Radiation Detectors

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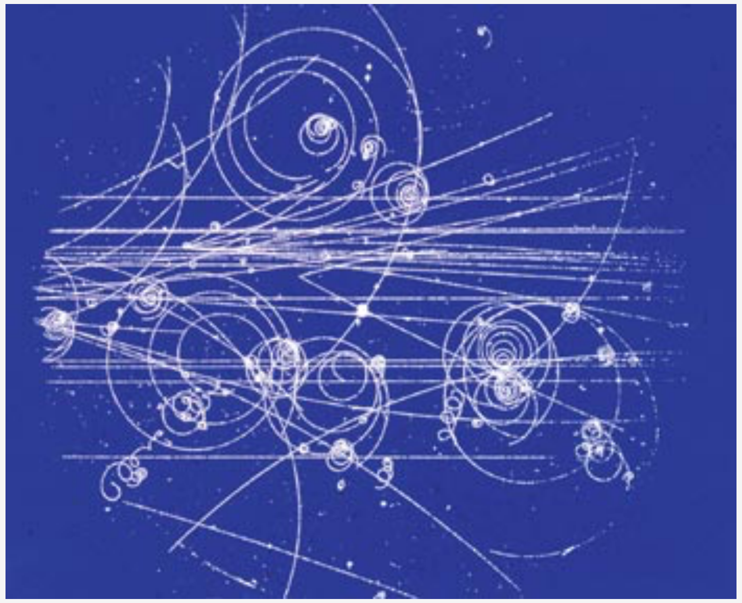
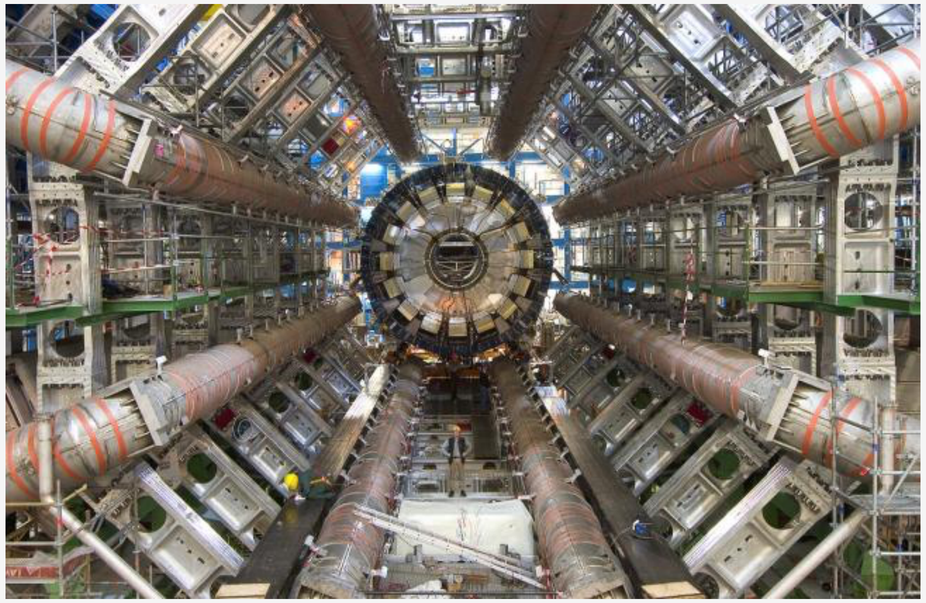
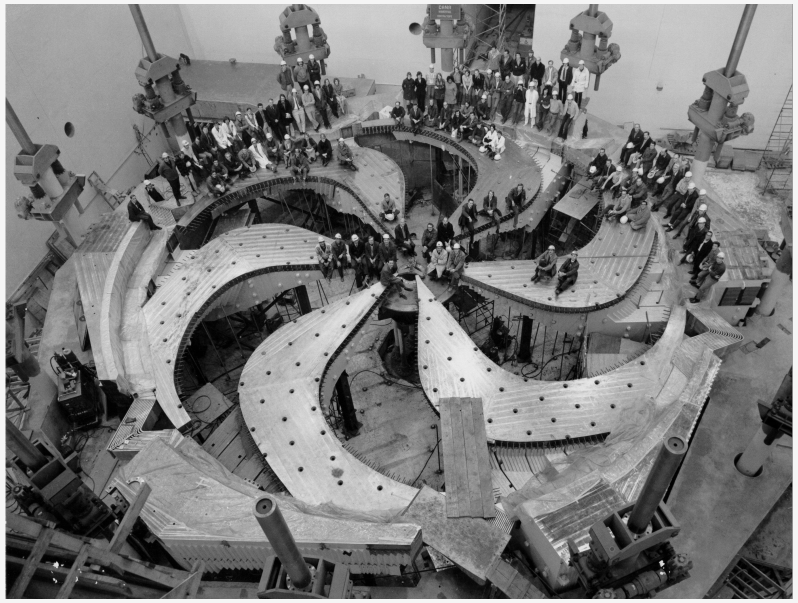
  

Particle Detectors

Particle Detectors are fundamental tools in physics experiments involving radiation measurements. They can be broadly divided in scintillation, Cerenkov, gaseous and semiconductor detectors, according to the physics principle they exploit. Another possible classification is based on the best application in measuring a physical quantity.
The following table provides a summary about the detectors types and their most common application.

	Counting	Energy	Momentum	Position	Time	Particle ID
Scintillation Detector	X	X			X	X
Cerenkov Detector	X				X	X
Gas Detectors			X	X		X
Semiconductor Detectors	X	X	X	X		

Scintillation Detectors

In **scintillation detectors** , the incoming radiation is converted into light. The working principle of this kind of detectors can be summarized in the following steps:

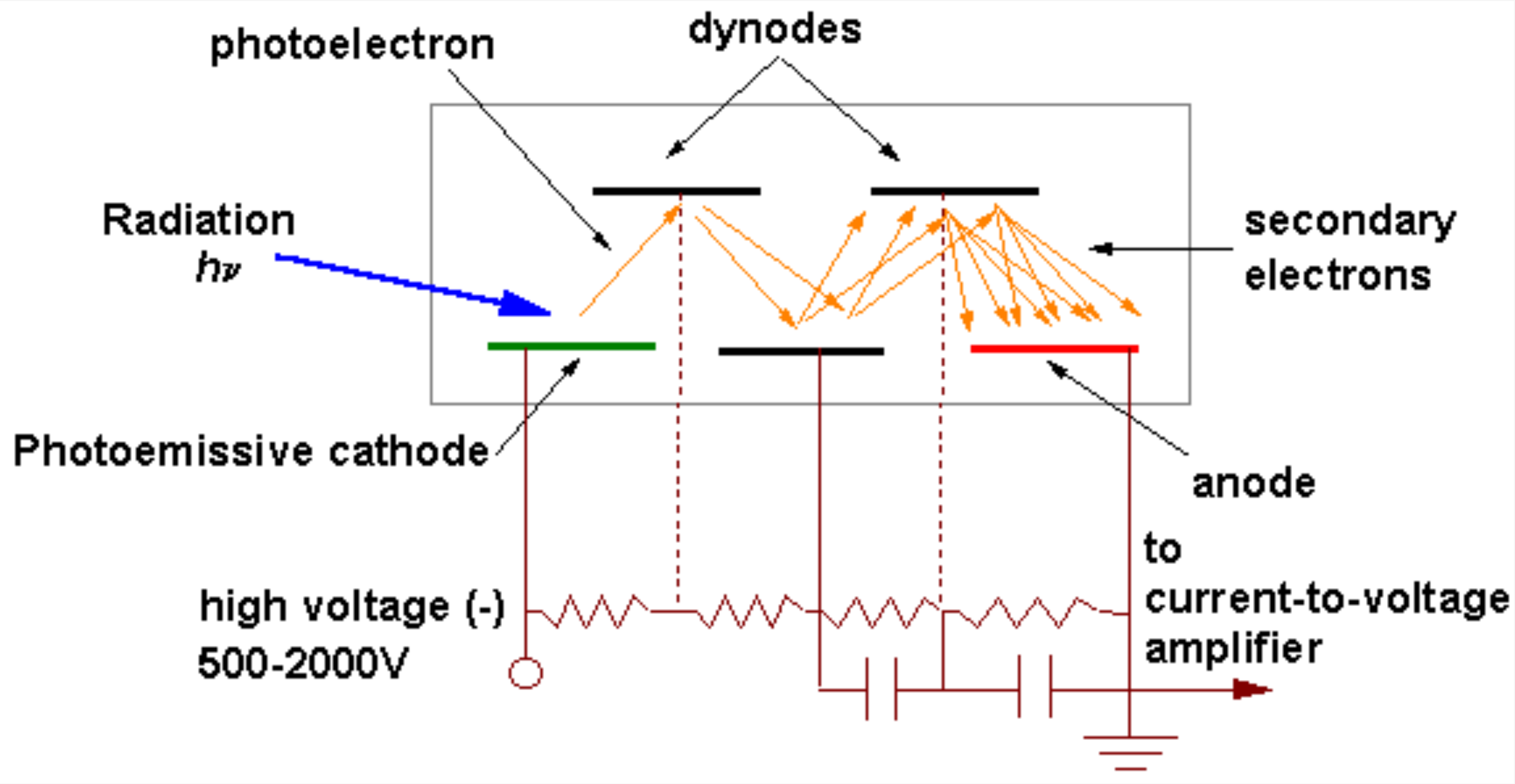
1) Heavy charged particles, photon, electrons etc, entering a material undergo primary interactions according to the particle type.

2) Electrons (mainly) produced in the primary interactions ionize and excite more atoms or molecules. The de-excitation of atoms and molecules gives rise to low-energy photons. This process continues until no more energy is available. In general, the radiation induces in the material what is called fluorescence.

3) The fluorescence photons are guided to a photocathode which is a metallic film from which it is easy to extract electrons. Usually each photon extract at most one photoelectron.

4) The cathode is followed by a device which is able to multiply the electrons by huge factors. The most common device is the photomultiplier tube (PMT), with multiplication factors of 10^6-10^7 times. In this way,
the PMT produces a signal which can be easily measured.
NOTE: Nowadays, devices based on semiconductor technology might replace PMTs in some physics applications: examples are e.g. APDs (avalanche photodetectors) or SiPM (silicon photomultipliers).

Photomultiplier Tubes



PMTs are made of a cathode and an amplification chain.
The multiplication stages are called dynodes and they are usually separated by ~100V potentials. About 5 electrons are liberated on a dynode by a single electron coming from the previous stage. At the end of N stages, the electron current from the cathode is amplified $\sim5^N$ times.

Silicon Photomultipliers (I)

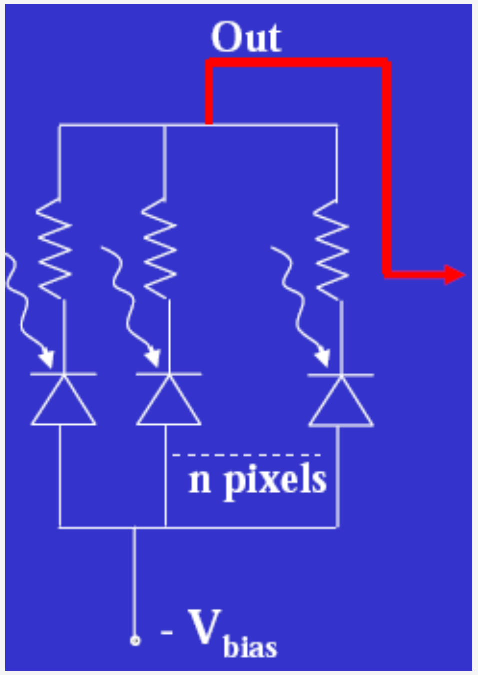
SiPM are solid state silicon based photomultipliers. These devices are based on an array of SPADs (single-photon avalanche diode) which operate in Geiger-Mueller ("digital") mode. The electric readout of many "digital" SPADs gives rise to a continuous output signal. The APD pixels have a very high surface density (~1000/mm^2) on a SiPM.

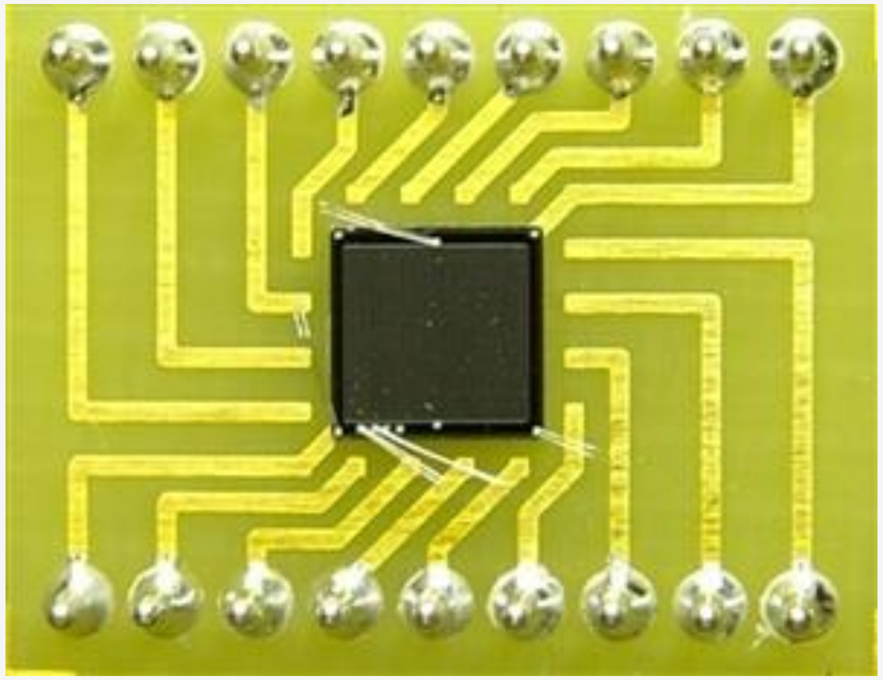
Advantages over PMTs:

- More compact and robust
- Less voltage required (~70V vs >1000V)
- Less generated heat
- Almost insensible to magnetic fields (up to 15T)
- Gain comparable to PMTs
- Low cost

Drawbacks

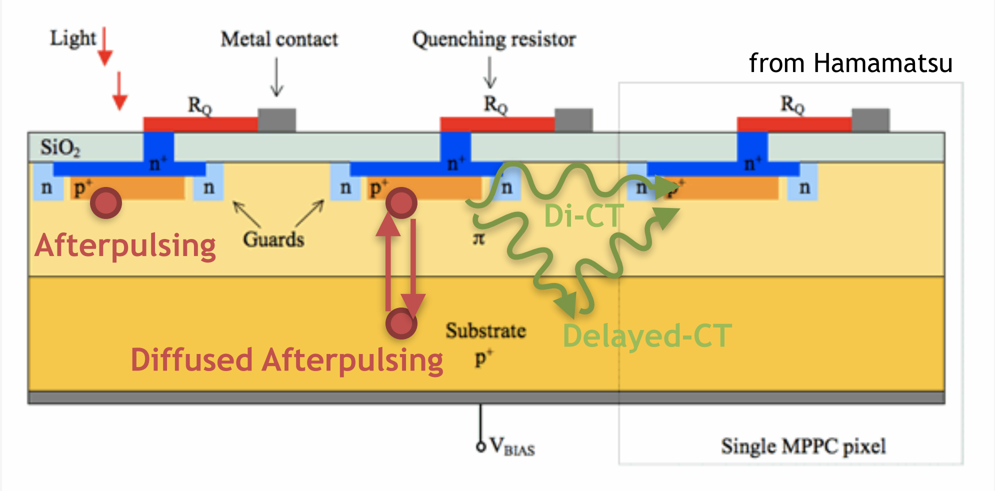
- Dark Counts
- Optical Cross-Talk
- Afterpulse effects due to impurities
- Long recovery time of pixels can limit rate

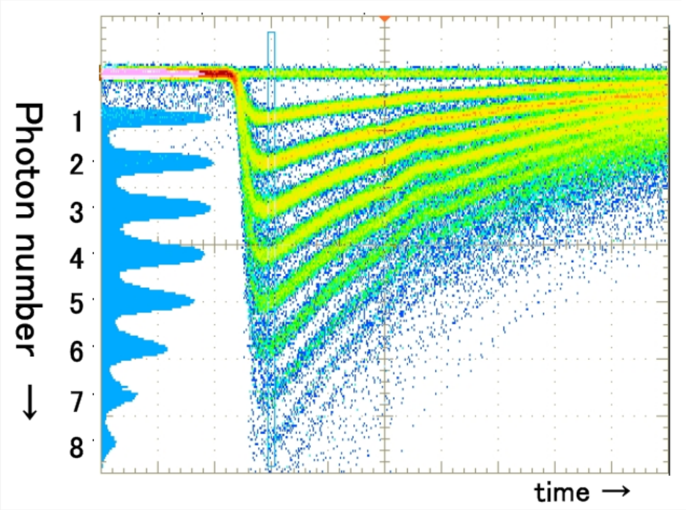


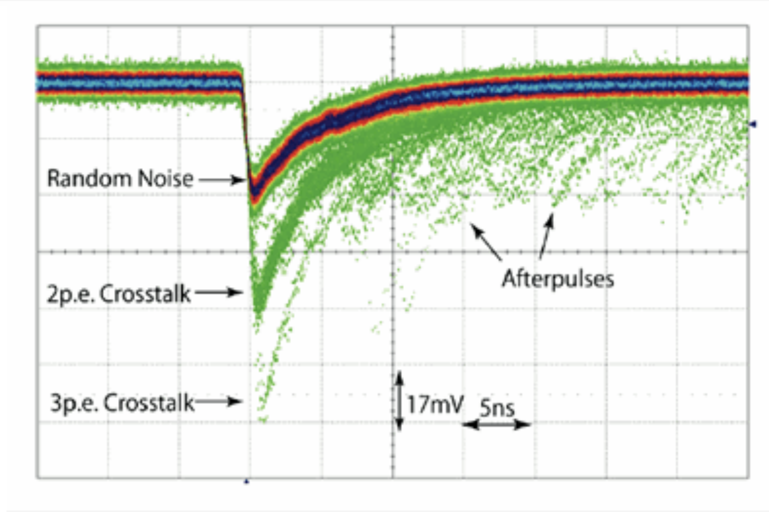


Silicon Photomultipliers (II)

