Introduction of CMS Detector

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Layout of my Lectures:

1) Introduction of CMS Detector
2) CMS sub-detectors
3) CMS Trigger System

Contents

Background

- LEP closure in 2000
- Tevatron still running
- Questions remain unanswerable
- Lack of evidence of Higgs boson
  - Dark matter
  - Anti matter

The Large Hadron Collider and the associated experiments are designed to address a number of these questions.

CMS……..

Introduction of LHC

Luminosity

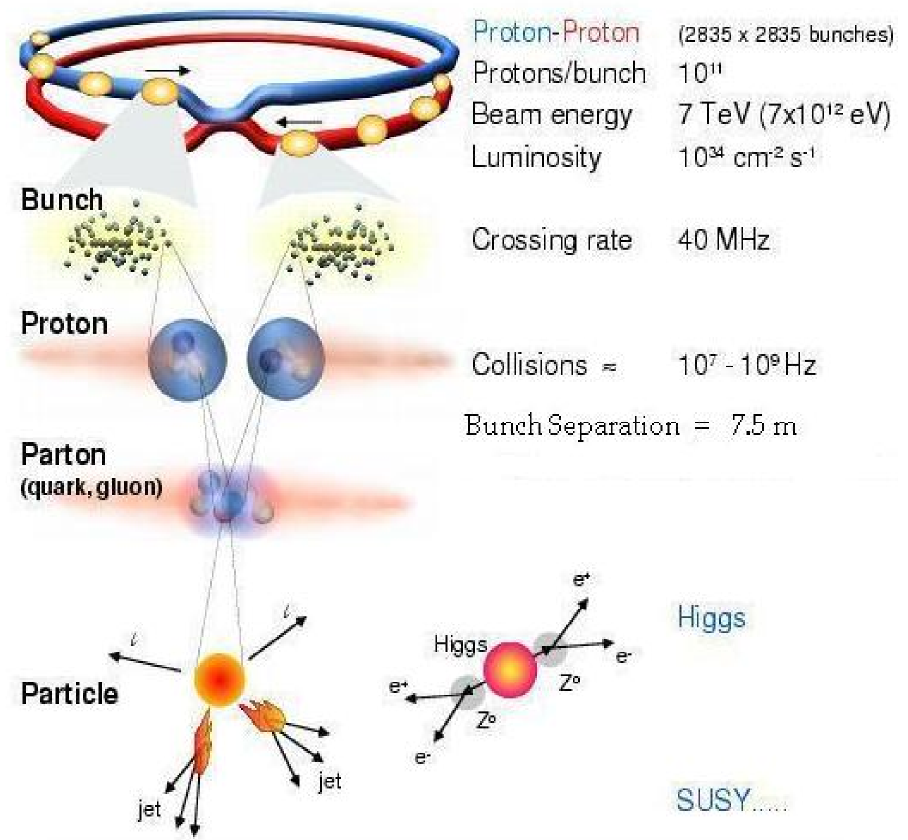
$$L = \frac{\gamma f k_b N_P^2}{4\pi\varepsilon_n\beta^*}F = 10^{34}\,cm^{-2}s^{-1}$$

Event Rate

$$R = \sigma \times L = 80mb \times 10^{34}cm^{-2}s^{-1} \approx 10^9 / s$$

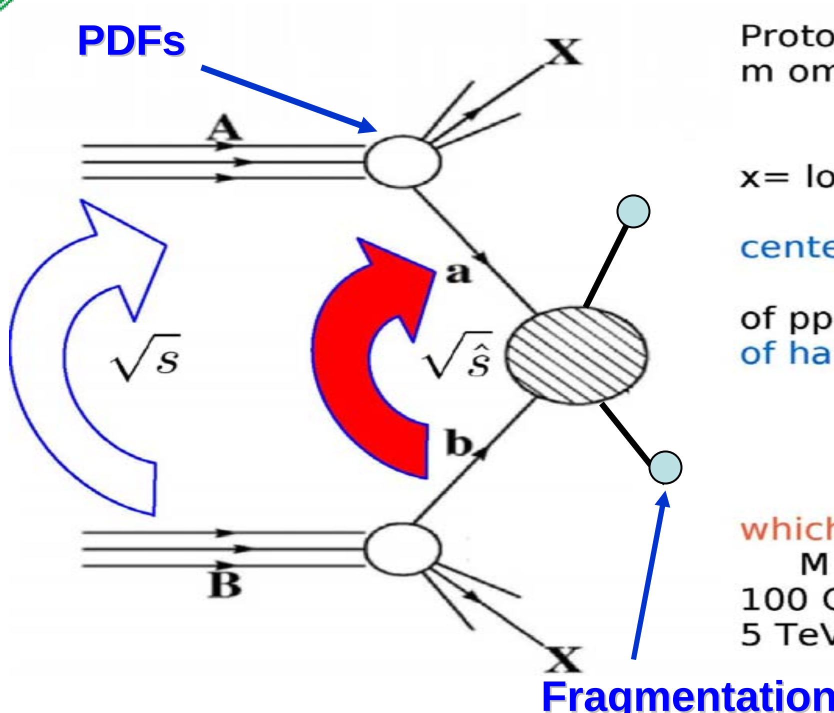
- ❑ Large distance collisions
  - o Soft scattering
- ❑ Short distance collisions
  - o Hard scattering (rare events)

Collisions at LHC



Selection of 1 in 10,000,000,000,000

PP collisions



Proton momenta $p_A = p_B = p = 7\text{TeV}$
m ometum of partons in proton

$$x_a \cdot p \qquad x_b \cdot p$$

x= longitudinal momentum fraction

center of mass energy

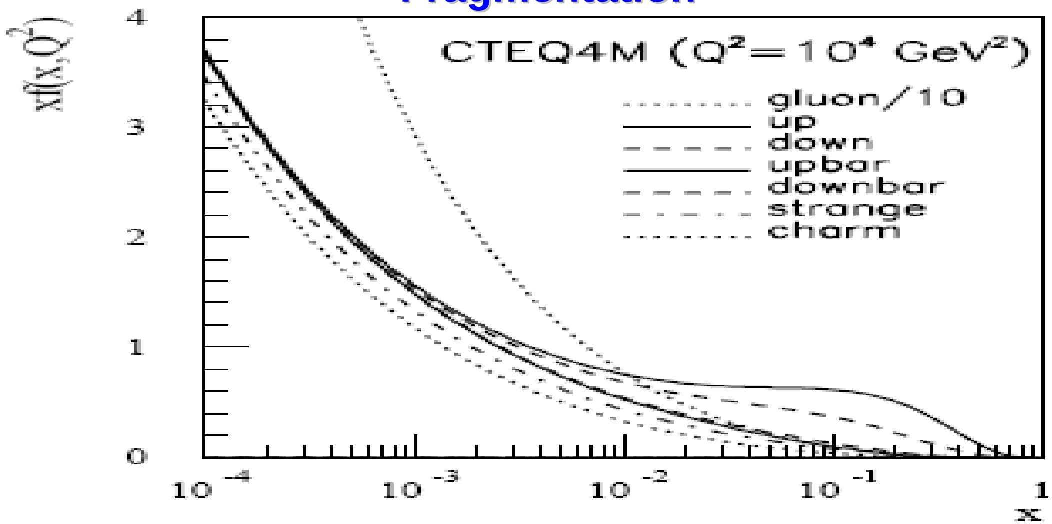
of pp collision: $\sqrt{s} = 2E_{beam}$
of hard subprocess:

$$\hat{s} = x_1 x_2 2 p_A p_B = x_1 x_2 s$$

$$\sqrt{\hat{s}} = < x > \sqrt{s}$$

which x needed to produce masses M ?

M	<x>	LHC	Tevatron
100 GeV		~0.007	~0.05
5 TeV		~0.36	⚡



Minimum-bias Events

Inelastic pp scattering cross section (70 mb = very large)
dominated by

long distance interaction between pp with low momentum transfer
- final state very little pT, very large pL
- pt of charged tracks ~ 500 MeV
- # charged particles dN/dη ~ 7

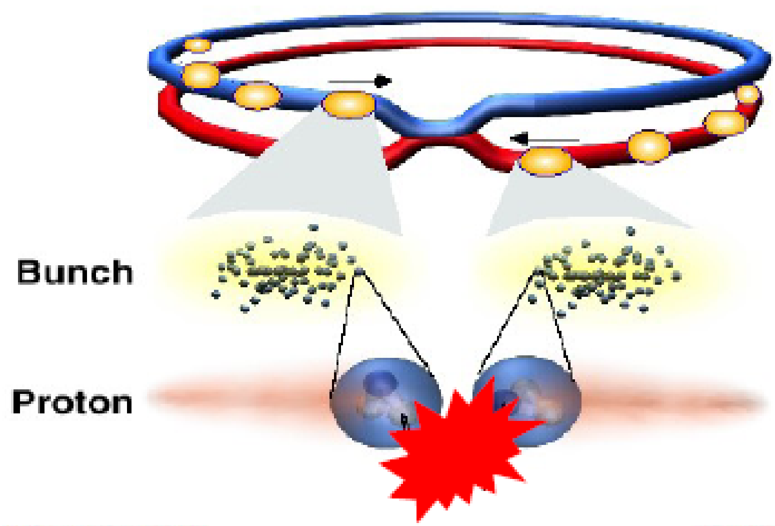
so-called **minimum-bias events**
why this name ? Trigger on... almost nothing = minimum bias

why interesting?
Underlying event = everything but what I'm interested in
e.g. everything except the hard subprocess

min.-bias events = part of underlying event, Lumi dependent pile-up

all interesting events come along with underlying min-bias events!

