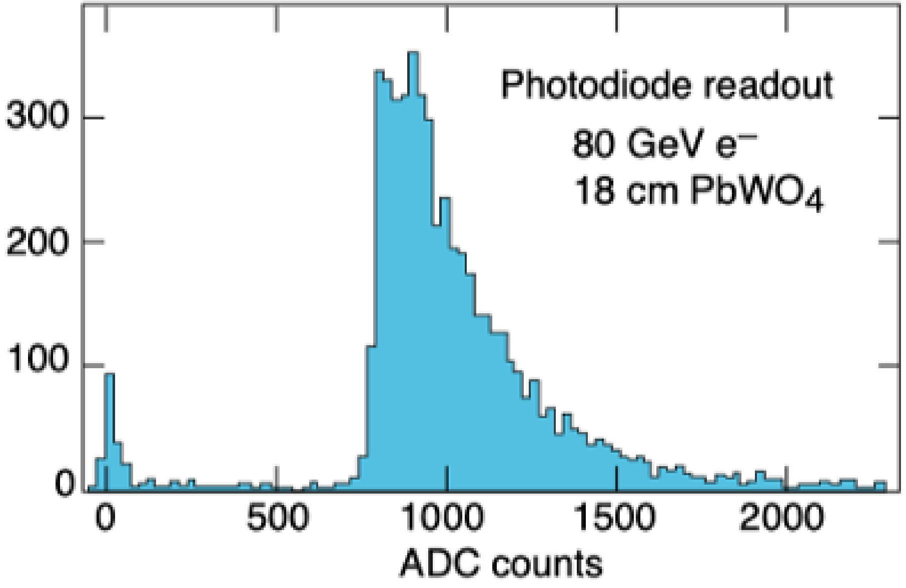
Idea to Discovery
Δt ~ 20 years !!!

