Muon detection

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Particle detection

Study the particles (mass, chargeS, interactions…)

Use them (identity, time, momentum, trajectory)

- detect as precisely as possible, if possible without interfering with the particle
- use an interaction strong enough to "see" a maximum of particles and weak enough to conserve their characteristics (energy, momenta)

➡ Best choice: electromagnetic interactions

Charged particle interaction with matter

- inelastic collision with the electrons (the most frequent)
  - electron changes its orbit: atom excitation
  - electron ejected (ionisation)
  - electron ejected with lots of energy and can continue to ionise the medium: δ ray

- elastic collision with the nuclei

  ➥ energy loss and deflection

- quantum processes : statistical fluctuation though weak on macroscopic distances

- mean energy loss per length unit $\frac{dE}{dx}$

$$\frac{dE}{dx} = -4\pi r_e^2 m_e c^2 z^2 \frac{N_A Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I\sqrt{1+\epsilon}} - \beta^2 - \frac{\delta}{2} \right]$$

Ionisation : creation of positive ions and electrons in the medium ➥ the free charges (current) can be used to detect the particles

Spatial resolution & digital detectors

- Detector segmentation : if the position of the detector element is known, gives the particle position

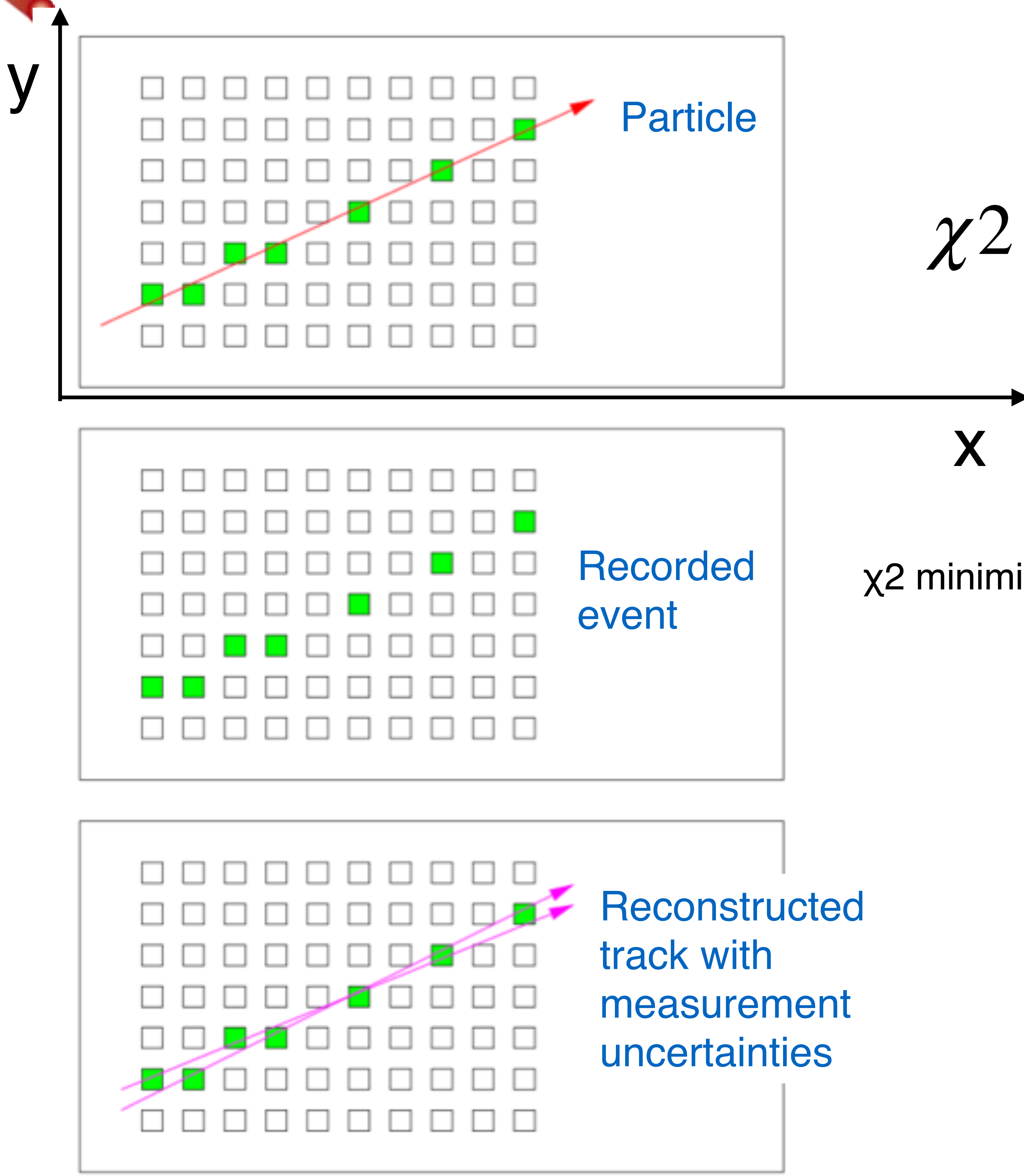
- Digital readout : yes/no response to the particle passing through

- Multiplicity : number of detector elements responding to the particle passing through

- Example of resolution in digital readout for a detector element of size L and multiplicity 1 (no charge sharing between neighbour detector elements)
  - true position: uniform between (x-L/2, x+L/2)
  - measured position: X
  - uncertainty on position: (-L/2, L/2)
  - resolution: L/sqrt(12)

$$\sigma_x^2 = \int_{-L/2}^{L/2} (< x^2 > - < x >^2) dx = \int_{-L/2}^{L/2} < x^2 > dx = \frac{1}{L} \int_{-L/2}^{L/2} x^2 dx = \frac{L^2}{12}$$

From position to trajectory



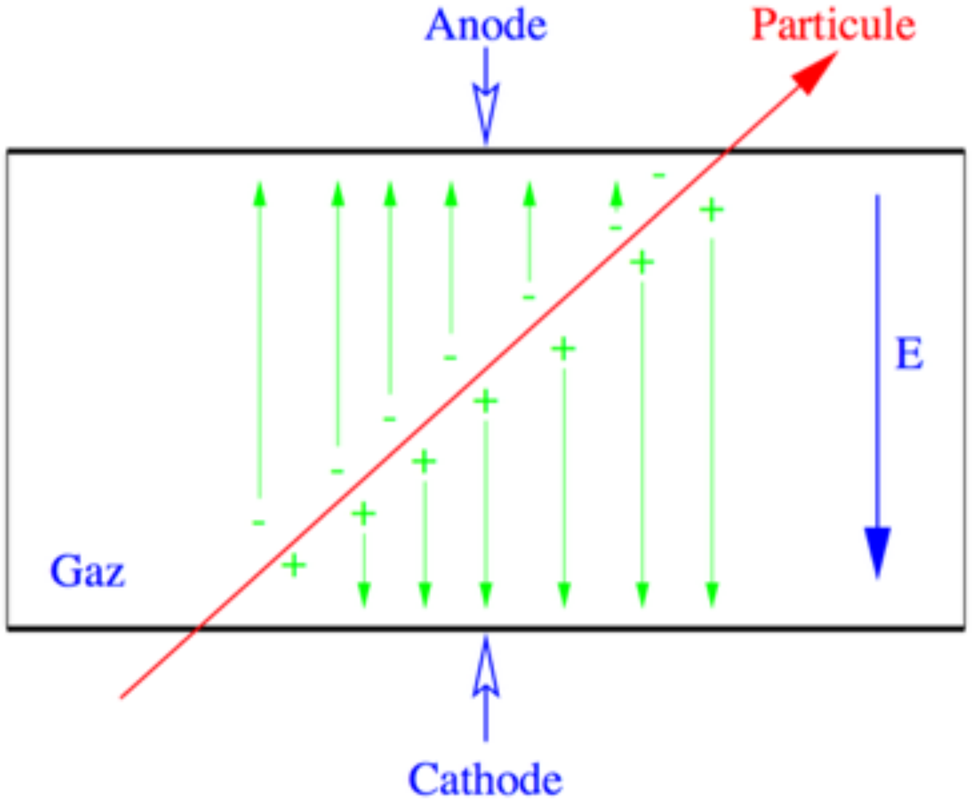
$$\chi 2 = \sum_1 \frac{(yi - axi - b)2}{\sigma y2}$$

$\chi 2$ minimisation -> trajectory (a & b parameters)

Gas detectors: basics ...

W= mean energy to create a electron/ion pair
(~ 30 eV)

Gaz	*Ionisation (eV)*	*W (eV)*
H_2	15	37
He	25	41
N_2	16	35
O_2	12	31
Ne	22	36
Ar	16	26
Kr	14	24
Xe	12	22
CO_2	14	33
CH_4	13	28



Drift velocity:

$v = \mu \frac{E}{P}$ $\mu(\text{électron}) \sim 1\ \text{m}^2.\text{V}^{-1}.\text{s}^{-1}.\text{atm} \sim 1000\mu(\text{ion})$

$v \sim 10^4\ \text{m/s}$ for 10kV/m and atmospheric pressure

~ 1 µs to collect the charges over 1 cm …

Discovery: Anderson & Neddermeyer, 1936

Phys. Rev. 50 (1936) 263

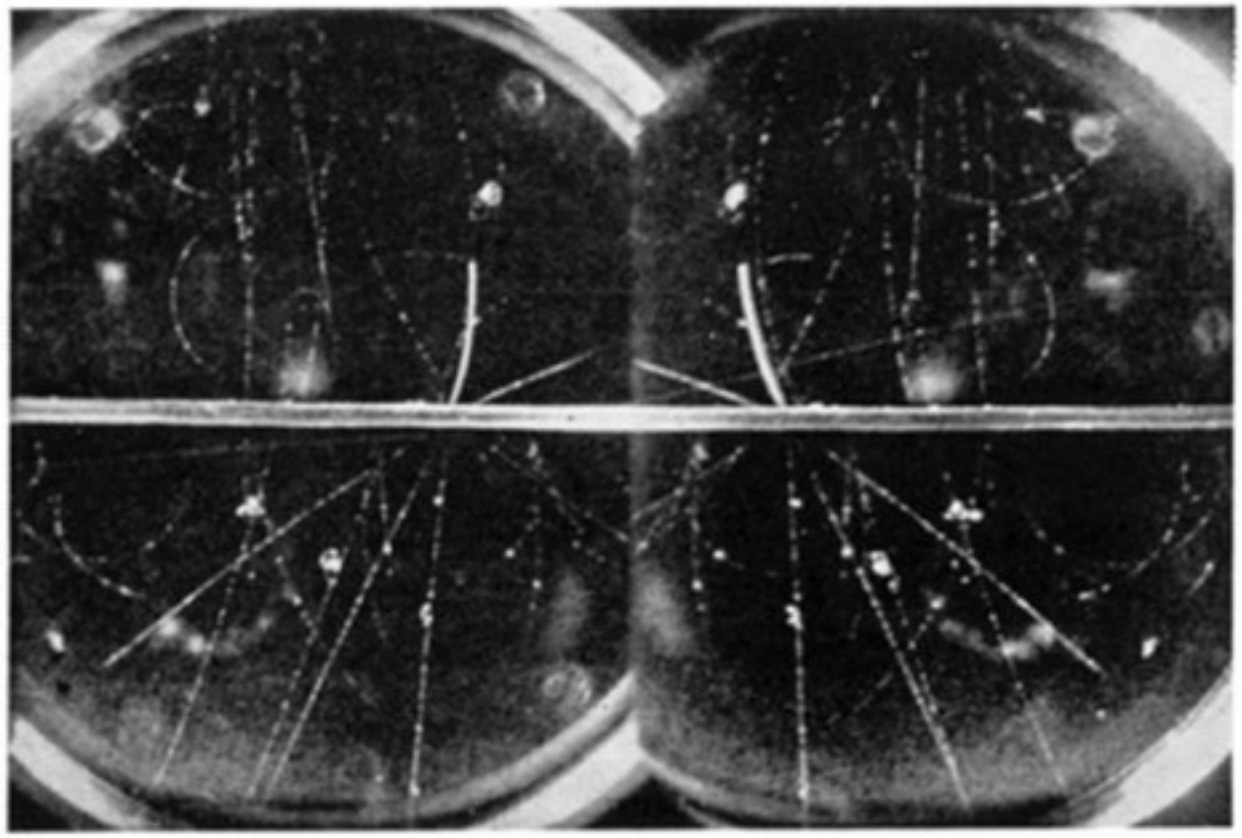


FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple scattering of low energy protons in argon it is difficult to

