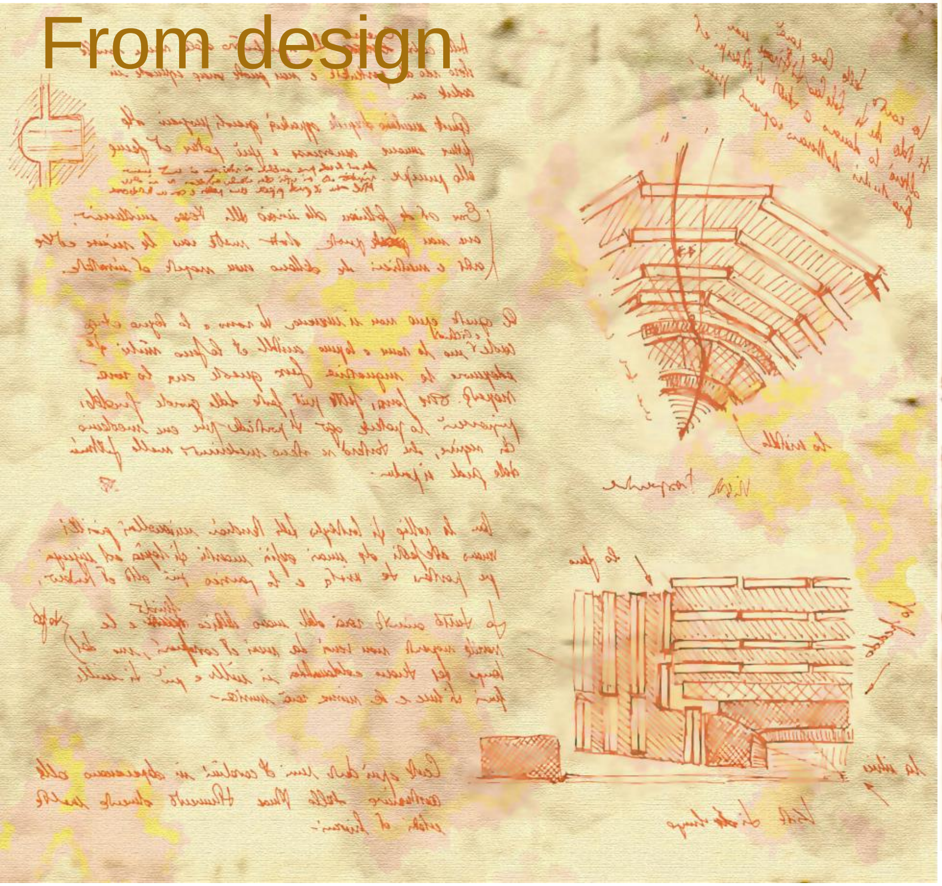
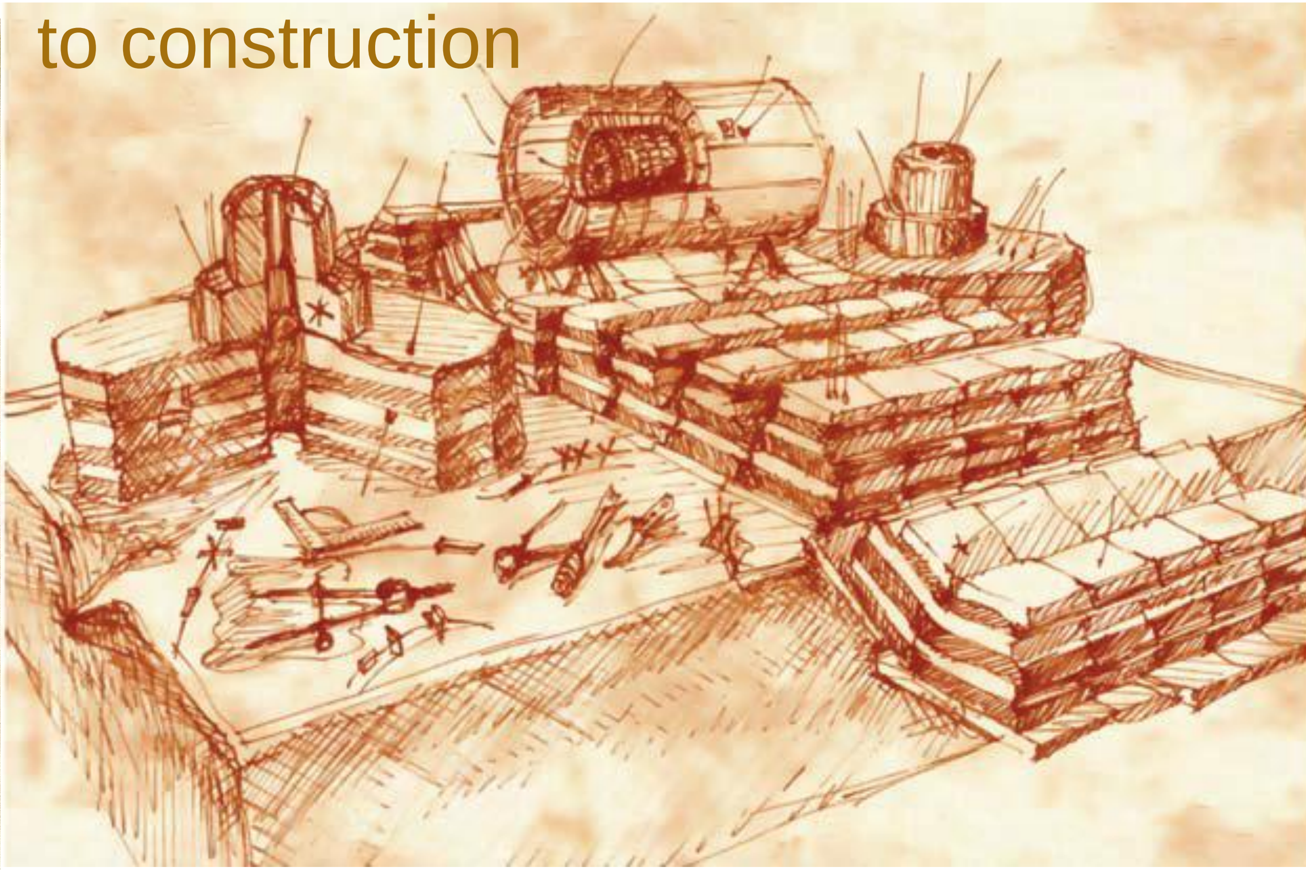
Early days of CMS.

25 years of LHC

CERN, 15 December 2017





Sergio Cittolin

Michel Della Negra

Imperial College, London and CERN, Geneva

The standard model (SM) in the 80's

At the end of the 1980s the **UA1+UA2 community** was preparing to move to the next hadron collider to be installed in the existing LEP tunnel.

The SM was given tremendous support by the UA experiments:

- QCD : Jets abundantly produced and studied in gluon-gluon collisions
- EWK theory: W and Z discovered and properties were studied.

Two fundamental pieces were missing:

- the top quark:
  $m_t < 200$ GeV (indirect LEP 1) ; $m_t > 77$ GeV (CDF)
- the Higgs boson:
  $m_H > 44$ GeV (LEP 1); $m_H < 1$ TeV (Theory : WW scattering unitarity)

No lose theorem: A machine able to probe WW scattering > 1 TeV will either find the Higgs boson or discover new (strong) forces beyond the SM.

- The LHC project (16 TeV pp in LEP tunnel) was really launched in the **Aachen workshop in 1990** (Rubbia, Brianti). To compete with the SSC (40 TeV pp in Texas, USA) a very high luminosity (10^{34} $cm^{-2}s^{-1}$) was mandatory.
- Physics working groups were formed. First studies on physics reach at 10^{34} $cm^{-2}s^{-1}$ were presented.

1990 Aachen volume II: Higgs Studies

"The observation of the intermediate mass Higgs, $m_Z < m_H < 2m_Z$, is one of the most difficult experimental challenge …" Two possible discovery channels:

Aachen 1990

1) **SEARCH FOR $H \to Z^*Z^* \to$ 4 LEPTONS AT LHC**

Higgs Study Group

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

"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} (= 100 fb^{-1} ~ 1 year at $10^{34} cm^{-2}s^{-1}$)."

2) **Photon decay modes of the intermediate mass Higgs**

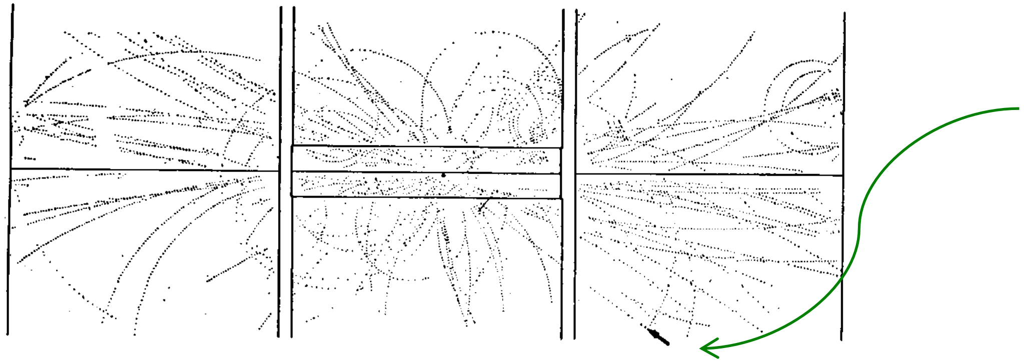
ECFA Higgs working group
C.Seez and T. Virdee
L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

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

"The jet background can be reduced below the direct di-photon spectrum (isolation and π^0 rejection). Need a superb electromagnetic calorimeter energy resolution ($2\%/\sqrt{E} \oplus 0.5\%$) to establish a $H \to \gamma\gamma$ signal for 80 GeV < m_H < 150 GeV and 10^5 pb^{-1}"

Which detector at LHC? Lessons from UA1

- **Discovering $W \to e\nu$ at UA1 (1981) turned out to be remarkably easy:**
  Electron: electromagnetic calorimeter + magnetic tracking
  Missing transverse energy: Hermetic Calorimeter



Electron E_T= 24 GeV well measured in em calorimeter + no visible jet on the away side (hadron calorimeter)

- **Demonstrating $W \to \mu\nu$ was a lot more difficult!**
  High p_T muons suffer from poor momentum resolution: B=0.7T (dipole)
  $\pi \to \mu\nu$ decays can fake high p_T muons and induce fake missing transverse energy.
  Low pT muons on the other hand have an advantage over electrons. They can be detected inside jets: B physics at hadron collider was pioneered by UA1.

First ideas for an LHC detector:

- A robust and redundant muon detector is a priority.
- Muon detection and measurement is guaranteed at any luminosity (Iron Ball) !
- Need a strong magnetic field (momentum resolution).

First conceptual design of CMS

Which magnet to choose to deliver a strong magnetic field ?

All kinds of magnetic configurations were discussed with the magnet group of H. Desportes in Saclay: solenoid, toroid, magnetised iron box.