Example of Challenging Technologies:
Development Photodetectors for ECAL: APDs

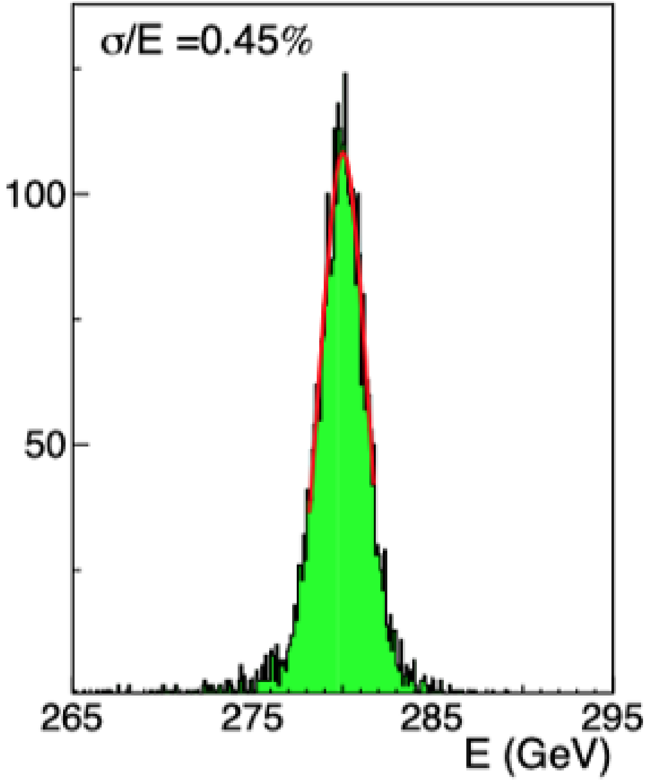
Photomultiplier Readout



Si Photodiode Readout



Avalanche Photodiode Readout

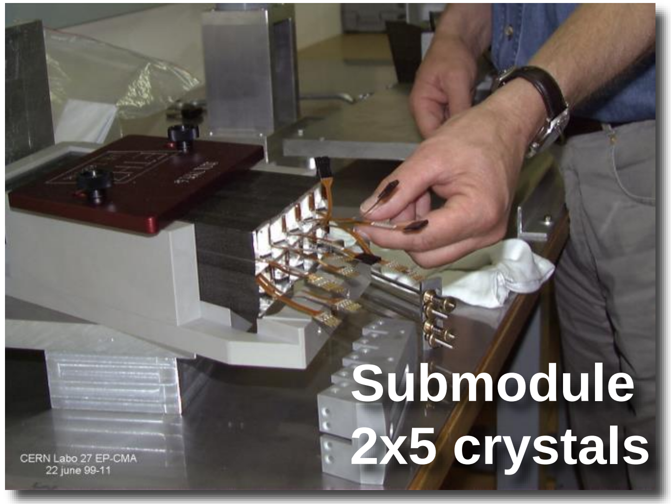


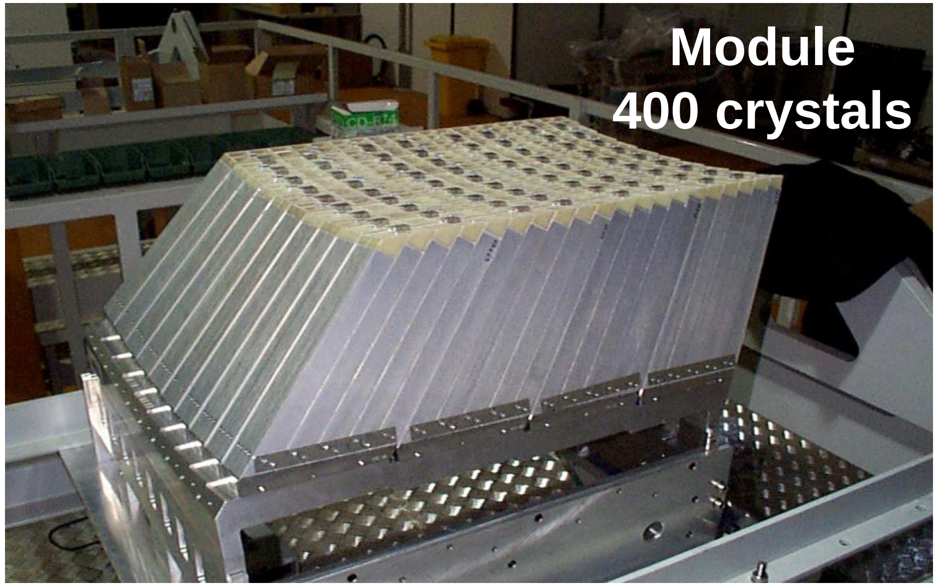
C. Seez, T. Virdee

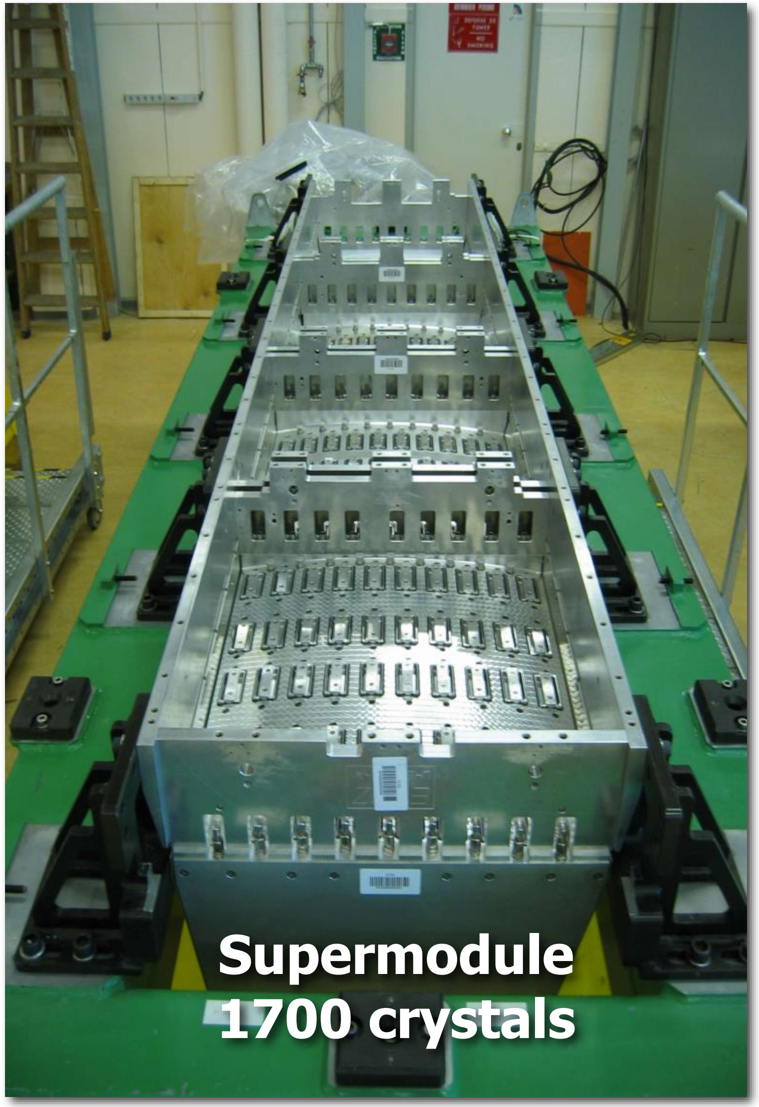
Slide from mid-90's

