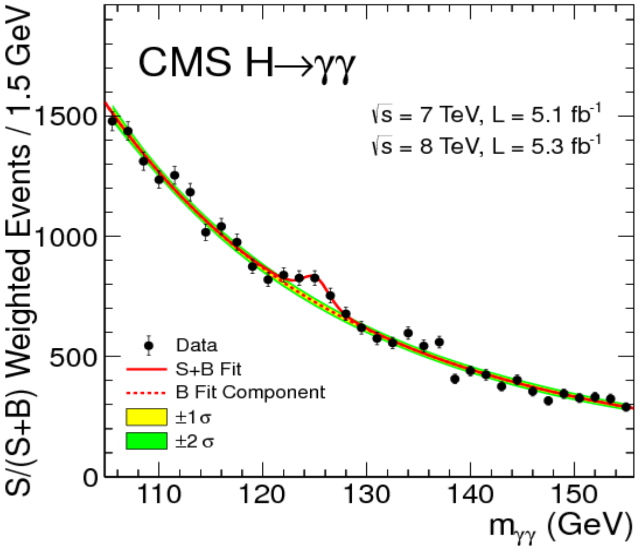
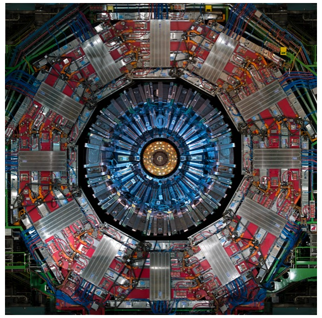
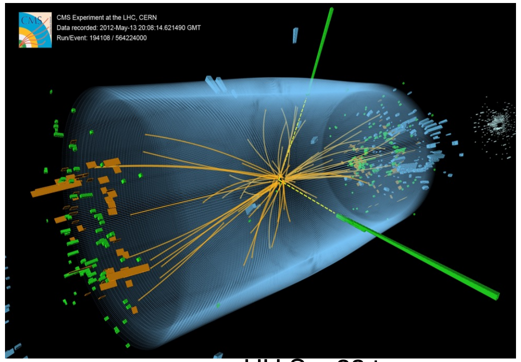
Imperial College London

Higgs Hunting 2022

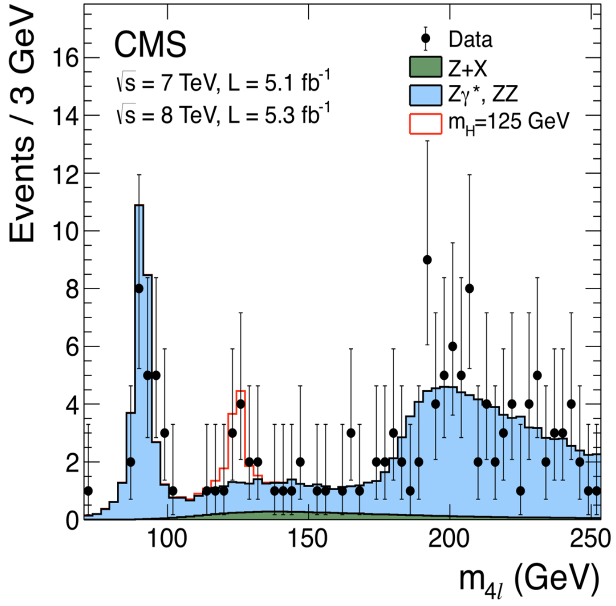
The Higgs boson Turns 10: CMS' Journey







HH Sep22 tsv



Tejinder Singh Virdee

Our Journey: As Seen by the Outside

During Construction

Upon Discovery

Physics Drives Detector Design

Questions wrt Hadron Colliders

1. SM 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, $M_Z \sim 100$ 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

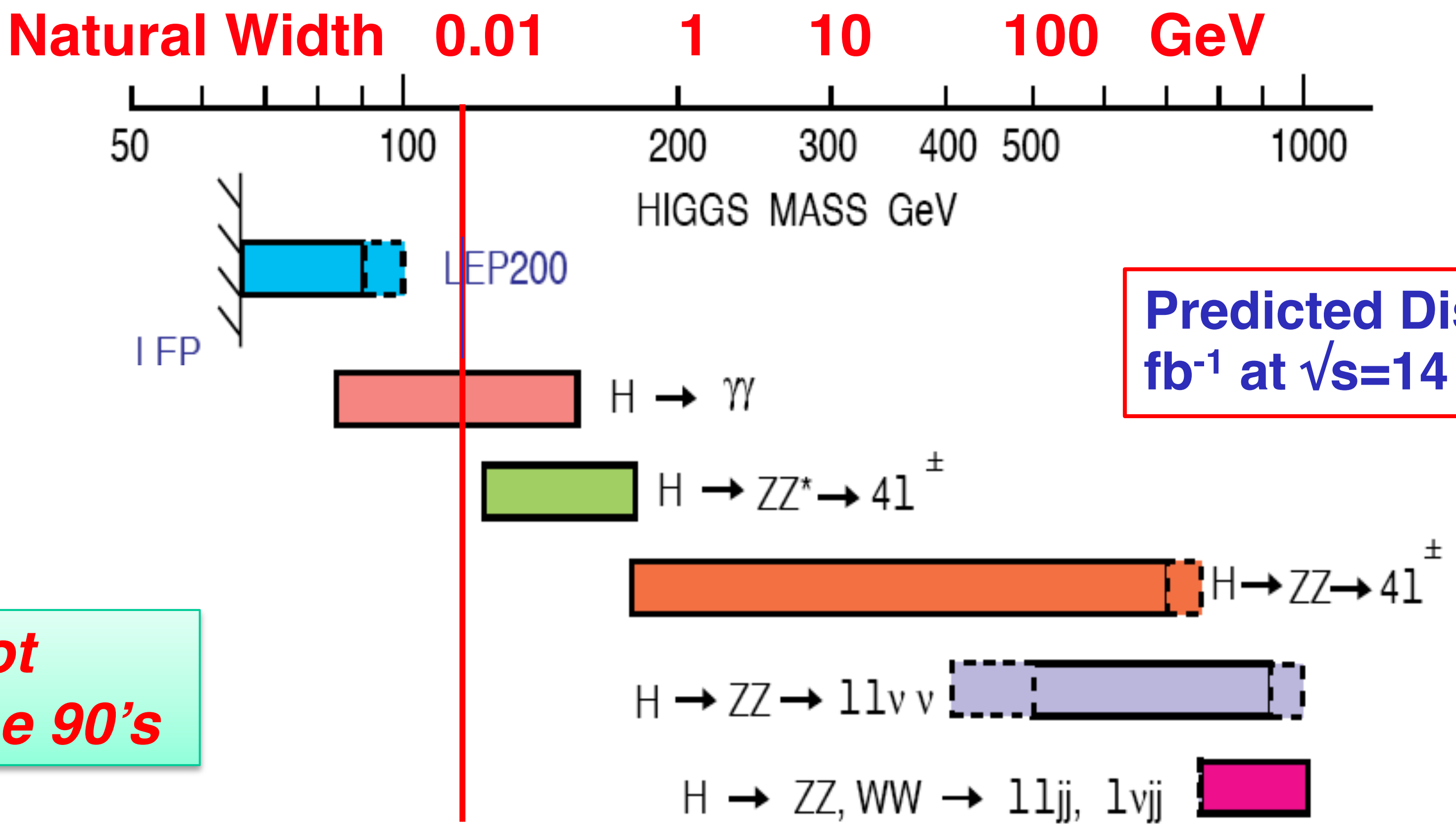
Superstring theory ⇨ dramatic concepts: supersymmetry , extra space-time dimensions ?

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
$\Gamma \sim h/\tau$

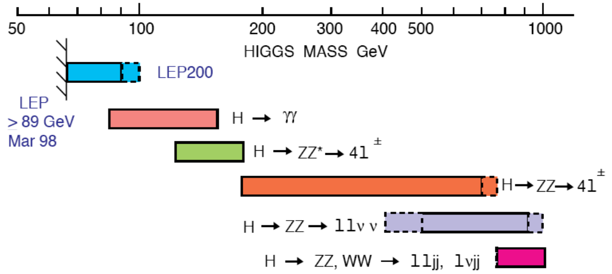
Predicted Discovery (5σ) with 100 fb^{-1} at $\sqrt{s}$=14 TeV !

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).

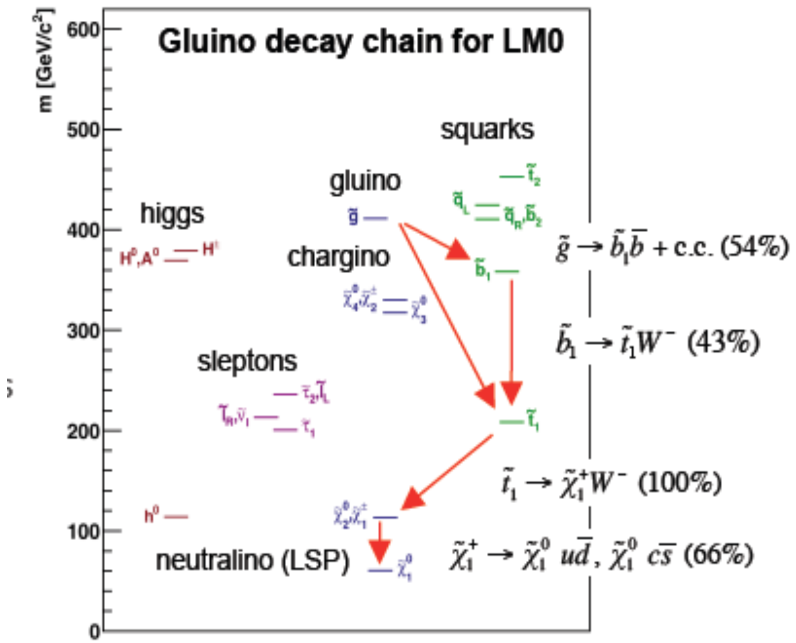
Physics Drivers 2: Other Physics and LHC Experiment design

SM Higgs boson



Low Energy Supersymmetry

Several high-p_T jets and charged leptons
Large missing E_T (calo. coverage $|\eta| < 5$)
Abundance of b-quarks (need for pixel detectors)
Wide scan of models indicated that $m_H \leq 135$ GeV

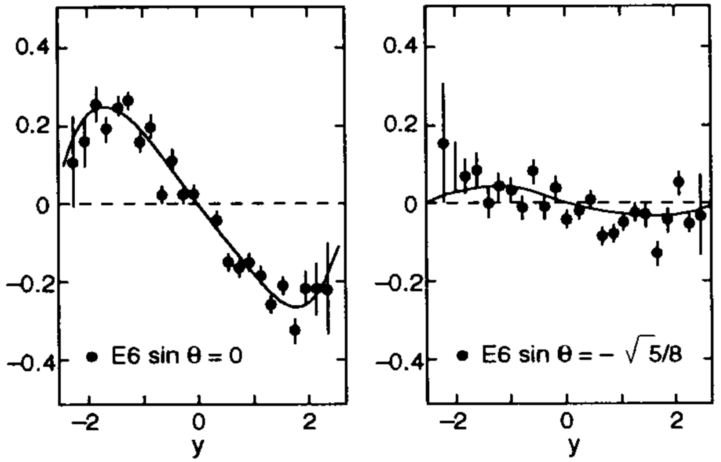


Heavy bosons (Z',…)

Measure the charge of TeV muons

dp/p ~ 10% at p_T = 1 TeV/c

High bending power



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.

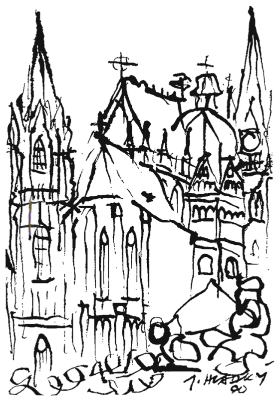
A report is given of studies of:

(a) H -> $\gamma\gamma$ (work done by C. Seez and T. Virdee)

(b) W H -> $\gamma\gamma$ (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

SEARCH FOR H $\rightarrow$ Z*Z* $\rightarrow$ 4 LEPTONS AT LHC

Higgs Study Group

M. Della Negra, D. Froidevaux, K. Jakobs, R. Kinnunen, R. Kleiss, A. Nisati and T. Sjöstrand

"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.

"Requires identification of both electrons and muons. After lepton isolation cuts a clear Higgs signal should be visible for a total integrated luminosity of 10^5 pb^{-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

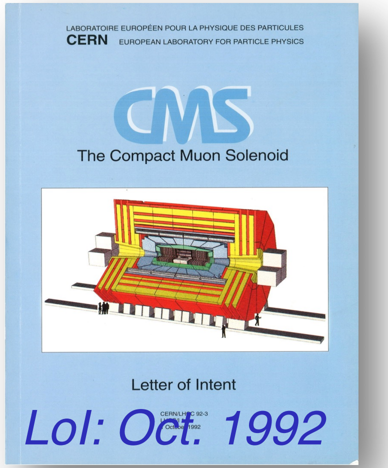
Extreme requirements in several domains (also at HL-LHC)

Limited budgets!

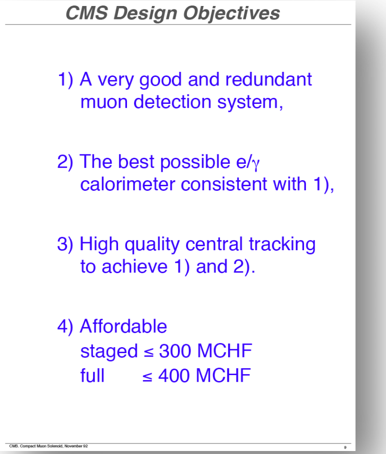
Looked at what existed, innovated and automated to drive costs down

The CMS Experiment: The Long Journey

Physics Goals to Design Objectives



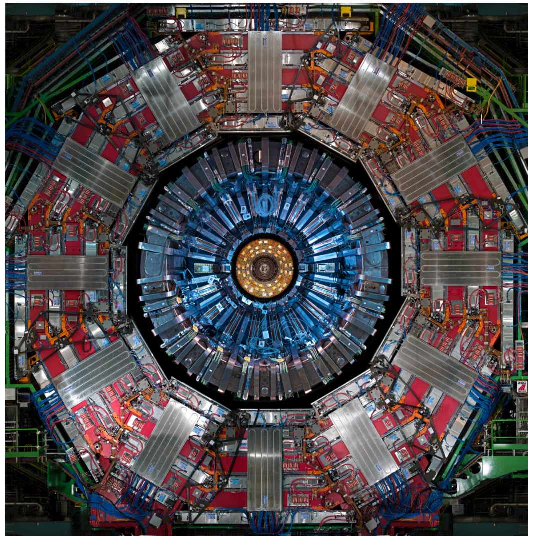
LoI: Oct. 1992



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

Into reality16 years later in 2008



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

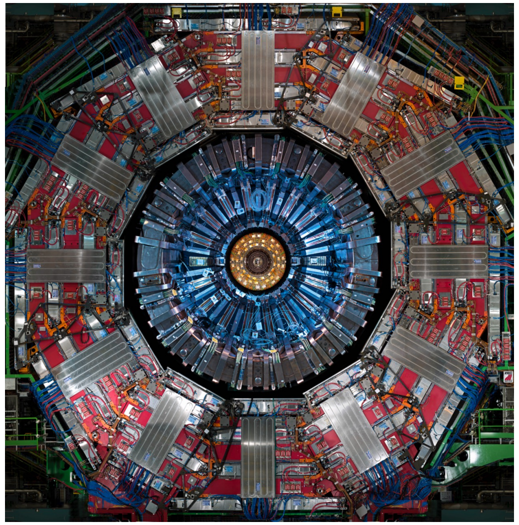
Some of the Enormous Challenges Faced During Construction of Phase 1 CMS Detector!

