Mitglied der Helmholtz-Gemeinschaft

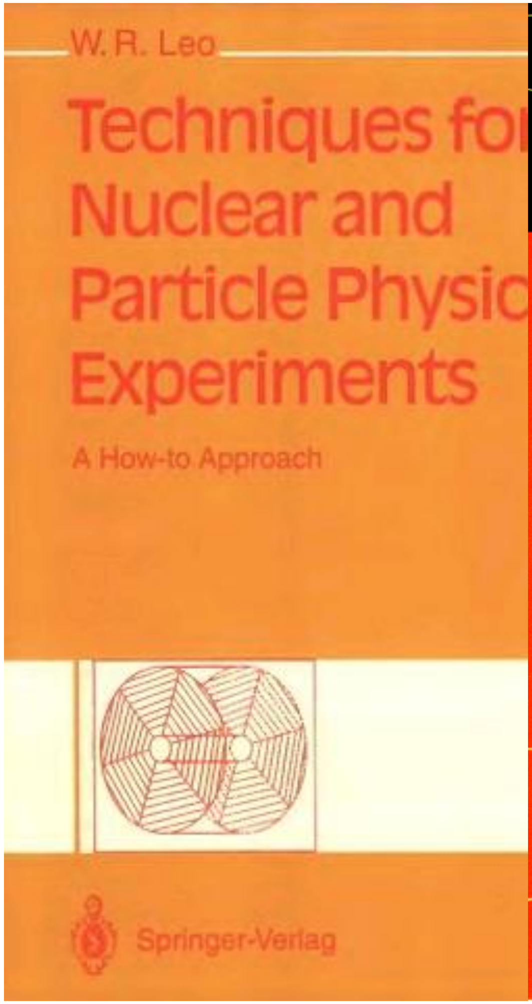
Autumn Lectures in Tbilisi

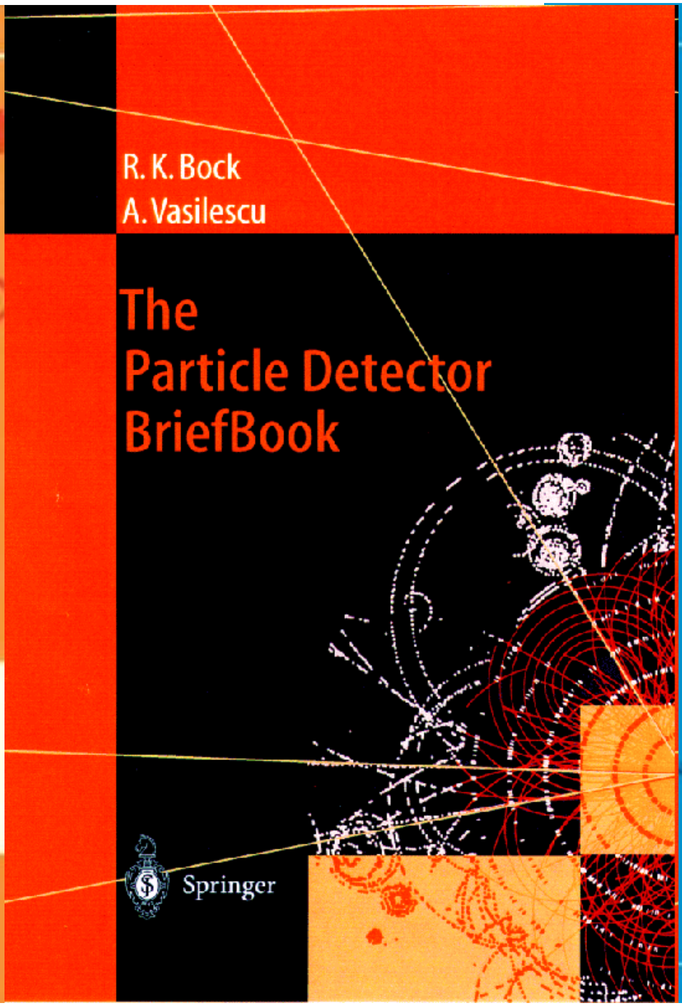
Georgian Technical University, October 15 – 22, 2013

Particle Physics Tools: Detectors

October 21, 2013 | Andro Kacharava (JCHP/IKP, FZ-Jülich)

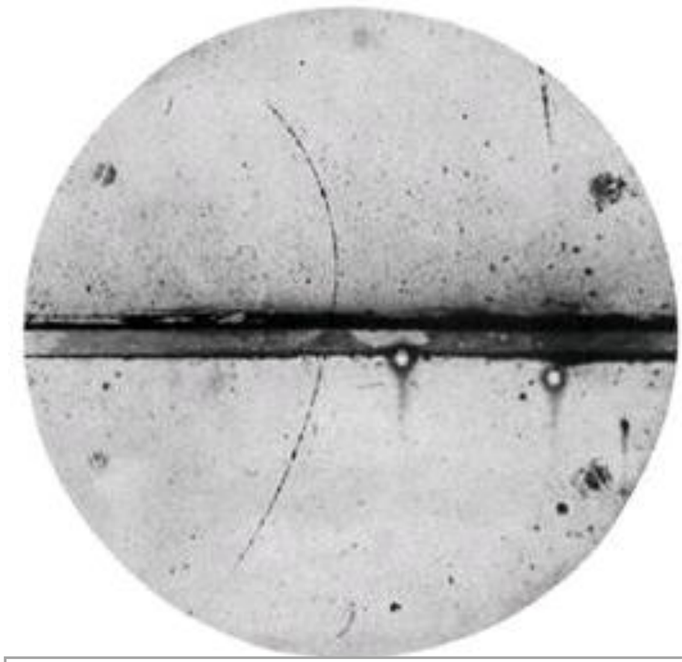
Particle Physics Tools – Introduction





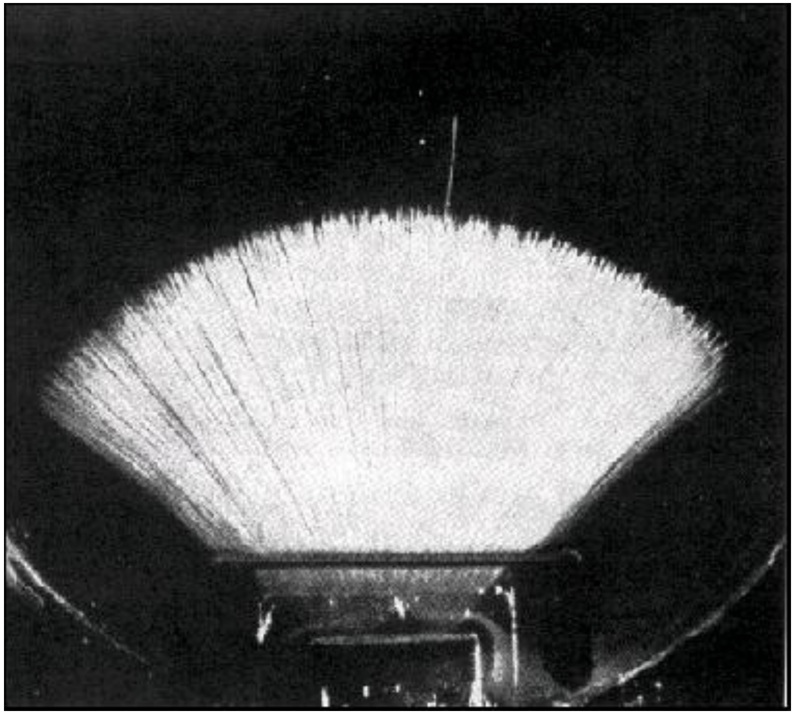
PP: Tools – Introduction

Vizualization



Cosmic-ray tracks in cloud chamber

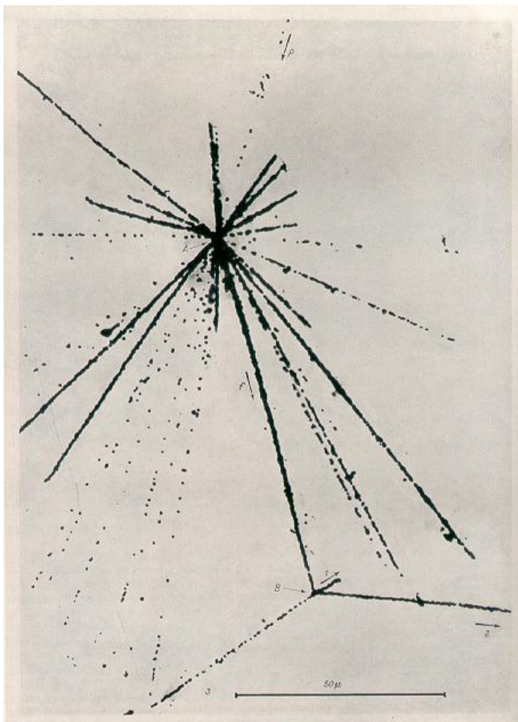
Positron discovery
(1932)



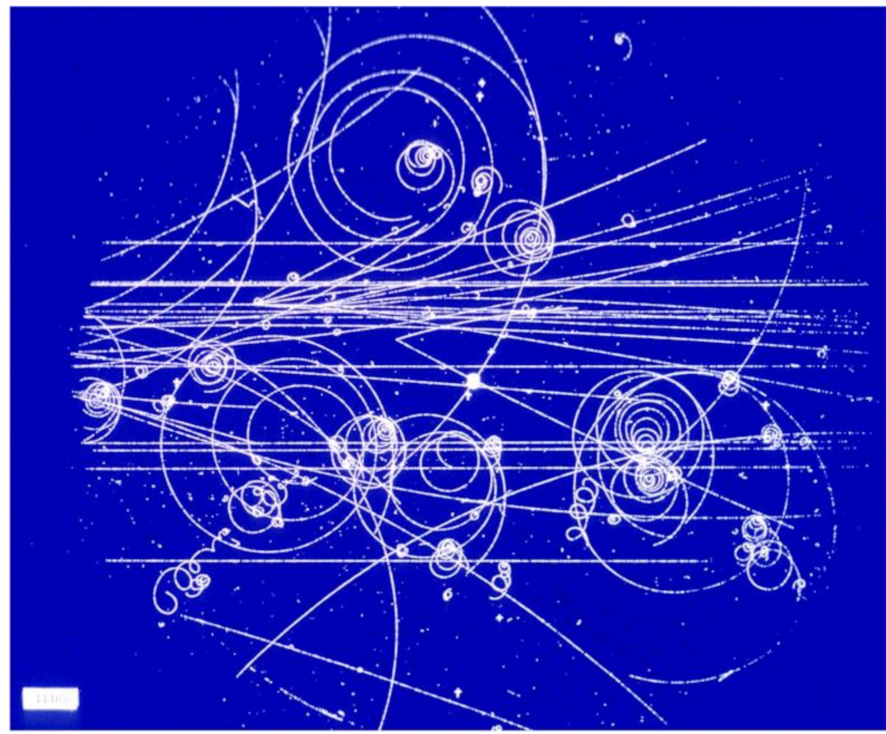
Tracks of α - decays

PP: Tools – Introduction

Vizualization



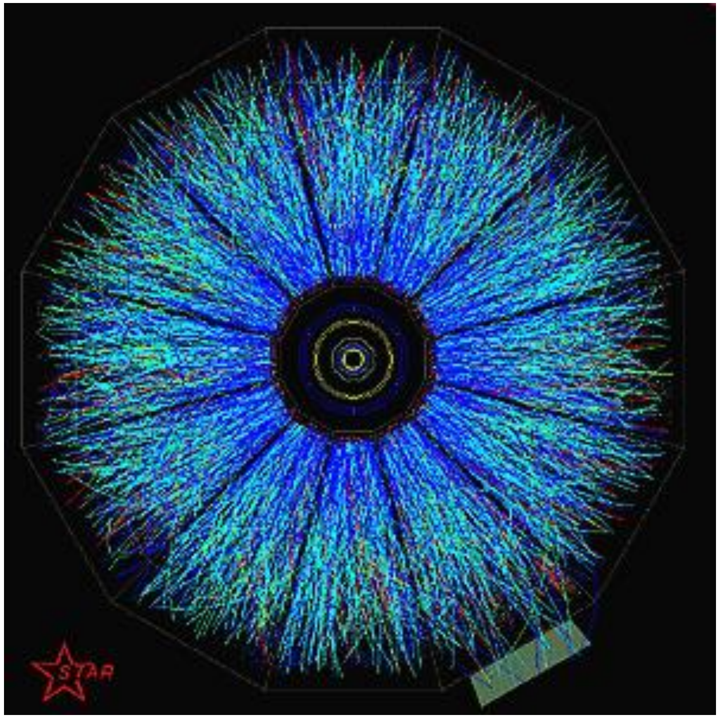
Tracks in an emulsion



Tracks in a bubble chamber

PP: Tools – Introduction

Reconstruction



Tracks in a modern detector (~200 tracks per event)
(Events display of a Au-Au collision in STAR at RHIC-BNL)

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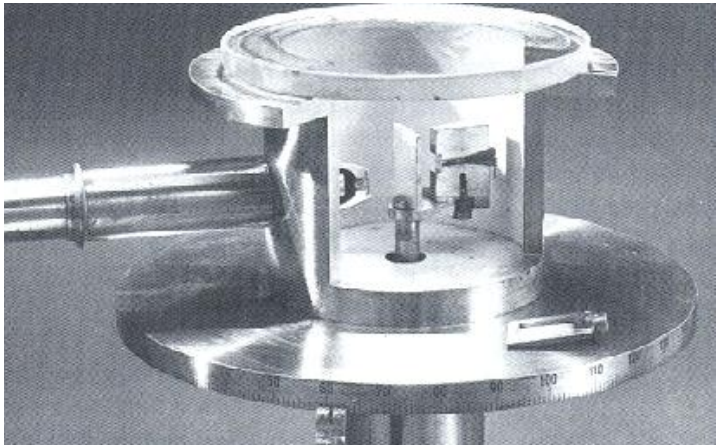
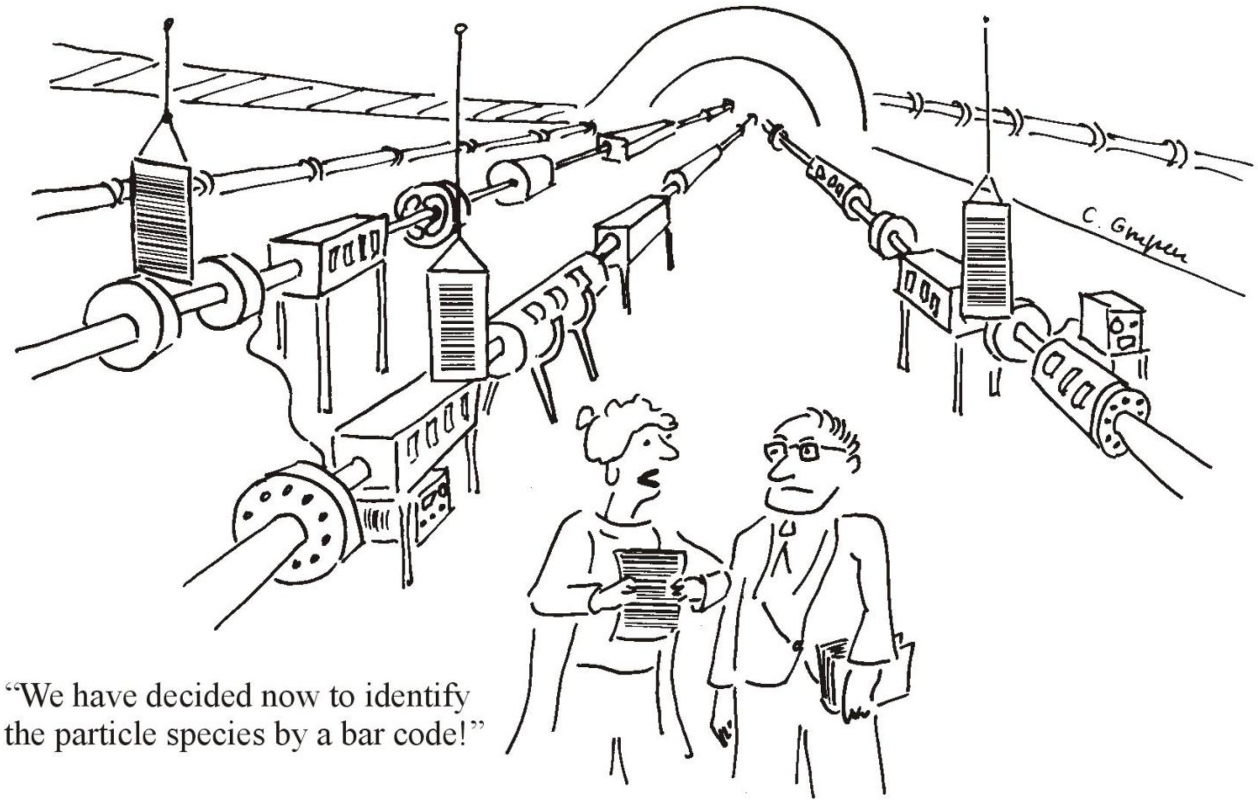


Rutherford
α - scattering

PP: Tools – Detectors

"Particles, particles, particles."

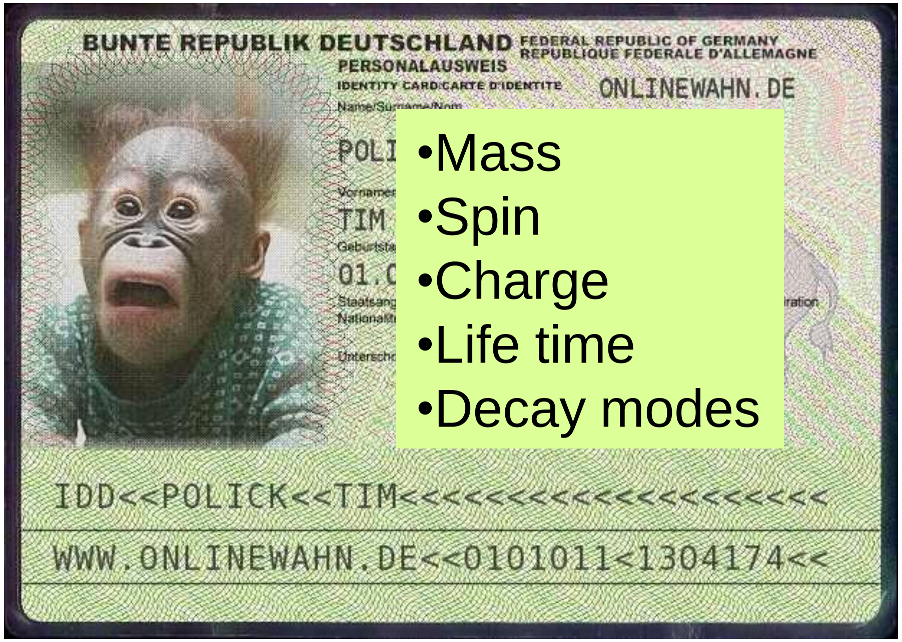
PP: Tools – Detectors



"We have decided now to identify the particle species by a bar code!"

PP: Tools – Detectors

Particle i.d.