Imperial College London

CMS Electromagnetic Calorimeter:
Lead Tungstate Scintillating Crystals





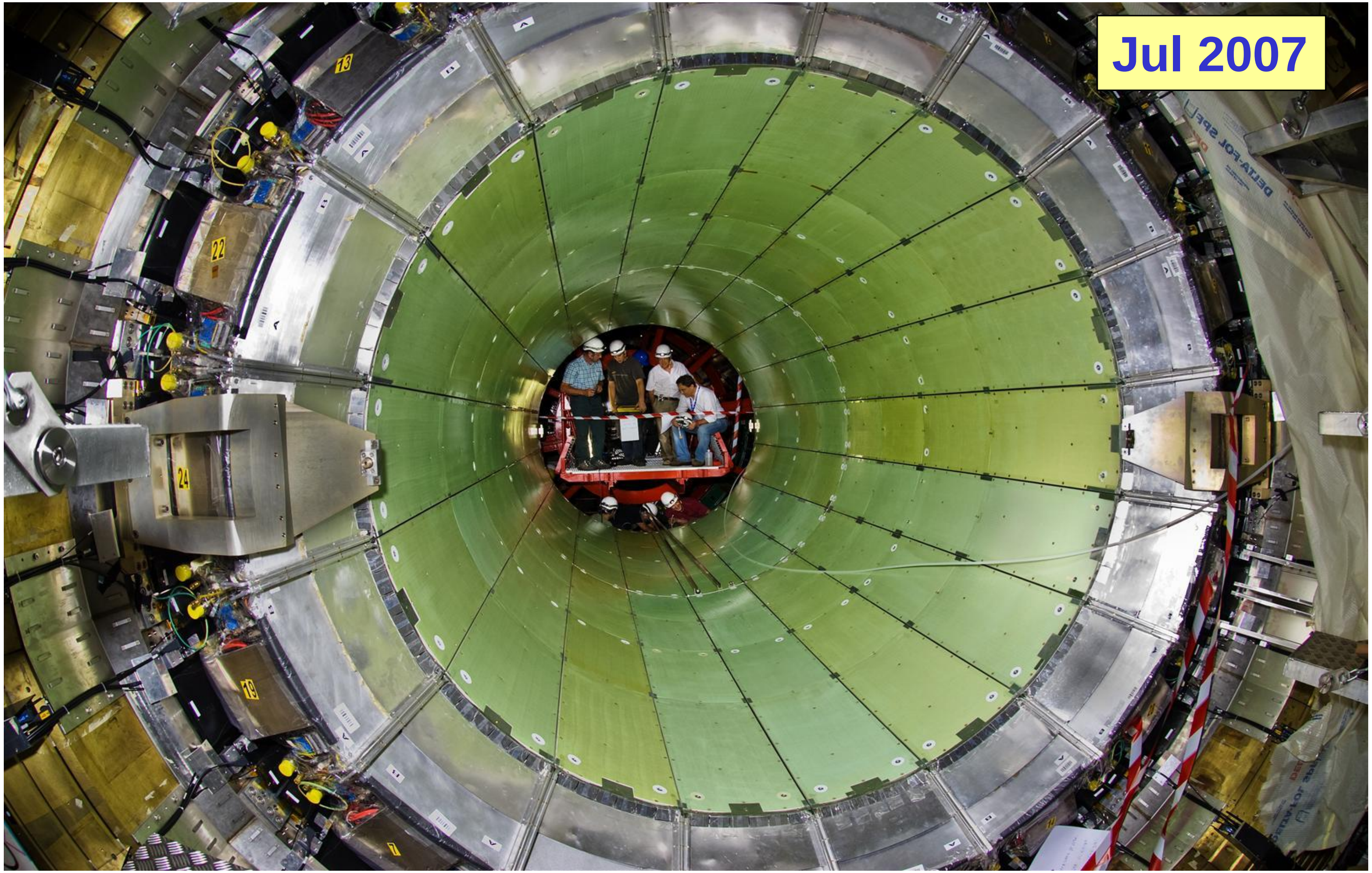


Total 36 Supermodules

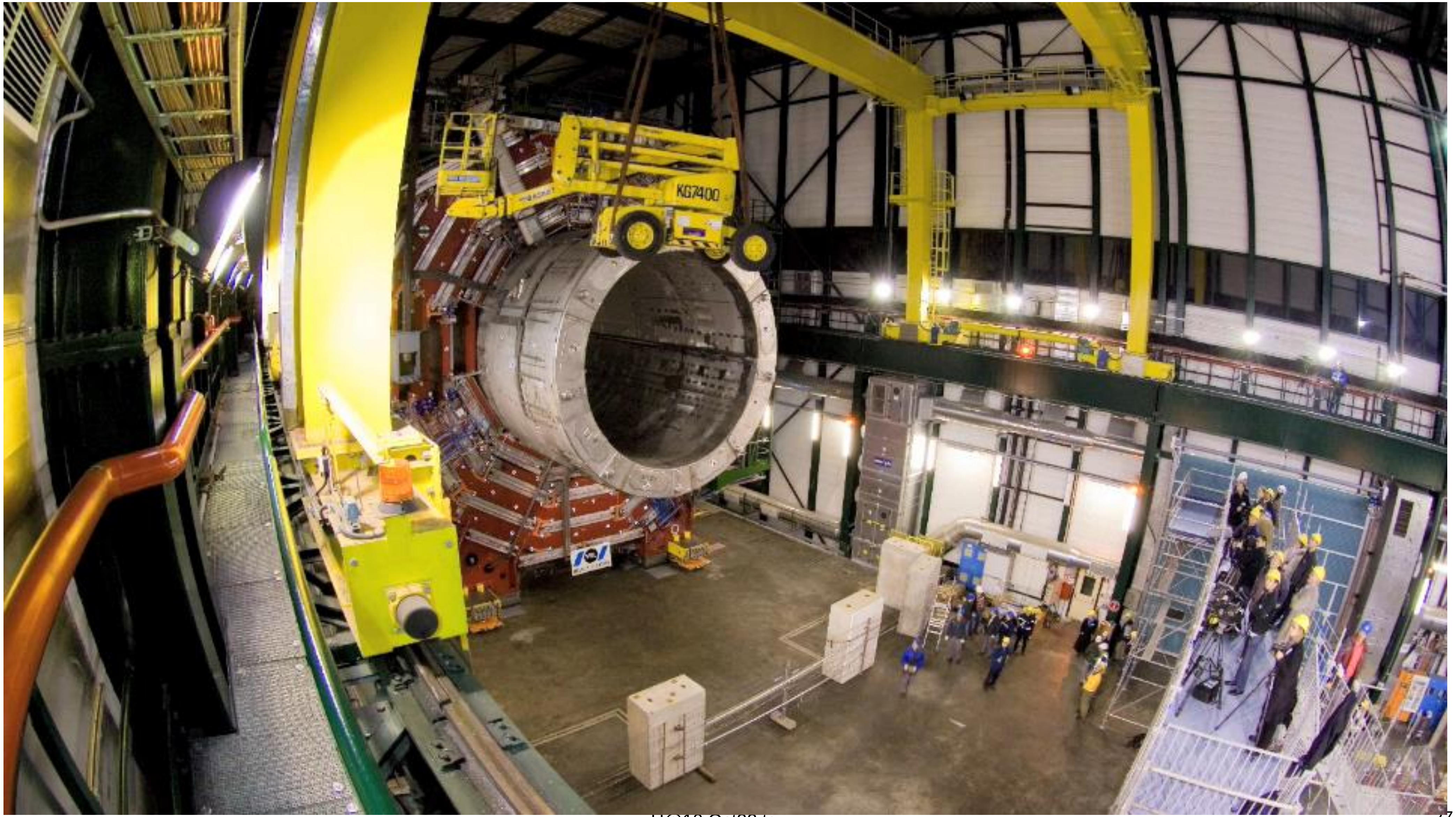
Imperial College London

CMS Electromagnetic Calorimeter:

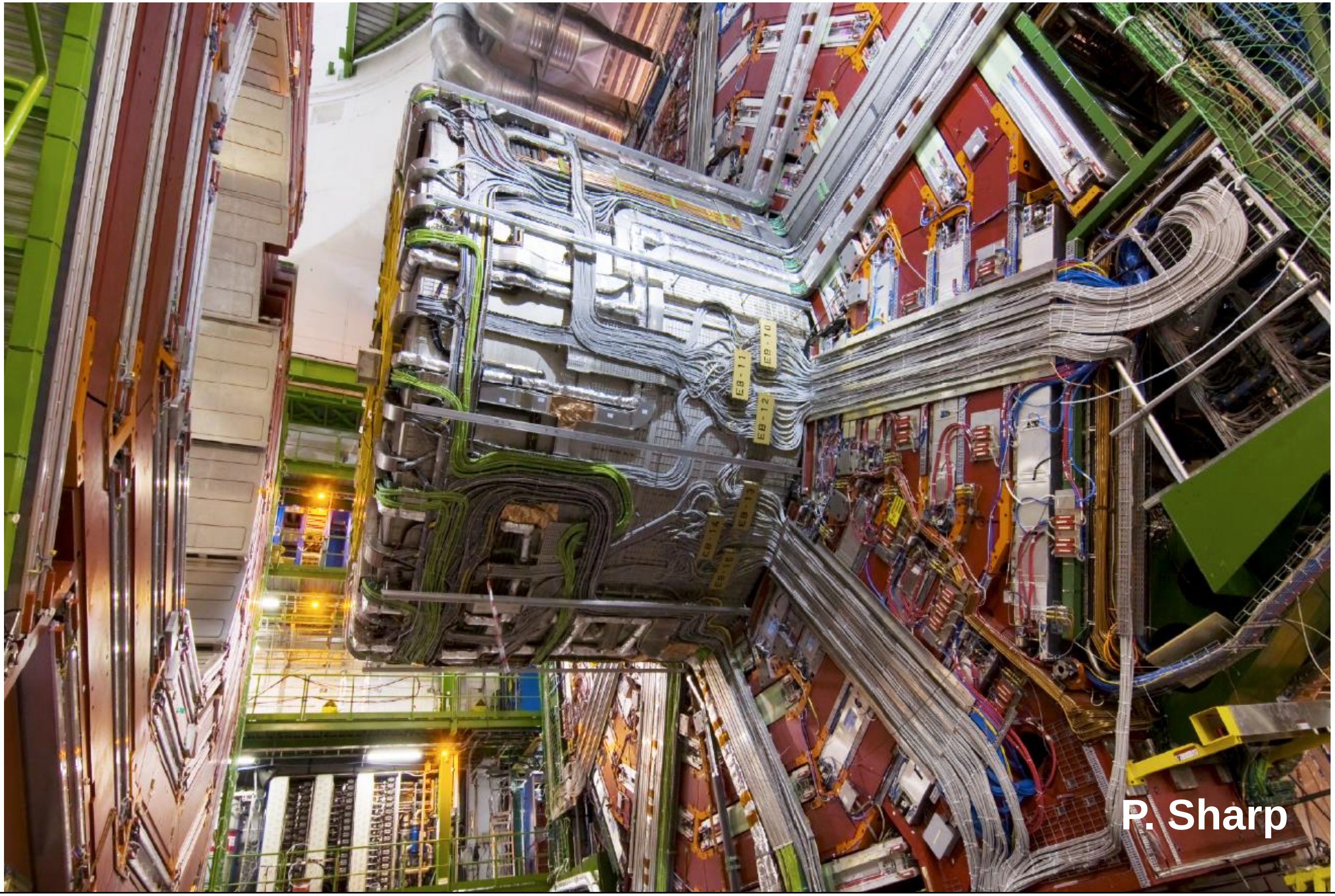
15 years from Concept - Installation



Extreme Engineering ! (Feb. 2007)



