Particle Detectors

Lecture 2
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Particle glossary

- Most important particle properties from the detector point of view are:
  - Mass
  - Charge (electric, "strong", "weak")
  - Interactions (EM, strong)
  - Lifetime
  - But also: **x**, **p**, E, β, radiation emission

Stable particles, life time $\tau = \infty$

- Can be used as beam particles
- Decay prohibited by *conservation laws*
  - Photon (γ)
  - Neutrinos (ν)
  - Electron/positron
- Proton/antiproton

Conservation Laws

Noether's Theorem: Every symmetry of nature has a conservation law associated with it, and vice-versa.

- **Energy, Momentum and Angular Momentum**
  - ➡ Conserved in all interactions
  - ➡ Symmetry: translations in time and space; rotations in space
- **Charge conservation e.g. electric charge Q, colour charge**
  - ➡ Conserved in all interactions
  - ➡ Symmetry: gauge transformation - underlying symmetry in QM description of electromagnetism / strong force
- **Lepton Flavour L_e, L_μ, L_τ and total quark number N_q**
  - ➡ Conserved in all interactions
  - ➡ Symmetry: mystery!
- **Quark Flavour $N_u, N_d, N_s, N_c, N_b, N_t$, Parity, π**
  - ➡ Conserved in strong and electromagnetic interactions
  - ➡ Violated in weak interactions
  - ➡ Symmetry: unknown!

Emmy Noether
1882-1935

Quark and Lepton Flavour Quantum Numbers

- **Lepton Number**, L: Total number of leptons – total number of anti-leptons
  - Electron number, L_e
  - Muon number, L_μ
  - Tau number, L_τ
  - $L = L_e + L_\mu + L_\tau$

$$L_e = N(e^-) - N(e^+) + N(\nu_e) - N(\bar{\nu}_e)$$
$$L_\mu = N(\mu^-) - N(\mu^+) + N(\nu_\mu) - N(\bar{\nu}_\mu)$$
$$L_\tau = N(\tau^-) - N(\tau^+) + N(\nu_\tau) - N(\bar{\nu}_\tau)$$

- **Quark Number**, N_q: Total number of quarks – total number of anti-quarks
  - Up quark number, N_u: *e.g.* $N_u = N(u) - N(\bar{u})$
  - Down quark number, N_d
  - Strange quark number, N_s
  - Charm quark number, N_c
  - Bottom quark number, N_b
  - Top quark number, N_t
  - $N_q = N_u + N_d + N_s + N_c + N_b + N_t$

- The lepton flavour quantum numbers (L, L_e, L_μ, L_τ) are conserved in **all** Standard Model interactions: strong, electromagnetic and weak.
- Quark number (N_q) is also conserved in all interactions.
- [Individual quark flavours (N_u, N_d, N_s, N_c, N_b, N_t) are conserved in strong and electro-magnetic interactions. They are not (necessarily) conserved in weak interactions.]

Average Life Time $\tau < \infty$

An unstable particle which is moving travels a distance before it decays. The average path length is:

$$\lambda_d = \gamma\beta c\tau = \left(\frac{p}{mc}\right)c\tau$$

The nbr of particles decaying in the length dx at the position x is proportional to the nbr of particles at x and to the probability of having an interaction in dx

$$dN(x) = -N(x)\cdot\frac{dx}{\lambda_d} \Rightarrow N(x) = N_0 e^{-x/\lambda_d}$$

→ This means that the number of particles surviving after a path legth x is an expo with slope λ_d (decay length)

Weakly decaying particles

- Decay "parameter" $\gamma c\tau = E c\tau / mc^2 = pc\tau / mc$
  - So cτ/m gives the mean decay distance for E = 1 GeV energy or cτ gives the mean distance for E = mc^2
- Neutron and muon ***n: 3×10^{11}m $\mu^{\pm}$: 6km***
- Light quark mesons: **$\pi^{\pm}$,$K^{\pm}$,K^0_L : 5-50m**

At high energy, 90% of detected particles from an hadronic interaction are charged pions!