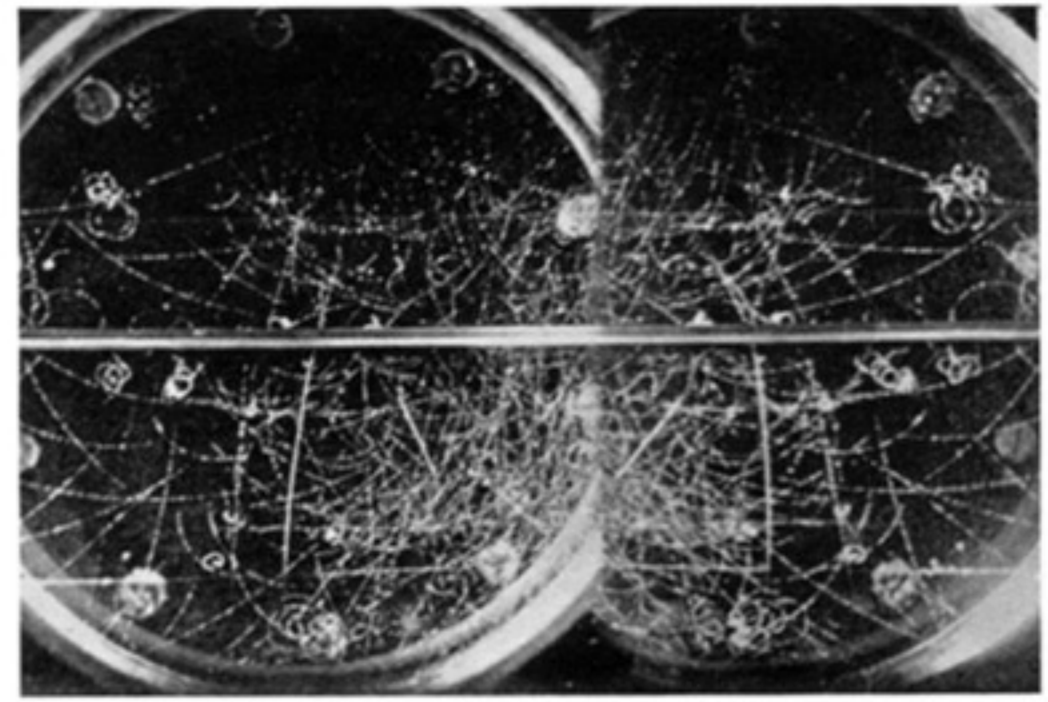
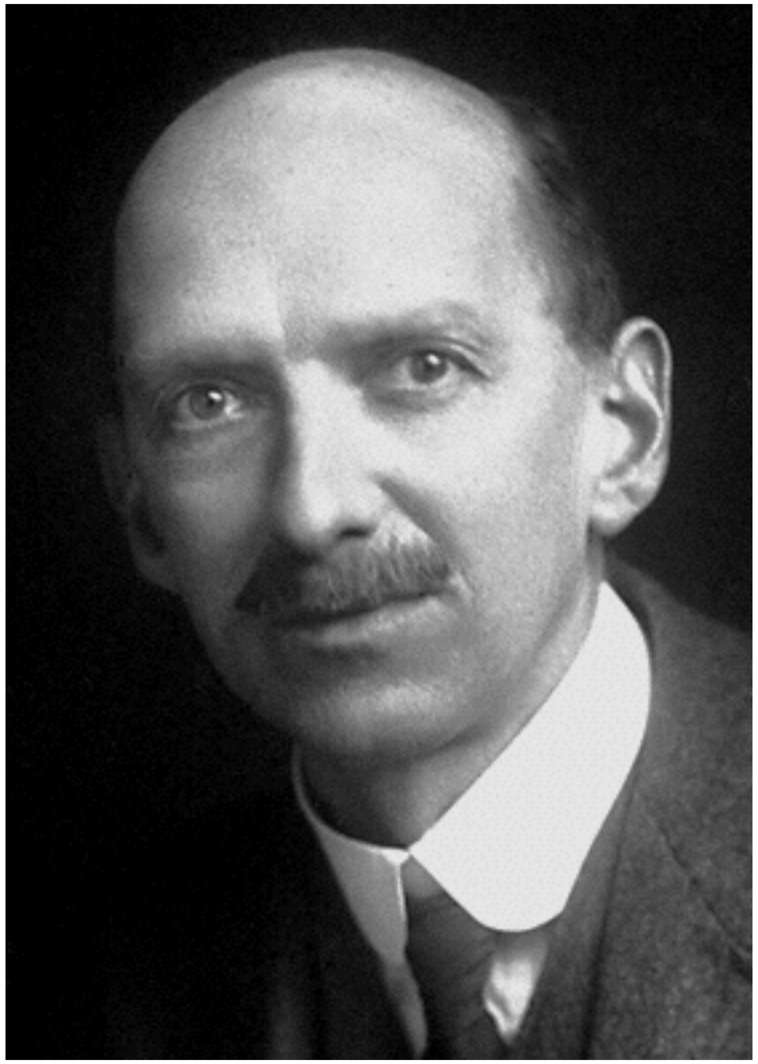
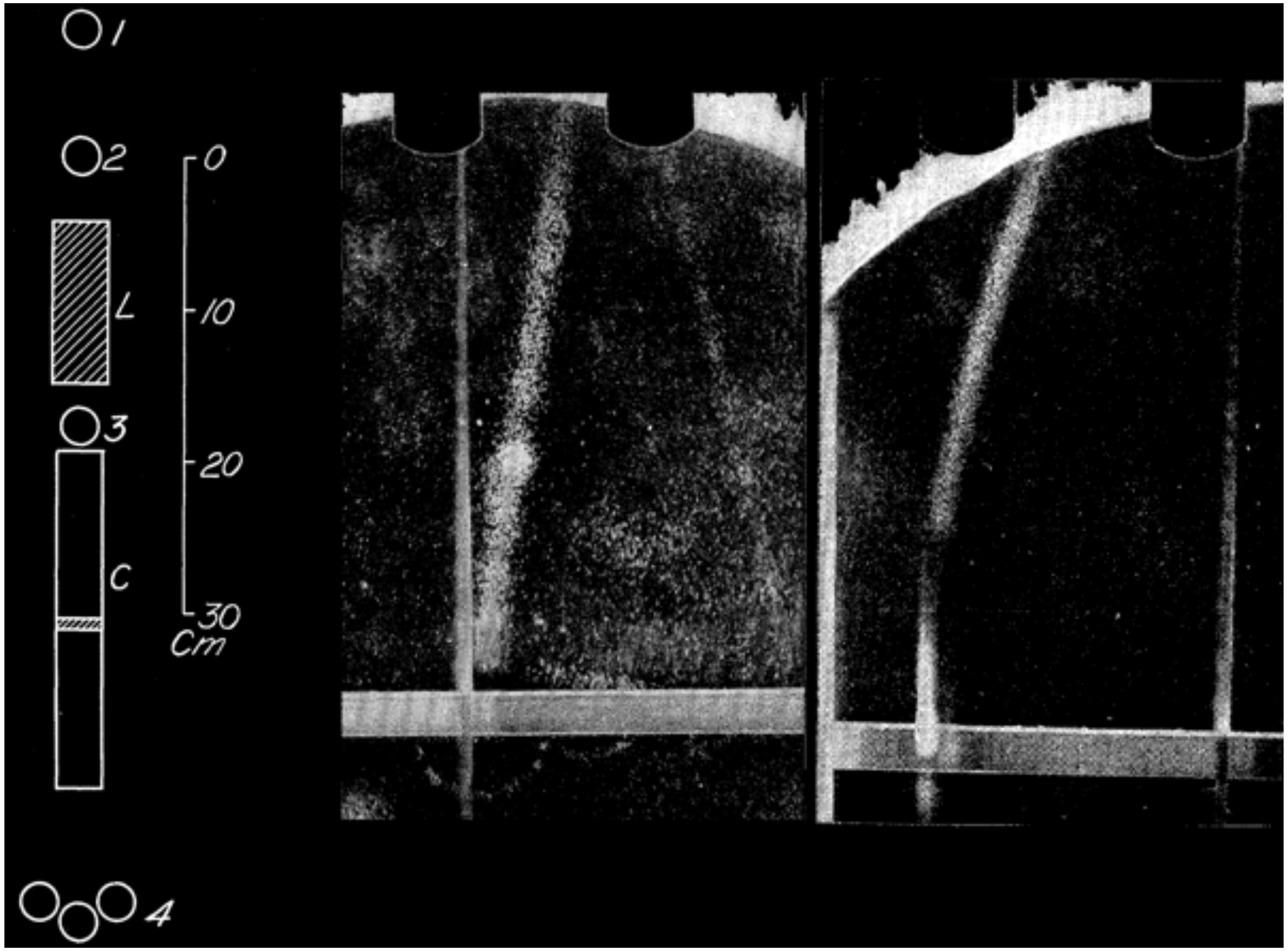


FIG. 13. Pasadena, 4500 gauss. A complex electron shower not clearly defined in direction, and three heavy particles with specific ionizations definitely greater than that of electrons. The sign of charge of two of these heavy particles represented by short tracks cannot be determined, but the assumption that they represent protons is consistent with the information supplied by the photograph. The third heavy track appears above the 0.35 cm lead plate where it has a specific ionization not noticeably different from that of an electron. It penetrates the lead plate and appears in the lower half of the chamber as a nearly vertical track near the middle. Below the plate it shows a greater ionization than an electron, and is deviated in the magnetic field to indicate a positively charged particle. Its $H\rho$ is apparently at most 1.4×10^5 gauss cm, which corresponds to a proton energy of 1 MEV and a range of only 2 cm in the chamber, whereas the observed range is greater than 5 cm. A difficulty of the same nature was discussed in the description of the previous photograph.

Cloud chamber (C. Wilson, 1895, 1896)

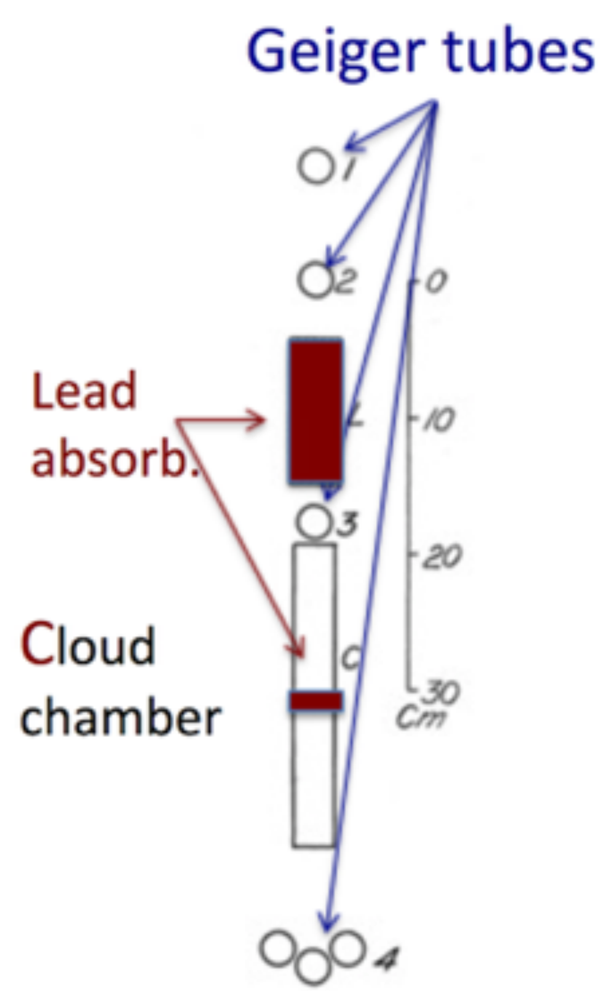


Mass: Steve & Stevenson, 1937



The first to measure simultaneously the momentum and the ionisation density :

- cloud chamber triggered by anti-coincident Geiger counters in order to increase the observation of the slowed down tracks
- B=3500 G
- expansions shifted by 1 s in order to allow the droplets to diffuse and be counted.

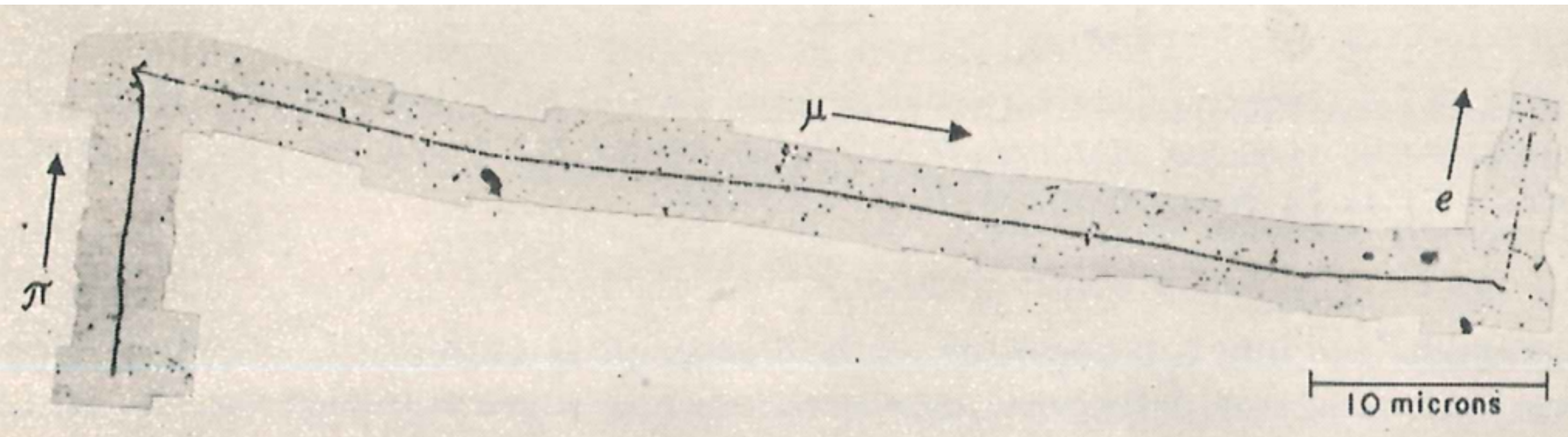


In these experiments already two types of muon detectors :

- Cloud chamber (Precision tracking)
- Geiger tubes (Trigger & veto)

1948: Kodak highly sensitive emulsions

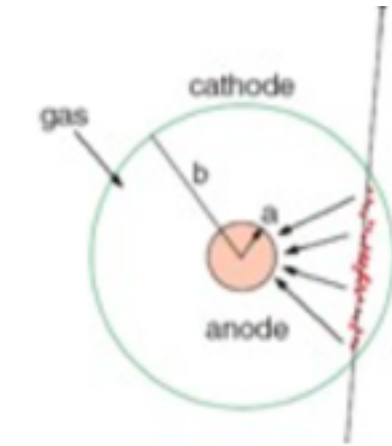
1949: Powell detects the pion and μ decay



Geiger Muller counter (1928)

- Tube filled with inert gas + organic vapour
- High voltage between wire and tube
- Central thin wire (20 – 50 µm)

$$E(r) = \frac{1}{r}\frac{V}{\ln(R_c/R_a)}$$



- Charged particle ionizes the gas, the electrons move to towards the anode wire, the ions towards the tube wall.
- Strong increase of the field close to the wire
- When E>10 kV/cm the electrons start ionizing themselves the gas, leading to an electron avalanche and a measurable signal on the wire
- The organic substances act as "quencher"

Signal amplification through avalanche if electric field > 1 MV/m

Nb of electrons /dx : $dn = n\alpha dx$, with α = Townsend coefficient. Typically 10^4

@ Joerg Wotschack

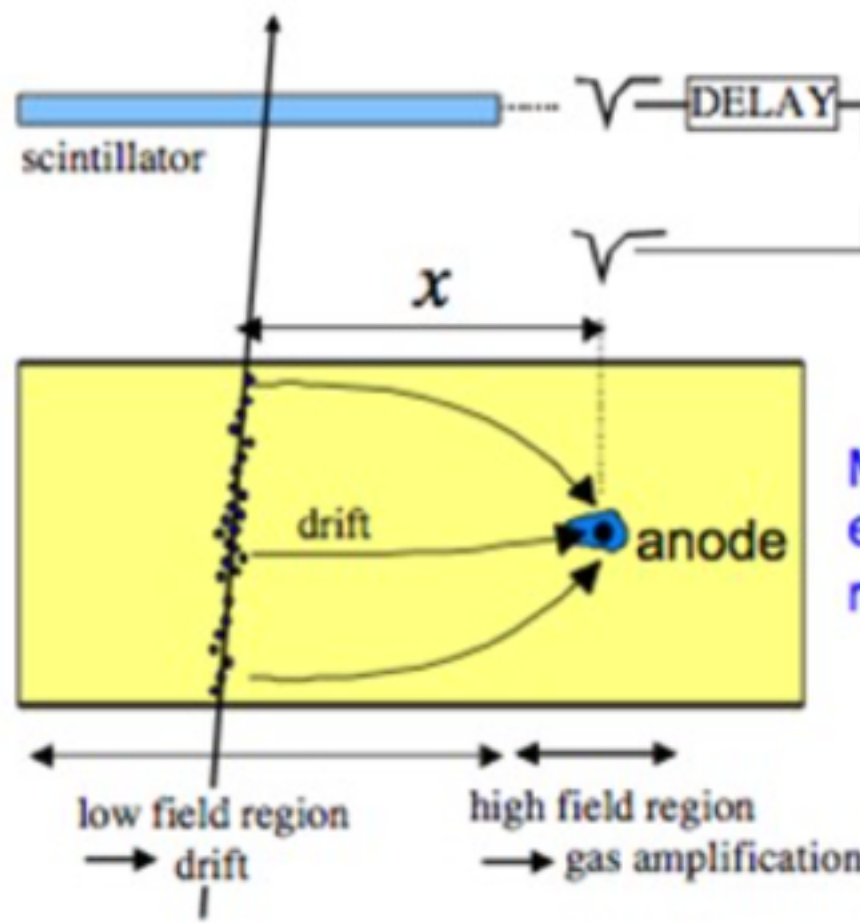
Position detection : trackers : drift chambers

A natural evolution of the MWPC was the drift chamber, it solved a number of shortfalls of the MWPCs.

