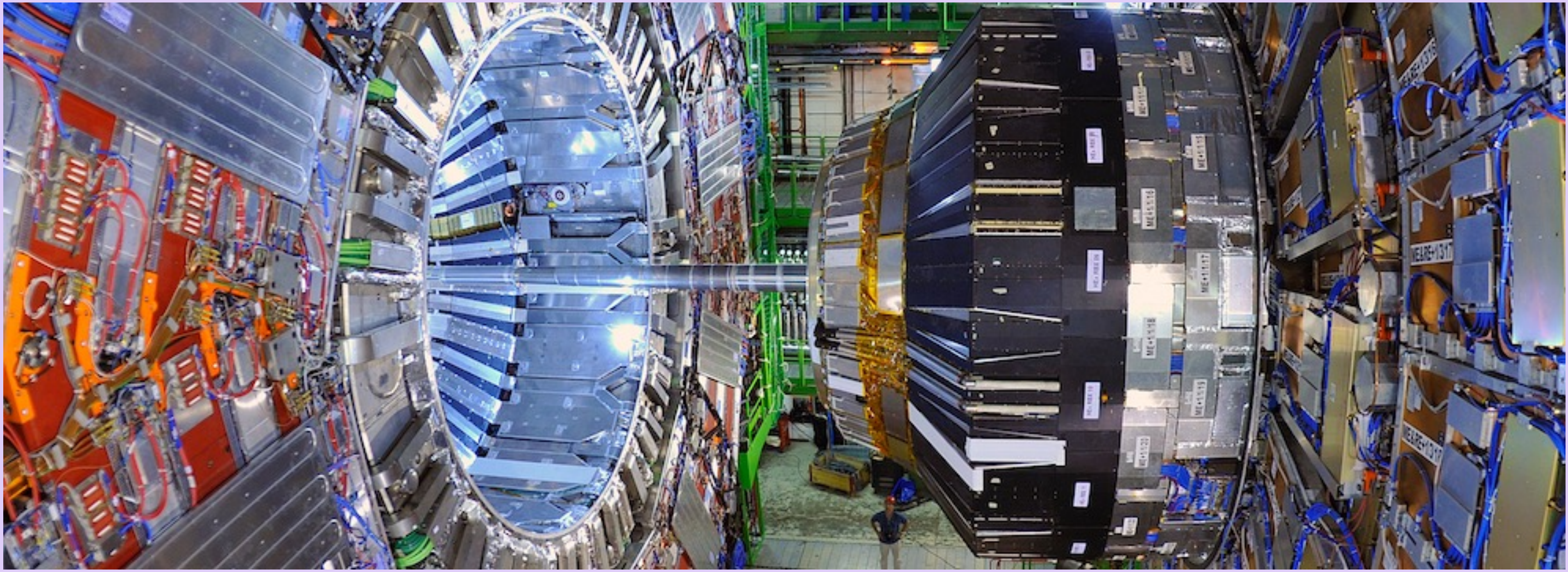
Compact Muon Solenoid (CMS)



Abdollah Mohammadi

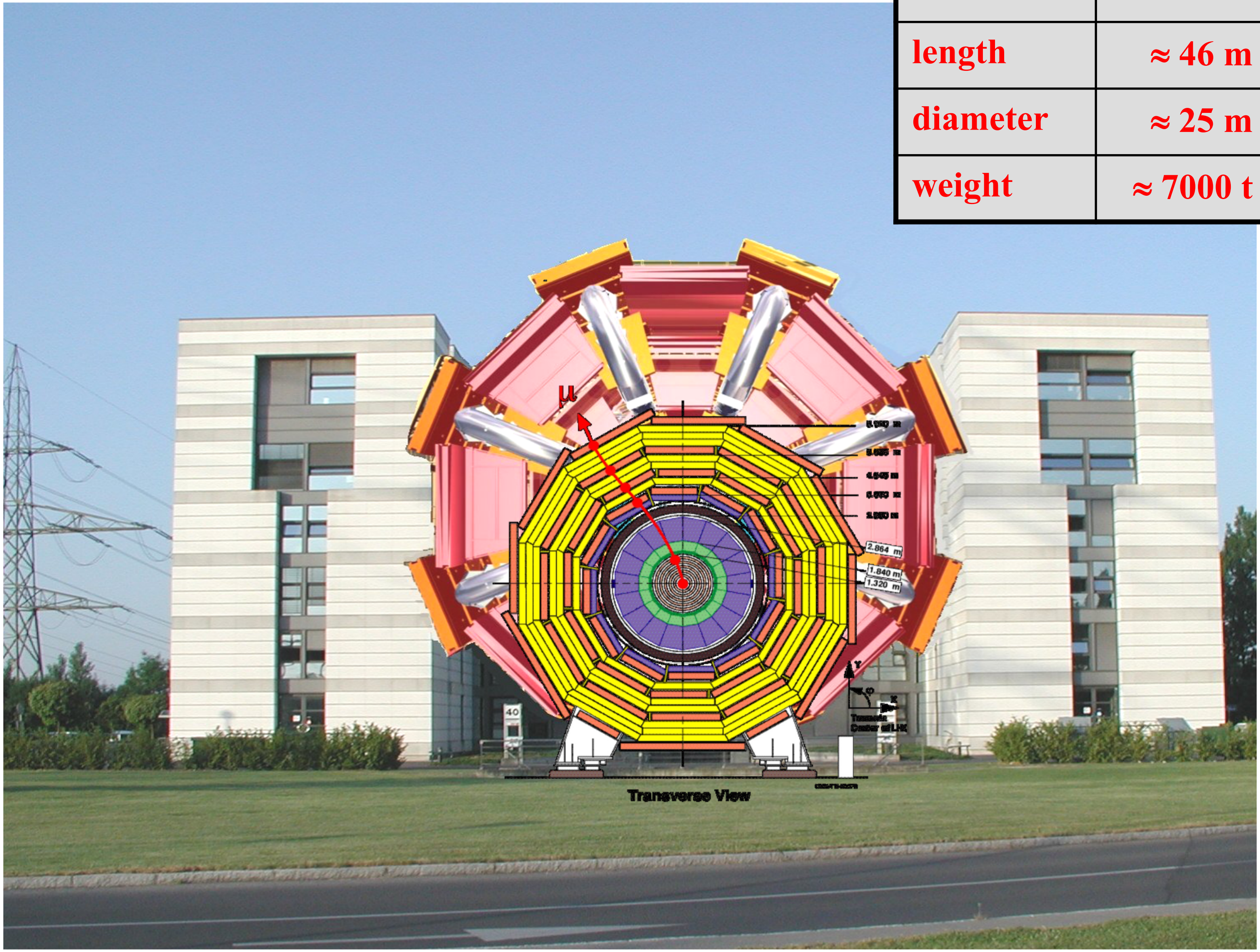
University of Wisconsin-Madison
September 11th 2021

2nd Iran-CERN Workshop

The Large Hadron Collider

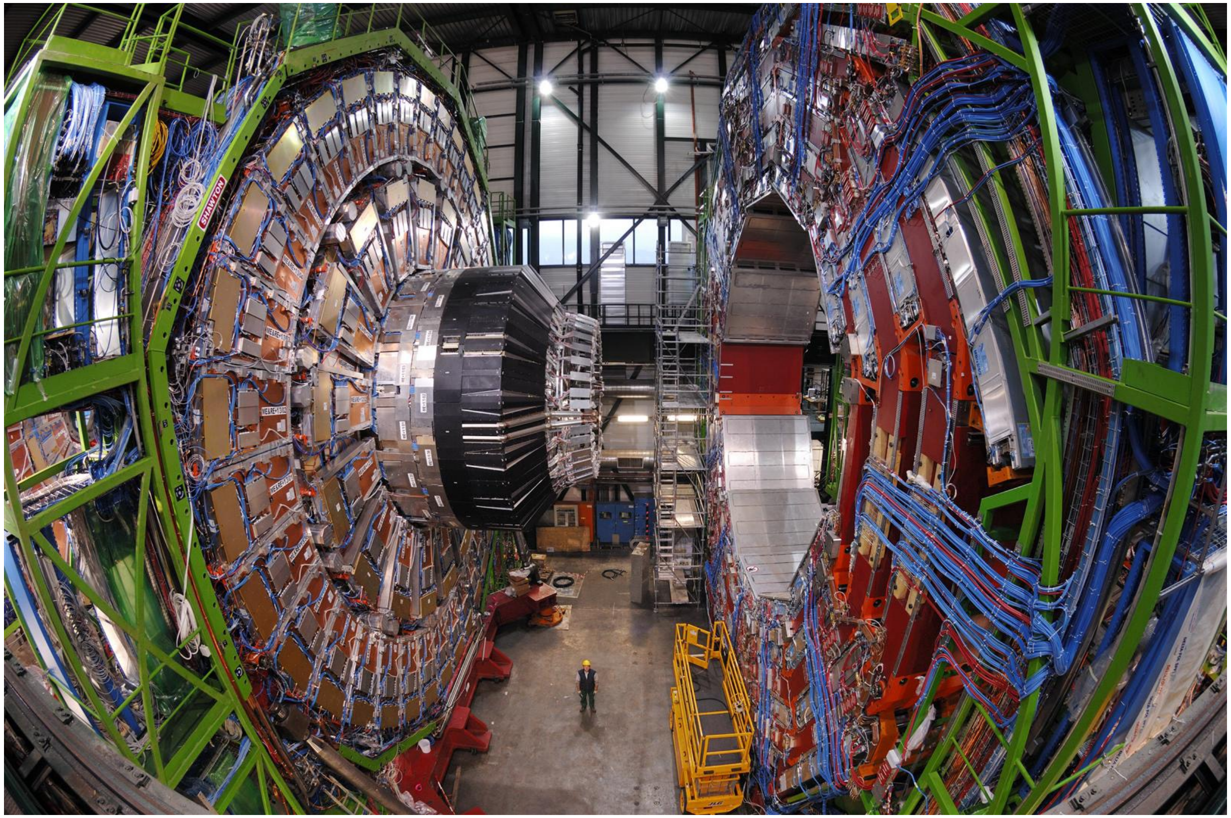
CMS v.s. ATLAS

	ATLAS	CMS
length	≈ 46 m	≈ 22 m
diameter	≈ 25 m	≈ 15 m
weight	≈ 7000 t	≈ 12000 t



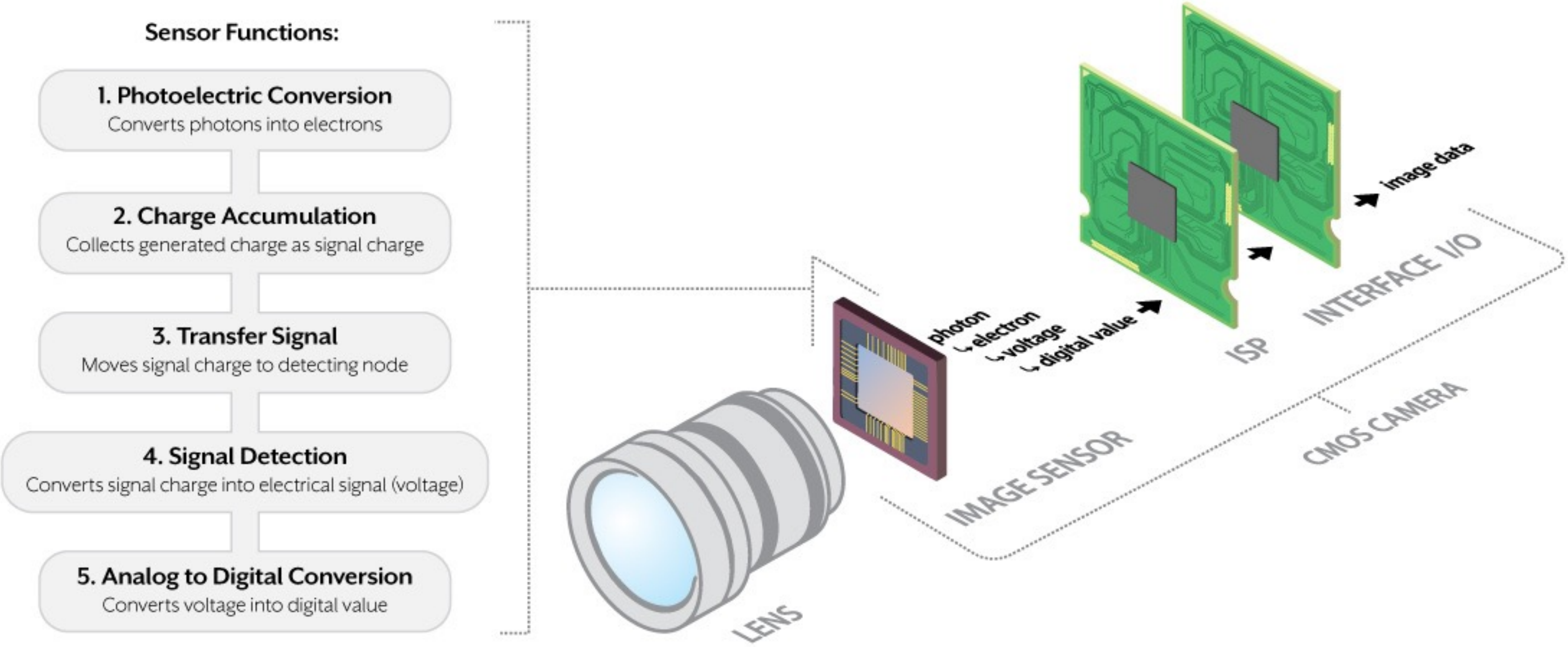
Compact Muon Solenoid (CMS)

V.S.



An onion-like 3D camera

Camera operation

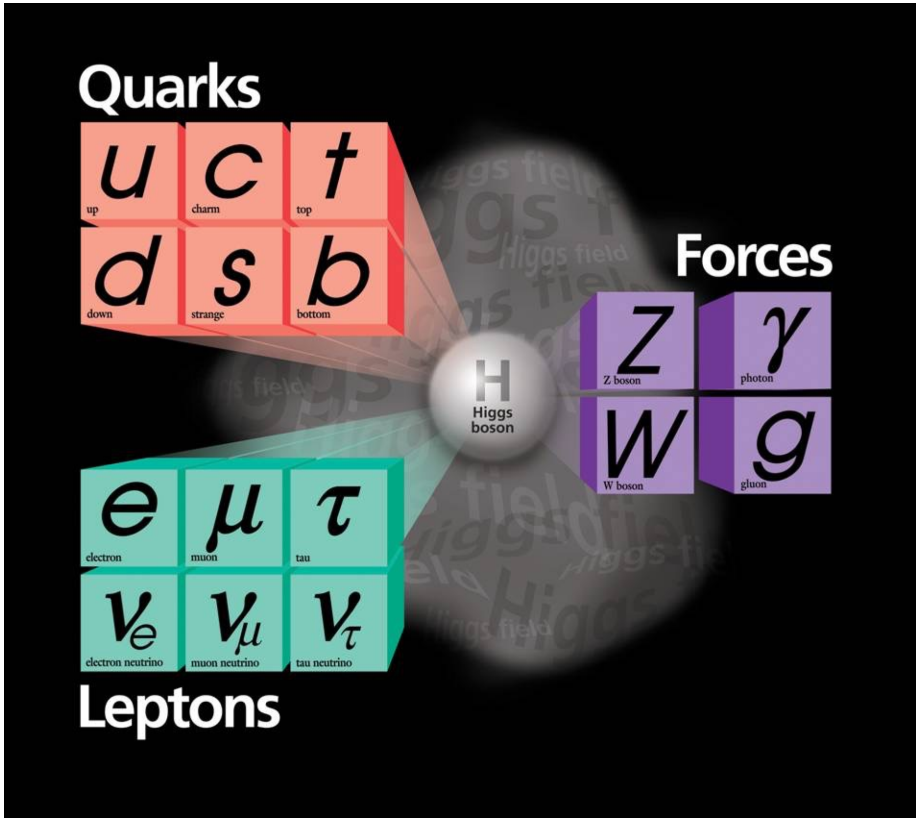


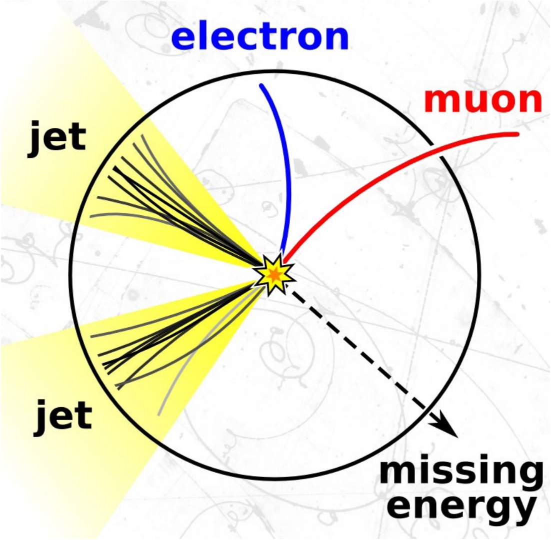
Sensor Functions:

1. **Photoelectric Conversion** Converts photons into electrons
2. **Charge Accumulation** Collects generated charge as signal charge
3. **Transfer Signal** Moves signal charge to detecting node
4. **Signal Detection** Converts signal charge into electrical signal (voltage)
5. **Analog to Digital Conversion** Converts voltage into digital value

Main goal of the sensors:
to convert incoming light (photons) into an electrical signal that can be viewed, analyzed, or stored.