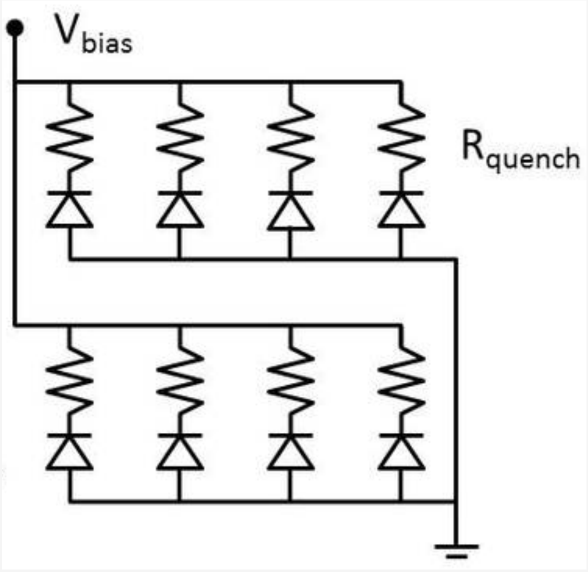
Cross-section of 3 siPM microcells







Connection Scheme

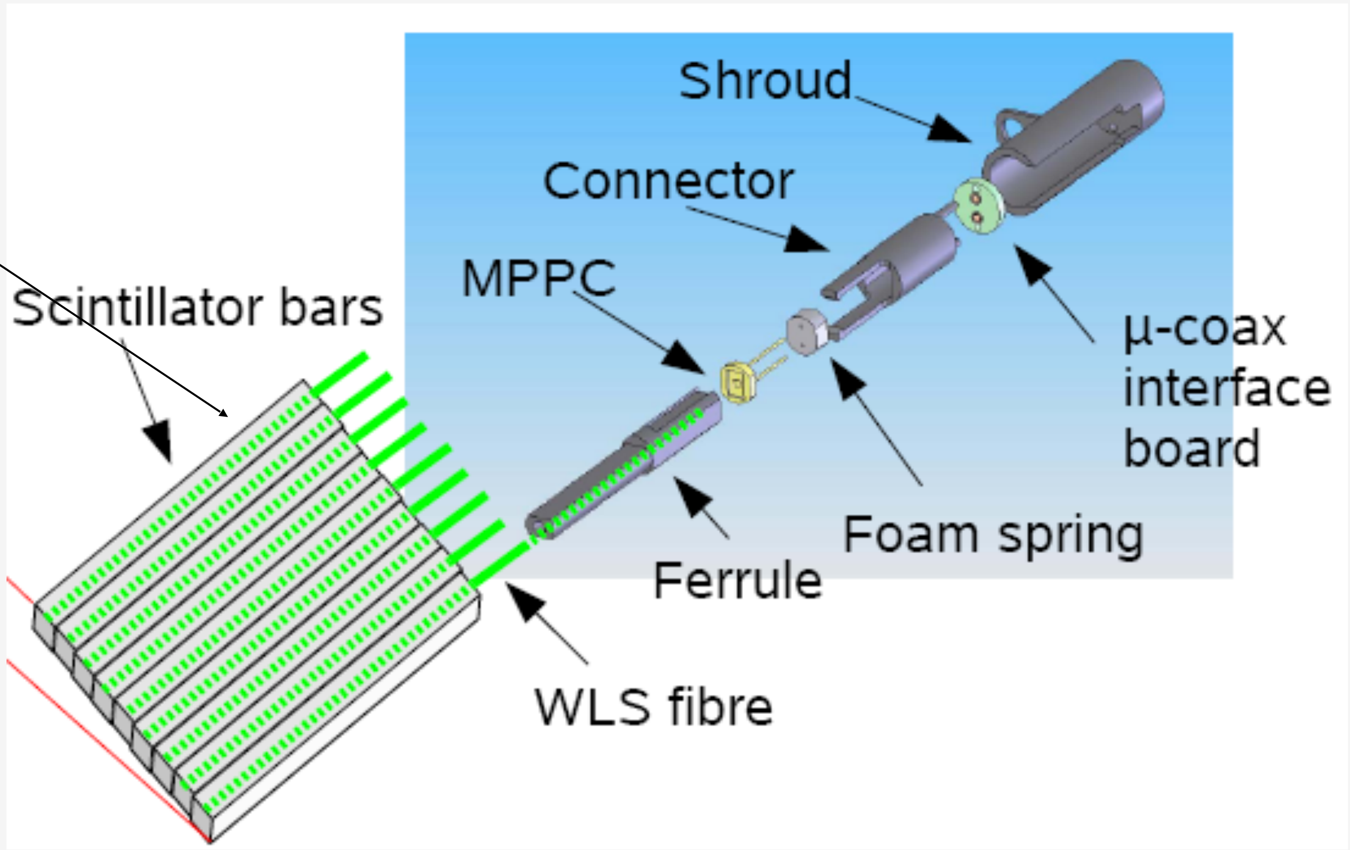


Output

$$A_i \propto C(V - V_{bd})$$

$$A = \sum_i A_i$$

Silicon Photomultipliers (III)



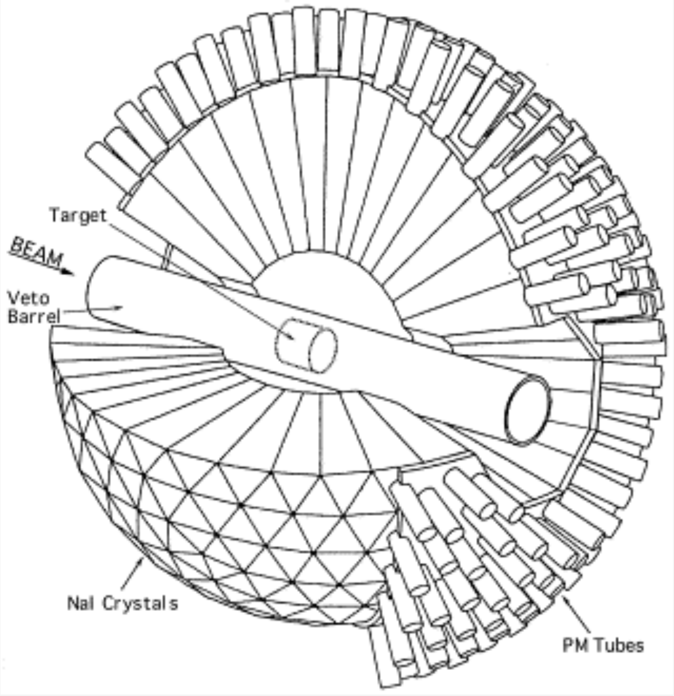
The T2K neutrino oscillation experiment was one of the first large scale applications of SiPMs. The light produced by extruded scintillator bars arranged in a XY scheme is collected by WLS fibers and read out by SiPMs.

Scintillation Materials

Inorganic Scintillators:

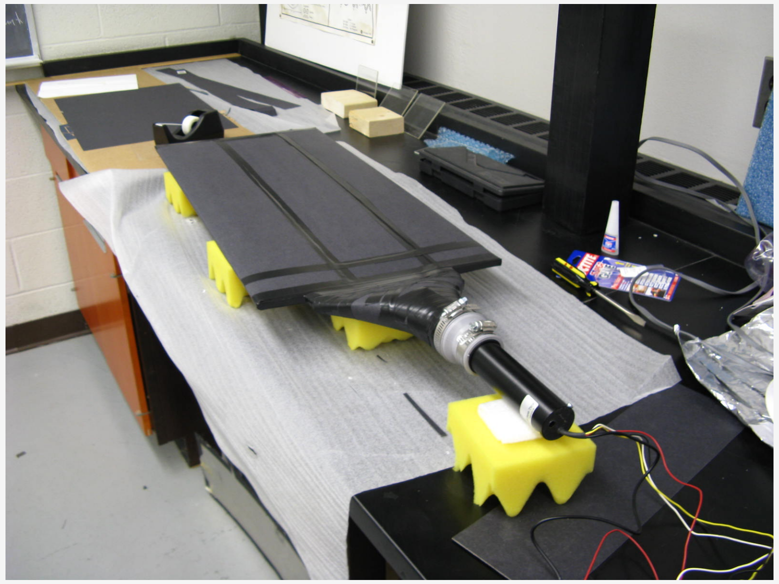
This kind of scintillators are mainly crystals which are grown industrially. The scintillation process is in general slower than in organic materials, but they have other interesting properties. They can be machined into small pieces (better position resolution) and can have very good energy resolution. Crystals are usually doped with small amounts of other atomic species for improving the scintillation process.

The main application of the scintillation crystals is calorimetry (energy measurements). They are also largely used in medical physics applications (e.g. PET). Commonly used crystals are: NaI(Tl), CsI, BGO, BaF_2 ...



Organic Scintillators:

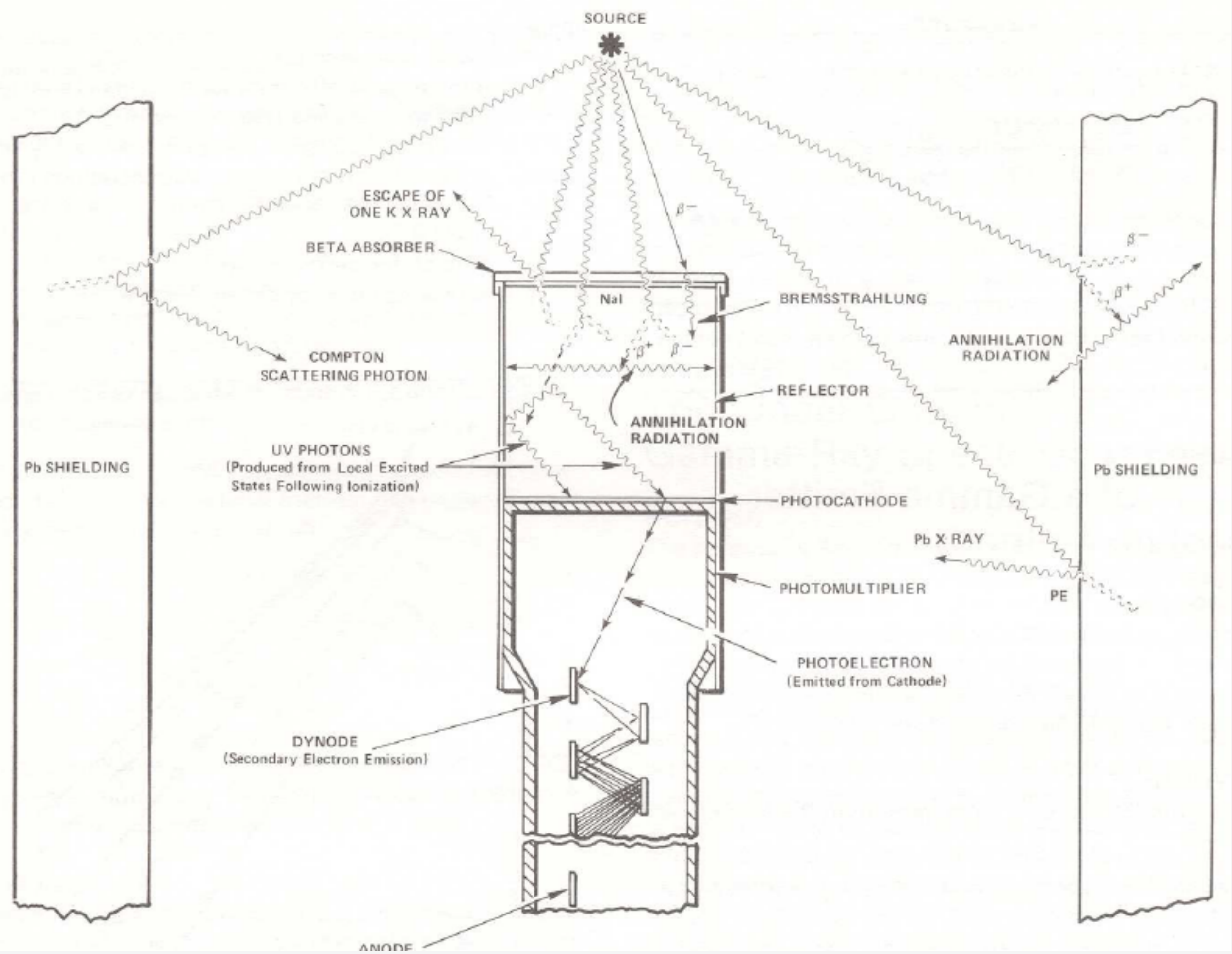
These scintillators are usually aromatic hydrocarbon compounds or fluorescent materials suspended in a plastic matrix. The scintillation process is very fast, therefore they can be used in timing measurements. Energy measurements are also possible and they can be manifacturedinmany different shapes quite easily. Usually solid organic scintillators are coupled to light guides which bring the scintillation light to PMTs. There are also liquid organic scintillators.



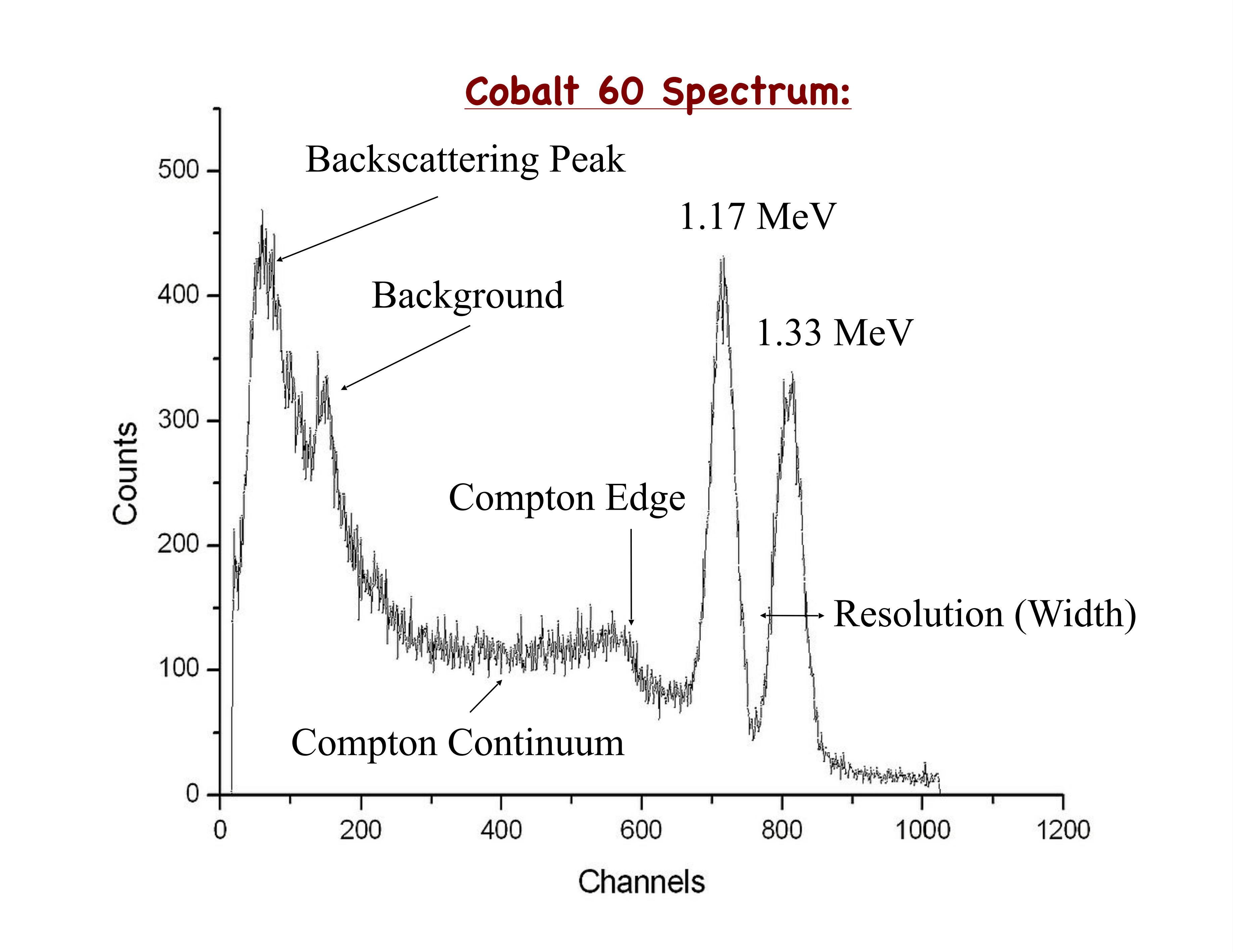
Energy Measurements with Scintillators (I)

Example: Nuclear Spectroscopy

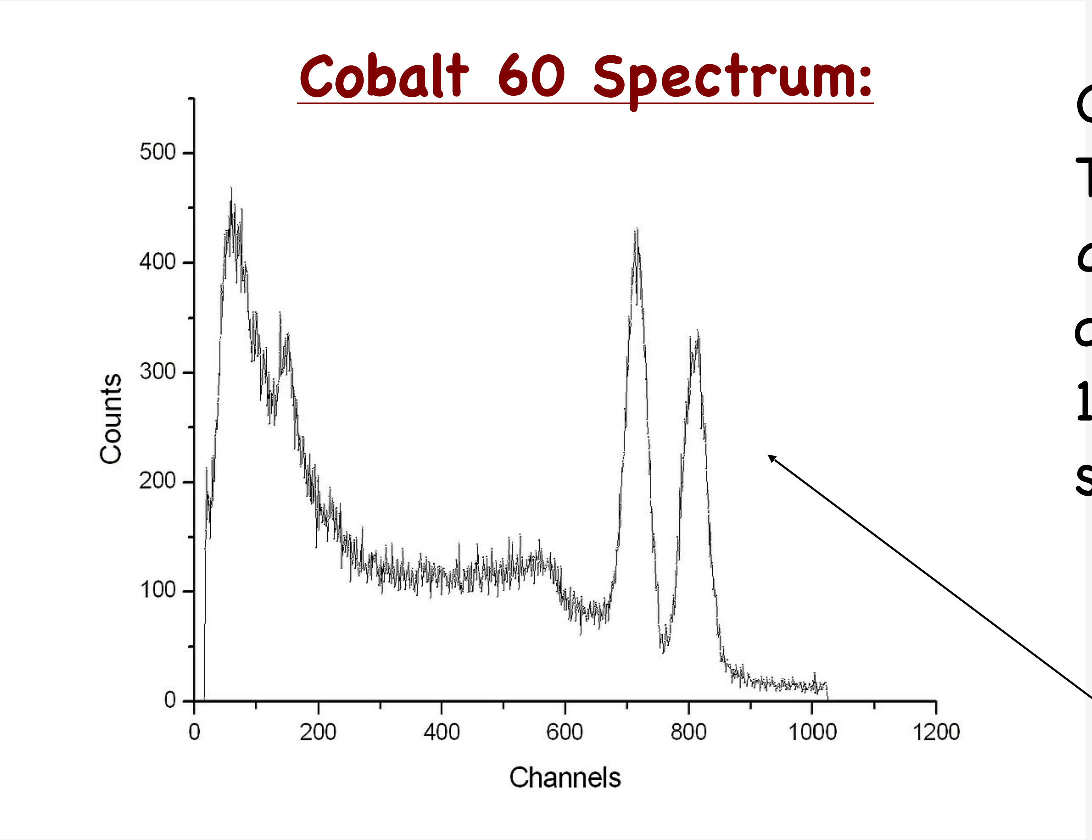
If a radioactive isotope emitting gamma photons is placed close to a scintillation crystal, it is possible to measure the energy distribution of the photons. The experimental apparatus is shown in the following figure:



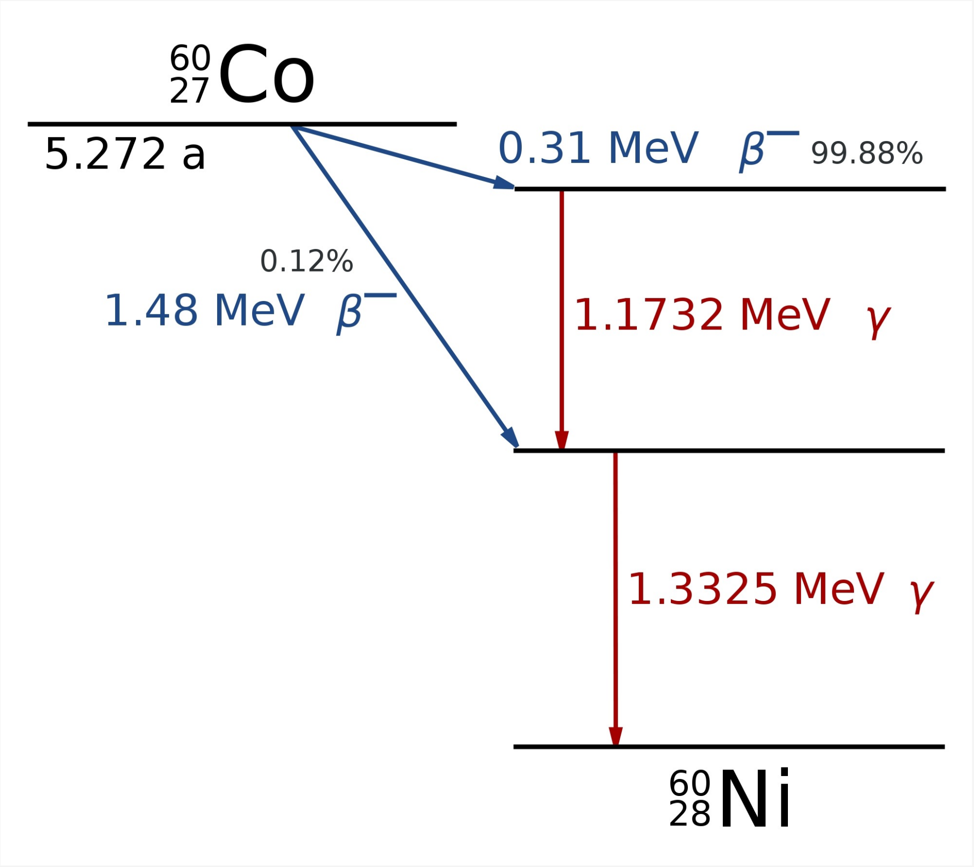
Energy Measurements with Scintillators (II)



