Instrumentation in Particle Physics: a bit of history and bit of intro

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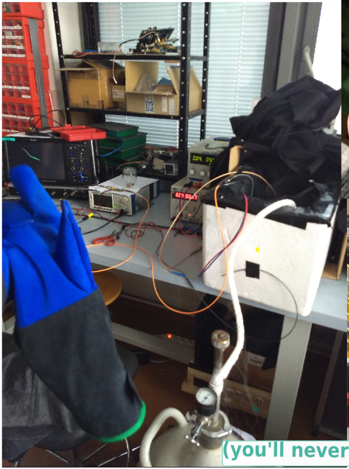
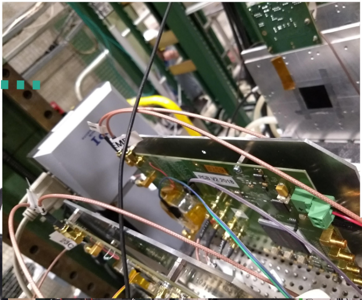
Astroparticule et Cosmologie

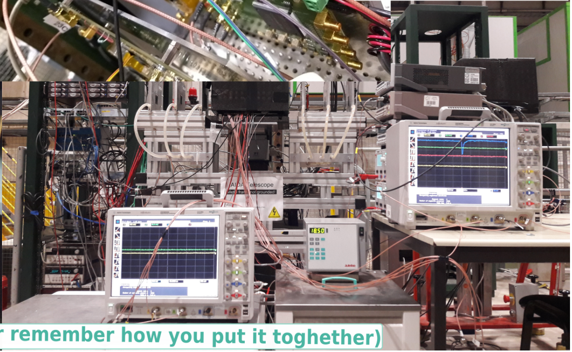
JRJC Instrumentation Session - October 18^{th} 2021

Working in beautiful surroundings....

Unique setups...

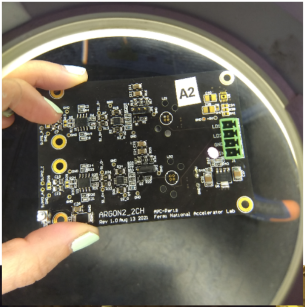


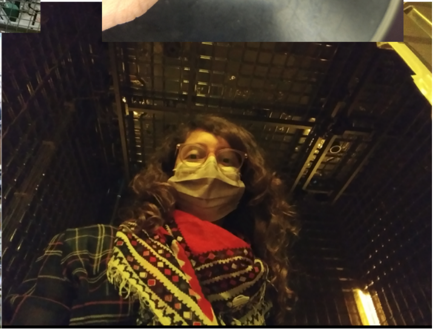




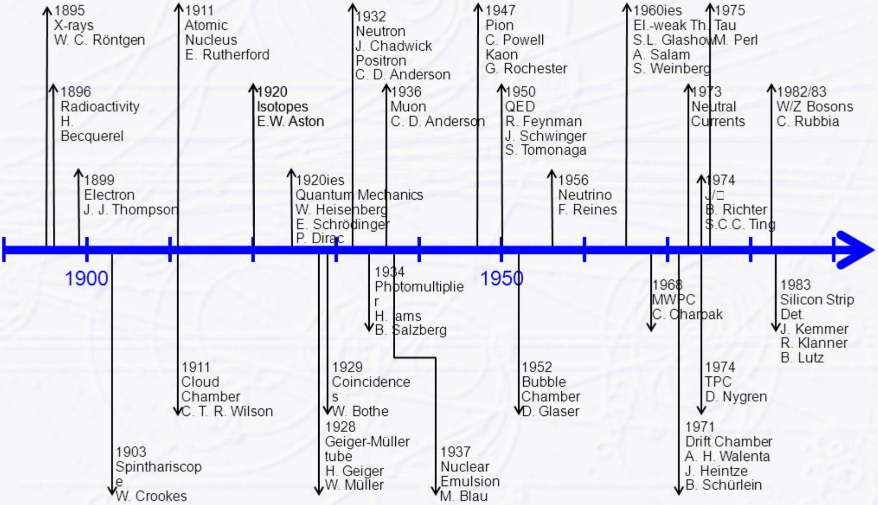
(you'll never remember how you put it toghether)

I just love the aesthetics of it...

