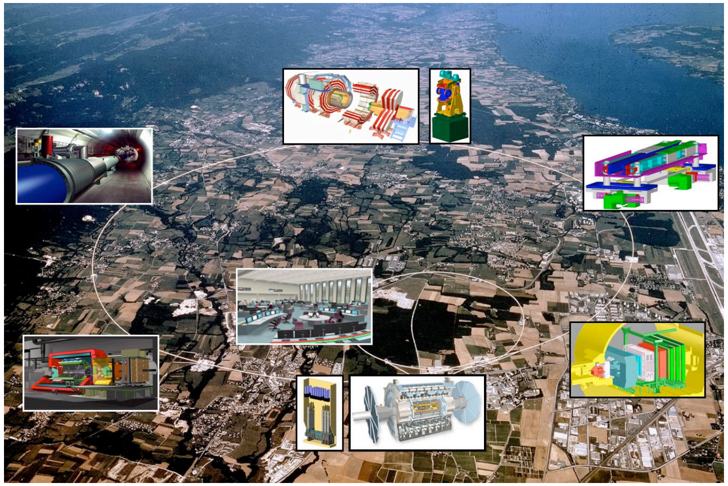
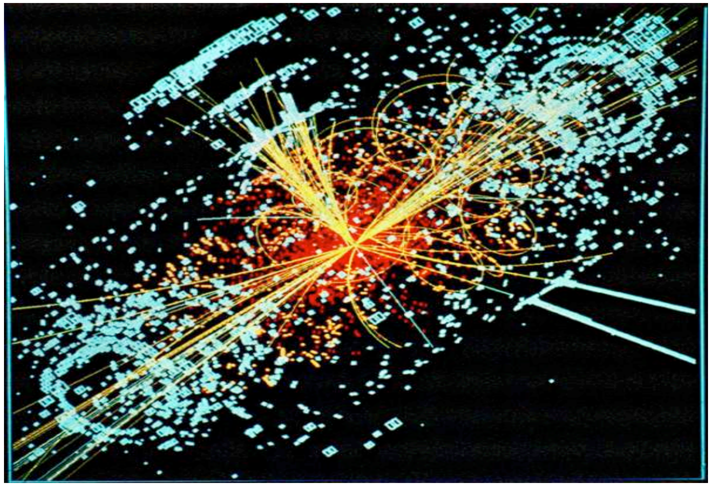
Introduction to Particle Physics
GRS PY 551

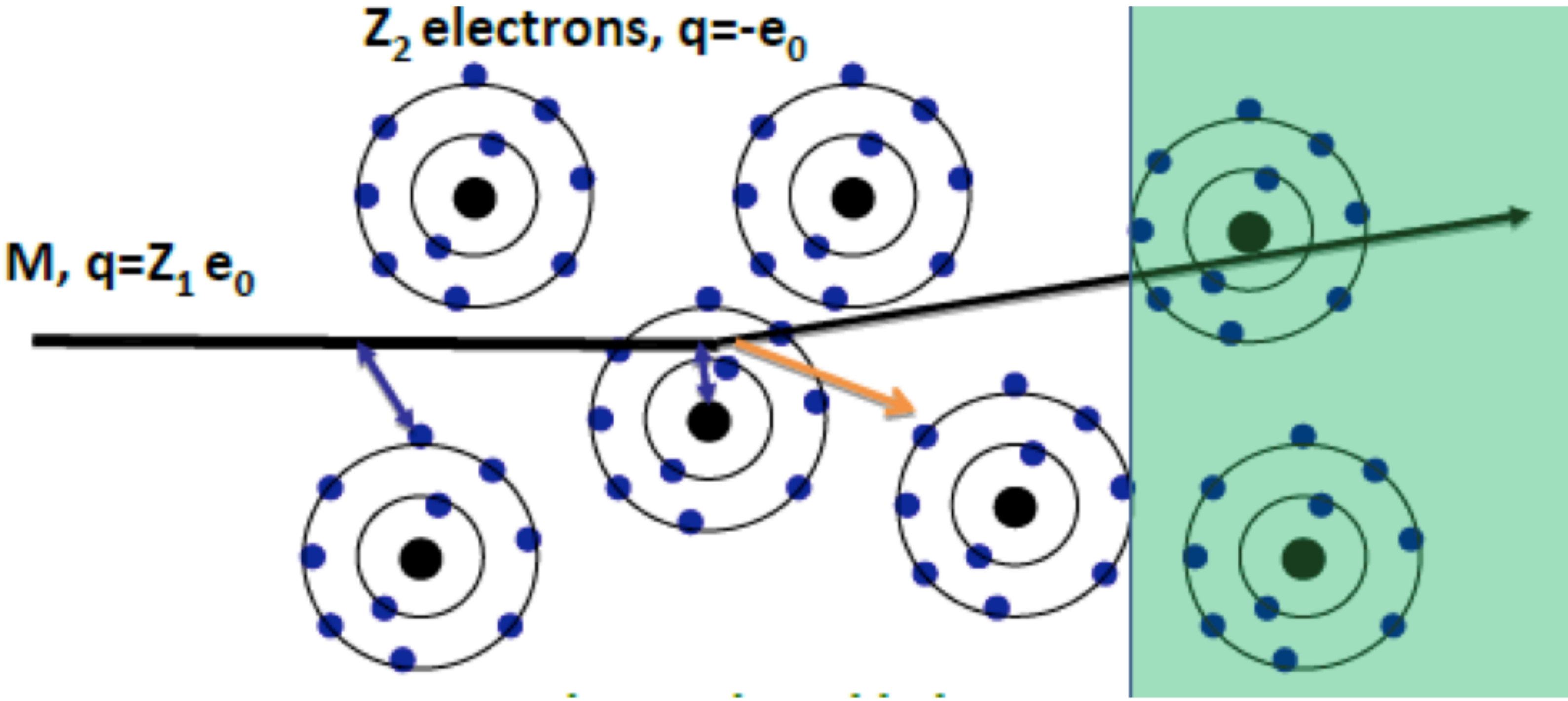
2/8/2012

Prof. Tulika Bose





Electromagnetic Interactions



Interaction with atomic electrons – ionization and excitation – produces measurable signals

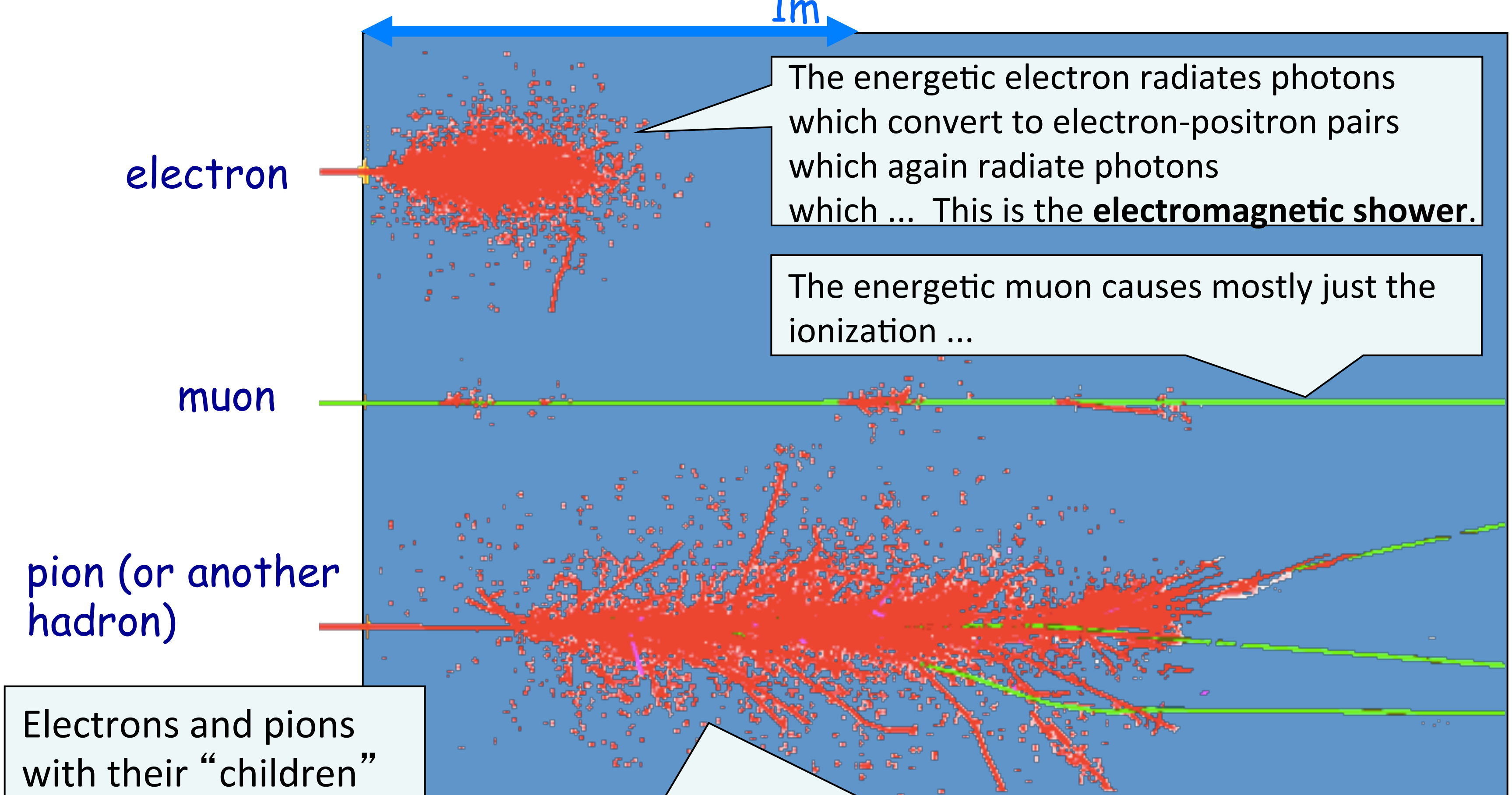
Interaction with atomic nucleus – bremstrahlung – shower production

If particle velocity is high enough (greater than speed of light in the medium) cherenkov radiation

Atomic Excitation

- Along with ionization, electromagnetic interactions of the charged particle with the Coulomb fields of the atoms/molecules of the material result in excitation.
- Excited states are unstable, return to ground state emitting a photon
- Timescale – excitation energy, number of available return paths
- When photons are in visible domain ➔scintillation
- Material that produces light – scintillators
  – signal readout by Photodetectors
    - Basis of detection for many calorimeters

Let us have a look at interaction of different particles with the same high energy (here 300 GeV) in a big block of iron:



The energetic electron radiates photons which convert to electron-positron pairs which again radiate photons which ... This is the **electromagnetic shower**.

The energetic muon causes mostly just the ionization ...

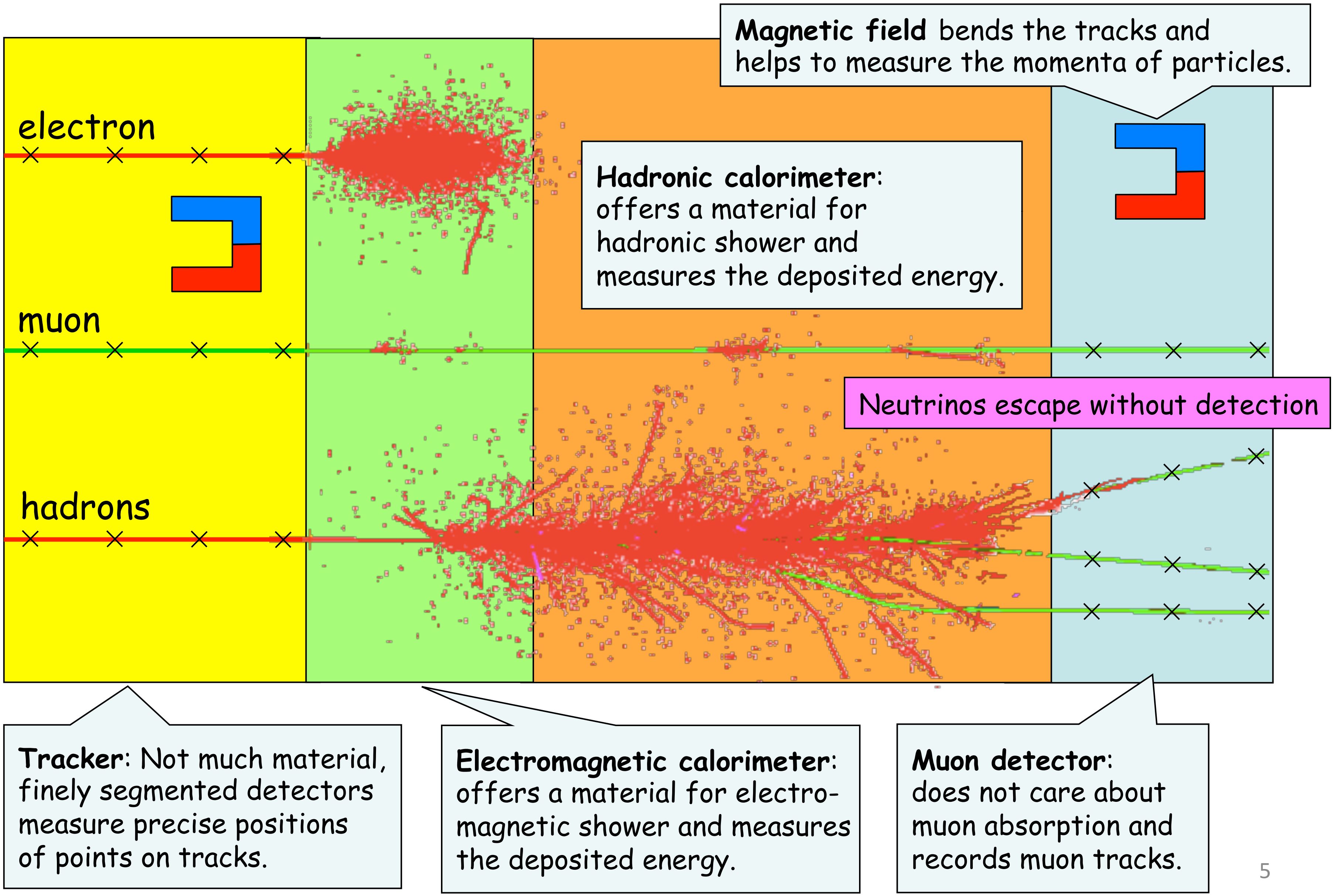
Electrons and pions with their "children" are almost comple-tely absorbed in the sufficiently large iron block.

The strongly interacting pion collides with an iron nucleus, creates several new particles which interact again with iron nuclei, create some new particles ...