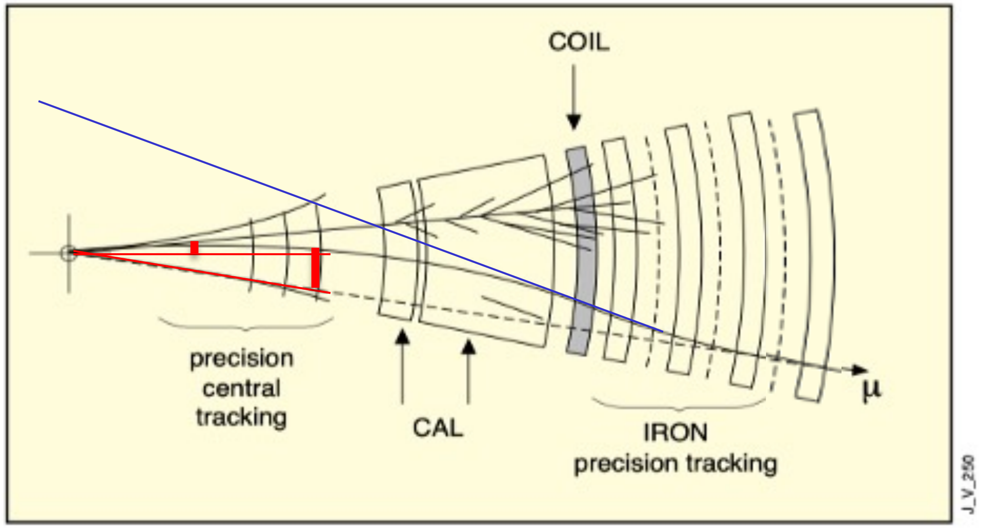
- **In addition to the efforts needed to obtain approval (LHCC, CERN, LoI, TP, TDR's, EDR's ….)**
- Engineering design – assembly on surface, construction of the solenoid coil (1997-2006)
- ***Redesign of tracker f.e. electronics in 0.25 μm (1999)***
  (severe mid-course correction – thrown back to zero !)
- Change to all-silicon tracker (1999)
- Redesign ECAL f.e. electronics in 0.25 μm technology (2001)
  (severe mid-course correction – thrown back to zero !)
- 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)***, 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 …)
- "Re-engineering" of reconstruction software (2005) & prepare CMS (sw/people) for physics extraction,
- ***Particle Flow reconstruction (2009)***

Magnetic Field Configuration

The most important single choice is that of the magnetic field configuration for muon identification and measurement.

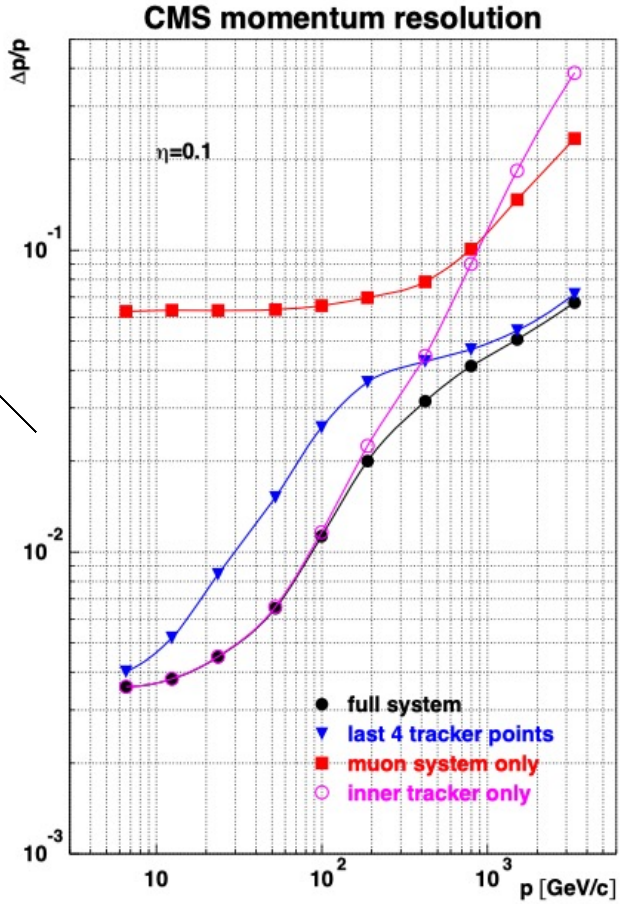
3. Combined measurement of μ momentum in Tracker and Flux Return - Identify μ after full absorption of hadrons





property of a solenoid
high momentum μ tracks point back
to vertex after flux return

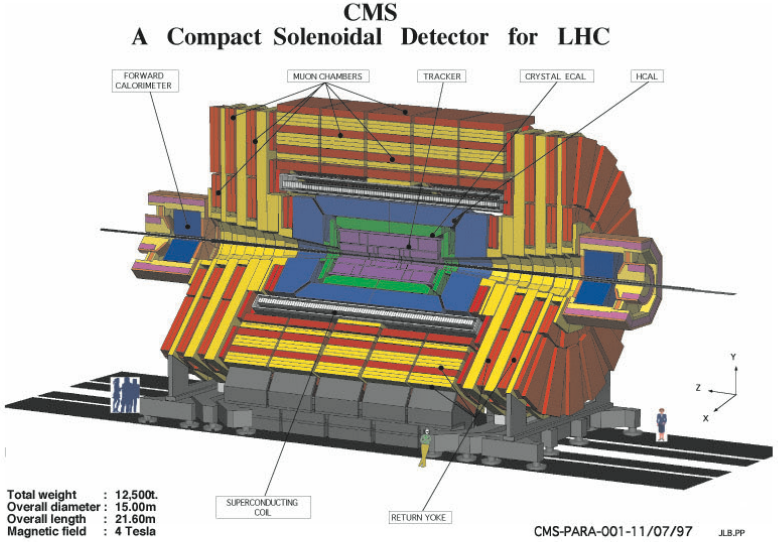
CMS

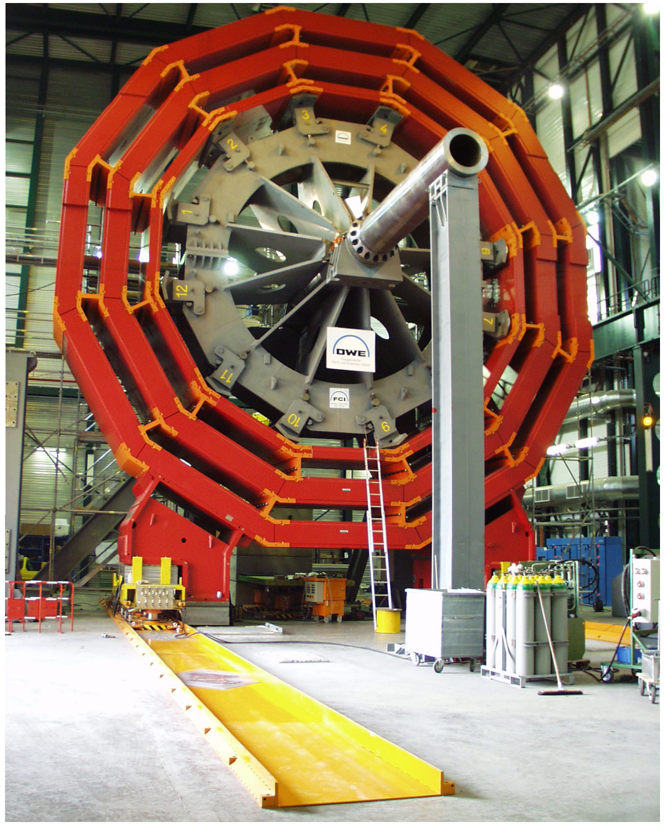


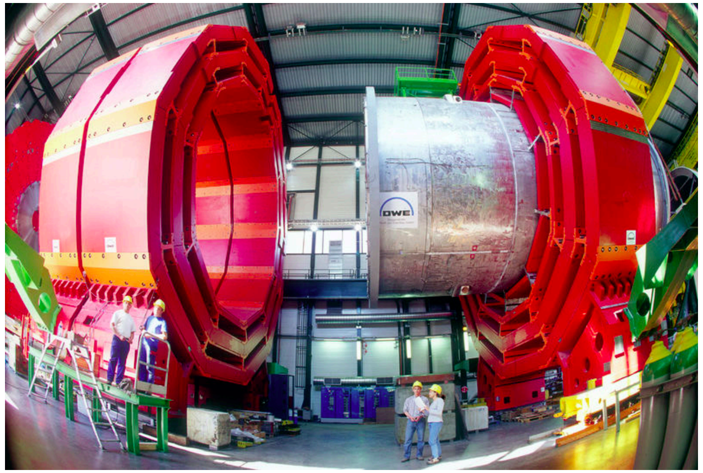
Vertex constraint – a free high precision (15μm) point
Momentum resolution for Level-1 Trigger (red) –
impact parameter (direction in MB1- vertex in r-ϕ)

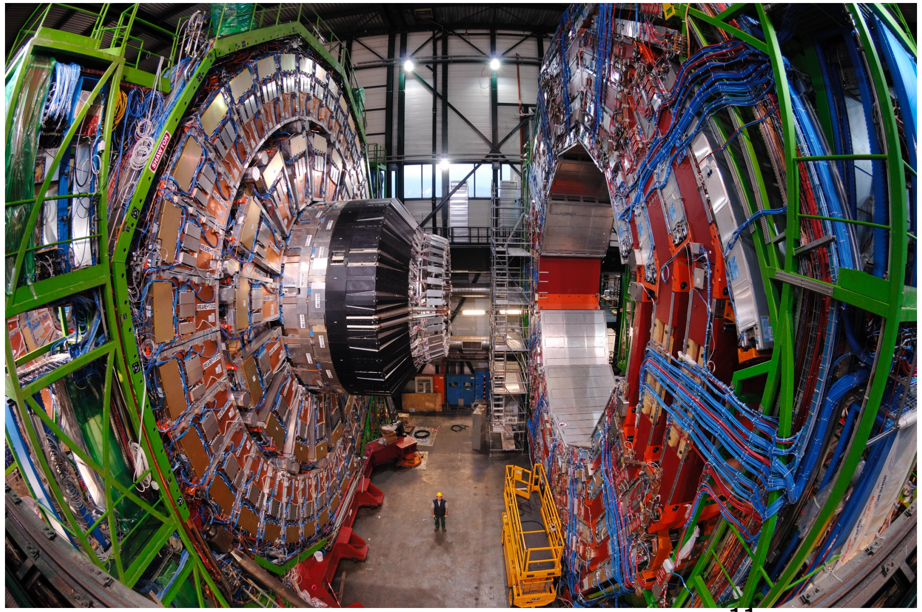
Engineering Design

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



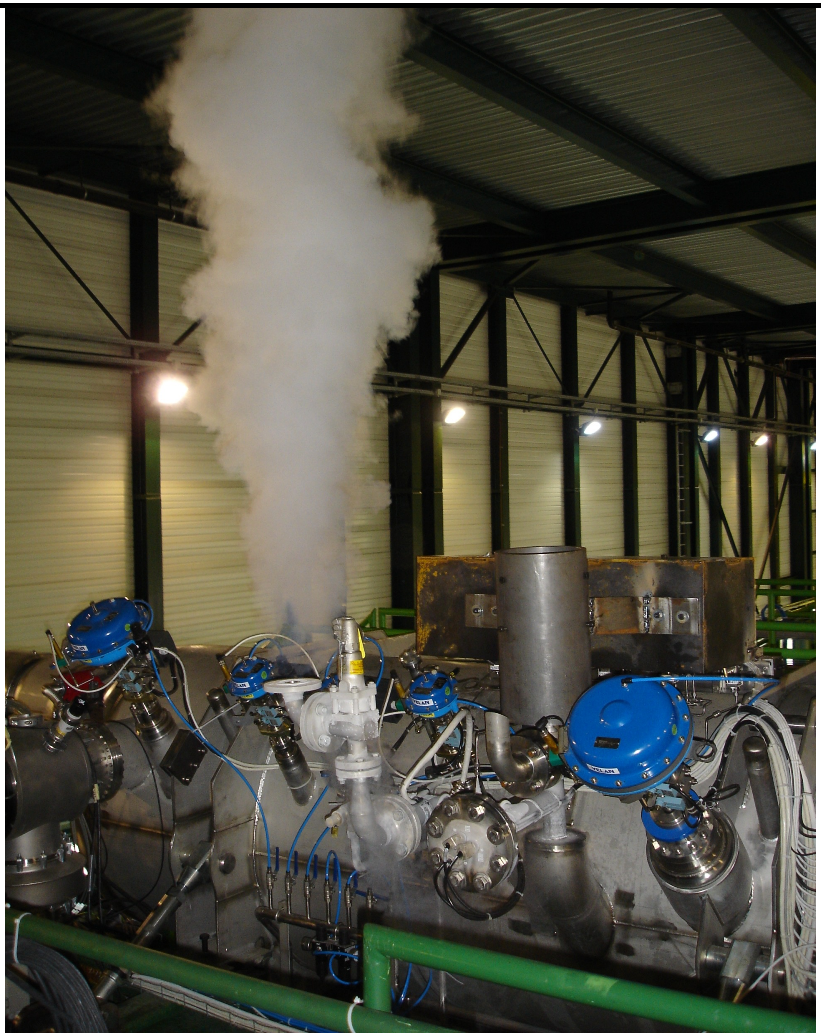






Examples of In-situ Testing

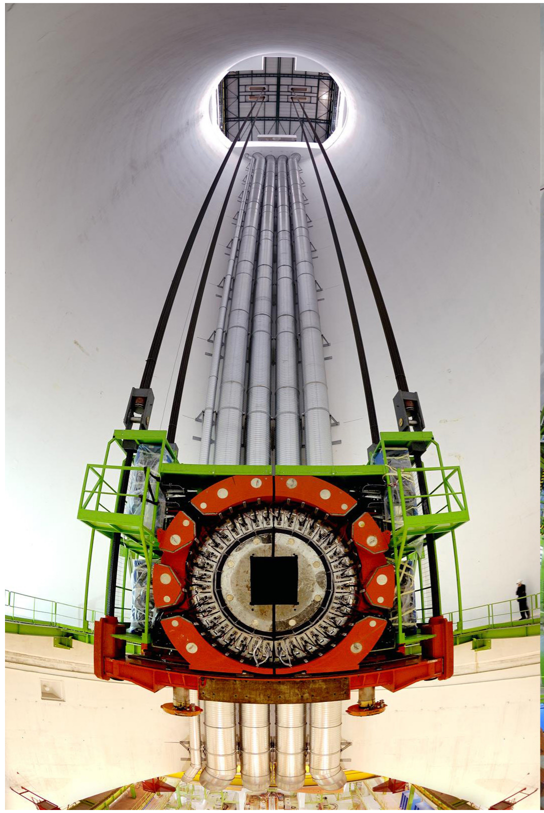
2006: Surface test of the Coil: provoked quench