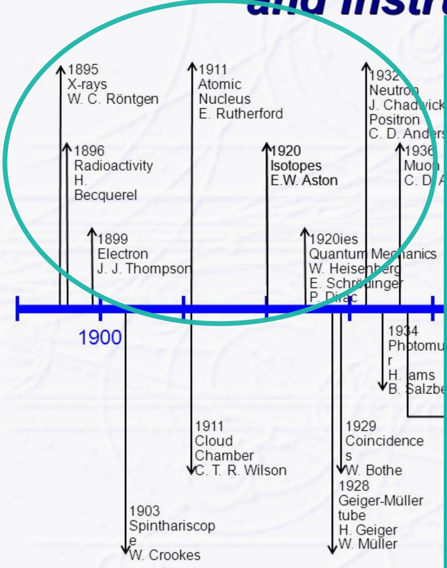




Timeline of Particle Physics and Instrumentation



Timeline of Particle Physics and Instrumentation



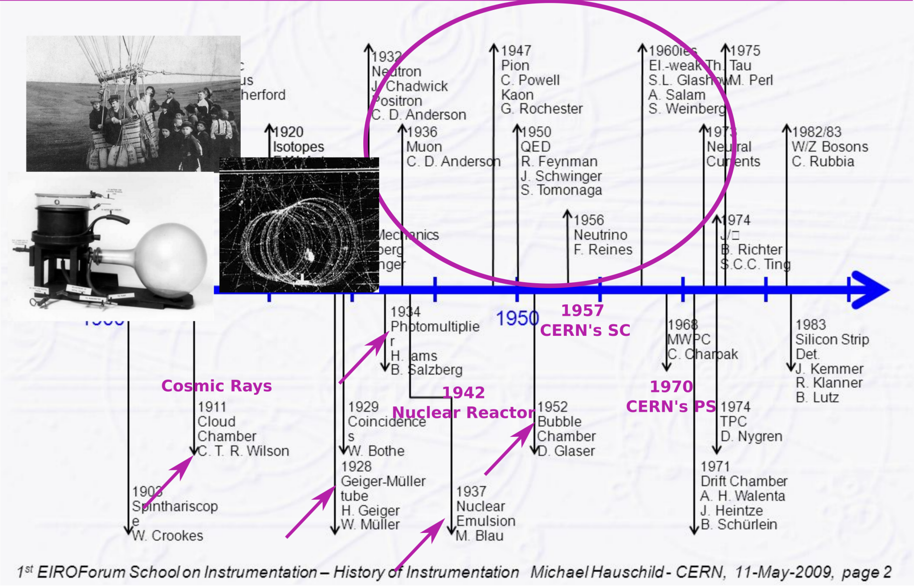
- The "atom structure" era
- Visible signals induced by many particles
- Particle sources:
  - Cathode tubes
  - Radioactive elements
- Magnetic field $\rightarrow$ sign of charge,
- Electric field $\rightarrow$ Millikan experiment
- Detection methods:
  - photographic plates
  - ionization chambers

1[st] EIROForum School on Instrumentation – History of Instrumentation Michael Hauschild - CERN, 11-May-2009, page 2

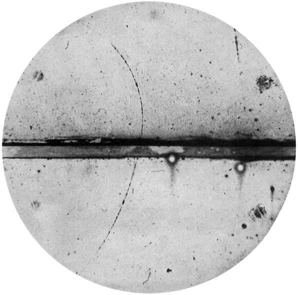
Single Particle Detection:

Sources: cosmic rays, nuclear reactors,synchrotrons ---> accelerators

Technology: cloud chamber, photomultipliers, bubble chambers --> image analysis

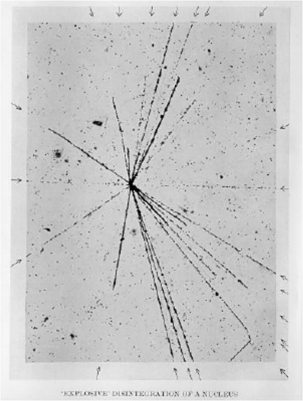


Cloud Chambers



- Originally developed for climate studies
- Supersaturated vapour condenses due to the passage of a charged particle
- Provides "amplification" of a single particle effect