Pile up of min-bias Events (1/2)

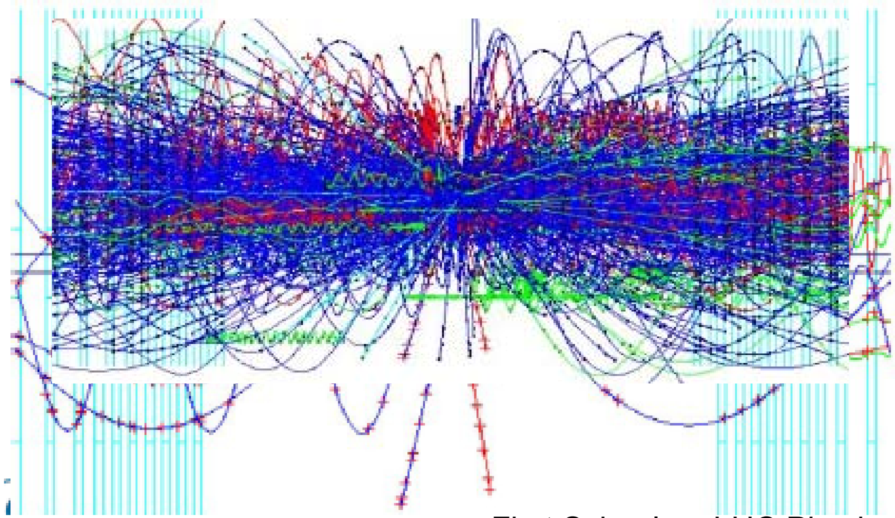


2835x2835 proton bunches
separation 7.5 m (25 ns)
10^{11} protons/bunch

bunch crossing rate: 40 MHz
Lumi (design): 10^{34} cm^{-2} s^{-1}

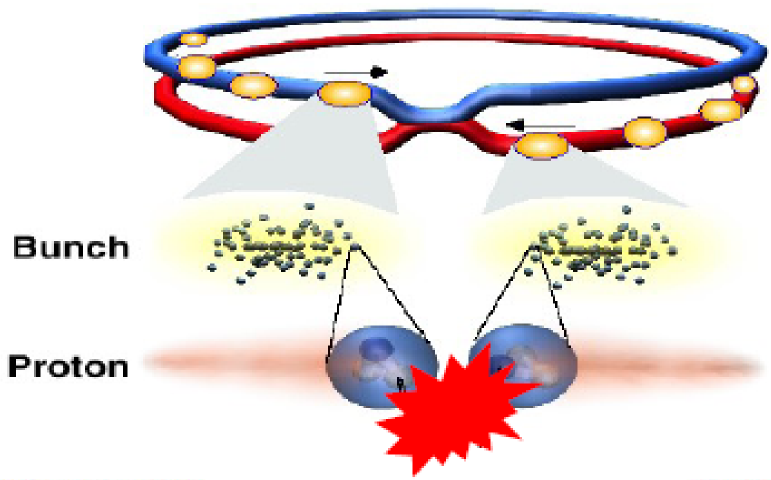
~10^{9} pp collisions / s and
10^{9} / 40 · 10^{6}

~ 25 pp interactions/bc = pile up!



Simulated event in CMS
$h \rightarrow \mu\mu\mu\mu$

Pile up of min-bias Events (2 / 2)



2835x2835 proton bunches
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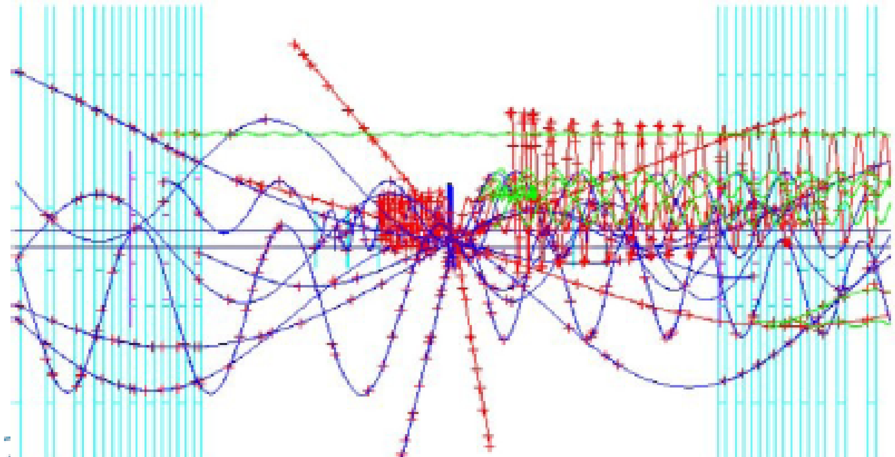
10^{11} protons/bunch

bunch crossing rate: 40 MHz
Lumi (design): 10^{34} cm^{-2} s^{-1}

~10^{9} pp collisions / s and
10^{9} / $40 \cdot 10^{6}$

~ 25 pp interactions/bc = pile up!



Simulated event in CMS
$h \rightarrow \mu\mu\mu\mu$

The pile-up is one of the most serious difficulties for the experimental operation at the LHC

To confront with Pile-up: detector demands

- **Fast response time**
- **High granularity**
- **Radiation resistant**

Triggering at LHC

Reminder of some numbers …

- LHC bunch crossing interval 25 ns
  event rate of 40 Mhz

in 25 ns particles at the speed of light travel only 7m
next bc while particles still traverse the detector!

- each bunch crossing ~23 piled up events
  leading to an interaction rate of 1 GHz

for triggering BC rate of 40 MHz is of interest

ATLAS has in total 140 mio channels

- size of events e.g. ATLAS : 1-1.5 MB
- affordable mass storage: ~300 MB/s or event rate of 200 Hz

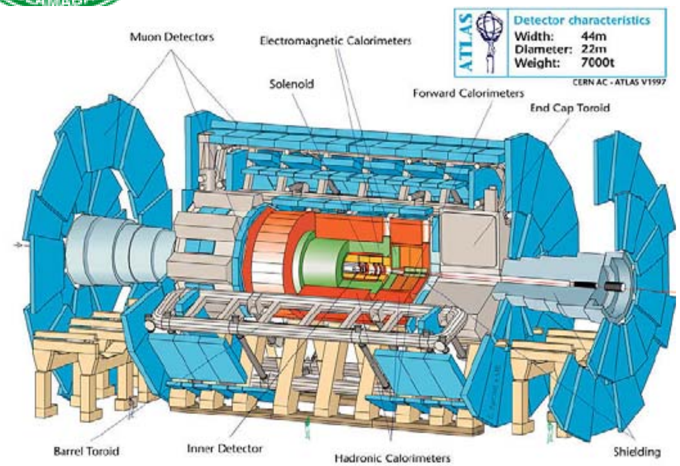
reduction needed 40 MHz down to 200 Hz reject 99.9995 %

interesting rare physics cross section $\sim 10^{-9}$ and lower w.r.t. Total cross section
but have to identify these events fast!

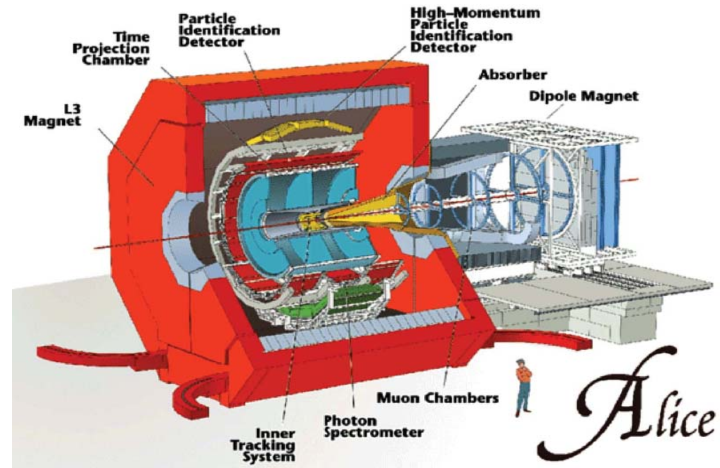
Physics Goals

- To explore physics at the TeV scale
- To discover the Higgs boson
- To look for evidence of physics beyond the standard model, such as supersymmetry, or extra dimensions
- To study aspects of heavy ion collisions

