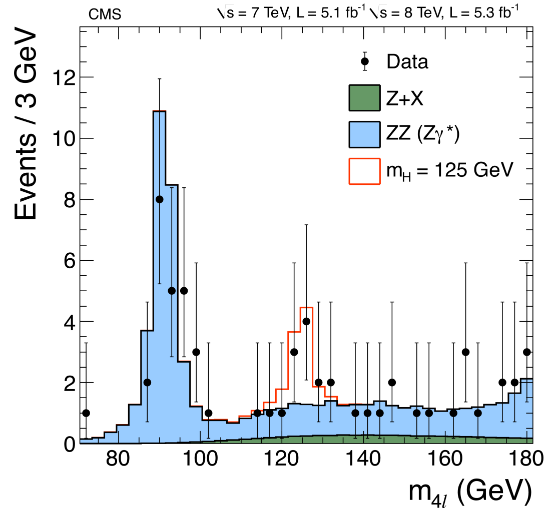
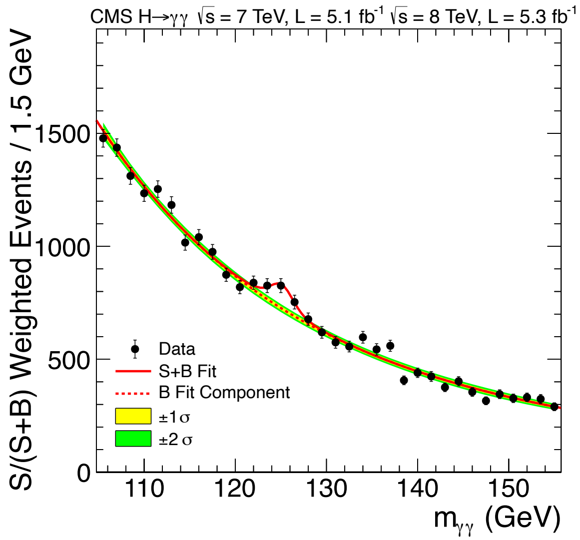
The CMS detector

From design to discovery





10 years of Higgs, CERN, 4 July 2022

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 up to ~ 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 $H \rightarrow Z^*Z^* \rightarrow$ 4 LEPTONS AT LHC**

Higgs Study Group

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

“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.

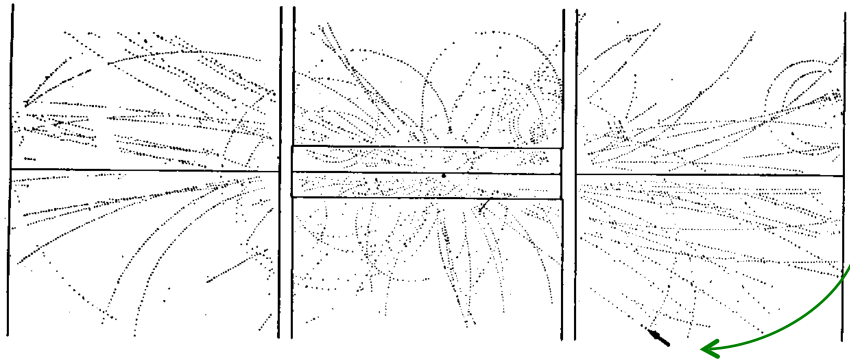
“The jet background can be reduced below the direct di-photon spectrum (isolation and π^0 rejection). Need a superb electromagnetic calorimeter energy resolution ($2\%/\sqrt{E} \oplus 0.5\%$) to establish a $H \rightarrow \gamma\gamma$ signal for 80 GeV $< m_H <$ 150 GeV and 10^5 pb^{-1}”

Which detector at LHC? Lessons from UA1

- **Discovering $W \rightarrow e\nu$ 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 $W \rightarrow \mu\nu$ was a lot more difficult!**

  High p_T muons suffer from poor momentum resolution: B=0.7T (dipole)

  $\pi \rightarrow \mu\nu$ 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 ?

Compact Muon Solenoid

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

Aachen Vol III

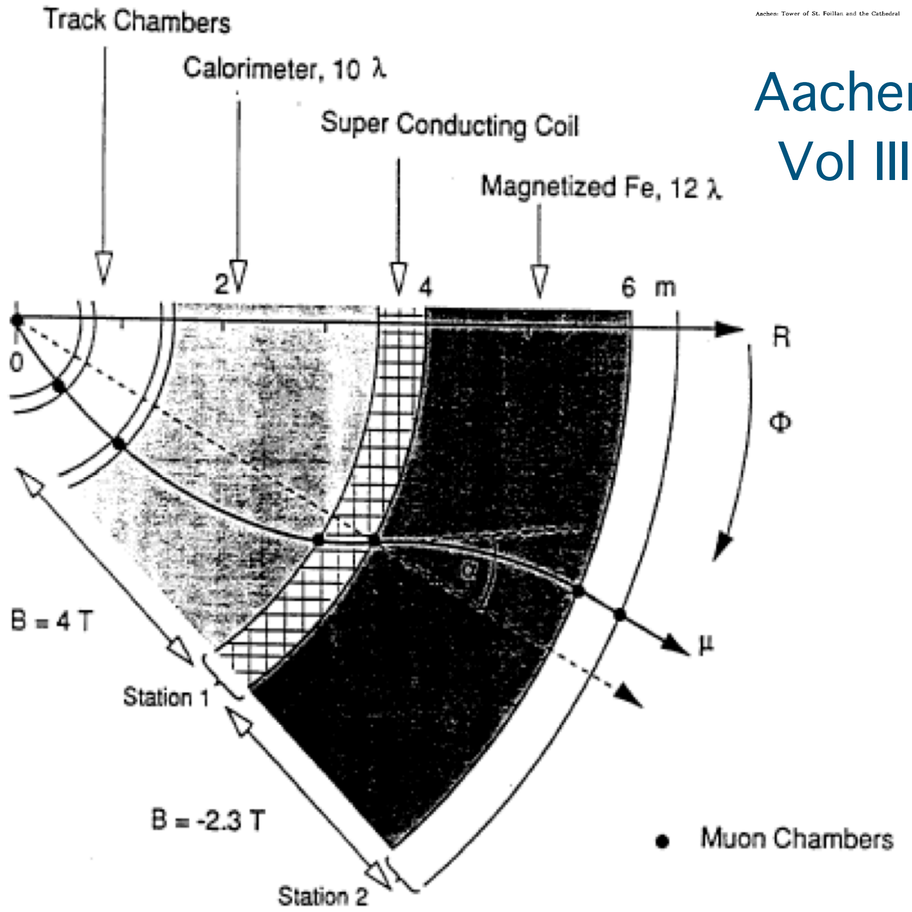
All kinds of magnetic configurations were discussed with the magnet group of H. Desportes in Saclay: solenoid, toroid, magnetised iron box.