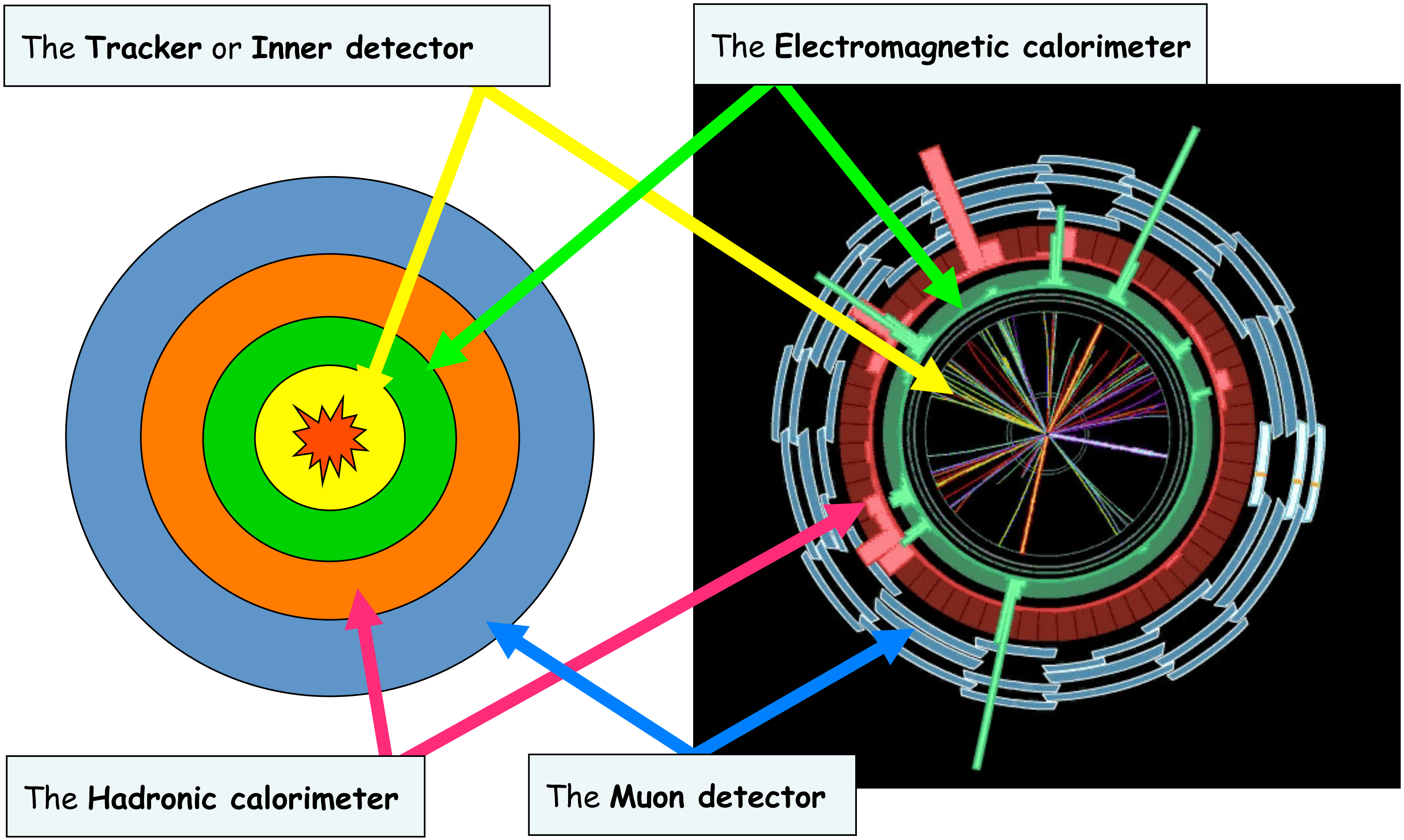
This is the hadronic shower.

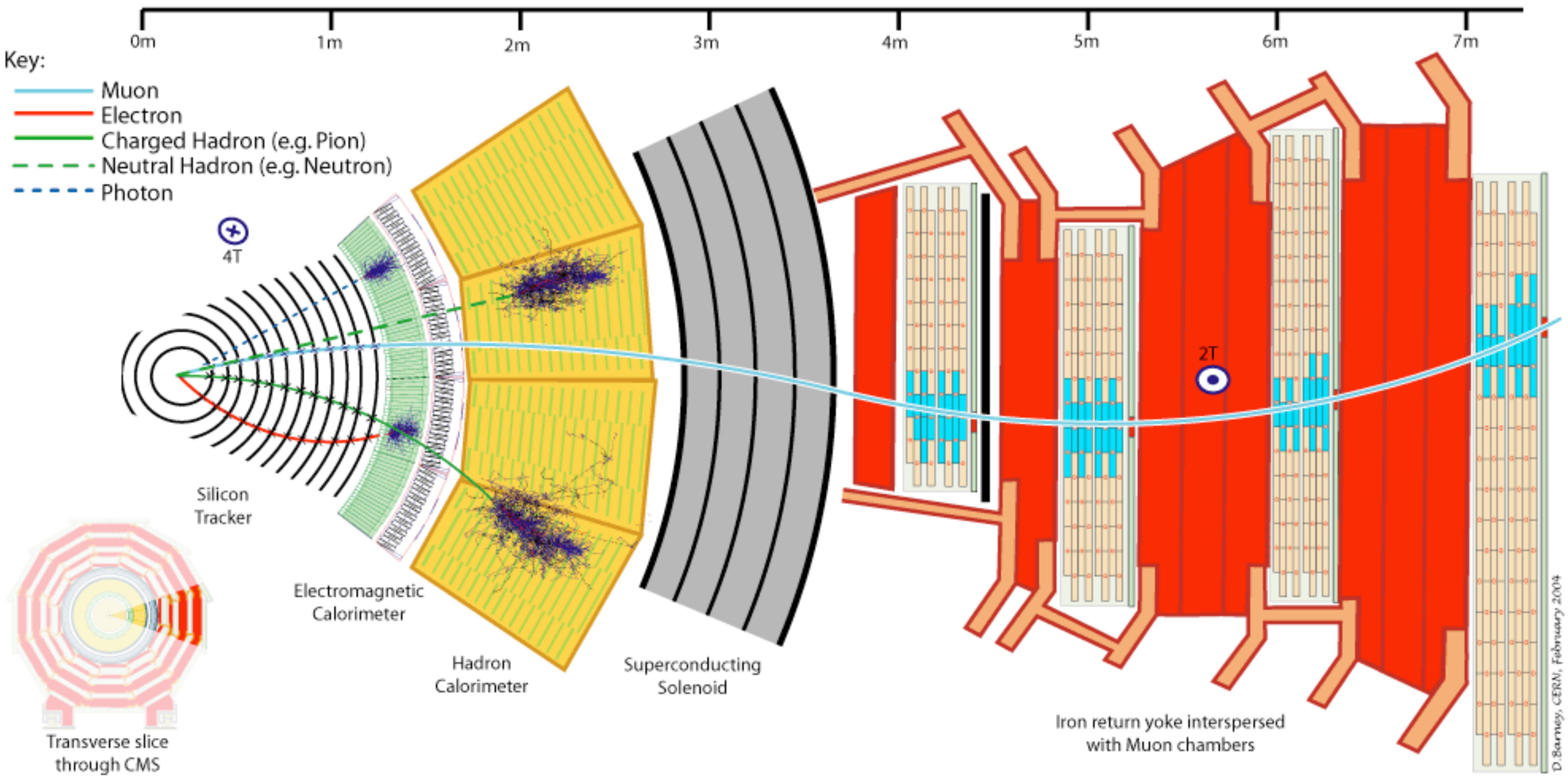
You can also see some muons from hadronic decays.

Here is the general strategy of a current detector to catch almost all particles:

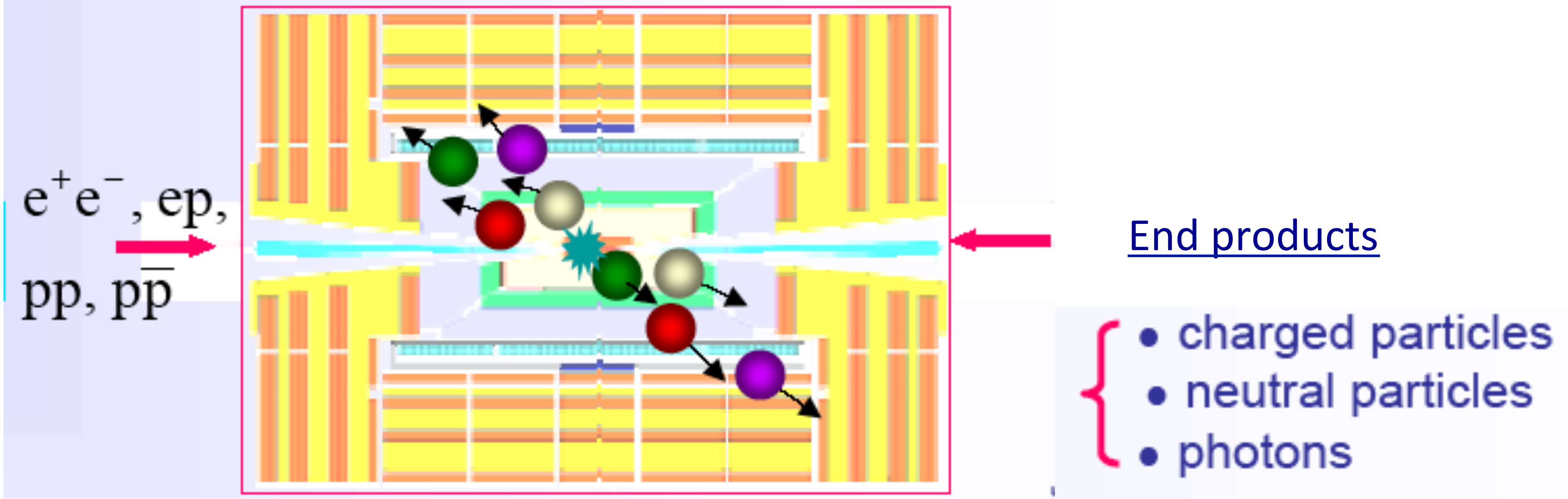


All the detectors are wrapped around the beam pipe and around the collision point: here are a schematic and less schematic cut through ATLAS




0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Ideal Detectors



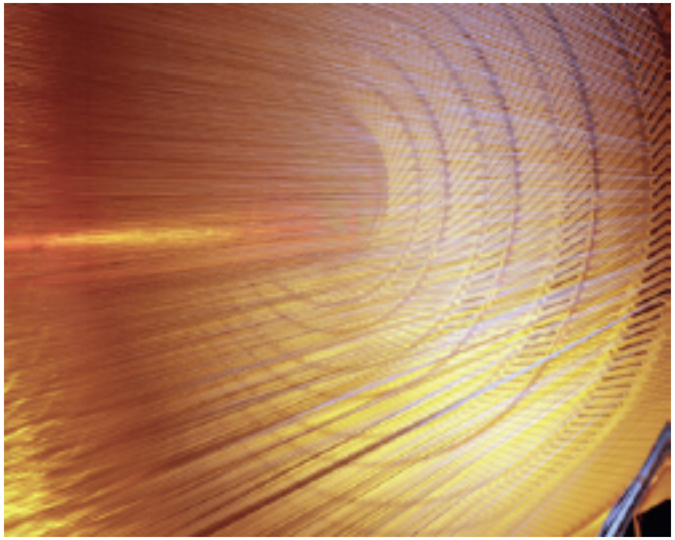
An "ideal" particle detector would provide…

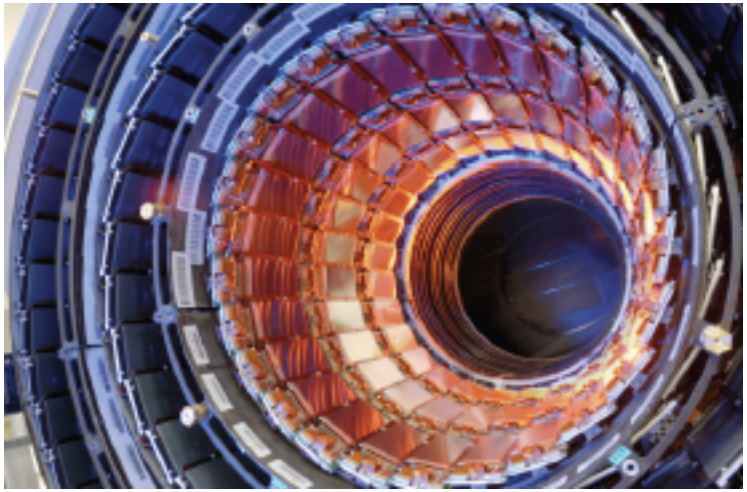
- Coverage of full solid angle, no cracks, fine segmentation
- Measurement of momentum and energy
- Detection, tracking, and identification of all particles (mass, charge)
- Fast response: no dead time

However, practical limitations: Technology, Space, Budget, and engineering prevent perfection…

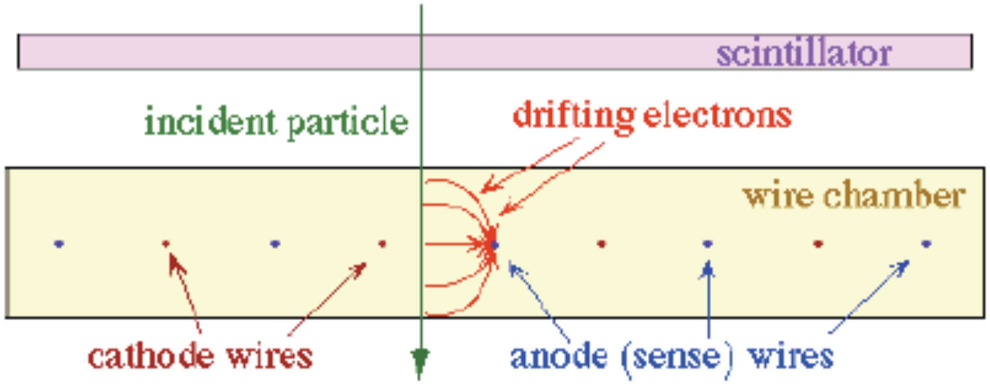
Tracking Detectors

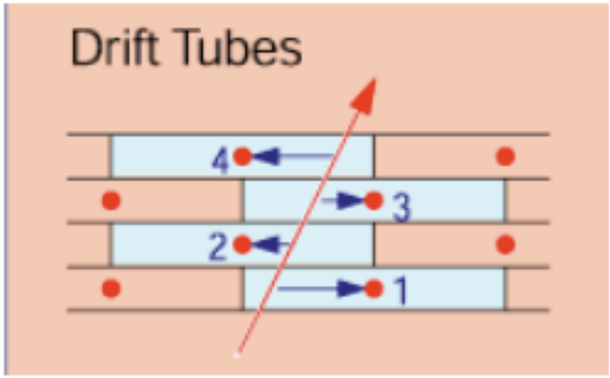
- Purpose: measure momentum and charge of charged particles
- To minimize multiple scattering, we want tracking detectors to contain as little material as possible
- Two main technologies
  - gas/wire drift chambers
  - solid state detectors (silicon)
- Silicon is now the dominant sensor material in use for tracking detectors at the LHC





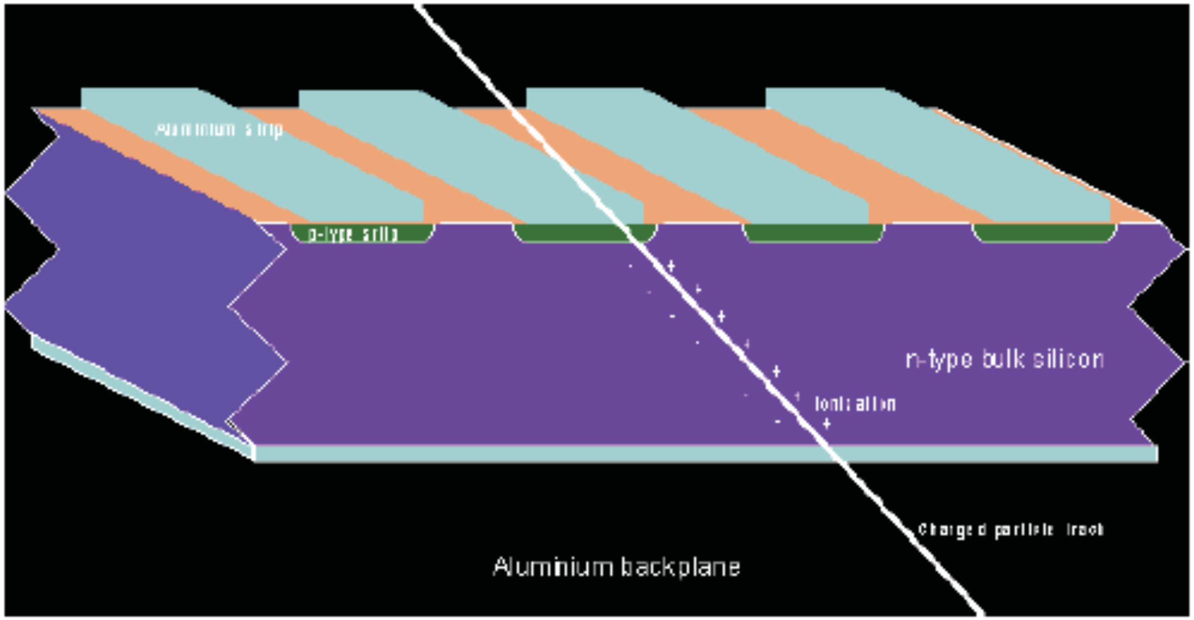
Gas/Wire Drift Chambers





- Wires in a volume filled with a gas (such as Argon)
- Measure where a charged particles has crossed
  - charged particle ionizes the gas
  - electrical potentials applied to the wires so electrons drift to the sense wire
  - electronics measures the charge of the signal and when it appears
- To reconstruct the particles track several chamber planes are needed
- Advantage:
  - low thickness (fraction of X_0)
  - traditionally preferred technology for large volume detectors

Silicon Detectors



~300μm

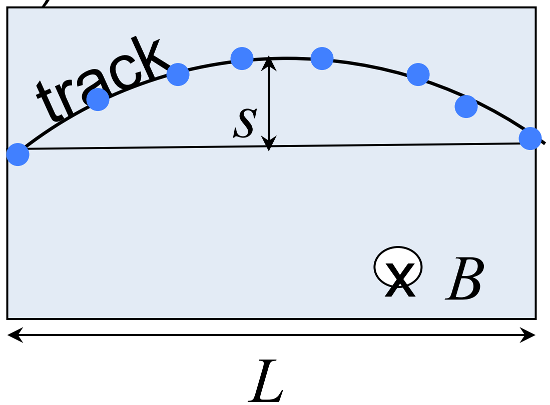
- Semi-conductor physics:
  - doped silicon: p-n junction
  - apply very large reverse-bias voltage to p-n junction
    - “fully depleted” the silicon, leaving E field
- Resolution 1-2% @ 100 GeV
- Important for detection secondary vertices
  - b-tagging (more on this later)

Momentum and charge

Tracks follow a helix in a uniform magnetic field.

