The CMS detector

From design to discovery

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10 years of Higgs, CERN, 4 July 2022

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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**:
  \[ m_t < 200 \text{ GeV (indirect LEP 1)} \; ; \; m_t > 77 \text{ GeV (CDF)} \]
- **the Higgs boson**:
  \[ m_H > 44 \text{ GeV (LEP 1)} ; \; m_H < 1 \text{ TeV (Theory : WW scattering unitarity)} \]

**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 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\) was mandatory.
- Physics working groups were formed. First studies on physics reach at \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\) were presented.
“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:

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 \( 10^5 \text{ pb}^{-1} \) (= \( 100 \text{ fb}^{-1} \sim 1 \text{ year at } 10^{34} \text{cm}^{-2}\text{s}^{-1} \)).”

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 \( \pi^0 \) rejection). Need a superb electromagnetic calorimeter energy resolution (\( 2%/\sqrt{E} \oplus 0.5\% \)) to establish a \( H \rightarrow \gamma \gamma \) signal for \( 80 \text{ GeV} < m_H < 150 \text{ GeV} \) and \( 10^5 \text{ pb}^{-1} \)”
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

  ![Diagram](image)
  Electron $E_T=24$ GeV well measured in electromagnetic 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 $p_T$ 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 $L = 15$ m
- Large coil radius to accommodate full calorimetry inside $R = 2.9$ m

Bending in plane transverse to the beam: one point (interaction vertex in z) with $\sigma = 15$ um 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
Radial pressure 64 atm → **Reinforced conductor** requires development on industrial fabrication.
Our physicists dreams…

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

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

Feb. 2005
Precise and Redundant Muon Detector

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
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

Figure 1.2: The muon transverse-momentum resolution as a function of the transverse-momentum ($p_T$) using the muon system only, the inner tracking only, and both. Left panel: $|\eta| < 0.8$, right panel: $1.2 < |\eta| < 2.4$. The ECAL is surrounded by a brass/scintillator sampling hadron calorimeter (HCAL) with coverage up to $|\eta| < 3.0$. The scintillation light is converted by wavelength-shifting (WLS) fibres embedded in the scintillator tiles and channeled to photodetectors via clear fibres. This light is detected by photodetectors (hybrid photodiodes, or HPDs) that can provide gain and operate in high axial magnetic fields. This central calorimetry is complemented by a tail-catcher in the barrel region (HO) ensuring that hadronic showers are sampled with nearly 11 hadronic interaction lengths. Coverage up to a pseudorapidity of 5.0 is provided by an iron/quartz-fibre calorimeter. The Cerenkov light emitted in the quartz fibres is detected by photomultipliers. The forward calorimeters ensure full geometric coverage for the measurement of the transverse energy in the event. An even higher forward coverage is obtained with additional dedicated calorimeters (CASTOR, ZDC, not shown in figure 1.1) and with the TOTEM tracking detectors. The expected jet transverse-energy resolution in various pseudorapidity regions is shown in figure 1.4.

The CMS detector is 21.6-m long and has a diameter of 14.6 m. It has a total weight of 12500 t. The ECAL thickness, in radiation lengths, is larger than 25 $X_0$, while the HCAL thickness, in interaction lengths, varies in the range 7–11 $l_I$ (10–15 $l_I$ with the HO included), depending on $|\eta|$.
Precise Photon Detector: PbWO4 Crystal Calorimeter

PbWO4 crystal: 2cm x 2cm x 23cm (EB), $X_0 = 8.9$ mm
Radiation Hard: 10 Mrad
Photodetectors: APD (EB), VPT (EE) work in $B = 4$T

Test beam resolution. Target for the intercalibration < 0.5%
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 ~ 2m$^2$ in LEP detectors)

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

Hermetic Hadron Calorimeter inside the coil: Brass absorber/scintillator tiles
\[ \sigma/E = 110\%/\sqrt{E} \pm 9\% \]

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

![Graphs showing electron and muon ID efficiency for CMS at 7 TeV and 8 TeV with data and simulation results.](image-url)
Dimuon mass resolution – out of the box!

CMS Preliminary

$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 40$ pb$^{-1}$

$qq$ composites

$\rho, \omega, \phi, J/\psi, \eta, \psi', Y(1,2,3S)$

$Z$ fundamental spin-1 boson
Dielectron mass resolution

Better resolution achieved with muons

CMS Preliminary 2010
\( \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 35 \text{ pb}^{-1} \)
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.

![Graph showing events vs mass](image)

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<th>Int. Luminosity at 7, 8 TeV</th>
<th>mH [GeV]</th>
<th>Expected [st. dev.]</th>
<th>Observed [st. dev.]</th>
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<tr>
<td>CMS</td>
<td>10.4 fb(^{-1})</td>
<td>125.3 ± 0.6</td>
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4 July 2012: Higgs announcement at CERN

Joe Incandela (CMS)  
Fabiola Gianotti (ATLAS)  
François Englert and Peter Higgs

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<th>Experiment</th>
<th>Int. Luminosity at 7, 8 TeV</th>
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<tr>
<td>ATLAS</td>
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