- Mass
- Spin
- Charge
- Life time
- Decay modes

PP: Tools – Detectors

Measured quantities

Mass / energy

$$E = \sqrt{p^2c^2 + m^2c^4} = T + mc^2 = \gamma mc^2$$

- *calorimeter*
- *momentum (particle mass known)*

Momentum

$$p = \gamma mv = \gamma m\beta c$$

- *velocity*
- *deflection in el.-mag. fields ('tracks')*

Charge

- *deflection in el.-mag. fields (e/m)*

Life time

- *decay vertices, width*

$$\Gamma = \hbar / \tau$$

suitable units
[m] = MeV/c^2
[p] = MeV/c
[E] = MeV
[t] = s
[length] = fm = 10^{-15} m

PP: Tools – Detectors

Principle: Detectors are based on the interaction of particles (leptons, ions, photons) with matter (gaseous, liquid, solid). Discrimination between species are based on their different behaviour.

Types:
(I) Energy (-loss) measurements
→ Bethe-Bloch
(II) Time-of-flight measurements (velocity)
(III) Momentum determination (magnetic rigidity)
(IV) Other:
Cherenkov
Transition Radiation
Electromagnetic or hadronic shower

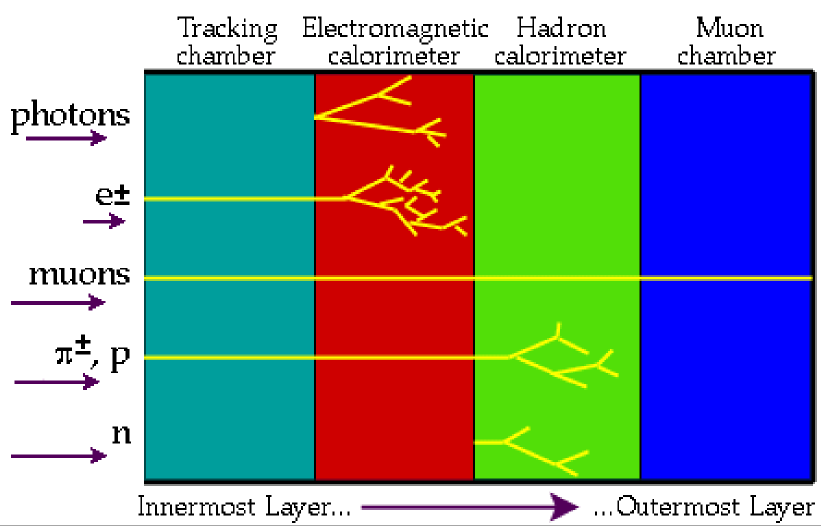
→ frequently: combinations

PP: Tools – Detectors

Requirements:

- Detection efficiency (as big as possible; $\varepsilon < 1$)
- Solid angle (as large as possible; $\Omega < 4\pi$)
- Resolutions in energy, time, … (as good as possible)
- Rate capability (as high as possible)

→ usually different detector(-type)s are needed !



The imprints of different particle types in the different layers of a particle detector

PP: Tools – Detection techniques

Energy loss

In order to detect a particle:

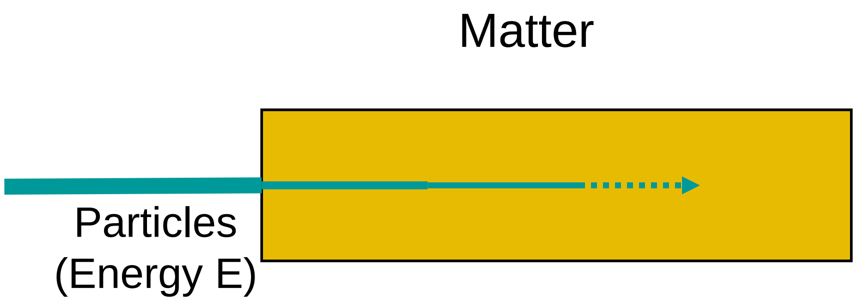
- it must interact with detector material
- transfer energy in a recognizable fashion

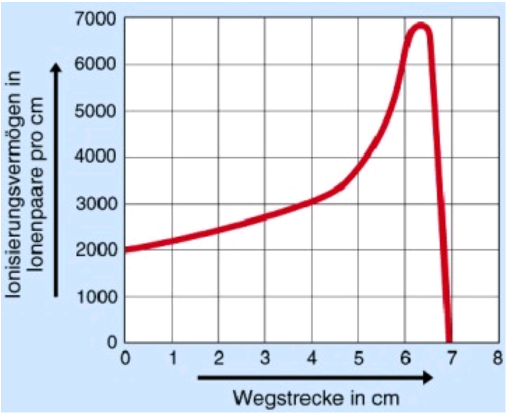
i.e.

The detection of particles happens via their energy loss in the material it traverses !

Possibilities:

Charged particles - Ionization, Cherenkov, ...
Hadrons - Nuclear interactions
Photons - Photo/Compton effect
Neutrinos - Weak interactions



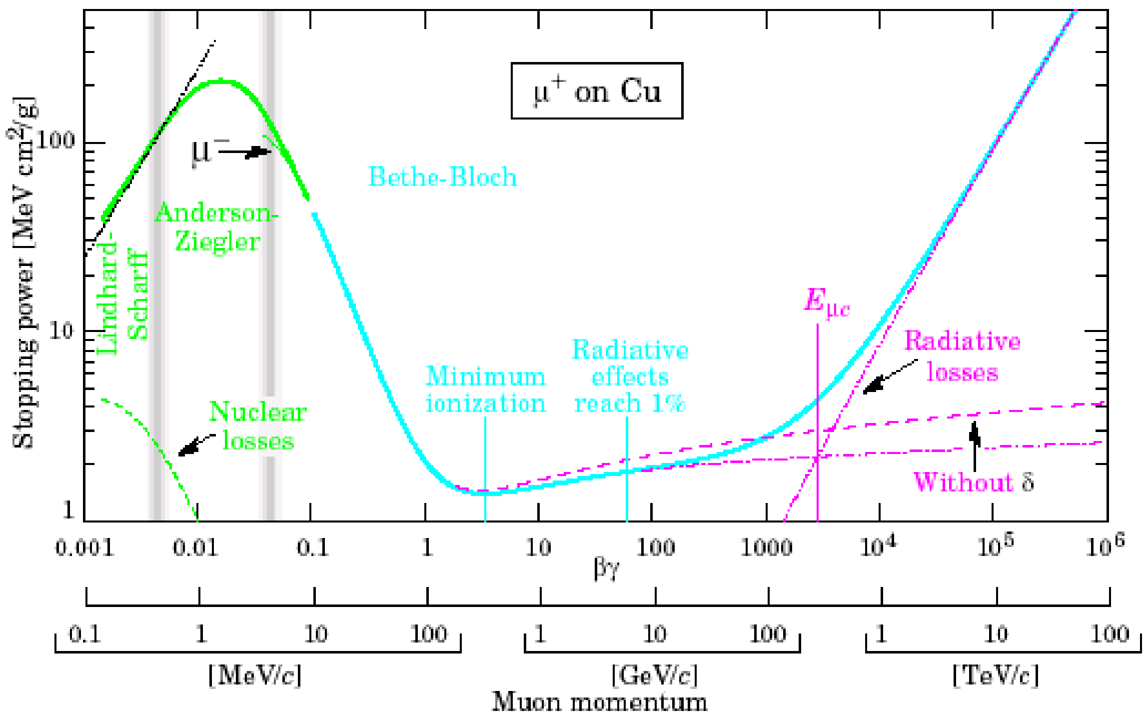


α – particles traverse in air

PP: Tools – Detection techniques

Energy loss (Bethe-Bloch)

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e c^2 \beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$



Stopping power <-dE/dx> for **μ⁺ in copper** as a function of $\beta\gamma = p/Mc$

<u>Charged particles in matter</u>:

- at very low *βγ*, large energy loss due to atomic effects
- for large range of relativistic *βγ*, energy loss is small (min ionizing particle "mip")
- ultra-relativistic particles lose energy mostly via gamma radiation

JÜLICH FORSCHUNGSZENTRUM

PP: Tools – Detection techniques

Passage of radiation through matter

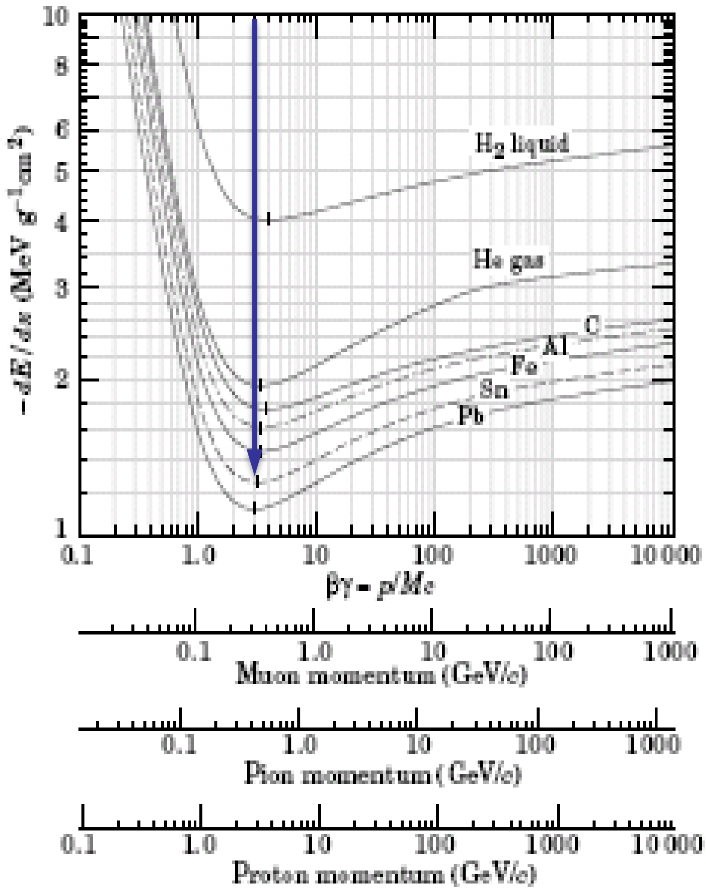


Figure 27.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-Z absorbers. See Fig. 27.21.

Energy Loss dependence on:

Mass (A) and Charge (Z)

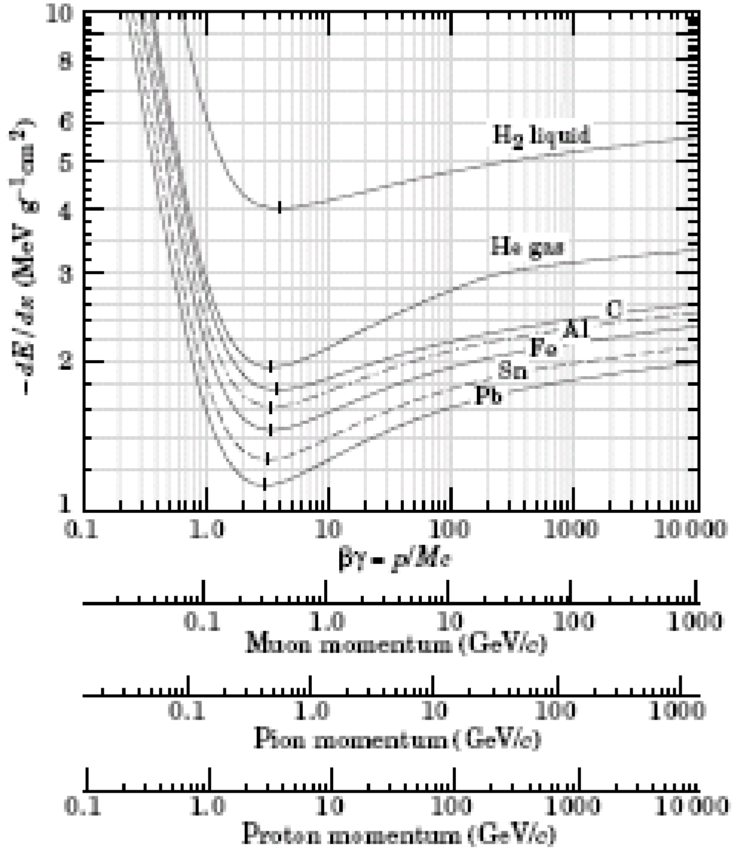
of target nucleus

Stopping power in several materials:

- curves scale reasonable well
- scaling with medium ~Z/A, but I rises with Z
- note larger relativistic rise in Helium gas; less rise in liquids and solids (screening due to density)
- MIP’s stopping power ~ 2 MeV/g cm^{-2}

PP: Tools – Detection techniques

Passage of radiation through matter



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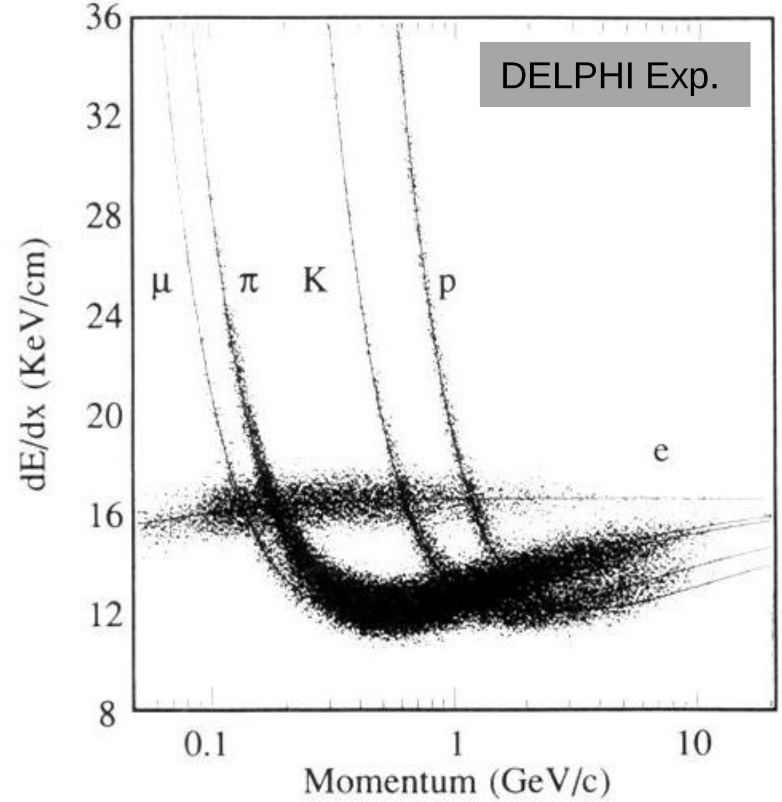
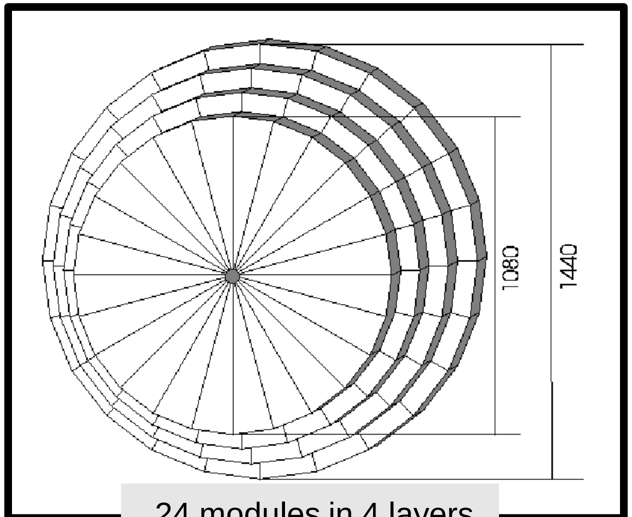
Measured energy loss:

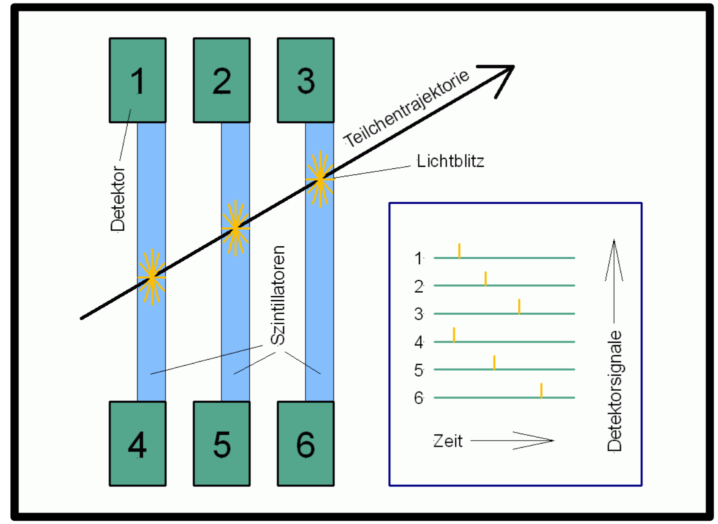


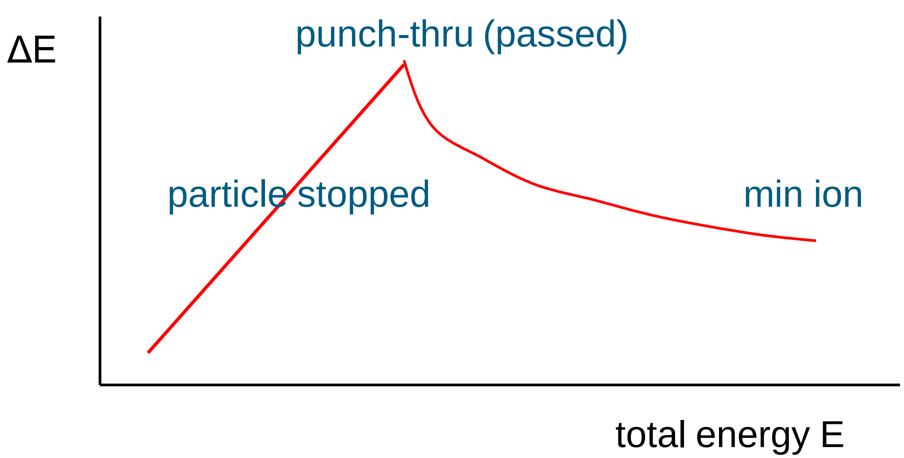
PP: Tools – Detection techniques

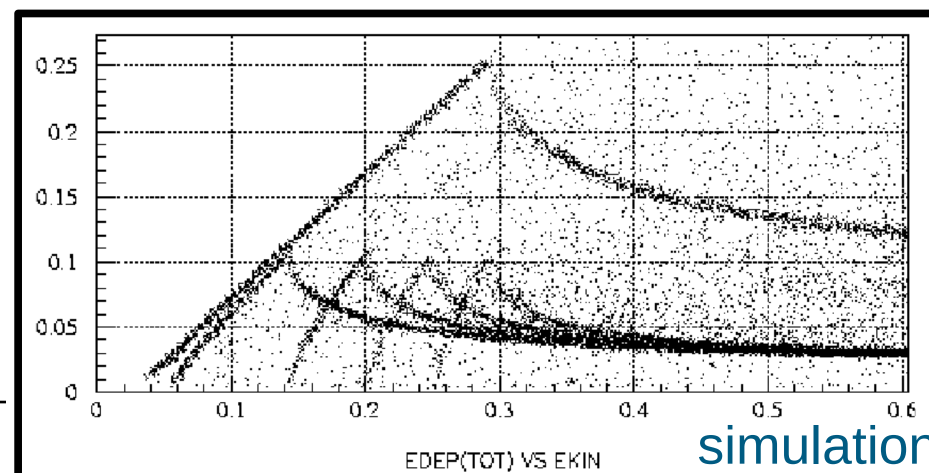
Particle tracking with hodoscopes (WASA)