Strong forces exerted on the conductor can be better managed with a circular coil. Preferred choice: Long solenoid with large inner radius:

- Highest possible field? B = 4 Tesla
- Long solenoid for good forward acceptance L = 15m
- large coil radius to accommodate full calorimetry inside R = 2.9m

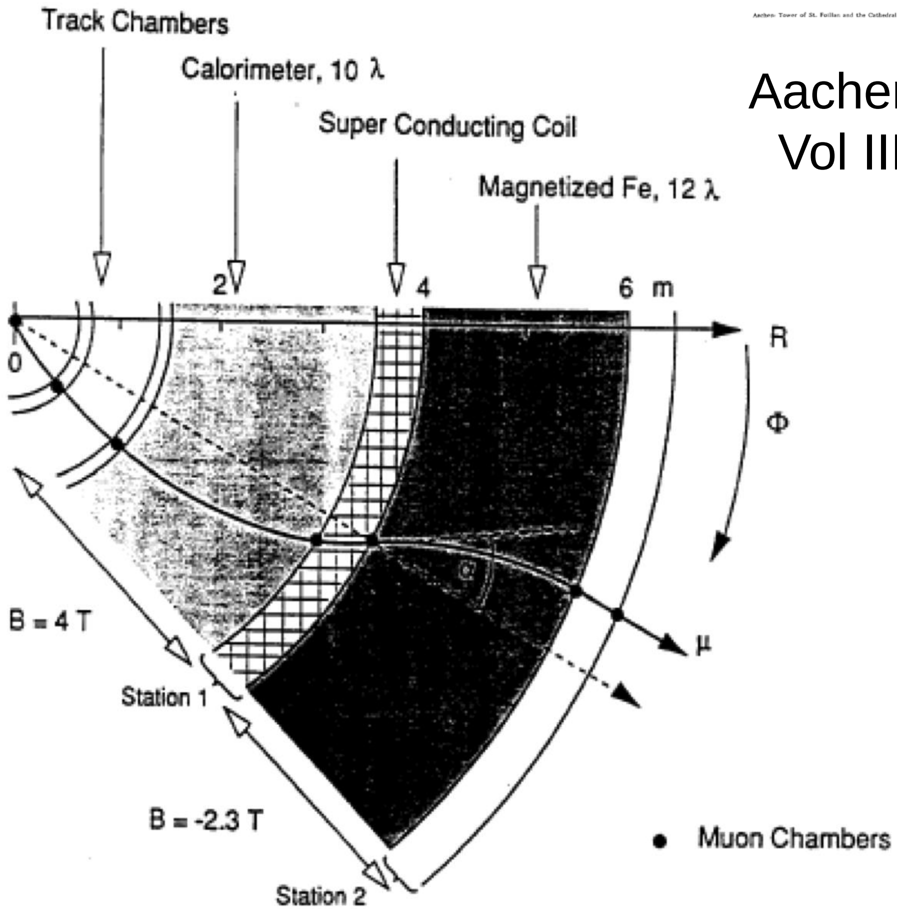
Bending in plane transverse to the beam: one point (interaction vertex in z) with σ=15um for free.

Momentum resolution improved at v.high momenta by using muon and tracker systems

Compact Muon Solenoid

M. Della Negra, K. Eggert, M. Lanzagorta, M. Pimiä,

Aachen
Vol III



Design of LHC Detectors

Search for the SM Higgs boson played a crucial role in the design of CMS. A general purpose detector is needed.

It was not at all clear that a general purpose detector could work at a luminosity of 10^{34} cm^{-2} s^{-1} :

- Fast detectors (25ns between bunch crossings)
- Radiation Hard (more than 10 Mrad forward)
- Very high granularity: minimize cell occupancy and pile-up
- Event size and rate, trigger selection, bandwidth of readout network

Much R&D was needed & started after the 1990 Aachen workshop.

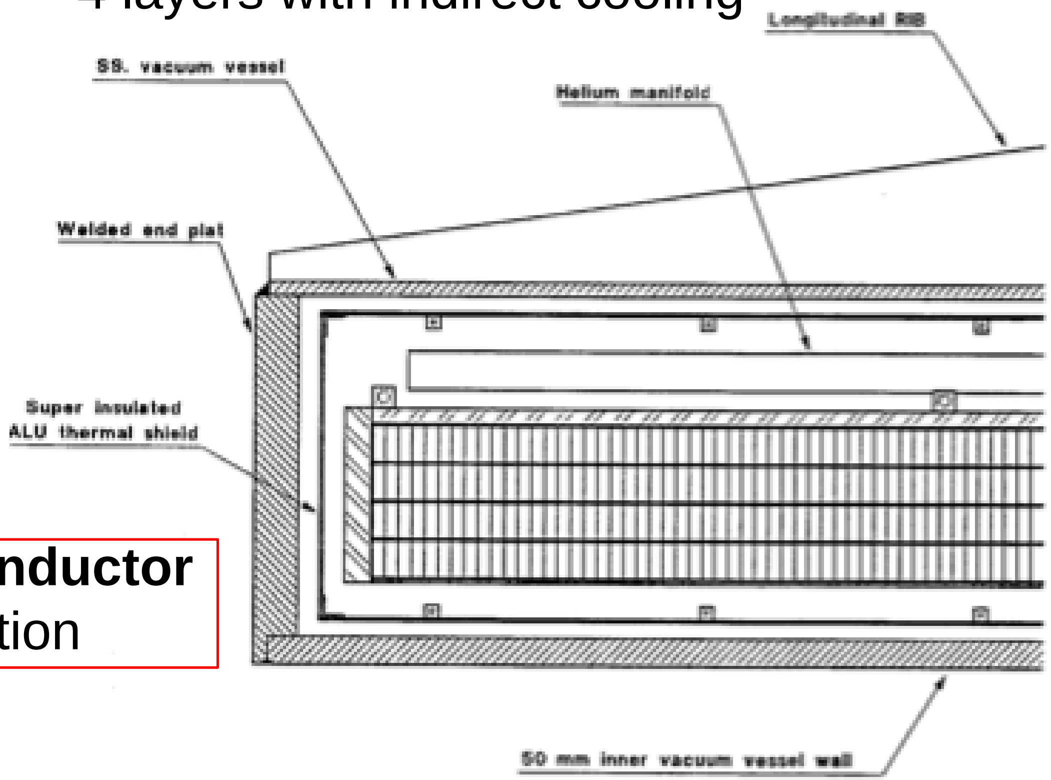
CERN setup the Detector R&D Committee to guide this.

Expressions of Interest (EoI) presented in Evian (March 1992) by four proto-collaborations: Ascot, Eagle, CMS, L3P

CMS Expression of Interest: Evian March 1992

Slides from Henri Desportes

4 layers with indirect cooling

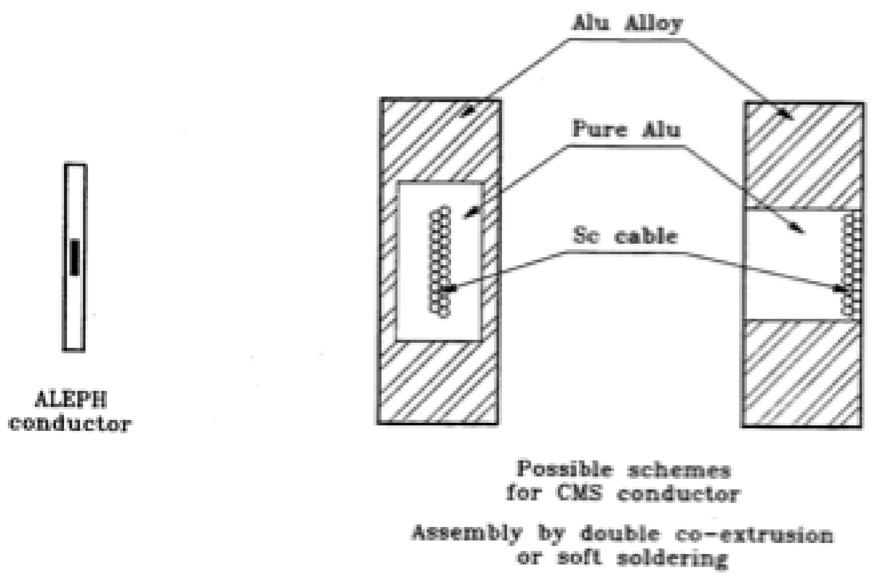


CONCEPTUAL DESIGN OF THE CMS
4 TESLA SOLENOID

J.M. BAZE, H. DESPORTES, R. DUTHIL, C. LESMOND,
J.C. LOTTIN, Y. PABOT

CEA - Saclay - DAPNIA / STCM

Radial pressure 64 atm → **Reinforced conductor** requires development on industrial fabrication



