Some things you might have wanted to know about detectors* (*But were afraid to ask)

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

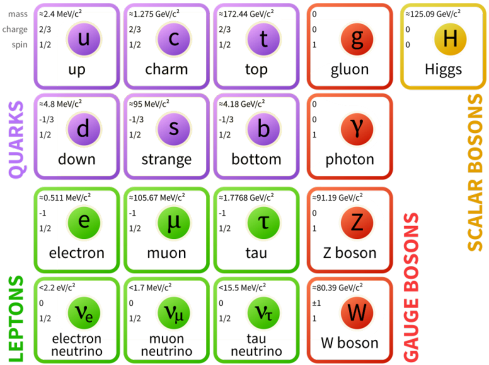
First and foremost

- At anytime if you have a question
  - ↳ Ask! (but remember that you can either email me or contact me at anytime if you have additional questions or need additional information, geoffrey.mullier@cern.ch)
- If you spot a mistake
  - ↳ please let me know, nobody's perfect!
- This is meant to be a showcase and an introduction of sorts for the ones of you that are less familiar with the detector physics world
  - ↳ Sorry if this might be boring for some of you.

What the hell are we talking about here?

Standard Model of particle physics

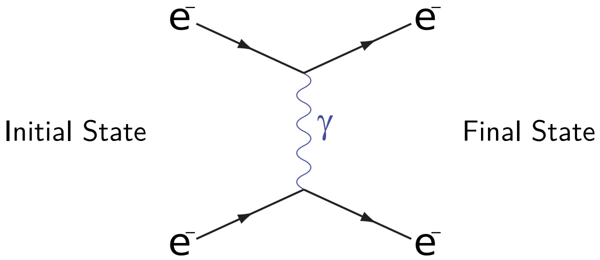
- Lagrangian describe interactions for three of the four fundamental forces of nature.
- In general, want to test the validity of the Lagrangian.
- Need to measure the parameters of the SM: Masses, couplings, mixing angles...



What is a measurement?

Not easy to answer in general

- Depending on whom you ask, the definition of measurement can be difficult to make (Ask your friends doing quantum information)
- Though for all intent and purpose we will define it as identifying the final state of a system (particle types, momenta)
- We want P_i^μ of all outbound particles (NB My time flows from left to right unless stated)



How on earth do we measure interactions?

I spoiled it a bit, but, short answer is: We do not

- We always measure secondary products of the interactions
- Secondary products, if stable enough, will interact with your detector
- The interaction that we can measure with the detectors are electro-magnetic (we are going to get back to this in a moment)
- There is no way to tell exactly what a single event was, the best one can get is a candidate final state that would correspond to the process one want to consider.
- One has to make counting experiments to see if it does correspond to what one was expecting or not

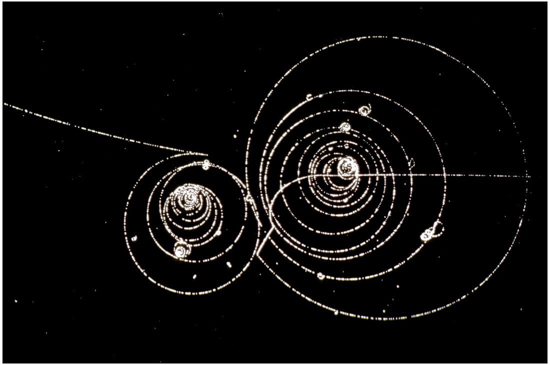
What does matter in particle detection?

Detection : Is it there or not?