Nuclear Emulsion



Bubble Chambers

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

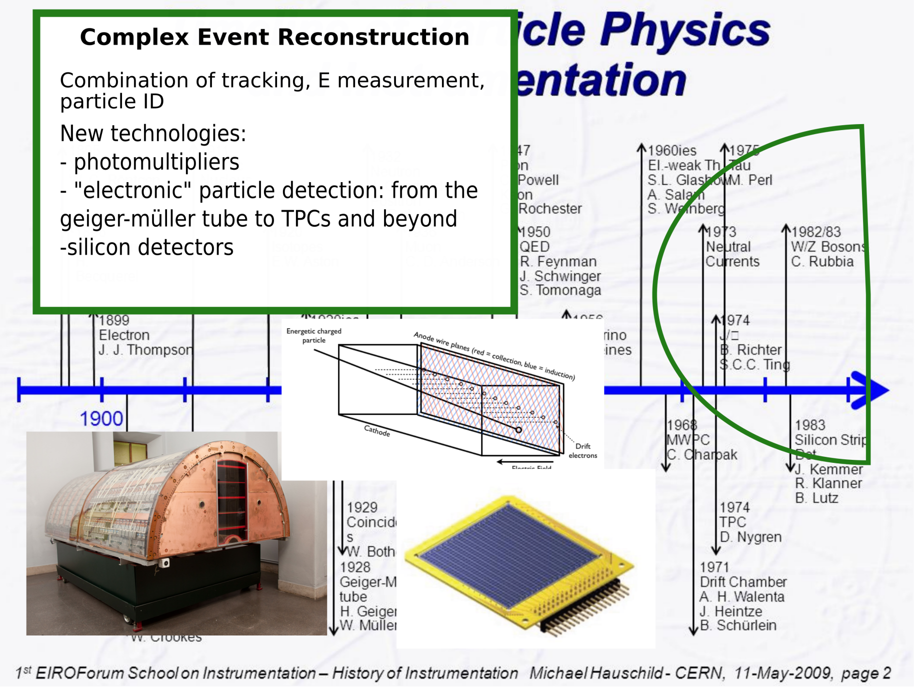
$\rightarrow$ Mostly based on image analysis

Complex Event Reconstruction

Combination of tracking, E measurement, particle ID

New technologies:

- photomultipliers
- "electronic" particle detection: from the geiger-müller tube to TPCs and beyond
- silicon detectors



What do we (usually) need in a particle physics experiment?

- A source of particles
- A medium with which the particles will interact
  $\rightarrow$ and understanding of the possible interactions
- A data acquisition system

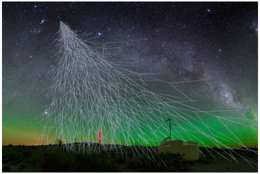
Particle sources

Natural

- radioactive sources
- cosmic rays

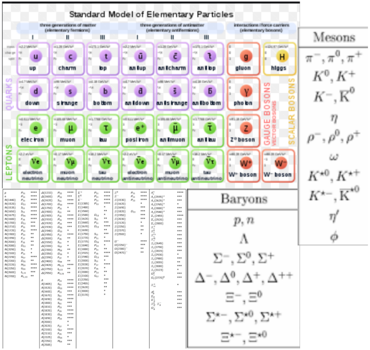
Artificial

- nuclear reactors
- accelerators



What do we want to measure?

Out of the huge zoo of known particles...



- Only 27 have a lifetime @GeV energies such that $c\tau > \mu$m
- There are 13 that a detector should measure:

$e^\pm$	$K^\pm$
$\mu^\pm$	$p^\pm$
γ	K^0
$\pi^\pm$	n

To be characterized by their mass, momentum, energy, charge...

Interactions

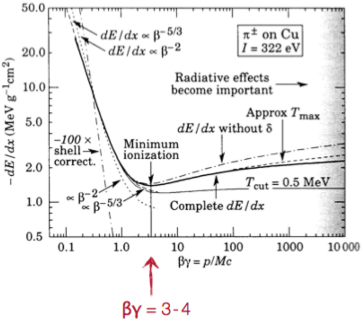
- Charged particles: ionisation,bremsstrahlung,Cherenkov
  $\rightarrow$ multiple interactions
- Photons: photoelectric/Compton effect, pair production
  $\rightarrow$ single interaction
- Hadrons: nuclear interactions
  $\rightarrow$ multiple interactions
- Neutrinos: weak interaction
  $\rightarrow$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

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

Radiation length (X_0): distance after which an incident electron's energy is $1/e$