Projected into *rφ* plane you get a circle. With the magnetic field (*B*) and radius (*R*): $p_T\left(\mathrm{GeV}/c\right) = 0.3 \times B\left(T\right) \times R\left(m\right)$

Usually only see tiny part of circle so actually measure sagitta *s* (deviation from a straight line).



With N (N>10) equally spaced measurements, the fractional uncertainty is

$$\frac{\sigma_{\mathrm{meas}}\left(p_T\right)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3 \cdot B \cdot L^2}\sqrt{\frac{720}{N+4}}$$

Worse with increasing p_T (tracks curve less)

Better with increasing B (tracks curve more)

Better with better hit resolution (better measurement of curve)

Better with more √hits (better measurement of curve)

Calorimeters

- Measure energy deposited by particles
- Electromagnetic (EM)
  - measure EM objects – electrons, positrons, photons
- Hadron – HCAL
  - Measure hadrons – pions, kaons etc.
- The calorimeter should absorb all of the energy of an incident particle
- Energy measurement by a calorimeter is a DESTRUCTIVE process.
  - Original particle no longer exists after the measurement.
- Calorimeter usually located behind charged particle tracking chambers
  - Drift chambers, silicon trackers are non-destructive measuring devices

$$\pi^- + p \rightarrow \pi^0 + n$$

$$\pi^0 \rightarrow \gamma\ \gamma$$

Particles do not come out alive of a calorimeter

EM Calorimeters

- Purpose: measure energy of EM particles (charged or neutral)
- How?
  - Use heavy material to cause EM shower (brem/pair production)
  - Total absorption / stop particles
  - Important parameter is X_0 (usually 15-30 X_0 or a high Z material)
  - There is little material before the calorimeter (tracker)
- Two types of calorimeters:
  - Sampling
  - Homogeneous
- Relative energy uncertainty decreases with E !

CMS EM Cal (PbWO)

Energy Resolution

$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus C \oplus \frac{N}{E}$$

- Stochastic term
  - Statistics-related fluctuations: shower fluctuations, dead material in front of the calorimeters, sampling fluctuations
- Constant term
  - Detector non-uniformity and calibration uncertainties
- Noise term
  - Electronics noise

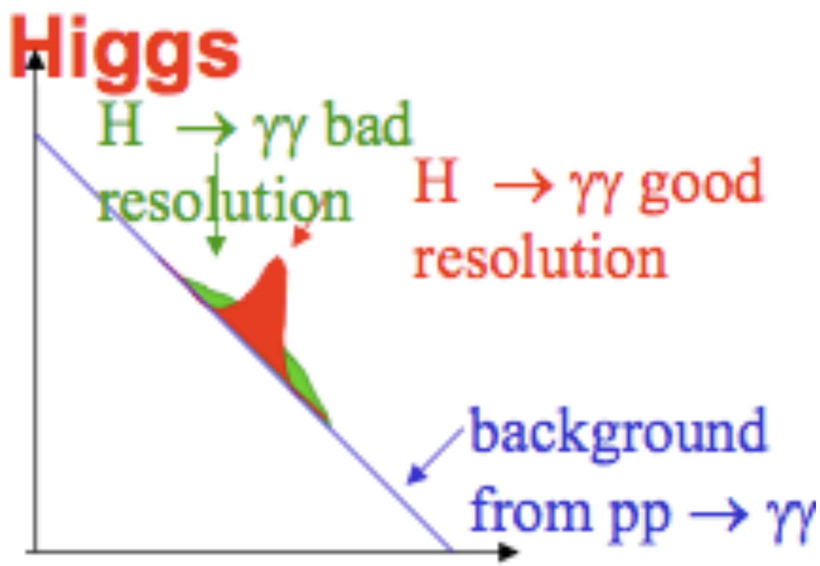
Since constant term and noise term are usually small energy resolution **improves** as E increases.
This is different than momentum resolution which gets worse as momentum increases.

Energy Resolution

Need excellent EM calorimeter resolution of electron/photons
In several scenarios moderate mass narrow states decaying into photons or electrons are expected

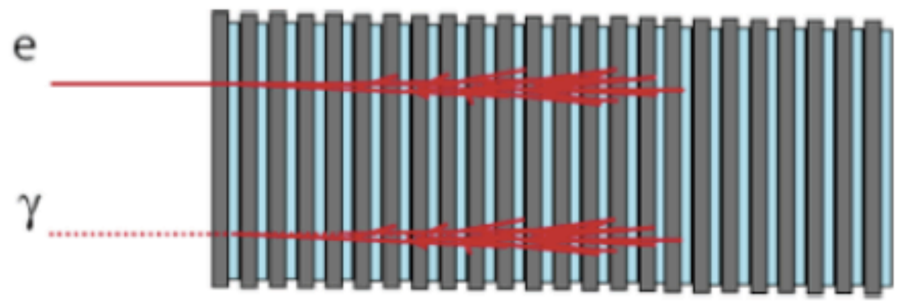
$H \rightarrow \gamma\gamma$, $H \rightarrow Z Z^* \rightarrow 4e$

Higgs width is very narrow
S/N directly proportional to signal resolution



Sampling Vs/ Homogeneous Calorimeters

- Sampling calorimeter
  - active medium which generates signal
    - scintillator, an ionizing noble liquid, a Cherenkov radiator…
  - a passive medium which functions as an absorber
    - material of high density, such as lead, iron, copper, or depleted uranium.
    - σE/E ~ 10%



- Homogeneous calorimeter
  - the entire volume generates signal.
  - usually electromagnetic
  - inorganic heavy (high-Z) scintillating crystals
    - CsI, NaI, and PWO, ionizing noble liquids…
    - σE/E ~ 1%

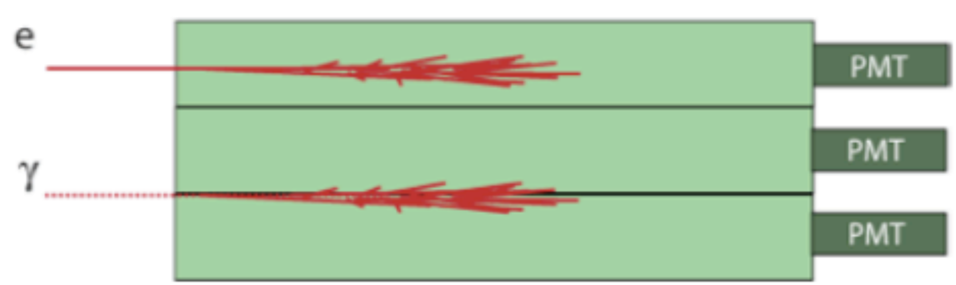


Table 28.7: Resolution of typical electromagnetic calorimeters. E is in GeV

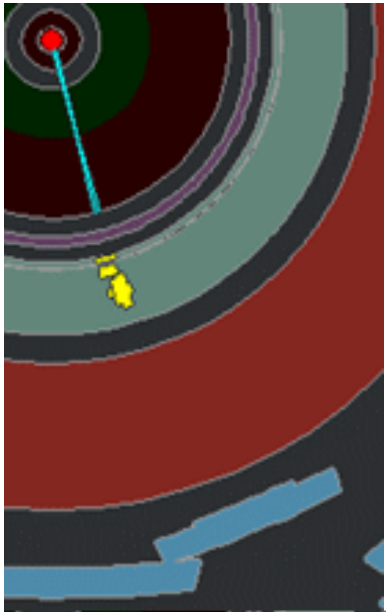
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

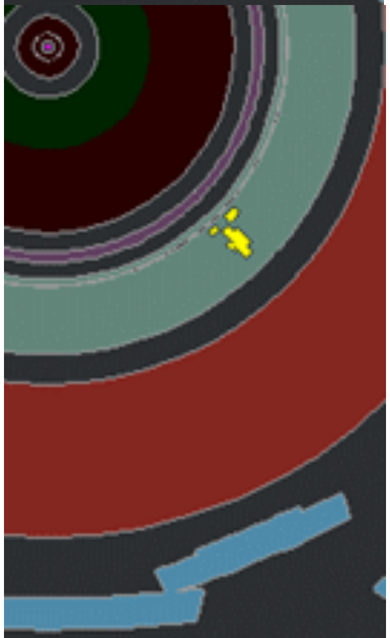
S ~ few %

S ~ 10%

Electrons and Photons

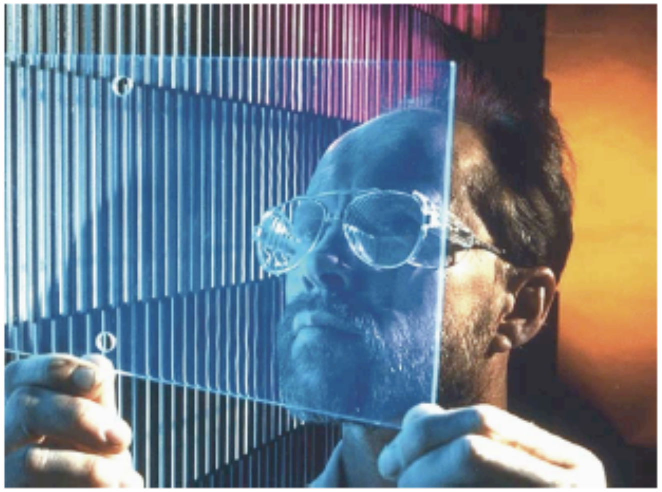
- Energy deposit in calorimeter
  - “Narrow“ shower shape in EM calorimeter
  - Energy nearly completely deposited in EM calorimeter
    - Little or no energy in had calorimeter (hadronic leakage)
- Electrons have an associated track in inner detector
- If there is no track found in front of calorimeter: photon
  - But be careful, photon might have converted before reaching the calorimeter





Hadronic Calorimeters

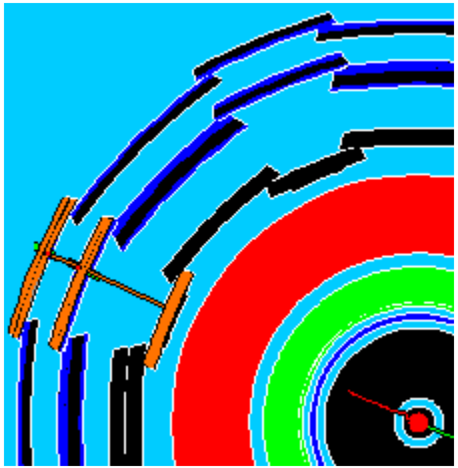
- Purpose: measure energy of hadronic/heavy particles
- How?
  - Similar to EM calorimeters but important parameter is λ_n (usually 5-8 λ_n)
  - Typically sampling calorimeters
  - Larger and coarser in sampling depth
- Resolutions typically a lot worse than EM cal.
  - Stochastic term 30-50% and higher (~80% at CDF)

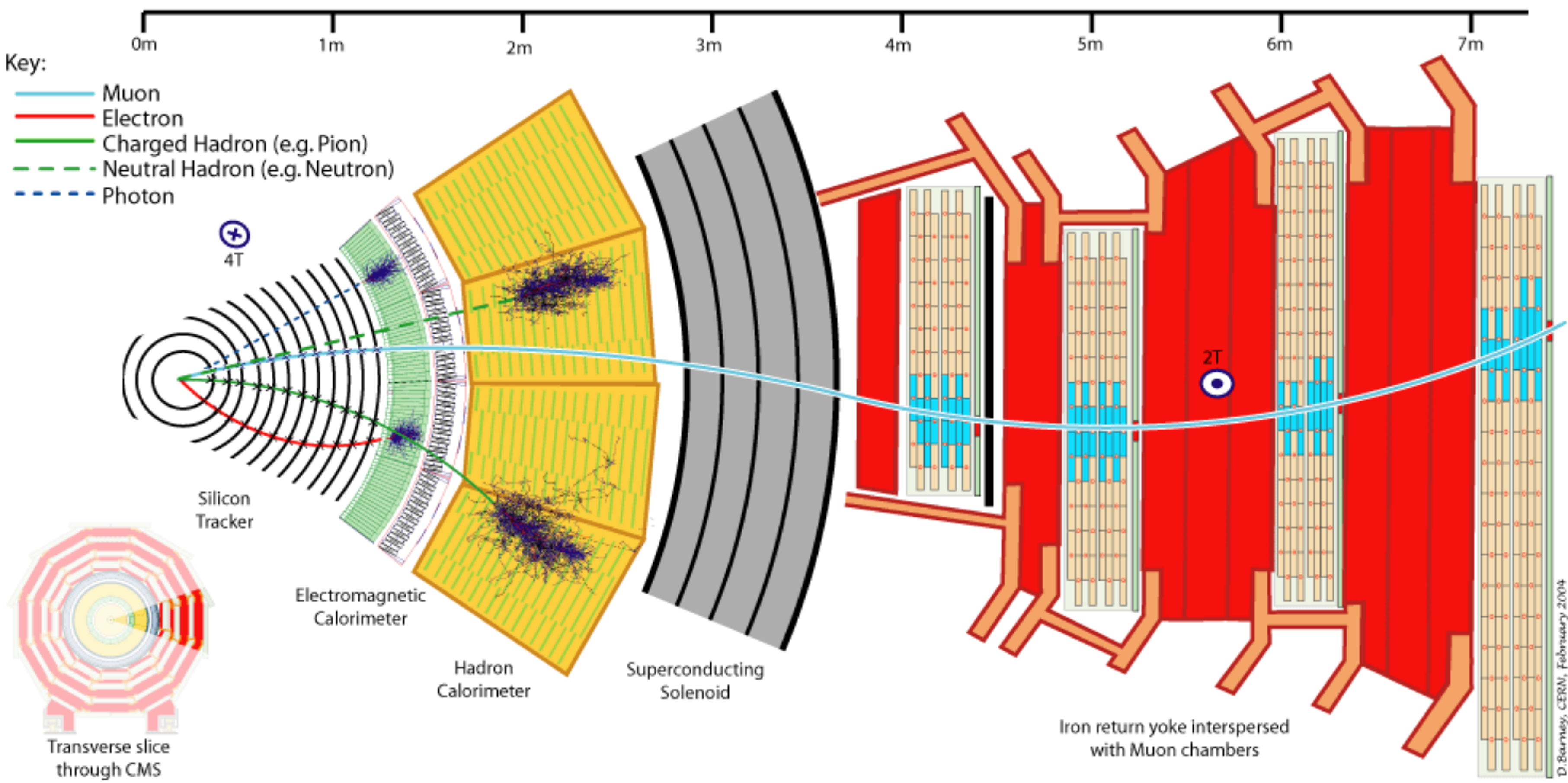


Atlas Tile Cal.