Energy Measurements with Scintillators (III)

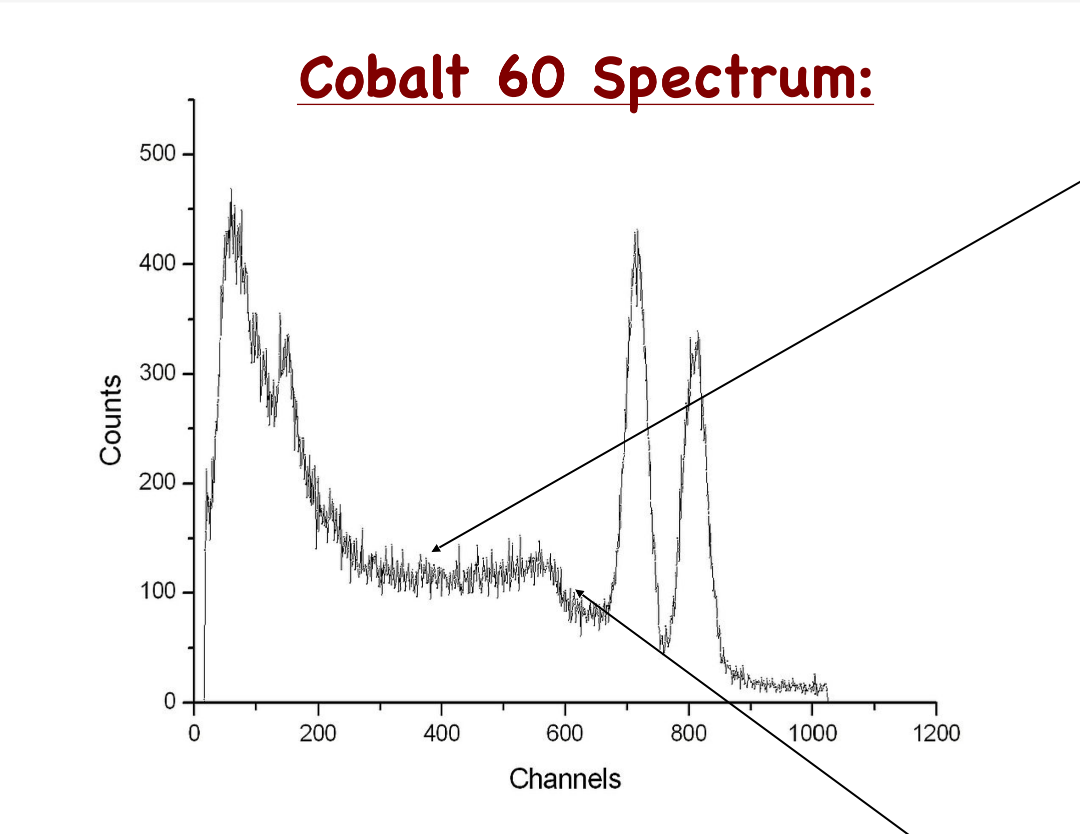


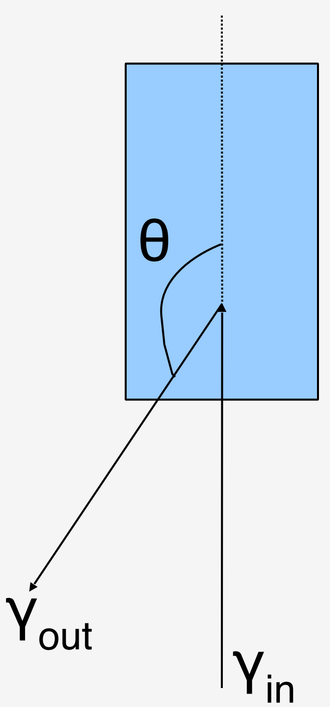
Cobalt 60 beta-decays into Nickel 60 in an excited state. The subsequent decay to the ground state goes through an intermediate excited state. The result of this two-step decay is the emission of two photons at 1.17 MeV and 1.33 MeV. This give rise to the two peaks in the gamma spectrum of Cobalt 60.



The two peaks are ΔE~ 0.16 MeV apart. In order to resolve them, the gamma detector should have a resolution $R < \Delta E$.

Energy Measurements with Scintillators (IV)





Compton Continuum:

Gamma rays entering the crystal can undergo Compton scattering. The resulting energy exchange with electrons depends from the scattering angle θ. Varying θ, the deposited energy varies continuously. If the primary gamma escapes the crystal after the scattering, only a fraction of its energy will be measured:

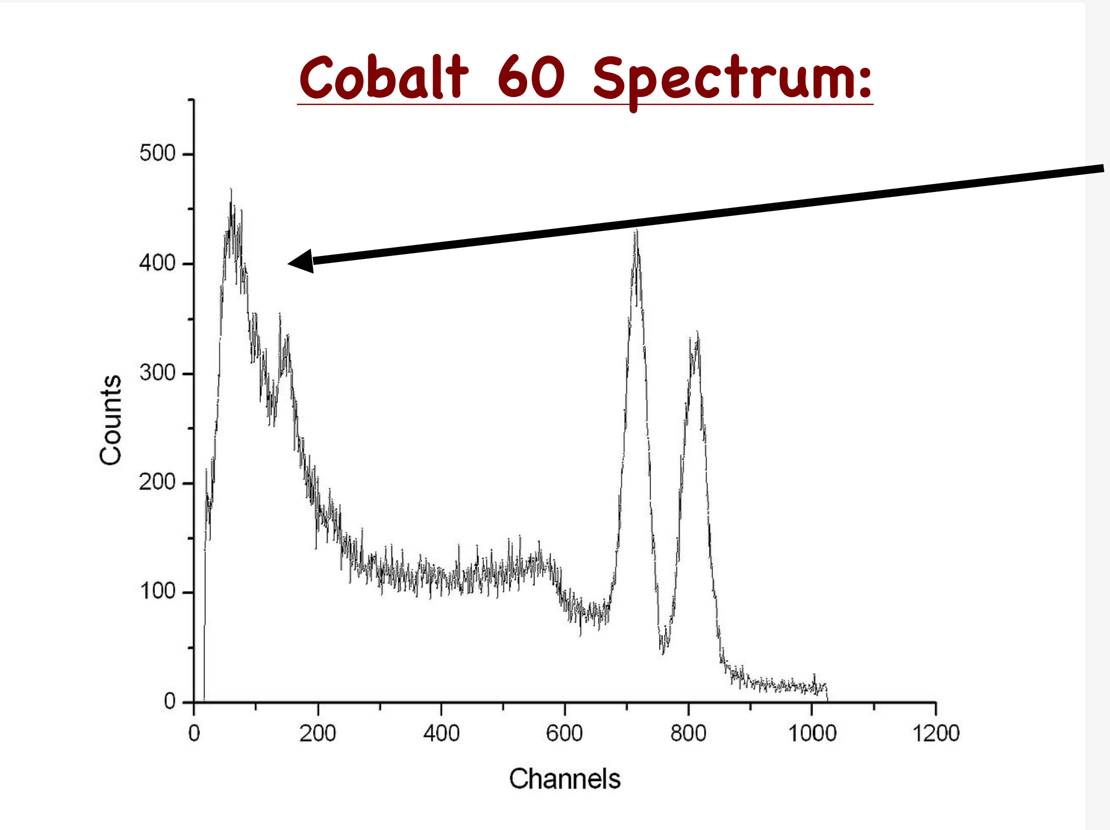
$$\frac{E_\gamma^f}{E_\gamma^i} = \frac{1}{1 + \left(\frac{E_\gamma^i}{m_e c^2}\right)(1 - \cos\theta)}$$

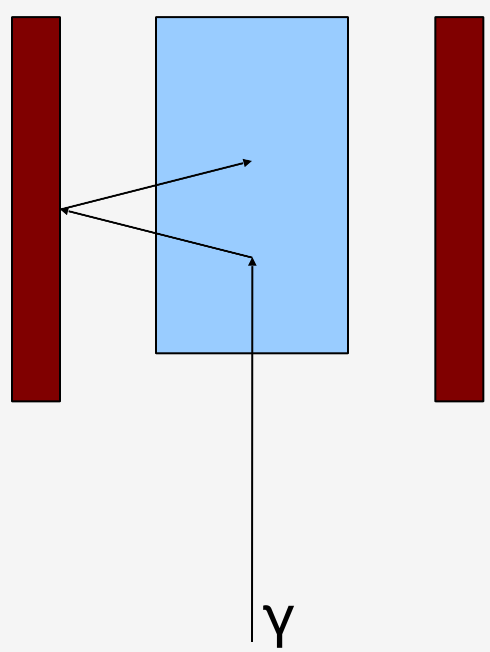
Compton Edge:

The gamma energy after a Compton scattering has a minimum at θ=180. This corresponds to the Compton "edge" in the energy spectrum (maximum energy transfer to an electron in the crystal):

$$E_{edge} = E_\gamma^i - \frac{E_\gamma^i}{1 + \frac{2E_\gamma^i}{m_e c^2}}$$

Energy Measurements with Scintillators (V)





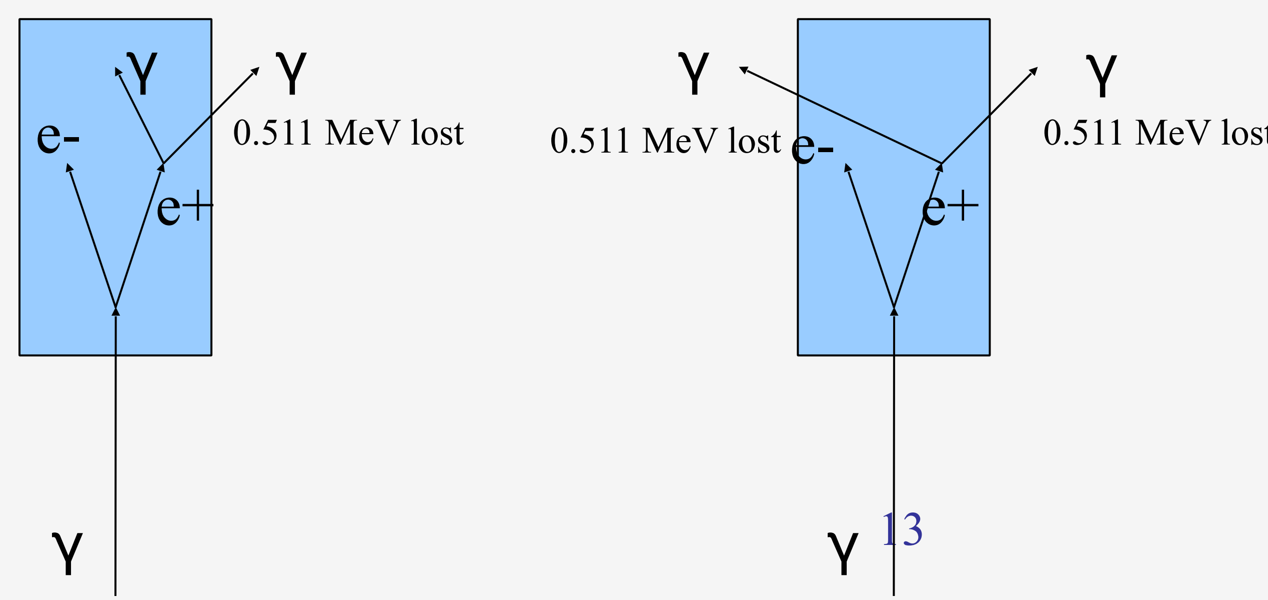
Backscattering Peak

Gamma rays escaping the scintillation detector can undergo Compton scattering in the surrounding materials. After the scattering they can come back to the detector, causing a peak in the low-energy region of the spectrum.

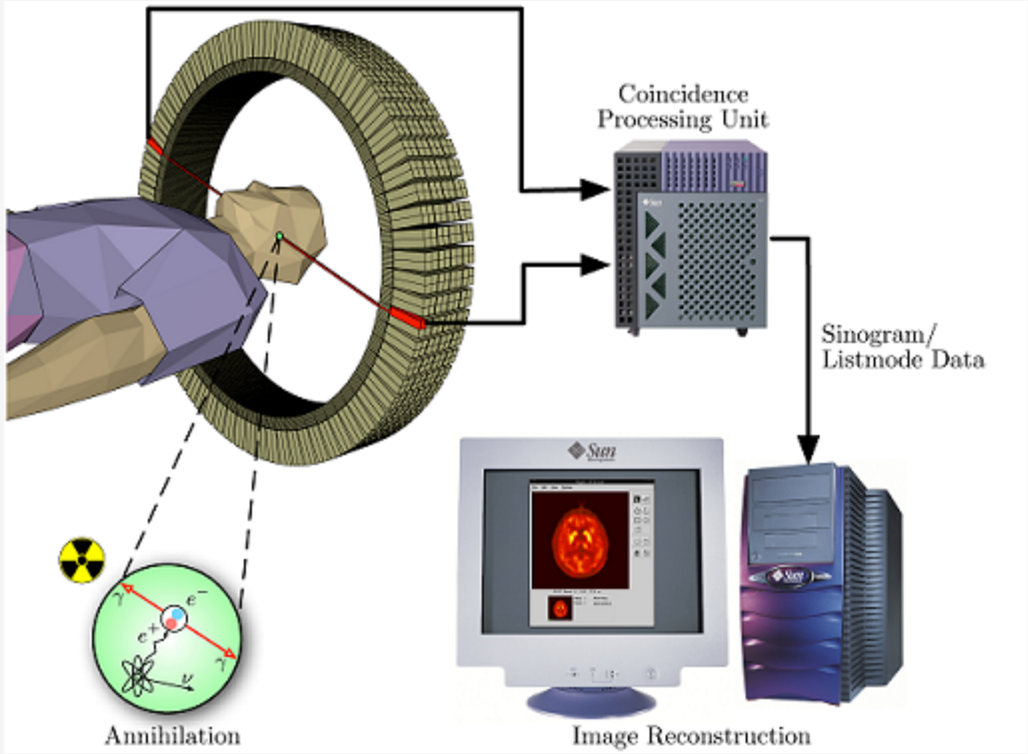
Other effects: 0.511 MeV and 1.022 MeV peaks

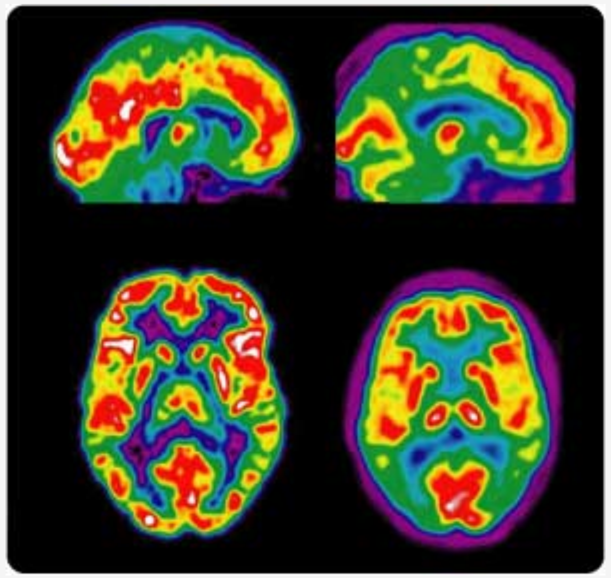
If pair creation takes place, positrons are produced. The positron can annihilate with an atomic electron.

If the two produced photons escape, an E_γ-1.022 MeV peak will be visible in the spectrum. If only one photon escapes, another peak will be visible at E_γ-0.511MeV.



Application: PET





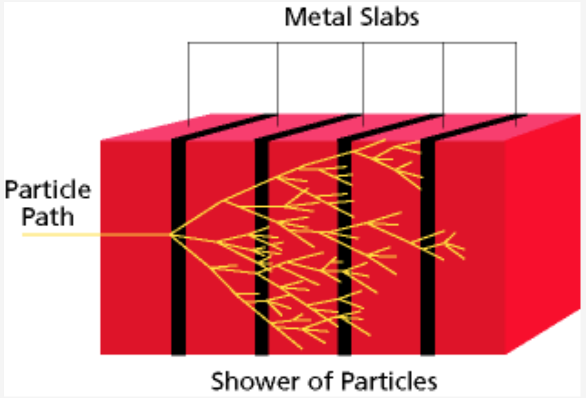
Positron Emission Tomogreaphy (PET)

Scintillation crystals are widely used in medical physics for PET applications. The crystals are arranged circularly around the patient for detecting photons coming from electron/ positron annihilation.

Positrons and electrons are emitted in opposite directions and looking for coincident signals among opposite crystals permits to reconstruct an image of the emission area.

Calorimeters (I)

Calorimeter is the generic name for a particle detector which measures the energy of a particle. Usually, the particle is completely stopped by the calorimeter which collects the full energy deposit. Calorimeters are made of scintillator materials like the ones seen before. Technically, there are two types of calorimeter:



Homogeneous Calorimeters: The full volume of the calorimeter is active

Sampling Calorimeter: Active and non-active layers are stacked.
The non-active layers serve as absorber/radiator.

Electromagnetic Calorimeters are optimized of the detection of electromagnetically interacting particles (electrons, positrons, photons) while **Hadronic Calorimeters** are optimized for hadronic particles detection.

Resolution: $$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$ (The circles with a + inside denote a sum in quadrature)

The resolution depends in general from 3 terms:
a: Stochastic term, connected to the fluctuation of the shower processes
b: Instrumental effects, like pedestal fluctuations or noise.
c: Systematic term, arising for example from energy calibration errors or radiation damage.

Calorimeters (II)

In subatomic physics experiments, sampling calorimeters can be specialized in electromagnetic or hadronic.
Hadronic calorimeters in particular have to be designed with care for obtaining an homogeneous response.

In hadronic showers, also photons, electrons and positrons are present.
If the response of the calorimeter is different for electromagnetic and hadronic particles, then the response is not linear with the energy of the particle starting the shower.
The hadronic energy fraction f_h as a function of the initial particle's energy E is given on average by

$$\langle f_h \rangle = 1 - \langle f_{em} \rangle \approx E^{m-1}$$

with m=(0.8-0.9).
In general if the response of the calorimeter is not the same, the resolution is degraded.
Such calorimeters are called "non-compensating".

Compensating calorimeters adopt construction techniques for restoring a more equal response to electromagnetic and hadronic particles.
Compensating techniques try either to reduce the em response (using low-Z materials) or enhance the hadronic response (using detectors sensible to signals given by secondary neutrons interactions).

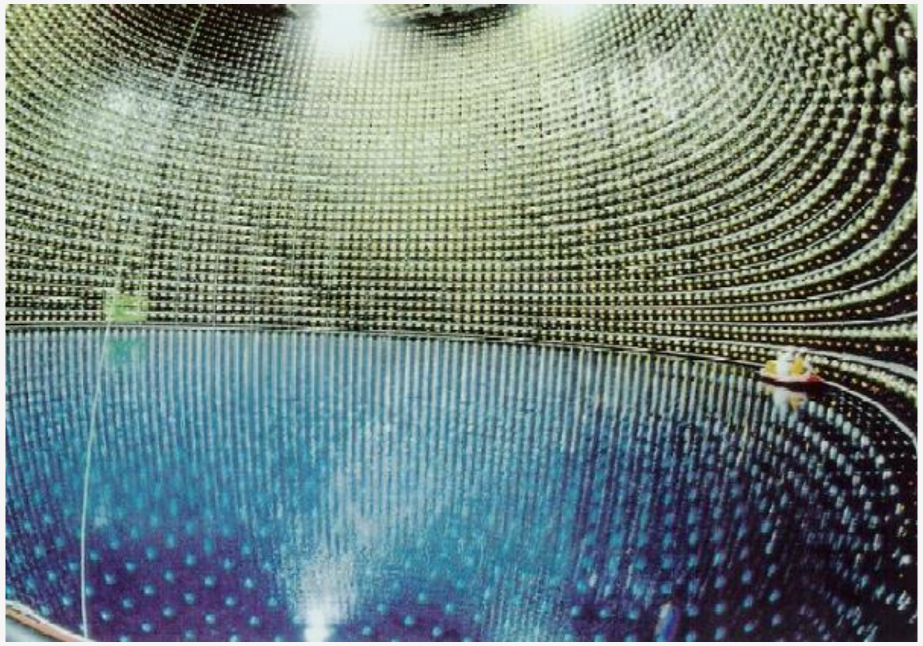
Other more elaborated techniques also exist.