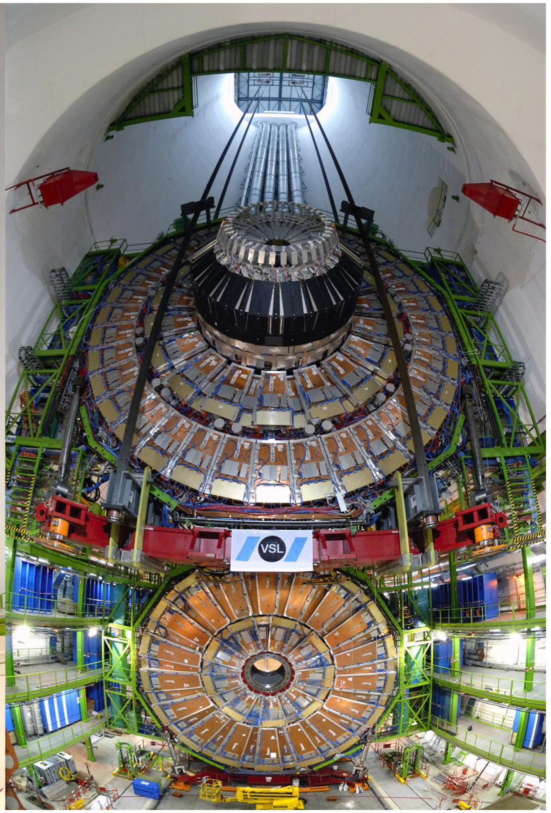


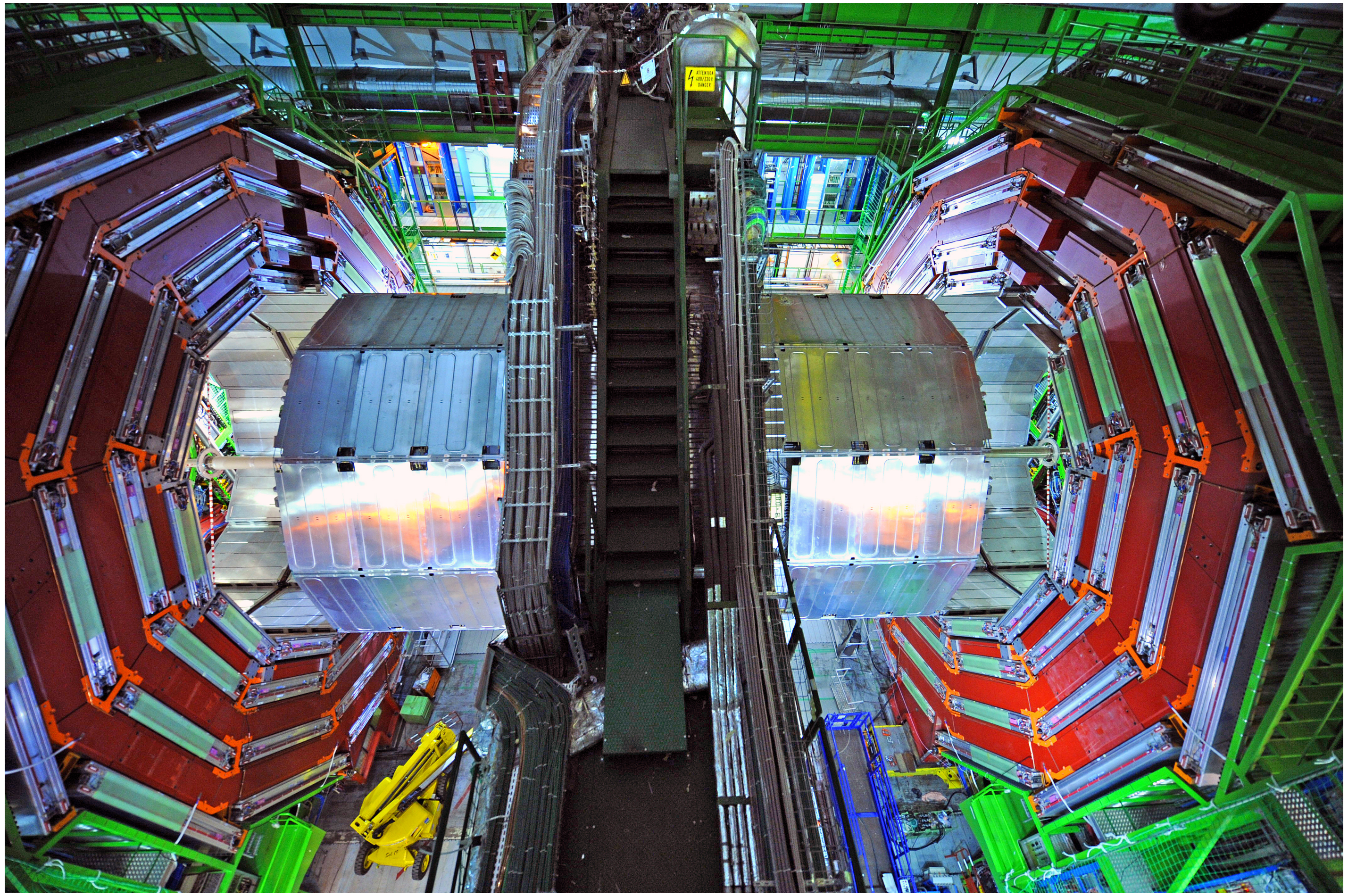
2006: Underground Cavern - test of foam Fire Safety System in UX5 before lowering

Engineering Design

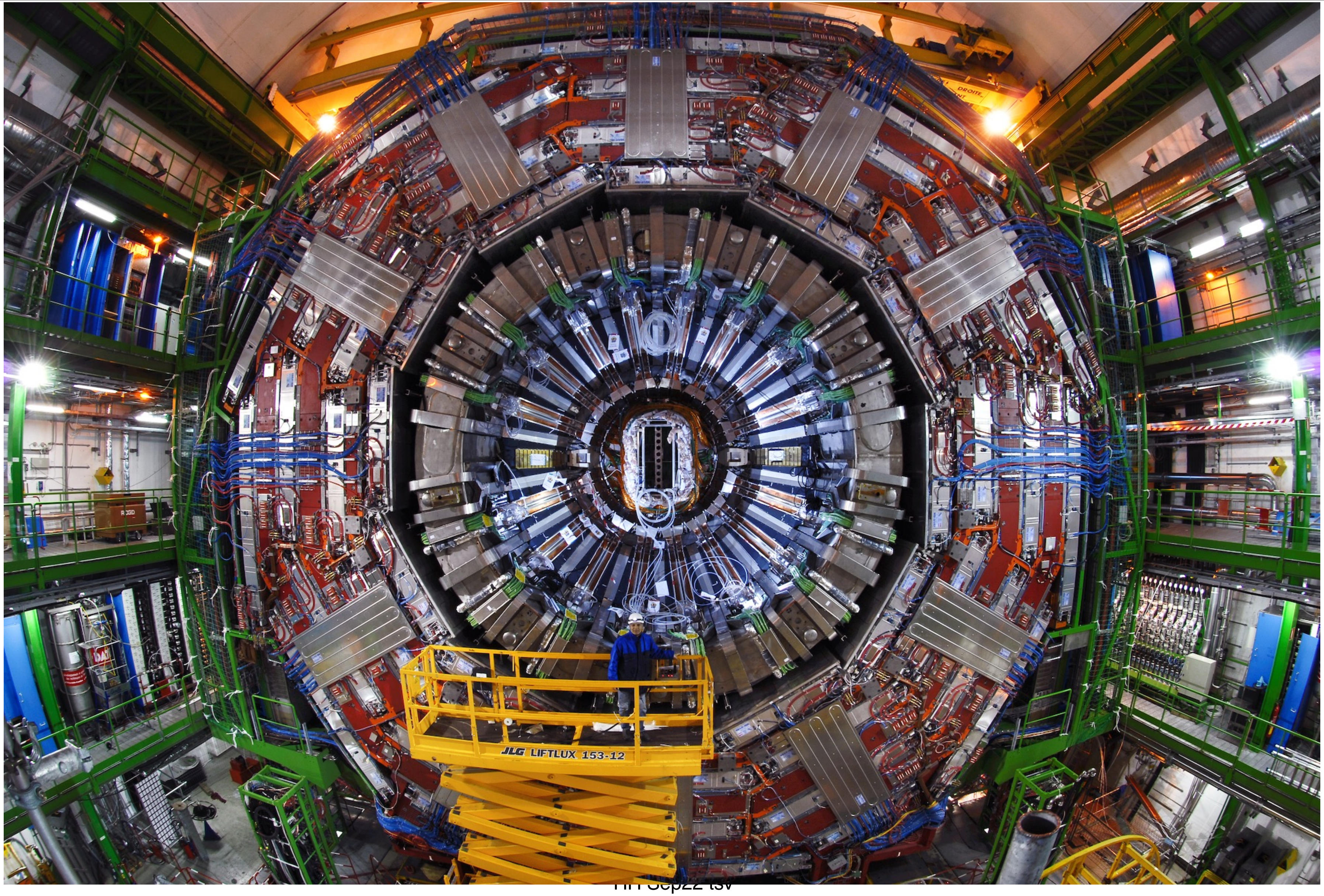
CMS Cut in 13 slices; much of the assembly done in surface hall and slices then lowered







Almost Ready to Go!



CMS: Concept to Data Taking took ~ 20 Years!