Measurement : If it is there, what energy/what momentum?

for particle of charge q with momentum p in a field B

$$R = \frac{|p|}{qB} = \frac{\gamma\beta mc}{qB}$$



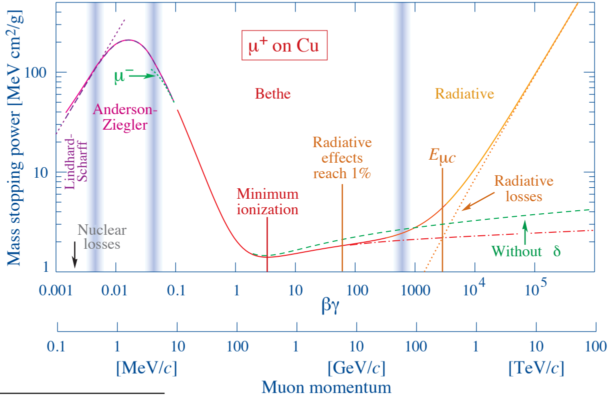
How to detect a particle

By its energy deposit in the medium it passes through

- Charged particles
  - Ionization of atoms
  - Excitation of atoms
  - Bremsstrahlung (only relevant for electrons and positrons)
  - Cherenkov radiation
  - Transition radiation
- Photons
  - Compton effect
  - Pair production

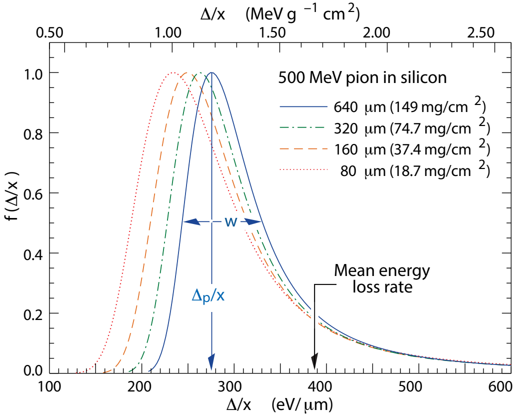
Bethe-Bloch equation: average energy loss in medium

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \, \frac{Z}{A} \, \frac{1}{\beta^2} \, \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta}{2} \right] \; ; \; K \equiv \frac{4\pi}{m_e c^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2$$



⚠ only applies for average in the $0.1 \leqslant \beta\gamma \leqslant 100$

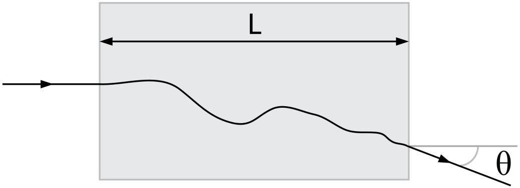
Landau-Vavilov: Variation of energy deposit for thin targets



Instantaneous deposit of energy is different than average

Not an easy problem to tackle since it does take into account the medium

Multiple Scattering



Interaction with the target nucleus follows a Coulomb scattering

Can repeat itself, causing multiple scattering of the particle in the target

Deviation of θ_0 in the initial direction given by the following relation, expressed in X_0, radiation length

$$\theta_0 = \frac{13.6\text{ MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

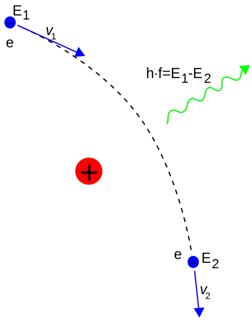
Only valid for small angles deviation, go see the reference for more infos!

Bremsstrahlung

If a particle interacts with the field of a nucleus, there is a probability to lose significant amount of energy by radiating a photon

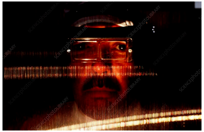
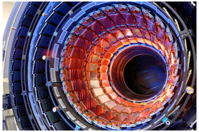
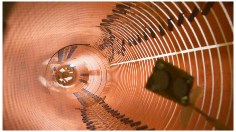
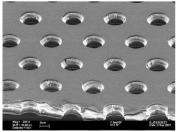
This effect is called Bremsstrahlung and the probability depends on the mass of the incoming particle

$$P_{\text{rad}} \propto m^{-4}$$ [1]



[1] Jackson, Classical EM 15.2

What type of detectors exists?

