European School of Instrumentation in Particle & Astroparticle Physics

Muon Detection

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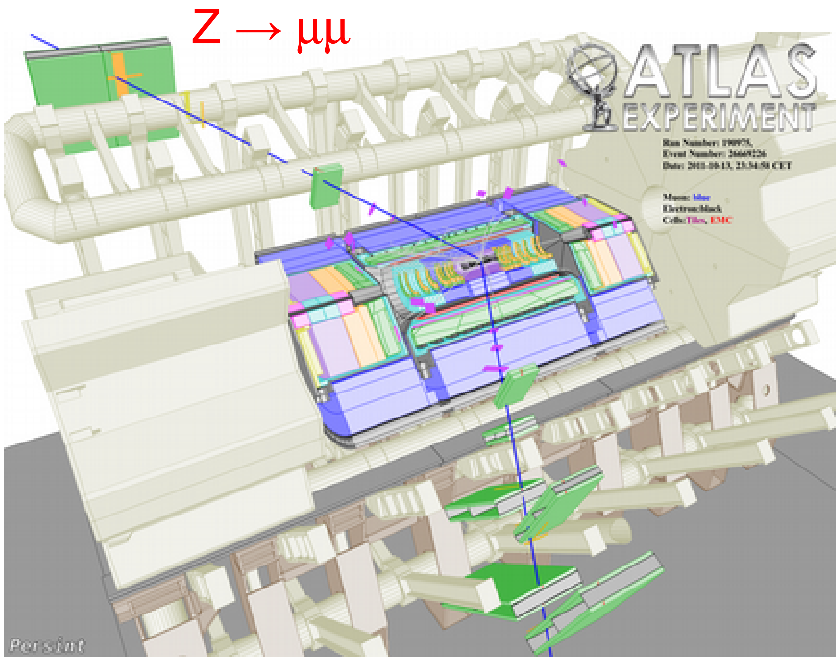
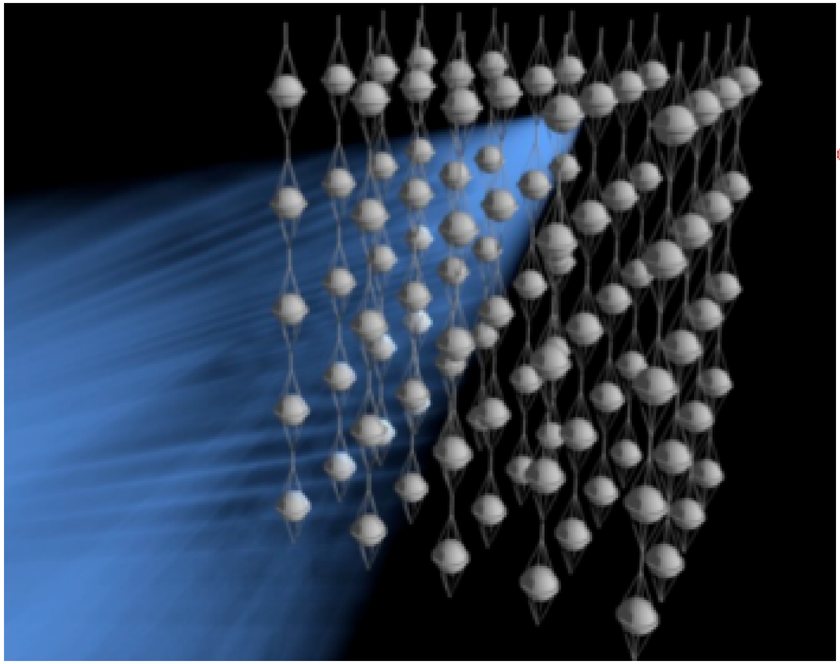
CEA-Saclay
8-10 February 2017

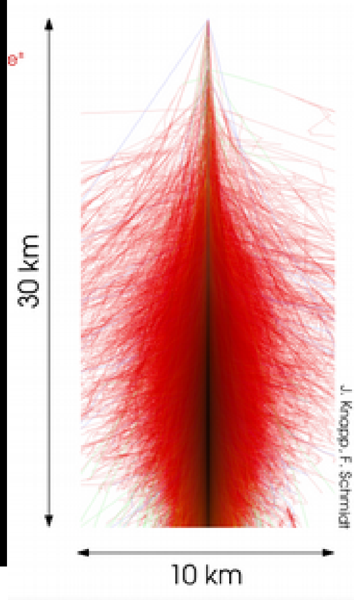
Muon Detection

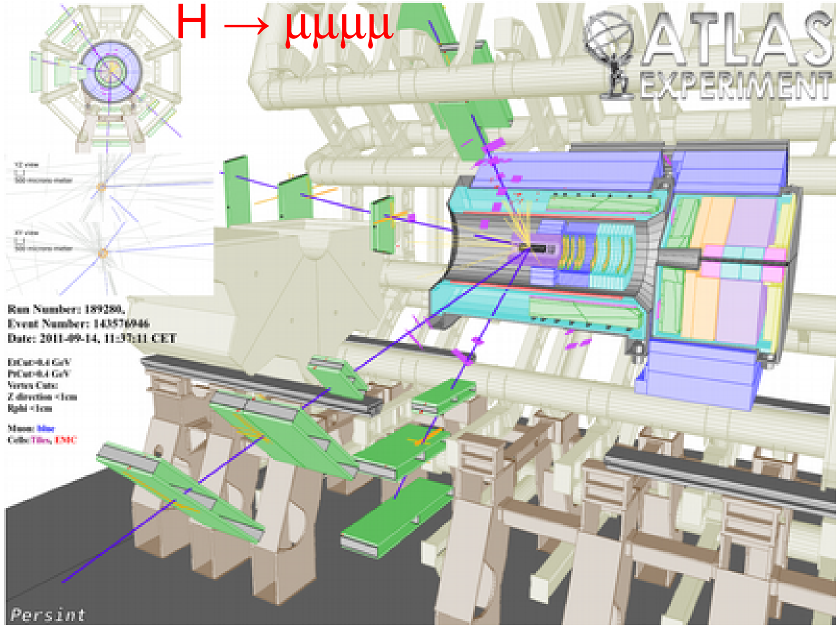
Outline

- Introduction
  - Why Muon Detection?
  - Muon in the Standard Model
  - Muon Discovery
  - Interaction Particle-Matter
- Detectors
  - Gaseous, Solid, Liquid, Mix
    - Interlude: Charged particle in magnetic field
    - Interlude: Detector conception
    - Interlude: Muography
- Summary







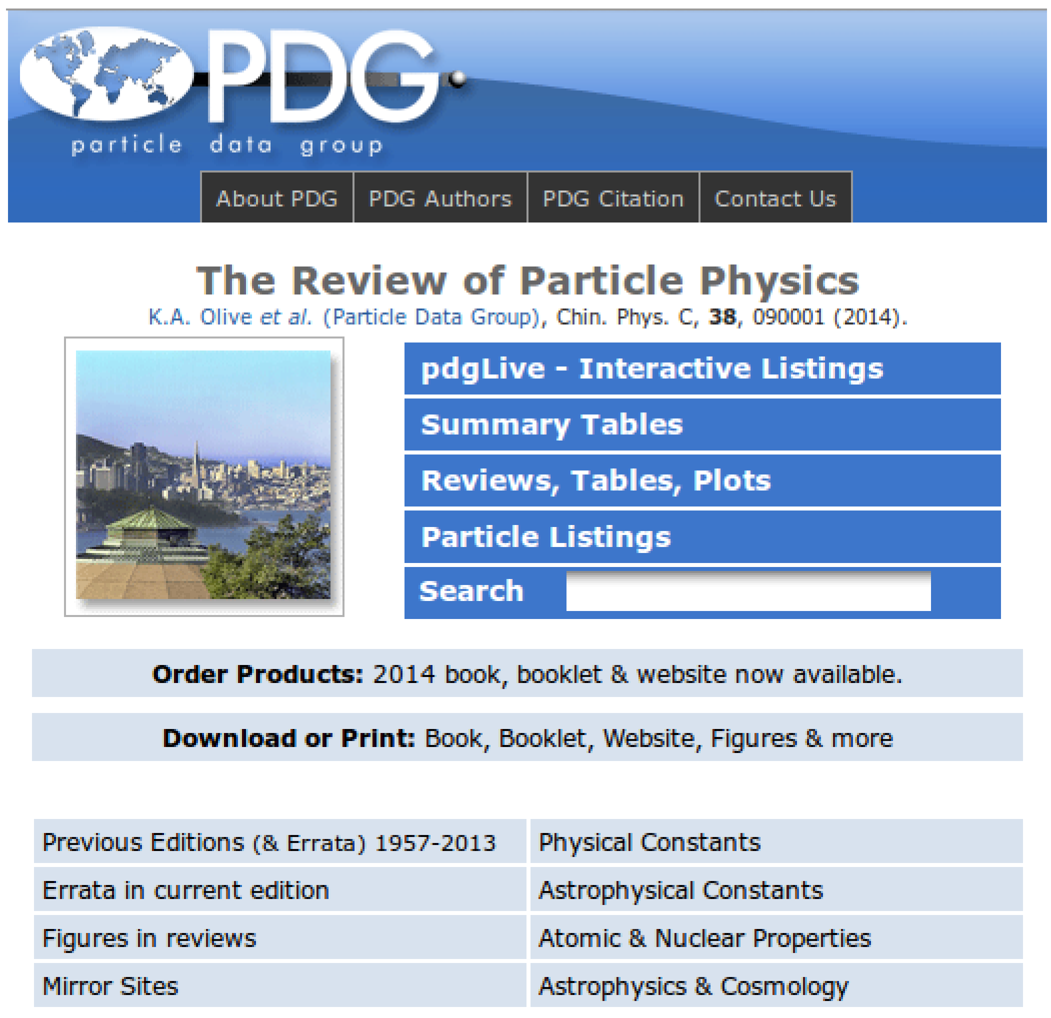


Muon Detection

Main source

- Remark: not only for muon but for all infos on particle physics/cosmology

http://pdg.lbl.gov/

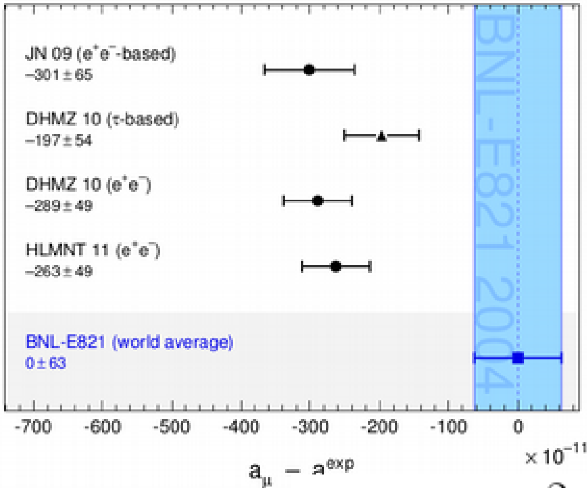


Introduction

Muon Detection

Why Muon Detection?

- Determine intrinsic properties of this elementary particle
  - Constraint on the Standard Model (SM) ex: $g_\mu - 2$
- Very clean probe for many physic domains
  - Astroparticle: proton(cosmic rays) + atm $\rightarrow \pi \rightarrow \mu$
  - Particle physics: Higgs $\rightarrow$ 4 μ
  - Neutrino signature for both domain
- As a tool:
  - Trigger
  - Veto
  - Detector calibration: MIP
  - Muo-graphy →
- How?
  - Detection mechanism:
    - Ionisation, Scintillation, Cherenkov radiation
  - Identification:
    - Tag after "walls", dE/dx, Cherenkov



$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

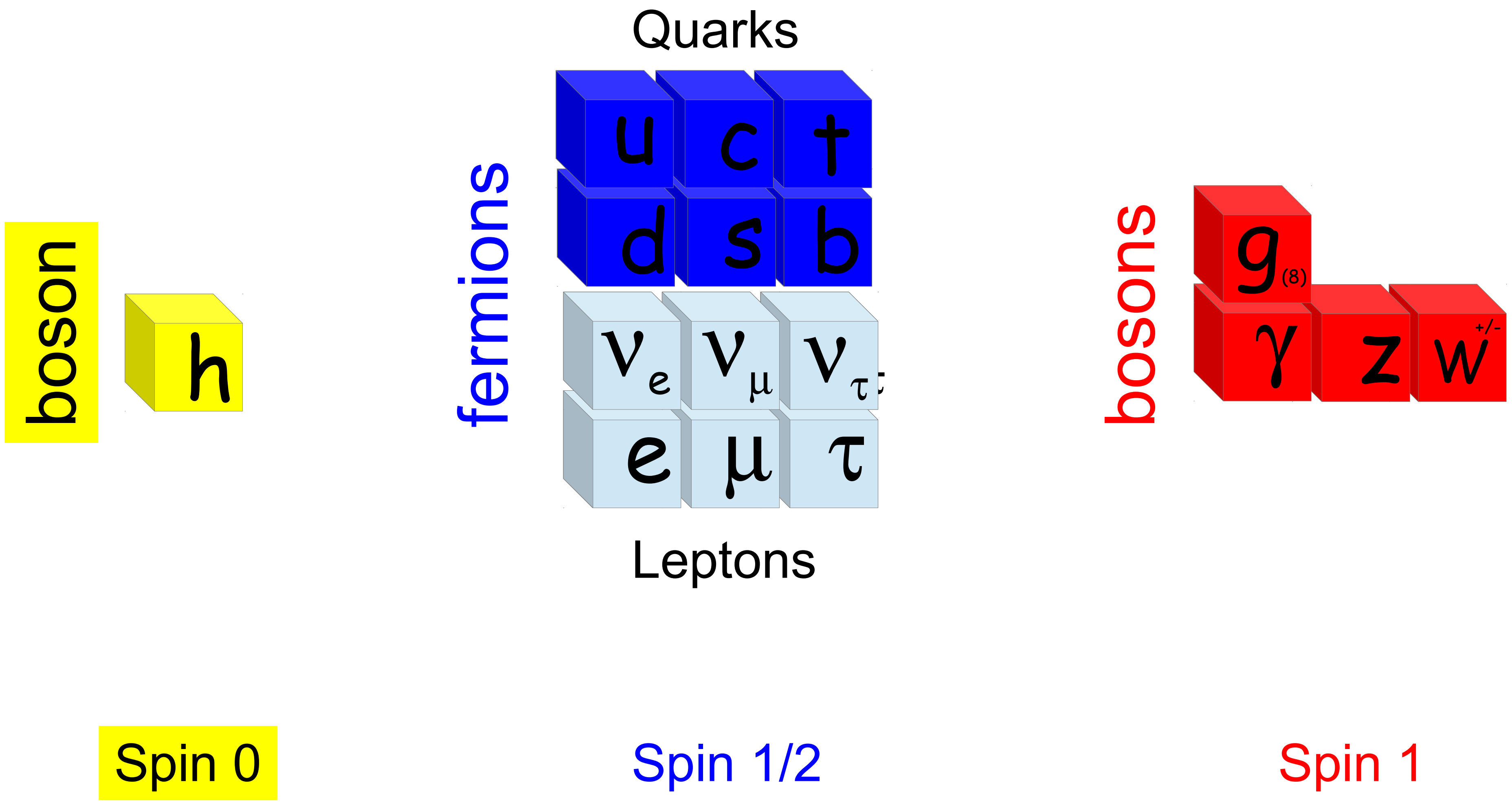
Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei,

Muon

Standard Model

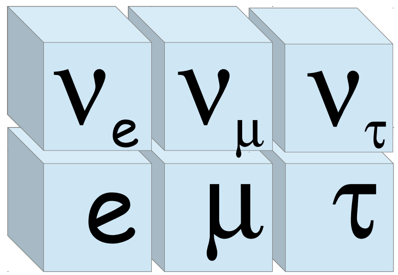


Muon

Standard Model

Leptons

fermions



Electromagnetic & weak interaction (& gravitation)

Muon

mass:	105.6583715±0.0000035 MeV
spin :	1/2
mean Life:	$(2.1969811 \pm 0.0000022) \times 10^{-6}$ s
τ^+/τ^- :	1.00002±0.00008 (CPT!)
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$	~100%
$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	~100%

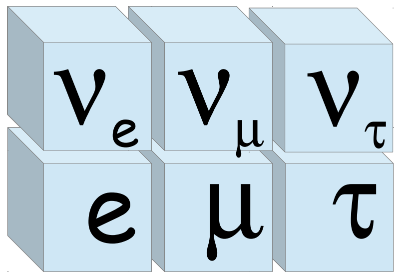
$m(K^0)-m(\overline{K^0}) \sim 4.10^{-10}$ eV

Muon

Standard Model

Leptons

fermions



Electromagnetic & weak interaction (& gravitation)

Muon

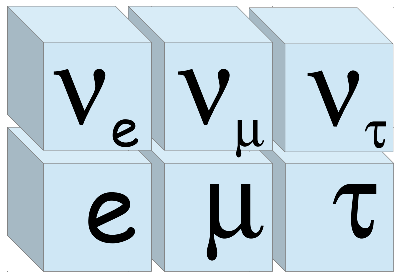
- ~207 times more massive than electron
- ~ 17 times less massive than the tau
- Unstable $c\tau \sim 660$m
  but the second longest mean life time after the neutrons
- Means: stable for some simulation in G4