24 modules in 4 layers

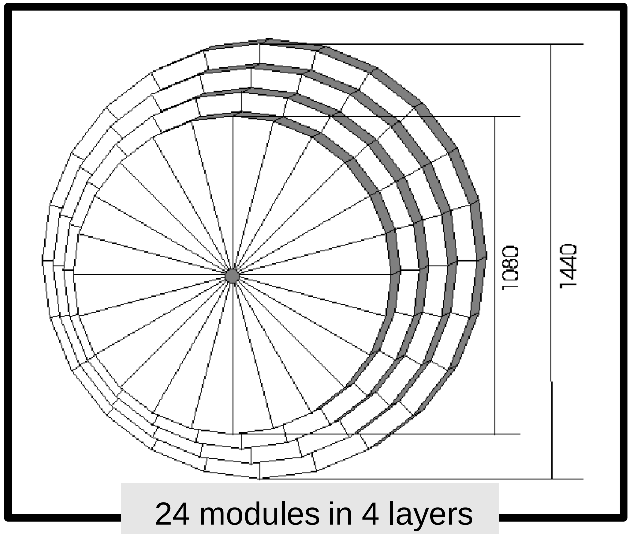




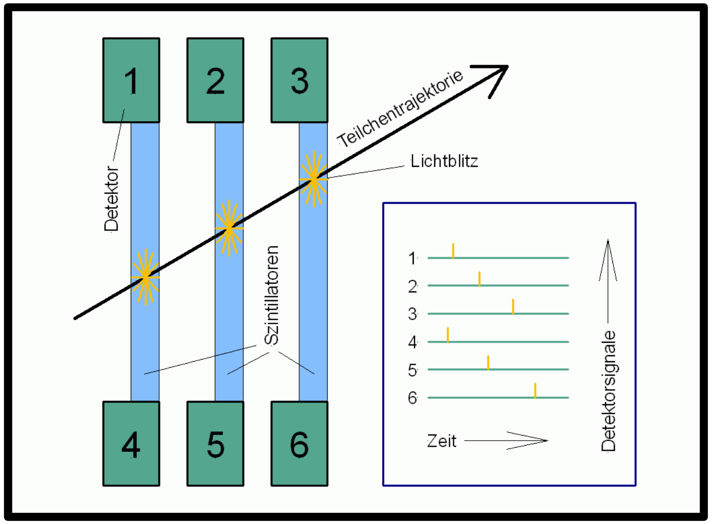


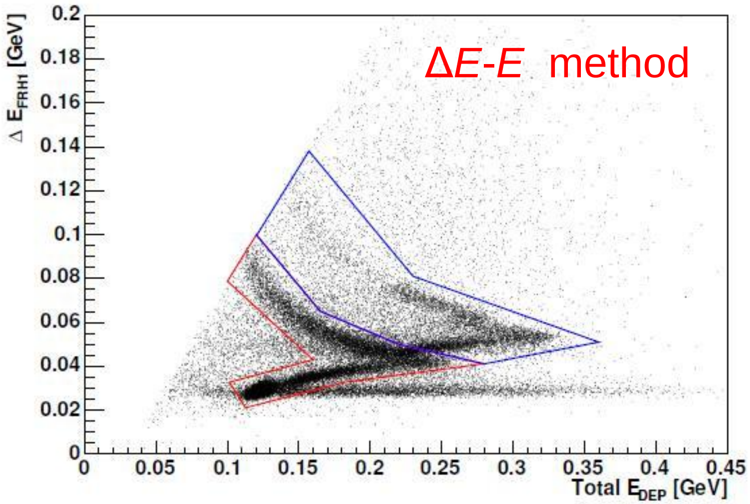
PP: Tools – Detection techniques

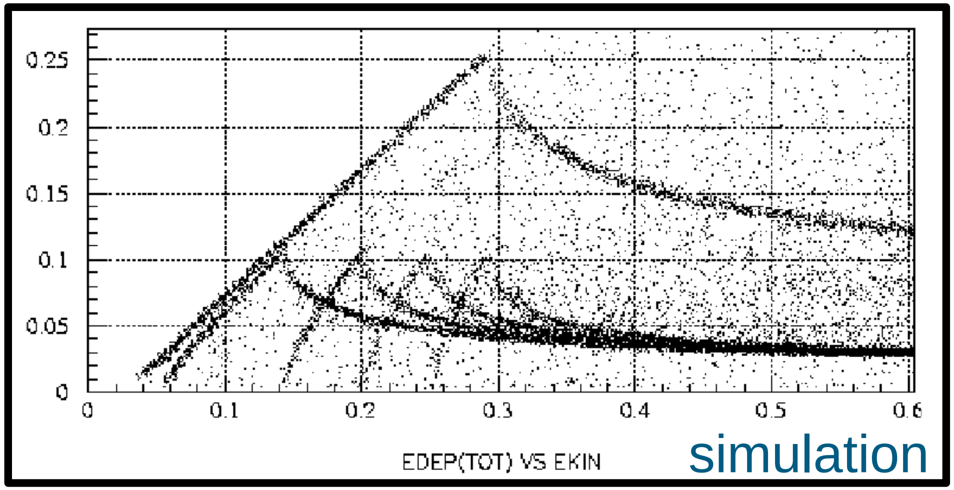
Particle tracking with hodoscopes (WASA)



24 modules in 4 layers





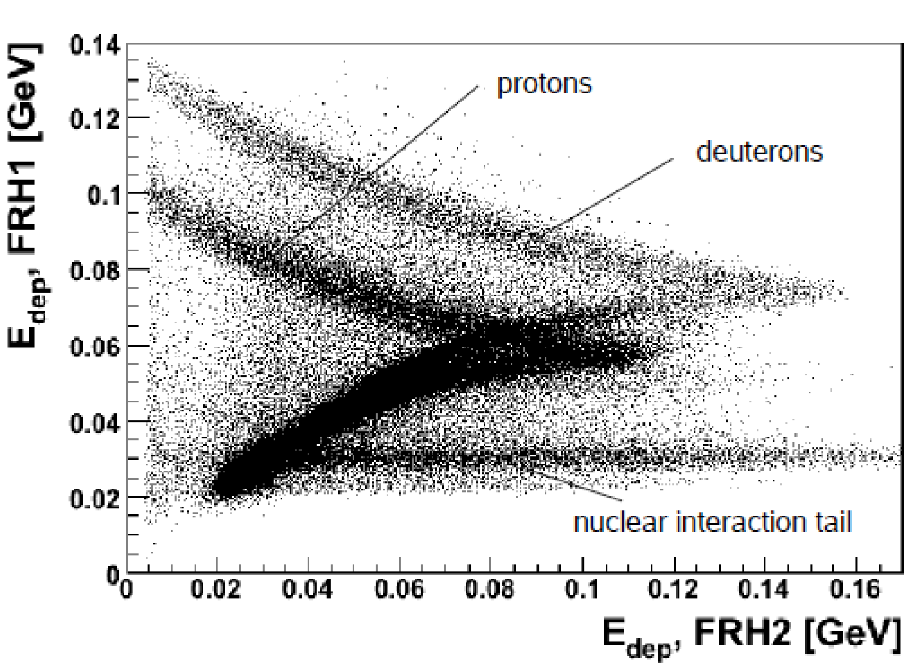


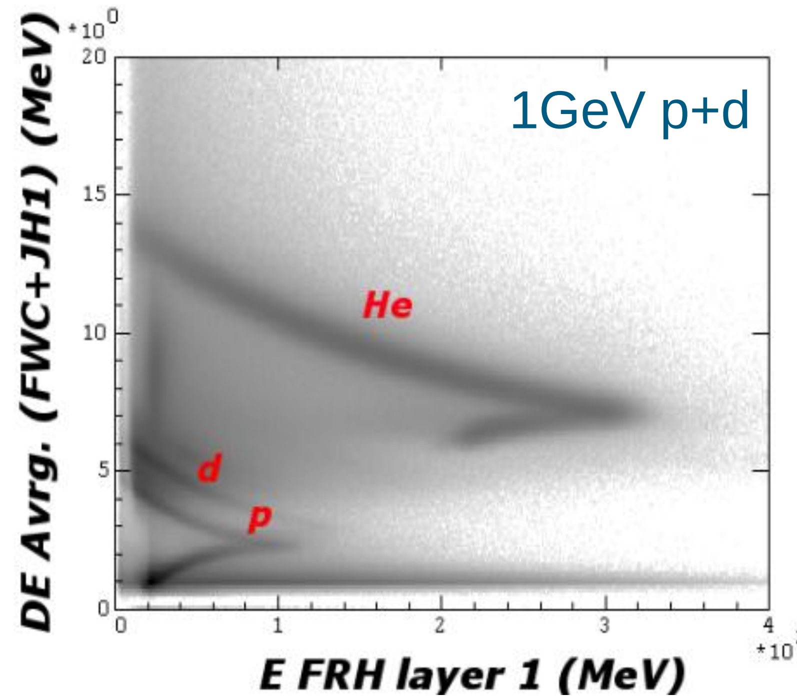
simulation

PP: Tools – Detection techniques

Particle tracking with hodoscopes

Example from real life (WASA forward hodoscope)
(as opposed to simulation we do not know the total energy yet)

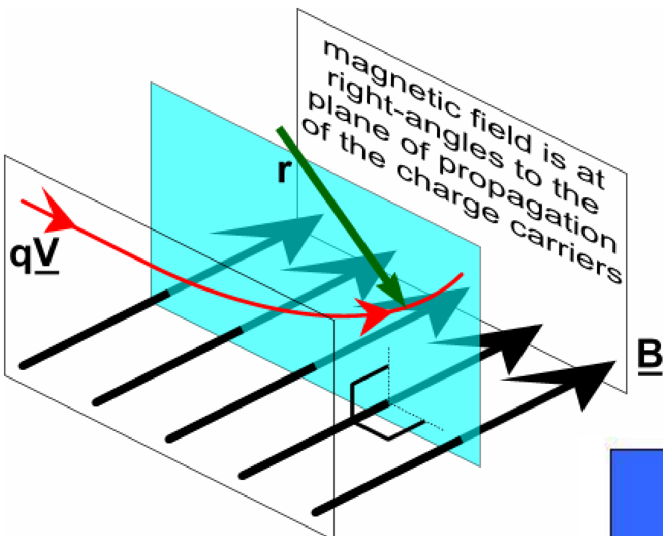


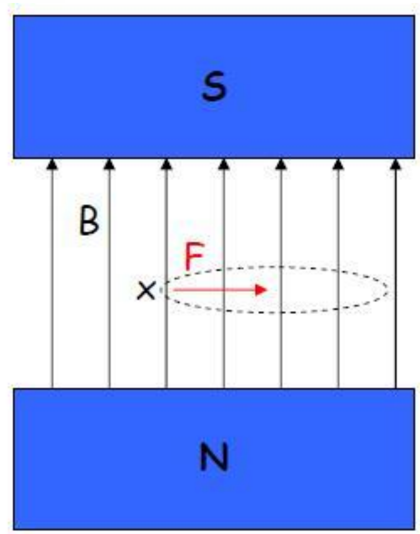


Particle identification: $\Delta E/E$ method

PP: Tools – Detection techniques

Magnetic Rigidity





$$B\rho = \frac{pc}{e} = \frac{\beta E}{e}$$

$$B\rho[\mathrm{T \cdot m}] = \frac{10}{2.998}\beta E[\mathrm{GeV}]$$

The Lorentz force, in the absence of an electric field, may be written **F**=q **v** × **B** = d**p**/dt, where q is the particle charge, **v** is its velocity, **B** is the magnetic field it is moving through, **p** is the particle momentum and d/dt is the derivative with respect to time.

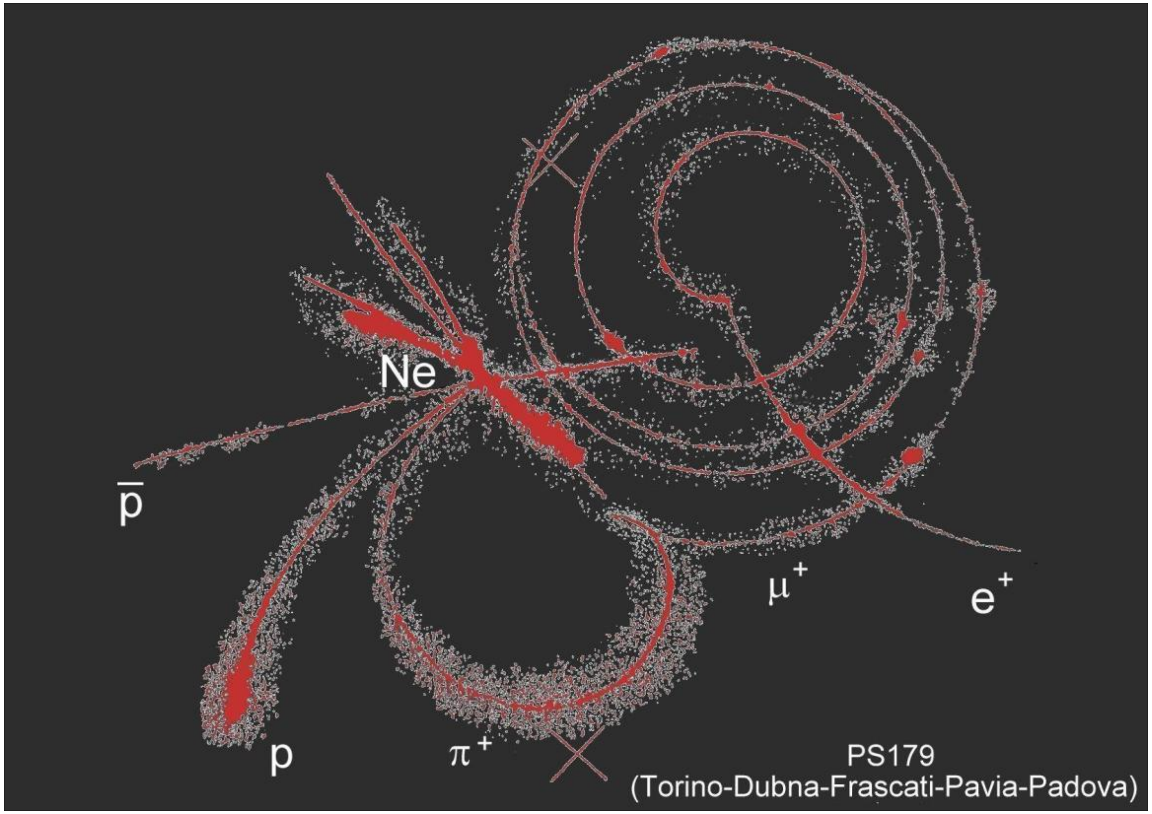
The magnetic rigidity Bρ is given in terms of the magnetic field normal to which the particle is travelling and its bending radius:

$$p/q = B\rho = 3.3356\ p(\mathrm{GeV}/c)$$

The magnetic rigidity is the momentum per unit charge of a particle.

PP: Tools – Detection techniques

Magnetic Rigidity



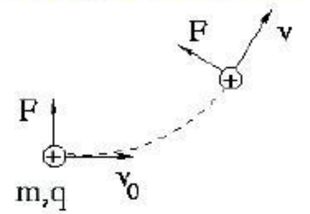
Streamer chamber photo of pion-muon-electron (pi-mu-e) decay chain resulting from antiproton annihilation. The antiproton annihilates with a proton in neon (Ne) gas filling the chamber.

PP: Tools – Detection techniques

Magnetic Rigidity

Charged particle moving in Uniform Magnetic Field

B direction into plane $\otimes$ B



$\vec{F} = q\vec{v} \times \vec{B}$ **magnetic force**

$\vec{F} \perp \vec{v}$ $\Rightarrow$ changes only $\vec{v}$ direction ($v = v_0$; F is centripetal force)

$$F = qvB = m\frac{v^2}{\rho}$$ → curvature radius

Bρ is called **magnetic rigidity**:

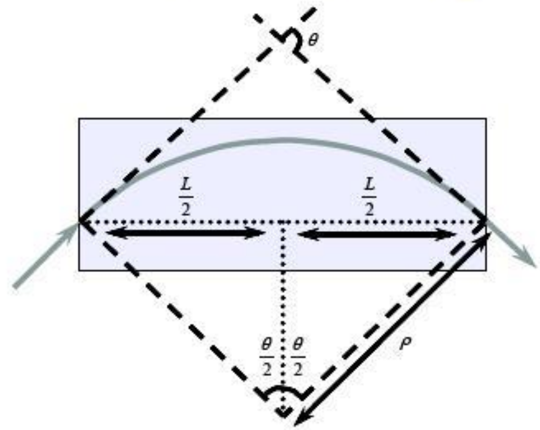
$$B\rho = \frac{mv}{q} = \frac{p}{q} = \frac{Av}{qc^2}$$ → momentum

using correct units:

Bρ = 33.356 p [kG m]
= 3.3356 p [T m] (if p is in [GeV/c])

Dipole Magnet

a **dipole** with a **uniform dipolar field** deviates a particle by an angle θ



θ depends on length L and field B:

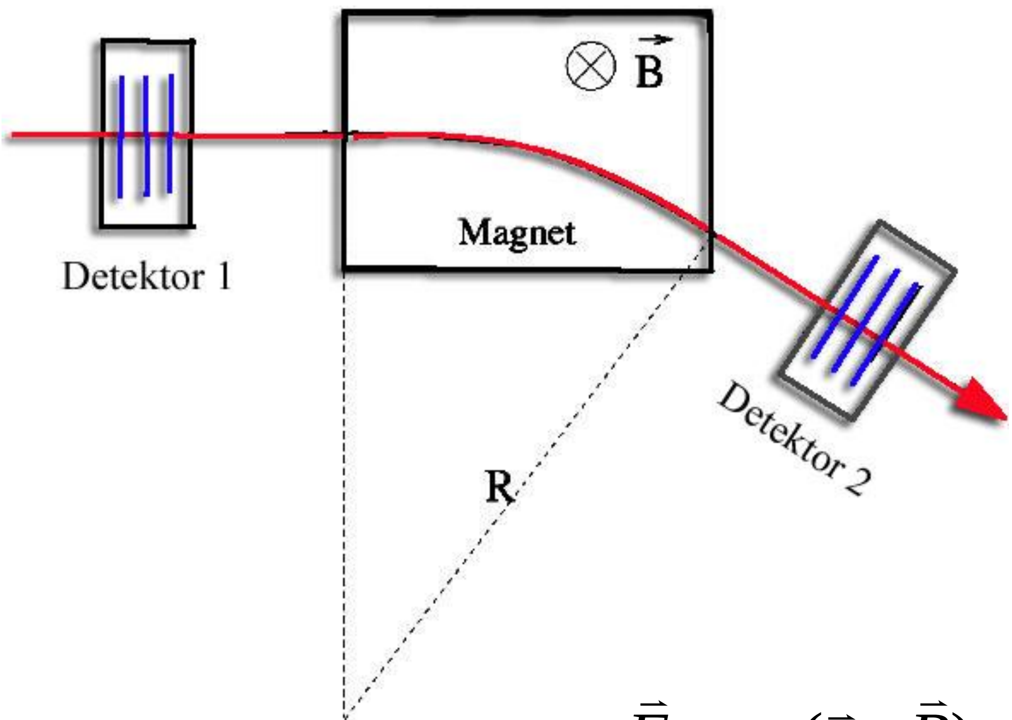
$$\sin\left(\frac{\theta}{2}\right) = \frac{L}{2\rho} = \frac{1}{2}\frac{LB}{(B\rho)}$$

if θ is small:

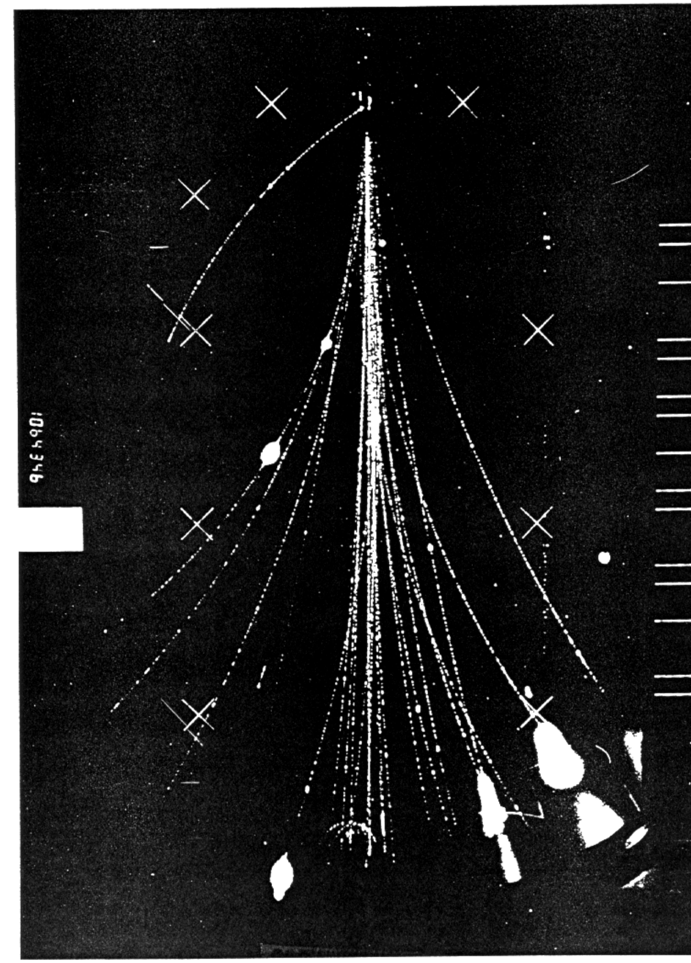
$$\sin\left(\frac{\theta}{2}\right) = \frac{\theta}{2} \rightarrow \theta = \frac{LB}{(B\rho)}$$

PP: Tools – Detection techniques

Measurement of momenta



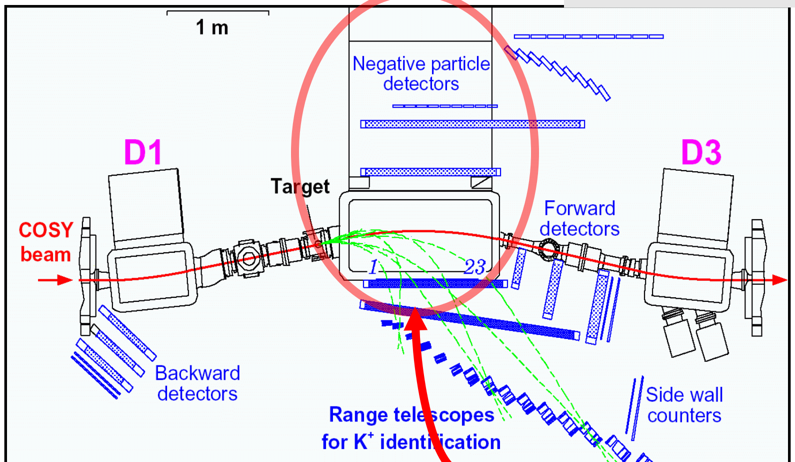
$$\vec{F} = q \cdot (\vec{v} \times \vec{B})$$

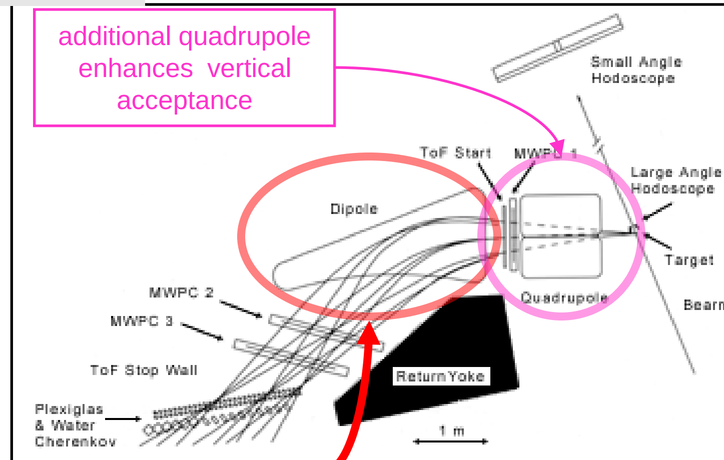


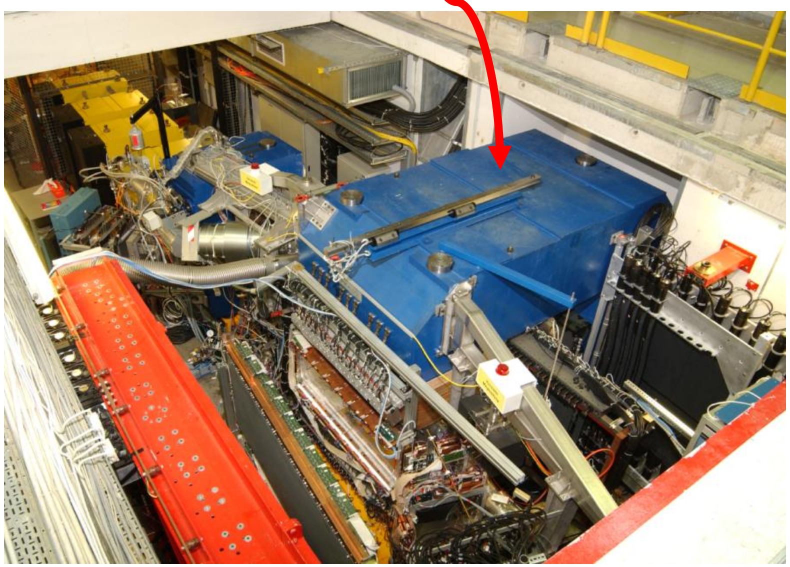
Total deflection behind magnet: $\Delta\vartheta = (0.3 \cdot \int B\,dl)/p \sim 0.3 \cdot (BL)/p$

PP: Tools – Detection techniques

Dipole spectrometers







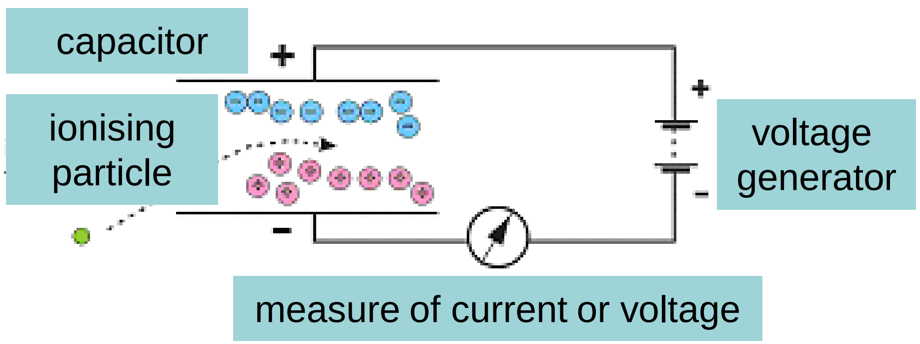
Apparatus for Nucleon and Kaonic Ejectiles (COSY-Jülich)

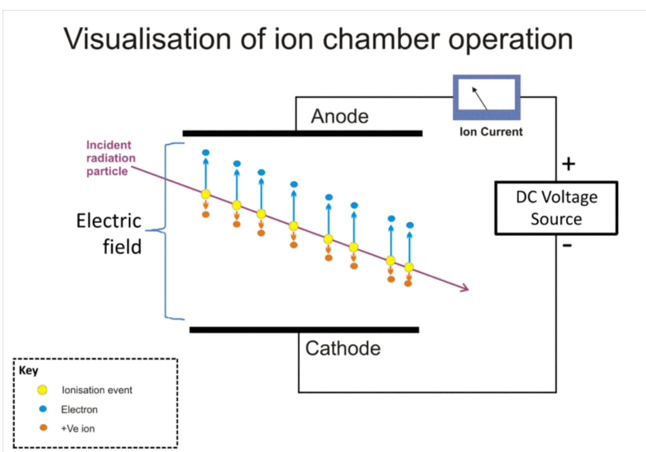
Kaon Spectrometer (GSI-Darmstadt, now MAMI-Mainz)

PP: Tools – Detection techniques

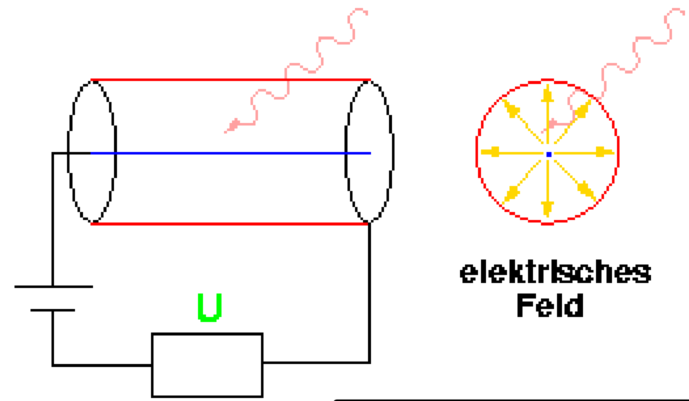
Charge in wire chambers

Ionization chamber

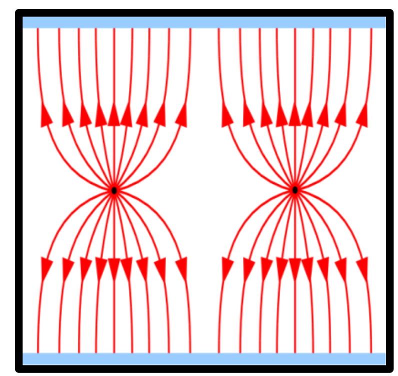




Geiger-Müller counter



- electric field in a wire chamber
- field strength close to the wires is highest (density of field lines)

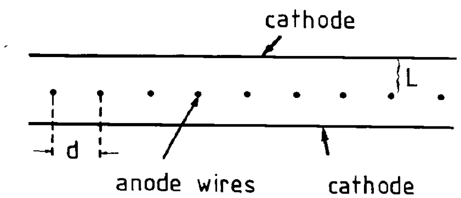


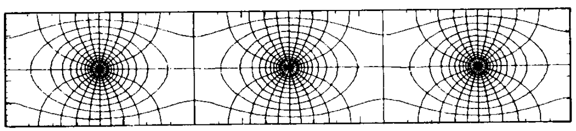
Charge created by charged particles or by „light“ is collected by applying a voltage by means of a curent or voltage detection

PP: Tools – Detection techniques

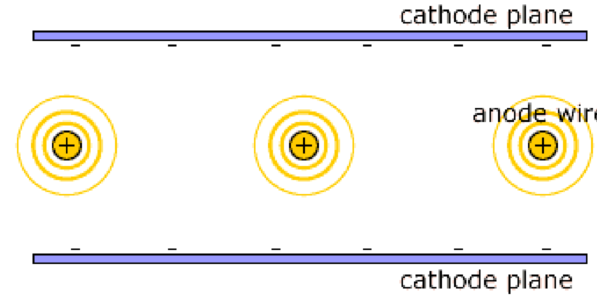
Multi-wire prop. chambers (MWPC)

(G. Charpak et al. 1968, Nobel prize 1992)



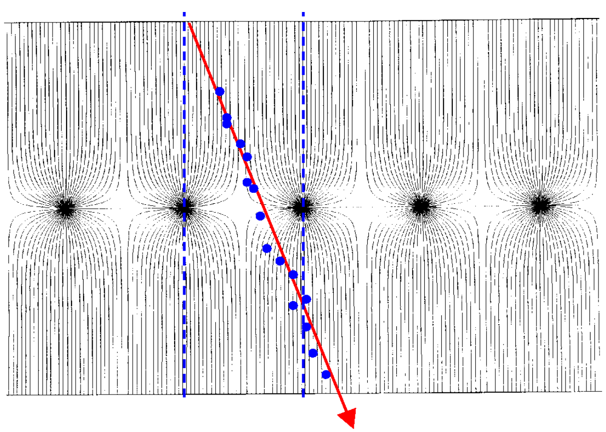


field lines and equipotentials around anode wires

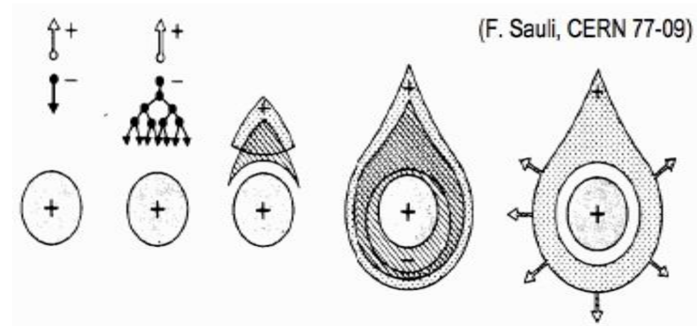


Electron multiplication around anode (fast)

Drift of Ions (slow)



multiplication → avalanche: ***gain 10^5 -10^6***



Typical parameters:
L=5mm, d=1mm,
a_{wire}=20mm.

to control avalanche: add quench gases, e.g. CO_2, CH_4, C_2H_6

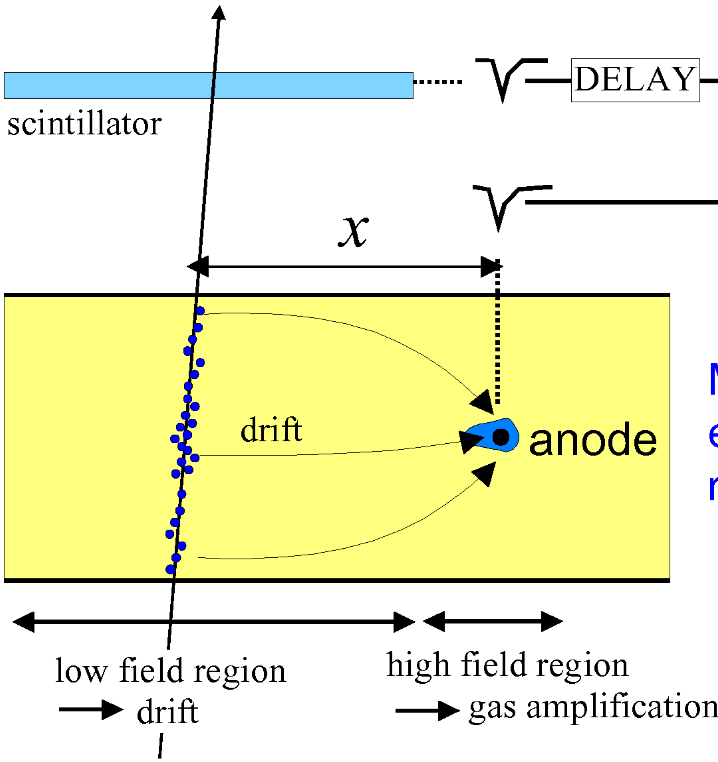
Normally digital readout:
spatial resolution limited to $\sigma_x \approx \frac{d}{\sqrt{12}}$ (d=1mm, σ_x=300 µm)

PP: Tools – Detection techniques

Drift chambers (MWDC)

(First studies: T. Bressani, G. Charpak, D. Rahm, C. Zupancic, 1969
First operation drift chamber: A.H. Walenta, J. Heintze, B. Schürlein, NIM 92 (1971) 373)

time ↔ position; external time reference, e.g. plastic scintillator



Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)dt$$

- The „drift“ in the name refers to the time it takes electrons to drift to the nearest sense wire from the place where the high-energy particle ionized an atom
- By measuring drift time, location of original track can be determined much more precisely than actual spacing between the wires
- The set of wires that give a signal can be used the paths (tracks) reconstruction
- Higher spatial resolution lower rate capacity

PP: Tools – Detection techniques

Drift chambers: example

KLOE experiment (Frascati): 50.000 wires

DC Requirements and Solutions

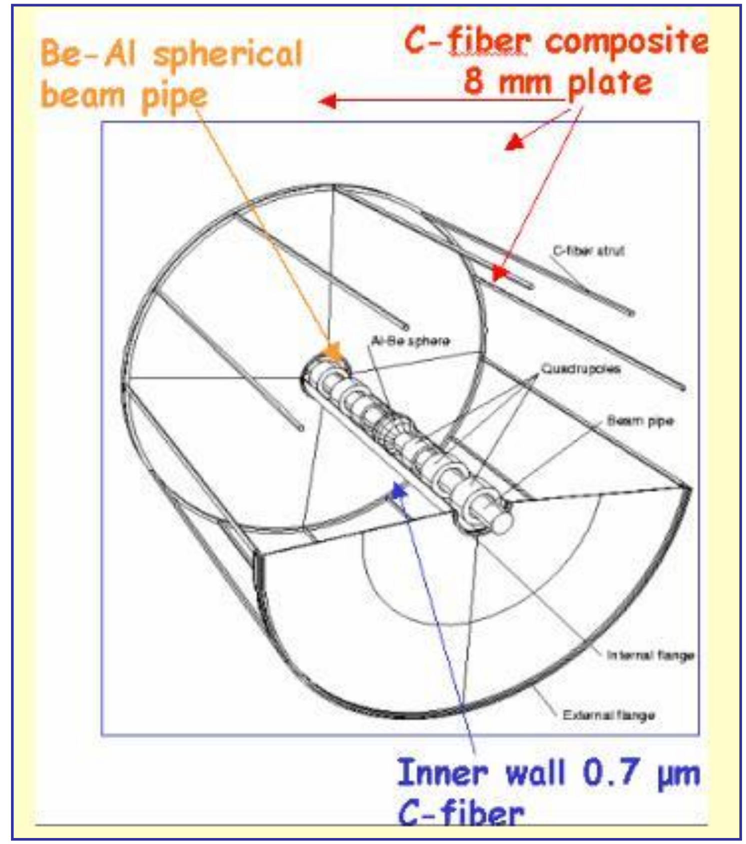
Requirements	Solutions
• Large tracking volume (K Long decay length= 340 cm)	• Diameter = 4 m, Lenght = 3.3 m
• High and uniform reconstruction efficiency (due to the K Long decays distribution)	• Uniform cells structure with spatial resolution r-phi resolution = 0.2 mm and z resolution = 2 mm
• Good momentum resolution @ 0.6 T (for kinematical rejection of the background for CP events)	• Relative momentum resolution = 0.5%
• Transparency to reduce regeneration, multiple scattering and conversion of low energy photons	• Light mechanical structure: C-fiber composite • Light drift medium: 90%He-10%iC_4H_{10} • 80 μm Al(Ag) field wires, 25 μm W(Au) sense wires

PP: Tools – Detection techniques

Drift chambers: example

KLOE experiment (Frascati): 50.000 wires

4 X 3.3 m



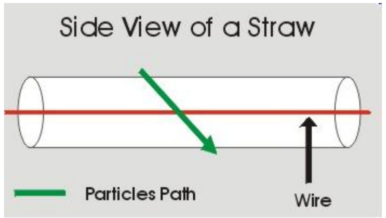
PP: Tools – Detection techniques

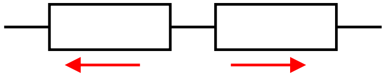
Straw tubes

individual counters, timing 20 ns
HV: coat, ground: sense wire (~ kV)
typical size: length 1 – 2 m, ϕ mm - cm