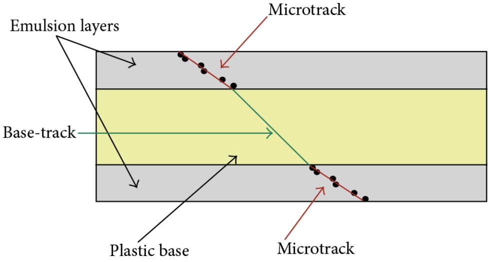
MWPC	Drift Tubes	Pixels	Cherenkov
GEMs	TPC	Planar	Geiger counter
RPC	Calorimeters	3D	Scintillator
CSC	Silicon detectors	HVCMOS	PMT
MicroMegas	Strips	Transition Radiation	SiPM
TGEMs	Bubble chamber	Cloud chamber	Monolithic Pixels

In short... LOADS!

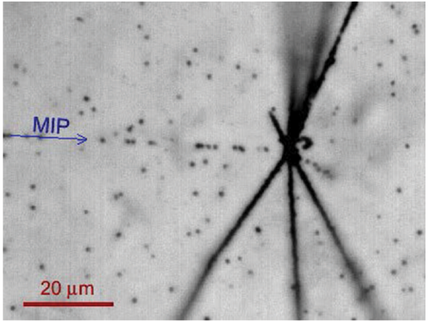
Though most of those abbreviations or terms are actually a variation on very basic principles/a different design for same detection principle

Nuclear Emultions : Same as photography plate, spiritually

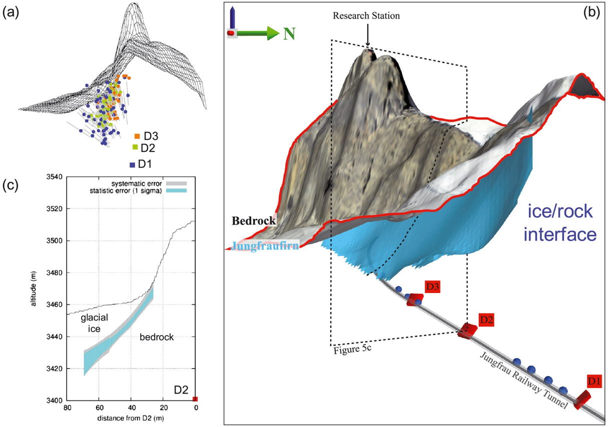
- Except you stack a large number on top of each other
- Require long time scanning surface for reconstructing particle tracks
- Unparalleled spatial resolution, can be equivalent to a voxel size of 0.125 μm^3

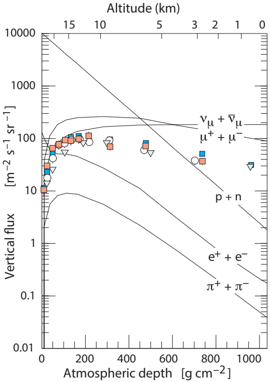


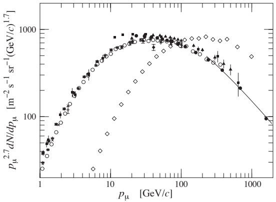
AEgIS Proton annihilation



Nuclear Emultions : Cool application, Muon tomography

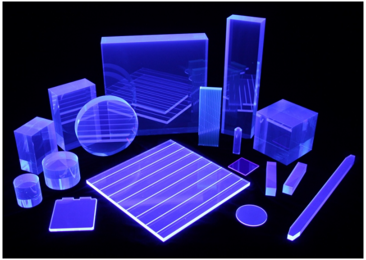






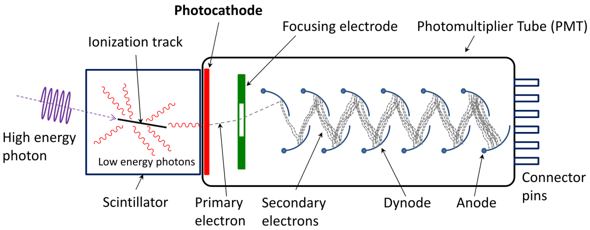
Scintillators & Photo Multipliers (PM)