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



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

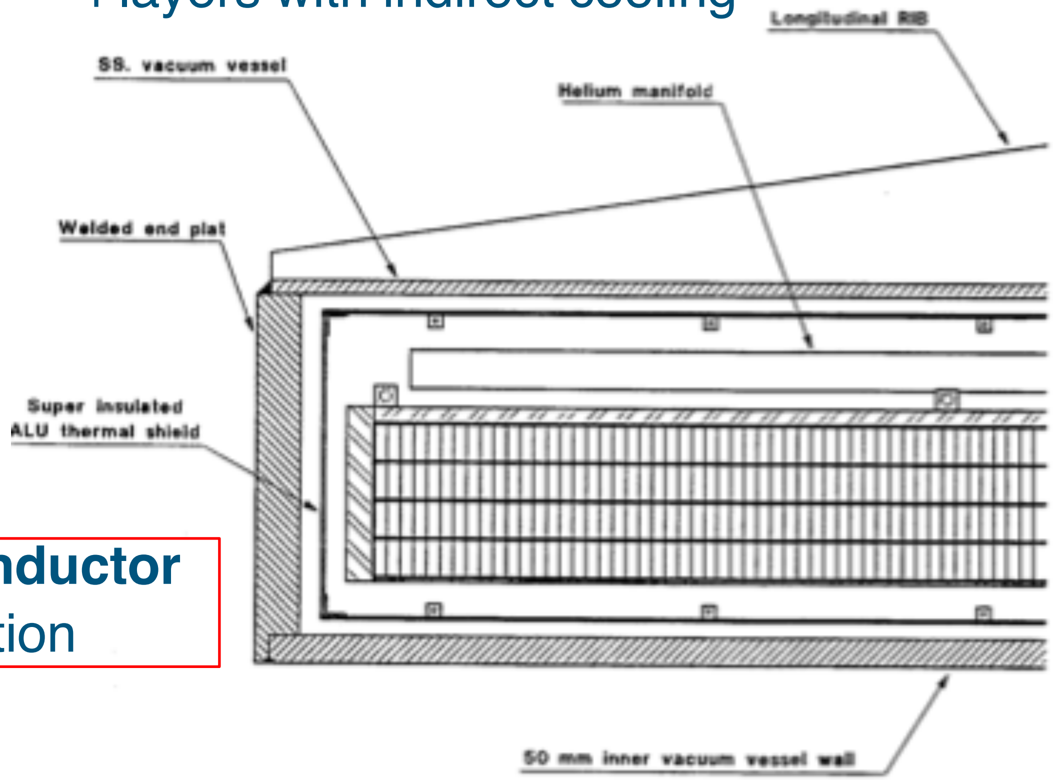
Slides from Henri Desportes

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

4 layers with indirect cooling



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

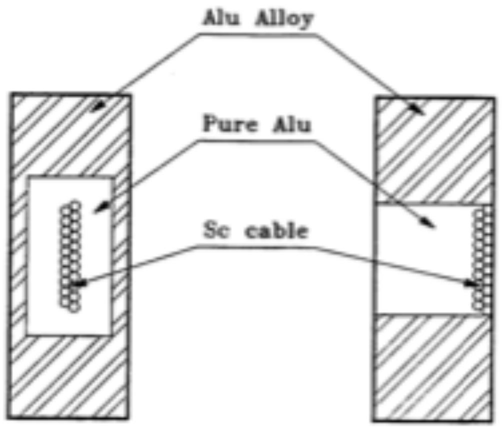
Conceptual design

Based on existing experience

No hazardous extrapolation

Feasibility well understood

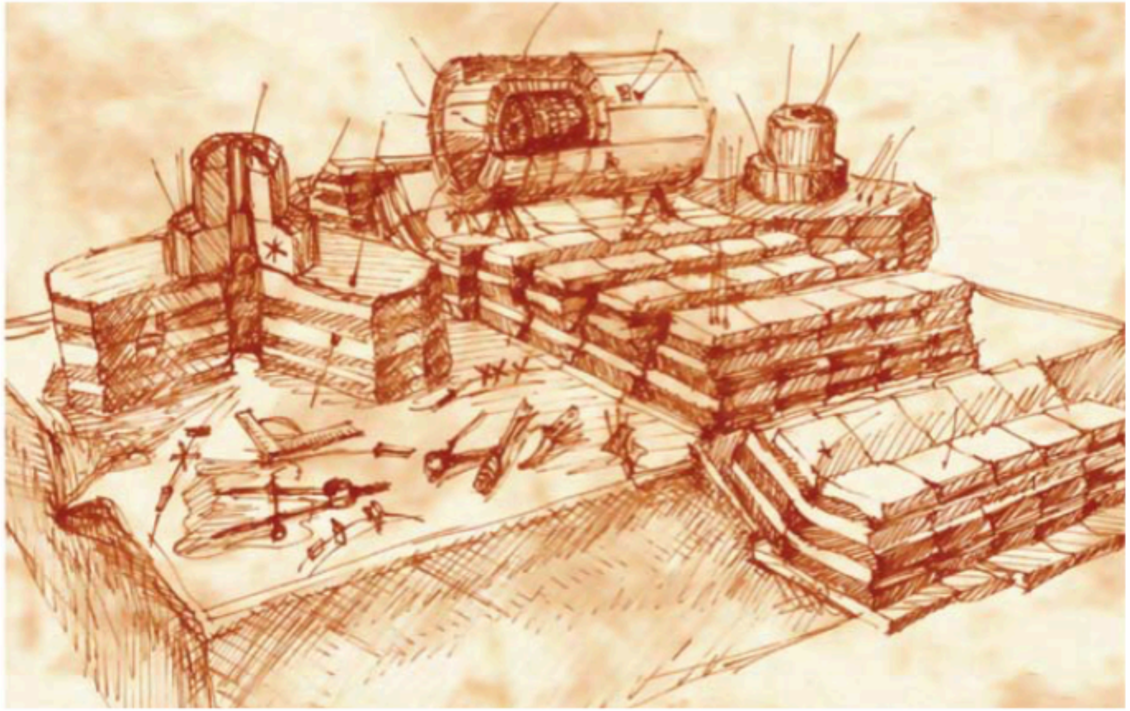
ALEPH conductor



Possible schemes for CMS conductor

Assembly by double co-extrusion or soft soldering

Engineering Form of CMS

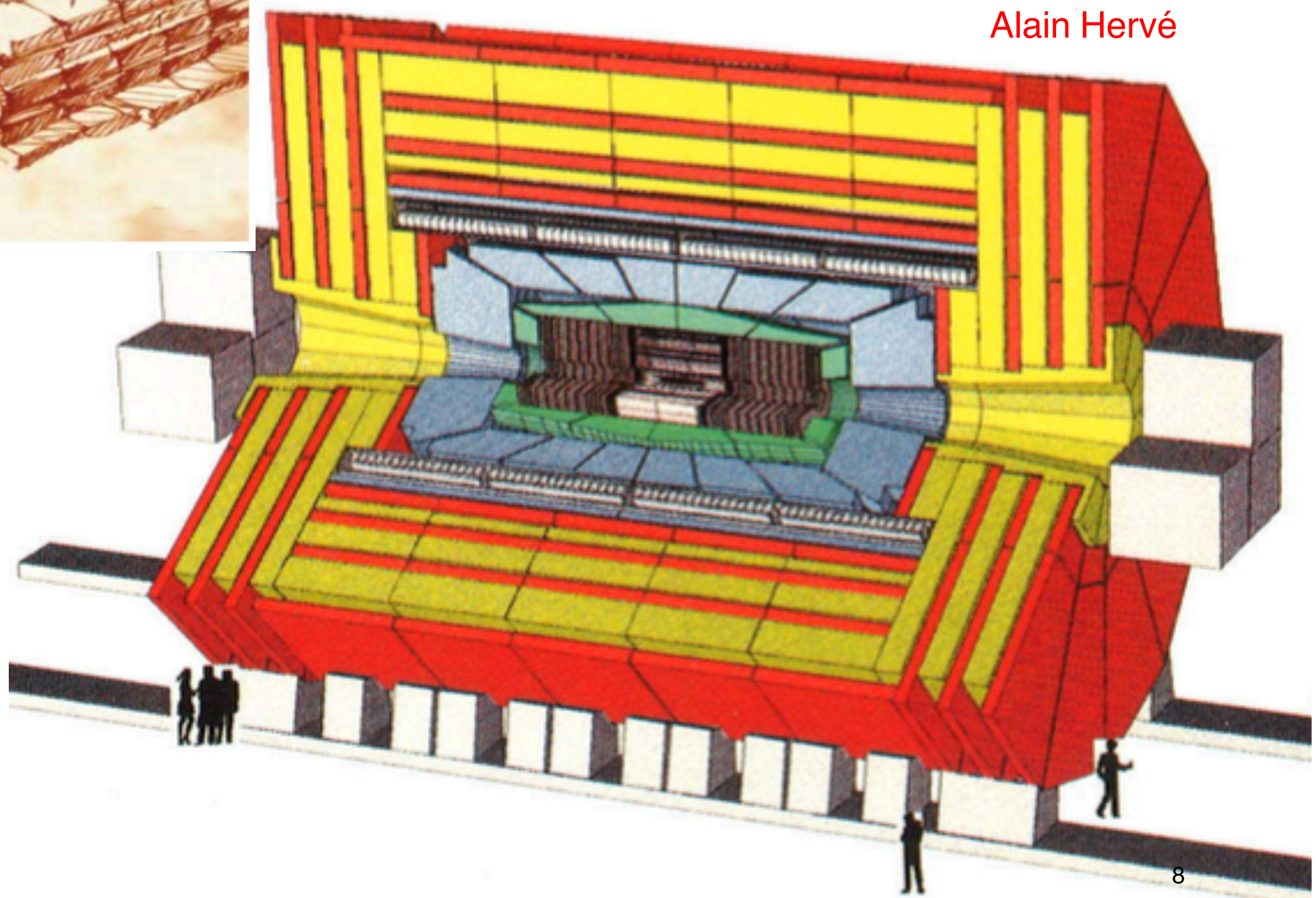


Sergio Cittolin

Our physicists dreams…

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

Alain Hervé



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),

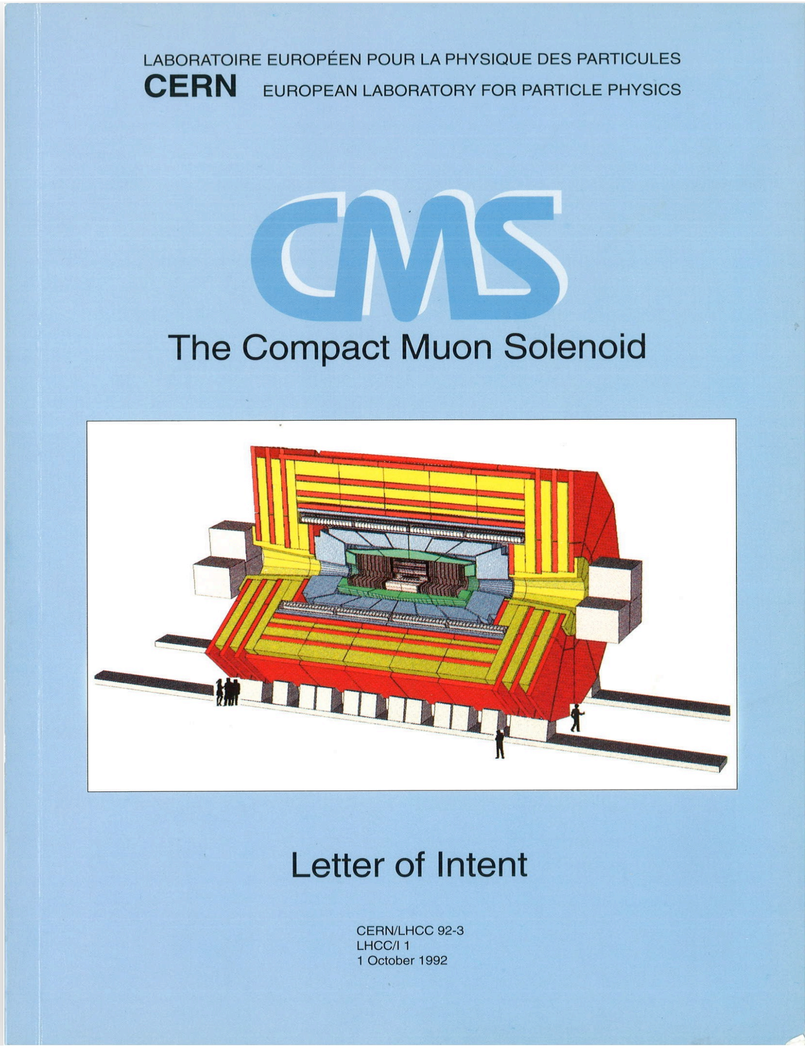
3) High quality central tracking to achieve 1) and 2).