"simple" mechanics
10 MHz rate

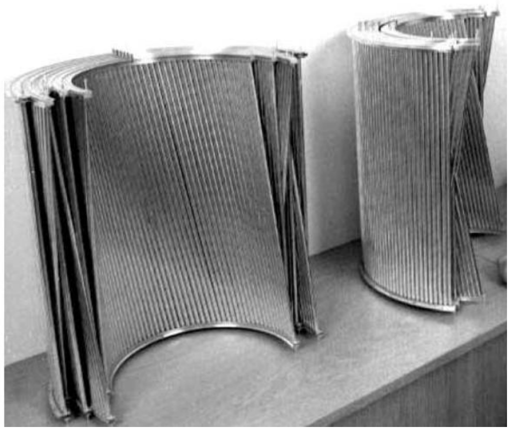
gas filling
e.g., Ar/C_2H_6



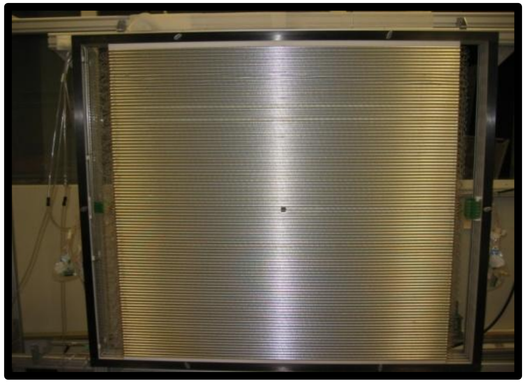


resistive read out
$\Delta z < 1$ mm
z

wall: aluminised mylar foils
anode wire: $\phi \approx 20$ µm

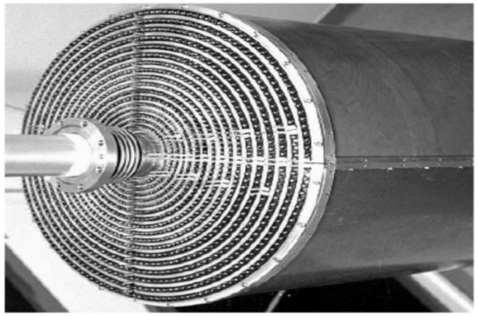


planar...



the forward projection chamber, FPC

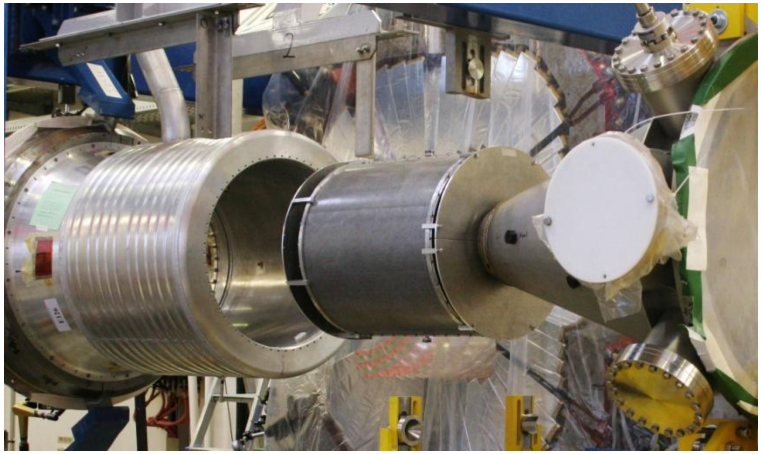
... or cylindrical



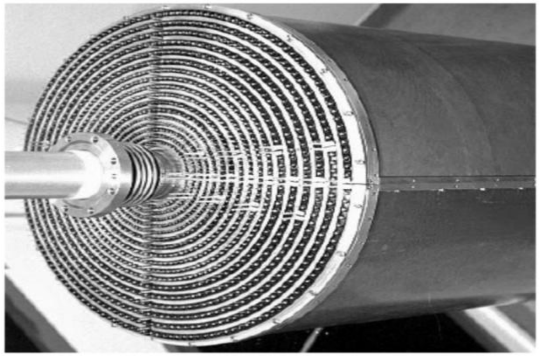
the central mini drift chamber, MDC

PP: Tools – Detection techniques

Mini drift chamber (WASA)

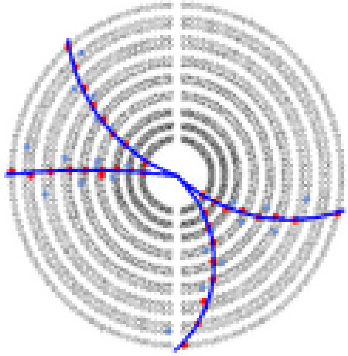


- 1700 drift tubes arranged in 17 cylindrical layers; straws are made 25 μm mylar foil coated with 0.1μm aluminum; in a center there is 20 μm gold plated tungsten sensing wire stretched with a tension of 40 g
- put in a magnetic field



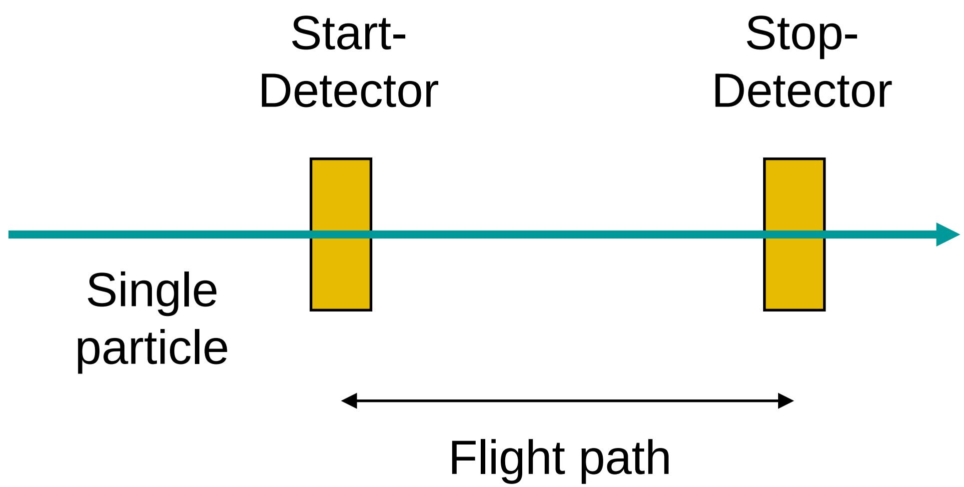
MDC is fitted inside a cylindrical cover made of 1 mm Al-Be and placed inside the solenoid.

Get a curved particle trajectories !



PP: Tools – Detection techniques

Time-of-flight (ToF)



→ velocity v (β)

PP: Tools – Detection techniques

Time-of-flight (ToF)

Distinguishing particles with ToF:
[particles have same momentum p]

Particle 1 : velocity v_1, β_1; mass m_1, energy E_1
Particle 2 : velocity v_2, β_2; mass m_2, energy E_2
Distance L : distance between ToF counters

$$\Delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

$$= \frac{L}{pc^2}(E_1 - E_2) = \frac{L}{pc^2}\left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4}\right)$$

Relativistic particles, $E \simeq pc \gg m_i c^2$:

$$\Delta t \approx \frac{L}{pc^2}\left[\left(pc + \frac{m_1^2c^4}{2pc}\right) - \left(pc + \frac{m_2^2c^4}{2pc}\right)\right]$$

$$\Delta t = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

For L = 2 m:

Requiring $\Delta t \approx 4\sigma_t$ K/π separation possible up to p = 1 GeV if $\sigma_t \approx 200$ ps ...

Cherenkov counter, RPC : $\sigma_t \approx 40$ ps ...
Scintillator counter : $\sigma_t \approx 80$ ps ...

Example:

Pion/Kaon separation ...
[$m_K \approx 500$ MeV, $m_\pi \approx 140$ MeV]

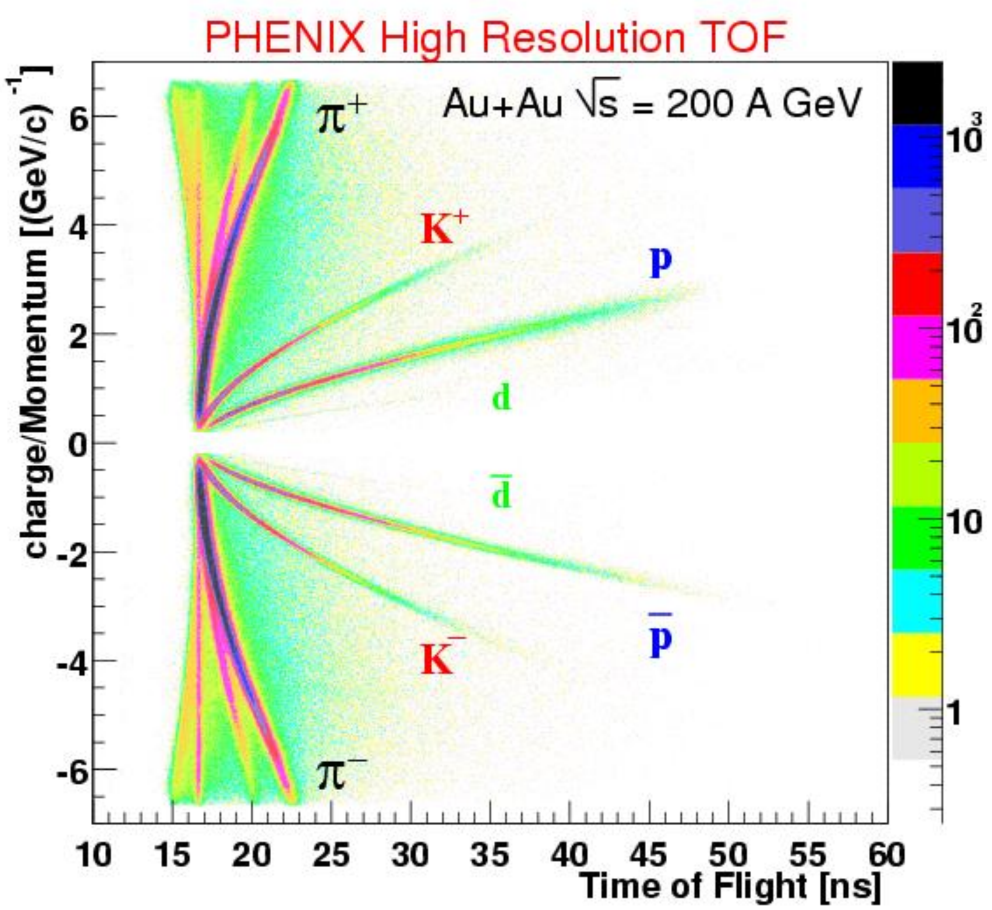
Assume:
p = 1 GeV, L = 2 m ...

$$\rightarrow \quad \Delta t \approx \frac{2\ \mathrm{m} \cdot c}{2\,(1000)^2\ \mathrm{MeV}^2/c^2}\left(500^2 - 140^2\right)\ \mathrm{MeV}^2/c^4$$

$$\approx 800\ \mathrm{ps}$$

PP: Tools – Detection techniques

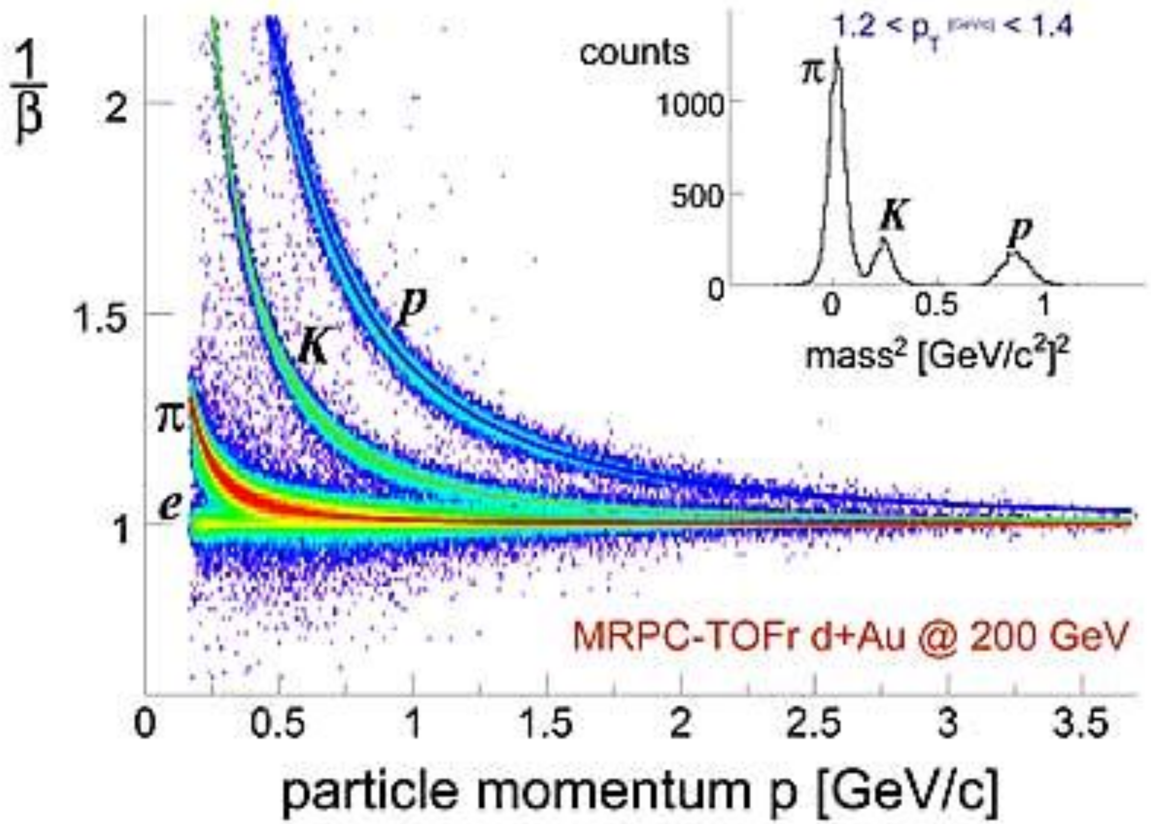
Time-of-flight (ToF)



PP: Tools – Detection techniques

Time-of-flight (ToF)

Particle identification: STAR at RHIC

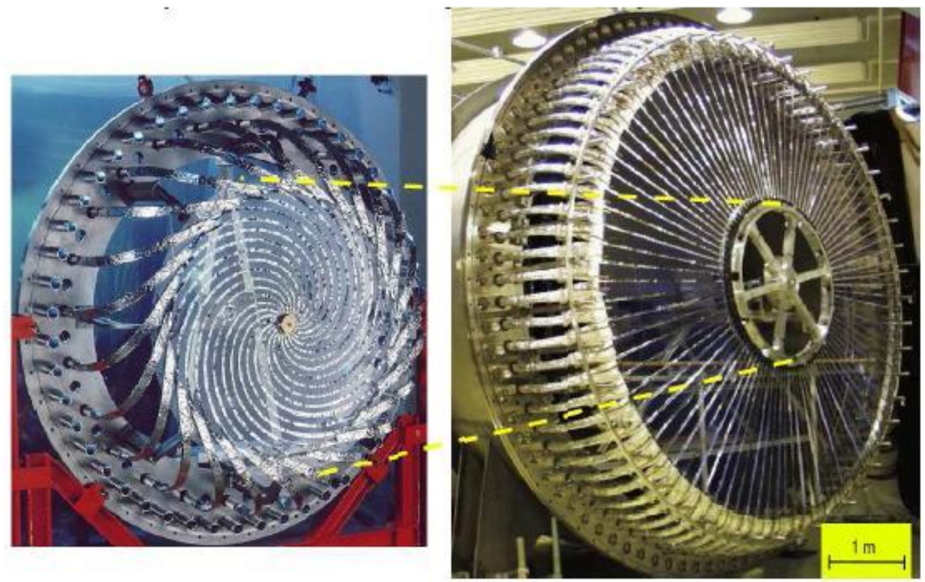


based on
MRPC:
Multi-gap
Resistive
Plate
Chamber

PP: Tools – Detection techniques

Time-of-flight (ToF)

TOF Spectrometer at COSY (Jülich)



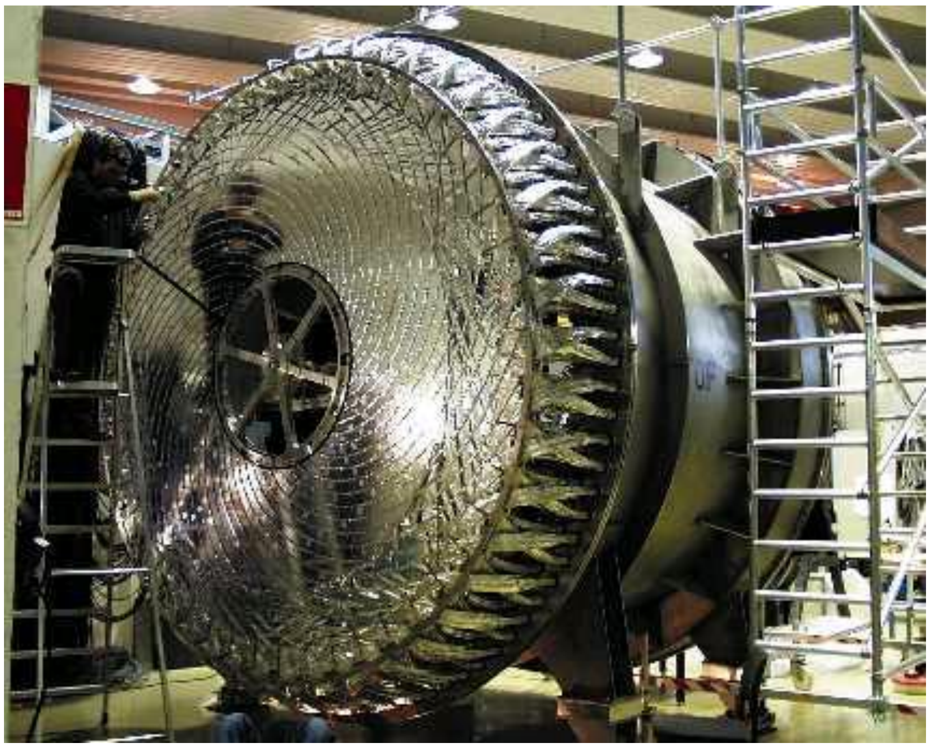
View on the tank of the TOF detector. The ring and centarl detector, the wedge shaped layer of the ring and the layer with Archimedian spirals of the central detector are shown.