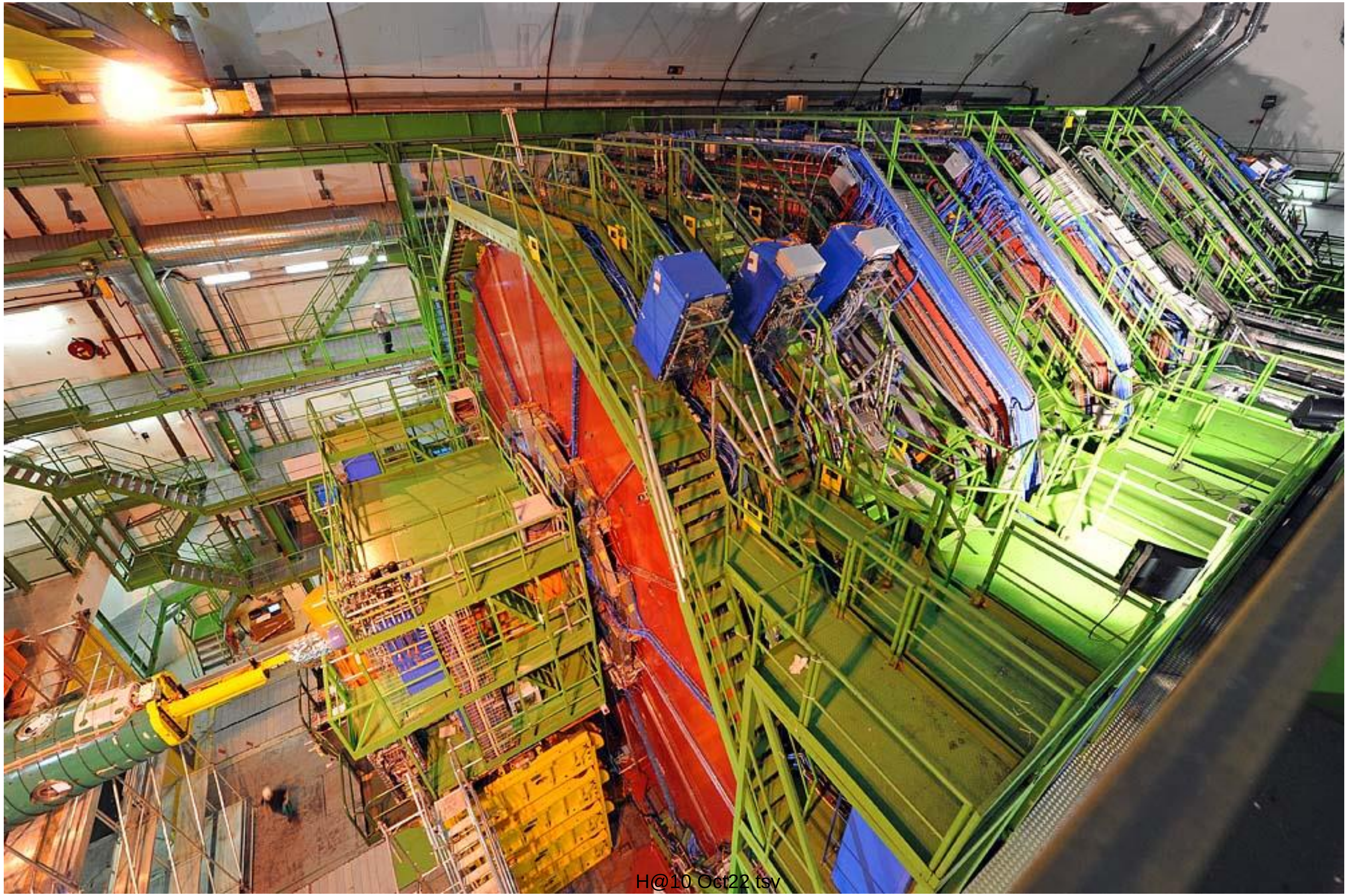
The Challenge of Services !



Nov. 2007

CMS: Services (cooling, LV, HV, optical fibres,…) for the Tracker, Barrel ECAL & HCAL

First Closing of the CMS Detector in UX5 (2008)