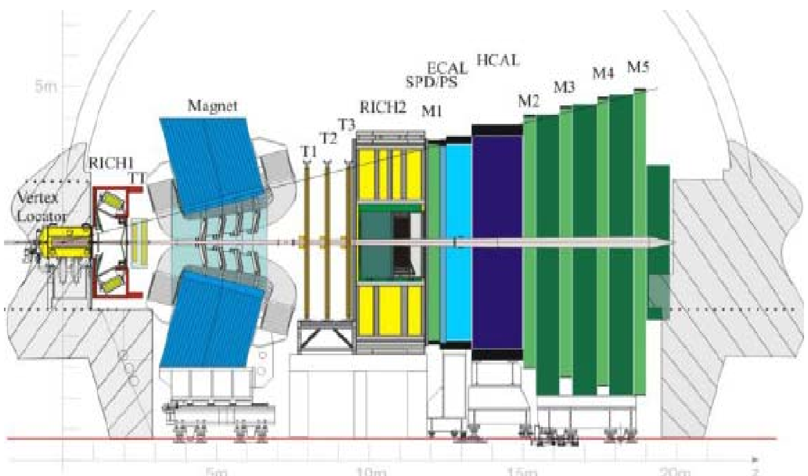
LHC experiments



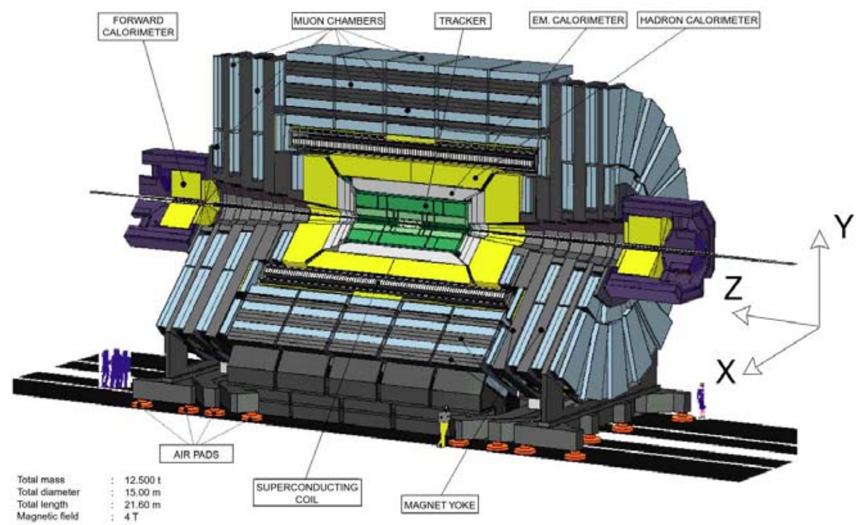
ATLAS



ALICE



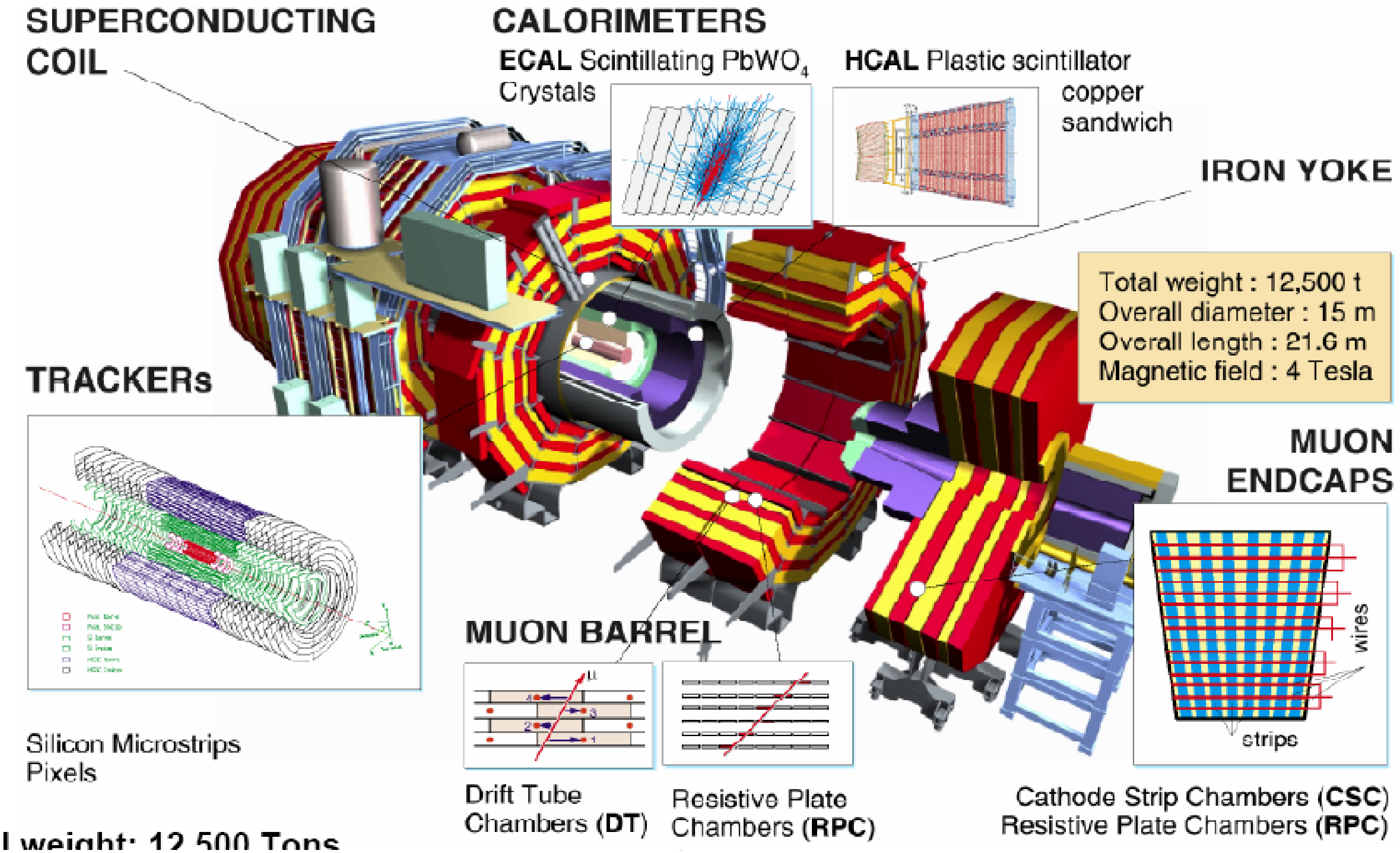
LHC-b



CMS

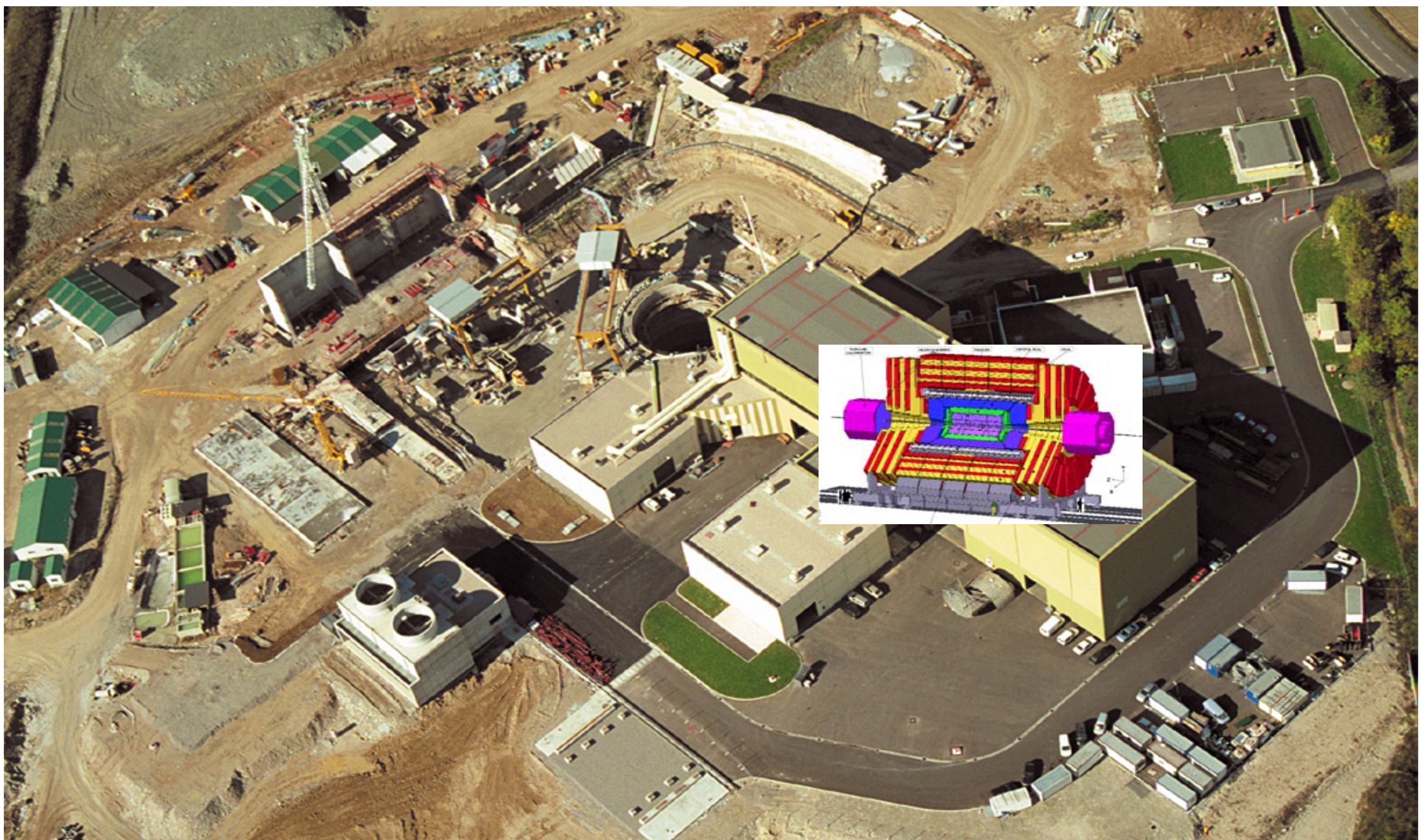
What is CMS

- ✓ CMS-stands for Compact Muon Solenoid
- ✓ General purpose detector
- ✓ Onion shape



How was CMS design

- Lessons learnt from LEP
- Fifteen separate sections lowered into cavern



Typical Signatures

The signatures we look for are characterised by...

- Leptons and photons at high p_T

  initial state pp : no leptons , no p_T

  hight pT leptons in final state :

  decay of heavy particles
  signature of interesting physics

- b quarks, tau leptons from decays

  long lived particles, decay vertex reconstruction

- missing Energy --> $E_T$miss

  Higgs, W decays involve neutrinos
  many SUSY and other BSM scenarios

  missing Energy
  measure missing transverse E

  why not $E_L$miss?

❖ Stable particles

❖ Quasi-stable particle

❖ Vertex tagged particles

❖ Short lived

❖ Missing particles

What we will see in CMS

Leptons	Vetexing	Tracking	ECAL	HCAL	Muon Cham.
$e^\pm$	$\times$	$\vec{p}$	E	$\times$	$\times$
$\mu^\pm$	$\times$	$\vec{p}$	$\surd$	$\surd$	$\vec{p}$
$\tau^\pm$	$\surd\times$	$\surd$	$e^\pm$	$h^\pm$; $3h^\pm$	$\mu^\pm$
ν_e, ν_μ, ν_τ	$\times$	$\times$	$\times$	$\times$	$\times$
Quarks					
u, d, s	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$c \to D$	$\surd$	$\surd$	$e^\pm$	h's	$\mu^\pm$
$b \to B$	$\surd$	$\surd$	$e^\pm$	h's	$\mu^\pm$
$t \to bW^\pm$	b	$\surd$	$e^\pm$	$b +$ 2 jets	$\mu^\pm$
Gauge bosons					
γ	$\times$	$\times$	E	$\times$	$\times$
g	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$W^\pm \to \ell^\pm \nu$	$\times$	$\vec{p}$	$e^\pm$	$\times$	$\mu^\pm$
$\to q\bar{q}'$	$\times$	$\surd$	$\surd$	2 jets	$\times$
$Z^0 \to \ell^+\ell^-$	$\times$	$\vec{p}$	$e^\pm$	$\times$	$\mu^\pm$
$\to q\bar{q}$	$(b\bar{b})$	$\surd$	$\surd$	2 jets	$\times$

Detector Requirements…

The signatures we look for ...