4) Affordable
staged ≤ 300 MCHF
full ≤ 400 MCHF

CMS. Compact Muon Solenoid, November 92 9

Slide from Open LoI Presentation Dec. 1992

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

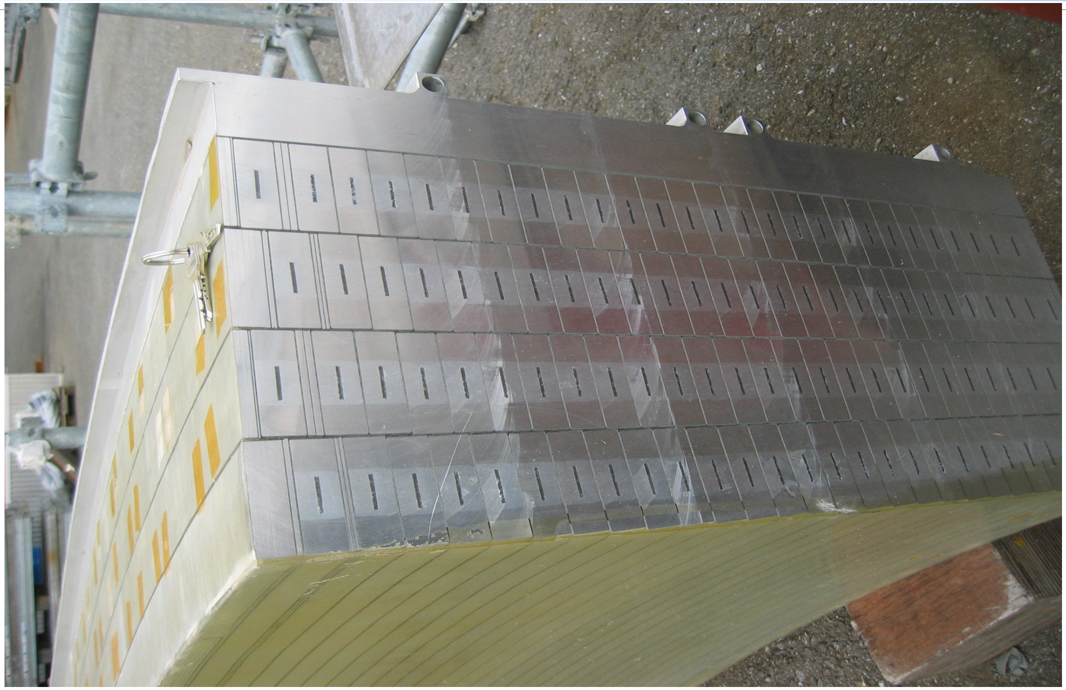


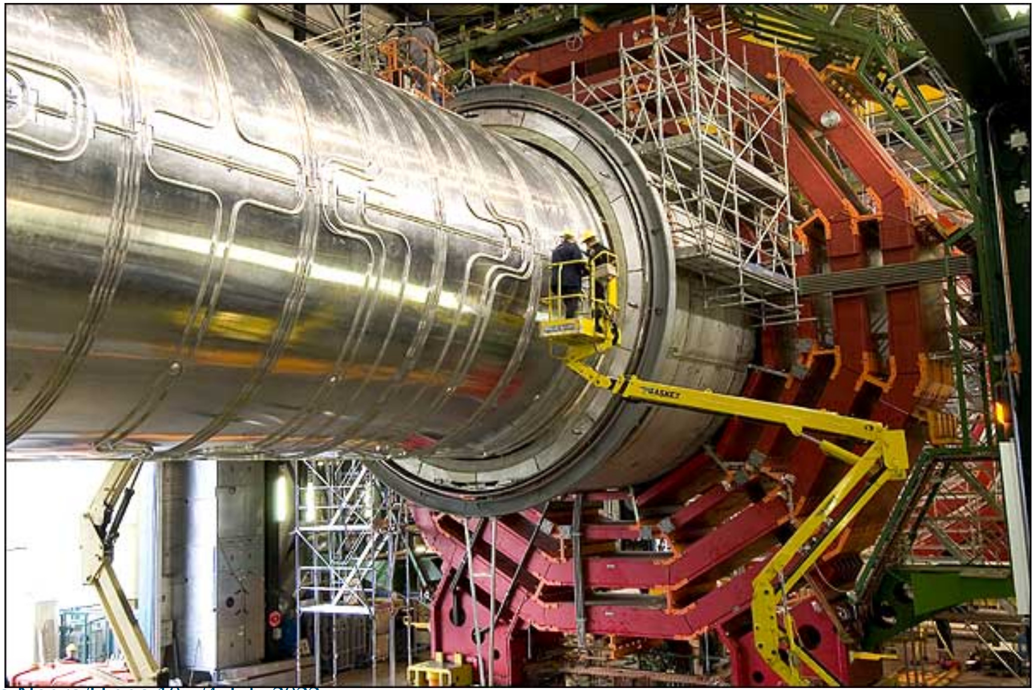
1993: Approval of ATLAS and CMS

Crucial Design Choices (Early 1990s)

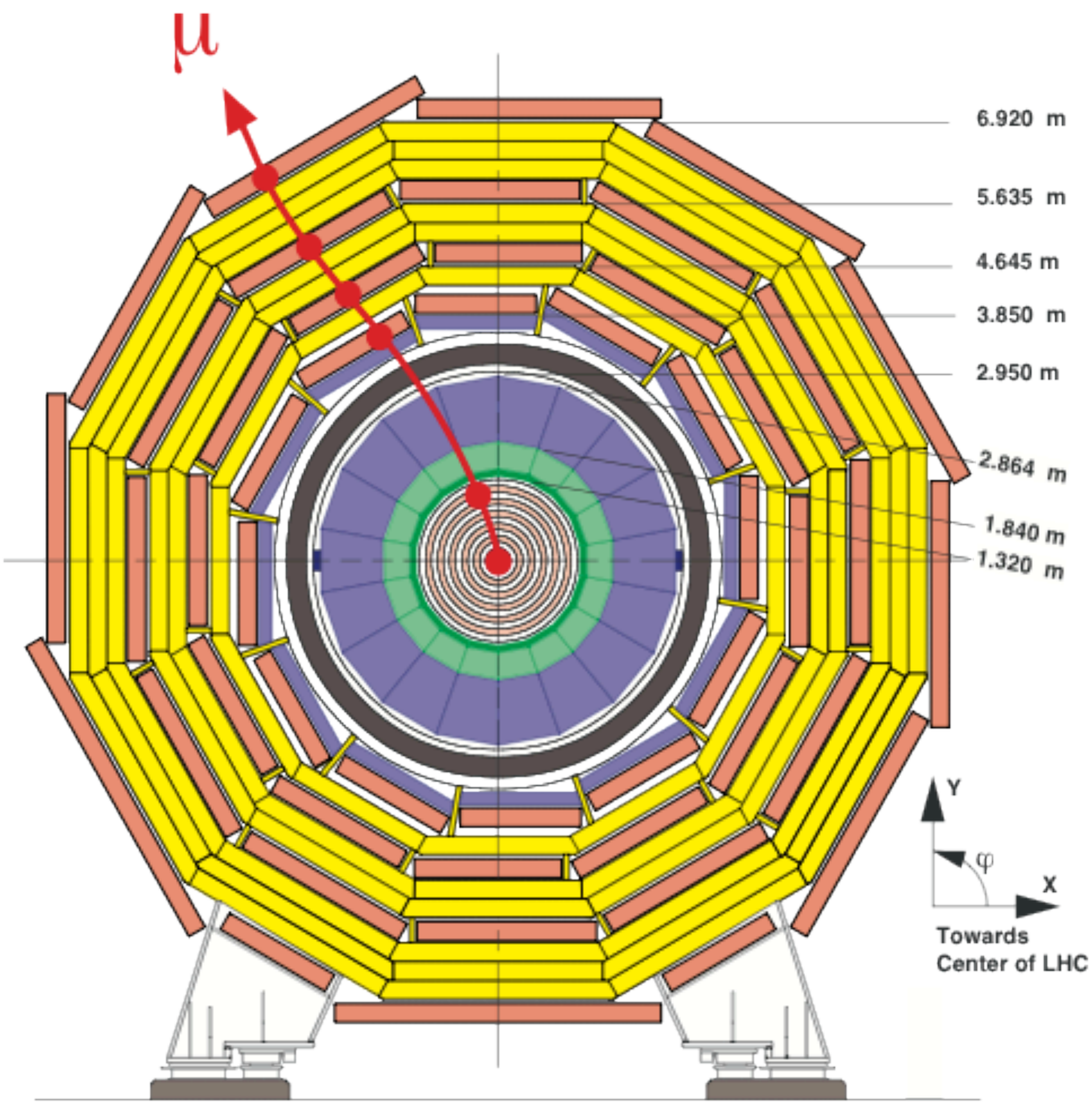
- A state-of-the-art superconducting high field solenoid.
- Muon chambers with triggering capabilities embedded in the magnet yoke. Three technologies:
  - Drift Tubes (DTs, barrel)
  - Cathode Strip Chambers (CSCs, endcaps)
  - Resistive Plate Chambers (RPCs, barrel and endcaps)
- Microstrip tracking 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")

State of Art: CMS Solenoid Coil





Precise and Redundant Muon Detector



Transverse View

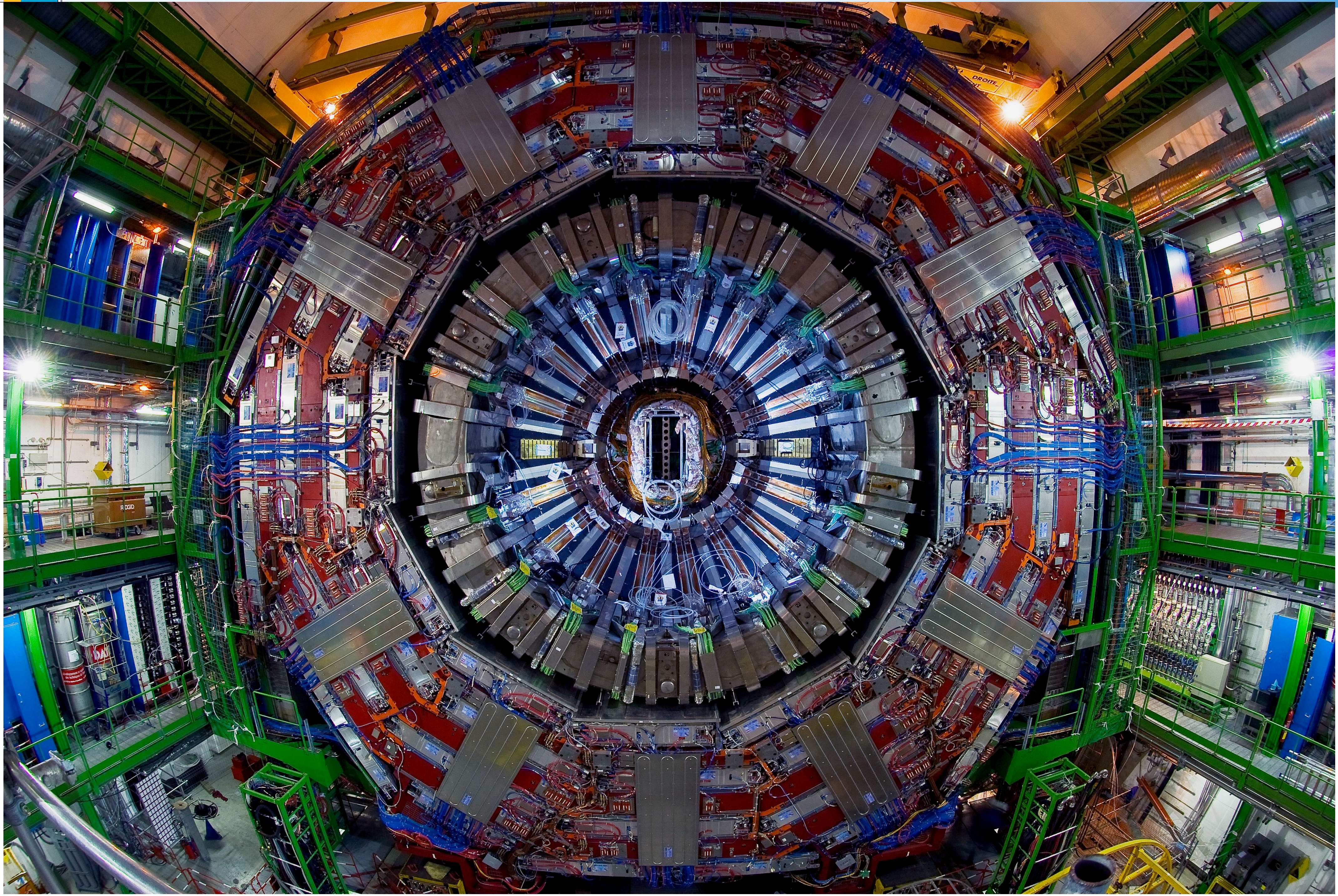
Barrel: four muon stations (DTs and RPCs) inserted in the magnet return yoke