Silicon Tracker

Gas ionization chambers

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

CMS cut in mid-plane

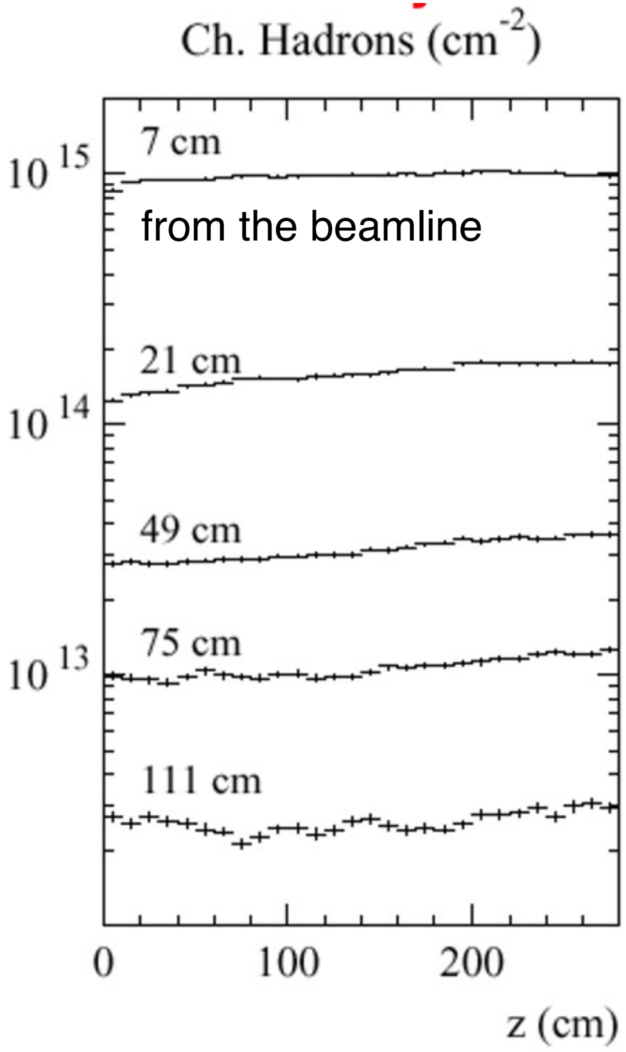
Scintillating Crystals

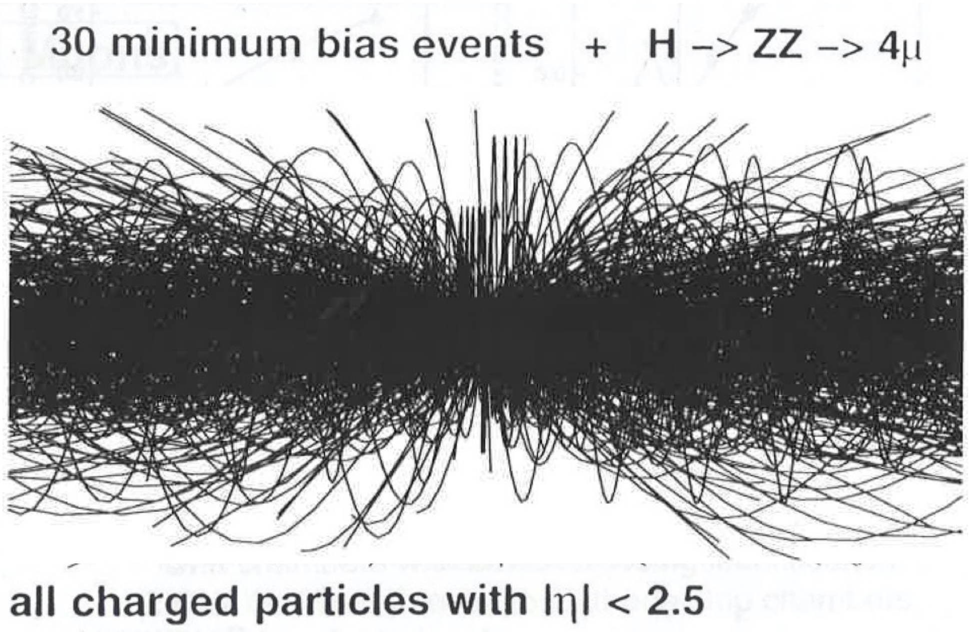
Brass plastic scintillator

Design of Inner Tracker: Environment

Fluence over 10 years

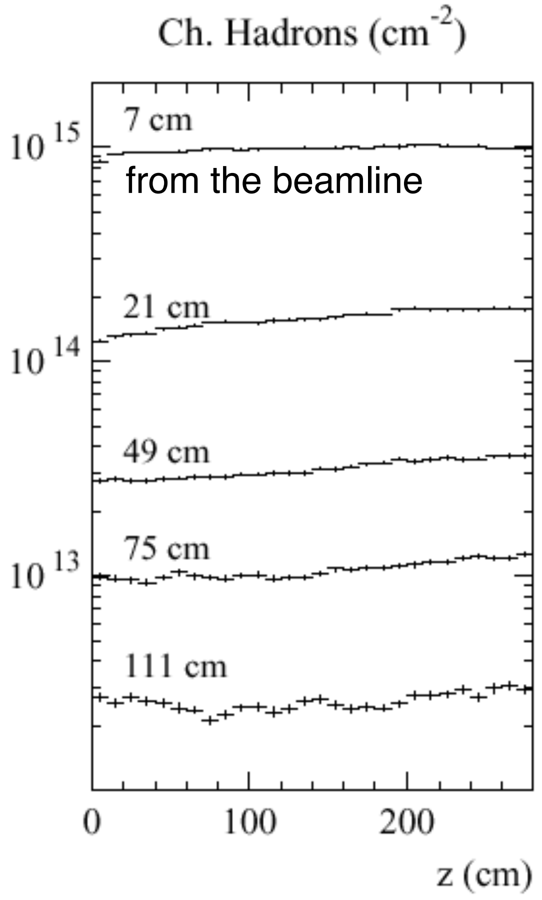
$\int L.dt = 300\ \text{fb}^{-1}$





Design of Inner Tracker

Fluence over 10 years



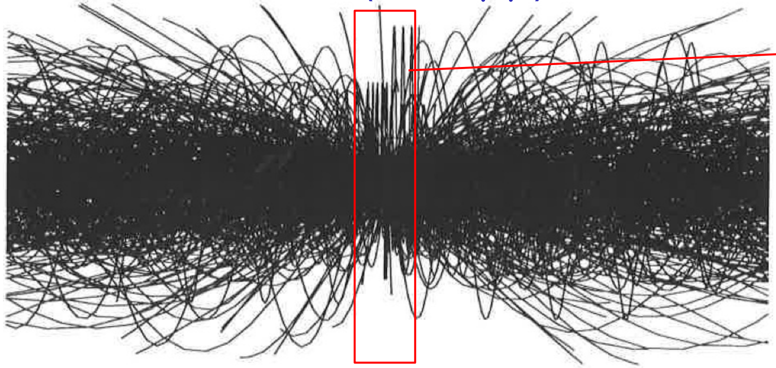
≤ 4.10⁷ h±/cm²/s
pixels (≈10⁴ μm²)
occupancy ≈ 10^{-4}

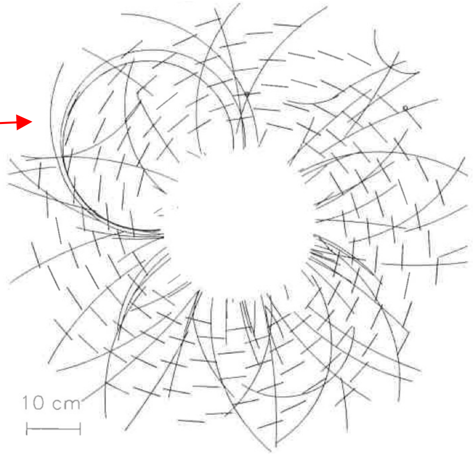
≤ 4.10⁶ h±/cm²/s
Si μ-strip det.
(≈10 mm²)
occupancy ≈ 1%

≤ 4.10⁵ h±/cm²/s
Si or Gas detectors.
(≈1 cm²)
occupancy ≈ 1%

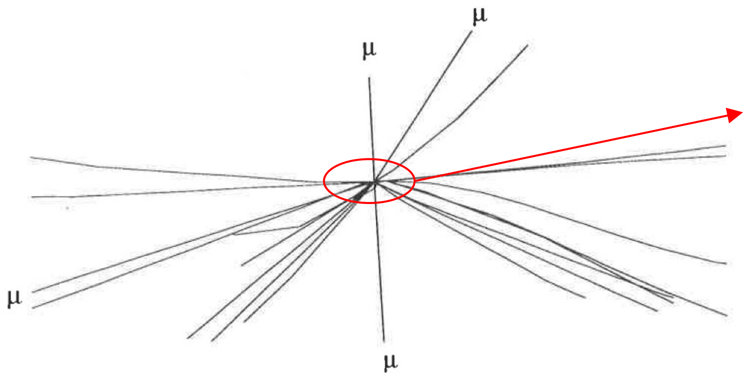
4T Field
30 min bias events +
H→ZZ (Z → μμ)

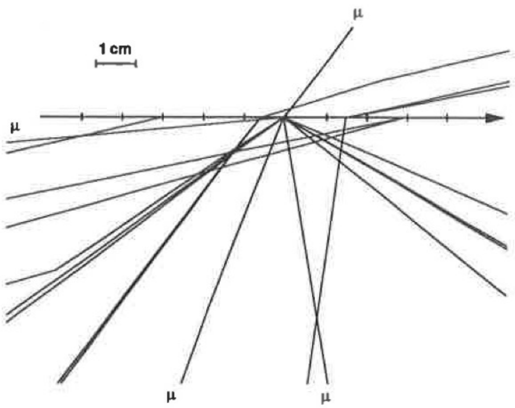
10 cm slice (in z)





All charged tracks within |η| < 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

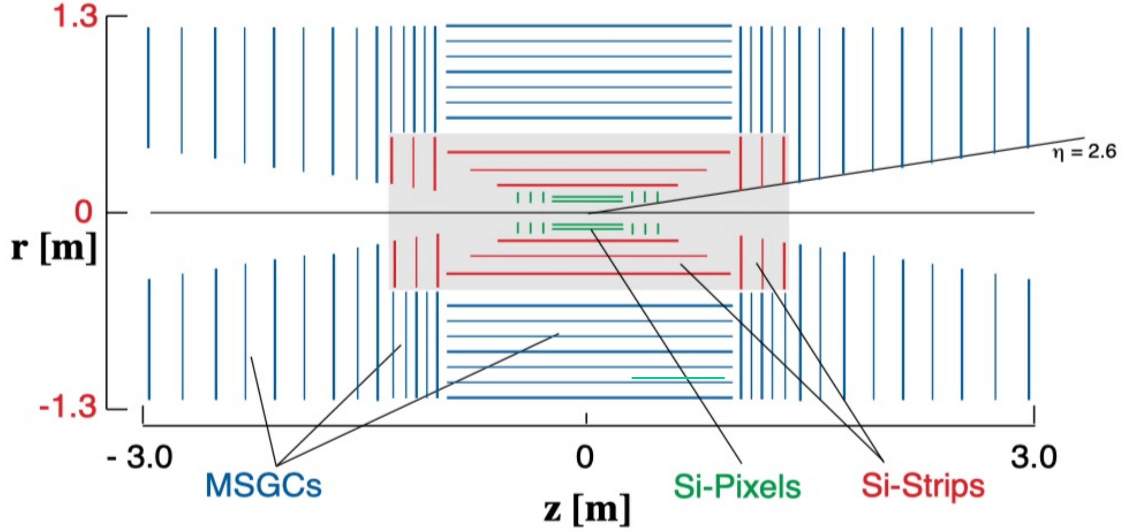
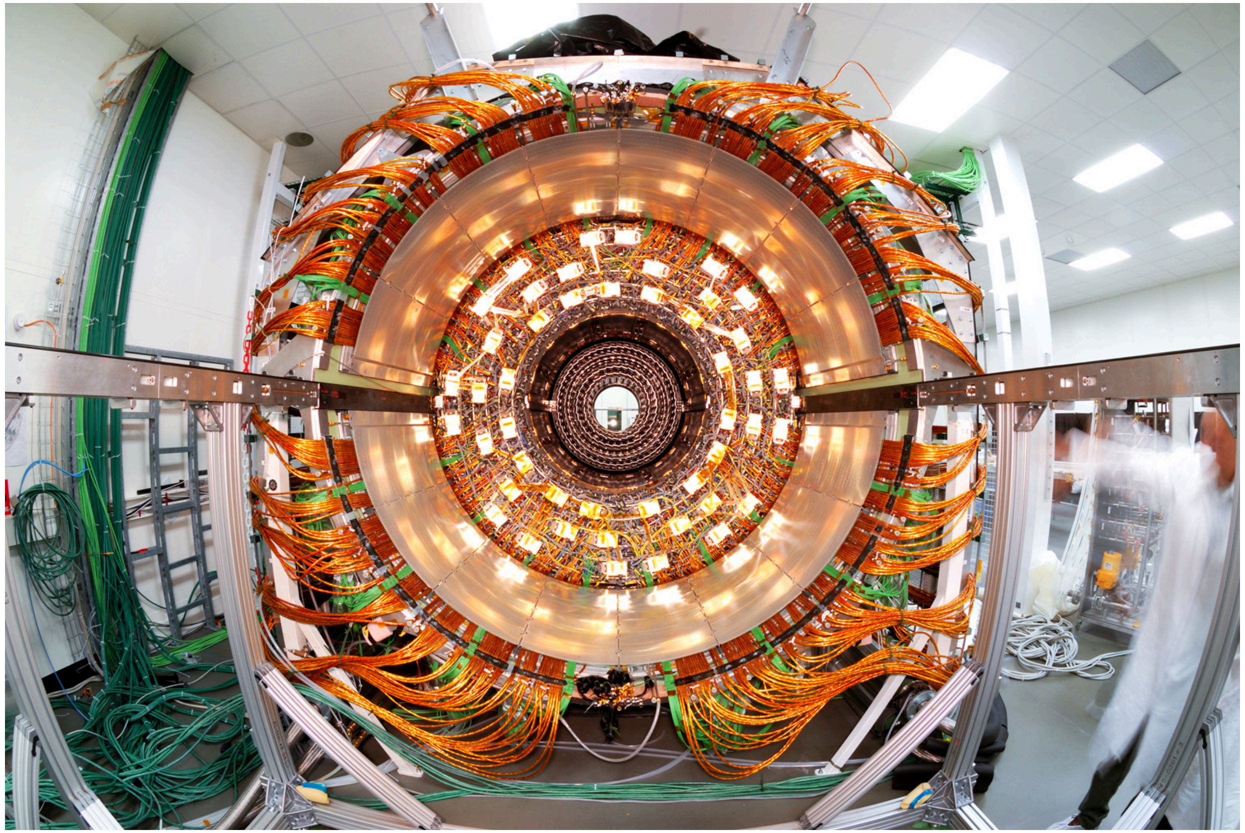


Fig. 3.1: Schematic of inner tracker. Thick lines denote double-sided readout.



Questions from the LHCC

CMS-LOI/92-LF

ANSWERS TO PROFESSOR LORENZO FOA

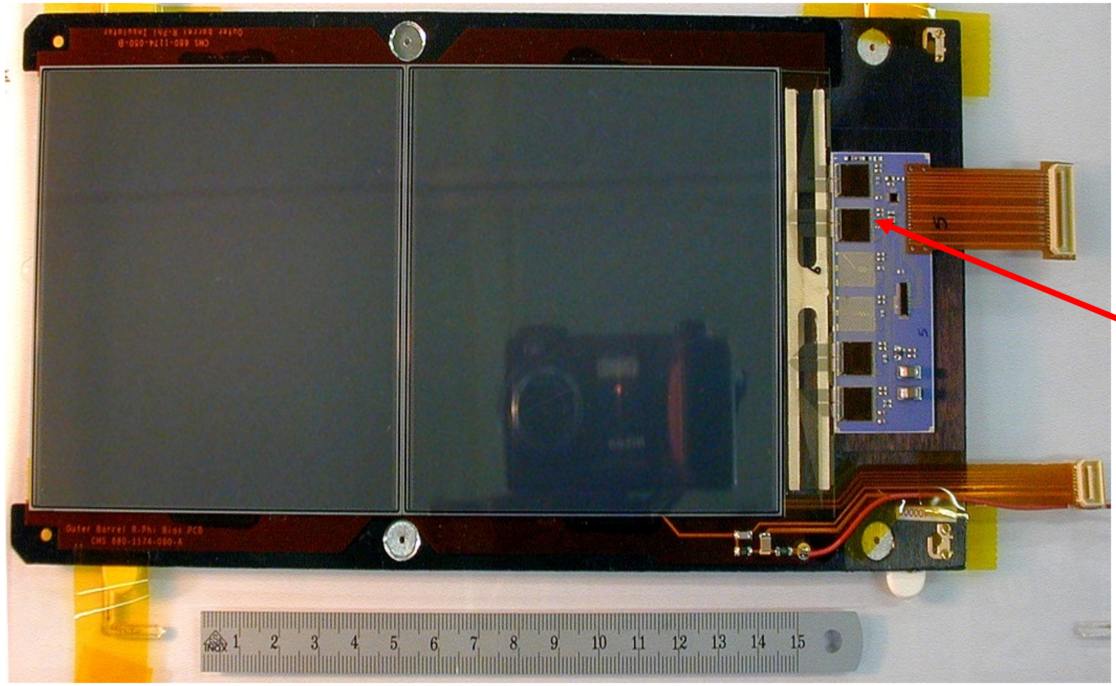
QUESTION 0:
General question that concerns all experiments: What can your e.m. calorimeter do in a "stand alone" mode, I mean if you have to switch off your inner tracking because of excessive rate ?

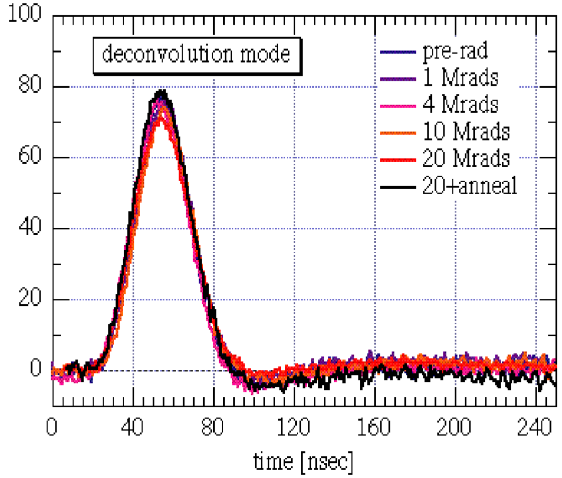
We would like to distinguish between two scenarios, namely:

i) all inner tracking fails. We consider this to be an unlikely scenario.

ii) tracking is still possible in the area close to the calorimeters i.e. the last four points are still measurable. We would like to stress that the 4 T field considerably reduces the density of charged tracks in the outer regions of the tracking cavity. Even if we have underestimated the minimum bias background by a factor of 10 the occupancies in this region will remain below a few percent. We do not believe that beam related backgrounds would drastically affect this region which is ≥ 1.2 m from the beam-line in the barrel.