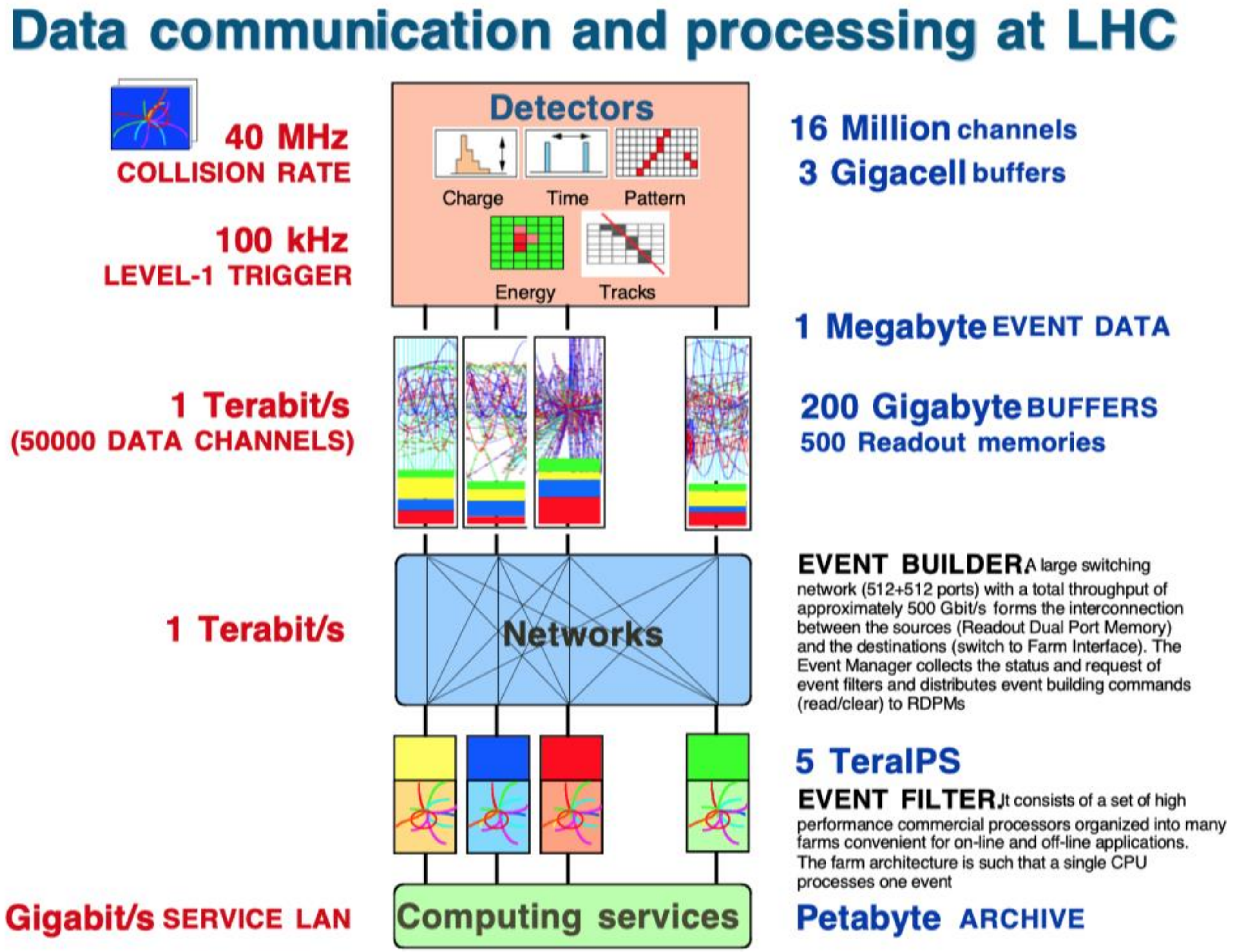


Triggering and Data Acquisition System

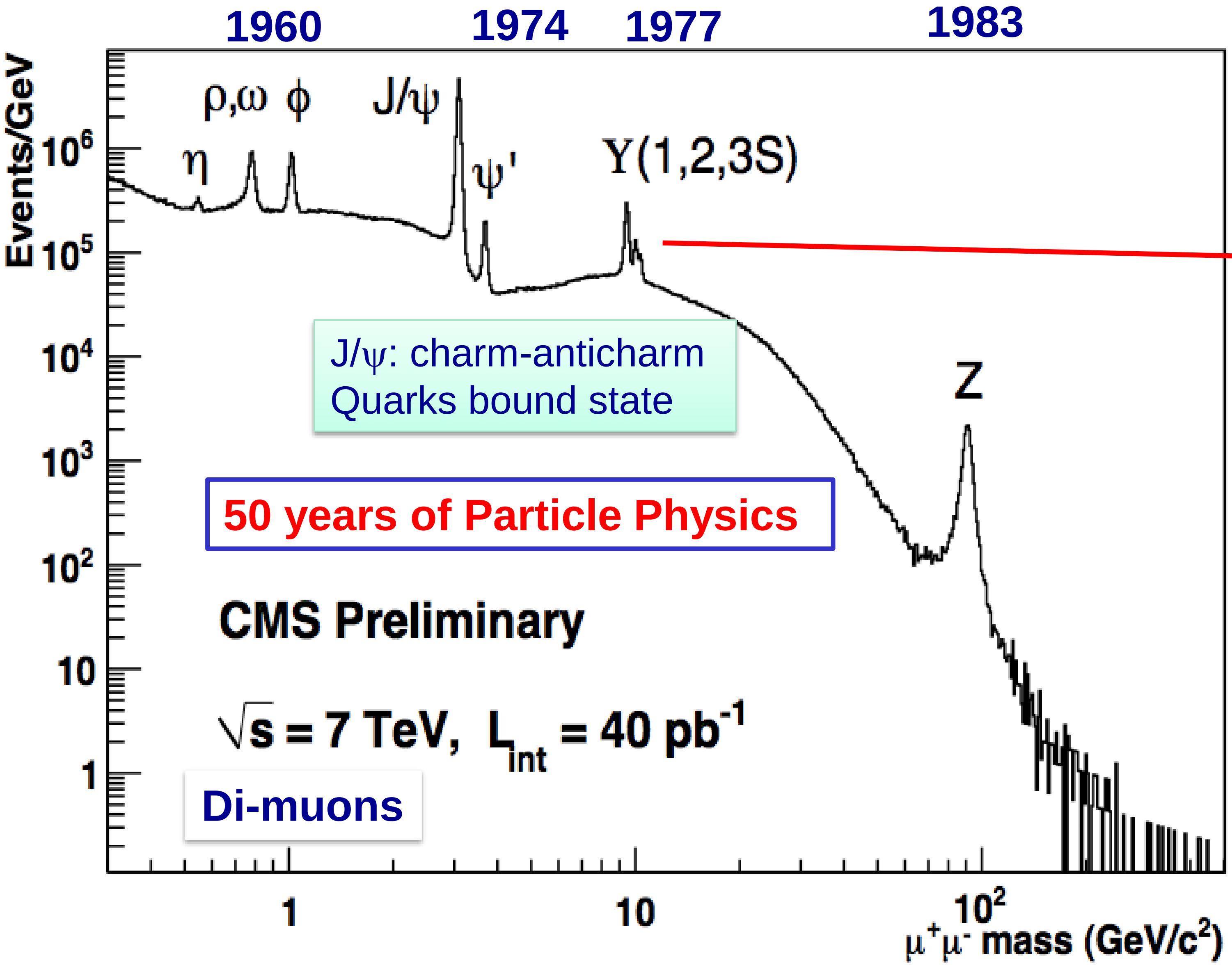
Critical Choice: Forego 2nd level of hardware trigger.
L1 triggered events data goes straight into a HLT CPU farm.

Level-1 Trigger
C. Foudas, A. Rose, G. Illes, A. Tapper, G. Hall
Introducing time-multiplexed calorimeter Level-1 trigger - analyse data from the whole calorimeter

Computing Tier 2
D. Colling et al.



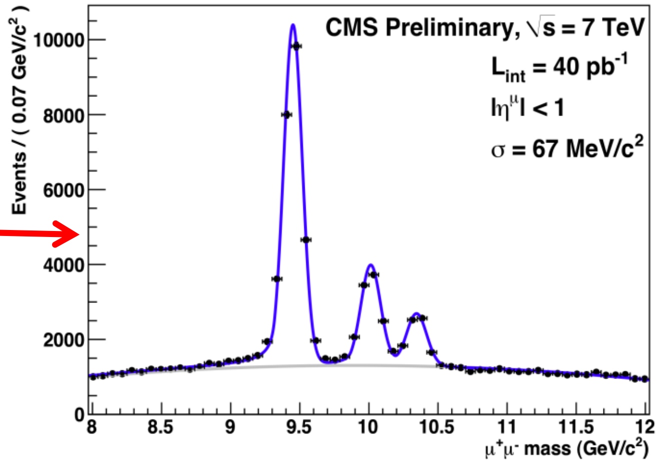
To the Science - Do experiments perform as designed?