- Strange baryons or "Hyperons" ***1-10cm***
- Heavy quark hadrons, τ lepton ***50-200μm***

Very short-lived particles $\tau < 10^{-12}$ s, $\lambda_d <$ ~$O(100\ \mu m)$

- Detectable *only* by their decay products, ie never reach the detectors
- Electromagnetic decays to photons or lepton pairs
  - Includes π^0 giving high-energy photons

Ex: π^0: $c\tau = 180 nm$

- Strongly decaying "resonances"

Very massive fundamental particles (τ~10^{-25} s)

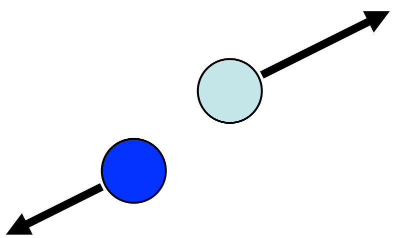
- $W^{\pm}, Z^{0}$
- top quark
- Higgs boson
- Super-symmetric particles, …

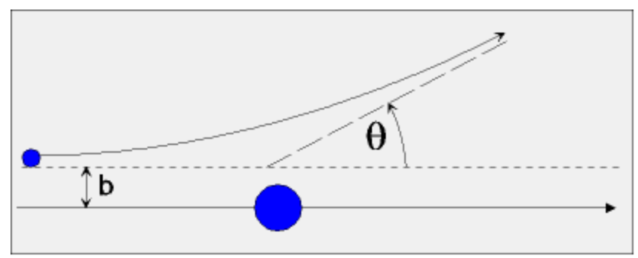
- Decay indiscriminately to lighter known (and possibly unknown) objects – leptons, quark “jets” (pions plus photons) etc.

What to measure, why?

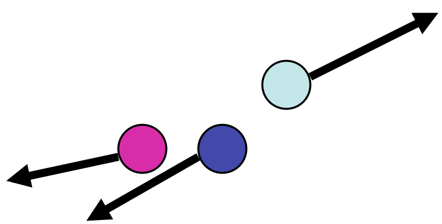
- Tipically in particle experiments we study interactions by:
  - particle-particle collisions
  - the decay products of unstable particles (eg radioactive decays)

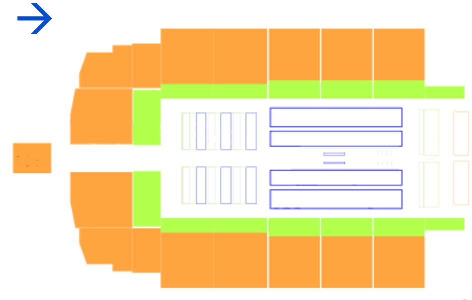
- The effects are:
  - *Change of the flight directions/ of the energy / of momentum of the original particles(eg e+e-→e+e- Bhabha)*





  - Production of new particles (e+e- → qq-bar → hadronization)

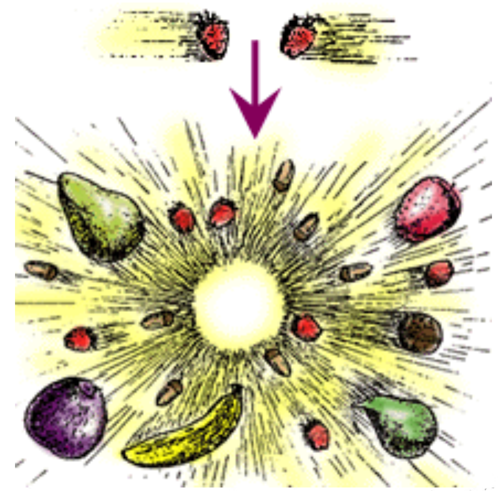


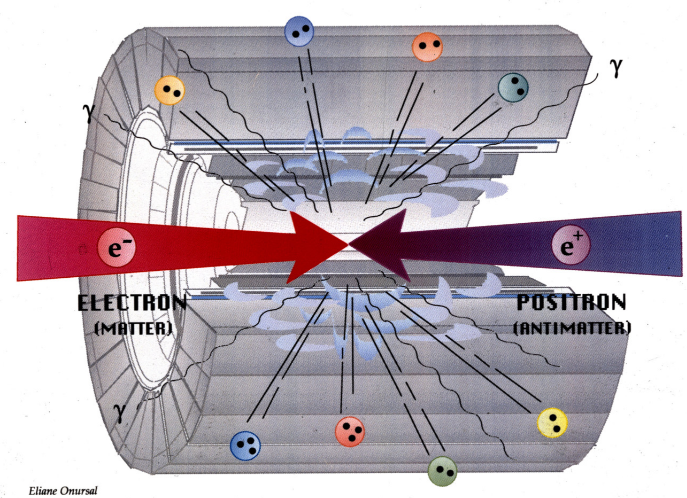


What can we detect?