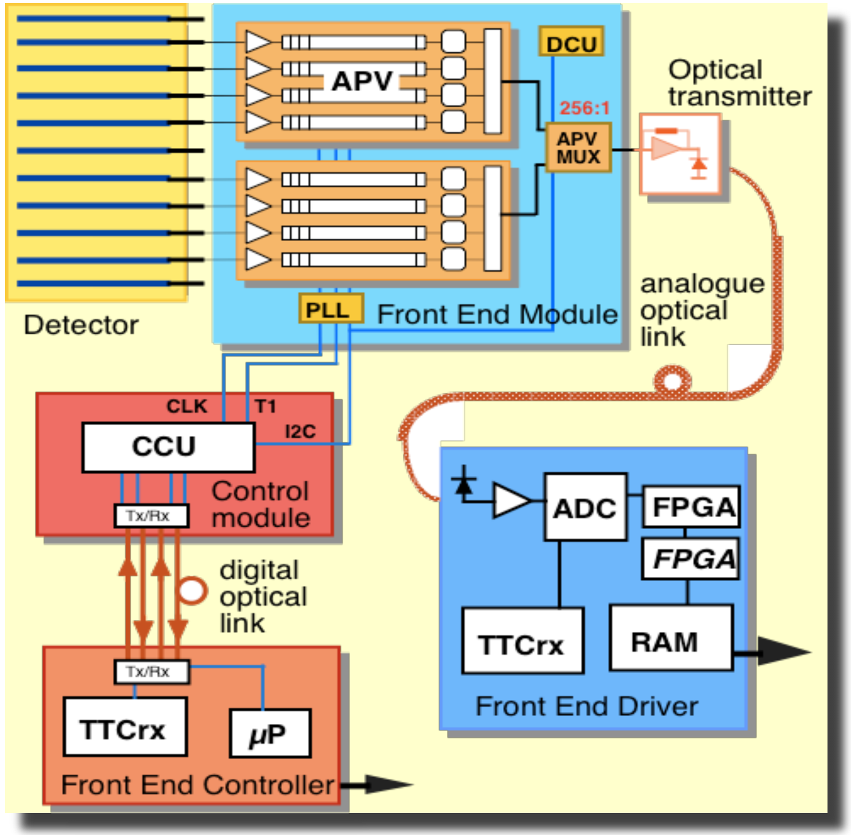
Si Modules and Electronics Chain





Riding the technology wave

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 national lab (RAL) and a university group (Imperial College) 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.**

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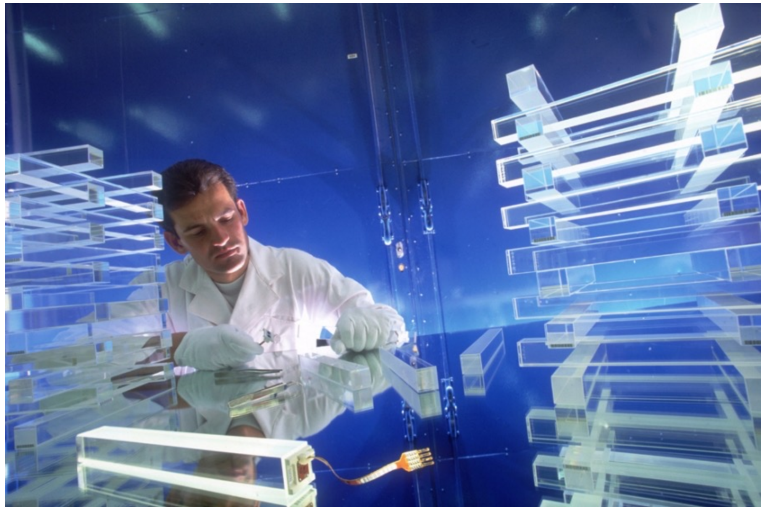
Another example of Challenging Technologies:
ECAL: Development of Lead Tungstate Crystals

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 !!!

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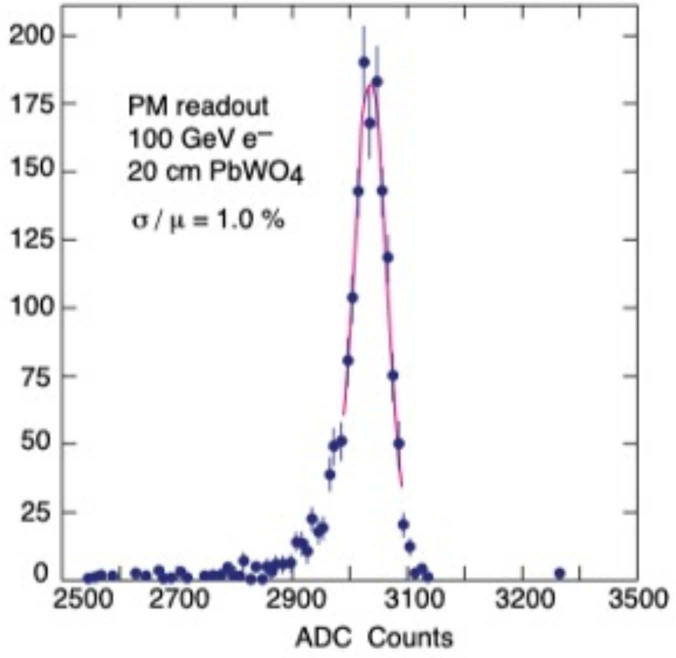
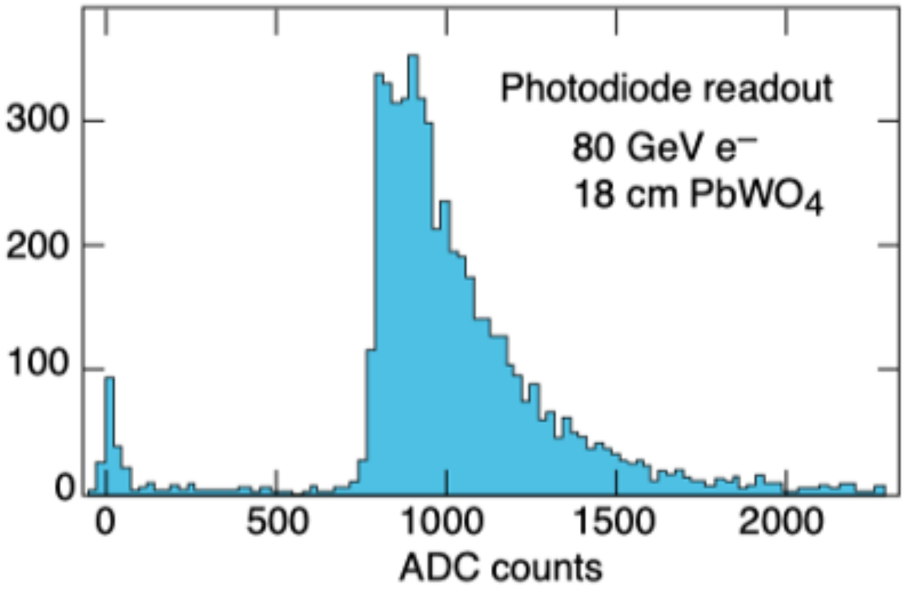
Example of Challenging Technologies:
Development Photodetectors for ECAL: APDs