Calorimeters

Cerenkov Detectors

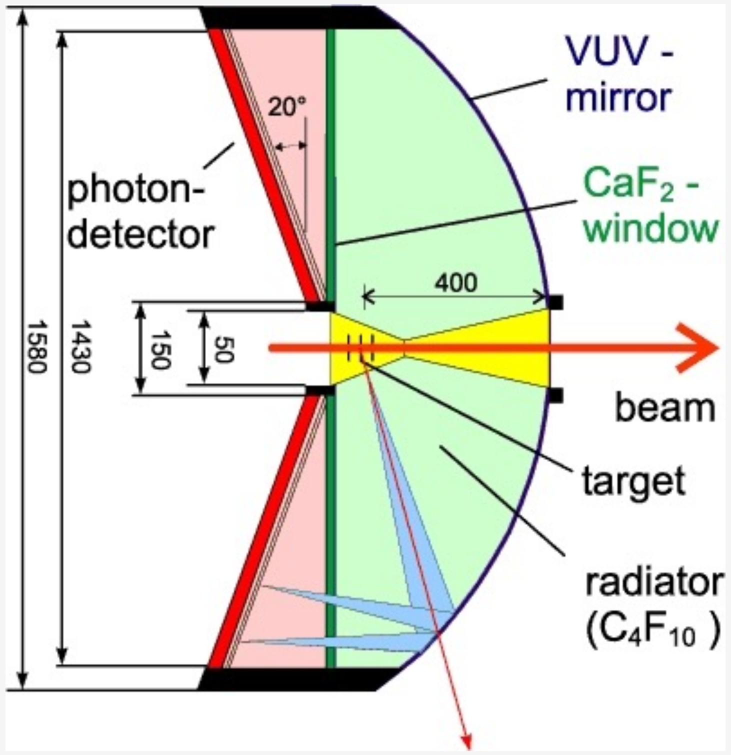
Cerenkov Detectors

There are many different kinds of Cerenkov detectors but all of them are based on the same effect: light produced by a particle which has a velocity higher than the speed of light in the medium.



The largest Cerenkov detector of the world: Super-Kamiokande. It is based on ultra-pure water and light detection by large area PMTs. The reconstructed Cerenkov rings provide direction and particle identification.

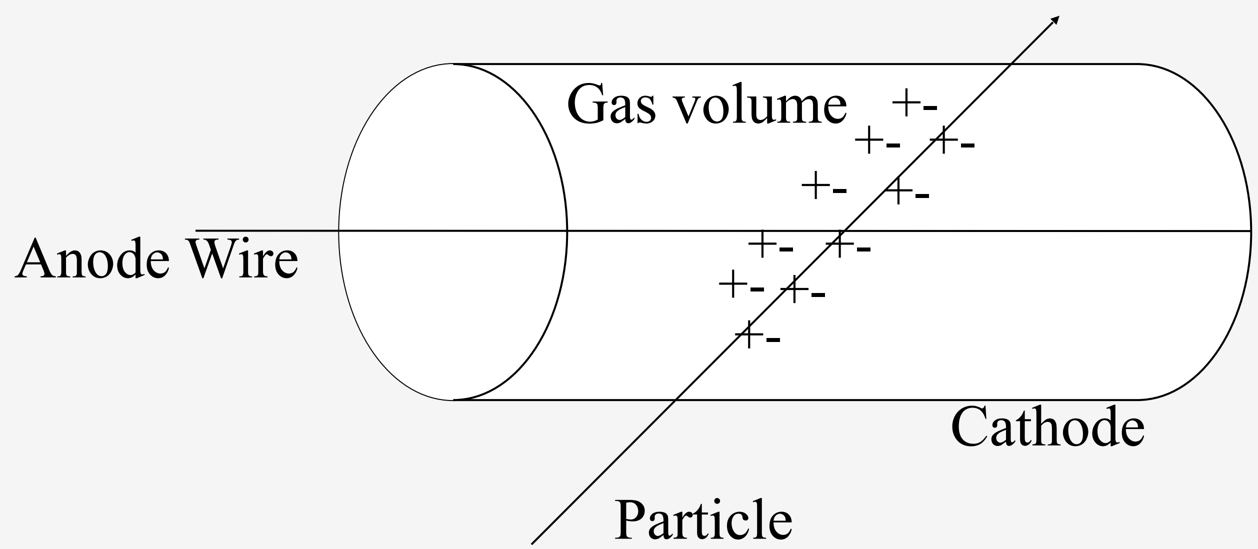
Another type of Cerenkov detector is the **RICH**, or ring-imaging Cerenkov Detector. The RICH uses mirrors to focus the Cerenkov light on photon detectors.



Gas Detectors

Gas Filled Detectors

Detectors can also use gaseous mixtures as active material for detecting particles. Particles traversing a gas-filled volume can ionize atoms or molecules. If the ionization electrons are sufficiently amplified, a signal can be recorded. The general basic layout of a gas-filled detector is the following:



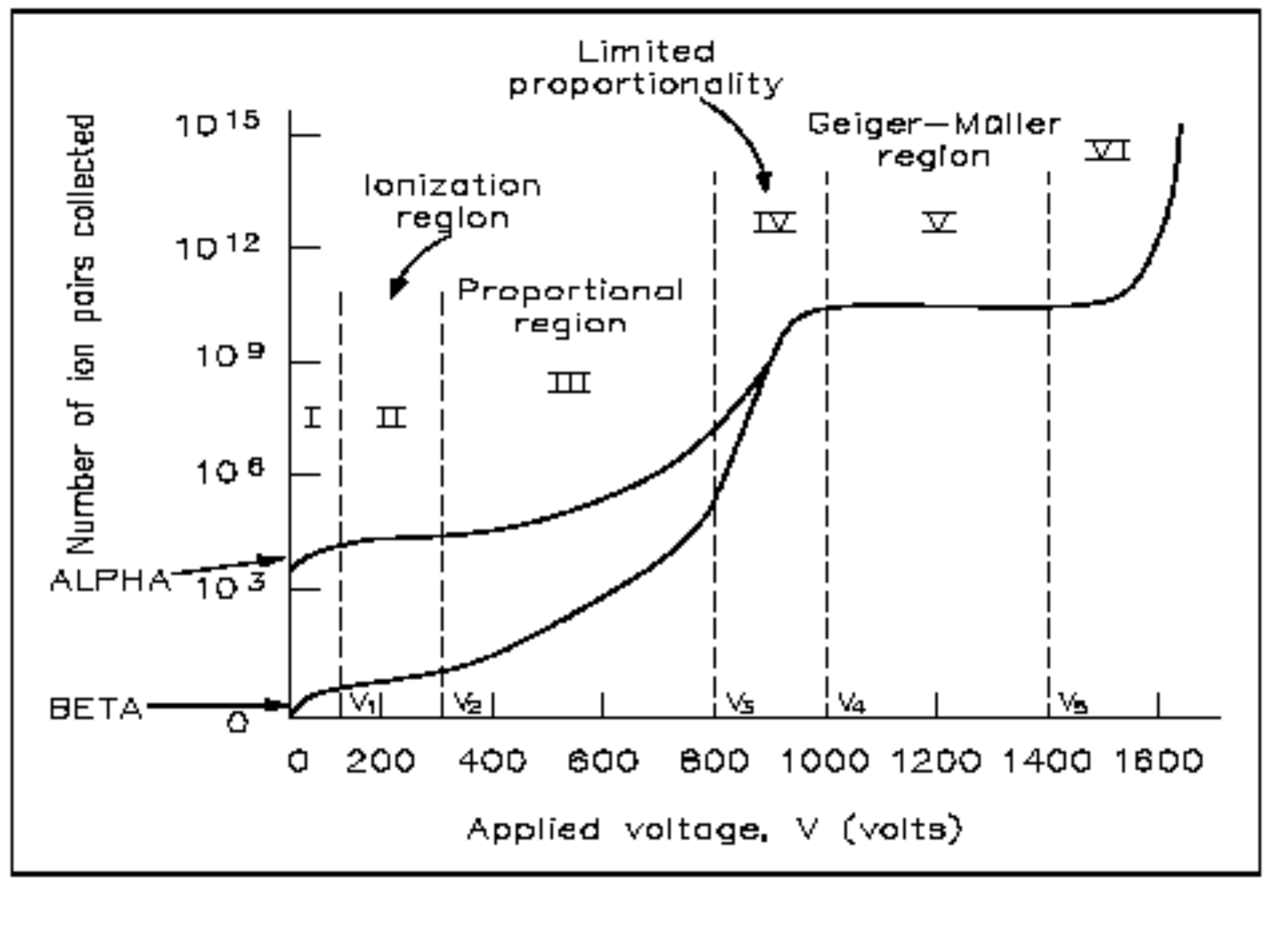
1) Along the track of the particle in the gas, electron-ion pairs are produced.
2) Electrons are collected by a (anode) wire set to positive potential with respect to the cathode, which surrounds the gas cell.
3) The high electric field ($E \sim 1/r$: near the wire the field is strong) of the wire accelerates electrons in the gas, causing them to collide with more atoms/molecules. The collisions liberate more electrons and an avalanche start to develop towards the wire. The ion-electron pairs are multiplied by a factor of $\sim 10^4$.
4) At the end of the process, all the electrons are collected by the wire which gives a measurable signal.

In these detectors, there are no PMTs: the amplification is done by the high electric fields that induce the formation of an electron avalanche. Commonly, at the end of the wire, an electronic amplification circuit is added for obtaining a better signal.

Gas Detectors Response

Ionization versus applied Potential

Gas detectors respond differently as a function of the applied potential. The most interesting regions for the applications are the proportional region and the Geiger-Mueller region.

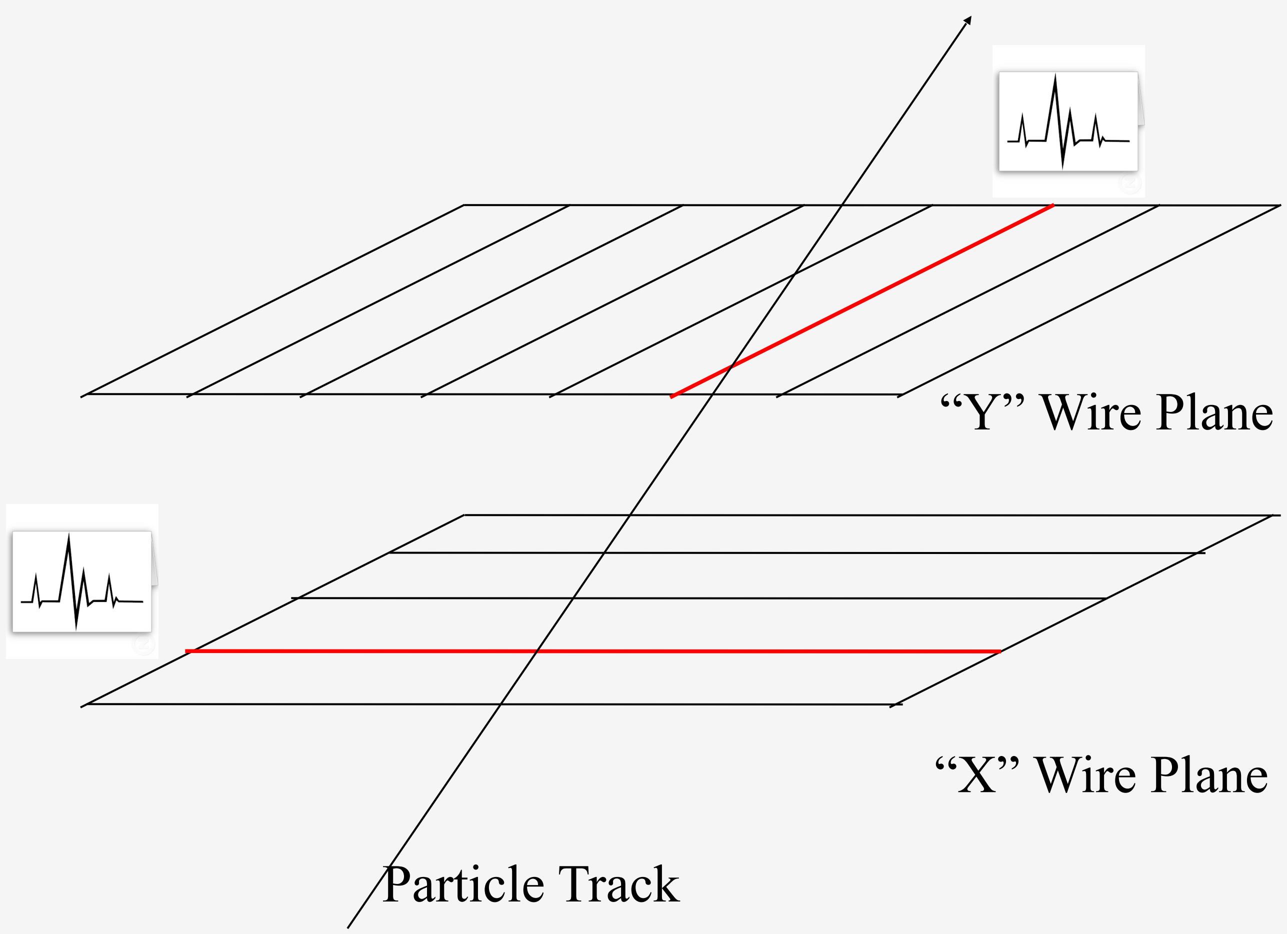


In the proportional region, the signal charge is proportional to the amount of ioniziation produced by the particle. Different particles species can be distinguished using this property. Gas detectors called proportional chambers work in this regime.

At higher voltages, the detector enters the Geiger-Mueller mode. In this case avalanches are created in the whole gas volume and the response of the detector is the same, regardless the amount of ionization produced. This means that every kind of particle will generate about the same collected charge. These detectors are therefore useful only for counting purposes.

Wire Chambers (I)

Multiwire Proportional Chambers (G.Charpak, 1992 Nobel Prize in Physics).
A proportional chamber are built with a set of parallel wires in a gas volume. According to which wire gives a signal, it is possible to reconstruct where the particle traversed the detector.
Combining more MWPCs with wires arranged in different directions it is possible to reconstruct in space the particle's track:



Tracking:
Many planes can be combined together and oriented in different directions. The knowledge of the wire spacing and wire signals permits the reconstruction of the track.

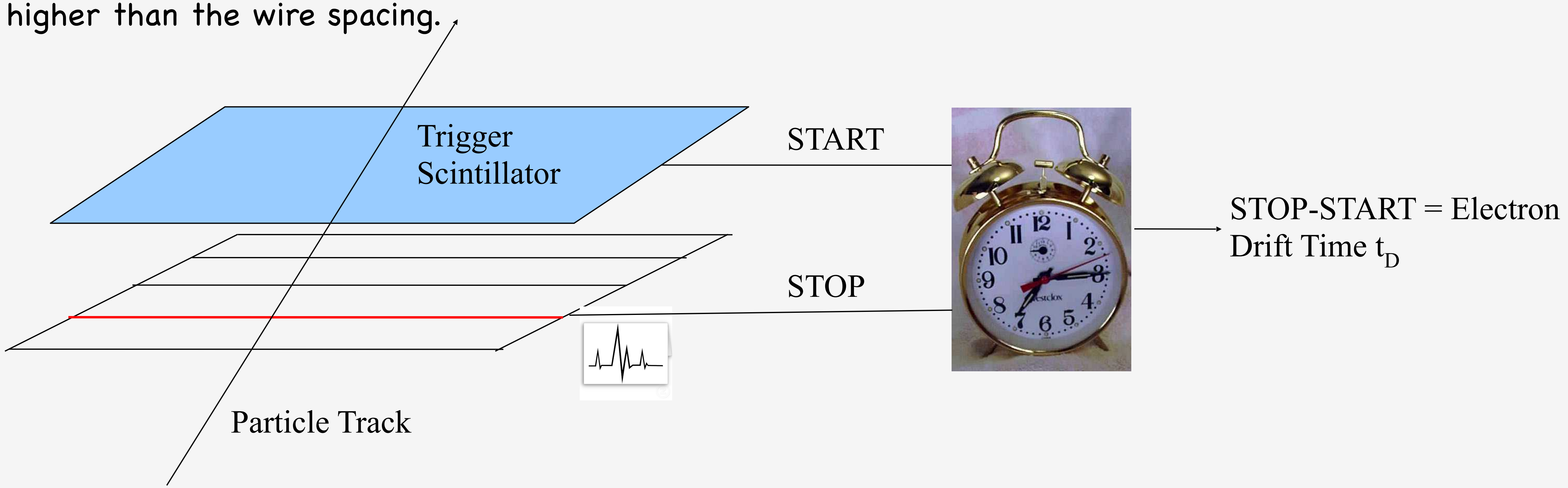
NOTE:
Although a wire chamber is a relatively simple detector, it has one main limitation:
If high position resolution is required, the number of wires has to be high. This implies more channels to read out (more expensive). Due to the stresses induced from the high electric fields the wires cannot be too close (typical distances ~mm), so the resolution cannot be lowered much below the mm scale.

Typical ion drift velocity: ~ cm/ms
Typical electron drift velocity: ~ cm/μs

Wire Chambers (II)

Drift Chambers

To overcome the resolution limitations of the wire chambers, drift chambers were developed. These detectors combine a wire chamber with a time measurement of the drift time of the electrons from the point of production to the signal wires. Knowing the drift-space/drift-time relationship and measuring the drift-time and the "firing" wire, it is possible to reconstruct the particle position with resolution much higher than the wire spacing.



Position reconstruction: $x \approx n\delta x + v_D t_D$

where n is the wire number, δx the wire spacing, v_D the drift velocity and t_D the measured drift time.

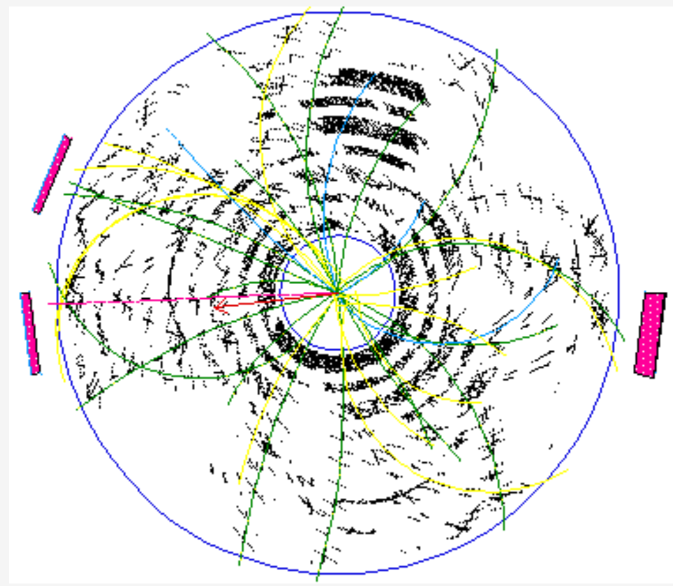
The drift-time/drift-velocity changes with temperature, pressure, gas mixture, voltage,... and it has to be known accurately.