Bethe-Bloch formula: energy loss by ionisation

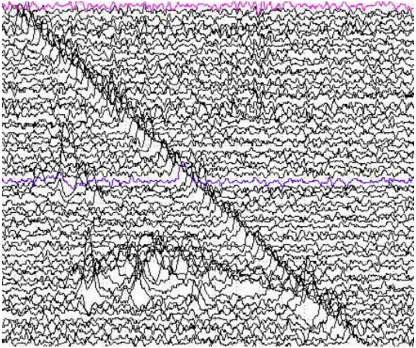
Energy loss of π in C_u



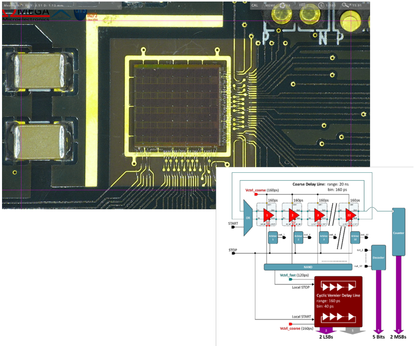
$\beta = v/c; \gamma = 1/\sqrt{1-\beta^2}$

Data Acquisition

- be able to recognise the interaction → trigger and event selection
- and record it!
- The development of the electronics is key
  (i.e. silicon detectors and ASICs)



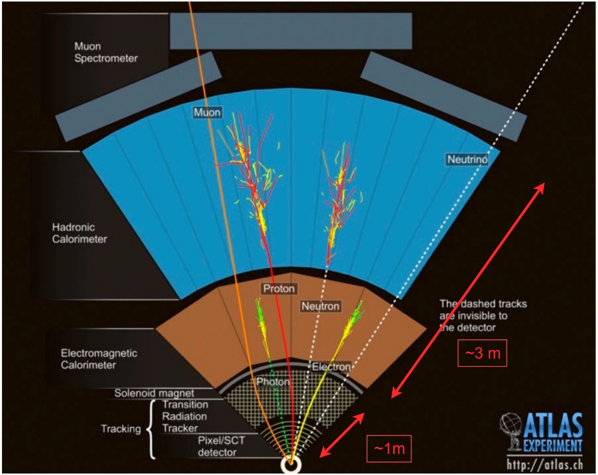
TPC continuous signal readout



ASIC die and TDC diagram

Detectors today...

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



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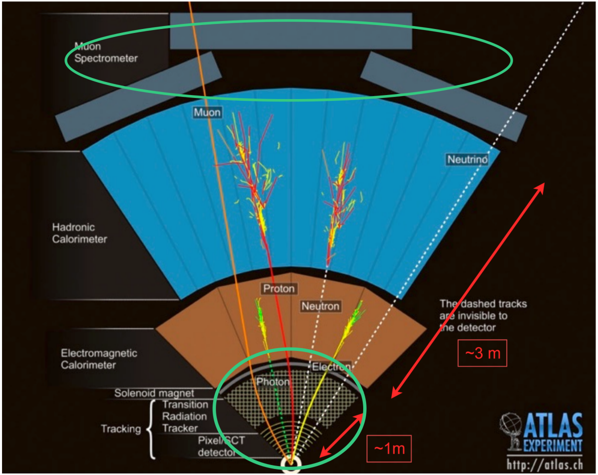
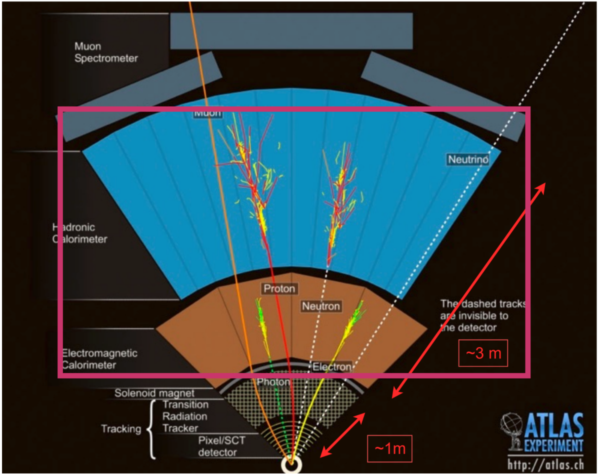


The tracker and muon spectrometer measure the momentum of passing charged particles - not modify particle's path and energy

Detectors today...