First studies: T. Bressani, G. Charpak, D. Rahm, C. Zupancic (1969)

First operation of a drift chamber: A.H. Walenta, J. Heintze, B. Schürlein (NIM 92 (1971) 373)

- By measuring the arrival time of the signals on the wire the distance between track and wire is determined
- Using this technique spatial resolutions much below 100 μm have been achieved
- At the same time the number of wires in a drift chamber is drastically reduced compared to a MWPC
- Drift distances can extend to several cm;

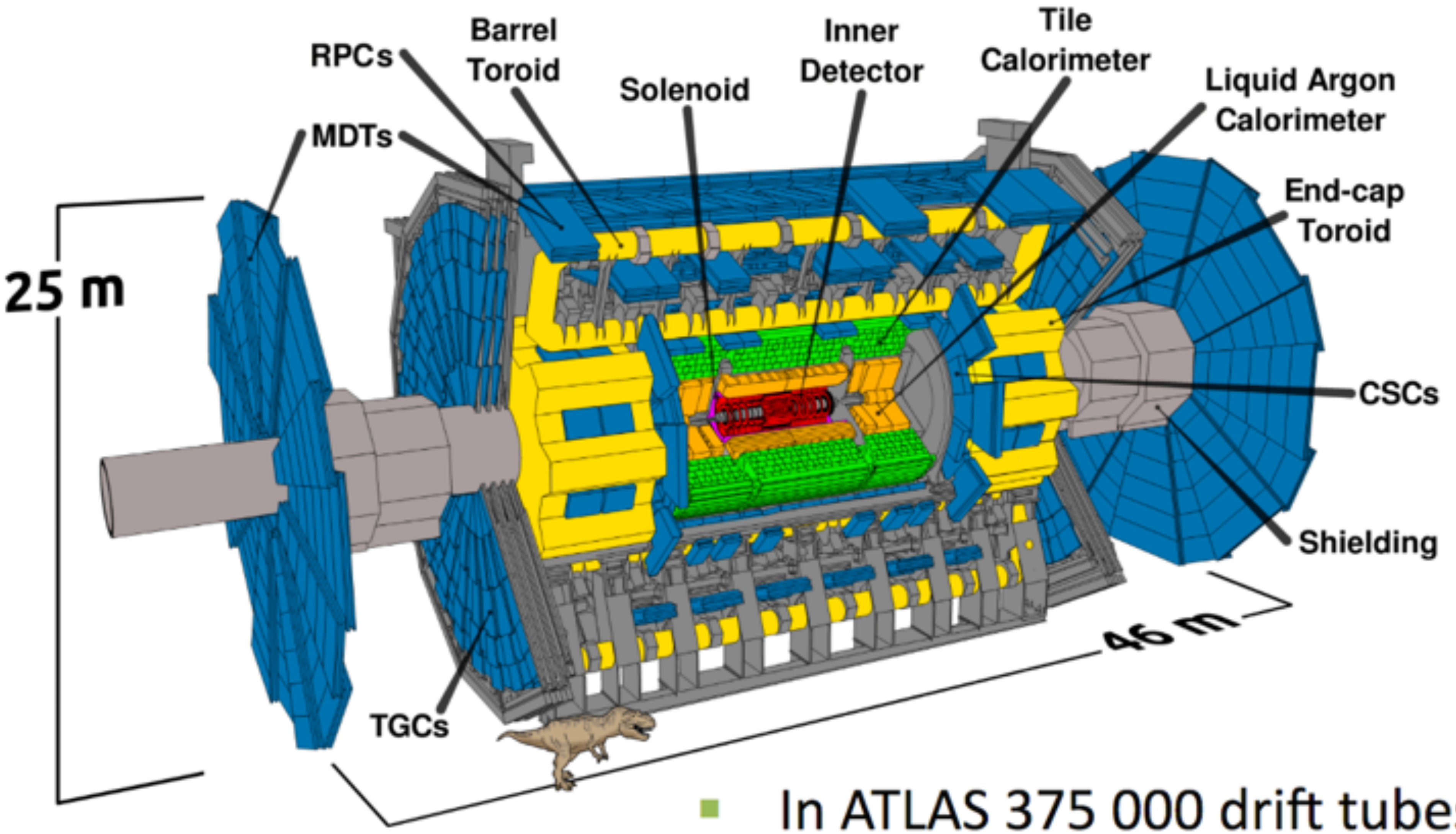


Measure arrival time of electrons at sense wire relative to a time t_0.

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

@ Joerg Wotschack

ATLAS : drift chambers

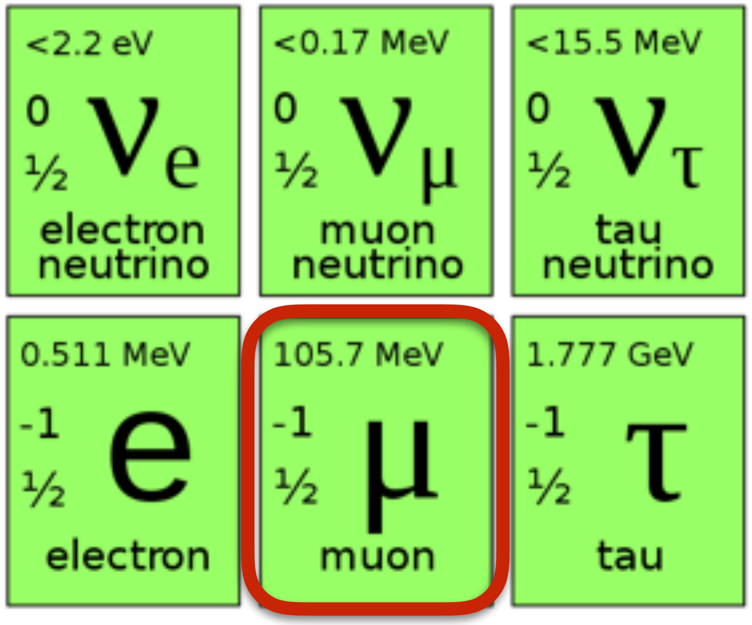


- In ATLAS 375 000 drift tubes are used as precision muon detectors, arranged in 1200 chambers, each consisting of 6 or 8 tube layers.
- They cover an area of about 5500 m^2.
- The largest chambers employ drift tubes of >7 m length.

ATLAS : a sector of drift chambers

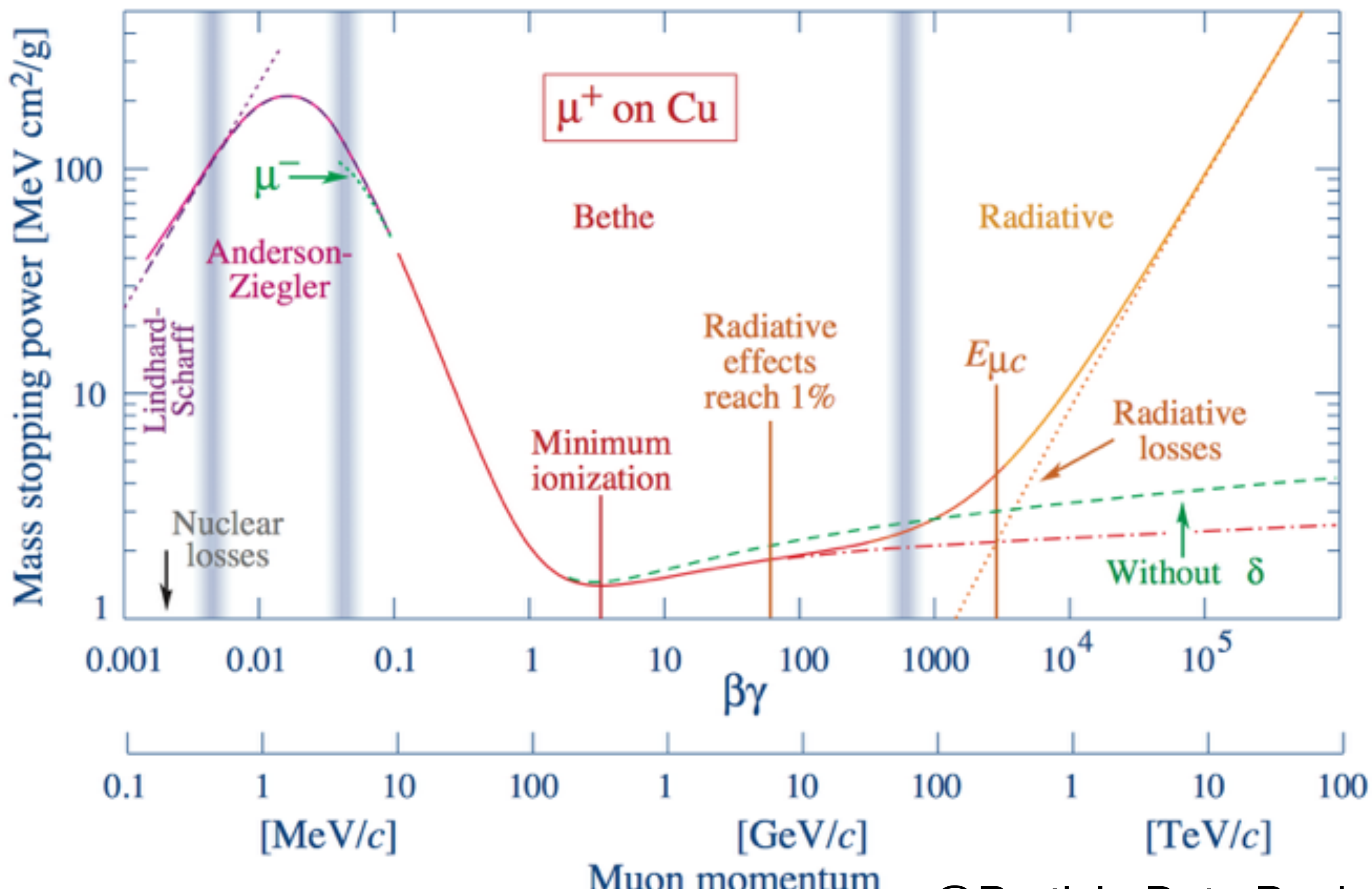
30 mm tubes …

Muons: Id card



$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$, $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

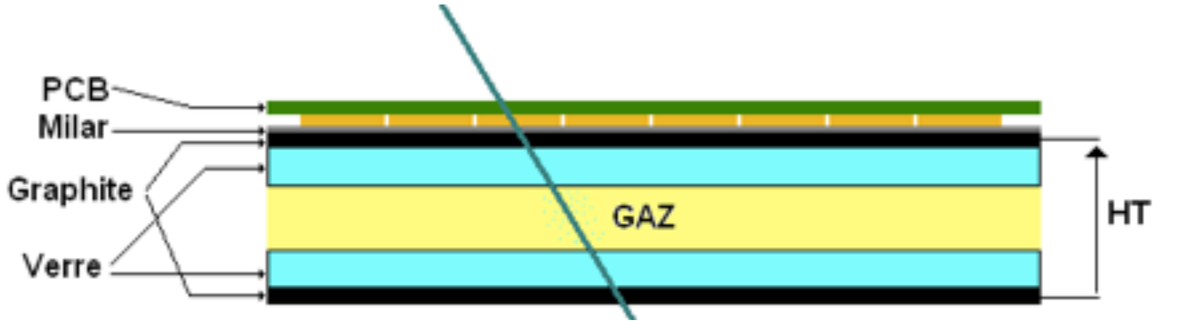
$\tau_\mu = 2.197\ \mu s$



pdg.lbl.gov/2013/listings/rpp2013-list-muon.pdf

@Particle Data Book

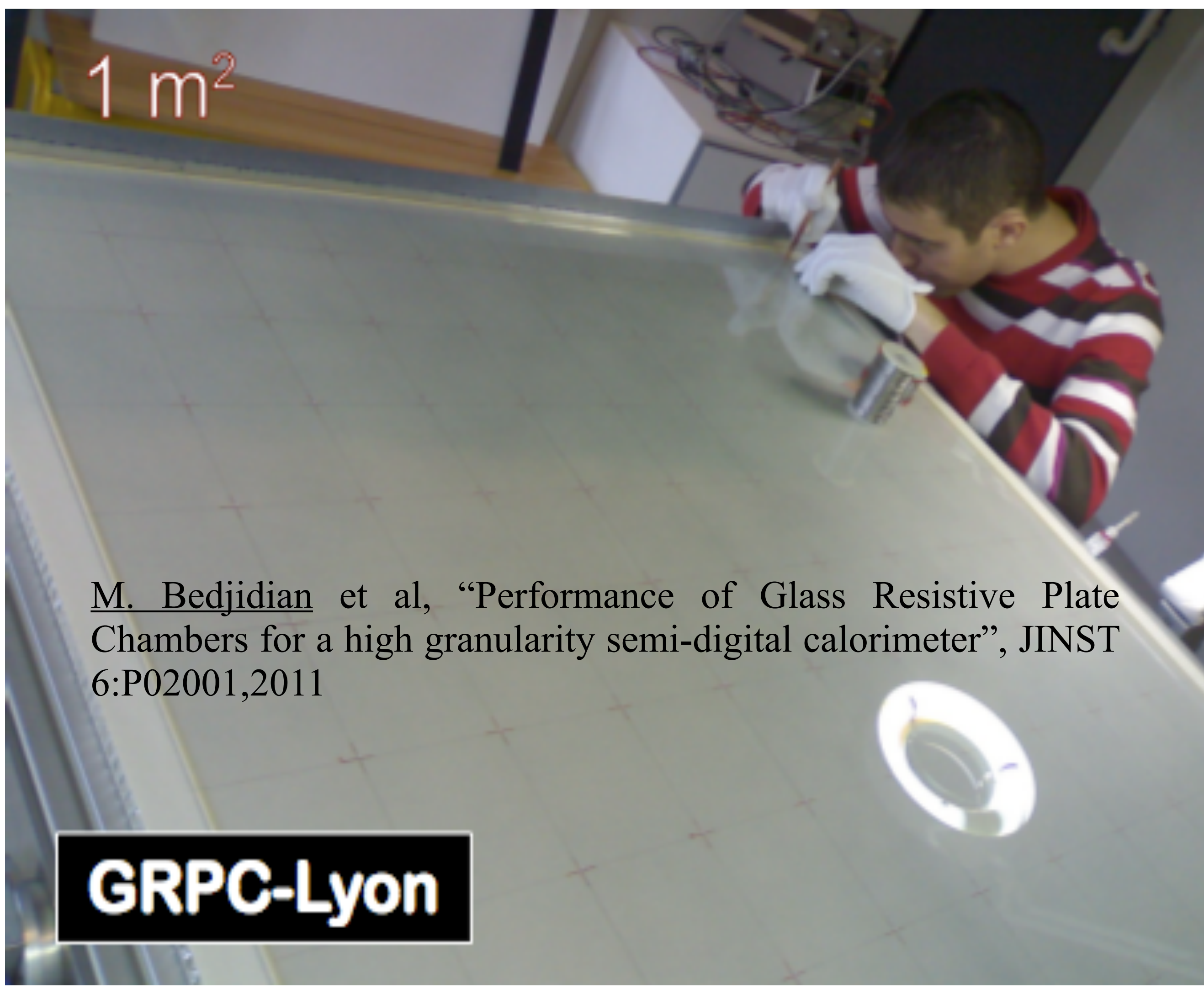
Position detection : trackers : resistive plate chambers (RPC)