- Directly observable particles must:
  - Be long lived ($\gamma c\tau$ sufficient to pass through sensitive elements of the detector)
  - Undergo strong or e.m. interactions
- We can directly observe:
  - electrons
  - muons
  - photons
  - neutral and charged hadrons/jets
    - $\pi^{\pm}$, K^{0}, $K^{\pm}$, p, n,…
    - Many physics analyses treat **jets** from quark hadronization collectively as single objects
- We can indirectly observe long lived weakly interacting particles (e.g. neutrinos) through **missing transverse energy**

Collide





What to measure, why?

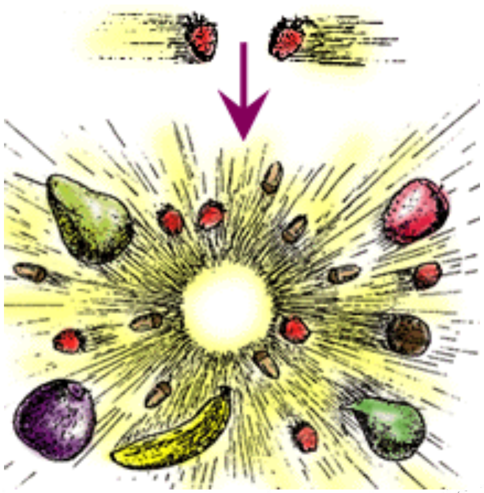
- Particle detectors need to provide:
  - Detection and identification of different particle types (mass, charge)
  - Measurement of particle momentum (track) and/or energy (calorimeter)
  - Coverage of full solid angle without cracks ("hermiticity") in order to measure missing E_T (neutrinos, supersymmetry) (if at accelerators) or large counting power (if not at accelerators)
  - Fast response (minimum dead time, eg LHC bunch crossing interval 25ns!)

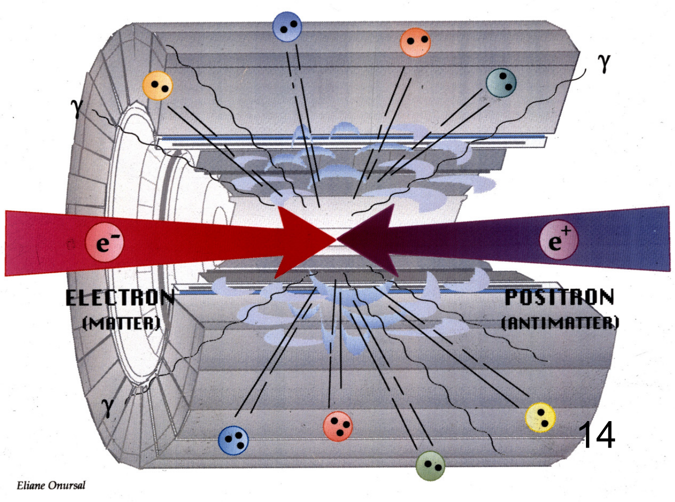
What to measure, why?

- A perfect detector should reconstruct any interaction of any type with 100% efficiency and unlimited resolution (get “4-momenta”of basic physics interaction)
- BUT not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas (holes, cracks for e.g. water cooling and gas pipes, electronics, mechanics), some do not give a signal, limited resolution.
- Efficiency is never 100%, errors are never negligible

Detected Particles: only stable or long lived

Collide





- Different particle types interact differently with matter (detector)
- (eg. photons do not feel a magnetic field)
  - need different types of detectors to measure different types of particles

Detection of Charged Particles

- Ultimately all detectors end up detecting charged particles:
  - Photons are detected via electrons produced through:
    - Photoelectric effect
    - Compton effect
    - e^+e^- pair production (dominates for E>5GeV)
  - Neutrons are detected through transfer of energy to charged particles in the detector medium (shower of secondary hadrons at high E, recoiling nuclei at low E)
- Charged particles are detected via e.m. interaction with electrons or nuclei in the detector material:
  - Inelastic collisions with atomic electrons → energy loss
  - Elastic scattering from nuclei → change of direction

Detection of Charged Particles

- Which kind of particle do we have to detect?
- What is the required dimension of the detector?
- Which “property” of the particle do we have to know?
  - Position, trajectory
  - Time
  - Number
  - Energy
  - Momentum