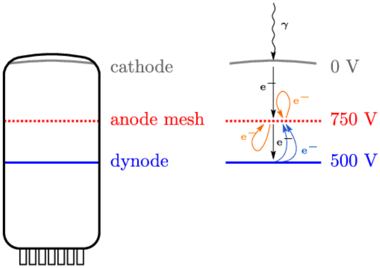
- Exist in different shape and forms and compositions (organic inorganic etc).
- Make use of the complex electronic structure of organic compounds to convert energy transferred to the medium to detectable photons.
- Often coupled to light guide/wavelength shifter (like this cool looking adiabatic light guide) to collect photons on detector downstream.
- Fast time response and usually cheap.
- Versatile but brutally complicated in the real details of operation.



Scintillators & Photo Multipliers (PM)

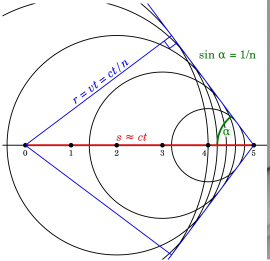
- ➢ Convert signal from a photon to many electrons
- ➢ Electron amplification chain
- ➢ Different structures the the PM itself but always same principle
- ➢ Might be sensitive to high magnetic field
- ➢ Can be solved using different geometries

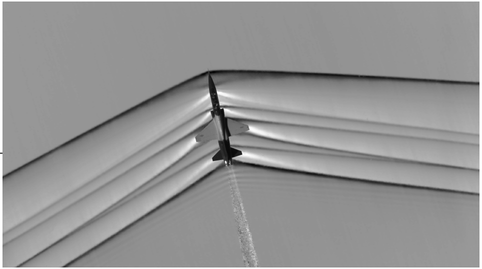




Cherenkov Radiation

If $v > c$ in the medium, an "EM shockwave", similar to a sound barrier shockwave, is created and known as Cherenkov Radiation.[2]



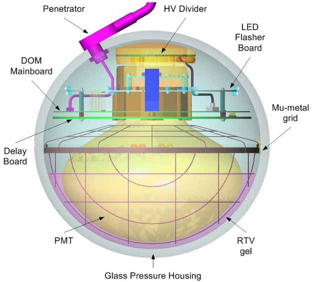


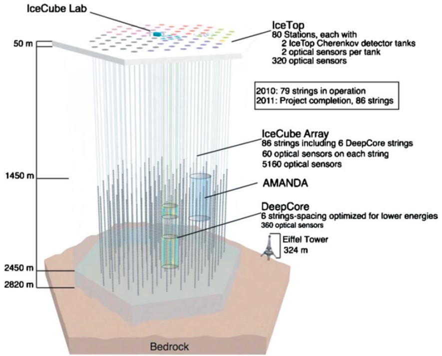
https://youtu.be/sve4qSlH3GE

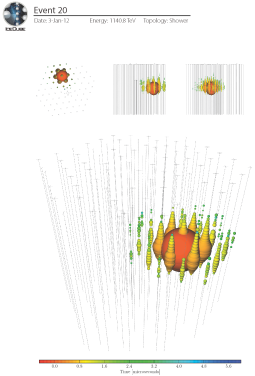
[2]See J.D. Jackson, Classical Electrodynamics, 3rd edition, (John Wiley and Sons, New York, 1998). for full demonstration

More information on the imaging technique for the plane https://www.nasa.gov/centers/armstrong/features/supersonic-shockwave-interaction.html

Cherenkov Radiation: ICE^3



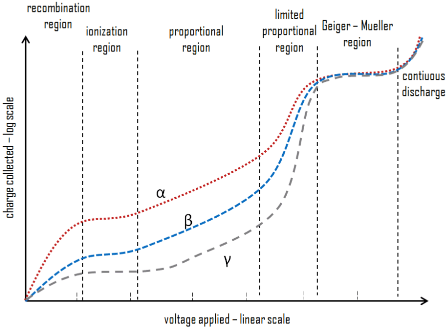


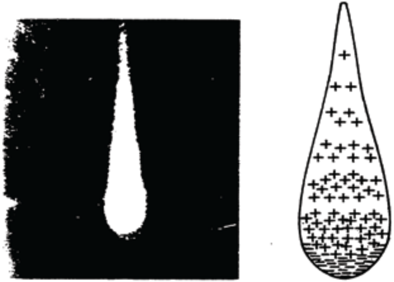


Detector making use of both the earth as a shielding material and south pole ice as its detection medium