Muons

- Because of it's long lifetime, the muon is basically a stable particle for us ($c\tau \sim 700$ m)
- It does not feel the strong interaction
  - Therefore, they are very penetrating
- It's a minimum ionising particle (MIP)
  - Only little energy deposit in calorimeter
- However, at high energies (E>0.2 TeV) muons can sometimes behave more like electrons!
  - At high energies radiative losses begin to dominate and muons can undergo bremsstrahlung
- Muons are identified as a track in the muon and in the inner tracking detectors
- Both measurements are combined for the best track




0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
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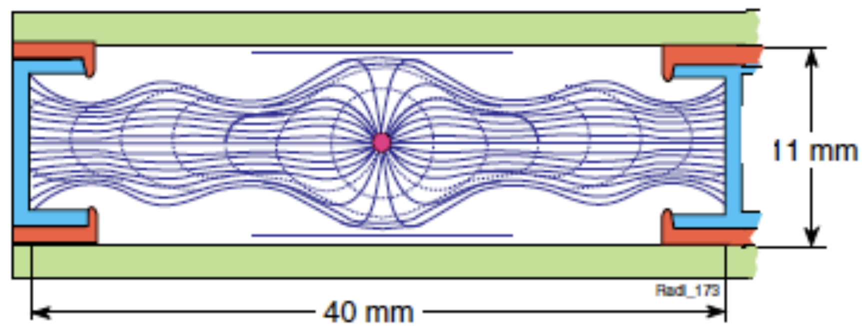
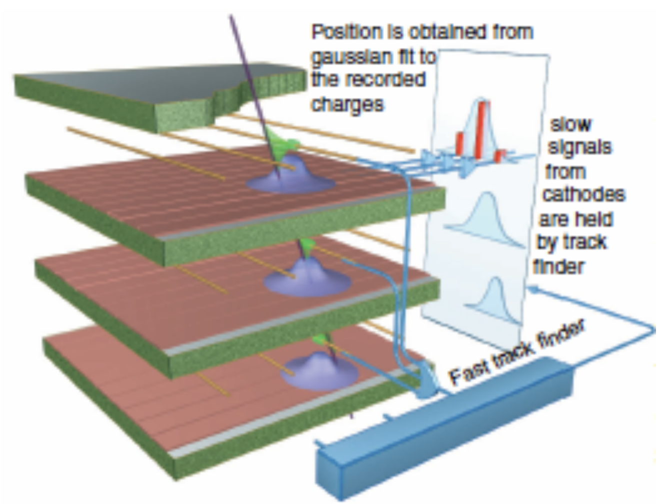
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

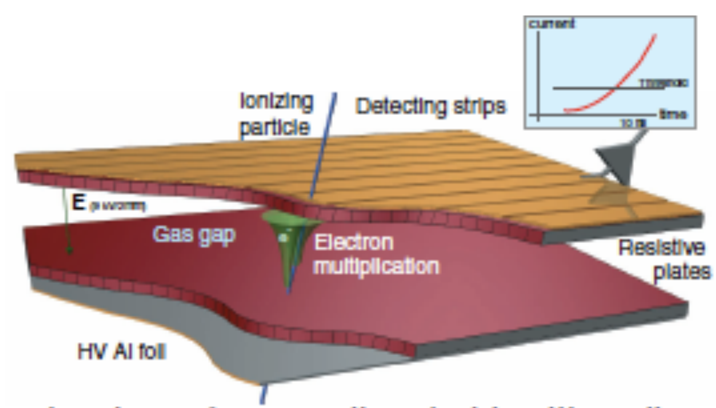
Muon Detectors

- Purpose: measure momentum and charge of muons
- Muon chambers are the outermost layer
- Measurements are made combined with the inner tracker

- Different types of technology used:
  - DT (Drift tubes)
  - CSC (Cathode Strip Chambers)
  - RPC (Resistive Plate Chamber)
  - TGC (Thin Gap Chamber)







Experiments @ LHC

- ATLAS : A Toroidal LHC Apparatus (pp)
- CMS : Compact Muon Solenoid (pp)
- ALICE : A Large Ion Collider Experiment (Pb-Pb)
- LHCb : LHC b-physics (CP violation in B-meson decays)

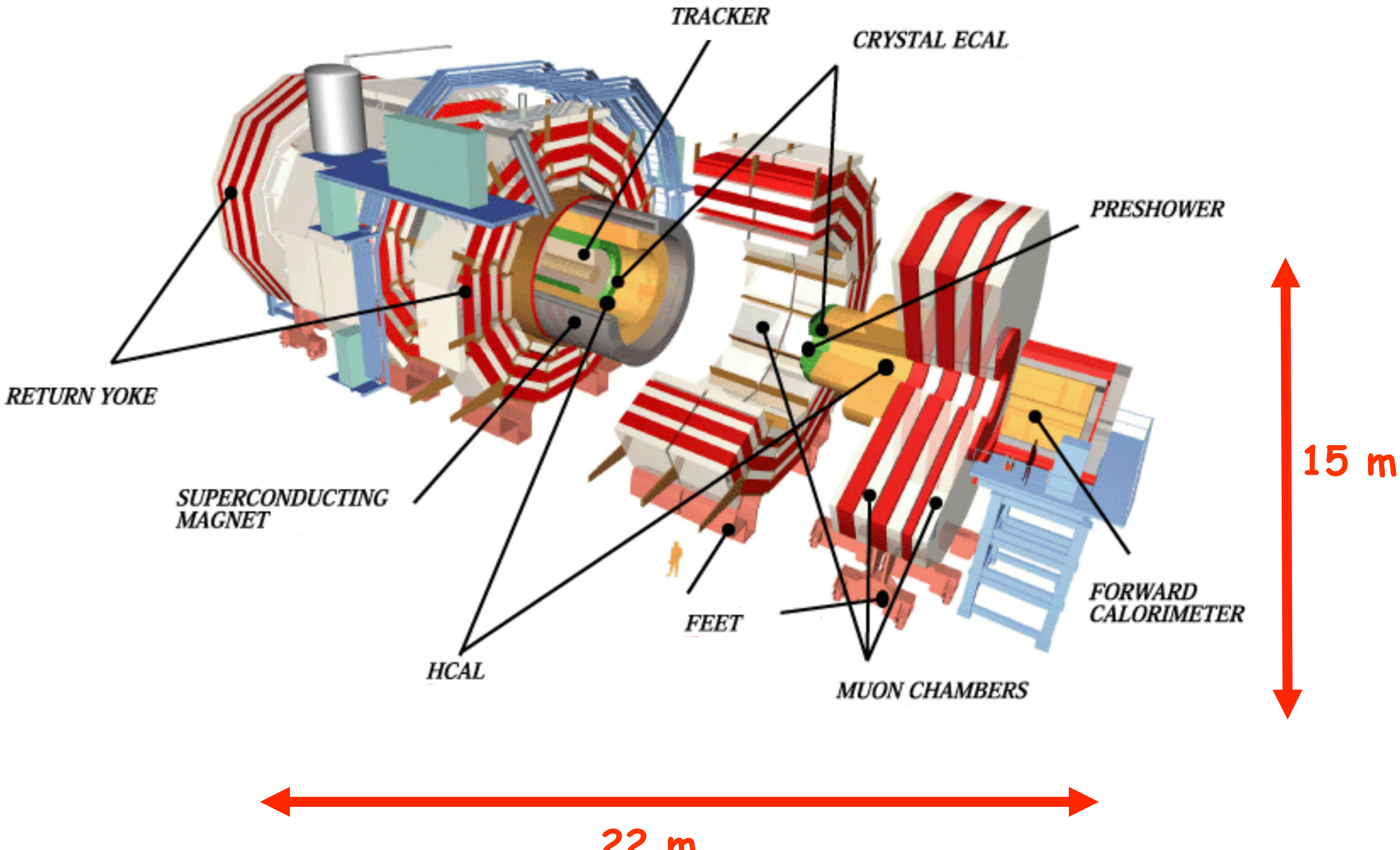
Also:

- TOTEM (precision (1%) measurement of total cross section)
- LHCf (study of forward production of π^0 s)
- Moedal (search for magnetic monopoles)

Here is one of them…

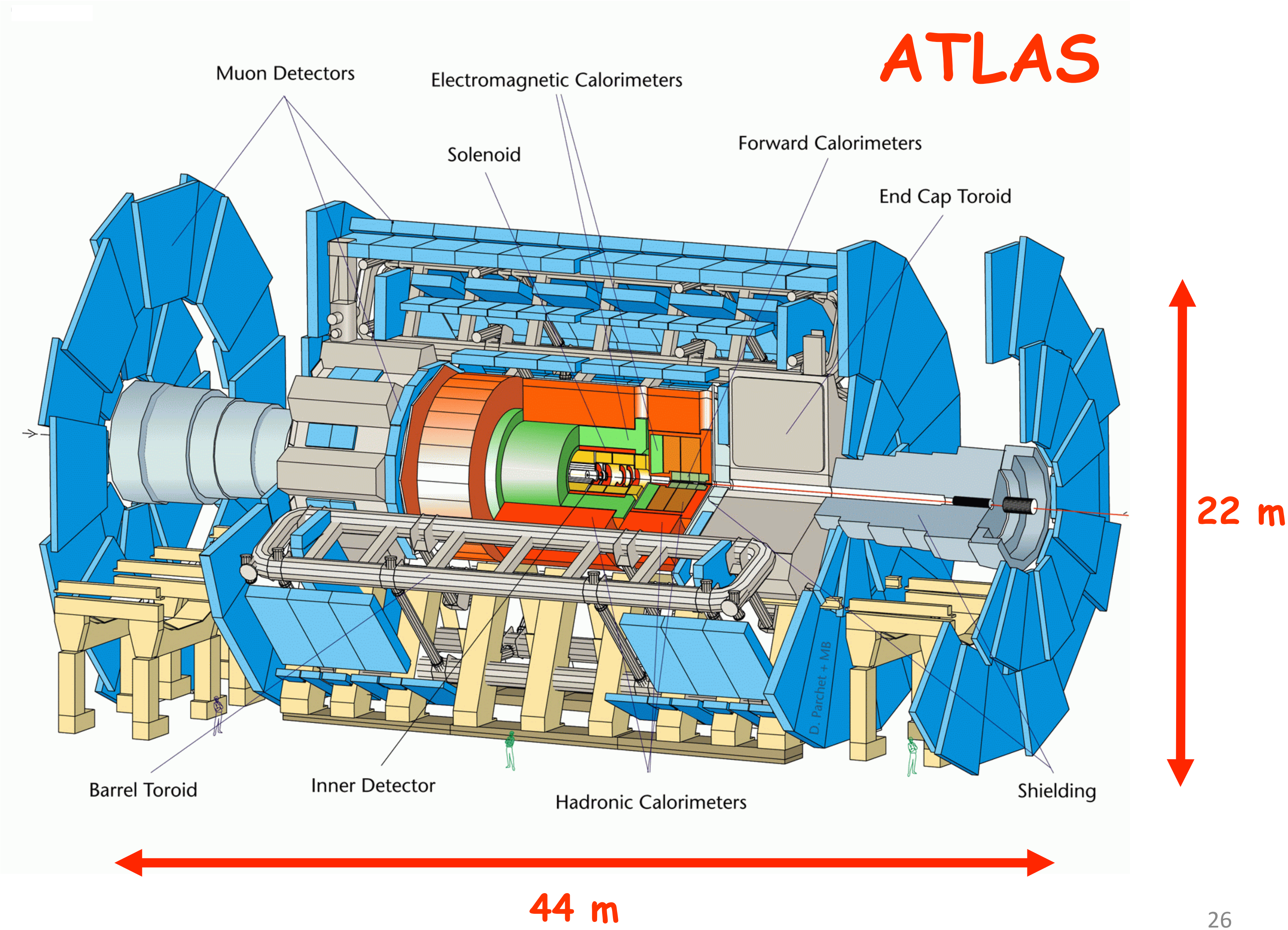
Compact Muon Spectrometer

CMS

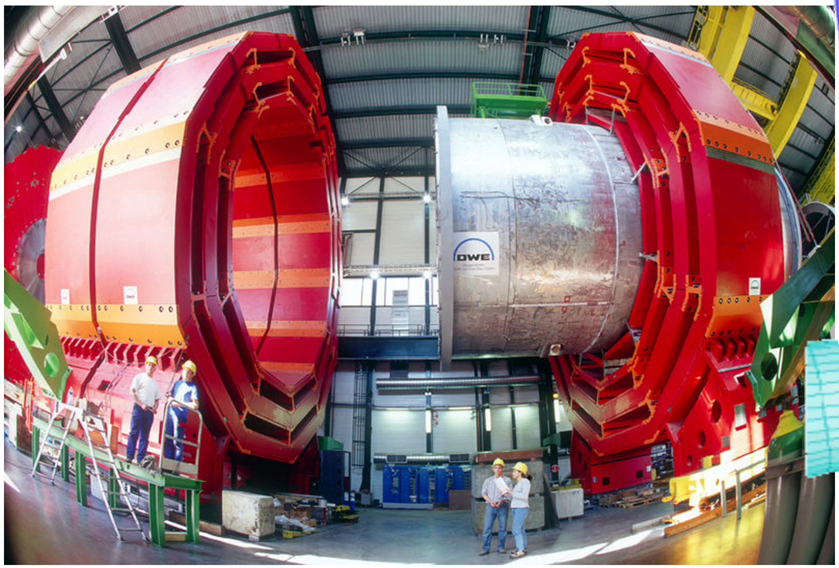


And another…

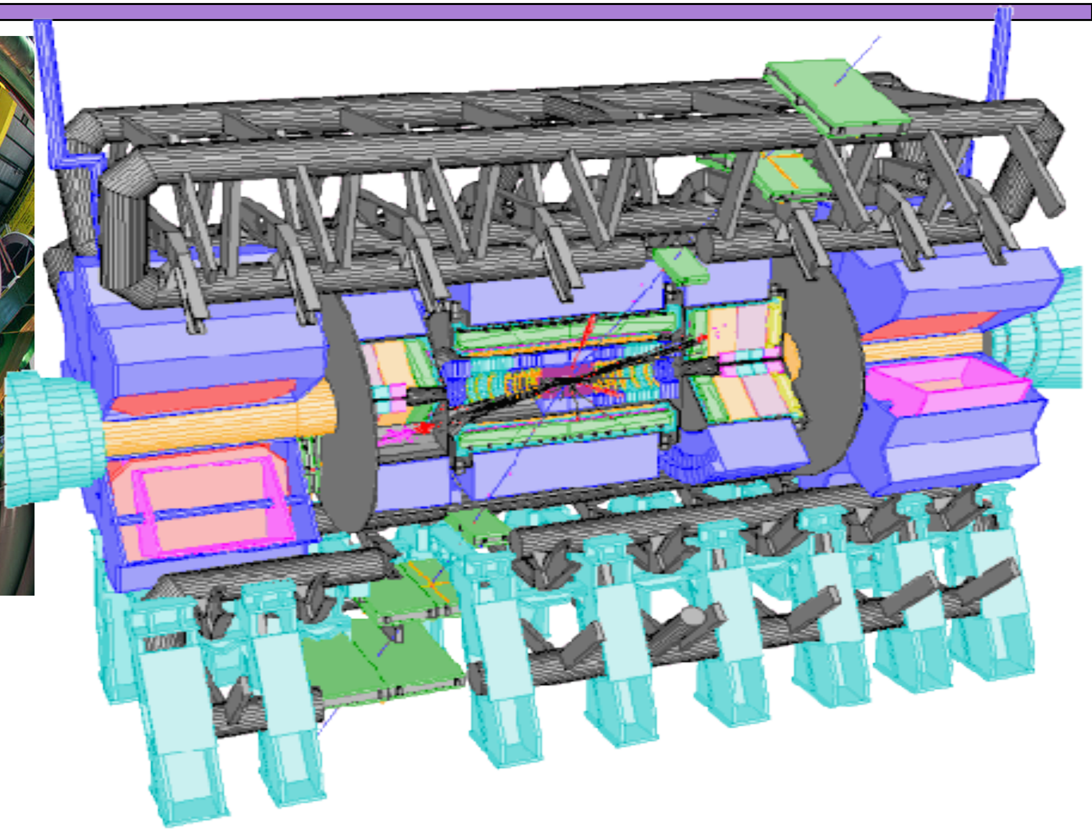
A Toroidal LHC ApparatuS



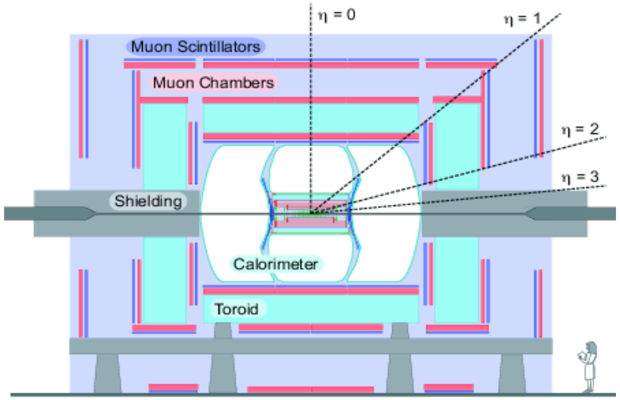
Growth of Detectors



CMS, 2310 authors, 48 ft high (14.6m)