Wire Chambers (III)

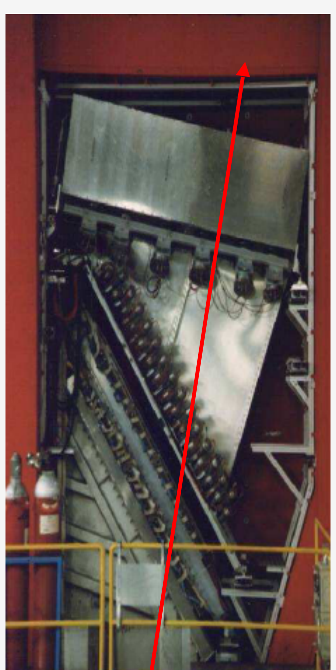
Drift Chambers

Drift chambers are widely used in many nuclear and particle physics experiments. Many geometries are possible for these detectors:

Cylindrical Drift Chamber (CDF Experiment @ FermiLab)

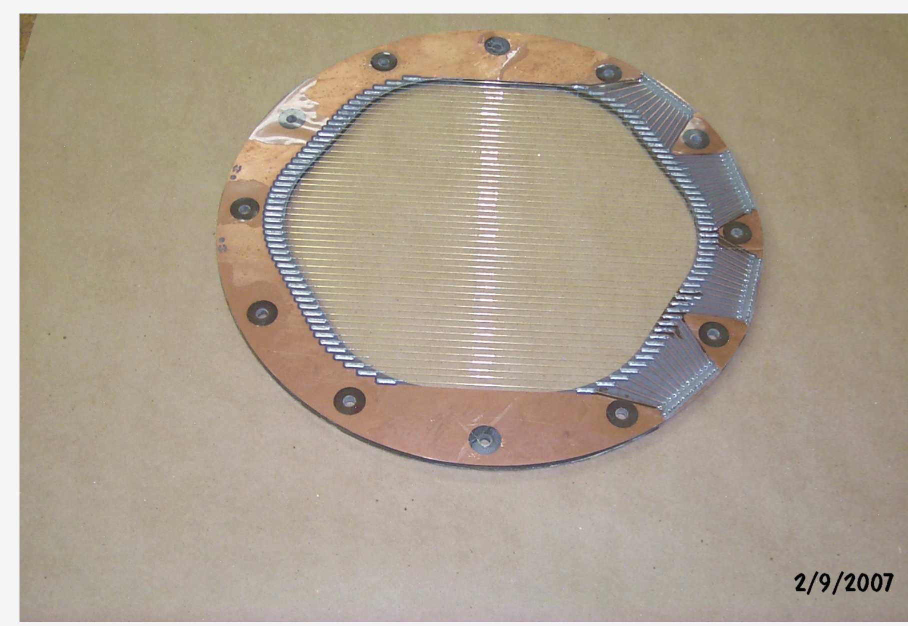


Cylindrical drift chambers are frequently used in collider experiments. Coupled with a magnetic field, a precise momentum measurement is possible.



Vertical drift chambers are planar chambers placed at an angle with respect to the particle tracks. This arrangement increases the number of wires activated, resulting in a better track reconstruction.

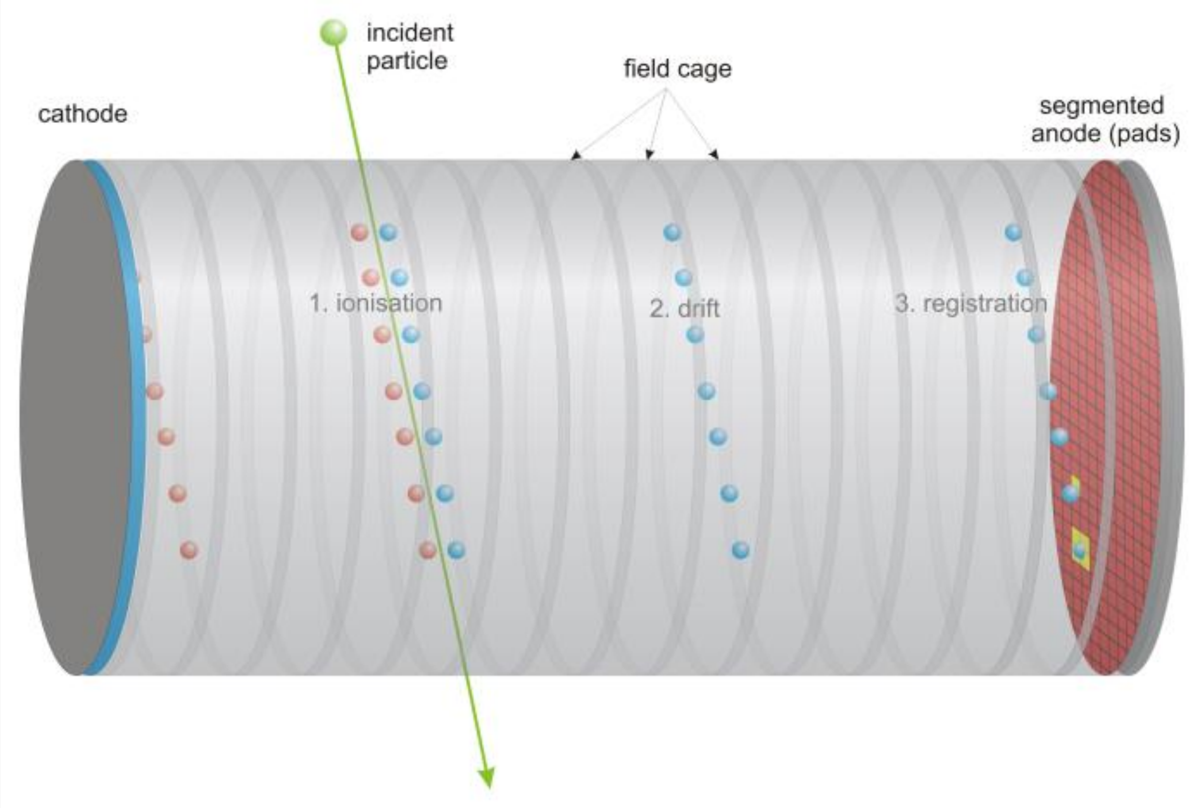
Wire Chamber anode wire plane



Time Projection Chamber

<u>**Time Projection Chambers**</u>

TPCs are a kind of gas detector which, like drift chambers combines position and drift time measurements for reconstructing particle tracks in 3D space.

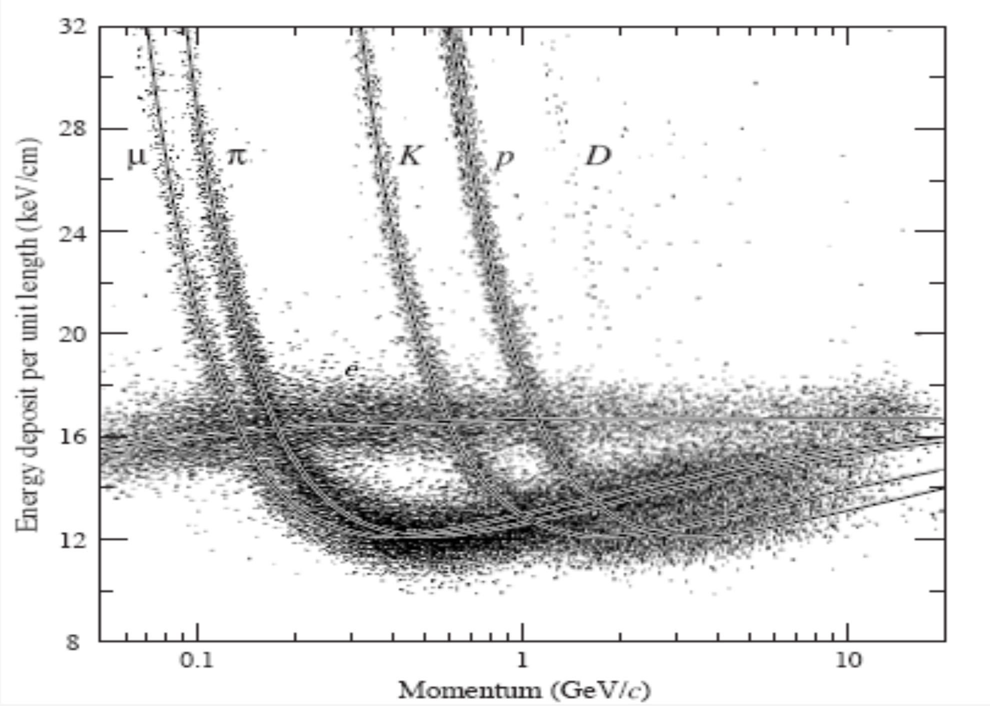


A gas-filled cylindrical volume is traversed by particles. The ionization electrons are collected on the sides by anode pads which give XY positions of the track. The Z coordinate is calculated measuring the drift time of the electrons.

Usually, a cathode plane is present also in the middle of the TPC, dividing it in two main active volumes delimited by anode pads on the other sides.

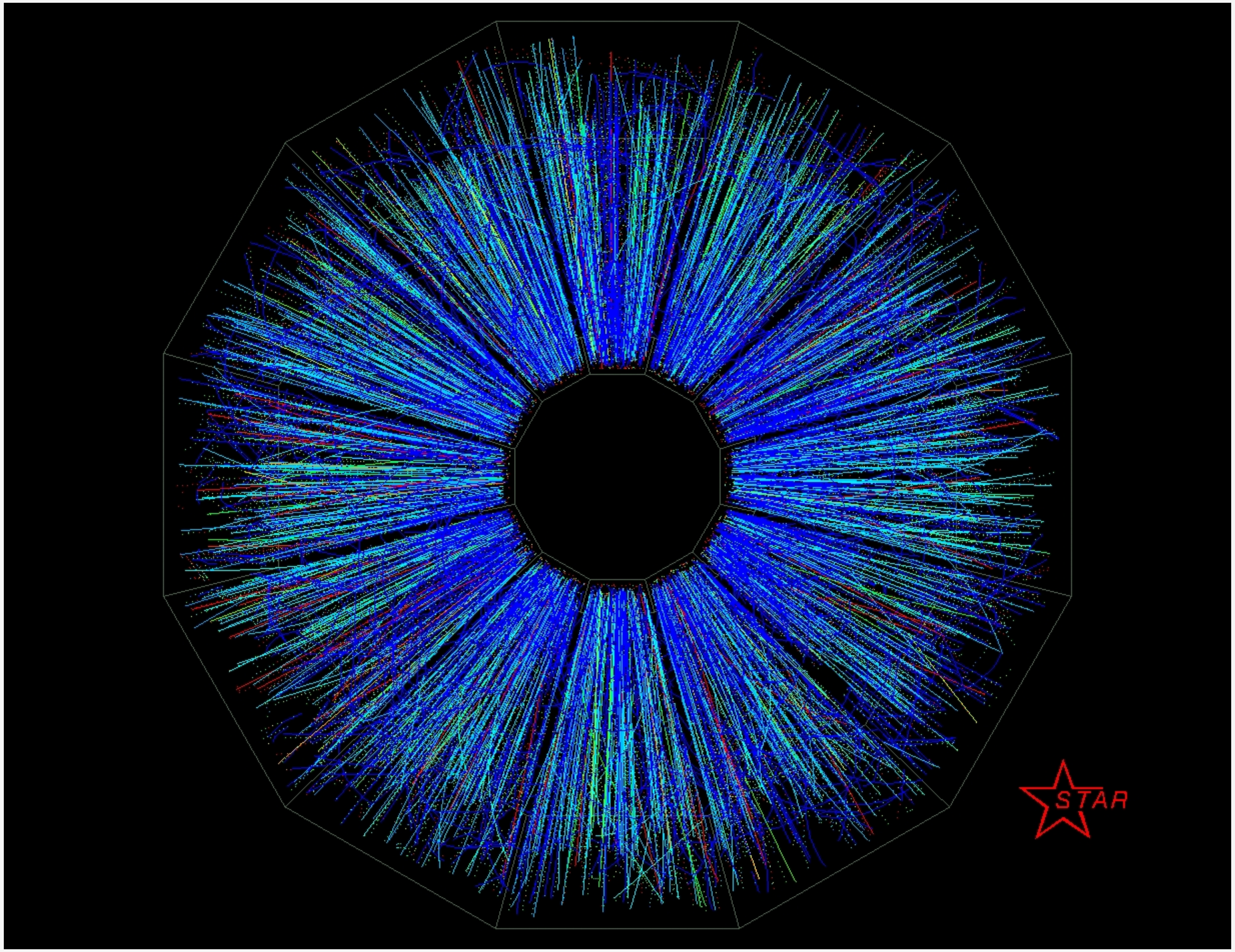
TPCs are able to track a huge number of particles at the same time.

Correlating the energy deposit in the gas (signal from the anode wires) and the momentum gives a powerful tool for particle identification.



Time Projection Chamber

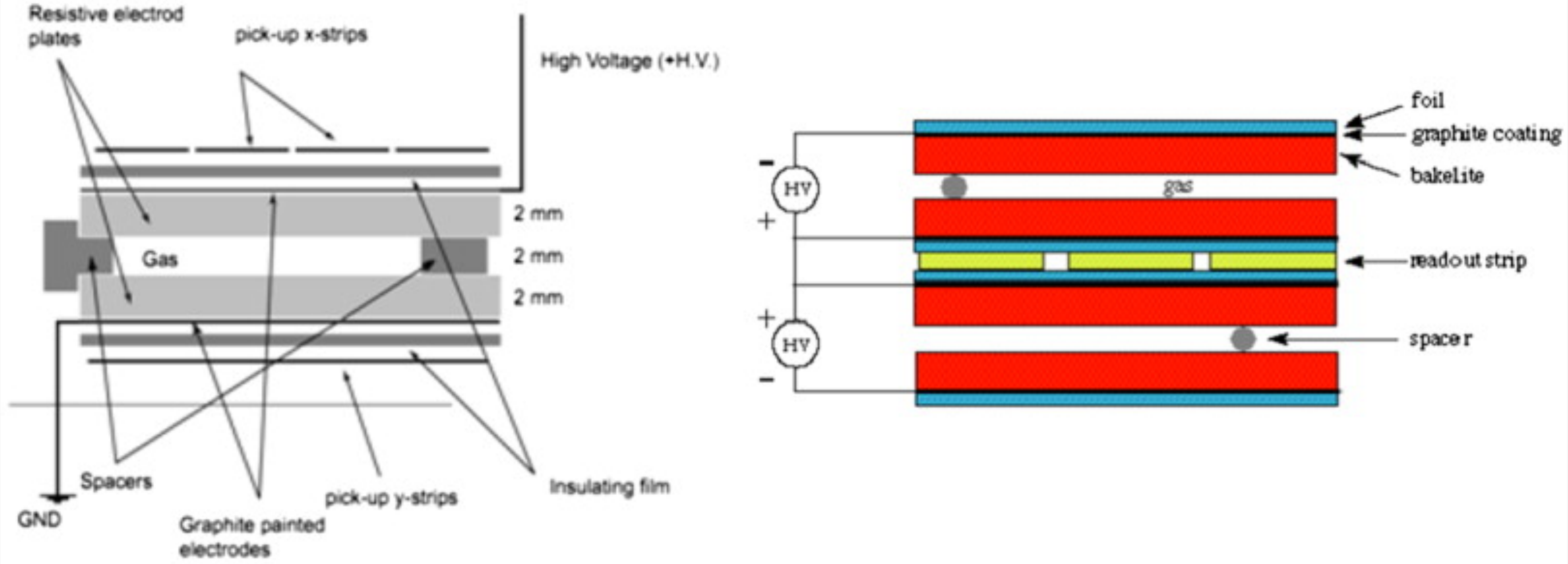
TPC of the START experiment at RHIC accelerator (BNL)



Resistive Plate Chamber

Resistive Plate Chambers are gas detectors composed by two parallel planes of high resistivity material ($\rho>10^9$ Ω-m). The thin gap (few mm) between the planes is gas-filled. The planes are at opposite electric potential. When a particle traverse the chamber, ionization occurs and if the electric field is high enough, there is signal amplification.

The signal is picked up by thin metal strips.



Advantages of these detectors are good spacial resolution and speed.

There are two modes of operation:

- "Streamer mode": the E-field is high and there is strong gas amplification (rate-limited)
- "Avalanche mode": lower field operation and amplification by external electronics (higher rates possible).

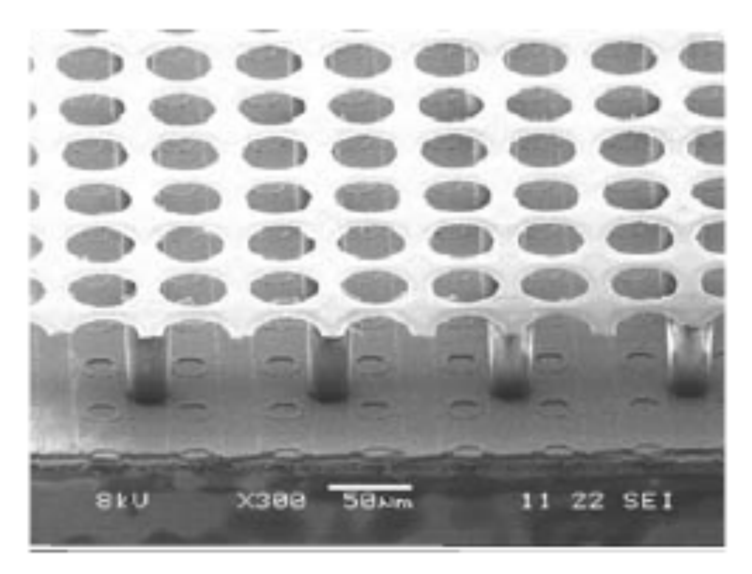
Other Gas Detectors

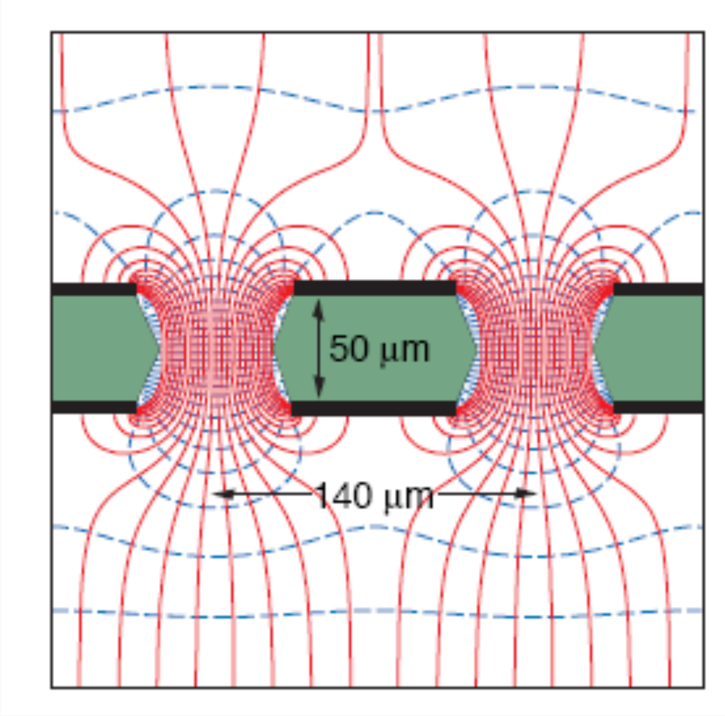
Micromegas and GEM (Gas electron Multiplier)

These detectors employ a different method for achieving electron amplification. In wire chambers the multiplication happens close to the wire. Here, a sum-millimeter mesh of holes on an appropriate material (usually a copper-insulator-copper sheet) is superimposed to a position-sensitive detector. With modern techniques, a spacial resolution of ~30μm can be achieved.

When an electric field is applied to the mesh, a strong electric field is created in the proximity of the holes, where the electron multiplication can occur.

Another advantage of these detector is the possibility of sustain very high rates.

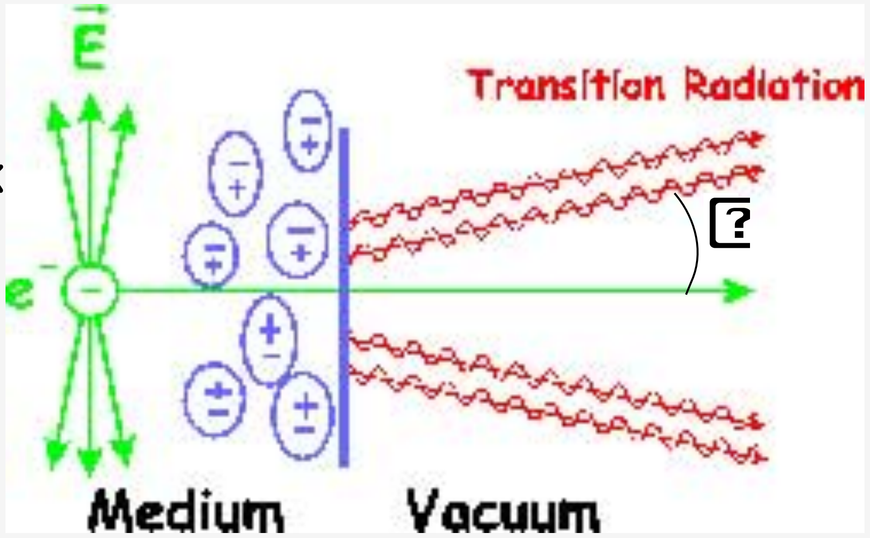




Transition Radiation Detectors

Transition Radiation Detectors (TDR)

These detectors are based on an effect called transition radiation. When a highly relativistic particle crosses a refractive index surface, X-rays are emitted at a characteristic angle:



$$\theta = \frac{1}{\gamma}$$

with respect to the particle's trajectory. The radiation yield grows with higher γ factors.
Since the amount of radiation emitted is small, often these detectors are composed from many layers. Interference effects among light emitted by different layers determines a saturation effect of the total light yield emitted.
There are two main construction concepts of a TDR:
- Radiator concept: >100 layers of radiator material are stacked and interleaved with active material (e.g. Xe gas).
- Granular concept: The active material between the radiators is segmented and gives position measurements.