Particle detectability in detector

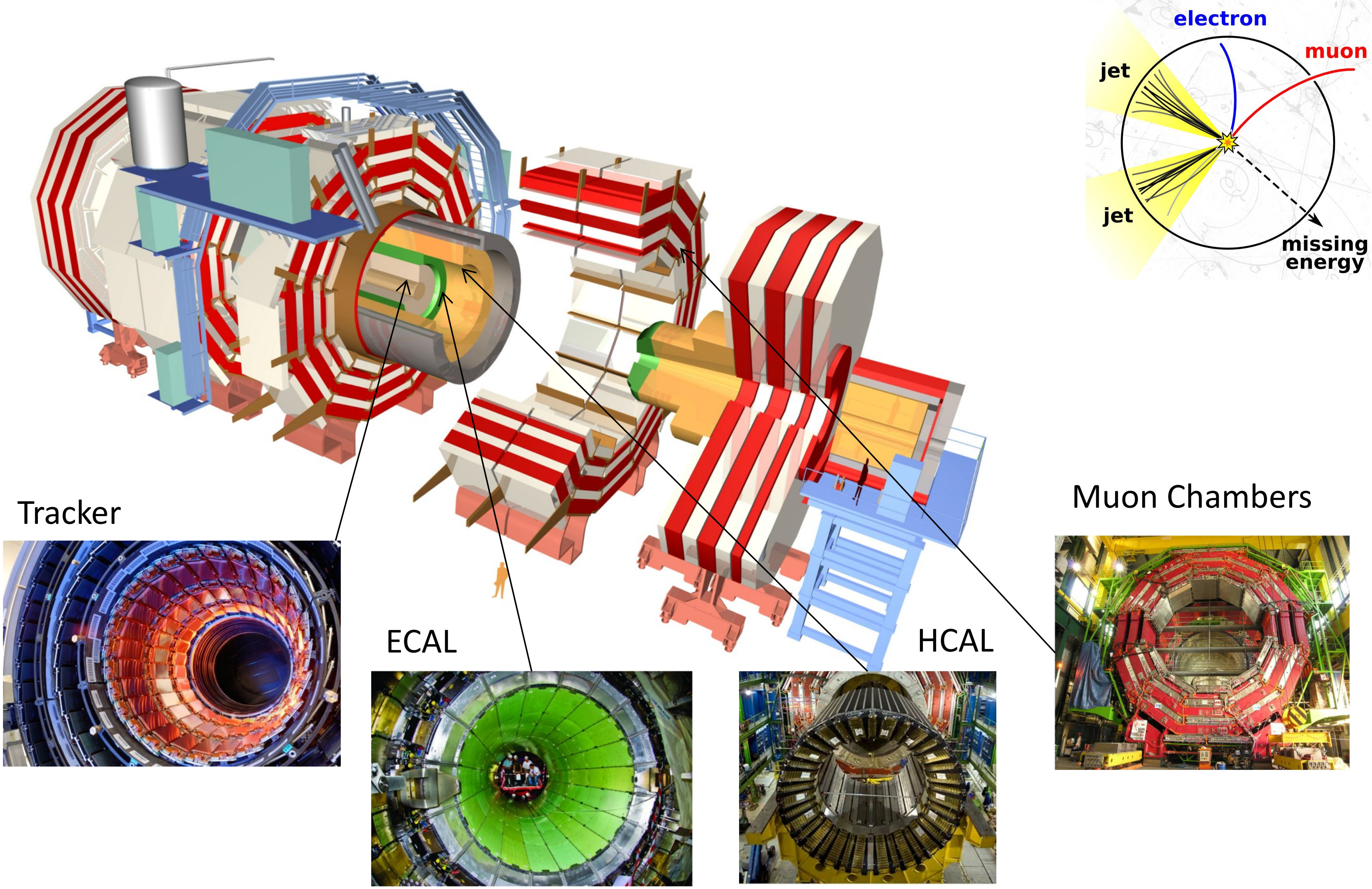


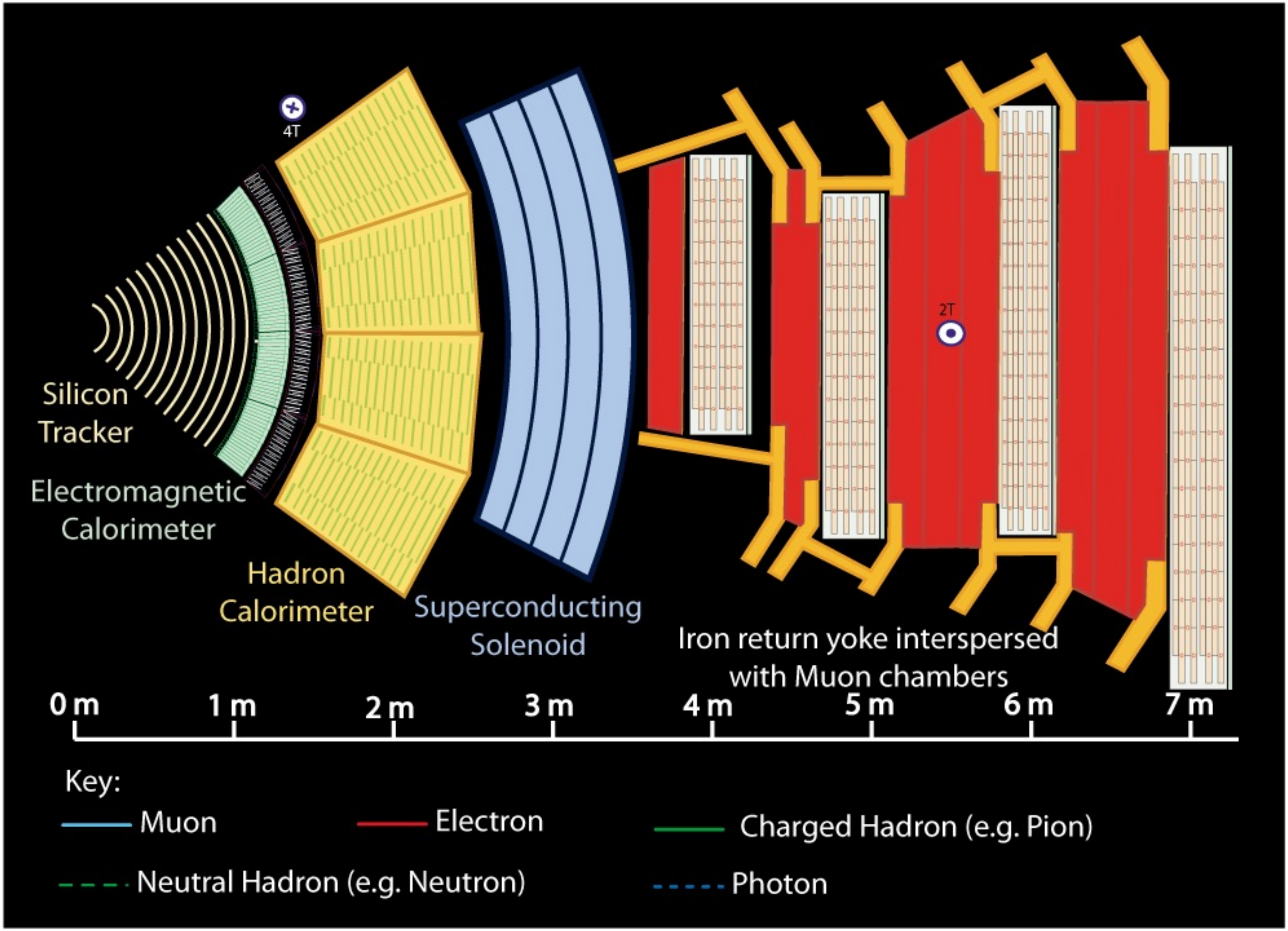


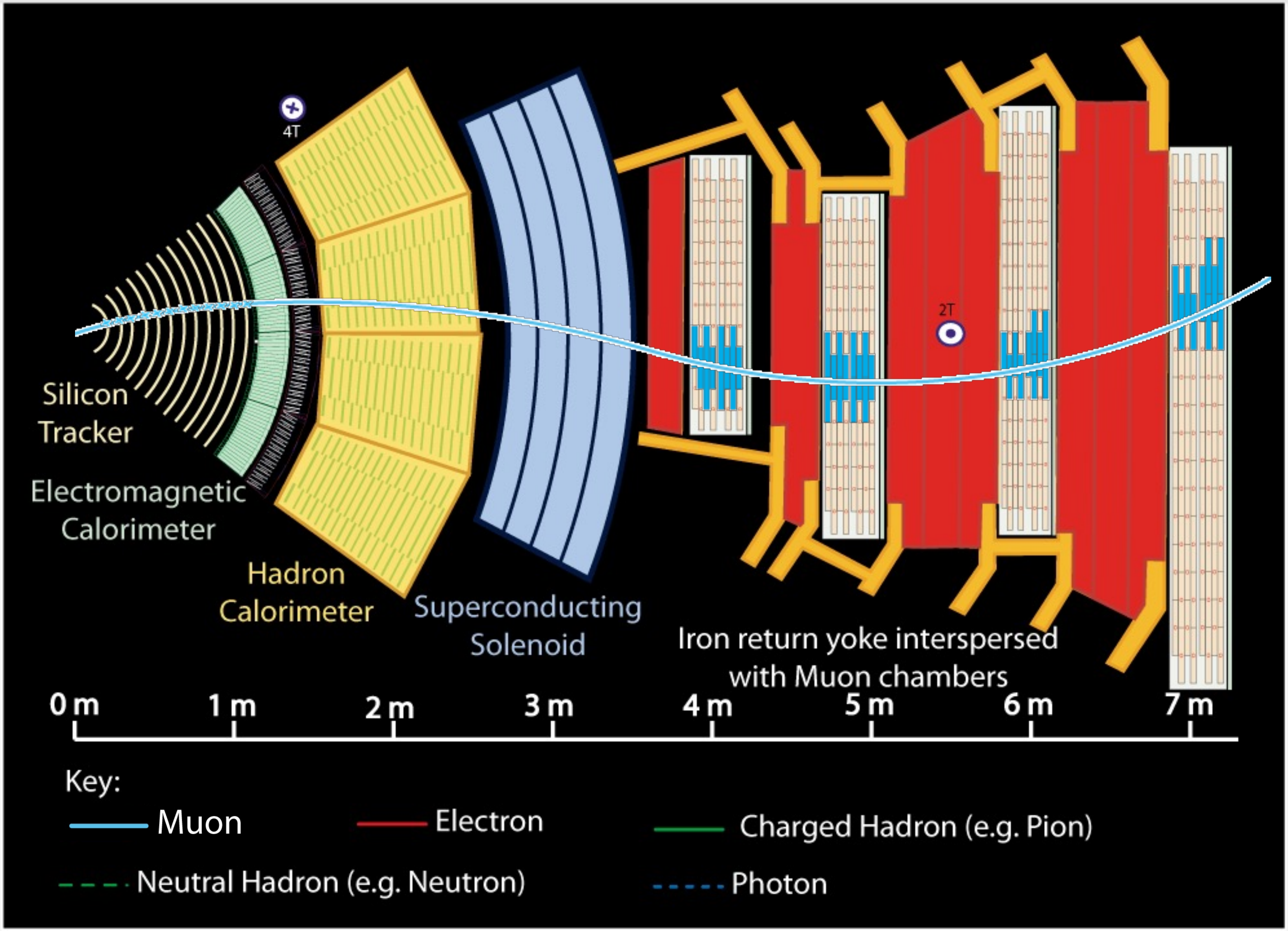
Particle categorization based on detectability:

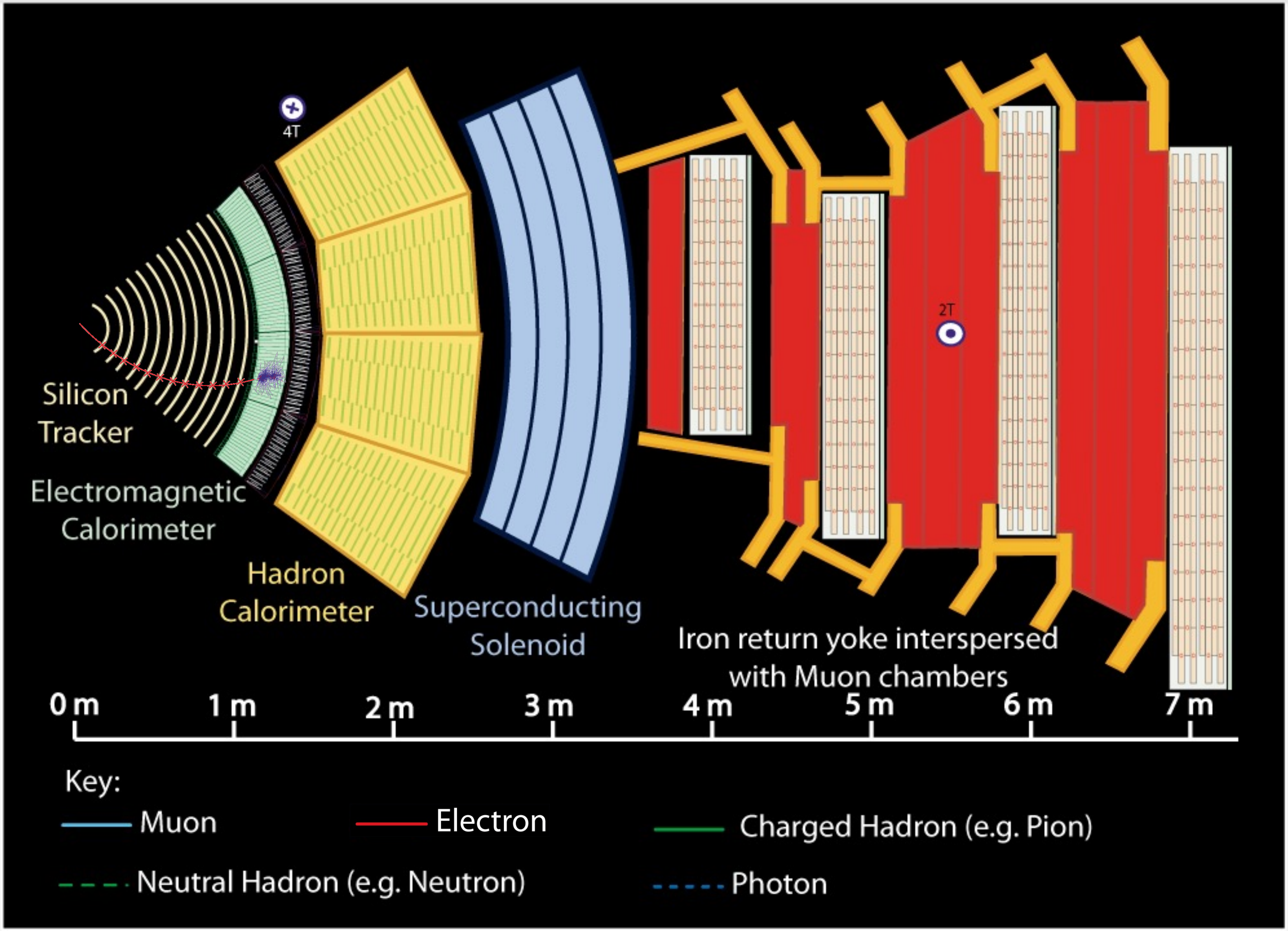
- Interact with detector materials: e, μ, γ, q …
- Escape from detector: ν
- Decay to either types of particles: τ, Z, H, …

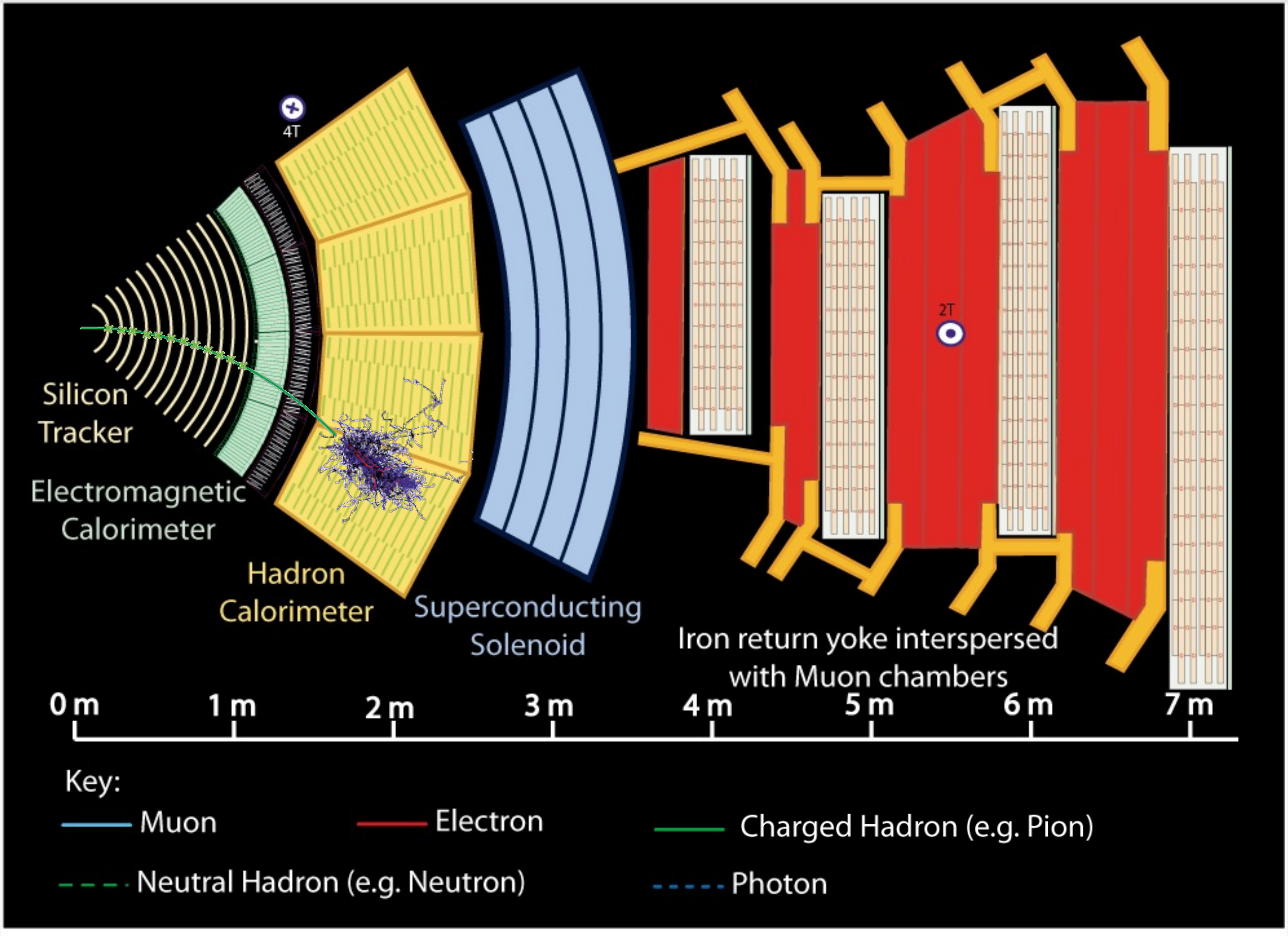
Compact Muon Solenoid (CMS)