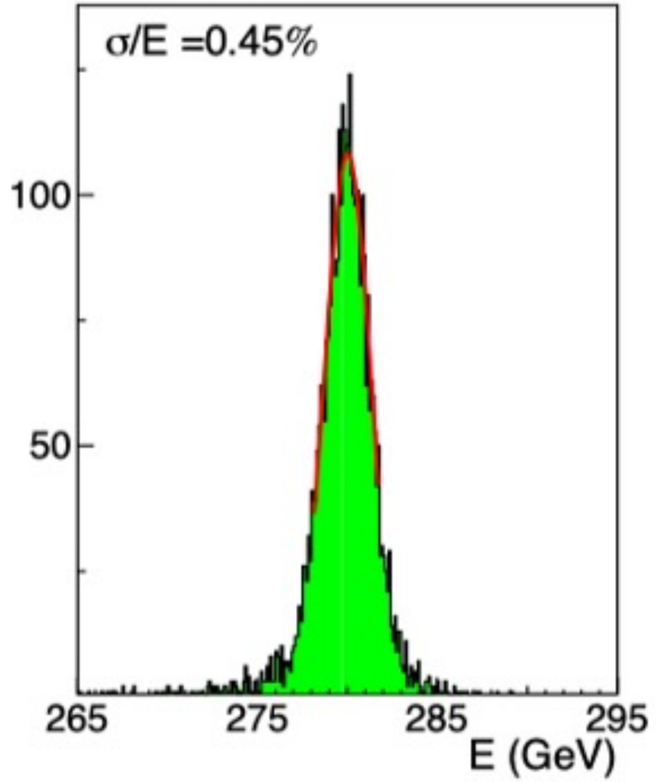
Photomultiplier Readout



Si Photodiode Readout

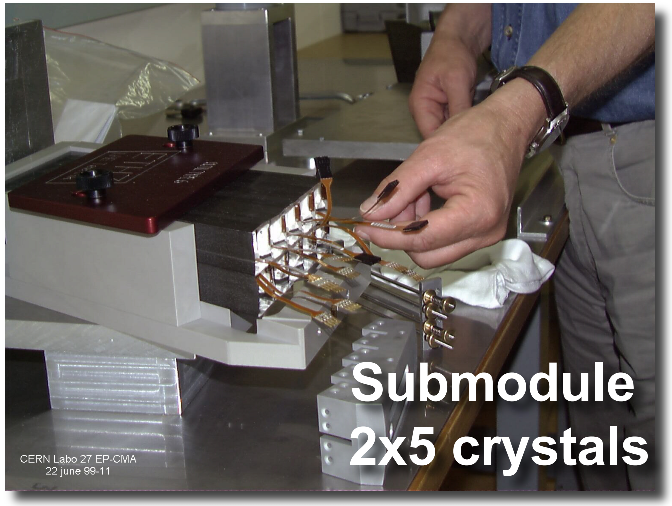


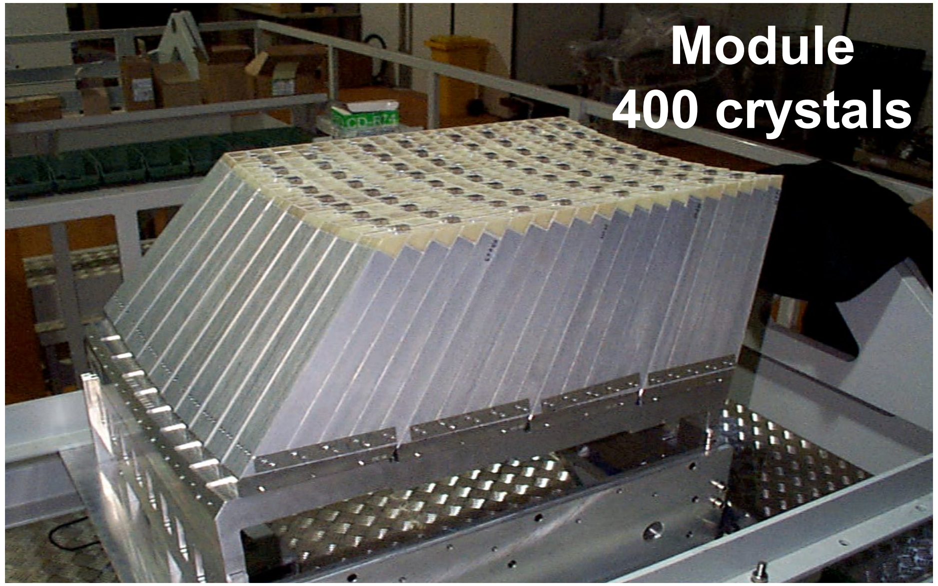
Avalanche Photodiode Readout

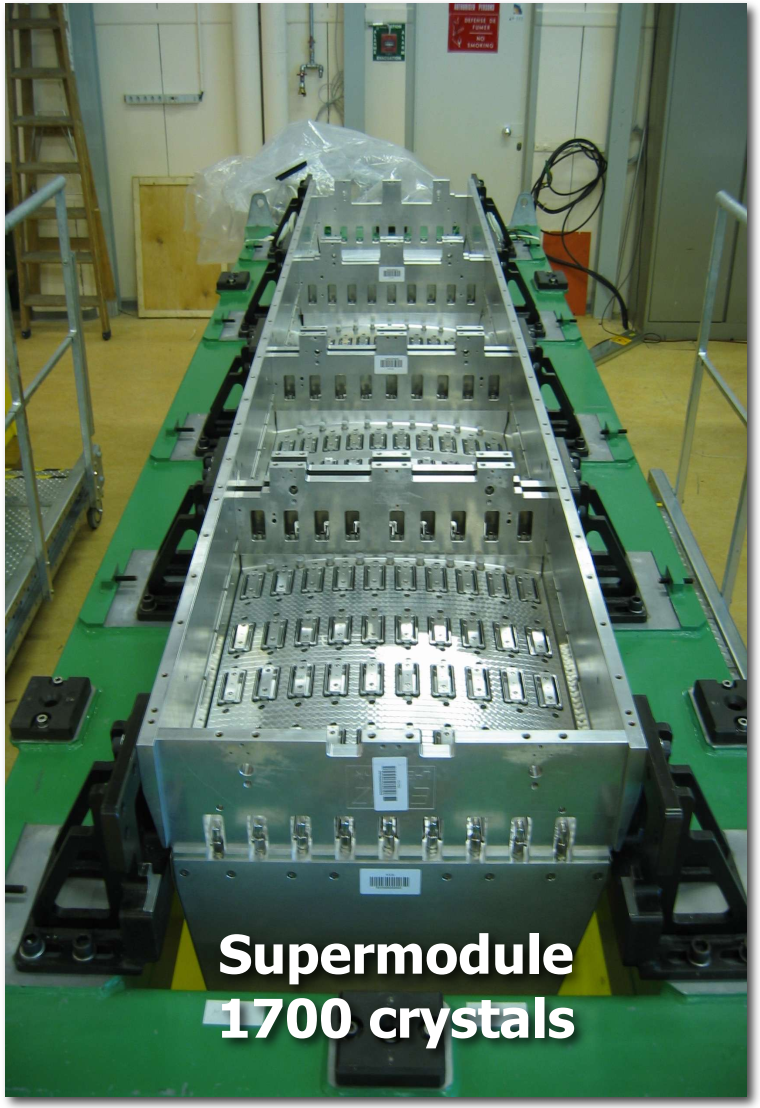


Slide from mid-90's

CMS Electromagnetic Calorimeter:
Lead Tungstate Scintillating Crystals







Total 36 Supermodules

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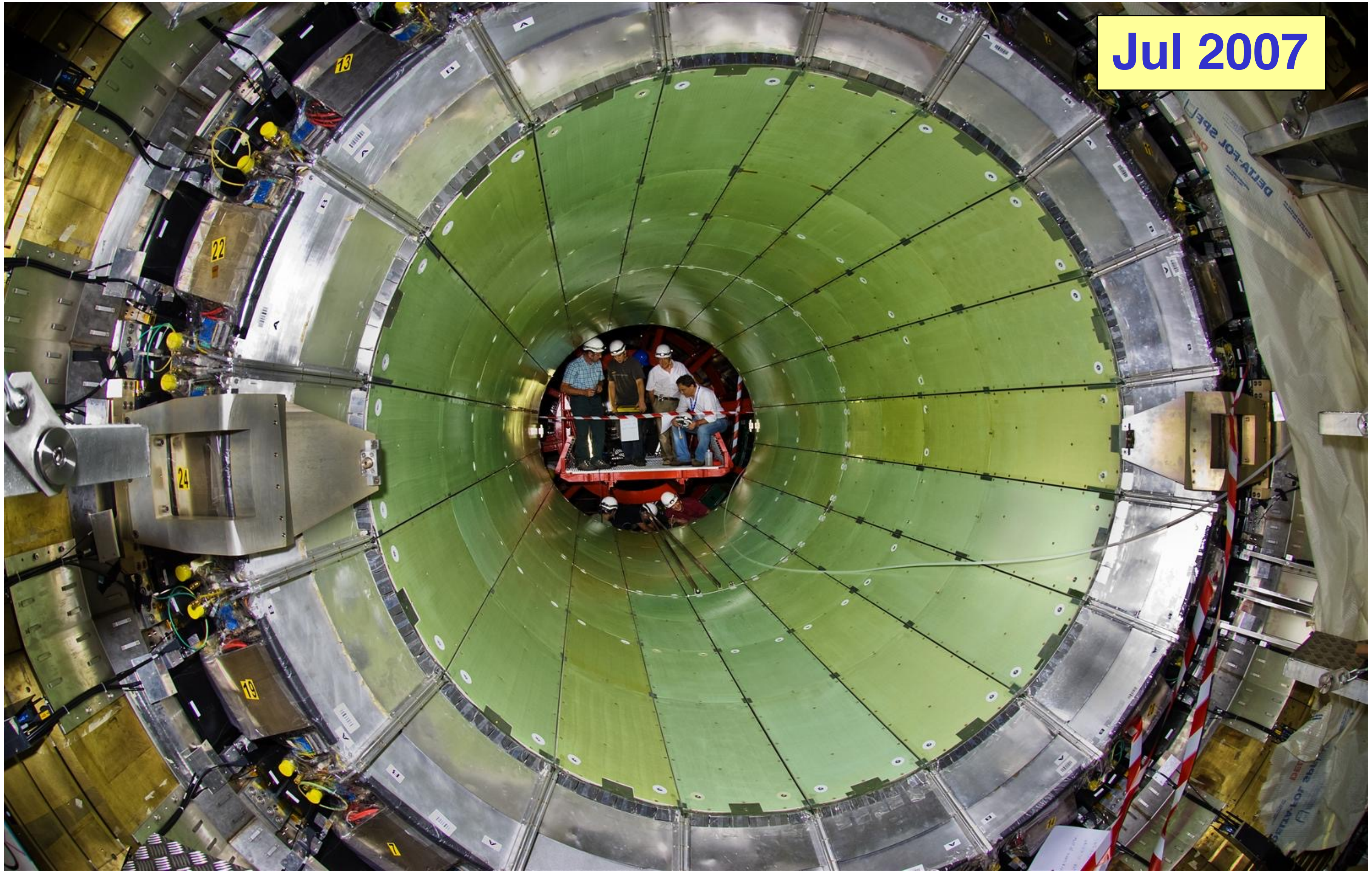
CMS Electromagnetic Calorimeter:

15 years from Concept - Installation



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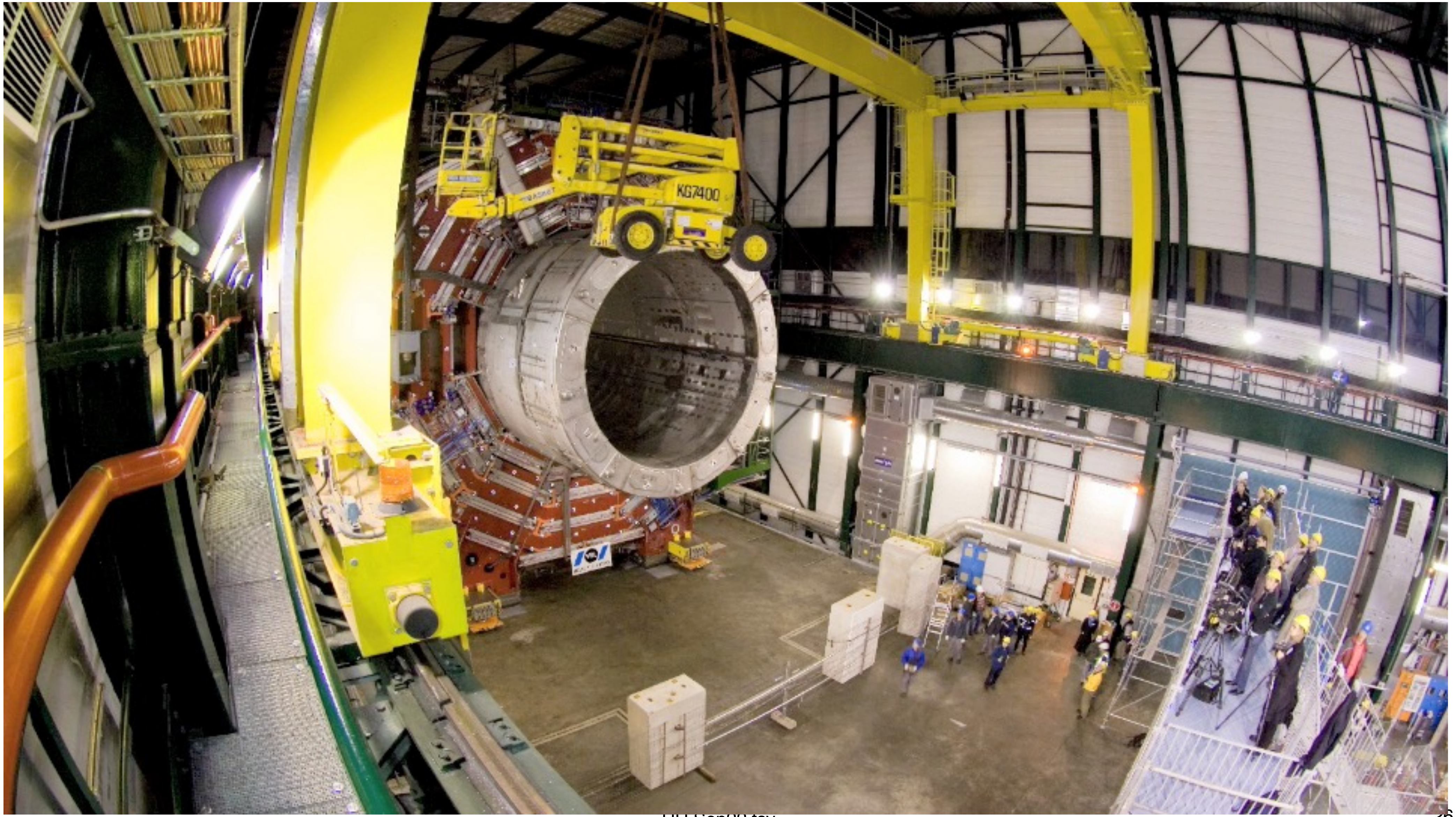
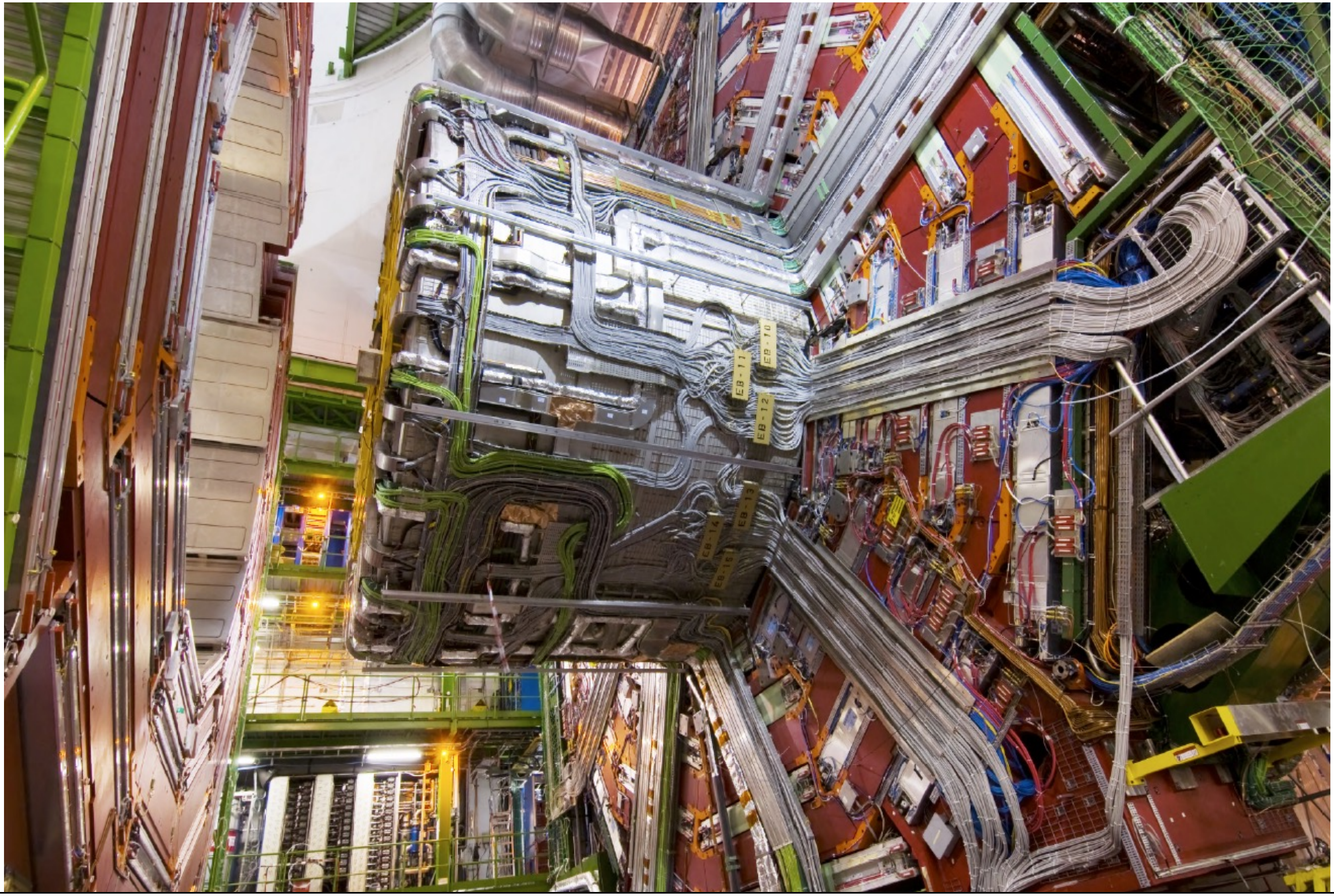
Extreme Engineering ! (Feb. 2007)



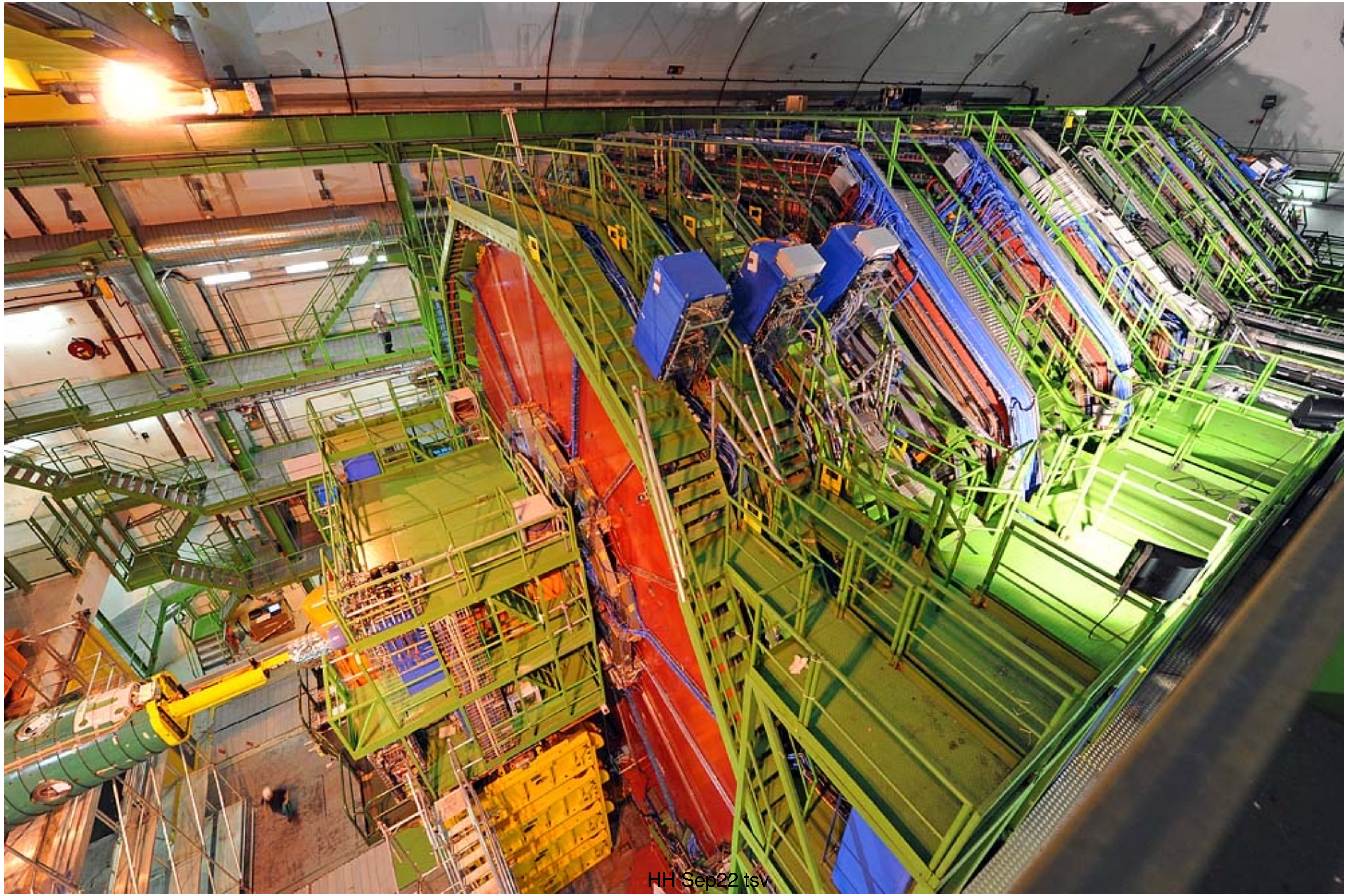
The Challenge of Services !