Muon

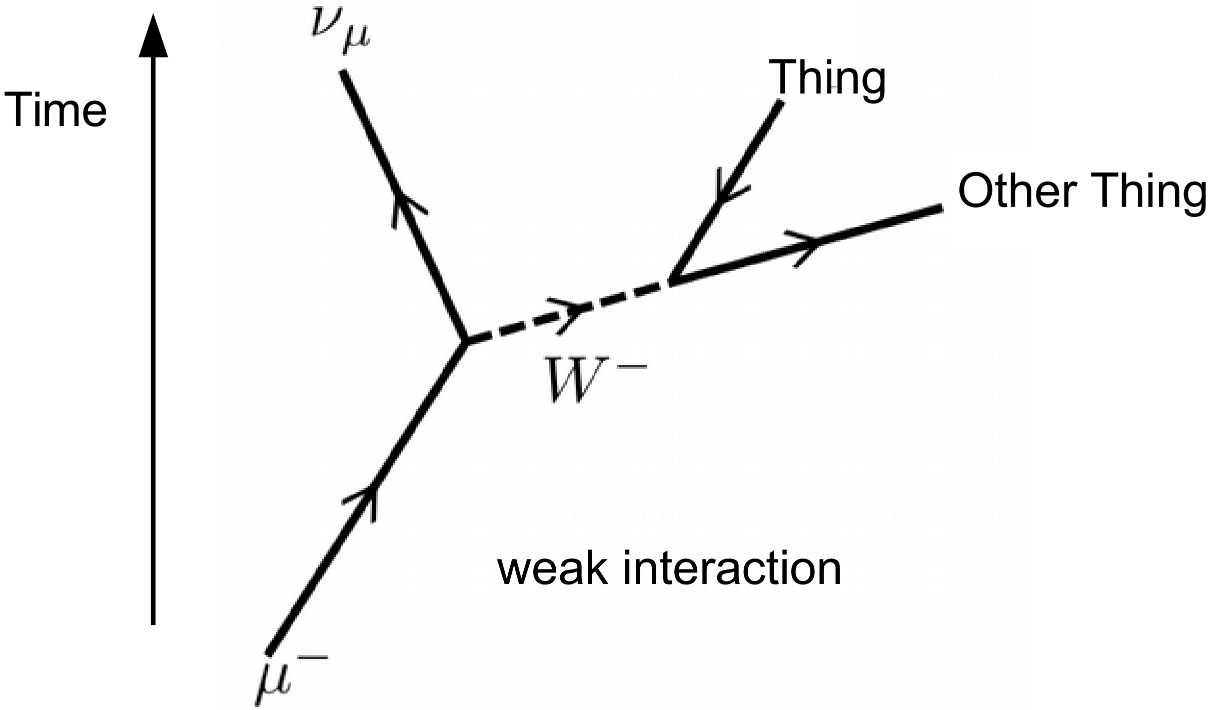
Standard Model

Leptons

fermions

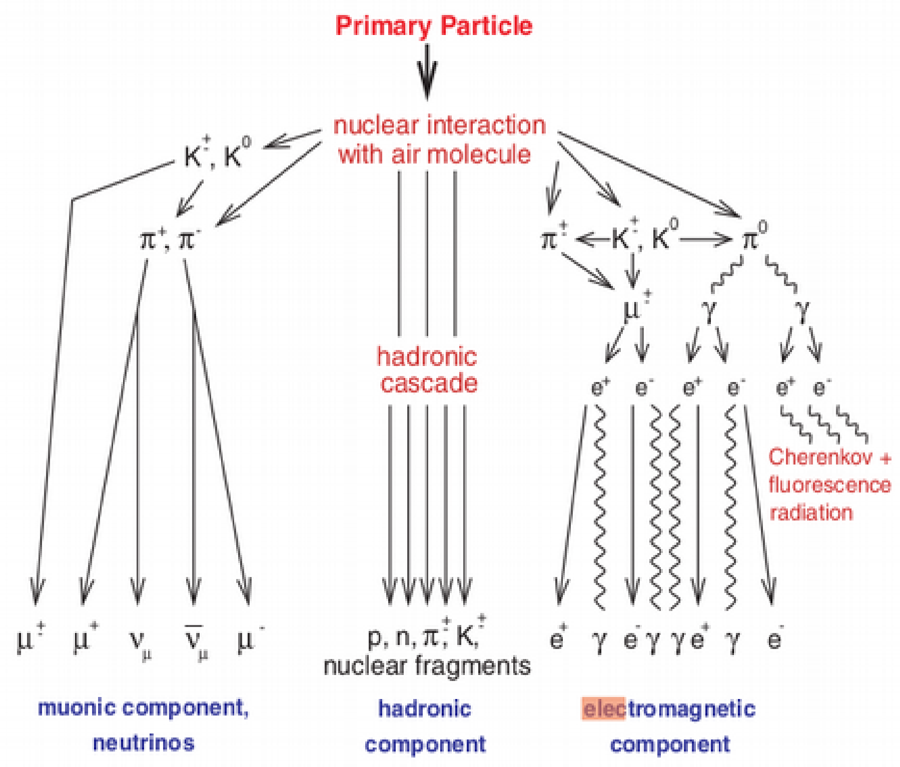


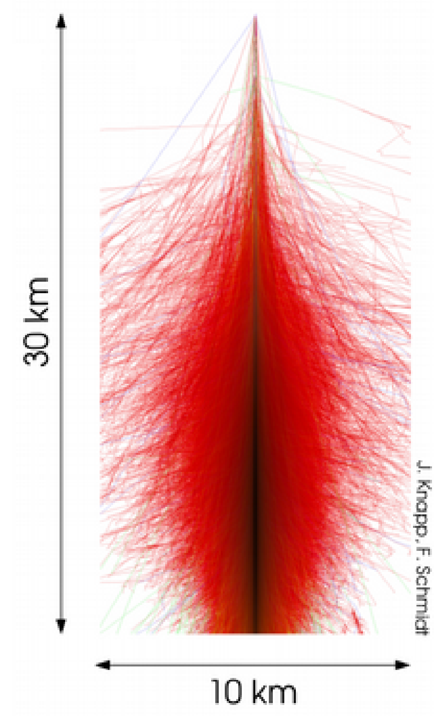
Electromagnetic & weak interaction (& gravitation)

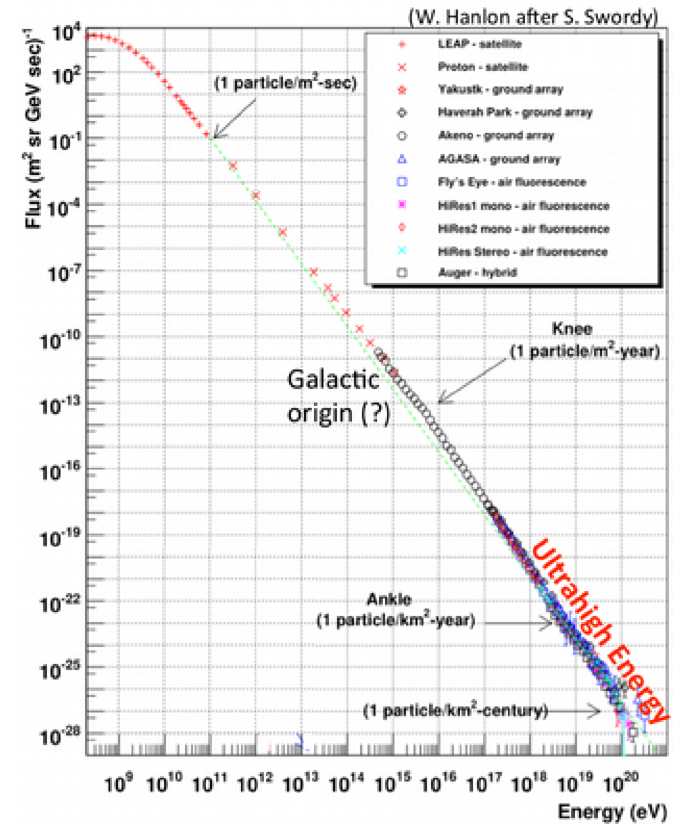


Muon discovery

Cosmic rays





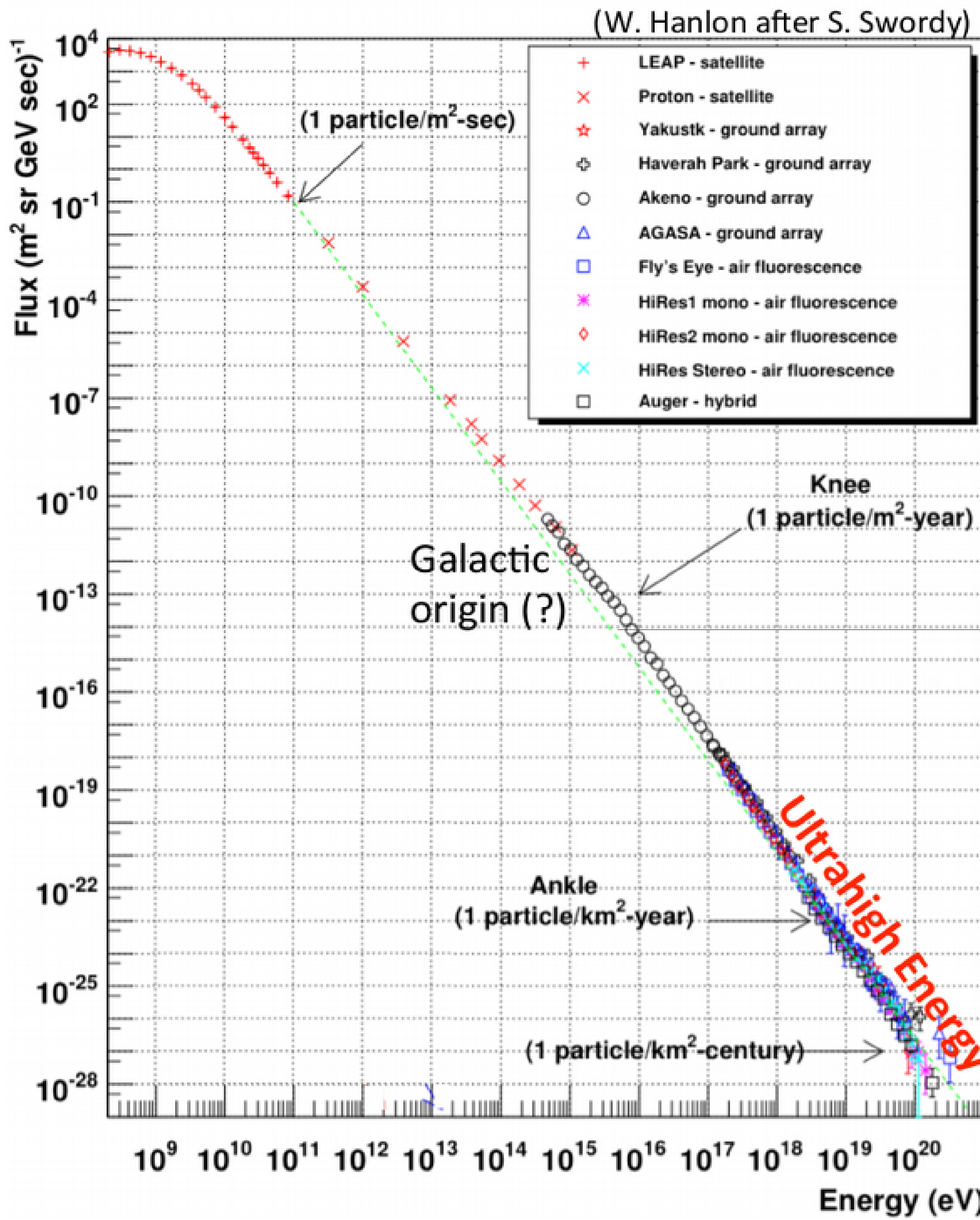


Simulation proton 10^{14} eV

- The most penetrating component of atmospheric showers: the muon component
- At sea level muons represent about 80% of the cosmic ray flux
  - averaged over all energies
  - above E ≈ 1 GeV they contribute almost 100%
- Below 1 GeV the energy spectrum of muons is almost flat
- Above 100 GeV falls exponentially
- It extends to extremely high energies
- The average cosmic ray muon energy is 4 GeV

Muon discovery

Cosmic rays



Galactic phenomenon
- -Super Novae
- -Neutron stars
- -???

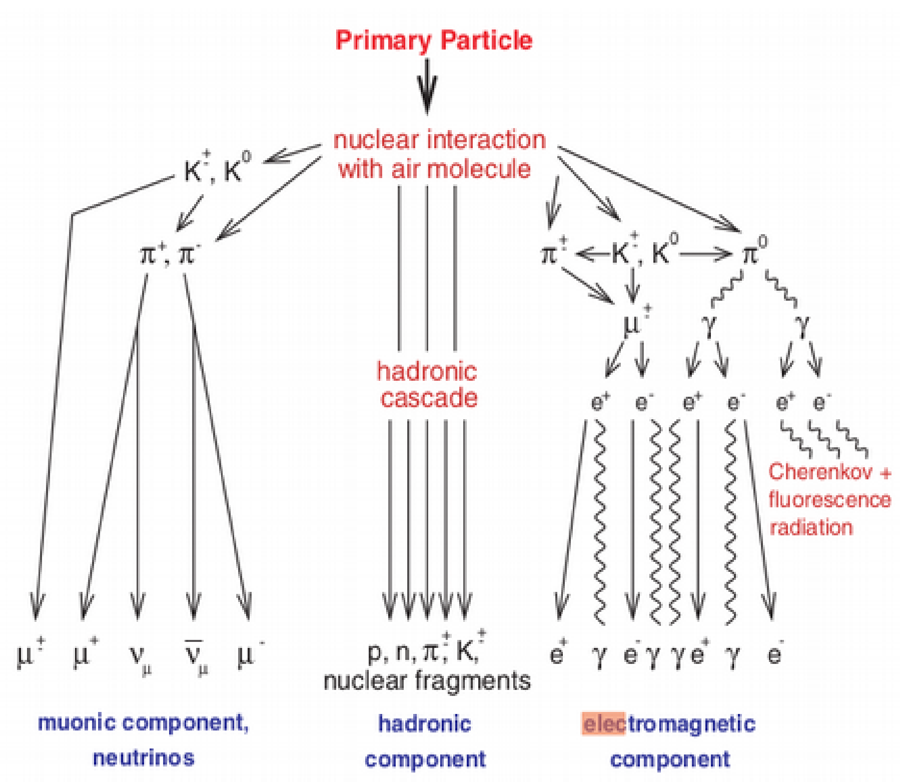
Satellite detection

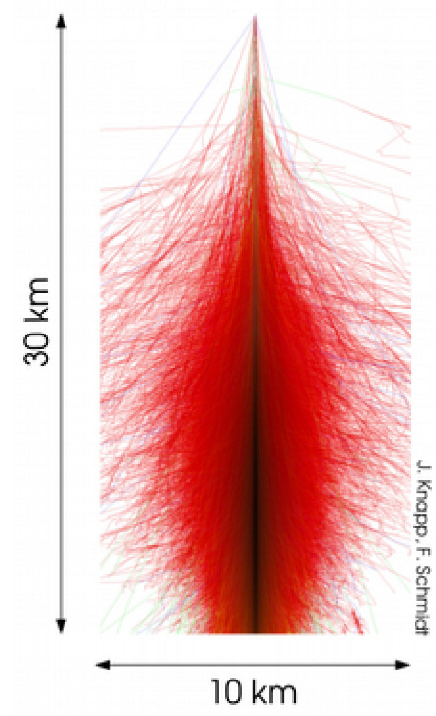
Ground detection

Extra-galactic phenomenon
- -Galaxy collisions
- -Gamma Ray Burst
- -Active Galactic Nucleus
- -???

Muon discovery

Cosmic rays





Simulation proton 10^{14} eV

Thomas A. Anderson
(matrix 1)

Cloud chamber

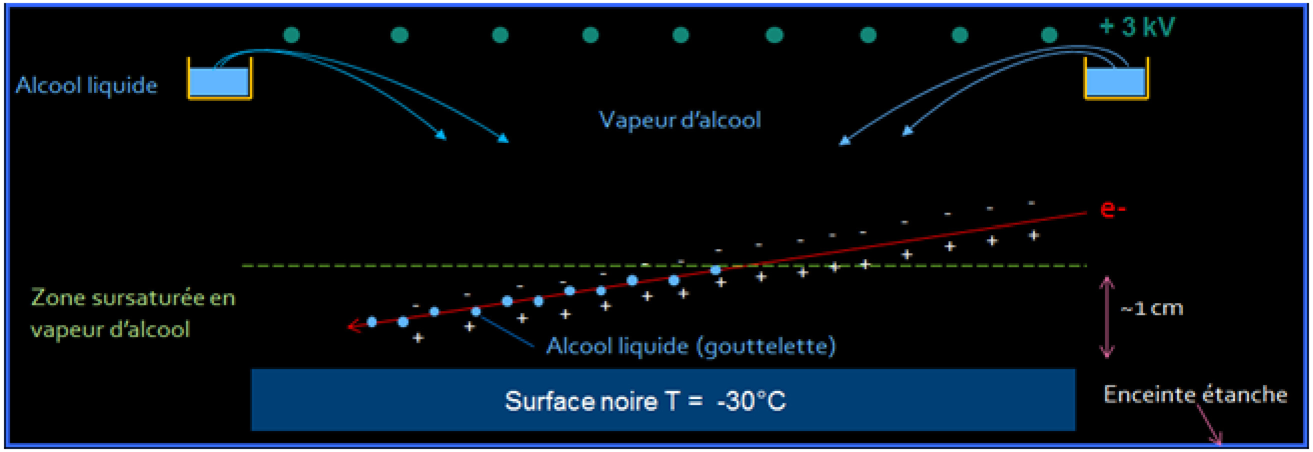
$$p + N \rightarrow X + \begin{cases} \pi^0 \rightarrow \gamma\gamma & \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu & \sim 100\% \\ \pi^+ \rightarrow \mu^+ + \nu_\mu & \sim 100\% \end{cases}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

(+ k⟶ π,μ,... +...)

Muon discovery

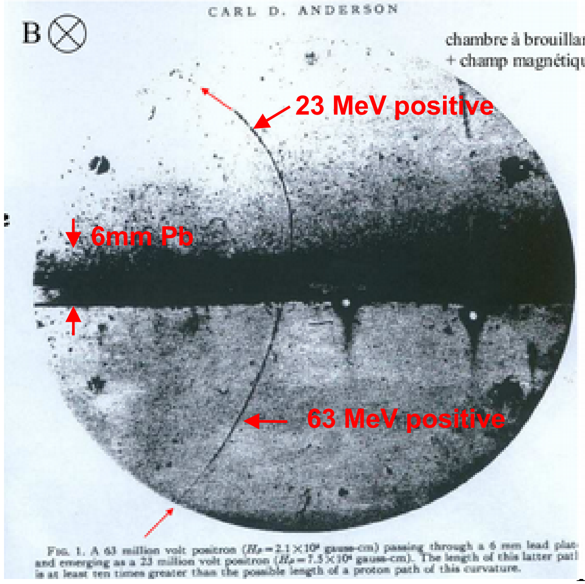
Cosmic rays



Cloud chamber

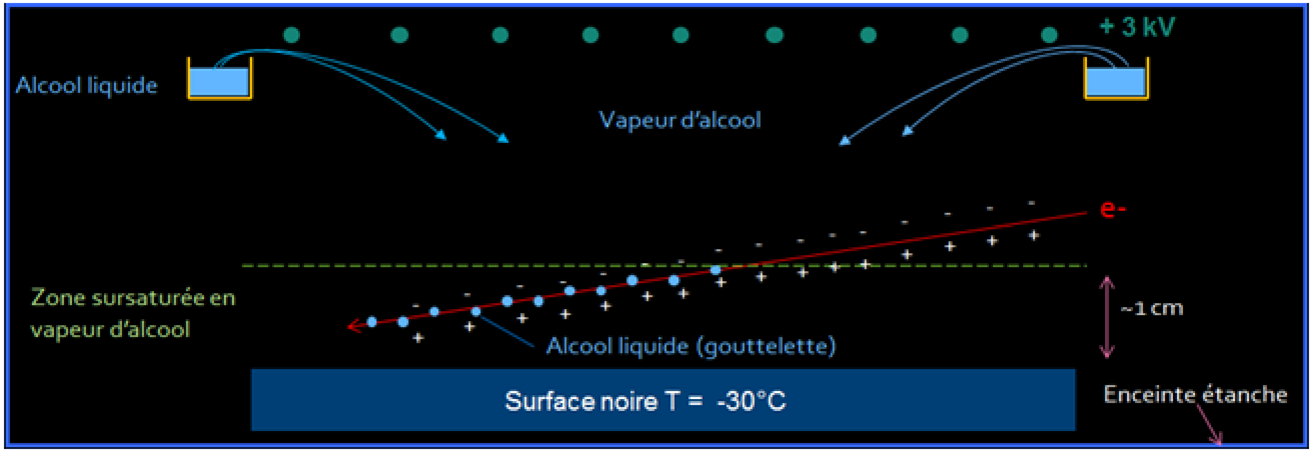
Carl David Anderson
(1905-1991)

1932 Positron discovery
anti-electron,Paul Dirac's theoretical prediction



Muon discovery

Cosmic rays



Cloud chamber

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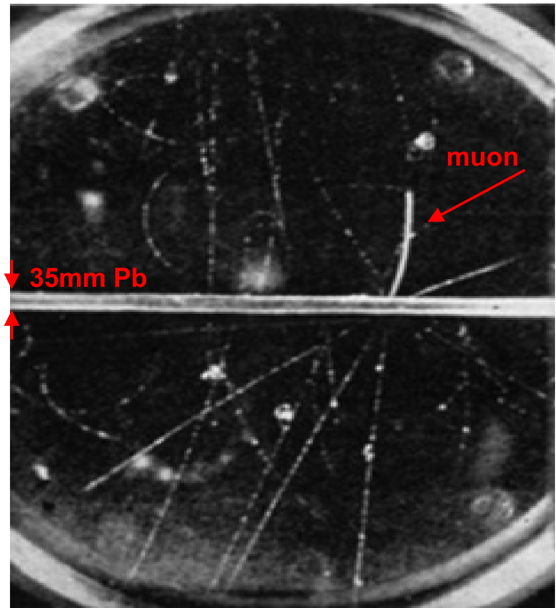
(1905-1991)

1932 Positron discovery
anti-electron,Paul Dirac's theoretical prediction

1936 Muon discovery
Mu-meson* ! (wrong naming)
"Who ordered that?" (I. I. Rabi)



* meson: 1 quark + 1 anti-quark

Muon discovery

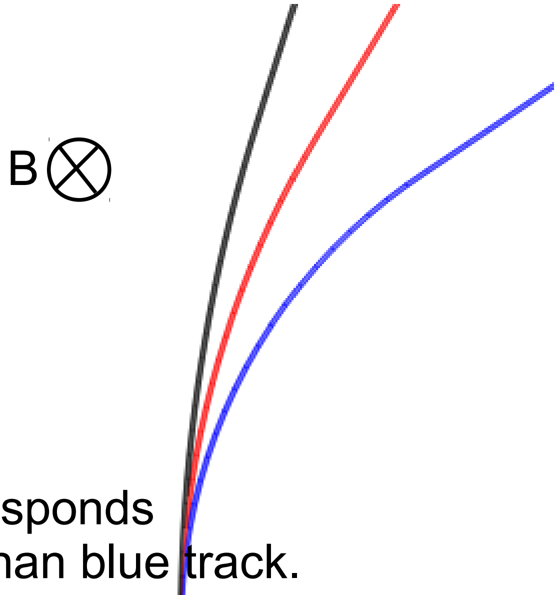
Phys. Rev. 51 (1937) 884

The experimental fact that penetrating particles occur both with positive and negative charges suggests that they might be created in pairs by photons, and that they might be represented as higher mass states of ordinary electrons.