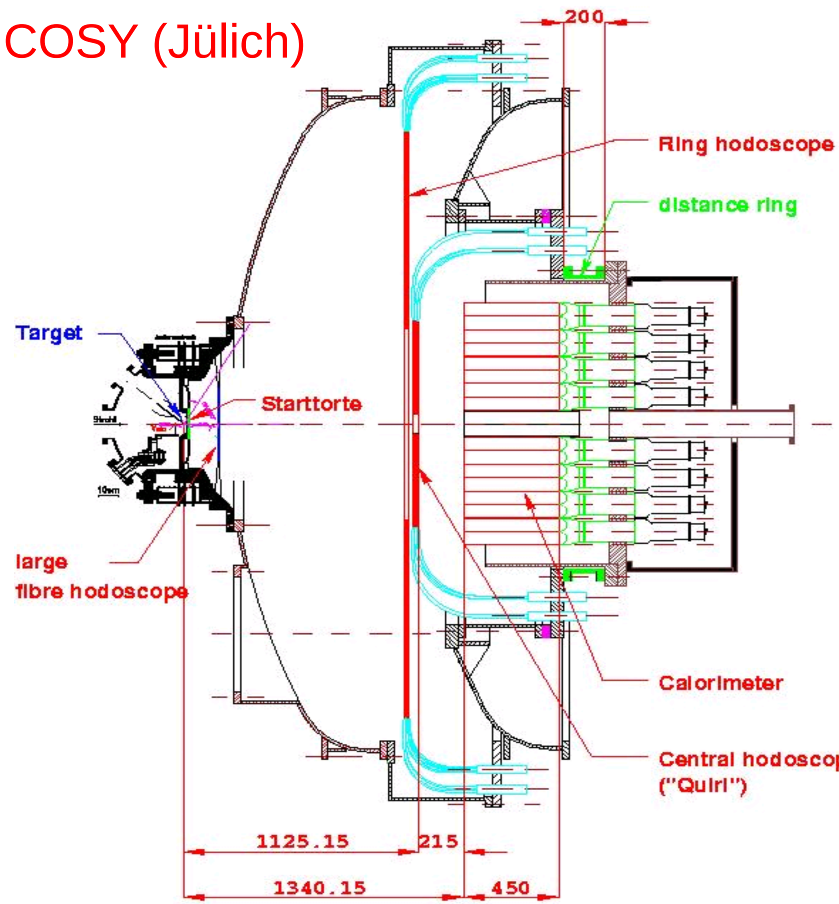
Excelent tracking capability with large acceptance and full azimutal symmetry !

PP: Tools – Detection techniques

Time-of-flight (ToF)

TOF Spectrometer at COSY (Jülich)



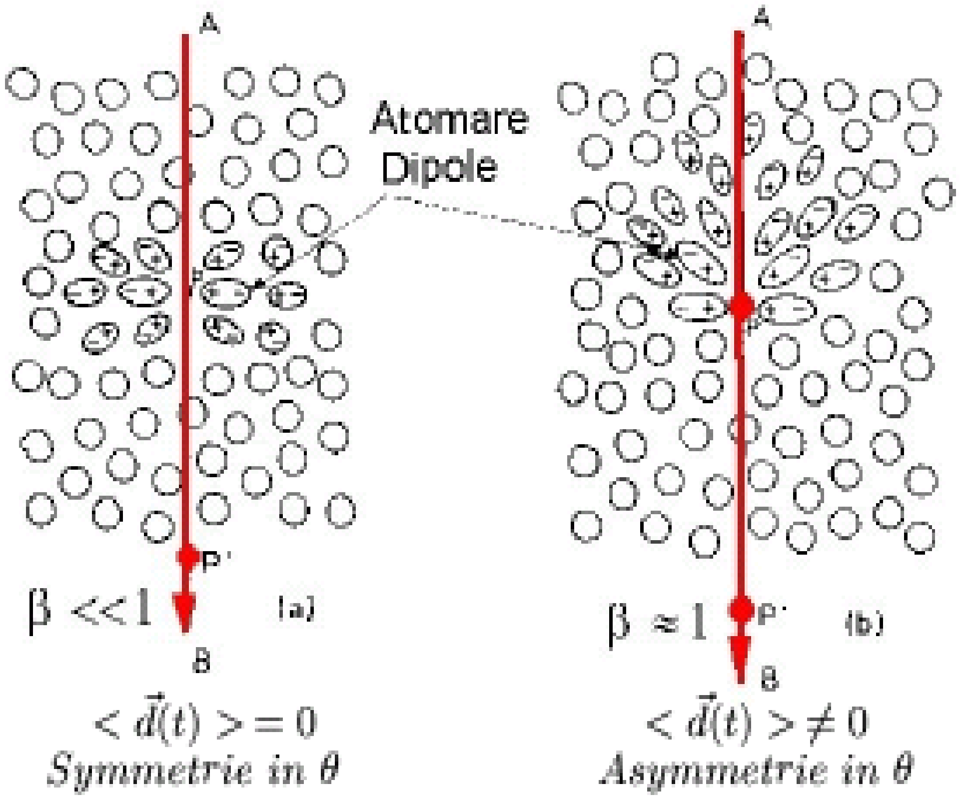


ToF + Tracking information close to interaction point: determination of 4-vectors of produced particles

PP: Tools – Detection techniques

Cherenkov effect

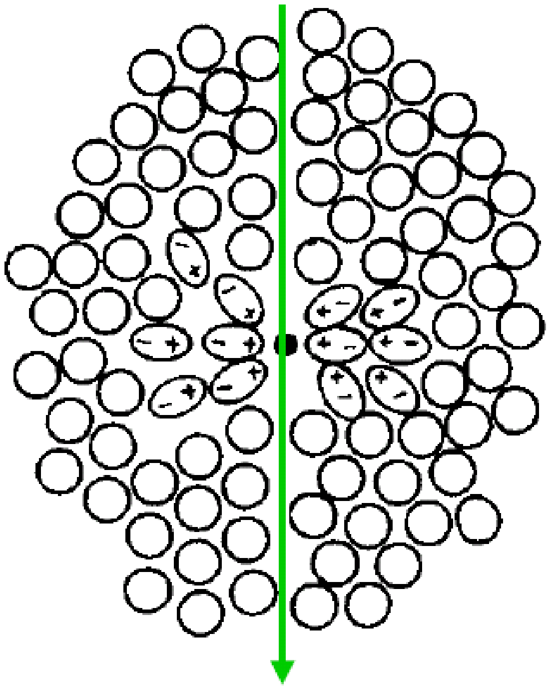
- The charge polarizes the medium



- Emission under specific angle Θ_C

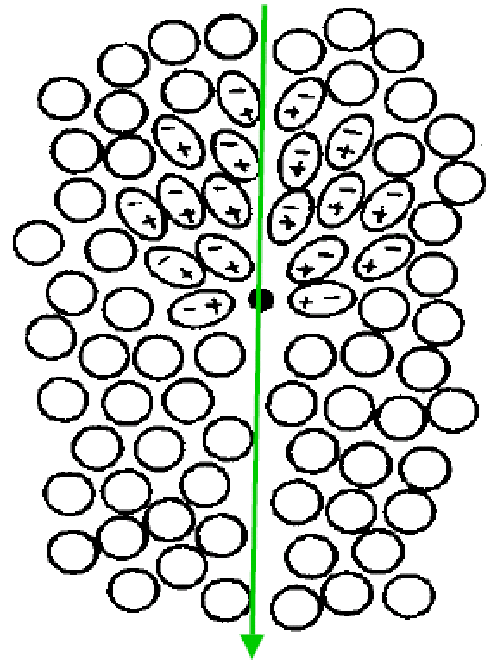
PP: Tools – Detection techniques

Cherenkov effect



V<c/n

Induced dipoles symmetrically arranged around particle path;
no net dipole moment;
no Cherenkov radiation !



V>c/n

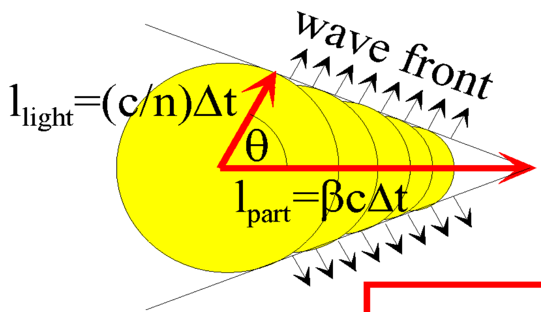
Symmetry is broken as particle faster the EM waves;
non-vanishing dipole moment;
radiation of Cherenkov photons !

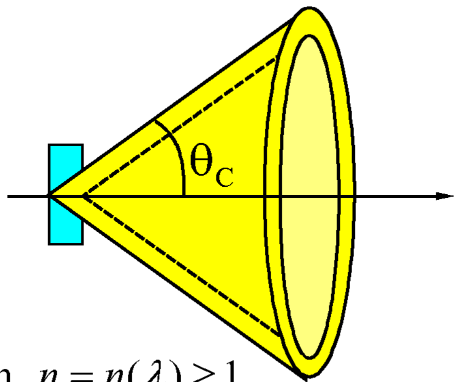
PP: Tools – Detection techniques

Cherenkov radiation

Cherenkov radiation is emitted when a charged particle passes a dielectric medium with velocity

$$\beta \geq \beta_{thr} = \frac{1}{n} \quad n: \text{refractive index}$$





$$\cos\theta_C = \frac{1}{n\beta} \quad \text{with} \quad n = n(\lambda) \geq 1$$

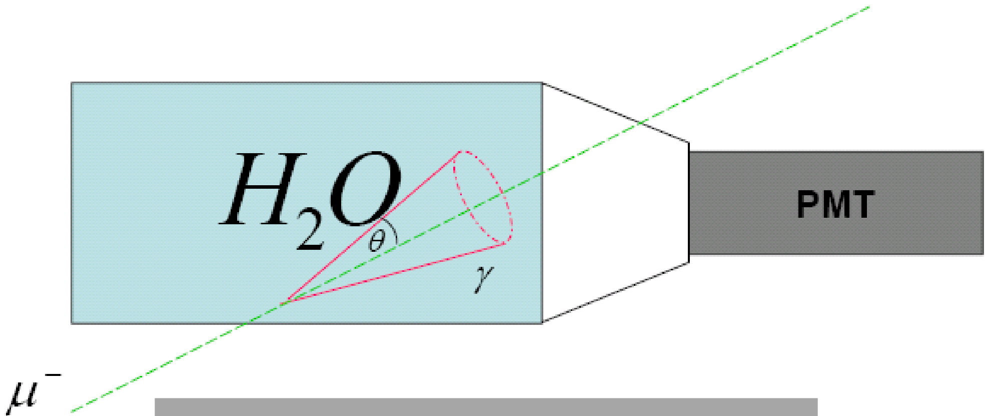
$$\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$$ threshold

$$\theta_{max} = \arccos\frac{1}{n}$$ 'saturated' angle (β=1)

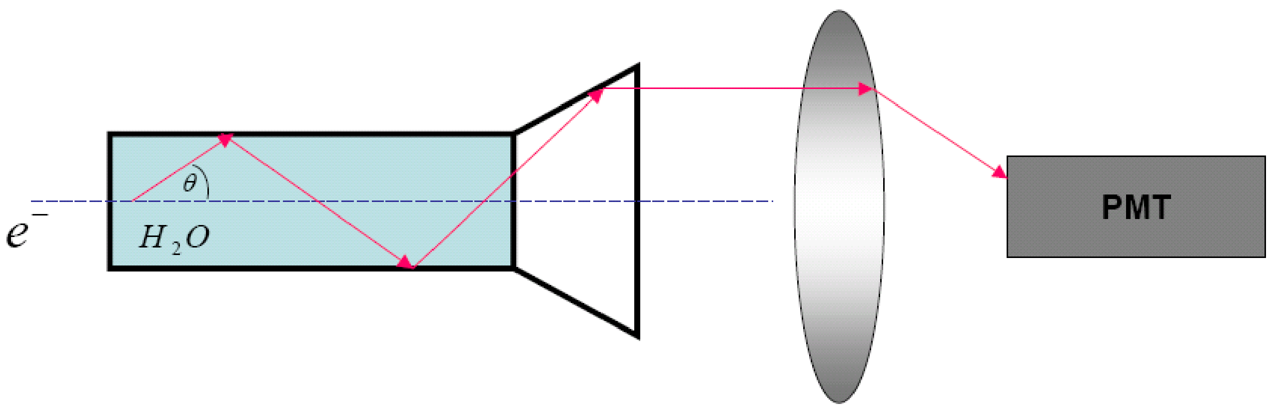
Θ_C measures the velocity of the particle !

PP: Tools – Detection techniques

Threshold Cherenkov Counter



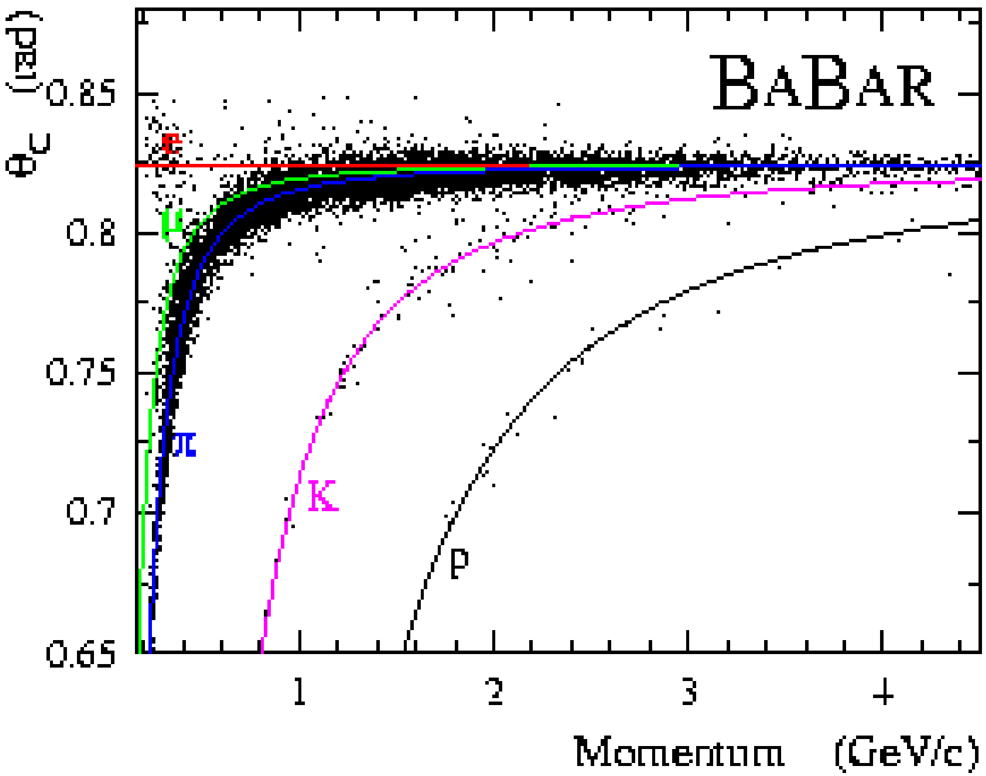
Cherenkov radiation → $\beta > \beta_{thr} = 1/n$



Optical system: combination of lenses and mirrors; collect all emitted light by PMT

PP: Tools – Detection techniques

Cherenkov radiation



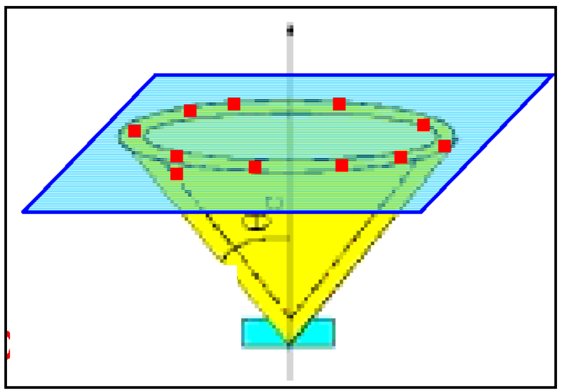
- For a given index of refraction (n) and a given particle (mass), the Cherenkov emission angle θ_c depends on the particle velocity (momentum)
- Below a threshold (θ_c ~ 0), no Cherenkov light is emitted at all (→ threshold C-detector)
- For a given momentum, the angle discriminates between particle species
- Determination of θ_c and knowledge of the particle mass gives its velocity

PP: Tools – Detection techniques

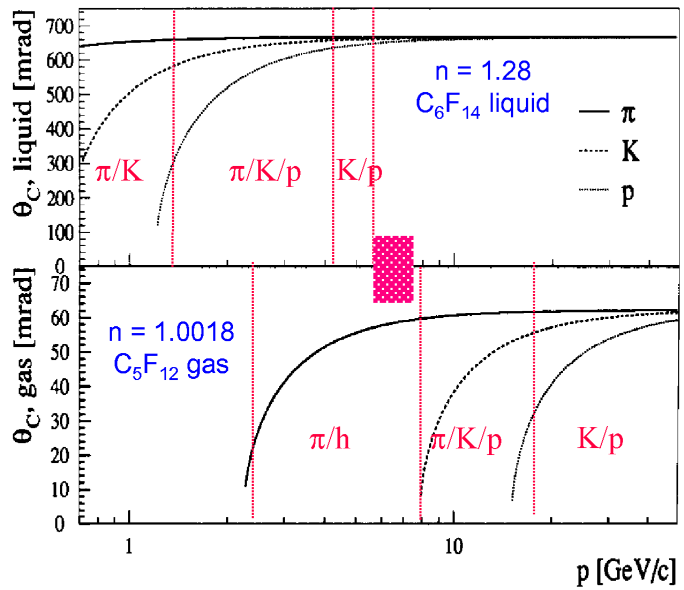
Ring Imaging Cherenkov Detectors (RICH)

- Determine θ_C by intersecting the Ĉ-cone with a photosensitive plane
- Requires large area detectors, e.g. MWPCs or PMT arrays
- Radius is a measure of θ_C

$$\theta_C = \arccos\left(\frac{1}{n\beta}\right) = \arccos\left(\frac{1}{n}\cdot\frac{E}{p}\right) = \arccos\left(\frac{1}{n}\cdot\frac{\sqrt{p^2+m^2}}{p}\right)$$



Ring tichkness determined by thickness of radiator (gass, liquid)



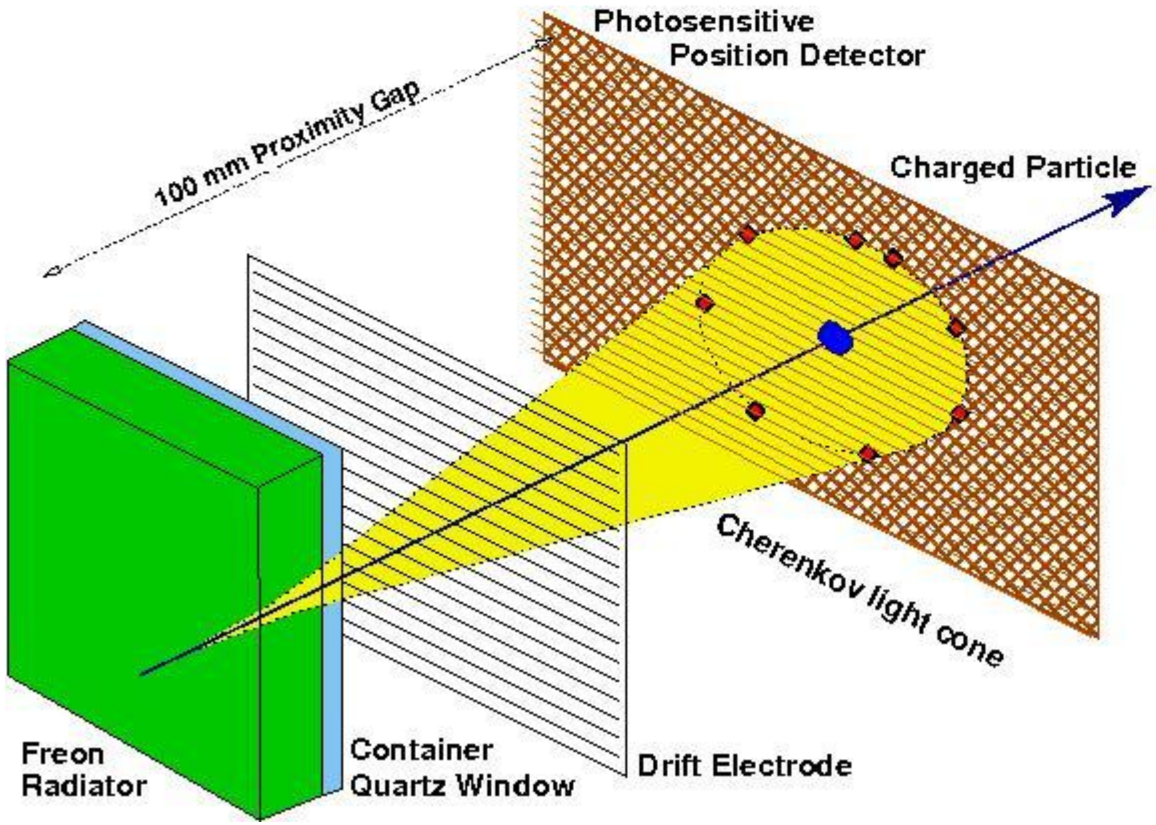
DELPHI

$$\frac{\sigma_\beta}{\beta} = \tan\theta \cdot \sigma_\theta$$

Detect N photons (p.e.) → $\sigma_\theta \approx \frac{\sigma_\theta^{p.e.}}{\sqrt{N_{p.e.}}}$ → minimize σ_θ → maximize $N_{p.e.}$