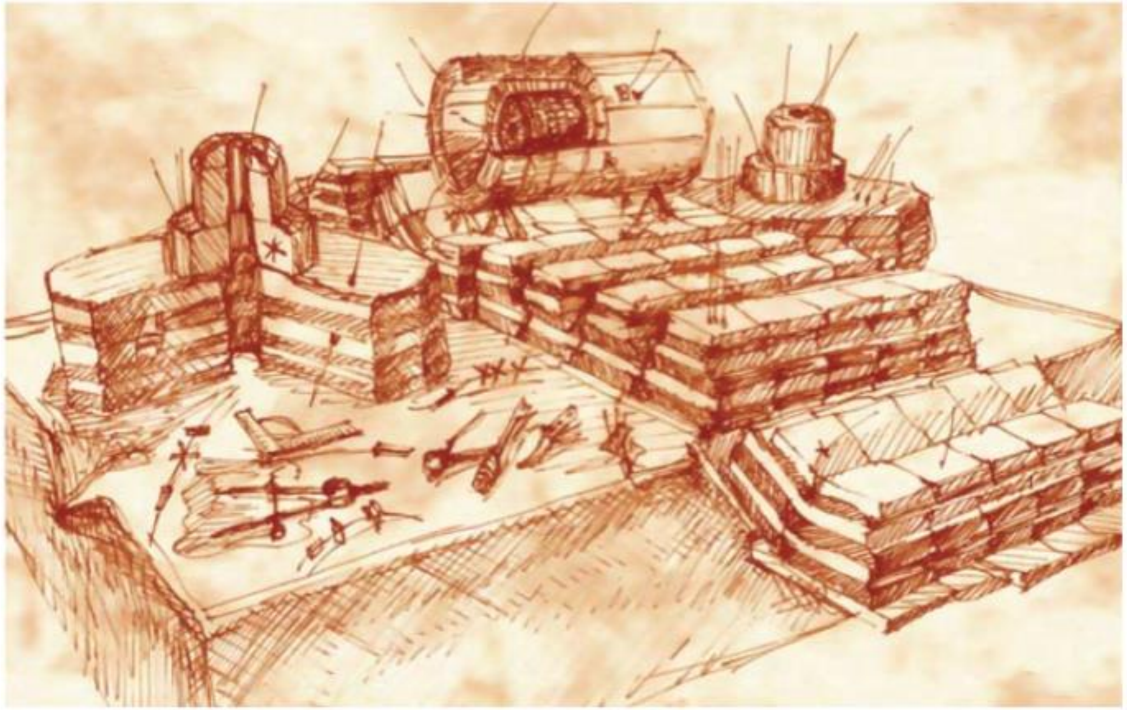
Conceptual design

Based on existing experience

No hazardous extrapolation

Feasibility well understood

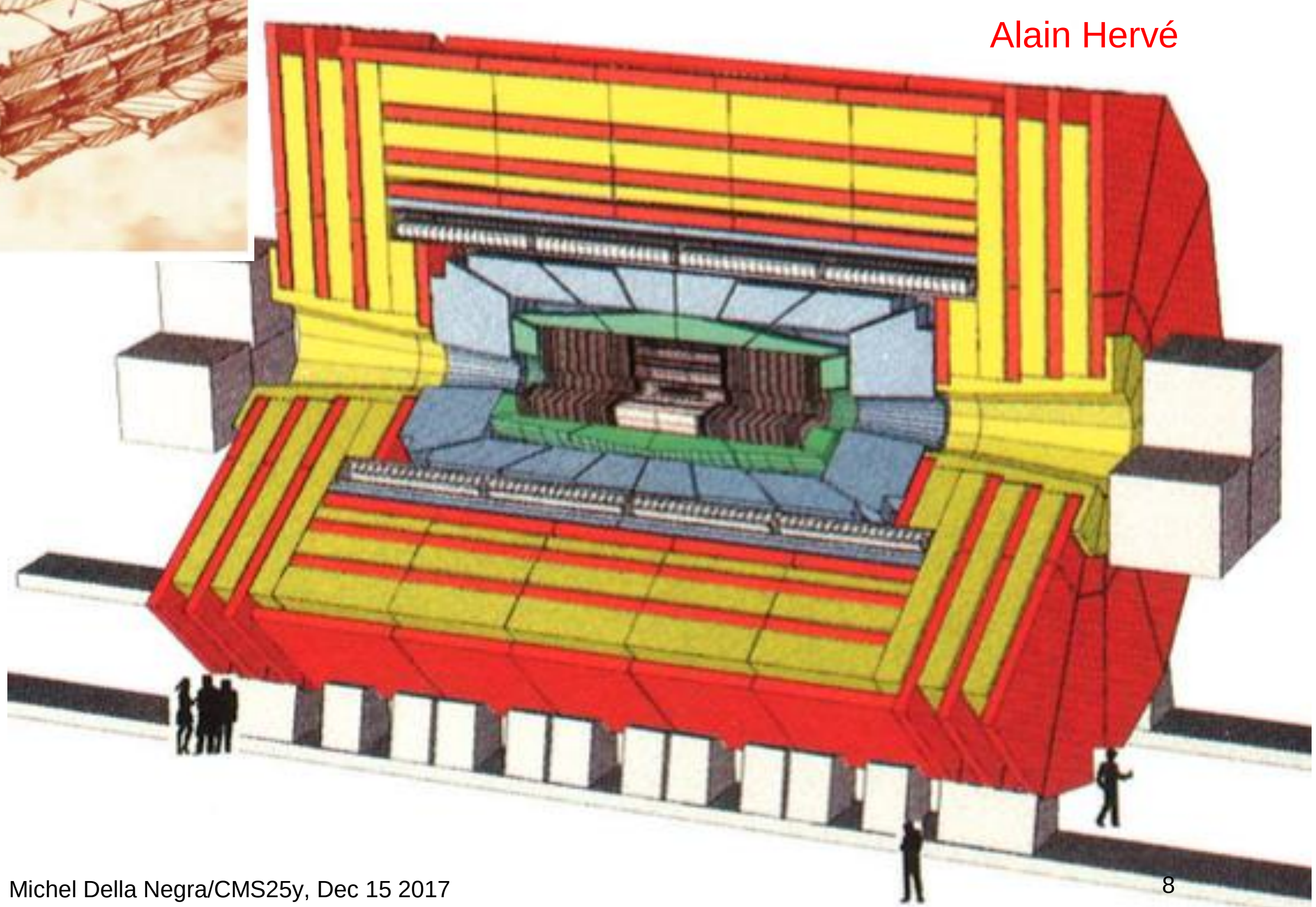
Engineering Form of CMS



Sergio Cittolin

were given an engineering form by Alain Hervé: sectioning CMS in 13 independent pieces

Alain Hervé



Our physicists dreams…

CMS Letter of Intent: November 1992

CMS Design Objectives

1) A very good and redundant muon detection system,

2) The best possible e/γ calorimeter consistent with 1),

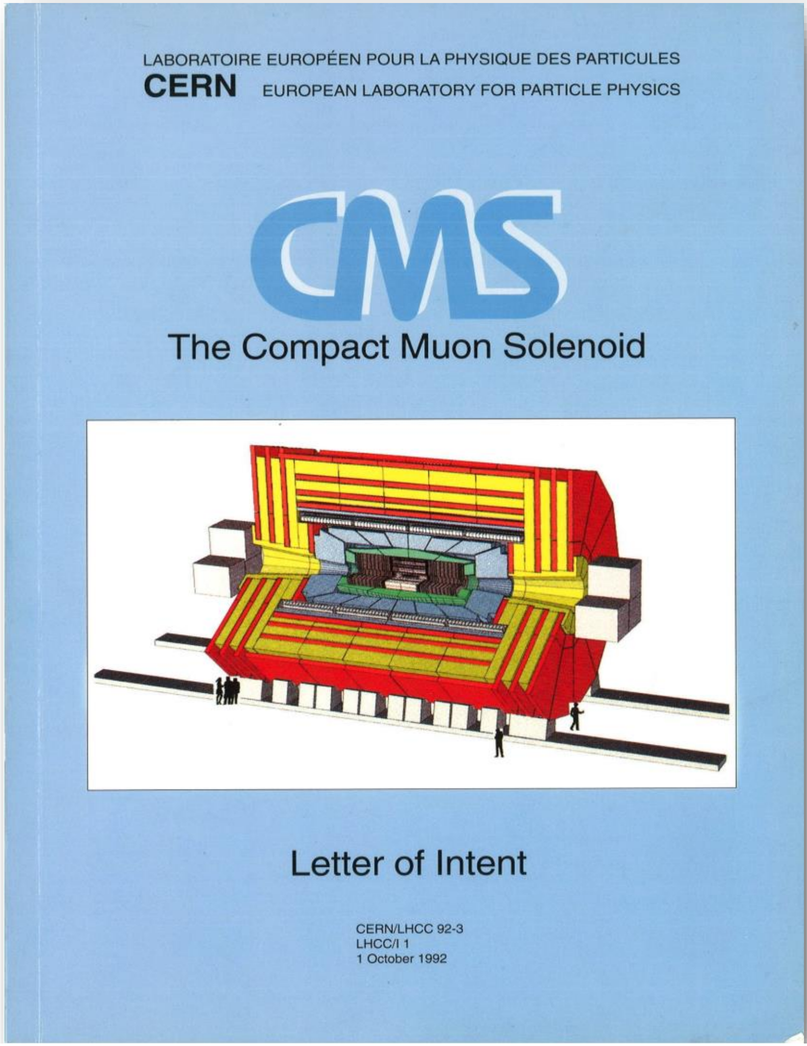
3) High quality central tracking to achieve 1) and 2).

4) Affordable
   staged ≤ 300 MCHF
   full ≤ 400 MCHF

Slide from Open LoI Presentation
Dec. 1992

CMS. Compact Muon Solenoid, November 92 9

After Evian three LoIs: ATLAS, CMS and L3P were submitted, followed by open presentations in Dec 1992



1993: Approval of ATLAS and CMS

Crucial Design Choices (Early 1990s)

- A state-of-the-art superconducting high field solenoid.
- Muon chambers with triggering capabilities embedded in the magnet yoke. Three technologies:
  - Drift Tubes (barrel)
  - Cathode Strip Chambers (endcaps)
  - Resistive Plate Chambers
- Microstrip tracking relying on **relatively few** high precision points (unprecedented area)
- Novel Lead tungstate scintillating crystals for ECAL (1994)
- Pixels detectors over a large surface area (1994)
- HCAL inside the coil: Brass/Scintillator
- Only one custom level trigger (Level 1), then go straight into commercial processors through a commercial telecommunications switch for HLT (with full event information to make the selection of events to be recorded on "tape").

Preoccupations of Reviewers at the time

Review questions from the Chairperson of the CMS LHCC Review Panel: Lorenzo Foa

CMS-LOI/92-LF

ANSWERS TO PROFESSOR LORENZO FOA

QUESTION 0:

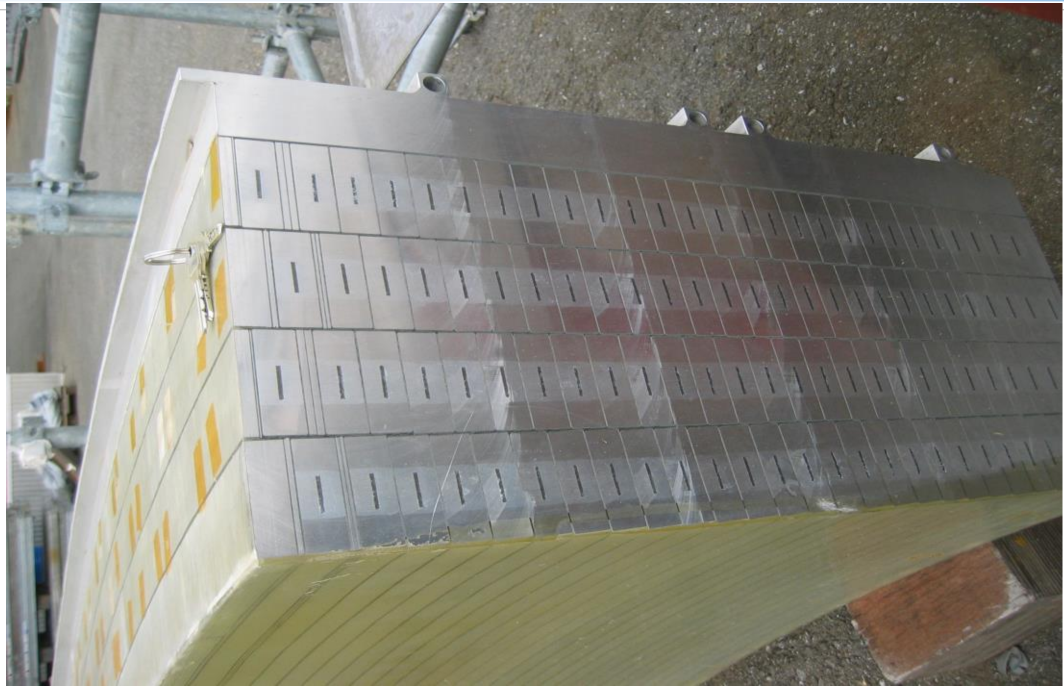
General question that concerns all experiments: What can your e.m. calorimeter do in a "stand alone" mode, I mean if you have to switch off your inner tracking because of excessive rate ?

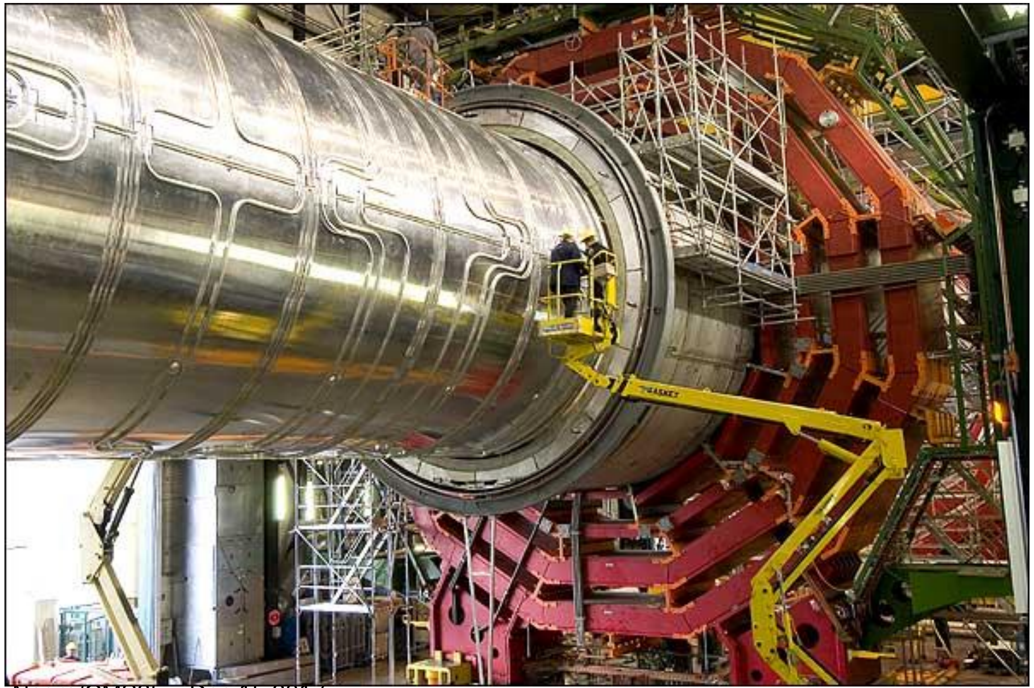
We would like to distinguish between two scenarios, namely:

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

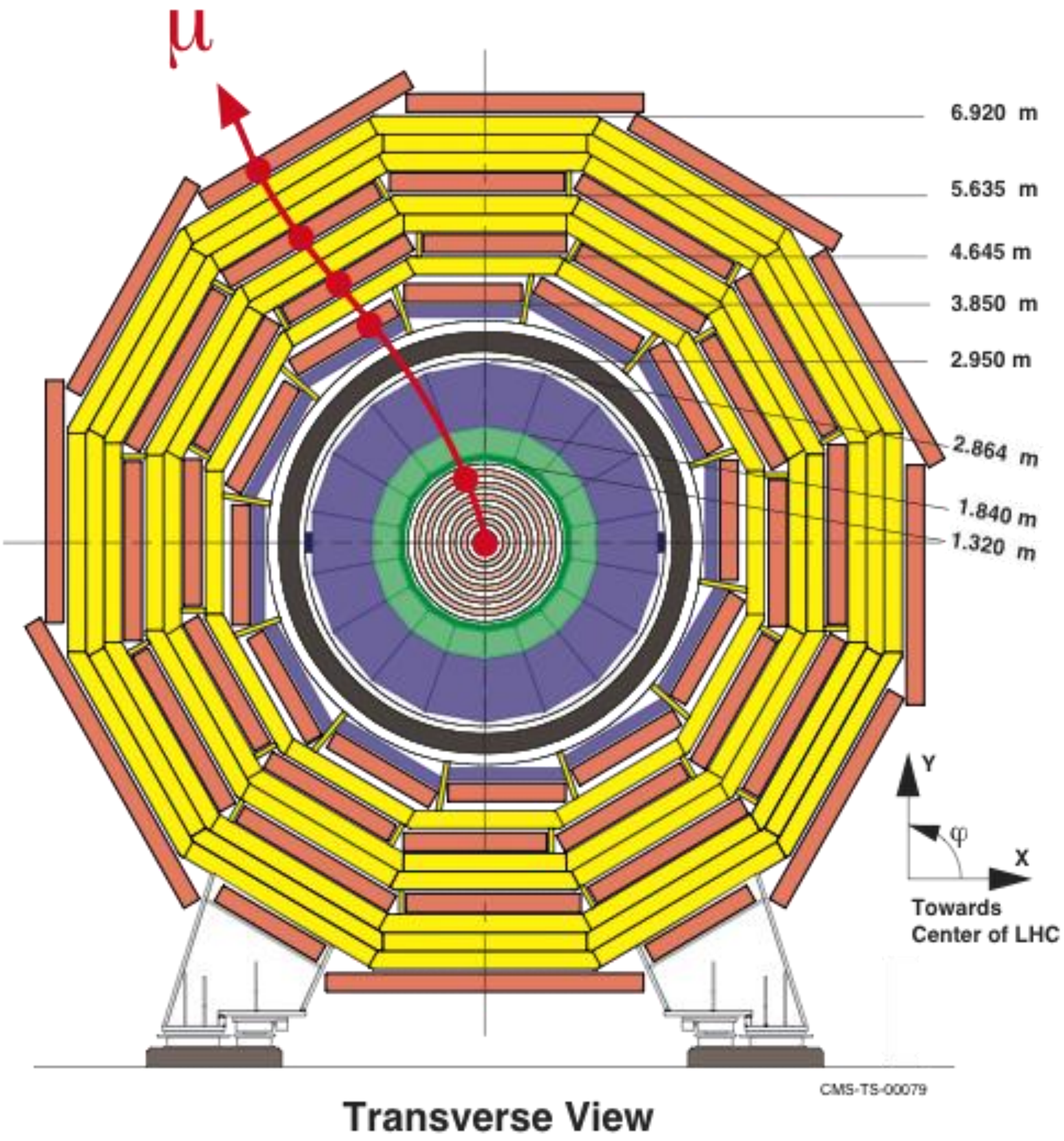
ii) tracking is still possible in the area close to the calorimeters i.e. the last four points are still measurable. We would like to stress that the 4 T field considerably reduces the density of charged tracks in the outer regions of the tracking cavity. Even if we have underestimated the minimum bias 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.

State of Art: CMS Solenoid Coil





Precise and Redundant Muon Detector



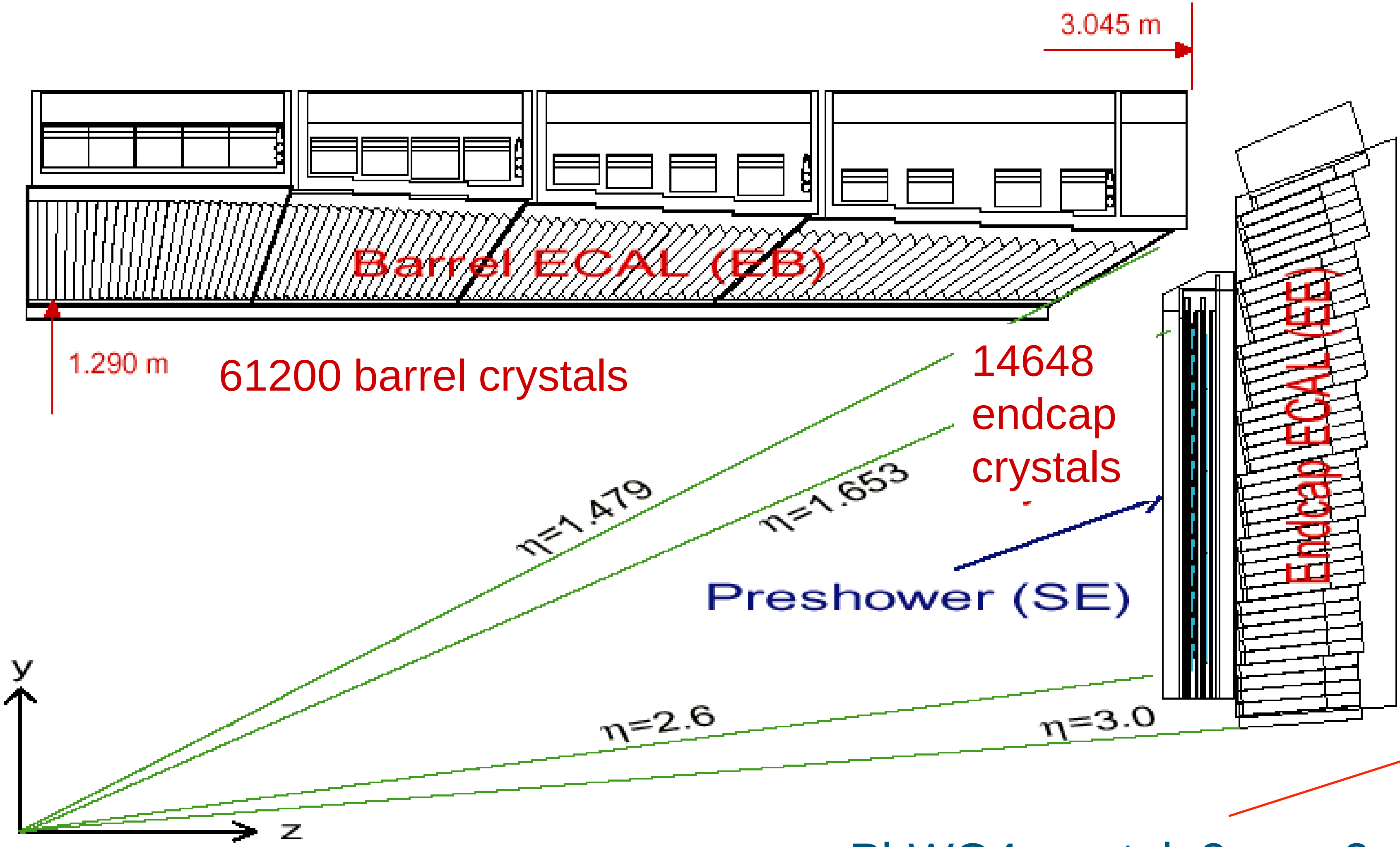
Barrel: four DT muon stations inserted in the magnet return yoke

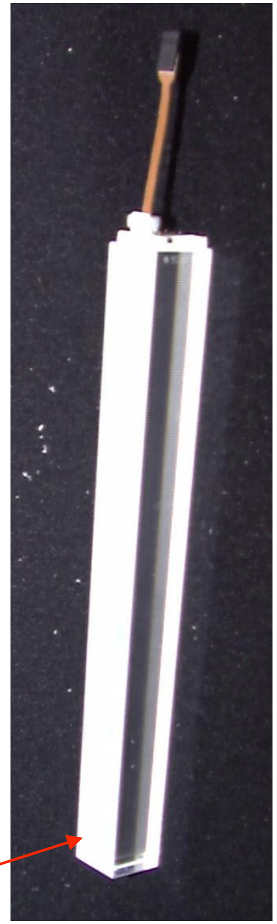
Redundancy: Each muon station has 12 layers of drift cells: 8 r-phi + 4 theta measurements

$\Delta P_t/P_t \sim 5\%$ @1TeV for reasonable space resolution of muon chambers (200μm)