Independent evidence indicating the existence of particles of a new type has already been found, based on range, curvature and ionization relations; for example, Figs. 12 and 13 of our previous publication.[1] In particular the strongly ionizing particle of Fig. 13 cannot readily be explained except in terms of a particle of e/m greater than that of a proton. The large value of e/m apparently is not due to an e greater than the electronic charge since above the plate the particle ionizes imperceptibly differently from a fast electron, whereas below the plate its ionization definitely exceeds that of an electron of the same curvature in the magnetic field; the effects, however, are understandable on the assumption that the particle's mass is greater than that of a free electron. We should like to suggest, merely as a possibility, that the strongly ionizing particles of the type of Fig. 13, although they occur predominantly with positive charge, may be related with the penetrating group above.

Carl David Anderson
(1905-1991)

Observation



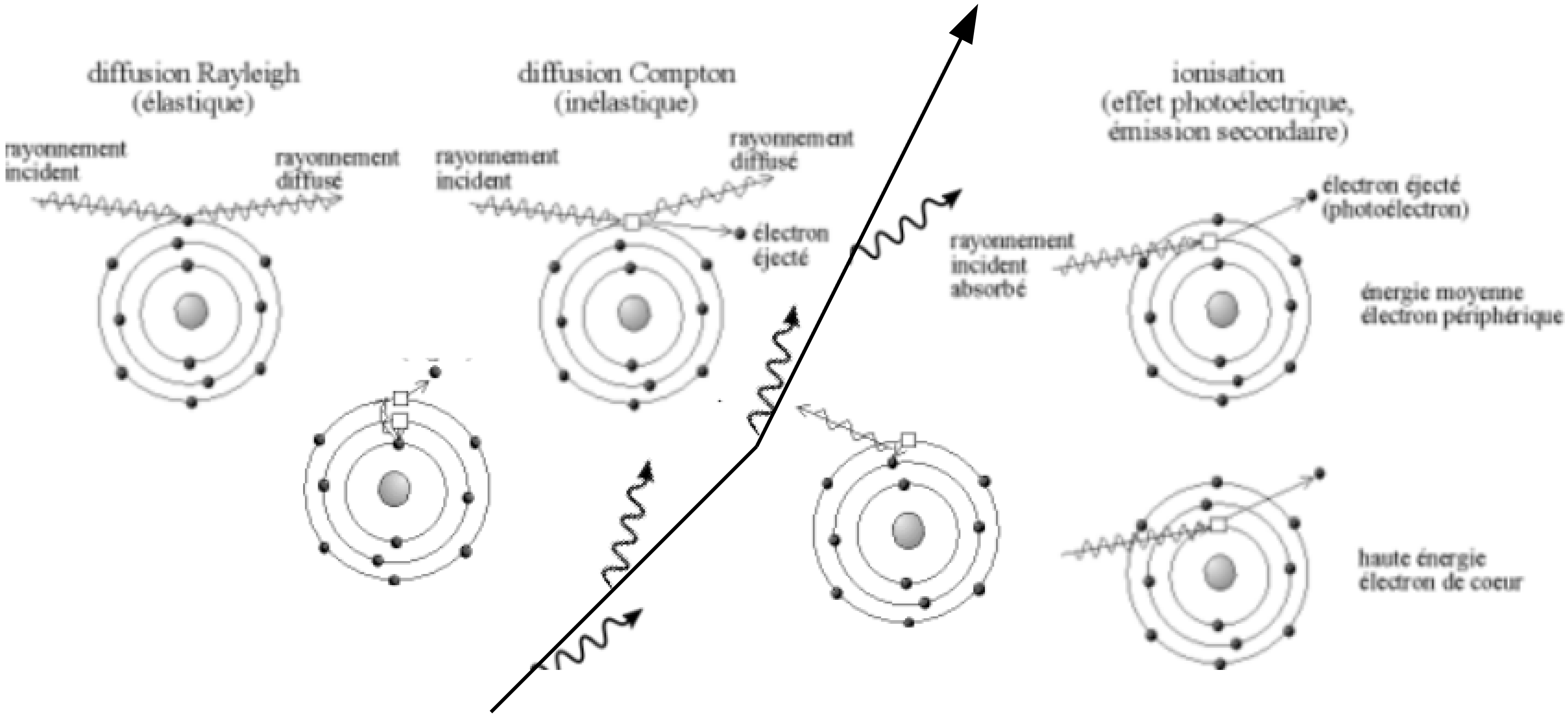
For a given B and P
the black track corresponds
to a heavier object than blue track.
So the red track correspond to an intermediate mass object

Example:proton,muon,electron

Interaction Particle-Matter

Charged particle trajectory through matter

- Many different mechanisms occur
- Marco Delmastro
  - Particle interactions in particle detectors



Interaction Particle-Matter

Particles are detected by their interactions with the traversed medium

- Electromagnetic, strong & weak interactions (and gravity...must be forgotten)

Mainly Electromagnetic mechanism is used in our detectors

- Ionisation (dE/dx)
- Bremsstrahlung radiation
- Cherenkov radiation
- Transition radiation

Perturbations

- Landau fluctuations
- Multiple scattering
- Pairs creation (e+/e-)

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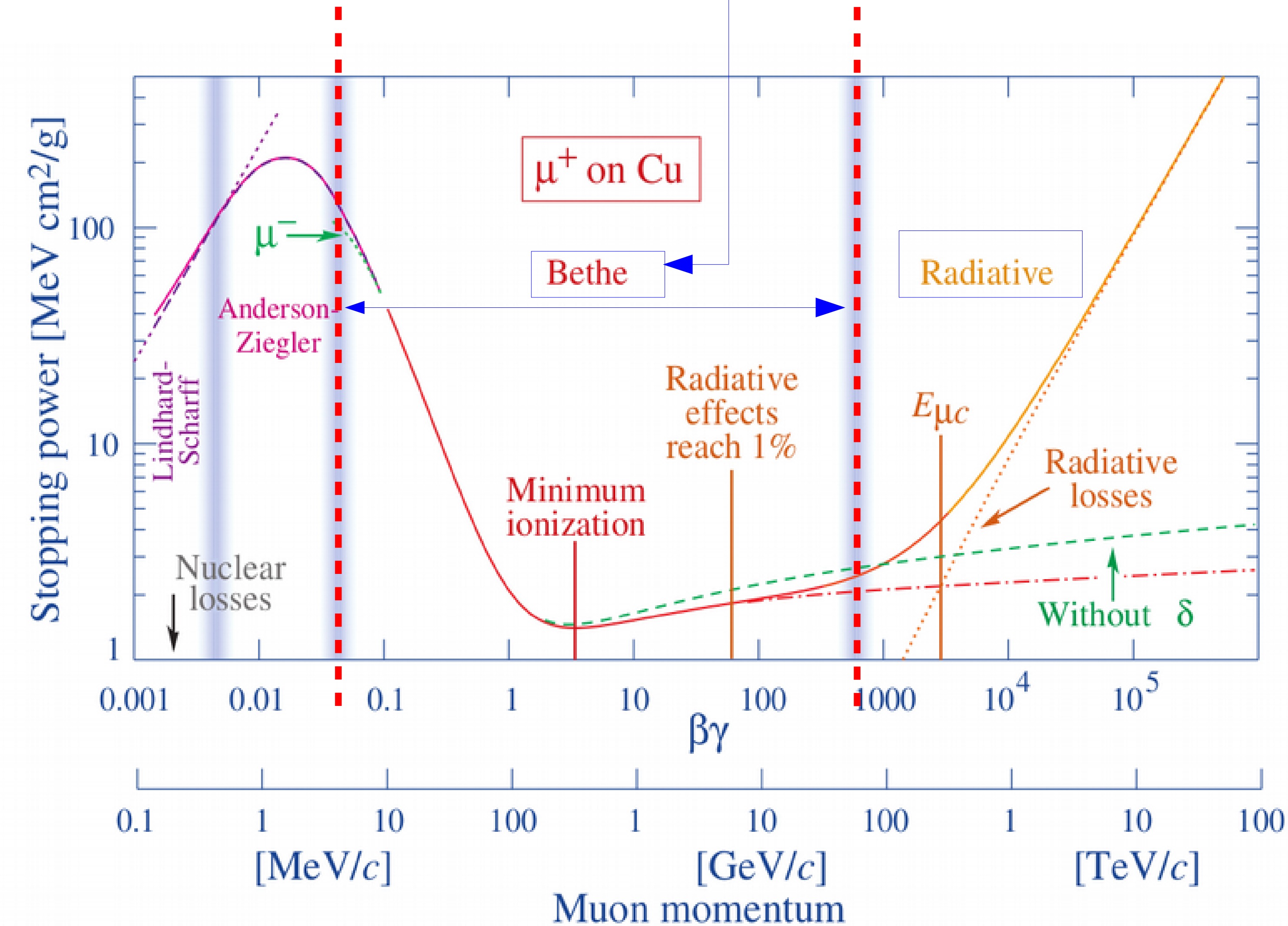
Interaction Particle-Matter

Marco Delmastro
(in particular for T_{max},I,K)

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



Interaction Particle-Matter

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}]$$

Remarks:

$$\frac{dE}{dx} \; \alpha \; \frac{1}{\beta^2} \ln(\beta^2 \gamma^2)$$

Interaction Particle-Matter

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$$\beta\gamma = \frac{P}{m}$$

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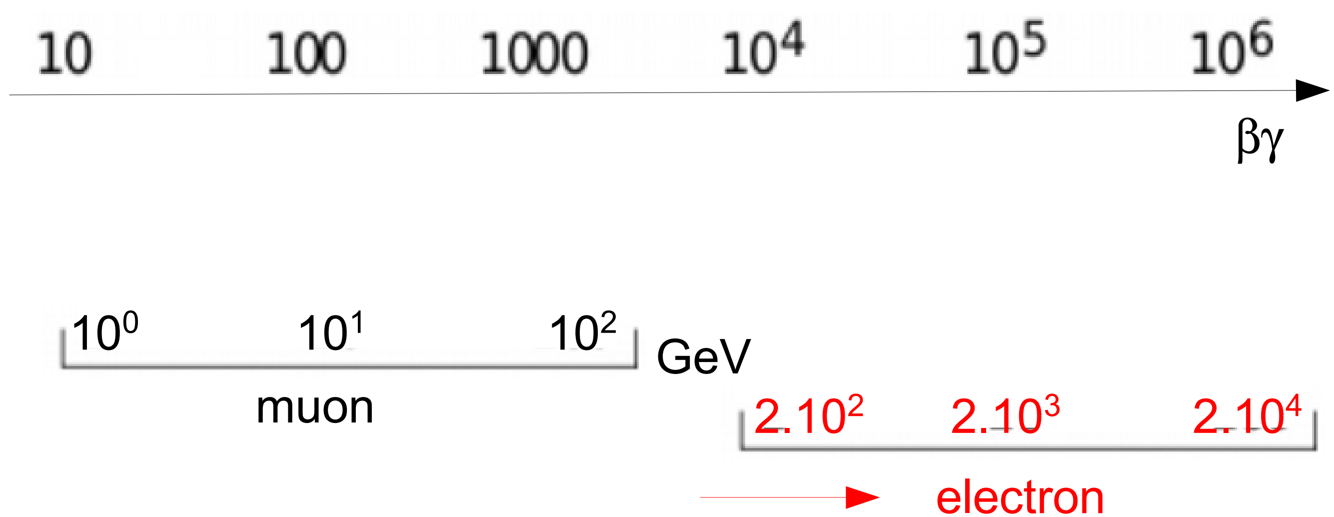
Remarks:

$$\frac{dE}{dx} \;\alpha\; \frac{1}{\beta^2}\ln(\beta^2\gamma^2)$$

$$\beta\gamma = \frac{P}{m}$$

$$\beta\gamma \longrightarrow \text{muon}$$

$$\frac{P}{m_\mu} * 207 = \frac{P}{m_e}$$



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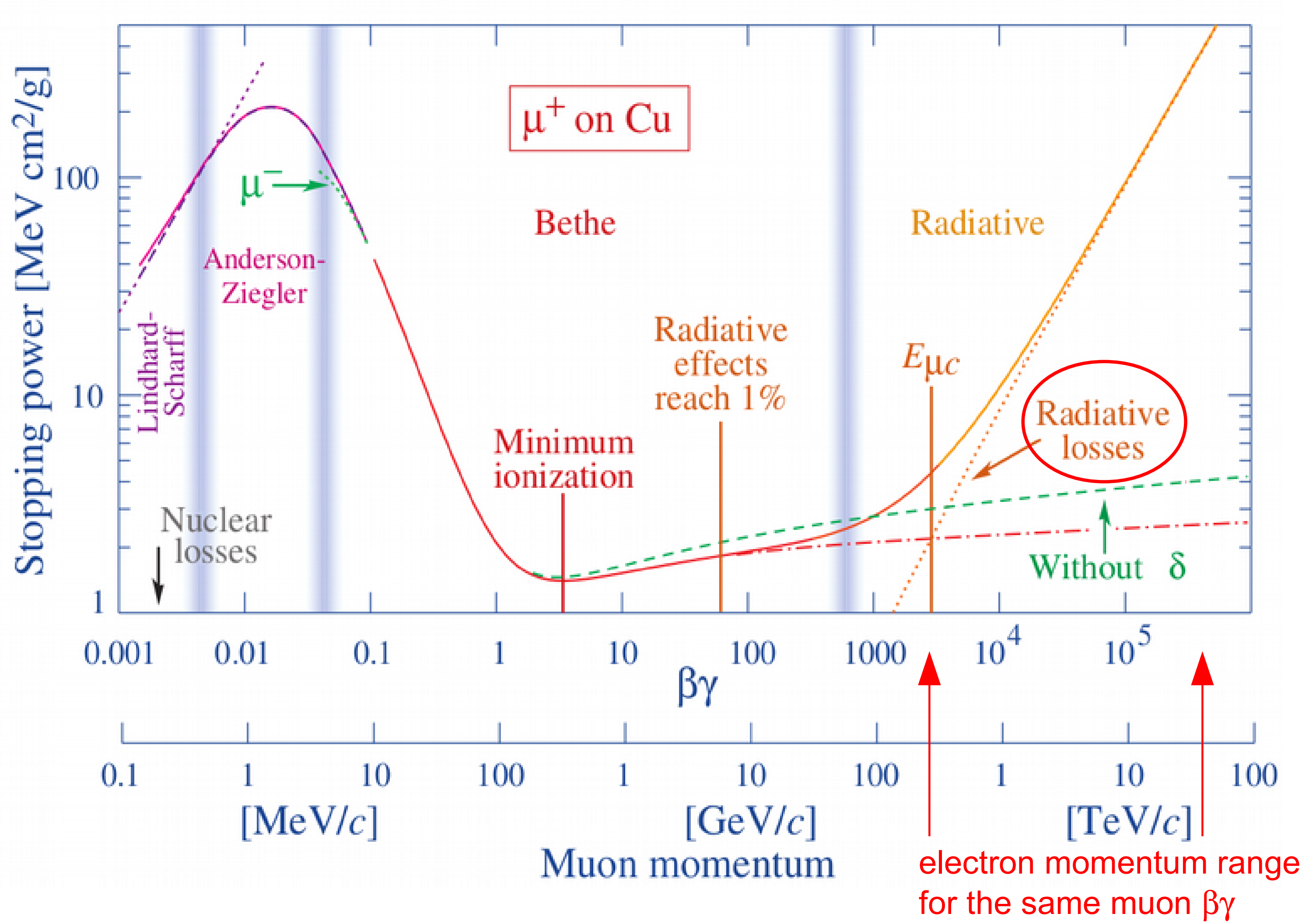

