European School of Instrumentation in Particle & Astroparticle Physics

Muon Detection

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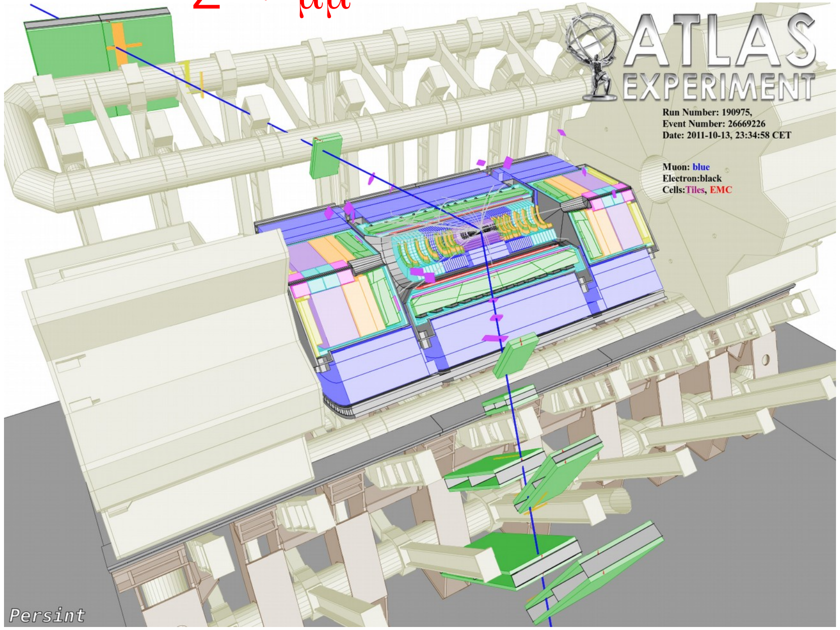
CEA-Saclay
9 February 2018

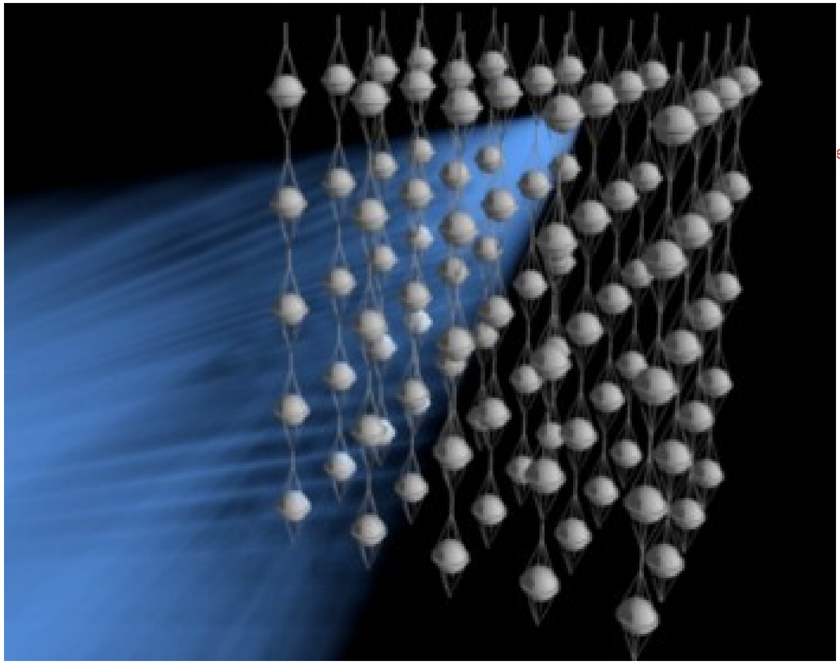
Muon Detection

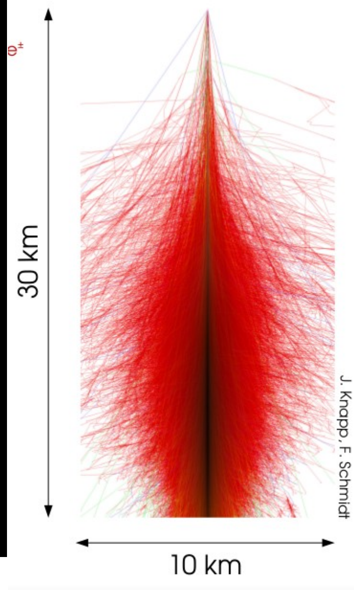
Outline

- 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

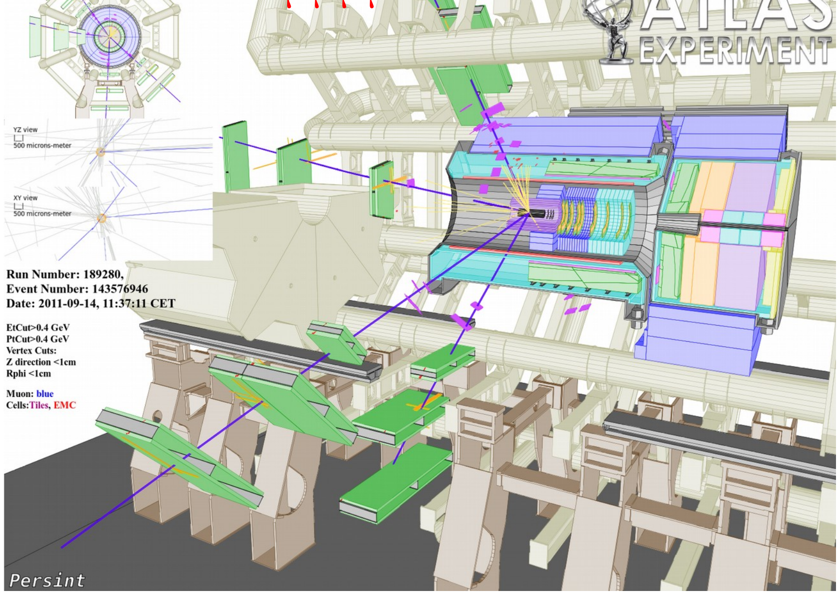
$Z \rightarrow \mu\mu$







$H \rightarrow \mu\mu\mu\mu$

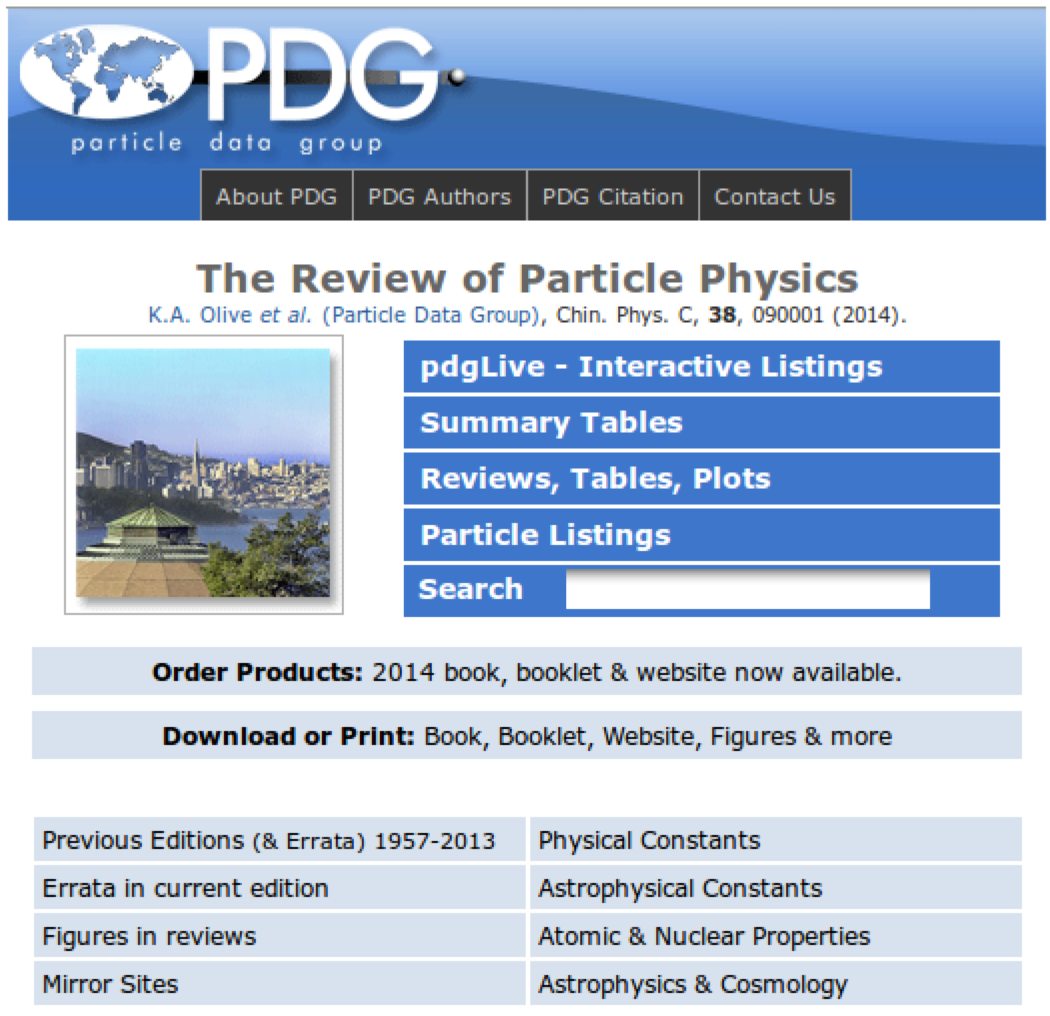


Muon Detection

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_{μ} - 2
- Very clean probe for many physic domains
  - Astroparticle: proton(cosmic rays) + atm → π → μ
  - Particle physics: Higgs → 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

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 Detection

Why Muon Detection?

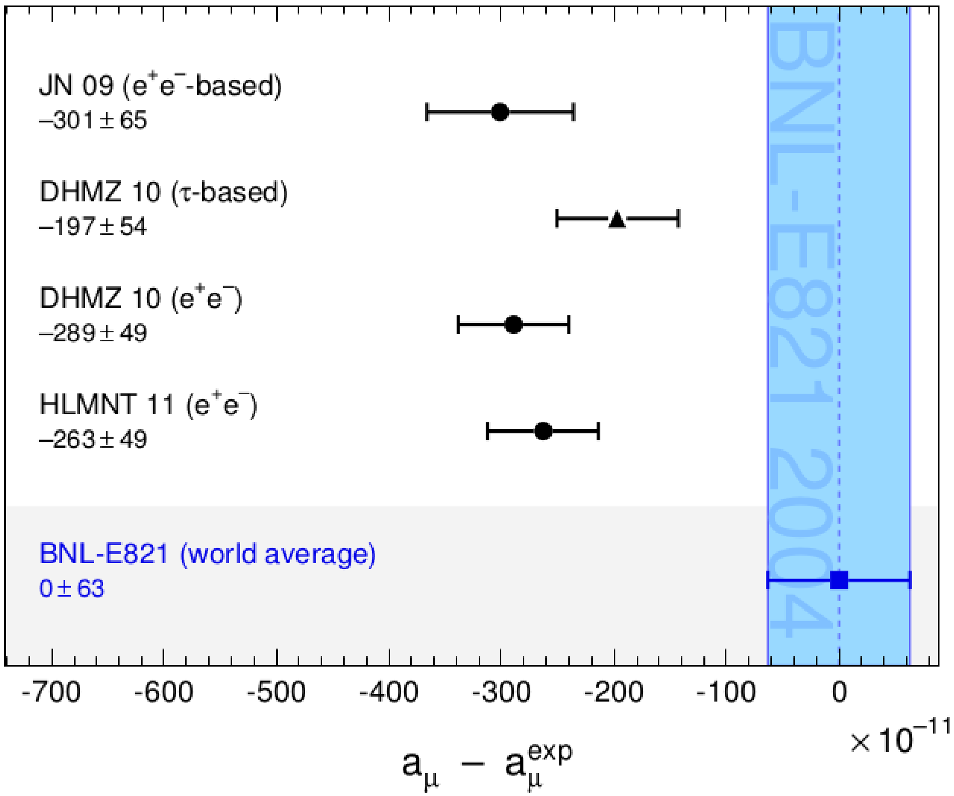
- Determine intrinsic properties of this elementary particle
  - Constraint on the Standard Model (SM) ex: $g_\mu - 2$

electron

$$\vec{\mu} = g_e \frac{e\hbar}{2m_e c}\vec{s}$$

muon

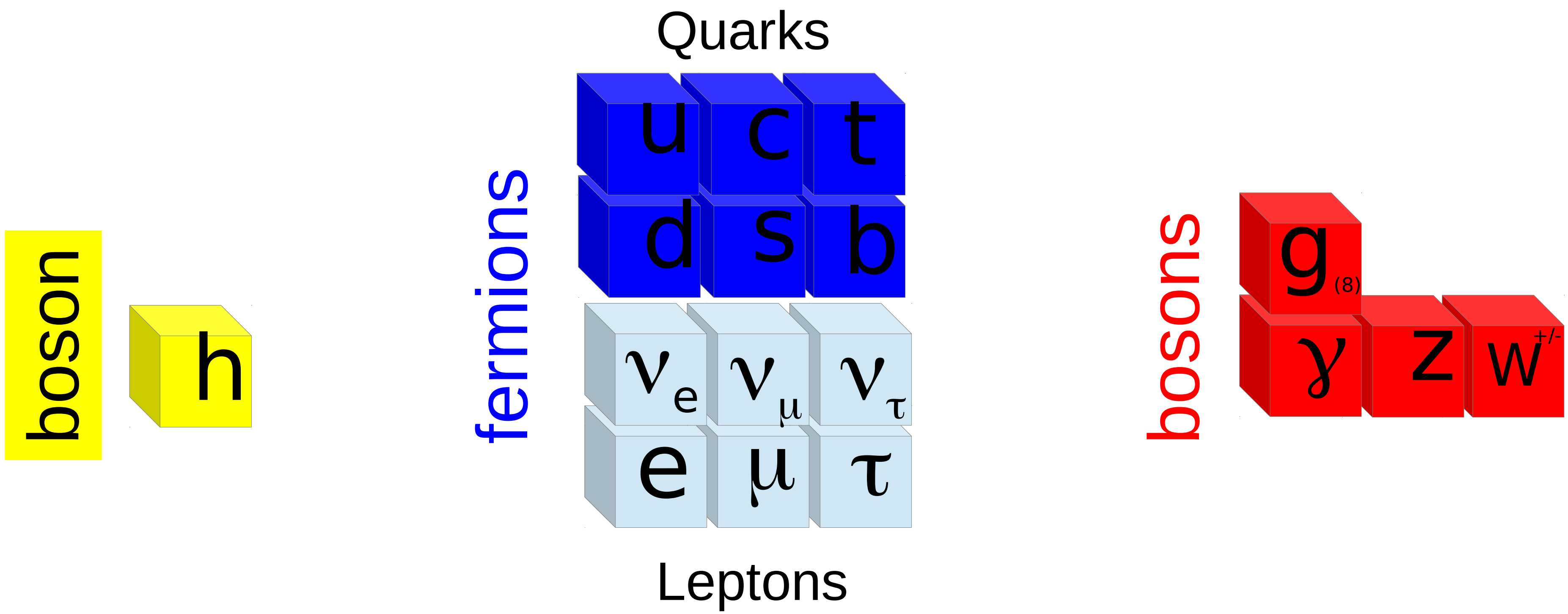
$$a_\mu \equiv \frac{g_\mu - 2}{2}$$



$$\begin{aligned} g &= 1 \quad \text{classic} \\ &= 2 \quad \text{Dirac} \\ &= 2.0023193043 6 \end{aligned}$$

Muon

Standard Model



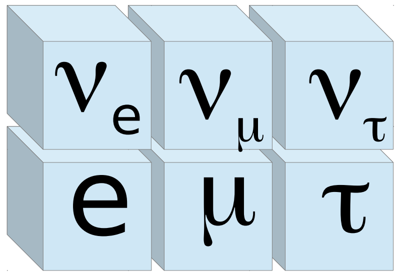
Spin 0 | Spin 1/2 | Spin 1

Muon

Standard Model

Leptons

fermions



Electromagnetic & weak interaction (& gravitation)

Muon

- mass: $105.6583715 \pm 0.0000035$ 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%

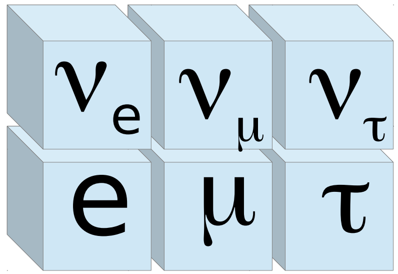
$m(K^0) - m(\bar{K}^0) \sim 4.10^{-10}$ eV

Muon

Standard Model

Leptons

fermions



Electromagnetic & weak interaction (& gravitation)

Muon

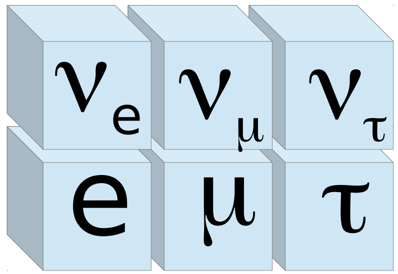
- ~207 times more massive than electron
- ~ 17 times less massive than the tau
- Unstable $c\tau \sim 660$m
  but the second longest mean life time after the neutrons
- Means: stable for some simulation in G4

Muon

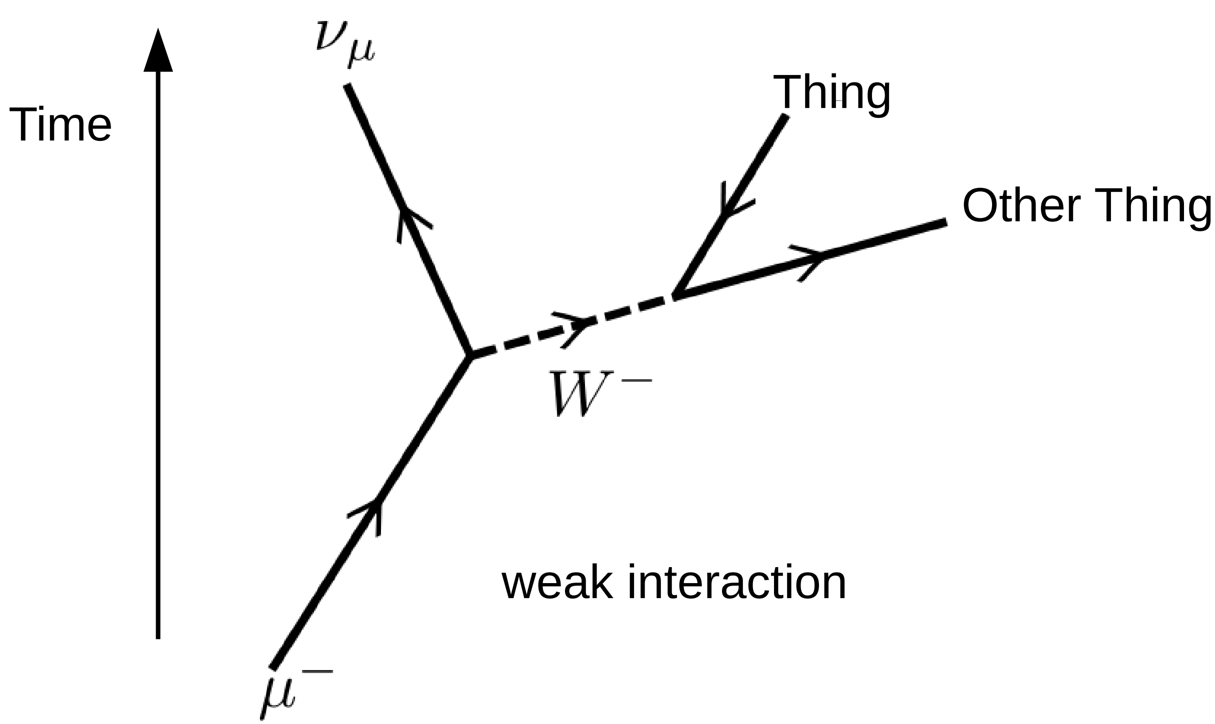
Standard Model

Leptons

fermions

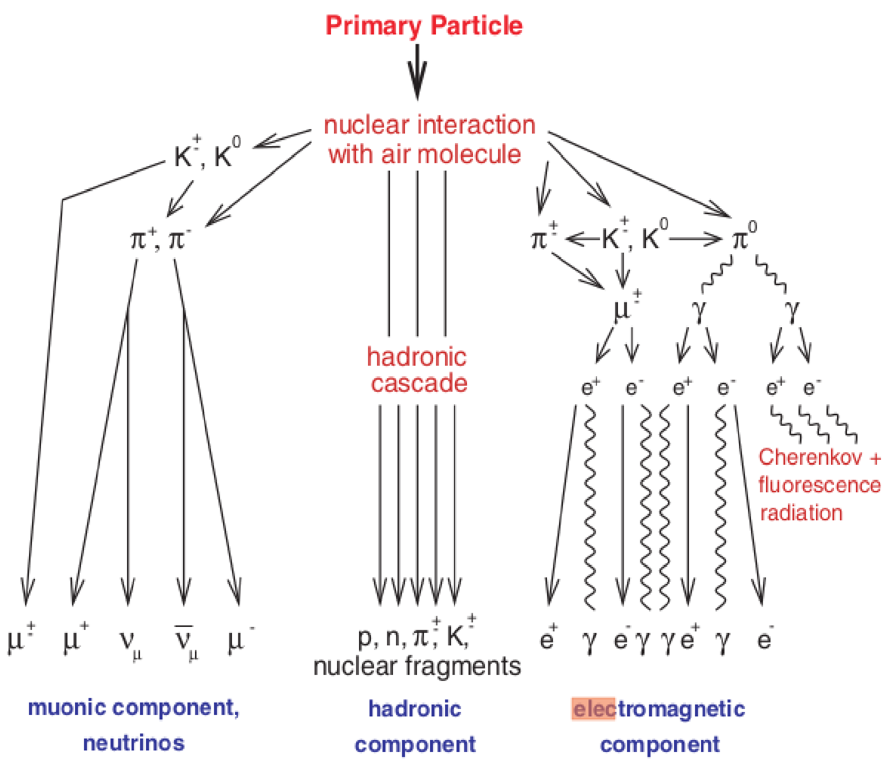


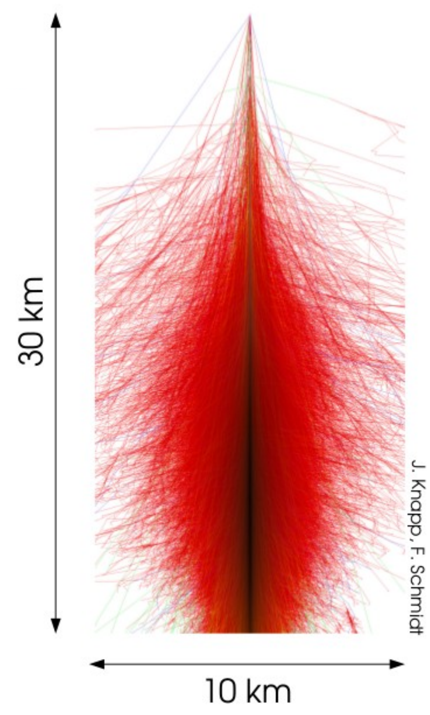
Electromagnetic & weak interaction (& gravitation)

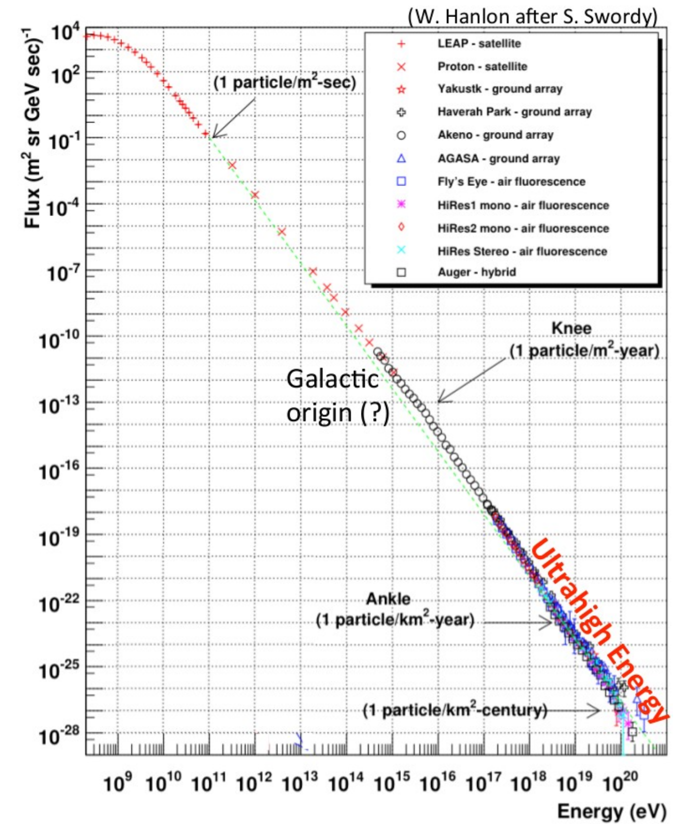


Muon discovery

Cosmic rays





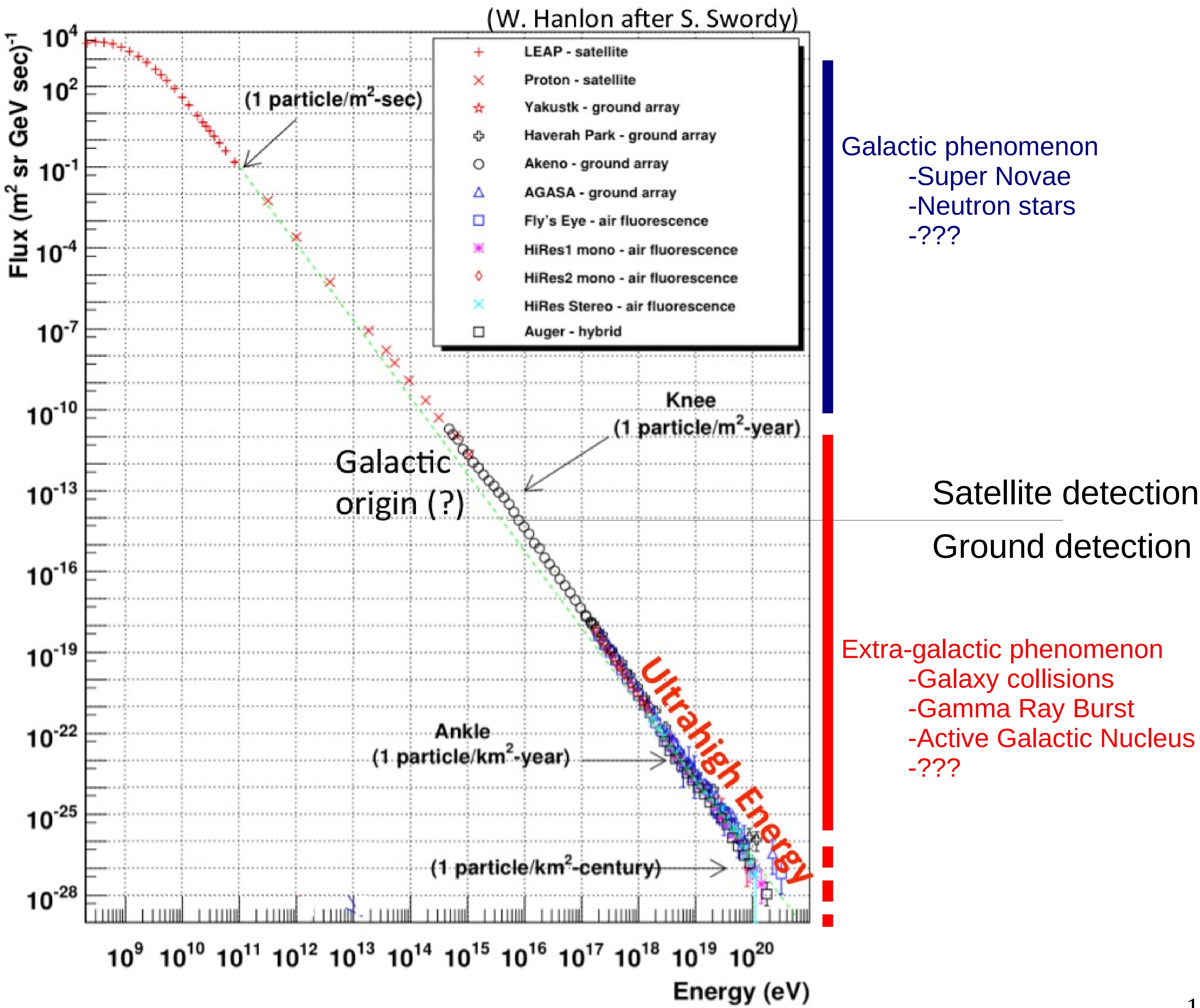


Simulation proton 10^{14} eV

- 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

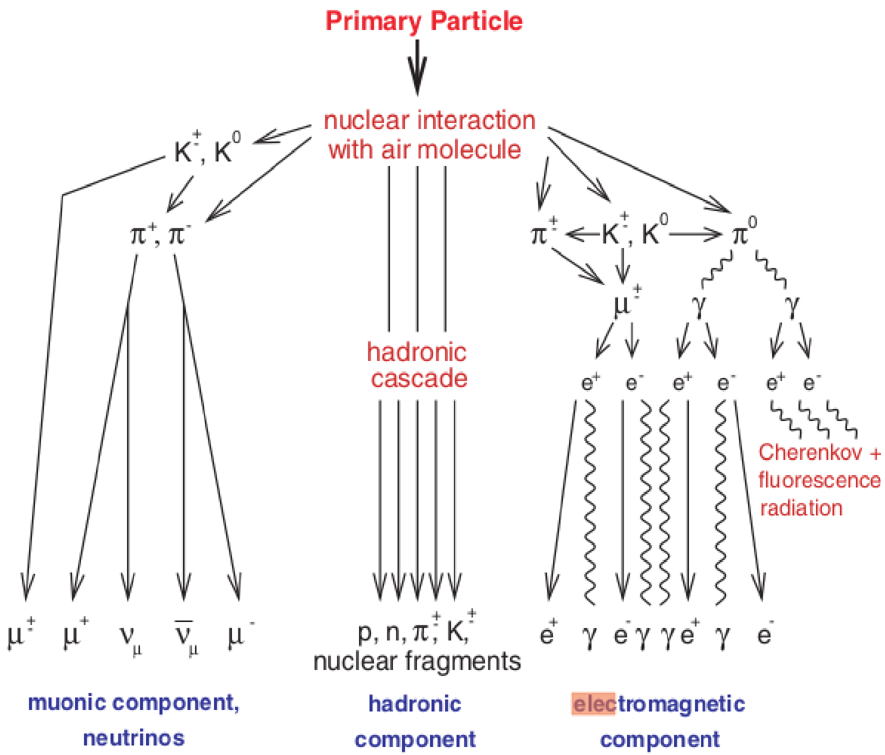
Muon discovery

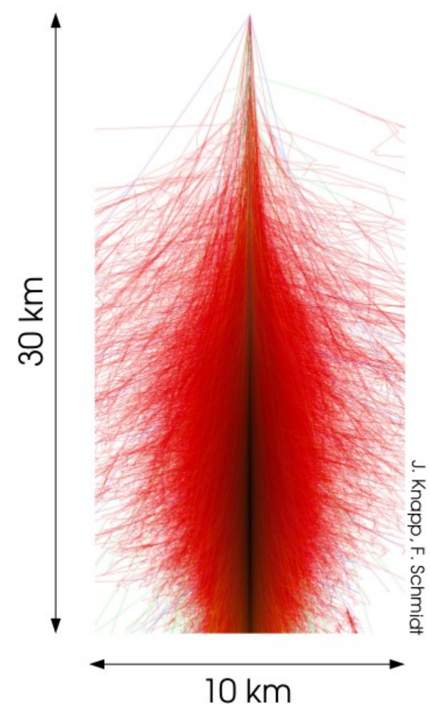
Cosmic rays



Muon discovery

Cosmic rays





Simulation proton 10^{14} eV

Thomas A. Anderson
(matrix 1)

Cloud chamber

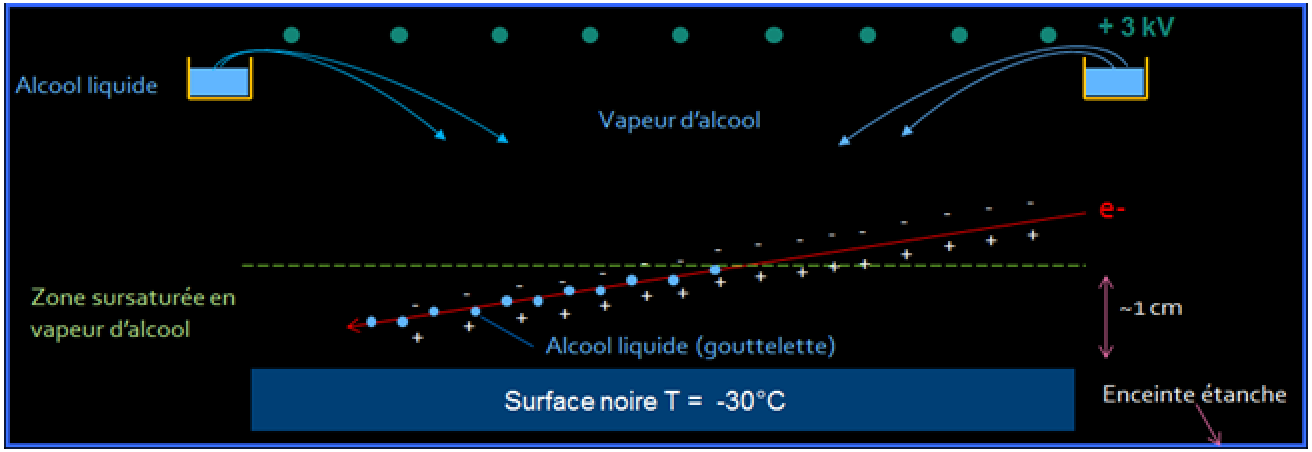
$$p + N \rightarrow X + \begin{cases} \pi^0 \rightarrow \gamma\gamma & \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu & \text{~100\%} \\ \pi^+ \rightarrow \mu^+ + \nu_\mu & \text{~100\%} \end{cases}$$

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

(+ k → π,μ,... +...)

