A brief view of a biased selection of particle-detecting methods

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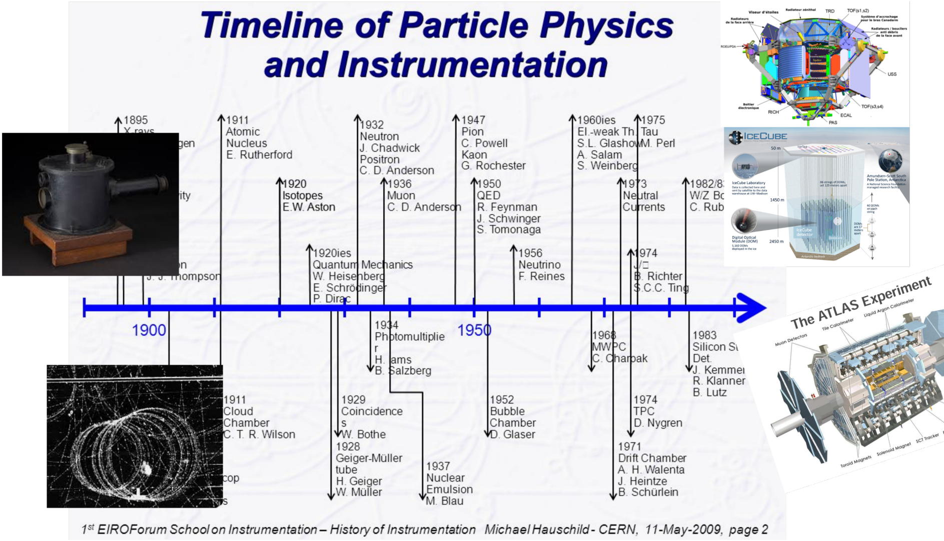
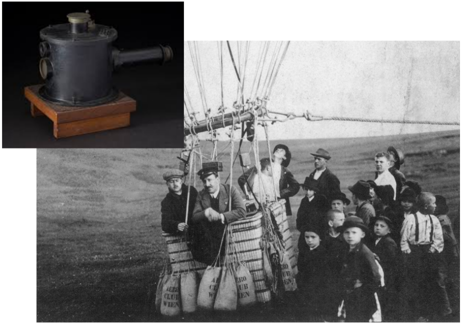
Laboratoire de l'Accelerateur Lineaire

JRJC Instrumentation Session - October 15th

Contents


Timeline of Particle Physics and Instrumentation
1895
1911 Atomic Nucleus E. Rutherford
1932 Neutron J. Chadwick Positron C. D. Anderson
1947 Pion C. Powell Kaon G. Rochester
1960ies El.-weak Th. S.L. Glashow A. Salam S. Weinberg
1975 Tau M. Perl
1920 Isotopes E.W. Aston
1936 Muon C. D. Anderson
1950 QED R. Feynman J. Schwinger S. Tomonaga
1973 Neutral Currents
1920ies Quantum Mechanics W. Heisenberg E. Schrödinger P. Dirac
1956 Neutrino F. Reines
1974 B. Richter S.C.C. Ting
1900
1950
1934 Photomultiplier H. Iams B. Salzberg
1968 MWPC C. Charpak
1983 Silicon Det.
1911 Cloud Chamber C. T. R. Wilson
1929 Coincidences W. Bothe
1928 Geiger-Müller tube H. Geiger W. Müller
1937 Nuclear Emulsion M. Blau
1952 Bubble Chamber D. Glaser
1974 TPC D. Nygren
1971 Drift Chamber A. H. Walenta J. Heintze B. Schürlein
IceCube
The ATLAS Experiment
Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
1st EIROForum School on Instrumentation – History of Instrumentation Michael Hauschild - CERN, 11-May-2009, page 2

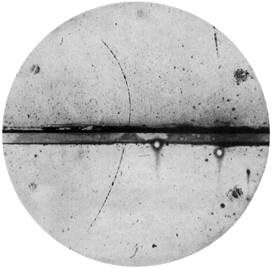
Some time ago you just needed a balloon



- Elesctroscope: ionisation detector
- Photographic plates
- Cosmic ray discovery (1911)