Gaseous detectors

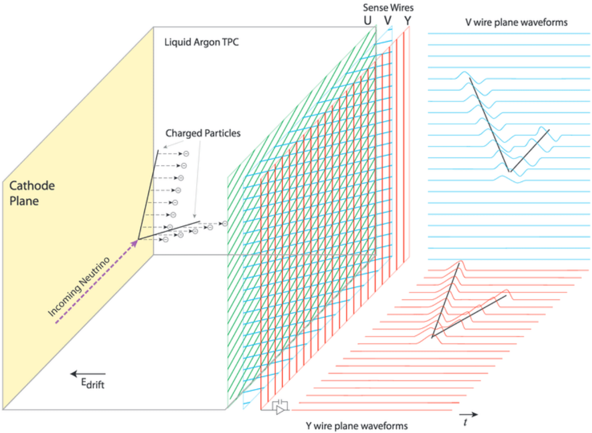
- If a potential difference is applied in the gas, charges will move (electron/ion)
- If field is high enough, an electron can kick others electrons off
- Those electrons can kick other electrons off...

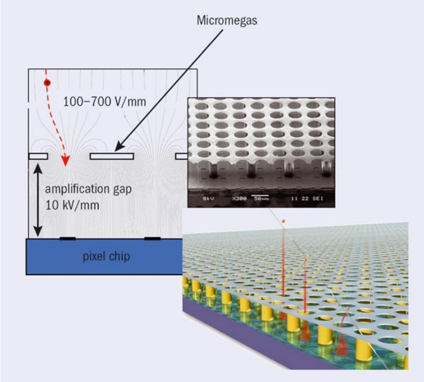




Gaseous detectors

- Time Projection Chambers (TPC)
- Micro Pattern Gaseous Detectors (MPGD)





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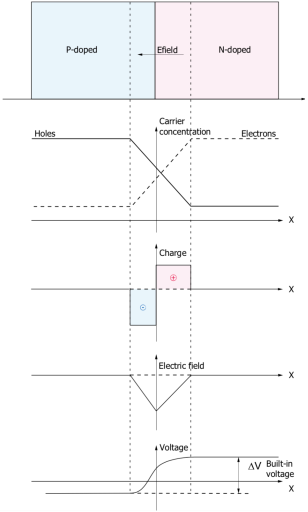
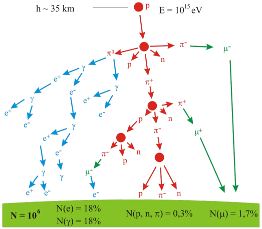
Semi-Conductors

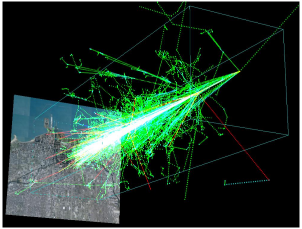
- Two pieces of semi-conductors are put in contact
- Each of the pieces are doped in different way, either as hole donor or electron donor
- The charges move to counter balance the deficit causing a depleted area with a field
- Biasing the semi-conductor further increases the depleted area
- If a particle passes through it will produce e^{-} hole pairs that will drift



Funny application: Use your phone as a particle detector

- ➢ Be part of a large particle detector array https://crayfis.io/[3]
- ➢ Turn your phone into a Radiation detector http://www.hotray-info.de/html/radioactivity.html[4]





[3] https://arxiv.org/pdf/1410.2895.pdf This being said I would do it with a busted phone rather than a new one, it uses the phone extensively...

[4] The video is hilarious, watch until the end https://youtu.be/qJc0q5sLxPo

Which one should I use?

What do you want to do?

How good do you need to do it?