- Leptons and photons at high p_T
- missing Energy --> E_t^{miss}
- b quarks, tau leptons
- Jets

with high backgrounds and low pT pile up

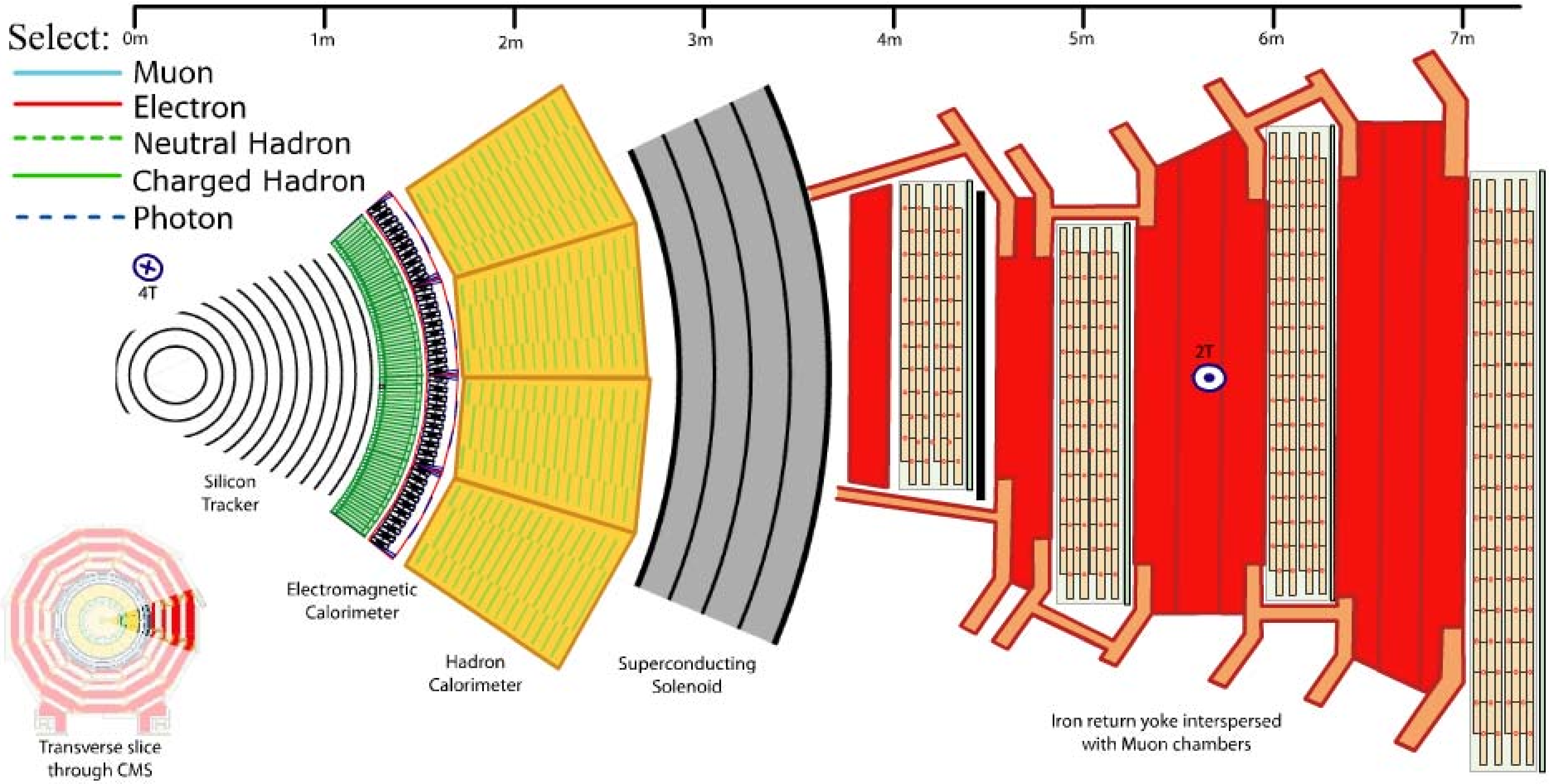
Detector requirements ...

- radiation hardness
- timing 25 ns
- identify and measure leptons, photons at high pT
  lepton ID over huge background e/jet ~ 10^{-5}
- good measurement of missing transverse Energy energy measurement in forward region ($|\eta|<5$)
- b and τ tag (silicon detectors)
- highly selective and fast trigger
  signal xs ~ 10^{-14} of total xs

Specific Design

- A high performance system to detect and measure muons,
- A high resolution method to detect and measure electrons and photons (an electromagnetic calorimeter),
- A high quality central tracking system to give accurate momentum measurements, and
- A "hermetic" hadron calorimeter, designed to entirely surround the collision and prevent particles from escaping

Working Principle



Why is it so Big

- Record the Universe's tiniest
- Possibility of obtaining more accurate measurements
- Need a strong magnetic field to bend the particles trajectories

Total weight: 12,500 Tons
Diameter: 15m
Length: 21 m
Field: 4 Tesla
Readout channels: ~80M

Coordinate conventions

- **transverse momentum p_T:** momentum perpendicular to the beam axis

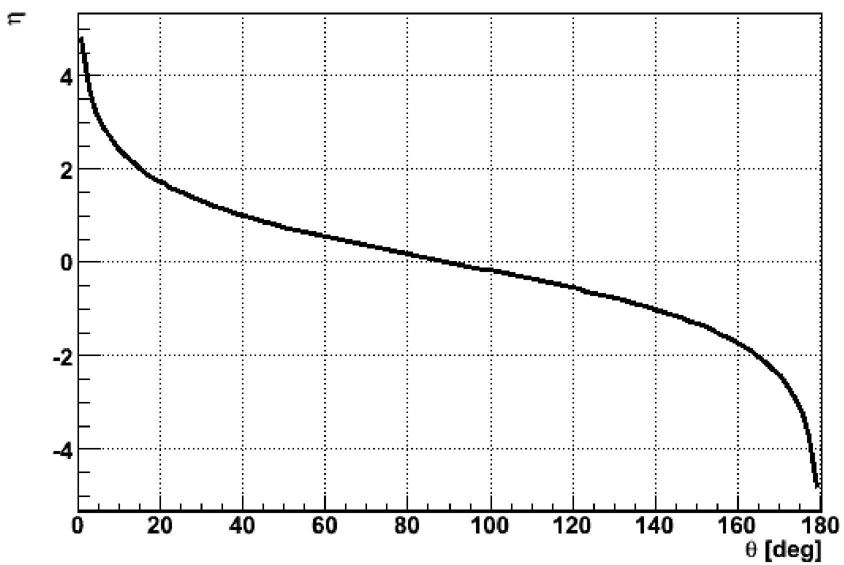
- **pseudorapidity η**

rapidity $$y = \frac{1}{2}\ln\frac{E+p_L}{E-P_L}$$

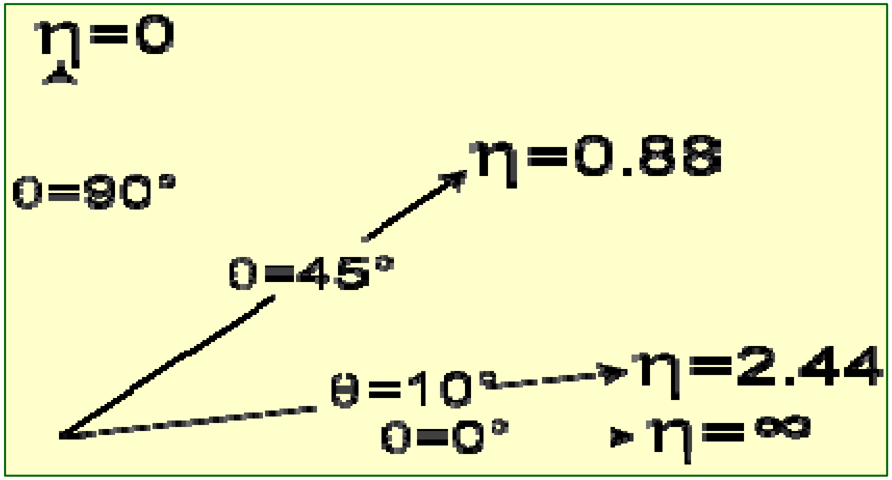
massless particles (mass unknown) use pseudorapidity instead:

$$\eta = -\ln\tan\theta/2$$

θ (degrees)	η
0	infinite
5	3.13
10	2.44
20	1.74
30	1.31
45	0.88
60	0.55
80	0.175
90	0



Pseudorapidity



Experimental Challenge

High Interaction Rate

pp interaction rate **1 billion interactions/s**
Data can be recorded for only ~10^2 out of 40 million crossings/sec
Level-1 trigger decision takes ~2-3 μs
a electronics need to store data locally (pipelining)

Large Particle Multiplicity

~ <20> superposed events in each crossing
~ 1000 tracks stream into the detector every 25 ns
need highly granular detectors with good time resolution for low occupancy
a large number of channels (~ 100 M ch)