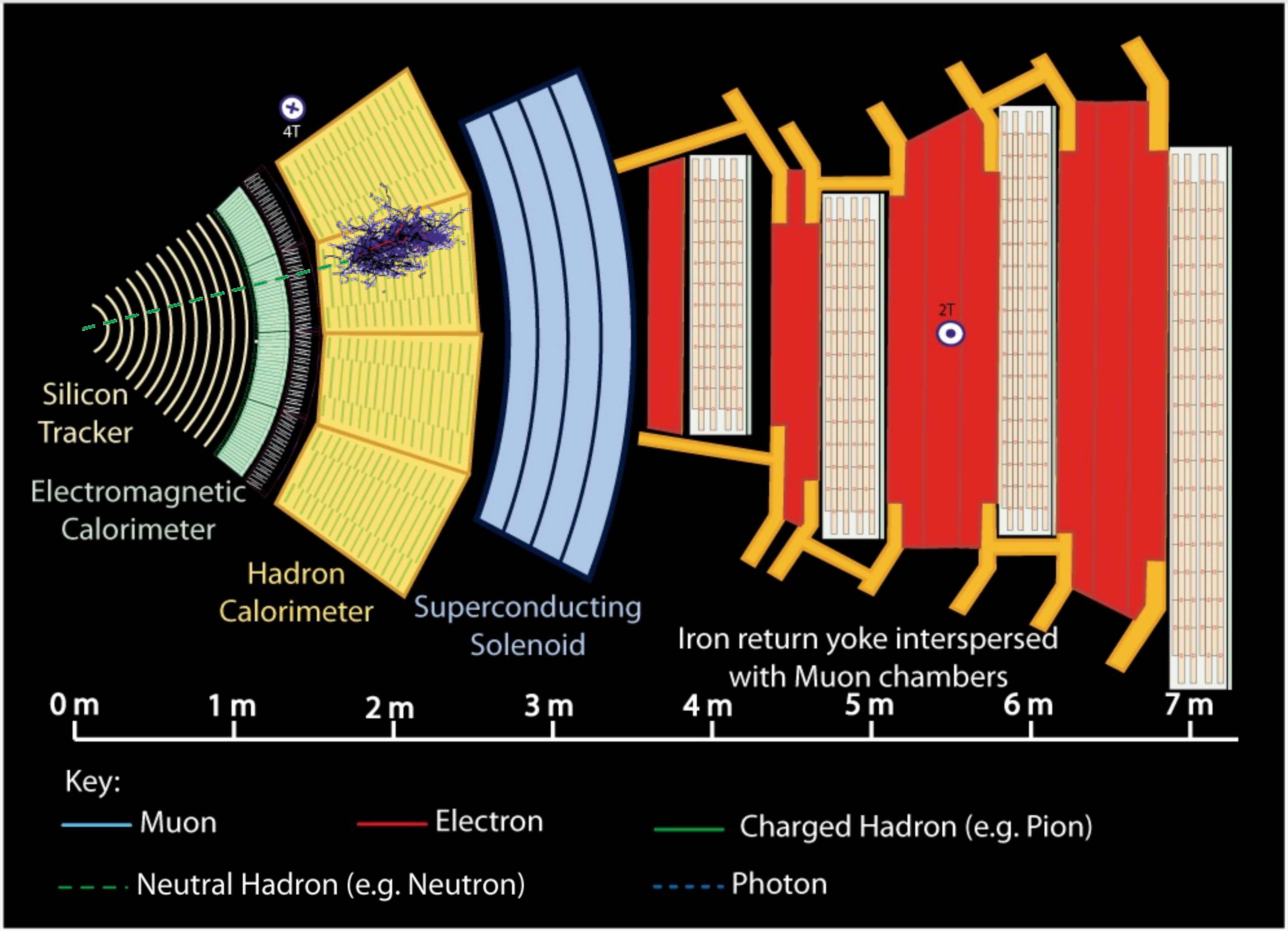


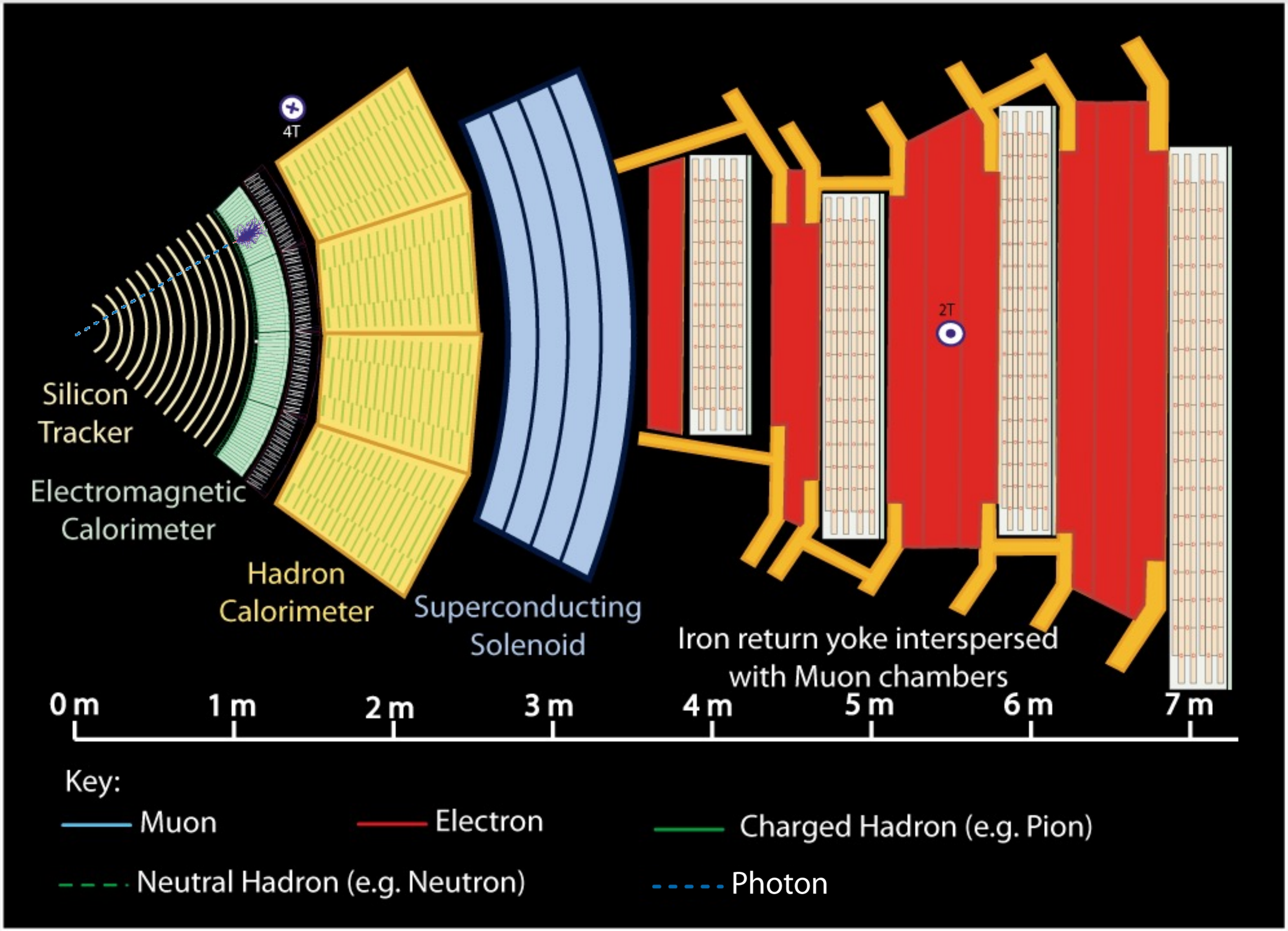

4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

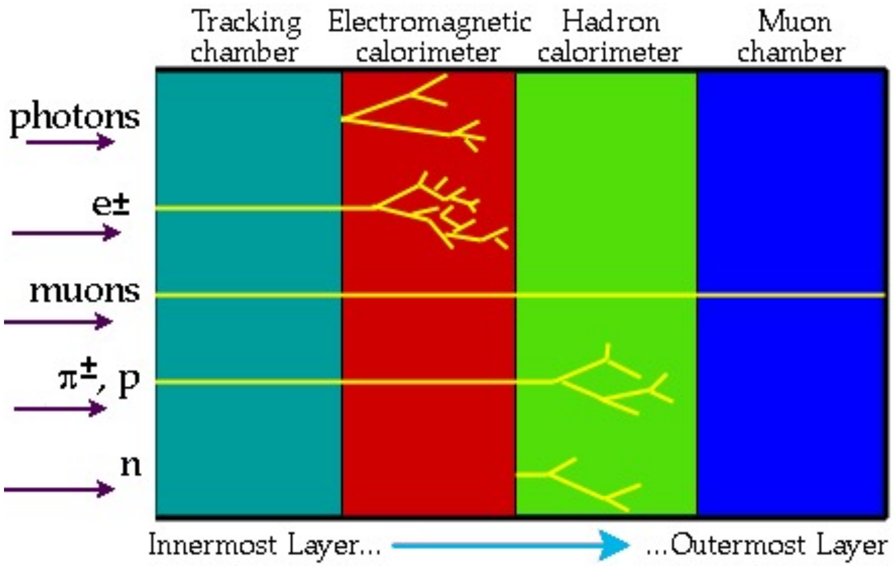

4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

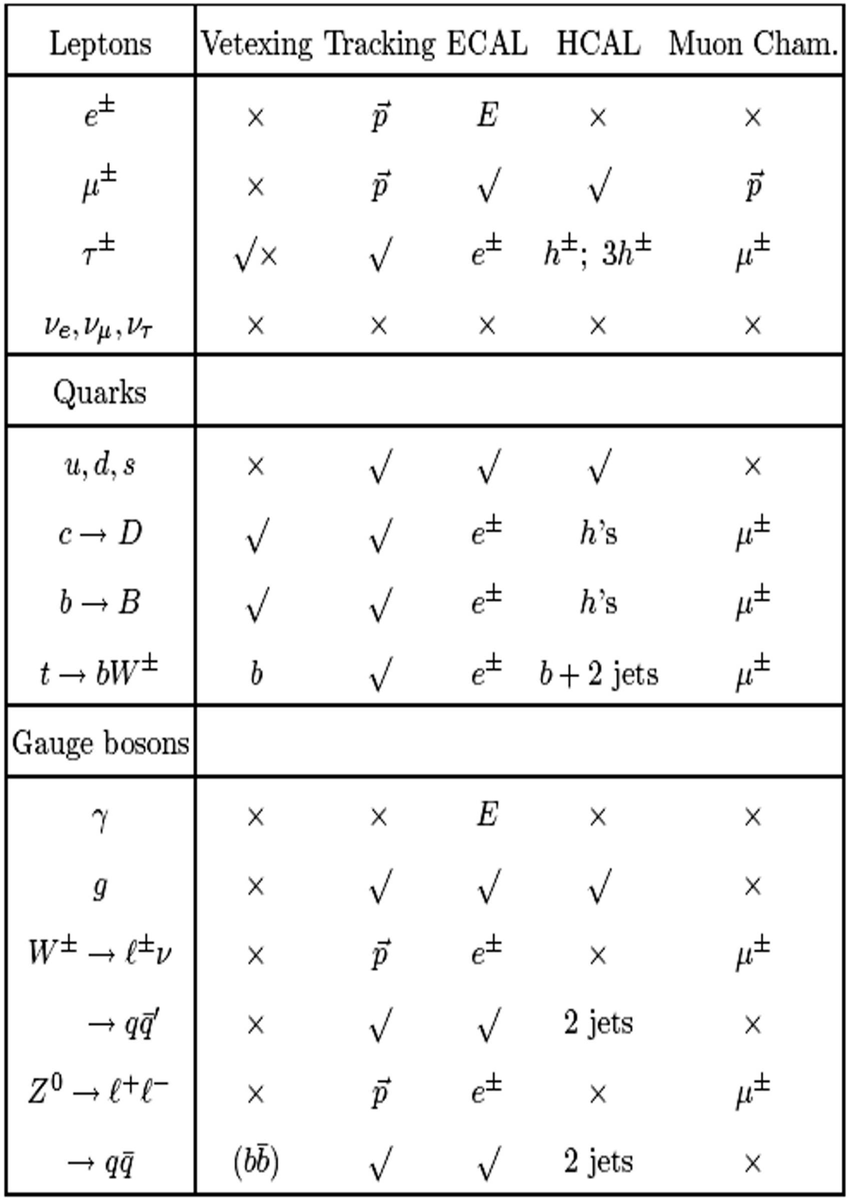

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
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
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

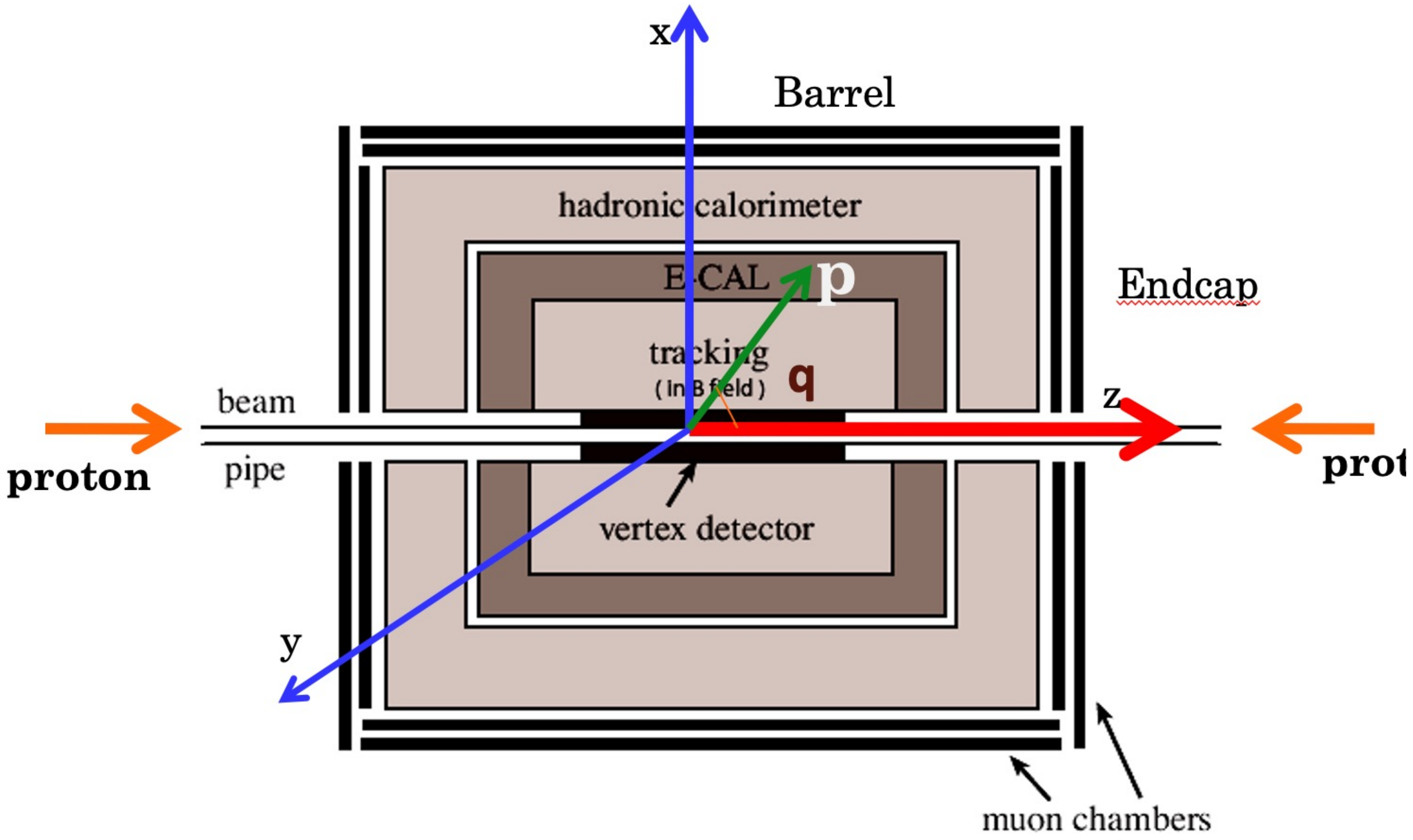
Summary of particles identification





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

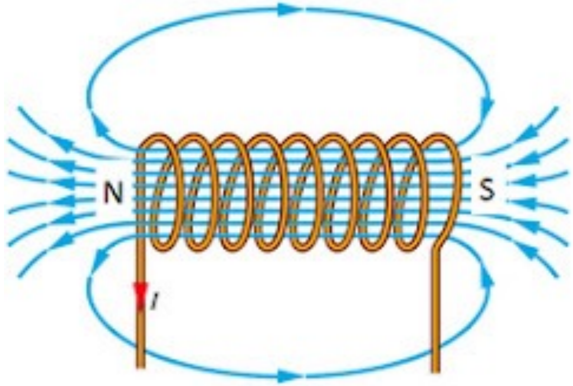
Two important variables



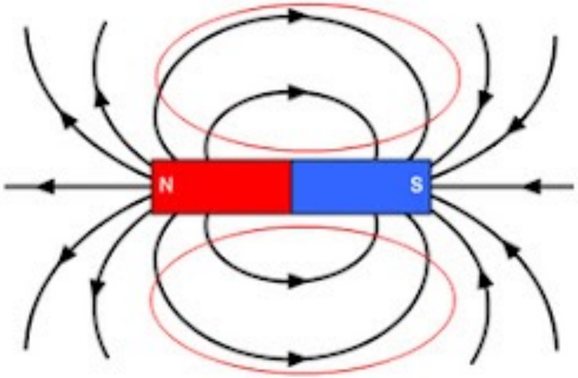
$$p_T = \sqrt{p_x^2 + p_y^2} = |\vec{p}|\sin\theta \quad , \quad \eta = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \approx -\ln\left(\tan\left(\theta/2\right)\right)$$

Solenoid

Magnet



Solenoid

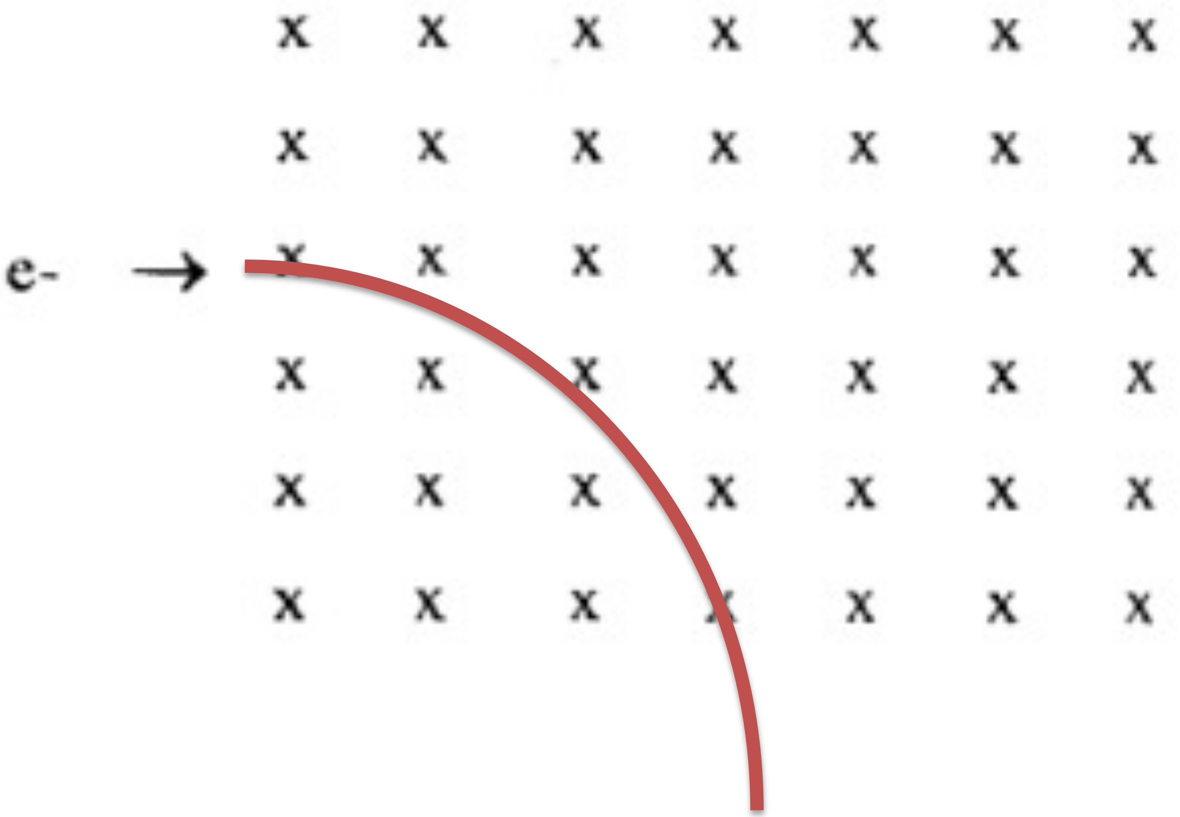


Magnet

$$B = \mu_0 n I$$

- CMS solenoid is 13m long and 6m in diameter.
- Superconducting niobium-titanium coils
- Carry 20 kA current
- 3.8 T magnetic field that is 100,000 times stronger than the Earth's
- Stored energy of 2.66 GJ, equivalent to about half-a-tonne of TNT