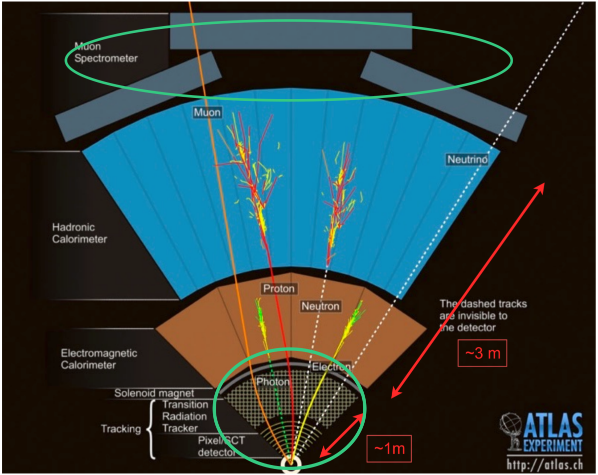
Combine different technologies to measure the path and energy of the particles



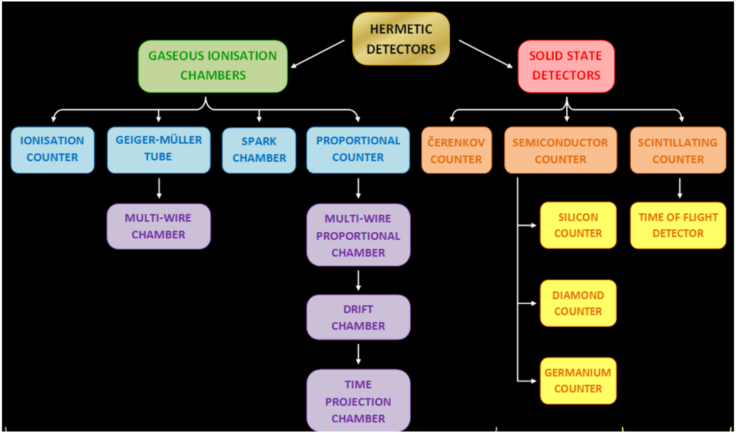
The calorimeters try to *stop* the particle to measure it's energy - destructive measurement

Detectors today...

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



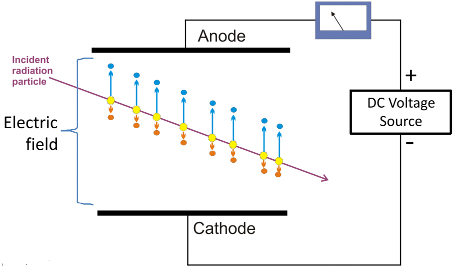
Types of detectors



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

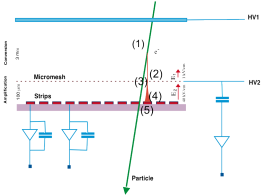
Geiger-Muller

- Main (well known) use: detect presence of radiation
- ~ 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



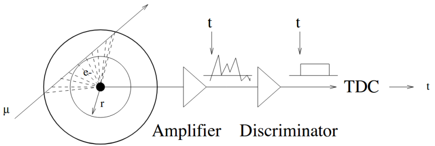
$\sigma \sim 100\mu$m

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



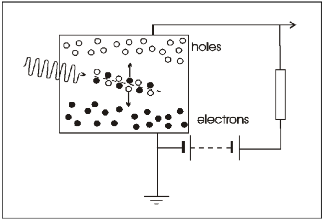
Particle position deduced from the wire position and time of the pulse

- 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...

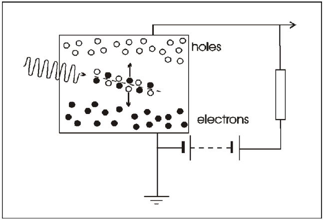
- A charged particle transverses a semiconductor material



Semiconductor Detectors

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

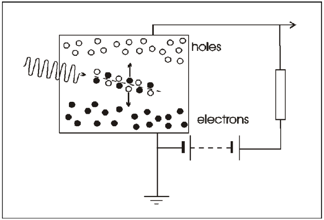
- A charged particle transverses a semiconductor material
  Semiconductor:
  - A crystal, like **silicon**, diamond, germanium
  - different *dopings* control the conductivity
  - n-type: excess of electrons
    p-type: excess of holes
  - n-p junctions $\rightarrow$ transistors/diodes
  - light emission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



Semiconductor Detectors

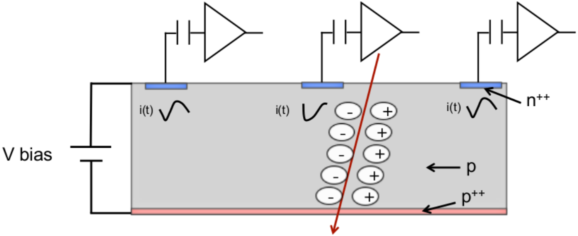
It is, basically, the same idea as before, but a lot more expensive...