High Radiation Levels

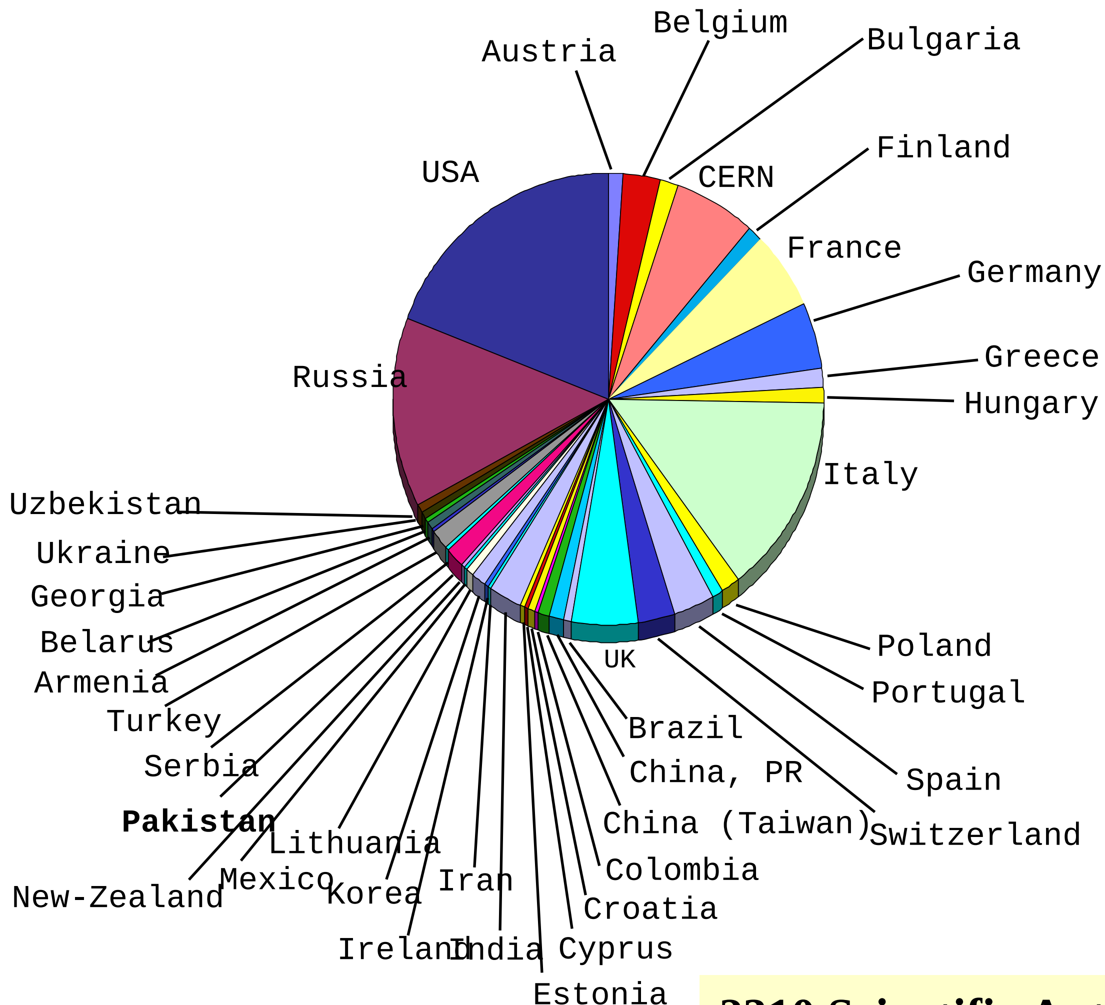
a radiation hard (tolerant) detectors and electronics

The CMS Collaboration

	Number of Laboratories
Member States	59
Non-Member States	67
USA	49
Total	175

	# Scientific Authors
Member States	1084
Non-Member States	503
USA	723
Total	2310

Associated Institutes	
Number of Scientists	62
Number of Laboratories	9



2310 Scientific Authors
38 Countries
175 Institutions

CMS Design Criteria

Very good muon identification and momentum measurement
Trigger efficiently and measure sign of TeV muons dp/p < 10%

High energy resolution electromagnetic calorimetry
~ 0.5% @ E_T ~ 50 GeV

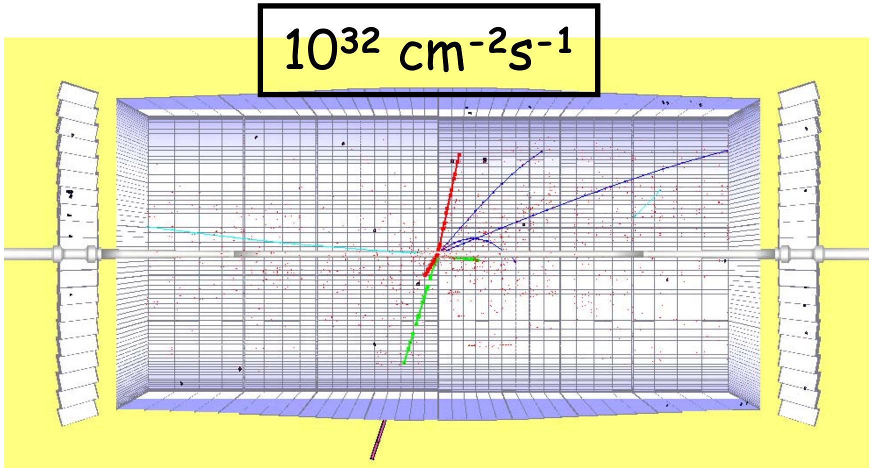
Powerful inner tracking systems
Momentum resolution a factor 10 better than at LEP

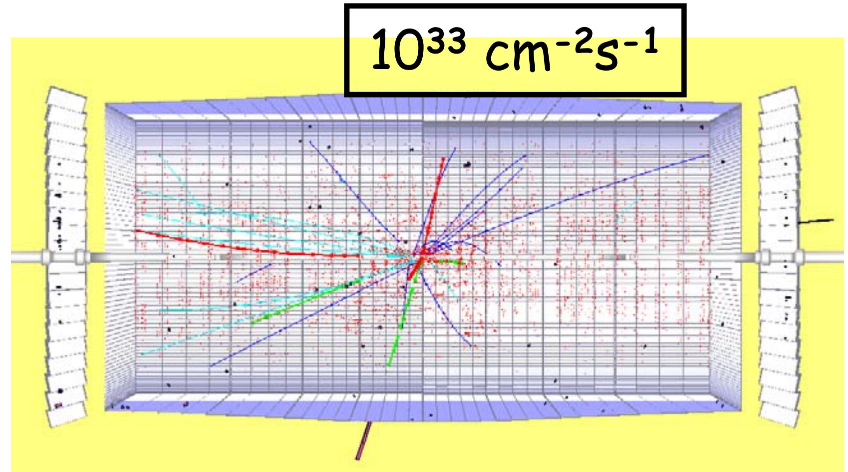
Hermetic calorimetry
Good missing E_T resolution

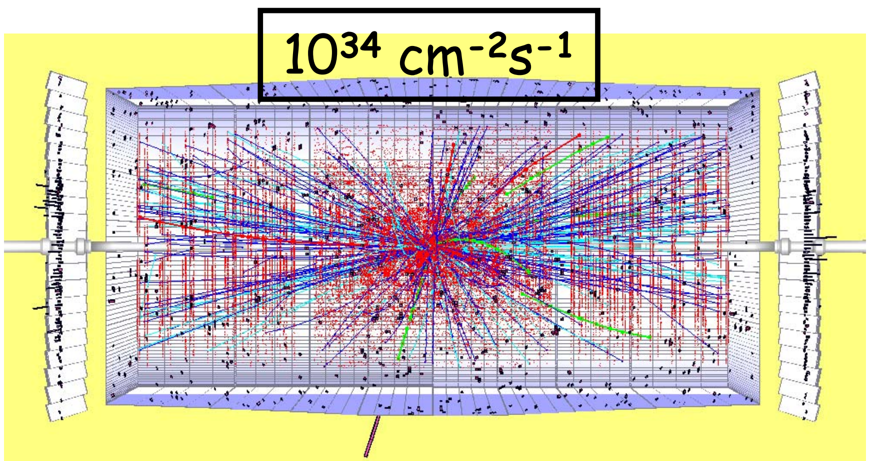
(Affordable detector)

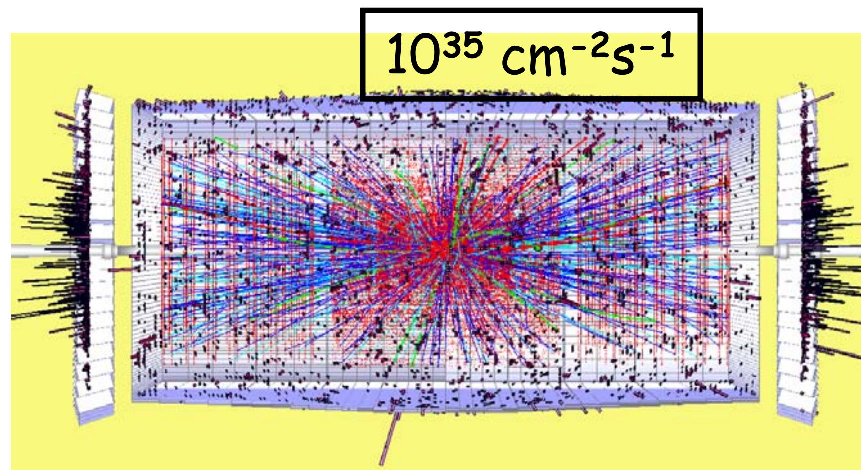
Luminosity Effects

$H \rightarrow ZZ \rightarrow \mu\mu ee$ event with M_H= 300 GeV for different luminosities