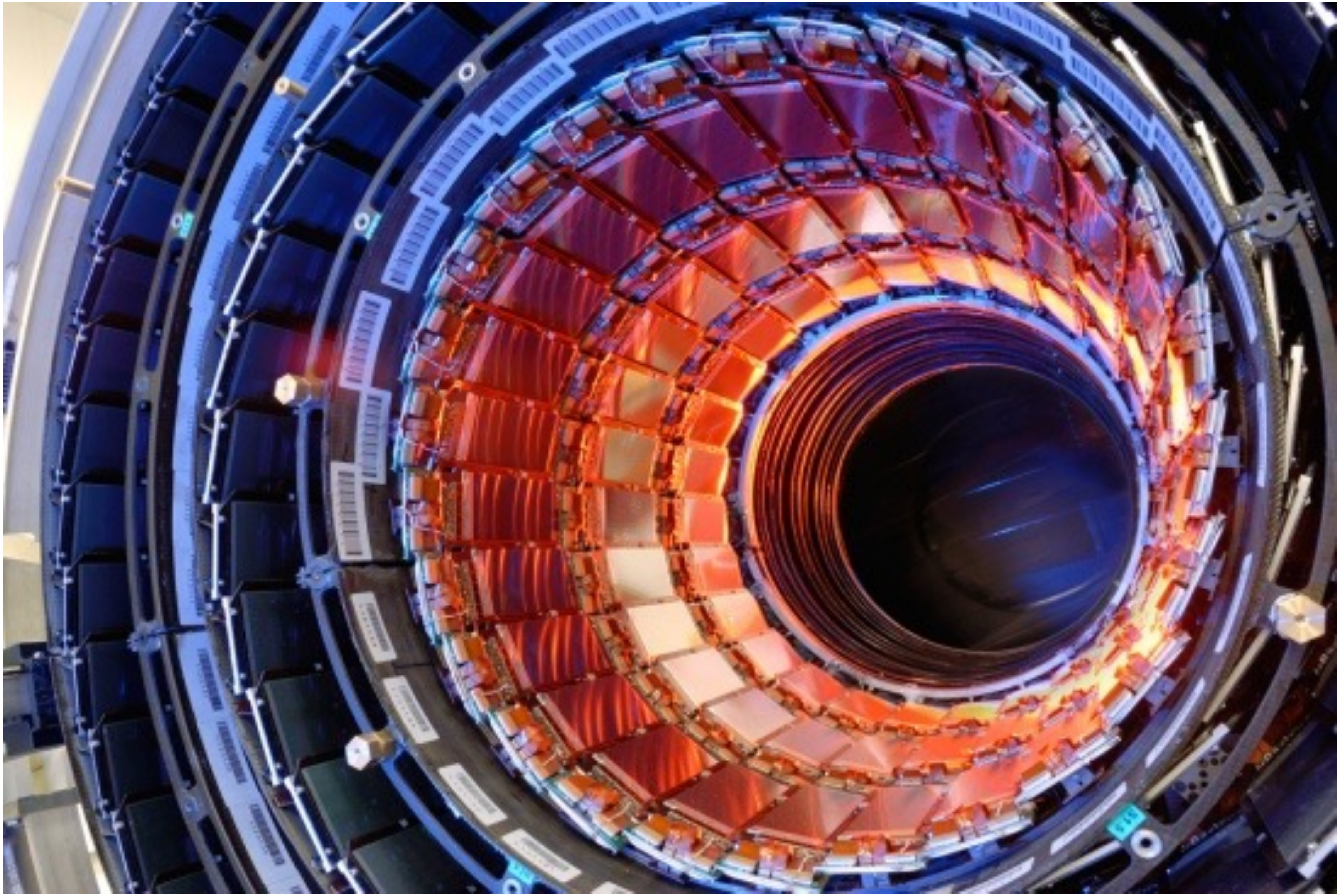
Charged particle in a magnetic field



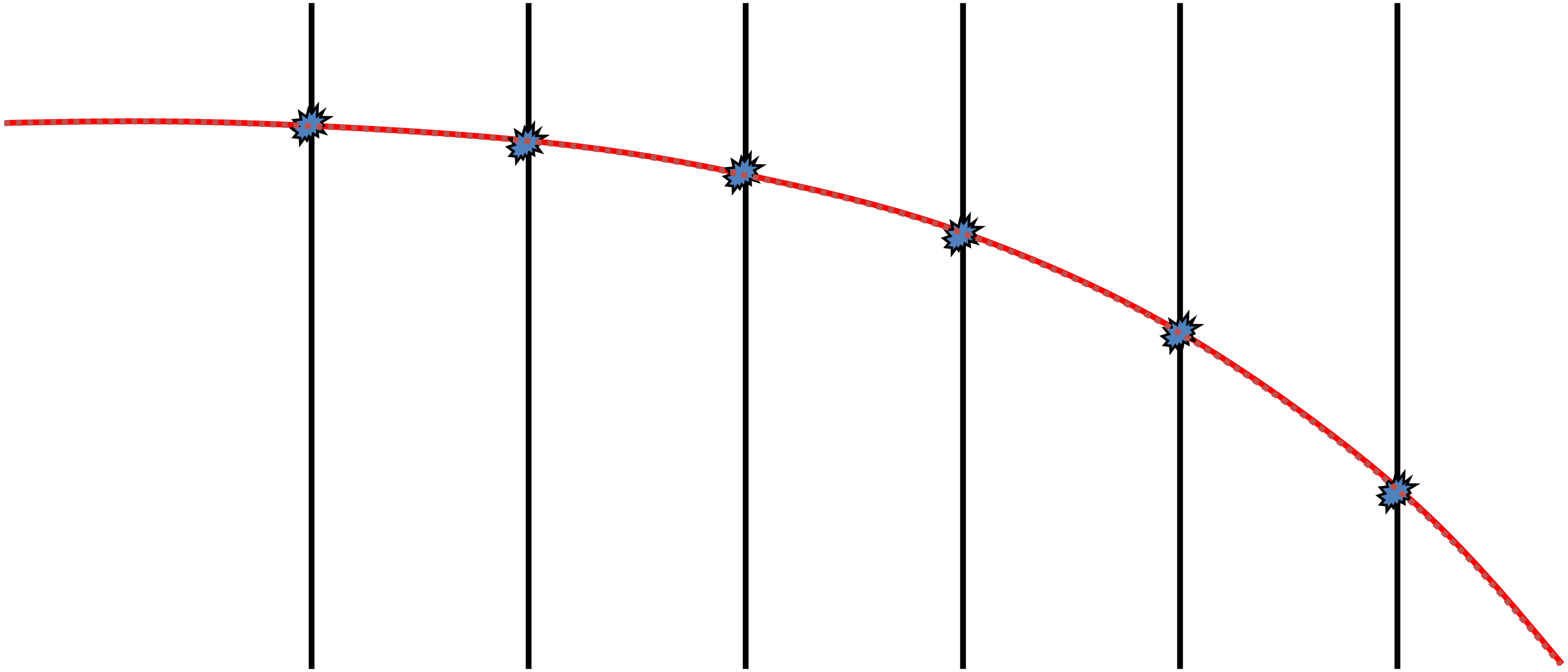
$$\vec{F} = q\vec{v} \times \vec{B}$$

$$r = \frac{p_T}{0.3B}$$

Tracker

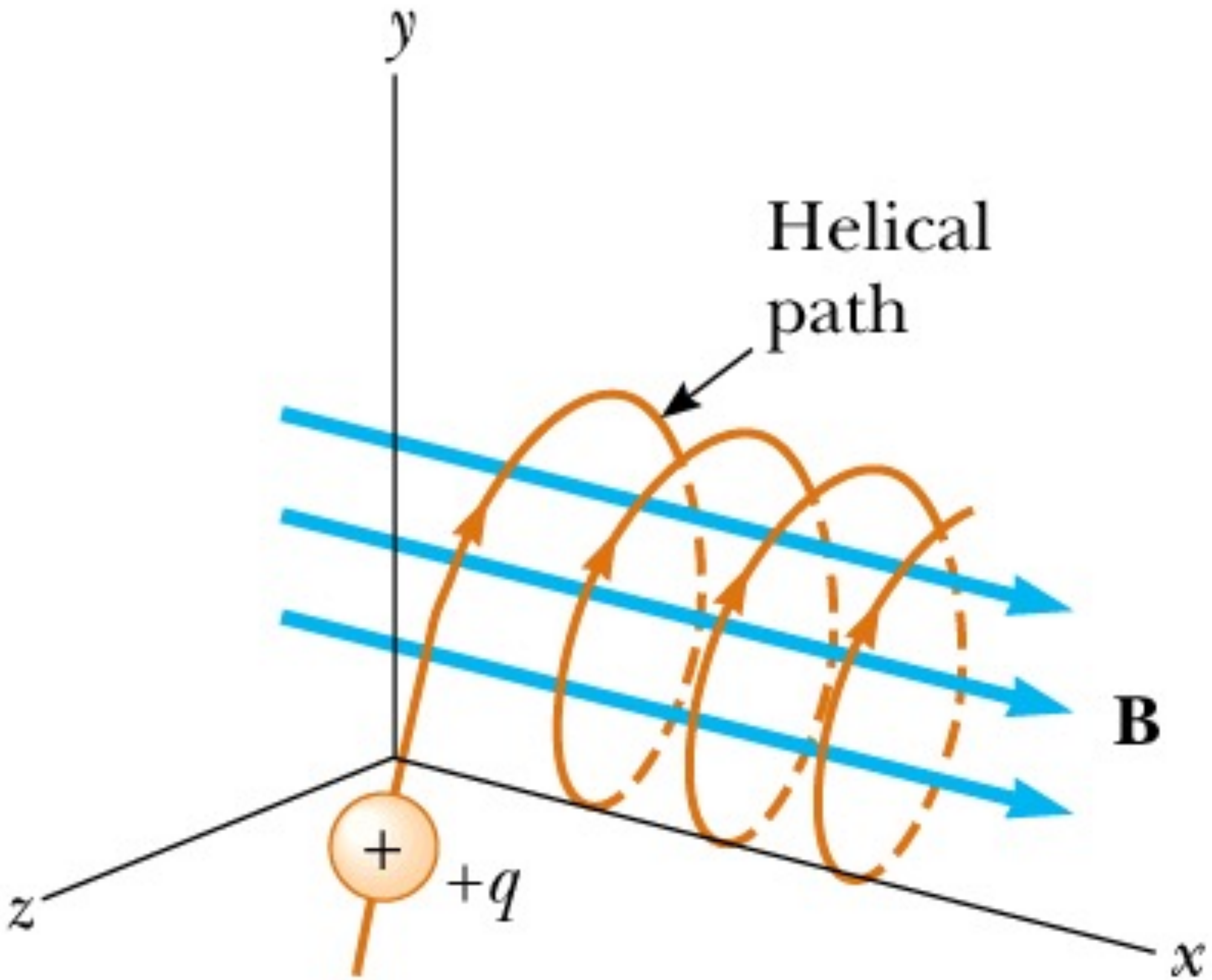


A basic “Tracker”

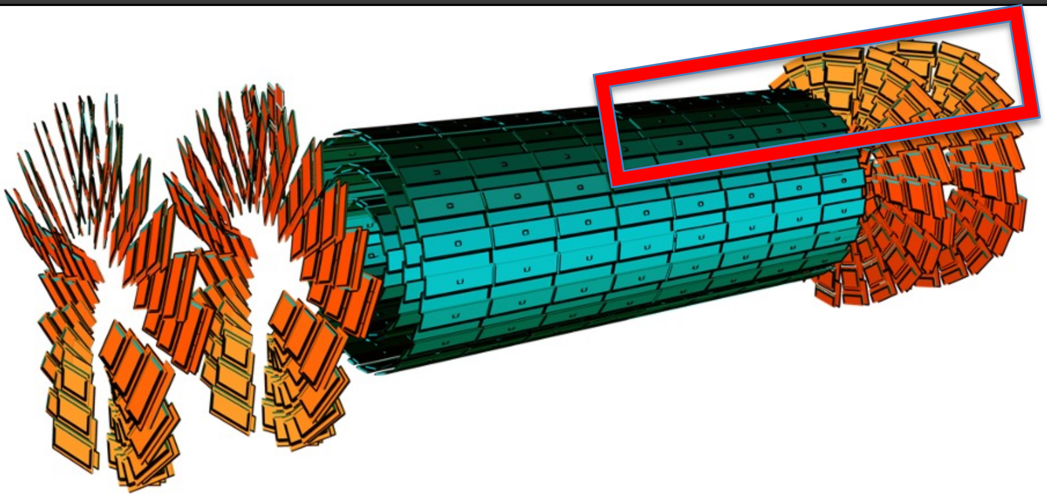


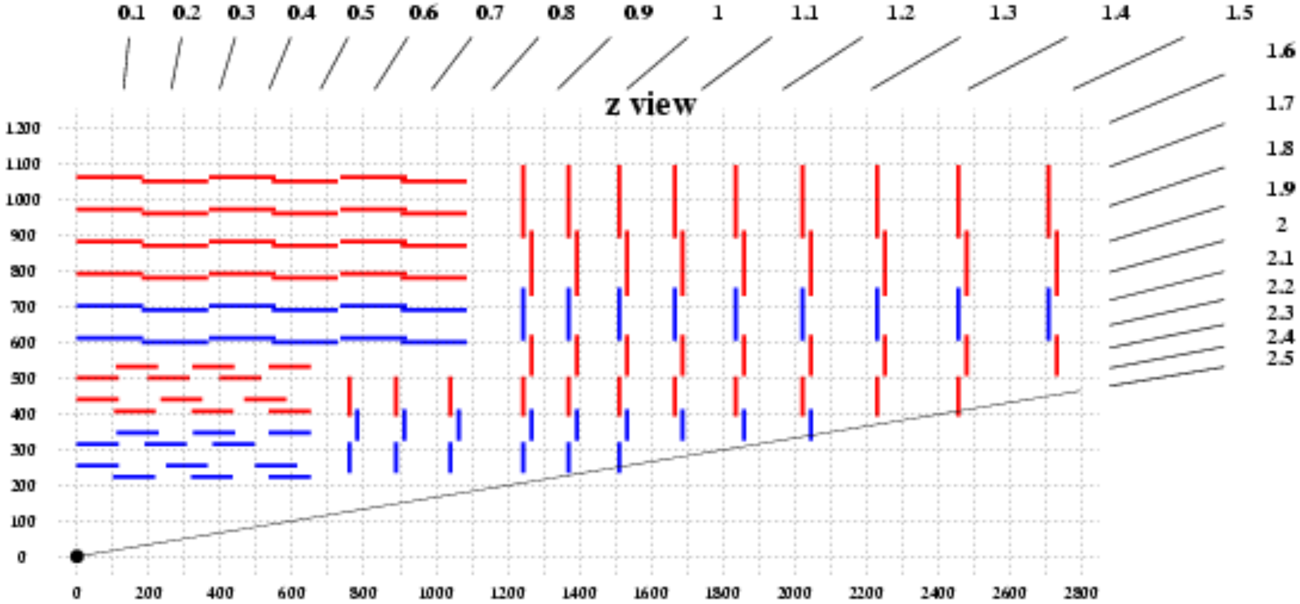
Multiple thin layers of, for example, silicon sensors

And a bit more advanced tracking …



A silicon-made tracker

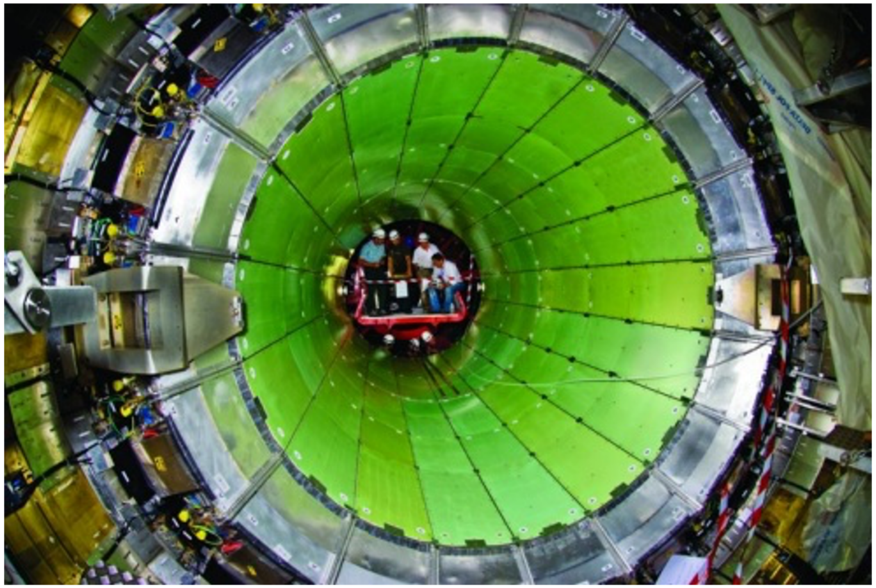


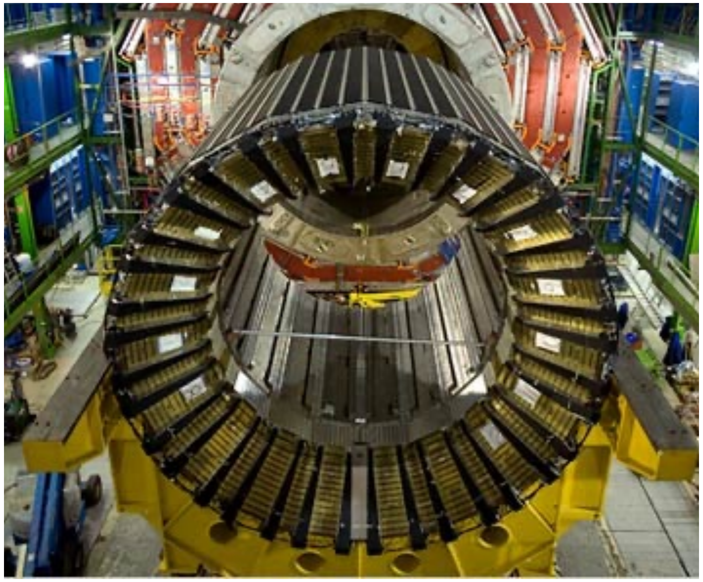


Technical Info on CMS tracker

- World's largest silicon detector
  - ~ 200 m^2 equipped with 9.3 million microstrip sensors
- Made of silicon
  - In form of Pixel (inner most) and strip (outer most)
- Radiation tolerant
  - Being the inner most layer of detector, it received the highest volume of particles and radiations
- 14 layers in the barrel region and 15 layers in the endcaps
- 124 million pixel at the size of 100 μm × 150 μm
- 9.6 million strip channel at the size of 10 cm × 180 μm silicon strips
- Particles barely deposit any energy in the tracker

Calorimeters





Calorimeter

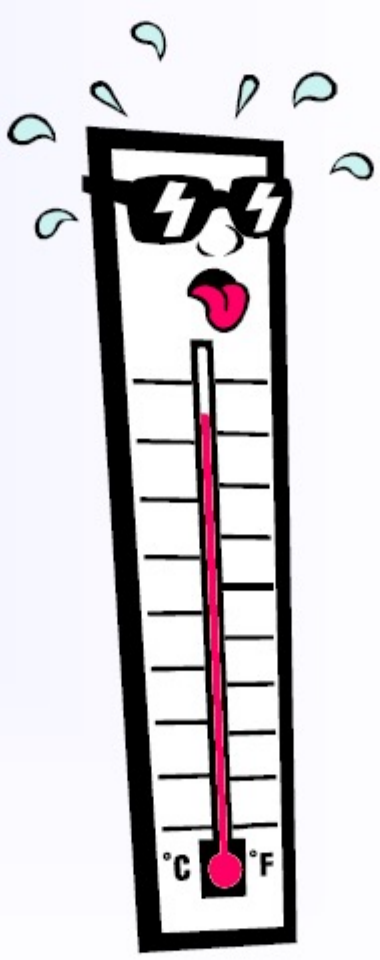
latin: calor = heat

Calorimetry = Energy measurement by total absorption, usually combined with spatial reconstruction.

What is the effect of a 1 GeV particle in 1 liter water (at 20° C)?

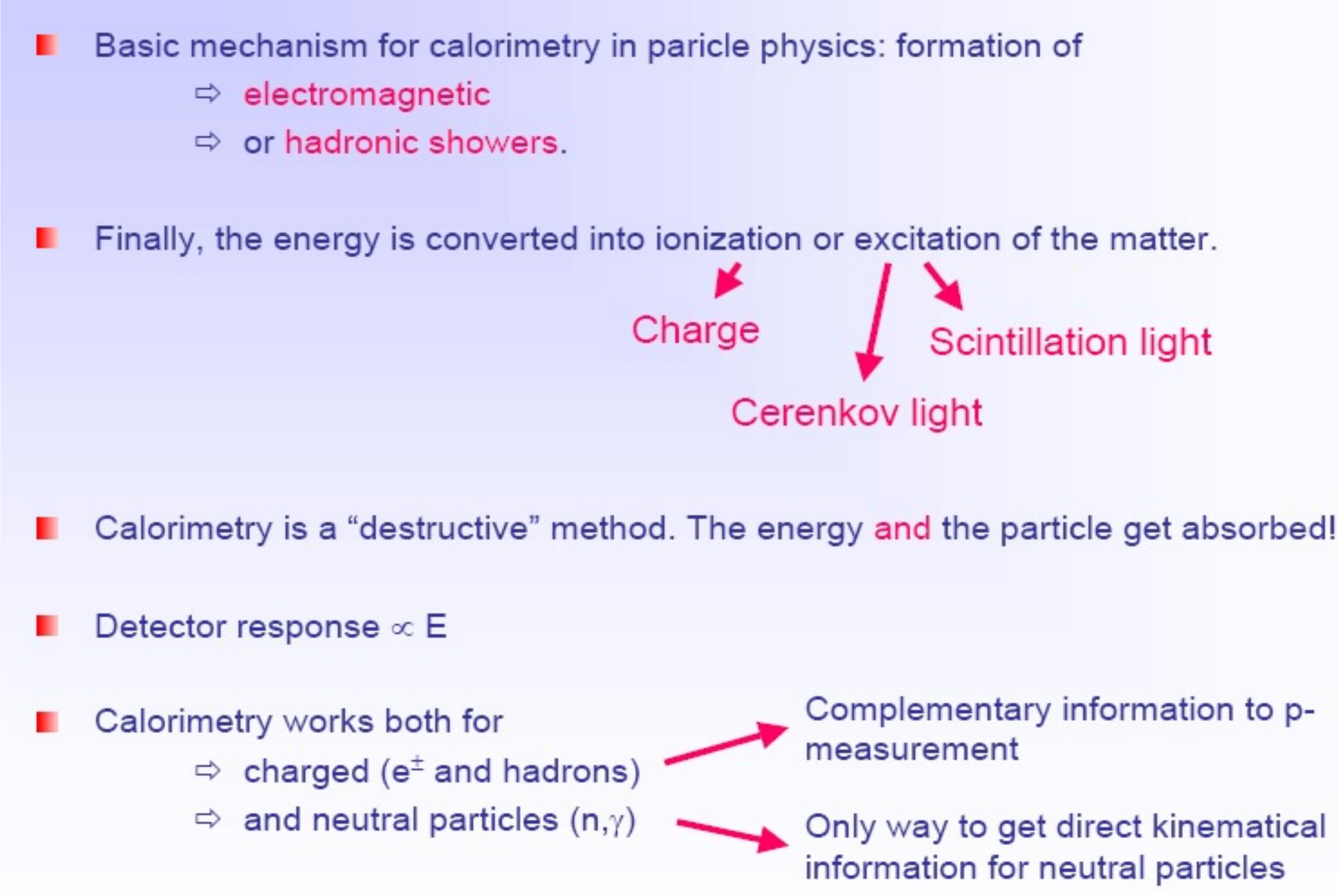
$\Delta T = E / (c \cdot M_{water}) = 3.8 \cdot 10^{-14}$ K !