Muon discovery

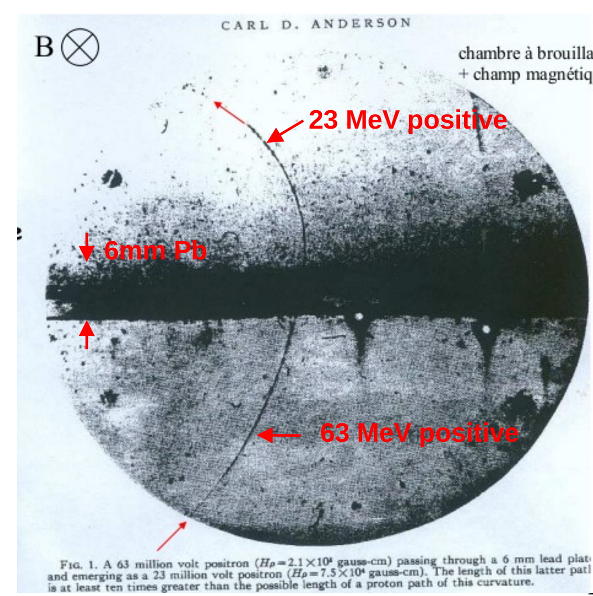
Cosmic rays



Cloud chamber

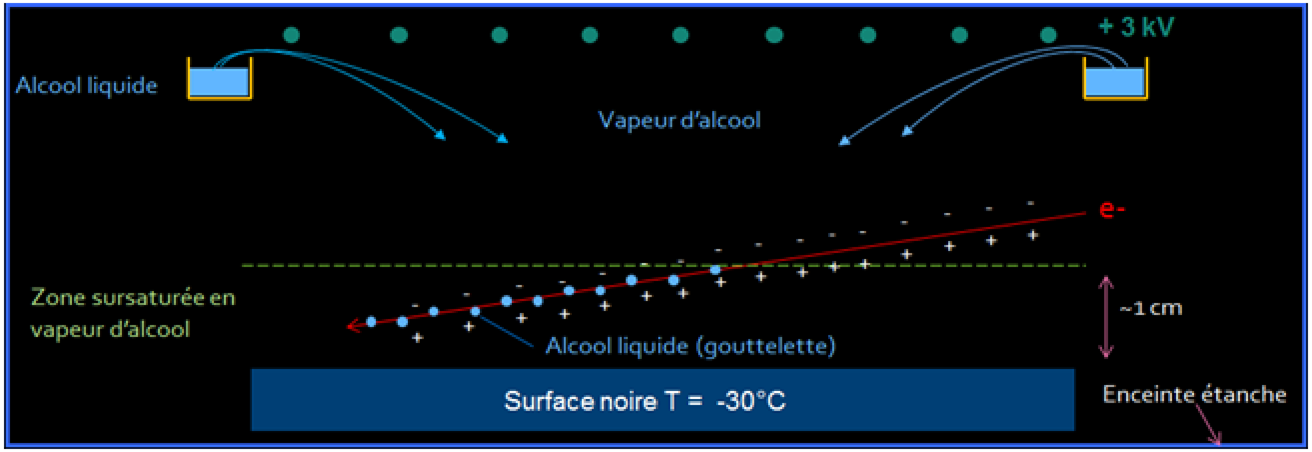
Carl David Anderson
(1905-1991)

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



Muon discovery

Cosmic rays

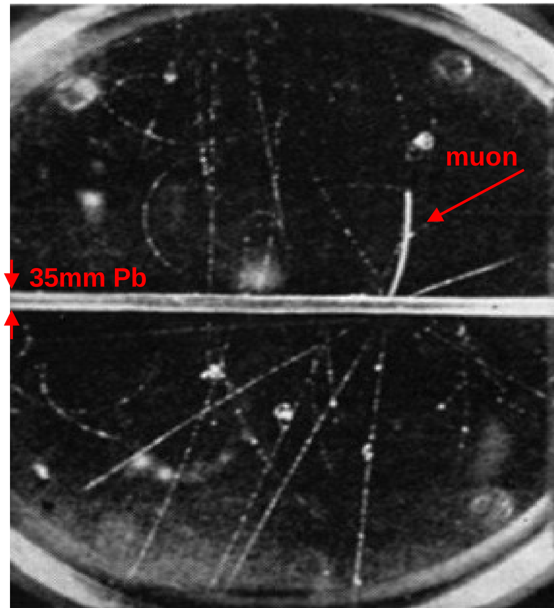


Cloud chamber

Carl David Anderson
(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

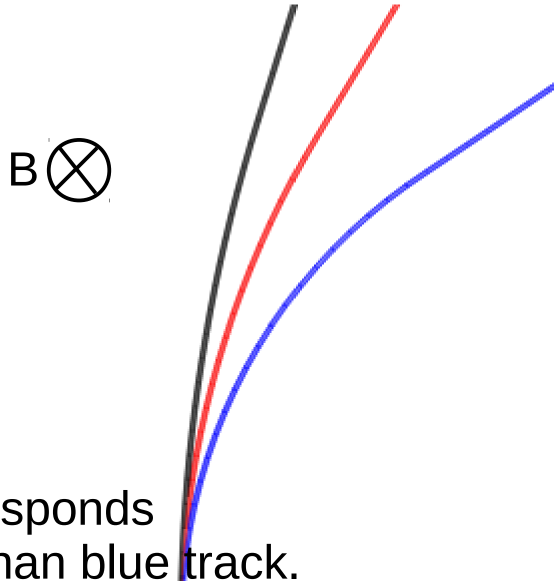
Phys. Rev. 51 (1937) 884

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



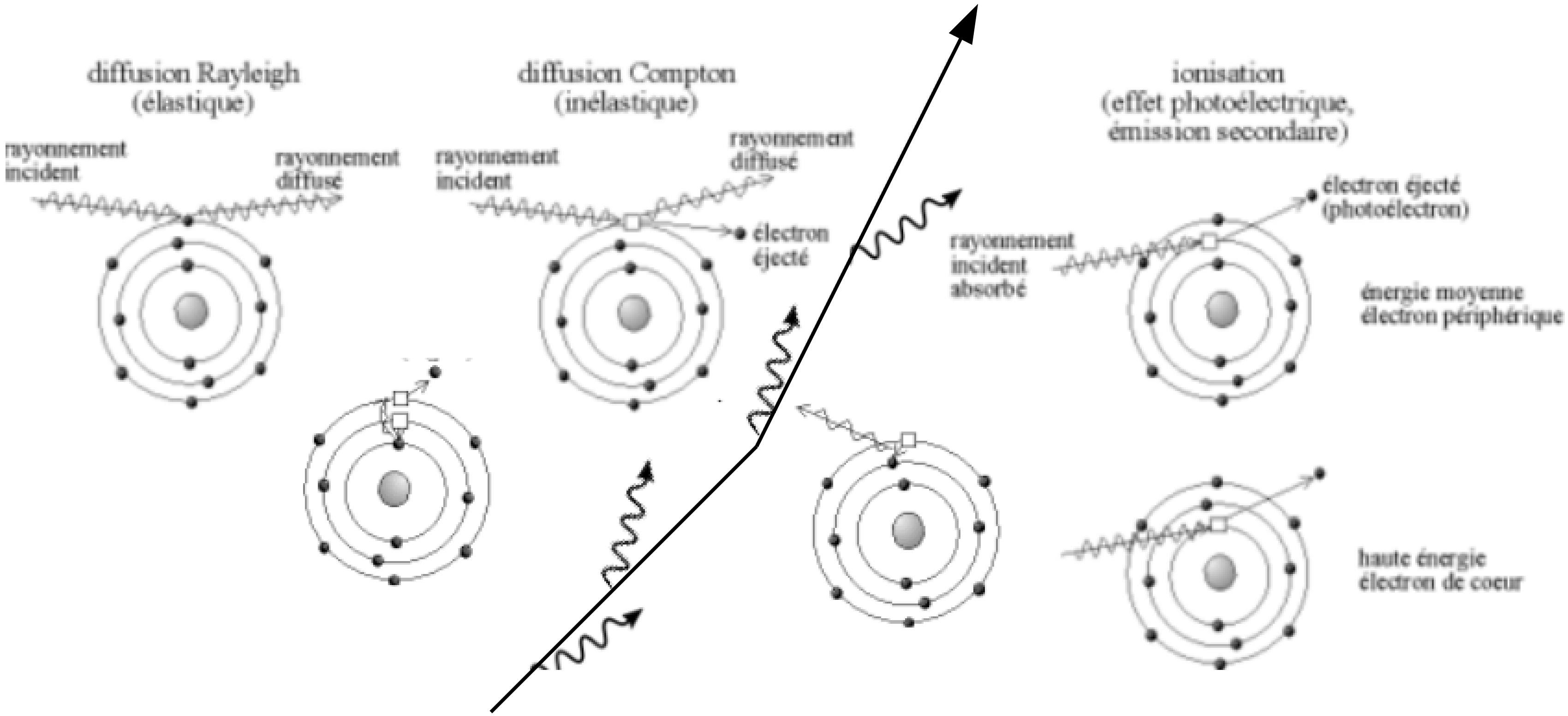
For a given B and P
the black track corresponds
to a heavier object than blue track.
So the red track correspond to an intermediate
mass object

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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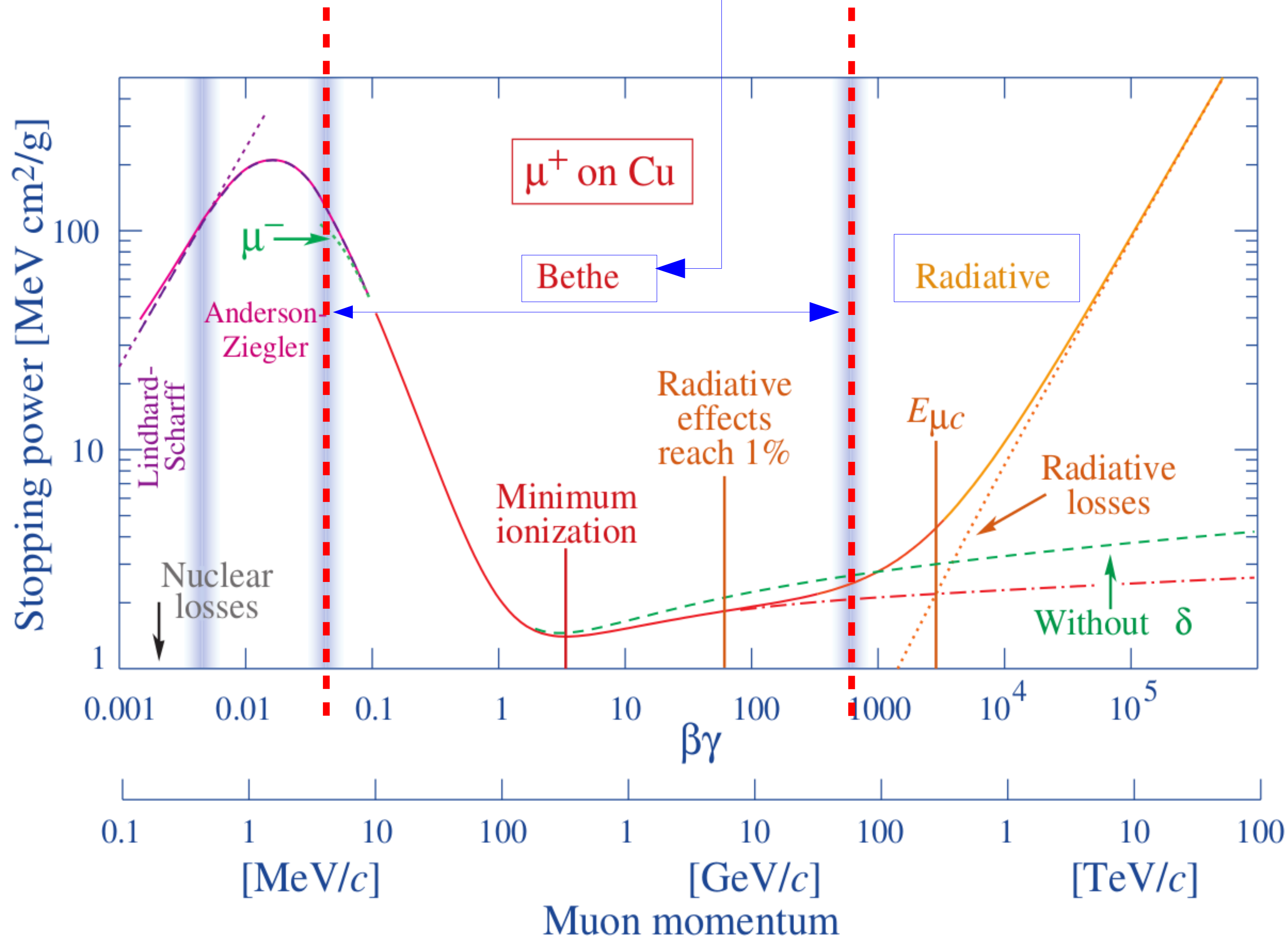
Interaction Particle-Matter

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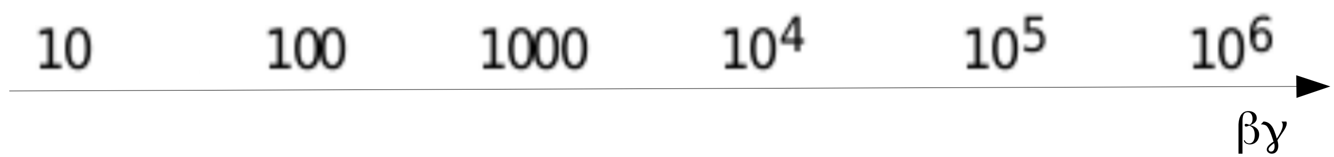
$$\beta\gamma = \frac{P}{m}$$



Interaction Particle-Matter

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

Remarks:

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

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

10 100 1000 10^4 10^5 10^6 → $\beta\gamma$

$\beta\gamma$ → muon

10^0 10^1 10^2 GeV

muon

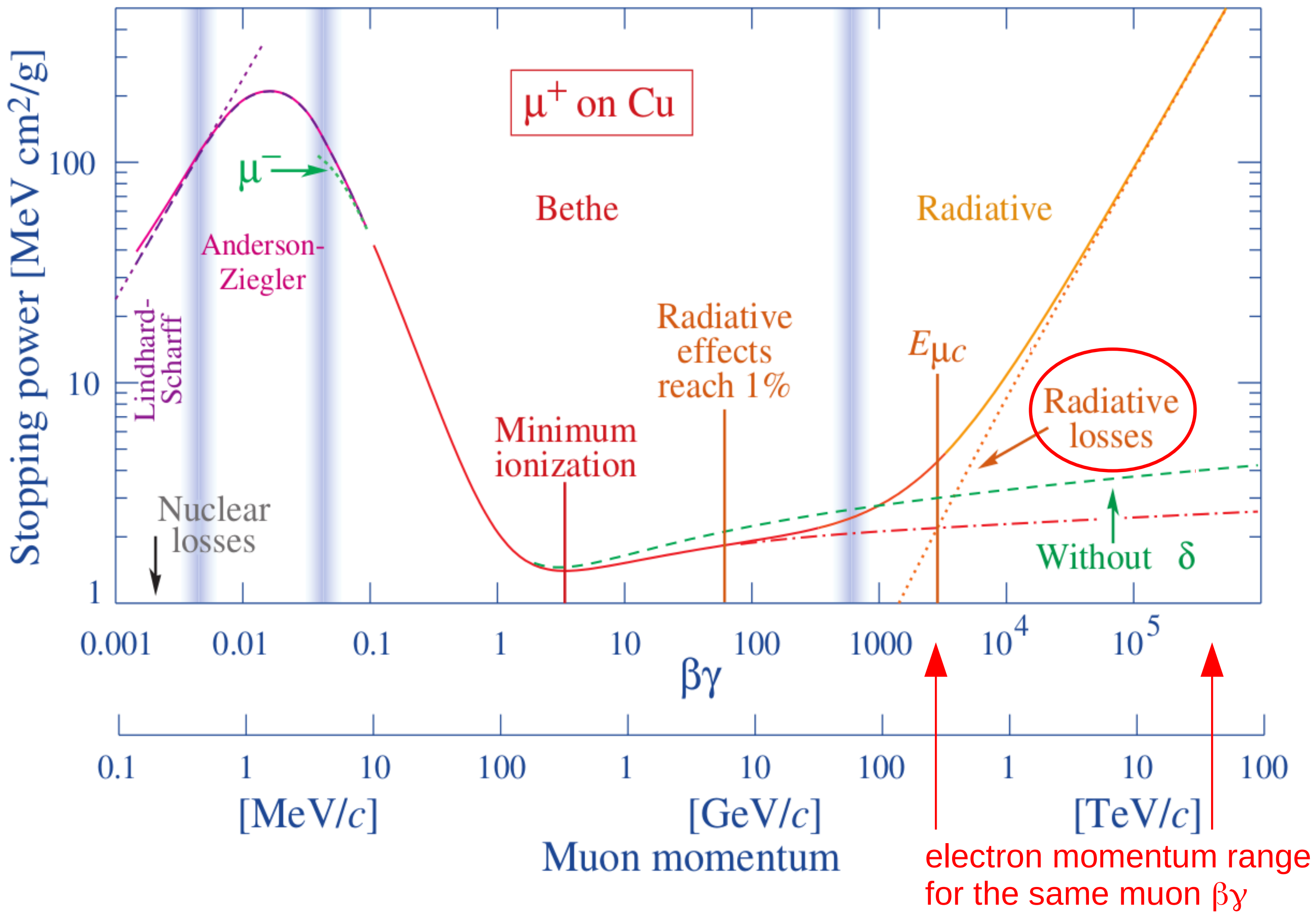
2.10^2 2.10^3 2.10^4

→ electron

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

Interaction Particle-Matter

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



Interaction Particle-Matter

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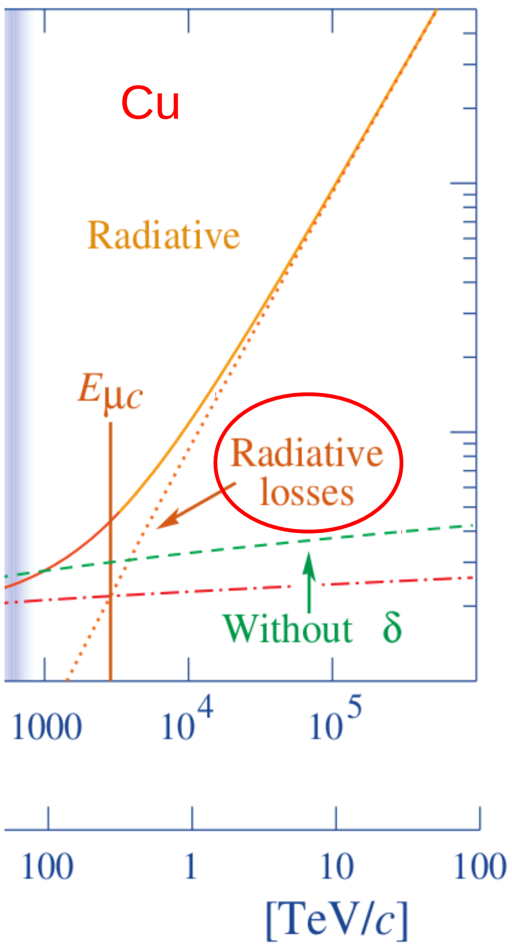
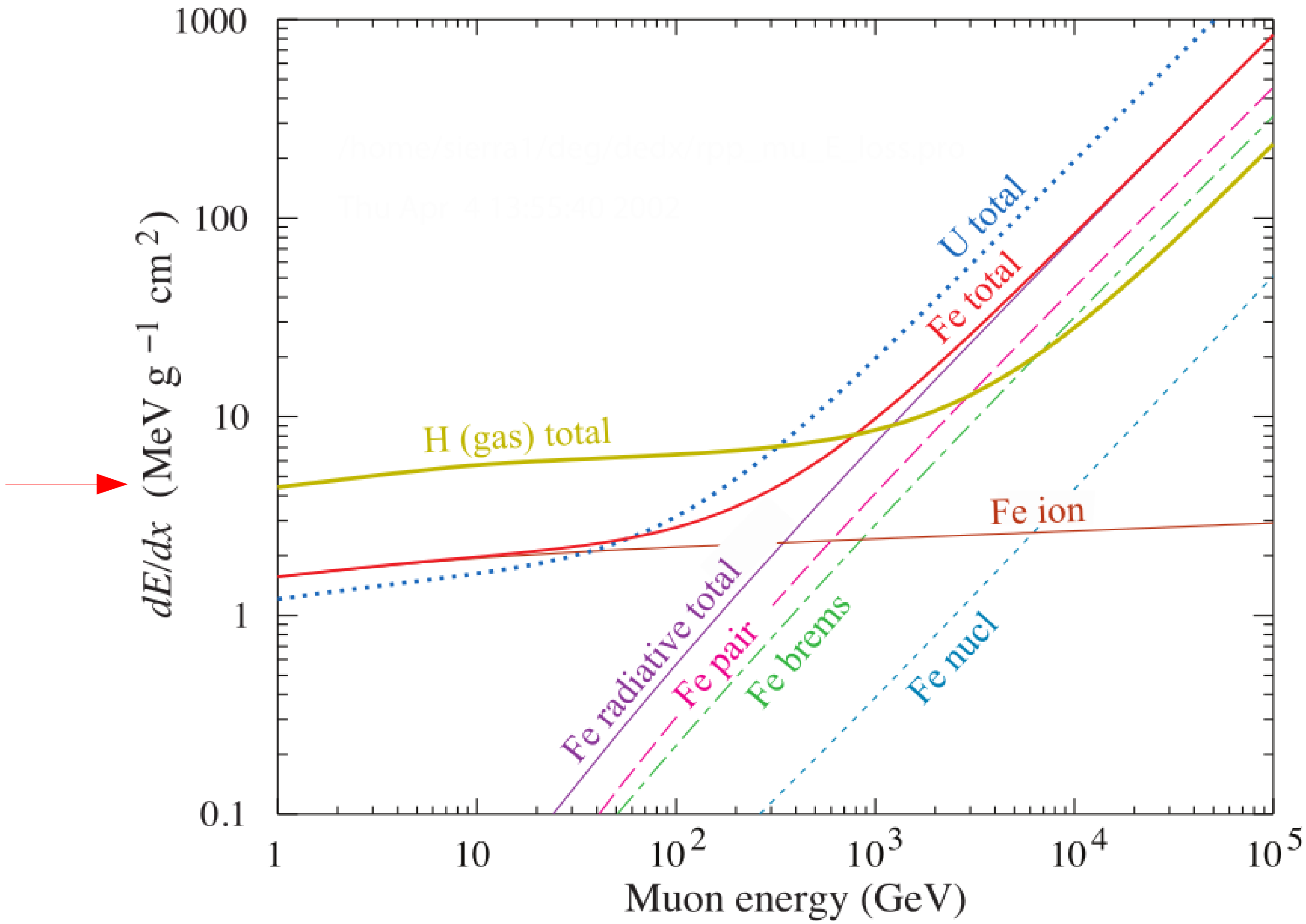
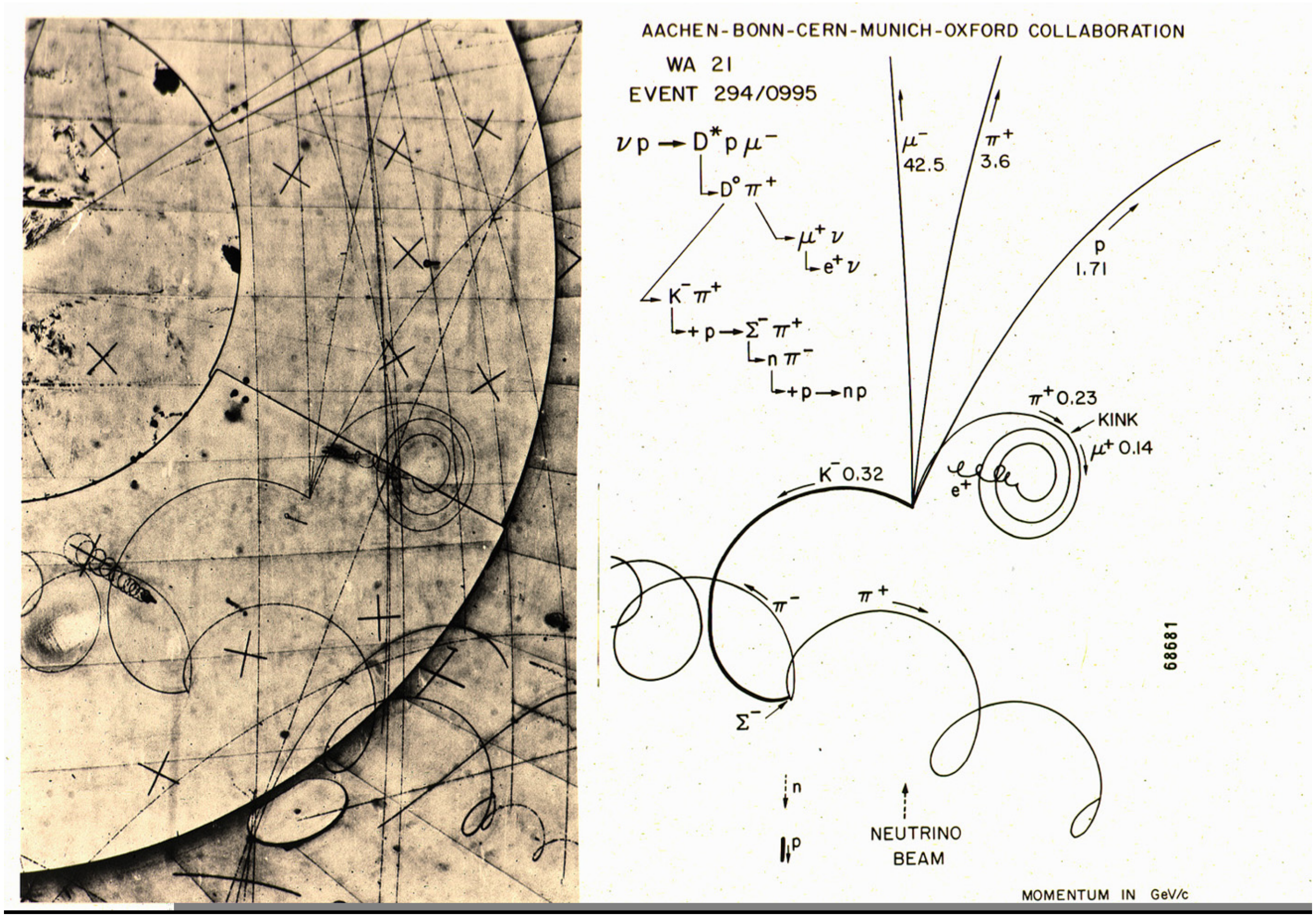




Detectors

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

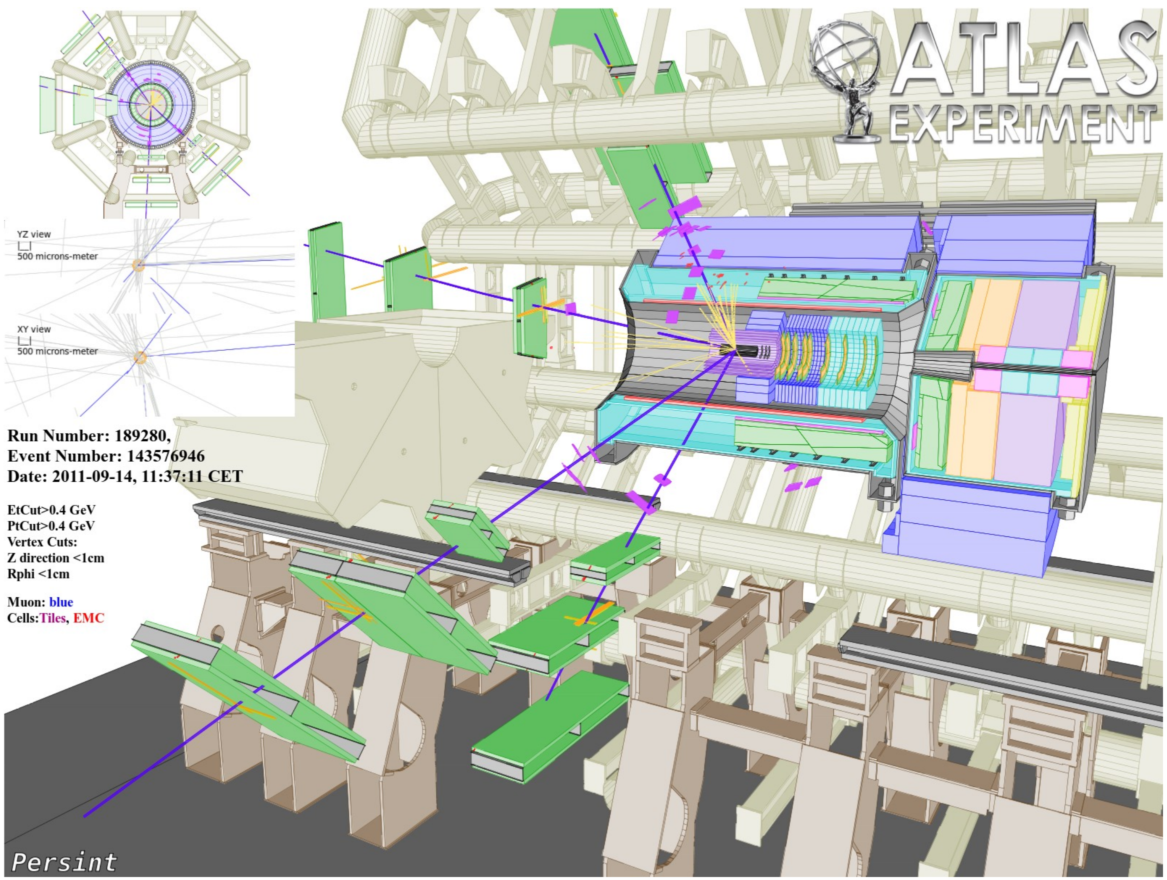
Bubble chambers

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

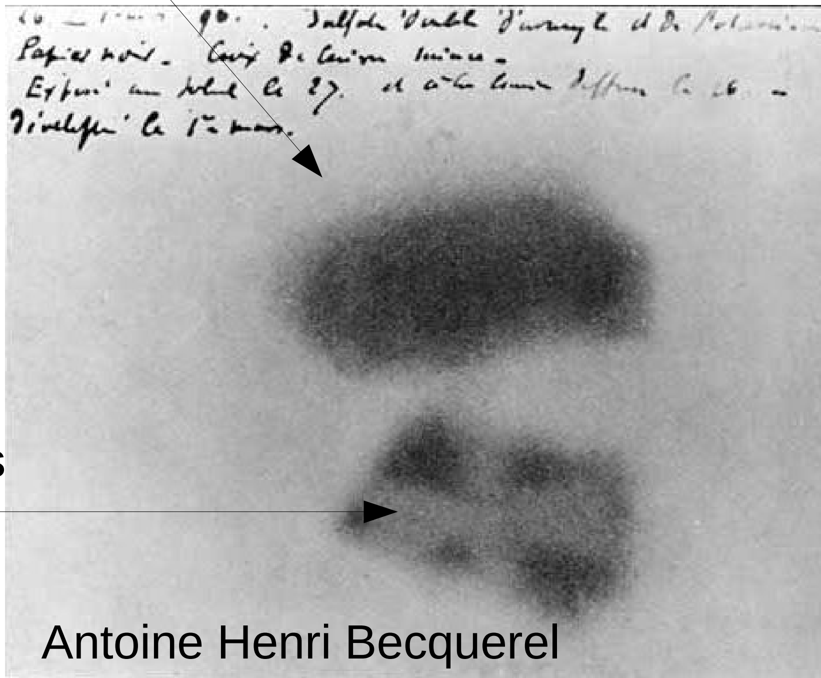
Detectors

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



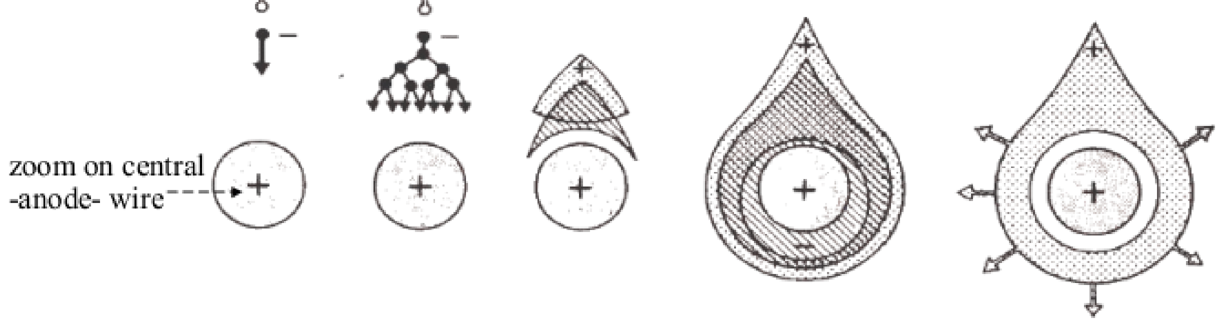
Antoine Henri Becquerel

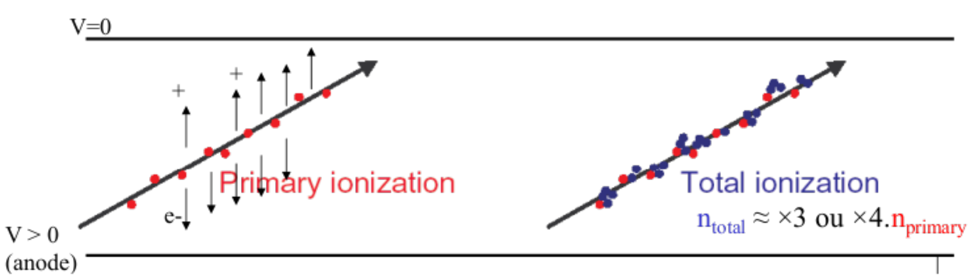
Detectors (Gaseous)

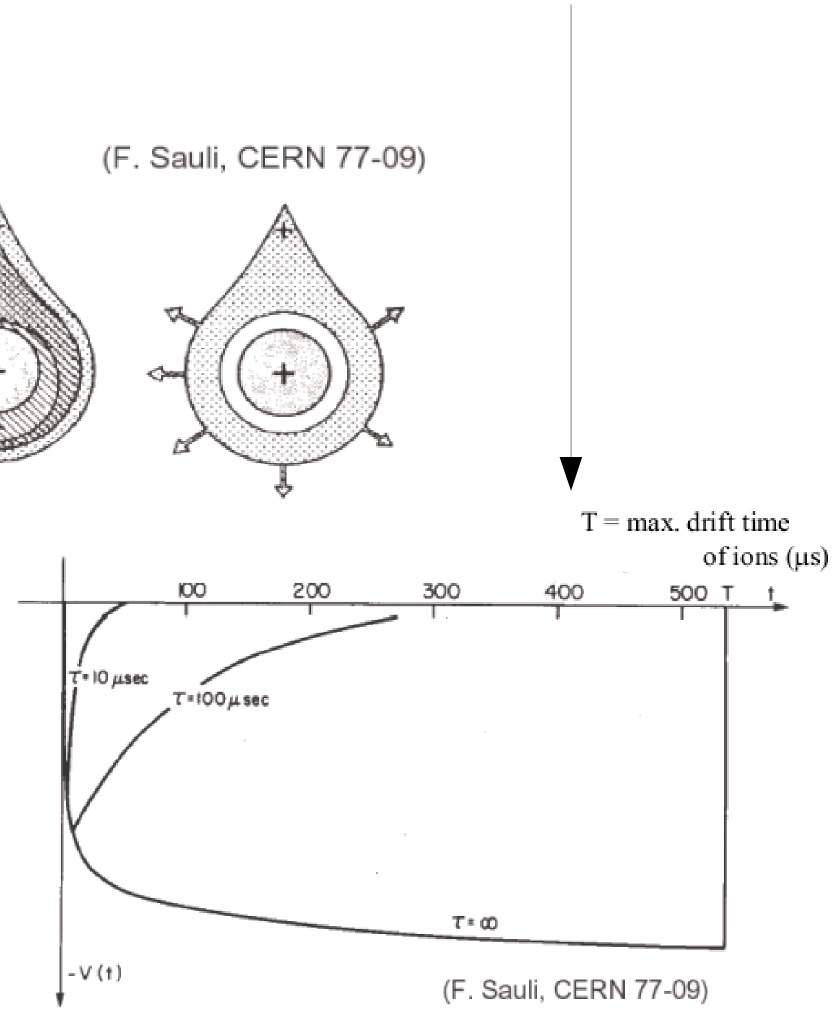
Principle:

- 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

(F. Sauli, CERN 77-09)





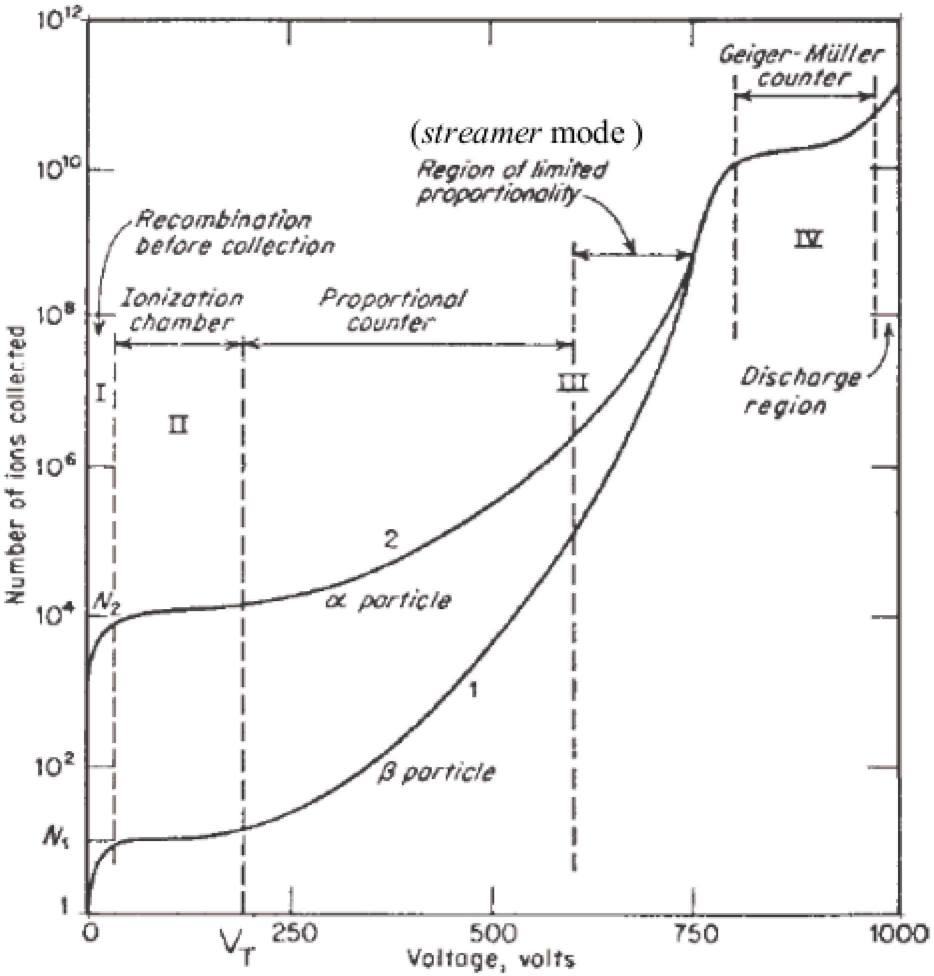


(F. Sauli, CERN 77-09)

Detectors (Gaseous)

Gain vs Electric field

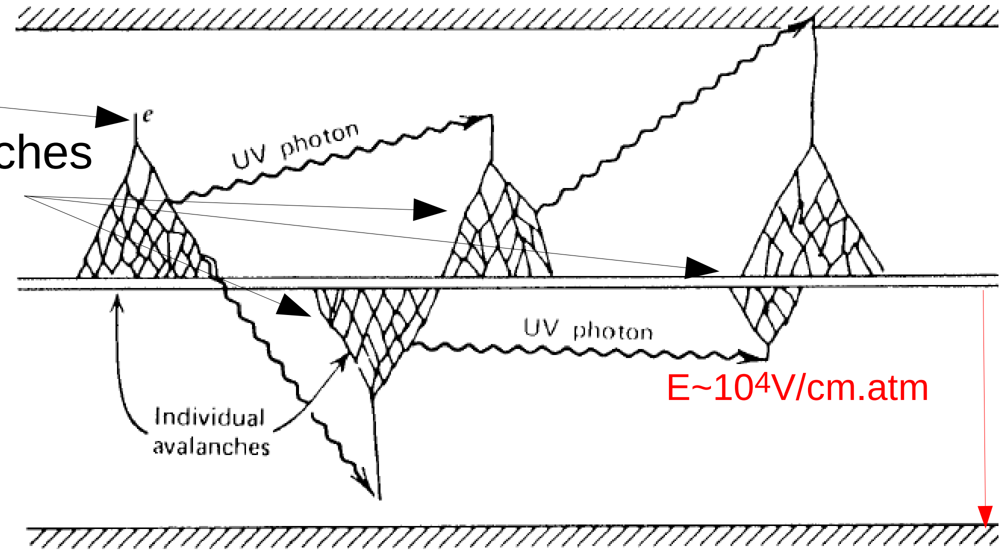
- I Potential too weak, pair recombination
- II Ionisation Chamber: no amplification
- IIIa Proportional mode, signal amplification
  - Proportional to ionisation.
  - Gain: 10^4 to 10^5
- IIIb Streamer mode, secondary avalanches
  - Need “quencher” (CH_4,CO_2,...)
- IV Geiger-Muller mode



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

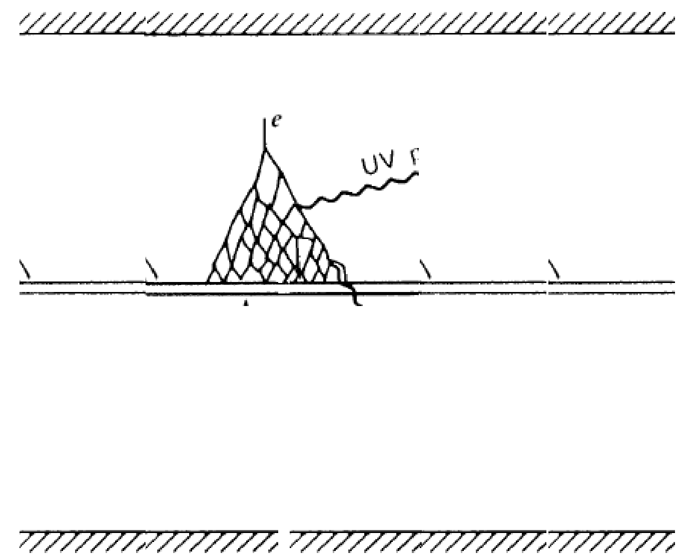
Detectors (Gaseous)

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

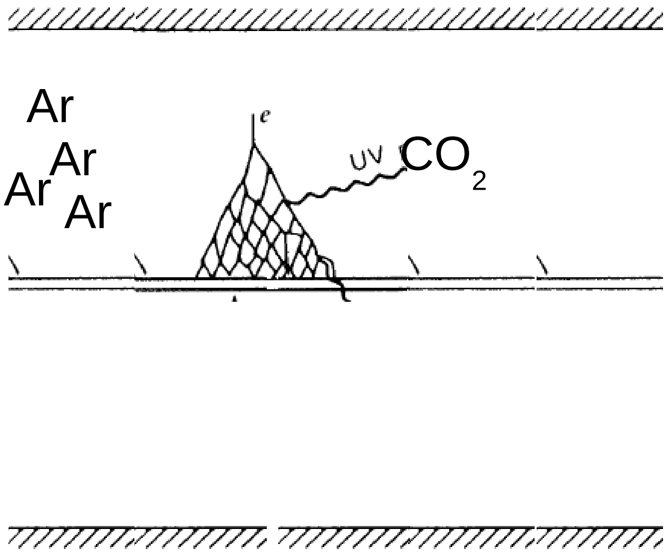


Spatial Resolution

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



Detectors (Gaseous)