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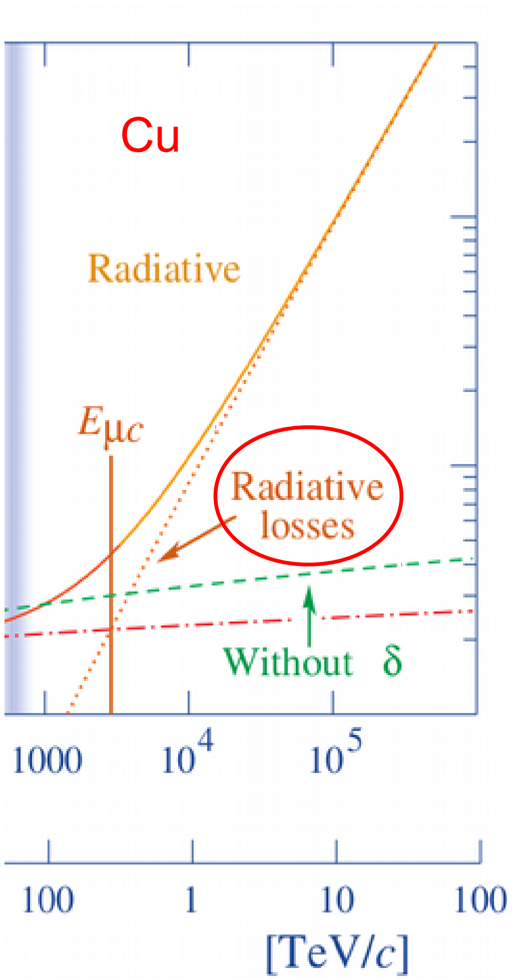
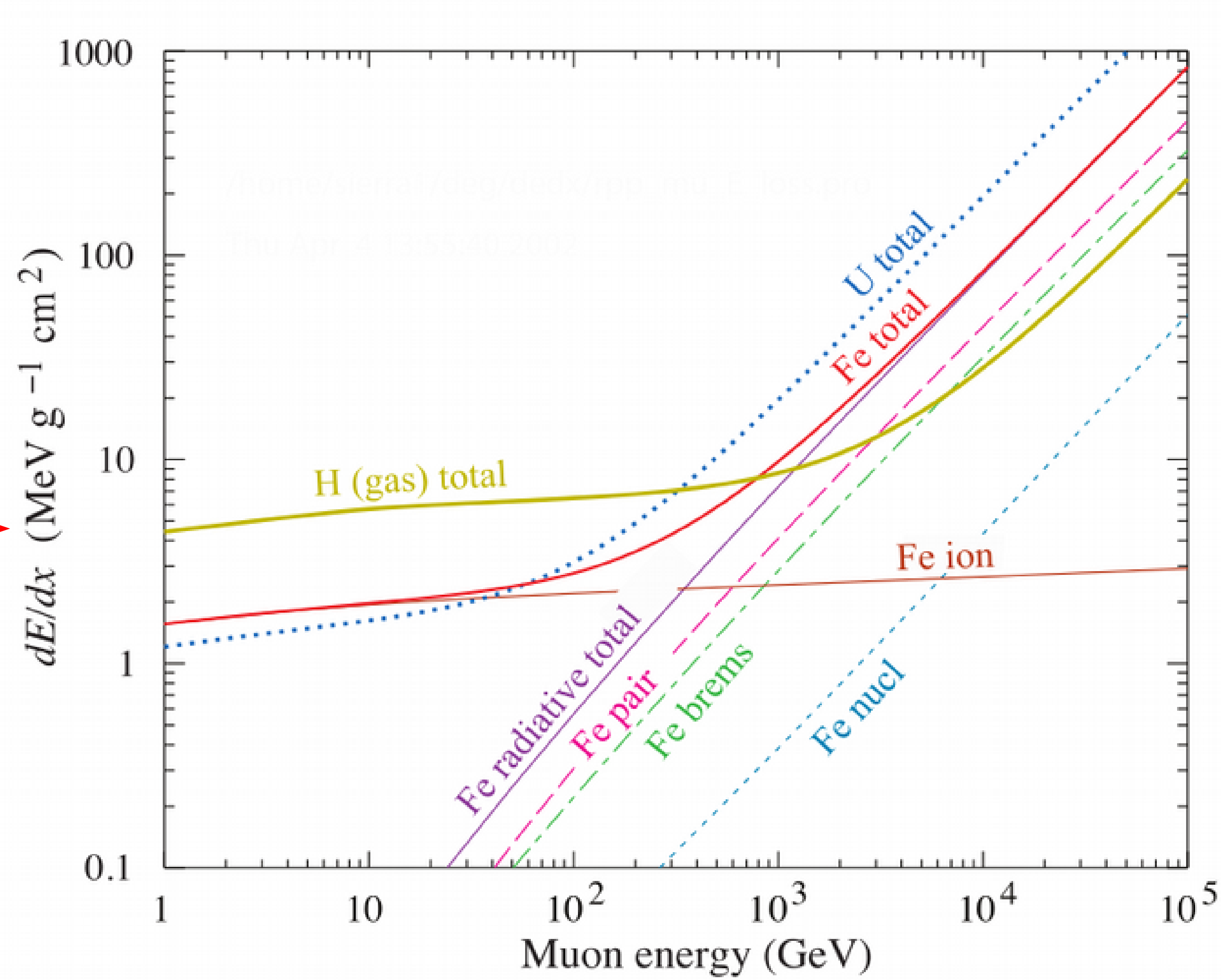
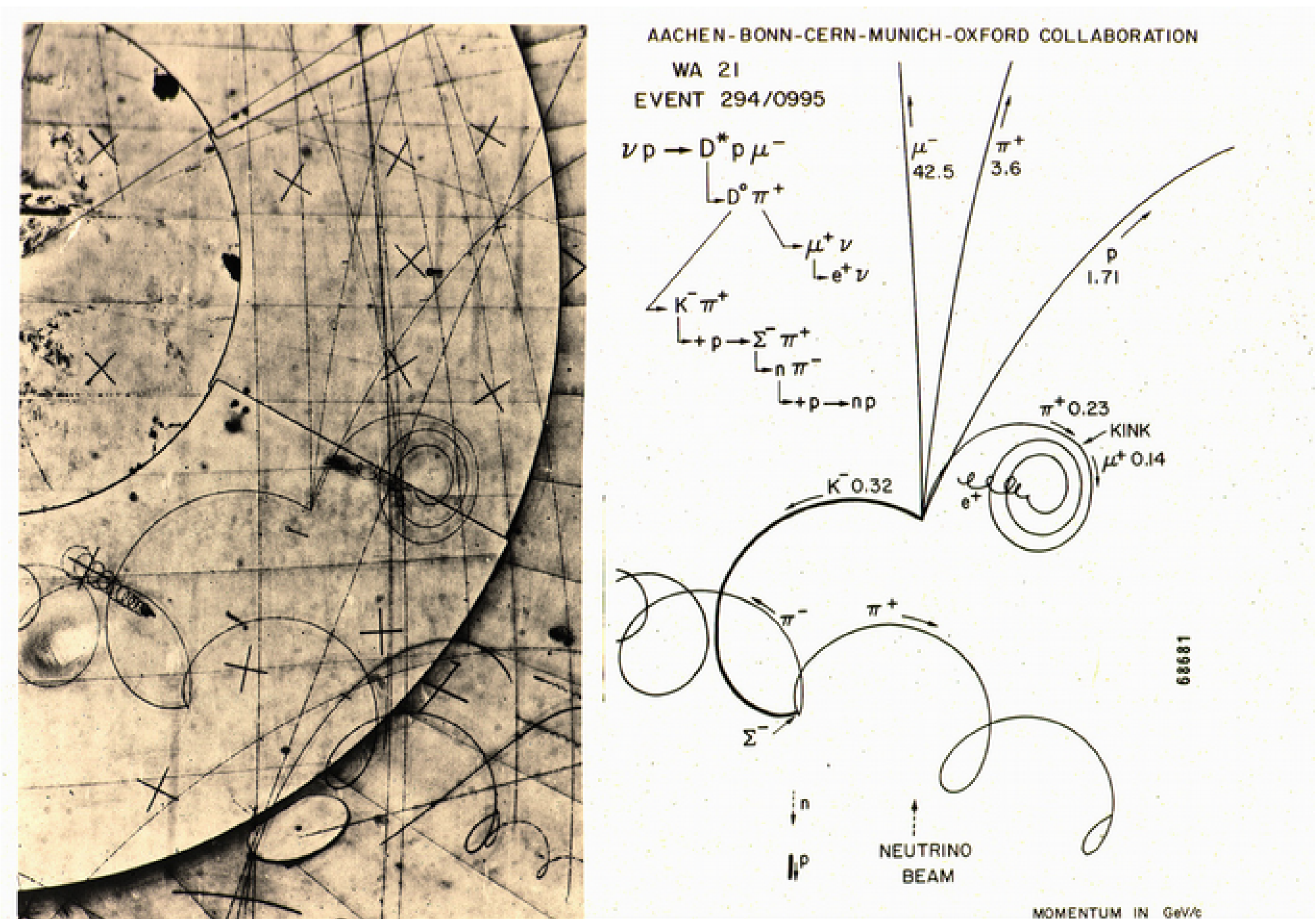




Detectors

Detectors

Definition:
a detector is an instrument which is used to keep a track of a phenomenon
- -trace in the sand
  - (sand is the detector)
- -visible light
  - (eyes are the detectors)



analogical

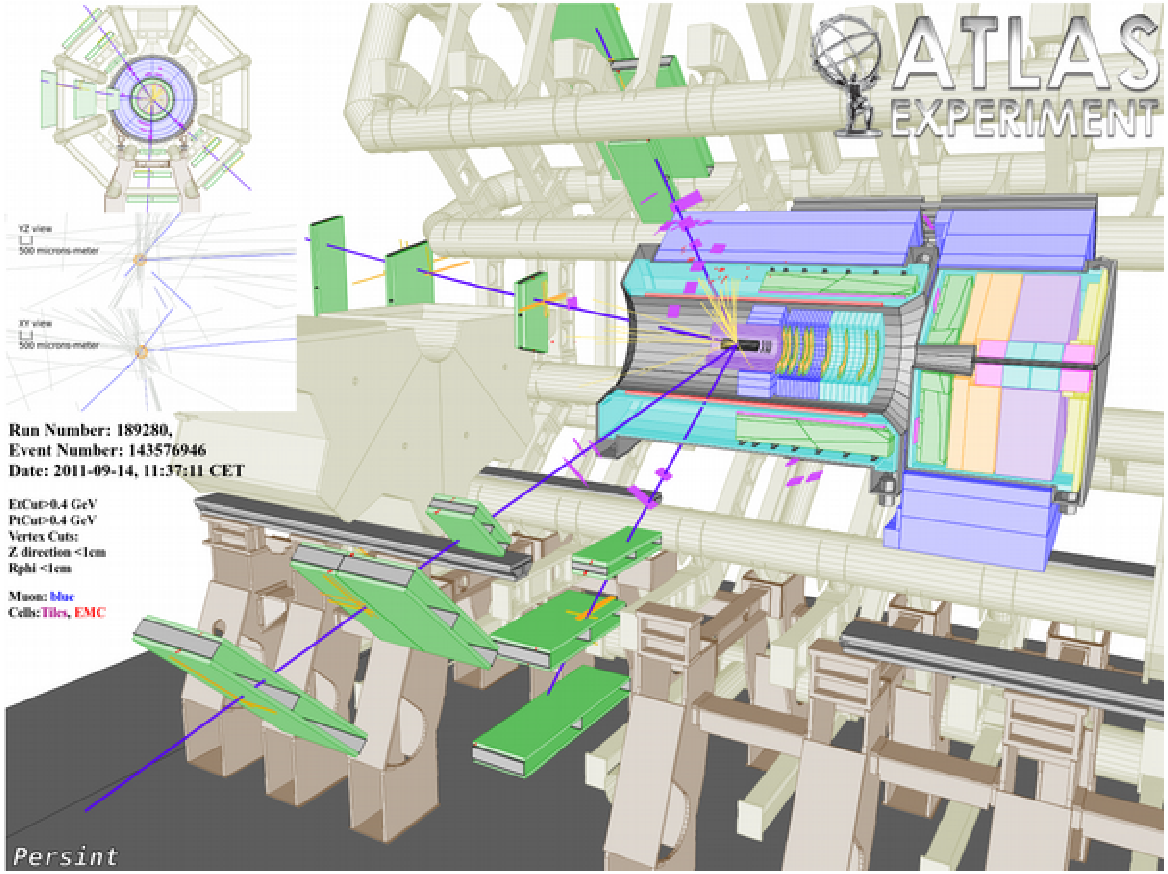
Bubble chambers

Detectors

Different types of detectors must be used
to understand and to keep the track of a phenomenon:

- -different types of particles,
- -different way to interact with matter,
- -fast detectors,
- -precise detectors (spatially)
- -...

One big detectors is made by many sub-detectors with precise tasks



numeric

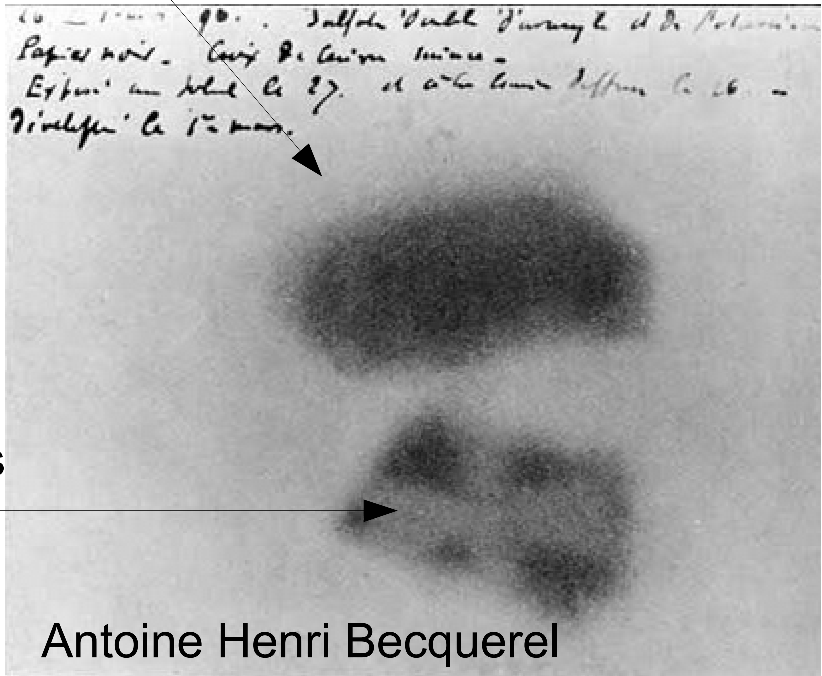
Detectors

Different types

- Gaseous
  - Geiger counter, wires chamber (TPC), Micro-Megas
- Liquid
  - Bubbles chamber
- Solid
  - Scintillator, Silicon, Photographic plates
- Mix

Principle:Ionisation

image of a copper cross

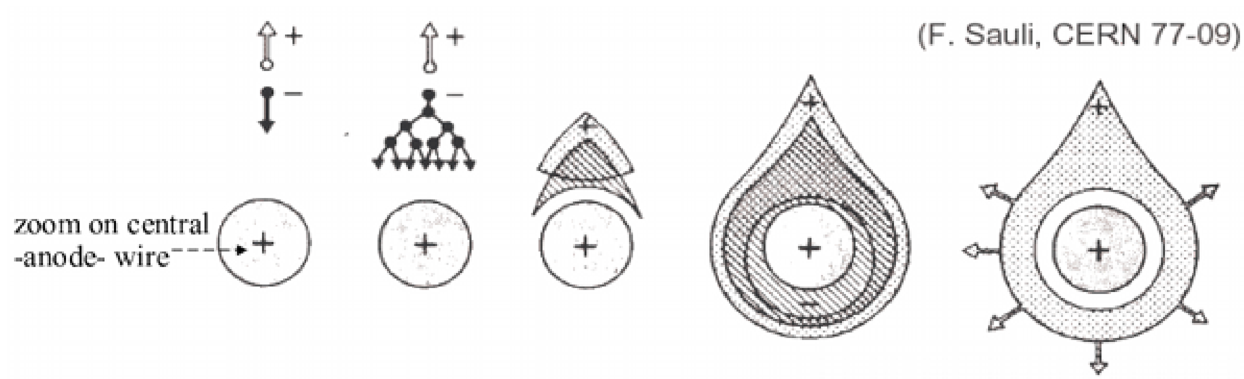


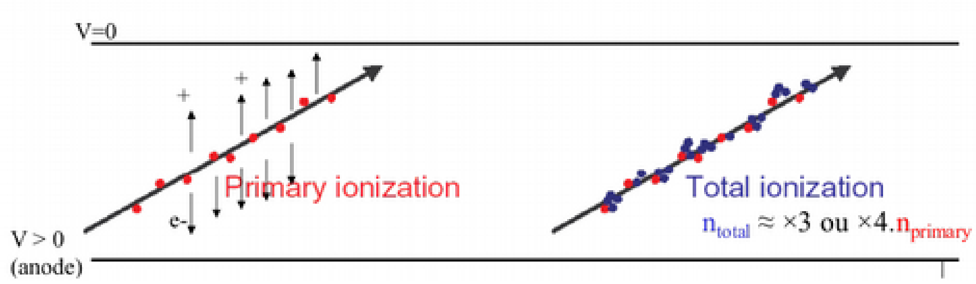
Antoine Henri Becquerel

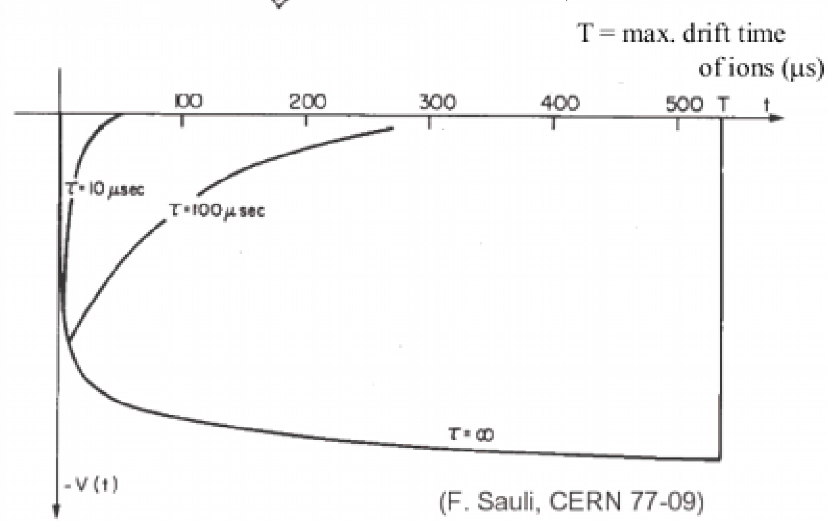
Detectors (Gaseous)

Principle:

- Primary and secondary ionisation not enough for a measurement
- Electric Field (high!) => Avalanche
  - Electric Field increase the number of electrons
  - The drift of Ions induces a variation of the potential, which is measured