Some time ago you just needed a balloon

Cloud Chambers

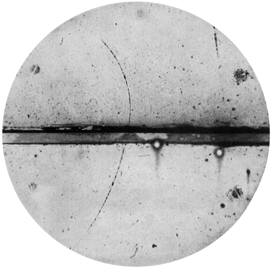


- Supersaturated vapour (alcohol or water)
- Charged, energetic particles
- ionise gas and leave a trail,
- vapour condenses around the ions
- Need to record images (positron - 1932)

Some time ago you just needed a balloon

- Superheated transparent liquid
- charged particles leave a trail of ions,
- vapour forms around the ions
- Large volume
- resolution of few μm
- weak neutral currents - 1973

Cloud Chambers

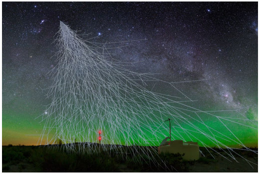


Bubble Chambers - 1952

Basic recipe of a particle detector

- Particles

  - radioactive source
  - cosmic rays
  - nuclear reactors/accelerators

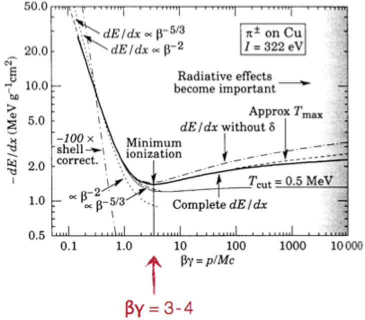


Basic recipe of a particle detector

- Particles
- Material that will interact with the particle

- Charged particles:
  ionisation,bremsstrahlung,Cherenkov
  $\rightarrow$ multiple interactions
- Photons: photoelectric/Compton effect, pair production
  $\rightarrow$ single interaction
- Hadrons: nuclear interactions
  $\rightarrow$ multiple interactions
- Neutrinos: weak interaction
  $\rightarrow$ good luck with that

The difference in mass, charge and type of interaction is key when trying to identify them!



$\beta = v/c; \gamma = 1/\sqrt{1-\beta^2}$

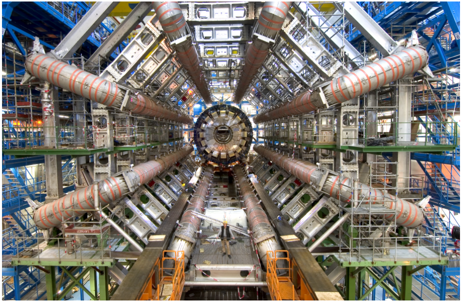
Basic recipe of a particle detector

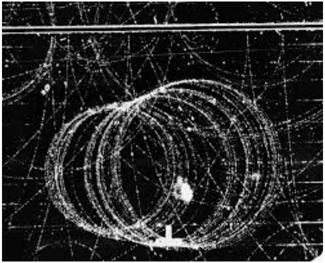
- Particles
- Material that will interact with the particle
- Signal
  - be able to recognise the interaction
  - and record it!
  - The development of the electronics is key (i.e. silicon detectors and ASICs)

(Don't forget the magnetic field)

Charged particles are deflected in a magnetic field

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





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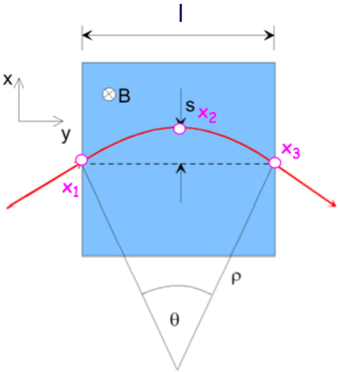
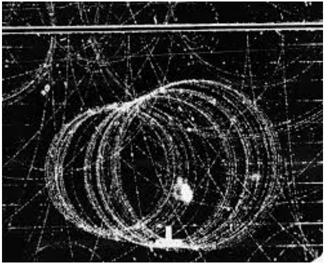