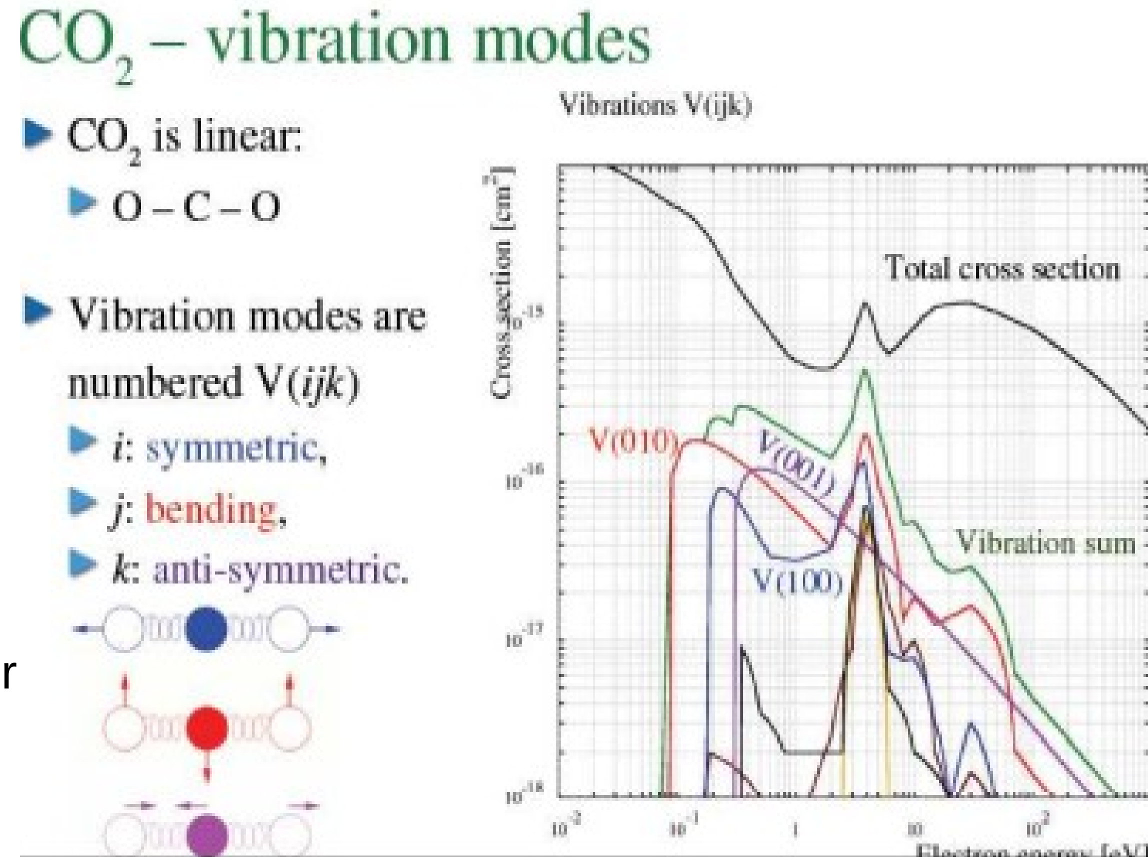


Spatial Resolution

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

“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



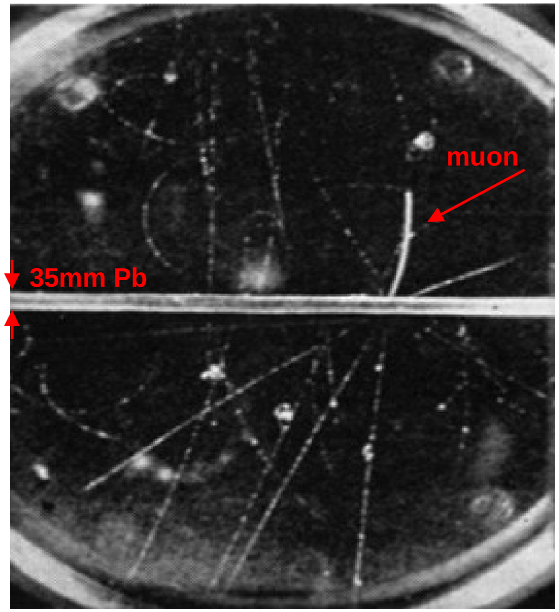
R.Veenhof (Garfield) http://cern.ch/garfieldpp

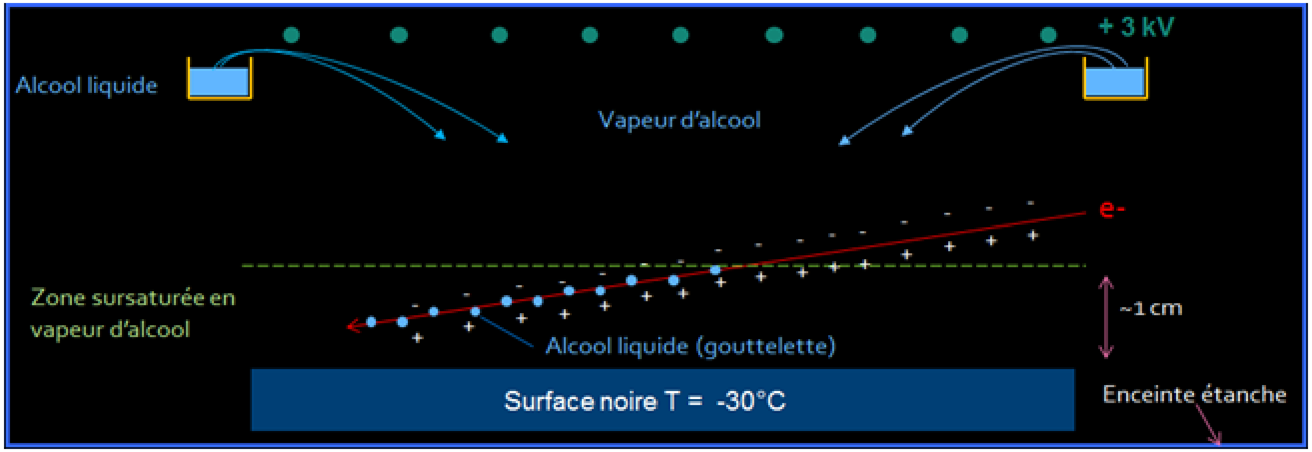
Detectors

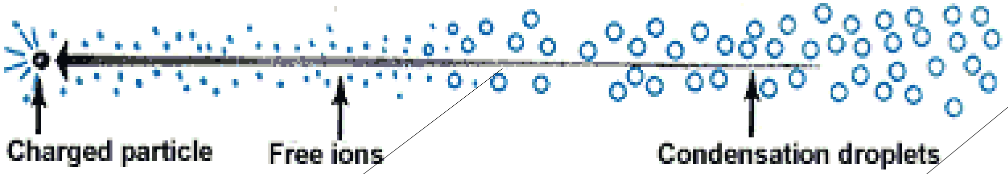
Clouds Chamber: Gaseous/Liquid

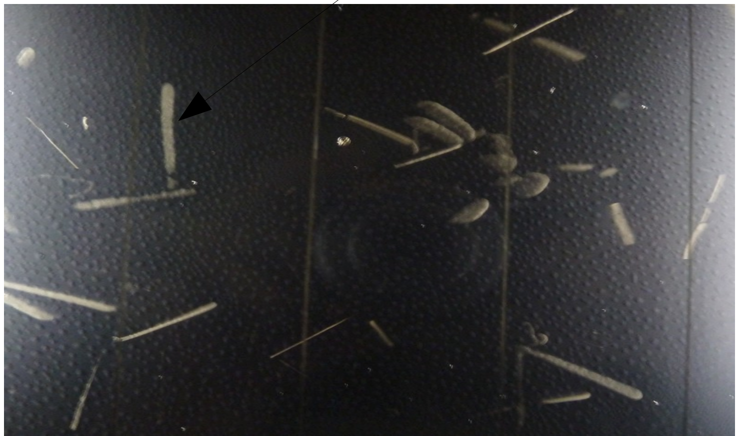
- C.T. R. Wilson 1911
- C.Anderson positron discovery 1932

Muon discovery 1936







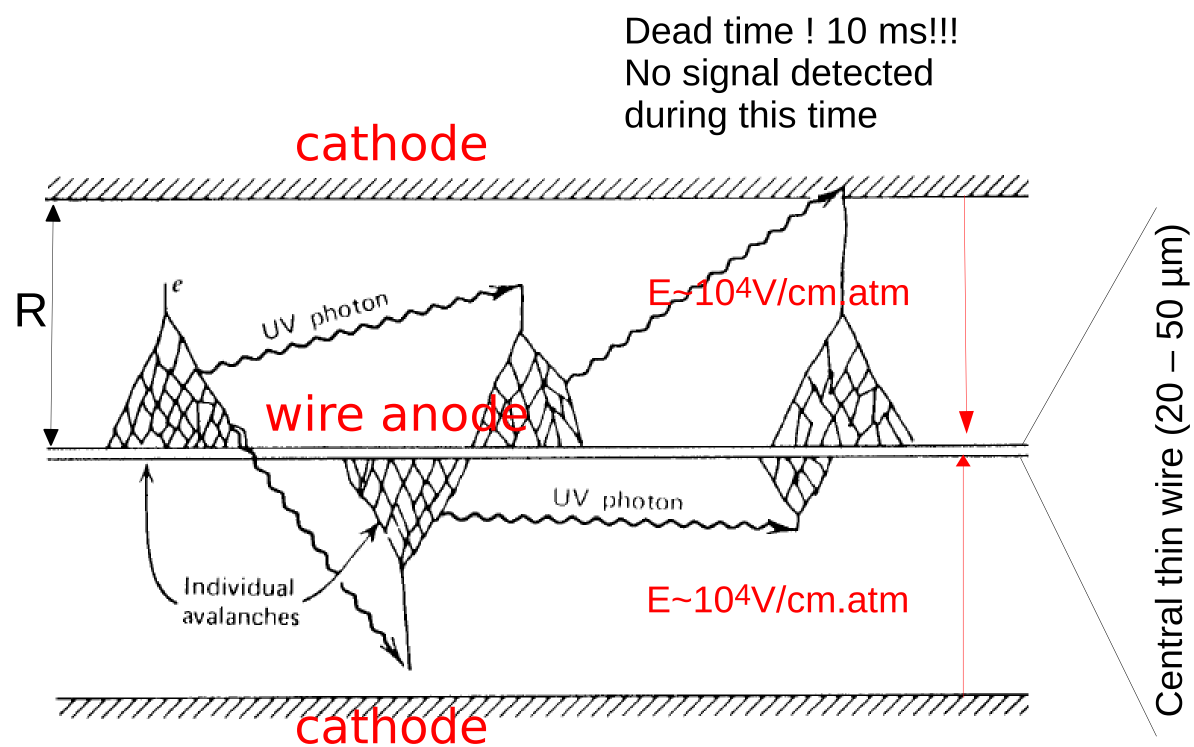


Broken cloud chamber
Physicist sad!

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,...



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

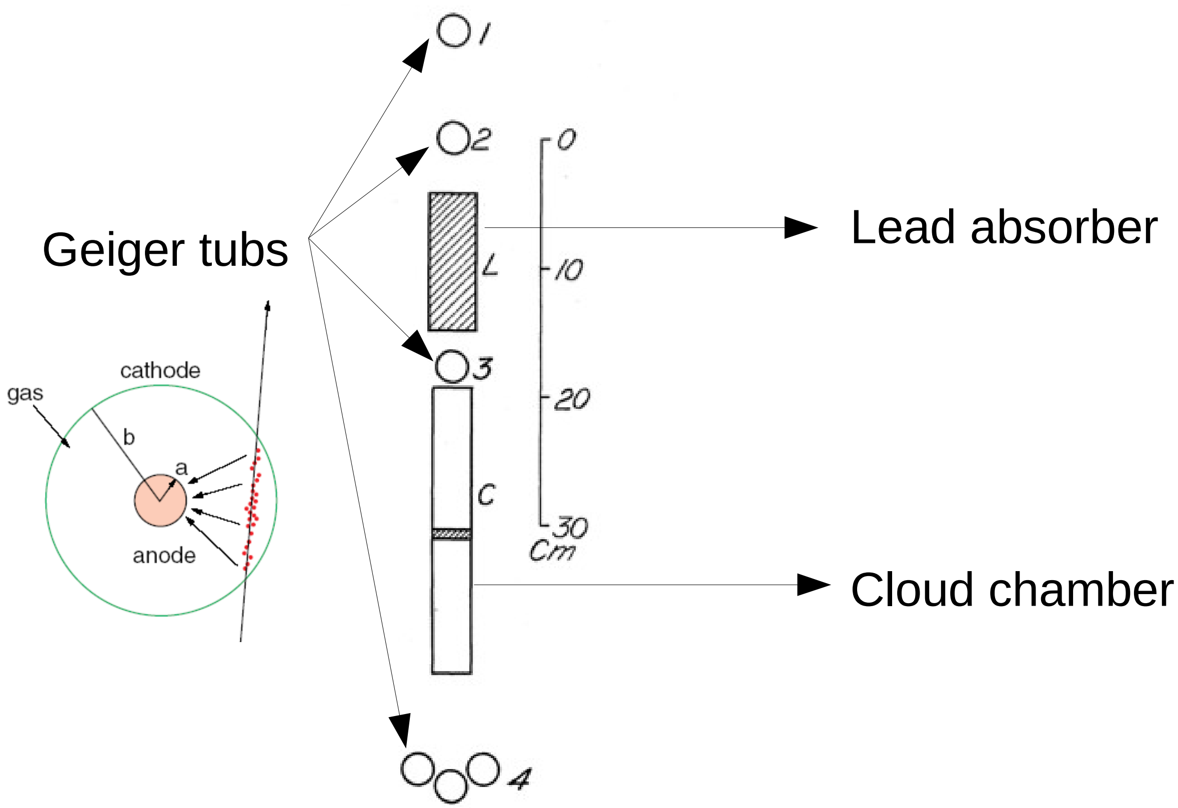
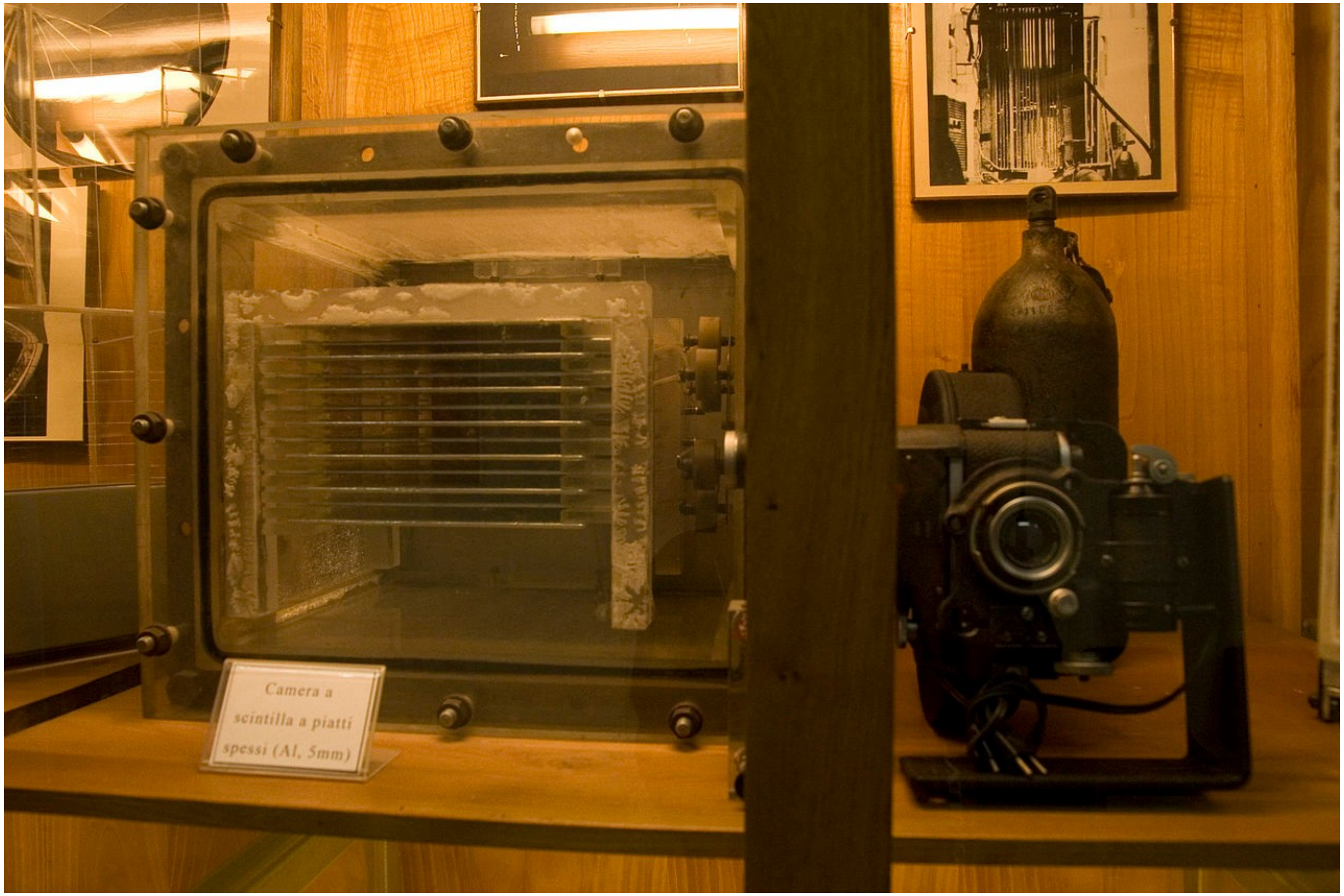


FIG. 1. Geometrical arrangement of apparatus.

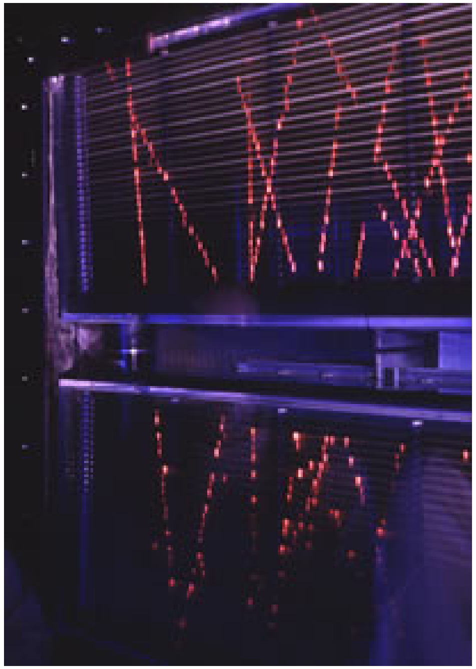
Detectors(Gaseous)

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.

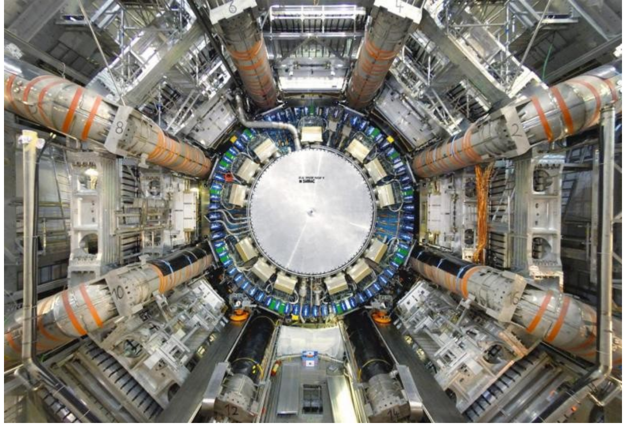


A spark chamber at the physics museum of the Sapienza University of Rome



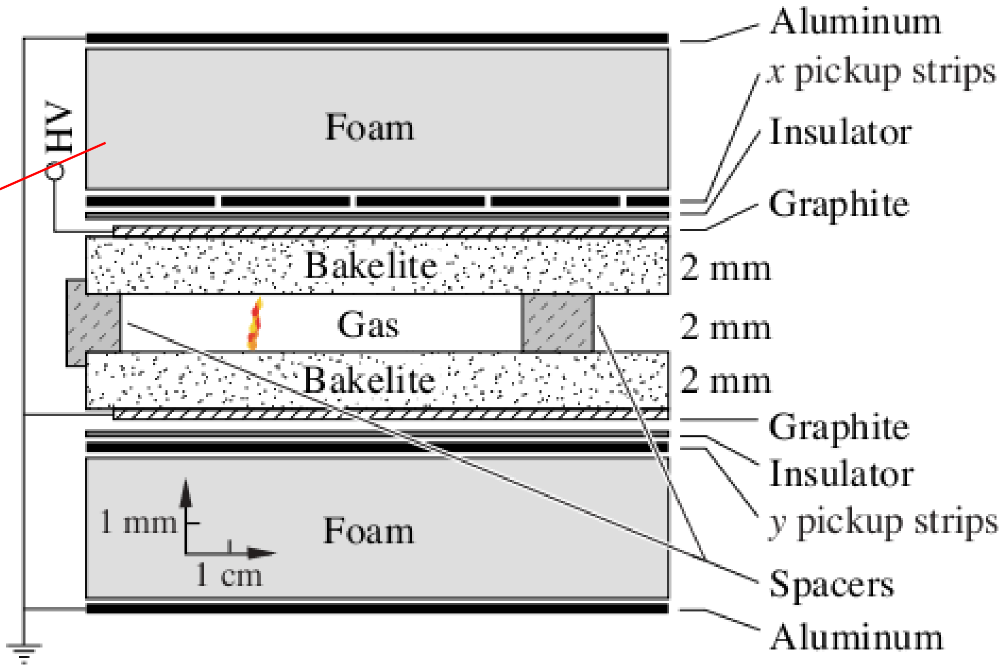
Remark:
HV applied 0,1 s à 1 μs
to avoid saturation

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

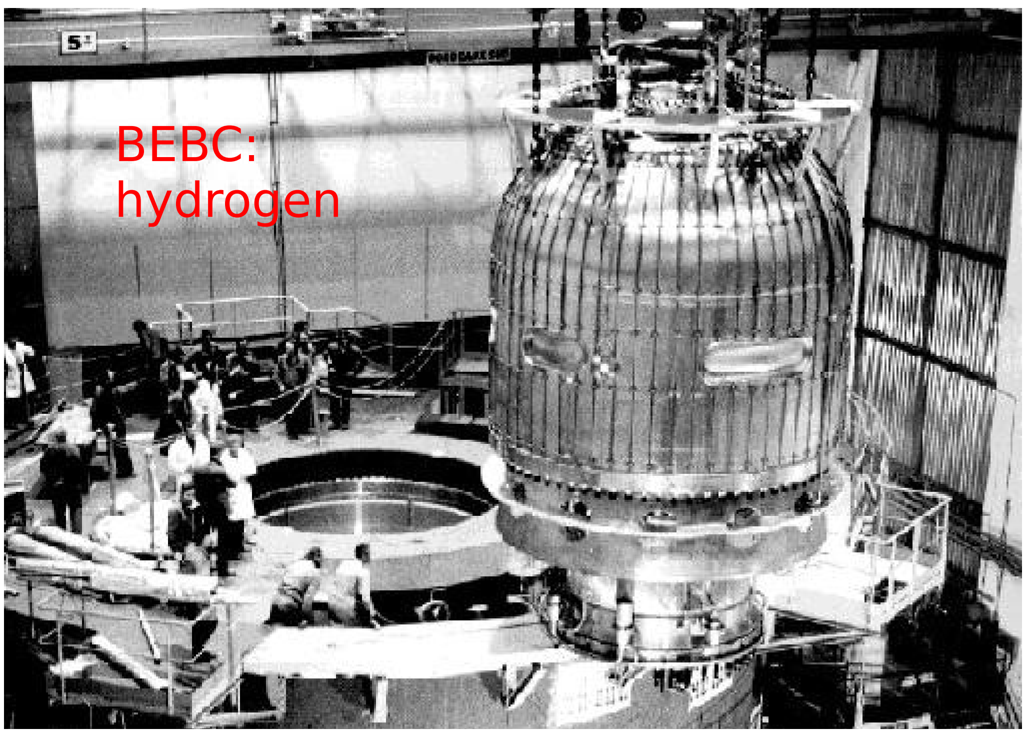
- ATLAS Muons spectrometer Trigger
- RPCs are robust detectors (no wire)
- The signal formation happens in the conversion gap as soon as the ionization electrons amplify and the avalanche develops. The signal is induced instantly on the readout strips placed on the outside of the resistive plates. RPCs 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

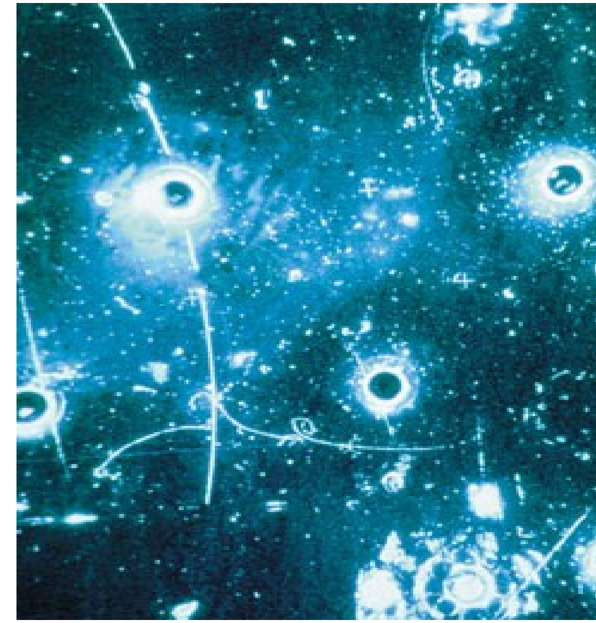
Detectors

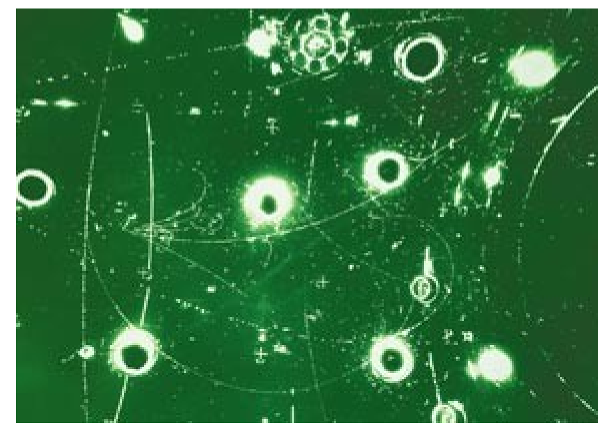
Bubbles Chamber : Liquid/Gaseous

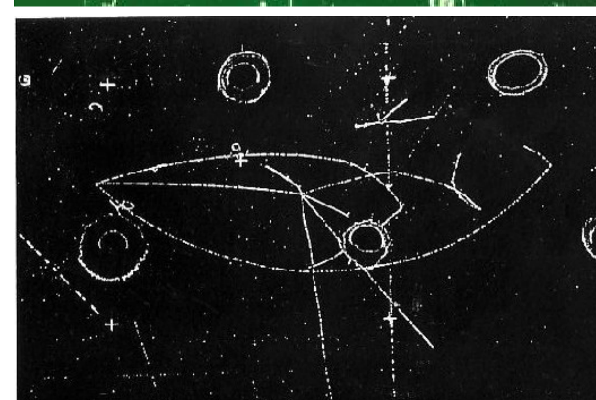
- C.Glaser 1952
  - Liquid phase + bubbles (gaseous)

- 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!

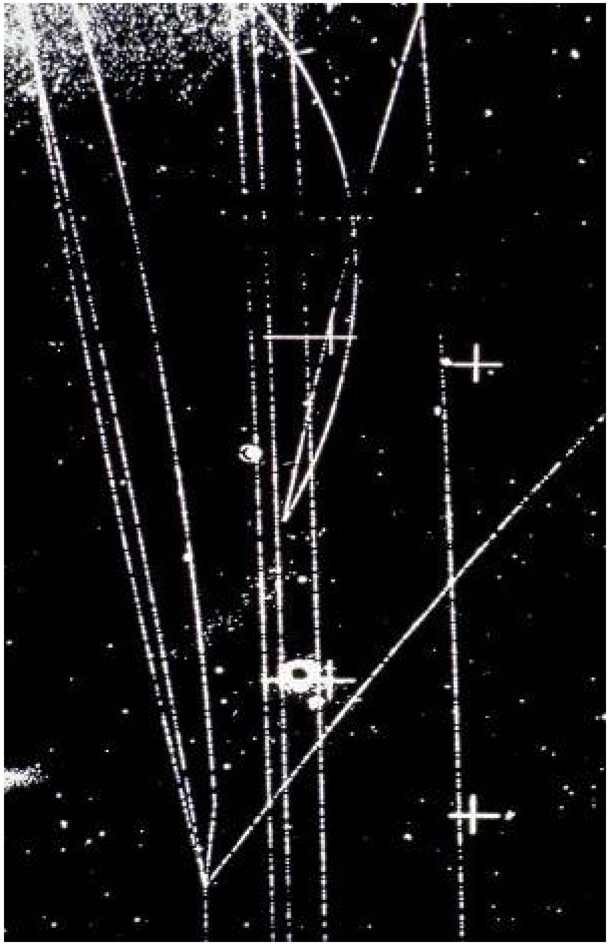
Detectors

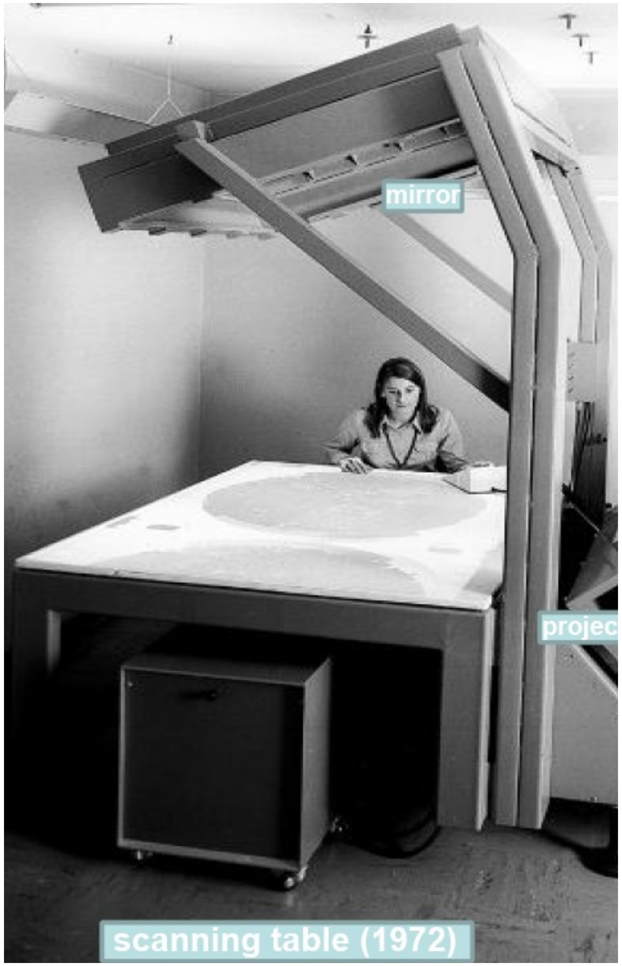
Bubbles Chamber

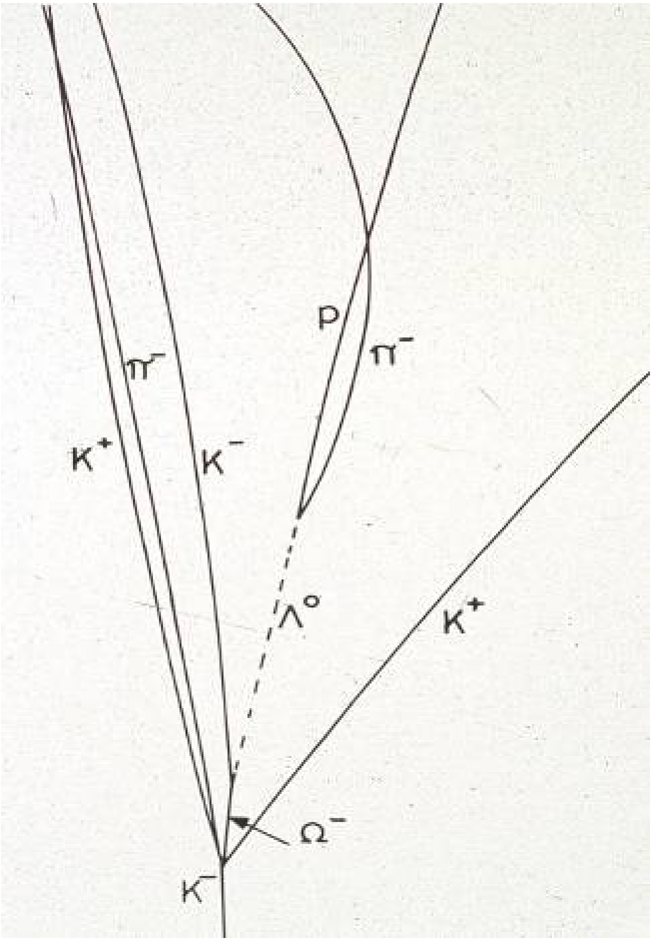
pictures

Reconstruction

Final plot



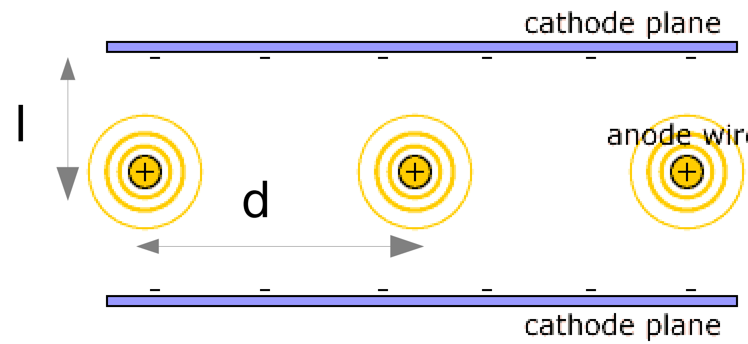


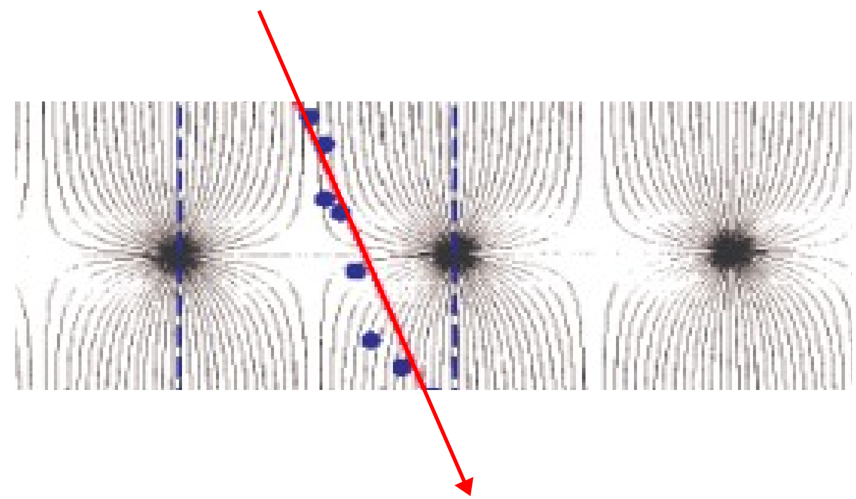


Detectors(Gaseous)

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



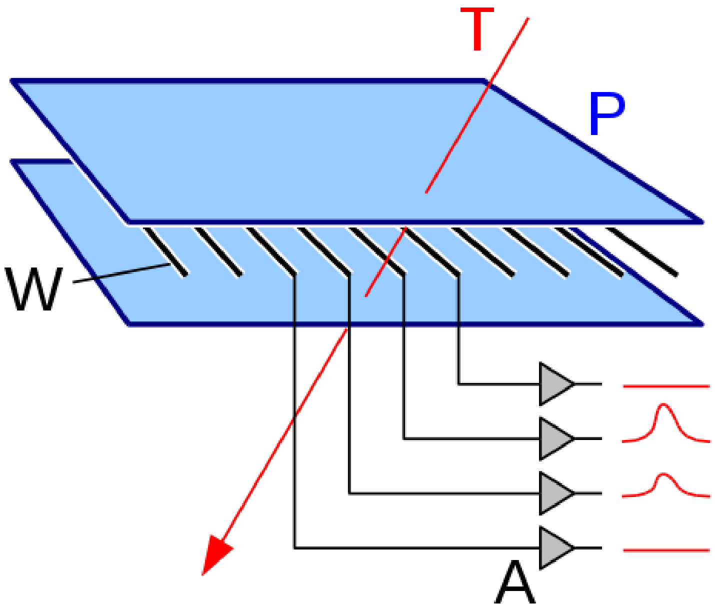


Detectors(Gaseous)

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
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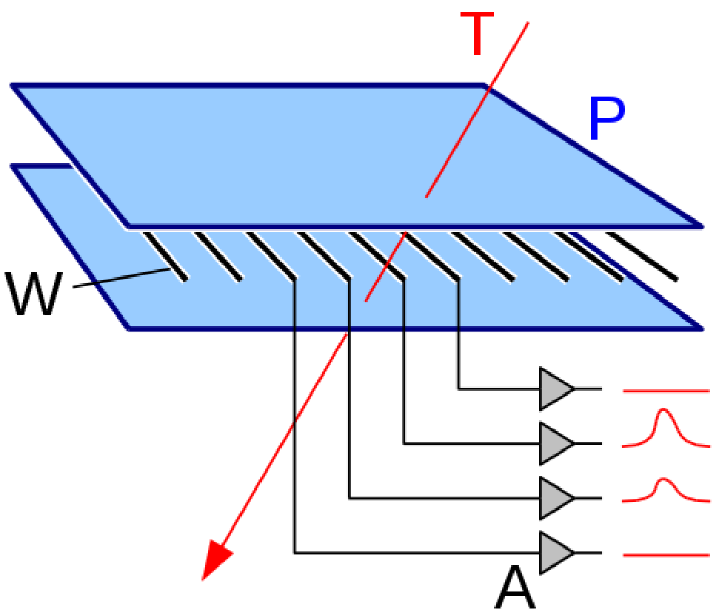
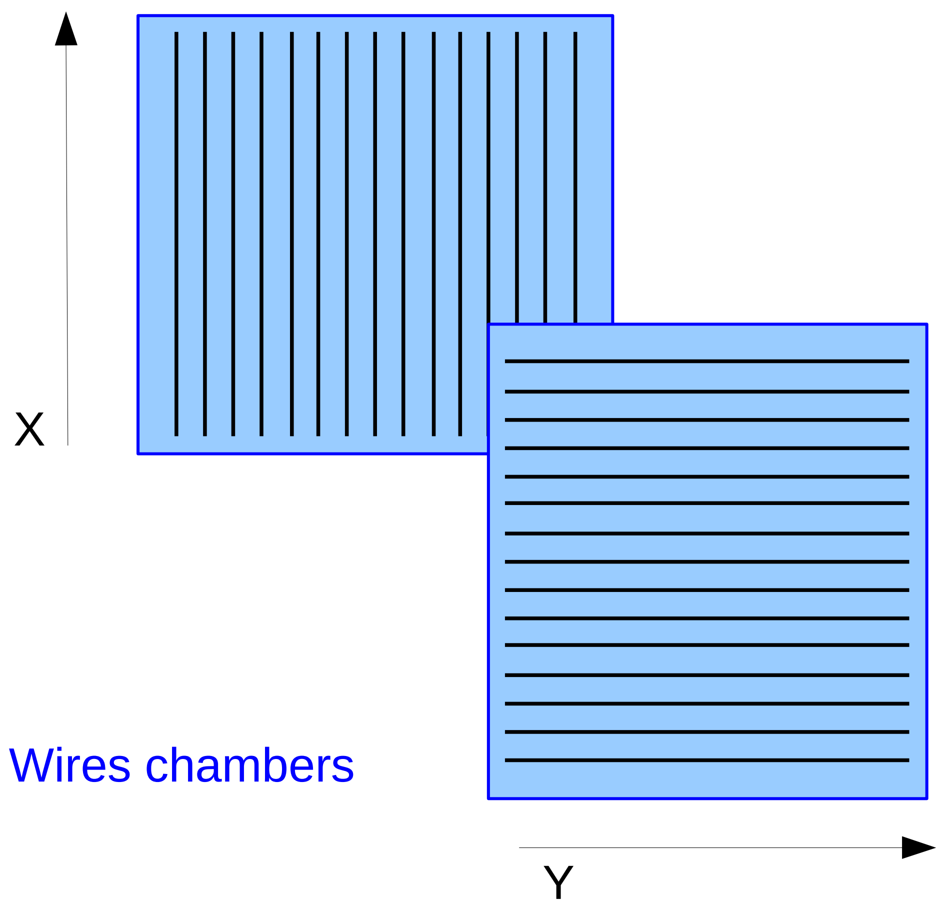
- Wires measure only one coordinate!!!