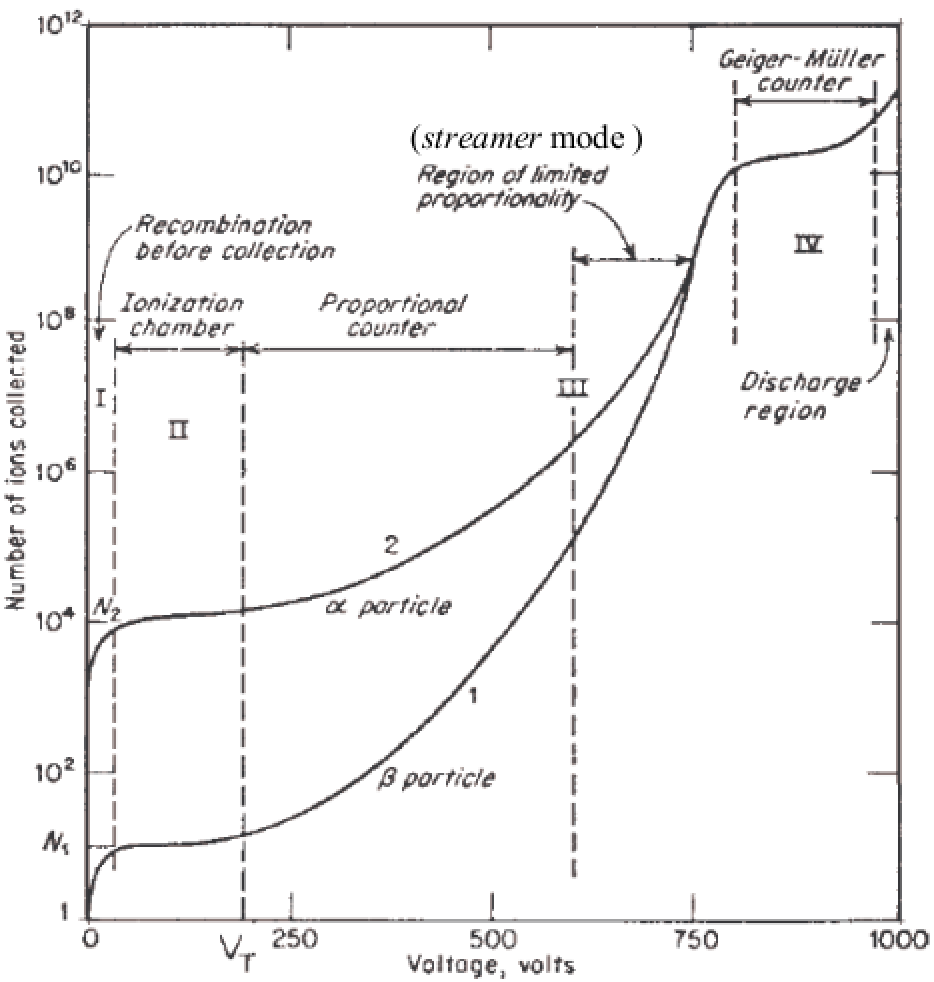




Detectors (Gaseous)

Gain vs Electric field

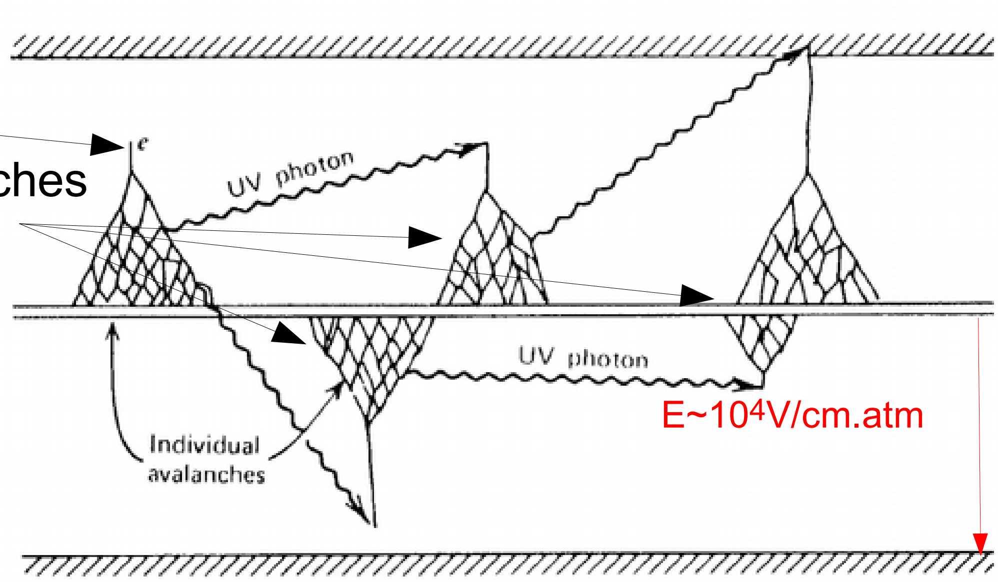
- I   Potential too weak, pair recombination
- II   Ionisation Chamber: no amplification
- IIIa Proportional mode, signal amplification
  - Proportional to ionisation.
  - Gain: 10^4 to 10^5
- IIIb Streamer mode, secondary avalanches
  - Need "quencher" (CH_4,CO_2,...)
- IV   Geiger-Muller mode



Remark: no electric field => no electrons acceleration: recombination

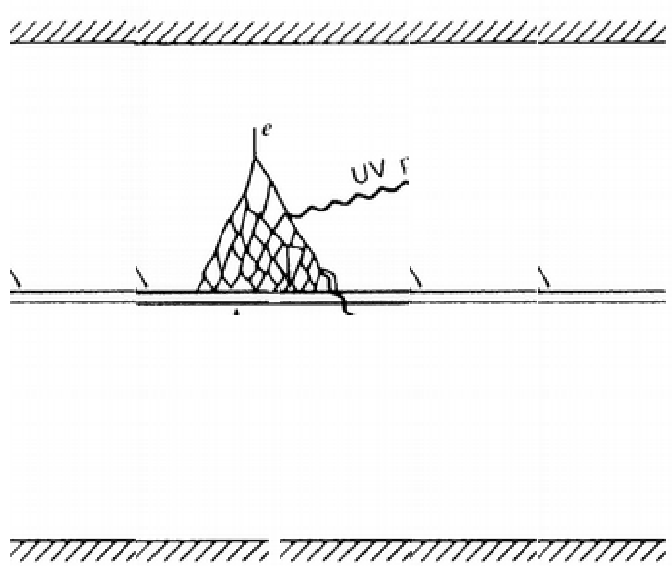
Detectors (Gaseous)

Primary electron + 10^4V/cm → Avalanche
UV photons (from the avalanche) → many Avalanches

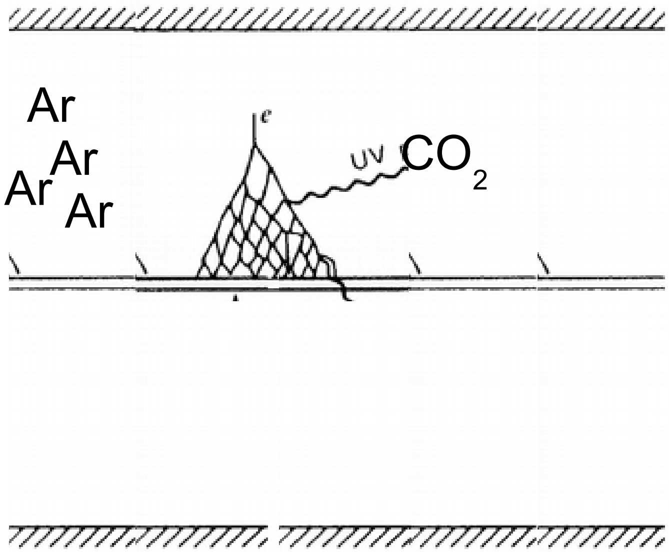


Spatial Resolution

- Avoid secondary avalanches
- Photons absorption (UV production)
- Noble gaseous (He,Ar,...)



Detectors (Gaseous)



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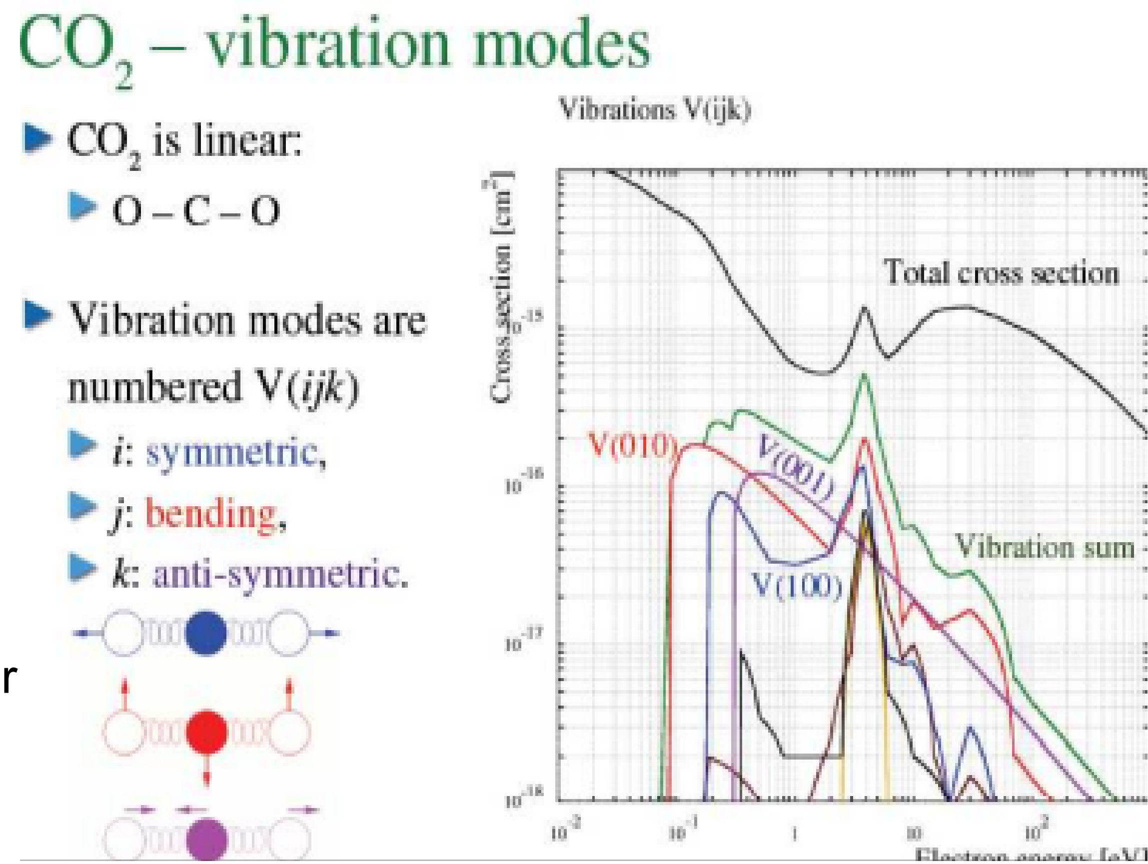


"Quencher"

- Polyatomic gaseous:
  - ex: CH_4,C_4H_{10},CO_2
- Photons absorption by vibration or molecule rotation
- No easy solution: should be tested
  - Ex: 70%Ar, 29.6%C_4H_{10} , 0.4% Fr

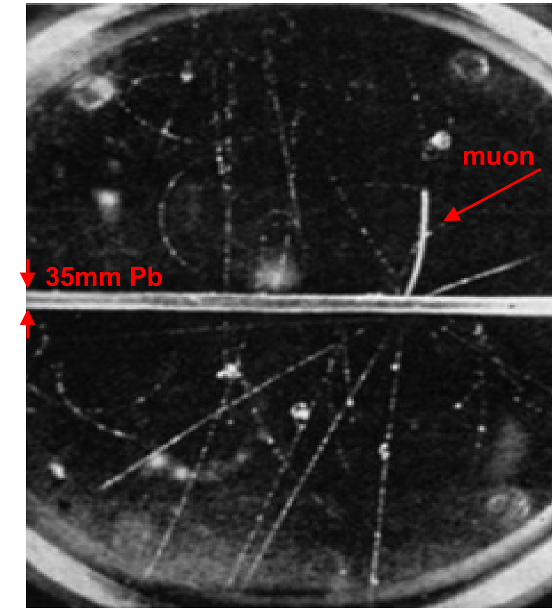
R.Veenhof (Garfield) http://cern.ch/garfieldpp

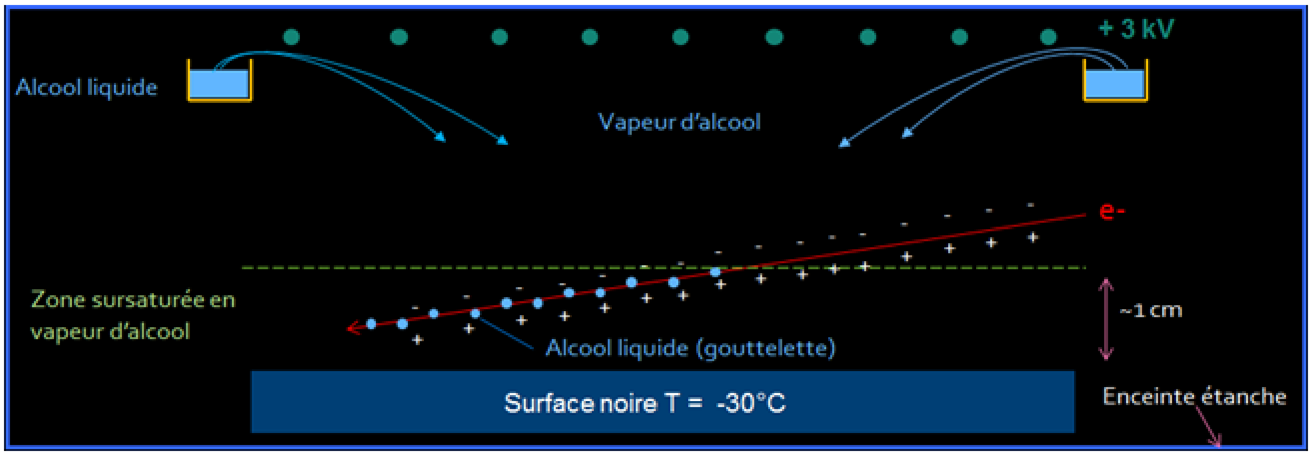
Detectors

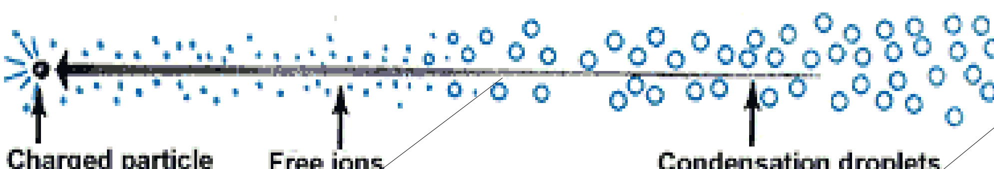
Clouds Chamber: Gaseous/Liquid

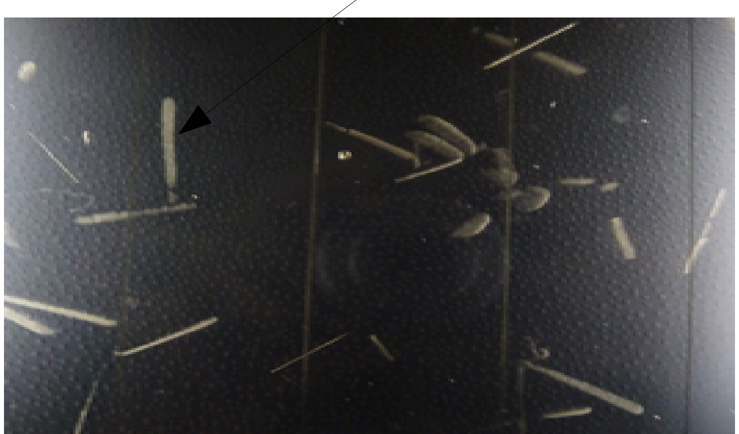
- C.T. R. Wilson 1911
- C.Anderson positron discovery 1932

Muon discovery 1936









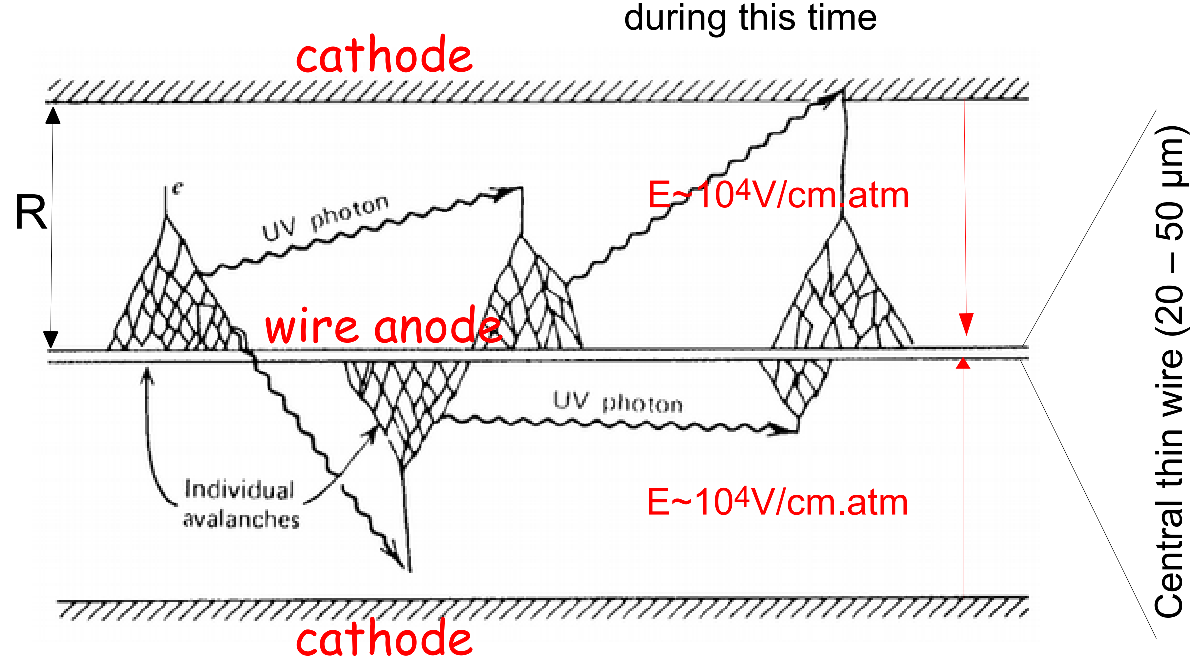
Broken cloud chamber
Physicist sad!

Detectors(Gaseous)

Geiger Counter

- H.Geiger-Muller 1928
  - Detection: Alpha(He), Beta (e+/e-), Gamma(photon), Muons
  - Gaseous: He, Ne, Ag
  - Avalanche: $n = n_0 e^{\alpha(E)x}$ (α Townsend coeff. function E or R)
  - > 10^8 electrons: sparks!!!
  - Particles counting only:
    - no measurement : position,energy,...