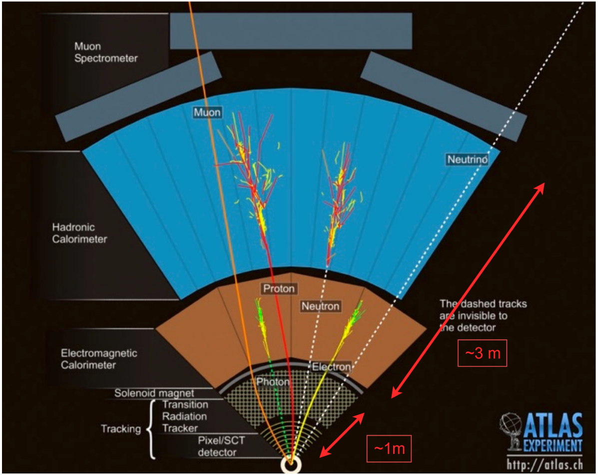


- If $m \sim 0$, for constant $\vec{B}$,
- then $|\vec{p}|$ is constant (assumption: no energy loss in the detector)
- helical trajectory
  - Measure 3 points $\rightarrow \sigma_s = \sqrt{3/2}\sigma_y$

$$\frac{\sigma_{p_T}}{p_T} \sim \frac{\sigma_y p_T}{n_{hits}}$$

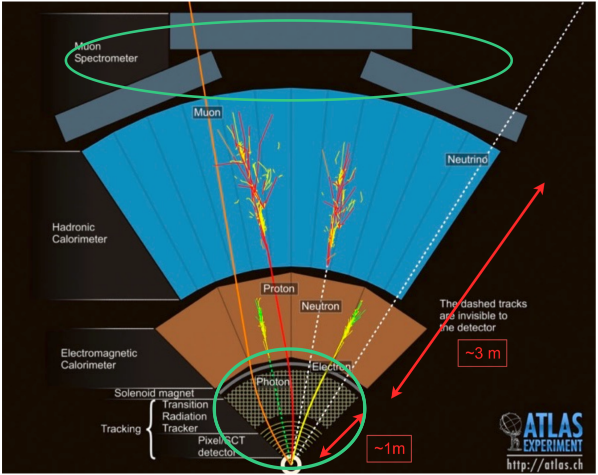
Detectors today...

Combine different technologies to measure the path and energy of the particles



Detectors today...

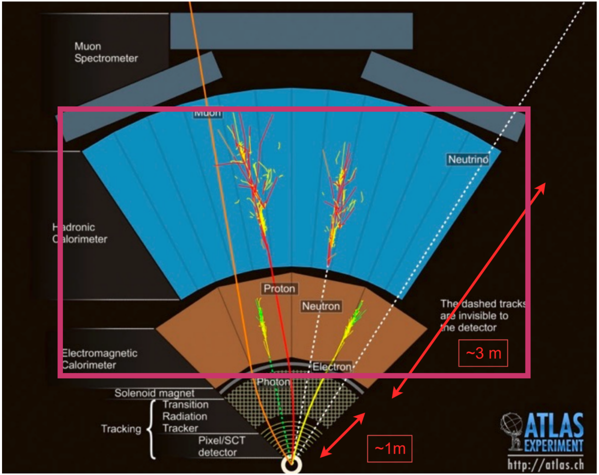
Combine different technologies to measure the path and energy of the particles



The tracker and muon spectrometer measure the momentum of passing charged particles - not modify particle's path and energy

Detectors today...

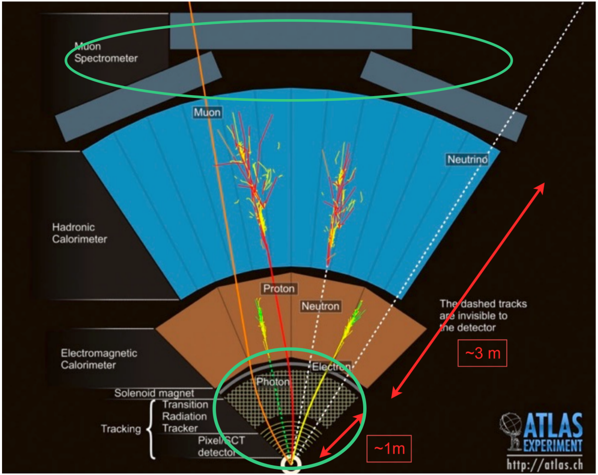
Combine different technologies to measure the path and energy of the particles