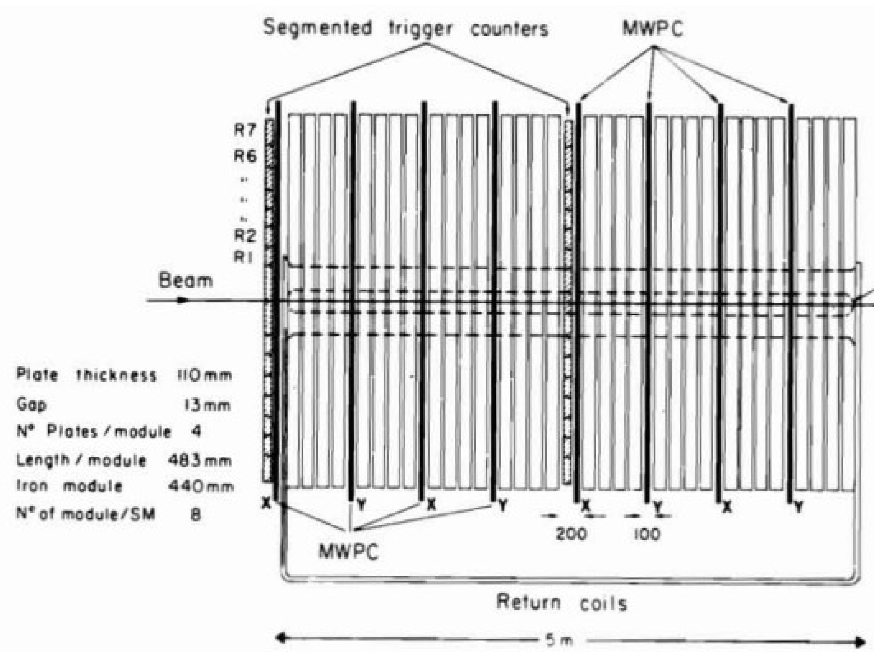


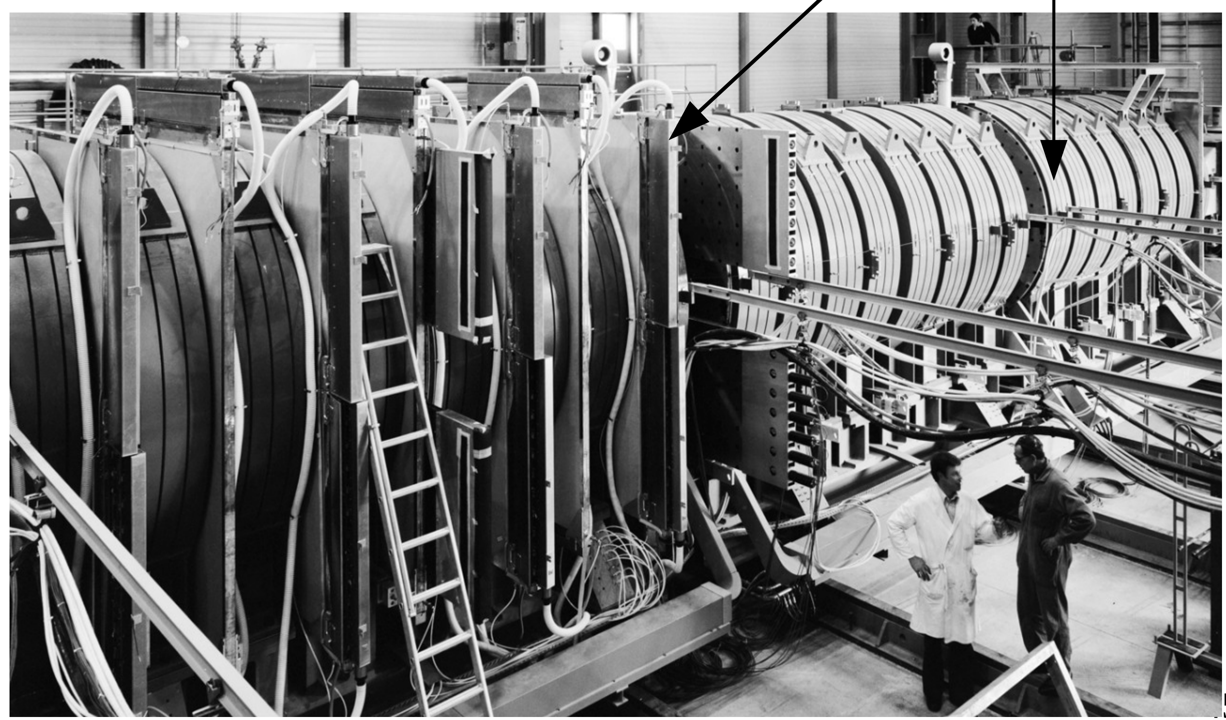
To get the second coordinate: 2 Wires chambers

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)

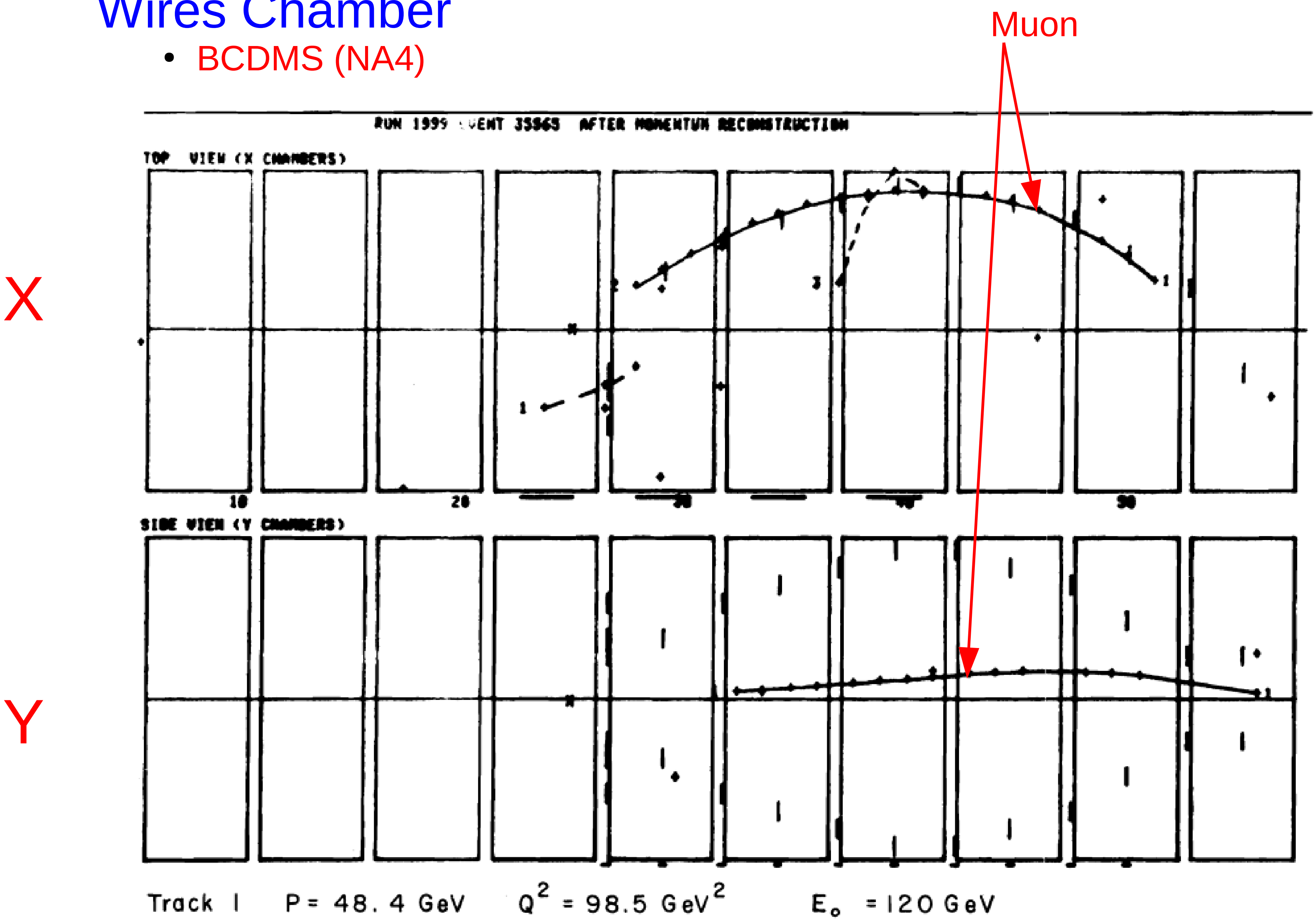
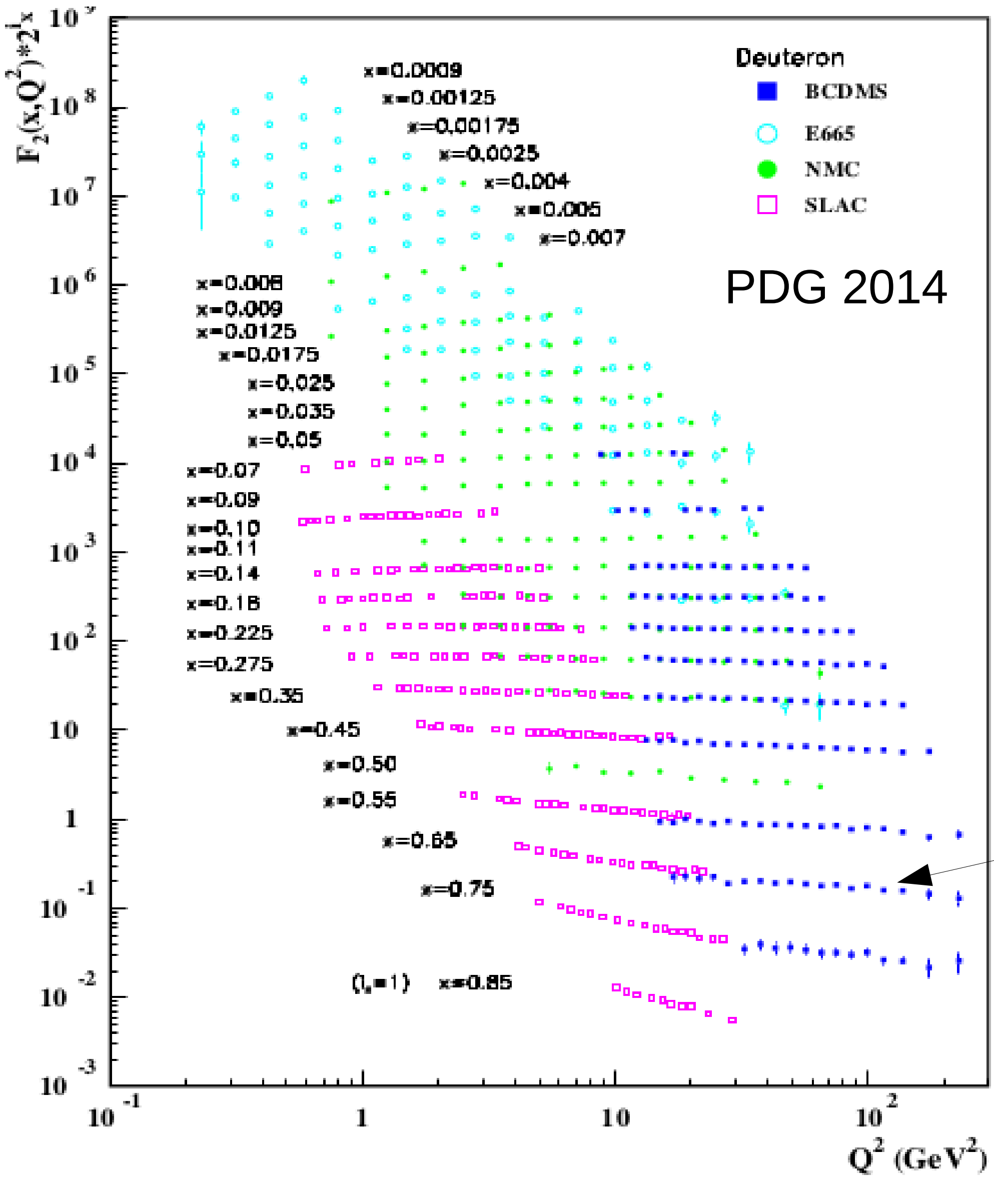


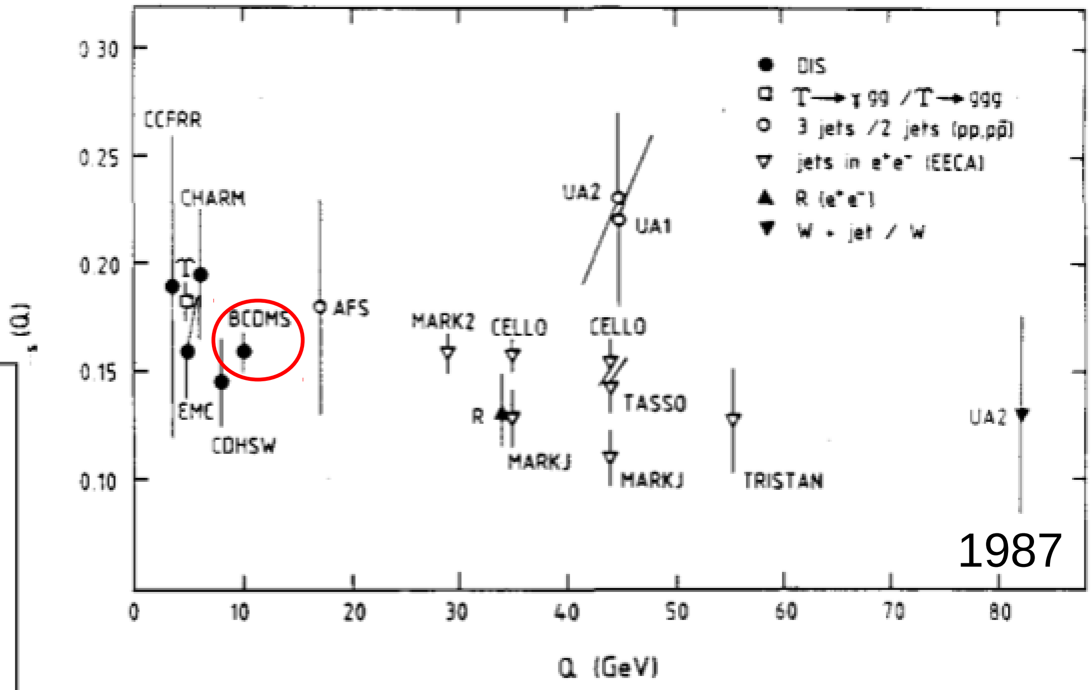
Fig. 14. Example of a deep inelastic muon scattering event at 120 GeV in the NA4 apparatus.

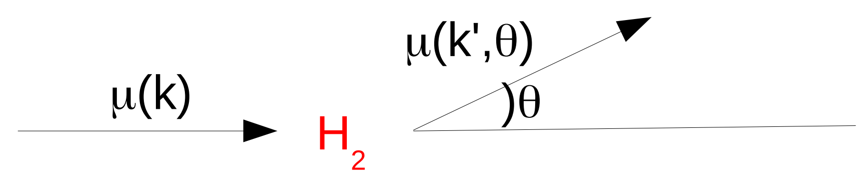
Detectors(Gaseous)

Wires Chamber

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





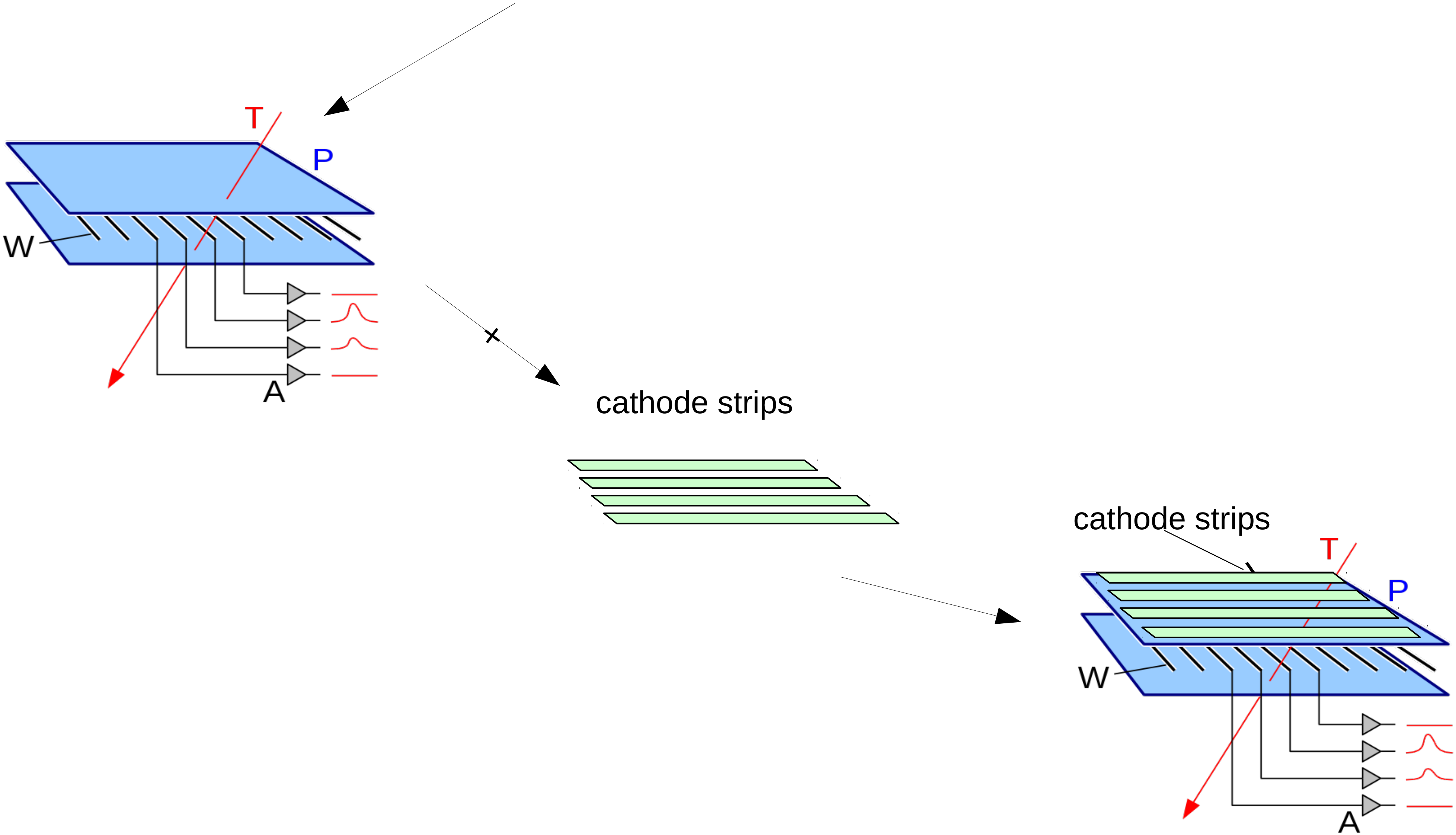


Slope proportional to α_s

Detectors(Gaseous)

TGC*

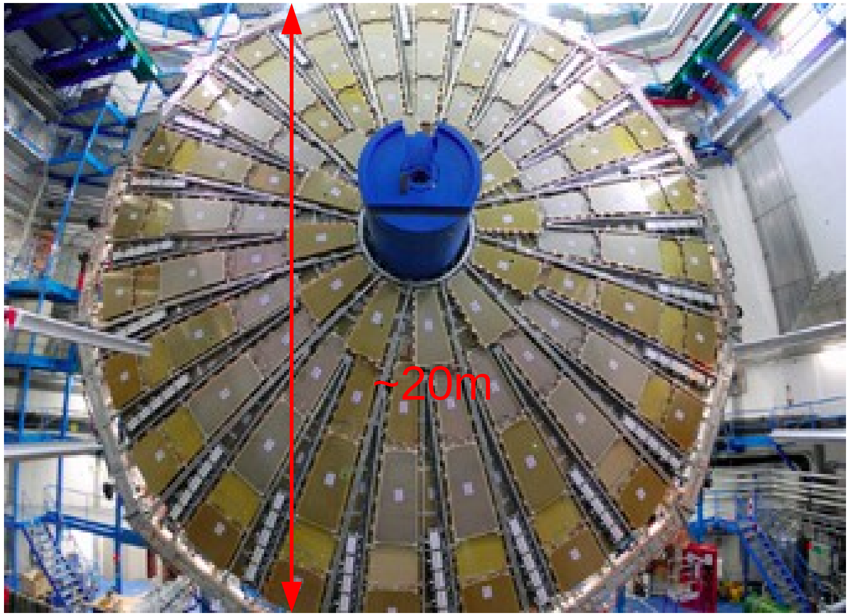
- Thin Gap Chamber
  - Go back to MWPC

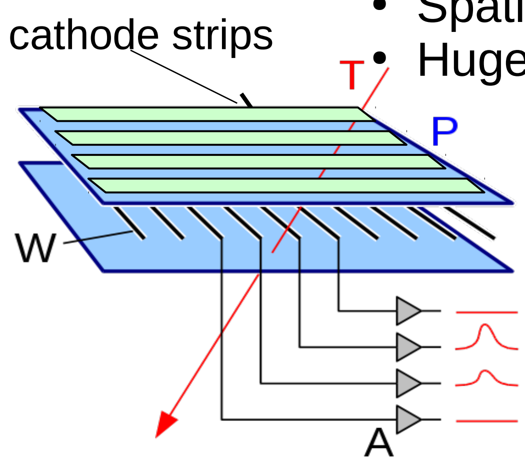


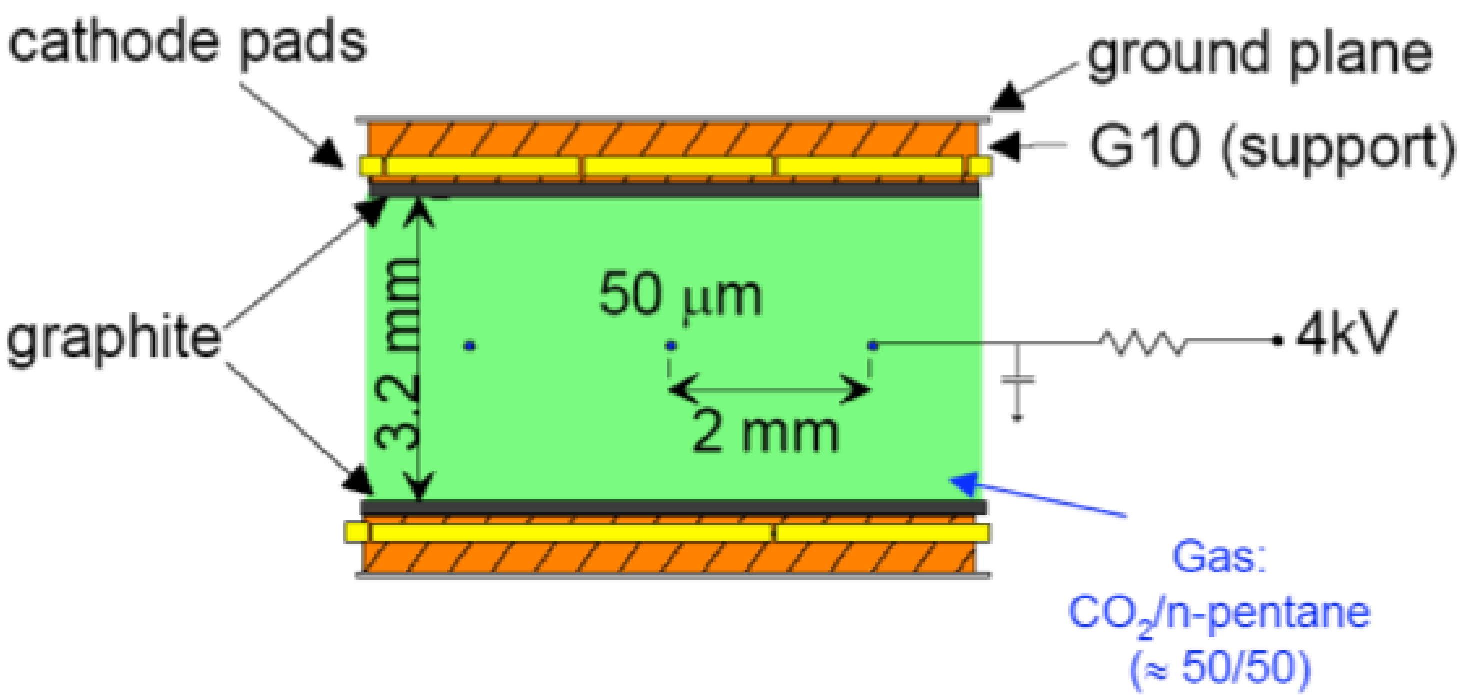
Detectors(Gaseous)

TGC*

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

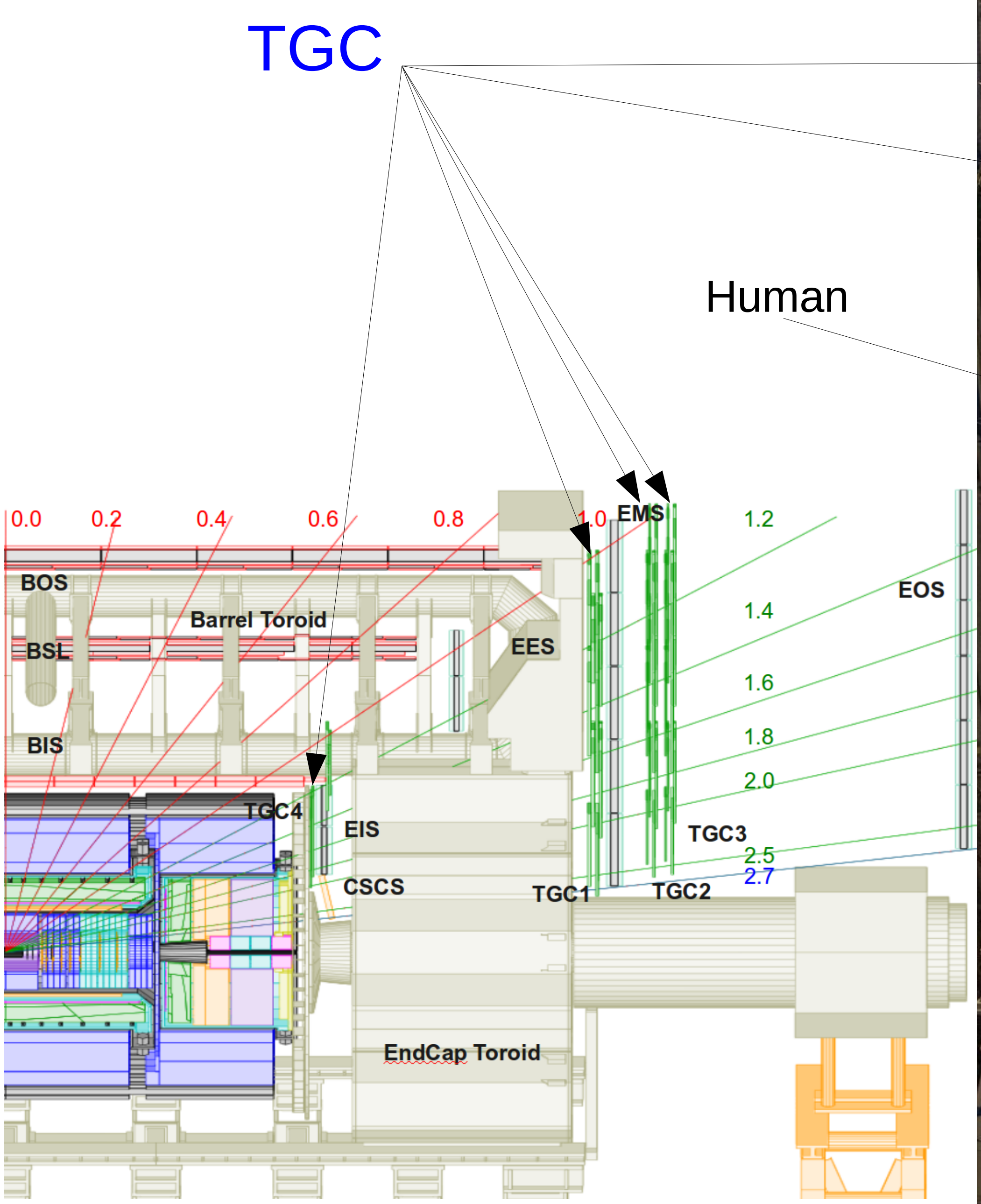


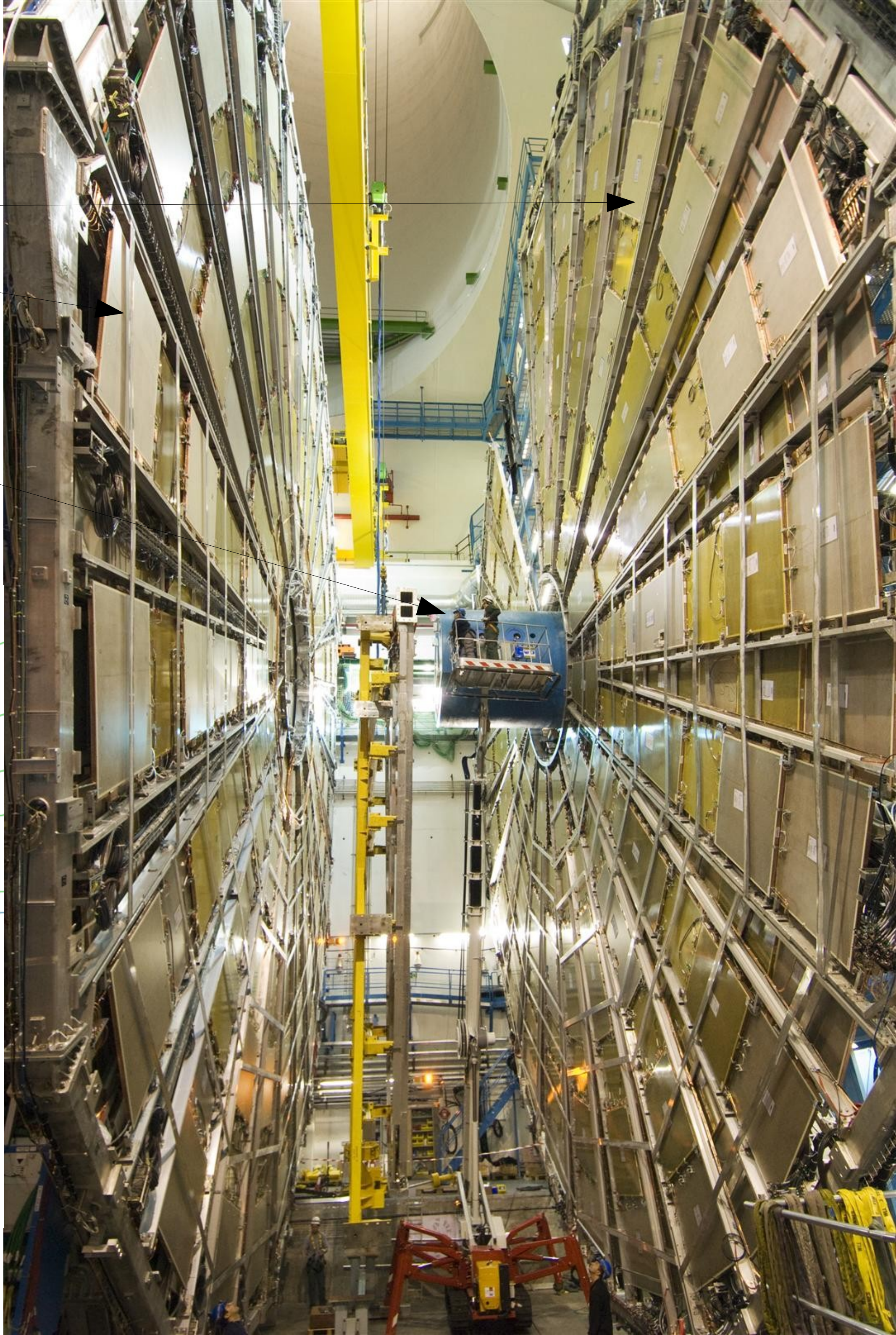




TGC used in ATLAS
for muon trigger

Detectors(Gaseous)





Interlude

Charged particle in magnetic field

Charged particle in magnetic field

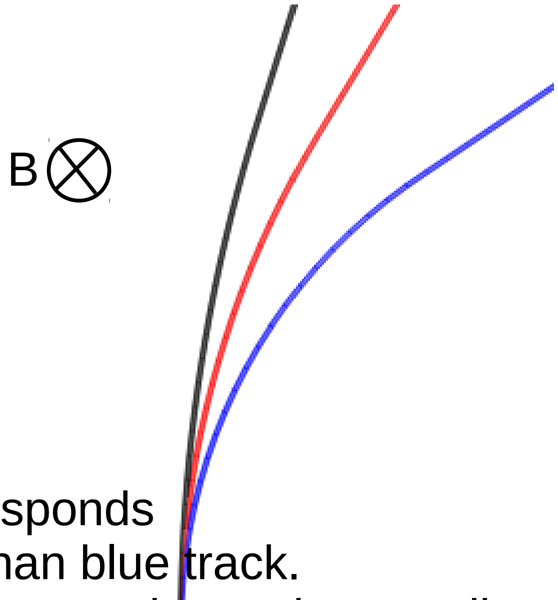
Phys. Rev. 51 (1937) 884

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

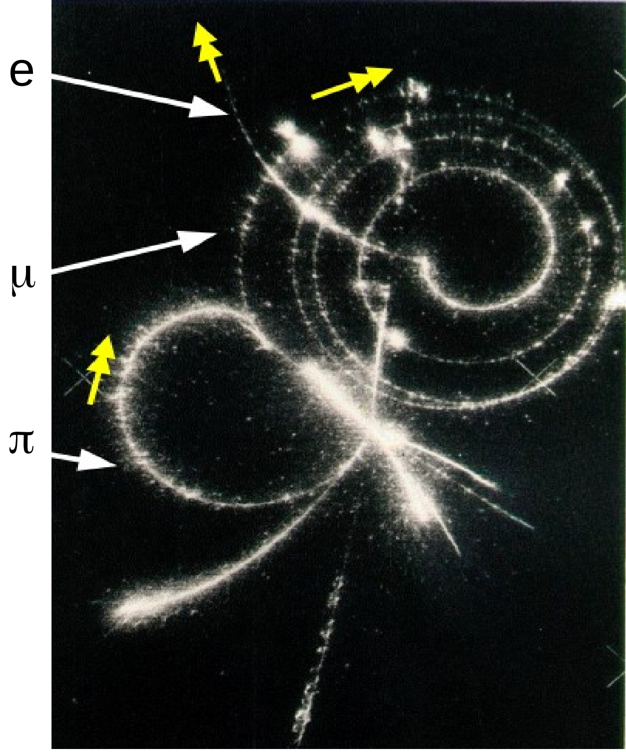
Charged particle in magnetic field

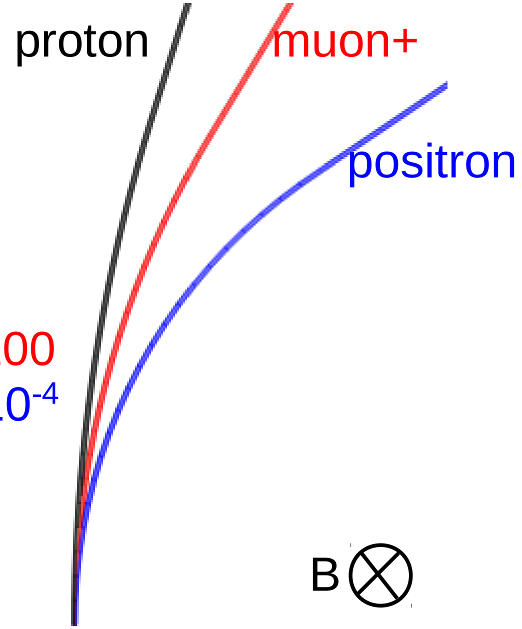
Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

$$P \sim 0.3 \cdot R \cdot B$$

P: momentum (GeV)
R: curvature (m)
B: Magnetic field (Tesla)

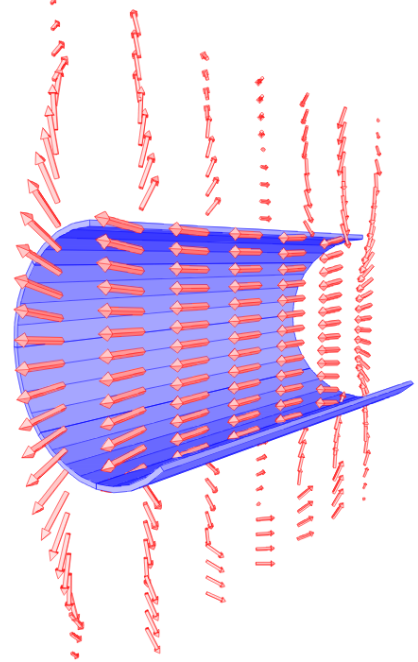




Proton mass: ~1
Muon mass: ~0.100
Electron mass: ~5.10^{-4}

Remark: the curvature in this example does not correspond to the relative curvature between proton, muon & electron

Charged particle in magnetic field



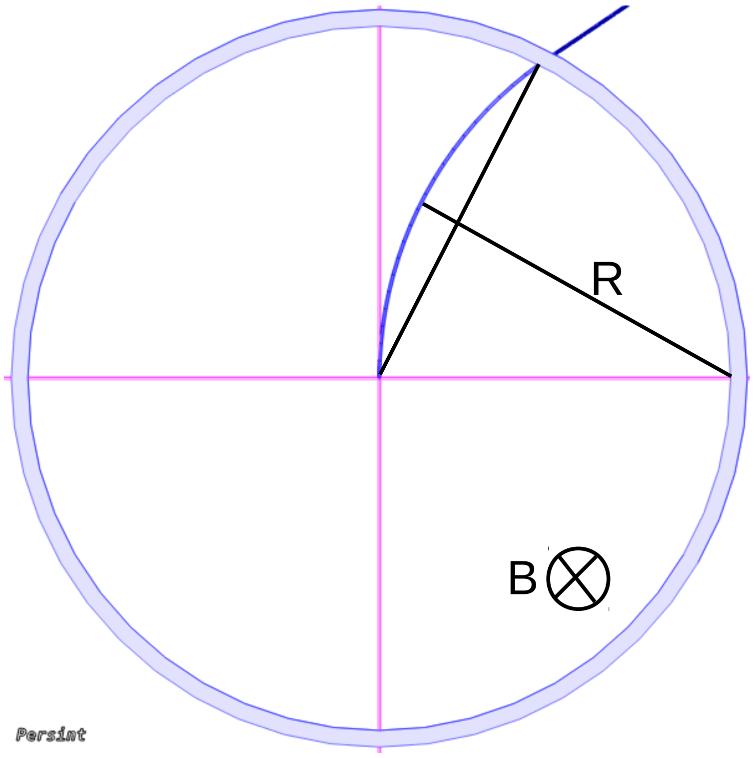
Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

$$P \sim 0.3 \cdot R \cdot B$$

P: momentum (GeV)
R: curvature (m)
B: Magnetic field (Tesla)

Solenoid (CMS,ATLAS,Delphi...)