- 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)

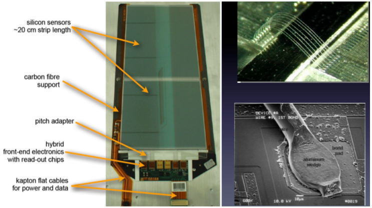
Silicon Detectors



- Example n-on-p silicon detector
- Inversely polarised by a bias voltage $\rightarrow$ 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

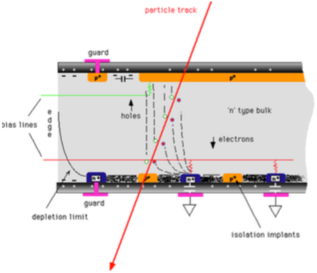
Pixel / Strips

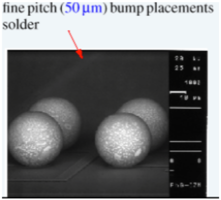
Silicon Strip module



- 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

Pixel





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

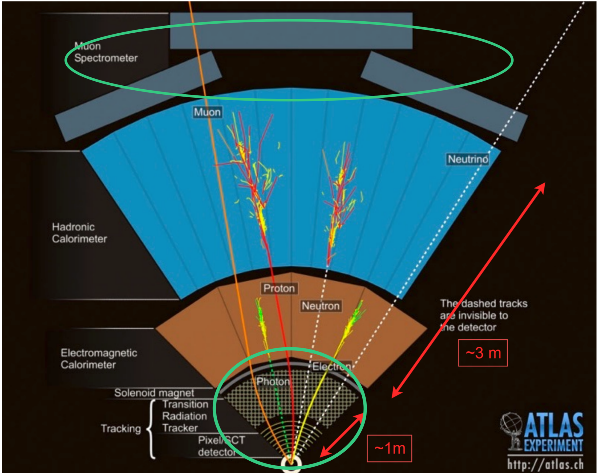
Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [Ref. 6]	$\sim$175–450 μm	$\sim$ 200 ns	$\sim$ 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 $\pm$150 μm parallel to anode wire.
[d] wirespacing/$\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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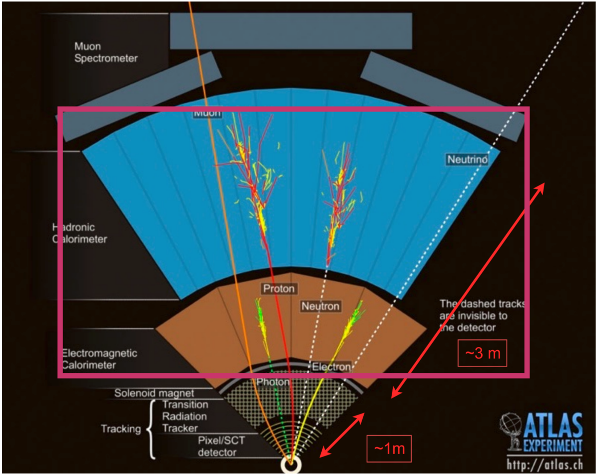
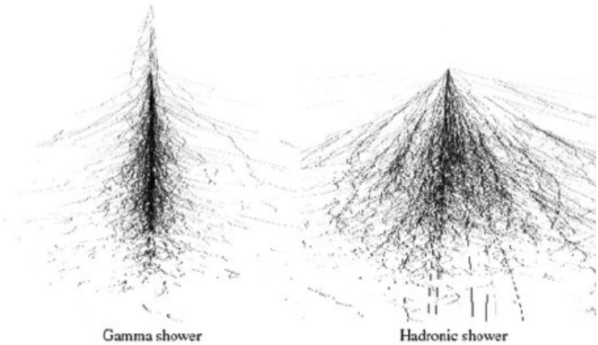