Dead time ! 10 ms!!!
No signal detected
during this time



Detectors(Gaseous)

Geiger Counter

Muon

- Used as a Trigger device
  New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron
  Phys. Rev. 52, 1003 – Published 1 November 1937

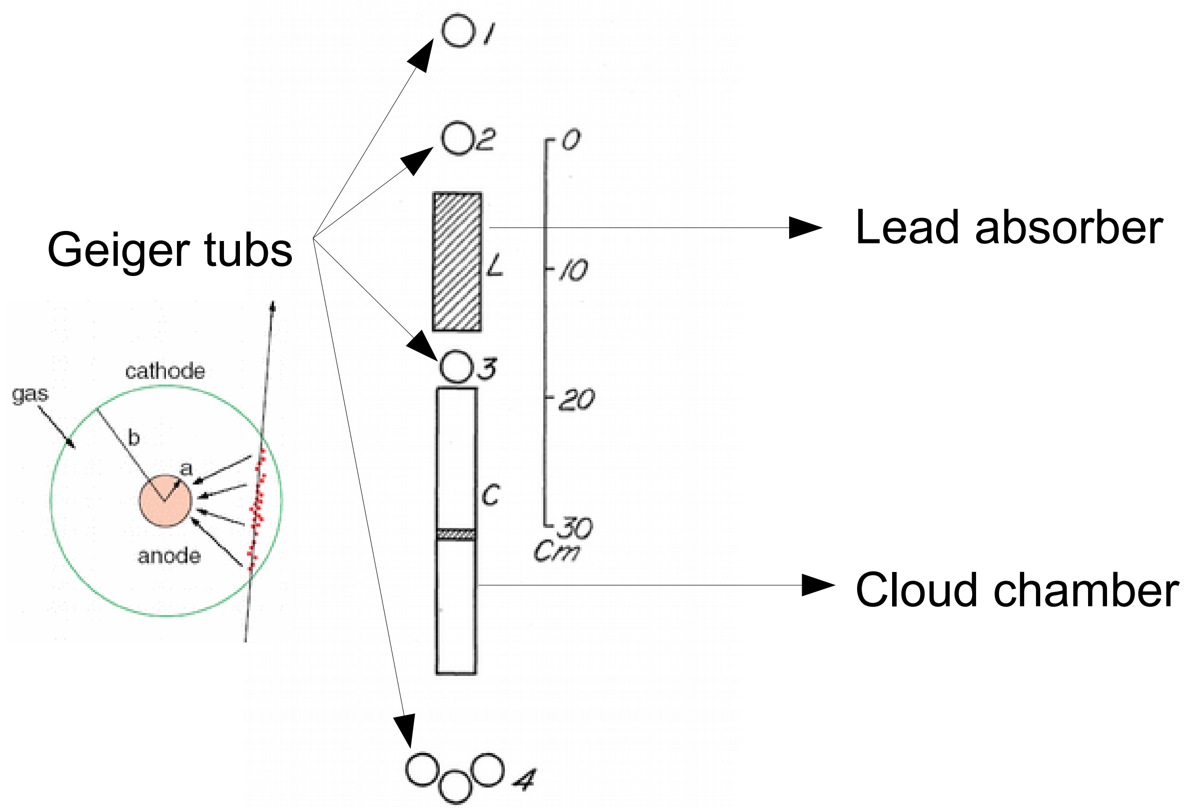


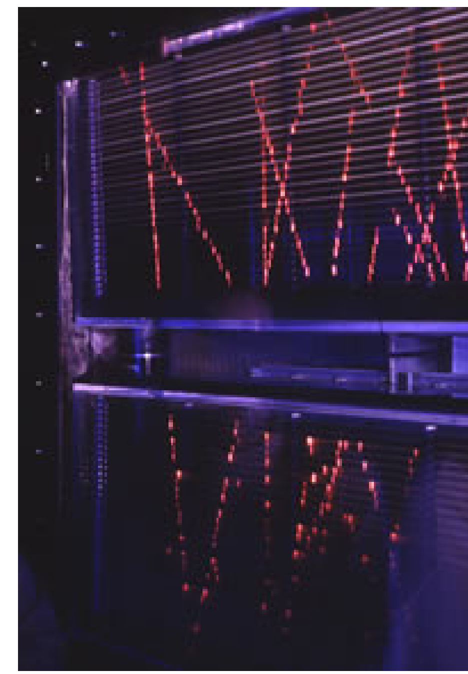
Fig. 1. Geometrical arrangement of apparatus.

Detectors(Gaseous)

Spark Chambers

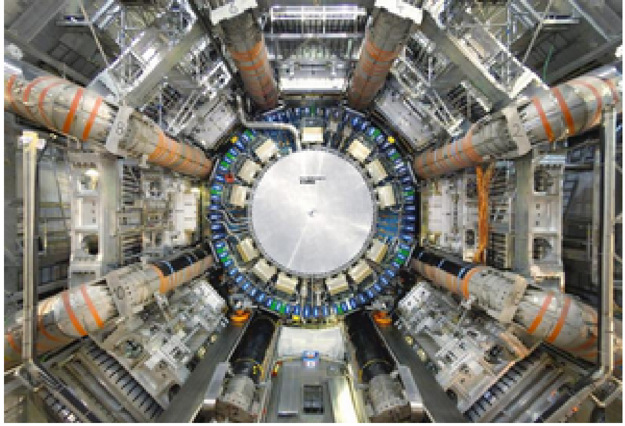
- Pairs of metal plates are connected to a HV ~10 kV creating a strong electrical field between the plates.
  Charged particles passing across the plates ionize the gas
  and create a conducting trace that leads to a spark between the two plates
  which is then photographed.

A spark chamber at the physics museum of the Sapienza University of Rome



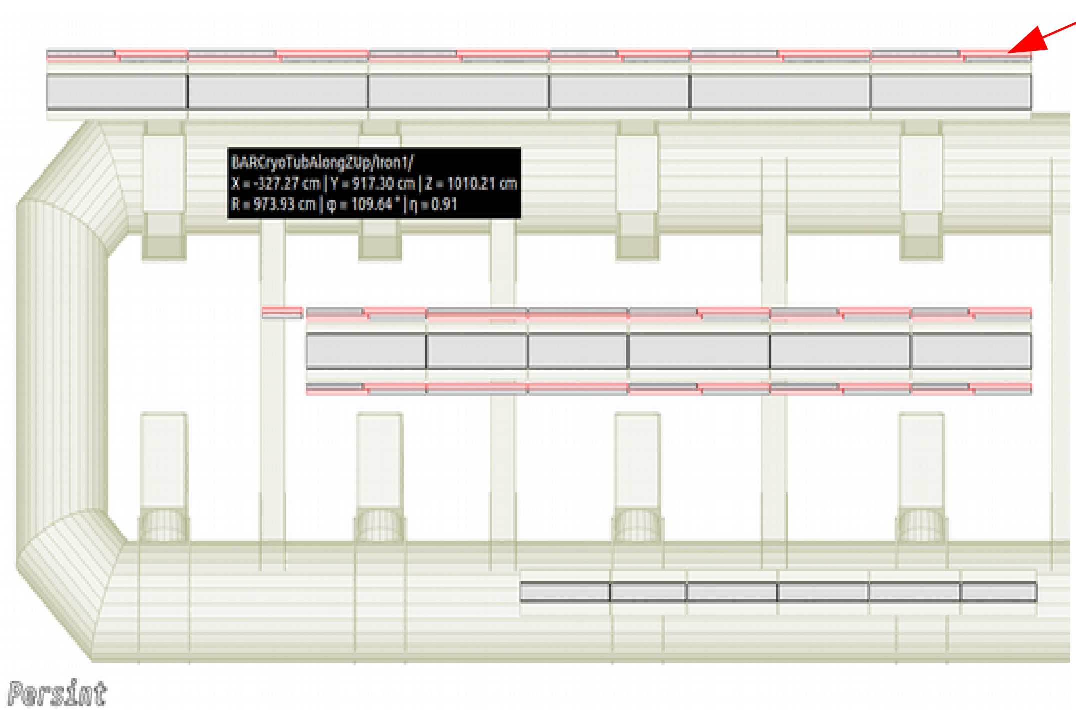
Remark:
HV applied 0,1 s à 1 μs
to avoid saturation

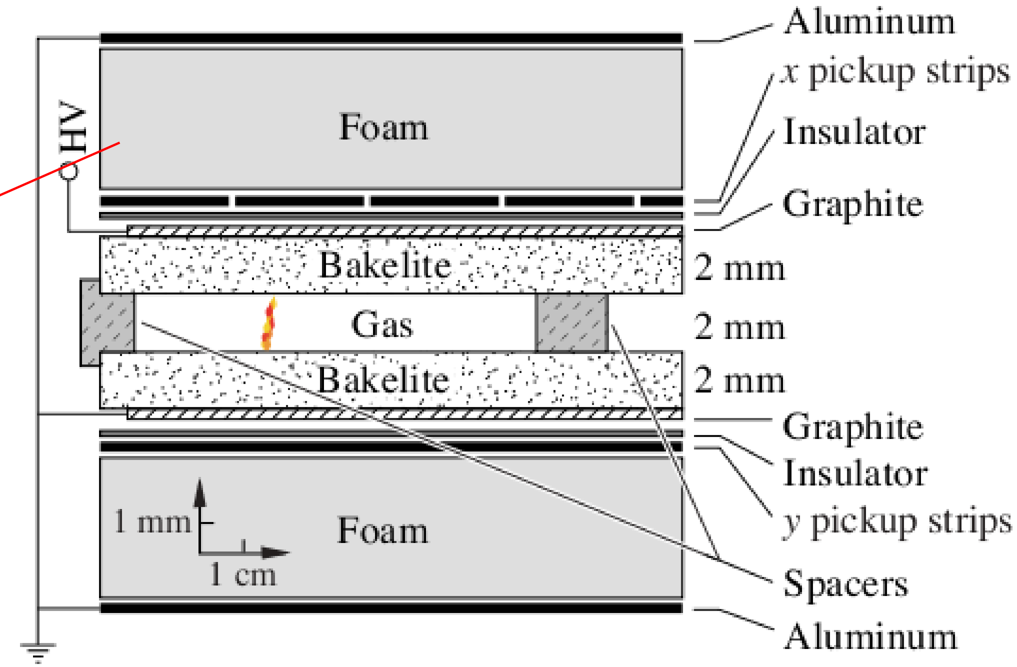
Detectors(Gaseous)



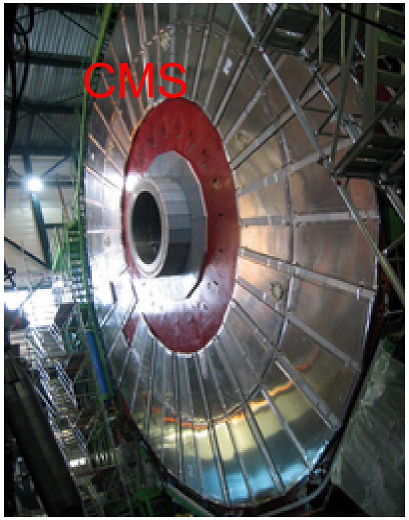
RPC: Resistive Plate Chamber

- ATLAS Muons spectrometer Trigger
- Time Resolution ~2ns!
- ~10KV between Bakelite plans
- Passage of the particle induced discharge (~ 300mV signal)
- Spatial resolution < ~1mm
- No wire !!!!
- Streamer (or avalanche) mode ATLAS/CMS





Detectors(Gaseous)



RPC: Resistive Plate Chamber

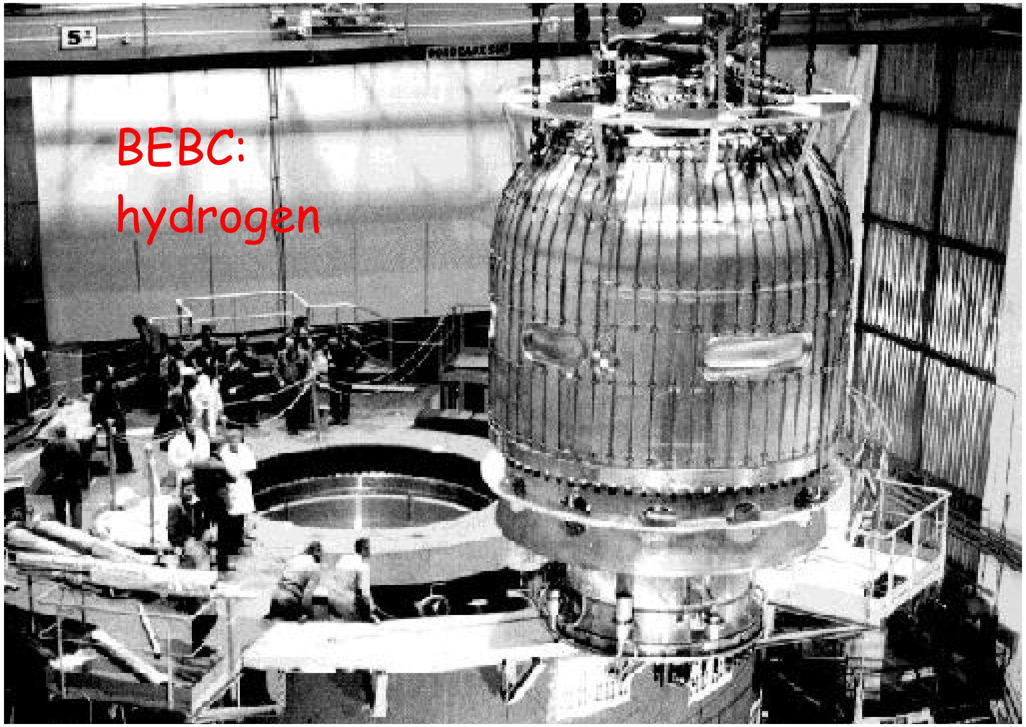
- ATLAS Muons spectrometer Trigger
- RPCs are robust detectors (no wire)
- The signal formation happens in the conversion gap as soon as the ionization electrons amplify and the avalanche develops. The signal is induced instantly on the readout strips placed on the outside of the resistive plates. RPCs are therefore fast detectors and achieve time resolutions in the ns range (or better)
- In standard RPCs the resistive plates are Bakelite with a bulk resistivity of ≈1010 Ohm/cm (CMS, ATLAS, Babar, …)
- The weak point of the RPCs is their rate limitation owing to the high bulk resistivity in the resistive plates, leading to local charging up, followed by a loss of efficiency.
- RPCs are considered safe up to rates of about a few kHZ/cm2

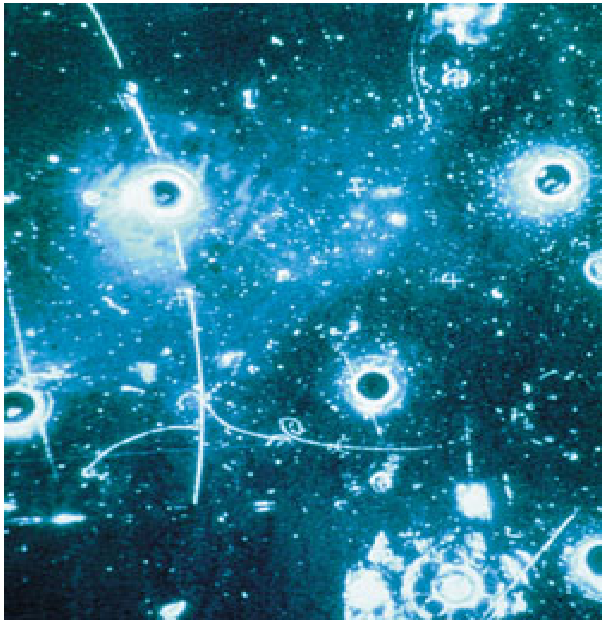
Detectors

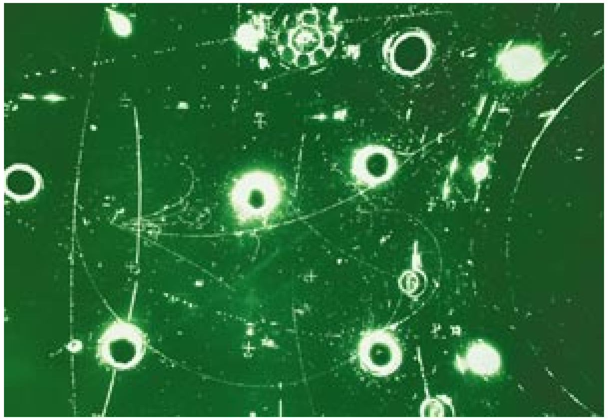
Bubbles Chamber : Liquid/Gaseous

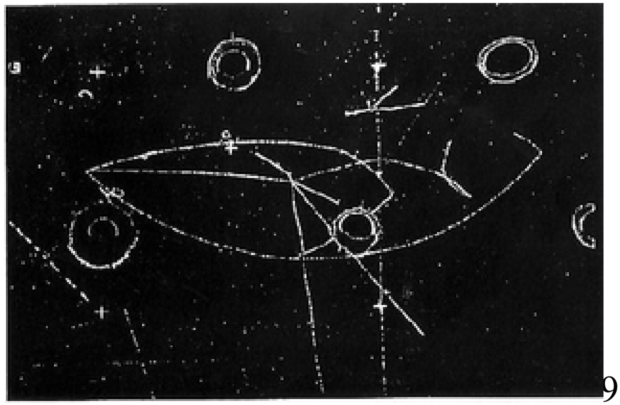
- C.Glaser 1952
  - Liquid phase + bubbles (gaseous)

- Gargamelle: neutral weak curent 1973
  - Pressure de 1.3 à 4 atm (temp. ~24K): relaxation
  - particles create bubbles, see pictures
  - 4 m long, 2 m diameter , 1000 tons,
  - 18 tons (liquid fréon)







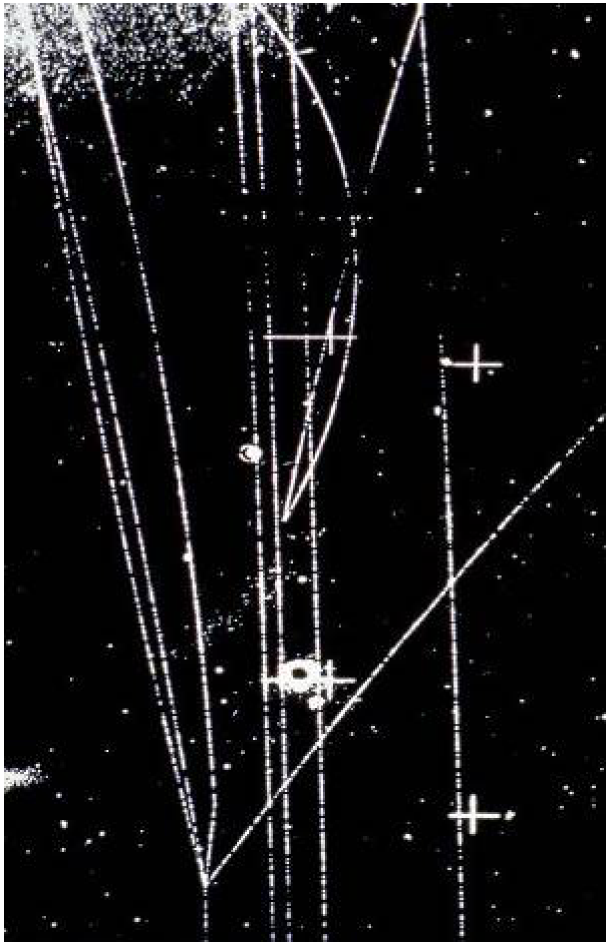


3D reconstruction!