Charged particle in magnetic field

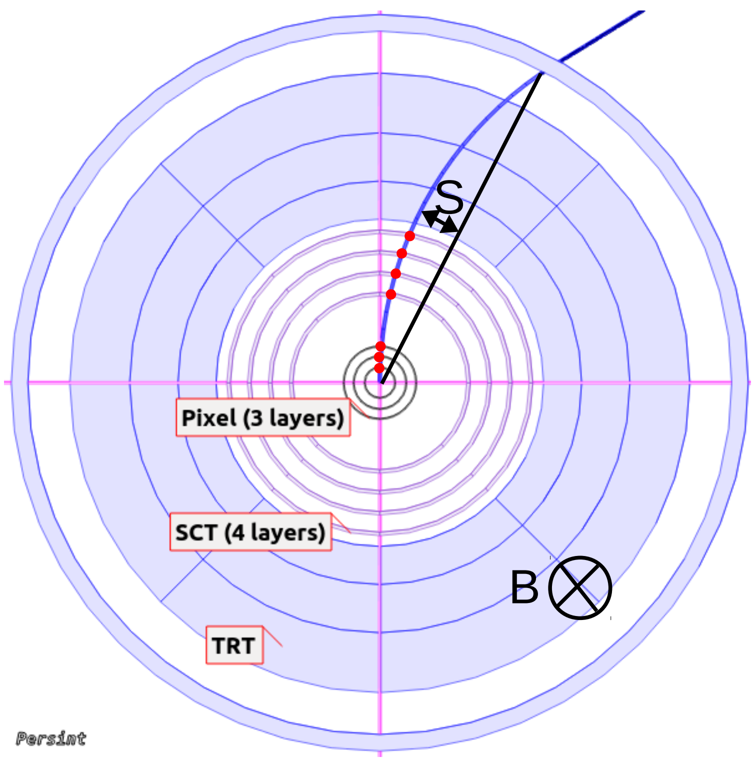
Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

$$P \sim 0.3 \cdot R \cdot B \qquad R \rightarrow \frac{1}{S}$$

P: momentum (GeV)
R: curvature (m)
B: Magnetic field (Tesla)

Solenoid (ATLAS Inner Tracker)



Charged track => signal in detectors
=> reconstruction program
=> Sagitta (=1/R) determination

Charged particle in magnetic field

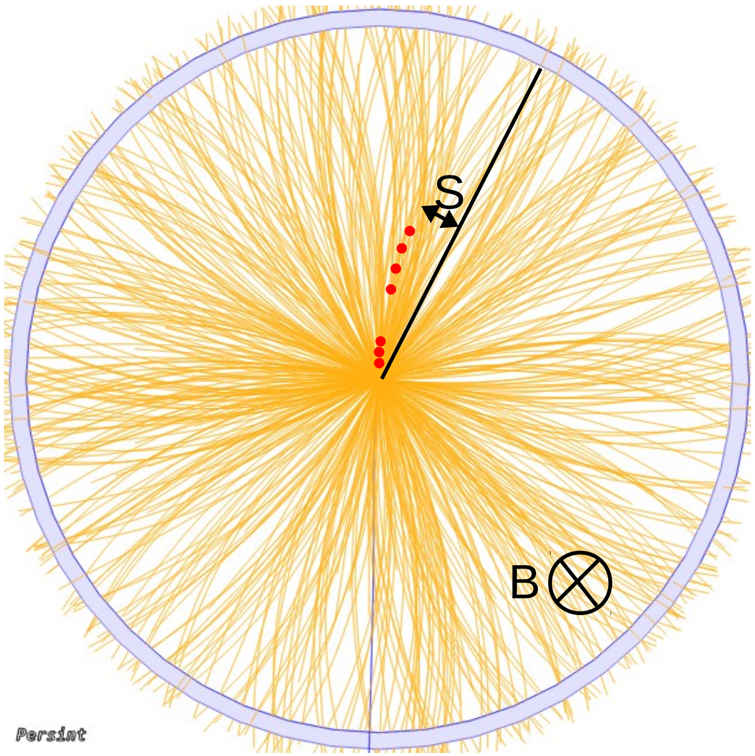
Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

$$P \sim 0.3 \cdot R \cdot B \qquad R \rightarrow \frac{1}{S}$$

P: momentum (GeV)
R: curvature (m)
B: Magnetic field (Tesla)

Solenoid (ATLAS Inner Tracker)



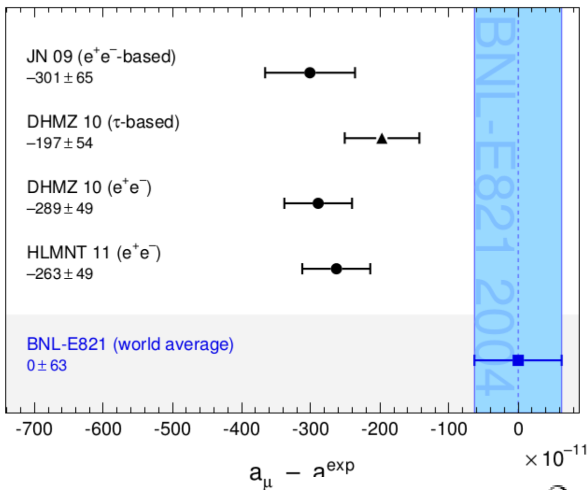
Charged track => signal in detectors
=> reconstruction program
=> Sagitta (=1/R) determination

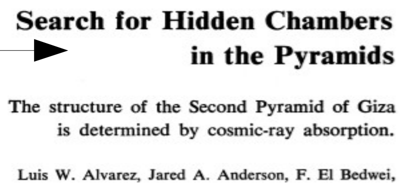
Reconstruction can be complicated

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 $\rightarrow 4\mu$
  - Neutrino signature for both domain
- As a tool:
  - Trigger
  - Veto
  - Detector calibration: MIP
  - Muo-graphy





Search for Hidden Chambers in the Pyramids

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

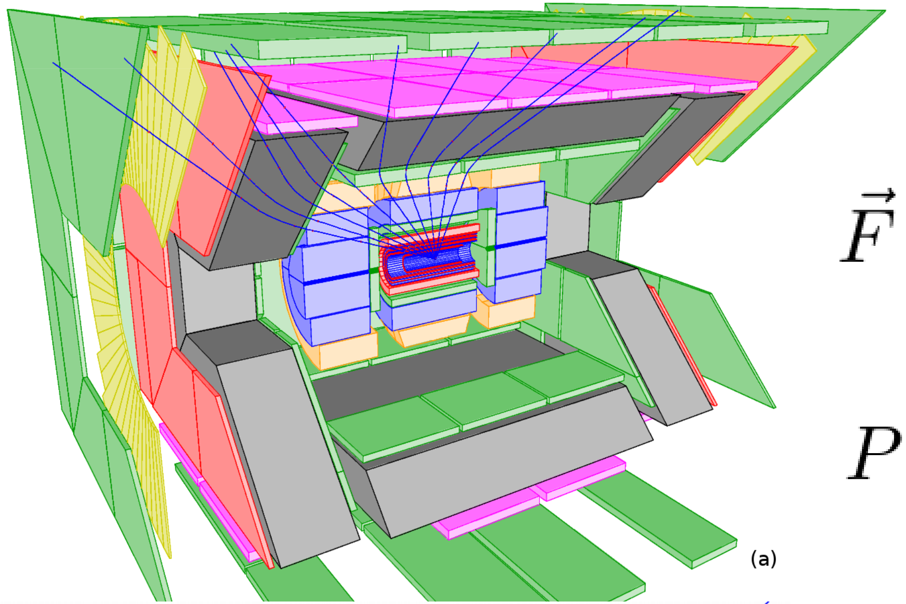
Luis W. Alvarez, Jared A. Anderson, F. El Bedwei,

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

- How?
  - Detection mechanism:
    - Ionisation, Scintillation, Cherenkov radiation
  - Identification:
    - Tag after “walls”, dE/dx, Cherenkov
  - \+ Magnetic Field => momentum measurment

Charged particle in magnetic field

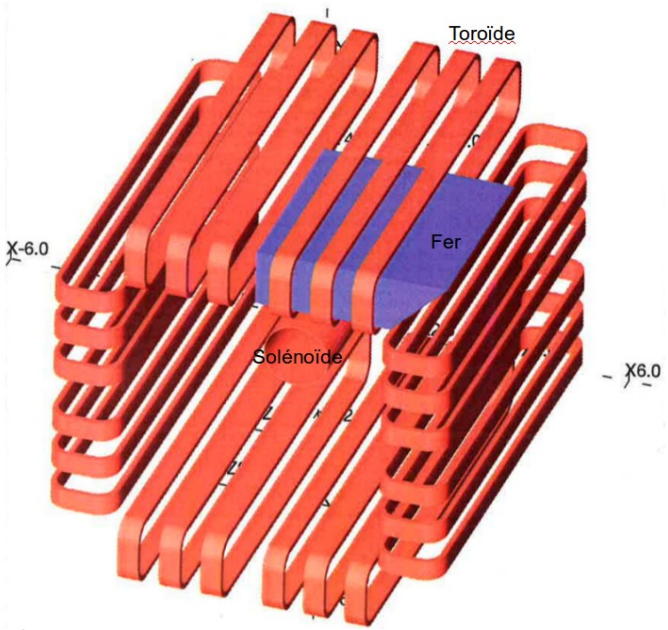
All detectors D0 to ATLAS,CMS,...until AMS are using Magnetic Field to measure the particle momentum.

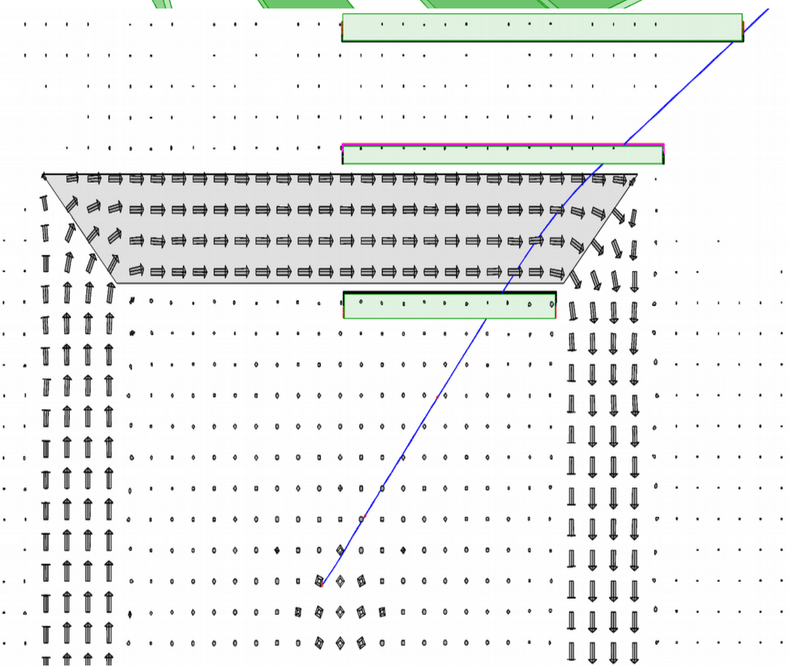


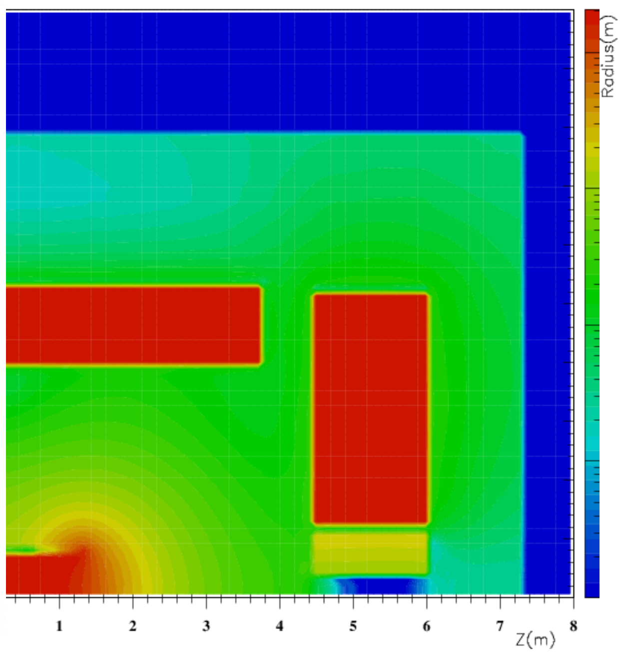
$$\vec{F} = q\vec{v} \times \vec{B}$$

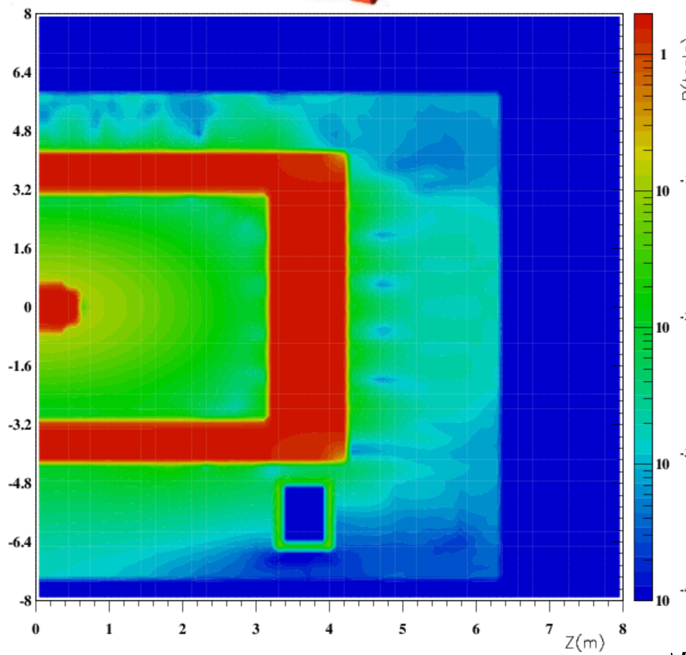
$$\downarrow$$

$$P \sim 0.3 \cdot R \cdot B$$

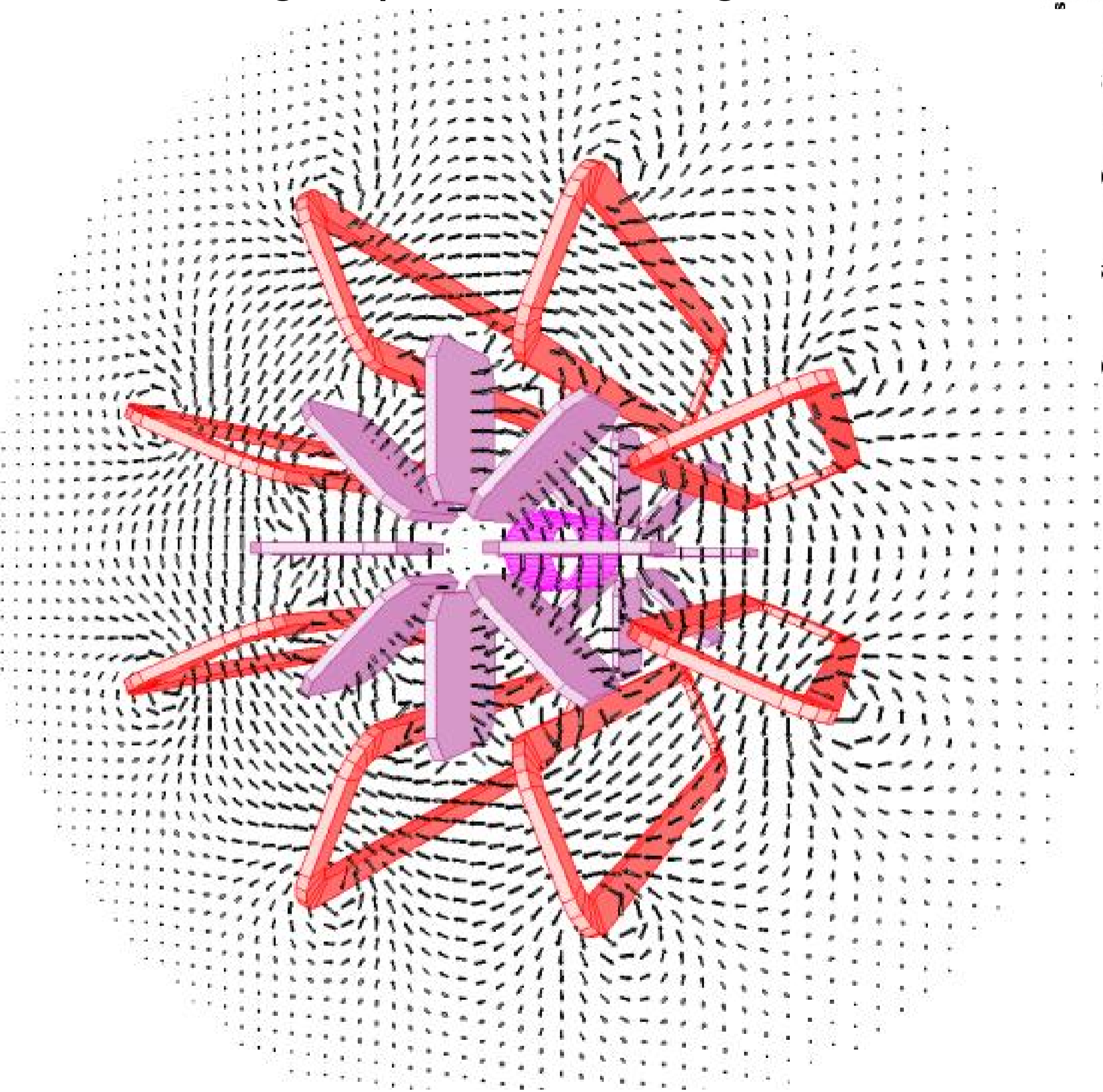


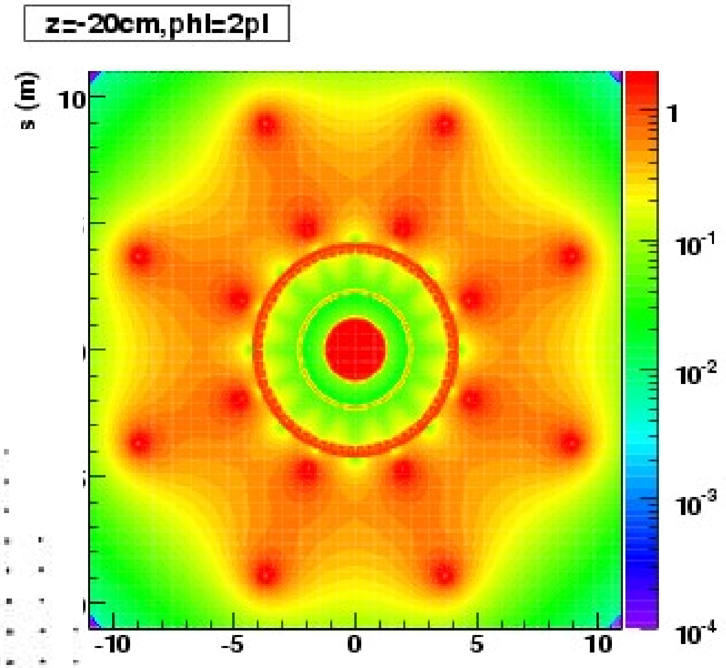






Charged particle in magnetic field



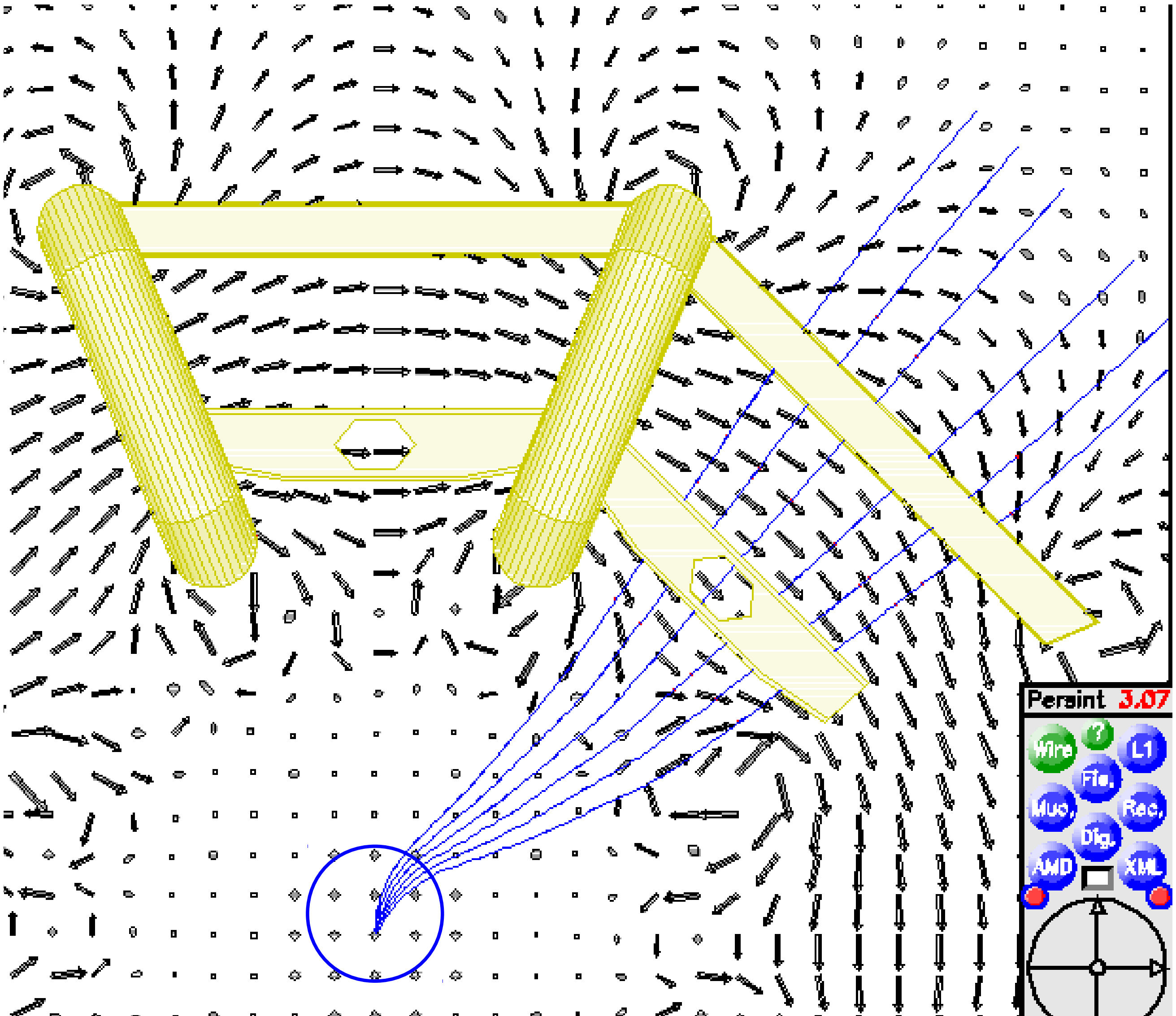


ATLAS magnetic field
1 solenoid
3 toroids

Charged particle in magnetic field

ATLAS magnetic field
1 solenoid
3 toroids

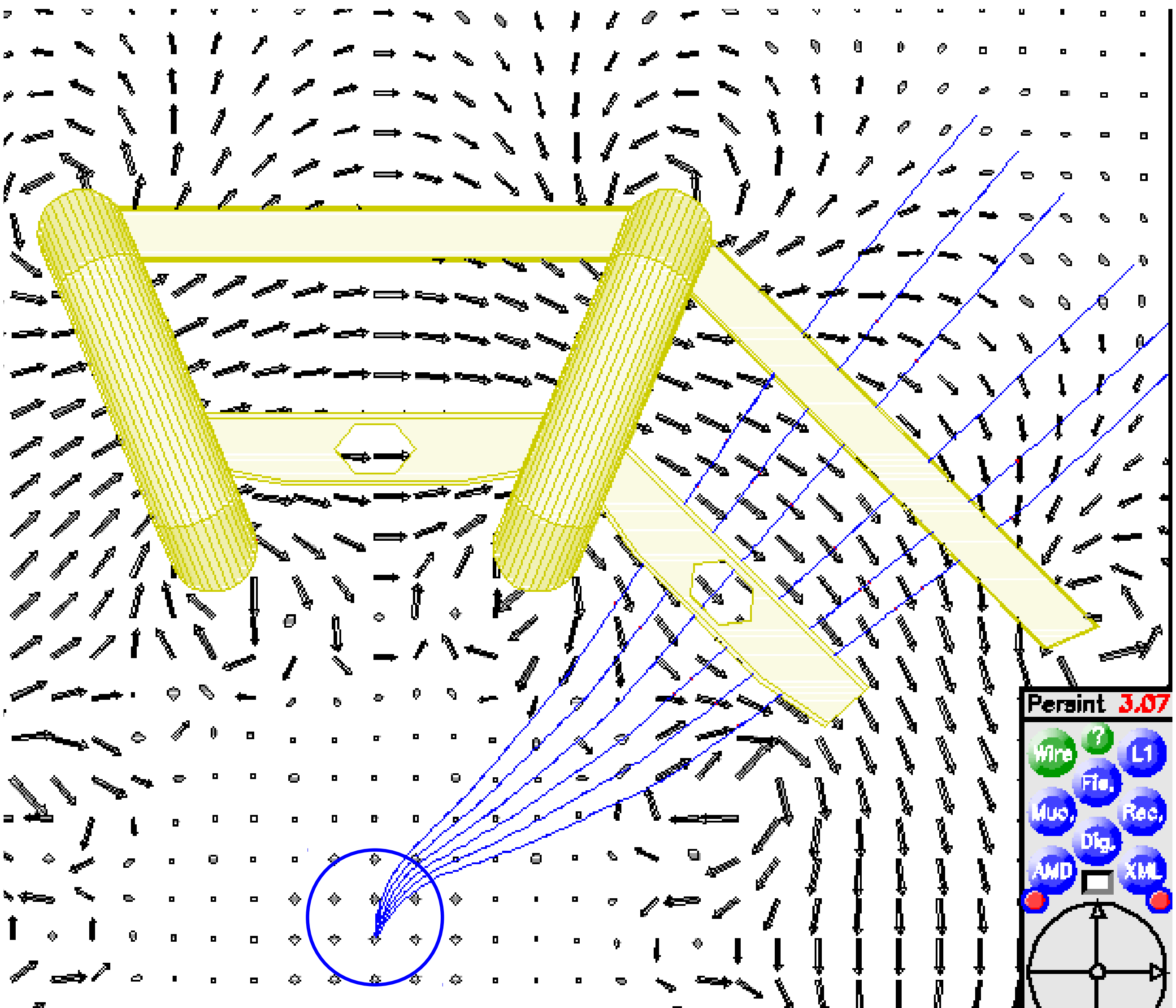
R-ϕ projection



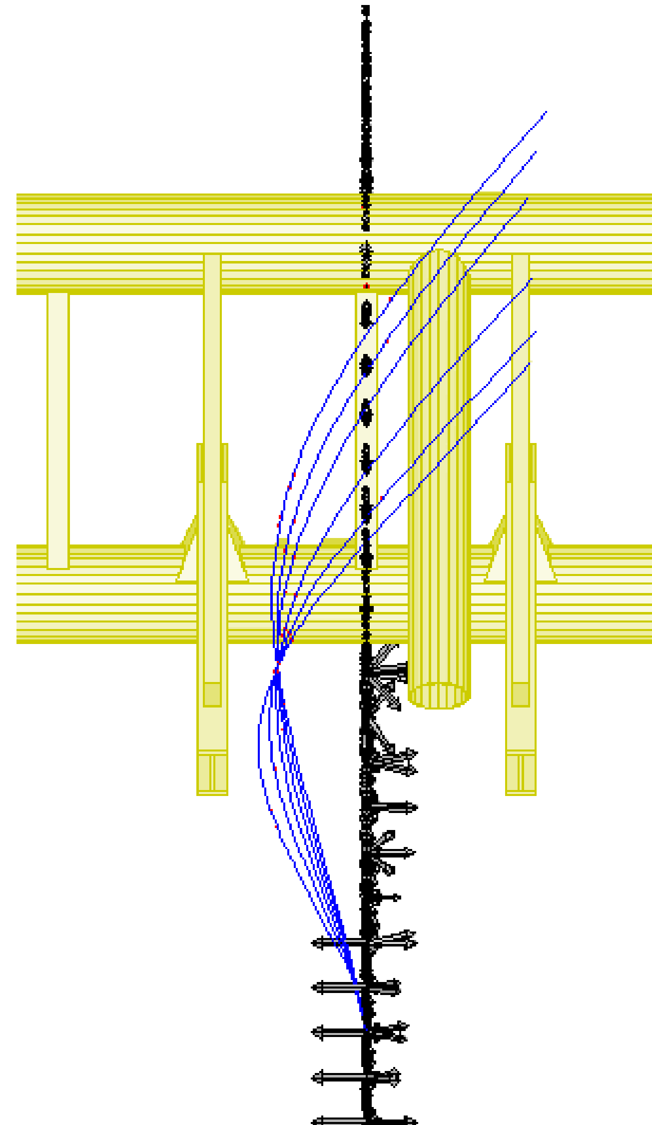
Charged particle in magnetic field

ATLAS magnetic field
1 solenoid
3 toroids

R-ϕ projection



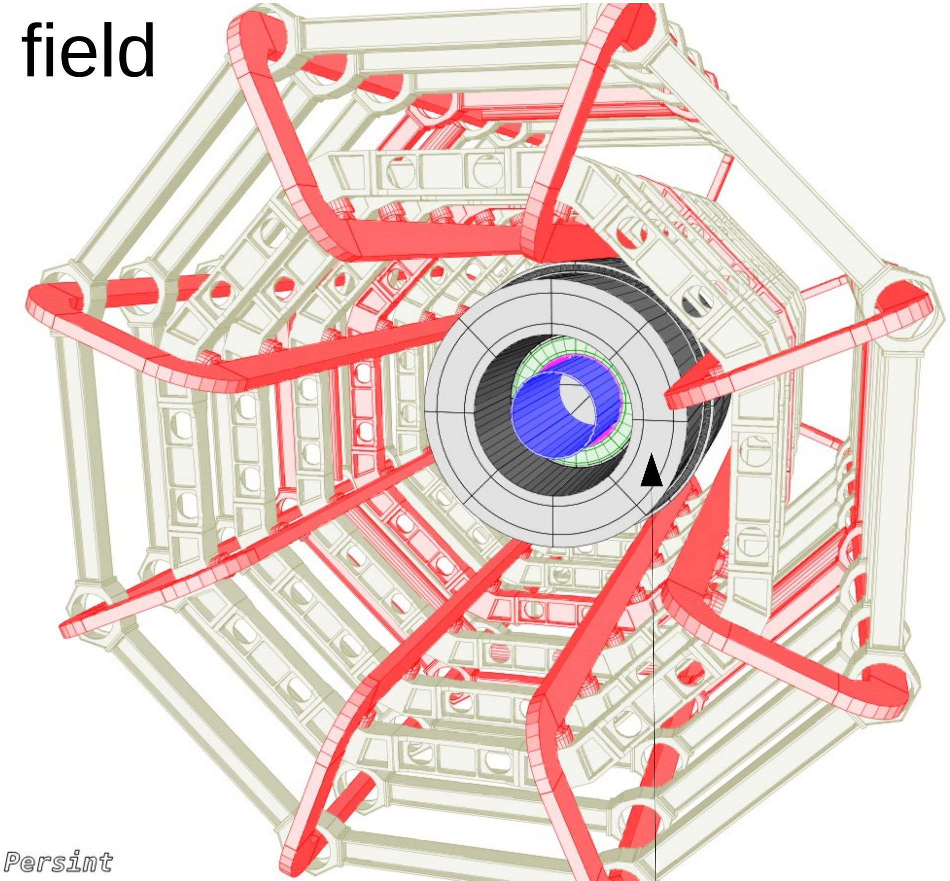
R-Z projection



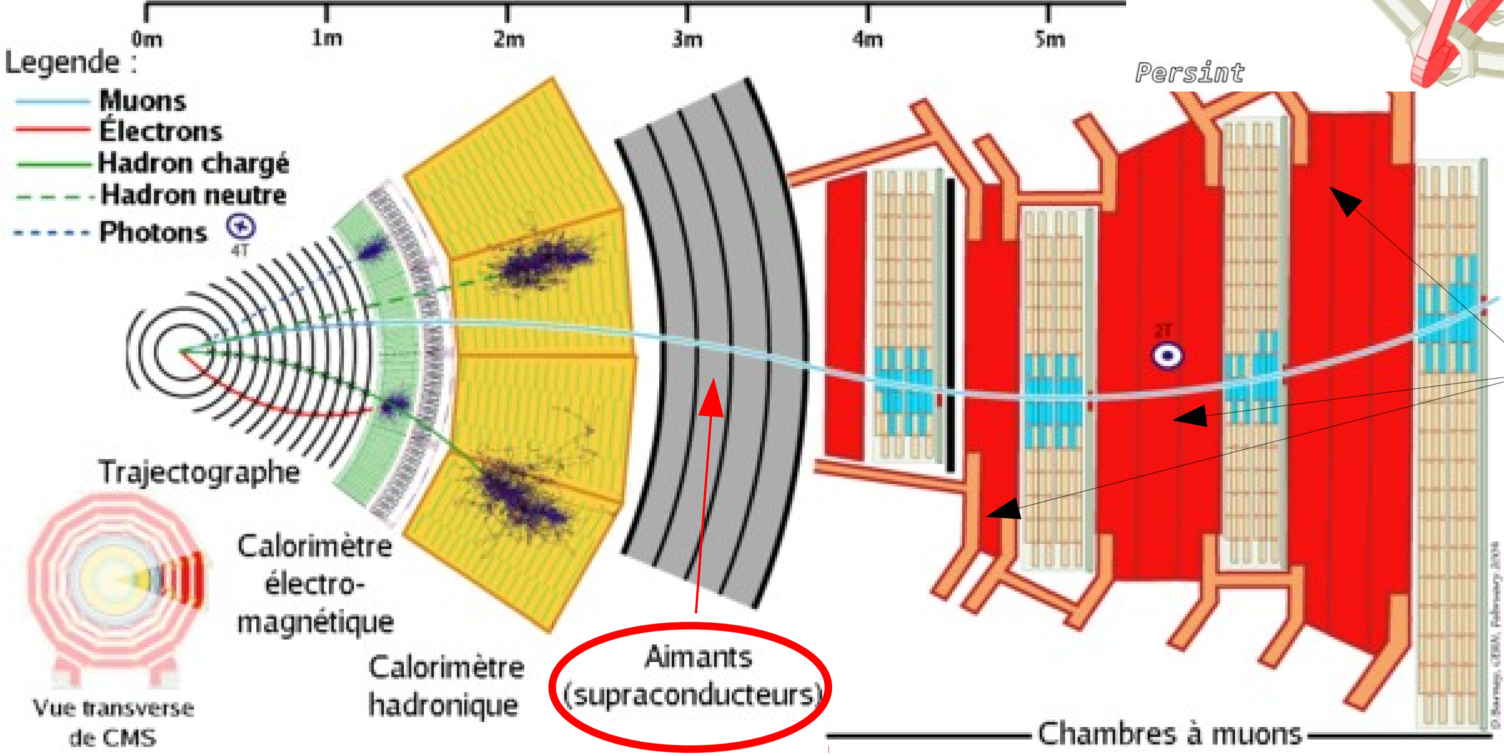
Charged particle in magnetic field

Order of Magnitude:

Toroid ATLAS: B~0.5 Tesla
Solenoid ATLAS(R=1m): B~2.0 Telsa
Solenoid CMS (R=3m): B~3.8 Telsa

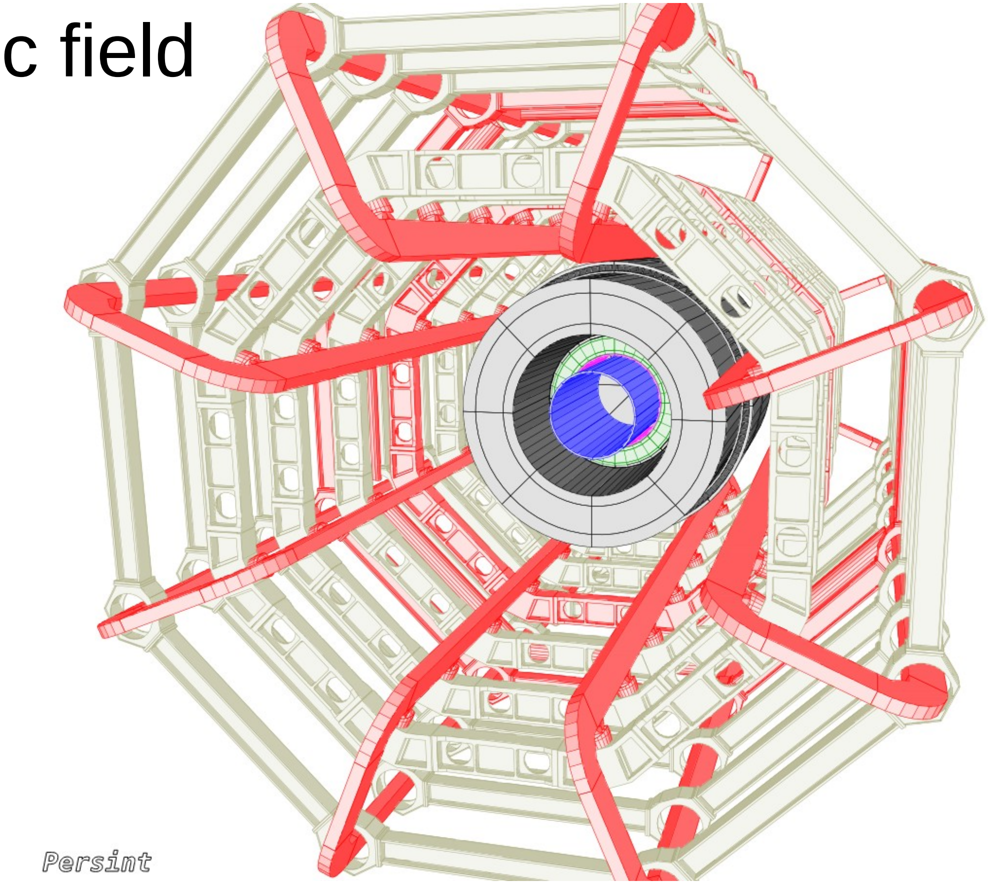


CMS



Solenoid Return Yoke

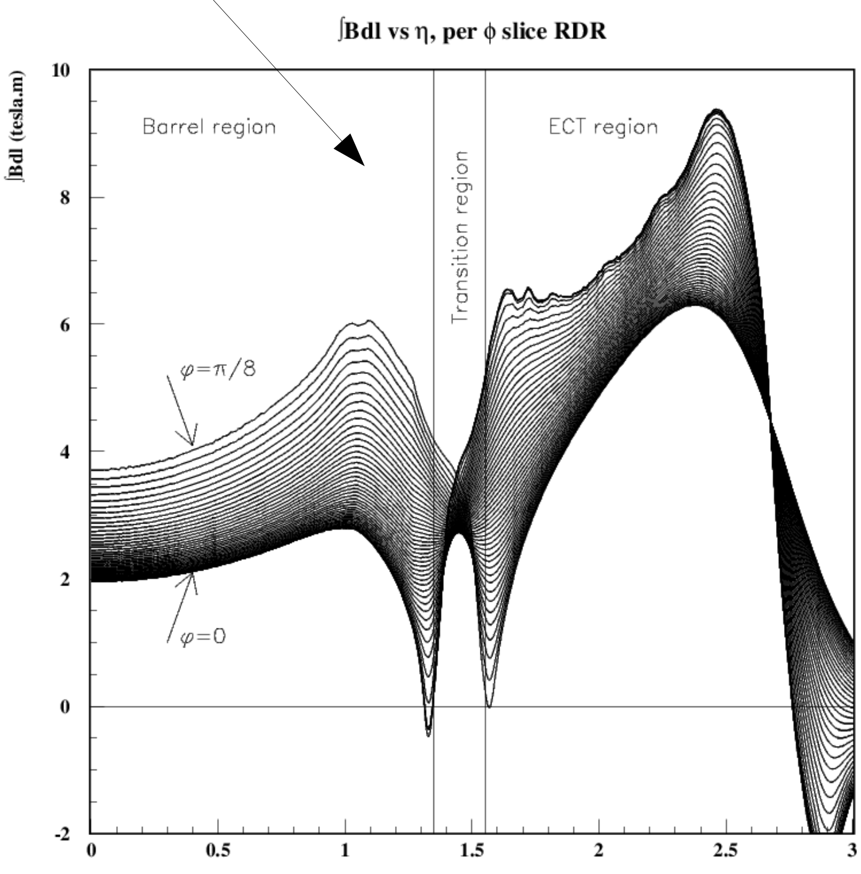
Charged particle in magnetic field



Order of Magnitude:

- Toroid ATLAS: B~0.5 Tesla
- Solenoid ATLAS(R=1m): B~2.0 Telsa
- Solenoid CMS (R=3m): B~3.8 Telsa

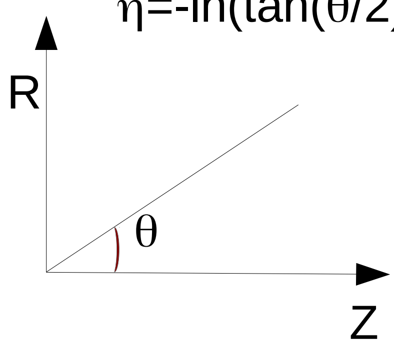
Int Bdl is the relevant parameter for a magnet