Usually, TRDs are "threshold" detectors. E.g. in the 1-150 GeV/c range, electron-pion separation can be done very efficiently.

Semiconductor Detectors (I)

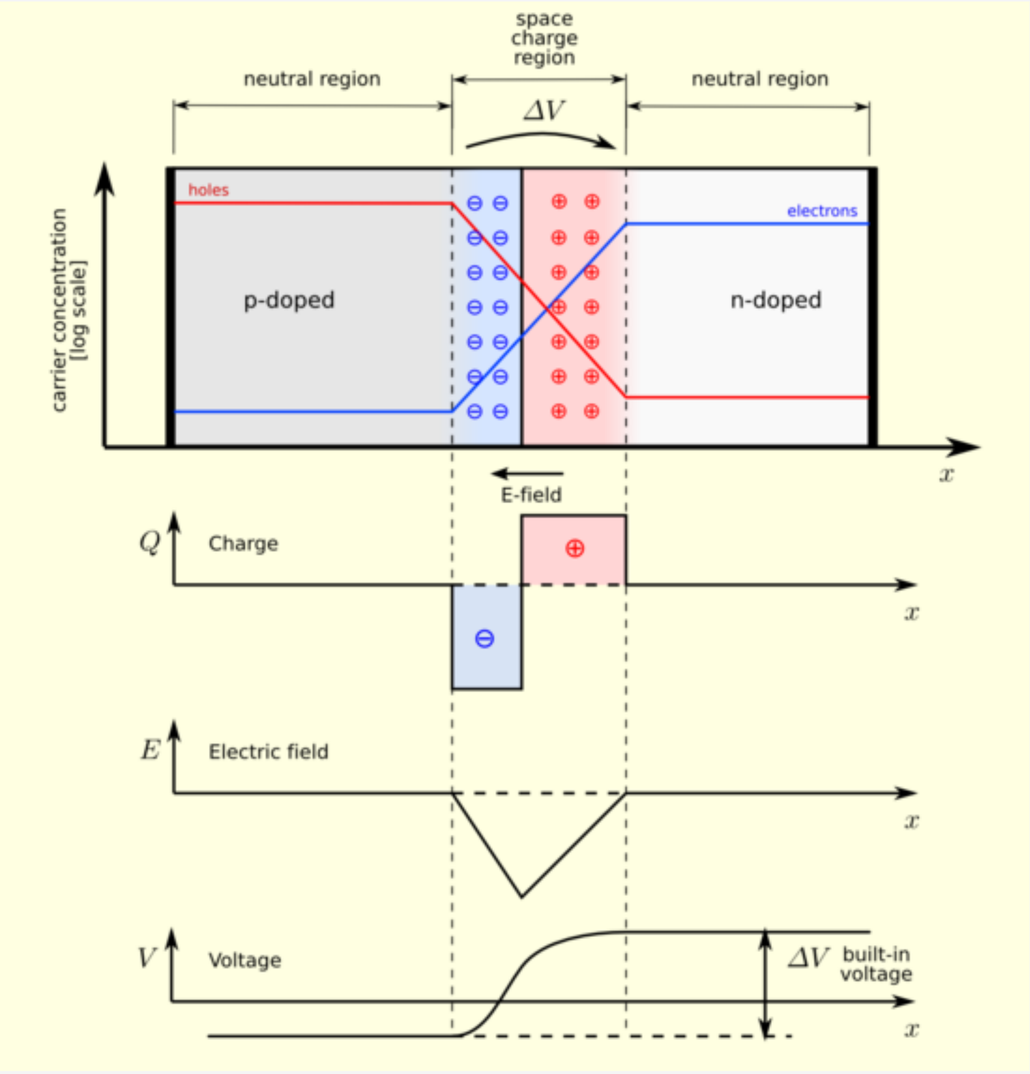
Semiconductor Detectors are based on the properties of diodes or similar devices. In the following we first review the basic properties of doped semiconductors.

Germanium and Silicon form crystals where each atom forms 4 covalent bonds with the neighbours. Since all the valence electrons are used, nothing is available as charge carrier.

If a small fraction of Ge or Si atoms are replaced with a valence 5 ones (e.g. P, As, Sb, ..) an extra electron is available for electric conduction. Such a material is called n-type semiconductor.

In the same way, if we add a small amount of valence 3 atoms (e.g.: B, Al,..), there are not enough electrons for saturating all the bonds and positive "holes" arise in the crystal structure. These holes are very mobile, as the electrons of n-type semiconductors. There material are called p-type semiconductors.

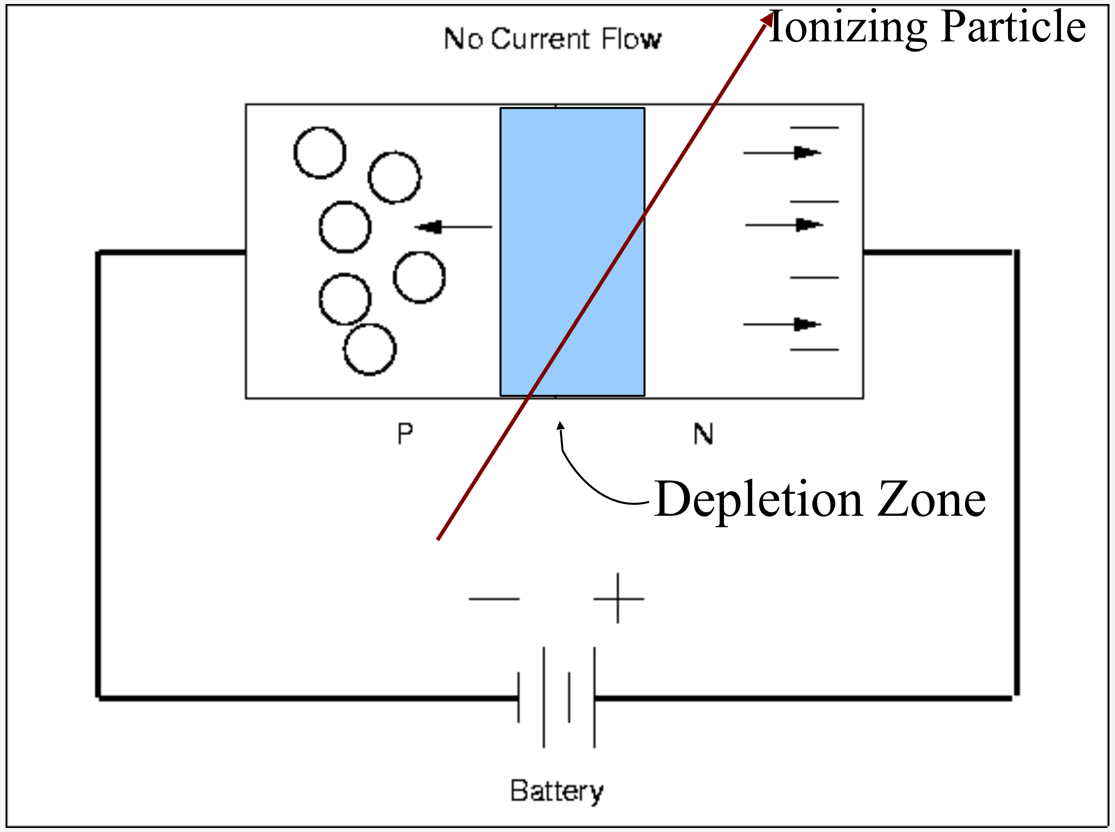
If we put in contact a p- and n-type semiconductors, at the interface the extra electrons and holes will combine giving rise to a depletion zone where there are no available carriers. Outside this zone, the remaining n-type material will acquire a positive charge and conversely the p-type material will acquire a negative one. The p and n semiconductors together form a junction diode.



Semiconductor Detectors (II)

Semiconductor Detectors employ as basic block a diode in reverse bias configuration.

If the n-type part if a diode is put to a higher potential than the p-type part, the depletion zone will be enlarged.



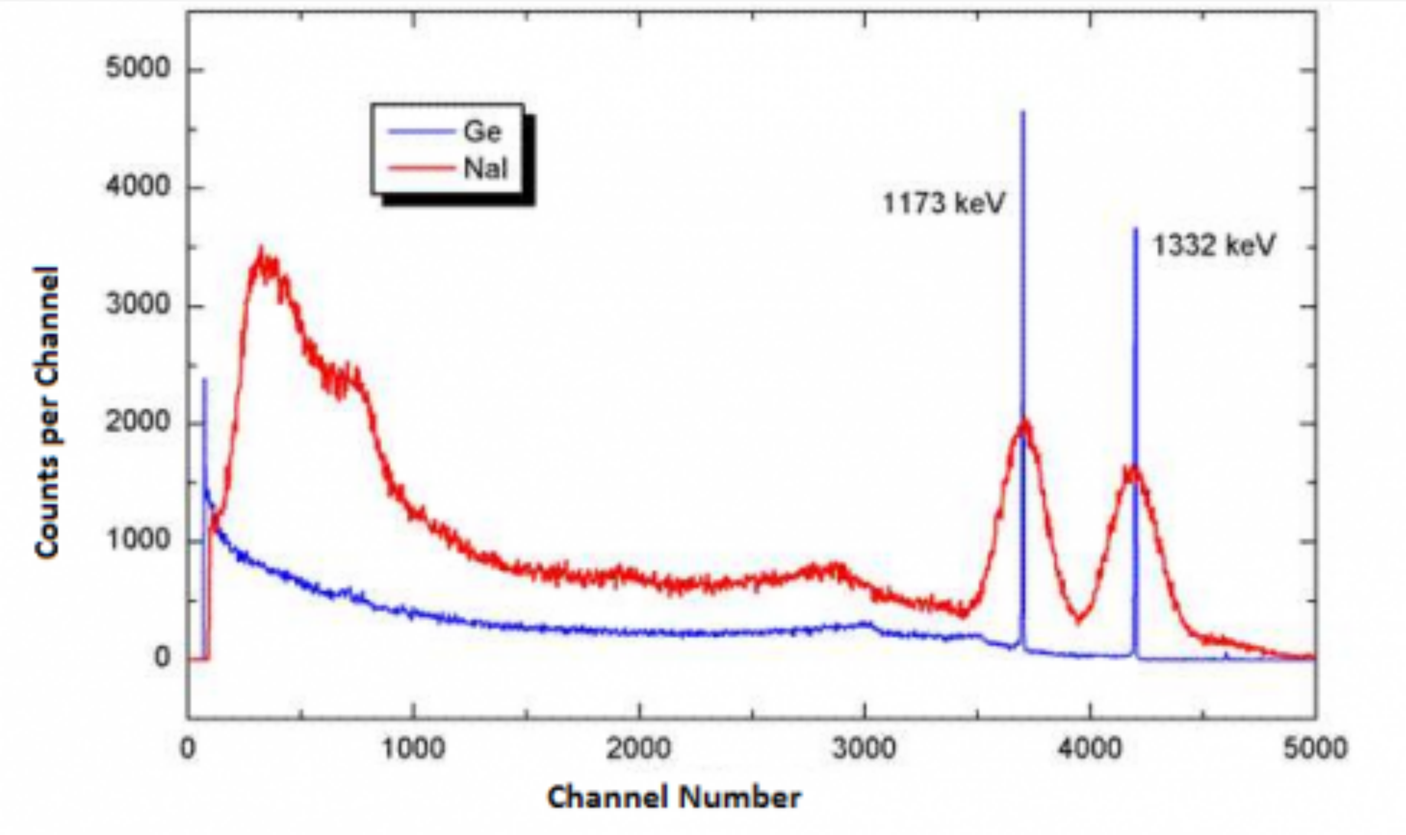
No current can in principle flow through a reverse-bias diode. If an ionizing radiation goes through the depletion zone, it can create electron-hole pairs: a net current can then be measured through the diode. The electric pulse measured at the ends of the diode will be proportional to the energy deposited by the particle.

Semiconductor Detectors (III)

Construction Technique: Usually, a silicon detector is made by a large n-type, lightly doped material coupled to a smaller p-type, highly doped electrode (or viceversa). In this asymmetric configuration, the depletion region is formed mainly in the lightly doped semiconductor (larger detection volume).

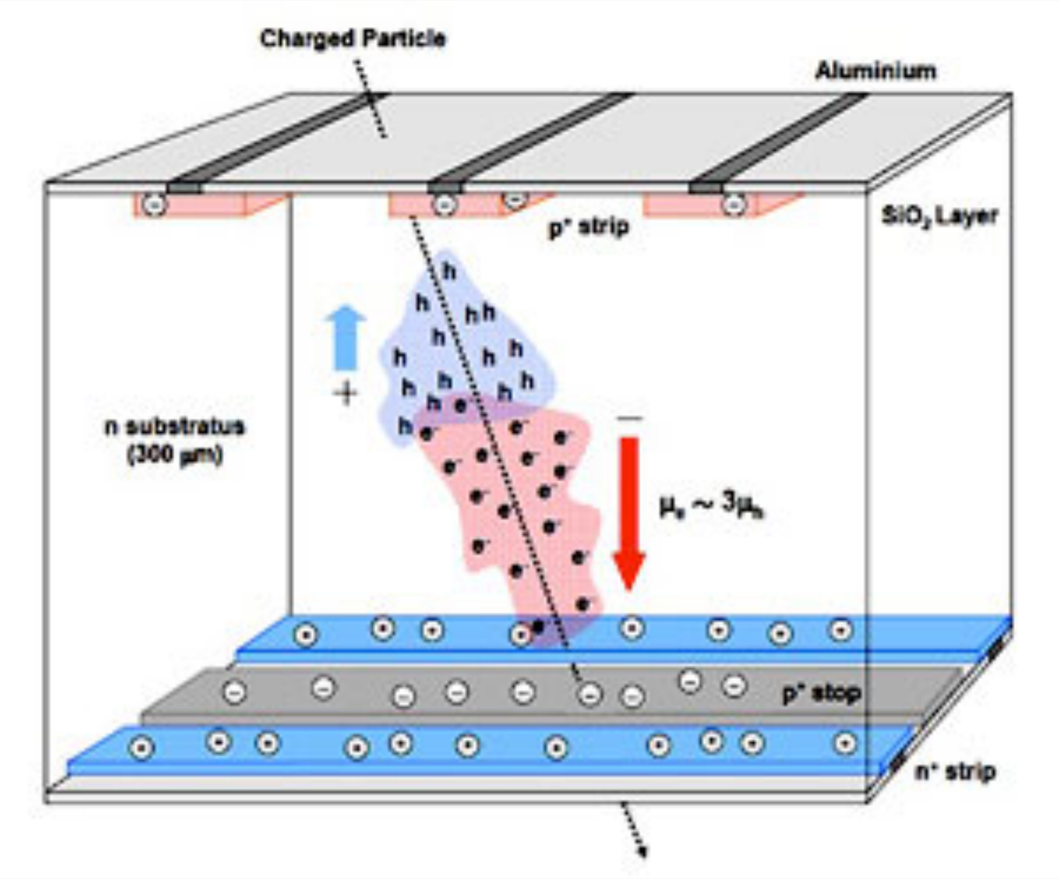
To prevent the dopants to diffuse and to improve the overall detector performance, often the semiconductor detectors are cooled to very low temperatures (liquid nitrogen). In these conditions their energy resolution is very high and make them well suited for precision spectroscopy, e.g. nuclear spectroscopy.

The resolution of a Germanium detector for nuclear spectroscopy is better than 1%. This can be compared to a NaI detector, which has resolutions around ~10% below 1MeV energies.



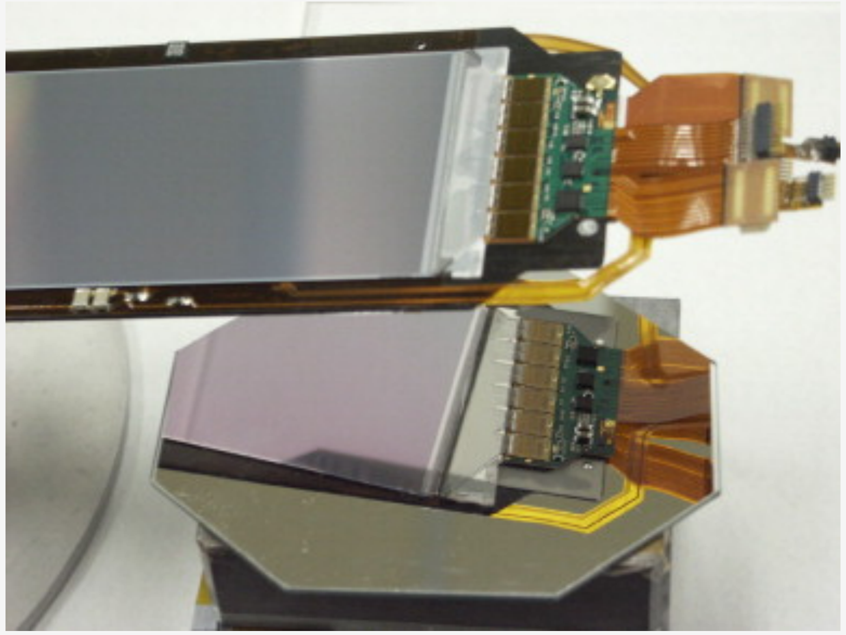
Microstrips and Pixels

Silicon Strip Detetectos and Silicon Pixel Detectors are now very common detectors in particle and nuclear physics. Their operation principle is again based on reverse bias diode structures, but these elements are arranged in strips or pixels on a plane of silicon.
Strips (or pixels) are separated by hundreds of microns and therefore these detectors can obtain high spacial resolutions.



Like wire chamber planes, silicon microstrips can be arranged in consecutive X/Y modules, achieving full tracking capabilities. Operating in magnetic fields, can provide momentum measurements.
Pixels are already a XY mesh of sensitive detectors.

Microstrips and Pixels have high resolution and radiation hardness to be ideal detectors to be placed very close to the collision point in a collider experiment.