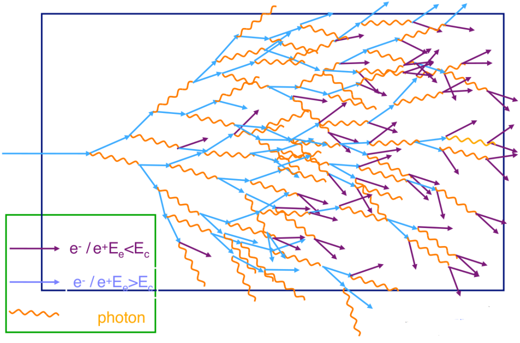
But what if we want to measure *everything*?
(or at least decently interacting charged and neutral particles)

What happens to particles when they interact?



EM shower

- An EM shower develops within the 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

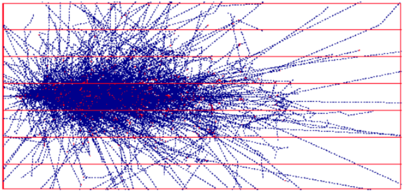
- Electromagnetic
- Hadronic

Types of calorimeters

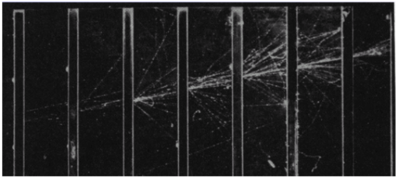
- Homogeneous
- Sampling

Homogeneous/Sampling

Homogeneous



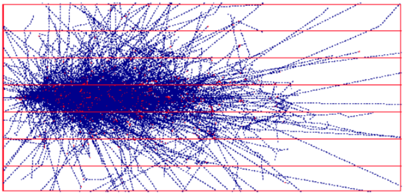
Sampling



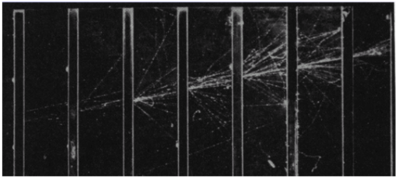
- All the energy is deposited in the active medium
- So the same material needs to stop the particle and generate a signal
- Heavy active material: lead tungstate PbWO (CMS calorimeter)
- Excellent energy resolution
- No longitudinal segmentation

Homogeneous/Sampling

Homogeneous



Sampling

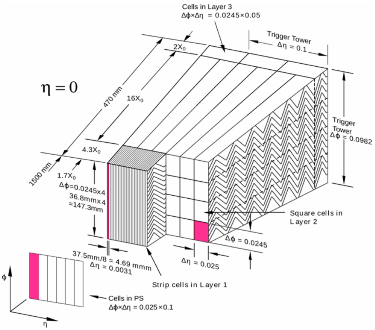


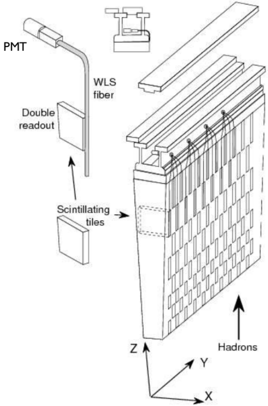
- Heavy stopper/absorber material (Cu, Pb, Fe)
- Sampled by an active material (scintillator plastic, semiconductor, gas)
- Limited energy resolution
- But gives information of the longitudinal deposition of the energy