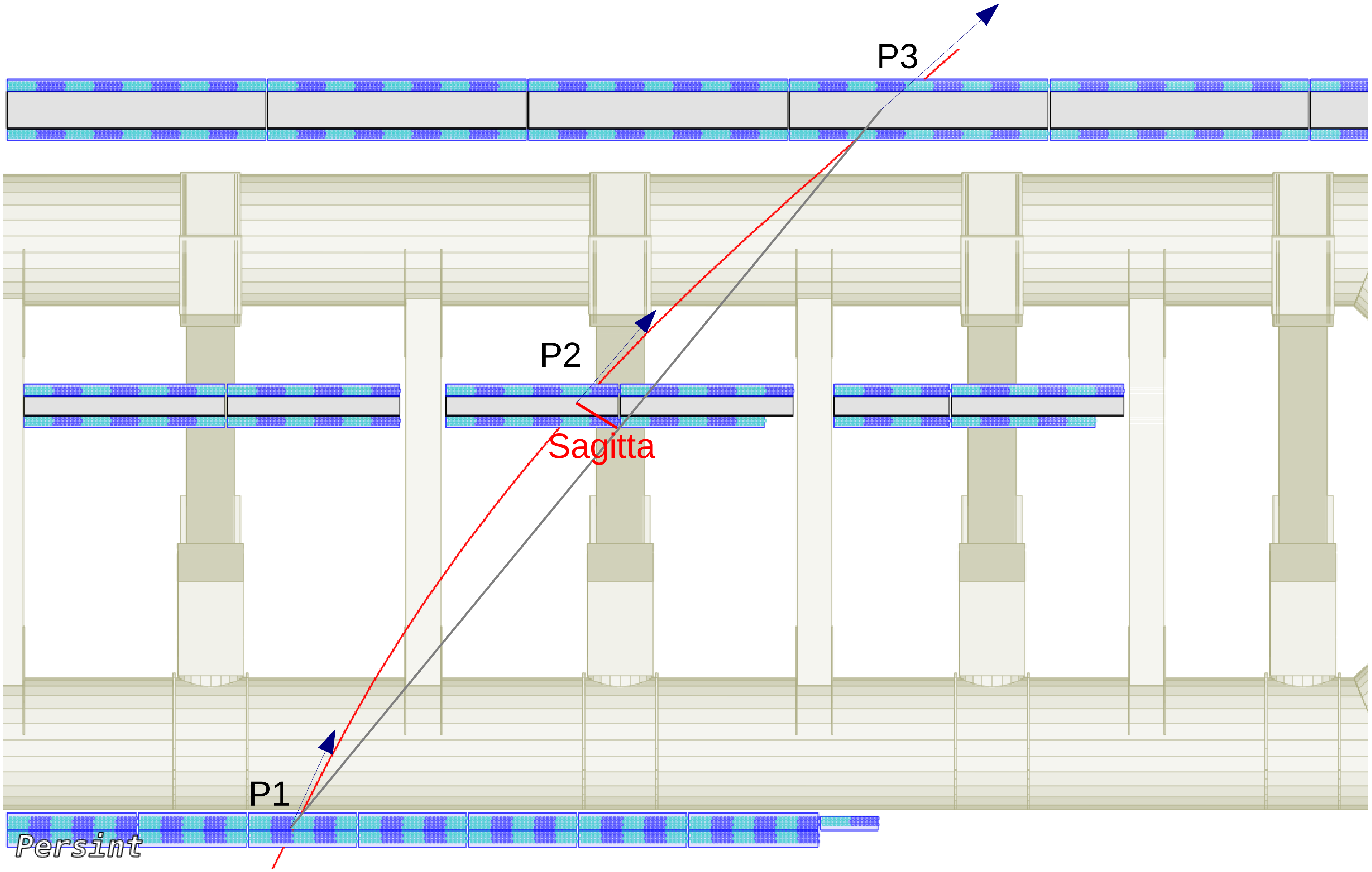
$\eta=-\ln(\tan(\theta/2))$

Solenoid: IntBdl ↘ η

Toroid: IntBdl → with η



Charged particle in magnetic field



3 measurement points (p1,p2,p3): d(p1,p3) straight line
Sagitta: distance between d(p1,p3) & p2

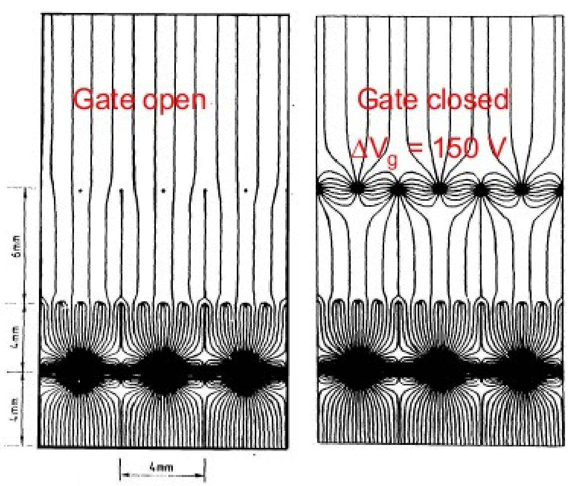
Interlude: Fin

Back to Detectors

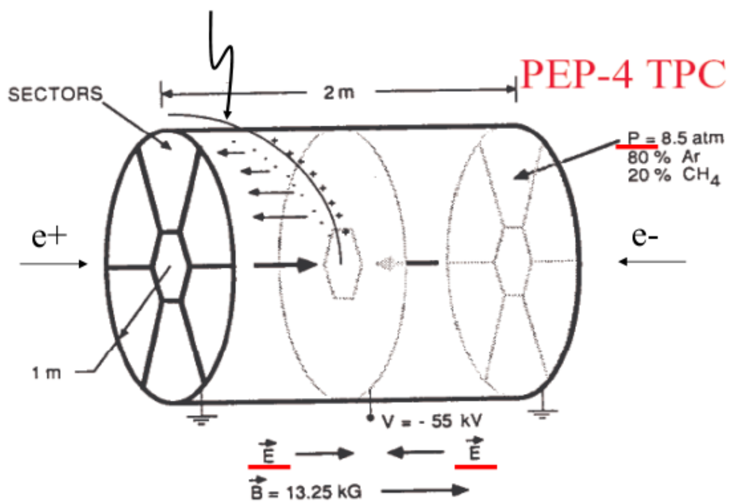
Detectors(Gaseous)

Time Projection Chamber (TPC)

- BNL (PEP-4) 1974
  - 3D tracks measurement (tracker) + particle identification!
  - Signal on 185 wires over 80cm (first coordinate Y)
  - Signal induced on the segmented cathode (8mm) (second coordinate X)
  - Drift time measurement (third coordinate Z, beam axis)
  - Gaseous: Ar-CH4, P= 8.5 atm
  - E (=150KV / m) // B (=1.5 Tesla)
  - Momentum measurement: Track + magnetic field
  - Control of the drift velocity of the ionization electrons! ~ 7cm / ms
  - Spatial resolution in Z (direction of field lines E & B) ~ mm / m
  - Drift electric field decoupled from the avalanche electric field



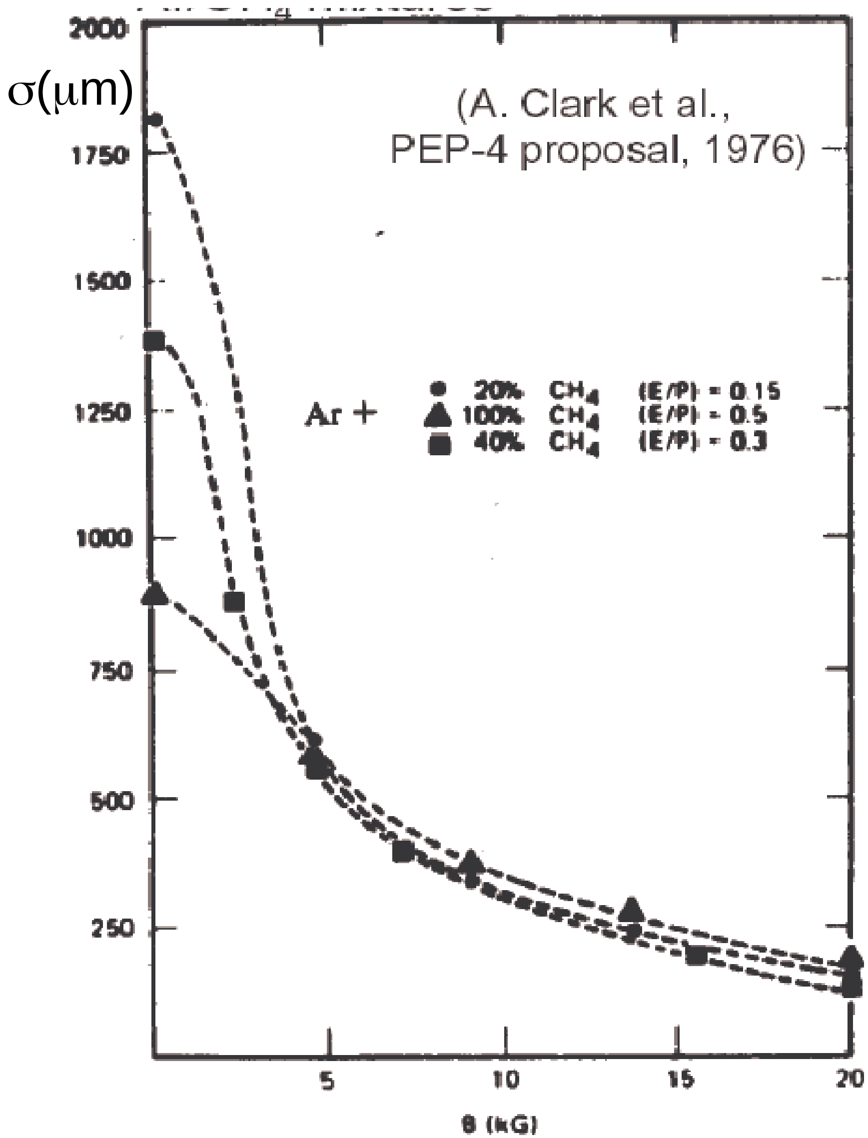
Remark:
To prevent that the ions disturb the TPC:
A gate (150V) is closed between collisions

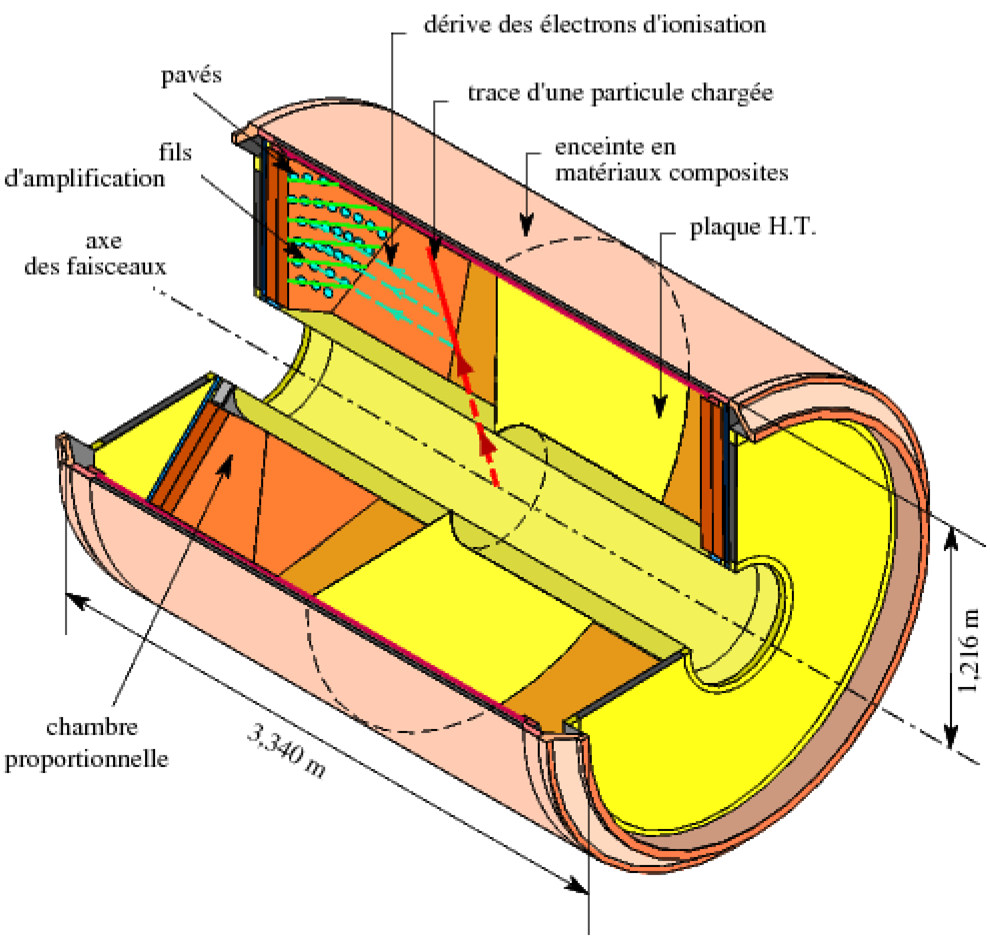


Detectors(Gaseous)

Time Projection Chamber (TPC)

- E//B transverse diffusion reduced by a factor 7
  - Thanks to Lorentz the drift of the ionization electrons spiral along the electric field line



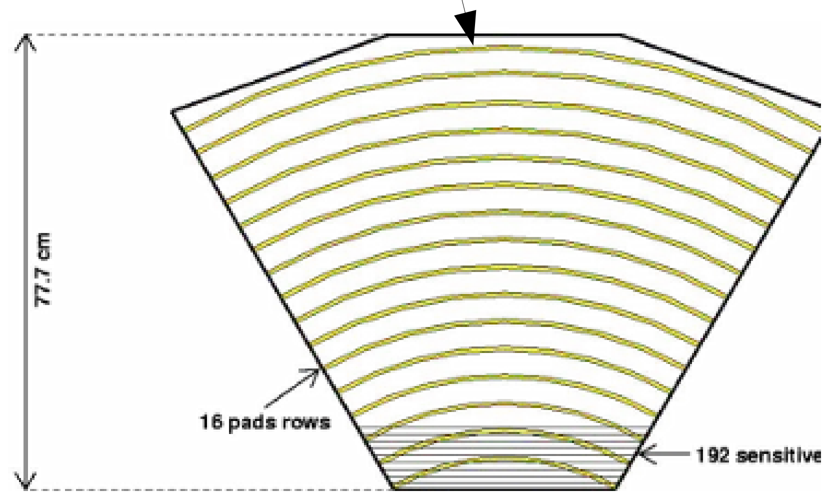


Detectors(Gaseous)

TPC: Delphi, Lep 1992

- PEP-4 close evolution, better spatial resolution
- B = 1.2T, E = 150 V / cm, Ar (80%) - CH_4 (20%) & P = 1atm
- 27 Primary & Secondary electrons / cm
- 6.7 cm / μs, transverse diffusion ~ 100 μm / sqrt (cm)
- 2 x 6 sectors, 192 wires, 16 Pad (segmented cathode)
- 16 three-dimensional points
- 2 x 1.34 m, 0.325 m < Radius < 1.160 m
- Spatial resolution: Rphi ~ 250μm, Z ~ 1mm

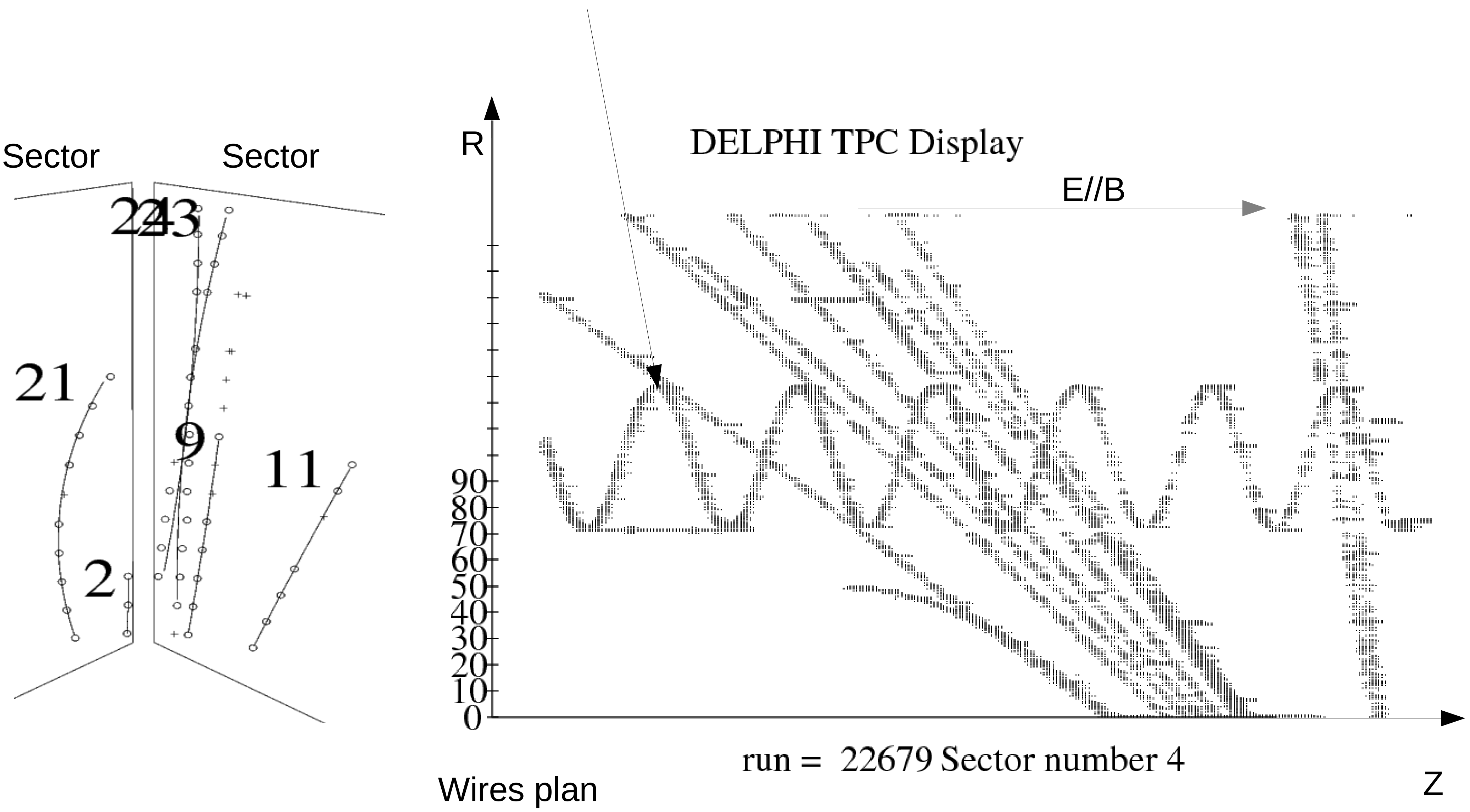
1 sector



Detectors(Gaseous)

TPC: Delphi

- 2 views: RZ (left) & Rϕ(right)
- We see clearly a spiralling electron

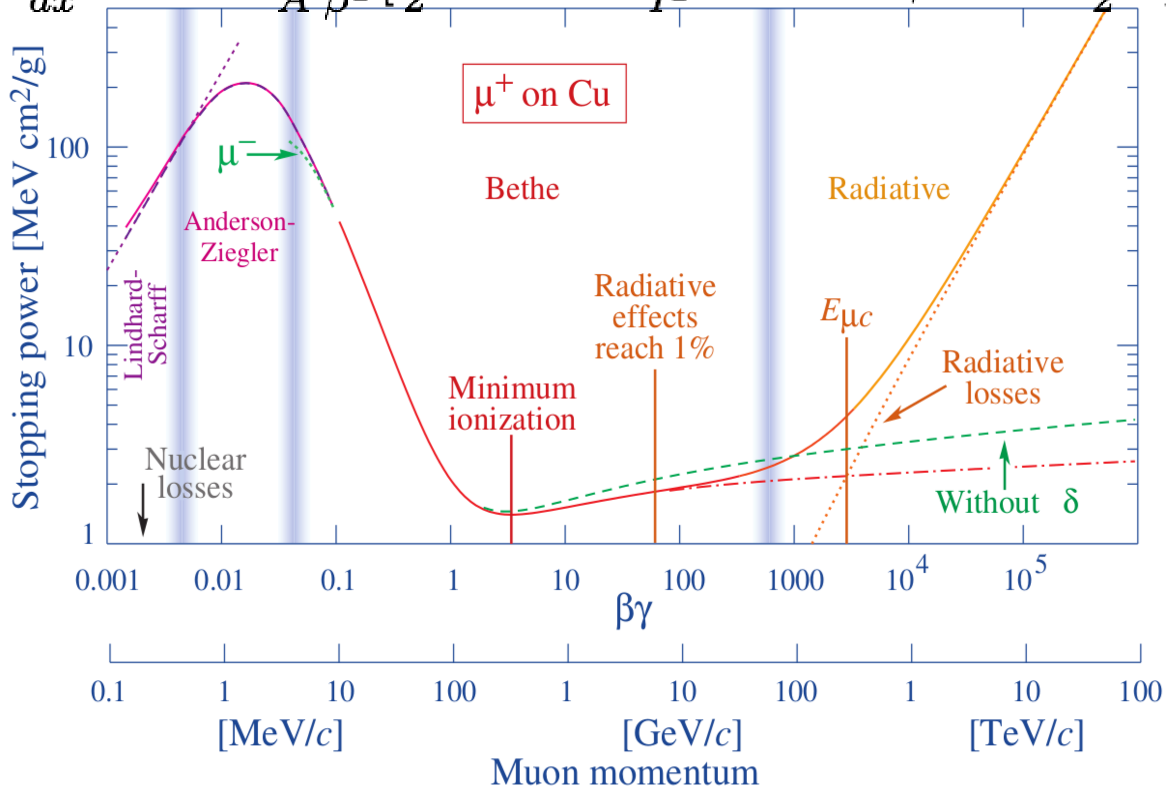


Detectors(Gaseous)

TPC: Delphi vs PEP-4

- No conceptual difference
- Only the Pressure is different: Delphi: 1 atm & PEP-4: 8.5 atm
  - Bigger Ionisation in PEP-4
    - More electrons S/B better
    - dE/dx resolution better
  - BUT
    - dEdx curves very close, improvement not so big
    - TPC walls thicker more X0 means more conversion

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

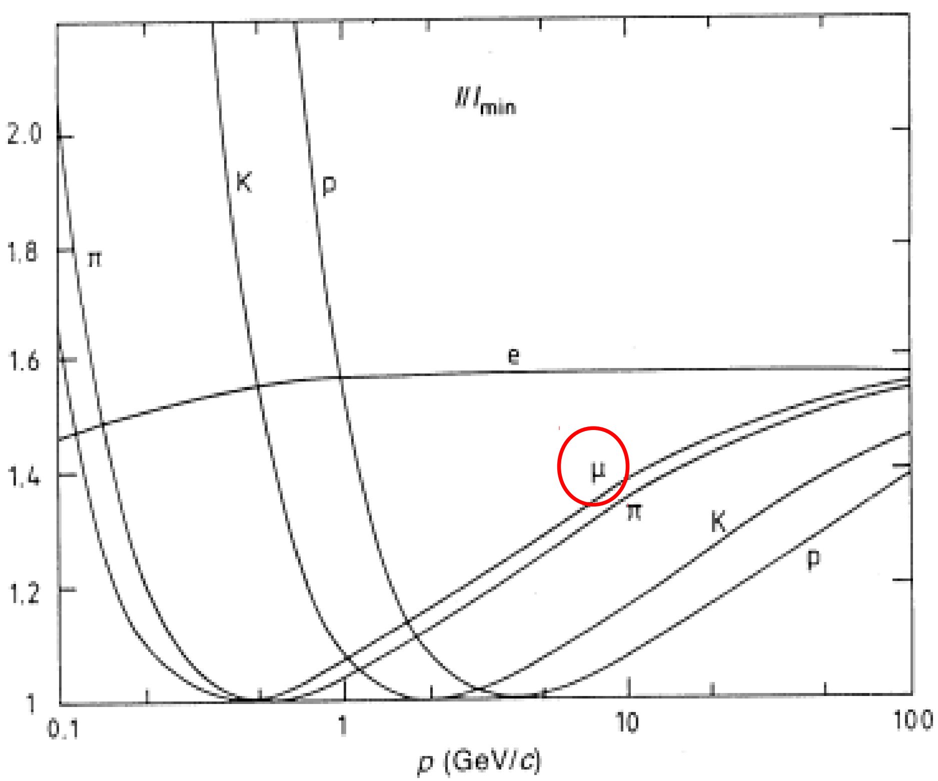


Detectors(Gaseous)

TPC: dE/dx

- Muon identification in the energy range: 1 to 10 GeV

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



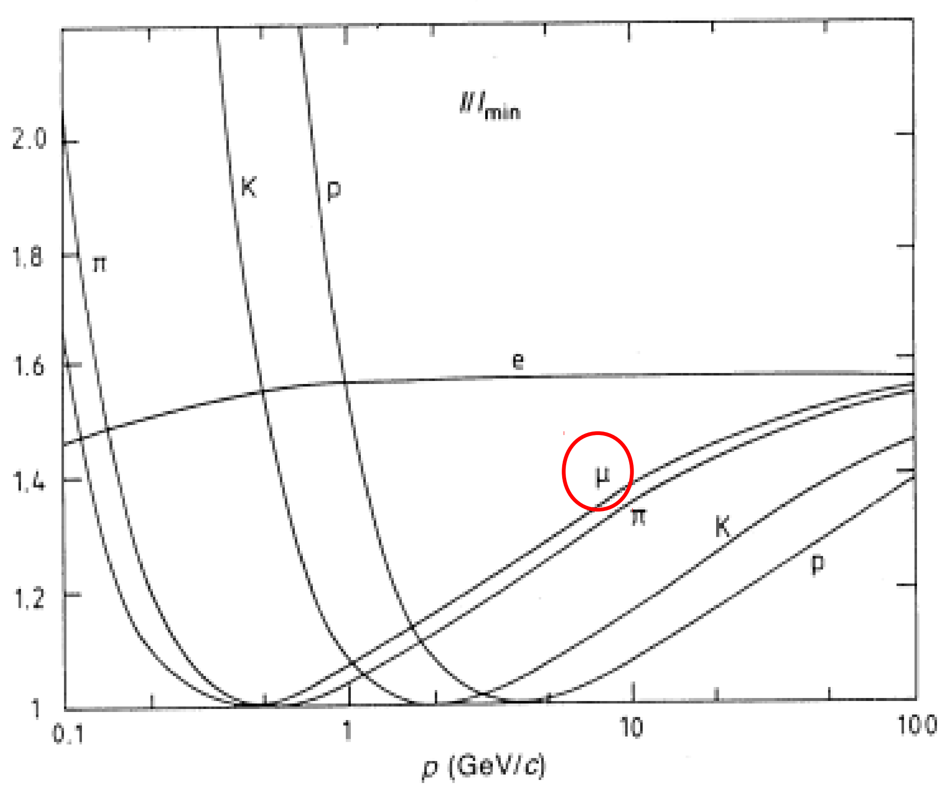
Calculation

Detectors(Gaseous)

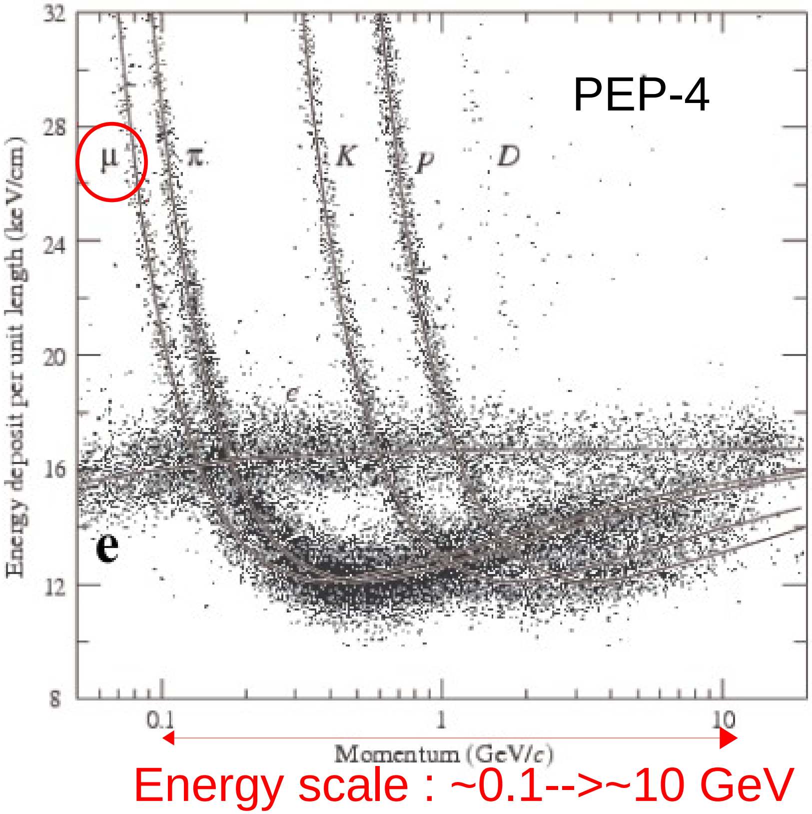
TPC: dE/dx

- Muon identification in the energy range: 1 to 10 GeV

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



Calculation

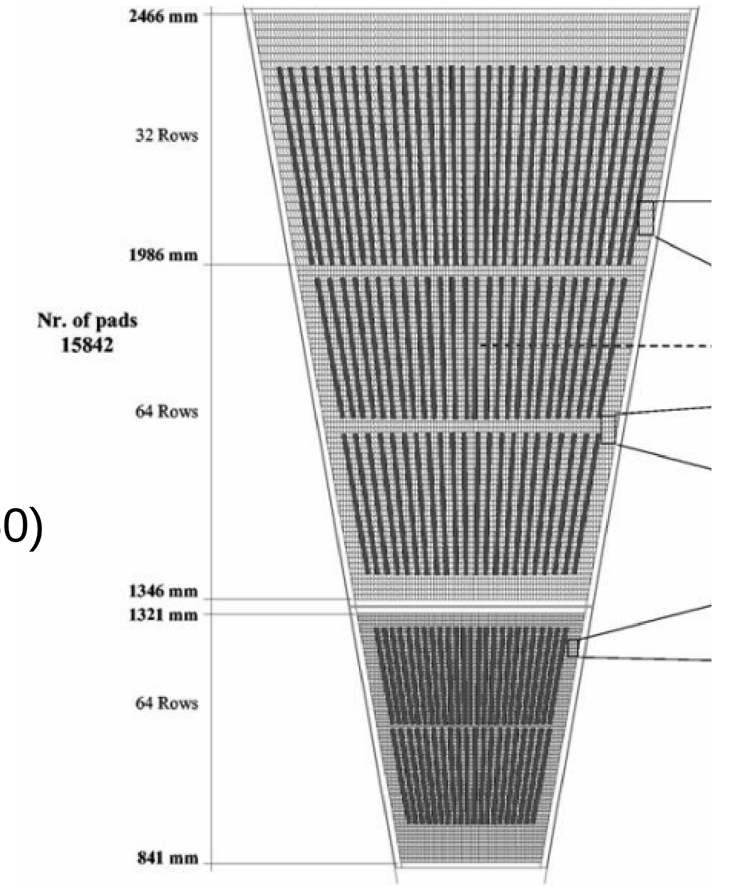


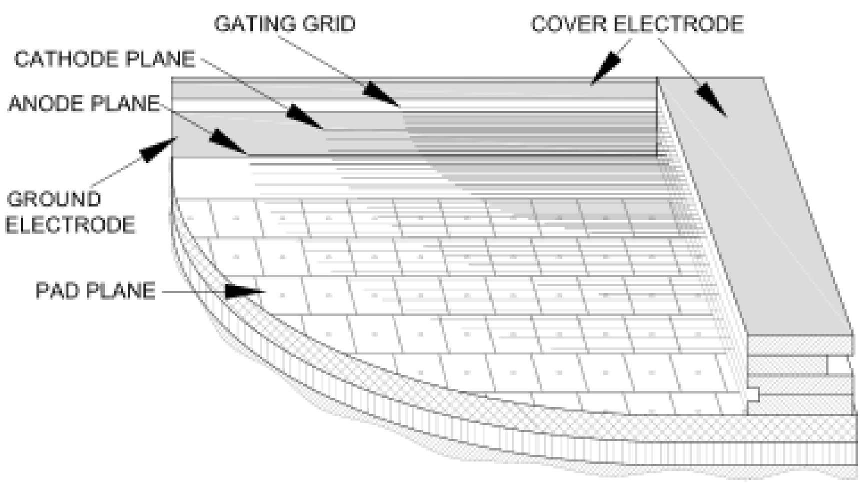
Data

Detectors(Gaseous)

TPC: Alice (LHC: Pb-Pb)

- Same principle as Delphi and PEP-4
- more complicated
  - 5.1m long (2x2.5m), 18 sectors (MWPC)
  - Diameter = 5.6 m, volume = 88 m3
  - Inner radius = 0.9 m, outer radius = 2.5 m
  - Number of Channels: 577568 (Delphi: 20160)





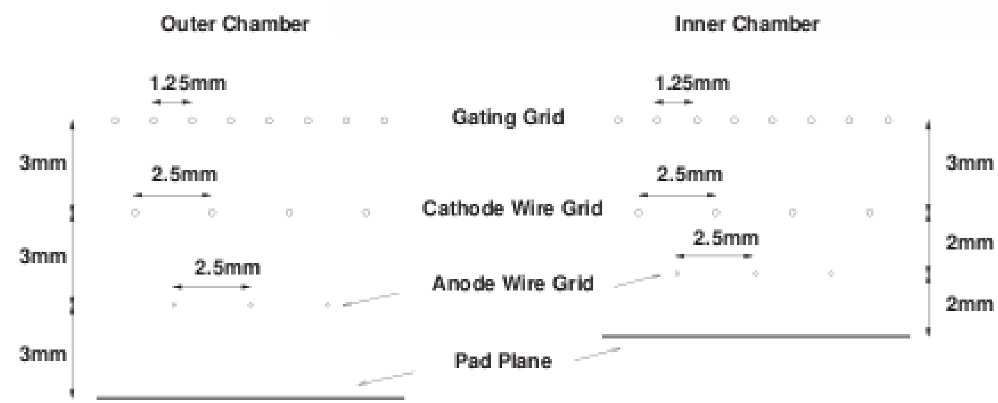
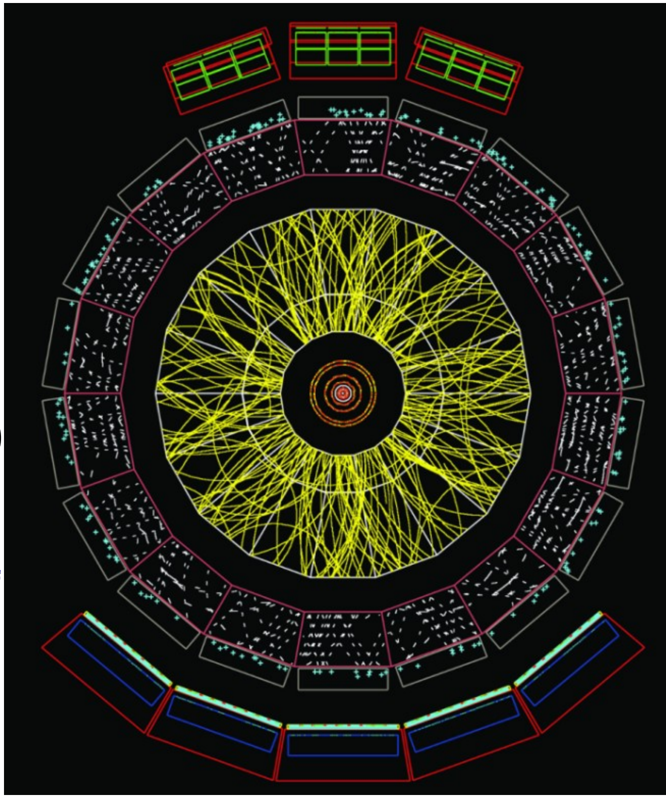


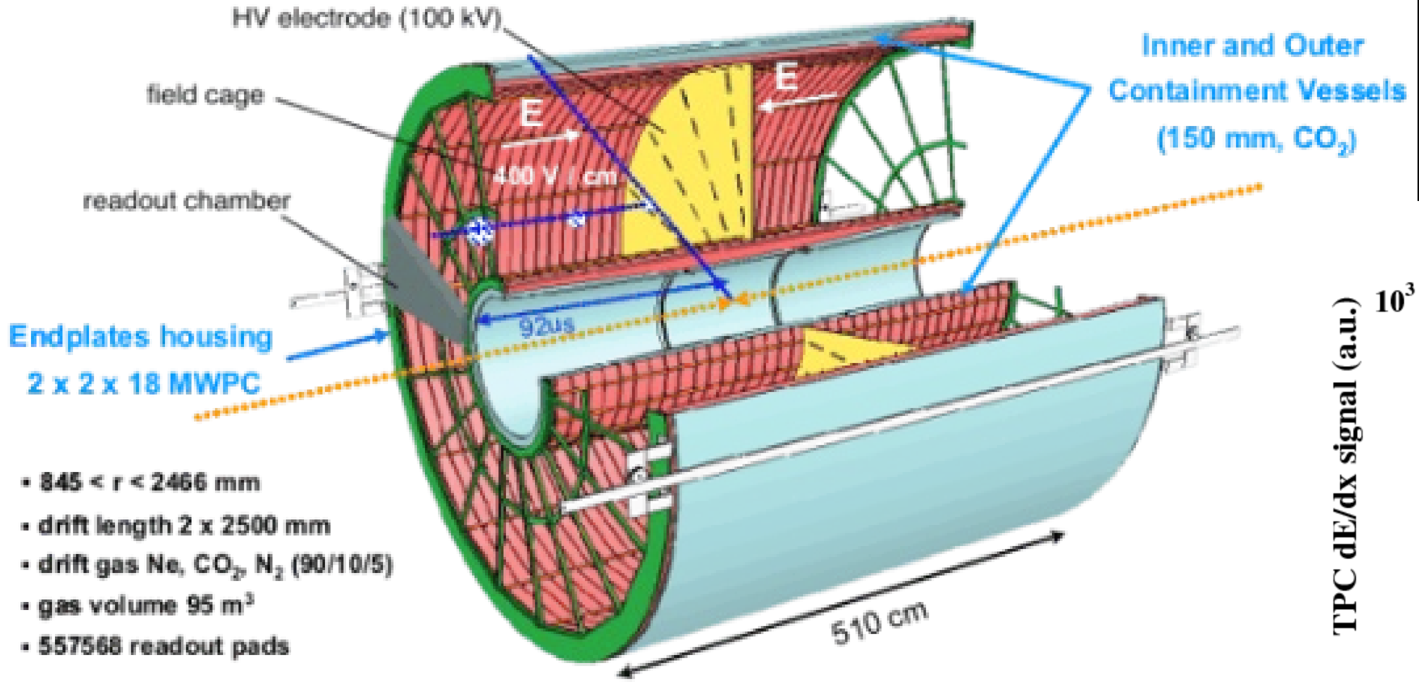
Figure 10: Wire geometries of the outer (left) and inner (right) readout chambers.