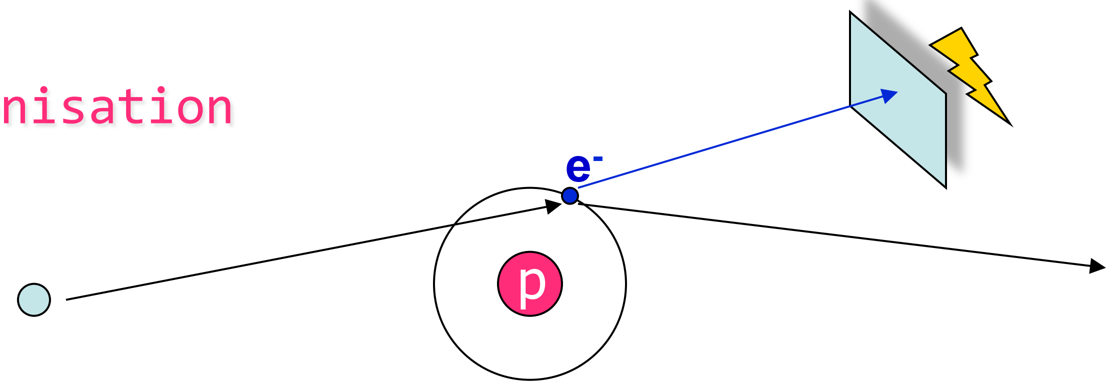
What is the required resolution?

- What is the maximum count rate?
- What is the time distribution of the events?
- And last, but not least, how much does it cost?

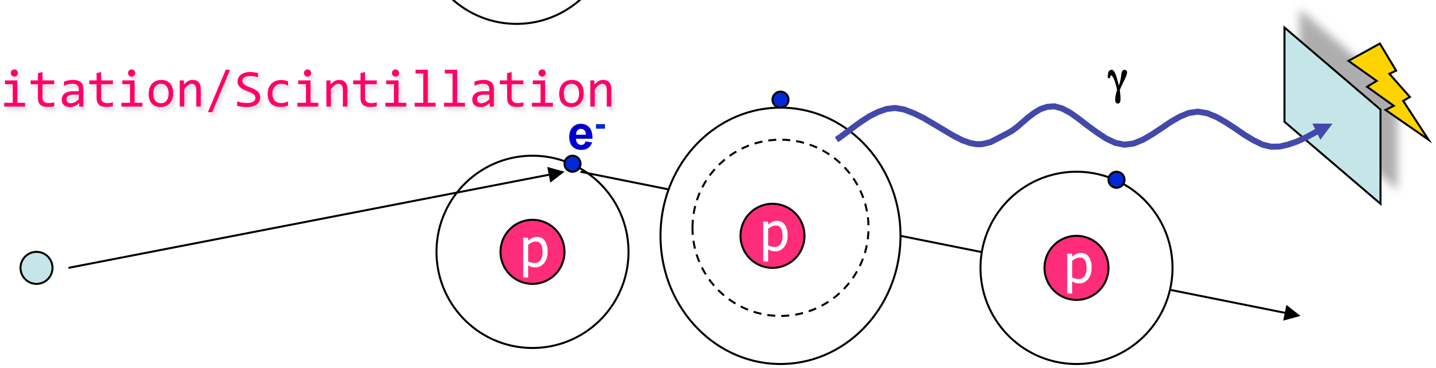
Principles of a measurement

- Measurement occurs via the interaction (again…) of a particle with the detector(material)
  - creation of a measureable signal