Muon P_t trigger in transverse plane

Precise Photon Detector: PbWO4 Crystal Calorimeter



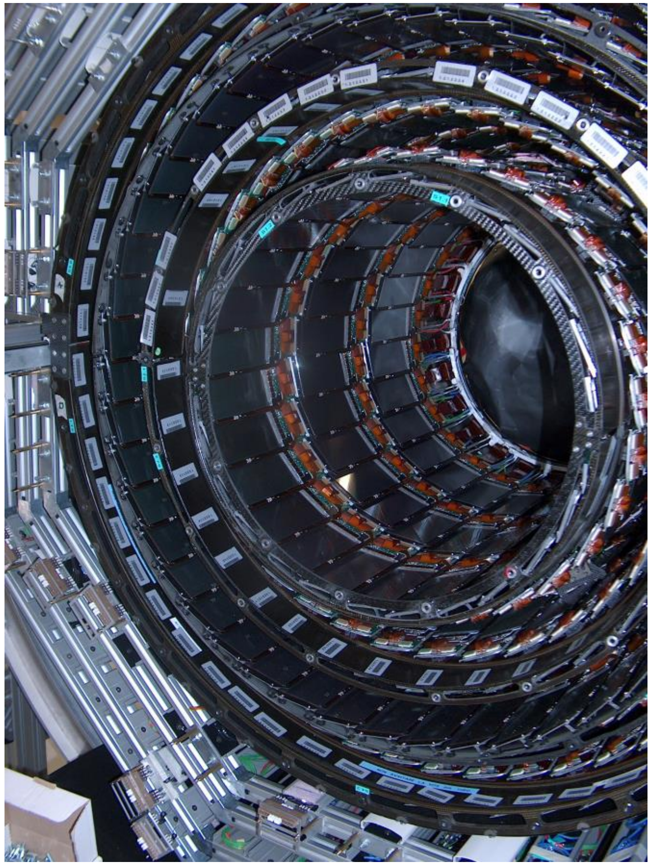


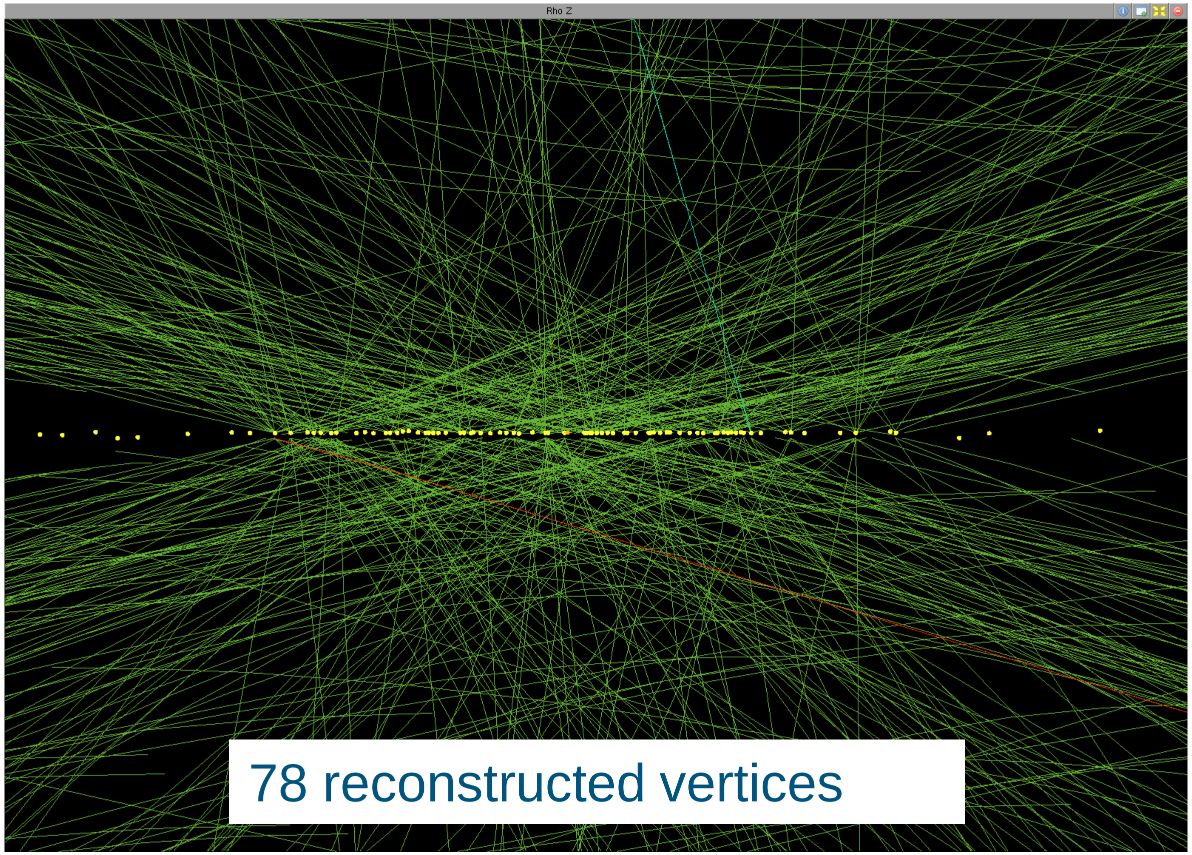
$$\frac{\sigma}{E} = \frac{3\%}{\sqrt{E}} \oplus 0.39\% \oplus \frac{129\,MeV}{E}$$

Target for the intercalibration < 0.5%

PbWO4 crystal: 2cm x 2cm, X_0 = 8.9 mm
Radiation Hard: 10^5 Gy (10 Mrad).
Photodetector: APD works in B = 4T

Tracking at LHC?





Question at the time: can tracking be done, in a congested environment, with a few (~10) points albeit precise ones?

66 million silicon pixels: $100 \times 150\ \mu m^2$

9.3 million silicon microstrips: 80μm - 180μm.

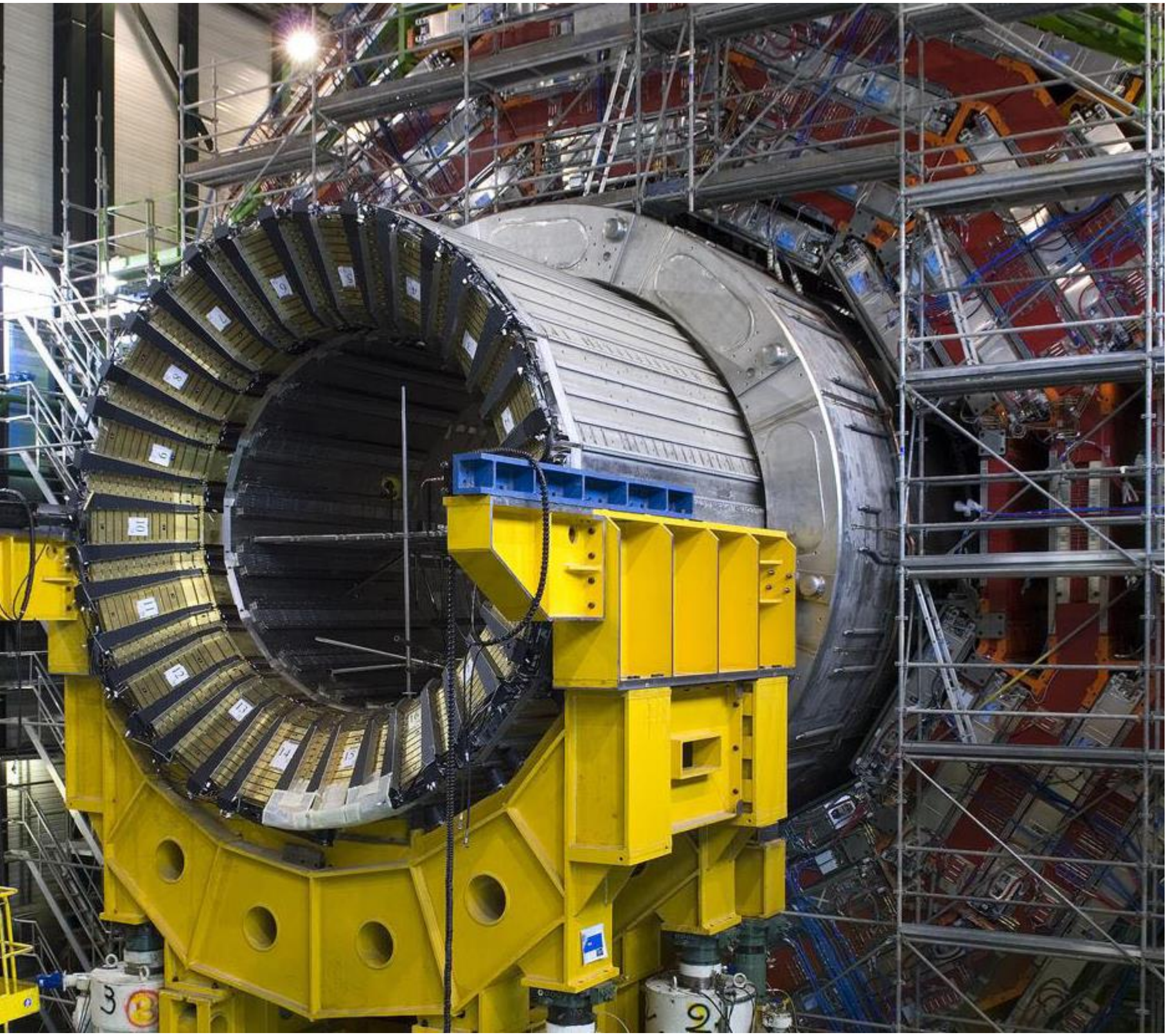
~200 m^2 of active silicon area (cf ~ $2 m^2$ in LEP detectors)

~13 precise position measurements (15 μm) per track.

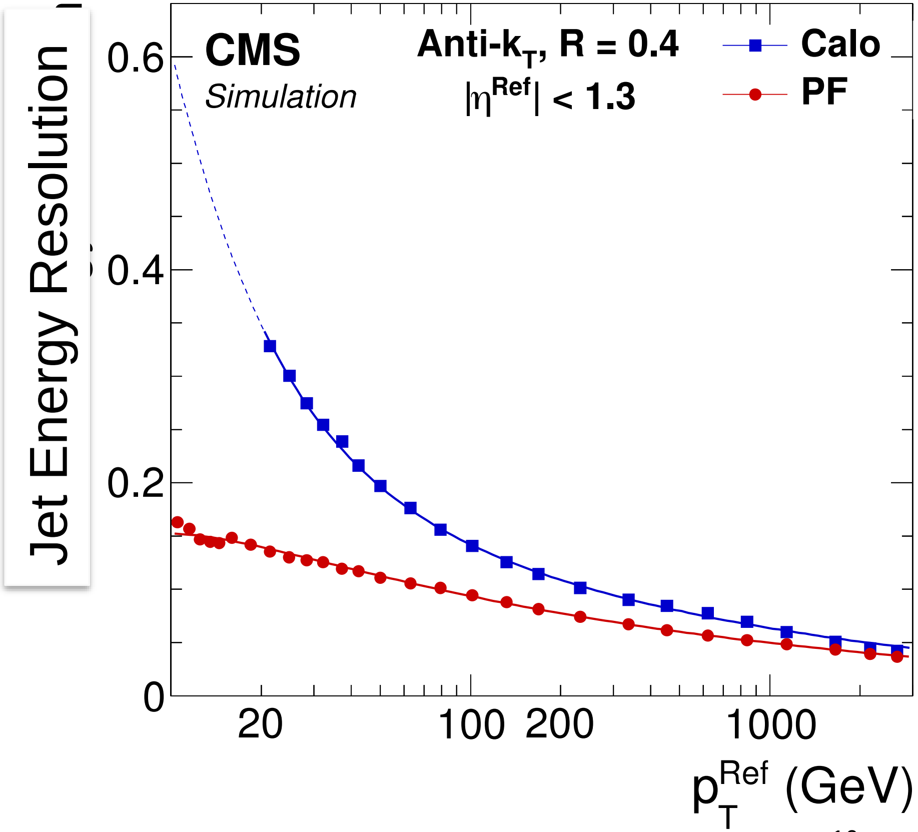
Hadron calorimeter

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

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



Particle Flow (PF) reconstruction (2009) pioneered by P. Janot and C. Bernet: 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)**:



Enormous Challenges!

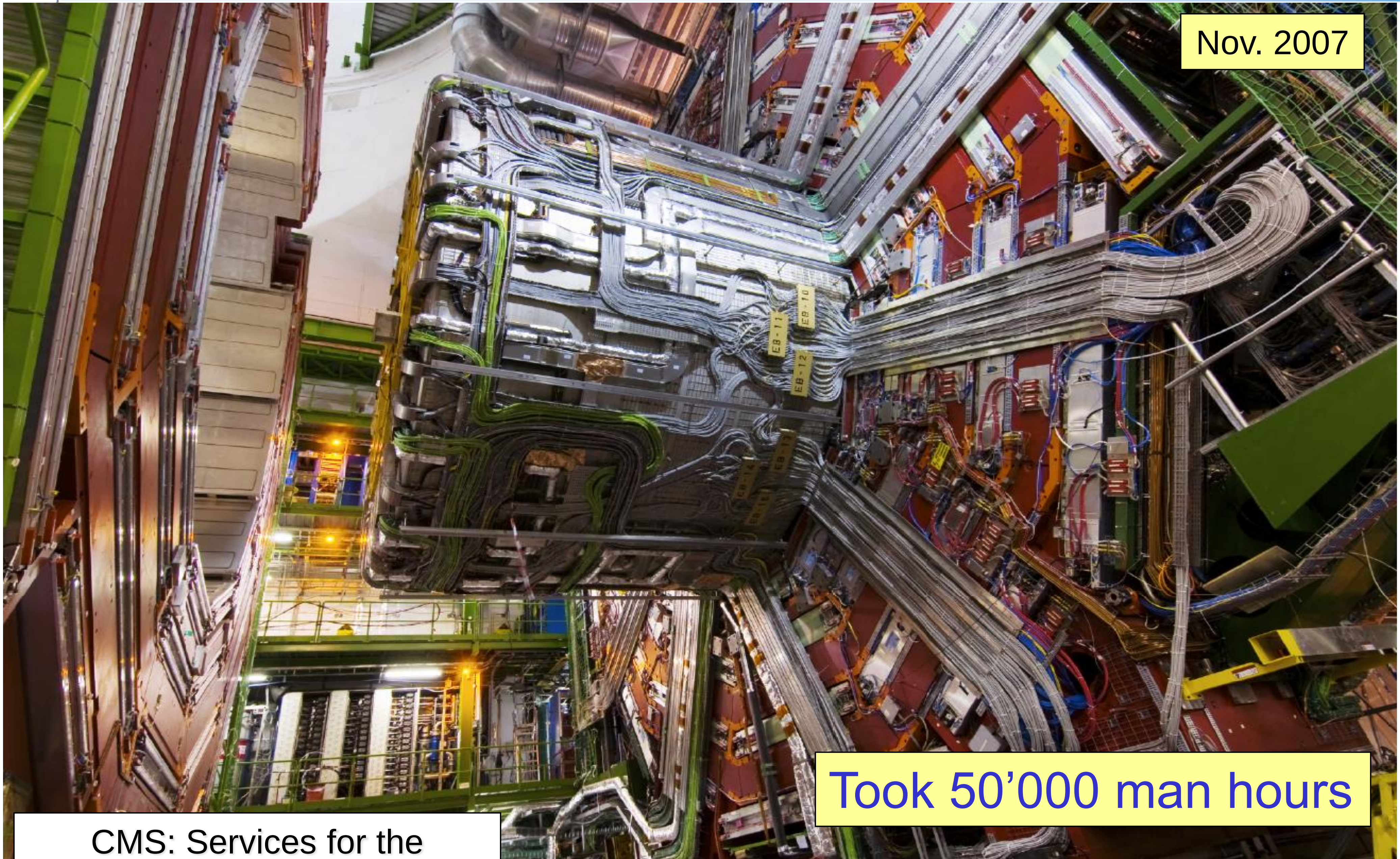
- Redesign tracker f.e. electronics in 0.25 μm (severe mid-course correction in 1999)
- Change to all-silicon tracker (1999)
- Redesign ECAL f.e. electronics in 0.25 μm technology (2001)
- Detector construction (production issues e.g. silicon sensors, crystals production, muon chambers factories...)
- 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)

- Individuals mattered in overcoming these challenges !