Avalanche mode: total mean MIP charge 2.6pC, RMS: 1.6pC

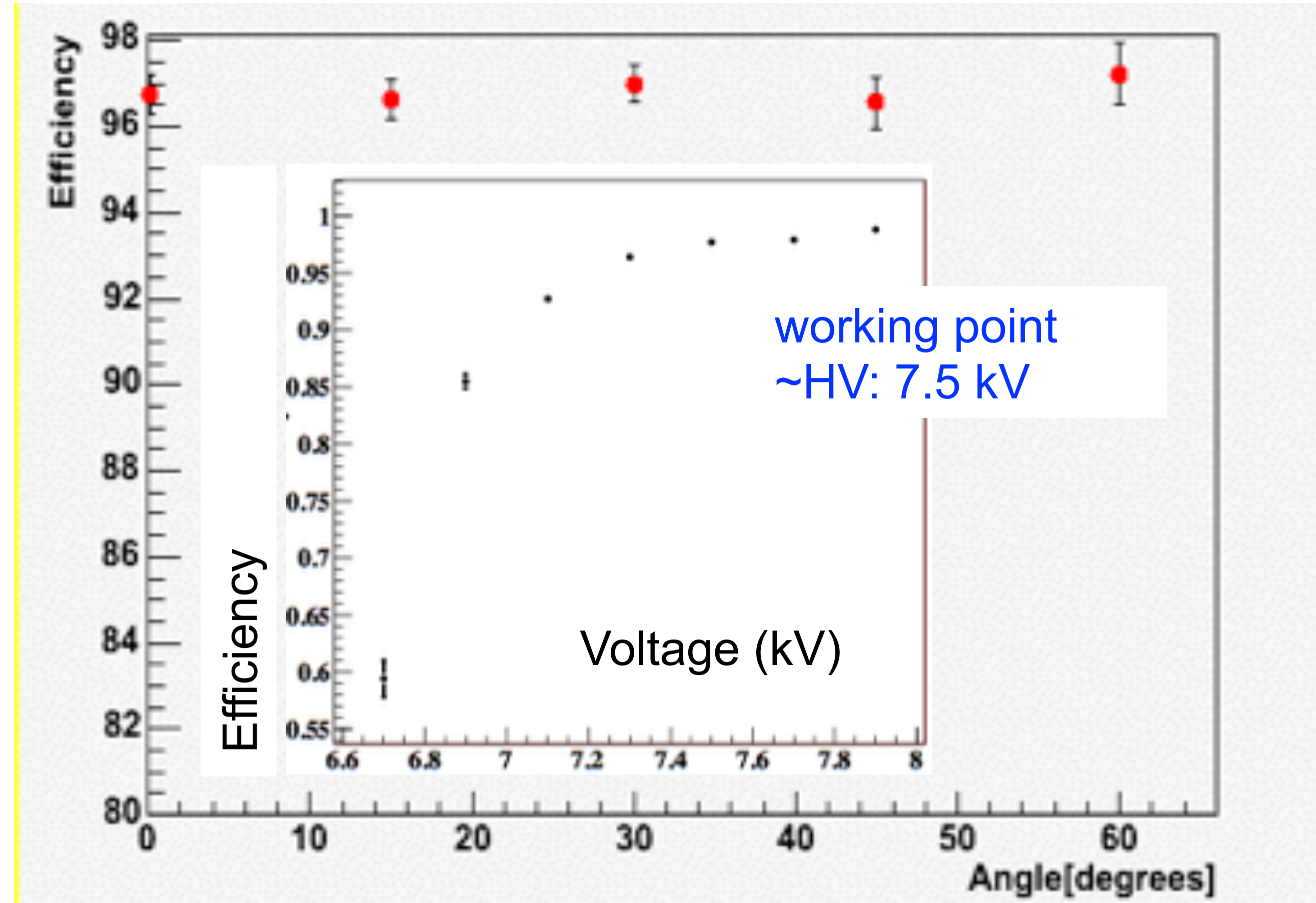
Muon

Gas: 93.5% TFE, 5% CO2, 1.5% SF_6

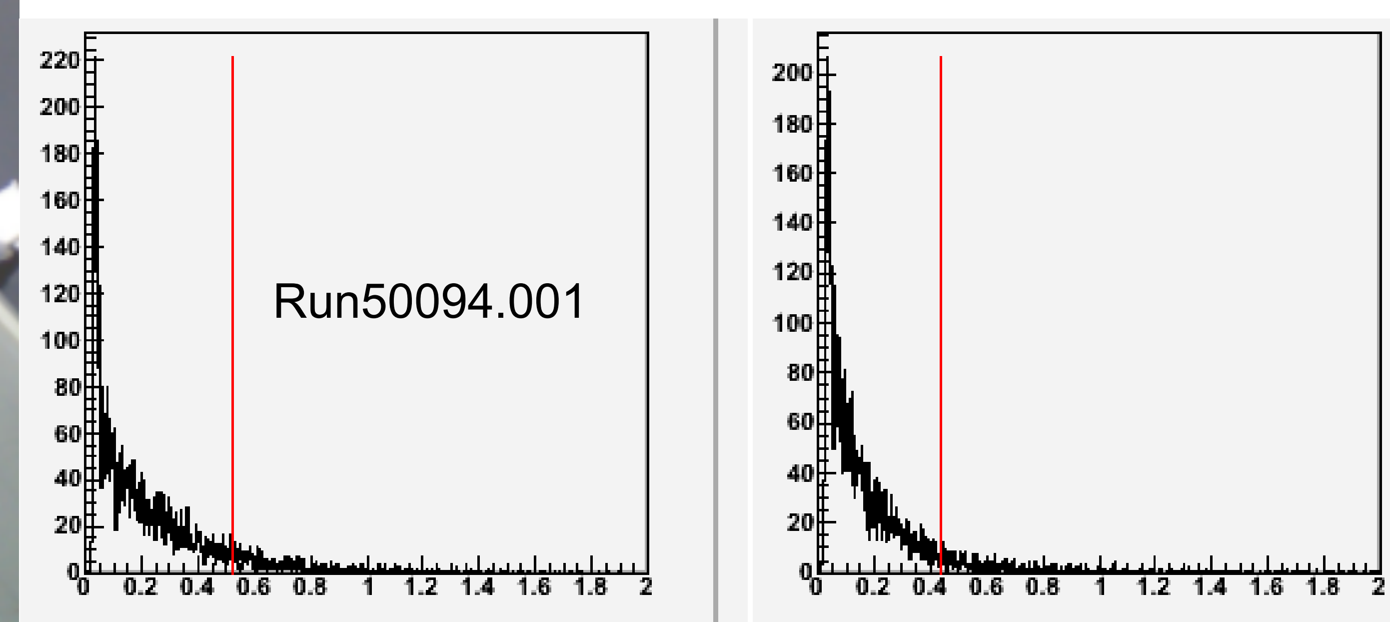


M. Bedjidian et al, "Performance of Glass Resistive Plate Chambers for a high granularity semi-digital calorimeter", JINST 6:P02001,2011

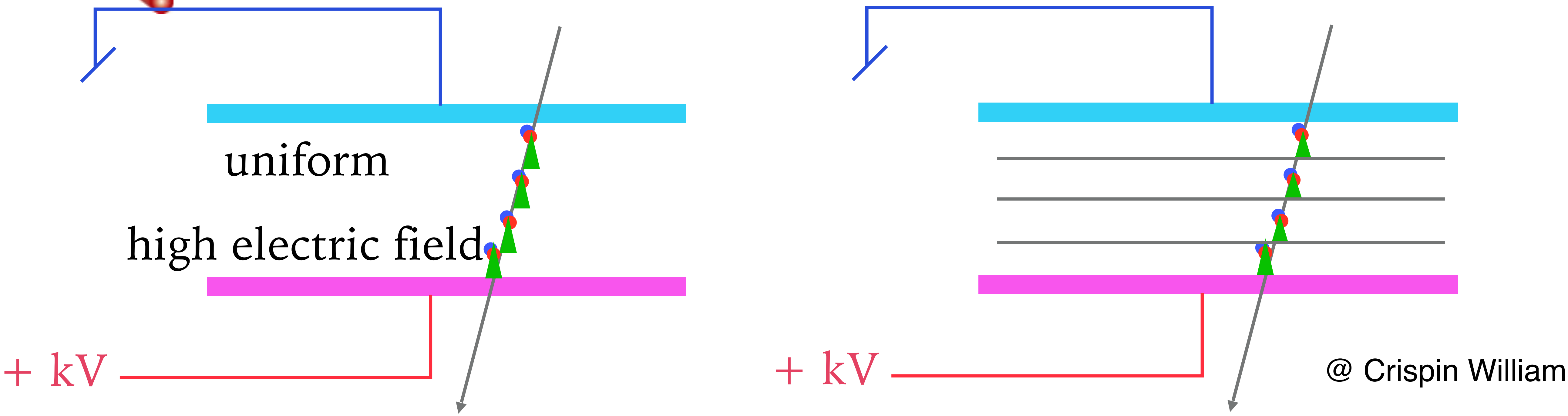
Efficiency vs. HV & track incident angle



Noise rate (Hz)/cm2



Trackers & timing : multi-gap RPC (Santonico, 1995)



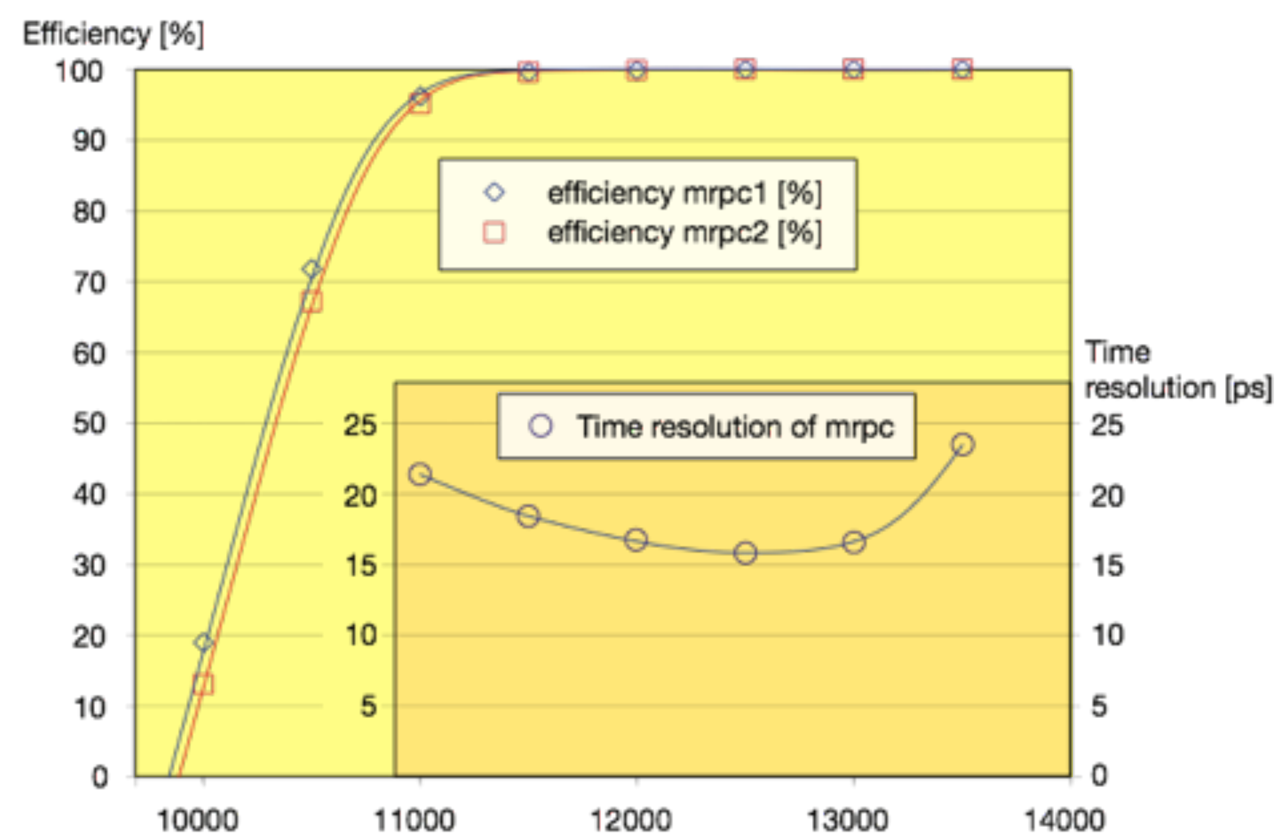
To improve time resolution: record only the very first avalanches … but we want amplification…