Redundancy: Each muon station has 12 layers of drift cells: 8 r-phi + 4 theta measurements, as well as 2 layers of double gap RPCs for the 2 inner stations, and one double-gap RPC layer for the outer stations

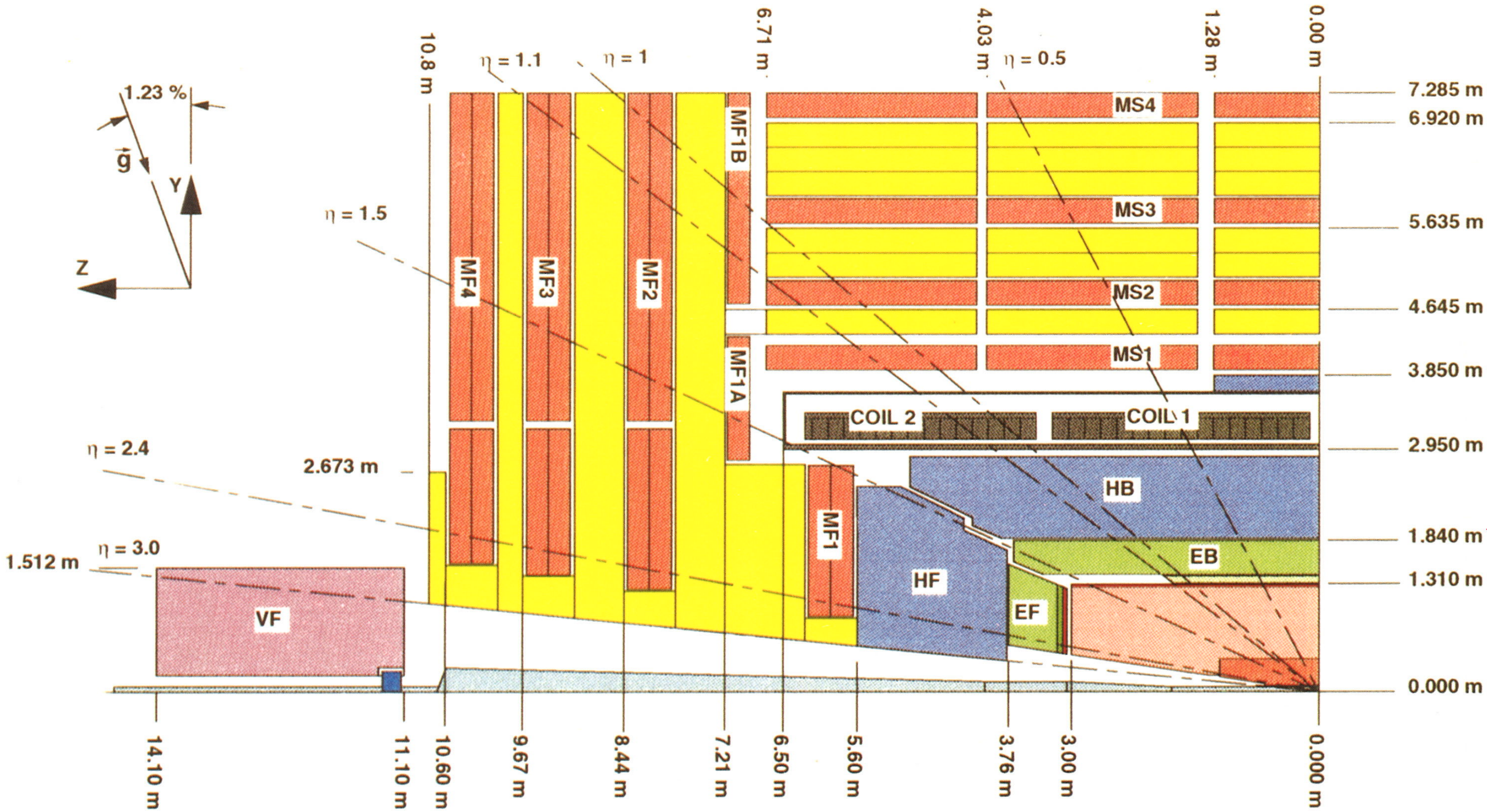
$\Delta P_t/P_t \sim 5\%$ @1TeV for reasonable space resolution of muon chambers (200μm)