J/ψ: charm-anticharm
Quarks bound state

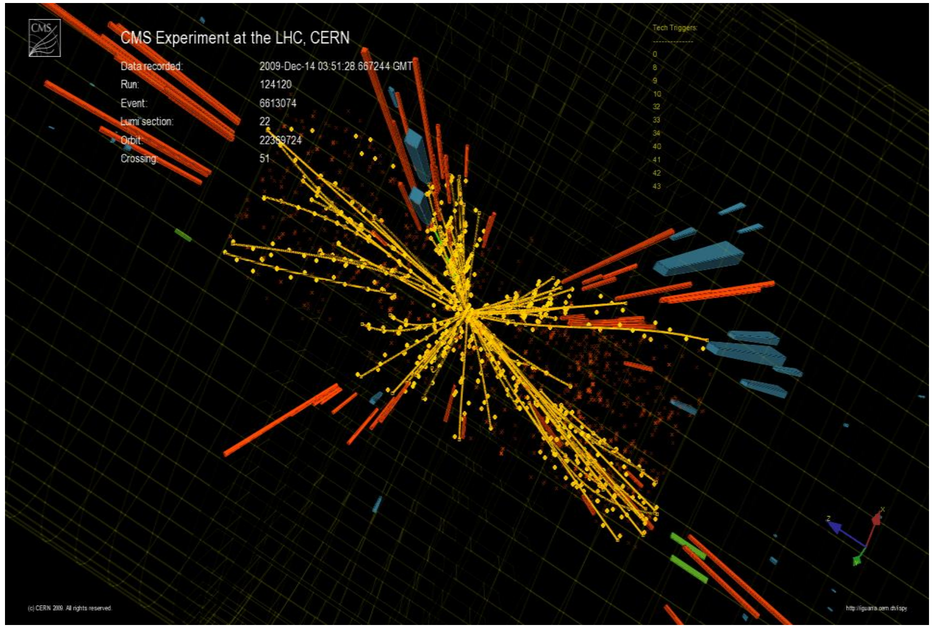
50 years of Particle Physics

Di-muons

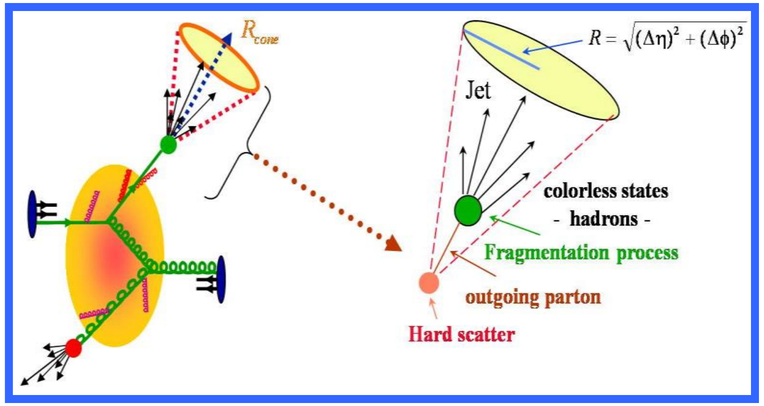


Υ: bottom antibottom
Quarks bound state

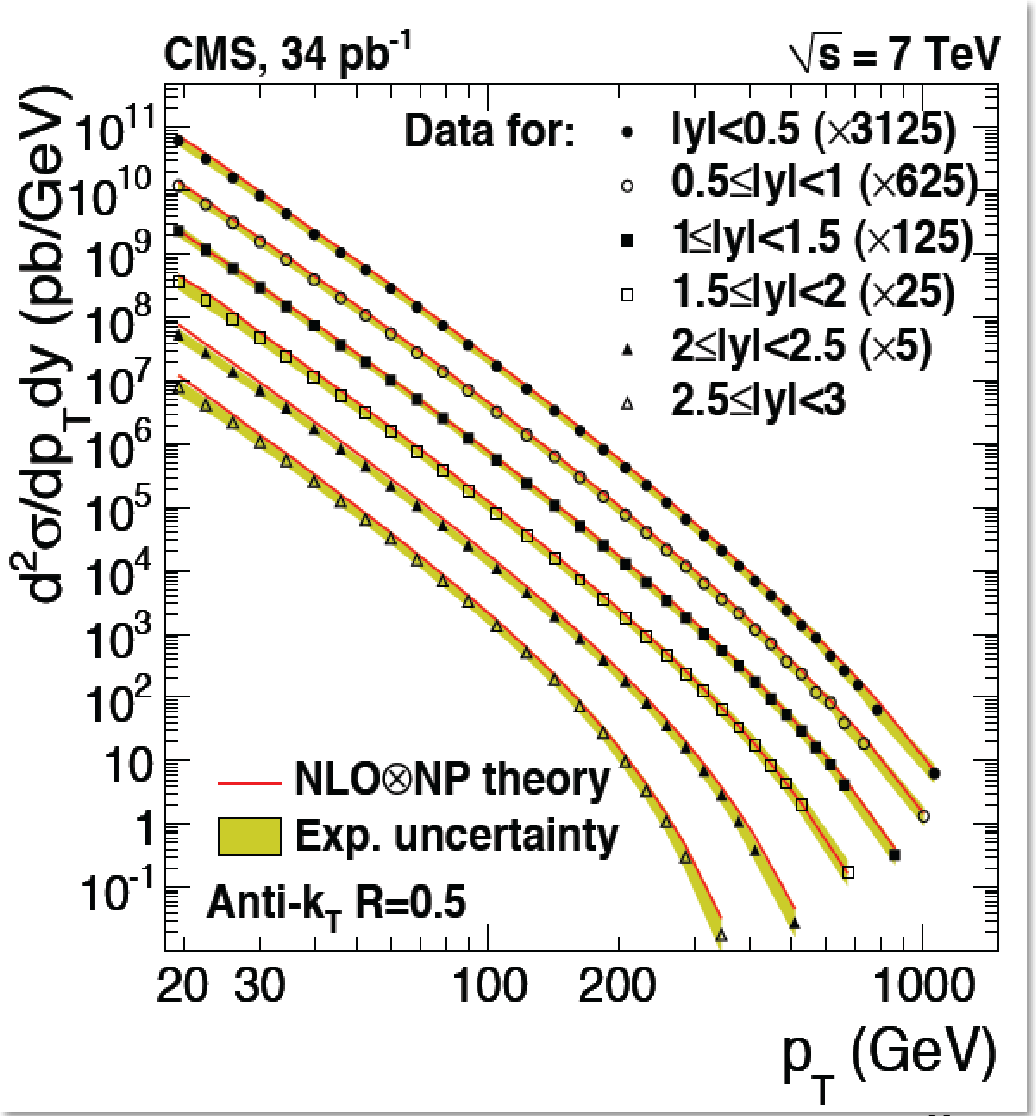
Is known physics correctly reproduced ?



Routinely and successfully analyse many hard collisions in terms of quarks and gluons

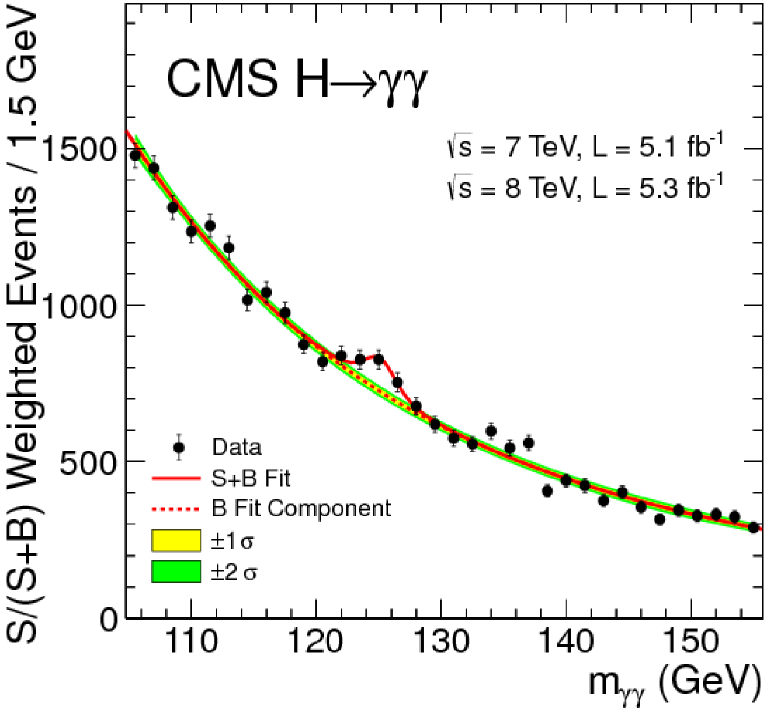


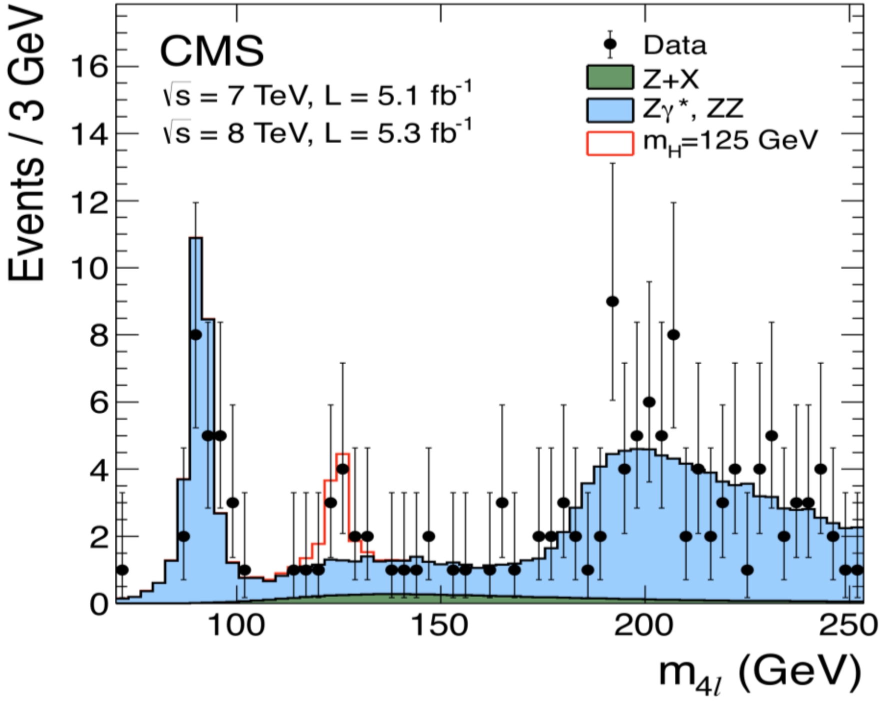
One month of data in 2010

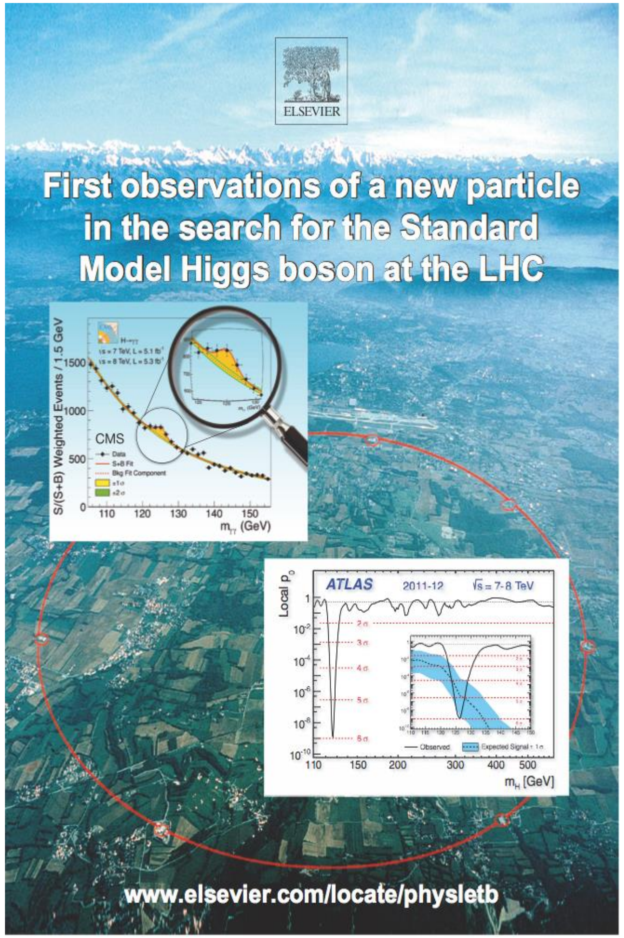


Discovery !