Solution: add barriers within the gas gap to stop development of the avalanche

24 gap MRPC each gap 140 micron

~ hundreds of microns position resolution

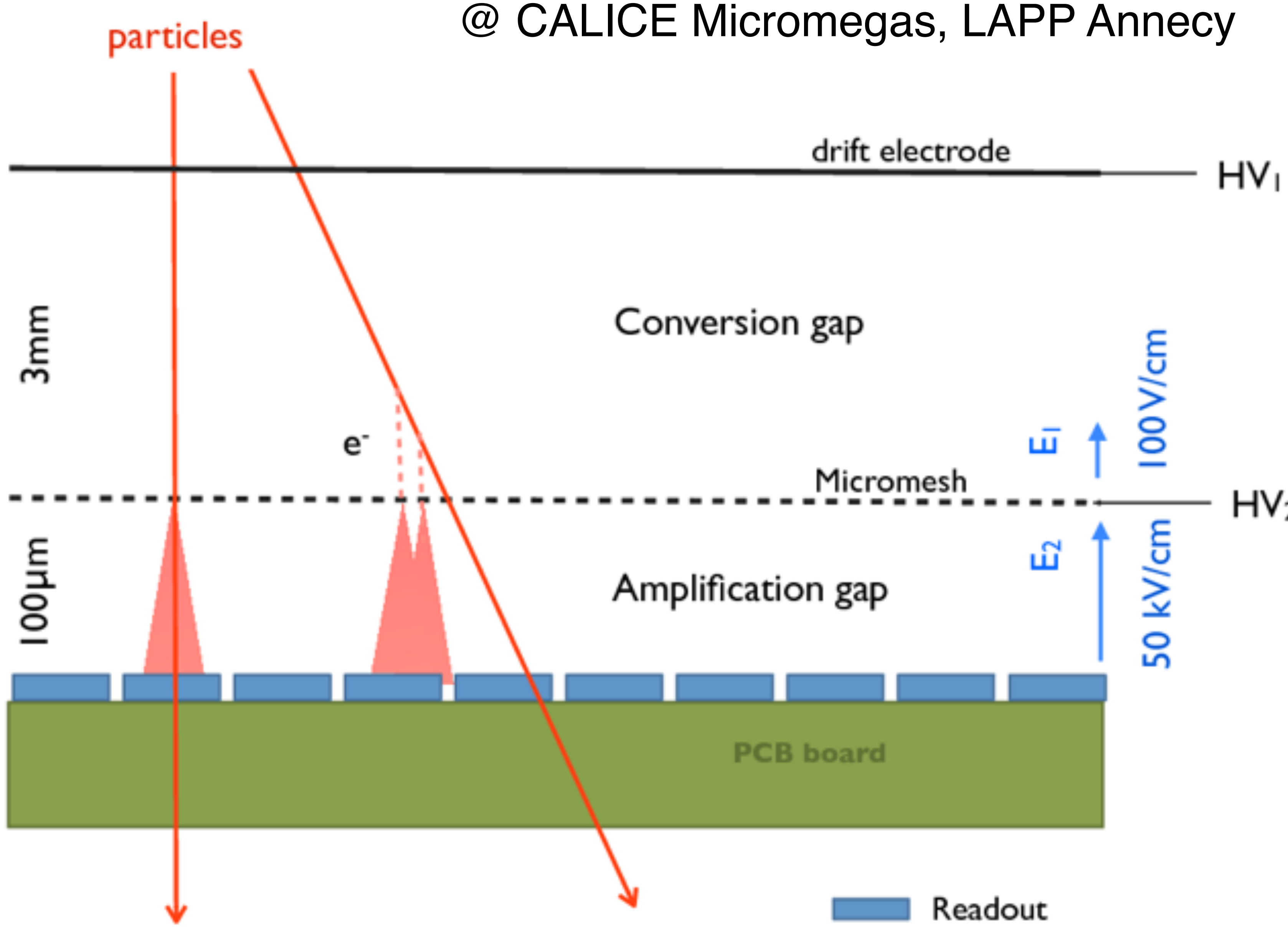
~ less than 30 ps time resolution



Gas detectors: Micromegas

Giomataris et al, NIM A 376 (1996) 29

@ CALICE Micromegas, LAPP Annecy



Operating principle

Ionisation in 3 mm gap

filled with argon

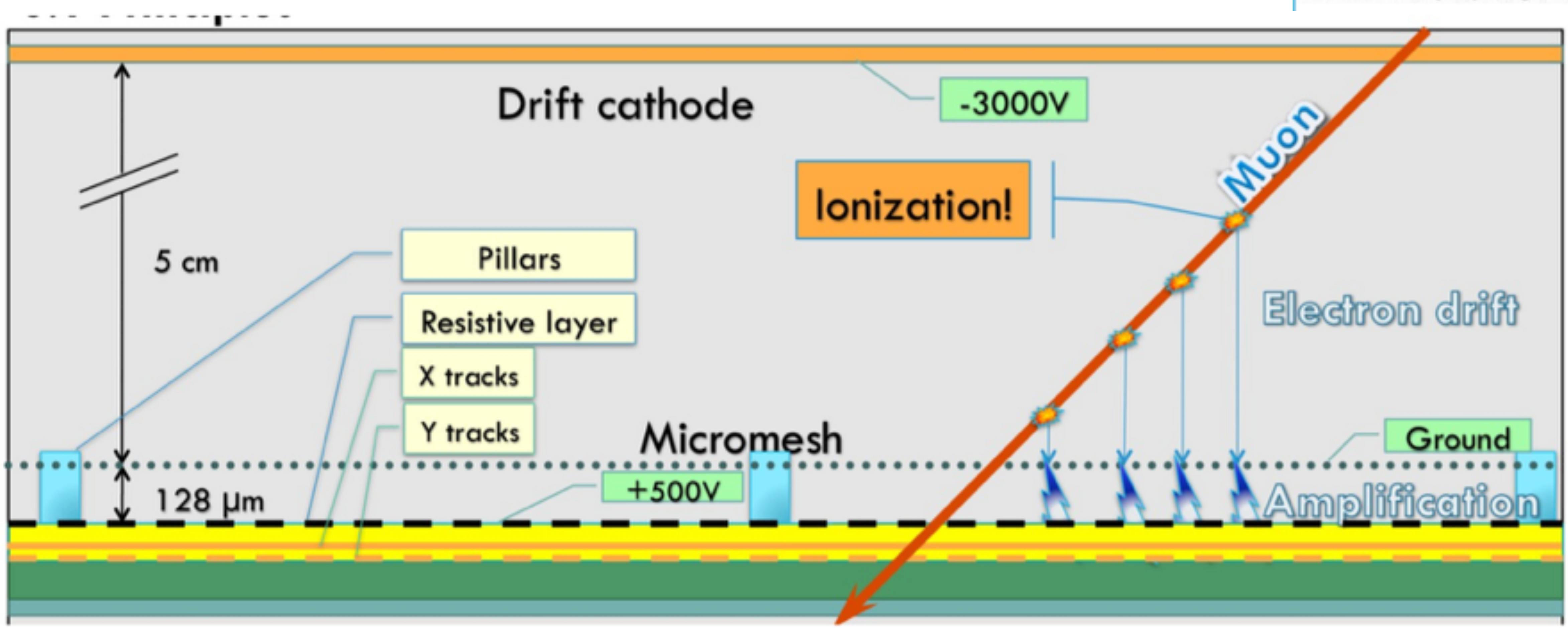
30 pairs in 3 mm from MIPs

Drift
Collection at the mesh in 50 ns

Multiplication in 128 µm gap
By factor > 10^4, controlled by the mesh voltage Takes ~1 ns for electrons and ~100 ns for ions

MIP signal between 1-20 fC depending on mesh voltage

Gas detectors: Micromegas + drift chamber



Both the position and direction (~degree resolution)

Position detection : trackers : scintillators

Principle

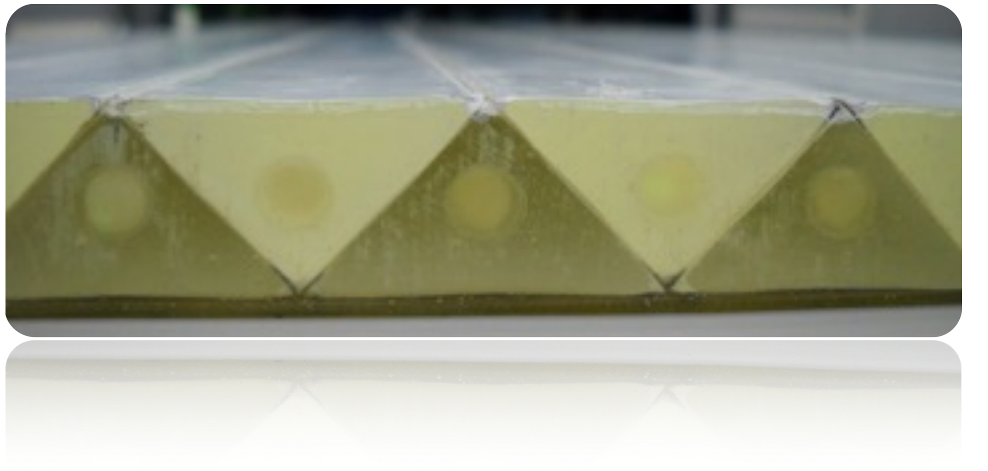
some of the energy deposit excites the atoms

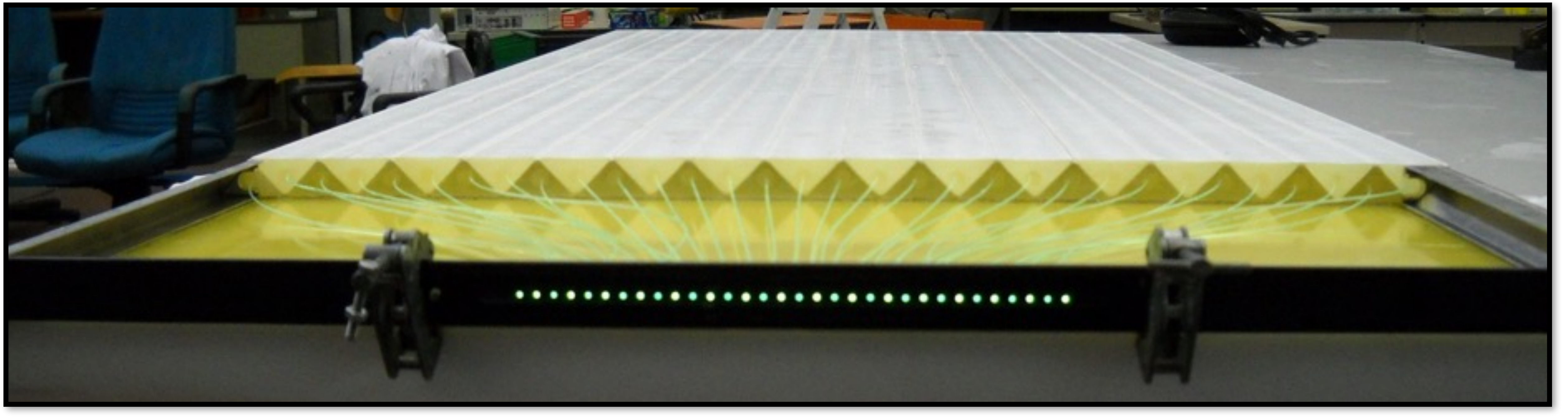
the atoms get back on ground state by emitting photons

Most commonly used organic scintillators (cheap, easy to use, rather fast)

Light read by photomultipliers or SiPMs

MuRAVES detector

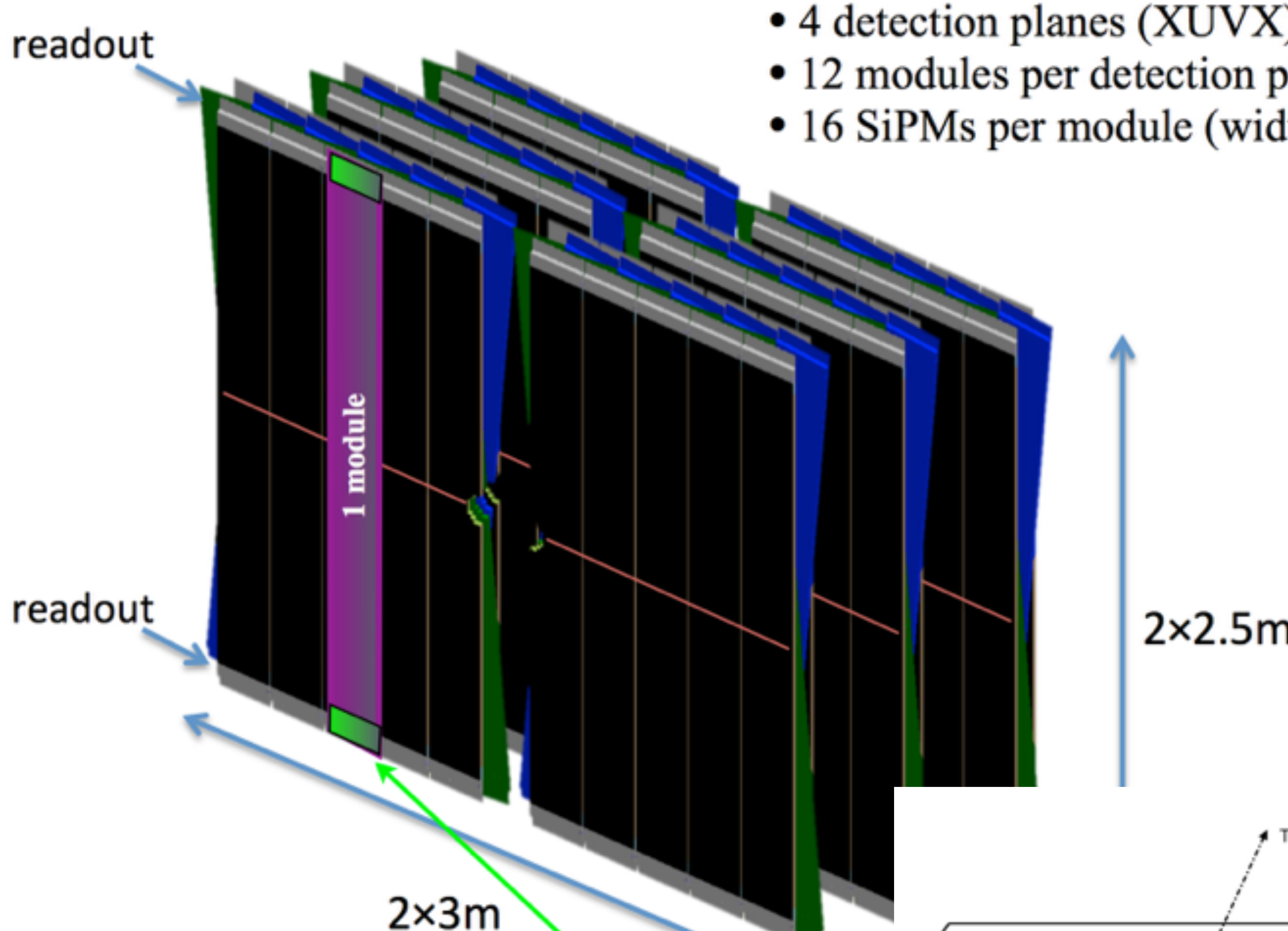




Position resolution : ~ cm, time resolution ns

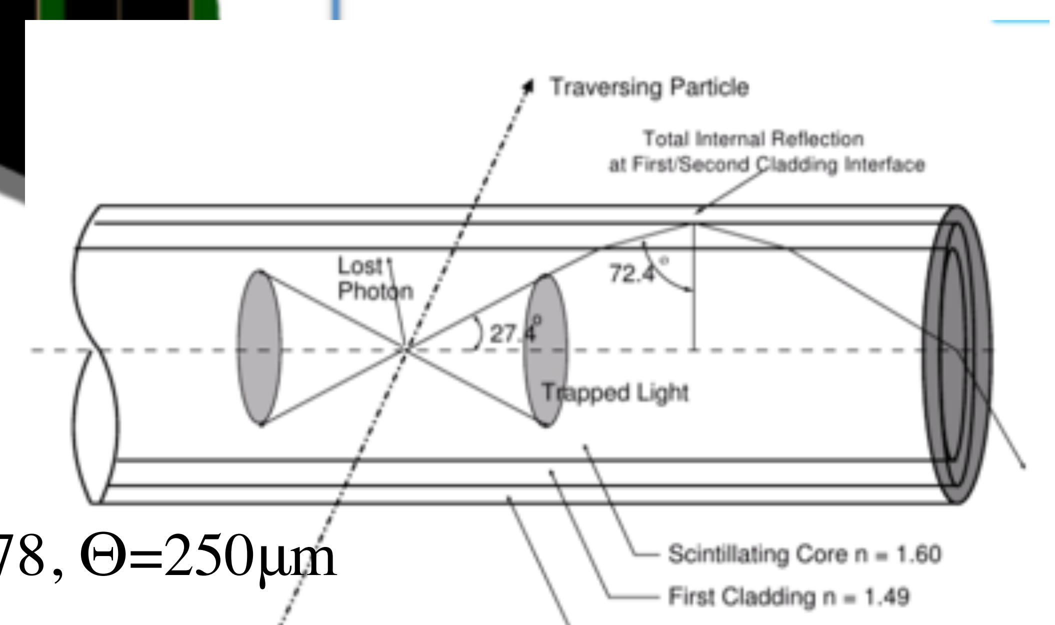
Scintillating Fiber tracker (LHCb)