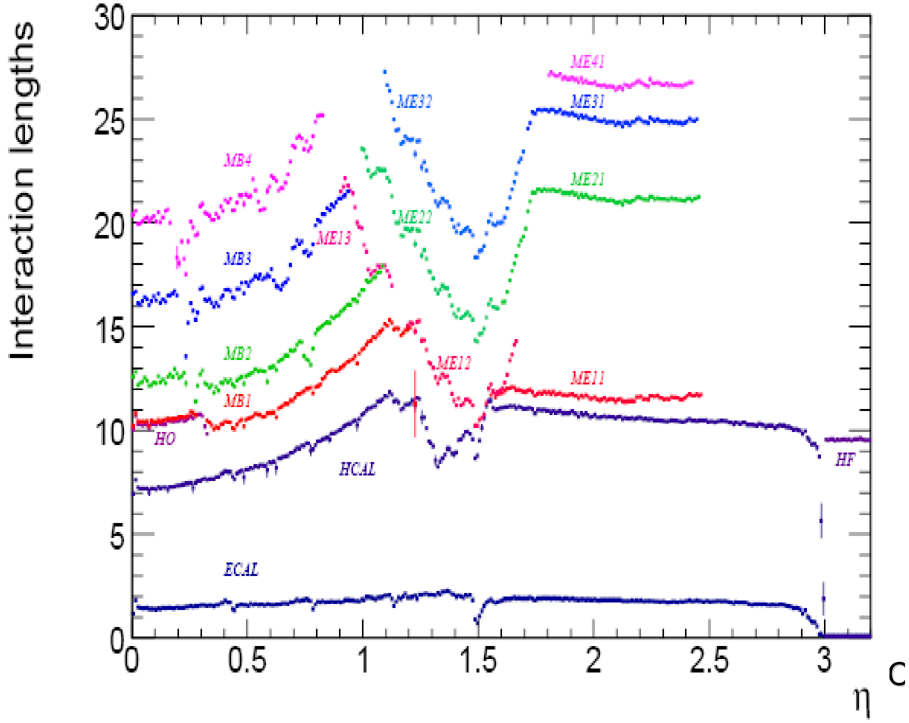


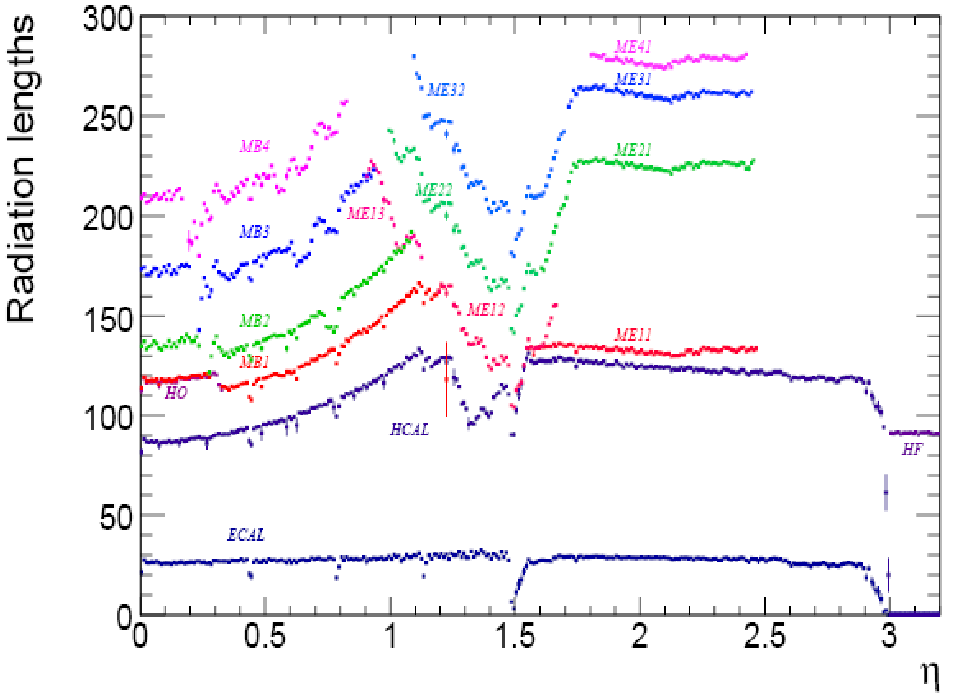




Detector Thickness

Material thickness in terms of radiation length and interaction length

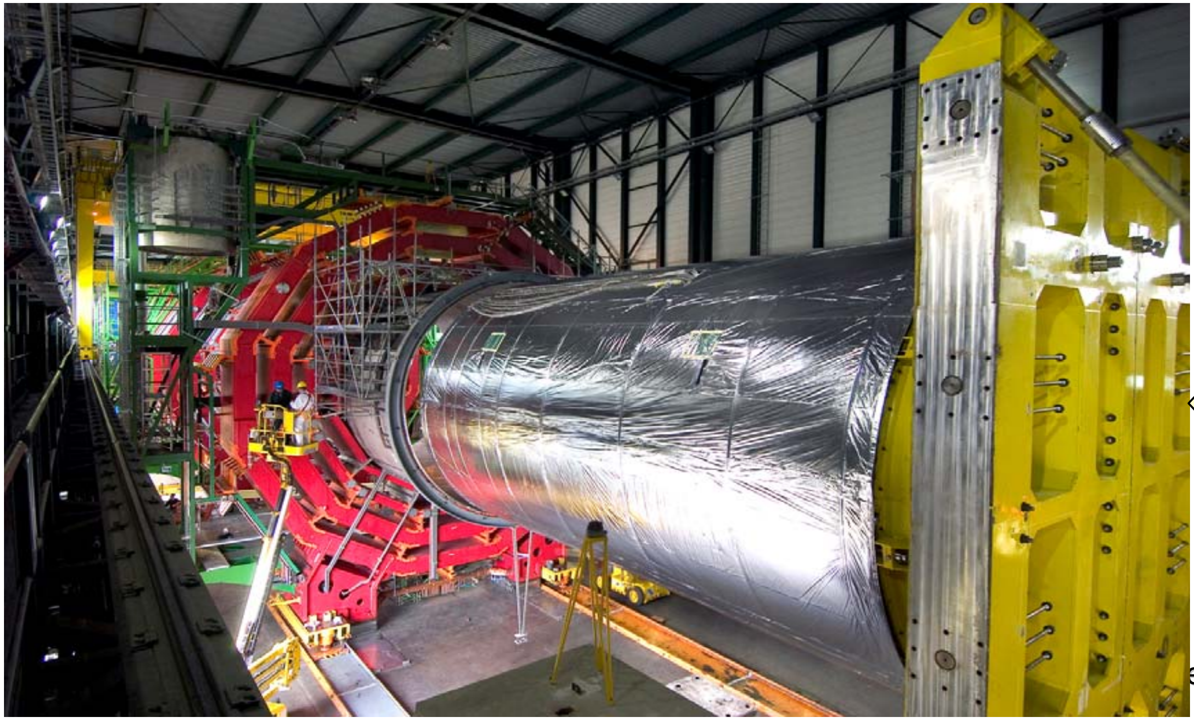




The CMS Solenoid

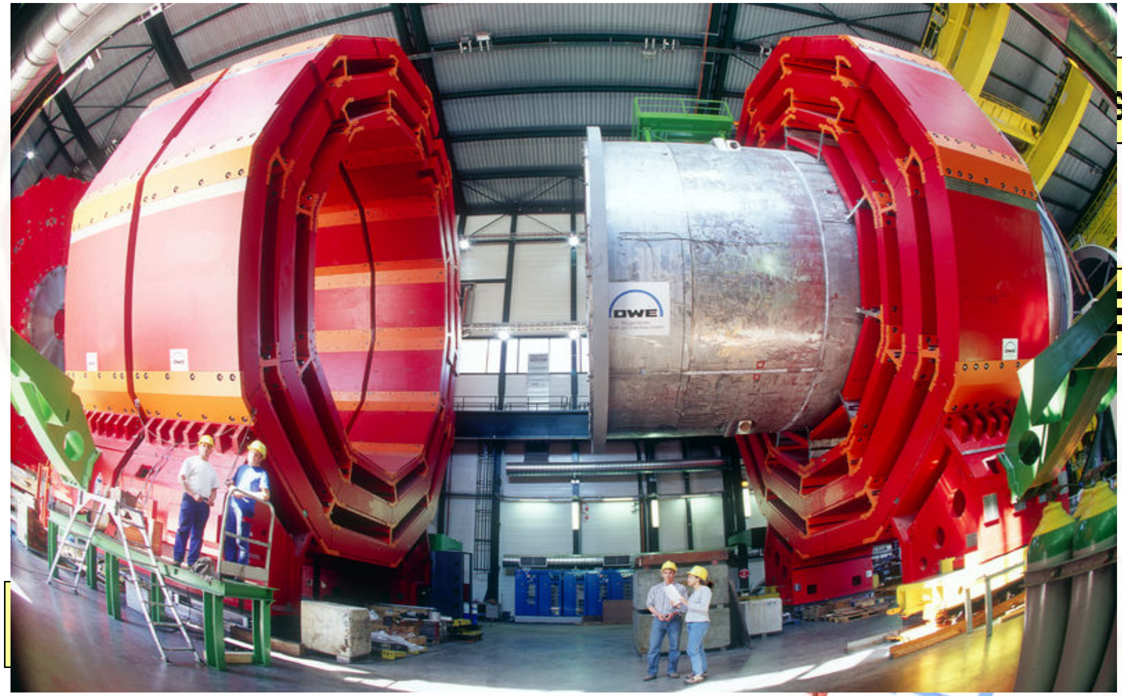
The CMS magnet…

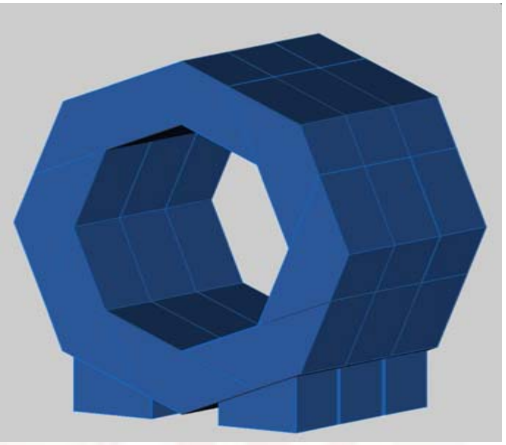
- ❖ is the largest superconducting magnet ever built
- ❖ weighs 12,000 tonnes
- ❖ is cooled to -268.5ºC, a degree warmer than outer space
- ❖ is 100,000 times stronger than the Earth’s magnetic field
- ❖ stores enough energy to melt 18 tonnes of gold
- ❖ uses almost twice much iron as the Eiffel Tower