ATLAS, 20m high



DØ, 1994, 351 authors, 28 ft high

CMS Trivia/Pictures

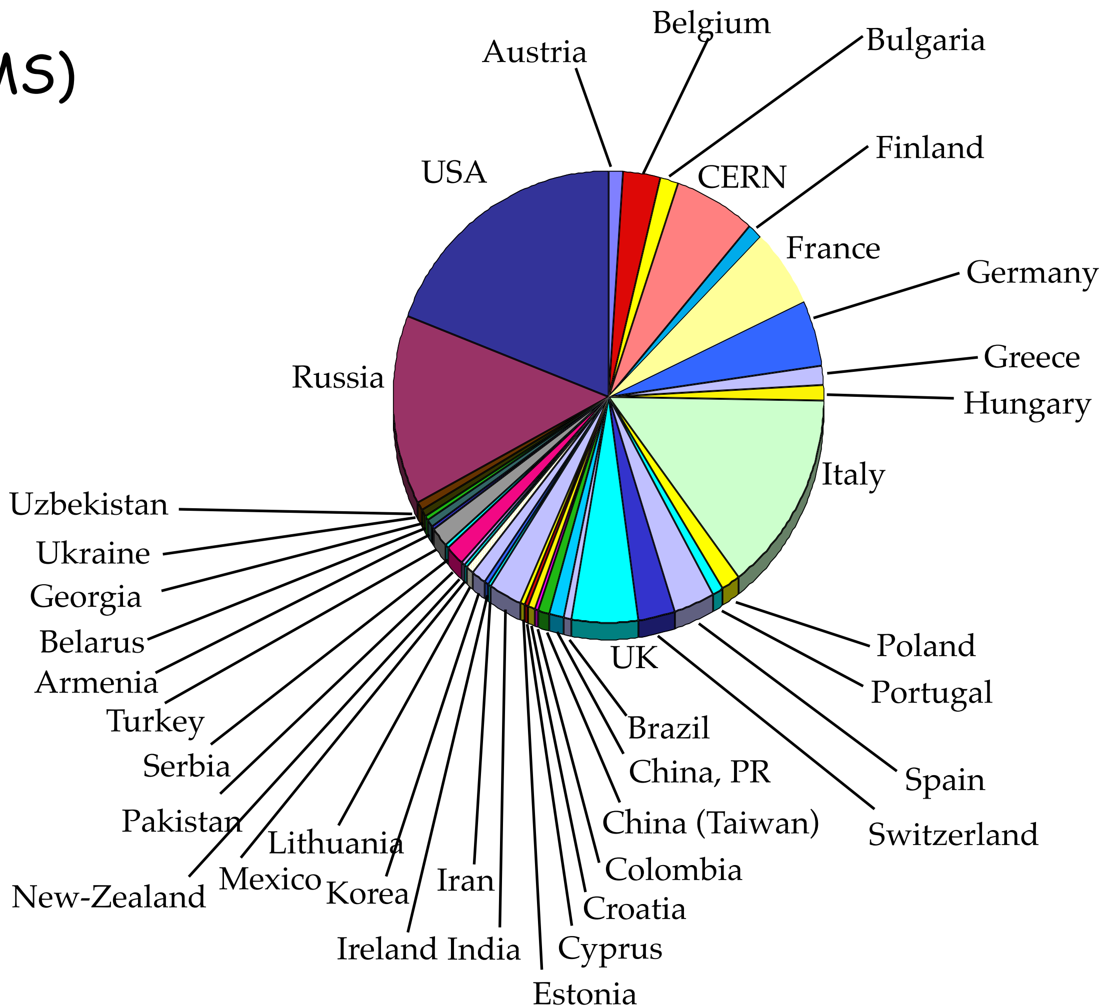
CMS Collaboration

Compact Muon Solenoid (CMS)

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

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

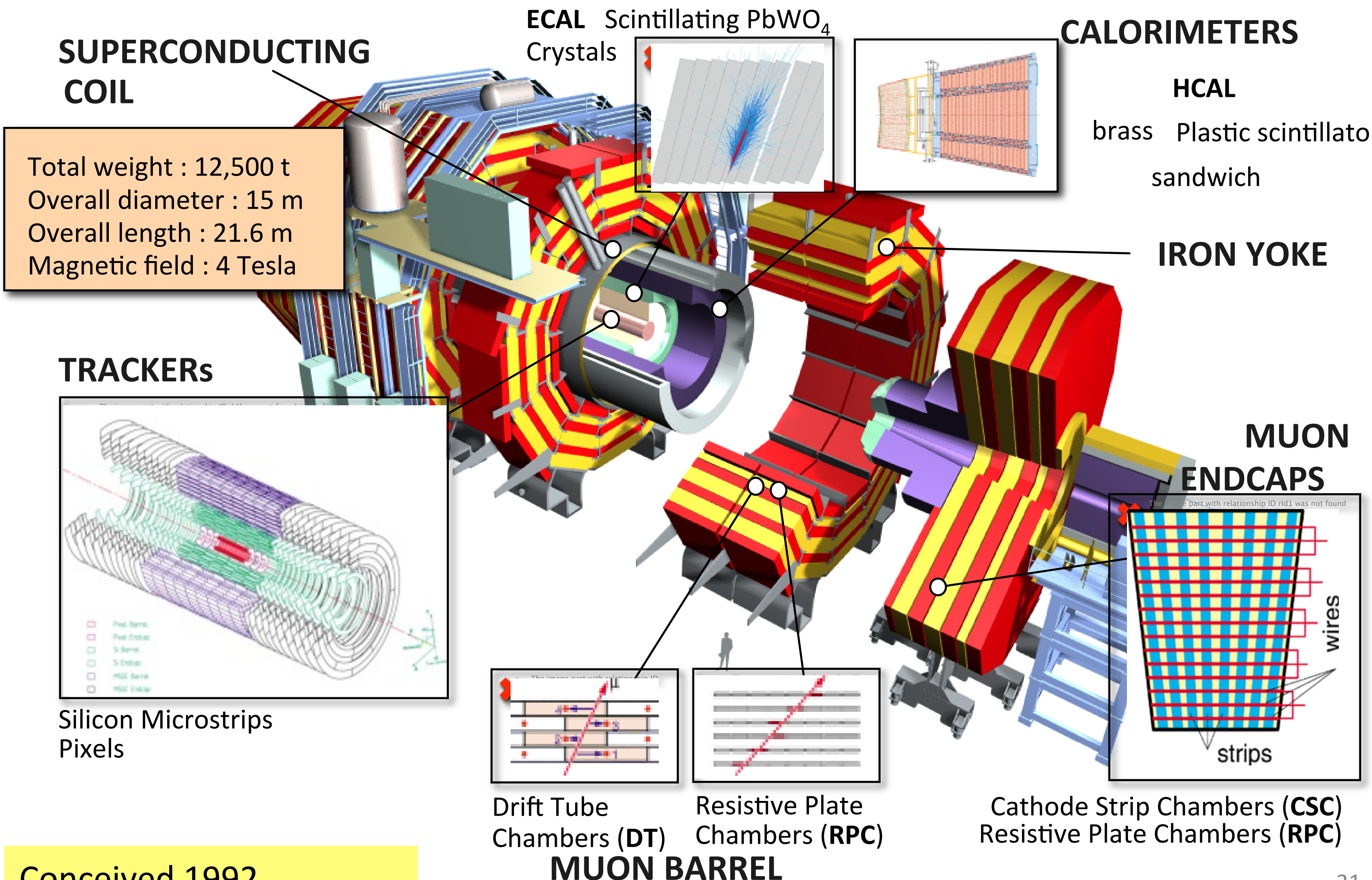
2310 Scientific Authors
38 Countries
175 Institutions



The CMS Detector @LHC

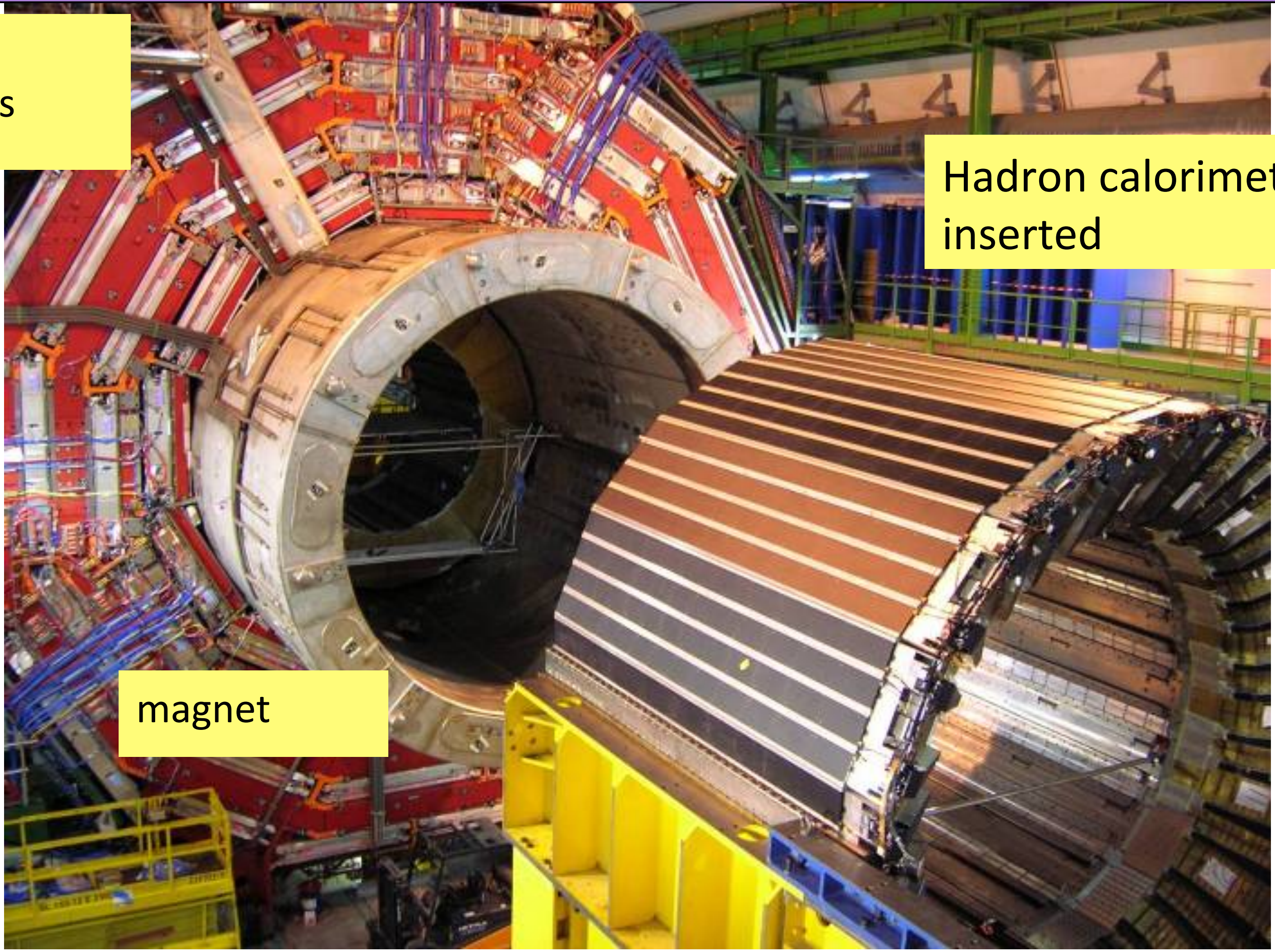
- Weighs about 12,500 tons
  - Equal to 40 large airplanes
- Highlights of a few components:
  - 205 m^2 of Silicon sensors (strips and pixels)
    - 93 million micro strips, 66 million pixels
  - 80,000 lead tungstate cyrstals
  - One of the sub-detectors (HCAL) uses brass recovered from Russian artillery shells, weighs 500-tons and uses 80,000 bolts to hold it together.
  - think your 6MP digital camera taking 40 million pictures a second
- Approx 1 Terabyte/sec raw data rate from the CMS detector
  - Recorded data capacity will be equivalent to CDs stacked at the rate of 20 km/year