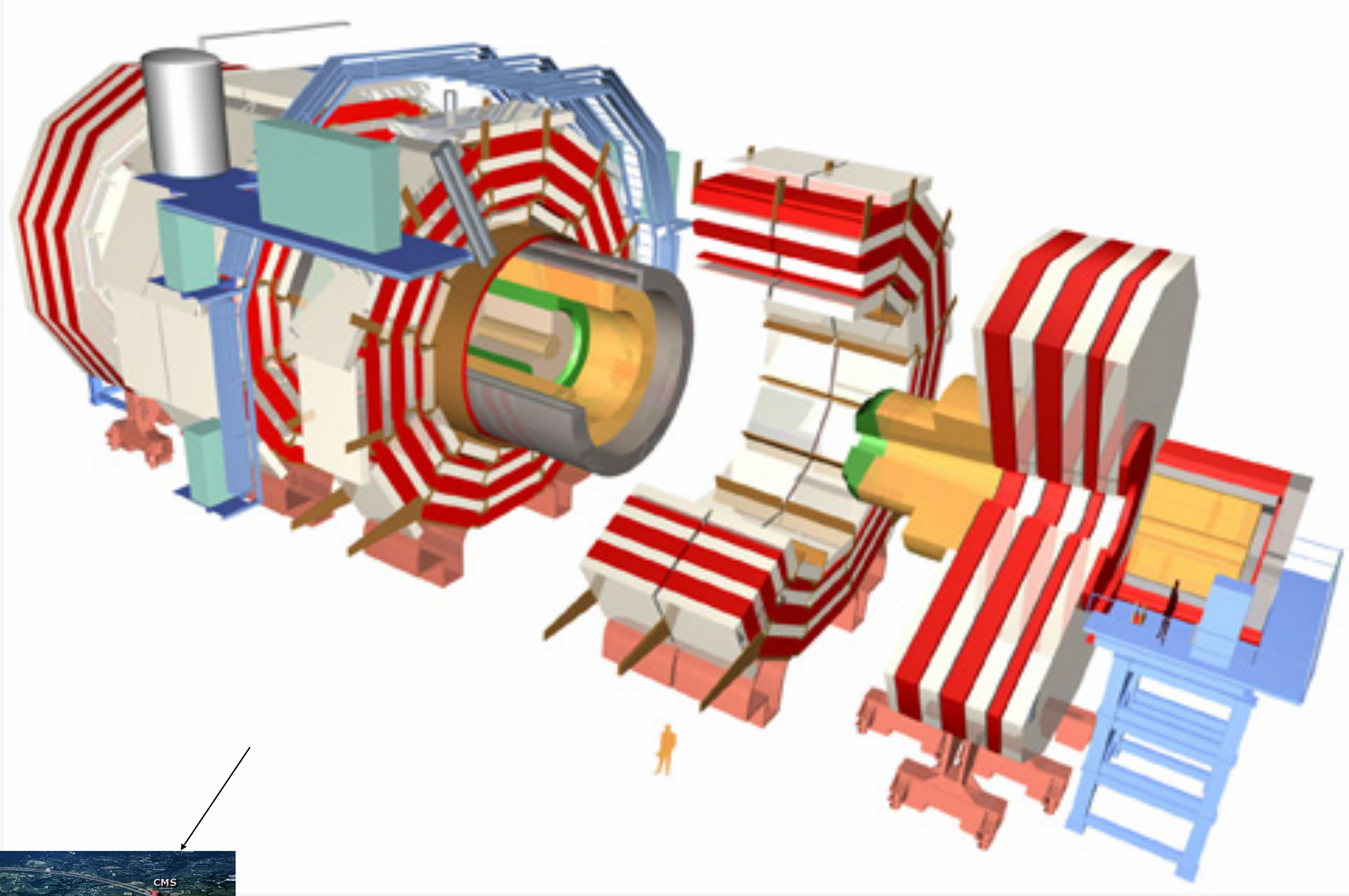


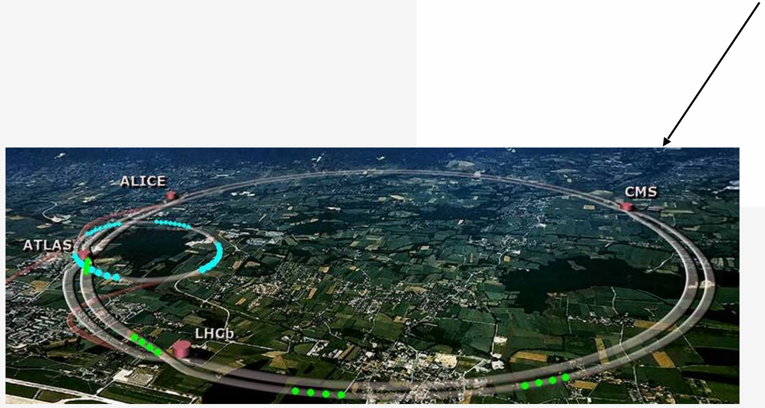
Detector Comparison

	Gamma Efficiency	Charged Particles Efficiency	Energy Resolution	Time Resolution	Spatial Resolution	Cost
NaI Crystal	good	good	~10%	fair	poor/fair	high
Plastic Scint.	poor	good	>10%	excellent	good if segmented	low
Semiconductor Detector	moderate	good	~0.3%	fair	Excellent for strips/ pixels	high
Wire Chamber	poor	good	poor	fair	Good, excellent for drift chambers	low

Putting Everything Together (I)

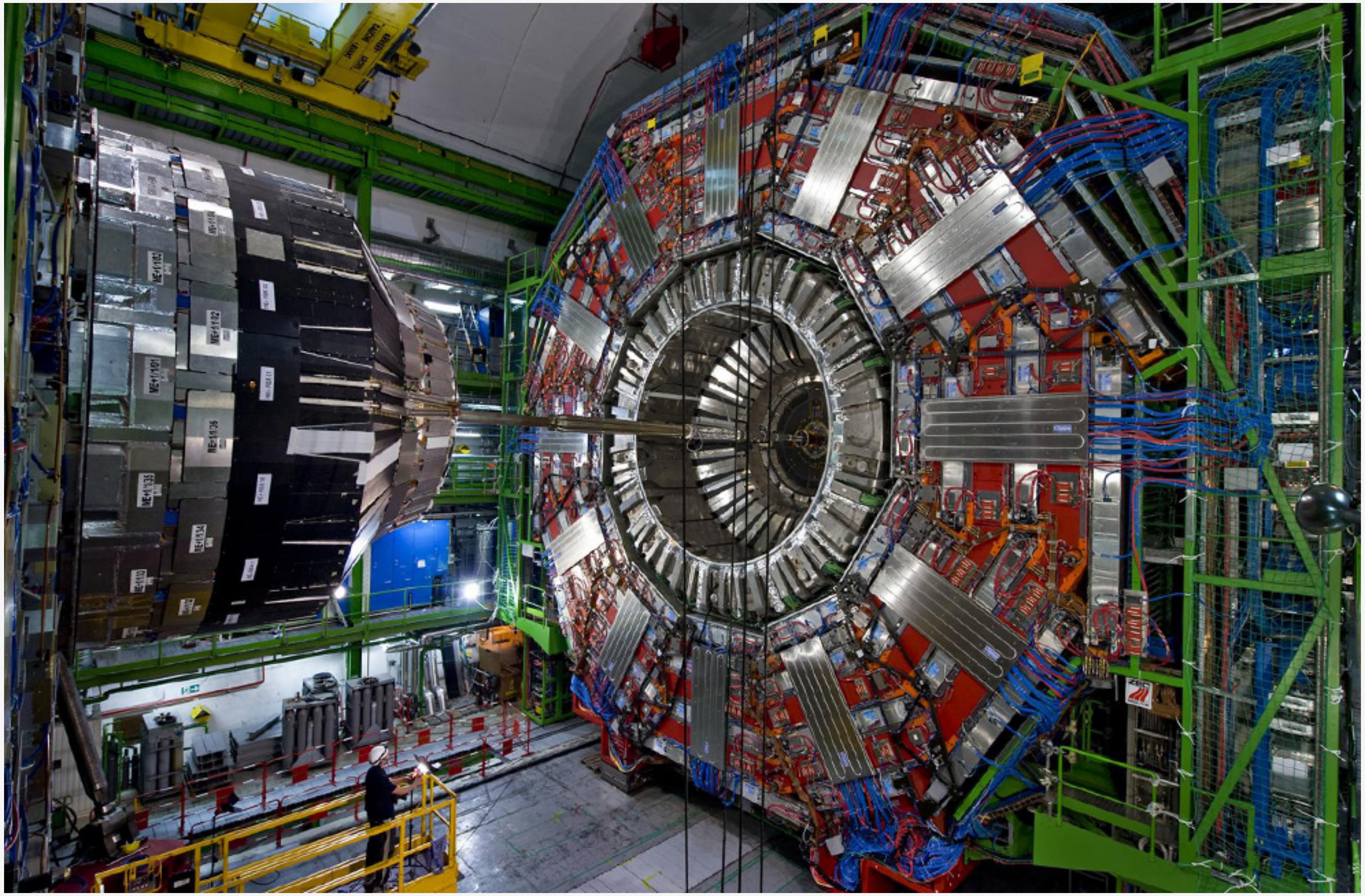
Example : The CMS detector at LHC





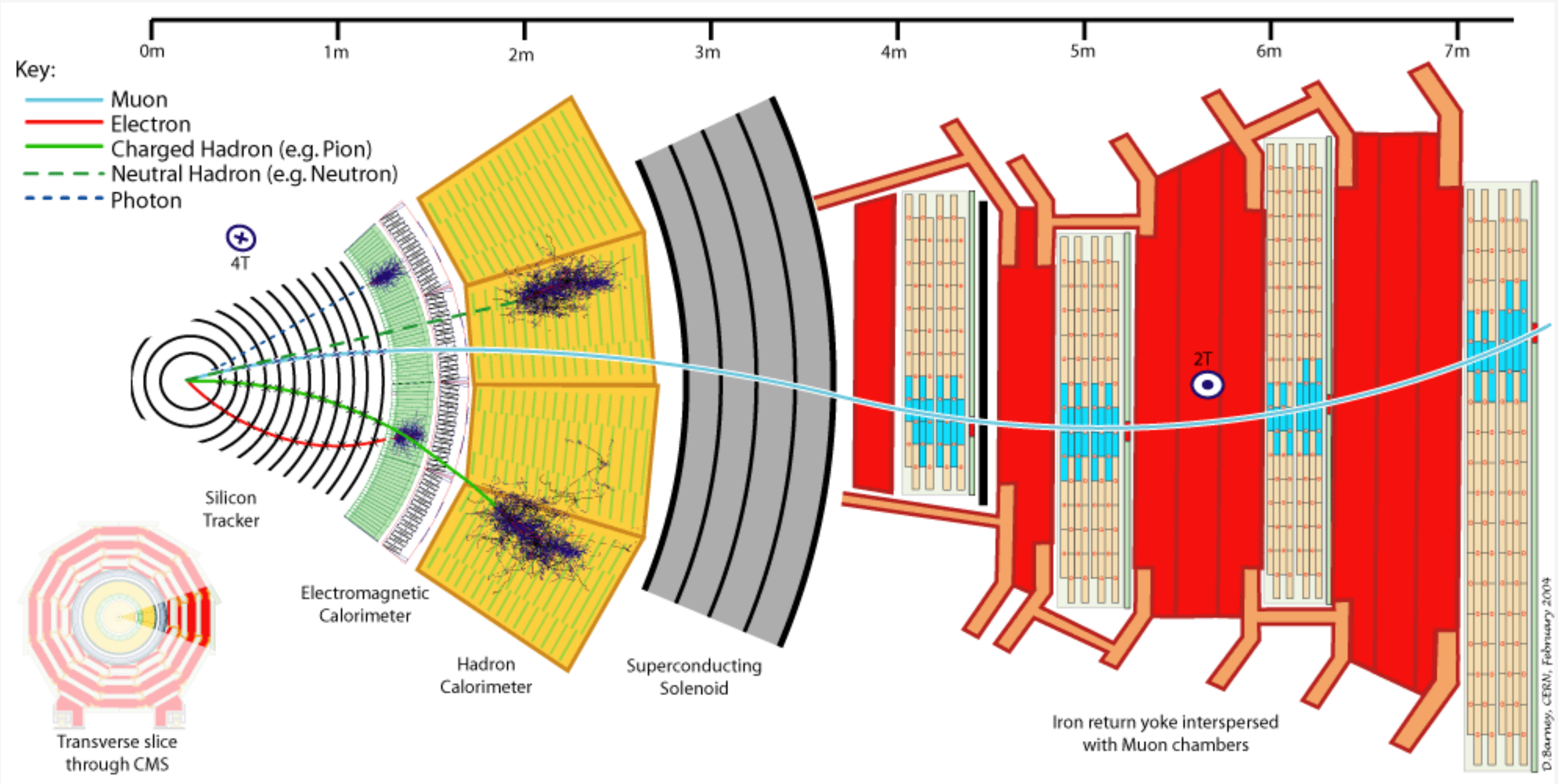
Putting Everything Together (II)

Example : The CMS detector at LHC



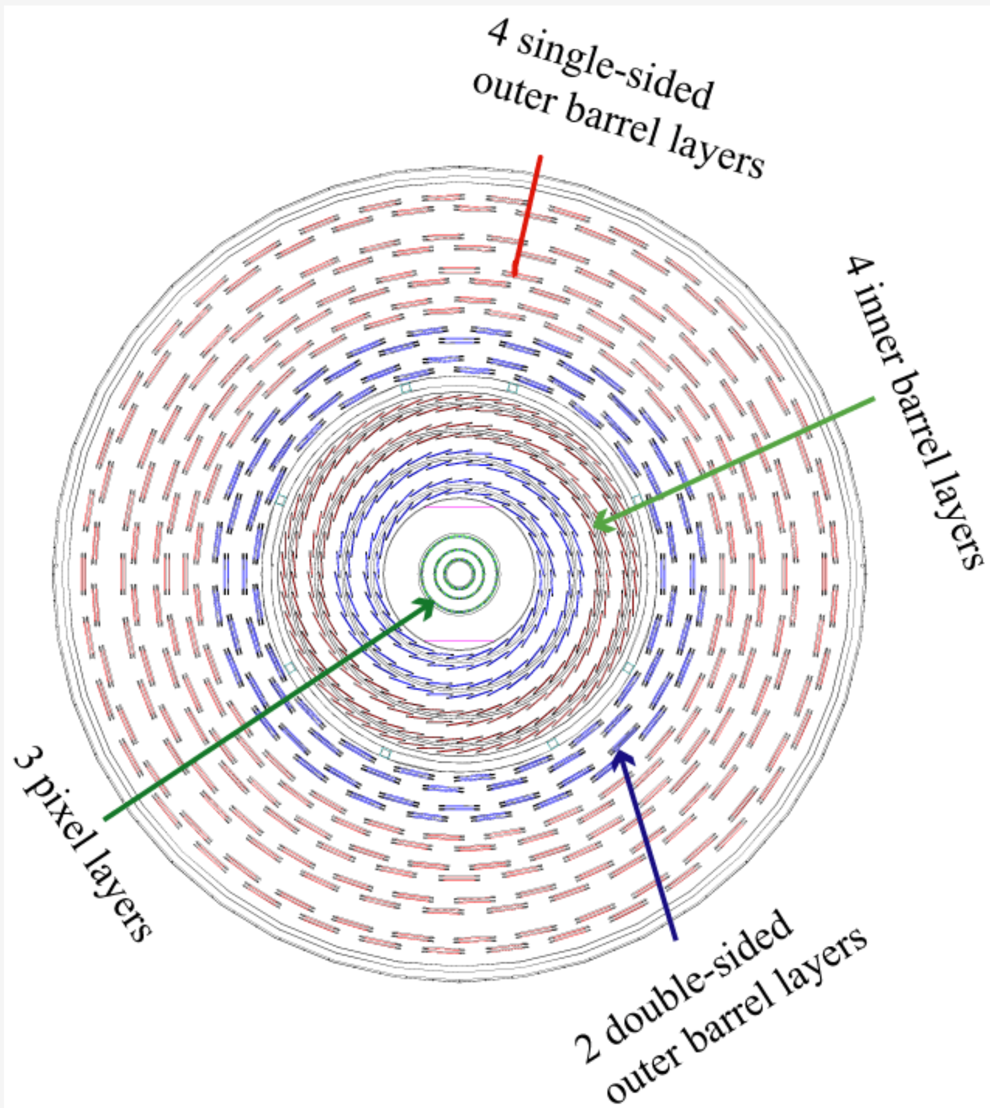
Length: 21.6m
Diameter: 14.6m
Weight: 12500tons

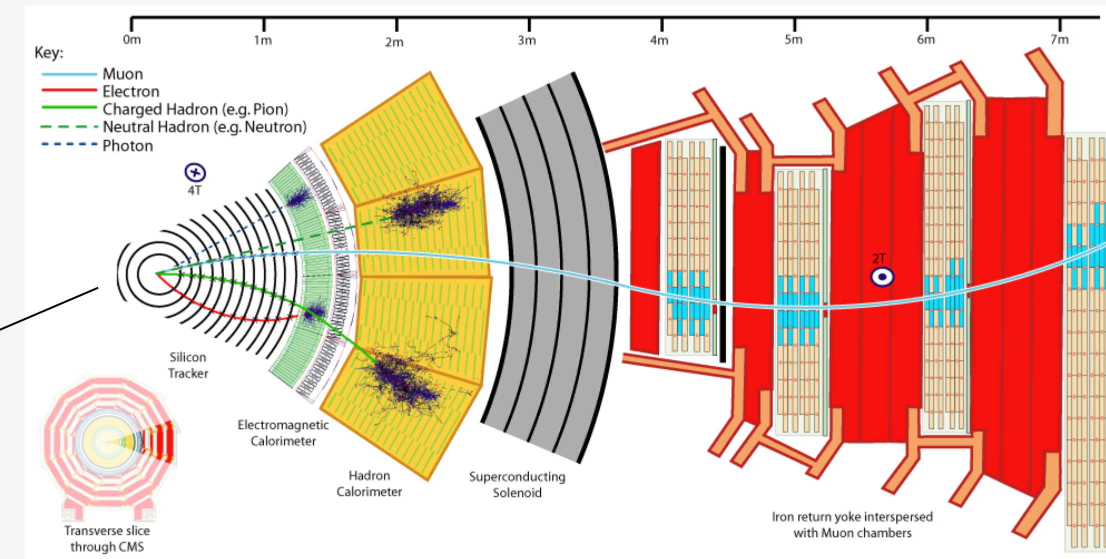
Putting Everything Together (III)

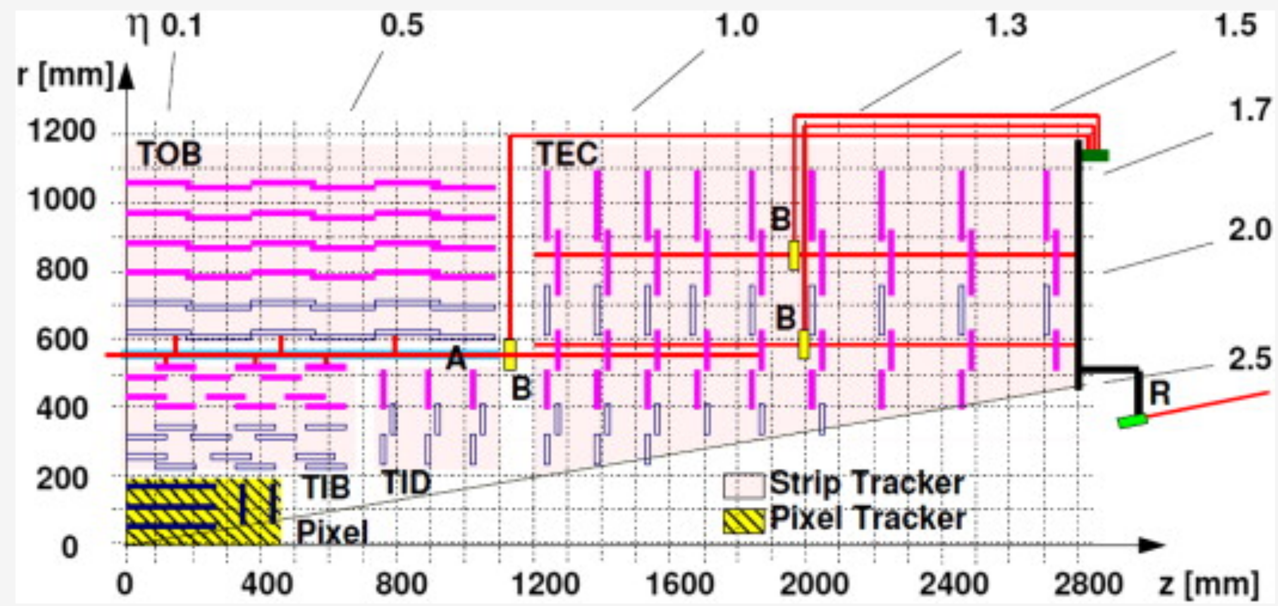


- The silicon Tracker is made of Pixel and Microstrip silicon detectors (momentum and secondary vertices).
- Electromagnetic (crystal) and Hadronic (sampling) calorimeters (energy measurement).
- The full system is immersed in a 4T magnetic field (momentum measurement).
- Muons are very penetrating: they are detected on the outermost layer of the detector.