Not one technology will answer all your desires

Type	Time resolution	Spacial Resolution	Energy resolution	Dead Time	Lifetime
Emultion	Non existant	$<1\mu$m	very good	Time it takes you to replace them	Depends on exposure
Scintillators	<1ns	$\approx$ mm	very good	depends on readout	Depends on exposure
Solid state	<1ns	$\approx 10\mu$m	very good	depends on readout	Depends on exposure
Gaseous	≈ 10ns	$\approx 100\mu$m	good	depends on readout/operation	Depends on exposure

NB: Some detectors might be able to achieve some of those numbers but not necessarily all at once or all ranges.
Most of those factors depends not only on the detector geometry, configuration and operation mode but heavily on the readout decisions.

Movements of charges in vacuum and gases (It's pretty useful to understand it in general)

Simple equation of motion of charges in an electric and in a magnetic field in addition of a friction term

$$m\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = e\left(\vec{E} + \vec{v} \times \vec{B}\right) - K\vec{v}$$

The average speed in the gas can be expressed as drift as components caused by the $\vec{E}$ and $\vec{B}$ fields[5]

$$\vec{v} = \frac{\mu E}{1+\omega^2\tau^2}\left[\overrightarrow{1}_E + \omega\tau\left(\overrightarrow{1}_E \times \overrightarrow{1}_B\right) + \omega^2\tau^2\left(\overrightarrow{1}_E \cdot \overrightarrow{1}_B\right)\overrightarrow{1}_B\right]$$

[5] With $\omega \equiv \left(\frac{e}{m}\right)|\vec{B}|$ and $K \equiv \frac{m}{\tau}$

Important elements from the previous solutions

$$\vec{v} = \frac{\mu E}{1+\omega^2\tau^2}\left[\overrightarrow{1}_E + \omega\tau\left(\overrightarrow{1}_E \times \overrightarrow{1}_B\right) + \omega^2\tau^2\left(\overrightarrow{1}_E \cdot \overrightarrow{1}_B\right)\overrightarrow{1}_B\right]$$

1. If no magnetic field is applied, the relation is linear, depends on the material via the coefficient μ which is called mobility, with respect to the electric field applied

$$\vec{v} = \mu\vec{E}$$

2. If there is both an electric and magnetic field applied one can see that the charge would drift in a direction which is a composite of the direction of the electric and magnetic field

Electrons instantaneous and average speed

$$v^2 = \frac{eE}{m_e N\sigma}\sqrt{\frac{E_{\text{Loss}}}{2}}$$

$$v_I^2 = \frac{eE}{m_e N\sigma}\sqrt{\frac{2}{E_{\text{Loss}}}}$$

Seemingly this is surprising, the instantaneous speed varies inversely with respect to the fraction of energy lost, whereas the average speed goes faster

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If the electron loses all its momentum at each collision it will only gain momentum in the desired direction, if it loses part of its momentum, it can travel back and hurt the average speed

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Note that those also depends on the cross section

Question of diffusion

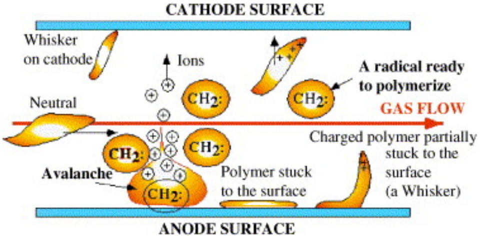
- Diffusion can be less straight forward to understand (at least under external field and not due only to brownian motion)
- Depending on the orientation of the fields and drift direction diffusion can be limited
- This results in different diffusion coefficient, longitudinal and transverse
- The diffusion coefficient is often expressed in term of the drift length

$$D_d = \frac{\sigma_x}{\sqrt{z}}$$

N.B. I am considering here a well behaved gas, things can get way less obvious if the gas conditions are more exotic

Ageing of detectors

- Usually people do not like to mention the fact that they age, and their detectors do too
- Detector ageing is a really complex topic and usually poorly understood for the most part because it relies on technicalities of the detector considered in general
- Following link focused on gaseous detectors http://www.desy.de/~agingw/preprints.html
- Extensive knowledge on solid state detector available for radiation damage in general.