CMS Detector



Conceived 1992

And in reality…

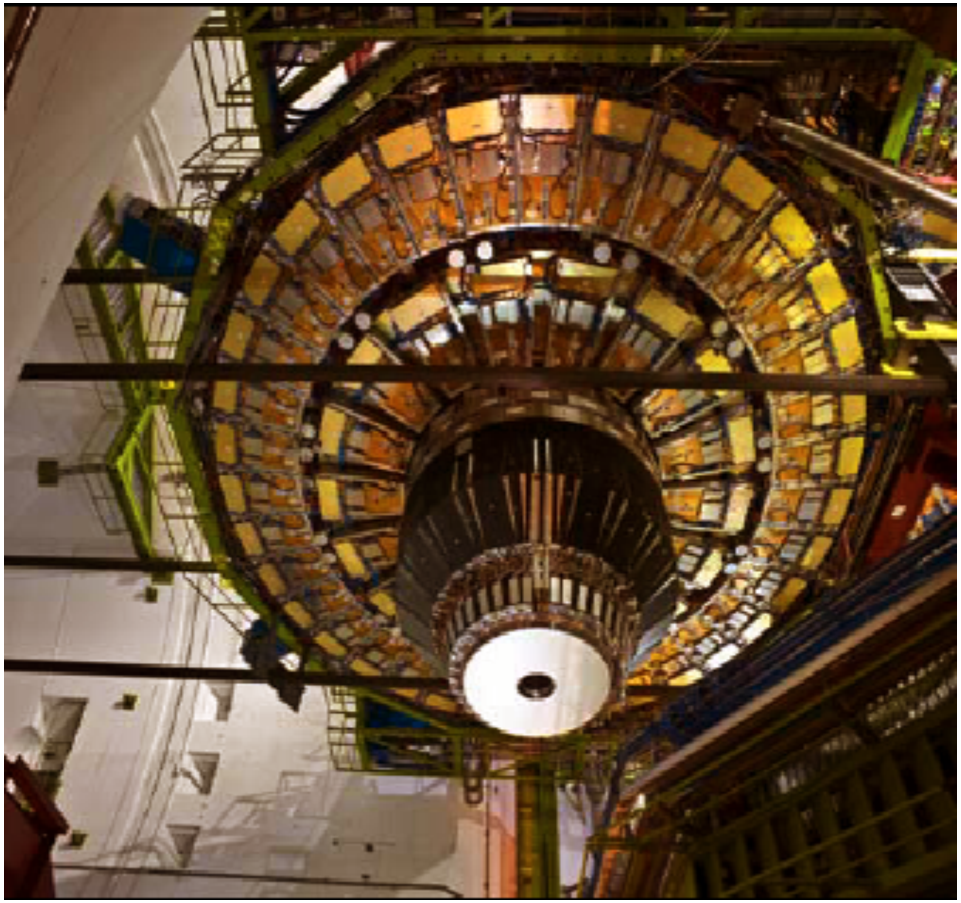


March 2007

CMS Caverns

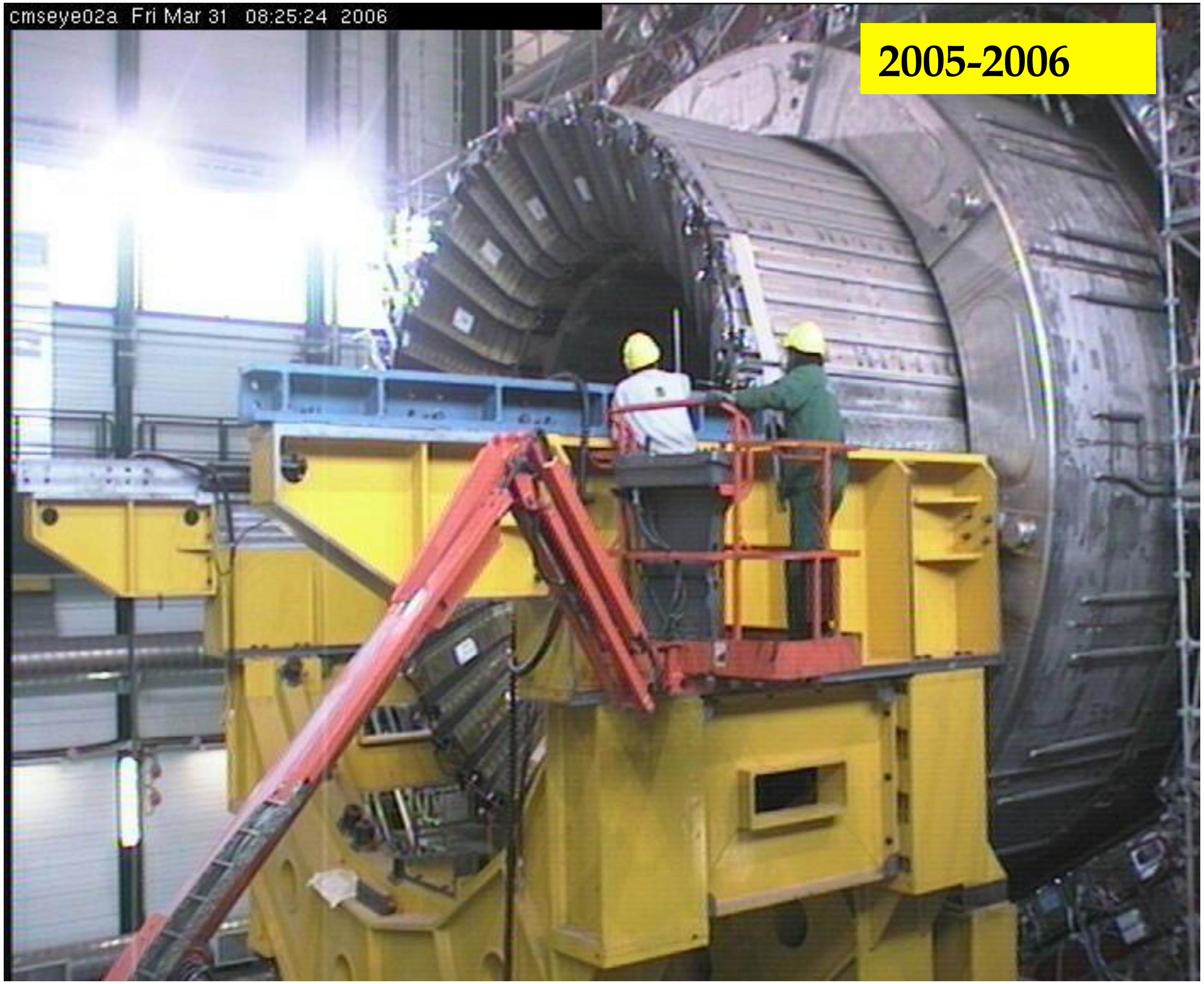
Heavy Lowering

CMS is the first large HEP detector that has been assembled, cabled and tested on the surface and then brought underground

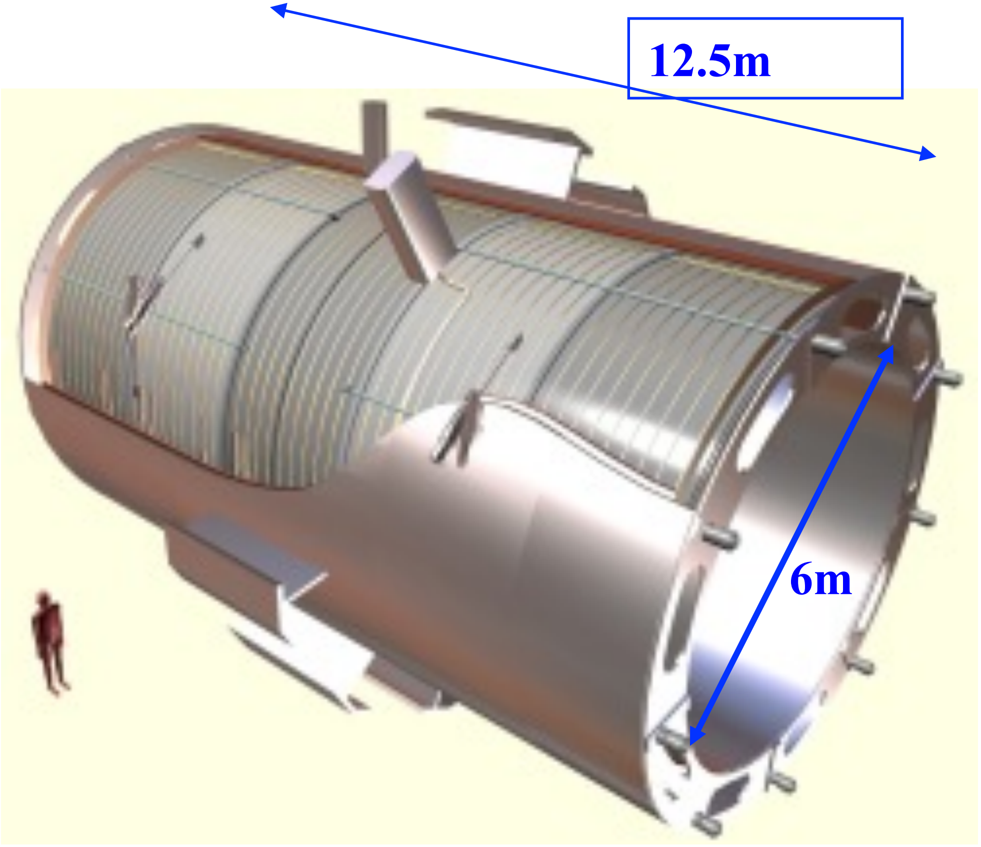


- 13 Heavy Lowerings
- Masses between 400 tons and 1920 tons
- YE1 most difficult: Mass 1430 tons
- Nose of 465 tons out of plane of disk –center of gravity in front of the the plane.

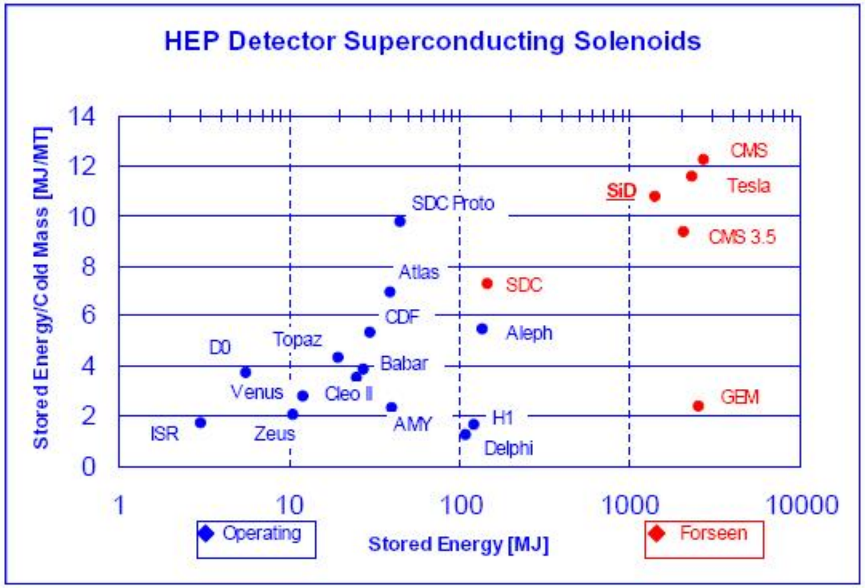
Assembly Hall – SX5



Solenoid

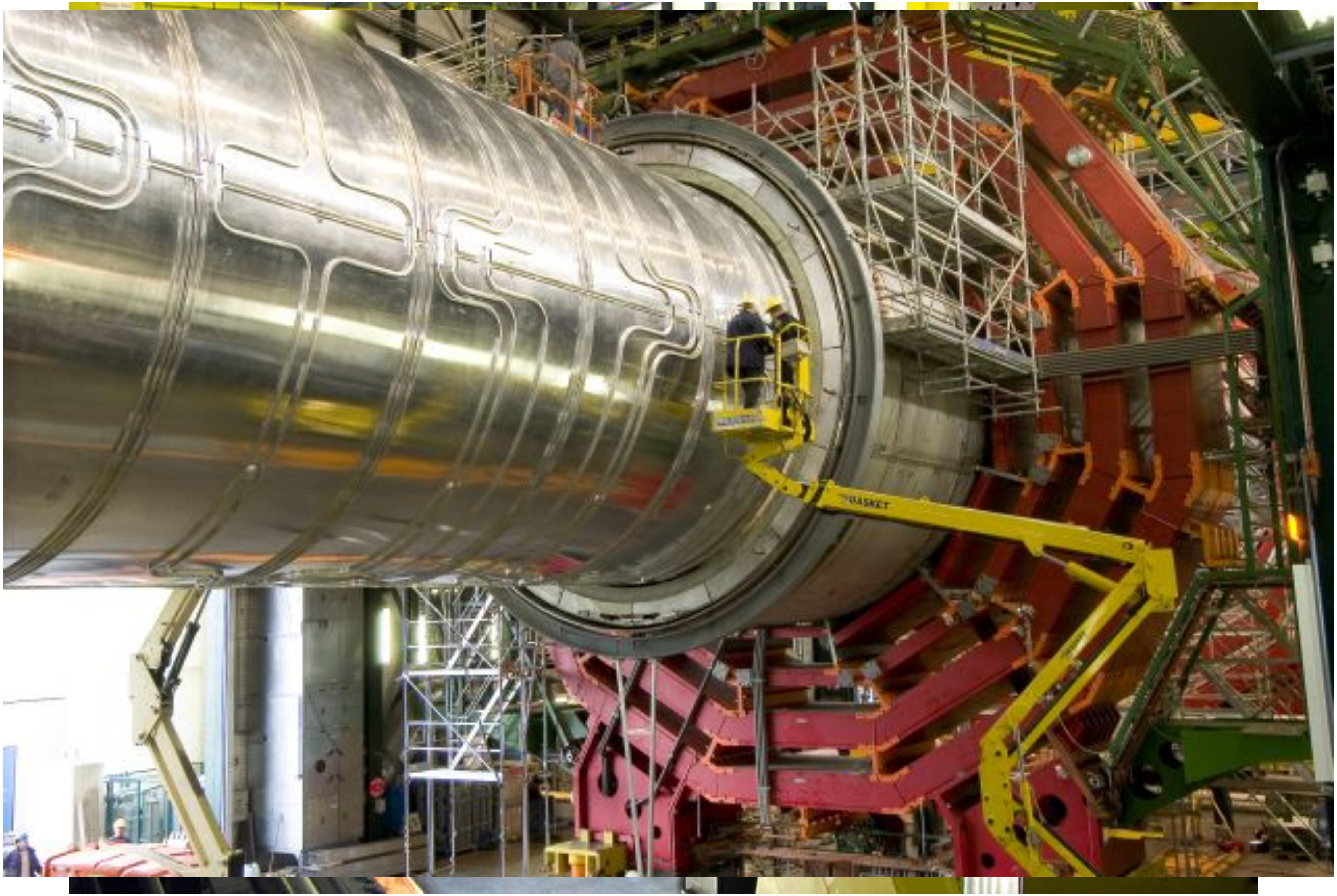


- diameter = 6 m (20 ft)
- Largest one ever built
- stores 2.7 GJ of energy

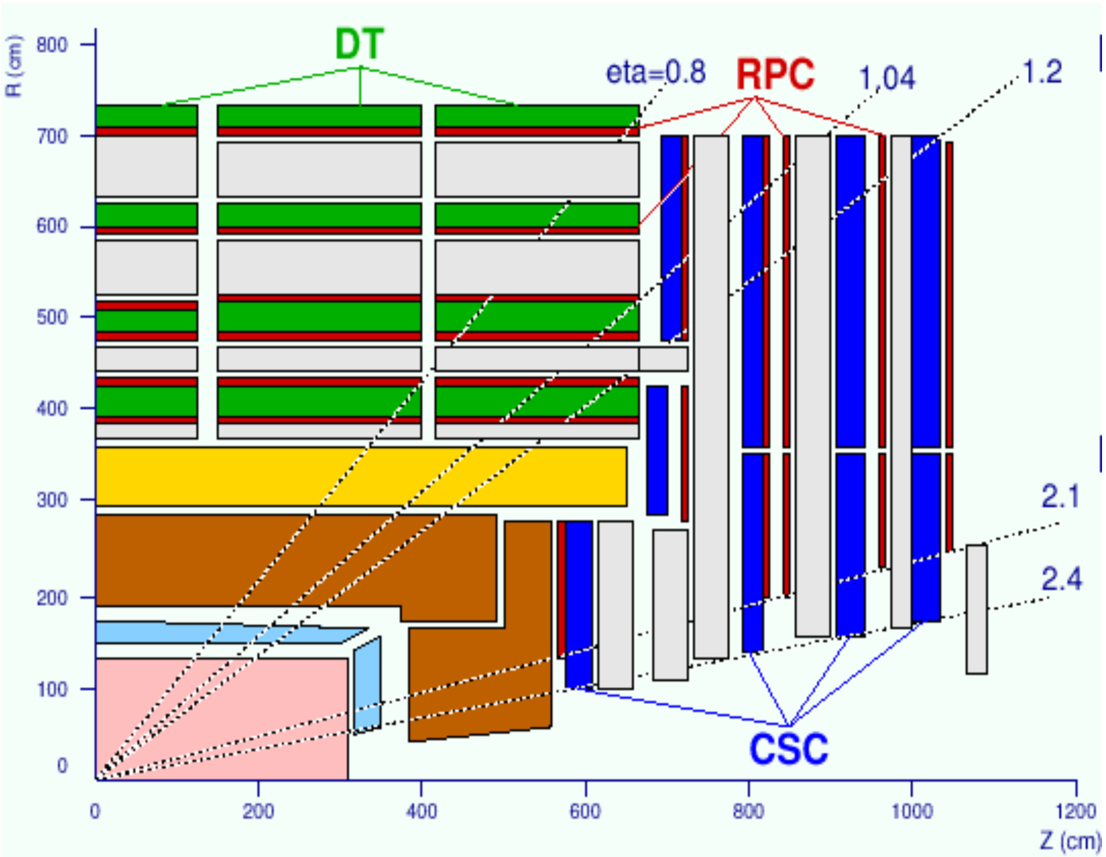


Solenoid

Successful Insertion 2005…



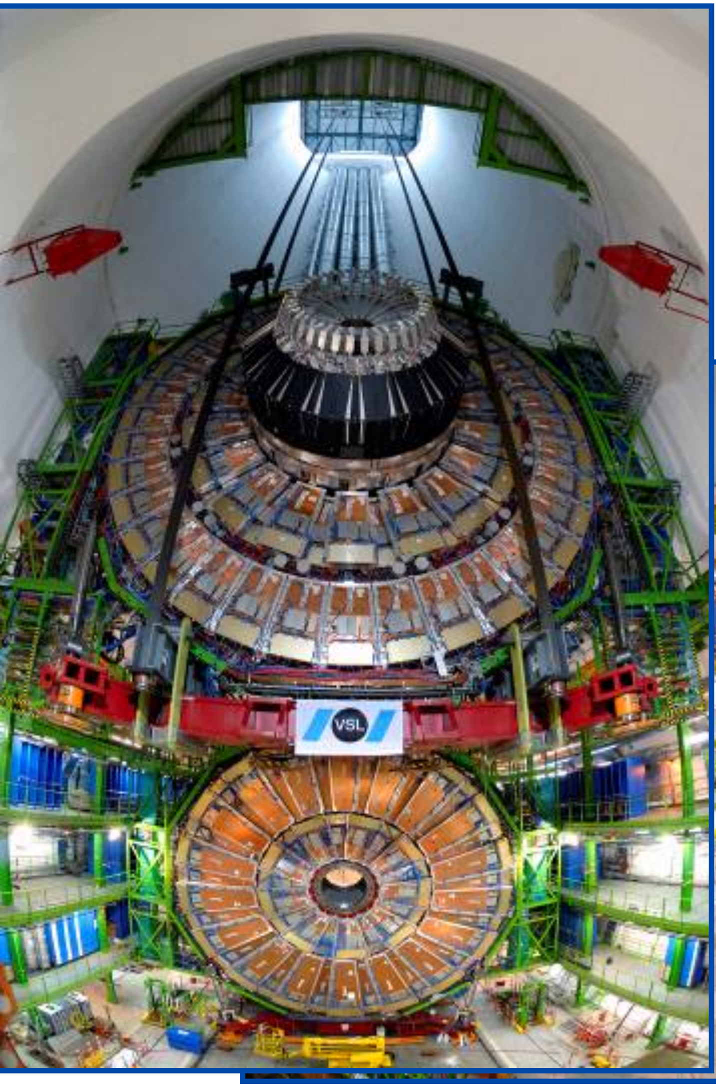
Muon System



•25000 m^2 of active detection planes
• 1,000,000 electronic channels
• measures muon trajectory to 100 μm at (up to) 44 points along the track.