Spectacular engineering operations

Descent of the central wheel (2000 tons, Feb 2007)

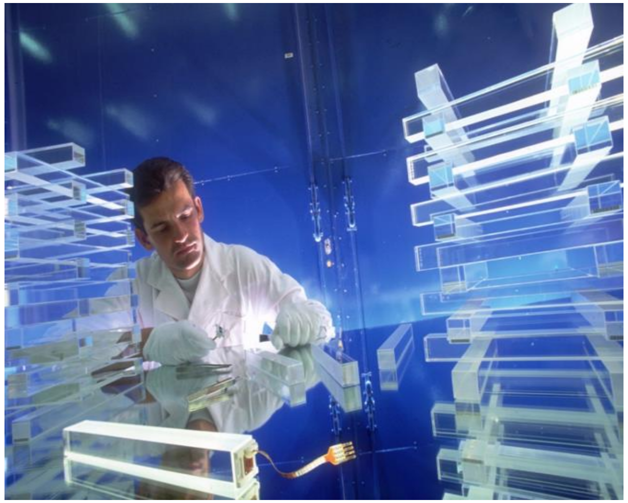
The Challenge of Services !



CMS: Services for the Tracker, Barrel ECAL & HCAL

Example of Challenging Technologies: Long lead times! ECAL: 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 cm³ 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 production, QC)**

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

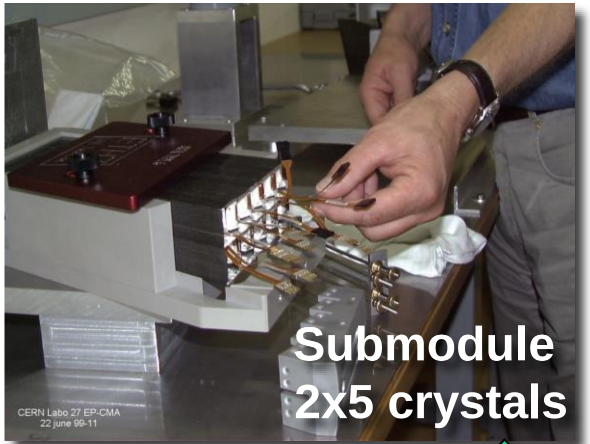
→ **Installation and Commissioning (2007-2008)**

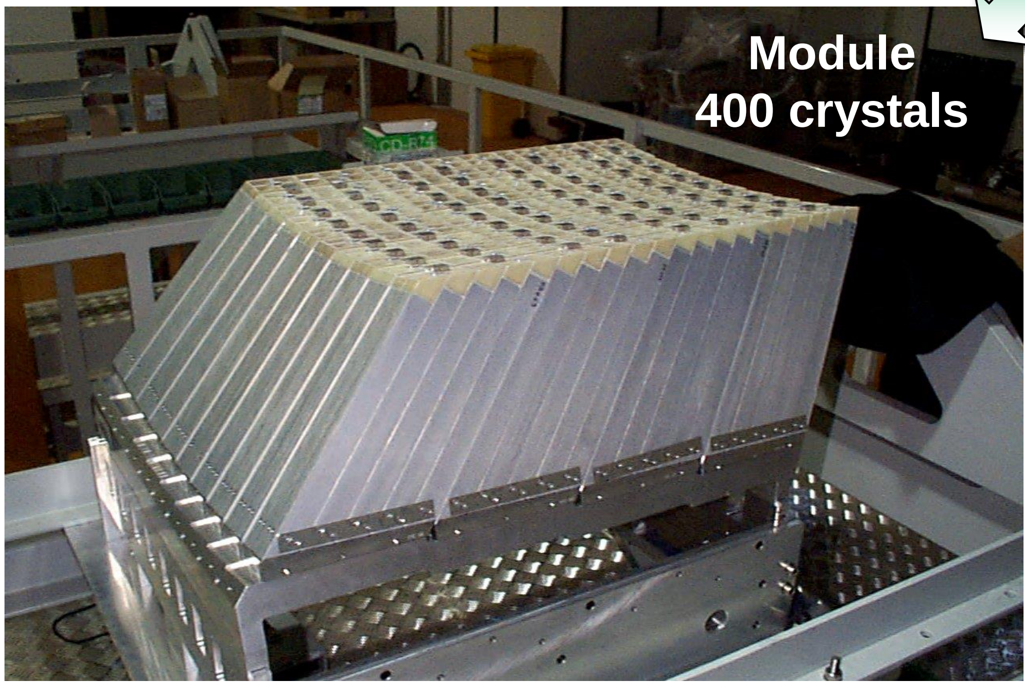
→ **Collision Data Taking (2009 onwards)**

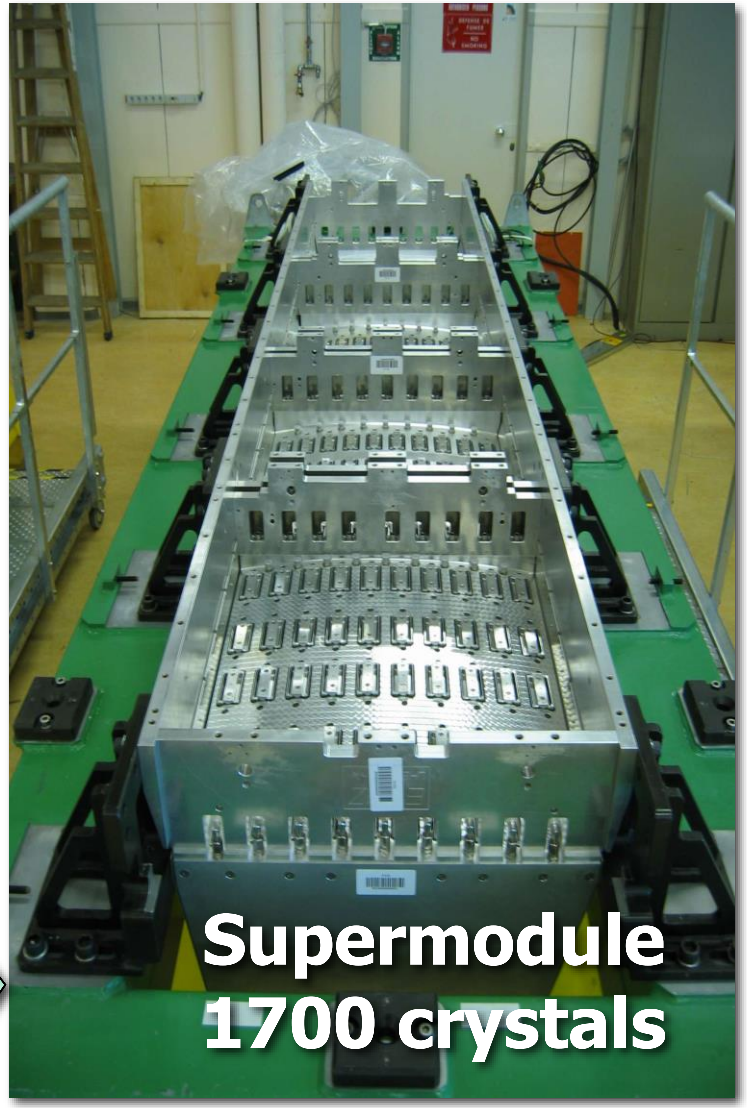
→ **Discovery of a new heavy boson (2012)**

Δt ~ 20 years !!!