Muon P_t trigger in transverse plane

Central barrel wheel with four muon stations



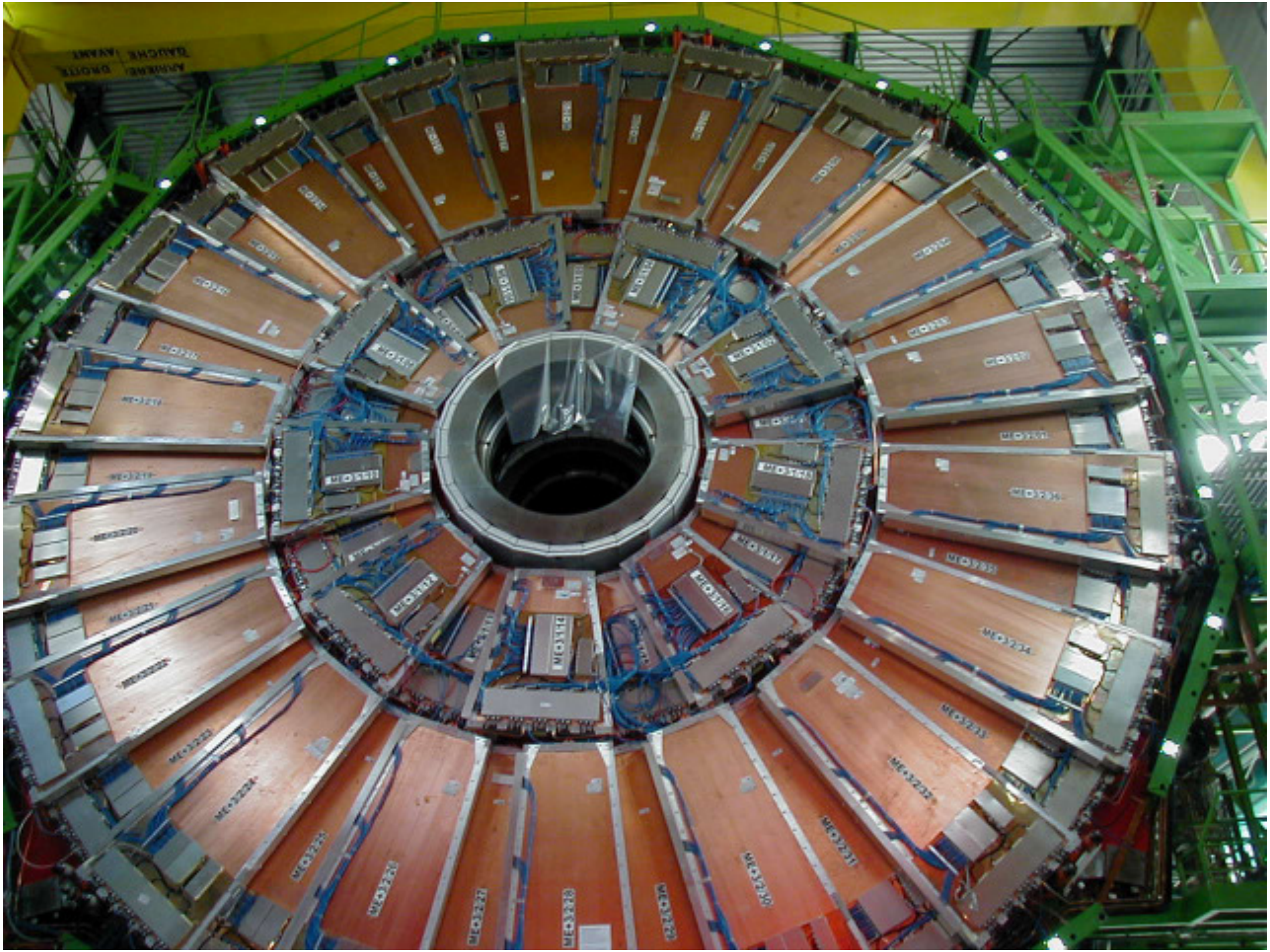
Endcap Muons



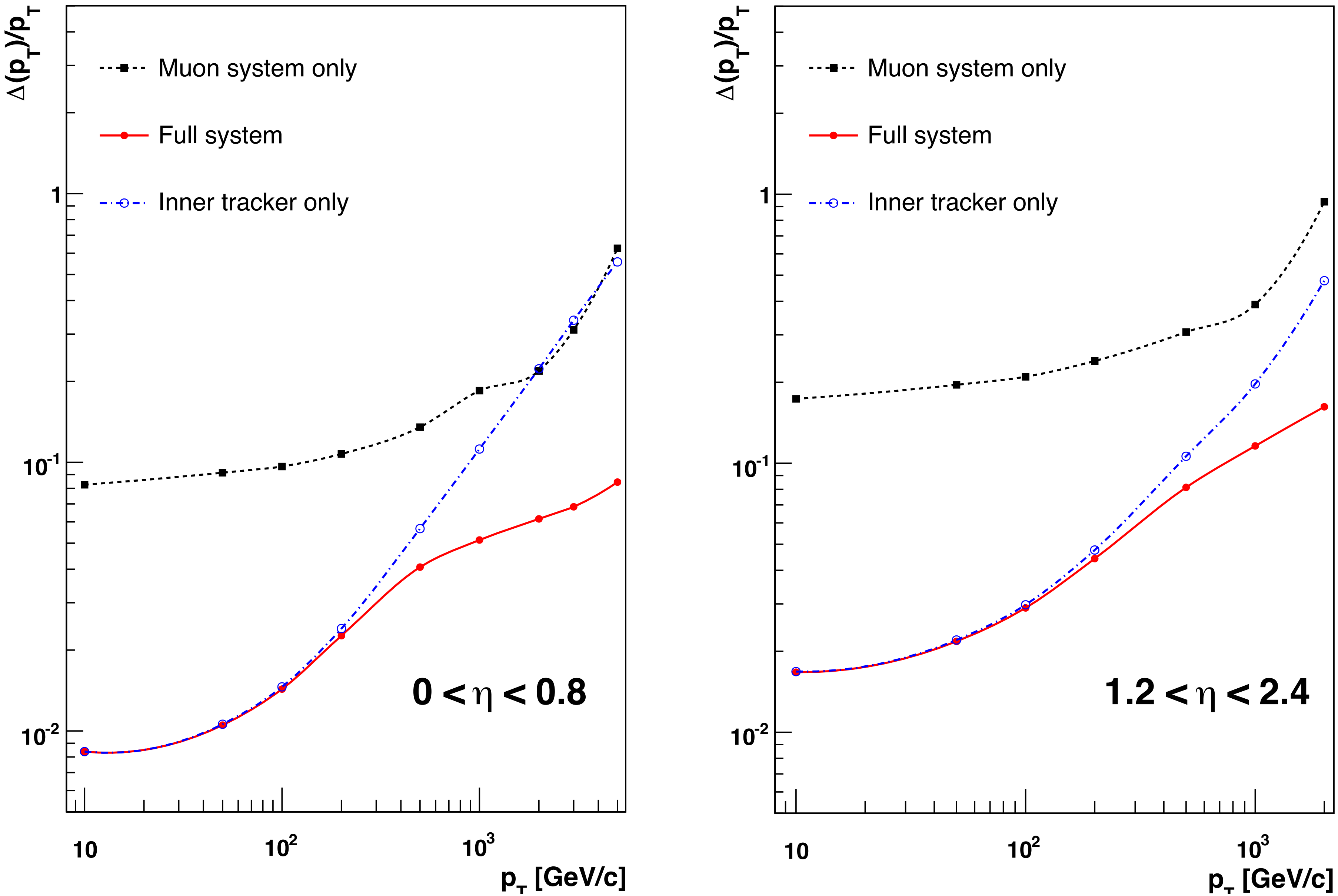
Four muon stations made of cathode strip chambers (CSC) mounted on 3 endcap disks extend the pseudorapidity coverage up to |eta| $= 2.4$. Each muon station has 6 layers of proportional chambers with cathode strips readout.

Three muon stations made of one-layer double-gap RPCs mounted on 3 endcap disks cover the range |eta| < 1.6

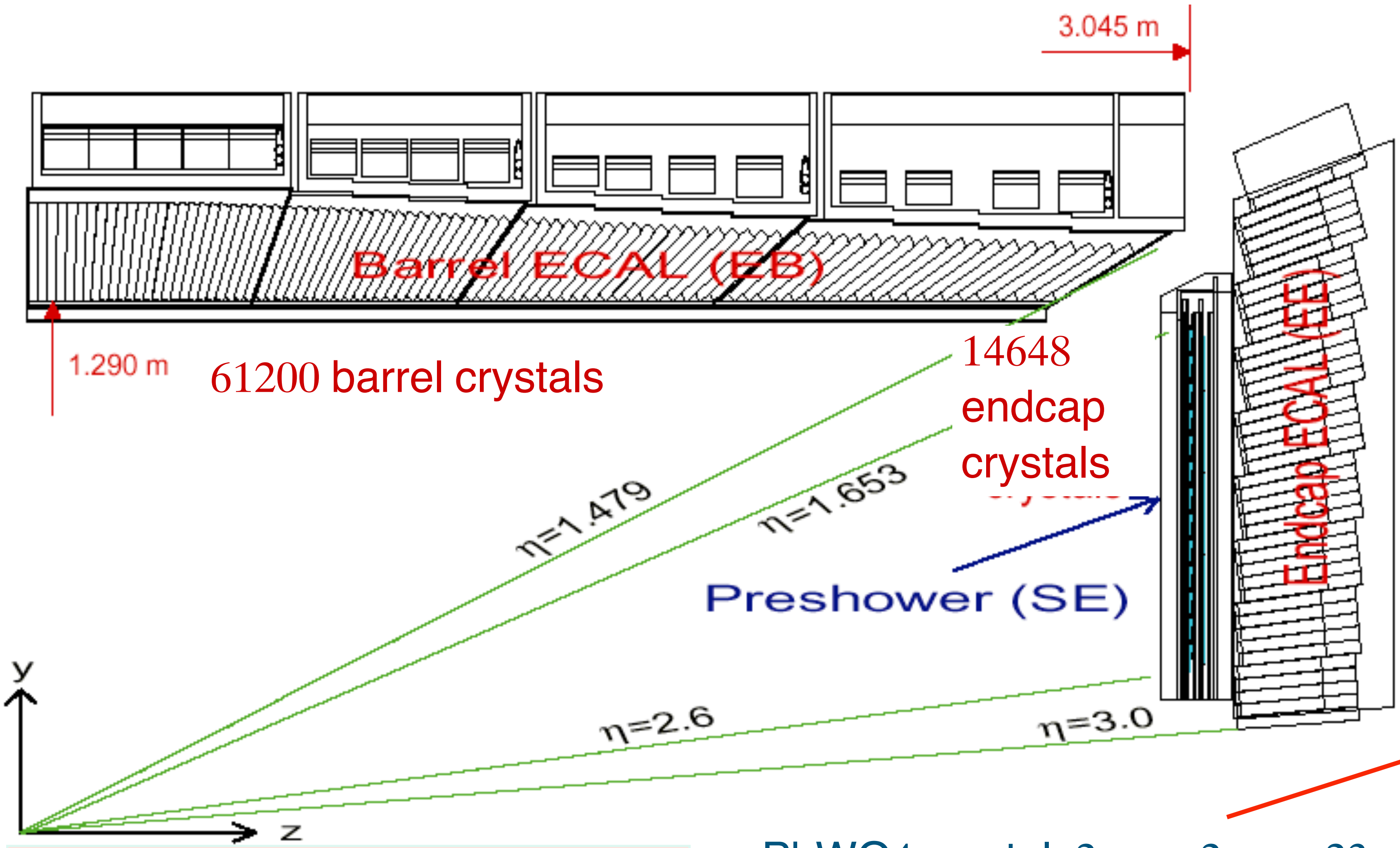
The third endcap muon station

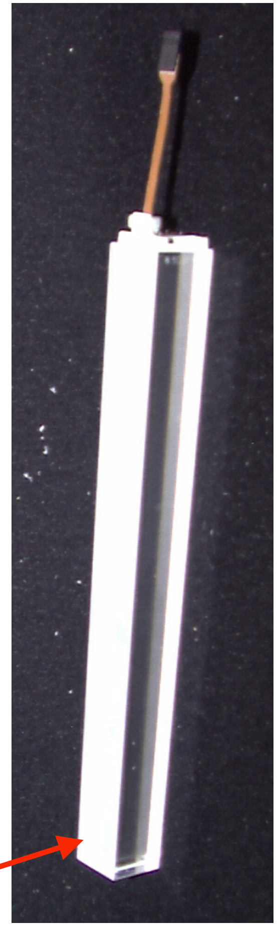


Muon pT Resolution



Precise Photon Detector: PbWO4 Crystal Calorimeter





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

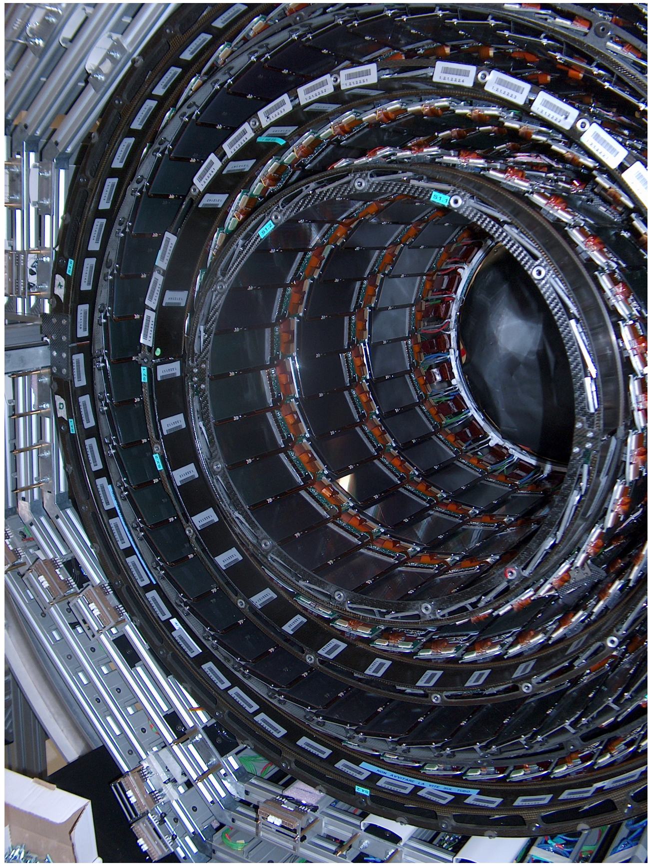
PbWO4 crystal: 2cm x 2cm x 23cm (EB), X_0 = 8.9 mm