Muon: σ/pt = 1% @ 50GeV to 10% @ 1TeV

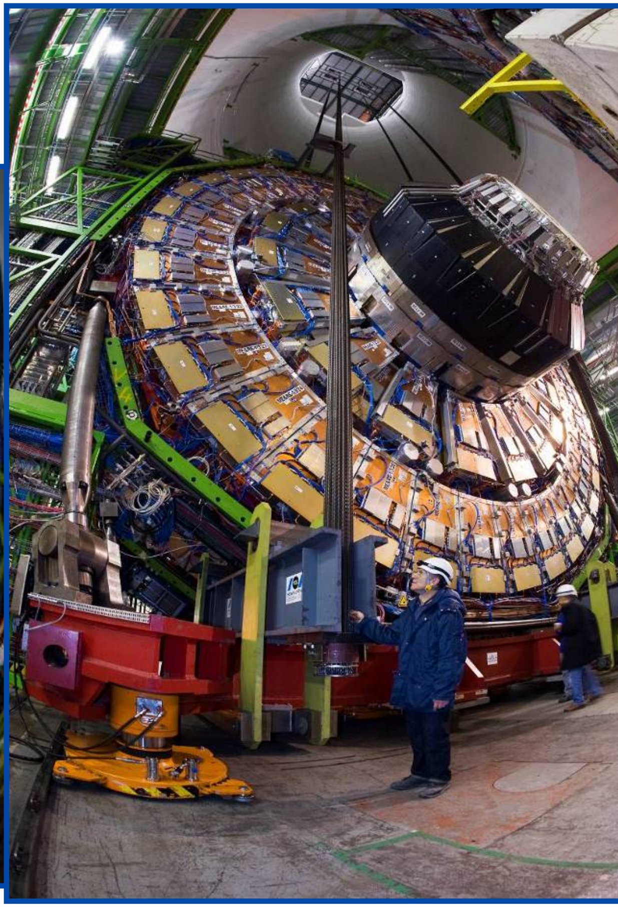
Lowering into the cavern…



Endcap disks:
Jan. 2007 to Jan. 2008

Barrel wheels:
Jan. – Oct. 2007

(1000-2000 ton structures!)



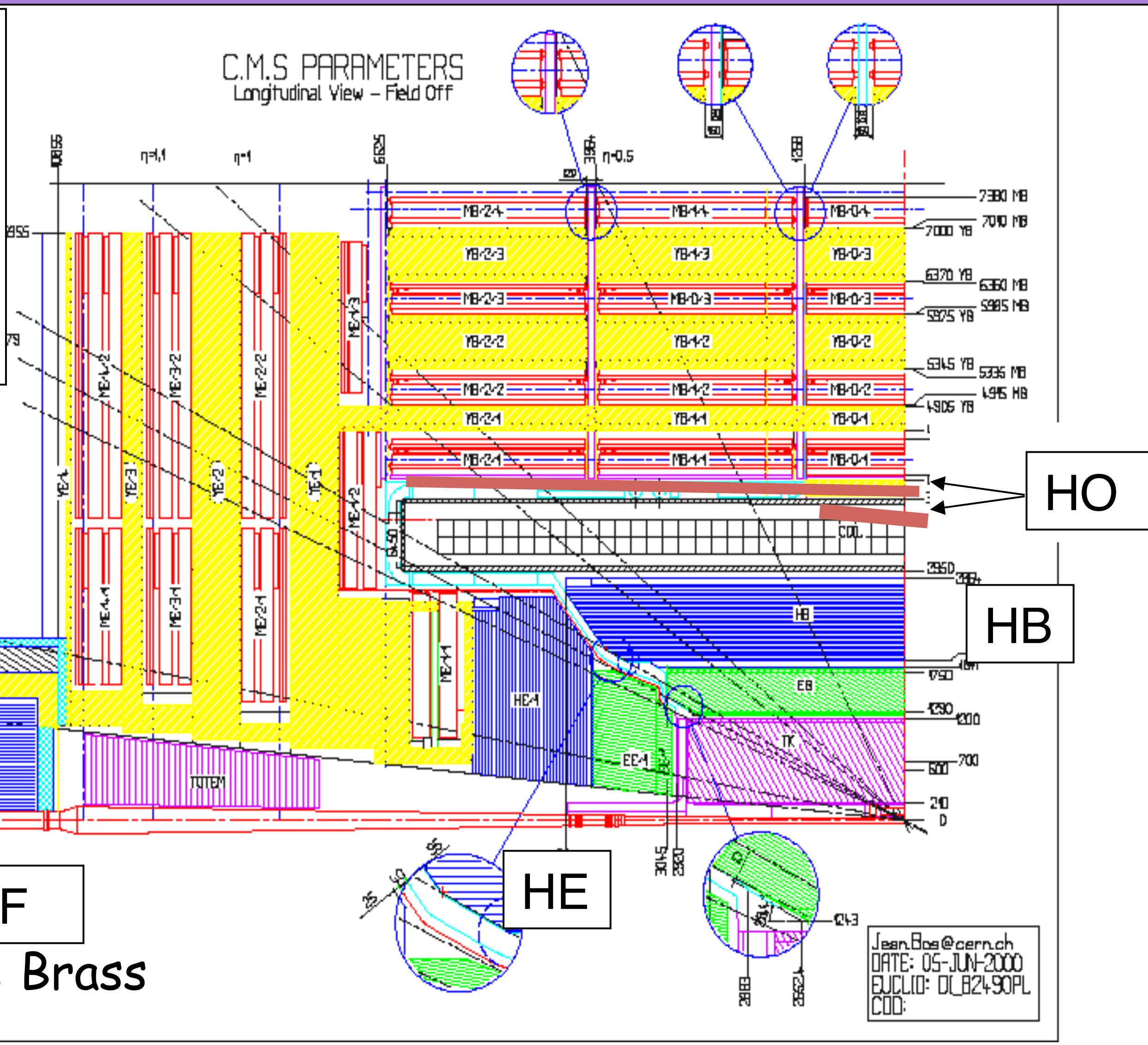
HCAL

Had Barrel: HB

Had Endcaps: HE

Had Forward: HF

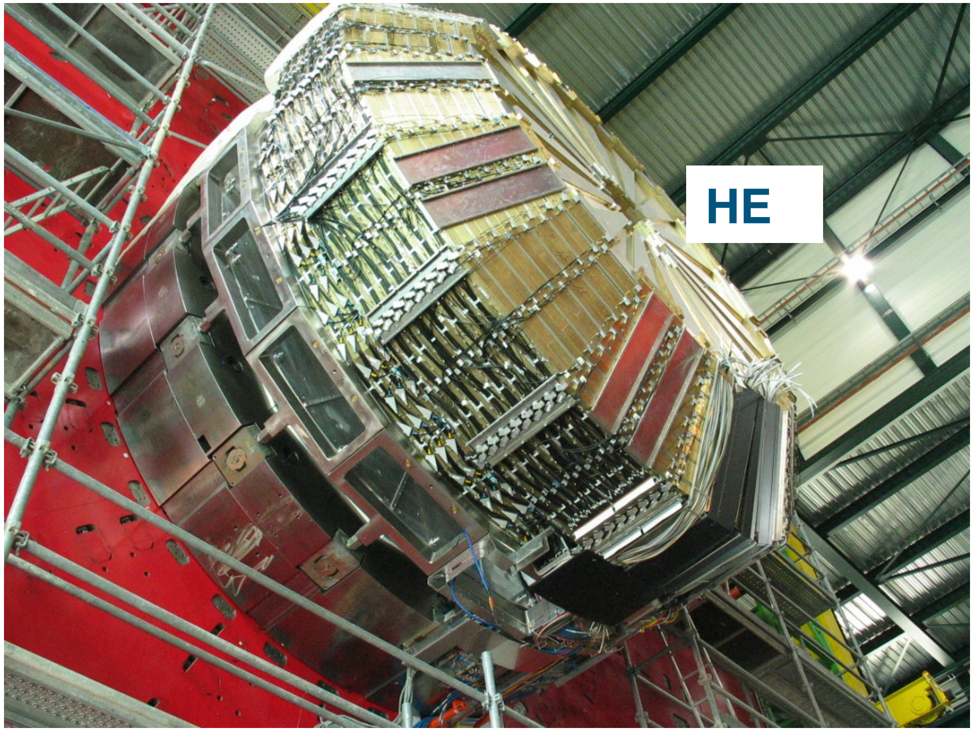
Had Outer: HO



Hadronic Calorimeter: Brass +Scintillator

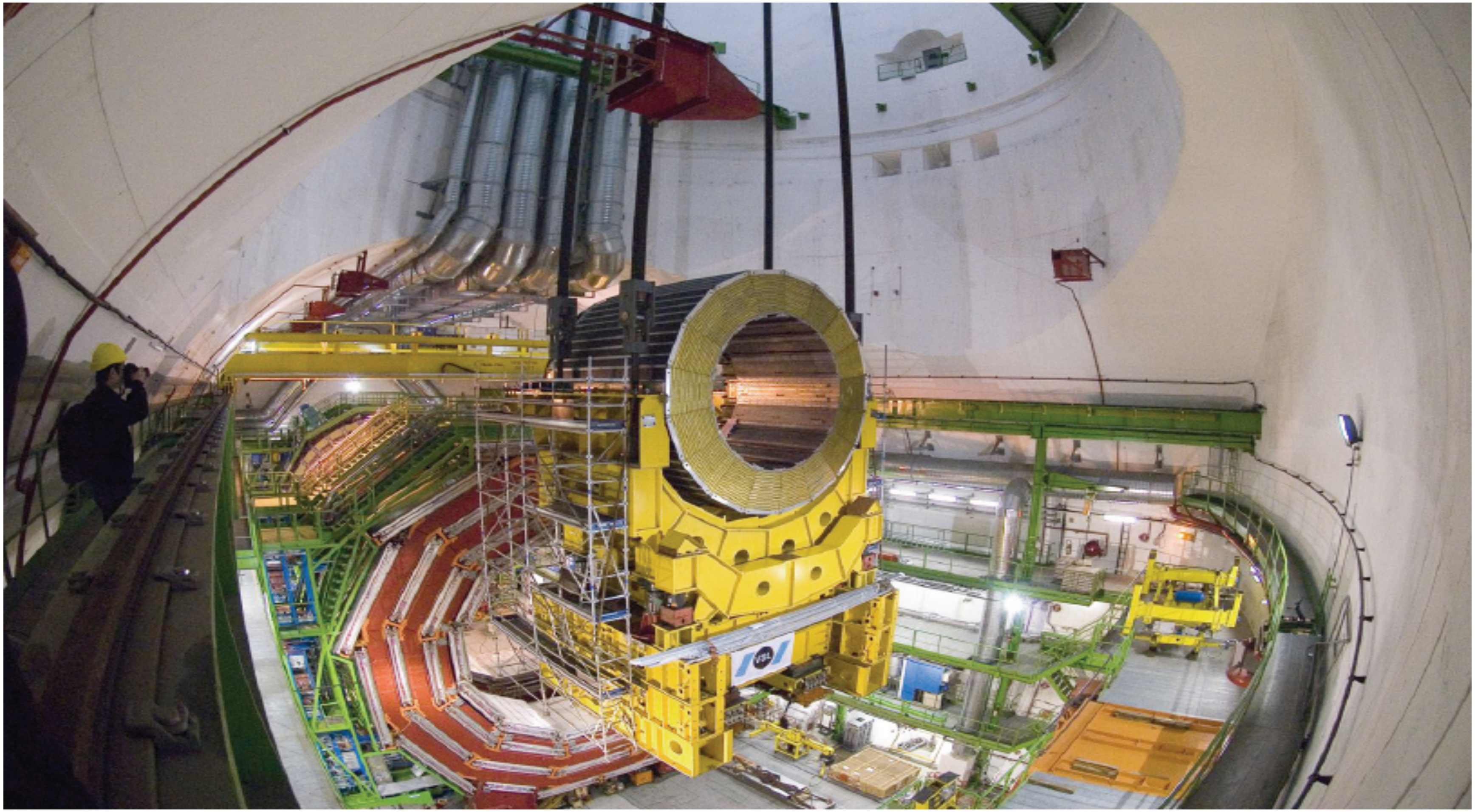
$\sigma/E = 100\%/E + 0.05$ GeV

HCAL



- brass for detector came from Russian artillery shells
- electronic signal is made by scintillating plastic
- 4608 “towers”

HB – Feb, 2007

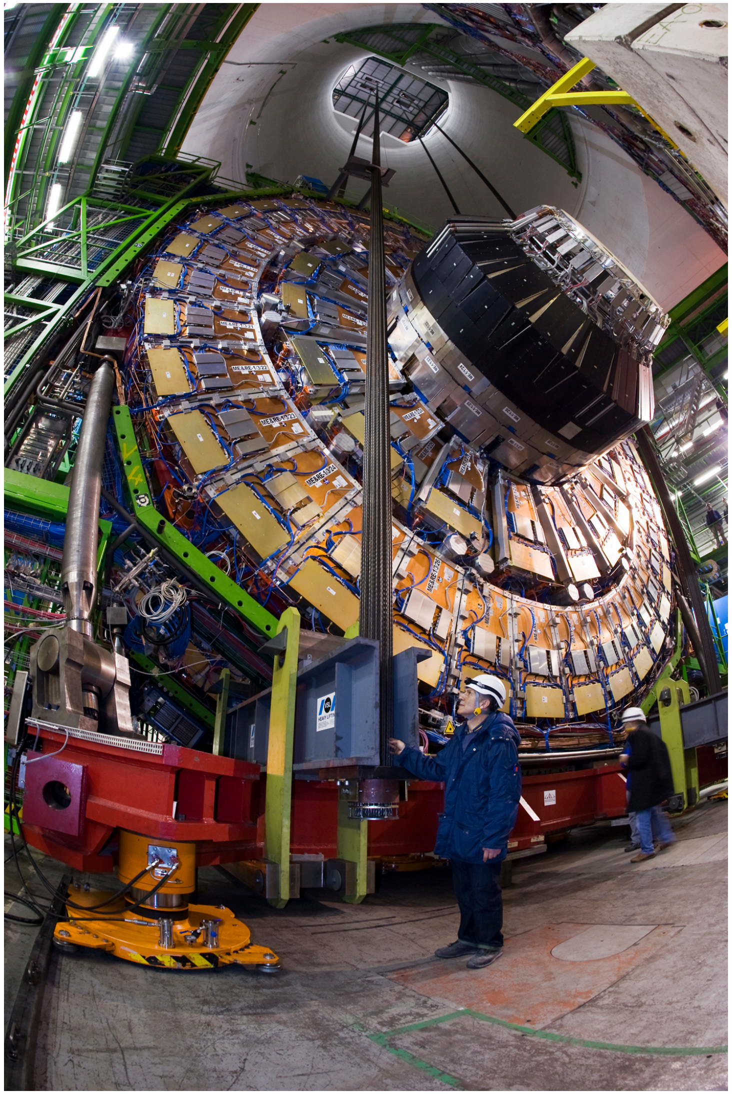


Lowering of YE-1

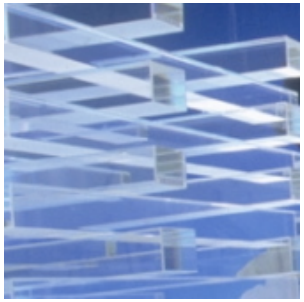
January, 2008

The last heavy element of CMS is lowered into the collision hall.