There must be more sensitive methods than measuring ΔT !



Particle interaction with Matter

- The main principle of particle detection: **Interaction with matter.**



- Basic mechanism for calorimetry in paricle physics: formation of
  - ⇨ electromagnetic
  - ⇨ or hadronic showers.
- Finally, the energy is converted into ionization or excitation of the matter.

Charge

Scintillation light

Cerenkov light

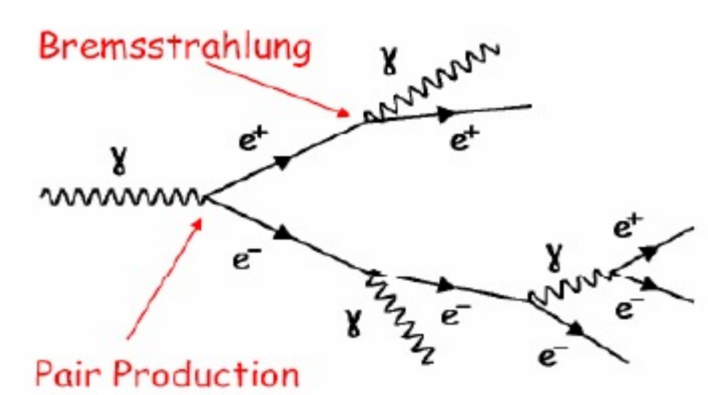
- Calorimetry is a “destructive” method. The energy and the particle get absorbed!
- Detector response $\propto$ E
- Calorimetry works both for
  - ⇨ charged ($e^{\pm}$ and hadrons)
  - ⇨ and neutral particles (n,γ)

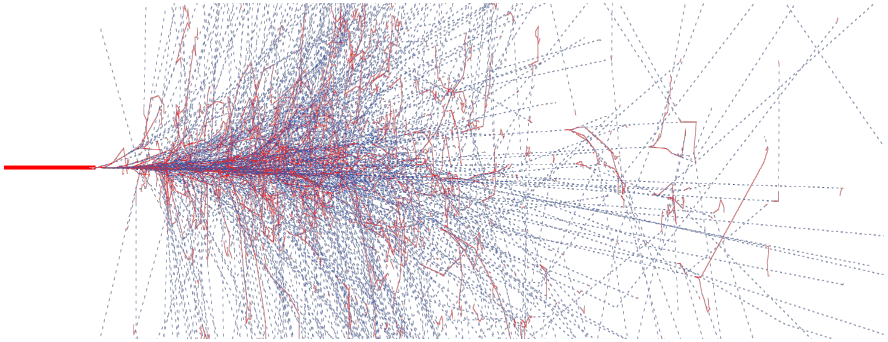
Complementary information to p-measurement

Only way to get direct kinematical information for neutral particles

EM showering

When a **high energy electron or photon** strikes on a thick absorber (such as Lead), a **cascade of secondary electrons and photons** via **Bremsstrahlung and pair production , respectively,** is initiated.





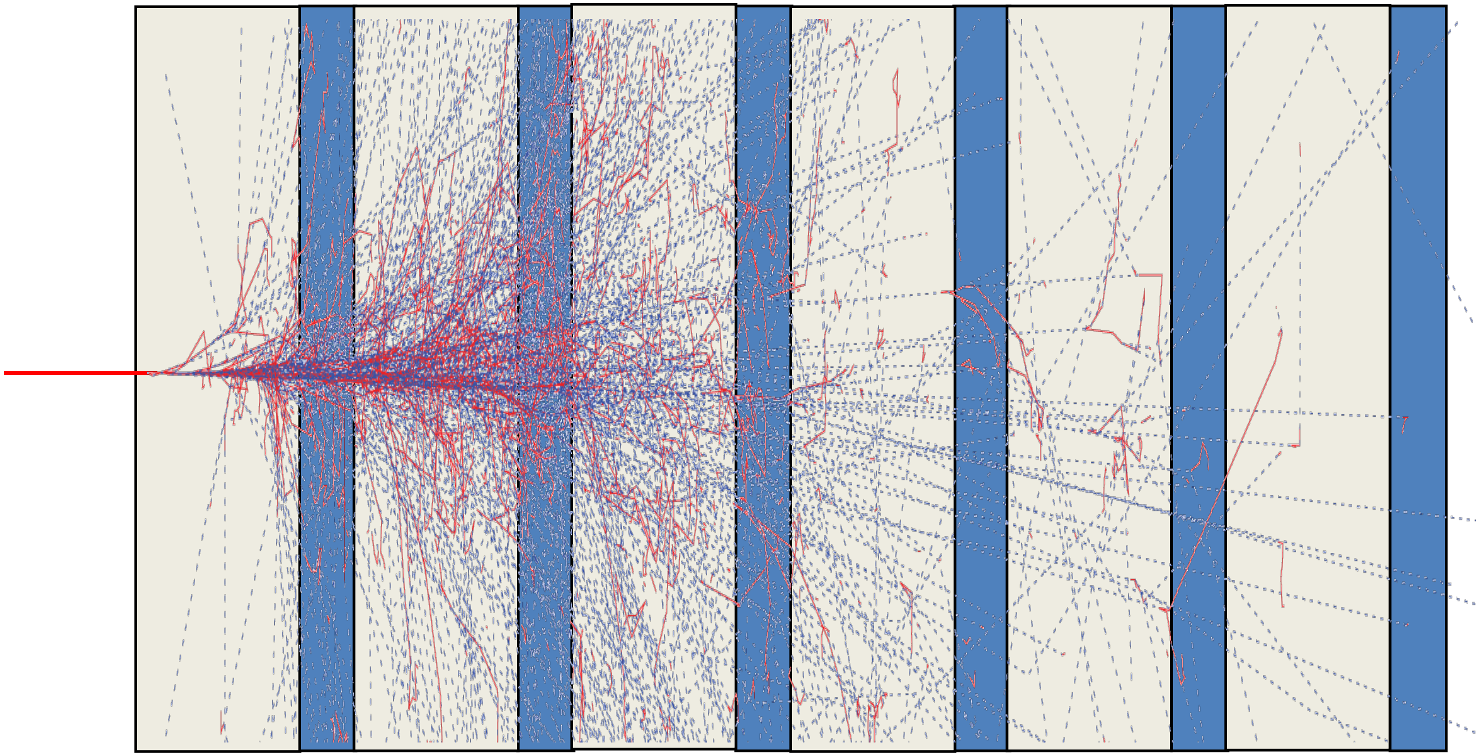
With increasing the depth

The number of secondary particles is increased

The mean energy of particles decreased

This multiplication continues until the energy of particles fall below the critical energy, after this Photons and Electrons start the Ionization and Excitation processes.

A basic calorimeter

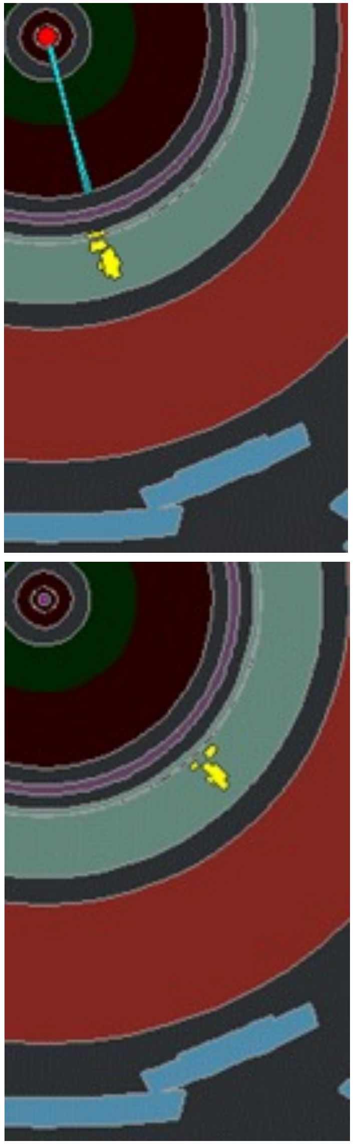


Total # of particles is proportional to energy of incoming particle

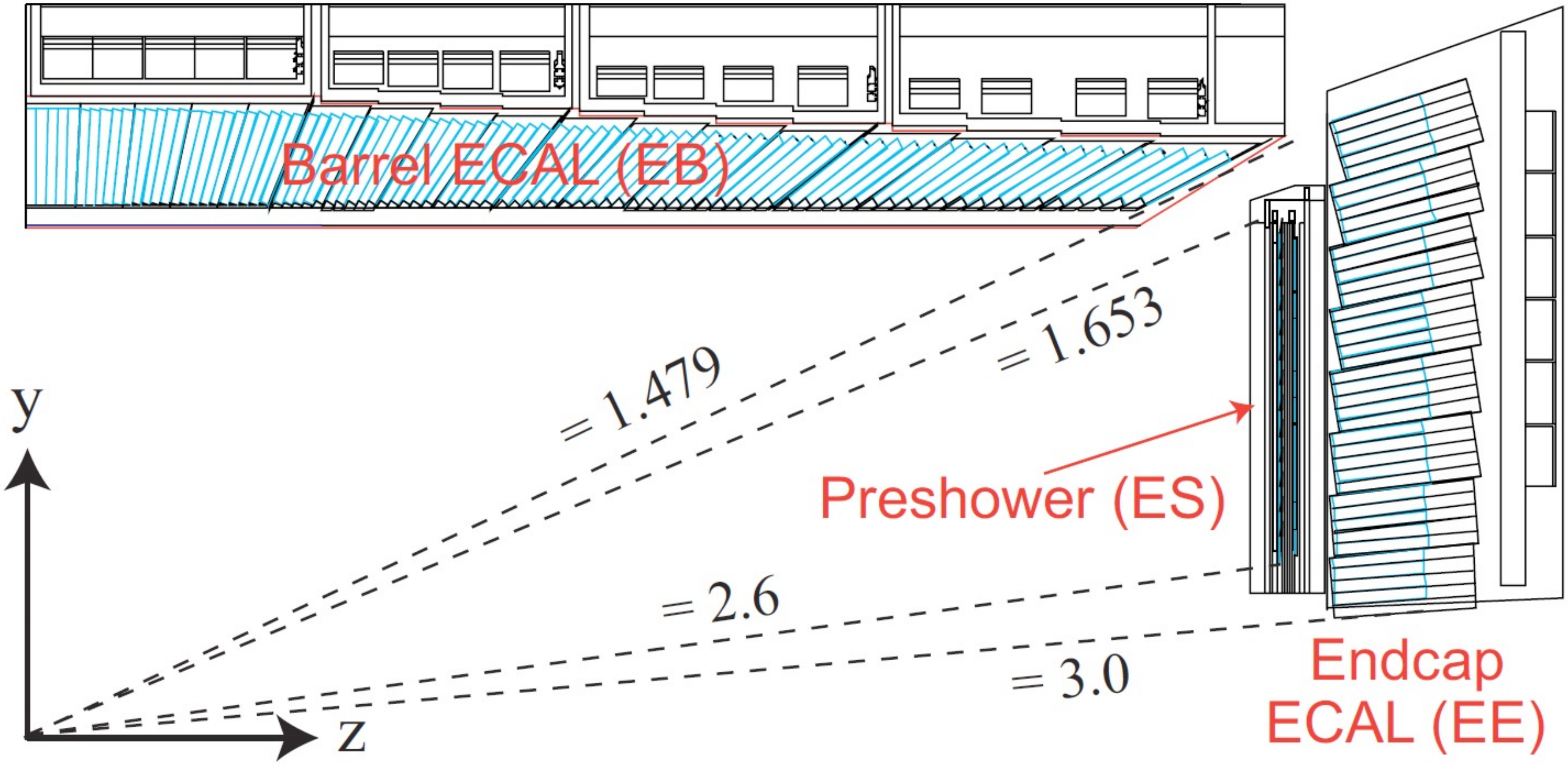
Light materials (blue) produce a signal proportional
to the number of charged particles traversing

Electron v.s. Photon

- 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

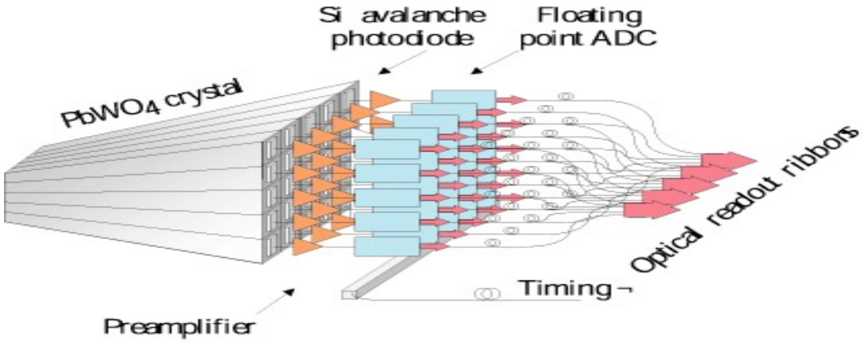


Ecal overview

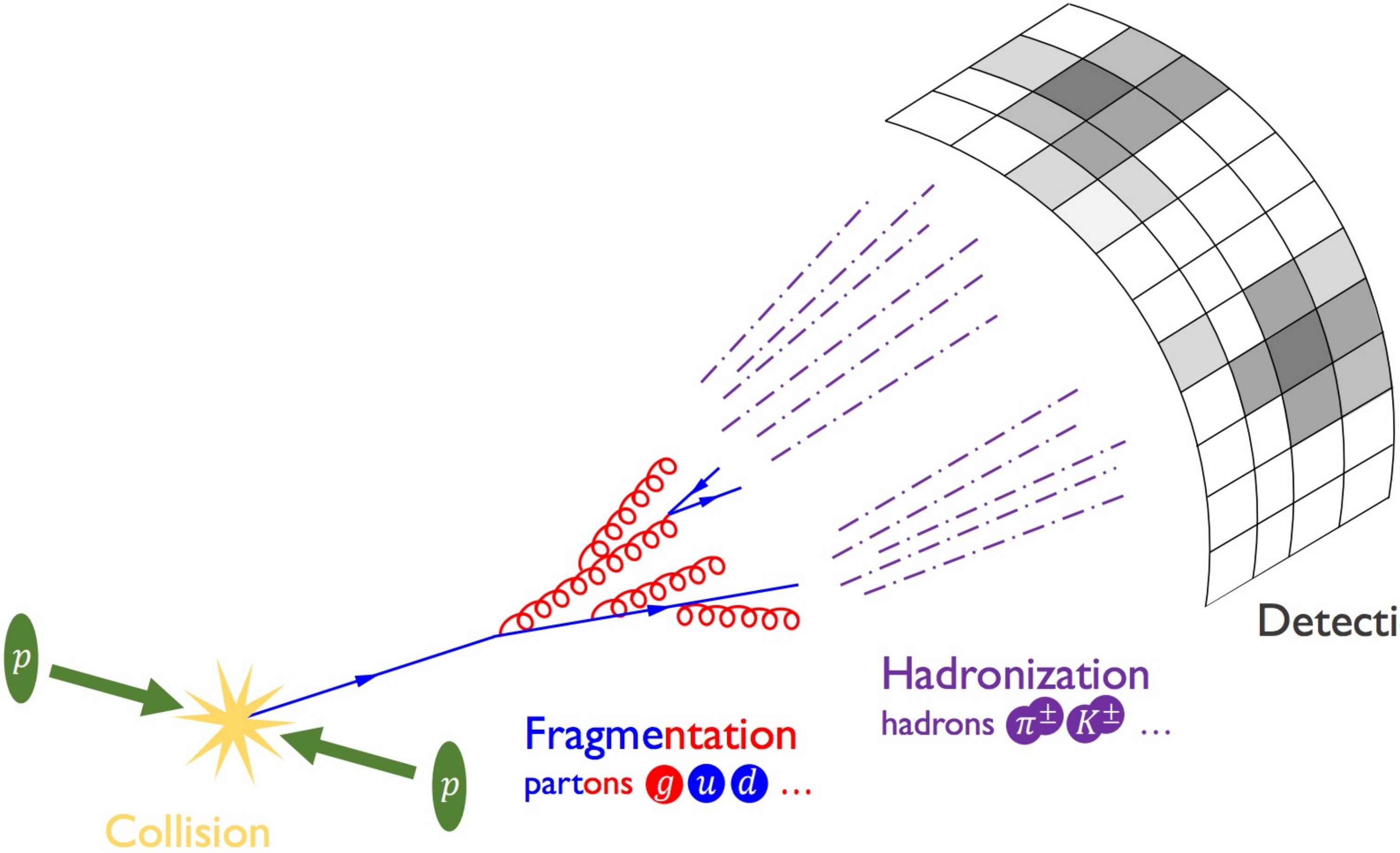


Technical Info on CMS ECal

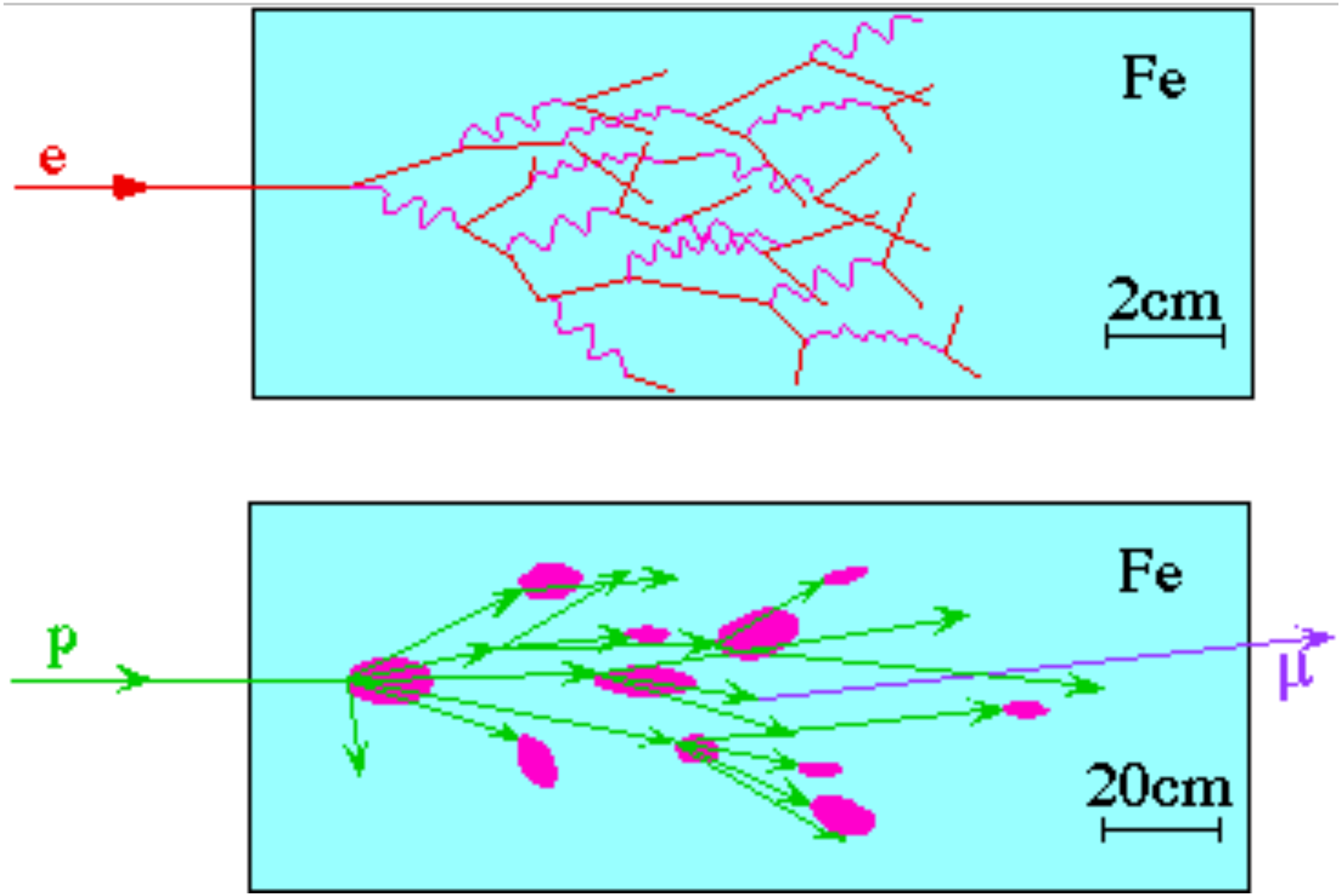
- ECAL is constructed from crystals of lead tungstate, $PbWO_4$
  - Very dense (heavier than steel) but highly transparent !!
- Crystals have a front size of 22 mm × 22 mm and a depth of 230 mm.
- They are set in a matrix of carbon fibre to keep them optically isolated
- "barrel" consists of 61,200 crystals formed into 36 "supermodules", each weighing around three tonnes and containing 1,700 crystals.
- The flat ECAL endcaps seal off the barrel at either end and are made up of almost 15,000 further crystals