- 3 stations
- 4 detection planes (XUVX) per station
- 12 modules per detection plane
- 16 SiPMs per module (width ~530mm)



@ Fred Blanc

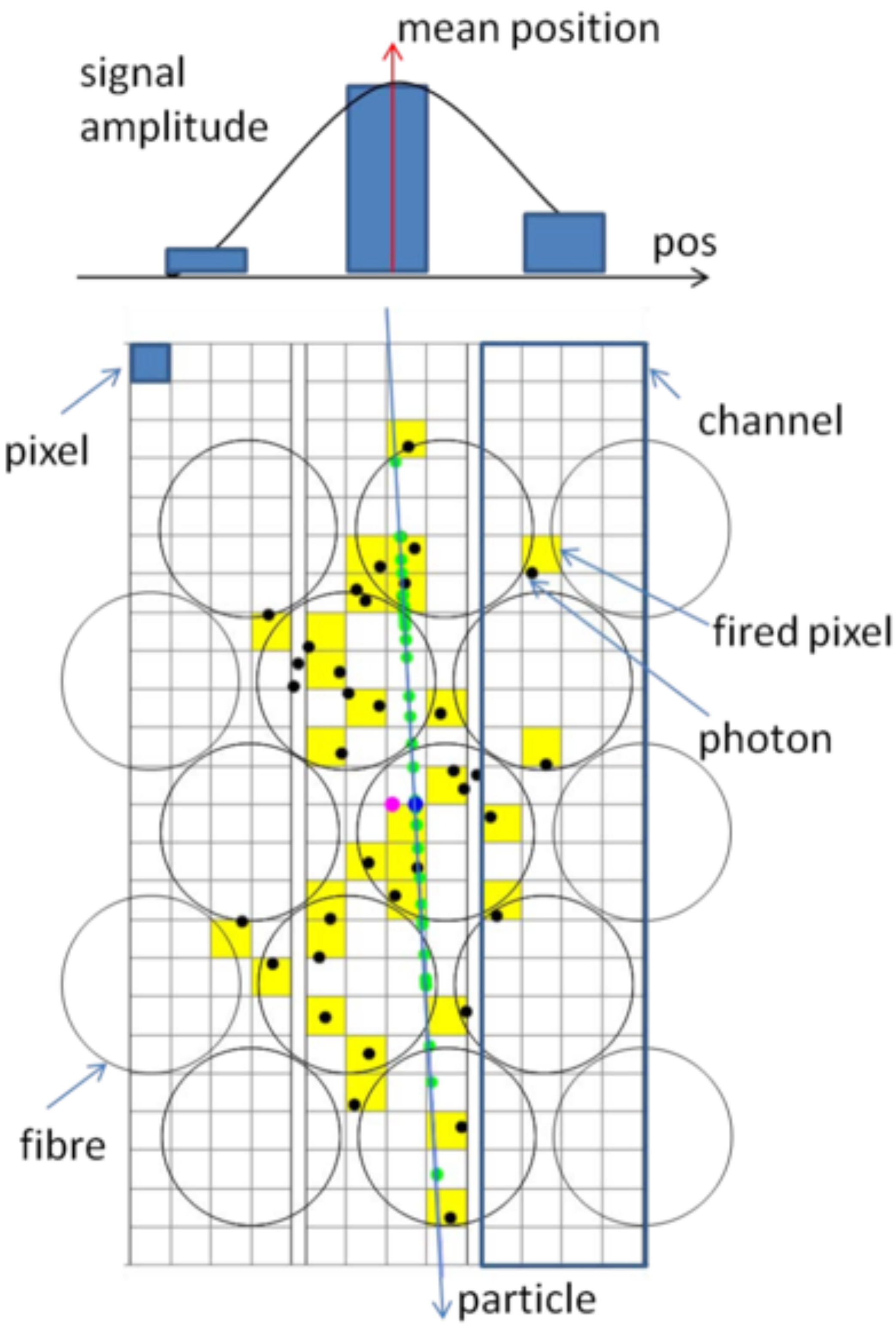
- Fibers read out at top and bottom
- SiPMs + FE electronics + services in a "Readout Box"

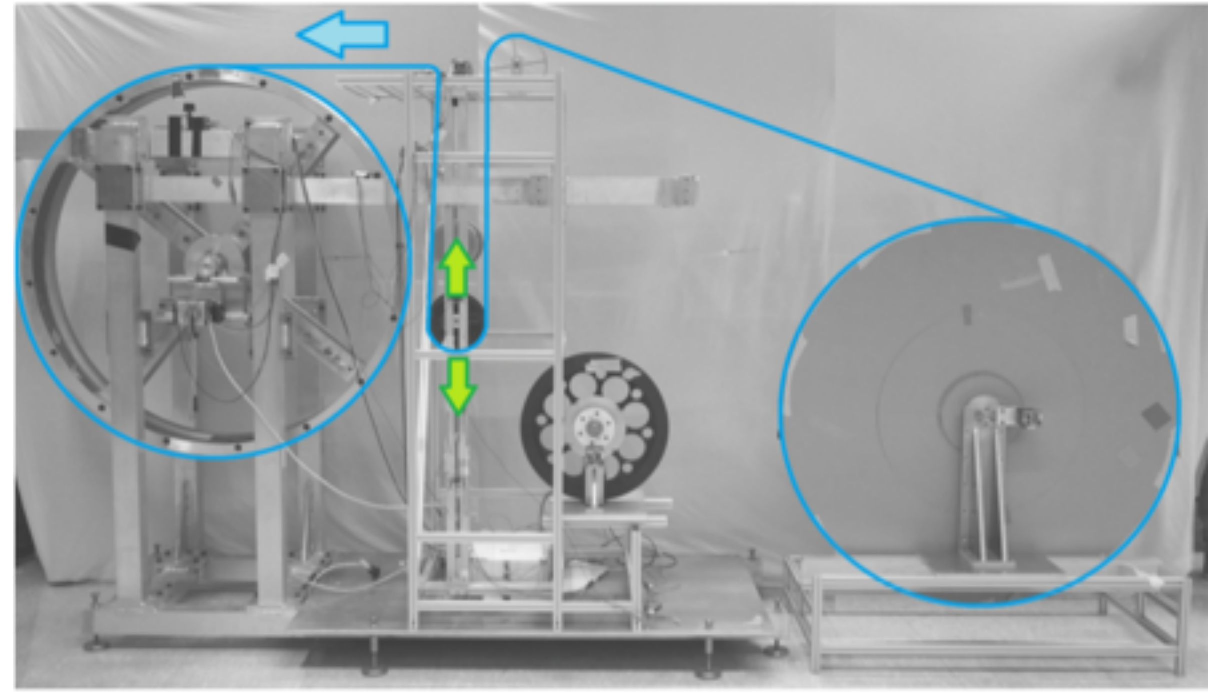


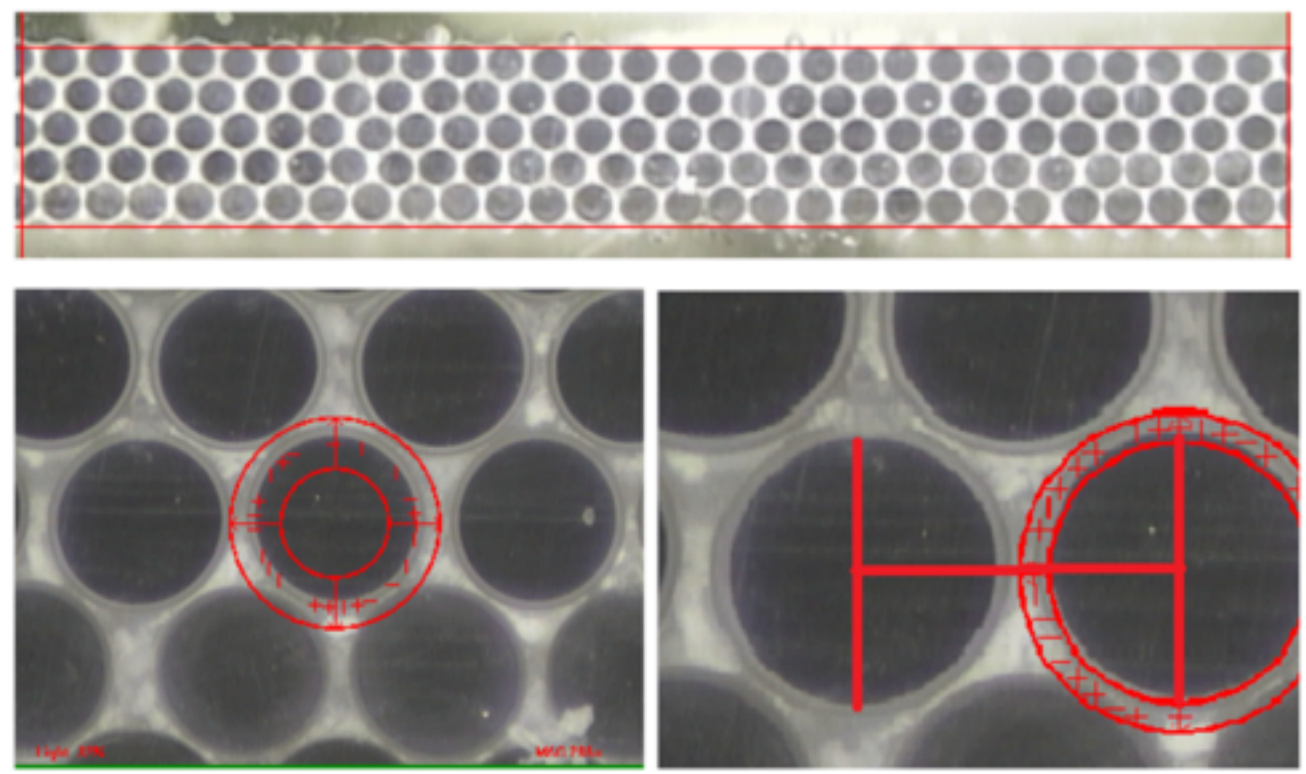
Double cladded scintillating fibres Kuraray SCSF-78, Θ=250μm

Scintillating Fiber tracker (LHCb)

< 100μm resolution





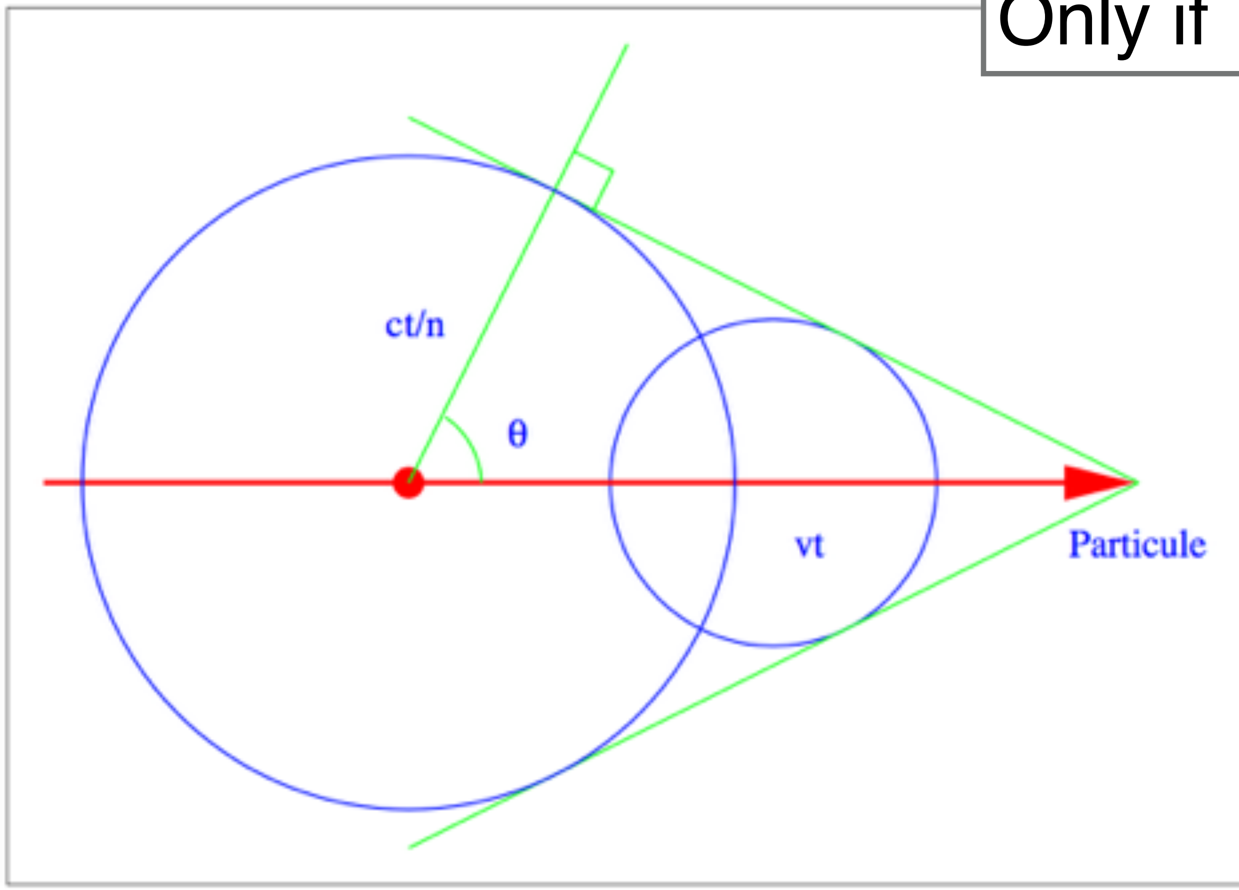


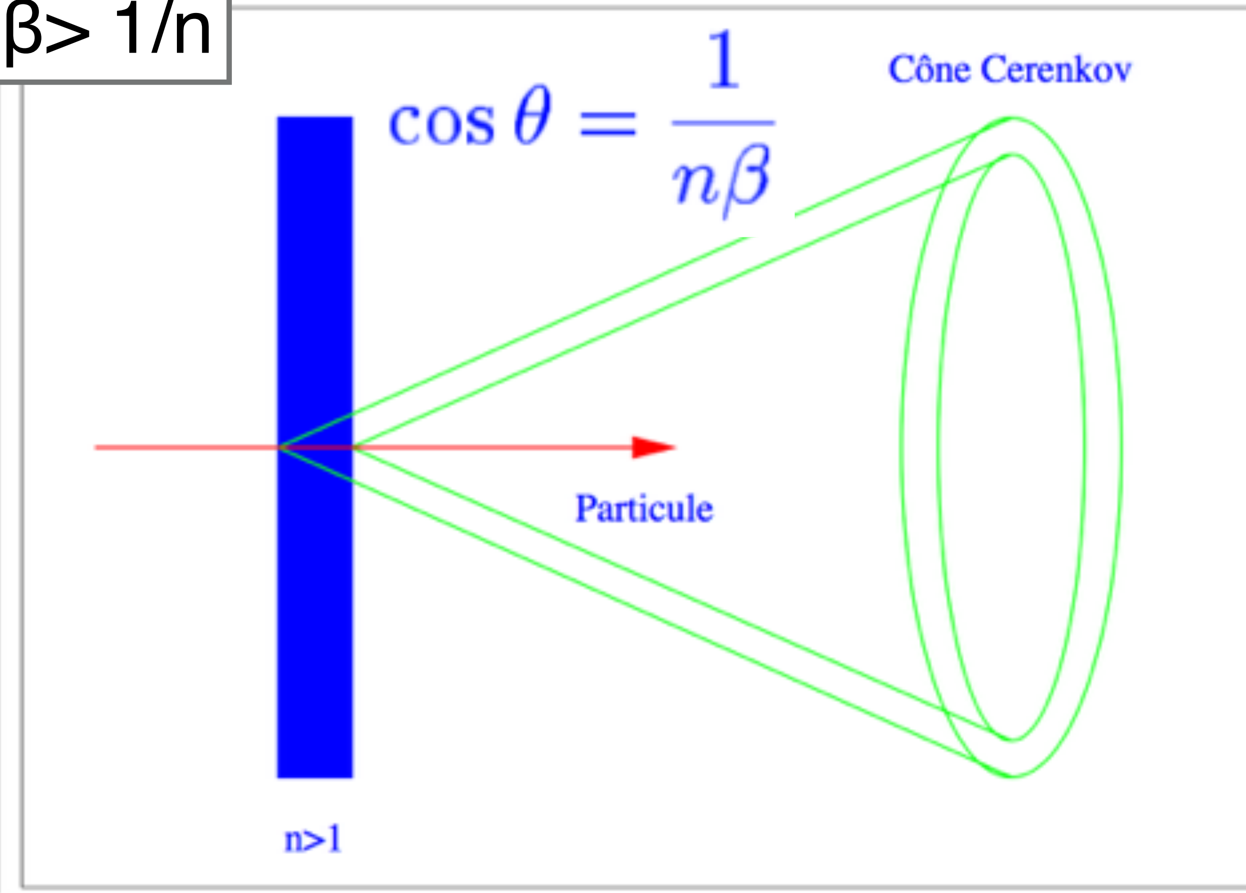
Fibres relative position within 16μm (5th layer)