    - Ionisation



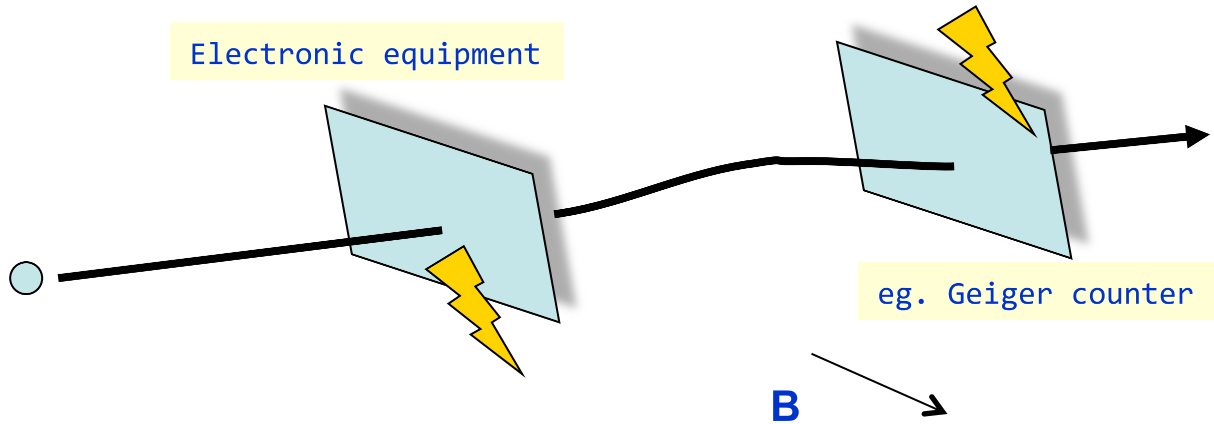
    - Excitation/Scintillation



    - Change of the particle trajectory
      - bending in a magnetic field,energy loss
      - scattering, change of direction, absorption

Measured quantities

- The creation/passage of a particle (--> type)



- Its four-momentum $\begin{pmatrix} \text{Energy} \\ \text{momentum in x-dir} \\ \text{momentum in y-dir} \\ \text{momentum in z-dir} \end{pmatrix} = \begin{pmatrix} E \\ \vec{p} \end{pmatrix}$ $\quad \vec{p} = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$

- Its velocity $\beta = v/c$

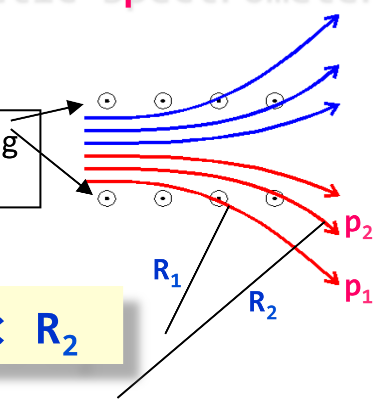
How measure the four-momentum?

- Energy : from "**calorimeter**" → E is absorbed in the active medium (ie showers)

Momentum :

- from "**magnetic spectrometer+tracking detector**"

Magnetic field, pointing out of the plane



$p_1 < p_2 \Leftrightarrow R_1 < R_2$

Lorentz-force

$q\ v\ B = m\ v^2/R$

⇓

$q\ B\ R = m\ v = p$

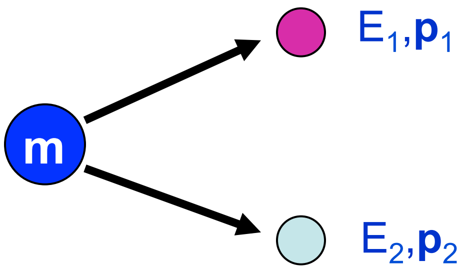
velocity :

- **time of flight** or **Cherenkov radiation**

$v\,t = L$

Derived properties

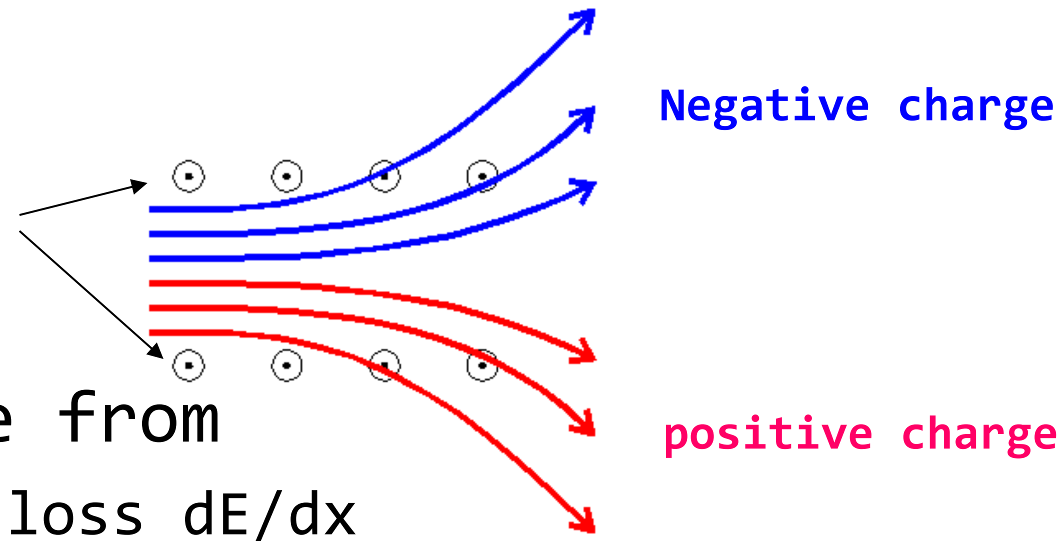
- Mass
  - in principle, if E and **p** measured: $E^2 = \mathbf{m}^2 c^4 + \mathbf{p}^2 c^2$
    - if v and **p** measured: $\mathbf{p} = \mathbf{m} v / \sqrt{(1 - \beta^2)}$
    - from E and **p** of decay products:
      - $\mathbf{m}^2 c^4 = (E_1 + E_2)^2 - (c\mathbf{p}_1 + c\mathbf{p}_2)^2$