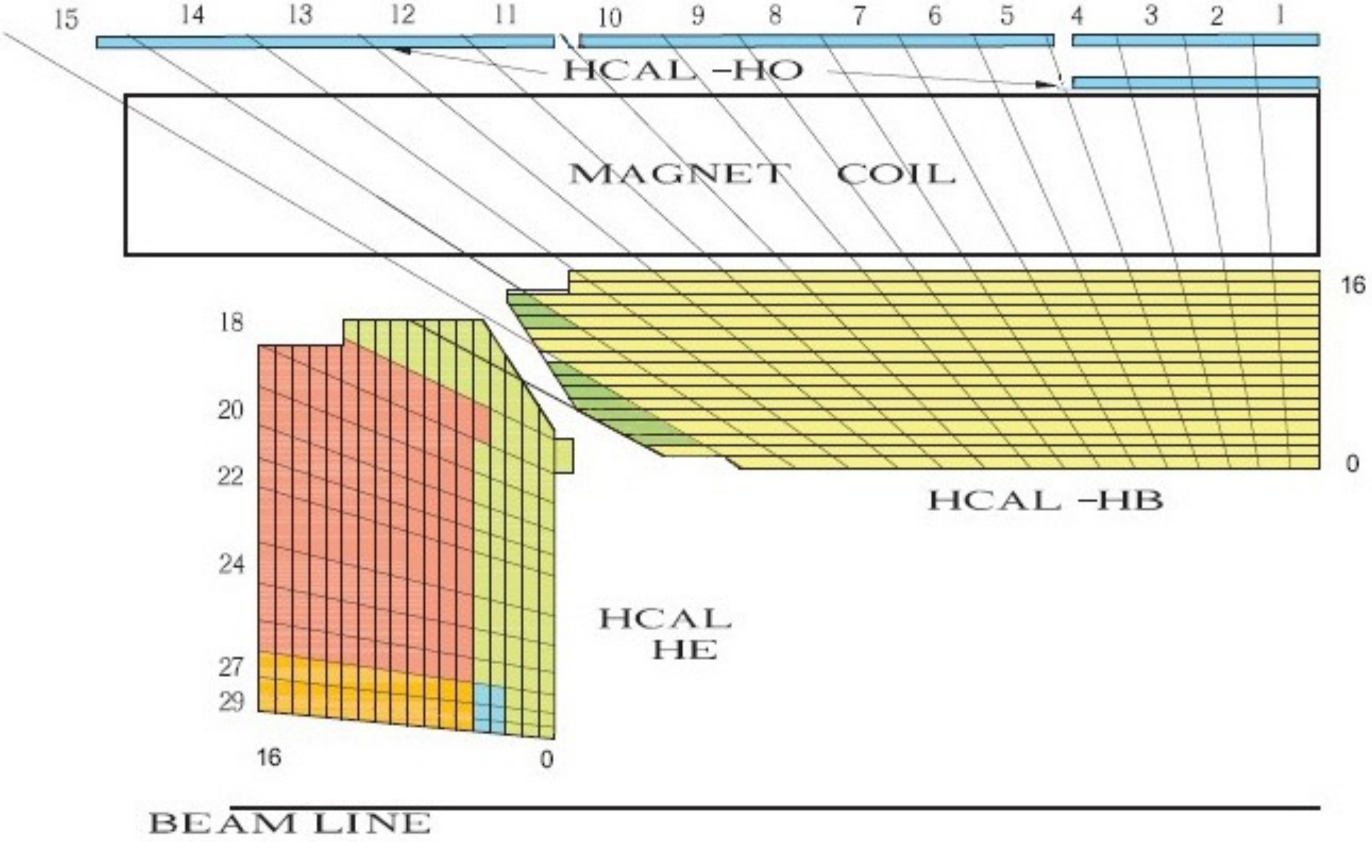
Hcal, hadron showering



Showering comparison



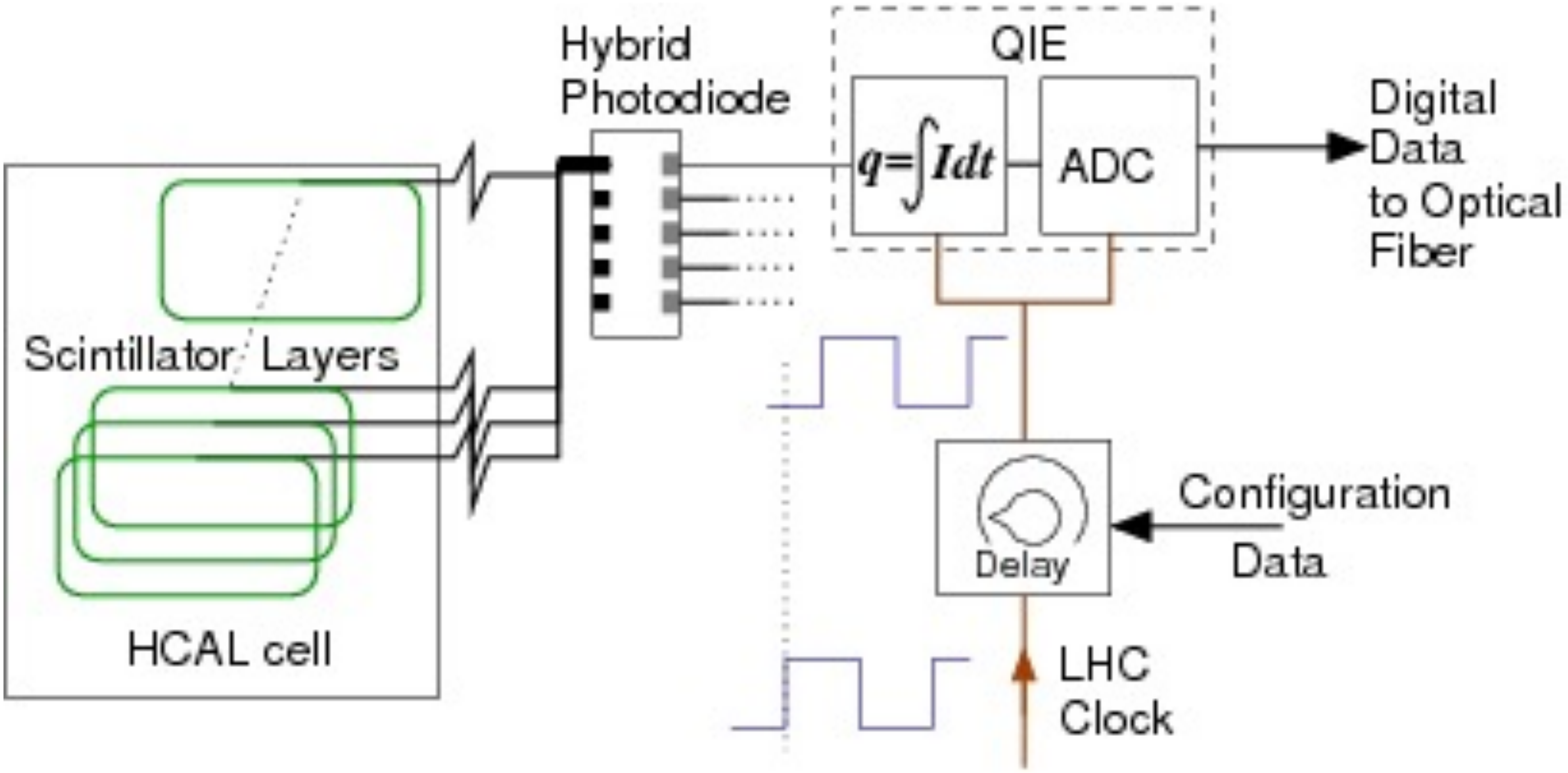
Hcal overview



Technical Info on CMS HCal

- HCAL is made of layers of dense material (brass or steel) interleaved with tiles of plastic scintillator
- About half of the brass used in the endcaps of the HCAL used to be Russian artillery shells.

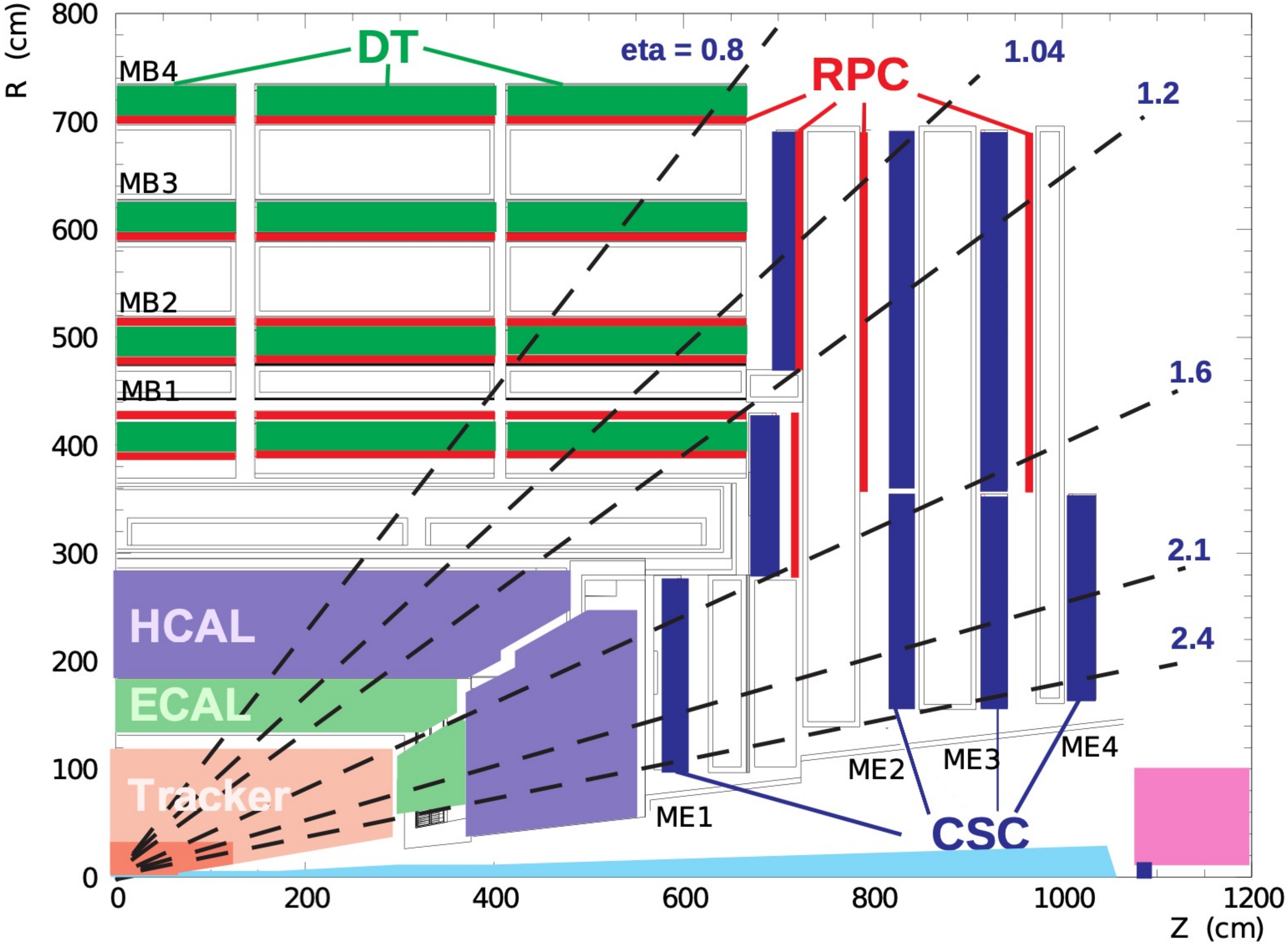
HCal front end electronics



Muon

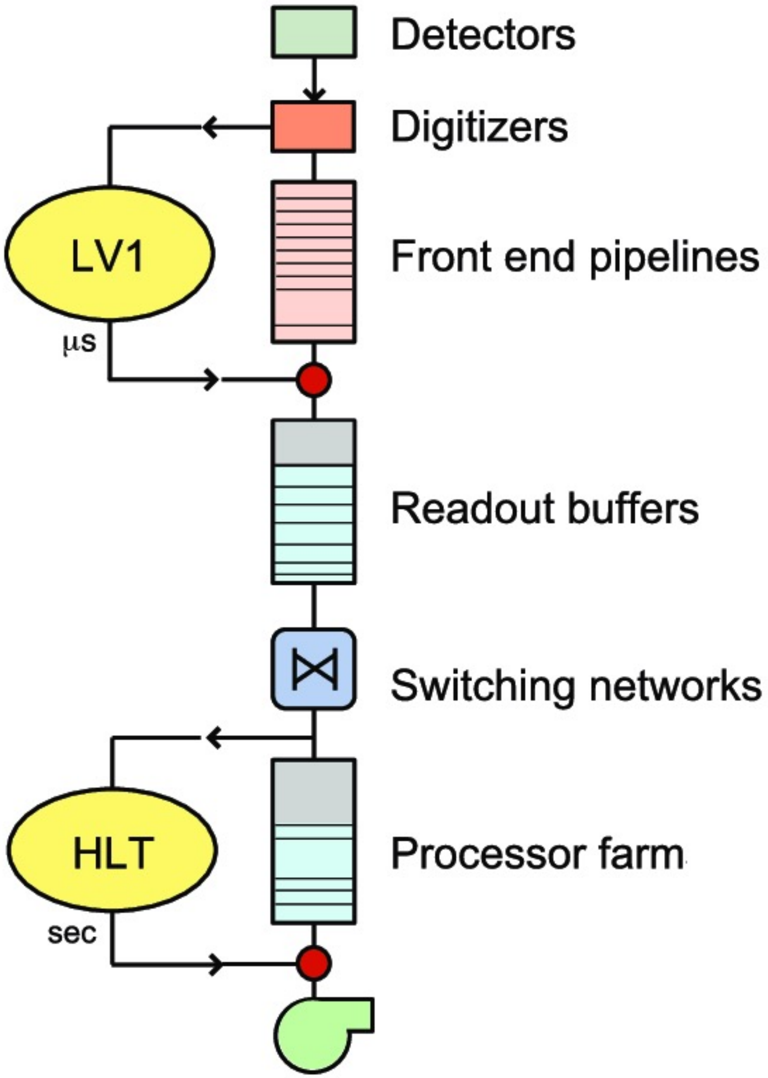
- Because of it’s long lifetime, the muon is basically a stable particle for us ($c\tau$ ~ 700 m)
- It does not feel the strong interaction
  - Therefore, they are very penetrating
- It‘s a minimum ionising particle (MIP)
  - Only little energy deposit in calorimeter
- However, at high energies (E>0.2 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 chambers and in the inner tracking detectors
- Both measurements are combined for the best track results

A quarter cross-section view of the CMS muon chambers

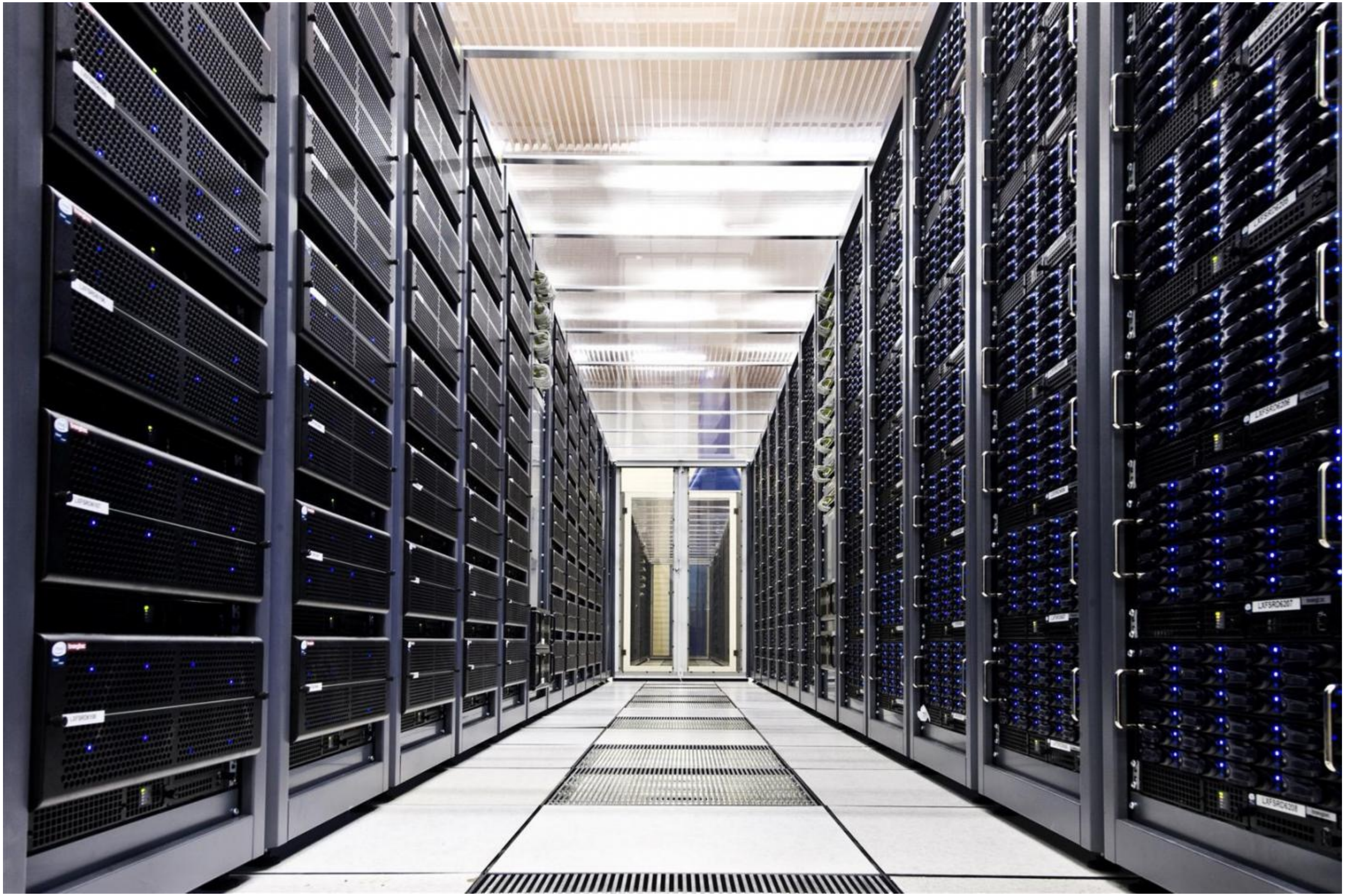


Trigger

- Most amazing feature of the CMS detector?
  - Taking data at 40 MHz rate
- Can NOT afford keeping all of them
- Data from each crossing is held in buffers. At L1 a decision is made with 1 μs using FPGAs.
- L1 reduces the rate at to 50 KHz
- HLT reduces the rate to just 1 KHz
- Data are then stored on tape for future analysis