A stronger field provides You more precise momentum and energy resolution

The return yoke-parameters



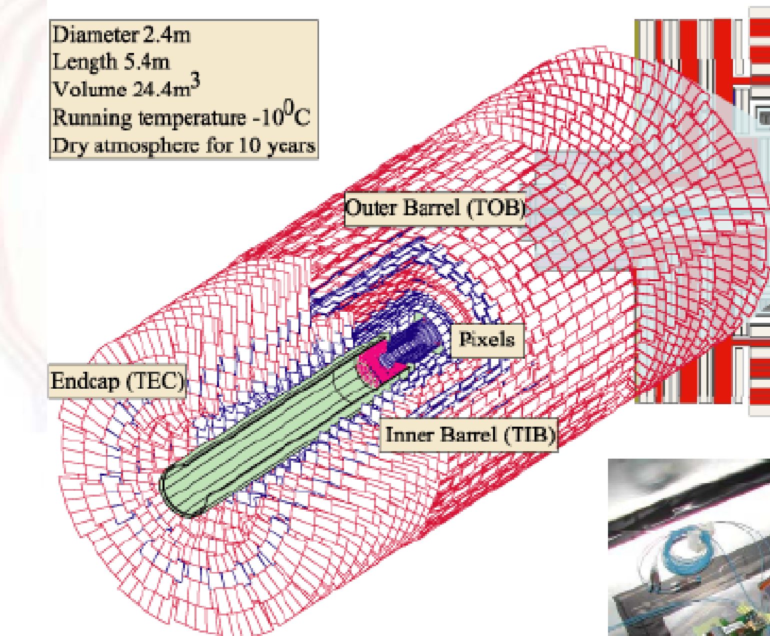


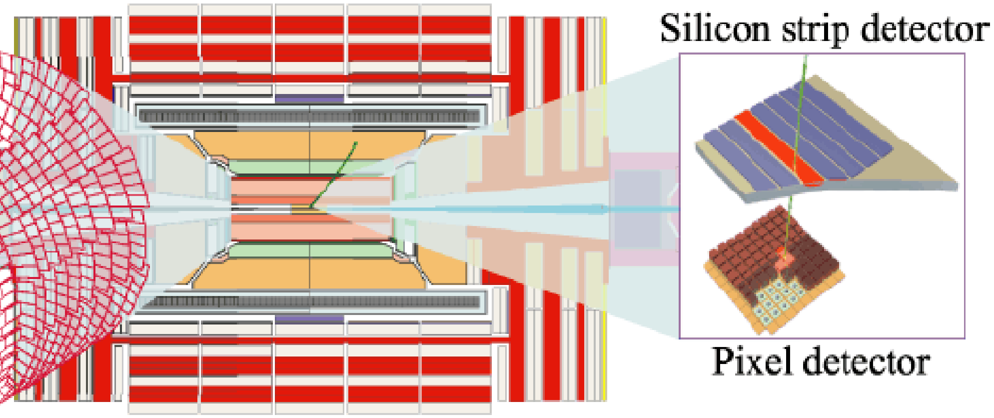
Total weight	**12500 tonnes**
Diameter	**15m**
Length	**21.6m**
Magnetic field	**4 Tesla**

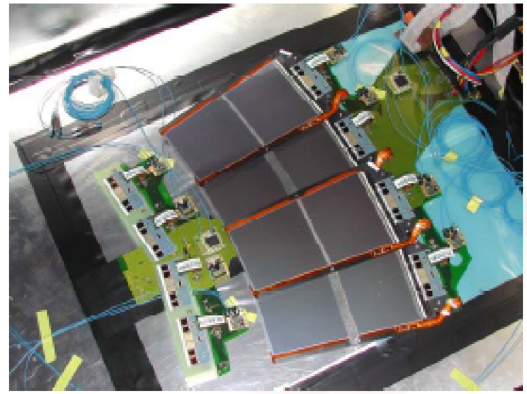
	Central Ring	*Outer Rings*
Barrel ring	1250 tonnes	1174 tonnes
Vacuum vessel	264 tonnes	-
Superconducting coil	234 tonnes	-
Support feet	72 tonnes	66 tonnes
Cabling on vacuum vessel	150 tonnes	-
Support for racks and cables	10 tonnes	10 tonnes
Total	**1980 tonnes**	**1250 tonnes**

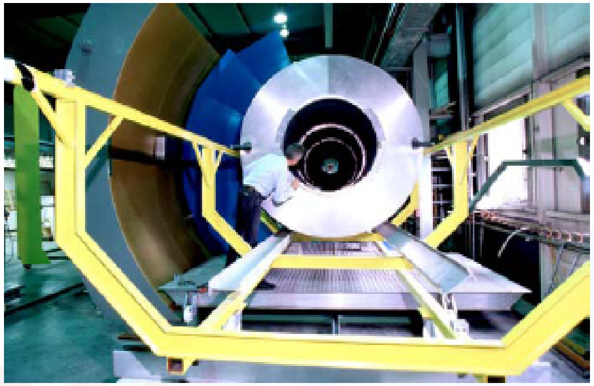
Endcap disk 1 (YE1)	~730 (disk) + 90 (cart) tonnes
Endcap disk 2 (YE2)	~730 (disk) + 90 (cart) tonnes
Endcap disk 3 (YE3)	~300 (disk) + 90 (cart) tonnes

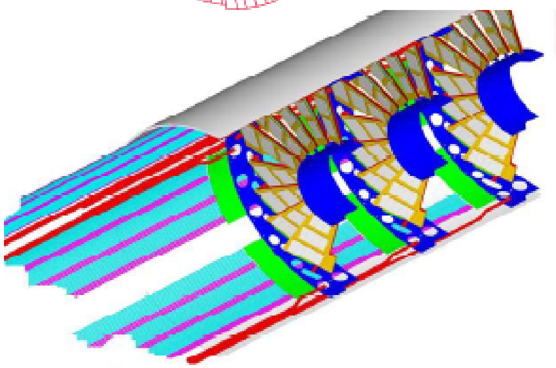
The Tracking System







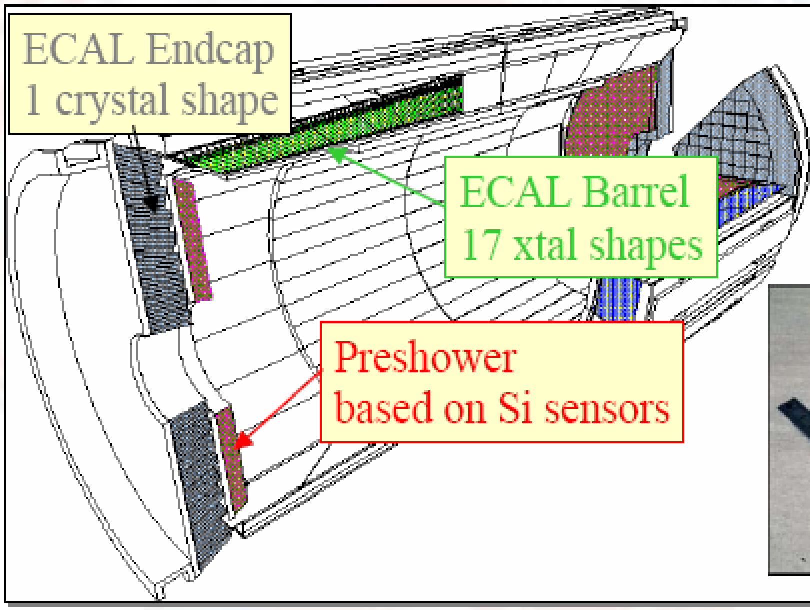




Pixel endcap disks

214m² of silicon sensors
11.4 million silicon strips
65.9 million pixels in final configuration!