G. Davies, P. Dauncey, C. Seez,
T. Virdee, N. Wardle et al







CMS Local significance
Expected: 2.8σ
Observed: 4.1σ

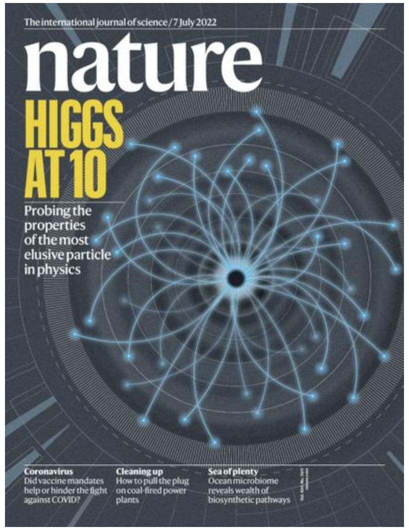
ATLAS Local significance
Expected: 2.4σ
Observed: 4.5σ

CMS Local significance
Expected: 3.8σ
Observed: 3.2σ

ATLAS Local significance
Expected: 2.6σ
Observed: 3.4σ

4 CMS editors incl.
C. Seez &
Main Editor: T. Virdee

Situation Ten Years Later …

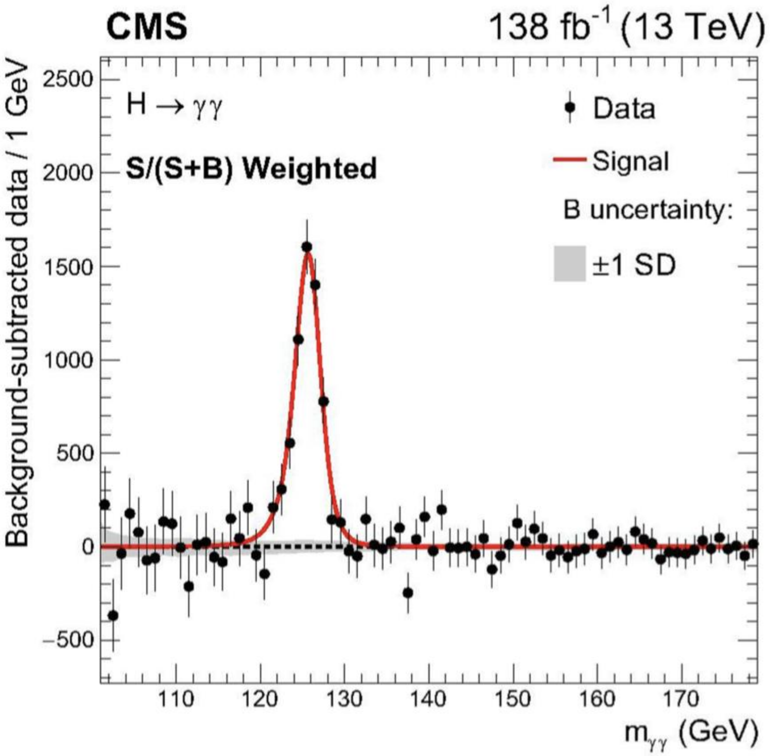


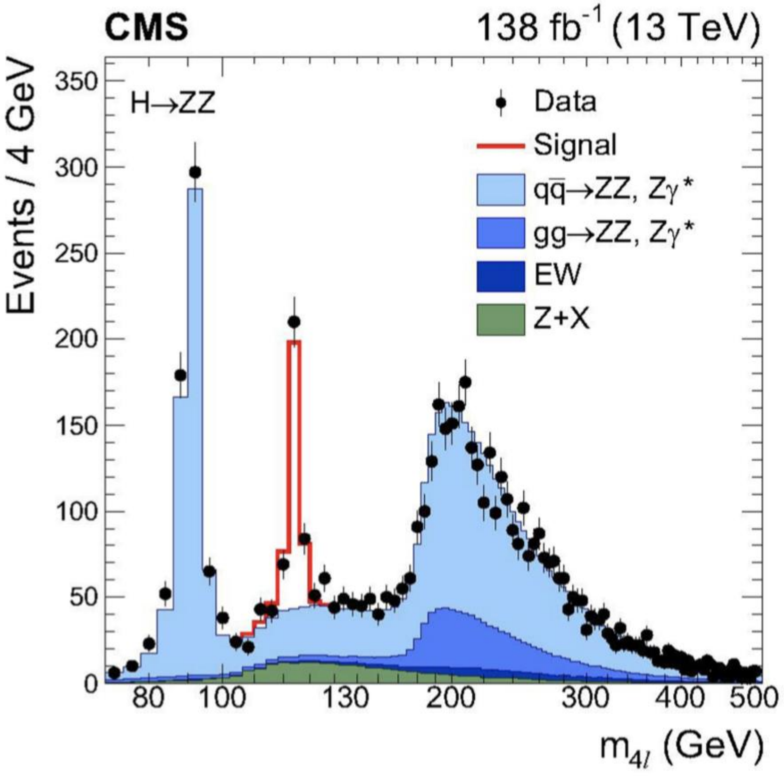
Nature 4 Jul 2022
4 CMS editors
Main Editor: T. Virdee

Article

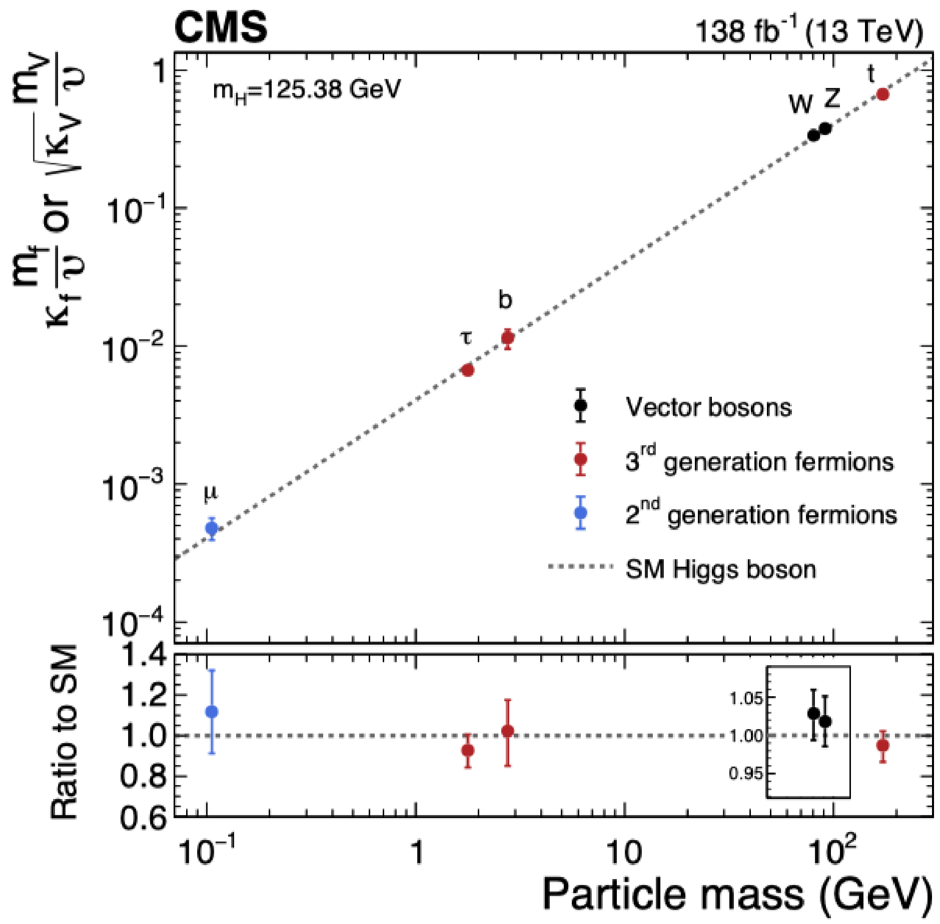
A portrait of the Higgs boson by the CMS experiment ten years after the discovery