Nov. 2007

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

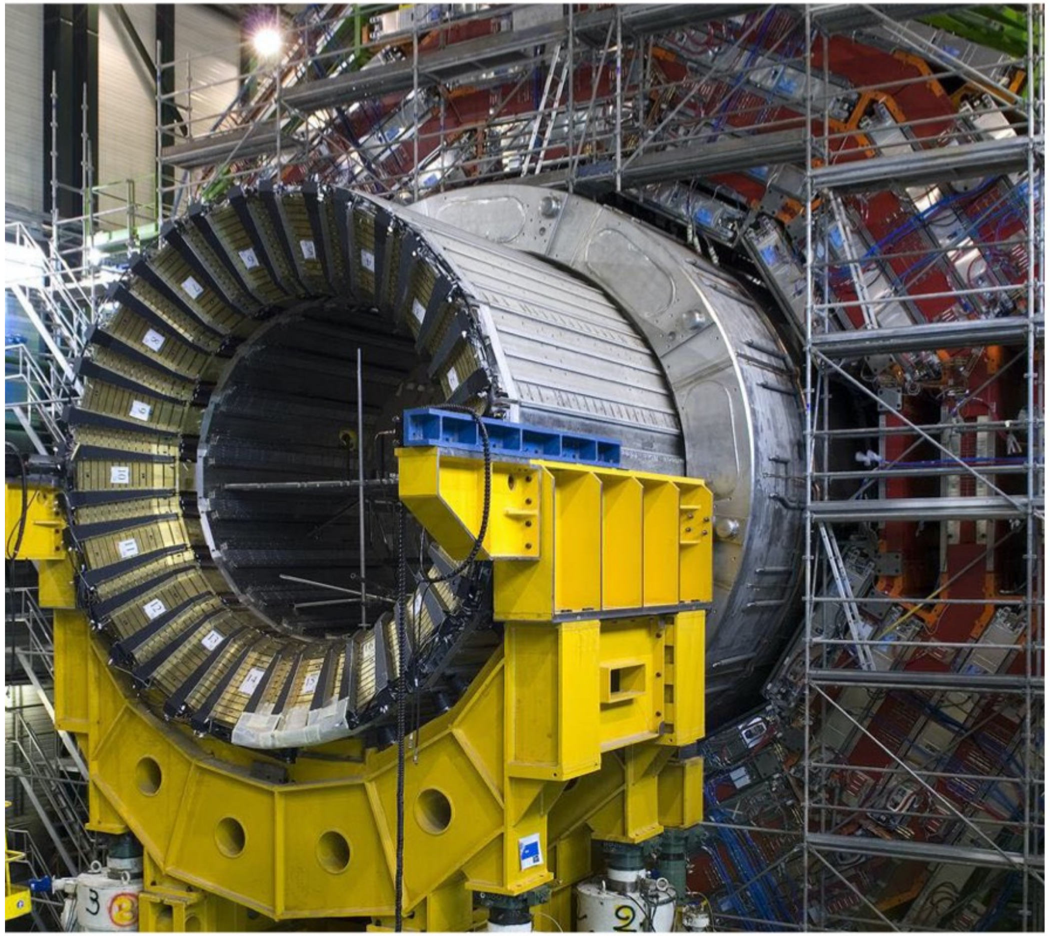
First Closing of the CMS Detector in UX5 (2008)



Particle Flow and Hadronic Calorimetry

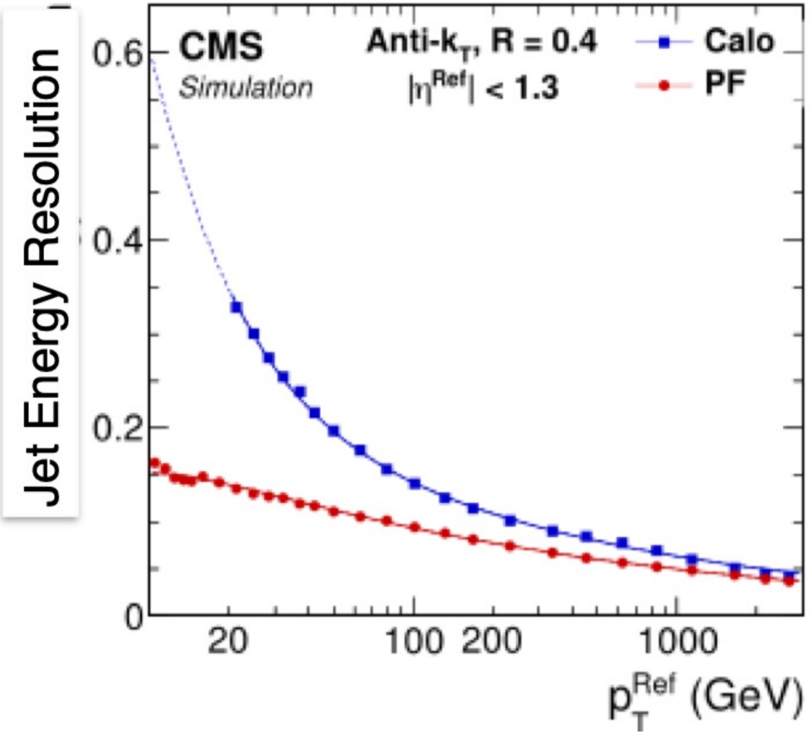
Hermetic Hadron Calorimeter inside the coil: Brass absorber/scintillator tiles

$$\sigma/E = 110\%/\sqrt{E} \oplus 9\%$$



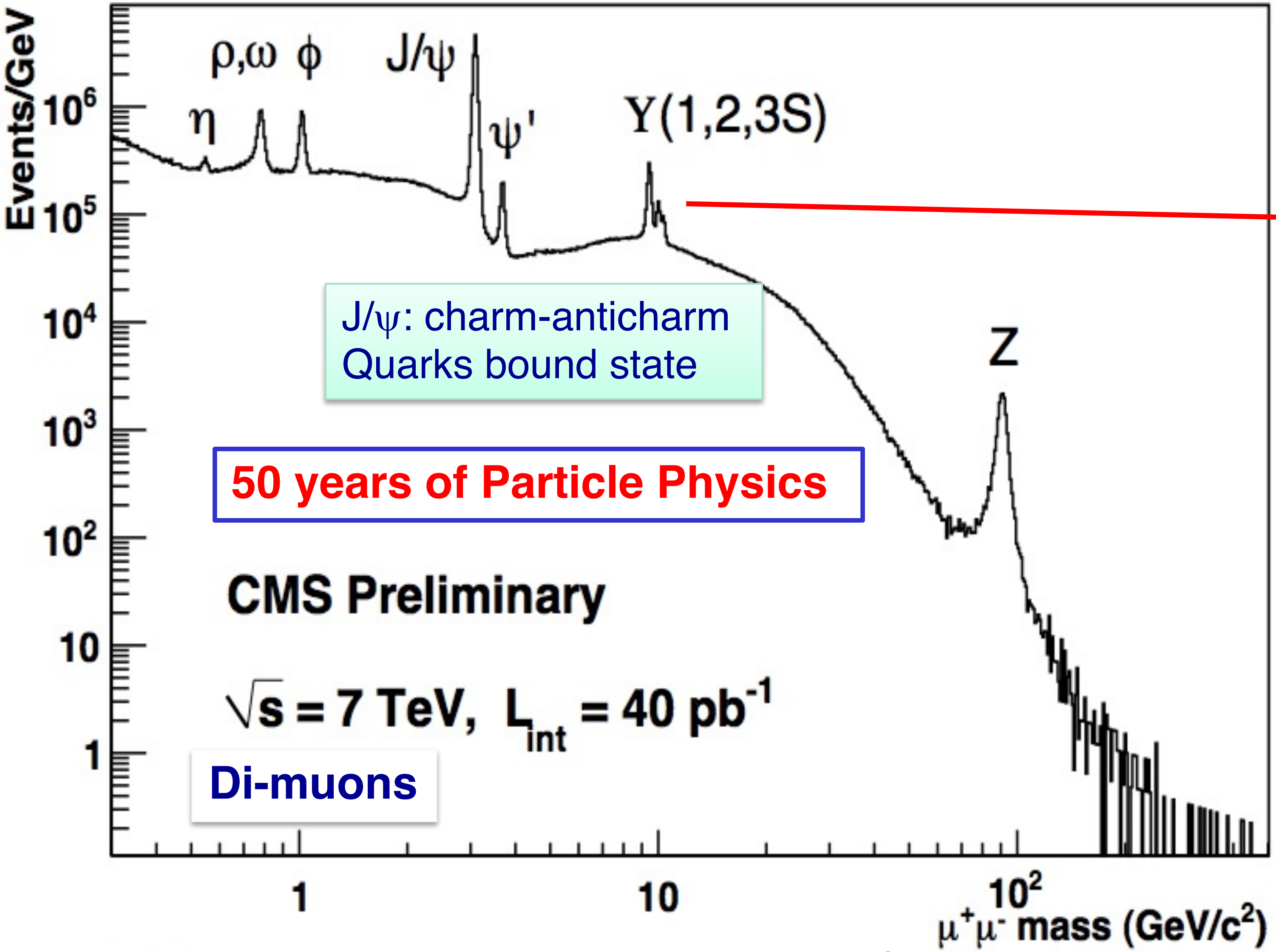
Particle Flow (PF) reconstruction (2009)

Combining track measurements and calorimeter clusters leads to substantial improvement of the missing transverse energy resolution and of the jet energy resolution (JINST **12 (2017) P10003)**:



To the Science - Do experiments perform as designed?