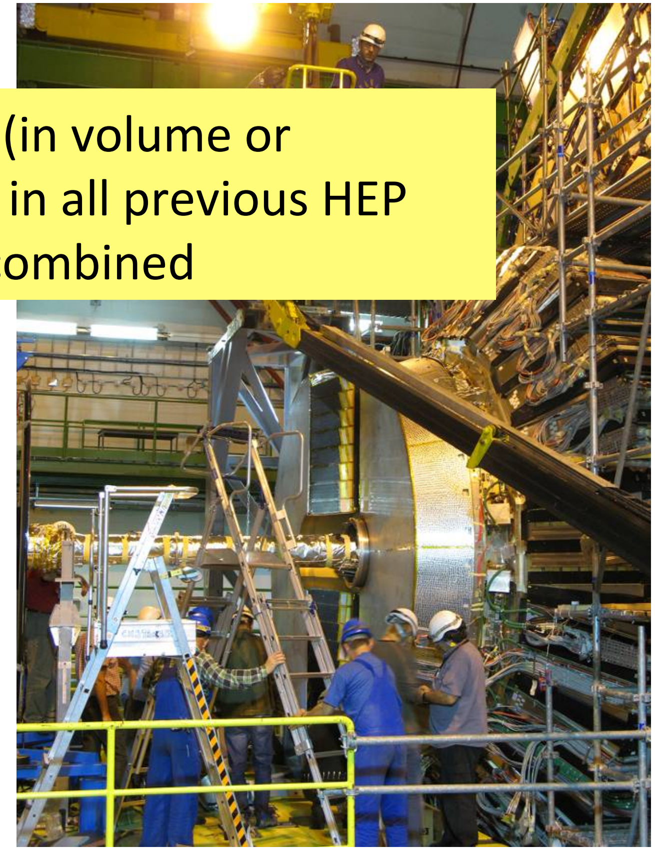
The Silicon Strip Tracker, the Silicon Pixels and the endcap ECAL remain to be installed.



CMS Crystal ECAL



76K $PbWO_4$ crystals for fine electron/photon energy measurements



More crystals (in volume or number) than in all previous HEP experiments combined

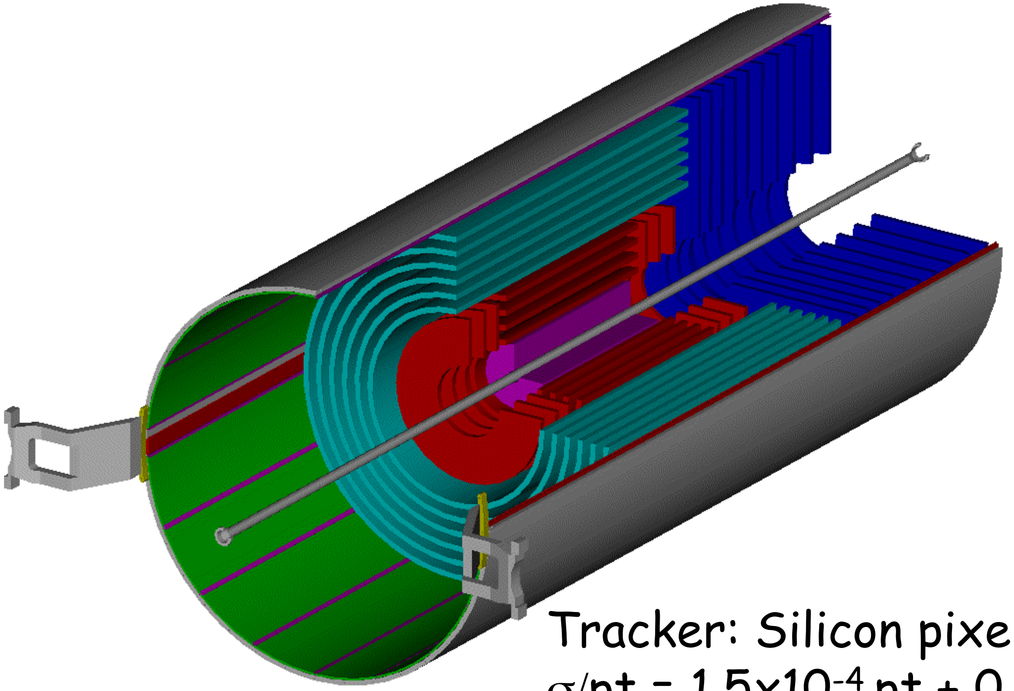
Barrel production and installation completed 27 July 2007

Endcap production complete and inserted 1 August 2008 →

EM Calorimeter: $PbWO_4$ crystals, σ/E = 3%/E + 0.003, $25X_0$

CMS Tracker

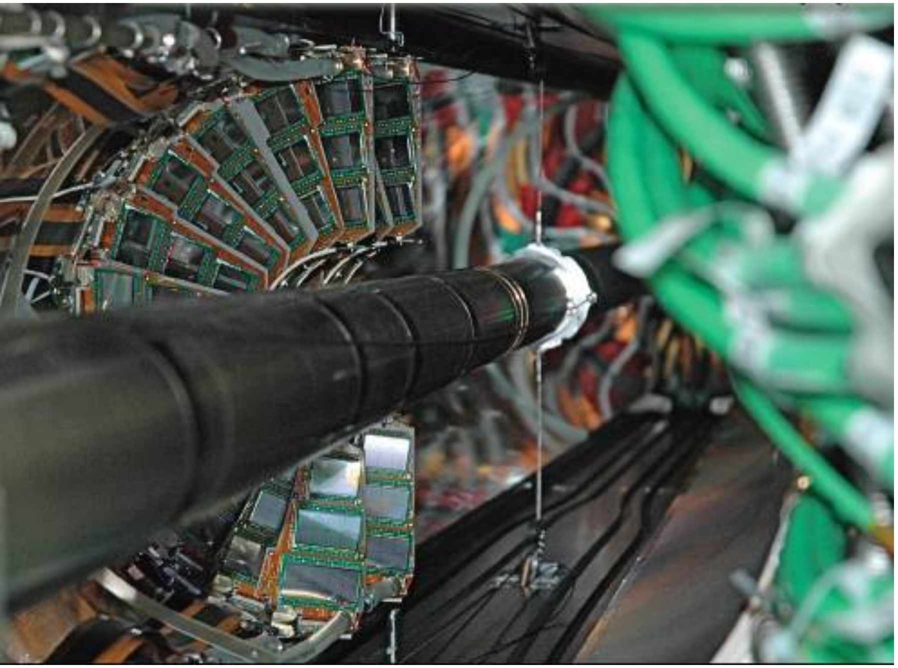
- tracker is made from silicon
- inner tracker; 76,000,000 channels
- forward tracker, 45,000,000 channels
- total area: 210 m^2



Tracker: Silicon pixels and strips,
$\sigma/pt = 1.5x10^{-4}\, pt + 0.005$

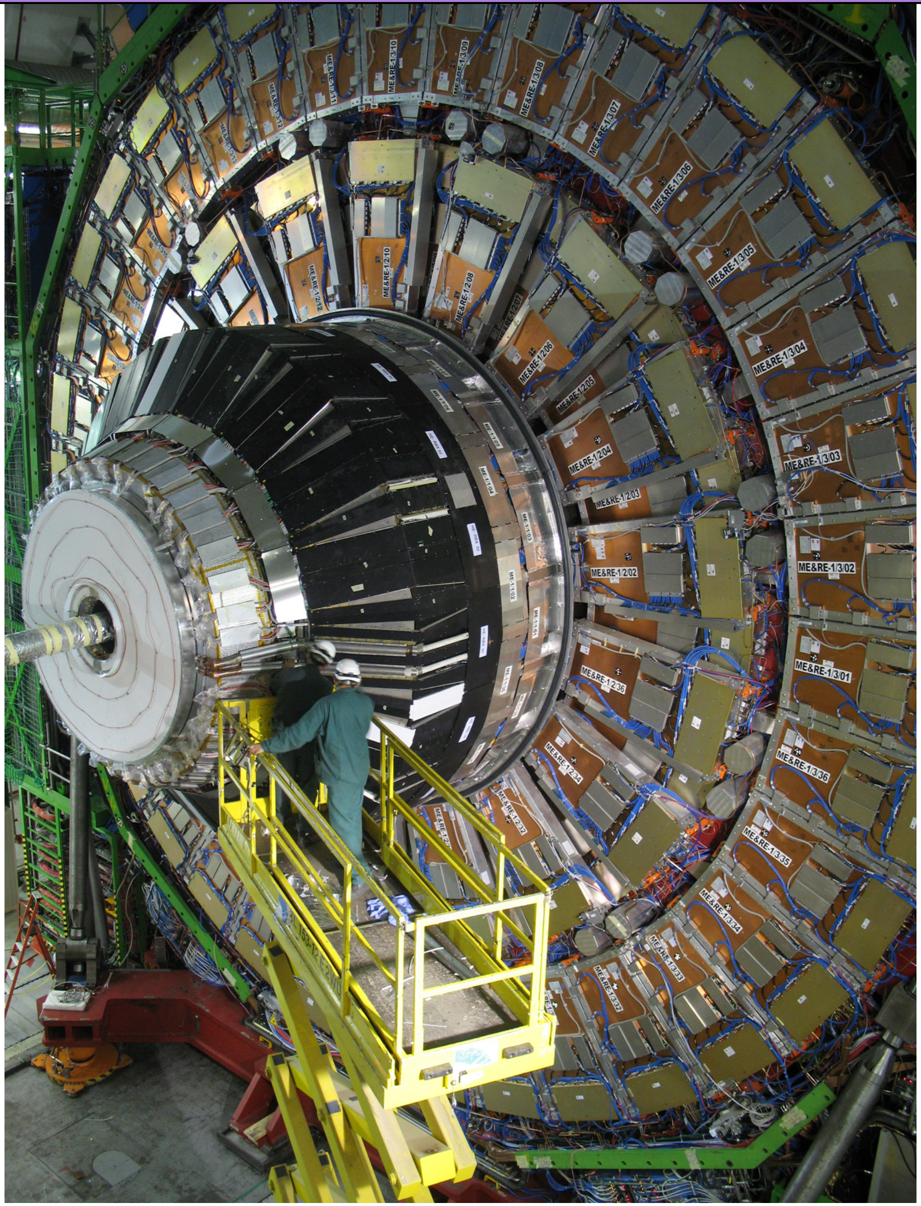
Installation of the Pixel System, August 2008

A 66 megapixel “camera” !
Makes precise measurements of charged particle impact parameters to tag particles with a small but finite lifetime



Before Closure

Closure


ME&RE-1/3/04
ME&RE-1/3/03
ME&RE-1/3/02
ME&RE-1/3/01
ME&RE-1/2/02


ME-1/1/16
ME-1/1/17
ME-1/1/18
ME-1/1/19

CMS Completed!
August 25, 2008 – 16 years after its Letter of Intent

Ready for the LHC

Silicon-based detectors

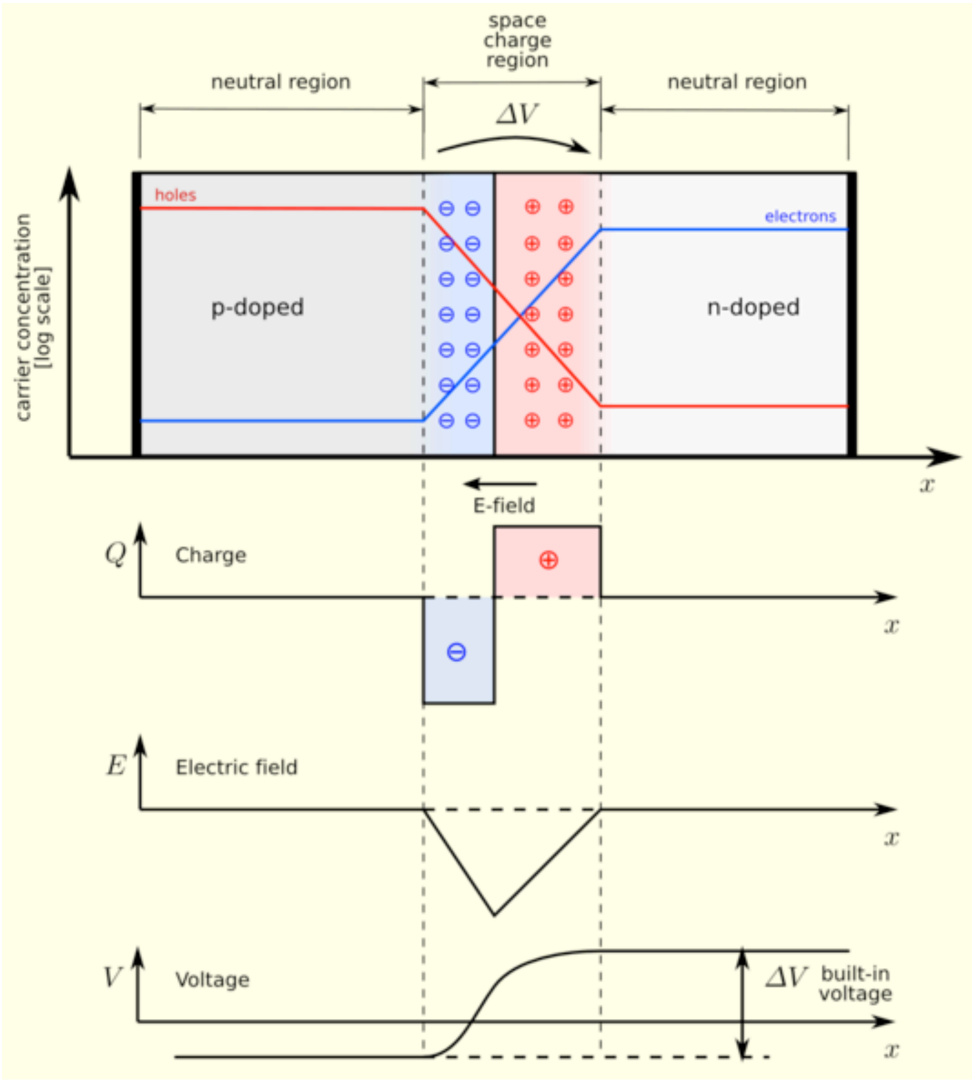
Principle: charged particles ionize electrons which are collected

In bulk silicon, electrons and holes recombine immediately.

Solution is a pn junction; similar in operation to a photodiode.

Doping silicon makes excess electron (n-type) or holes (p-type)

Joining p-type and n-type silicon makes a pn junction. Electrons and holes diffuse across junction and combine, making a small "depletion region" with no free charge carriers.



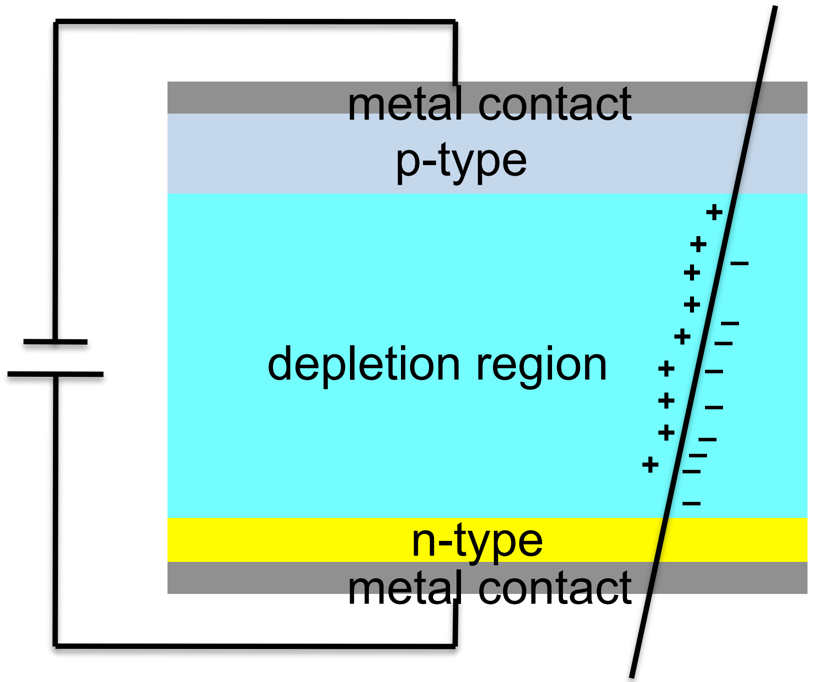
Operating a reverse-biased pn junction

Metal contacts are placed on each side of the junction.

In forward-biased mode, current flows after overcoming 0.7 V potential difference (in silicon).

In reverse-biased mode, increasing voltage causes more electrons and holes to combine, increasing the depletion region.

When the depletion region is as large as the silicon the detector is "fully depleted" and there are (almost) no free carriers (~100V).



When a charged particle goes through, the current from the liberated electrons/holes can be measured.