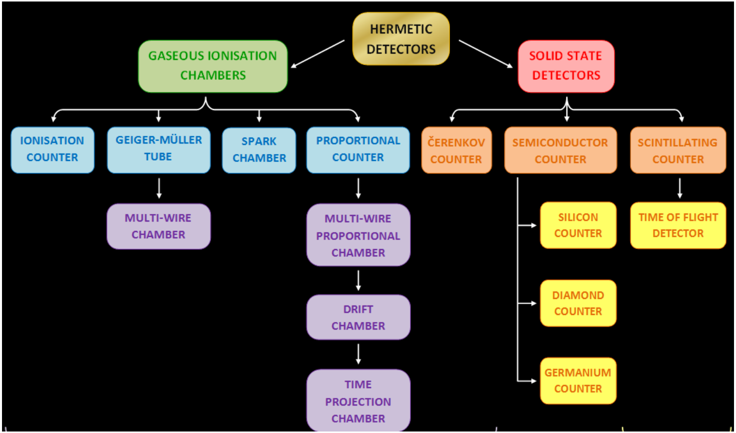
The calorimeters try to *stop* the particle to measure it's energy - destructive measurement

Detectors today...

Combine different technologies to measure the path and energy of the particles



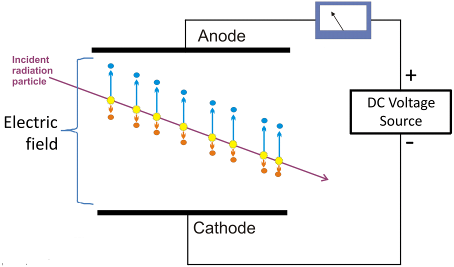
Types of detectors



Gas Detectors

Basic principle:

- A charged particle transverses a *carefully chosen* gas/gas mixture
- enclosed within en electric field $\vec{E}$
- gas is ionised by the particle
- generated charges drift towards cathode/anode
- measure current!



Gas Detectors

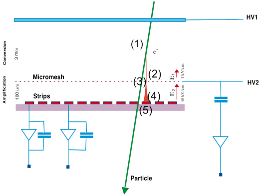
Geiger-Muller

- Main (well known) use: detect presence of radiation
- $\sim$ 0.1 atm gas
- High V, several hundred volts $\rightarrow$ high electric field
- gas multiplication (scattered e^- and UV photons)
- Gives one pulse per incident particle
- No energy measurement $\rightarrow$ no particle ID

Ionization Chambers

- No multiplication (only direct ionisation)
- Small current signal: $\sim 10^{-12} - 10^{-15}$ A
- Can measure total ionisation
- Achieve spatial resolution through smart design/placement of electrodes
- MicroMegas, Gas Electron Multiplier, Resistive Plate Chambers

MicroMegas



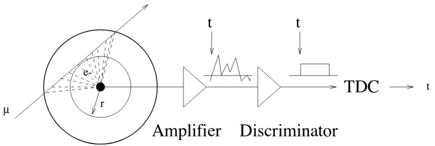
$\sigma \sim 100\mu$m

Gas Detectors

Proportional Counters

- Pulse height $\propto$ radiation absorbed by the detector
- Gas mixture of inert gas (to be ionised) and quenching gas (to terminate the pulse)
- Relatively low $\vec{E}$: no recombination, avalanche only close to electrode $\rightarrow$ single avalanche per generated ion

Drift Chamber



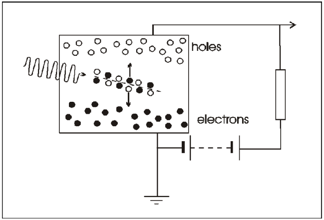
Particle position deduced from the wire position and time of the pulse

- Many of these detectors used currently in LHC experiments: TRT, MDT,RPC,CTC,TGC
- Most of these have $\sigma \sim 100\mu$m

Semiconductor Detectors

It is, basically, the same idea as before, but a lot more expensive...

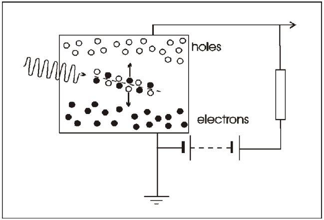
- A charged particle transverses a semiconductor material



Semiconductor Detectors

It is, basically, the same idea as before, but a lot more expensive...