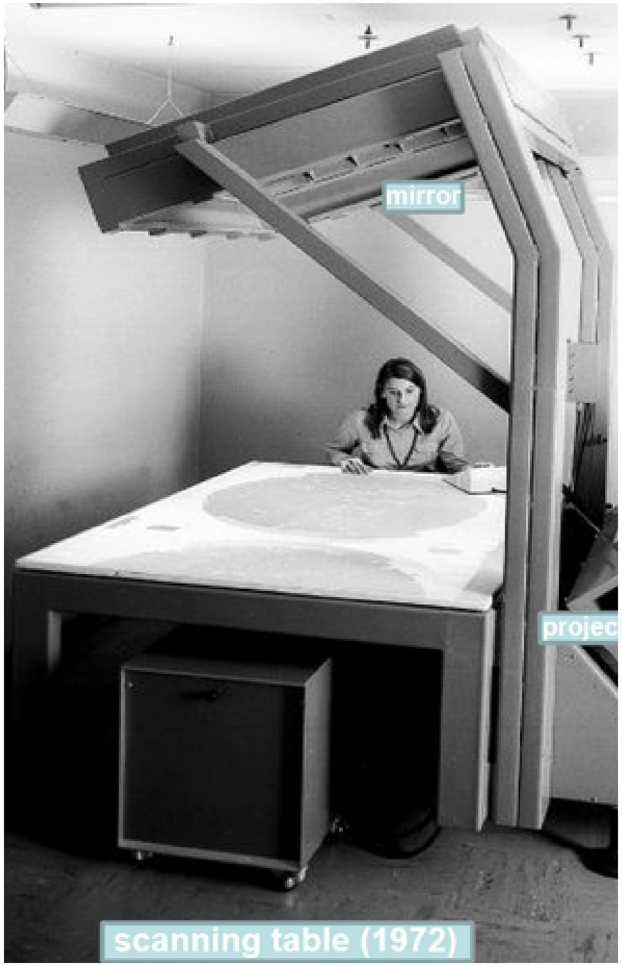
Detectors

Bubbles Chamber

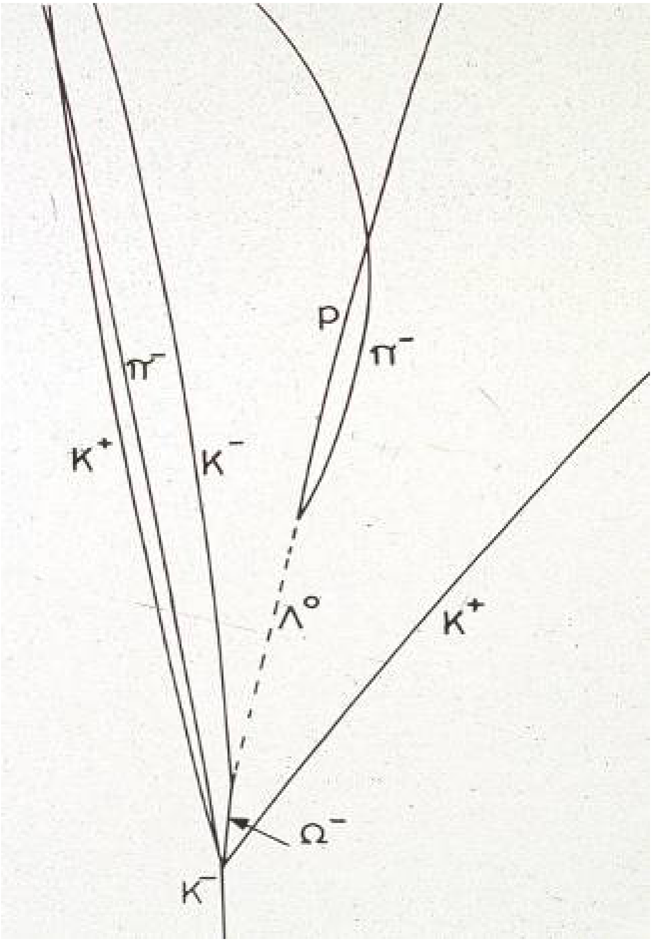
pictures



Reconstruction



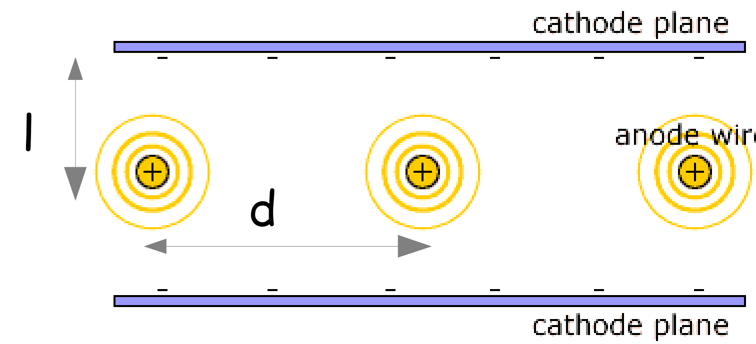
Final plot

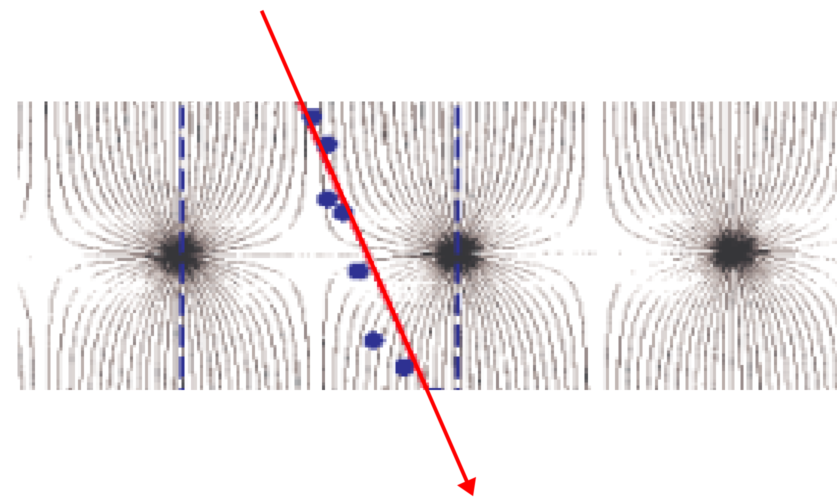


Detectors(Gaseous)

Wires Chamber

- G.Charpak 1968
  - Multi Wires Proportional Chamber (MWPC)
  - flattening of the proportional counter
  - Time resolution : 200 ns
  - Spatial resolution: < mm
  - Signal on wire: ns
  - l~5mm, d~1mm, E~50 V/mm



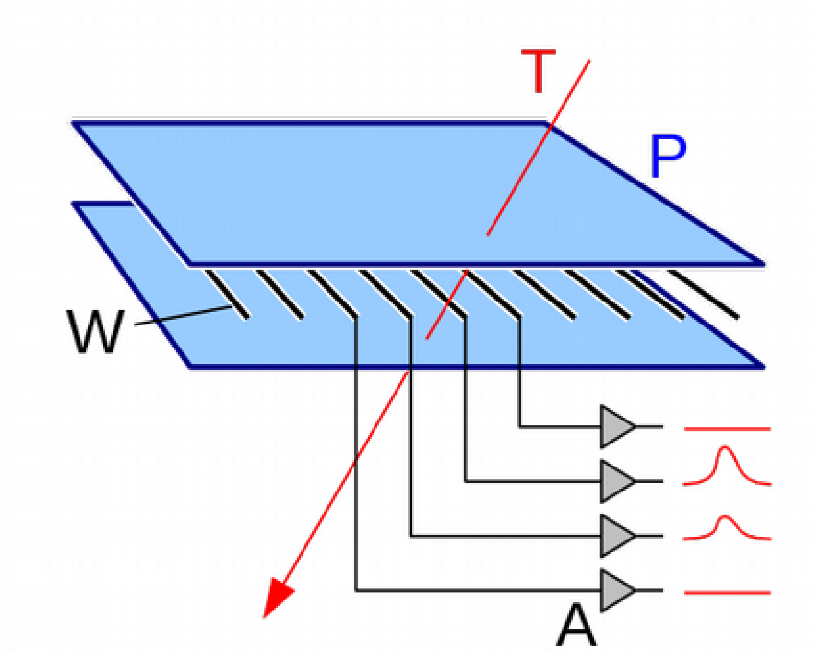


Detectors(Gaseous)

Wires Chamber

- Large area (and volume) tracking detectors
- Accuracy is function of the wire distance, ~1 to 2 mm

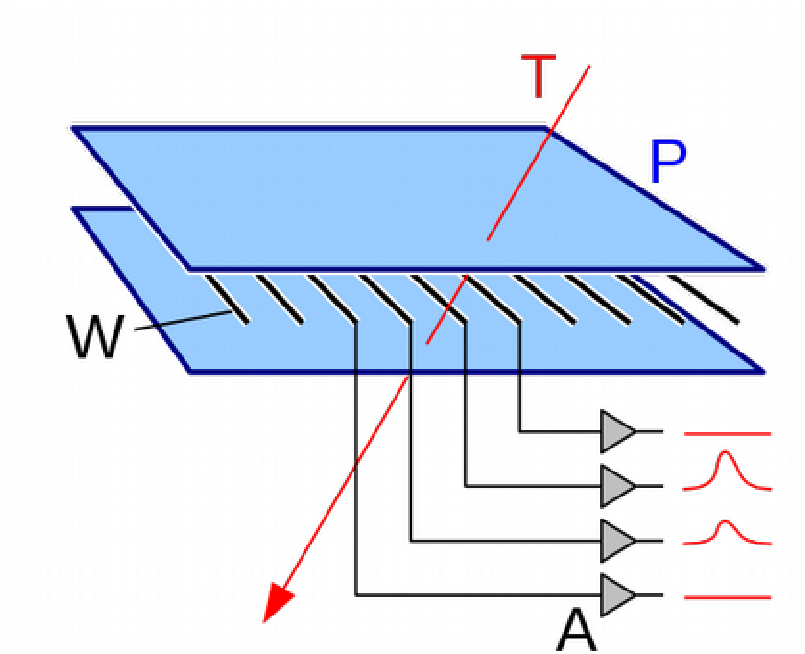
  Spatial resolution $= d/\sqrt{12}$ (for d=1 mm, σ~300 μm)
- Wires measure only one coordinate!!!

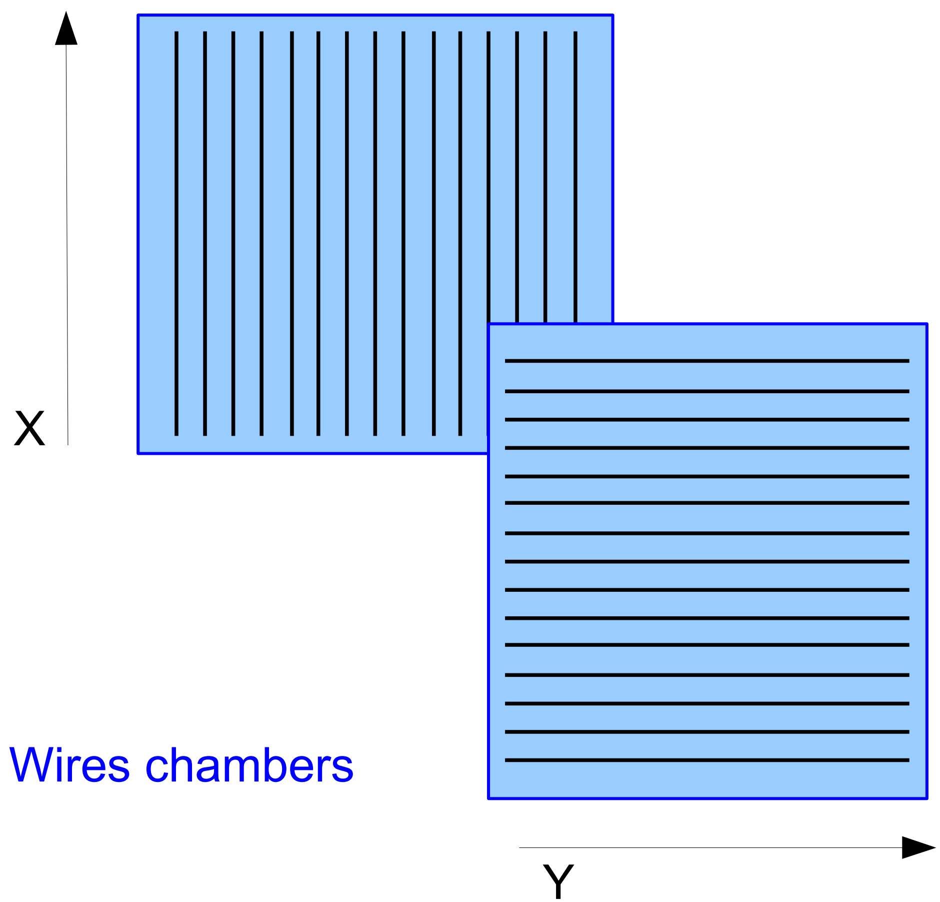


Detectors(Gaseous)

Wires Chamber

- Large area (and volume) tracking detectors
- Accuracy is function of the wire distance, ~1 to 2 mm
  Spatial resolution = $d/\sqrt{12}$ (for d=1 mm, $\sigma \sim 300\ \mu m$)
- Wires measure only one coordinate!!!



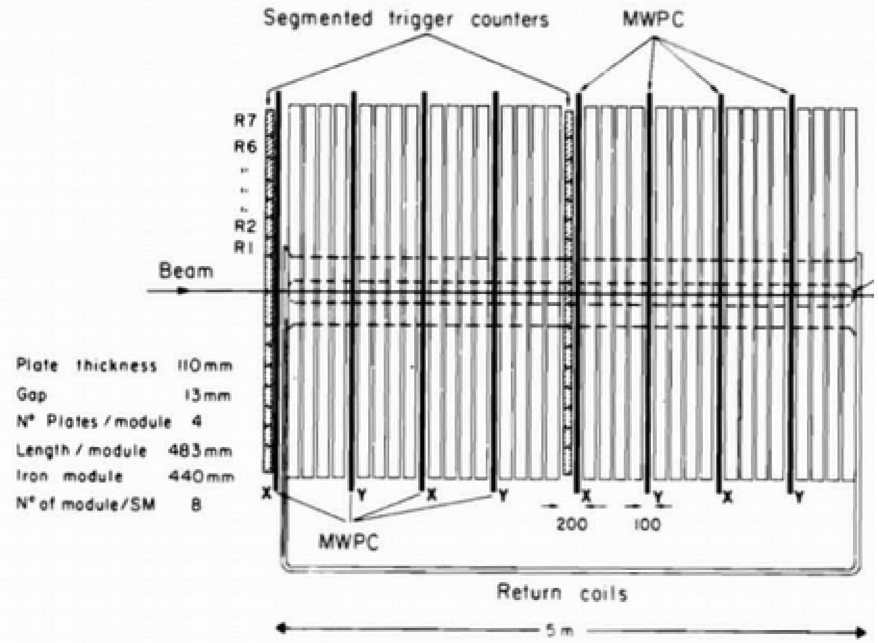


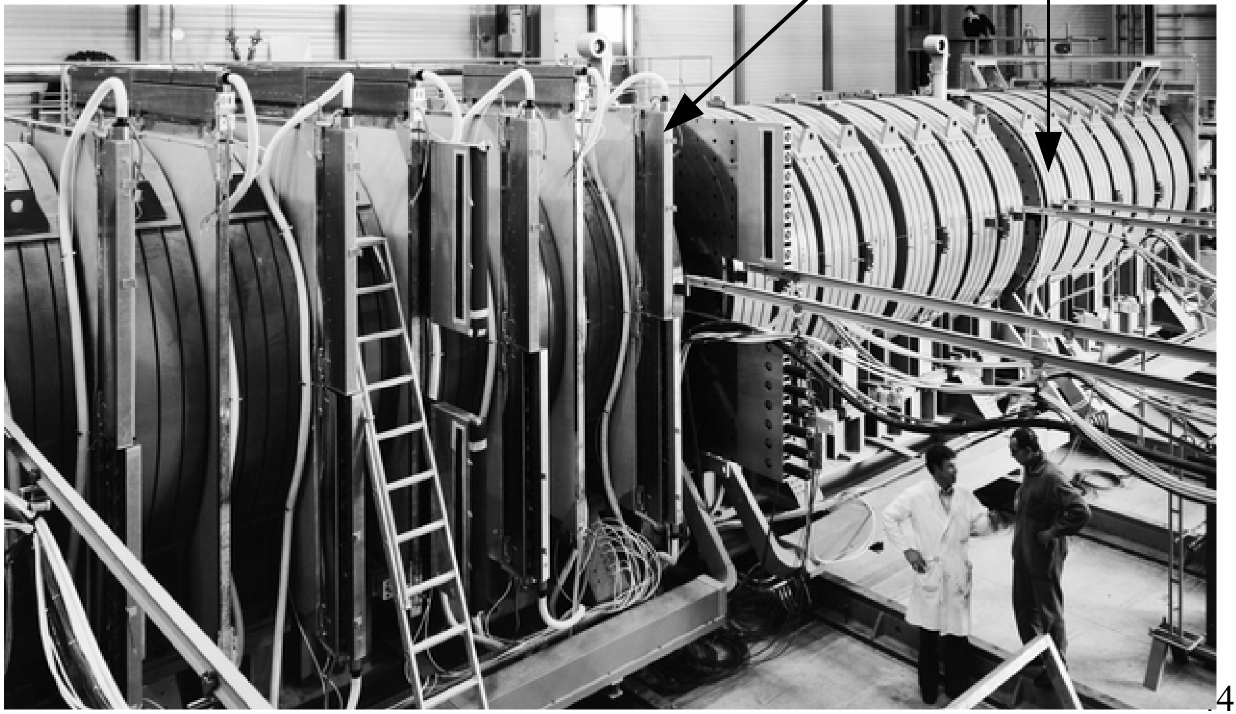
To get the second coordinate: 2 Wires chambers

Detectors(Gaseous)

Wires Chamber

- BCDMS (NA4) & CDHS (NA2) at CERN ~1977-1980
- Muon Spectrometer :
- Sandwich of wires chamber (X,Y) inside iron magnet
- 10 super modules of 8 (10) MWPC
- Spatial resolution < mm
- Multiple diffusion in iron degrade the resolution
- 3D track reconstruction (close to bubbles chambers)





Detectors(Gaseous)

Wires Chamber

- BCDMS (NA4)