The must do in the lab

WRITE EVERYTHING DOWN!

- You **WILL** forget things, and recovering from something forgotten takes usually much more time than checking your notes.
- In addition writing things down help you track and debug things more clearly as well as thinking about the problem at hand.

READ EVERYTHING SEVERAL TIMES!

- You **WILL** misunderstand things, and misunderstanding can lead to damages to equipment, yourself or others.

DO NOT ASSUME!

- Be certain, take your time when doing something.

Coding

DO NOT TRY TO BE CLEVER!

- Any attempt to be clever always end up with you, in the future, wondering why or how the hell you thought this was OK.
- Think before implementing something but do not think too long either start on paper and go from there
- In most of the cases the compiler is smarter than you[6]

WRITE CLEAR AND COMMENTED CODE!

- Any piece of code you write should have
  - Useful comments (I will metaphorically bash your head in if you tell me that your code is self documenting)
  - Human readable variables and methods names
- At some point either you will be the one dealing with your mess or someone that is going to hate your guts

[6] Well... sometimes it is pretty much not...

Debugging hardware or software

DO NOT ASSUME!

- The error is always in what you supposed was fine
- Debug step by step and **DO NOT SKIP** a step
- "When you have eliminated the impossible, whatever remains, however improbable, must be the truth."

ESTABLISH MINIMAL WORKING BLOCKS!

- Be it in hardware or software, go back to the basics and work your way from there
- Testing units help you move forward in design and implementations
- It is like building Legos, except it is not Legos, and then you do not get a cool looking spaceship at the end...

Debugging relationships

LEARN TO APOLOGISE!

- This goes a long way to recognise that you were wrong
- And it helps becoming both a better physicist and person

COMMUNICATE!

- 90% of the issues that are encountered with something due to miscommunication or misunderstanding
- Sometimes it can be hard, but do an effort to meet people in the middle

Some reading material 1/3

http://pdg.lbl.gov/index.html

J.D. Jackson, Classical Electrodynamics, 3rd edition, (John Wiley and Sons, New York, 1998)

Radiation Detection and Measurement, 3rd ed - Glenn F

J.G.Wilson,The Principles of Cloud Chamber Technique

A.Langsdorf,A Continuously Sensitive Diffusion Cloud Chamber

https://www.astro.rug.nl/~peletier/Bas%20Det%20Tech%202009%20scintillators.pdf

Nuclear and particle physics an introduction B.R. Martin

http://www.ep.ph.bham.ac.uk/general/seminars/slides/Laura-Gonella-2017.pdf

https://indico.cern.ch/event/587631/contributions/2467389/attachments/1415291/2166554/CMOS-TJ-Trento-Pernegger.pdf

Some reading material 2/3

https://doi.org/10.1016/j.nima.2017.07.046

https://indico.cern.ch/event/669866/contributions/3235298/attachments/1768859/2873169/PIXEL2018_MALTA.pdf

https://indico.cern.ch/event/669866/contributions/3235357/attachments/1770609/2876955/201812_CaicedoI_PIXEL2018_Monopix.pdf

https://www.researchgate.net/publication/275460138_The_Study_of_Neutrino_Oscillations_with_Emulsion_Detectors?fbclid=IwAR32l4owYDjgD7UTAhFR_qcLSmJYeoeRPoQIwEDj1kNM0HINXfcTv78ufNk

Werner Riegler Walter Blum and Luigi Rolandi. Particle Detection with Drift Chambers (Particle Acceleration and Detection).

Some reading material 3/3

https://academic.oup.com/ptep/article/2018/6/063H01/5045500?fbclid=IwAR2EI-AN8n1VLt3e6EwlZpEiD3c4mzReKv-lWm6kiJDmfJhcSsPfnQOAu_0

Particle Detectors Fundamentals and Applications Hermann Kolanoski and Norbert Wermes