@ Fred Blanc

Cherenkov effect

Only if β> 1/n





Number of emitted photons depends on β: $$\frac{d^2N}{dEdx} \simeq 370 \sin^2\theta \ \mathrm{eV}^{-1}\mathrm{cm}^{-1}$$

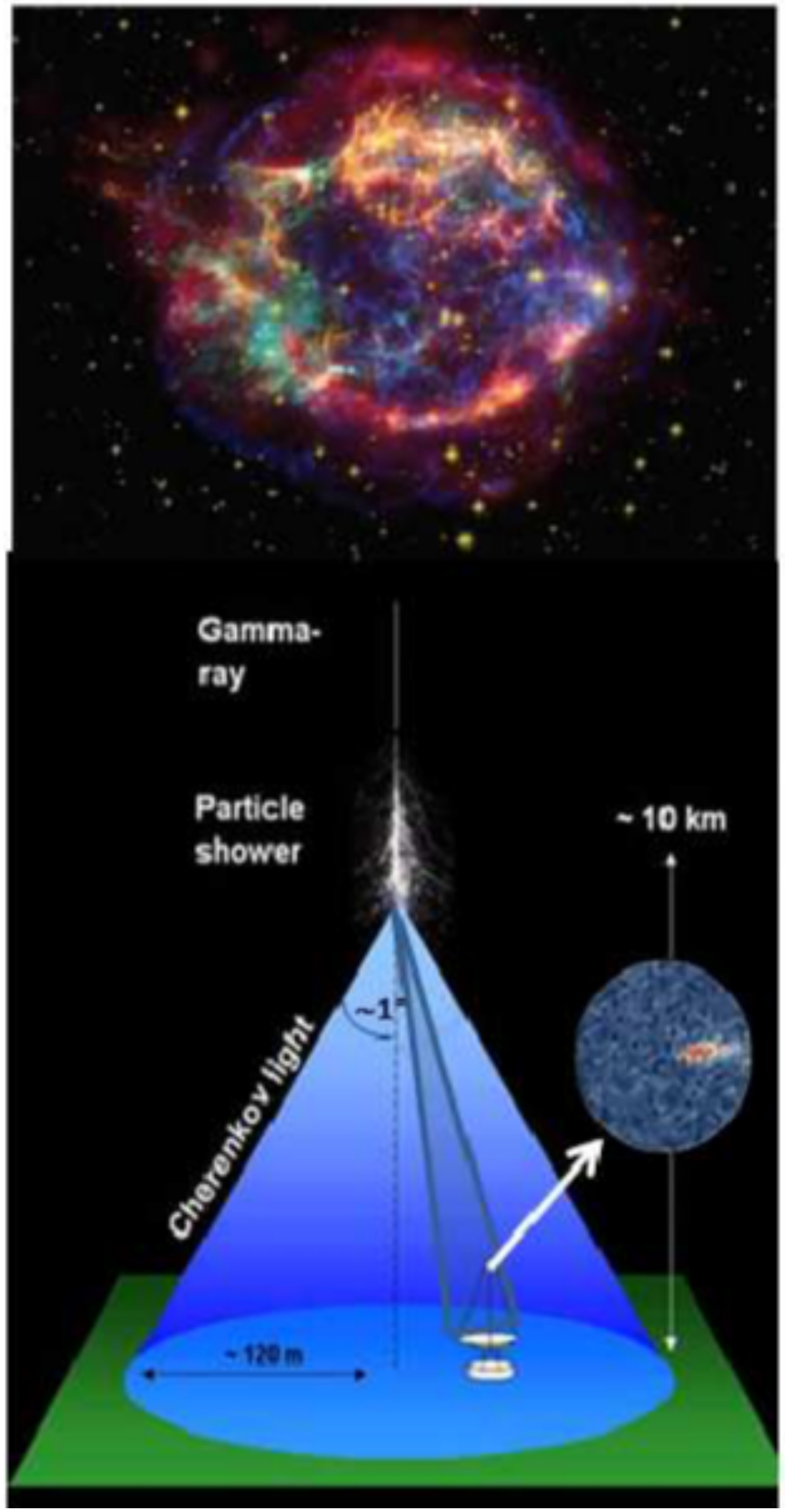
EG for a particle with β ~ 1

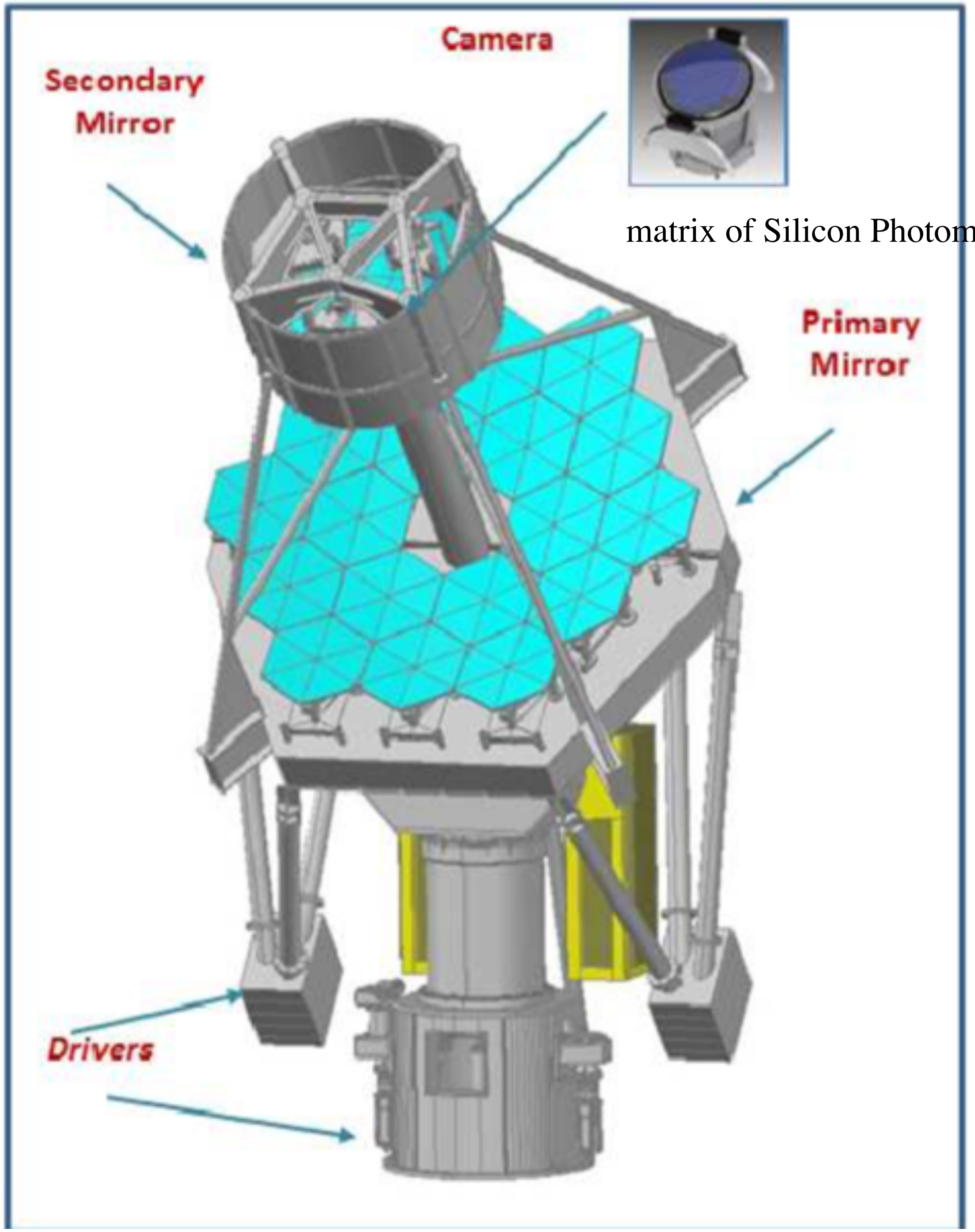
- in air $n = 1{,}00029,\ \theta = 1{,}4°,\ dN/dx = 0{,}3\ \mathrm{cm}^{-1}$
- in water $n = 1{,}33,\ \theta = 41°,\ dN/dx = 200\ \mathrm{cm}^{-1}$

Cone detection -> tracker
Cone angle and/or number of photons -> β

Cherenkov telescopes : CTA

secondary optics is a monolithic 1.8 m diameter mirror





matrix of Silicon Photomultipliers (SiPM)

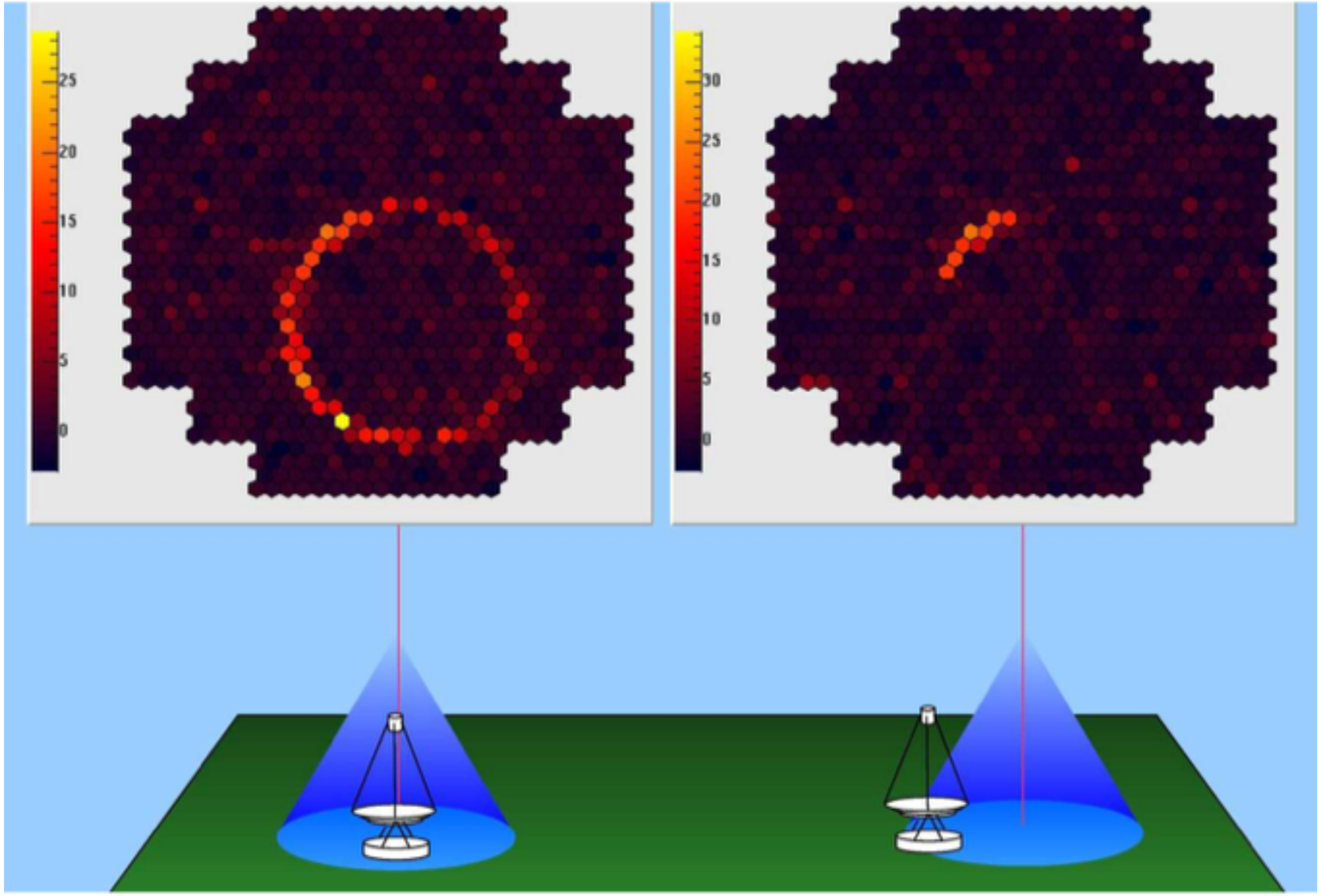
The primary mirror of the telescope has a 4.2 m diameter