The Electromagnetic Calorimeter- ECAL

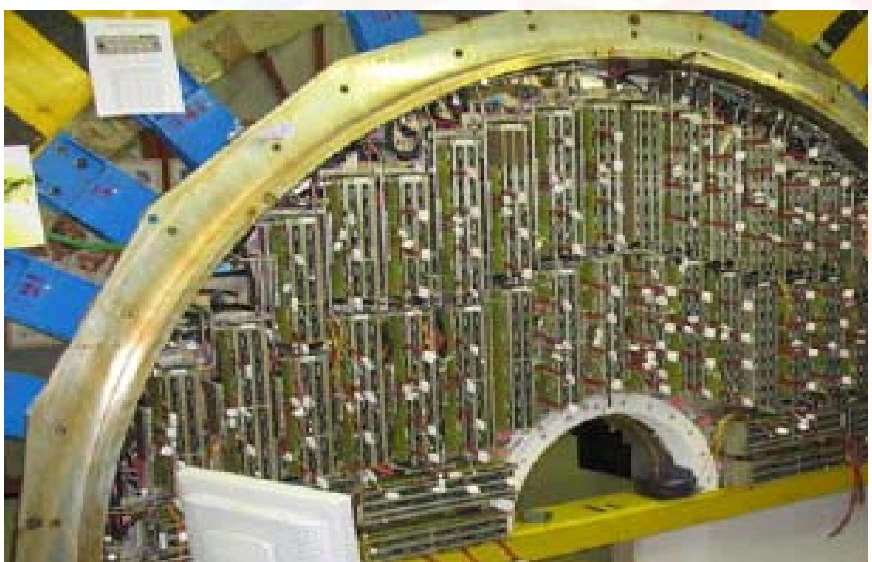


Characteristics of $PbWO_4$

$X_0 = 0.89$cm

$\rho = 8.28$g/cm^3

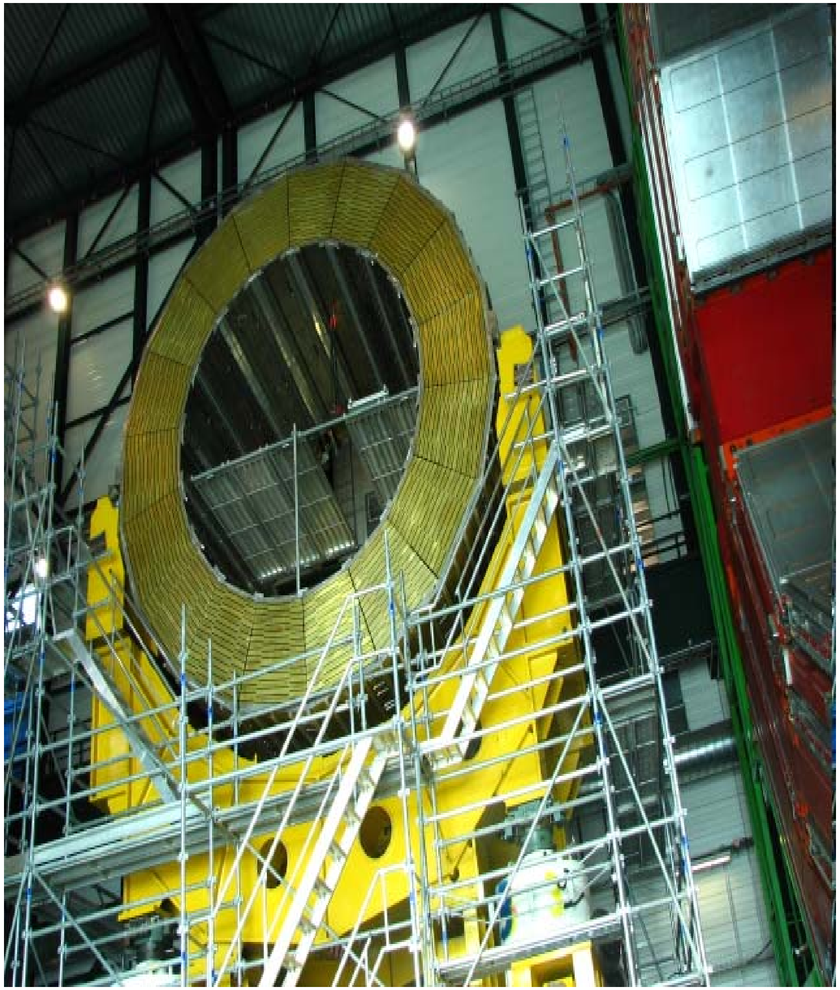
R_M (Molière radius) = 2.2cm



Parameter	Barrel	Endcaps
Coverage	$\|\eta\|<1.48$	$1.48<\|\eta\|<3.0$
$\Delta\phi$ x $\Delta\eta$	0.0175 x 0.0175	0.0175 x 0.0175 to 0.05 x 0.05
Depth in X_0	25.8	24.7
# of crystals	61200	14648
Volume	8.14m^3	2.7m^3
Xtal mass (t)	67.4	22.0

The Hadron Calorimeter-HCAL

- **CMS HCAL is constructed in 3 parts:**
  - Barrel HCAL (HB)
    - Brass (laiton) plates interleaved with plastic scintillator embedded with wavelength-shifting optical fibres (photo top right)
  - Endcap HCAL (HE)
    - Brass plates interleaved with plastic scintillator
  - Forward HCAL (HF)
    - Steel wedges stuffed with quartz fibres (photo bottom right)
- **~10000 channels total**

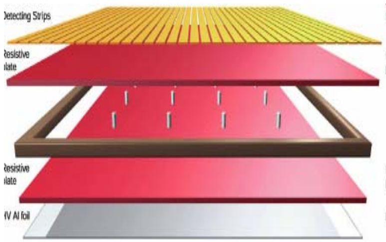


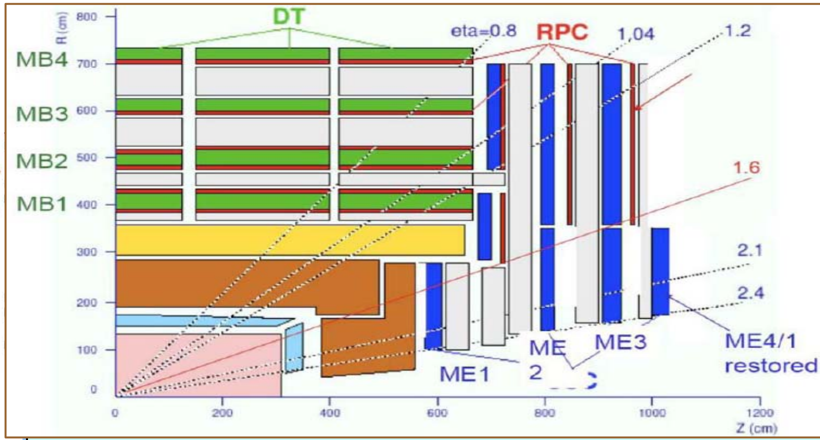
The Muon Chambers

Barrel region:

- ❖ DTs and RPCs
- ❖ Low almost uniform B field
- ❖ Low muon rate ~ 1 Hz/cm^2
- ❖ Negligible neutron induced background

RPC





CSC

- ➢ Stand alone
  - dp_t/p_t = 8 - 15% at p_t = 10 GeV
  - dp_t/p_t = 20 - 40% at p_t = 1 TeV
- ➢ Global
  - dp_t/p_t = 1 - 1.5% at p_t = 10 GeV
  - dp_t/p_t = 6 - 17% at p_t = 1 TeV

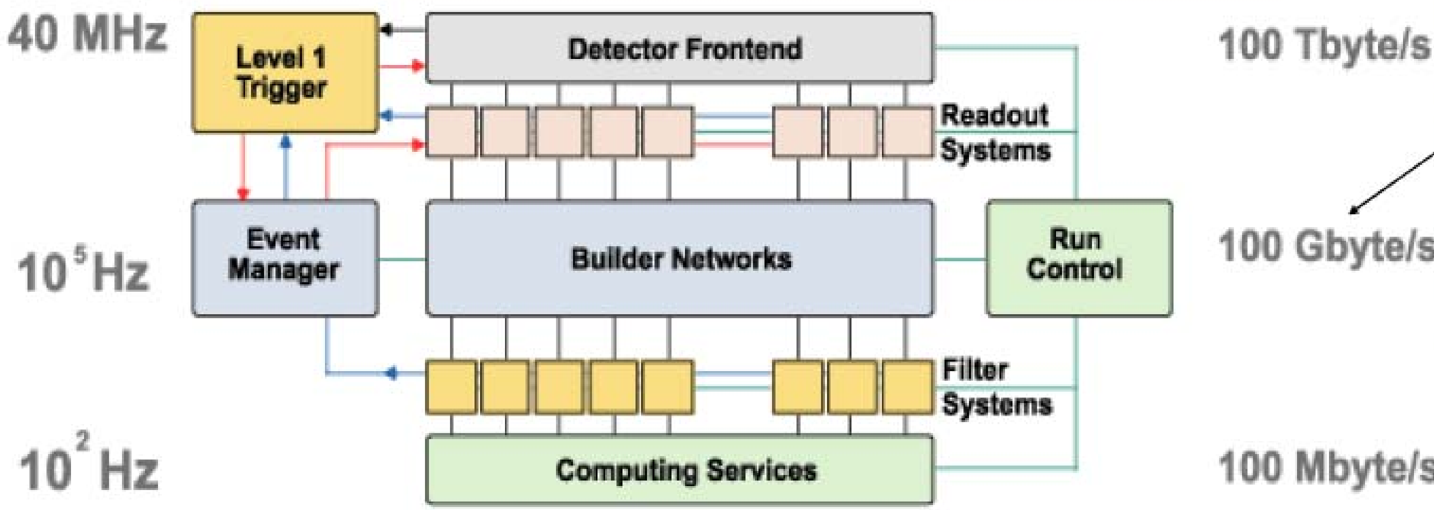
Endcap region:

- ❖ CSCs and RPCs
- ❖ Strong non-uniform B-filed (~ 3.5 Tesla)
- ❖ High muon rate ~ 1000 Hz/cm^2
- ❖ γ and neutron induced background are comparable

- Geometrical coverage up to η=2.4
- 128 BX Latency = 3.2 μs
- No Dead-time allowed: every BX must be processed
- Output Rate: ~ 30 KHz –> reduction factor > 10^3
- Ghost Rate < 0.5 %
- p_t threshold should be set in the range ~ 4 – 50 GeV

The Trigger and Data Acquisition System

Data Acquisition Main Parameters	
Collision rate	40 MHz
Level-1 Maximum trigger rate	100 kHz
Average event size	1 Mbyte
No. of electronics boards	10000
No. of readout crates	250
No. of In-Out units (200-5000 byte/event)	1000
Event builder (1000 port switch) bandwidth	1 Terabit/s
Event filter computing power	5 10^6 MIPS
Data production	Tbyte/day



Trigger and Data Acquisition baseline structure

~same as whole world's telecom network!

Backup

CMS Design Features

- Very large solenoid – 6m diameter x 13 m long
  - Tracking and calorimetry fits inside the solenoid
    - Particle energies are measured before they pass through the solenoid coil and cryostat, which would degrade their resolution
- Very strong field – 4T
  - Coils up soft charged particles
  - Excellent momentum resolution
- Tracking chambers in the return iron track and identify muons
  - This makes the system very compact
  - Weight of CMS is dominated by all the steel and is 12,500 Tonnes
- Tracking is based on all-silicon components
  - A silicon pixel detector (66 million pixels) out to ~ 15 cm
  - A silicon microstrip detector (11 million strips) from 30 cm out to 1.2 m
  - Gives CMS excellent charged particle tracking and primary and secondary vertex reconstruction
  - High segmentation results in very low occupancy
  - Silicon detectors are very radiation hard