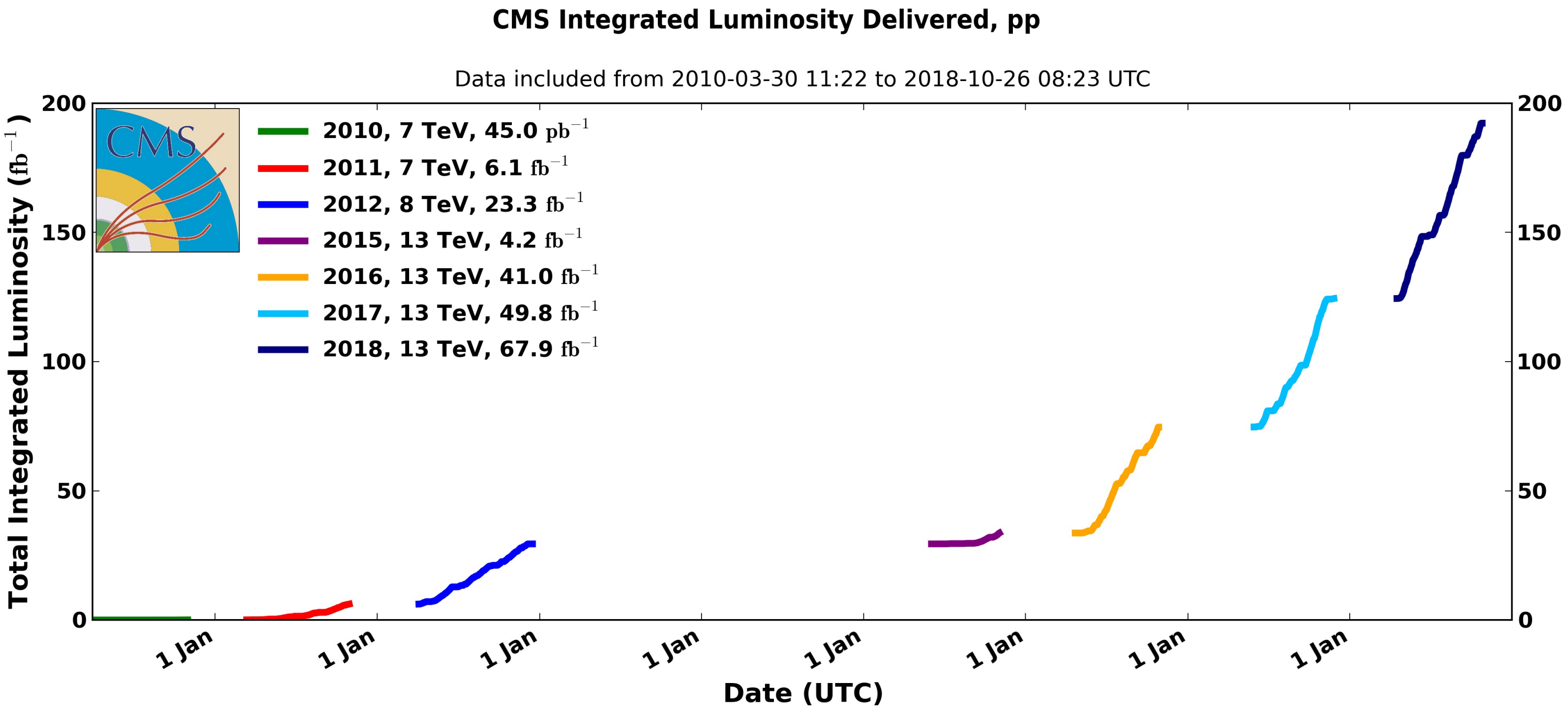


Computing



Data taken in the last decade

To see some rare processes, we need lots of data!



From RAW Data to Data Analysis

Reconstruction

Alignment

Calibration

Filtering

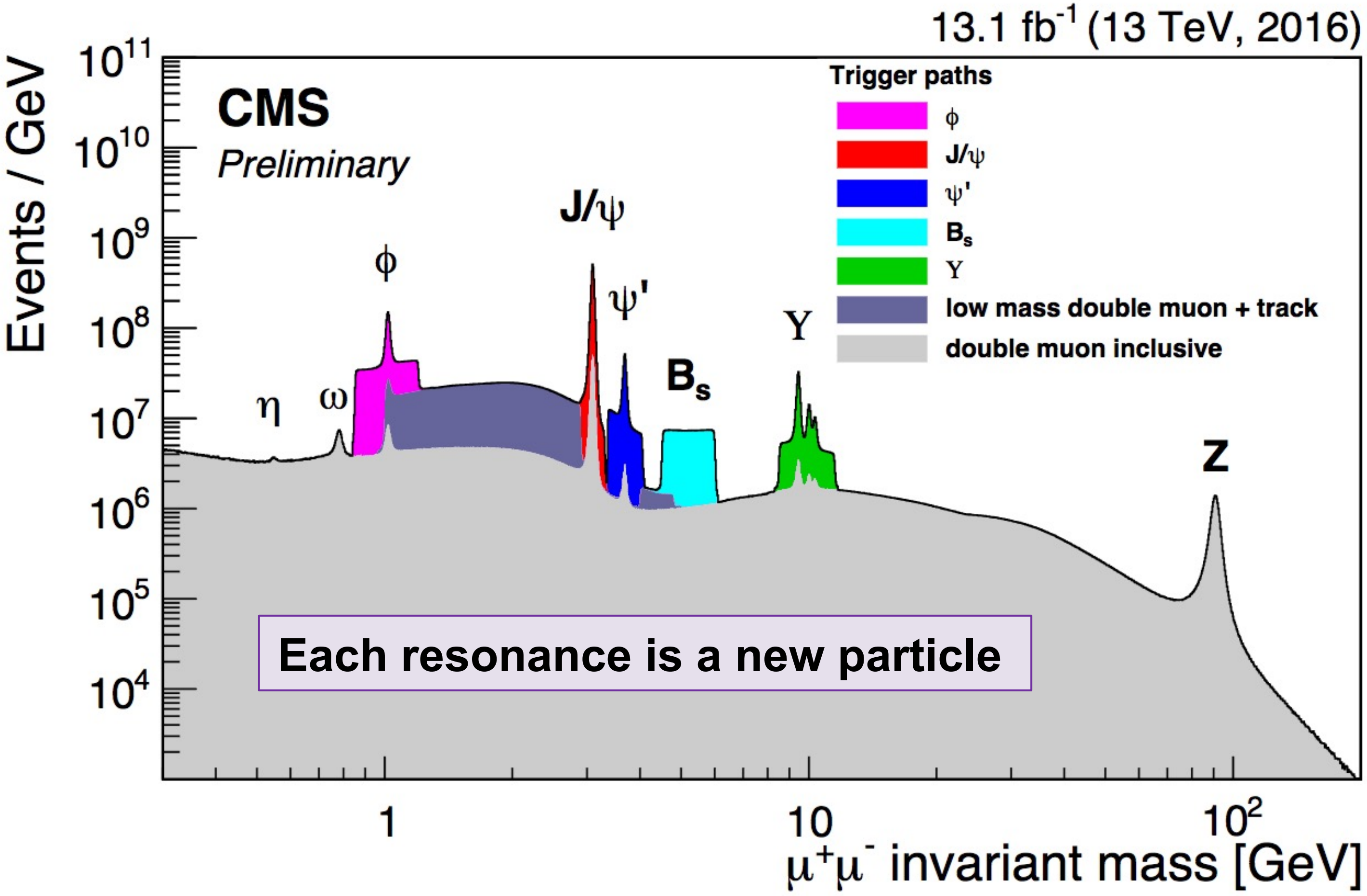
Validation

Skimming

…

\+ A huge effort on Simulation

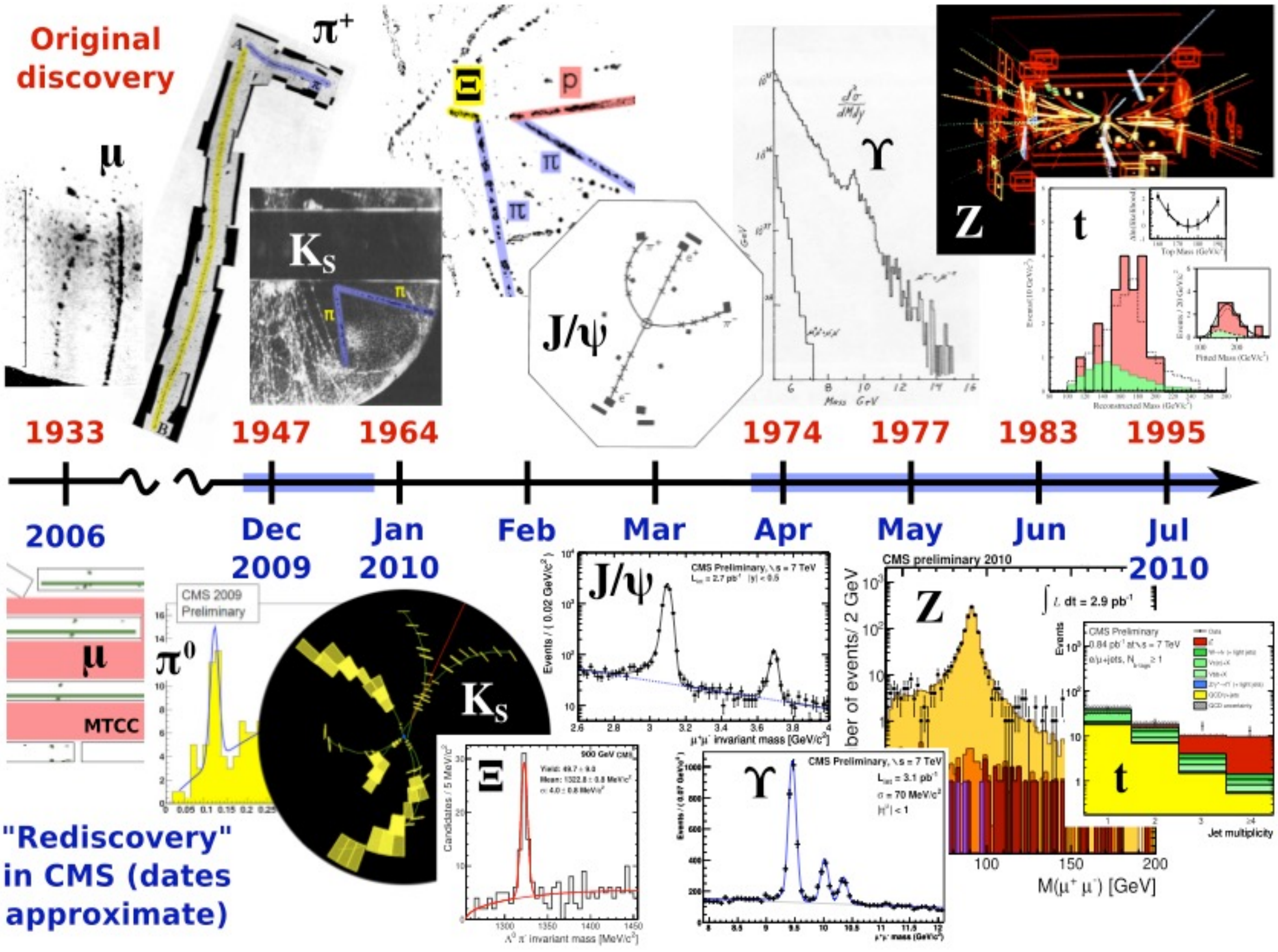
Di-muon resonances



Each resonance is a new particle

LHC was built to be a discovery machine, rather than only a re-discovery machine!

Re-discovery of the SM particles



Original discovery

1933	2006
1947	Dec 2009
1964	Jan 2010
	Feb
	Mar
1974	Apr
1977	May
1983	Jun
1995	Jul 2010

"Rediscovery" in CMS (dates approximate)

WHAT NEXT ?

And finally 4th of July 2012

CERN

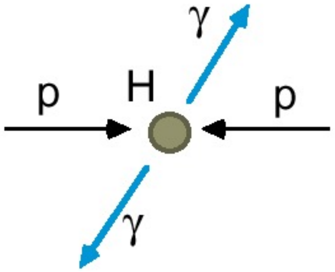
Melbourne

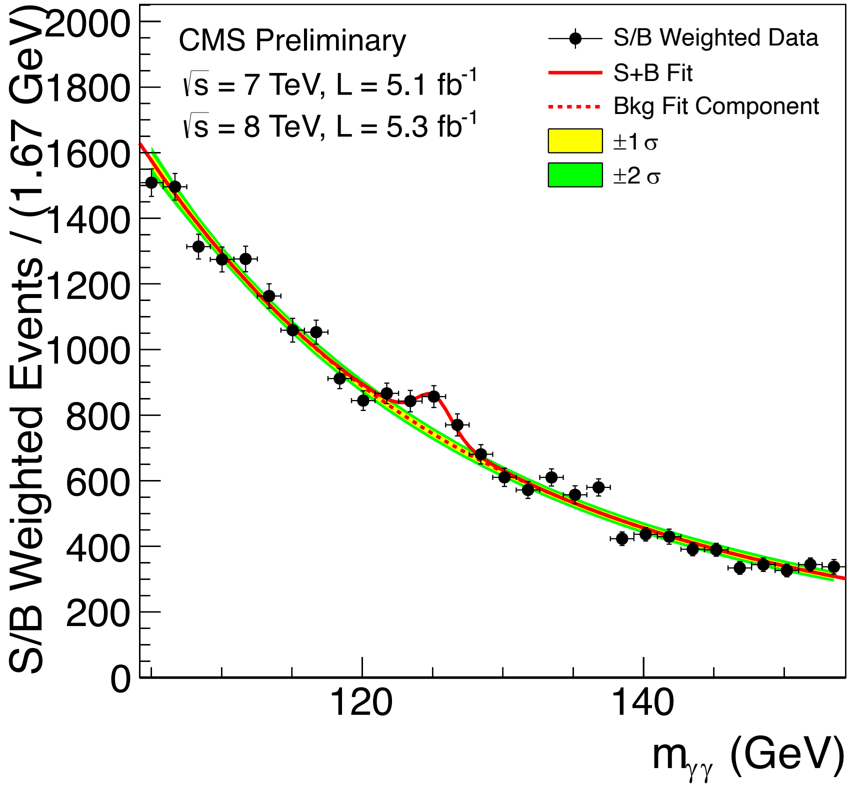
Rolf Heuer:

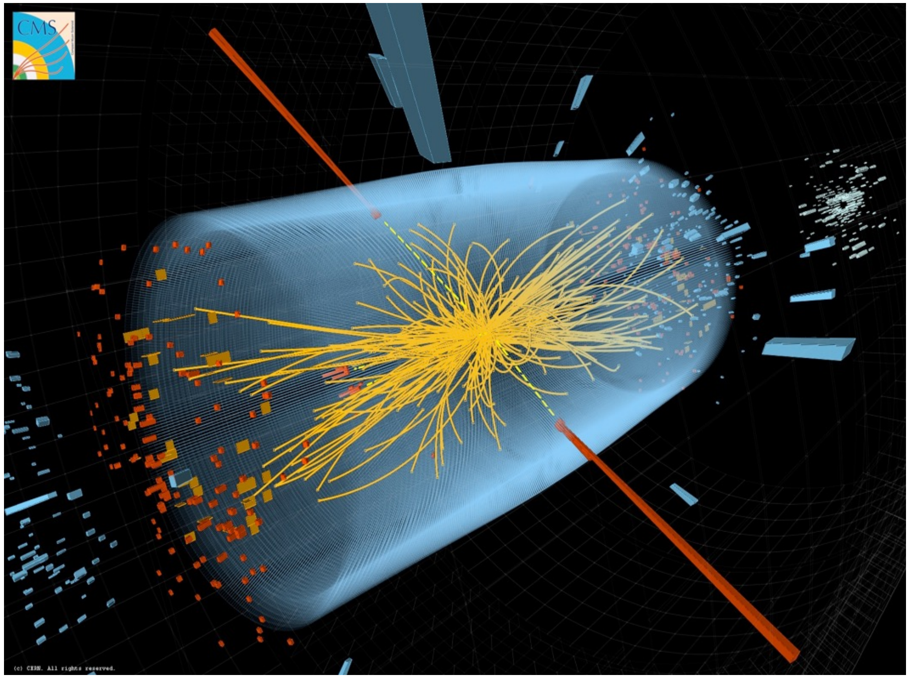
'We have it!'

4th of July 2012 – new Higgs–like particle discovery

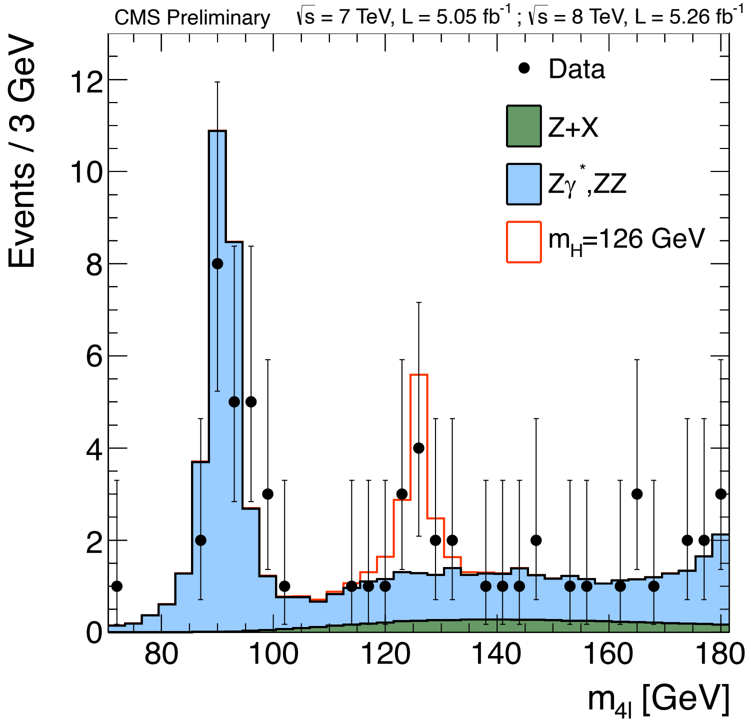
The first two discovery channels (**H**→γγ)

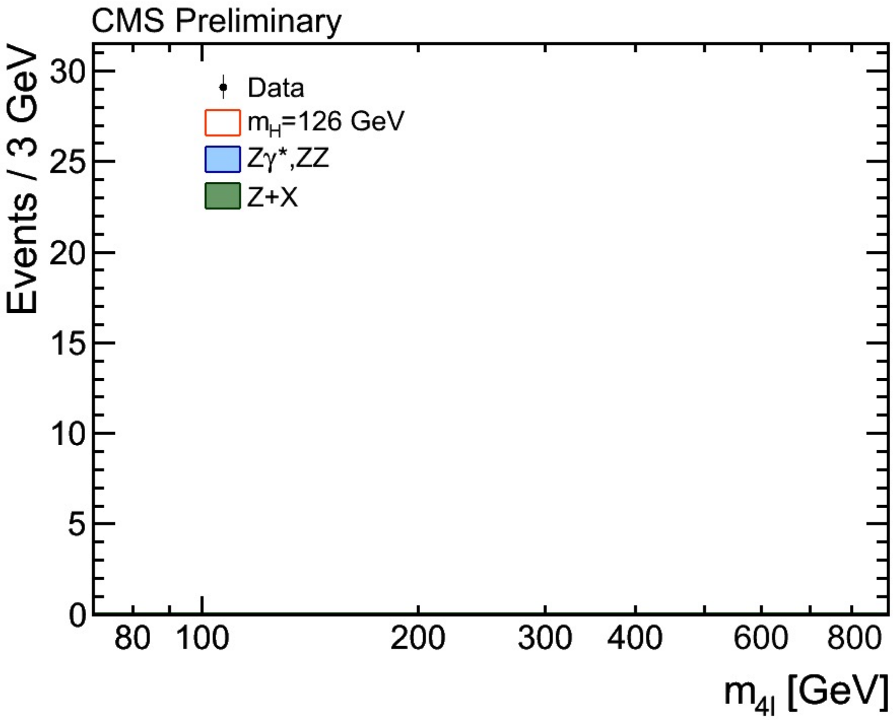






The first two discovery channels (**H→ZZ**)





Next?