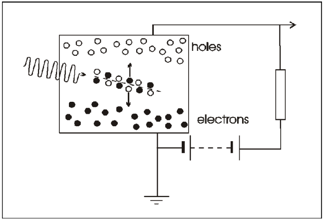
- A charged particle transverses a semiconductor material
  Semiconductor:
  - A crystal, like **silicon**, diamond, germanium
  - different *dopings* control the conductivity
  - n-type: excess of electrons
    p-type: excess of holes
  - n-p junctions → transistors/diodes
  - light emission
  - ... basically, the basis of a new technological era



Semiconductor Detectors

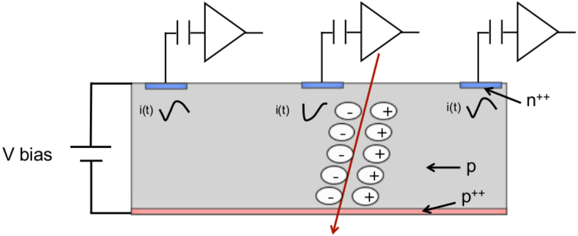
It is, basically, the same idea as before, but a lot more expensive...

- A charged particle transverses a semiconductor material
- Placed between electrodes, so that the electrons/holes generated drift due to the electric field
- A pulse can be measured - Shockley-Ramo theorem
$$i = E_v q v$$
- The number of e/h pairs created is proportional to the intensity of the incident radiation; the E necessary per pair is well known (eg 3.6 eV in silicon)



- Used in almost all HEP experiments for tracking in the innermost layers
- Price noticeably decreased throughout the years, combined with enough R&D, allowed to export this technology to *the real world* (medical imaging)

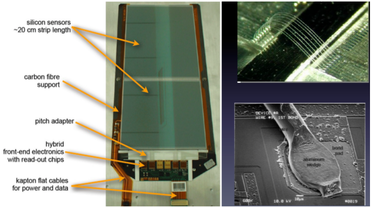
Silicon Detectors



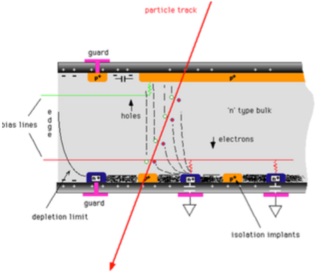
- Example n-on-p silicon detector
- Inversely polarised by a bias voltage → creates a depleted volume
- A charged particle crossing the sensor will create e/h pairs, which travel towards the electrodes
- $N(e/h)$ pairs depends on the type and energy of incident particle, and the thickness of the sensor
- Excellent spatial resolution

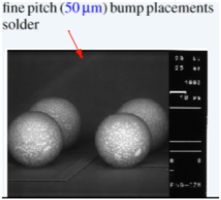
Pixel / Strips

Silicon Strip module



Pixel





- The resolution is given by the layout of electrodes
- 2D vs 3D tracking
- Pixels:
  - small area: low C, good S/N
  - small vol: low leakage current

Provide high precision tracking (vertex reconstruction) and momentum spectroscopy in large areas

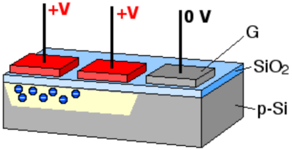
Charged-Coupled Device - CCD

The pixel consists of a MOS capacitor (p-doped metal oxide semiconductor)

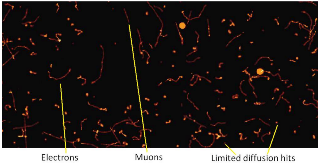
- semiconductor $\rightarrow$ silicon: active material, incident particle (usually photons) are converted into electrons
- oxide: insulator
- metal: voltage applied, collects the charge

Charged-Coupled Device - CCD

The pixel consists of a MOS capacitor (p-doped metal oxide semiconductor)



- biased before exposure to create a deep depletion region
- incoming particle generates e/h pairs charging the capacitor
- By applying potentials in a sequential way, the collected charge is moved to the end of the array
- At the end a charge amplifier collects the charge and transmits a voltage signal
  $\rightarrow$ the contents of the array are converted into a sequence of voltages



- Cooled CCDs are the most sensitive detectors for photons (single molecules, astrophysics), peak in 500-600 nm
- CMOS: commercial version, lower image quality

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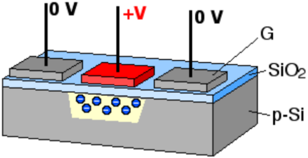

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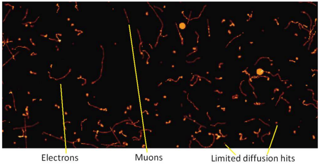

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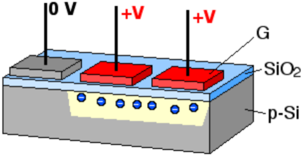