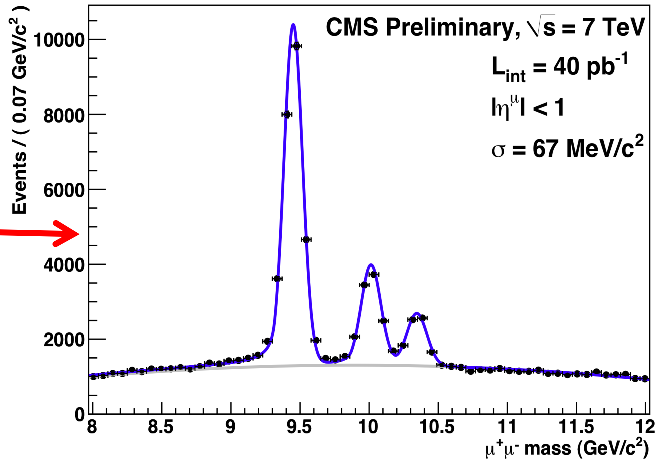
1960 1974 1977 1983



J/ψ: charm-anticharm
Quarks bound state

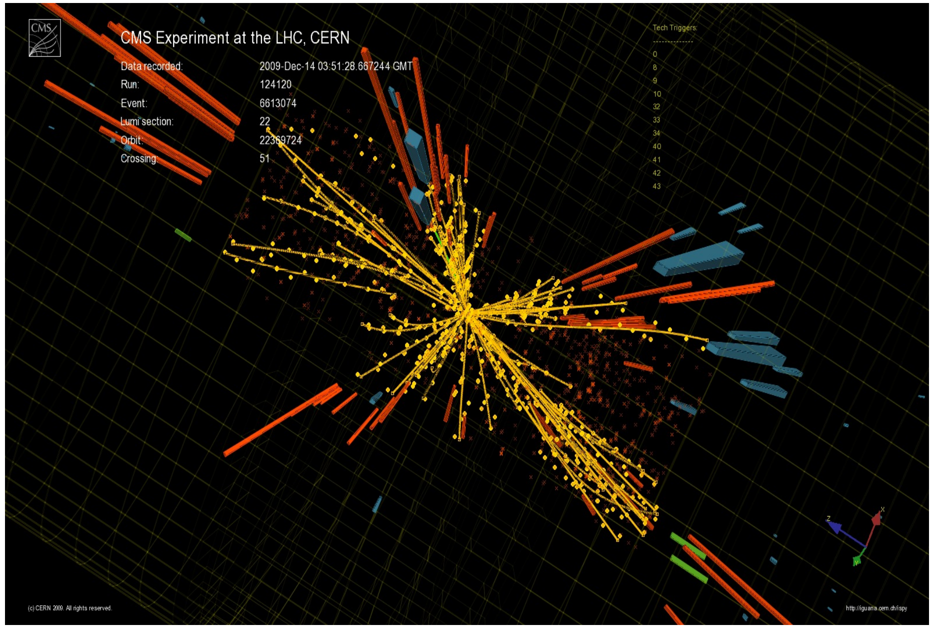
50 years of Particle Physics

Di-muons

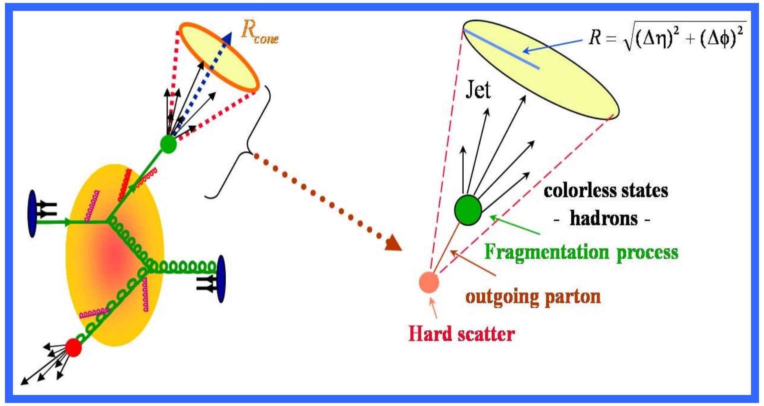


Υ: bottom antibottom
Quarks bound state

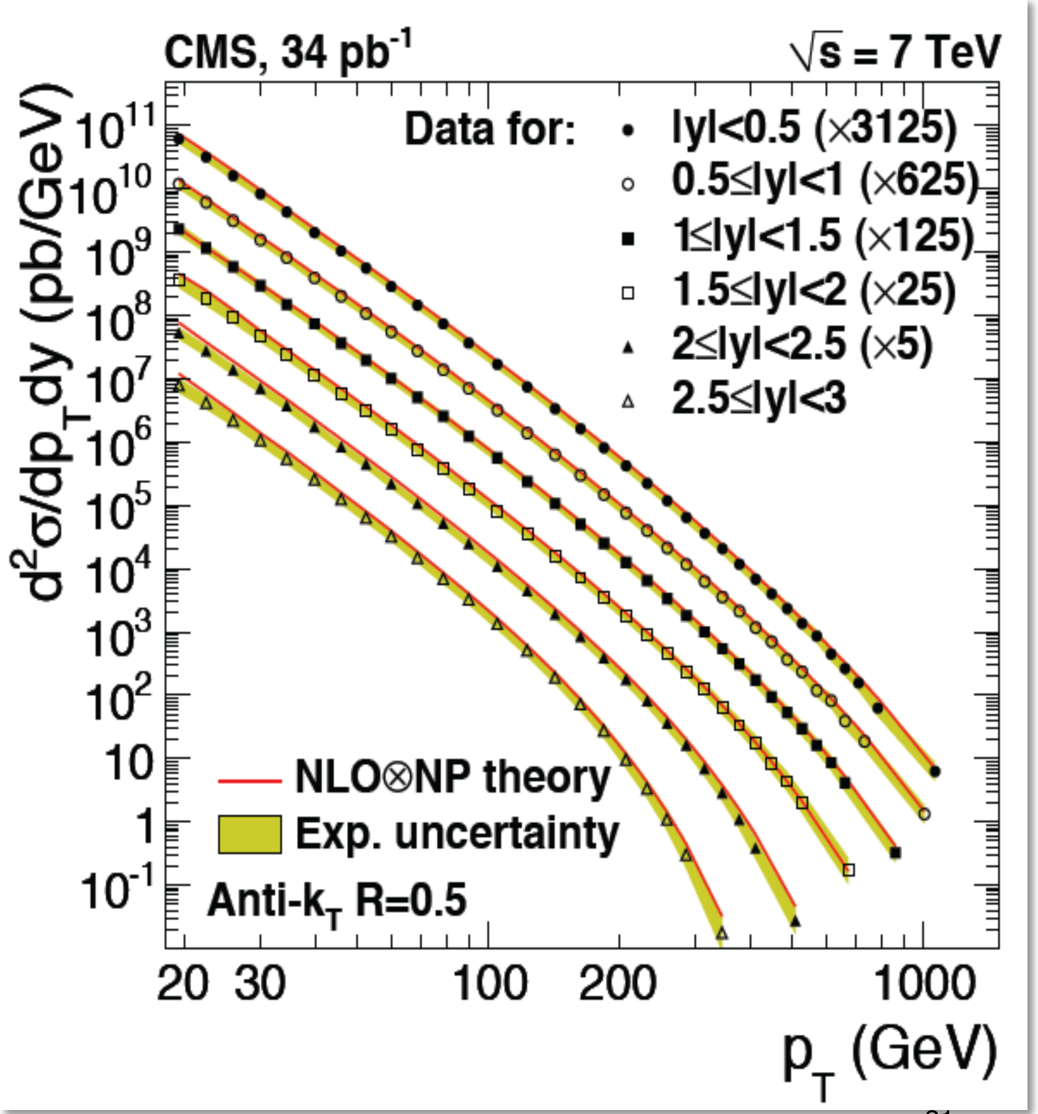
Is known physics correctly reproduced ?



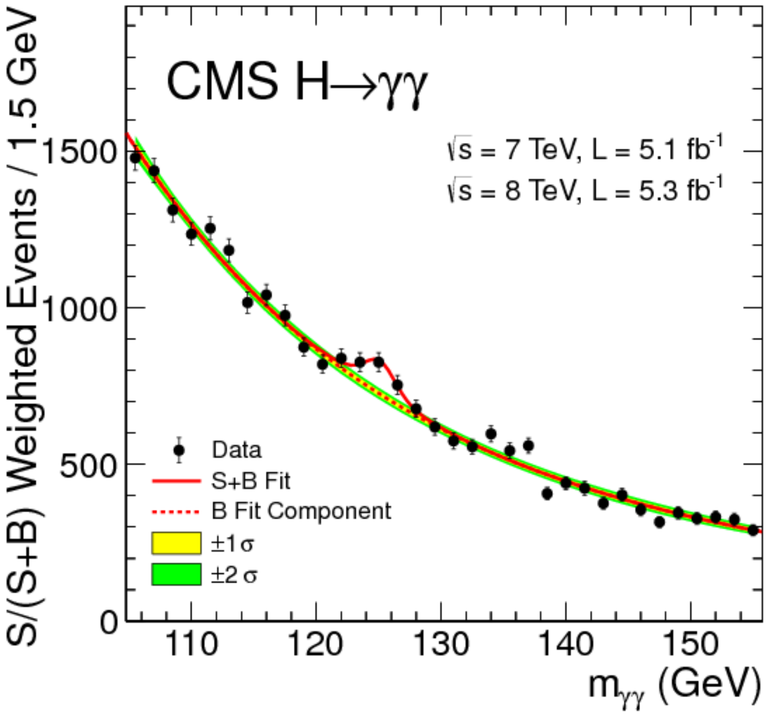
Routinely and successfully analyse many hard collisions in terms of quarks and gluons



One month of data in 2010

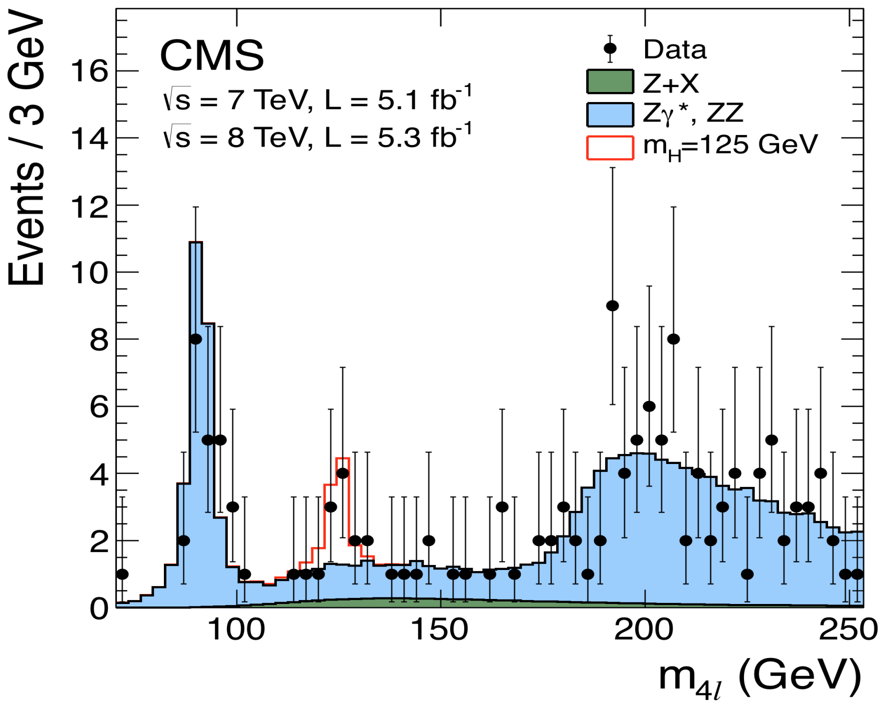


Discovery !



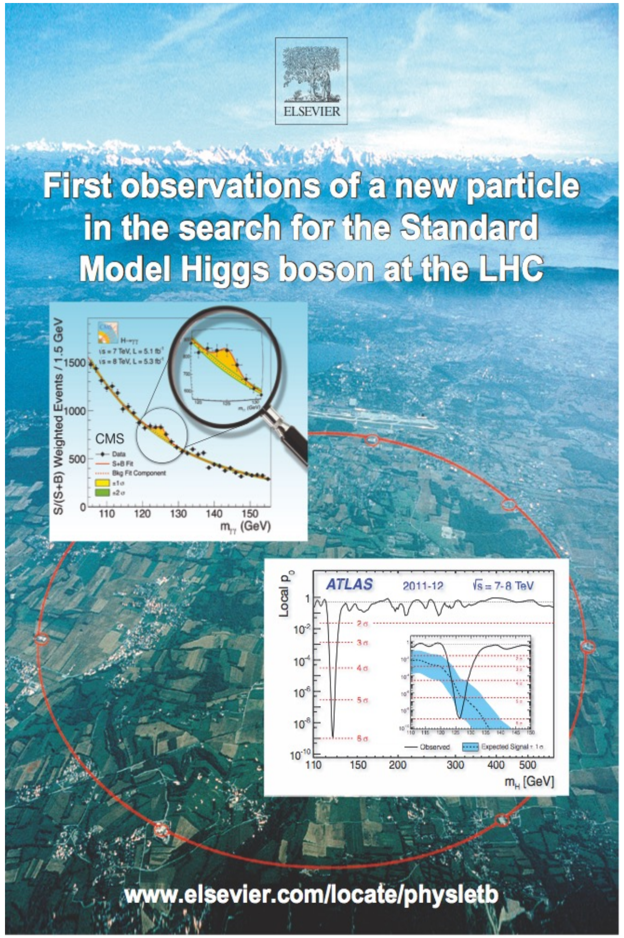
CMS Local significance
Expected: 2.8σ
Observed: 4.1σ

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



What makes it worthwhile to continue physics exploitation of an accelerator?

Ample observational evidence for physics Beyond the SM

World's Topmost Priority

exploitation of the full potential of the LHC

High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

1. **Higher centre-of-mass Energy**
   LHC is now running at 13.6 TeV (not much left to cash in)

2. **Higher Integrated Luminosity**
   Collect ten times more data than originally foreseen

3. **Qualitatively better detectors**

Imperial College London

Higgs Hunting 2022

Translation to Phase 2 CMS Detector Design

New higher granularity more radiation hard inner trackers

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

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

Replacement of front-end electronics

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

Introduction of precision timing (e.g. MTD)

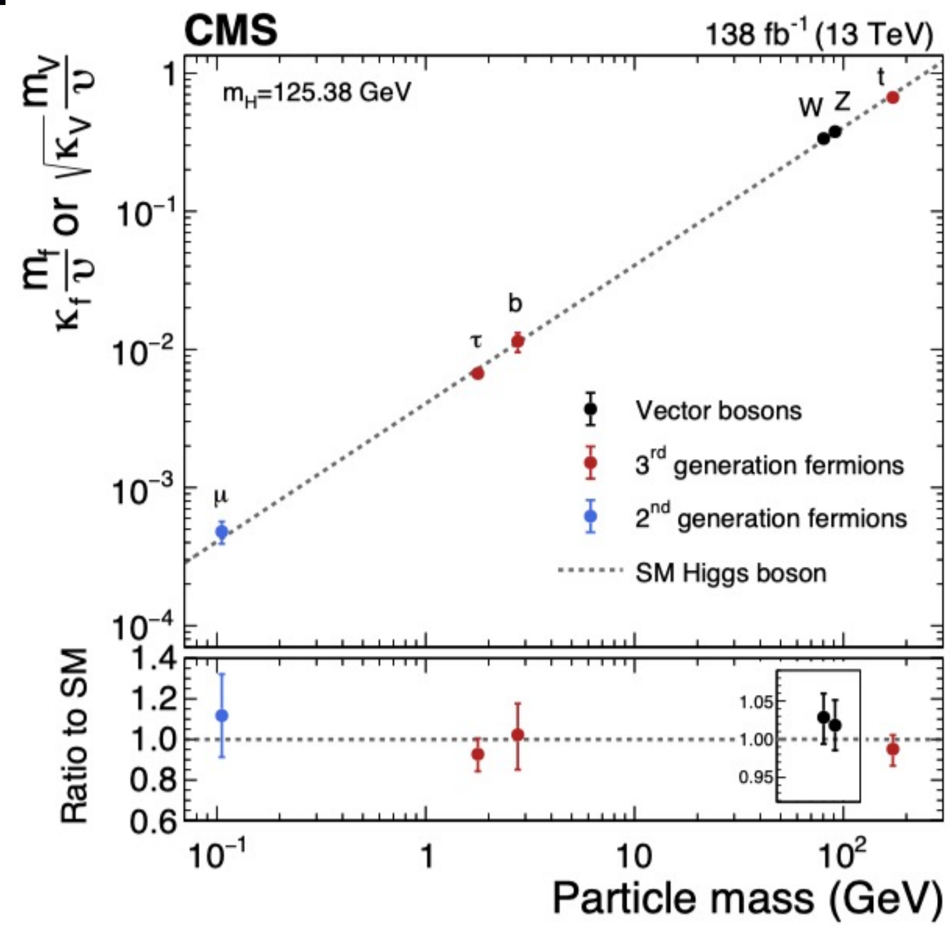
Vertex localization, pileup suppression, slow charged tracks, …

Recall: Enormous Challenges Faced During Construction of Phase 1 CMS Detector!

- Redesign tracker f.e. electronics in 0.25 μm (severe mid-course correction in 1999)
- Change to all-silicon tracker (1999)
- Redesign ECAL f.e. electronics in 0.25 μm technology (2001)
- Detector construction (production issues e.g. silicon sensors, crystals production, muon chambers factories...)
- Integration and installation (e.g. lowering of the experiment, services on coil, ...)
- "Re-engineer" reconstruction software (2005) & prepare CMS for physics extraction
- Particle Flow reconstruction (2009)
- **Expect challenges during the construction of Phase-2 HL-LHC detector.**

- Call to PhD students / postdocs: If not already so, join in and learn about hardware to become "rounded" physicists.

Higgs boson - Current Status (Run 2)

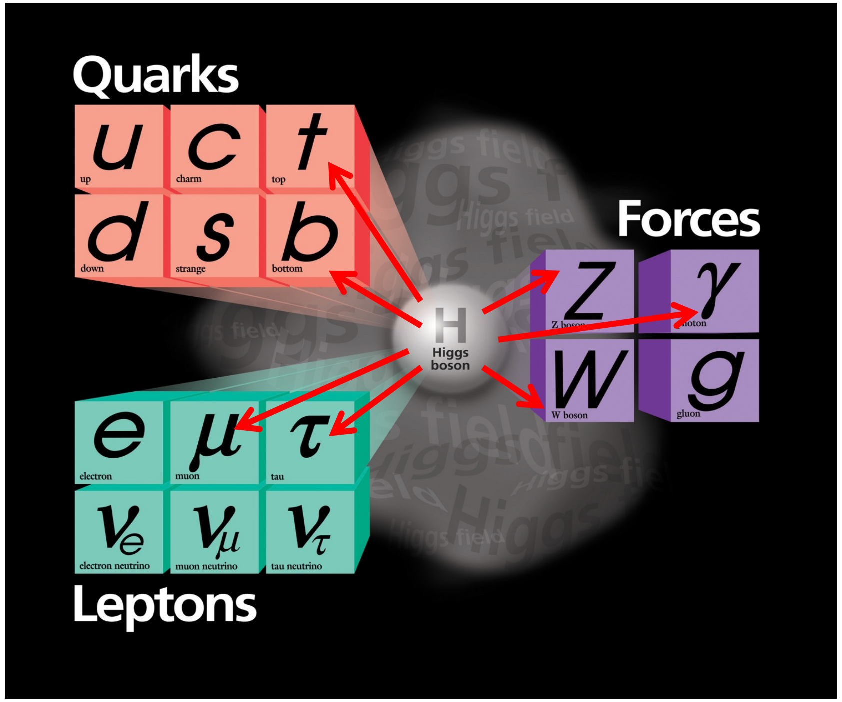


H coupling amplitudes for
Fermions α m_f
Bosons α M_V^2
Consistent with SM predictions

Recall

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

H→ bb
H→ ττ
H→ WW
H→μμ



Summary

- CMS had to overcome many challenges in its construction. Existing technologies had to be pushed to their limits and new ones invented.
- CMS has performed, and 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.

Only experiments reveal/confirm Nature's secrets