Cherenkov telescopes :CTA

https://arxiv.org/pdf/1511.01761v1.pdf

$$E_\mu = \frac{0.105}{\sqrt{1-(n\ \cos\ \Theta)^{-2}}}\ (\mathrm{GeV}).$$

Saturates towards
50 GeV @ 1800m

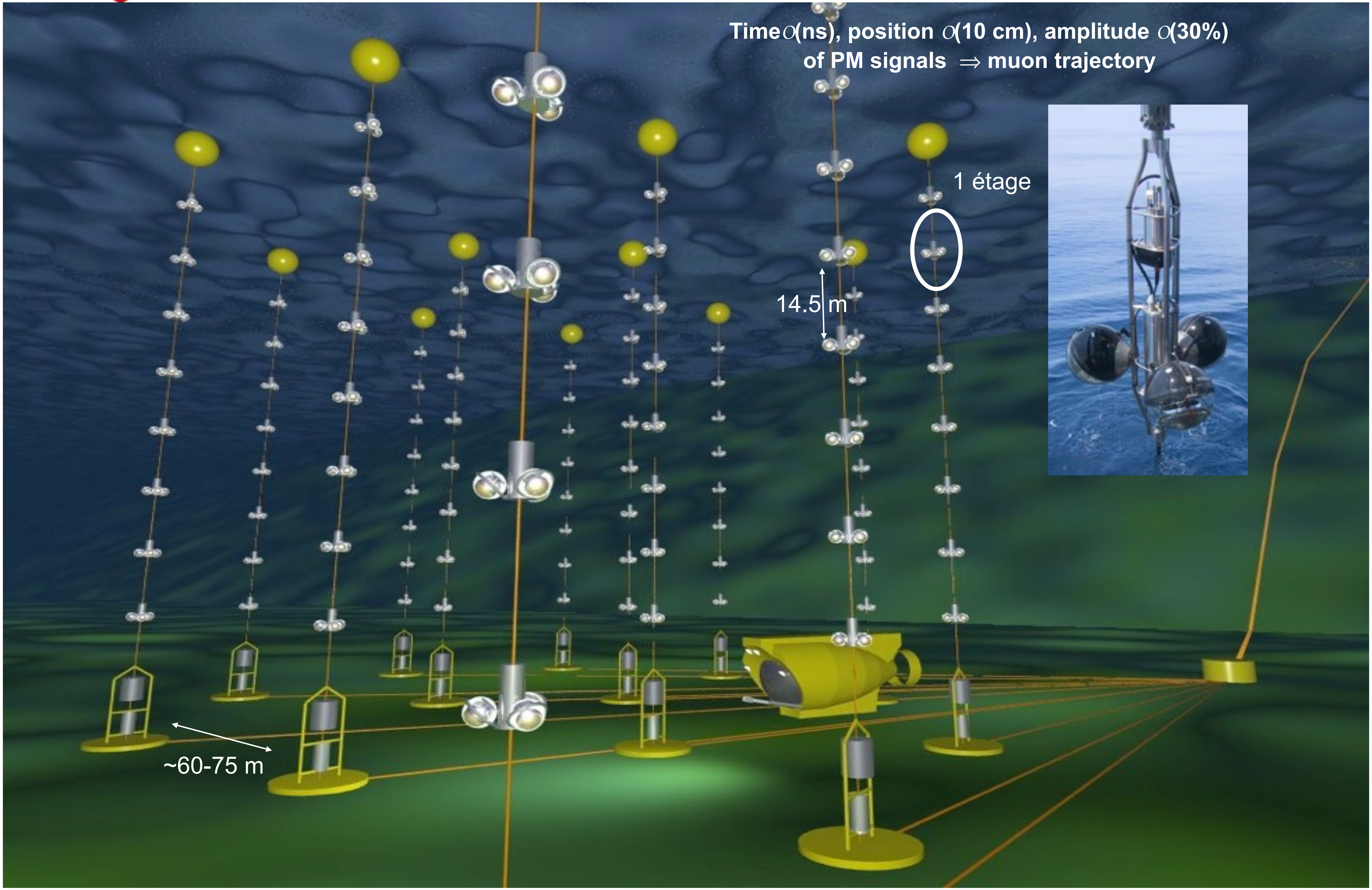


Ring centre = muon arrival direction with respect to the telescope optics axis. precision ~ 0.14°

detect muons by collecting in a single ring the light emitted along the last ~100 m of its path towards the primary mirror

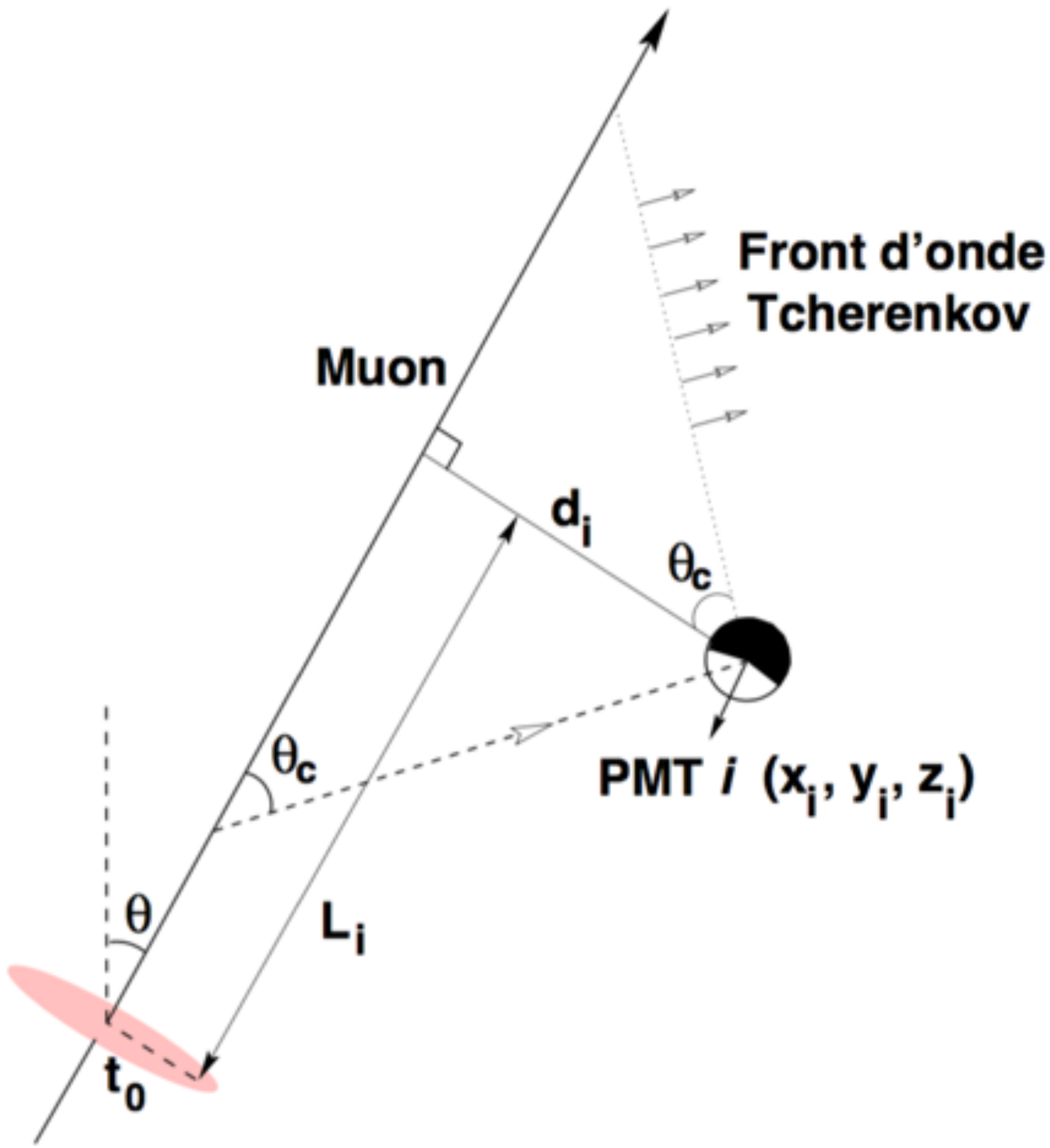
energy threshold ~20 GeV and the muon hits the primary mirror up to an off-axis angle of 3.6°

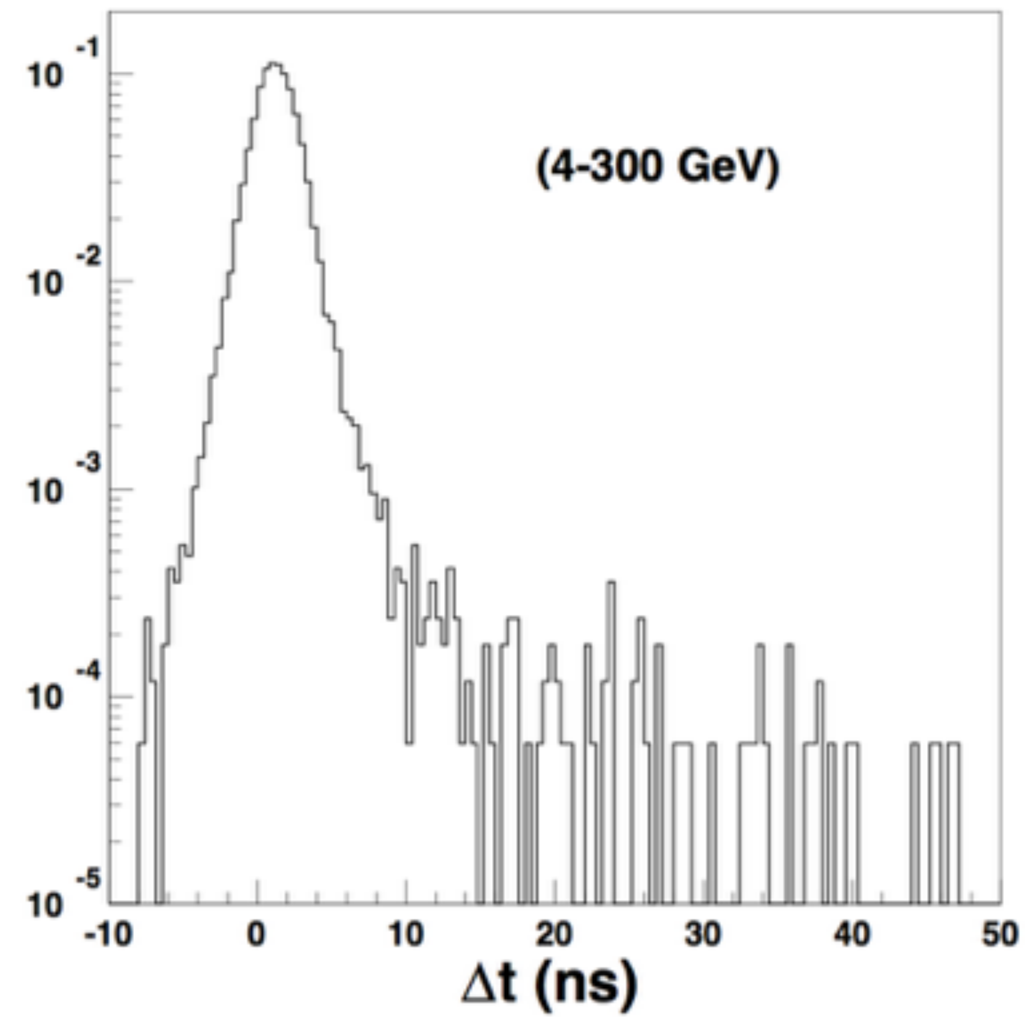
Water Cherenkov detectors: ANTARES



Water Cherenkov detectors: ANTARES

$$t_{i\mathrm{Cer}} = t_0 + \frac{L_i + d_i \tan(\theta_C)}{c}$$

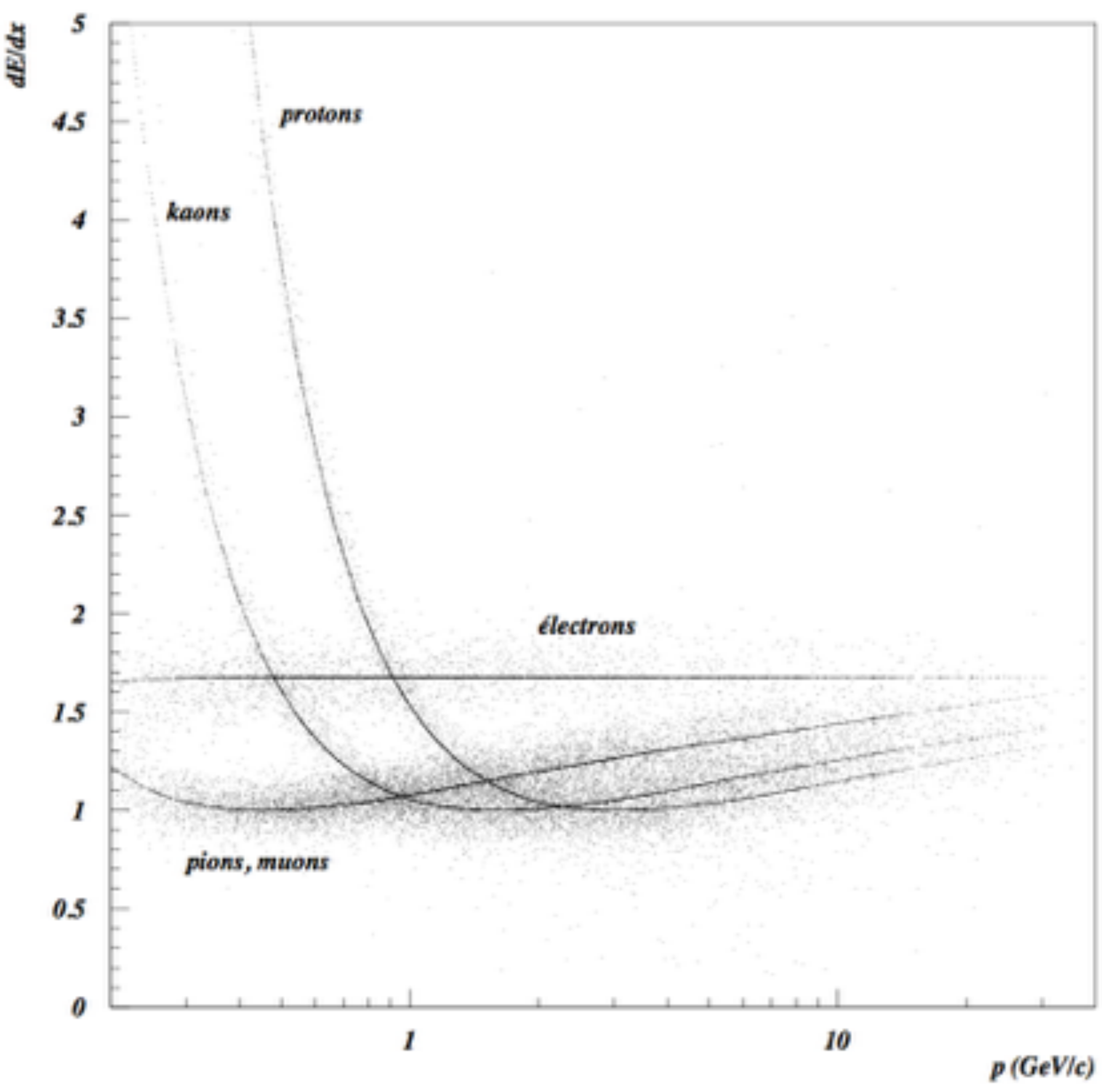




• $E\mu > 10$ TeV $\Rightarrow \sim 0.2°$

Particle identification

“Mass measurement”



β measurement : time of flight

Over 2.5 m and 1 GeV:

- $\pi^{\pm}$: 8,4 ns
- $K^{\pm}$: 9,3 ns
- $p, \bar{p}$: 11,4 ns

~ hundreds of ps/ns achievable with fast scintillators

~ better than 100 ps achievable with Multi Gap Resistive Plate Chambers

Identification of charged hadrons between 0.6 and few GeV where dE/dx is not feasible