CMS Electromagnetic Calorimeter:
Lead Tungstate Scintillating Crystals

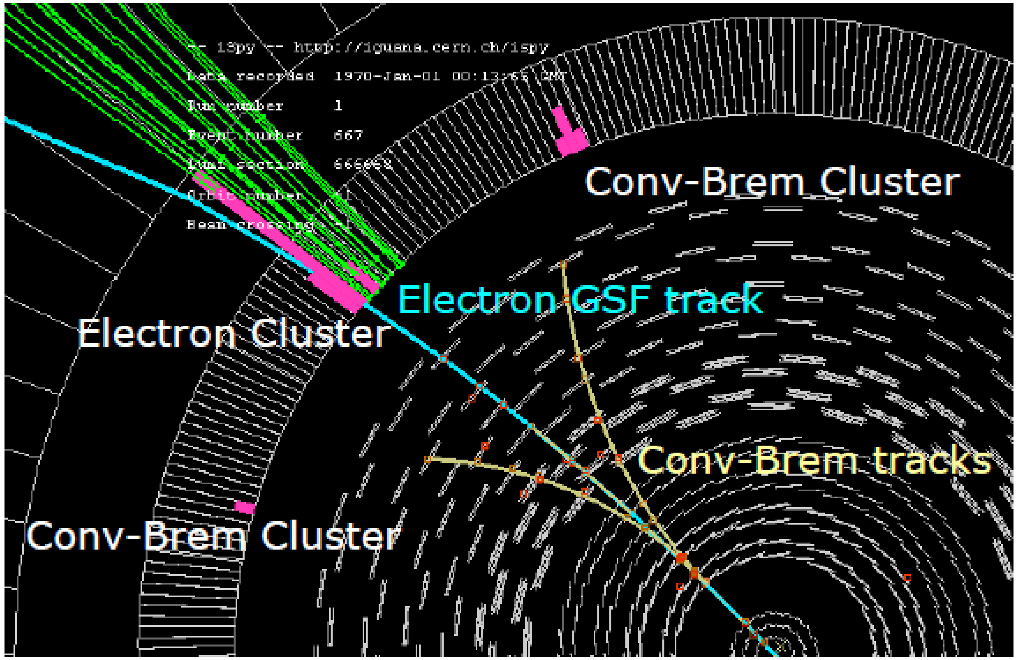


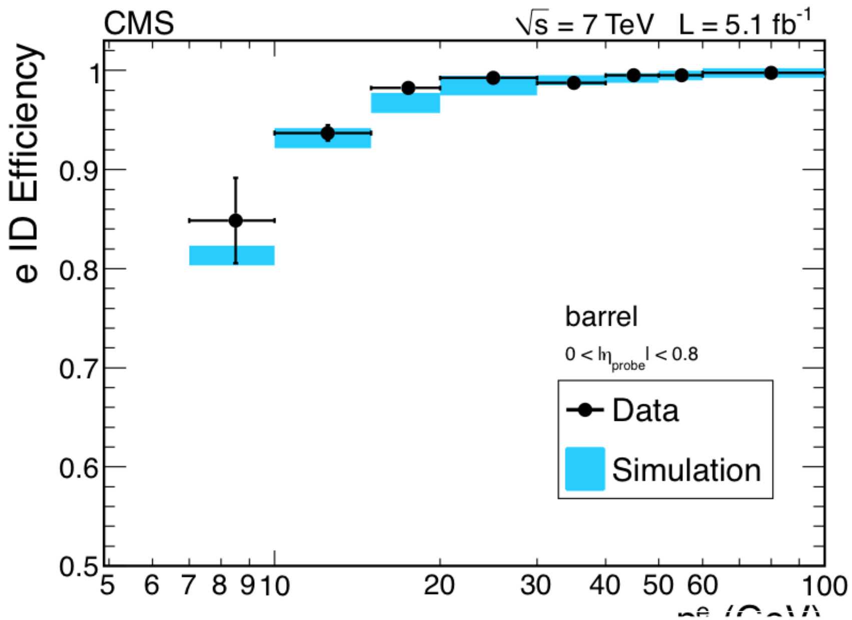


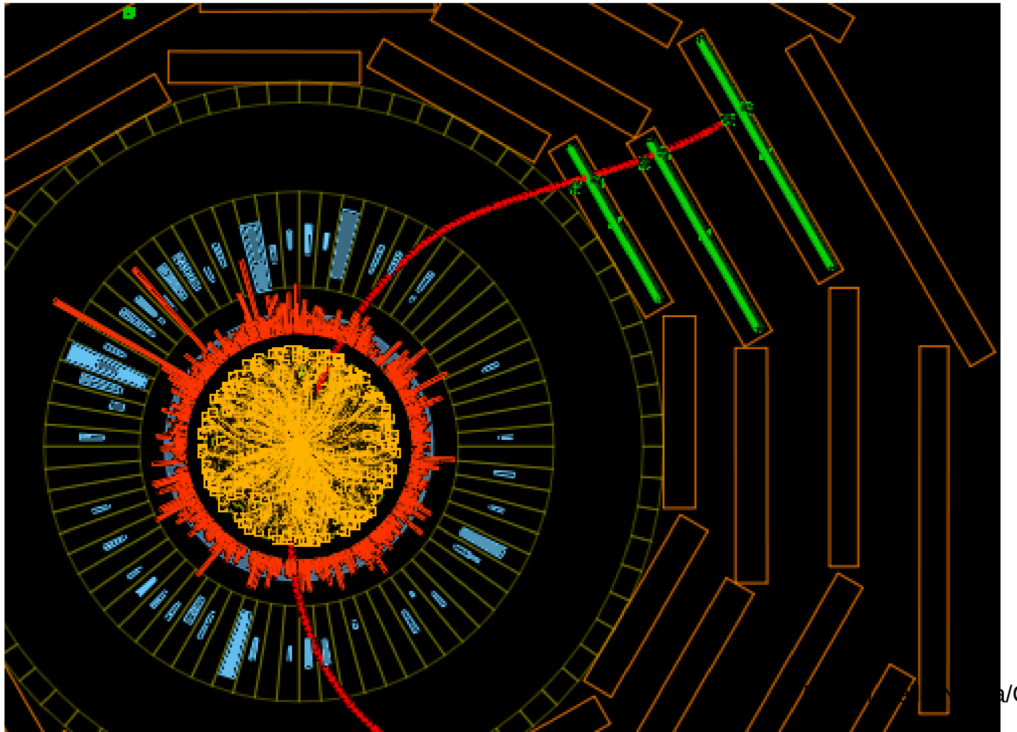


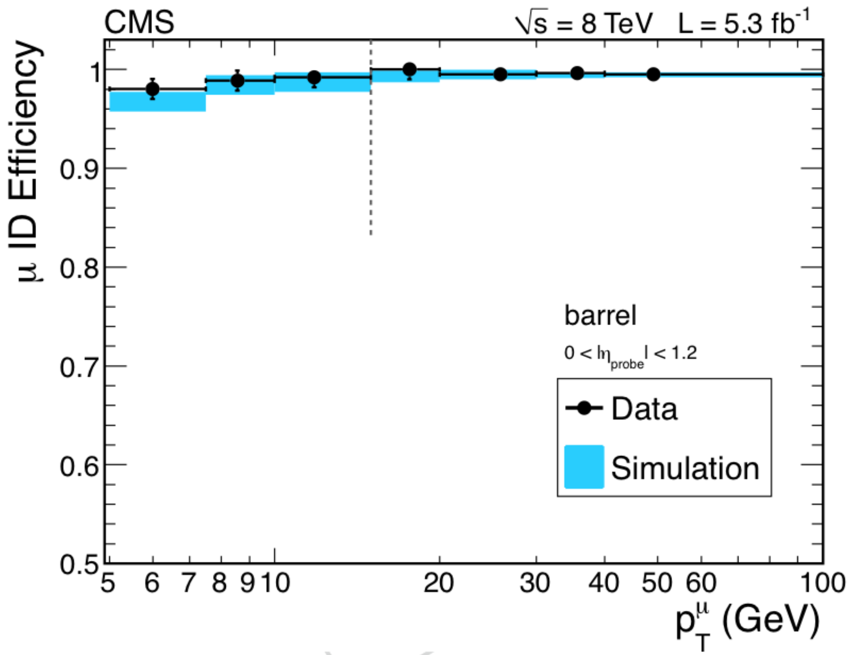
Total 36 Supermodules

Physics Performance: Electrons and Muons

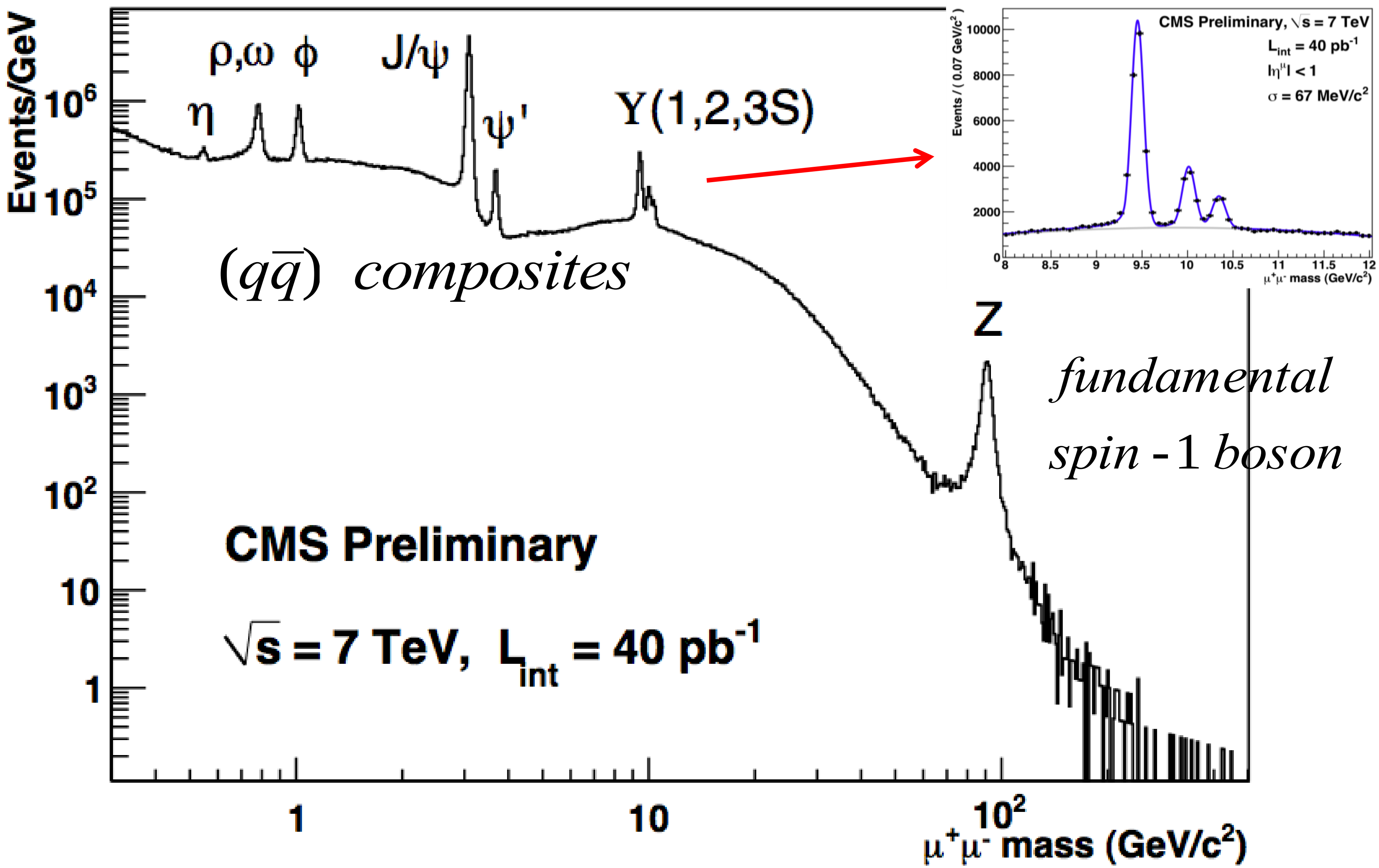




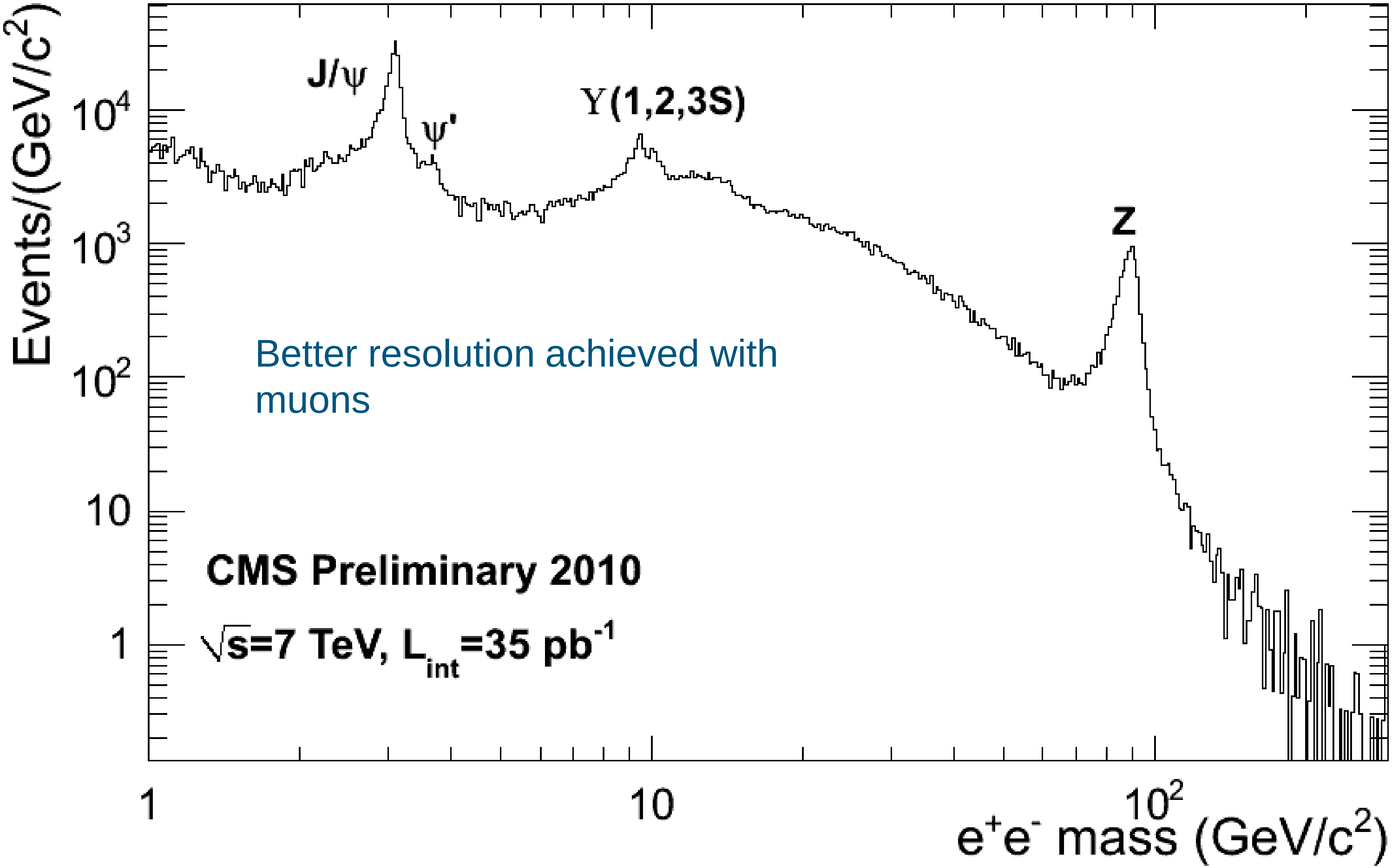




Dimuon mass resolution – out of the box!