Further properties...

- The charge (at least the sign…)
  - from curvature in a magnetic field

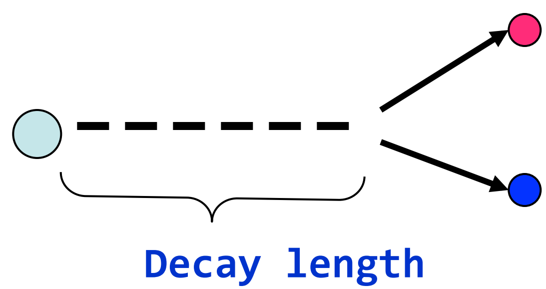
Magnetic field, pointing out of the plane



- The charge value from
  - Specific energy loss dE/dx
  - Cherenkov radiation

The lifetime τ

- from flight path before decay



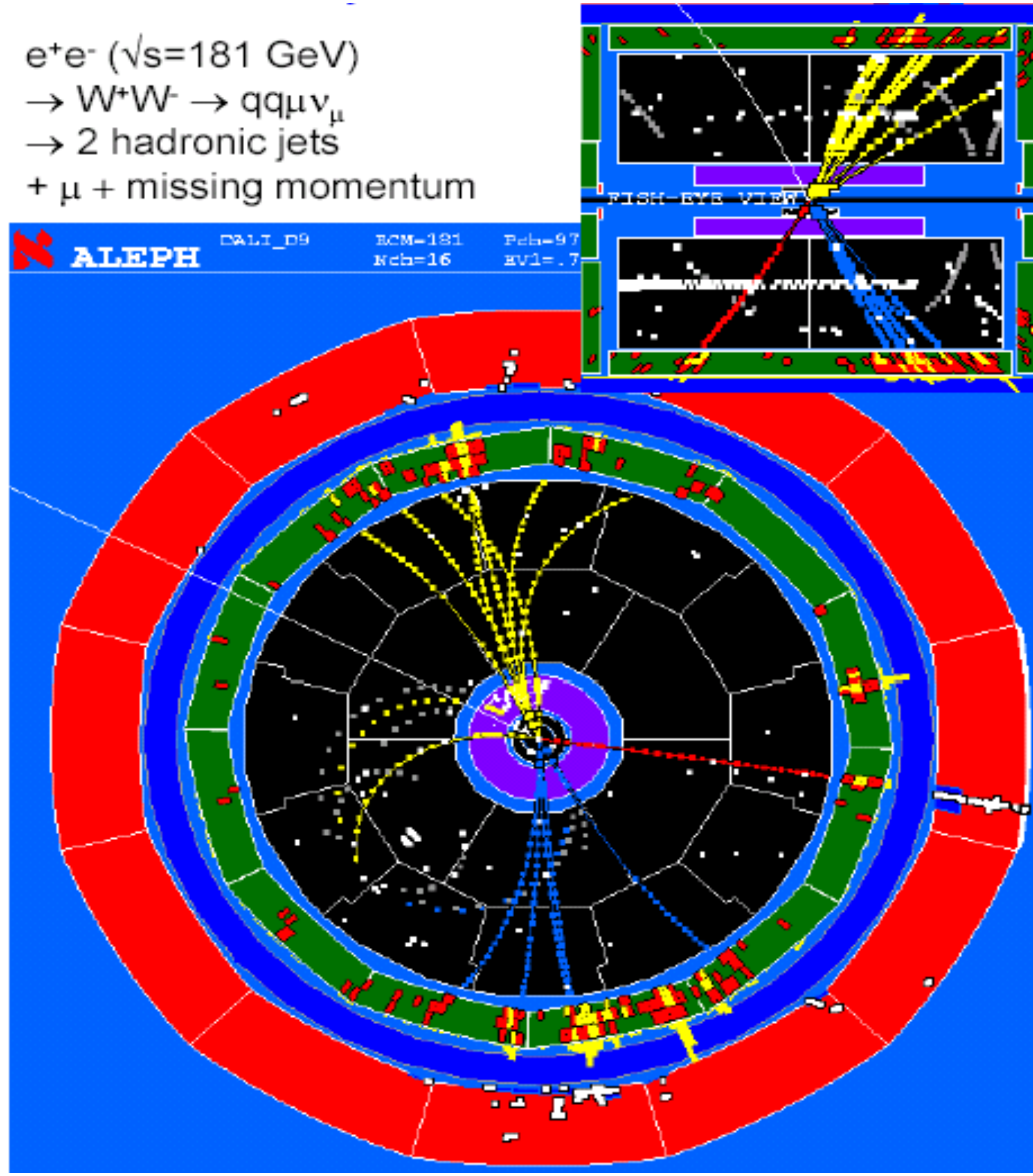
What to measure, why?