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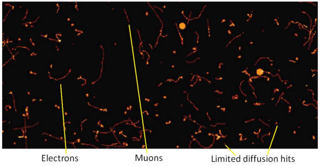

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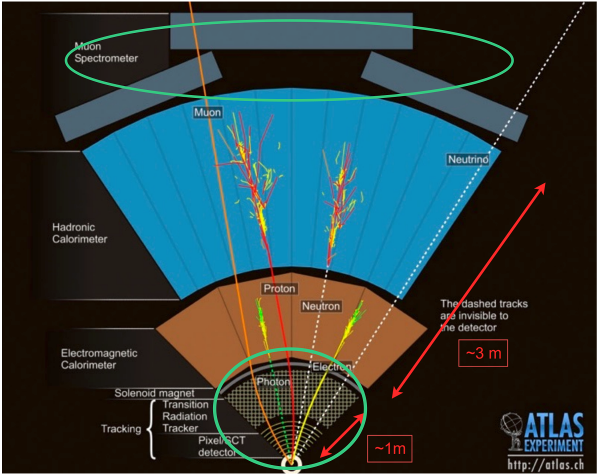
Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [Ref. 6]	~175–450 μm	~ 200 ns	~ 2 μs
Gas Micro Strip [Ref. 7]	30–40 μm	< 10 ns	—
Resistive Plate chamber [Ref. 8]	$\lesssim$ 10 μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	h	h
Silicon pixel	2 μm[i]	h	h

[a] Multiple pulsing time.
[b] 300 μm is for 1 mm pitch.
[c] Delay line cathode readout can give ±150 μm parallel to anode wire.
[d] wirespacing/$\sqrt{12}$.
[e] For two chambers.
[f] n = index of refraction.
[g] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$25 μm) with pulse-height-weighted center finding.
[h] Limited by the readout electronics [9]. (Time resolution of $\leq$ 25 ns is planned for the ATLAS SCT.)
[i] Analog readout of 34 μm pitch, monolithic pixel detectors.

*the readout electronics can limit the performance!

Tracker and Calorimeter

So far we've seen detectors that measure the *passage* of a particle..
But only for **charged particles**



Combining many of the previous detectors we form a **track**, the path of the particle through the detector

Tracker and Calorimeter

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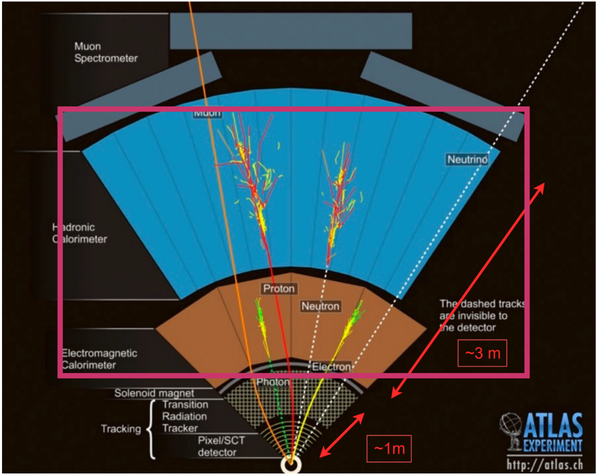
But only for **charged particles**

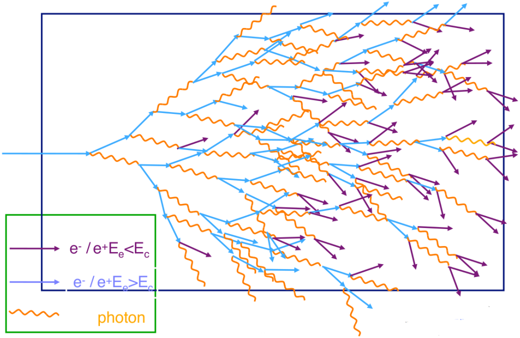


But what if we want to measure *everything*?