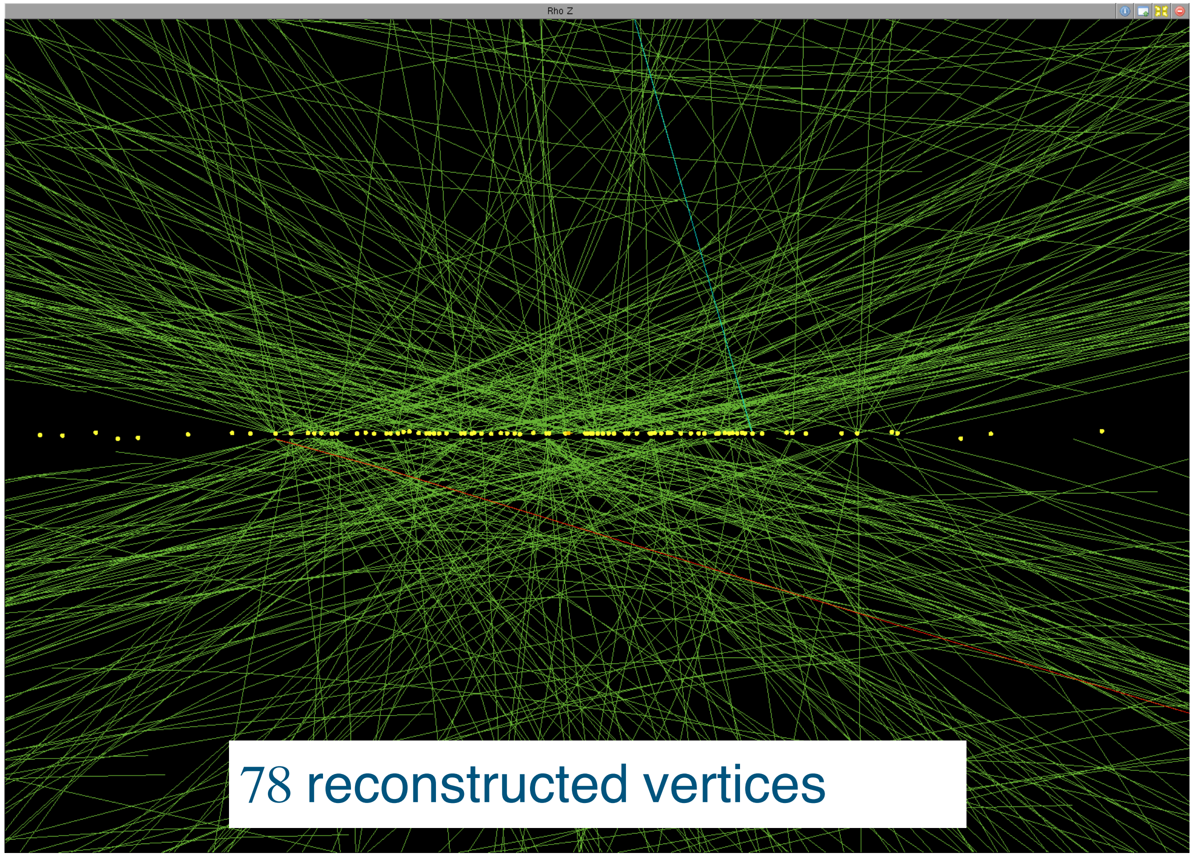
Radiation Hard: 10 Mrad

Photodetectors: APD (EB), VPT (EE) work in B = 4T

Test beam resolution. Target for the intercalibration < 0.5%

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: $80\mu m$ - $180\mu m$.

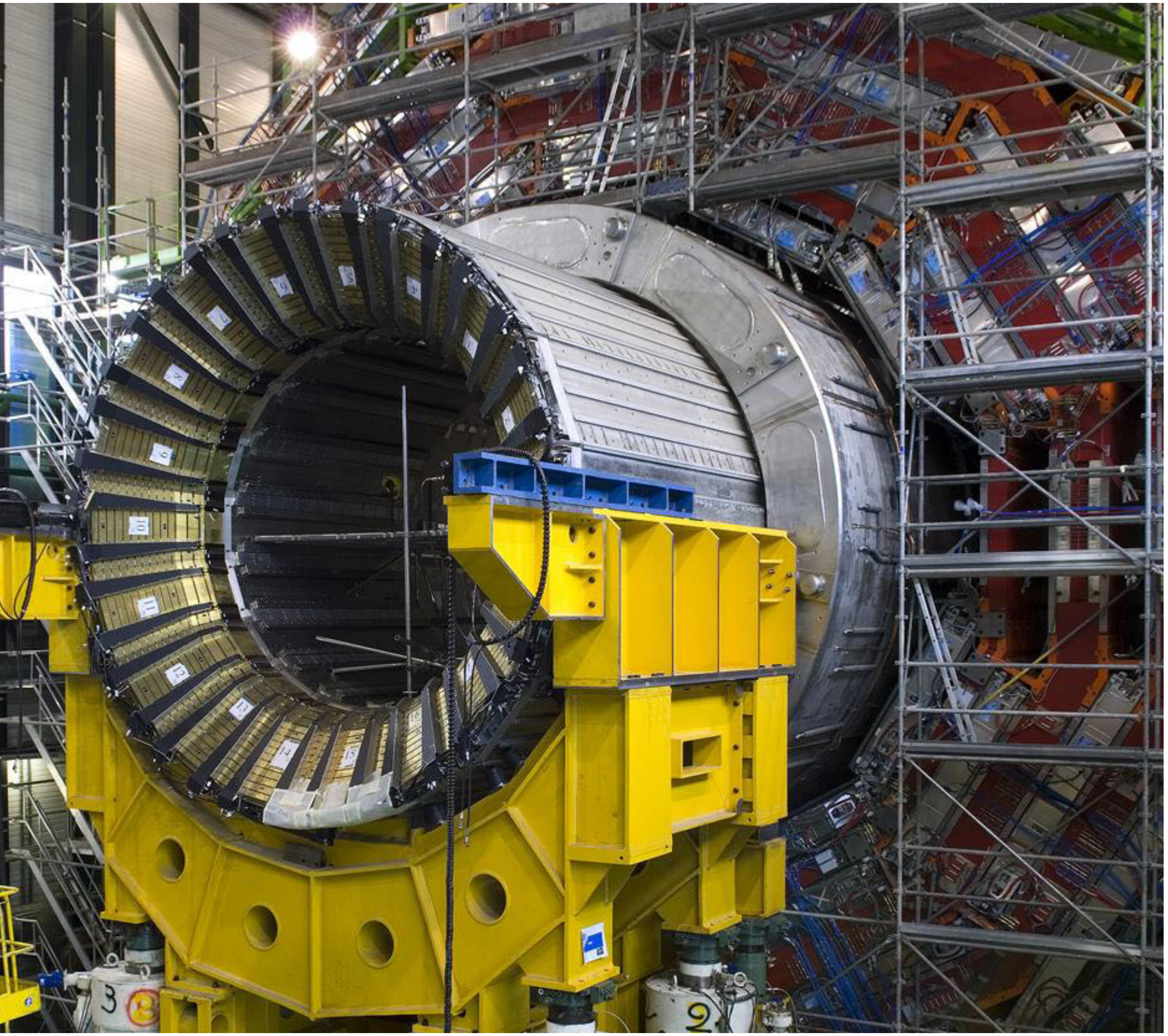
~200 m^2 of active silicon area (cf ~ $2 m^2$ in LEP detectors)

~13 precise position measurements ($15\ \mu m$) per track.