Dielectron mass resolution

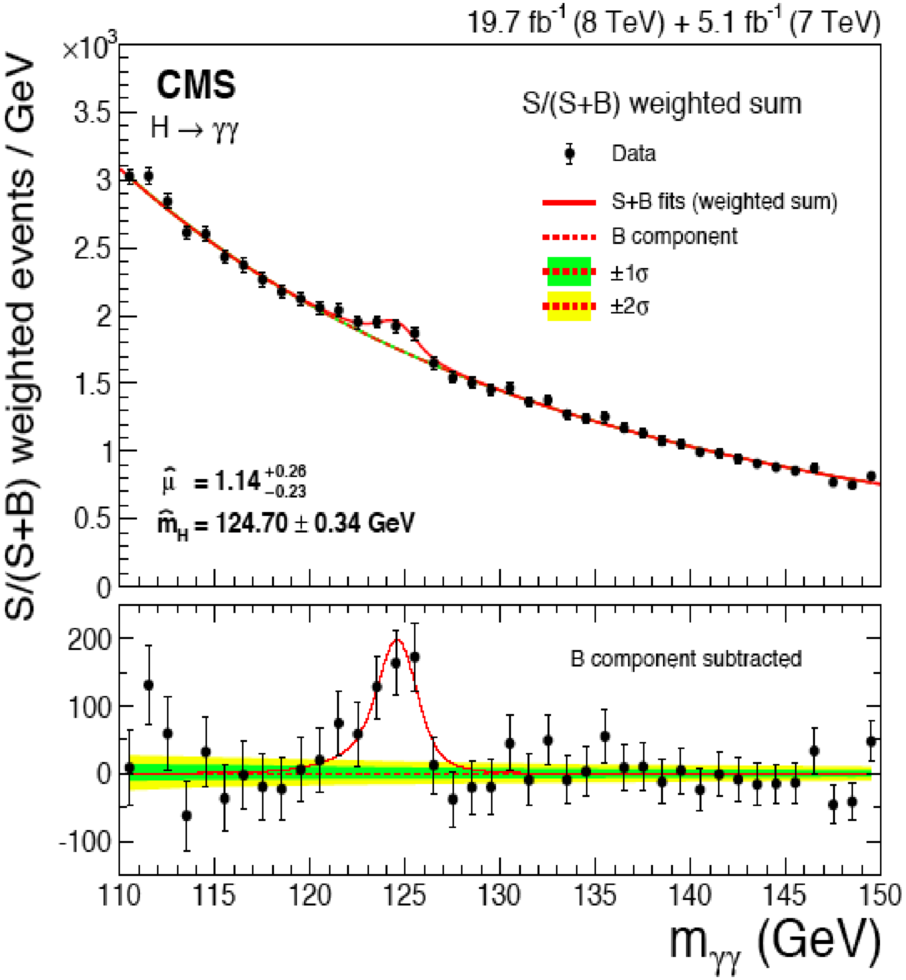


Better resolution achieved with muons

Run 1 Legacy Results: H Decays to bosons

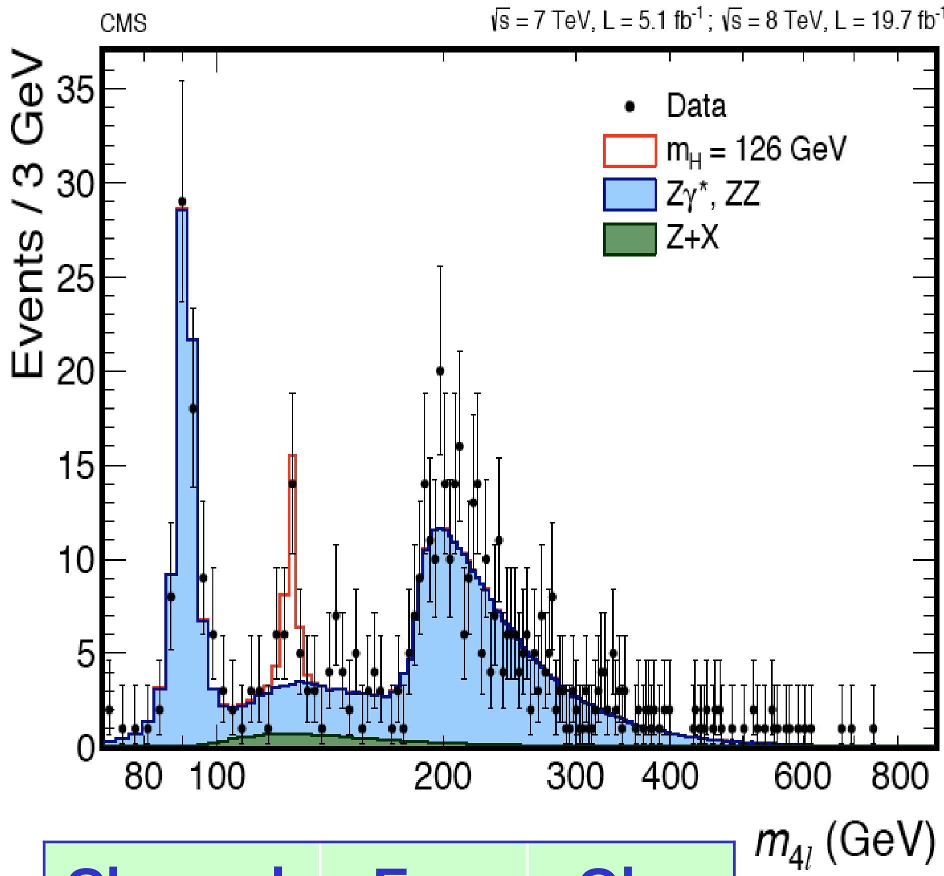
H→ 2γ Channel

EPJC (2014) 74:3076



H→ZZ→4*l* Channel

Phys. Rev. D89 (2014) 092007

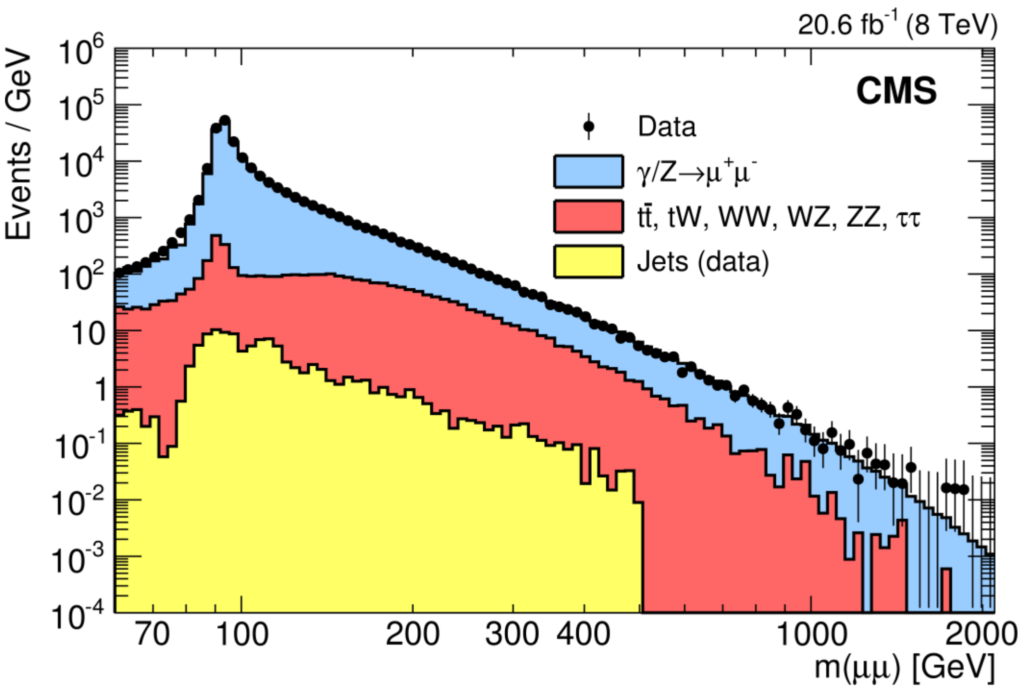


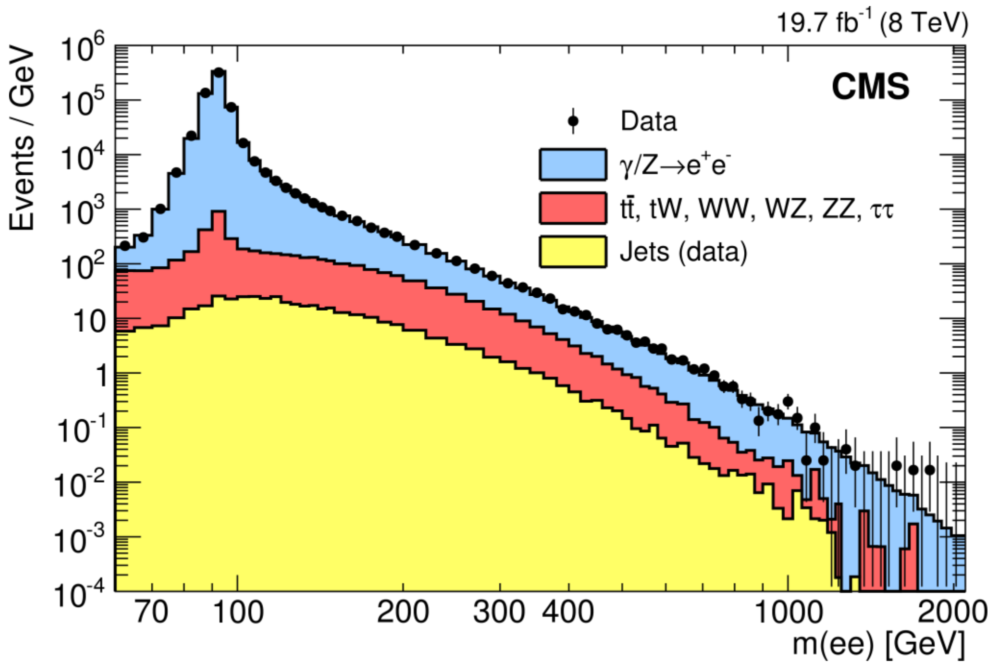
Channel	Exp	Obs
H→ 2γ	5.3 σ	5.6 σ
H→Z→4*l*	6.3 σ	6.5 σ

Extending dilepton mass spectrum up to 2 TeV!

Run 1 Legacy Results

JHEP 04 (2015) 025





No visible new peak above Drell-Yan continuum!

25 Years of LHC, CMS and ATLAS

Lyn Evans: Successful design and construction of the LHC

Peter Jenni and ATLAS : a friendly competition

Combined Measurement of the Higgs Boson Mass in pp Collisions at √s= 7 and 8 TeV with the ATLAS and CMS Experiments

Physical Review Letters 114, 191803 (2015)

$m_H = 125.09 \pm 0.24$ GeV

The CMS Collaboration

~ 4300 active people from 182 institutions and 42 countries

The success of CMS is a testament to the dedication and talents of the members of CMS that transformed a set of drawings into a historic experiment.
The success of CMS is also due to the fantastic work of the LHC accelerator and of the World LHC Computing Grid (WLCG).