Putting Everything Together (IV)



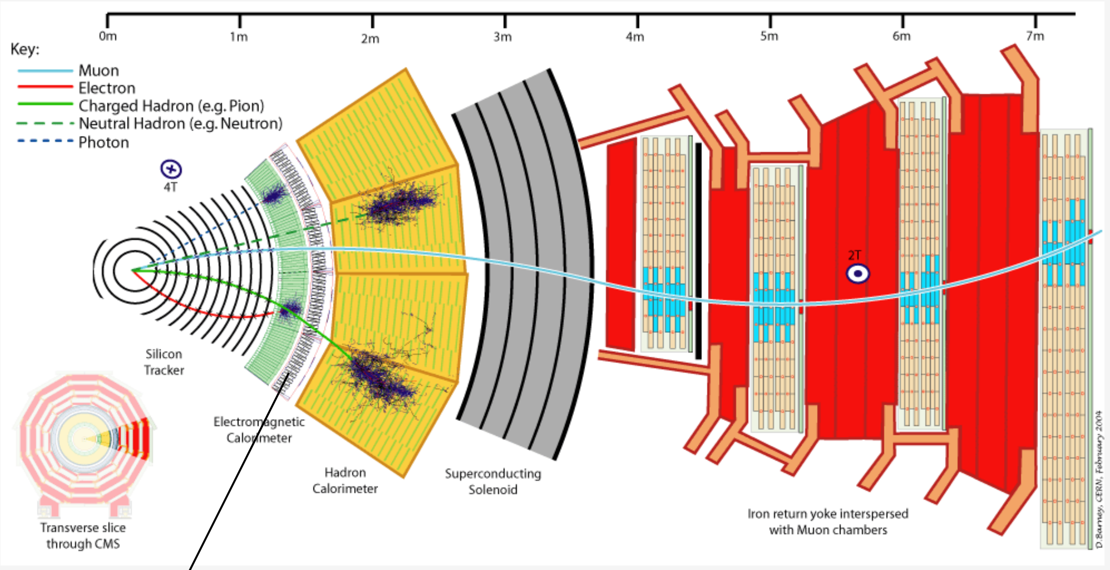


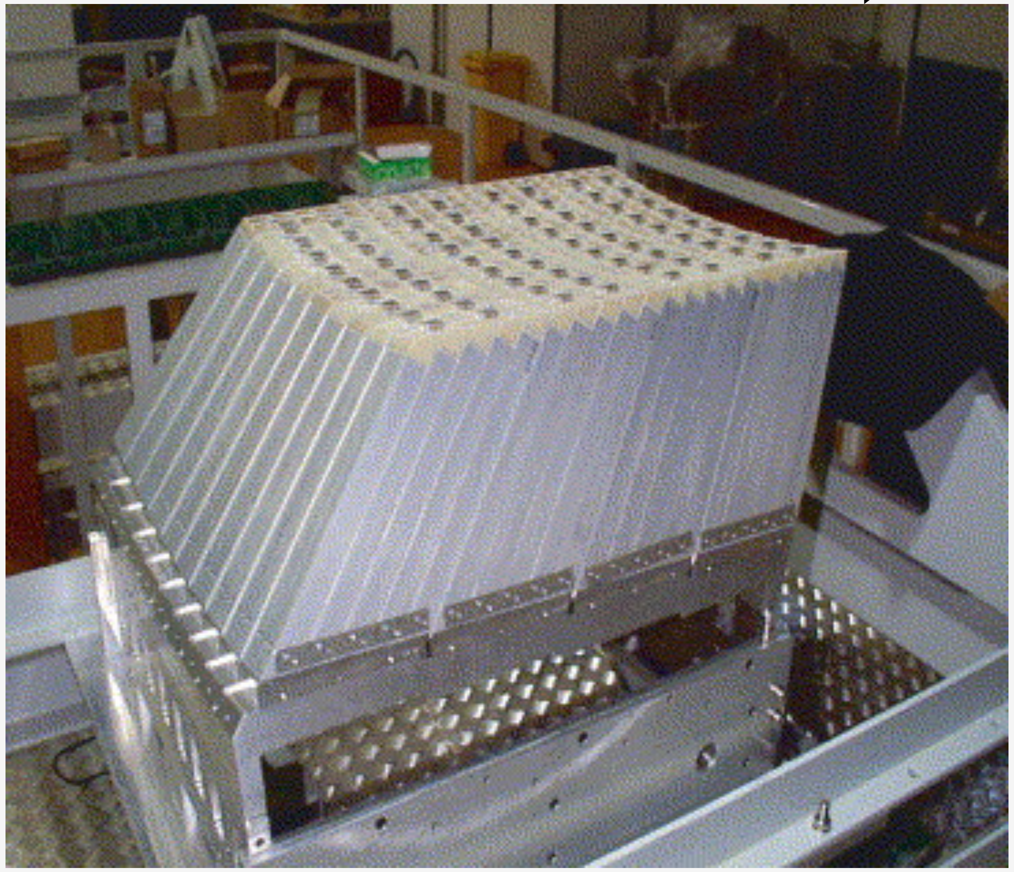


Pixel silicon detectors close to the interaction point
Silicon microstrip detectors constitute the tracker which is immersed in a 4T magnetic field.

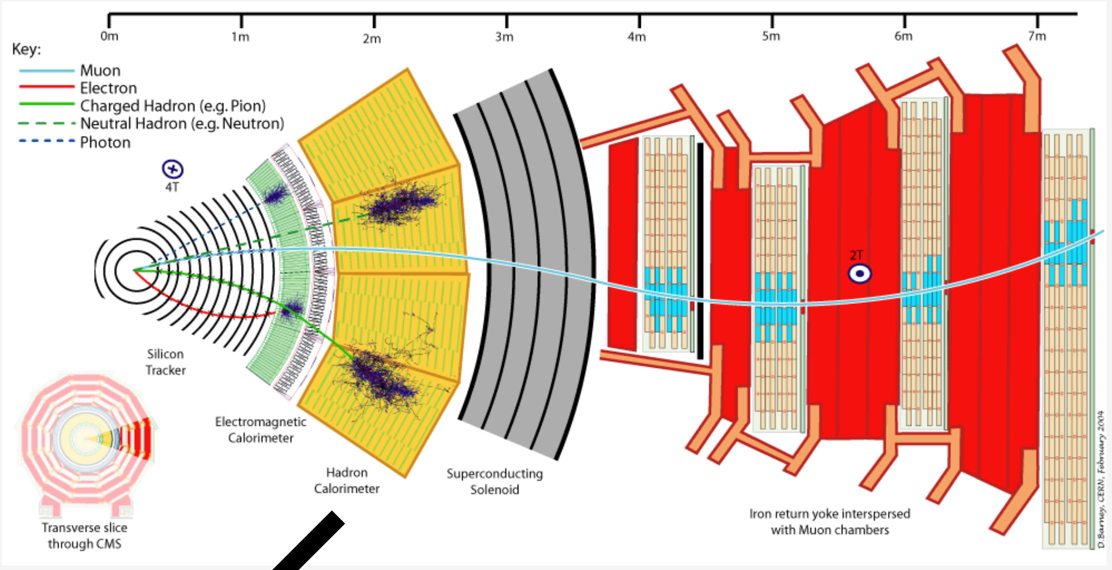
Putting Everything Together (V)

A module of the CMS electromagnetic calorimeter. In contains 440 lead-tungstenate ($PbWO_4$) crystals arranged in a "pointing" geometry.

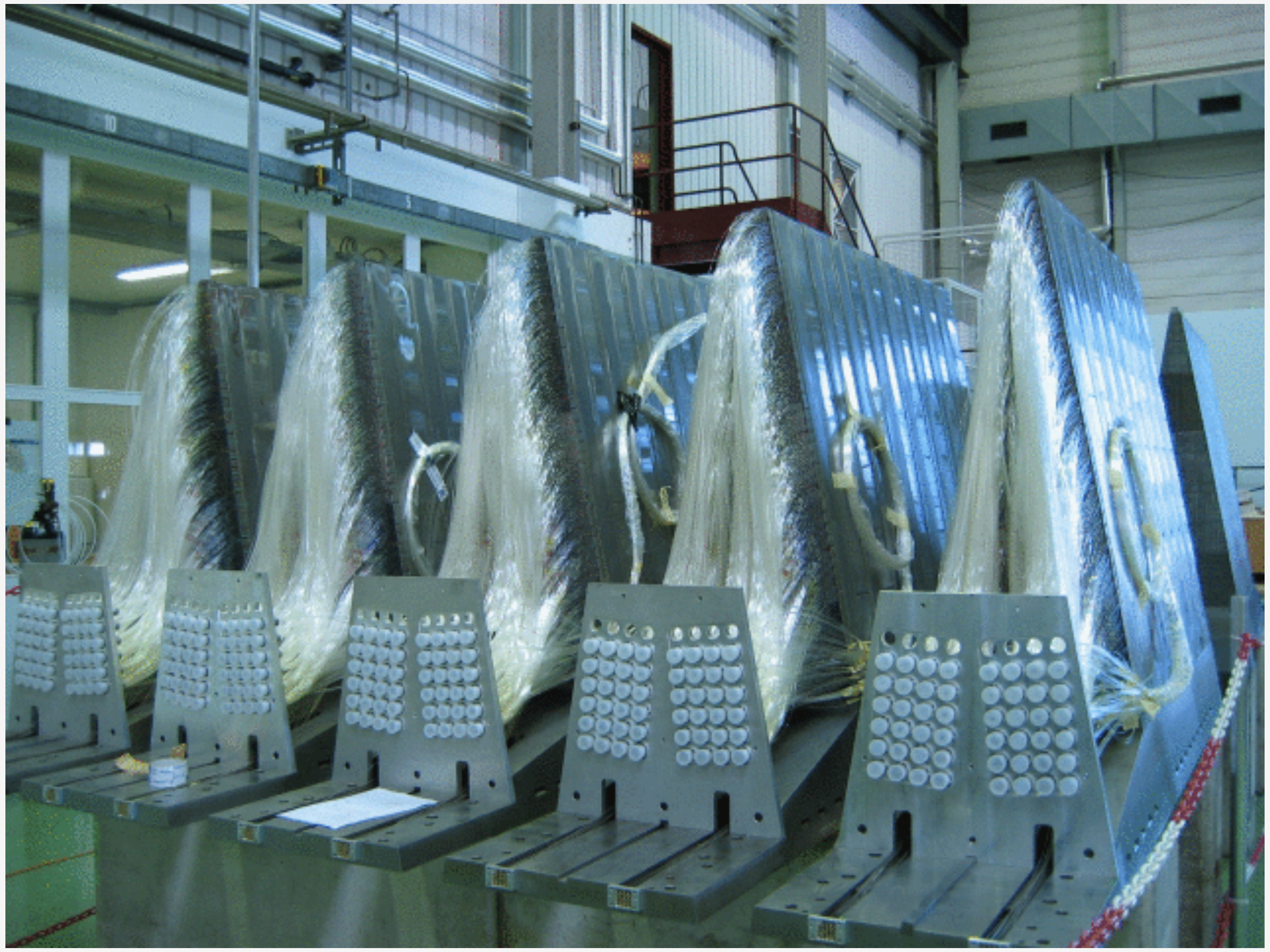




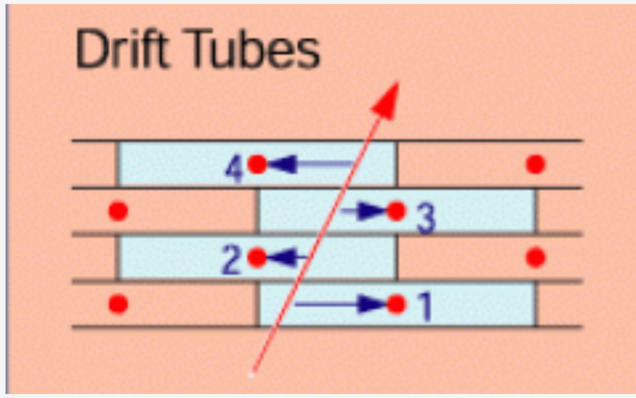
Putting Everything Together (VI)

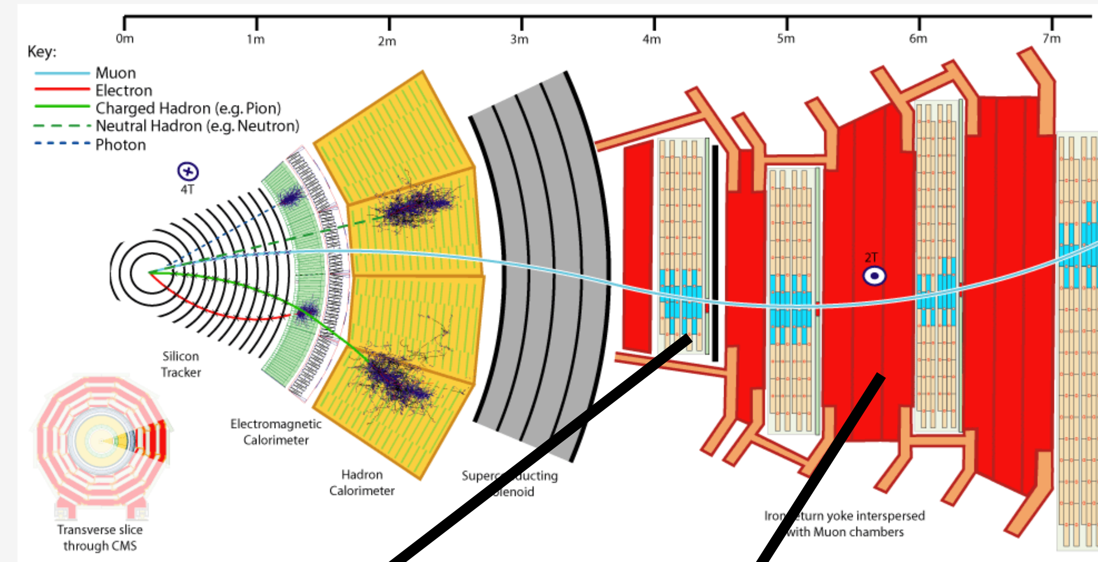


The hadronic calorimeter is a sampling calorimeter made of scintillator/brass layers. The scintillator tiles are read out by fibers.

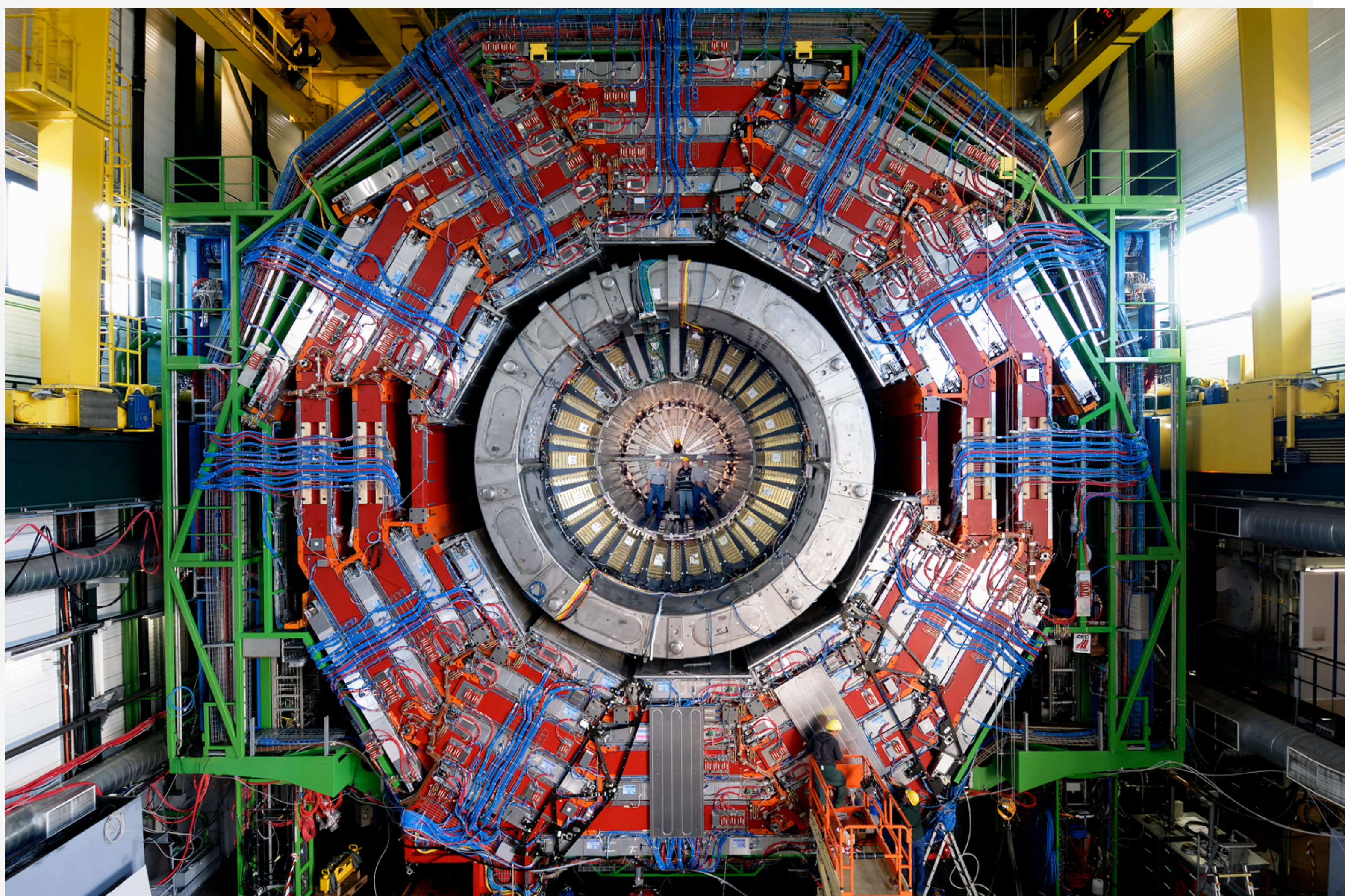


Putting Everything Together (VII)

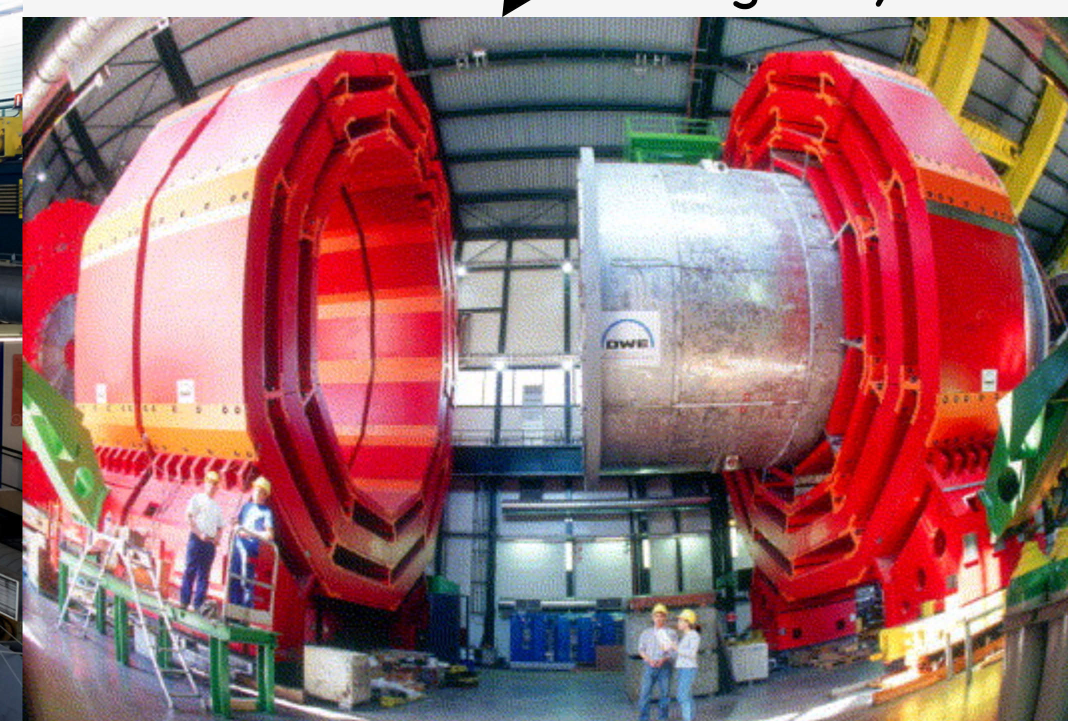




The muon chambers are composed by drift tubes.



Magnet yoke



Putting Everything Together (VIII)