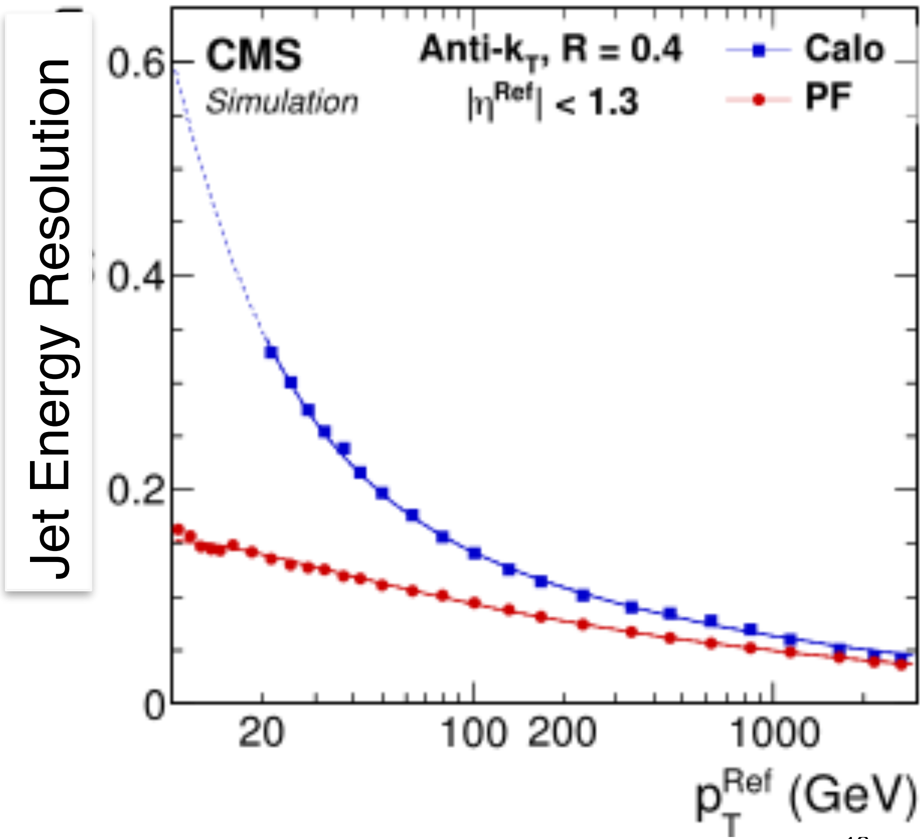
Hadron calorimeter

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

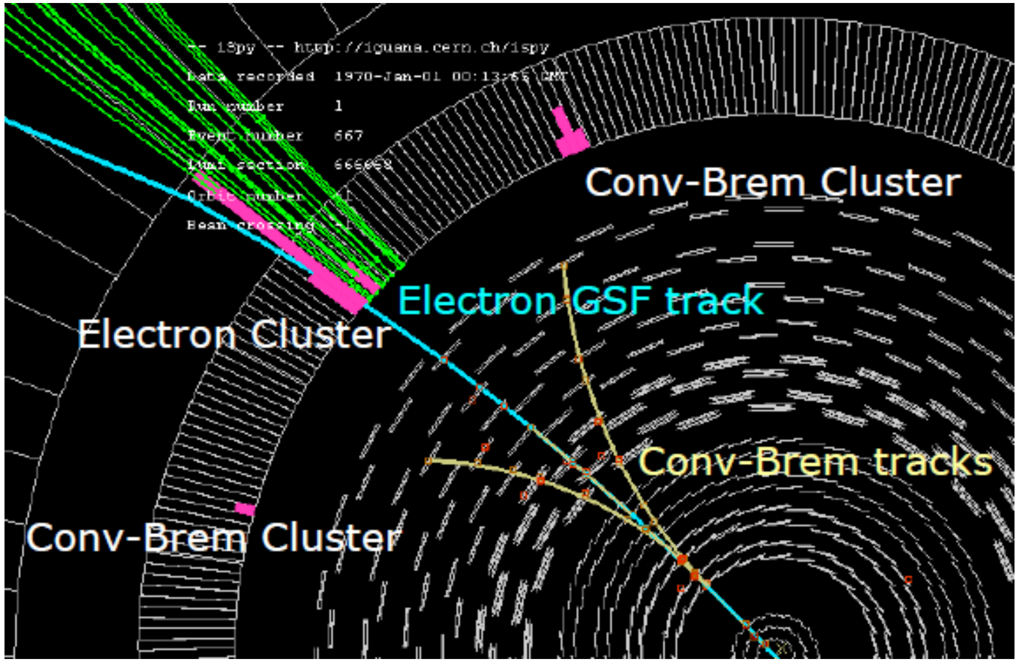
$\sigma/E = 110\%/\sqrt{E} \oplus 9\%$

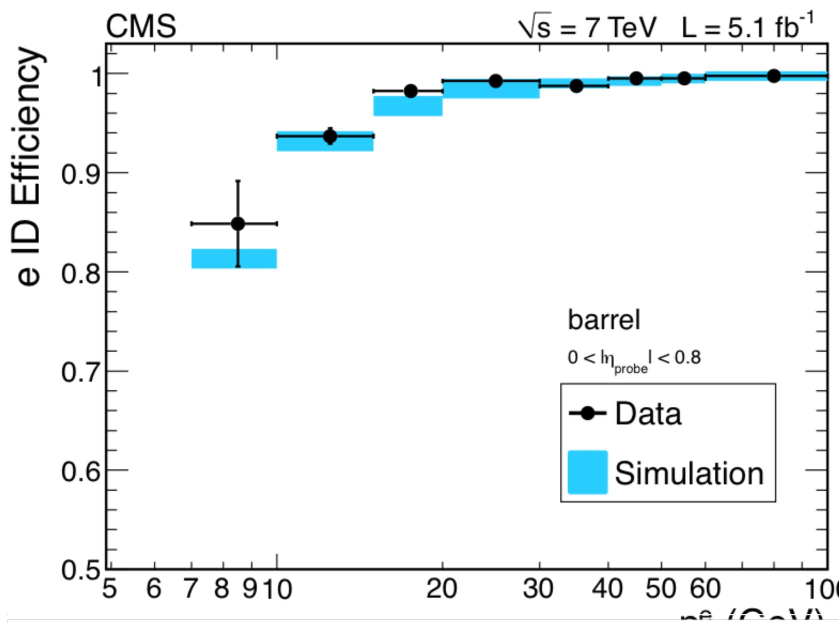


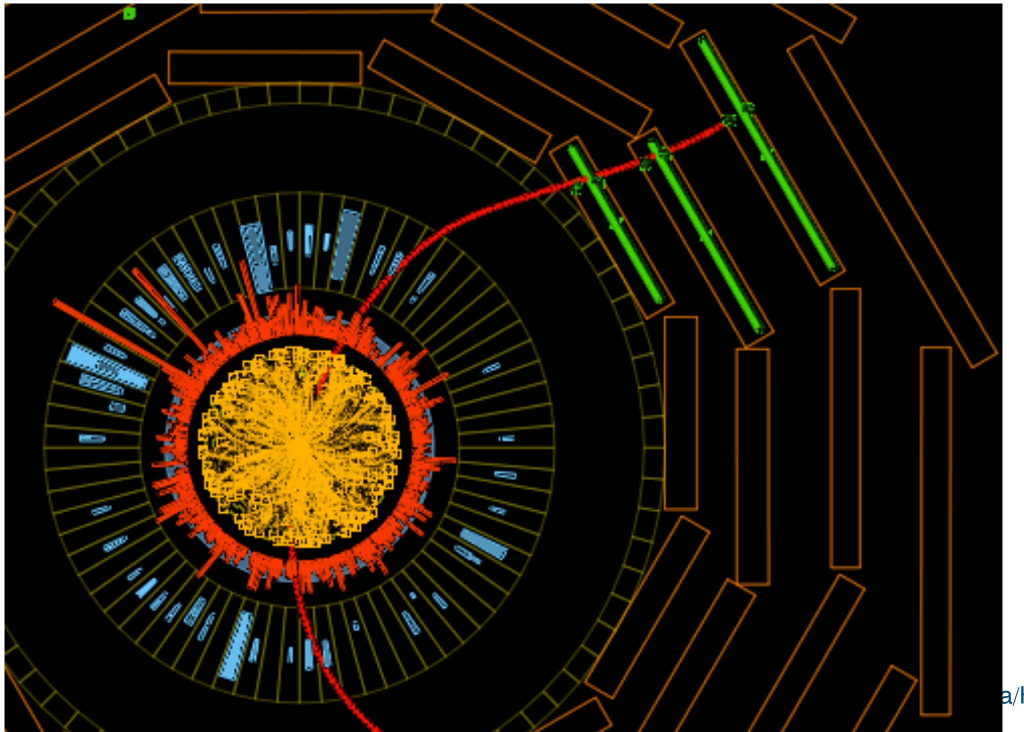
Particle Flow (PF) reconstruction (2009) pioneered by P. Janot and C. Bernet: Combining track measurements and calorimeter clusters leads to substantial improvement of the missing transverse energy resolution and of the jet energy resolution (JINST **12 (2017) P10003)**:

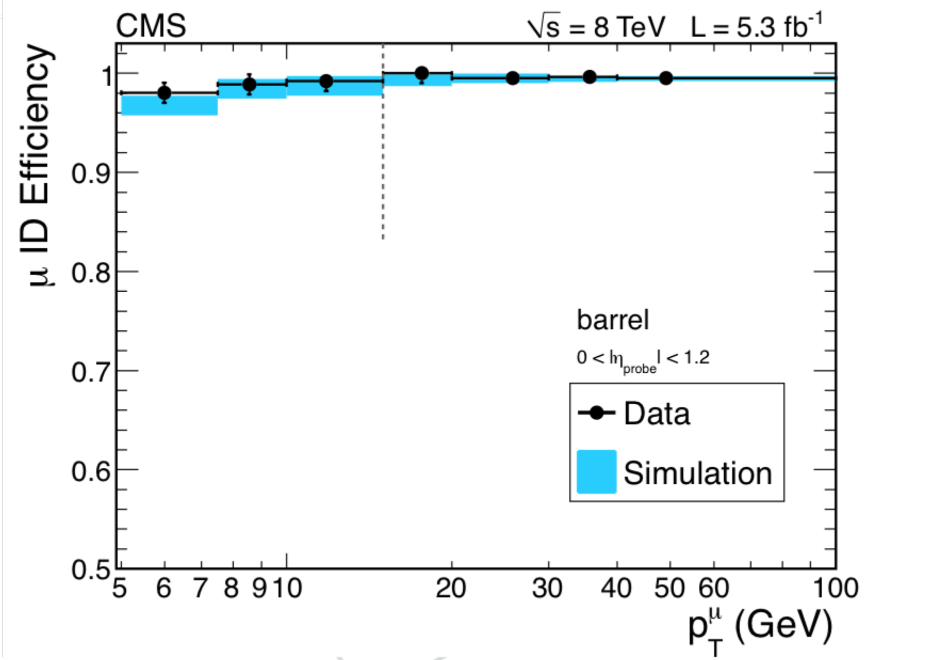


Physics Performance: Electrons and Muons

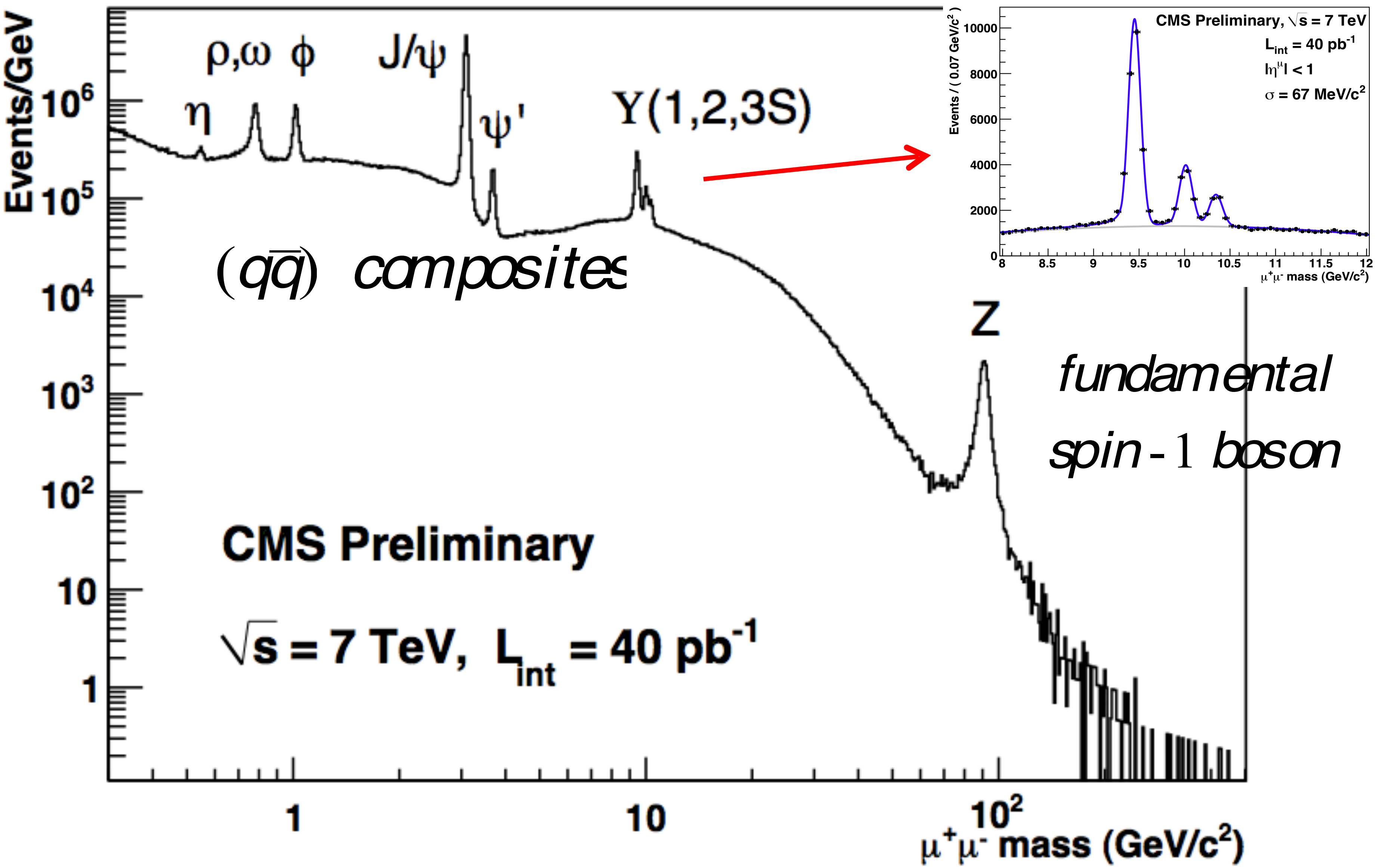




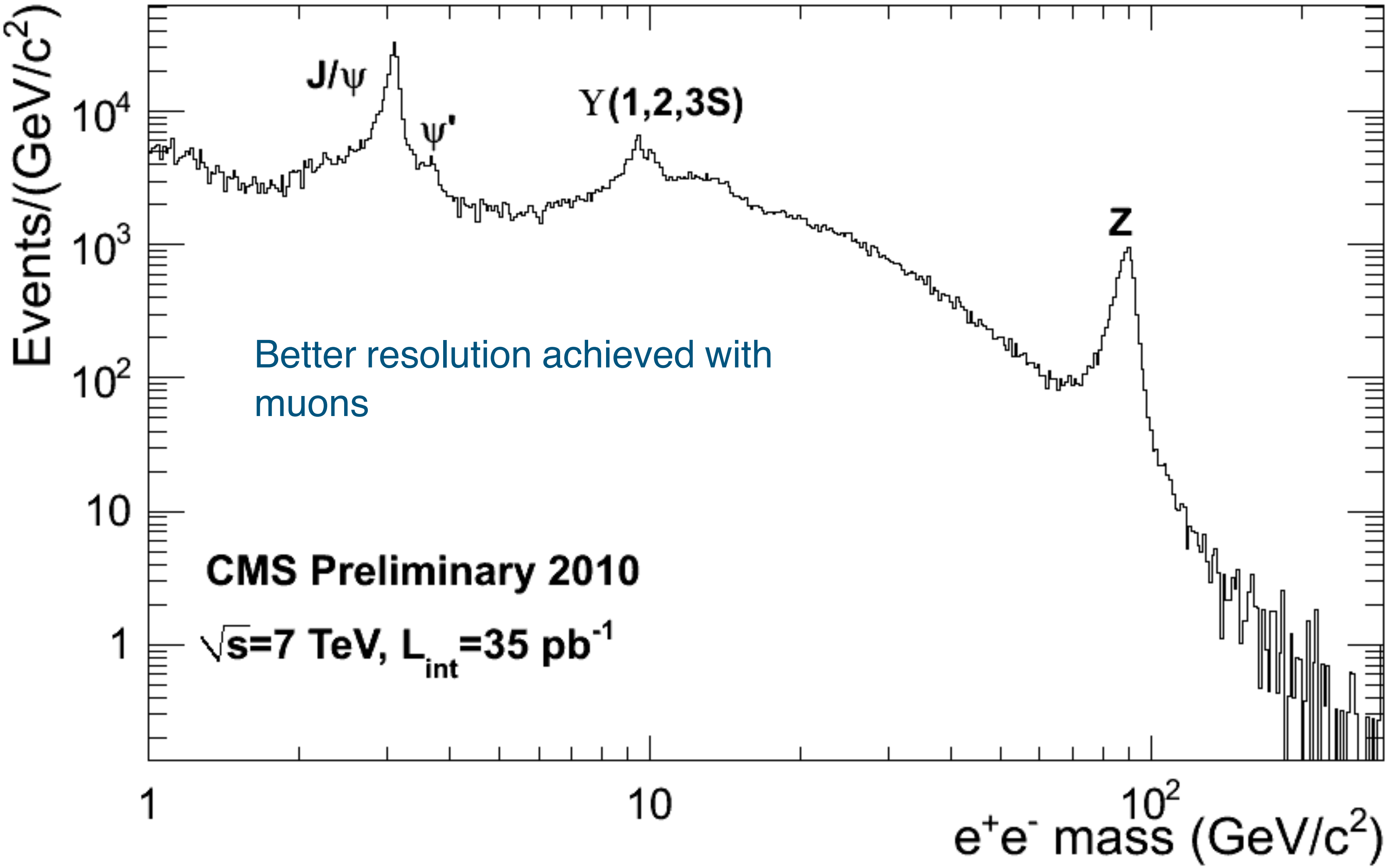




Dimuon mass resolution – out of the box!



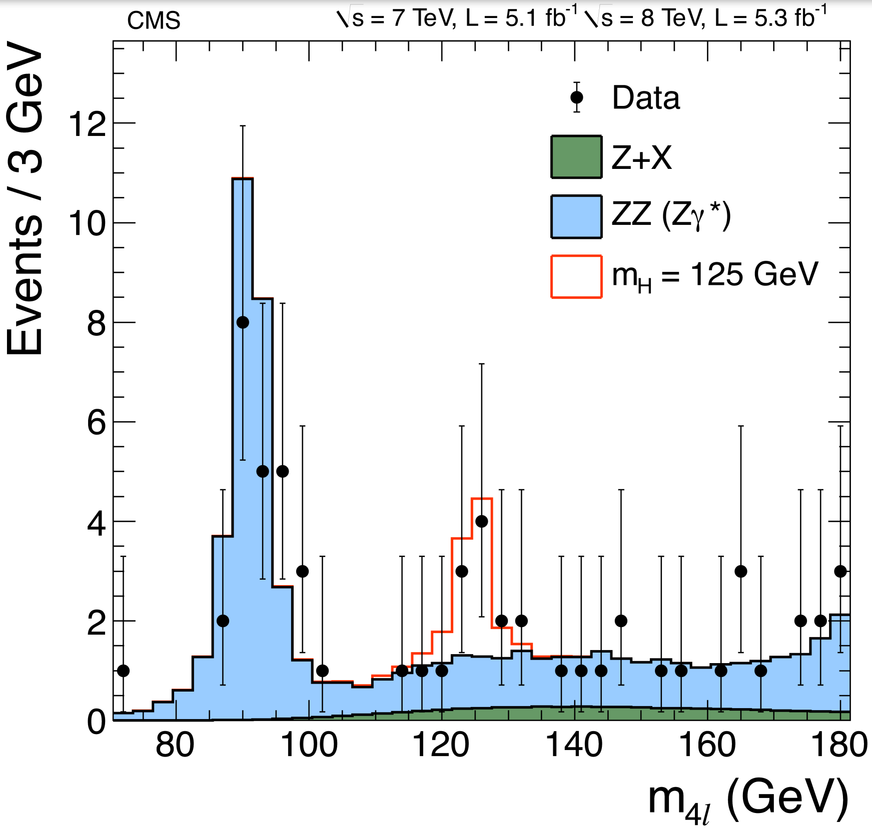
Dielectron mass resolution

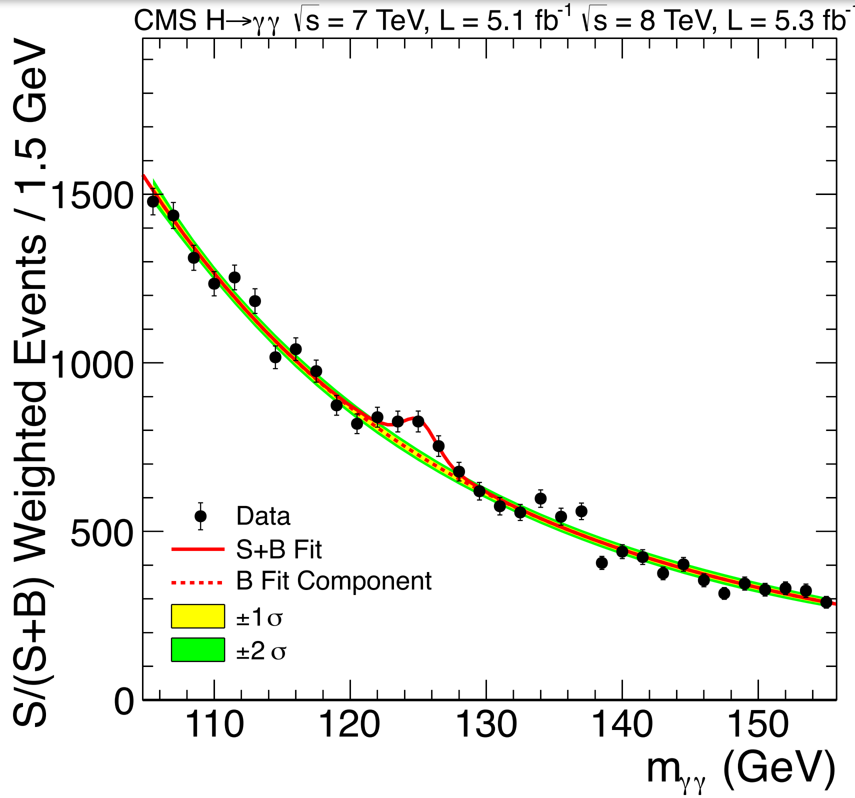


Better resolution achieved with muons

The Discovery

By summer 2012 CMS had accumulated ~10 fb^{-1} of pp collision data. A mass peak was observed at 125 GeV in the 4l (4e, 4mu, 2e2mu) and in the 2 photon final state as expected for a SM Higgs boson of that mass.





	Int. Luminosity at 7, 8 TeV	mH [GeV]	Expected [st. dev.]	Observed [st. dev.]
CMS	10.4 fb^{-1}	125.3 ± 0.6	4.7	5.0

4 July 2012: Higgs announcement at CERN

Joe Incandela (CMS)
Fabiola Gianotti (ATLAS)

François Englert and
Peter Higgs

	Int. Luminosity at 7, 8 TeV	mH [GeV]	Expected [st. dev.]	Observed [st. dev.]
ATLAS	10.7 fb^{-1}	126.0 ± 0.6	4.6	5.0
CMS	10.4 fb^{-1}	125.3 ± 0.6	5.9	4.9