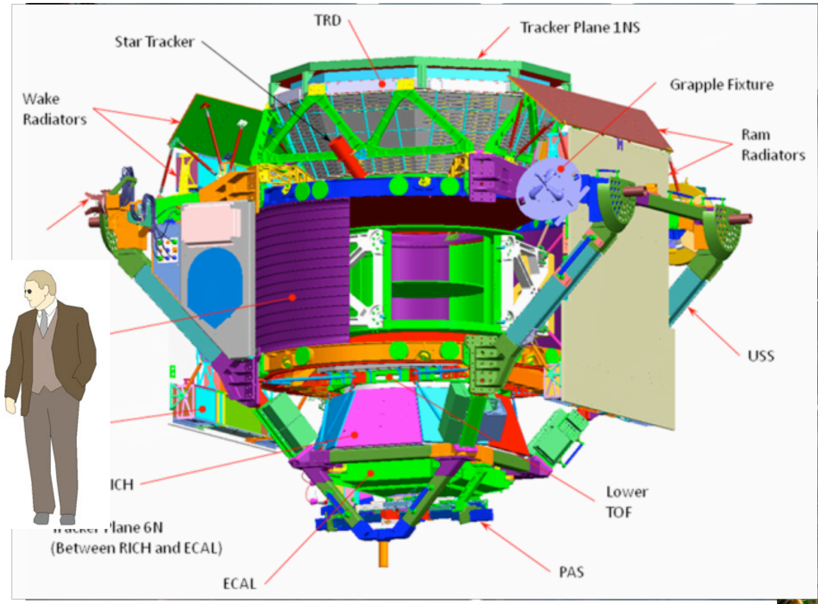
The key element for an experimental apparatus is the combination of different detectors to obtain a detector system: many (ie >2) detectors that works sinchronously/in parallel, providing a set of signals correlated spatially and temporally.