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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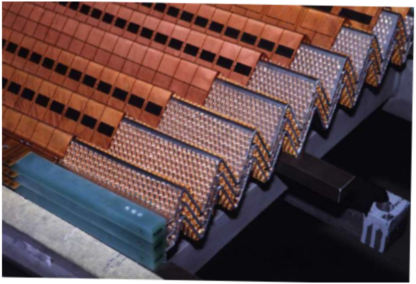
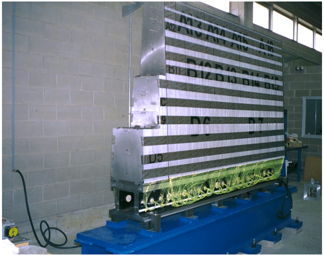
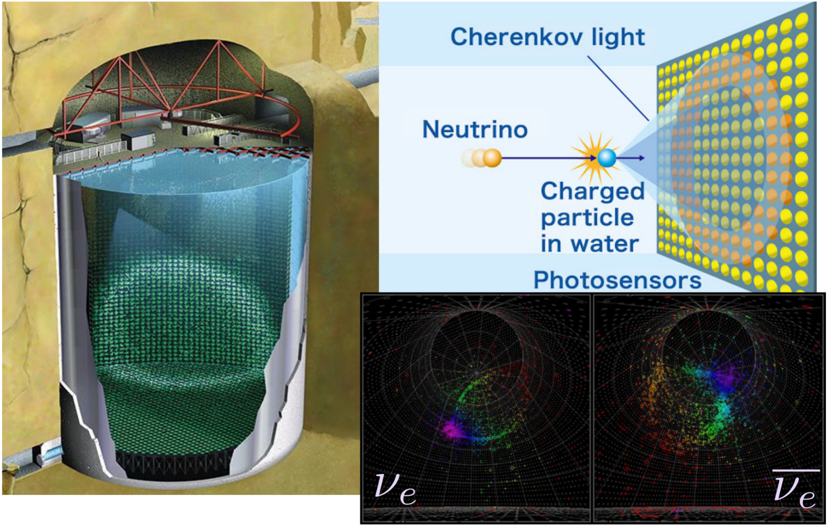
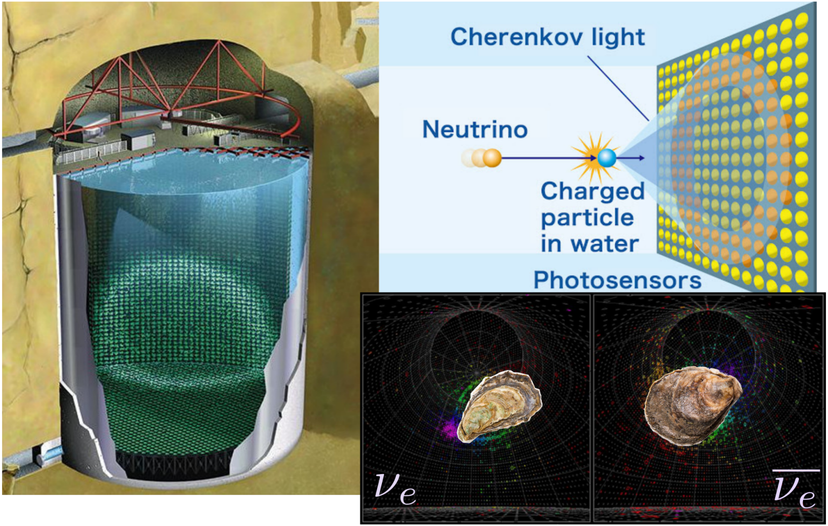




Cherenkov Detectors



Cherenkov Detectors



Conclusions

- Not very exhaustive basics of particle detectors[1]
  - Skipped details on electronics, accelerators, 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. . .

	Characterization of light scattering point defects in high-performance mirrors for gravitational wave detectors *Sihem Sayah*
15:00	**Conception of a PG detector for hadrontherapy online monitoring** *Maxime Jacquet* *Village La Fayette - La Rochelle* 14:53 - 15:18
	Development of a monolithic diamond ΔE-E telescope for particle identification and characterization of diamond detect... *Alexandre Portier*
	Simulation and instrumentation for the future Electron-Ion Collider *pu-kai WANG* *Village La Fayette - La Rochelle* 15:41 - 16:06
16:00	
	Pause café *Village La Fayette - La Rochelle* 16:10 - 16:45
	Machine Learning for Real-Time Processing of ATLAS Liquid Argon Calorimeter Signals with FPGAs *Lauri Laatu* *Village La Fayette - La Rochelle* 16:45 - 17:08
17:00	
	MACHINE LEARNING FOR REAL-TIME PROCESSING OF ATLAS LIQUID ARGON CALORIMETER SIGNALS WITH FPGAS *Nemer Chiedde*
	Improvement of the vertex detector resolution in the Belle II experiment *Lucas Martel* *Village La Fayette - La Rochelle* 17:33 - 17:56
18:00	**Silicon trackers for neutrino tagging at long baseline experiments** *Bianca DE MARTINO* *Village La Fayette - La Rochelle* 17:56 - 18:19
	Etude et développement de l'électronique cryogénique de lecture des détecteurs à très bas seuil de l'expérience Ricoc... *Jean-baptiste Filippini*