(or at least decently interacting charged and neutral particles)

EM shower

- An EM shower develops within de calorimeter, the energy of the incident particle is transferred to the generated $e^{+/-}$ and γ
- The number of cascade particles generated is proportional to the energy deposited by the incident particle
- it continues until $E < E_c$ (depends on the material)
- Radiation length (X^0) distance after which the incident e^- has irradiated 63% of its energy



Calorimeters

- Idea from thermodynamics:
  - 'adiabatic volume' (not loose energy)
  - Aim to collect all the energy of the particle (charged **and neutral**)
  - **destructive measurement**: no particles come out, except neutrinos and muons
  - fun fact: the sensitivity required is $\sim 10^9$ times larger than to measure a 1 ℃ shift in 1g of water

Types of particles

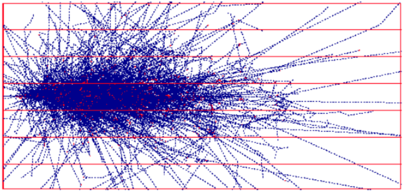
- Electromagnetic
- Hadronic

Types of calorimeters

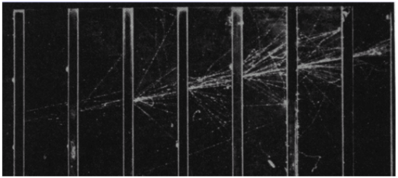
- Homogeneous
- Sampling

Homogeneous/Sampling

Homogeneous



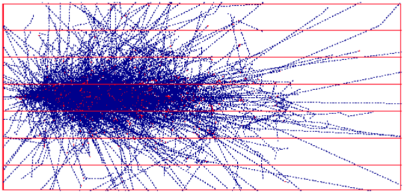
Sampling



- All the energy is deposited in the active medium
- So the same material needs to stop the particle and generate a signal
- Heavy active material: lead tungstate PbWO (CMS calorimeter)
- Excellent energy resolution
- No longitudinal segmentation

Homogeneous/Sampling

Homogeneous



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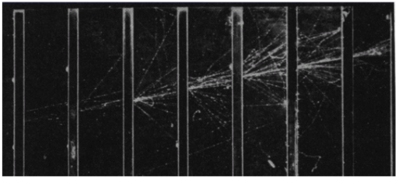
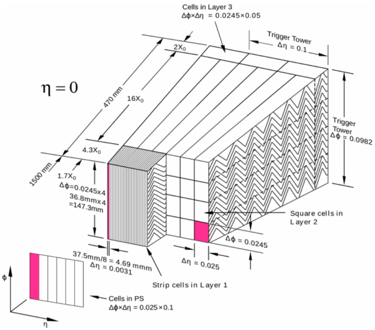


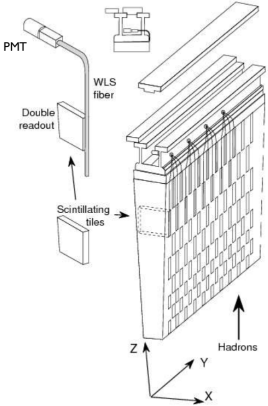
- Heavy stopper/absorber material (Cu, Pb, Fe)
- Sampled by an active material (scintillator plastic, semiconductor, gas)
- Limited energy resolution
- But gives information of the longitudinal deposition of the energy

EM and Hadronic calorimeters

Different concepts for different particles:

- EM : LAr as active material, Pb/Steel absorber, thin electrodes collect the signal
- TileCal: scintillator plastic as active material, F_e absorber.
  WS fibres take light towards PMTs
- Calibration: necessary to have a beam of known particles.
- Response to the EM and non-EM part of the shower is different, e/h degree of non-compensation





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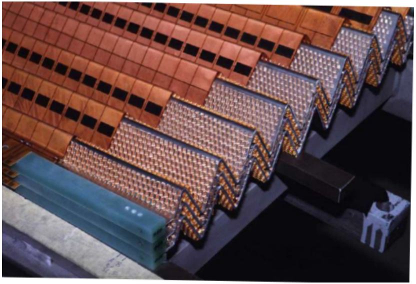

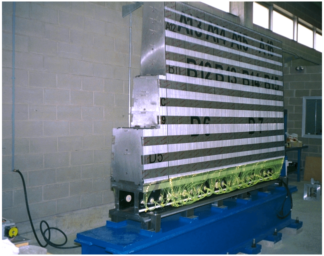

Conclusions

- Not very exhaustive basics of particle detectors[1]
  - Skipped Cherenkov detectors, photomultipliers, and many other topics
  - Mostly biased towards LHC experiments...
- But we got the basics:
  - key elements in a particle detector
  - some gaseous detectors
  - some solid state detectors
- Now lets hear your talks!

[1] Disclaimer: lots of material and pictures taken from Wikipedia, I. Winteger's CERN summer school lectures, papers, etc. . .