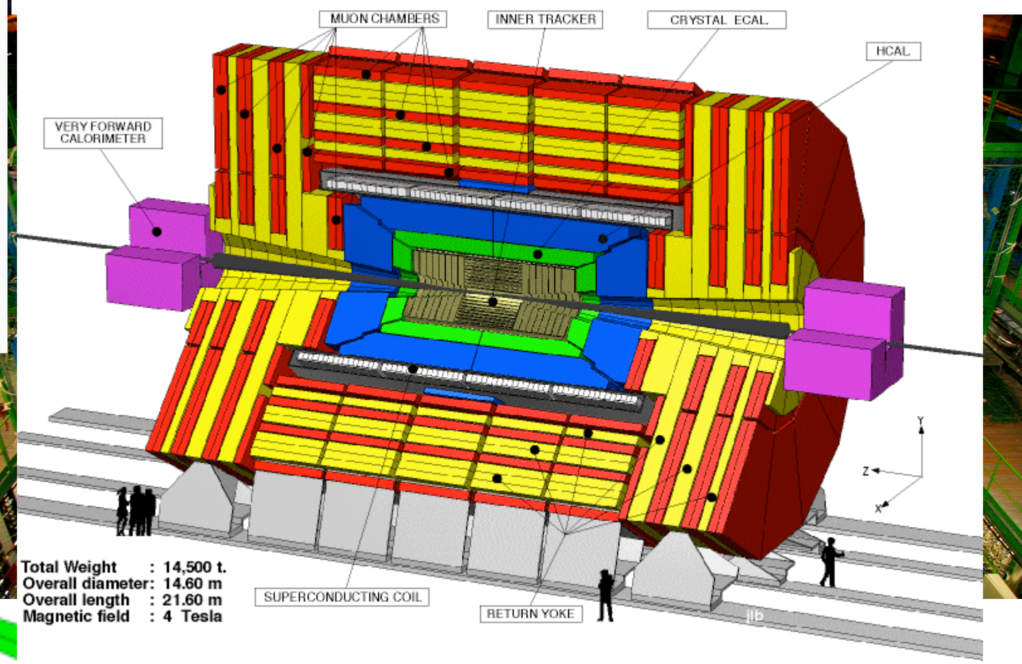
By the correlation of signals it is possible to measure some cinematic observables (as speed, energy, momentum, charge,...)

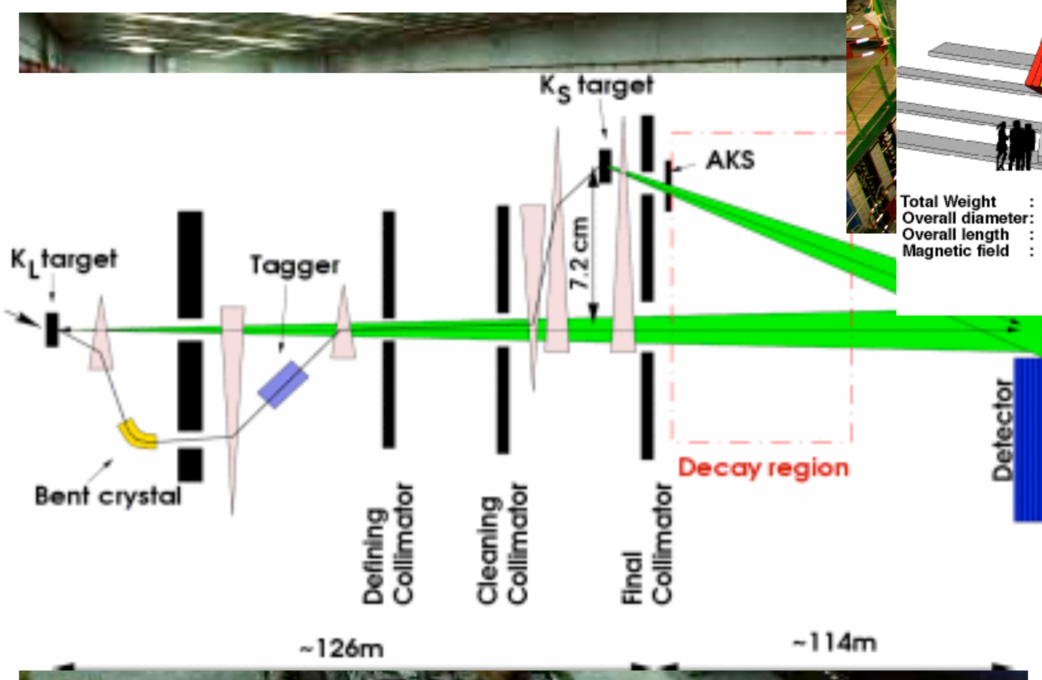
Example: a magnetic spectrometer is the combination of a tracking detector in a B field and a Time Of Flight (TOF) detector* in a suitable geometric setup

*which in turn is the combination of at least 2 scintillators with a time coincidence within a time window




TRD
Tracker Plane 1NS
Star Tracker
Grapple Fixture
Wake
Radiators
Ram
Radiators
USS
ICH
Lower
TOF
(Between RICH and ECAL)
ECAL
PAS


MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD
CALORIMETER
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla
SUPERCONDUCTING COIL
RETURN YOKE


K_S target
AKS
7.2 cm
K_L target
Tagger
Bent crystal
Defining
Collimator
Cleaning
Collimator
Final
Collimator
Decay region
Detector
~126m
~114m