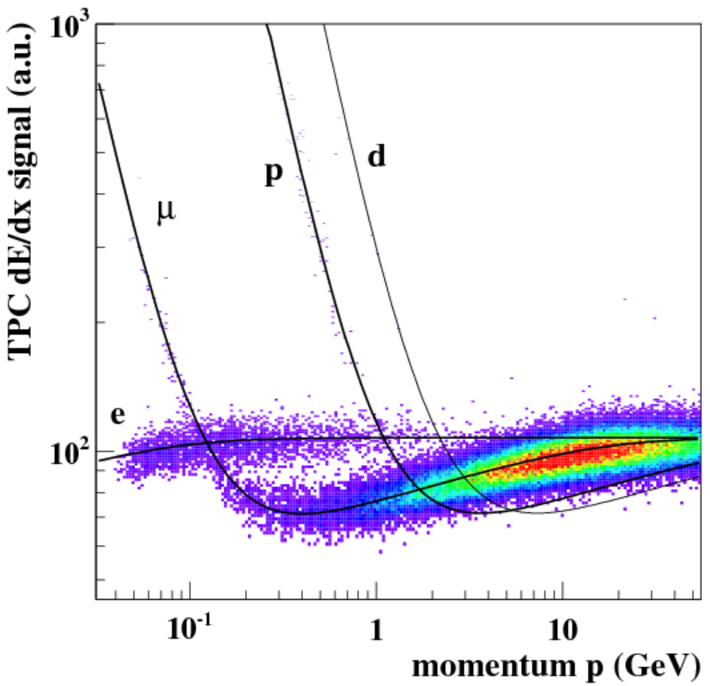
Detectors(Gaseous)

TPC: Alice (LHC: Pb-Pb)

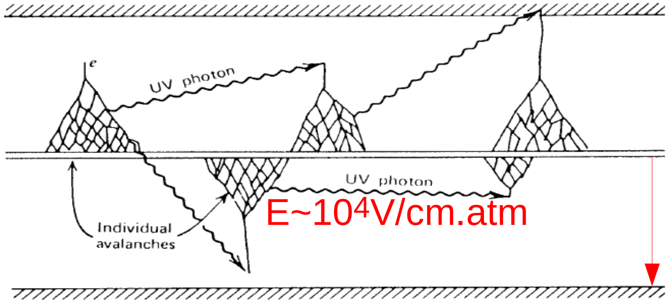
- Biggest TPC never built
- more complicated
  - Spatial resolution 500 μm
  - Momentum resolution 1% (1GeV), 5%(10 GeV)

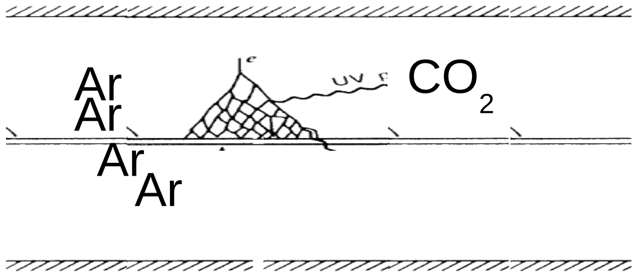






Previously





Geiger counter

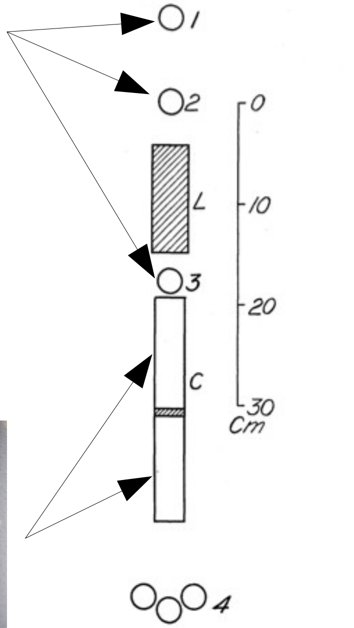
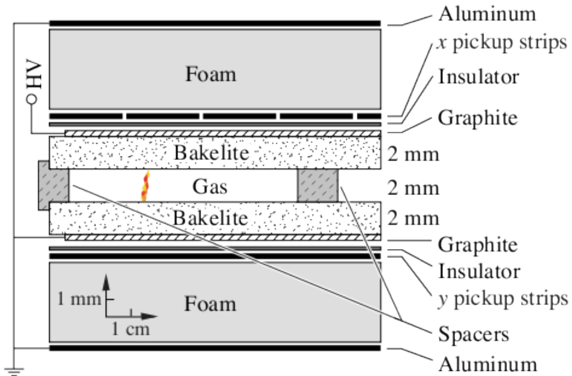
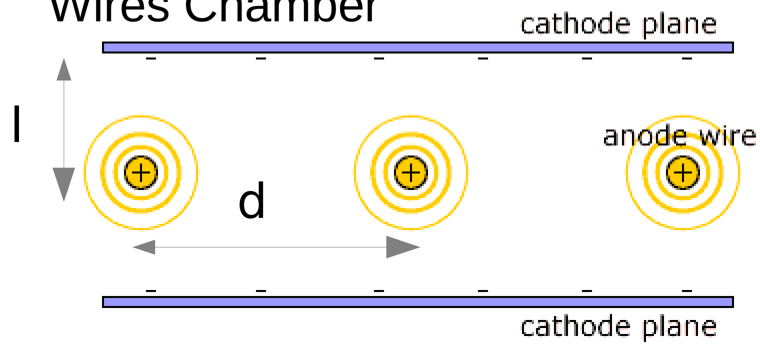


Fig. 1. Geometrical arrangement of apparatus.

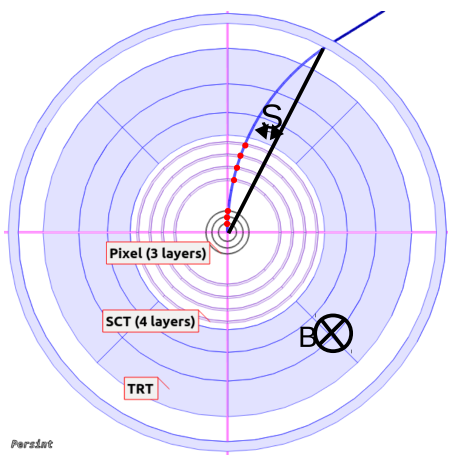
RPC



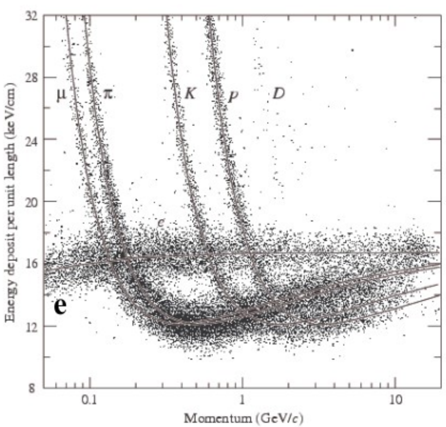
Wires Chamber



$$P \sim 0.3 \cdot R \cdot B$$



Particle identification:dE/dx

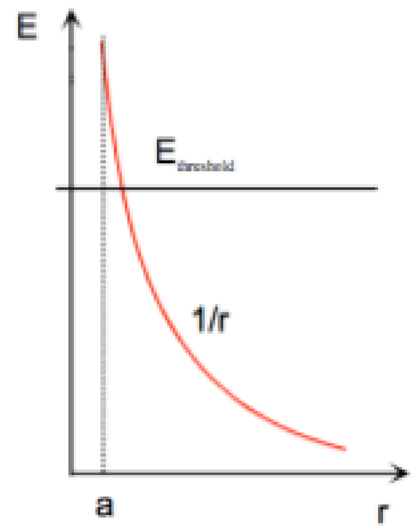


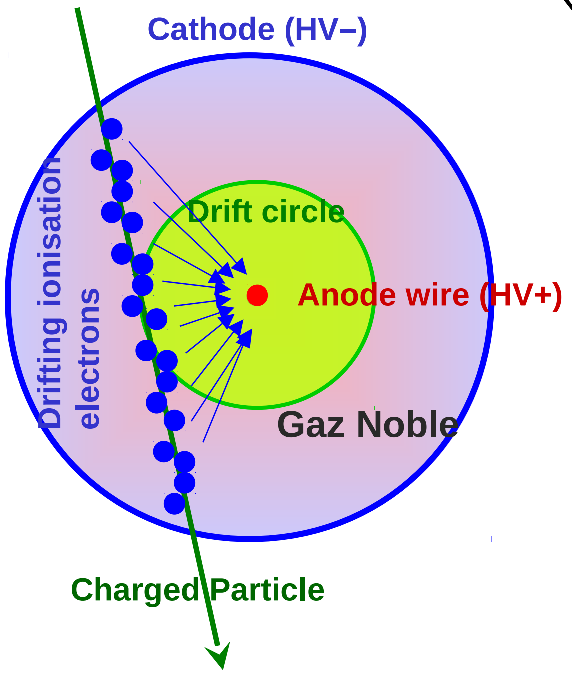
Detectors(Gaseous)

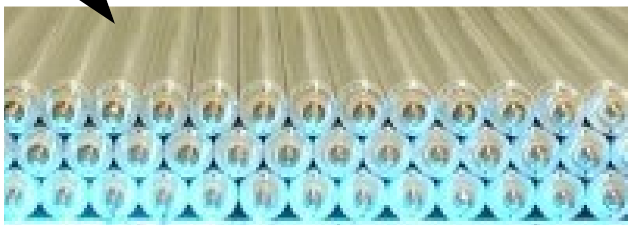
Drift Tube

- Back to Geiger tube
  - MWPC limits:
    - size, cross-talk, energy range
- ~100 e-
- Electric field in 1/r
- Gain ~10^4 to 10^5
- Not 1 tube but hundred of thousand tubes

$$E = \frac{C\,V_0}{2\,\pi\,\epsilon_0}\ln\left(\frac{1}{r}\right)$$





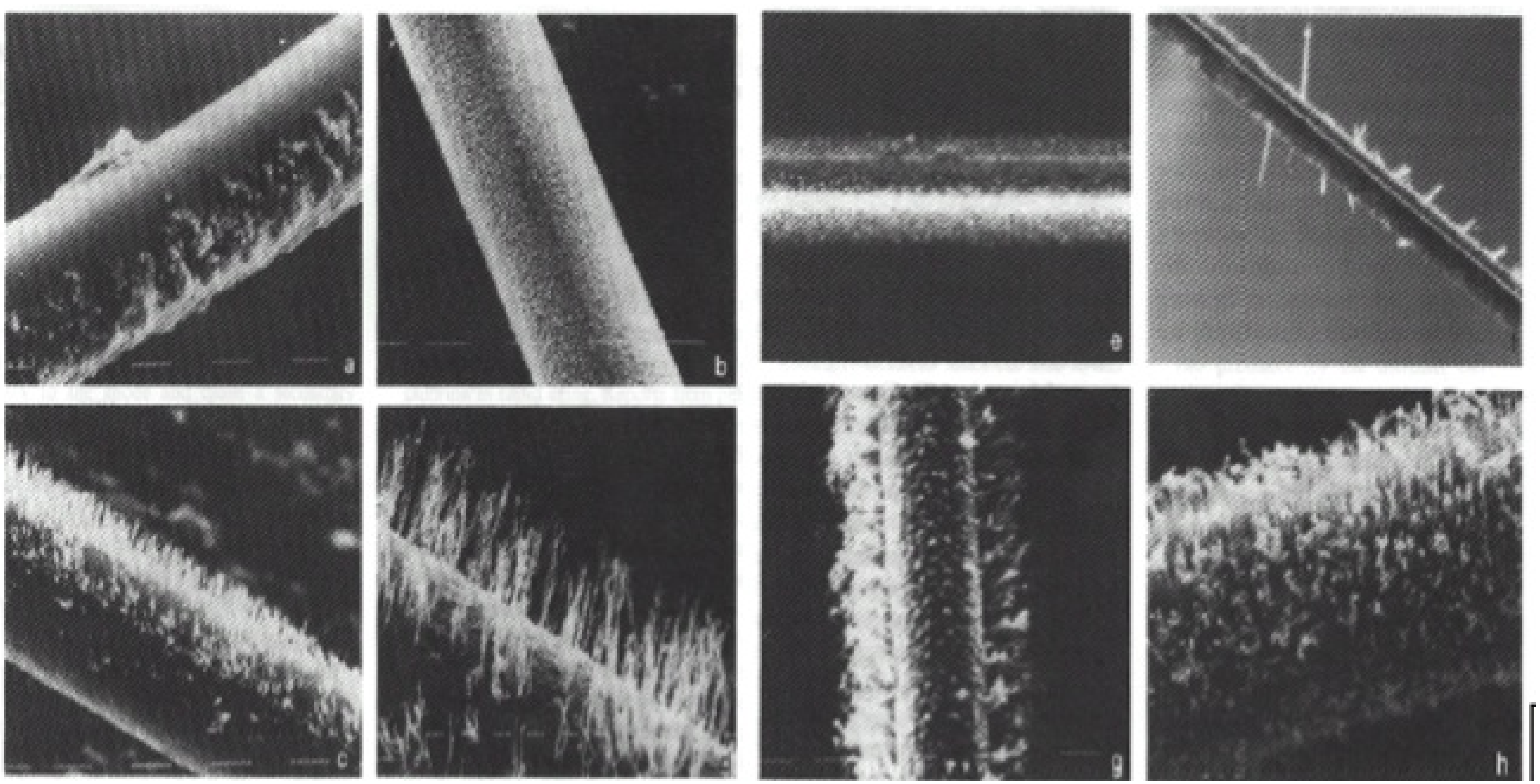


Charged particle: Muon

Detectors(Gaseous)

Drift Tube

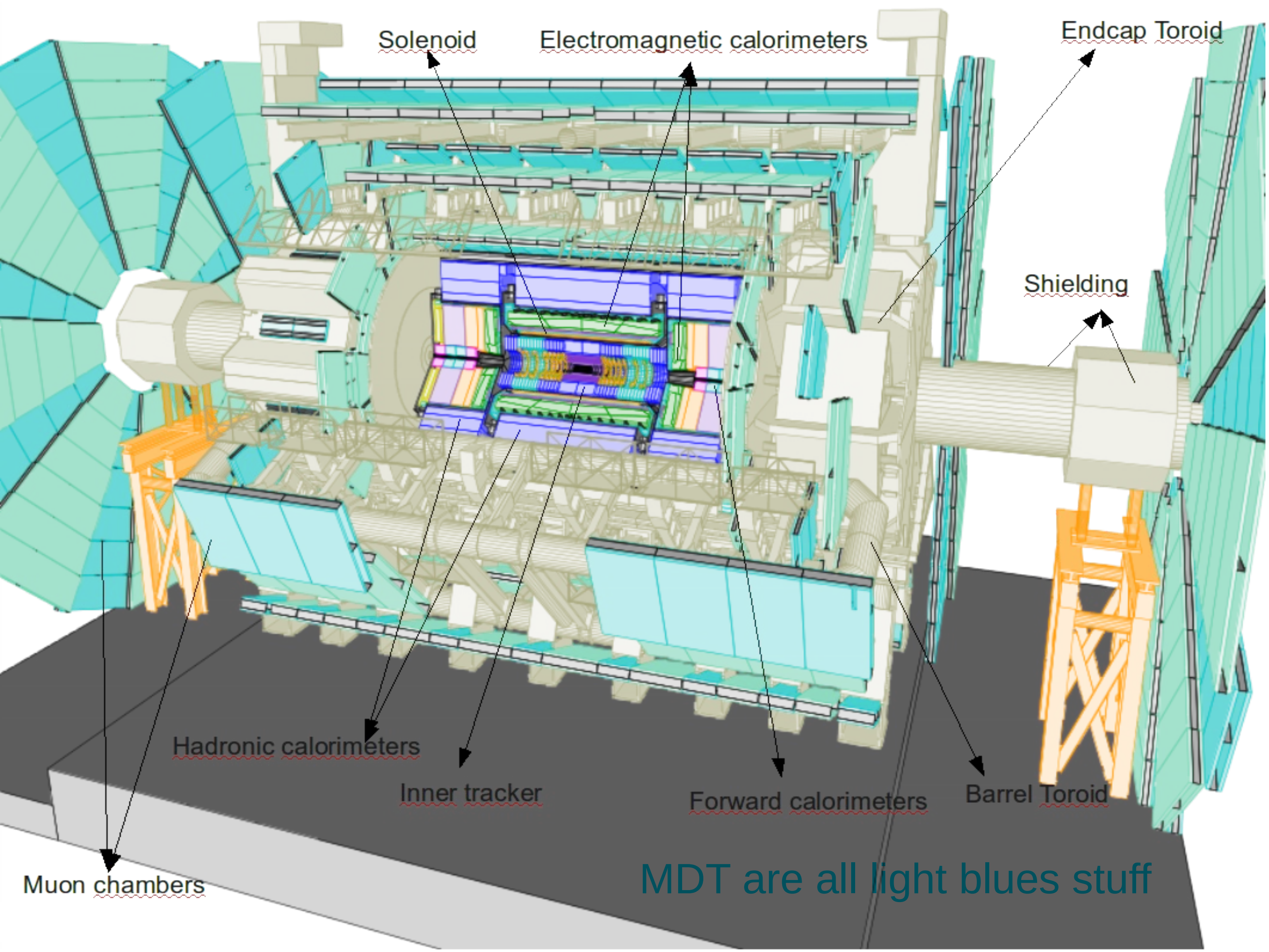
- Main problem: ageing!
  - Careful choice of materials (no Si or similar)
  - Highest gas gas purity
  - Avoid exceedingly high currents
    - Gas impurities or high currents may lead to the development of deposits on the wires in the form of tiny whiskers (polymerization of chemical elements in the gas)
      These may lead to HV instabilities and inefficiencies and in the worst case they may make chambers completely unusable

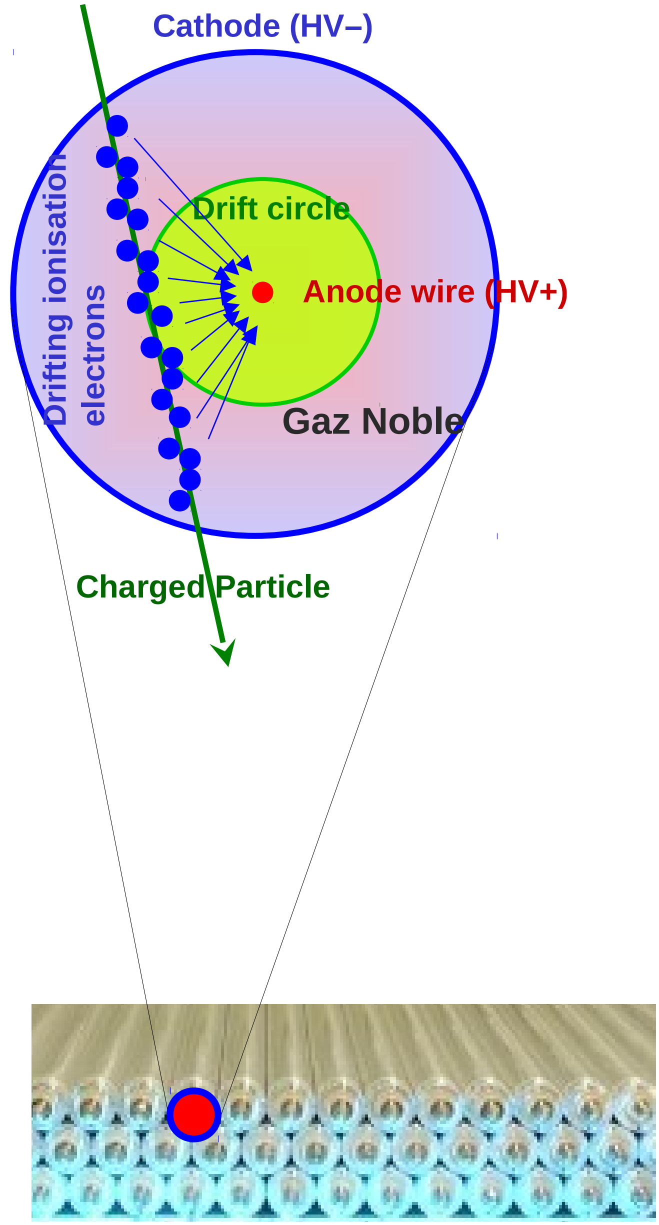


Detectors(Gaseous)

MDT: Monitored Drift Tube

- ATLAS ~3.7 10^5 tubes
  - ~5500 m^2 , 3 layers (barrel + endcap)

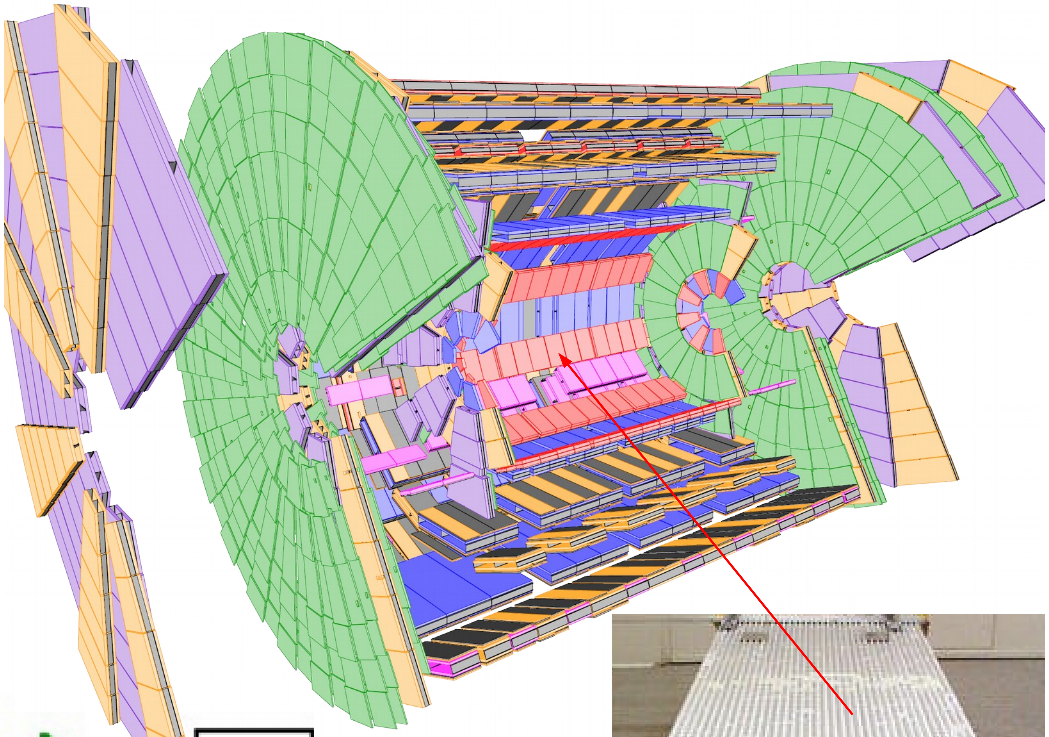


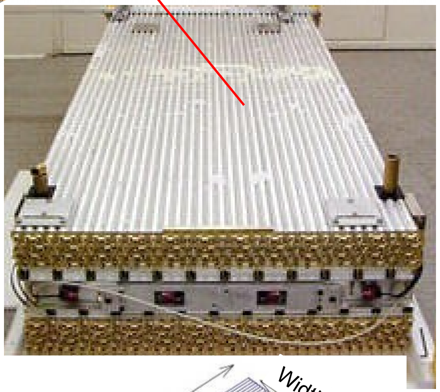


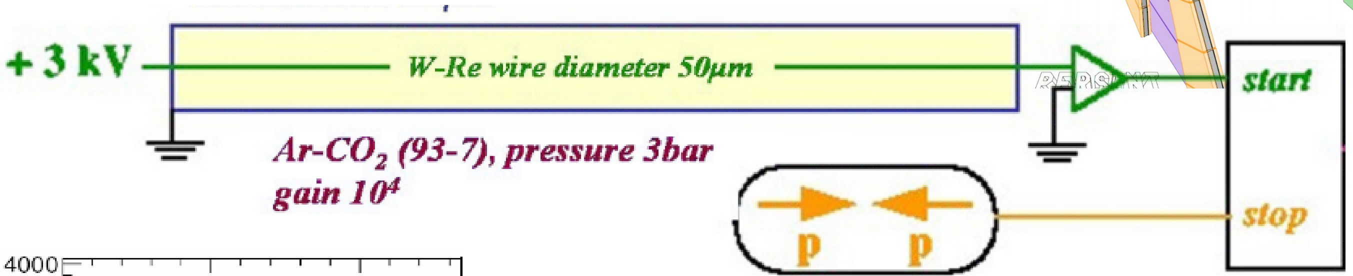
Detectors(Gaseous)

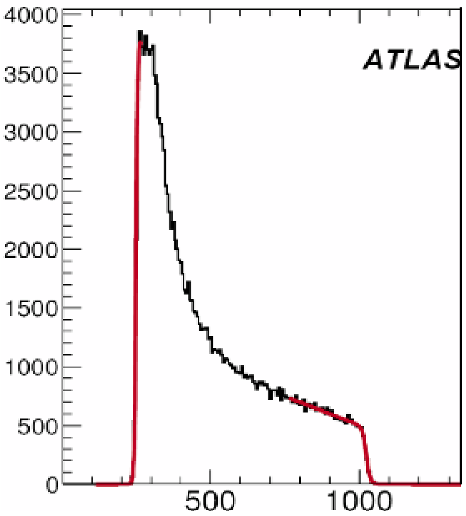
MDT: Monitored Drift Tube

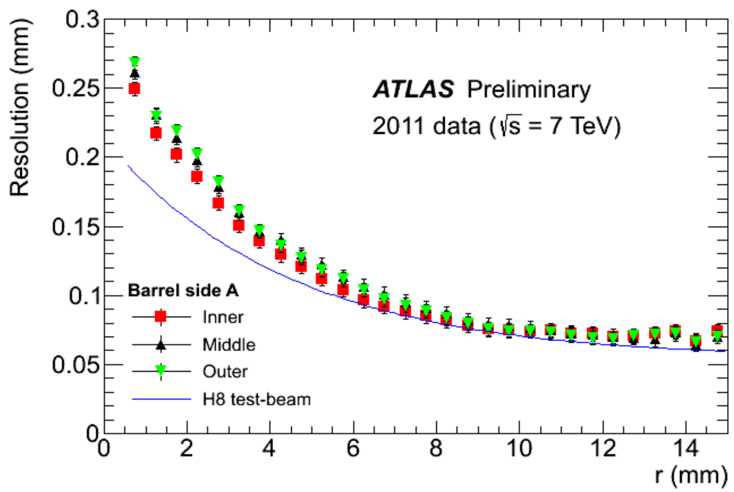
- ATLAS Muons spectrometer
  - Drift chamber (1 to 6m tube long)
  - Wire 50 μm, 30 mm diameter tube
  - V = 3000 volts
  - Pressure = 3 atm (300 pairs / cm)
  - Gain: 2.10^4
  - Max drift time: 700 ns
  - Drift velocity ~ 3cm / μs
  - Spatial resolution ~ 80 μm (→ ~100 μm data)
  - Ar (93%) - C02 (7%)

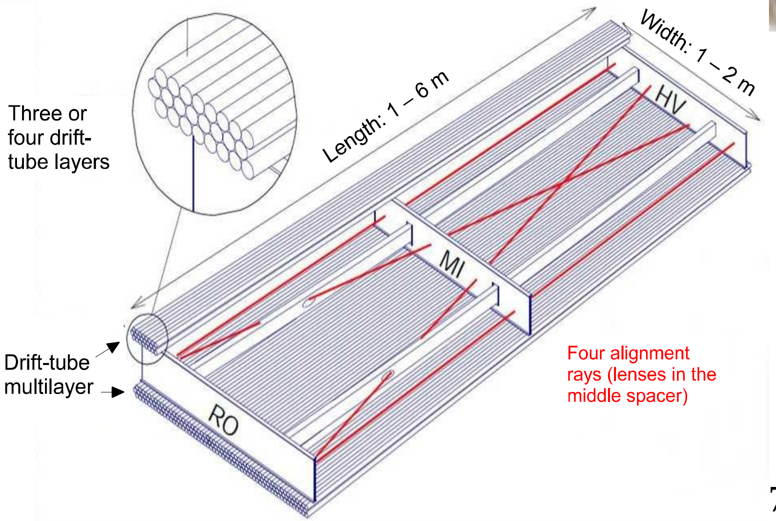








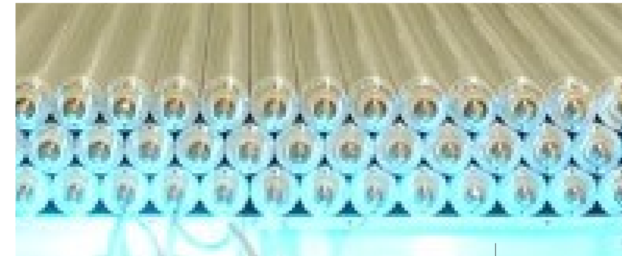


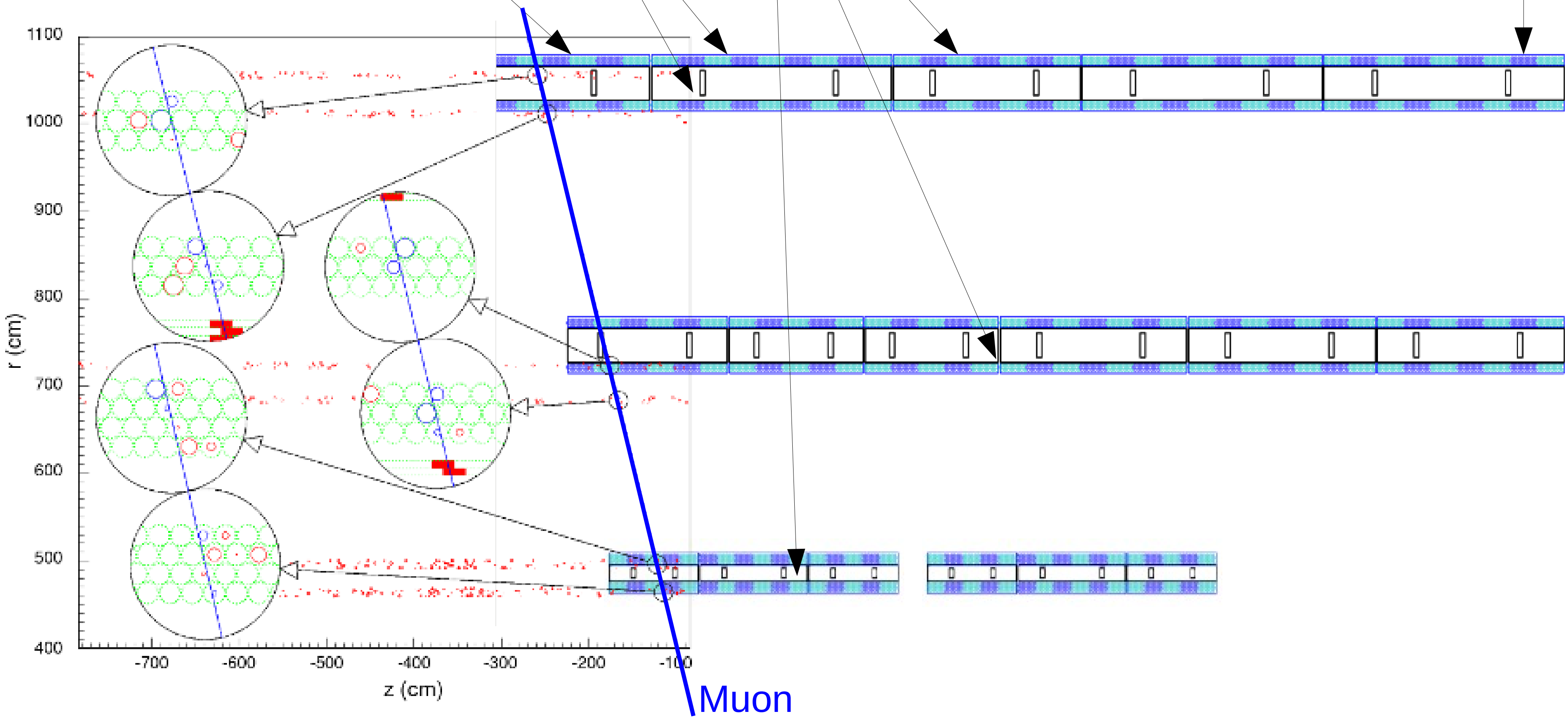


Detectors(Gaseous)

MDT: Monitored Drift Tube

- ATLAS Muons spectrometer
- 3 (4) tubes x 2 (layers) x 3 (positions)

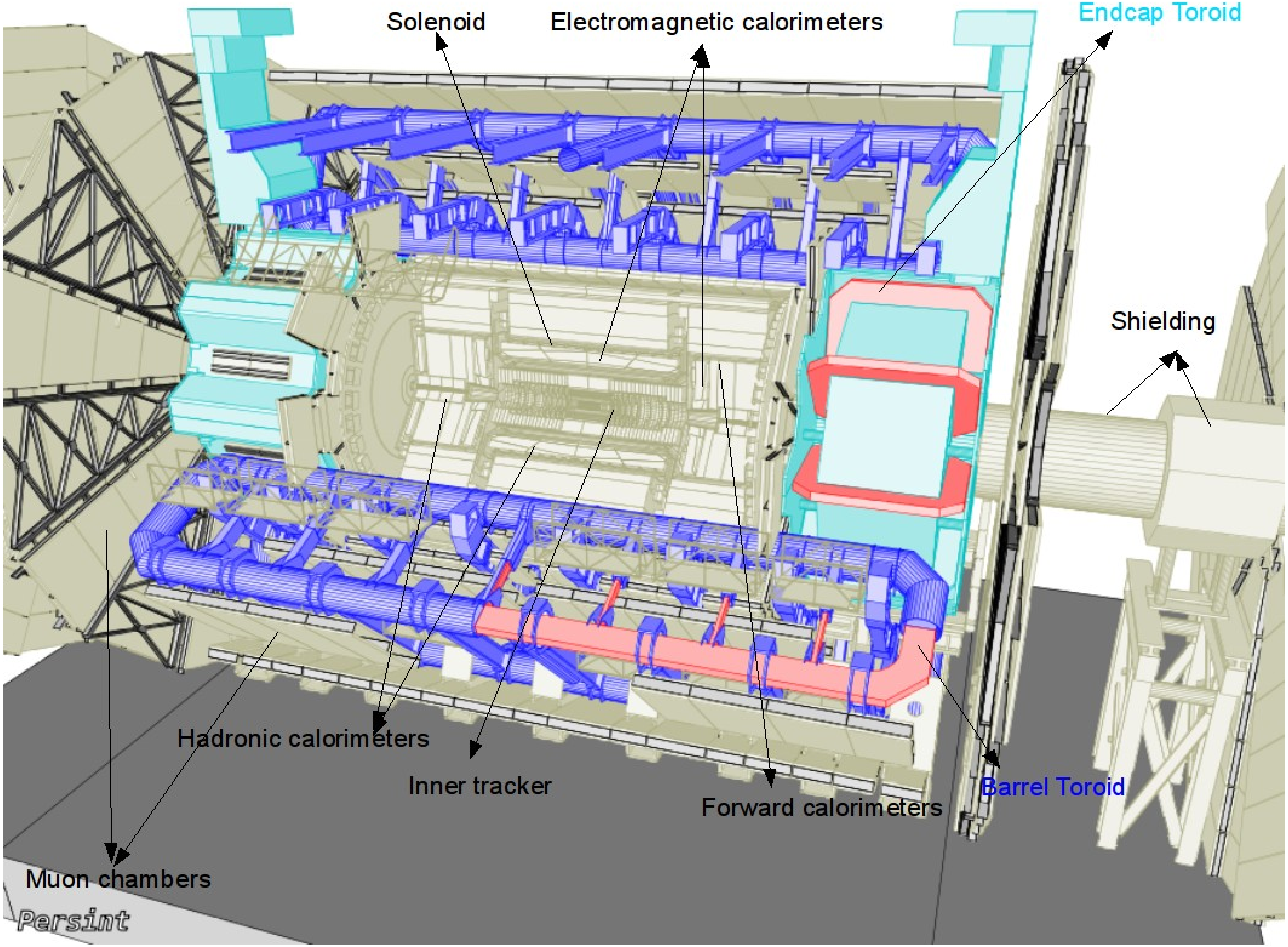




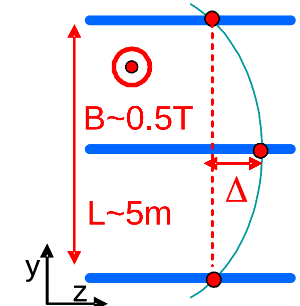
Detectors(Gaseous)

MDT: Monitored Drift Tube

- ATLAS Muons spectrometer
  - Air core Toroid => Magnetic field => Muon momentum measuremnt

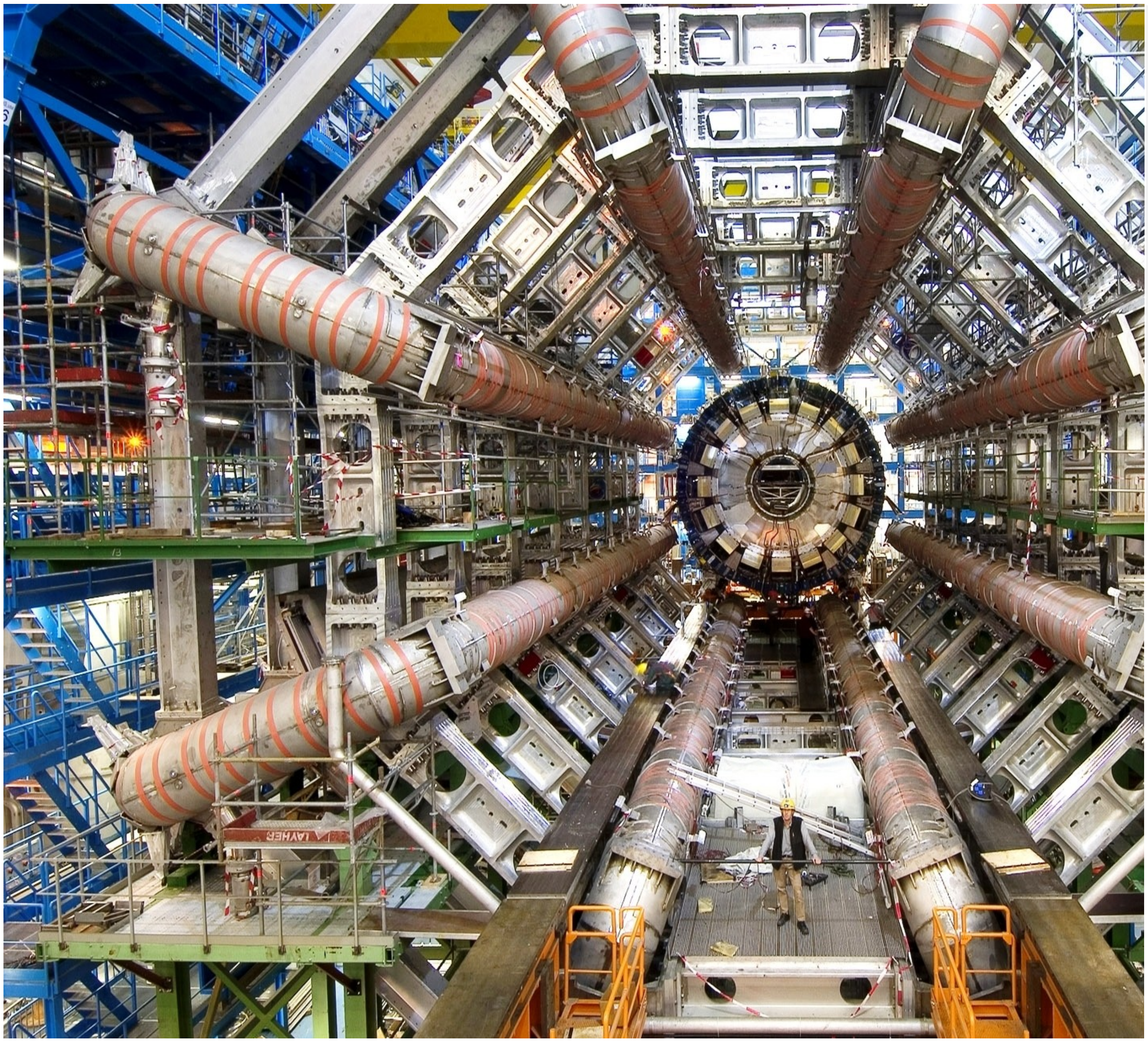


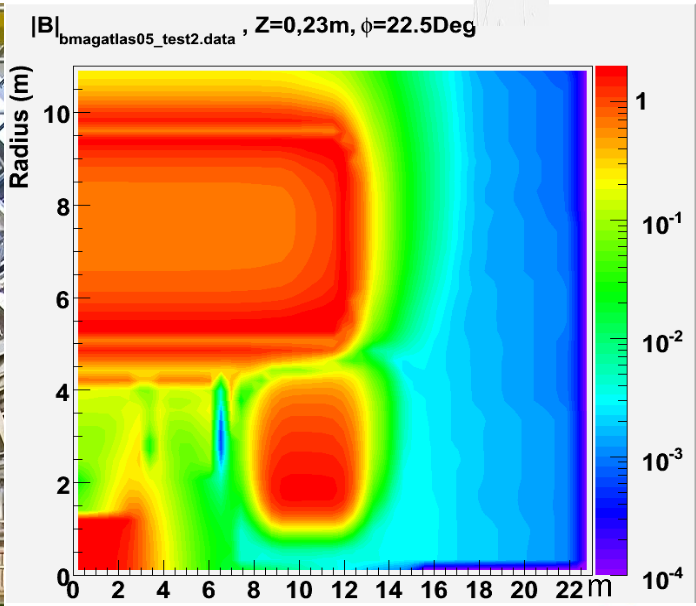
Detectors(Gaseous)