We have found the Higgs boson☺ and SM seems complete…

… but SM is not capable of addressing all of our questions☹

i.e. Hierarchy problem, dark matter candidate, matter-antimatter asymmetry, …

We need NEW Physics to answer our questions!

Direct search for new Physics

Heavy Gauge Bosons

Leptoquarks

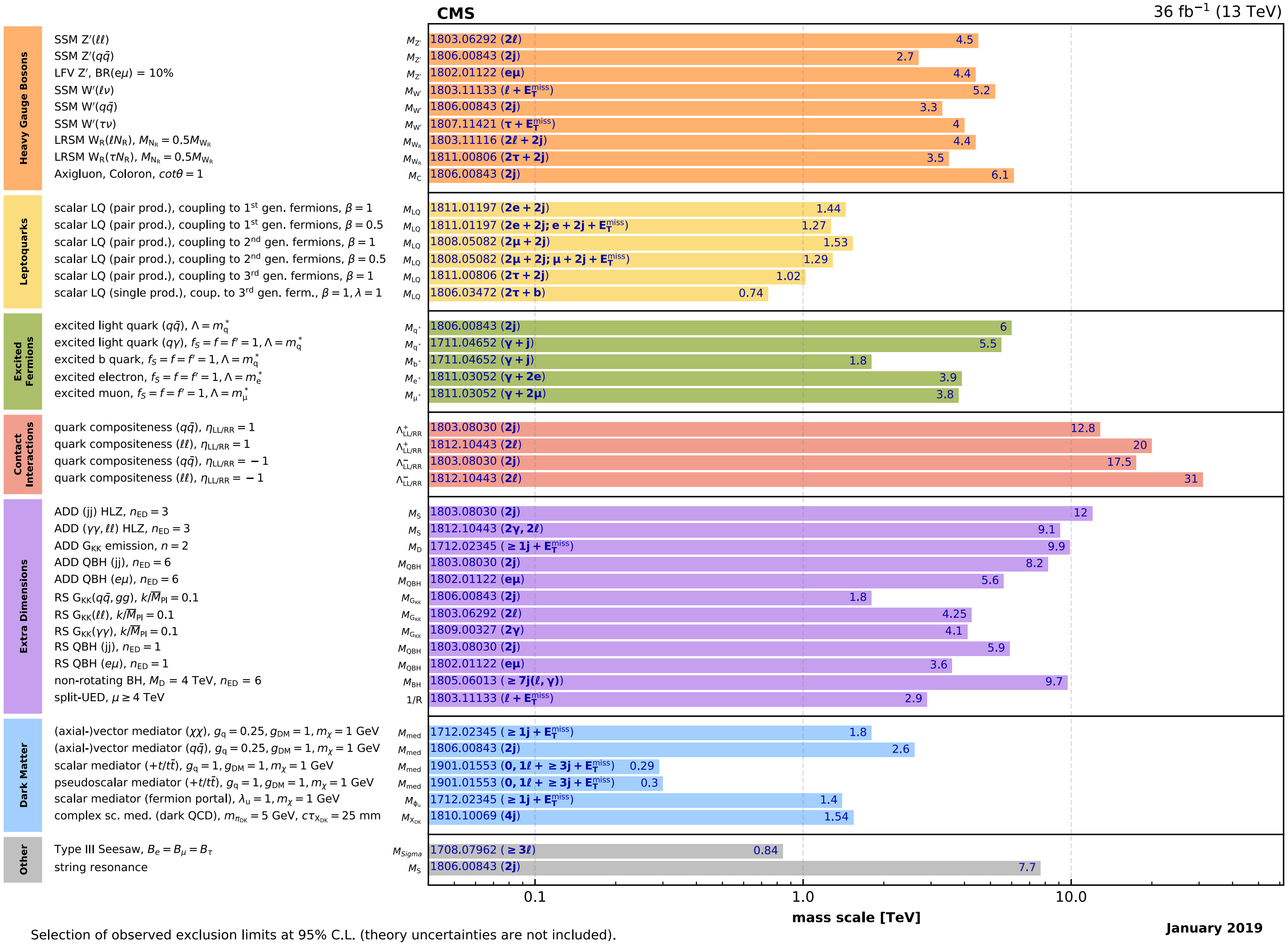
Exited fermions

Contact Interactions

Extra Dimensions

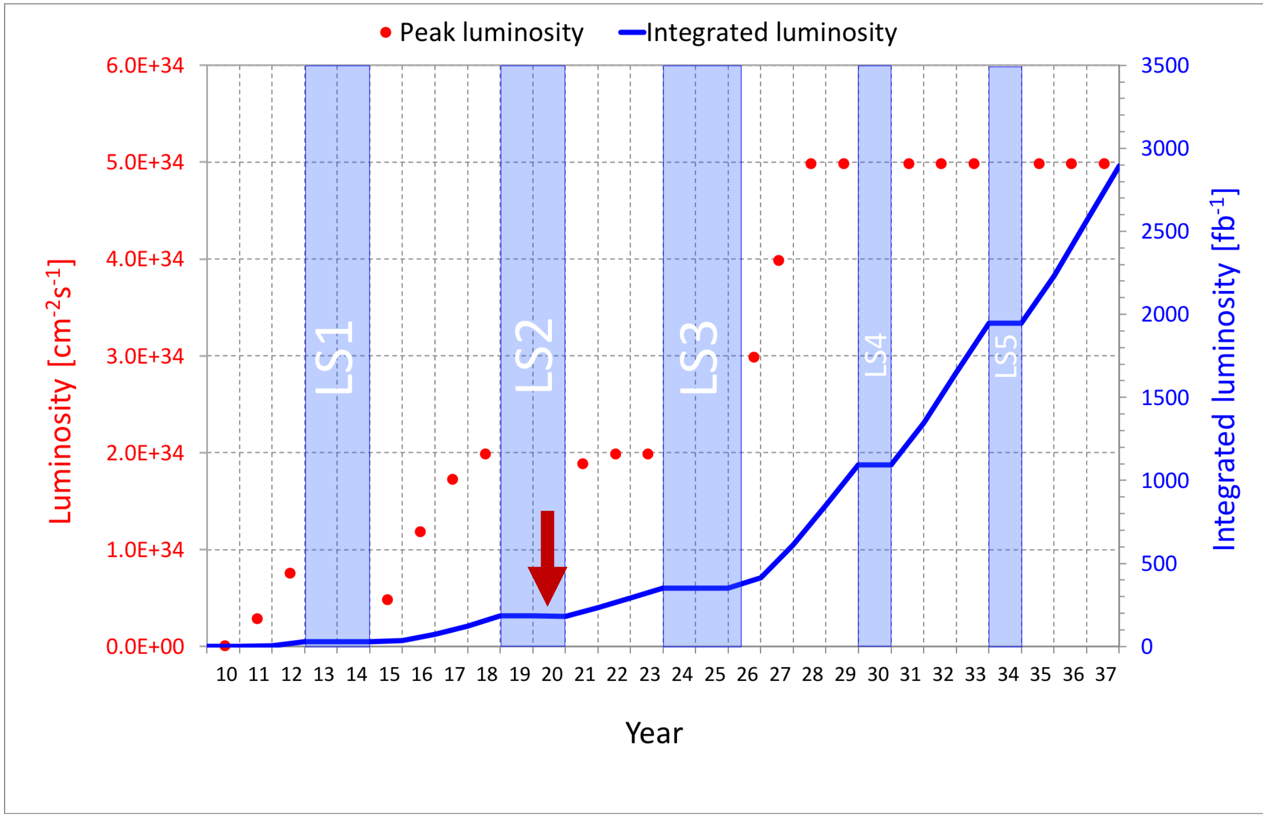
Dark Matter

Overview of CMS EXO results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

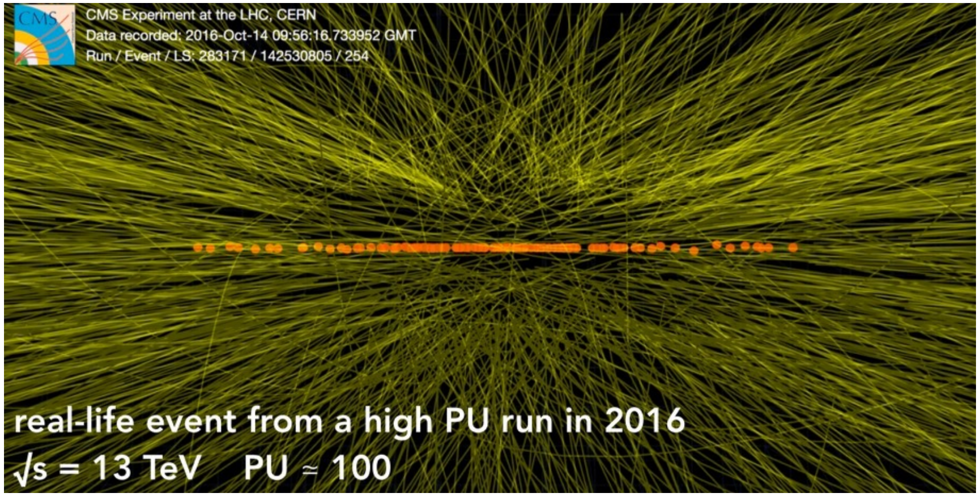
Luminosity projection in HL-LHC



- The current analyzed data is just a few % of the total data planned to be collected by the entire life of the LHC (particularly, during high luminosity phase)
- Collecting 300 fb^{-1} per year imposes several challenges to the experiments

Challenges with more data!

- Collecting a large amount of data per year imposes several challenges to the experiments
- The two main challenges are higher ***Pileup*** and ***Radiation***



Huge number of collisions pre-bunch crossing (pileup)

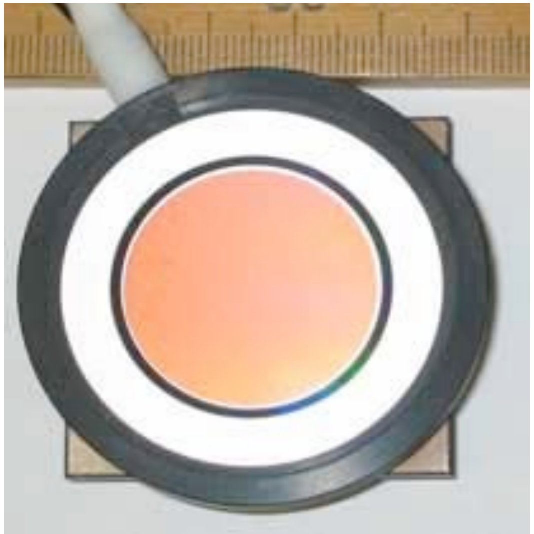
Example of plastic scintillator damaged by radiation

- Existing detectors are not capable of handling such conditions, thus we need a solution

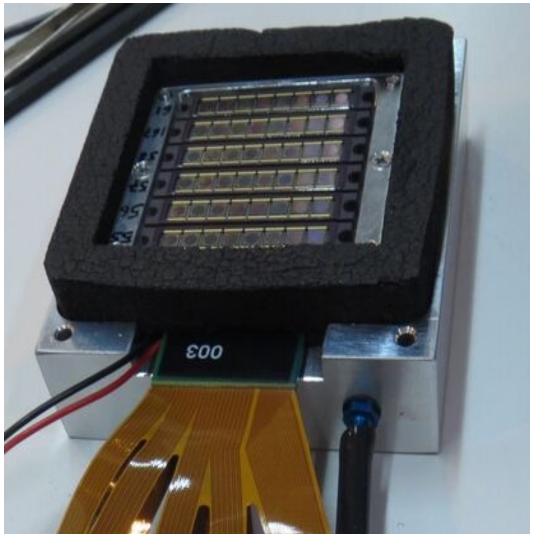
The solution is ….

Phase I upgrade

- Upgrade of various components of the CMS detector has planed in several phases
- Phase I is almost accomplished and Phase II activities are ongoing
- The main goal of phase 1 HCAL upgrade of front-end electronics was the replacement of the **H**ybrid**P**hoto**D**iode with **S**ilicon**P**hoto**M**ultiplier
- SiPMs operate at much lower voltage, they have higher gain, lower noise, and offer a better signal to noise ratio



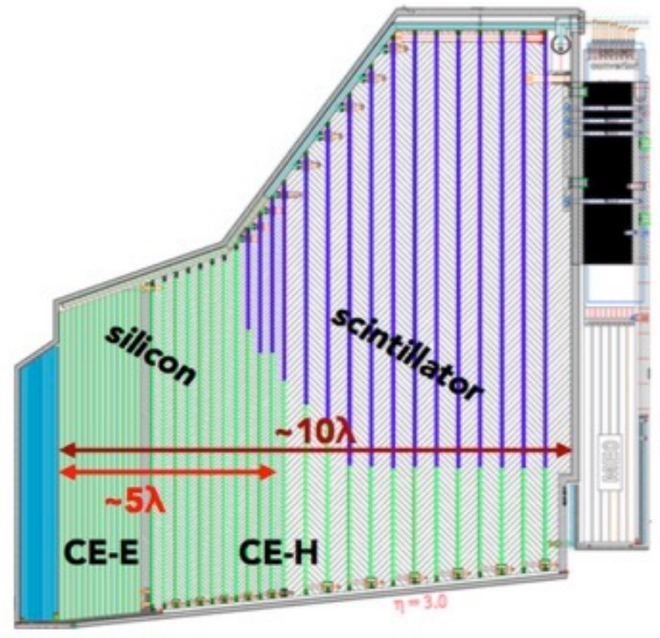
HPD Array (18 channel)

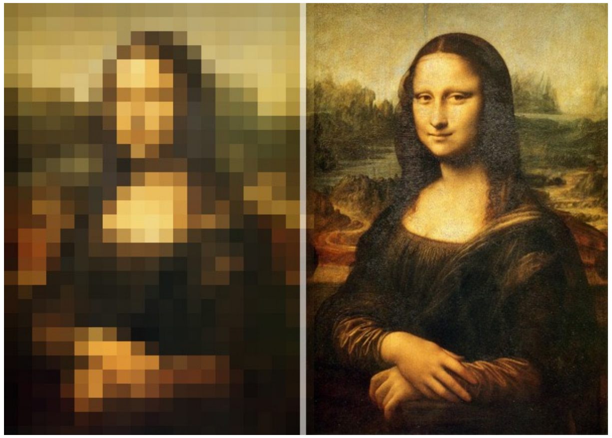


SiPM Array (48 channel)

Phase II upgrade: Forward calorimeter

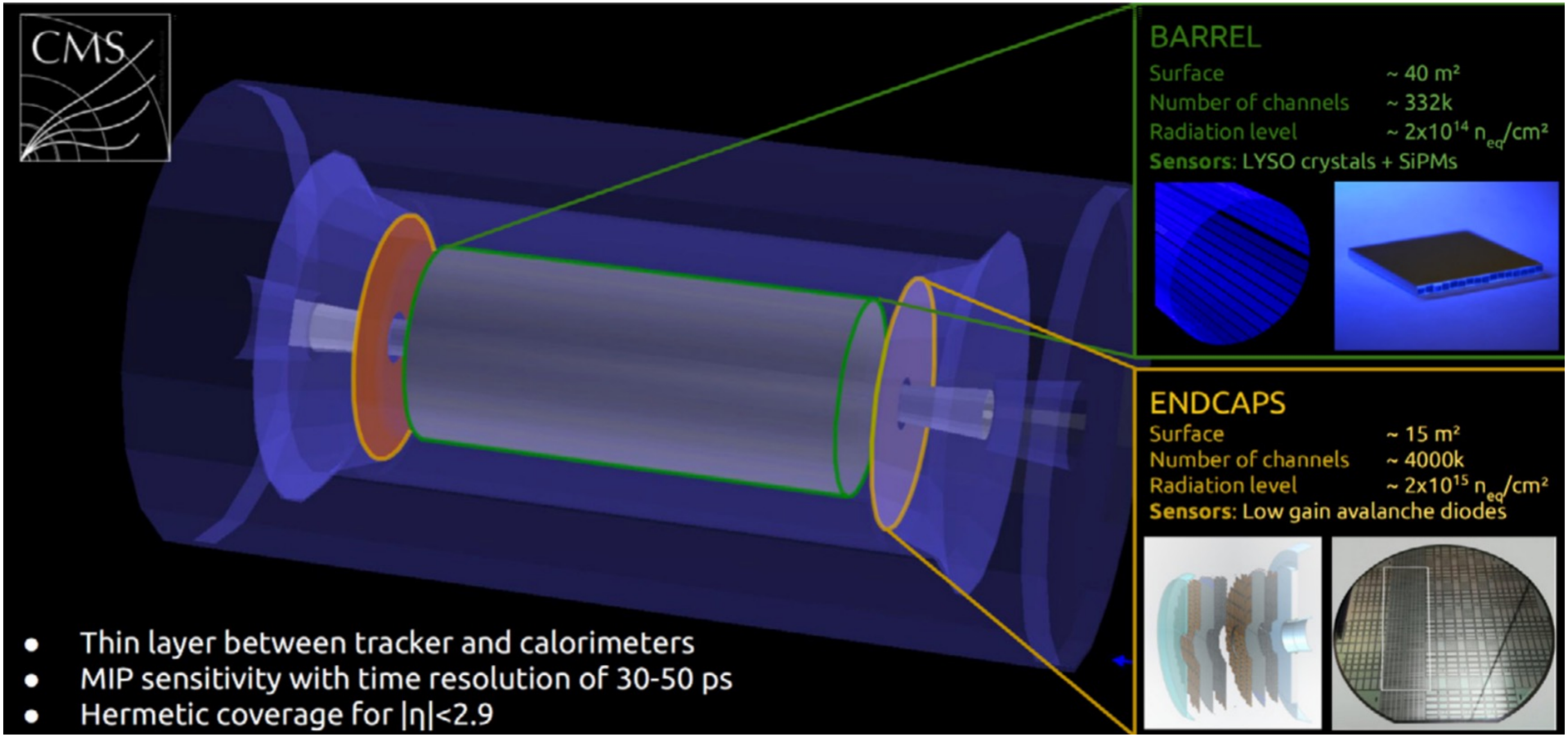
- The High Granularity Calorimeter (HGCal) will become the new Calorimeter Endcap
- Fine granularity enhances the particle flow reconstruction and ID/pileup mitigation
- More granular means adding more readout channels:
  - Low resolution → high resolution image
  - Better separating signal from noise.
- Radiation hard technology is used based on a mix of silicon and scintillator detector





Phase II upgrade: MIP Timing detector

- ➢A timing detector can help us to add a new dimension (time) to the reconstruction of the particles
- ➢Extremely useful in suppressing pileups
- ➢Provides unique tools for physics of long-lived particles!



BARREL

Surface	~ 40 m²
Number of channels	~ 332k
Radiation level	~ 2×10^{14} n_{eq}/cm²

Sensors: LYSO crystals + SiPMs

ENDCAPS

Surface	~ 15 m²
Number of channels	~ 4000k
Radiation level	~ 2×10^{15} n_{eq}/cm²

Sensors: Low gain avalanche diodes

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for |η|<2.9

Thanks
For Your Attention