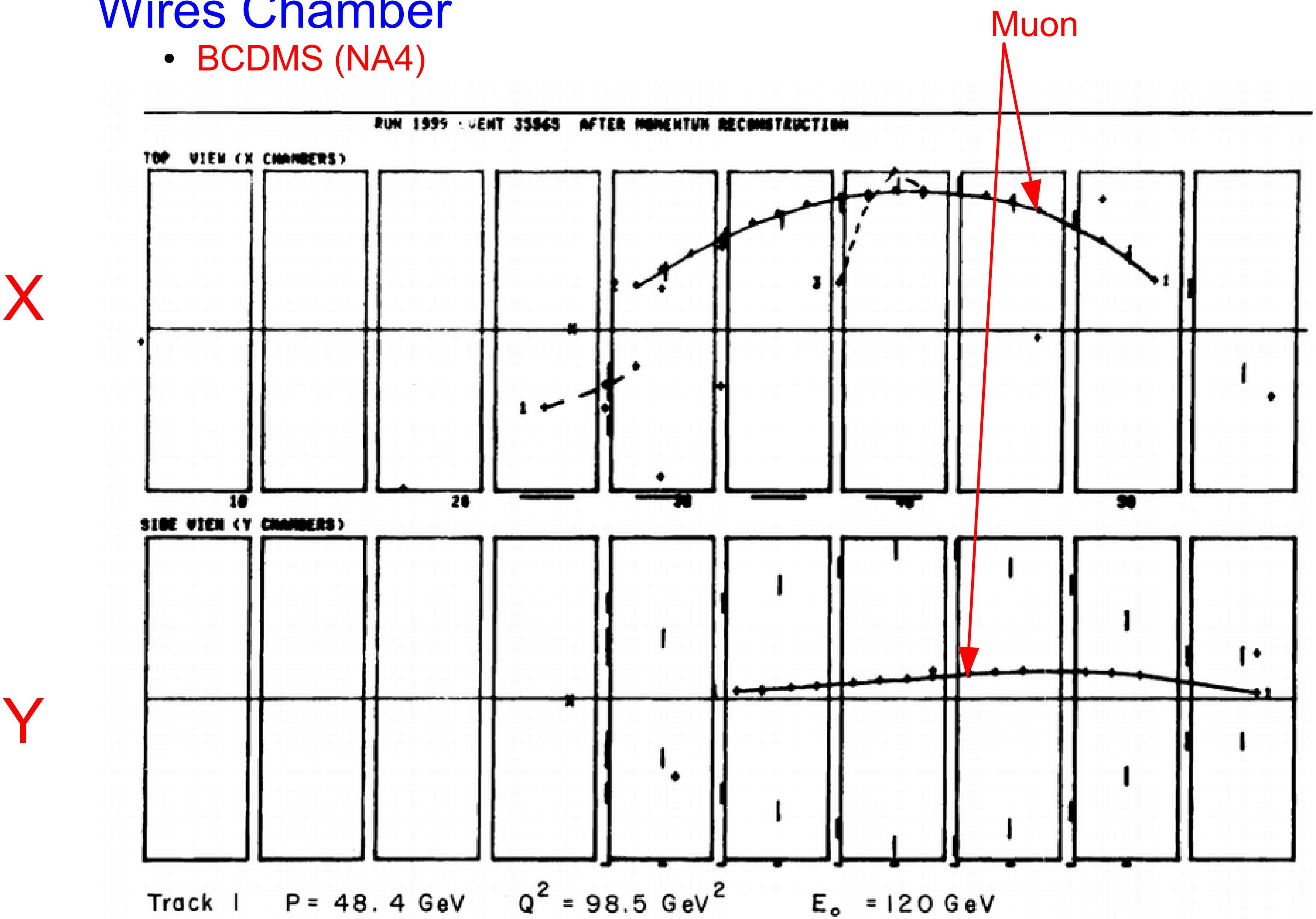
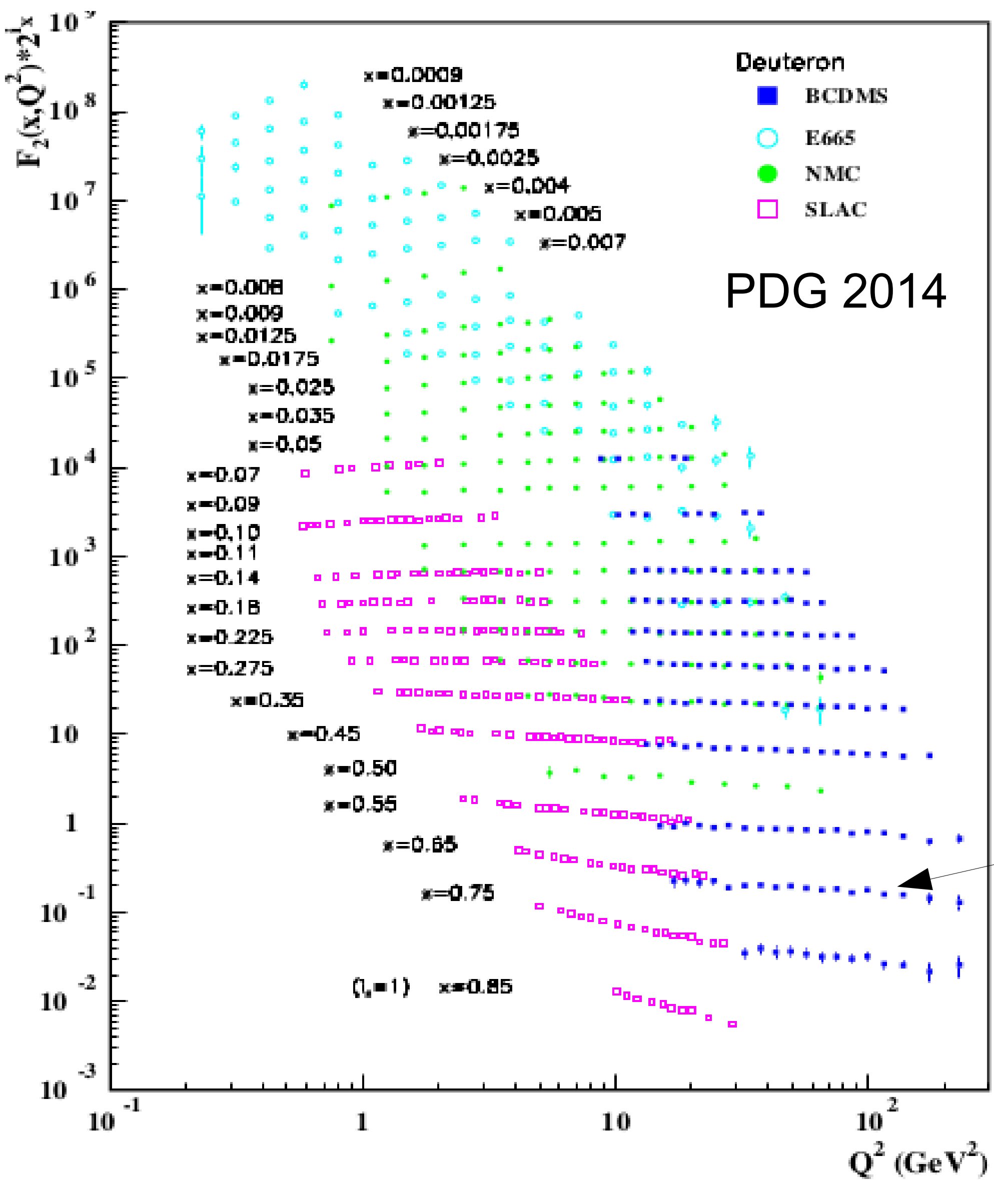


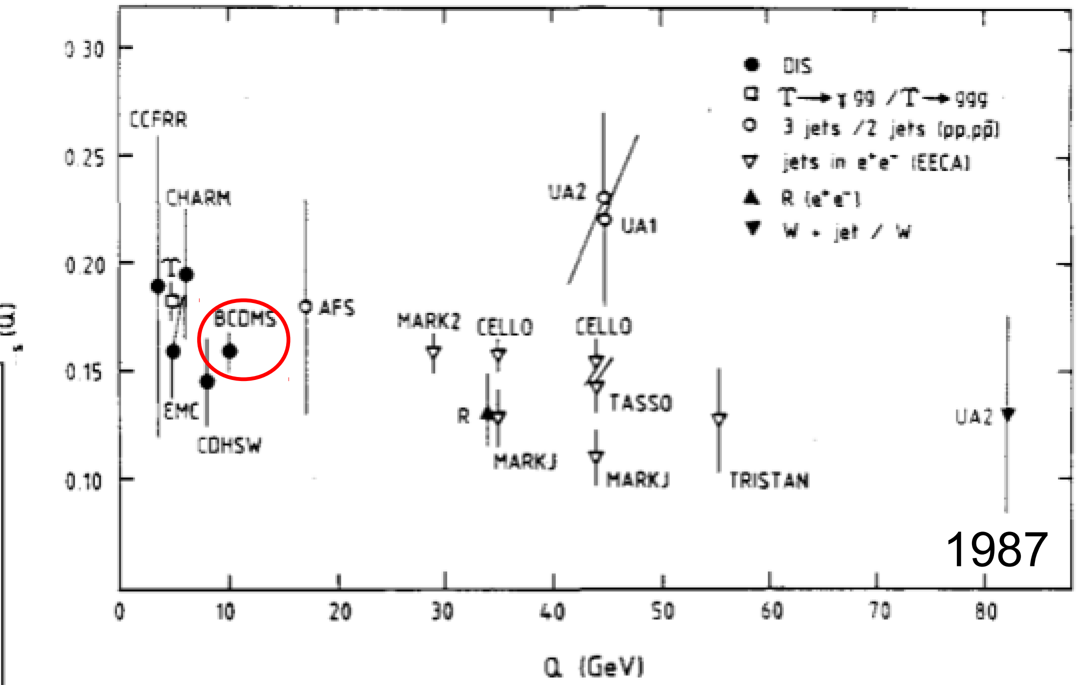
Fig. 14. Example of a deep inelastic muon scattering event at 120 GeV in the NA4 apparatus.

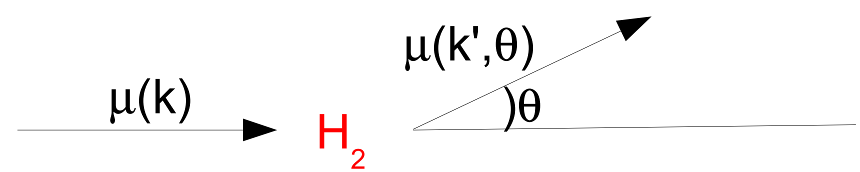
Detectors(Gaseous)

Wires Chamber

- BCDMS (NA4)
  - Muon diffusion on H_2,D_2,C





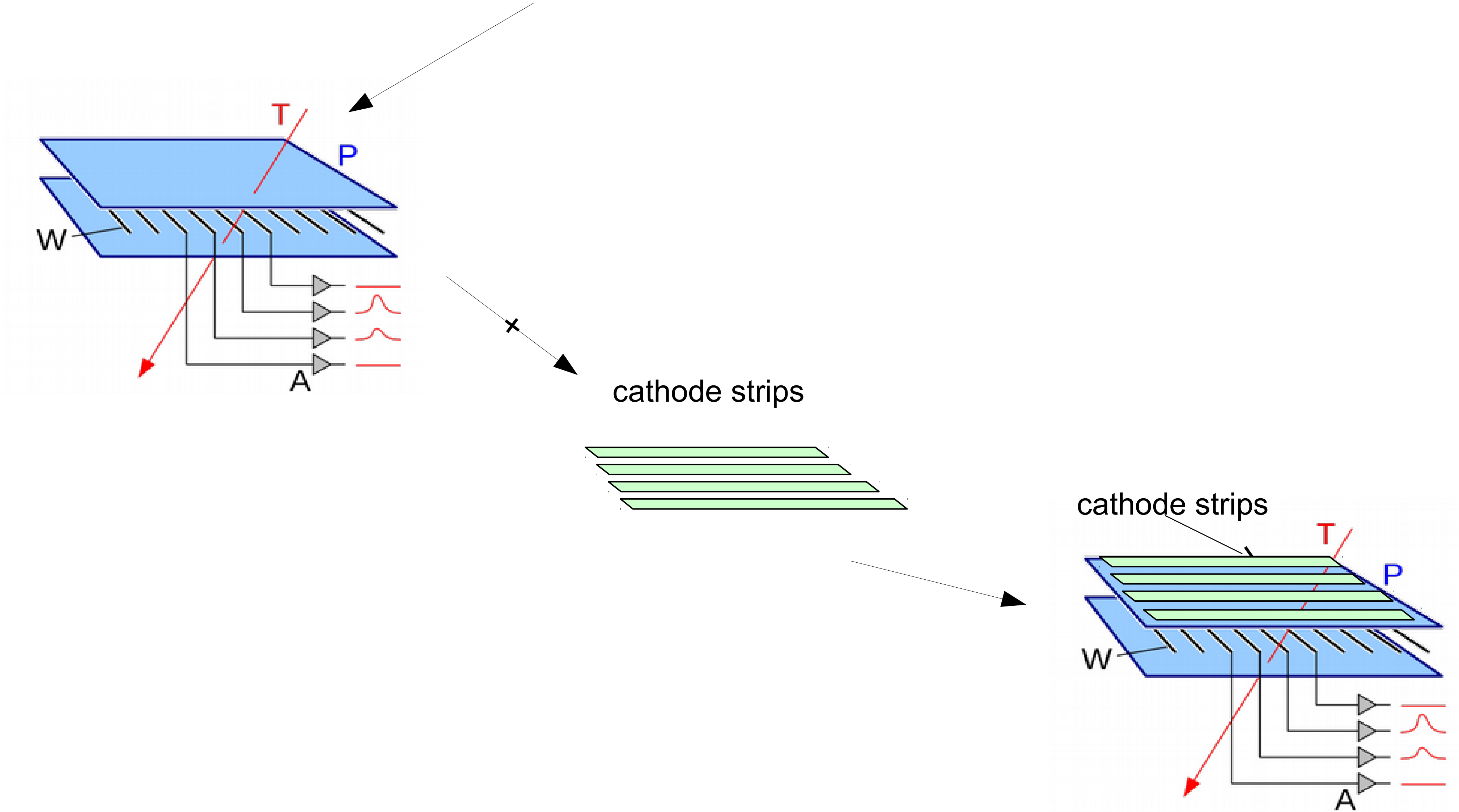


Slope proportional to α_s

Detectors(Gaseous)

TGC*

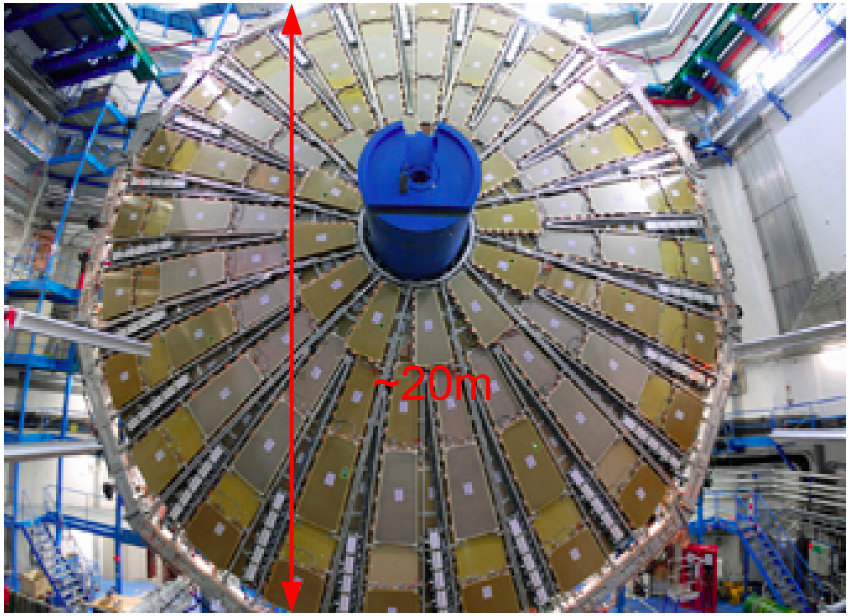
- Thin Gap Chamber
  - Go back to MWPC

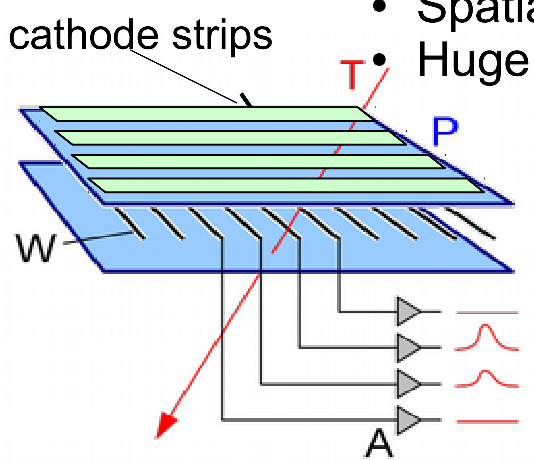


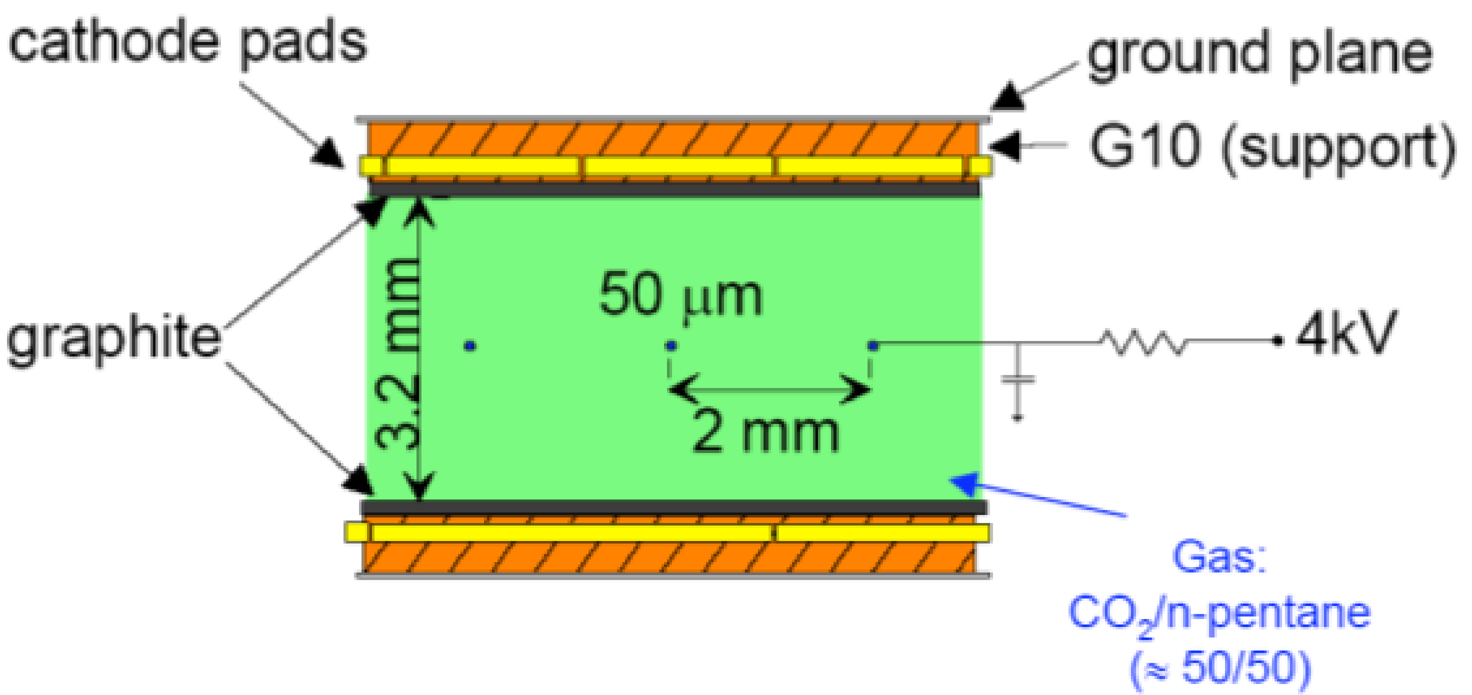
Detectors(Gaseous)

TGC*

- ATLAS
  - Saturated mode operation (Geiger)
  - Time response: ~2 ns : Trigger
  - Counting rate: 100 Hz
  - Spatial resolution ~mm
  - Huge surface







TGC used in ATLAS
for muon trigger

Detectors(Gaseous)