https://doi.org/10.1038/s41586-022-04892-x
The CMS Collaboration[1]✉
Received: 21 March 2022





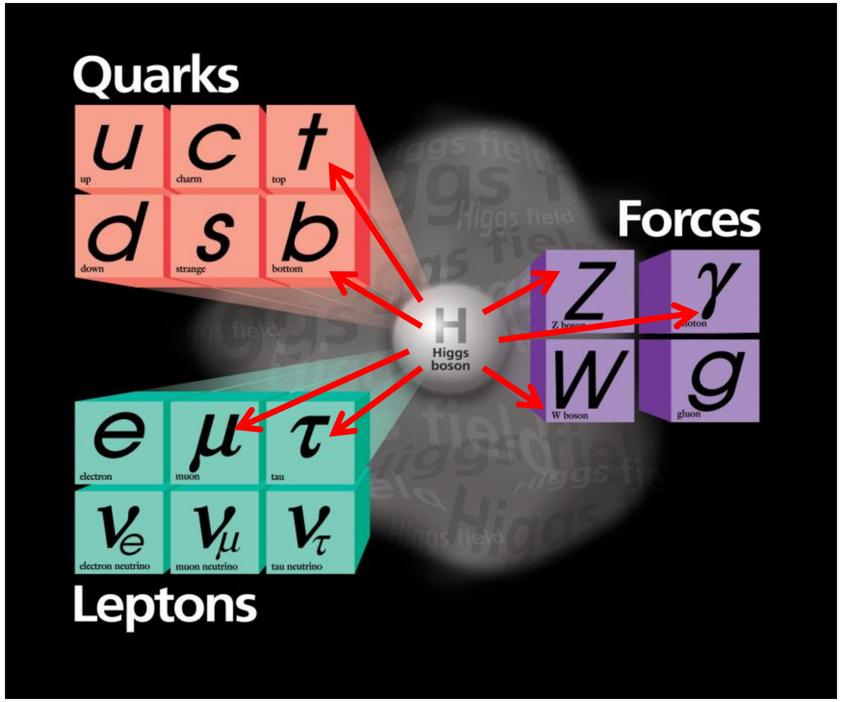
Situation Ten Years Later: Summary



H coupling amplitudes for
Fermions $\alpha\ m_f$
Bosons $\alpha\ M_V^2$
Consistent with SM predictions

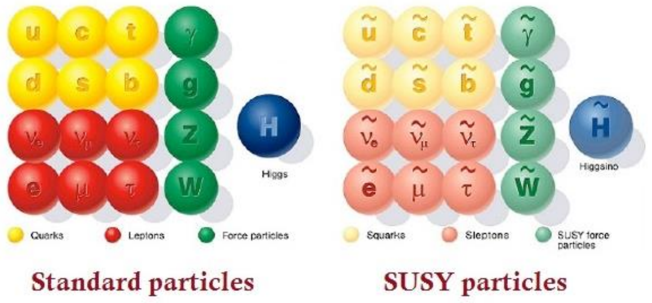
Recall
CMS TP(1994) did not include the search for the low-mass Higgs boson via the following decay modes

H→ bb
H→ ττ (D. Colling, A. Nikitenko et al)
H→ WW
H→μμ



Physics Beyond the SM: Conjectures

Supersymmetry (SUSY)



Intimately relates matter particles and force particles.

SUSY predicts the existence of a partner for every known SM particle with spin differing by half a unit and 5 Higgs bosons!

The lightest particle of this species is a candidate for dark matter
Would address the issue of the "lightness" of the Higgs boson.
Alas, no evidence has yet been found (O.Buchmuller, R. Bainbridge, S. Malik, P. Sphicas et al.)

Superstring Theory

Can gravity be unified with the other forces? Supersymmetry helps.

Extra Dimensions

Number of space-time dimensions determines the observed form of a force
Tell-tale signs are new heavy Z-like particles.

Translation to Phase 2 CMS Detector Design

New higher granularity more radiation hard inner trackers

G. Hall, M. Raymond, J. Borg

x10 more channels; sensors, f.e. electronics, 10 Gb/s data-links have to withstand doses of up to 500 Mrad and fluences of 10^{16} n/cm^2. $|\eta|$ coverage up to 4. Introduce Track Trigger in L1.

Replacement of components affected by radiation

Electromagnetic calorimeter - new electronics (read each crystal independently, improve timing resolution)

Endcaps calorimeter: new high granularity "imaging" calorimeter with timing info. (HGCAL) withstand doses of up to 500 Mrad and fluences of 10^{16} n/cm^2

C. Seez, P. Dauncey, G. Davies, T. Virdee

Higher bandwidth L1 triggers and DAQ

- Introduce Track Triggers in L1
- Higher L1 output rate [e.g. 100→750kHz and latency (>10μs)]
- Enhanced trigger processors (ASIC-based → FPGA-based).
- DAQ recording rate 1000→10k evts/s

**A. Rose, G. Illes,
M. Pesaresi, A. Tapper, G. Hall**

Replacement of other front-end electronics (muon system, VFCal)

Deal with higher rates, longer pipelines (e.g. >10 us)

Introduction of precision timing of minimum ionizing particles (e.g. MTD)

Vertex localization, pileup suppression, slow charged tracks, …

In red – defining contributions from Imperial scientists

Summary

- Members of Imperial College HEP Group have played seminal roles in CMS' design, construction and the extraction of physics, especially the discovery of the Higgs boson.
- They were at the forefront when overcoming the many challenges during CMS' construction.
- CMS has performed, & is performing, much better than their designers could have dreamed.
- The Higgs boson was discovered much earlier than anticipated and has been seen in channels which were thought impossible. It appears to be the one predicted by the SM. Now it is being studied in great detail.
- No evidence has yet been found for widely anticipated NEW physics, though there are hints.
- However, we are just at the start of the exploration of the Terascale. CMS will be upgraded to draw full benefit from the LHC Project, aiming to collect data corresponding to ten times larger integrated luminosity than originally foreseen.

- What further discoveries await us?
- Several of the open questions today are just as profound as those a century ago.
- LHC remains the foremost place to look for new physics and is fertile ground for young scientists.

Only experiments reveal/confirm Nature's secrets

Epilogue

5th July 2012

Acknowledge the contributions of all the members of the CMS Collaboration