PP: Tools – Detection techniques

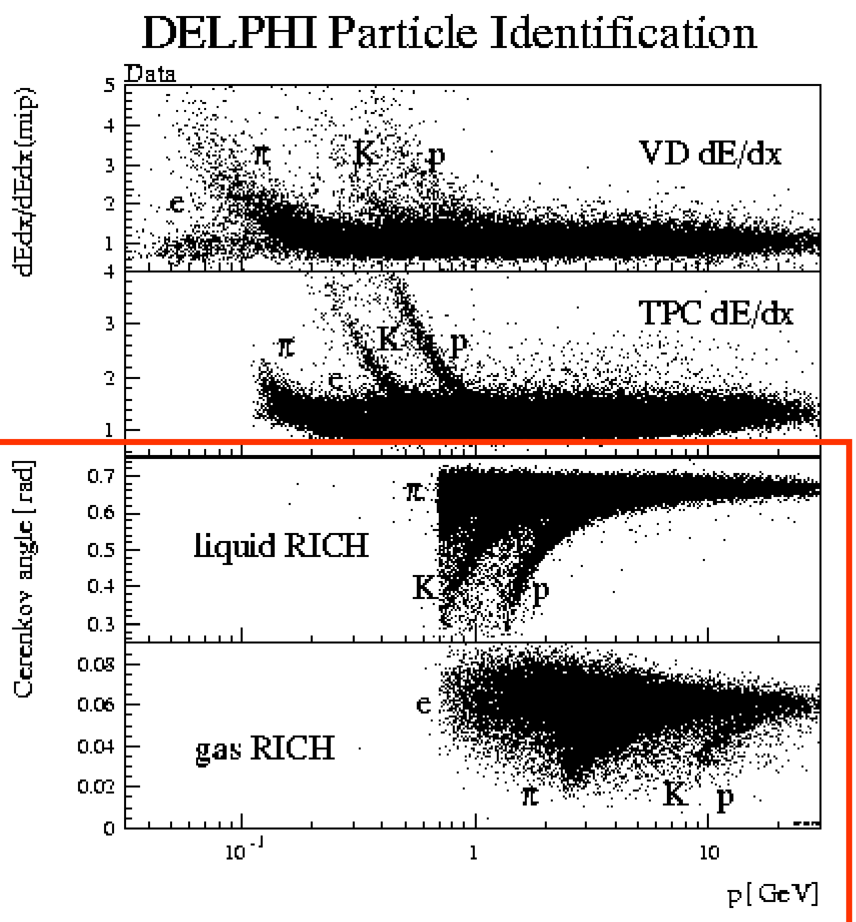
Cherenkov radiation (“RICH“)

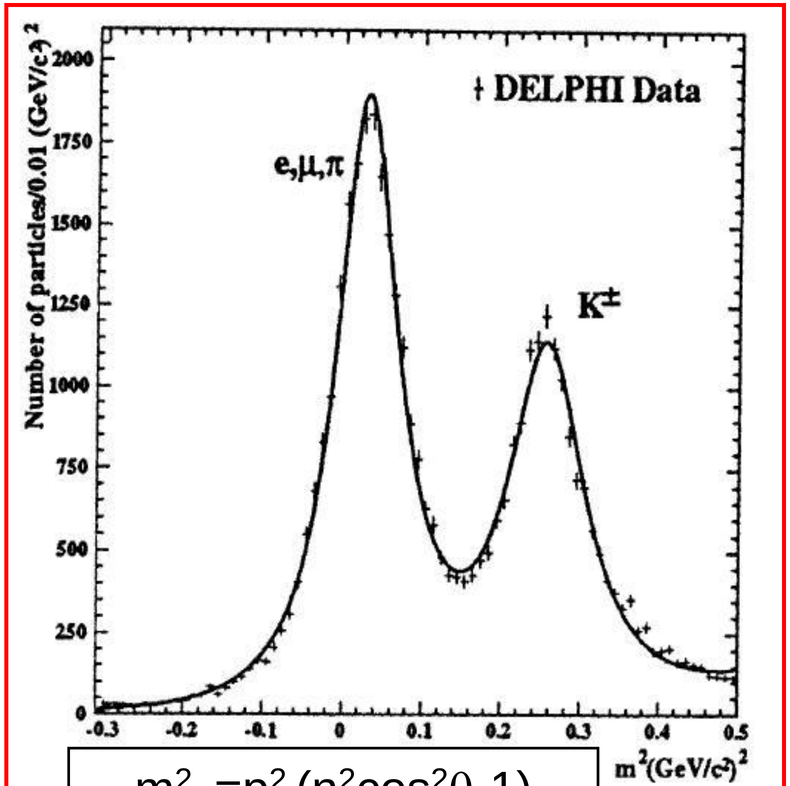


TWO main element: “radiator” and “photon detector”

PP: Tools – Detection techniques

Cherenkov radiation („RICH")

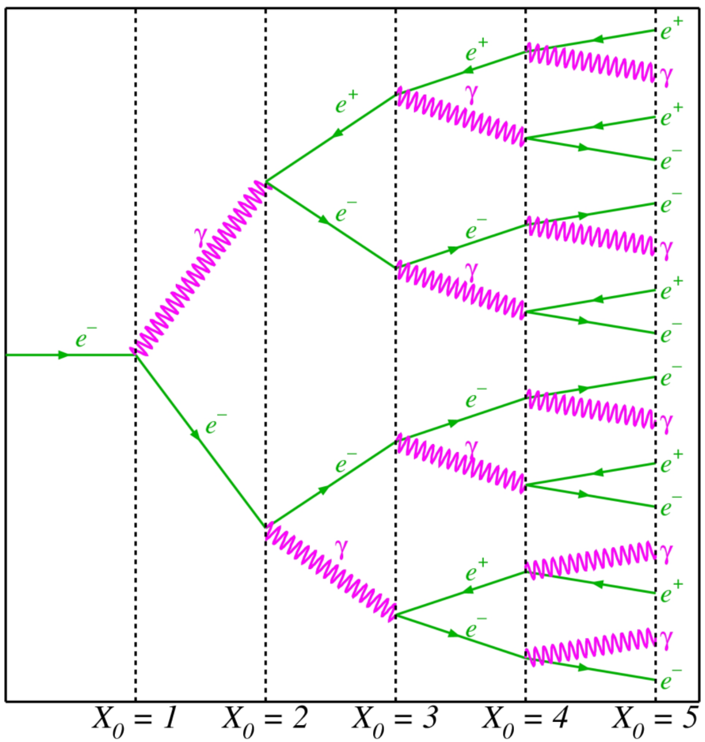




$$m^2 = p^2 (n^2 \cos^2\theta - 1)$$

PP: Tools – Detection techniques

Electromagnetic radiation



- When high-energy electrons interact with matter, only a small fraction of the energy is dissipated as a result of collision processes. A large fraction is spent in the production of high-energy photons (bremsstrahlung).

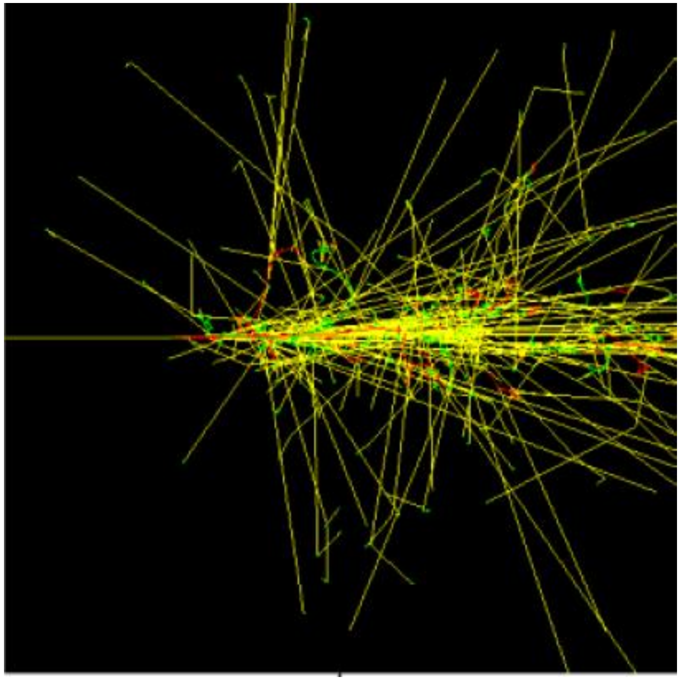
- These photons produce further electrons through pair production or Compton collisions. These new electrons radiate more photons, which in turn interact to produce more electrons:

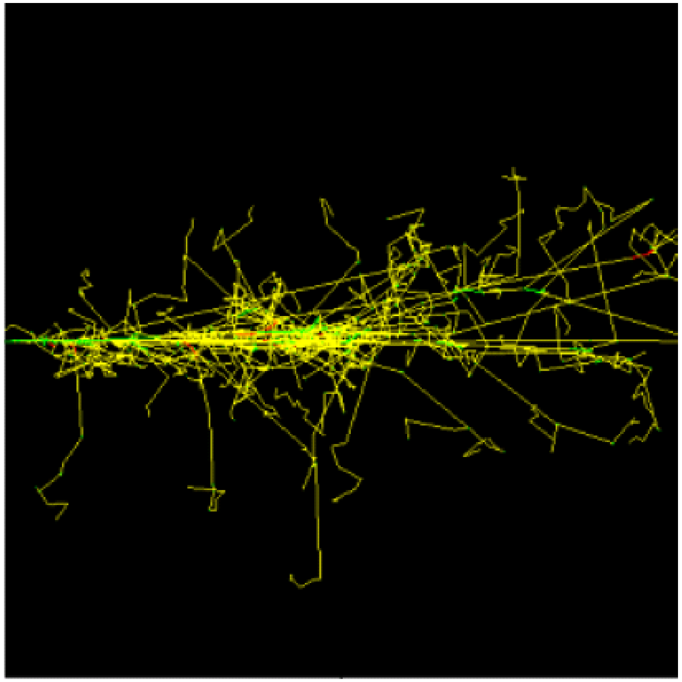
  "electromagnetic shower"

Electromagnetic shower

PP: Tools – Detection techniques

Electromagnetic radiation

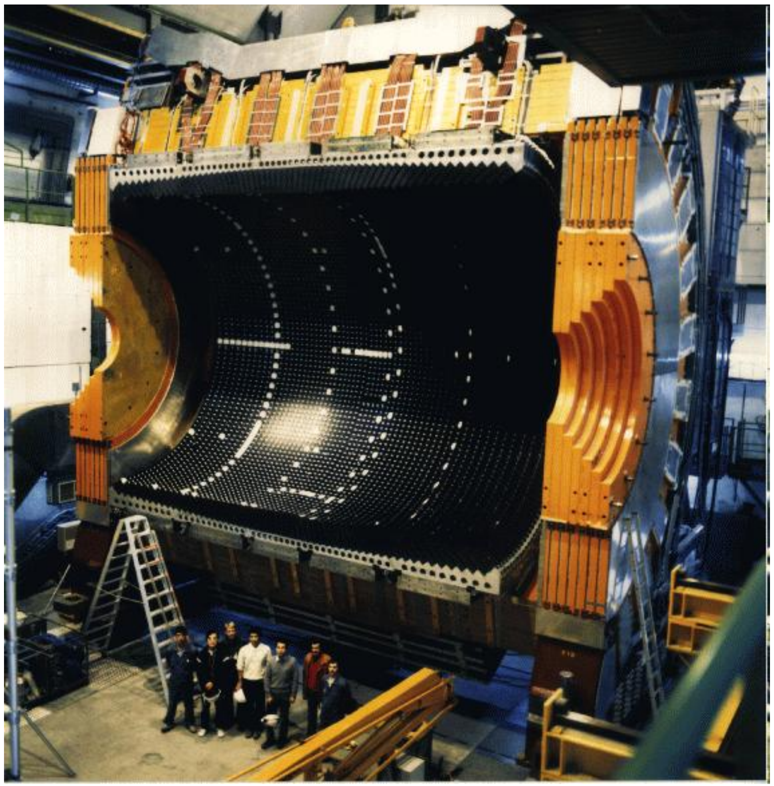


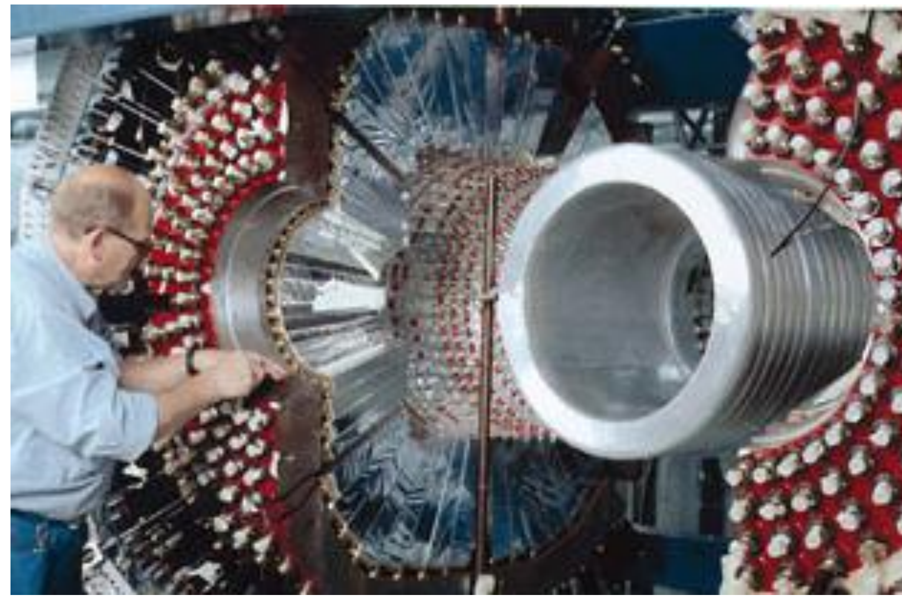


Simulations (1 GeV)
Photon, Electron

PP: Tools – Detection techniques

Electromagnetic radiation





WASA (COSY Jülich)

Electromagnetic calorimeter: measure of total energy

PP: Tools – Detection techniques

Detectors

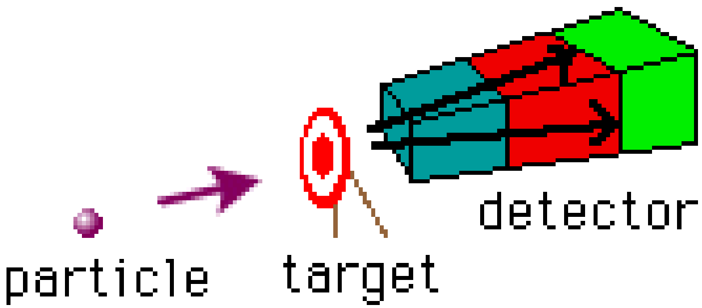
Detector-Type:

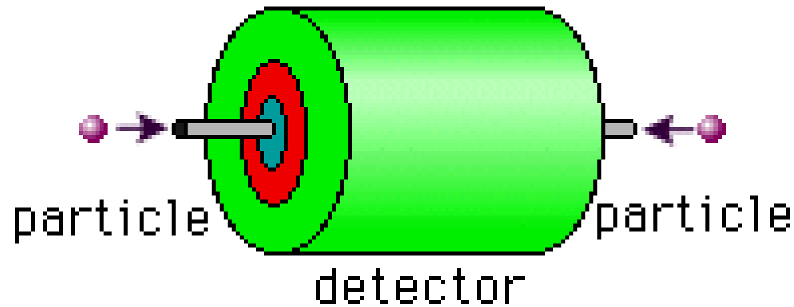
- Gas-detector (DC, PC, MWPC, TPC, …)
- Semiconductor-detector (Si, Ge)
- Scintillator-detector (organic, anorganic)
- Cherenkov-detector (threshold, RICH, DIRC)
- Transition radiation-detector
- …

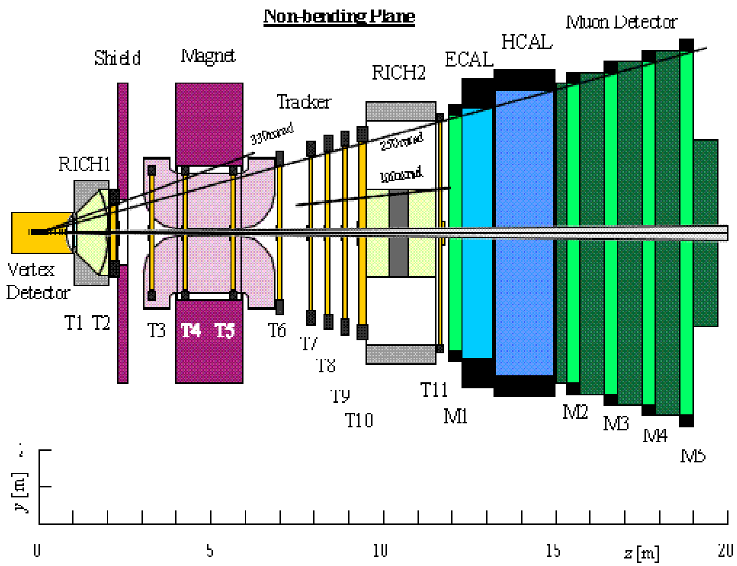
→ usually different detector(-type)s are needed !

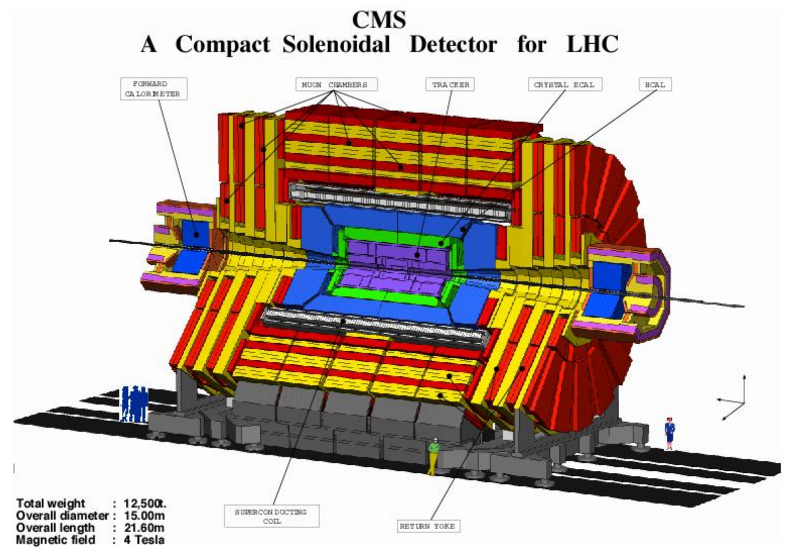
PP: Tools – Detection techniques

Fixed target, collider detectors



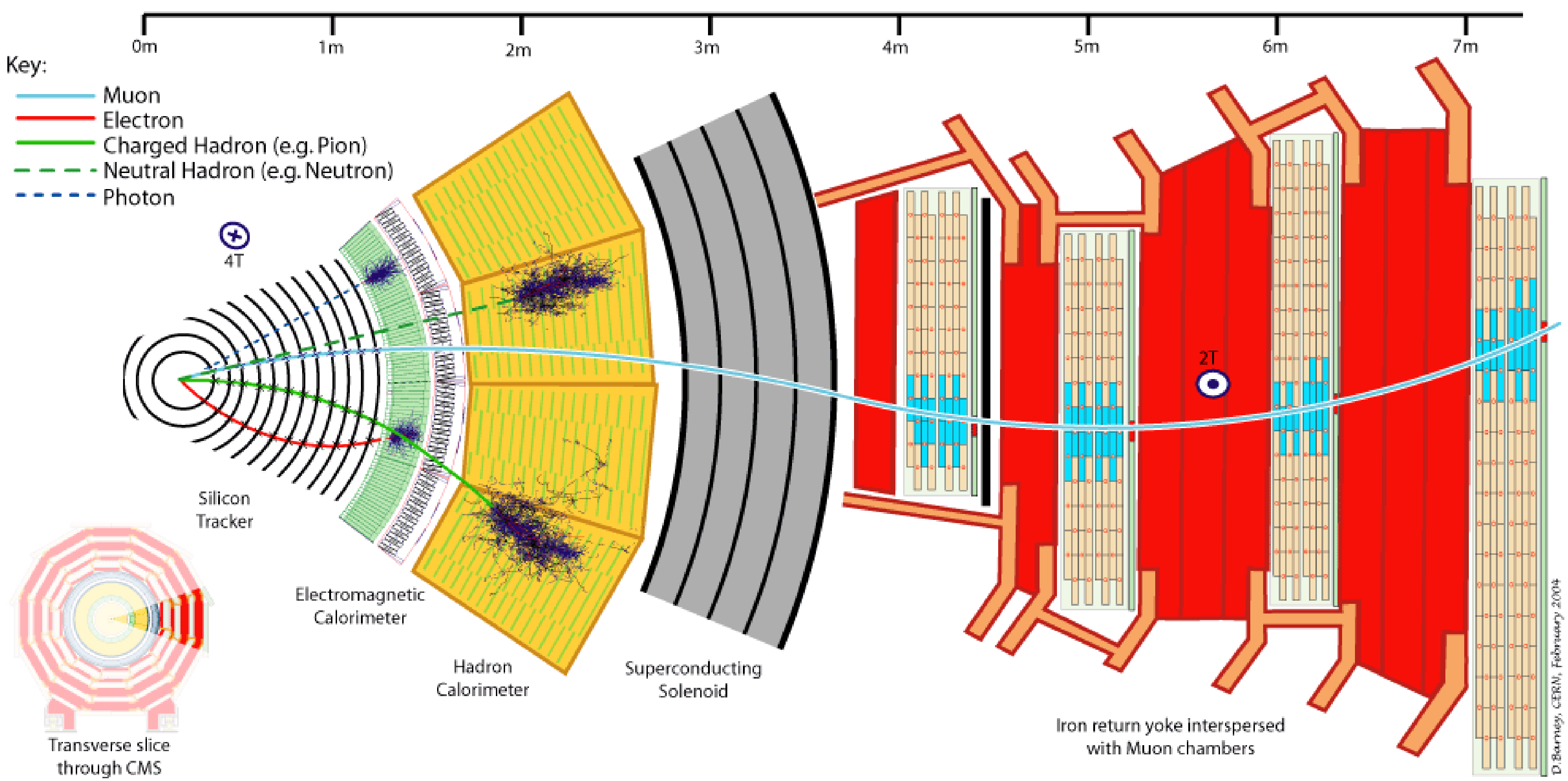






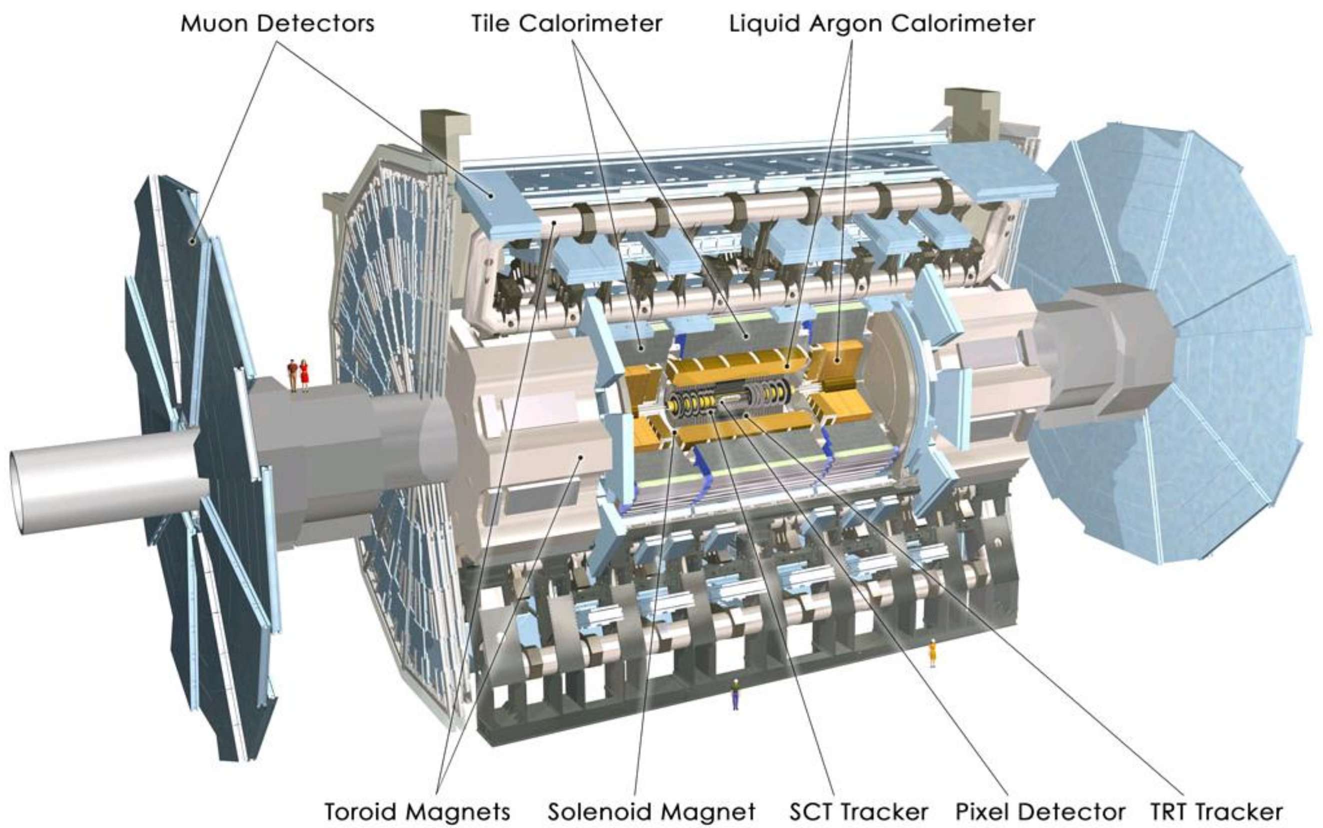
PP: Tools – Detection techniques

A collection of detectors (CMS)



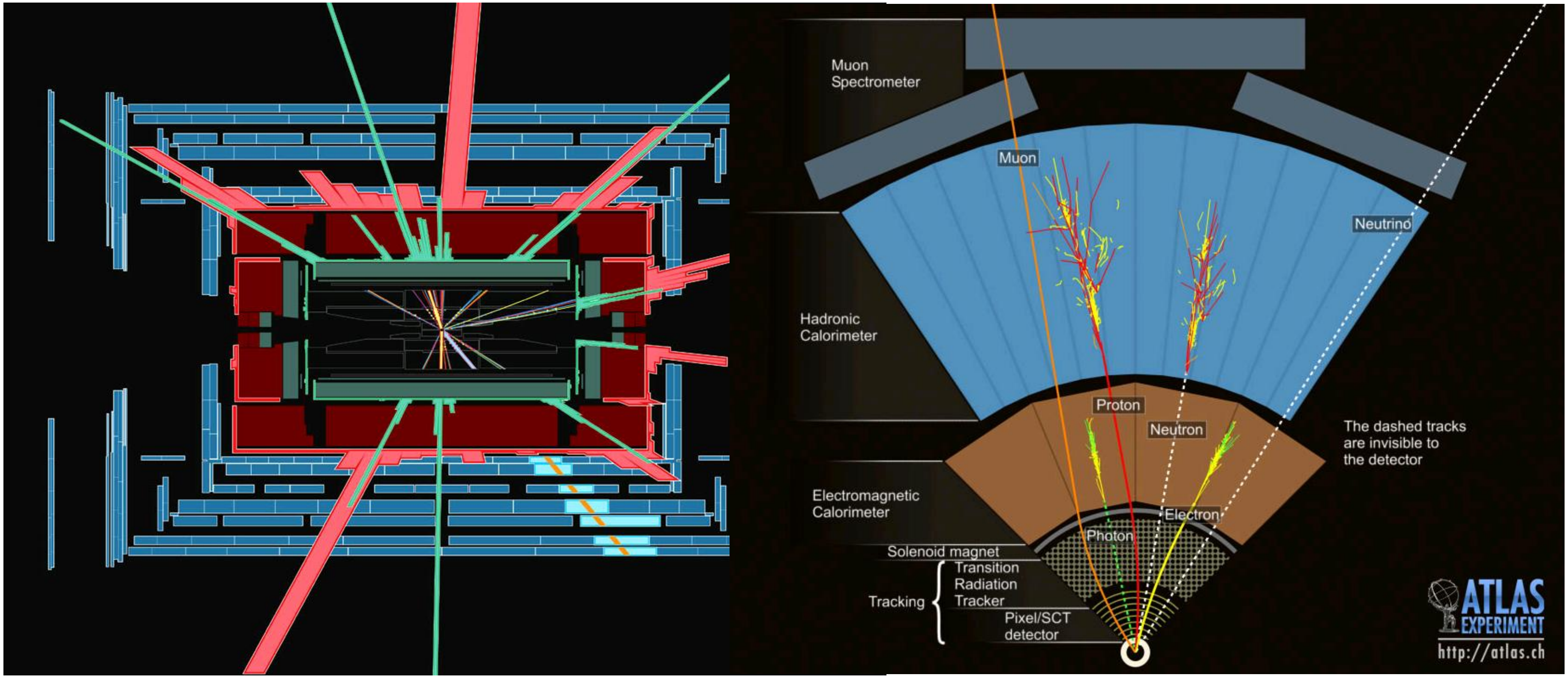
PP: Tools – Detection techniques

A collection of detectors (ATLAS)



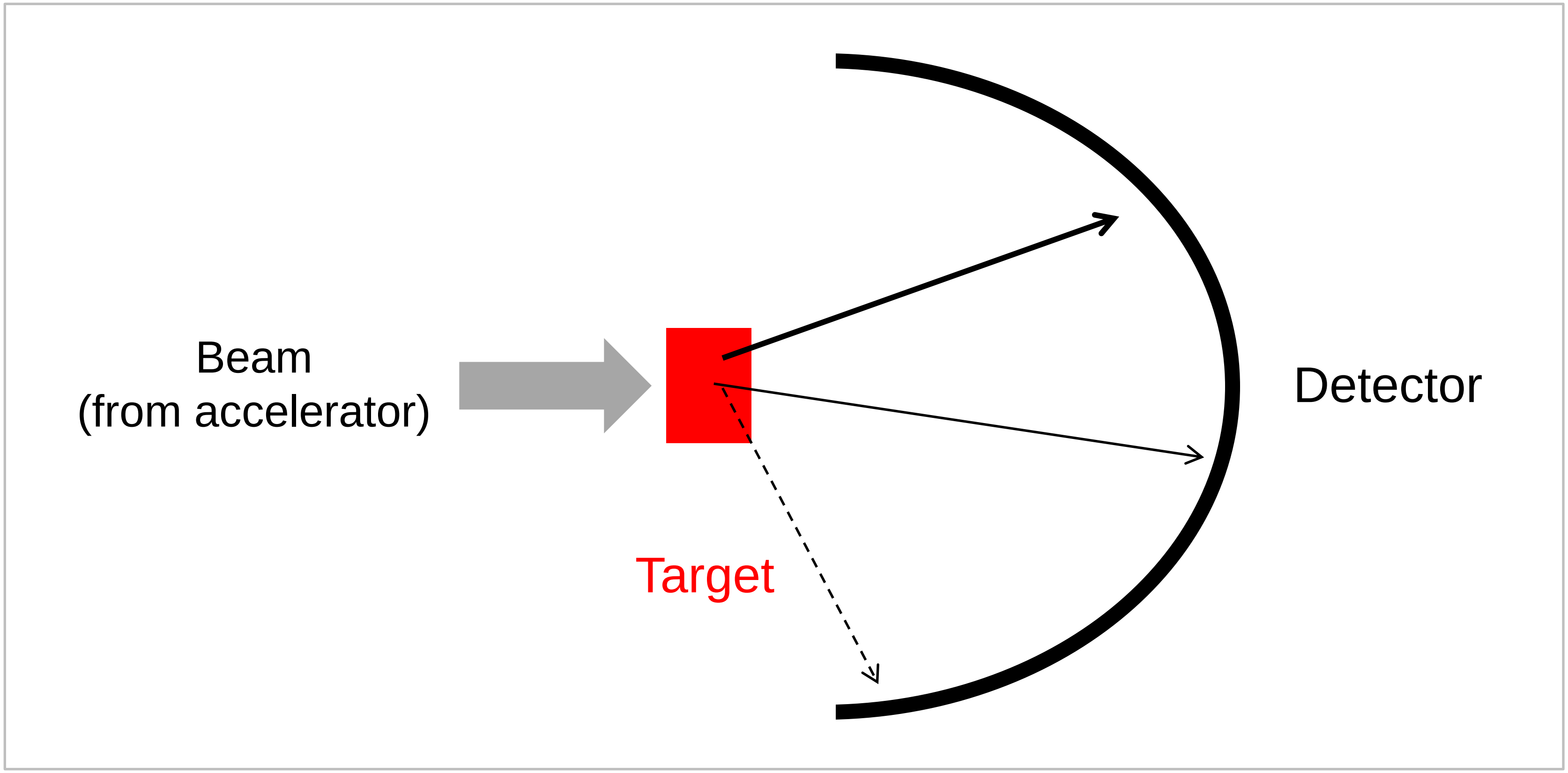
PP: Tools – Detection techniques

A collection of detectors (ATLAS)



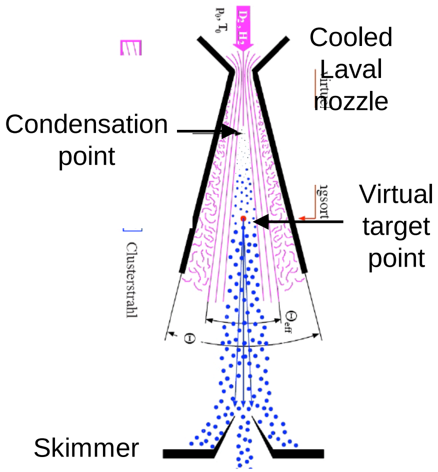
PP: Tools – Targets

Generic experimental set-up:

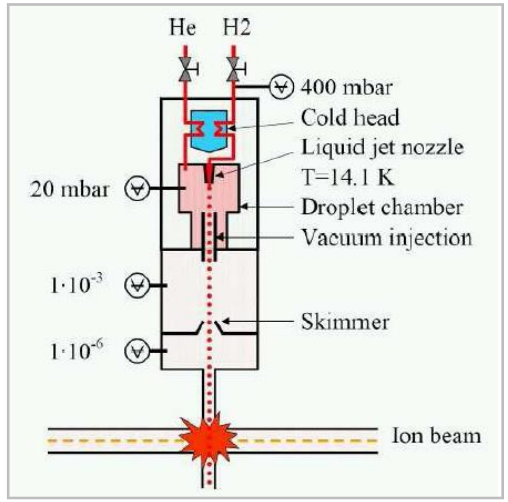


→ important issue: selection/design/operation … of target

PP: Tools – Targets



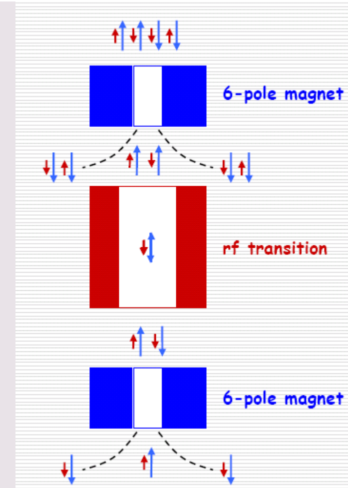
Cluster jet



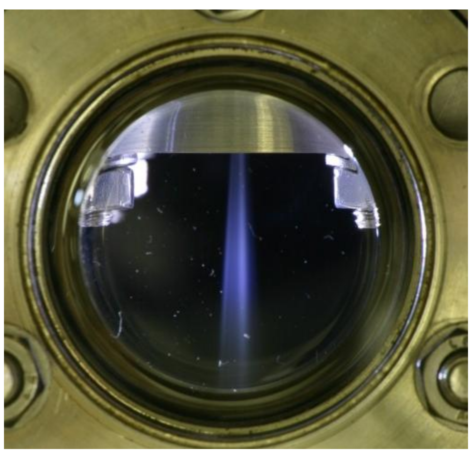
Pellet

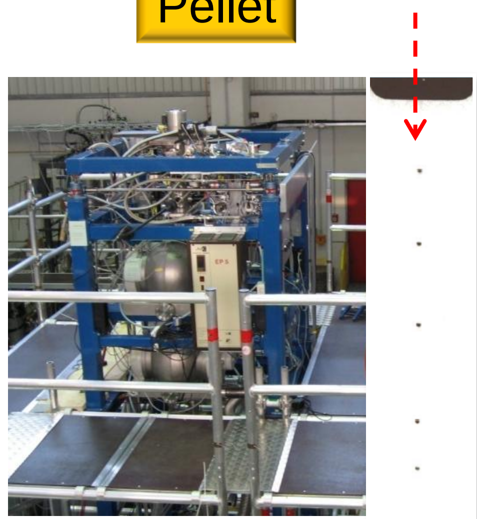
Operation principle:

Focussing and defocussing of hydrogen or deuterium hyperfine states



Polarized (ABS)





PP: Tools – Summary

- Silicon Vertex Tracker (SVT) - precise position information on charged tracks
- Drift Chamber (DCH) - the main momentum measurements for charged particles and helps in particle identification through dE/dx measurements
- Detector of Internally Refected Cerenkov radiation (DIRC or DRC) - charged hadron identification
- Electromagnetic Calorimeter (EMC) - particle identification for electrons, neutral electromagnetic particles, and hadrons
- Solenoid (not a subdetector) – high magnetic field for needed for charge and momentum measurements
- ***and more …***

PP: Tools – The End

Examples of combined detection systems:

NEXT Lecture ☺