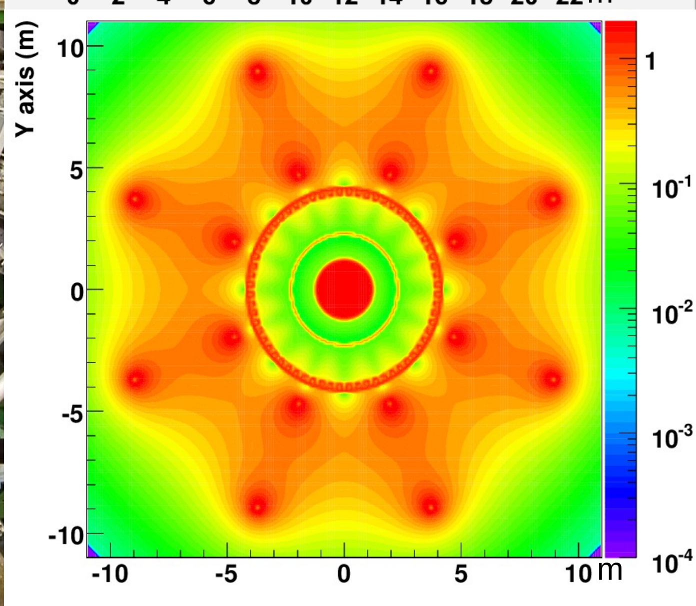


MDT: Monitored Drift Tube

- ATLAS Muons spectrometer
  - Air core Toroid => Magnetic field => Muon momentum measurement



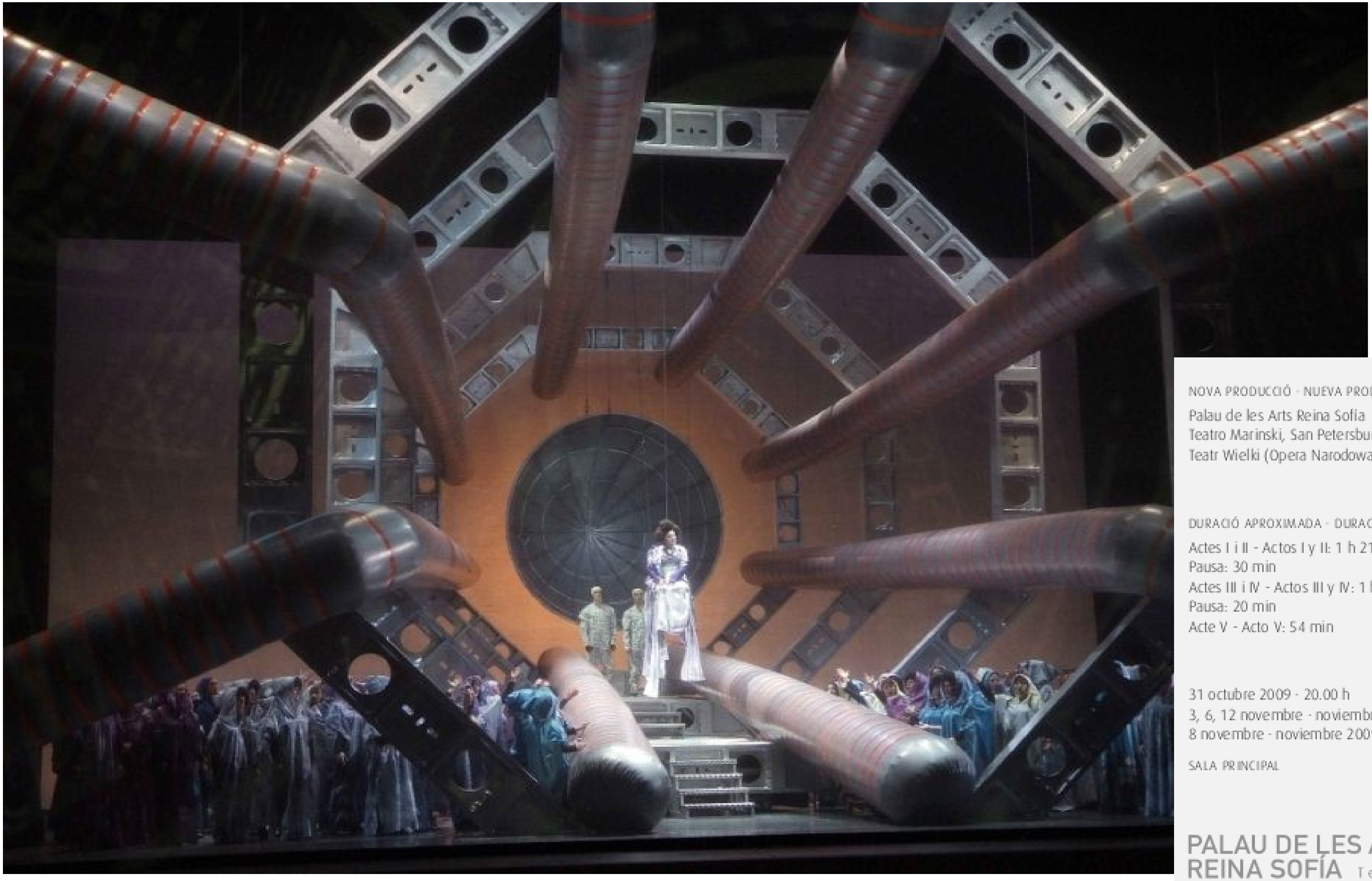




Detectors(Gaseous)

MDT: Monitored Drift Tube

- ATLAS Muons spectrometer
  - Air core Toroid => Magnetic field => Muon momentum measuremnt



NOVA PRODUCCIÓ · NUEVA PRODUCCIÓN

Palau de les Arts Reina Sofía
Teatro Marinski, San Petersburgo
Teatr Wielki (Opera Narodowa), Varsovia

DURACIÓ APROXIMADA · DURACIÓN APROXIMADA

Actes I i II - Actos I y II: 1 h 21 min
Pausa: 30 min
Actes III i IV - Actos III y IV: 1 h 42 min
Pausa: 20 min
Acte V - Acto V: 54 min

31 octubre 2009 · 20.00 h
3, 6, 12 novembre · noviembre 2009 · 20.00 h
8 novembre · noviembre 2009 · 19.00 h

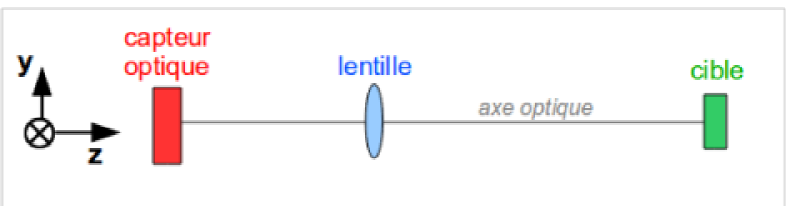
SALA PRINCIPAL

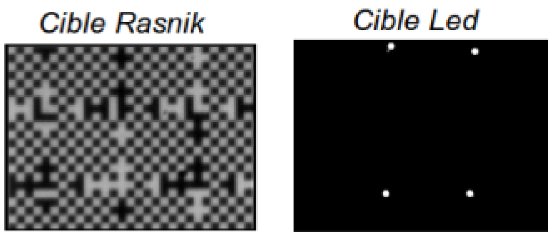
PALAU DE LES ARTS
REINA SOFÍA Temporada 2

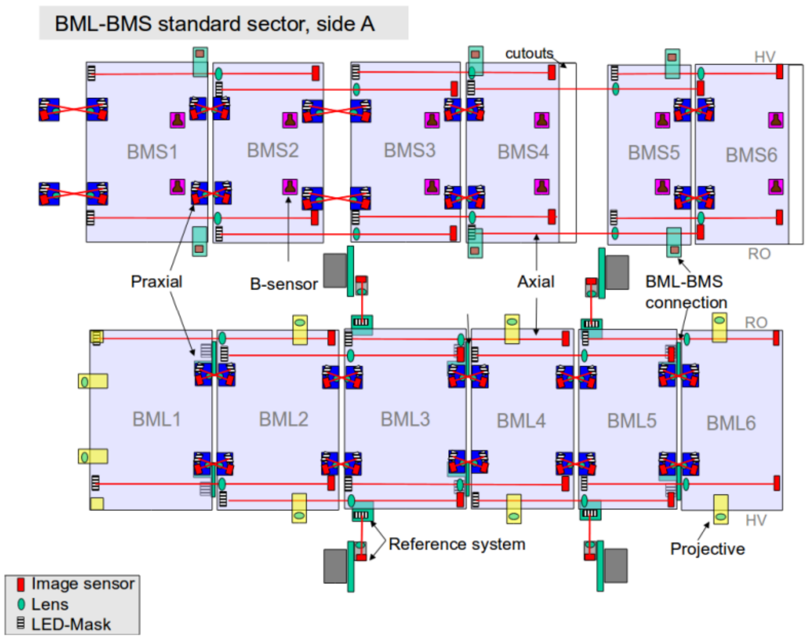
Detectors(Gaseous)

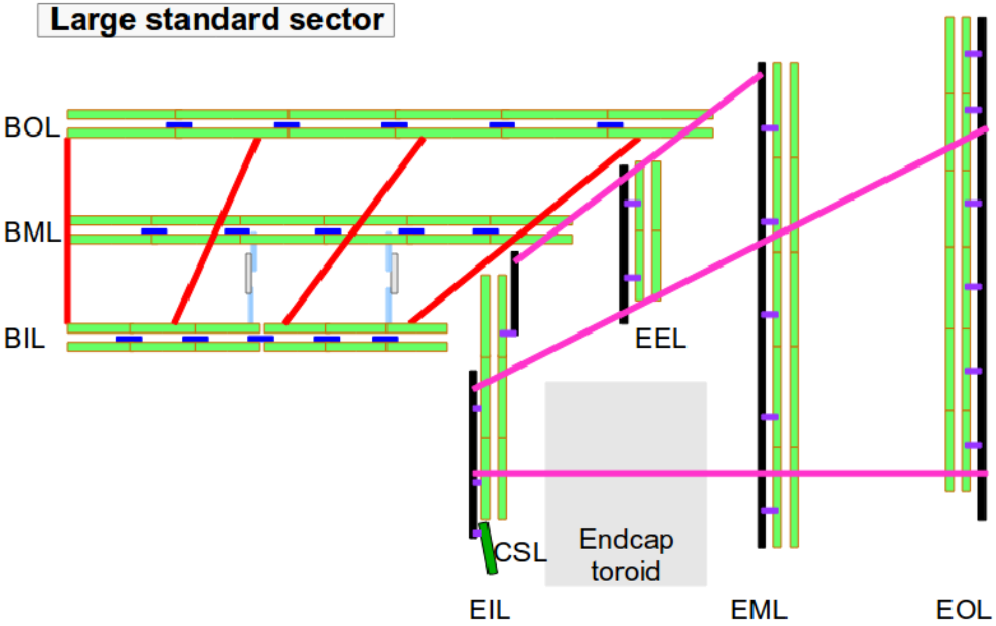
MDT: Monitored Drift Tube

- ATLAS Muons spectrometer
  - Relative Alignment of ~1200 chambers* 6 par. position + 11 par. Deformation
  - 20000 free parameters!







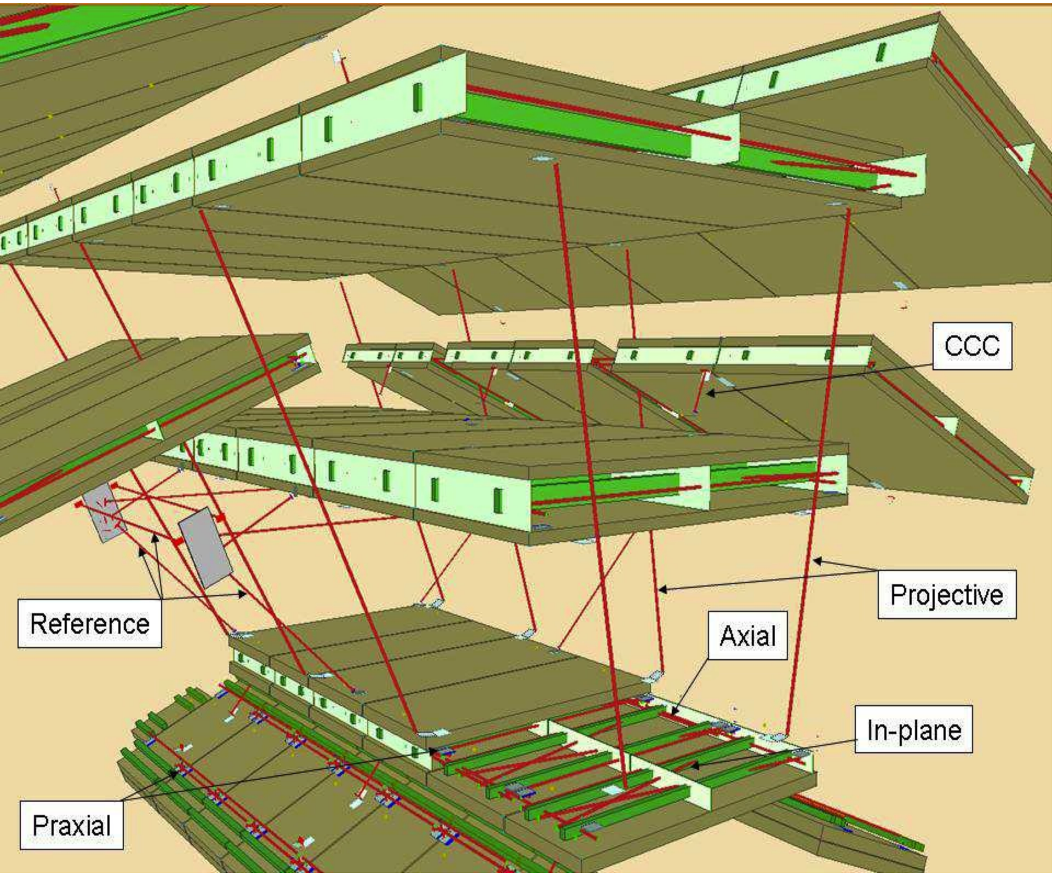


Detectors(Gaseous)

MDT: Monitored Drift Tube

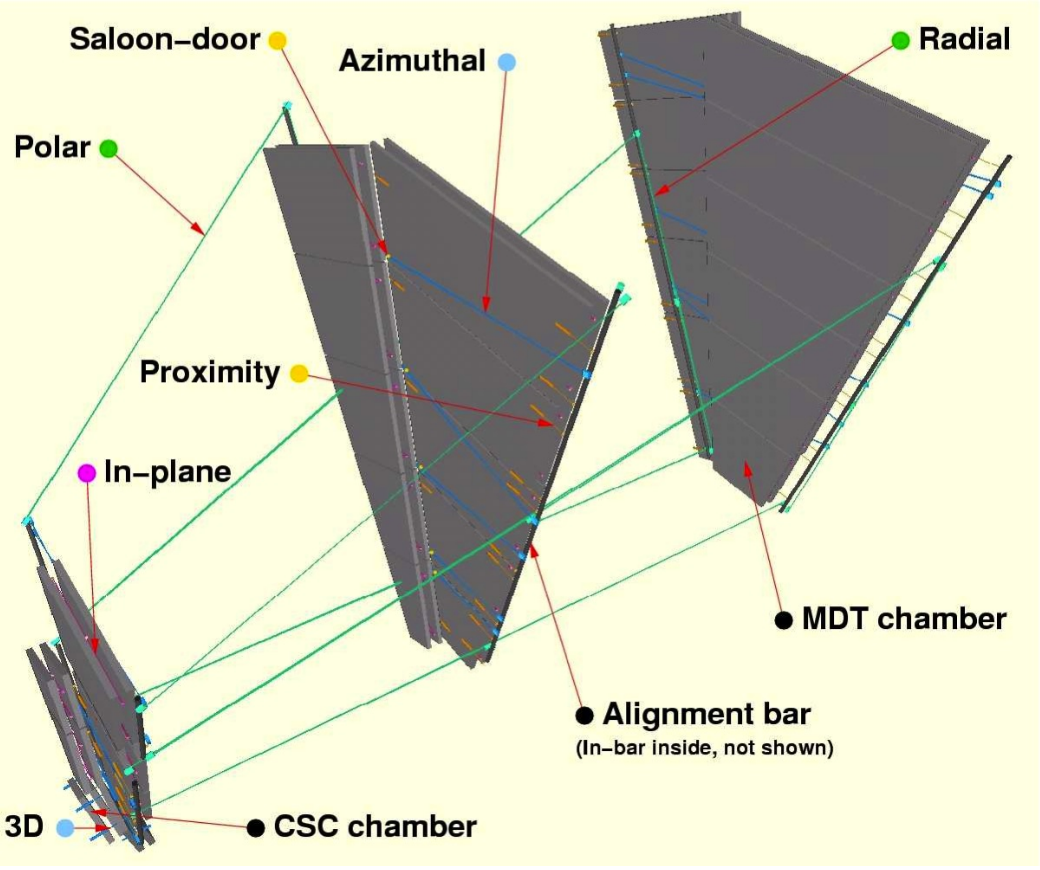
- ATLAS Muons spectrometer alignment

Barrel



Only the chambers in the odd sectors (between coils) are projectively 'aligned'.The chambers of the even sectors are aligned with tracks through chamber overlaps

endcap

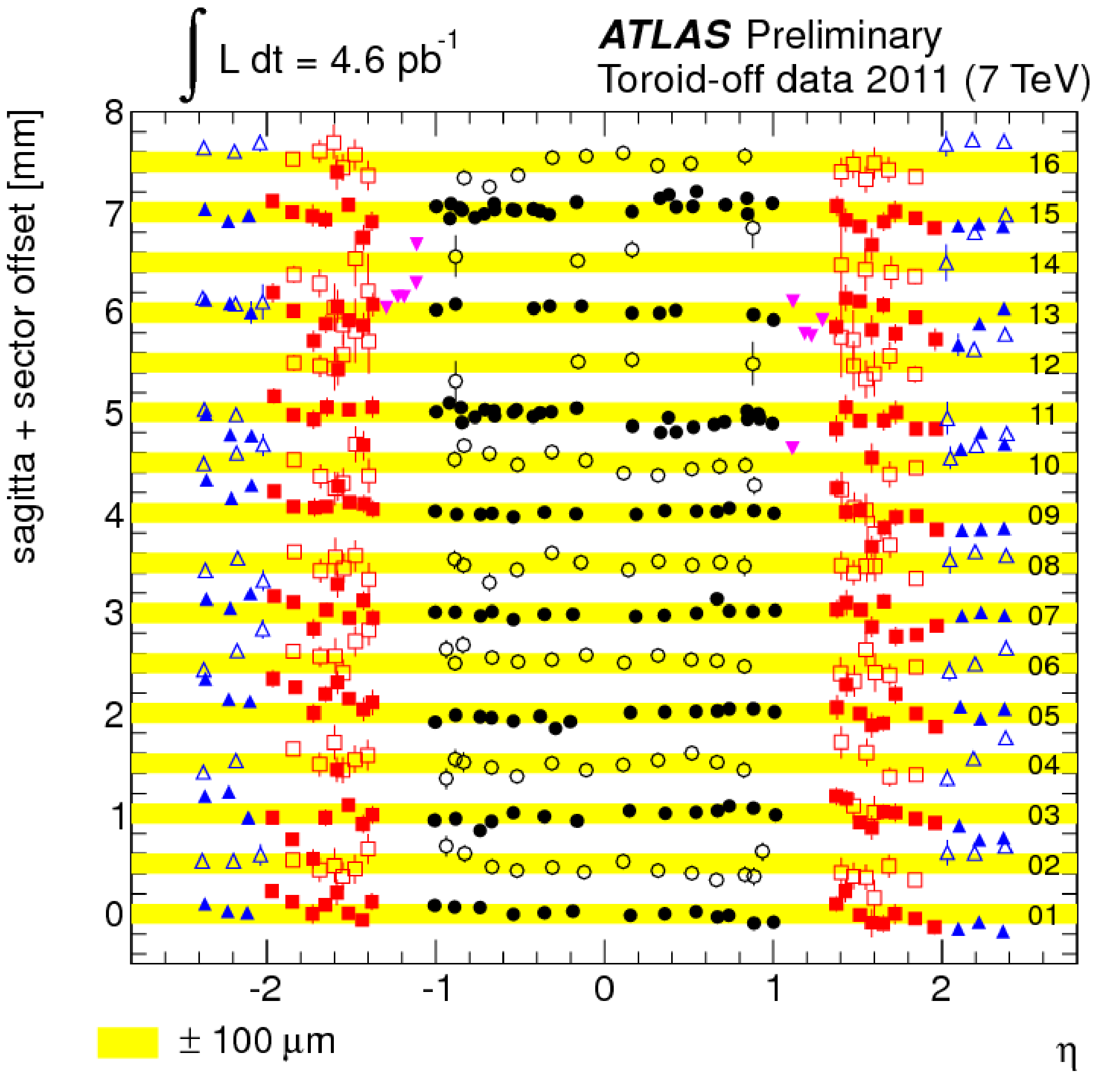


A set of alignment bars, optically interconnected, creates an external reference system. Azimuthal optical lines monitor the relative position of the chambers to these bars.

Detectors(Gaseous)

MDT: Monitored Drift Tube

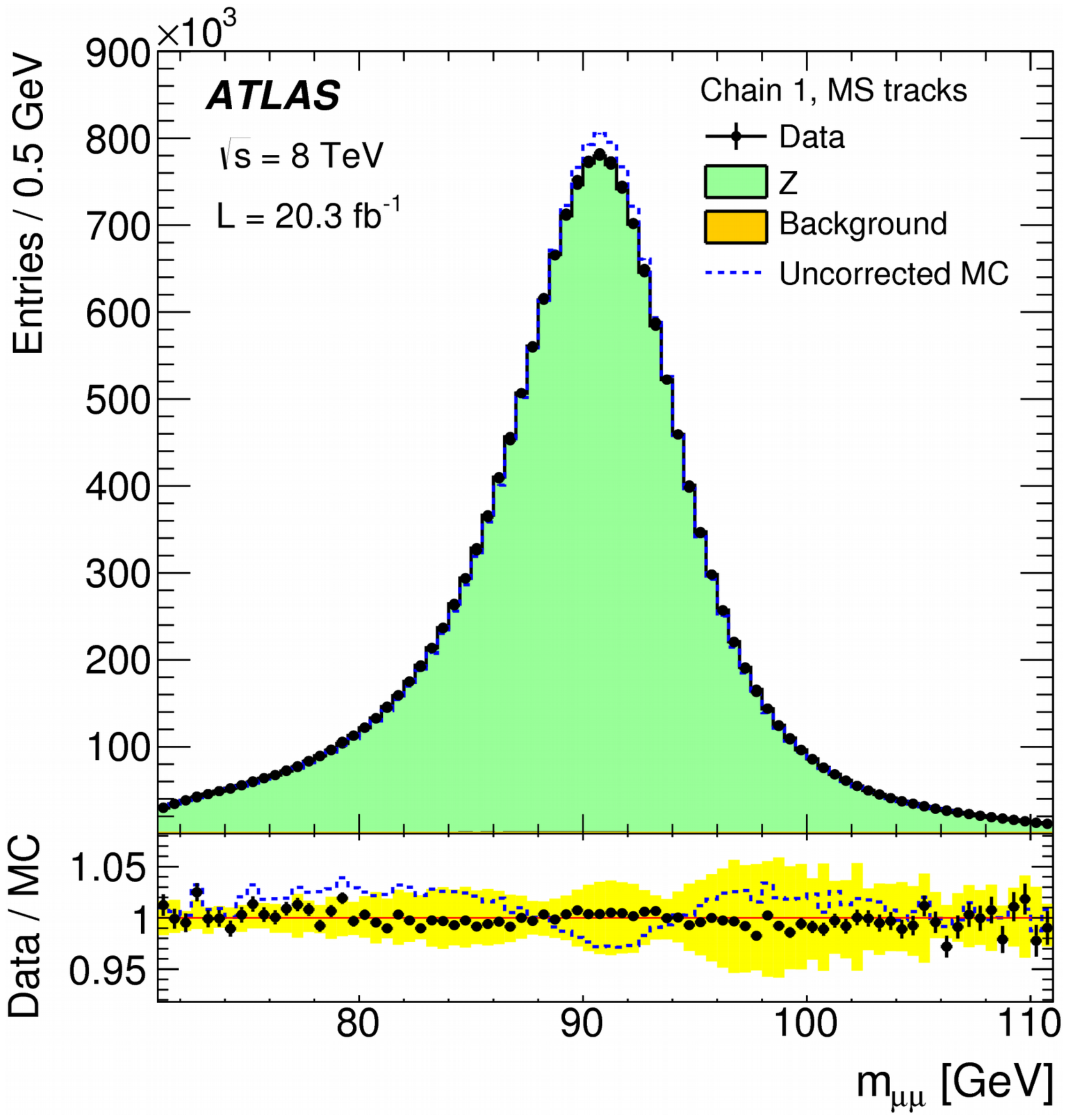
- ATLAS Muons spectrometer
  - To day sagitta is controlled at ~40μm

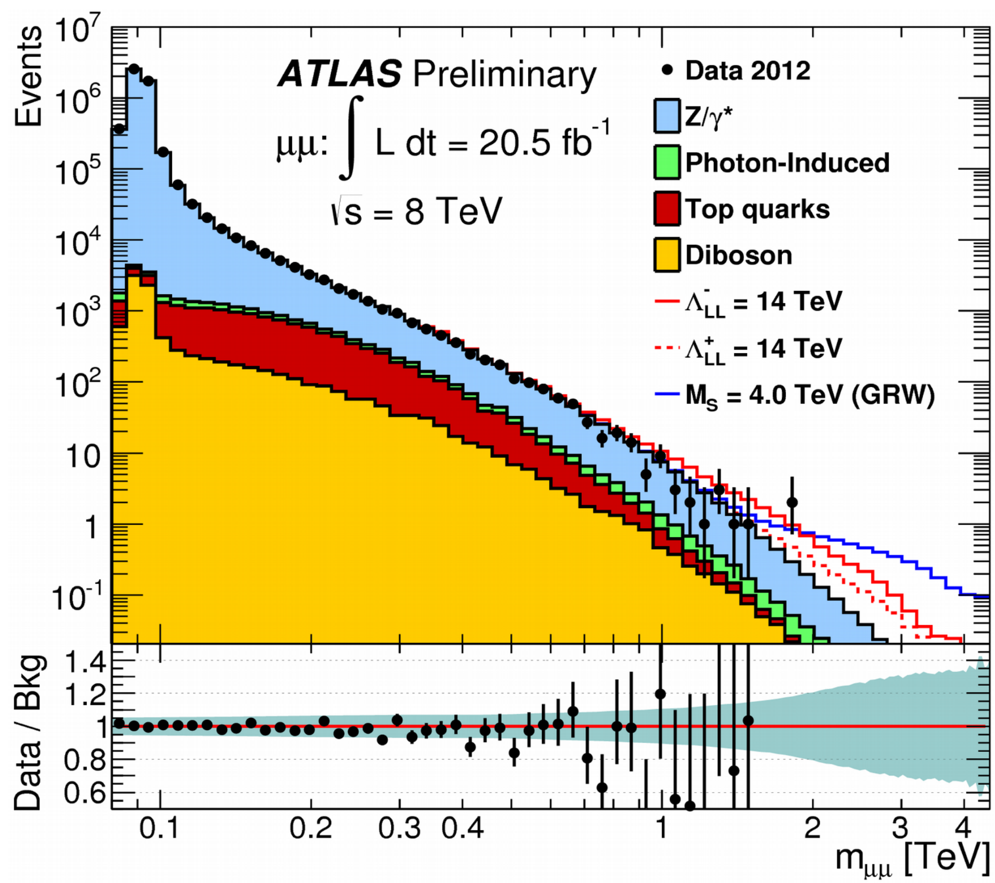


Detectors(Gaseous)

MDT: Monitored Drift Tube

- ATLAS Muons spectrometer: $\mu\mu$ invariant mass

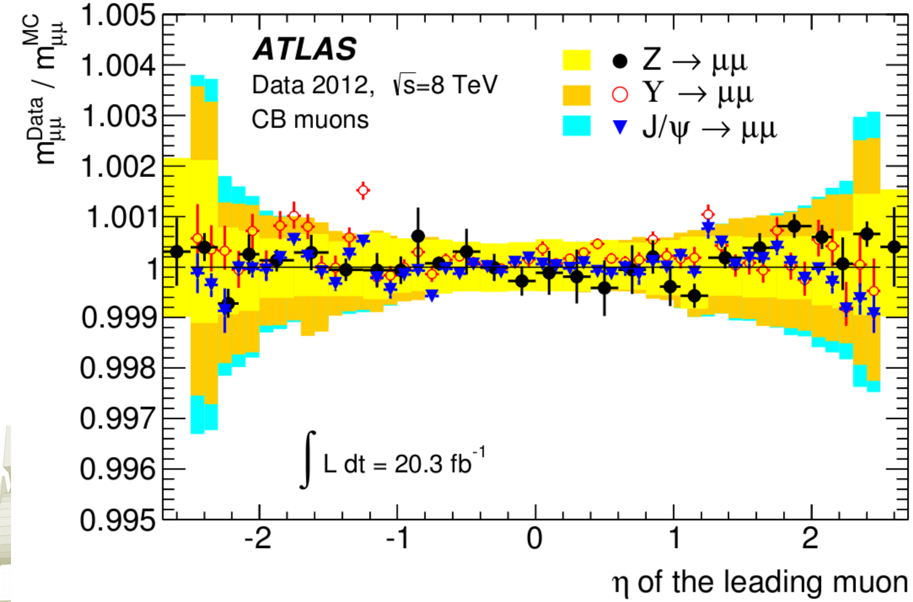


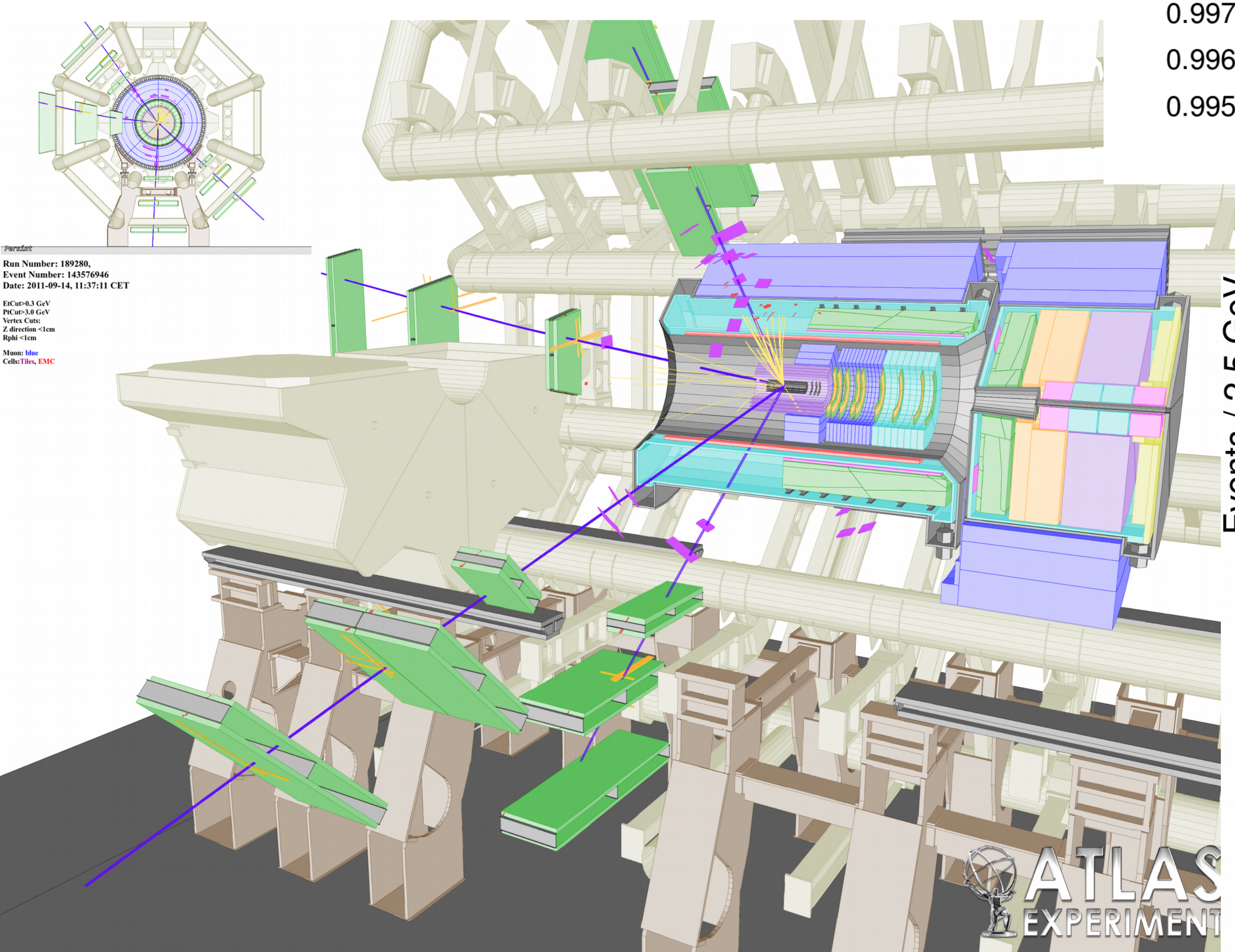


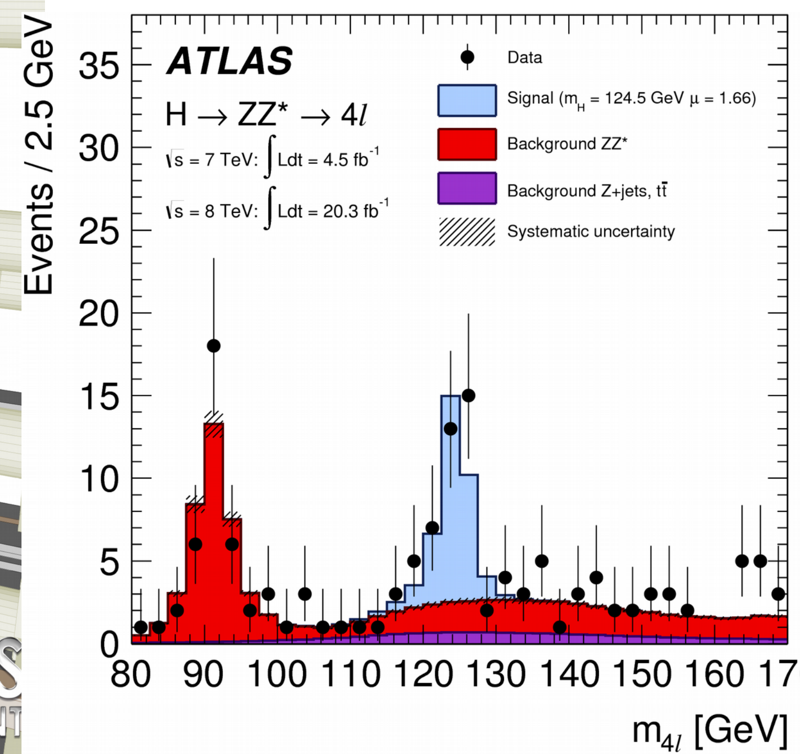
Detectors(Gaseous)

MDT: Monitored Drift Tube

- ATLAS Muons spectrometer: μμμμ invariant mass Higgs!



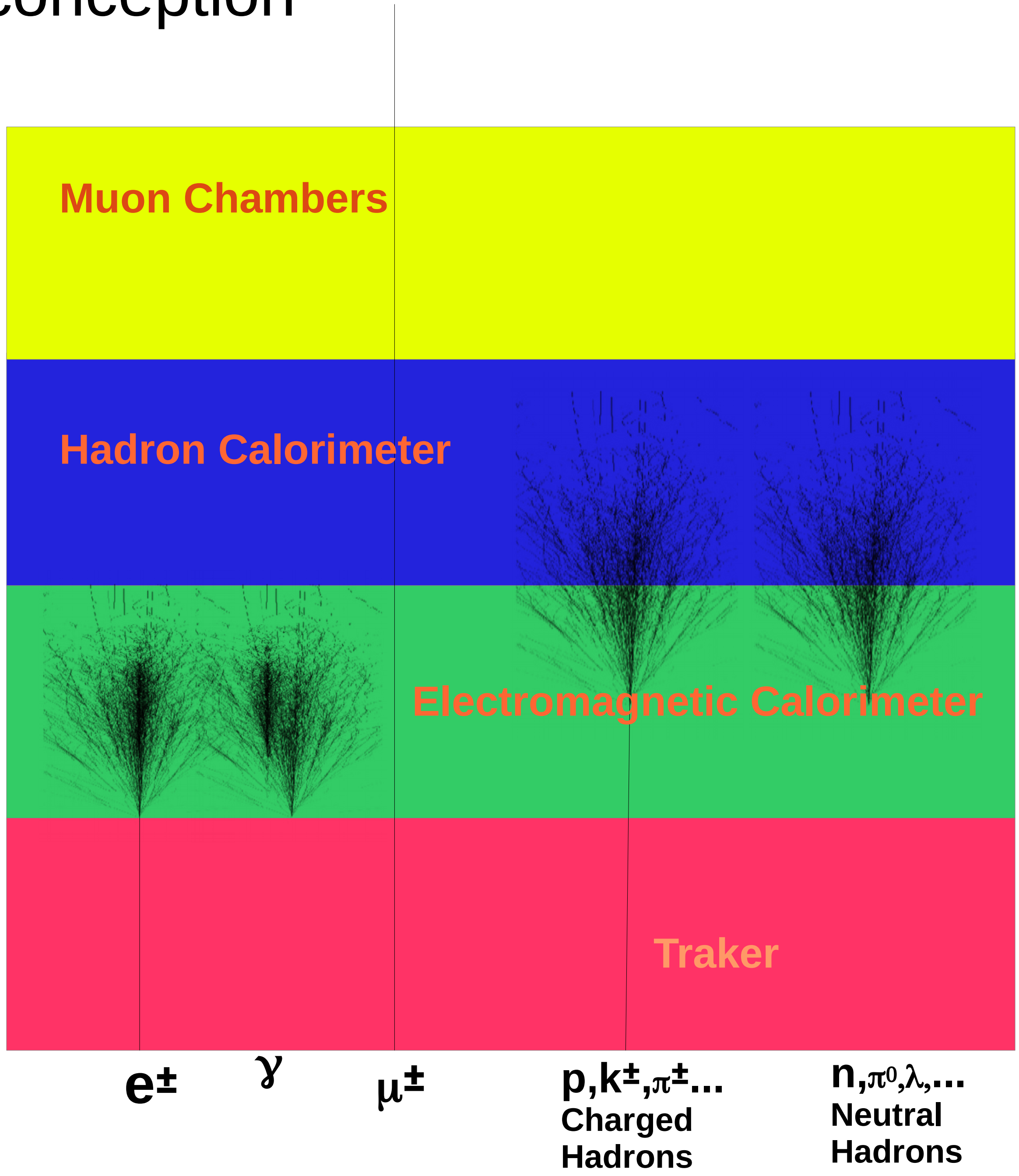




Interlude: Detectors conception

Principle

- Muon detection:
  - Tracker (charged particle)
  - MIP in calorimeter
  - Tracks in Muon chambers



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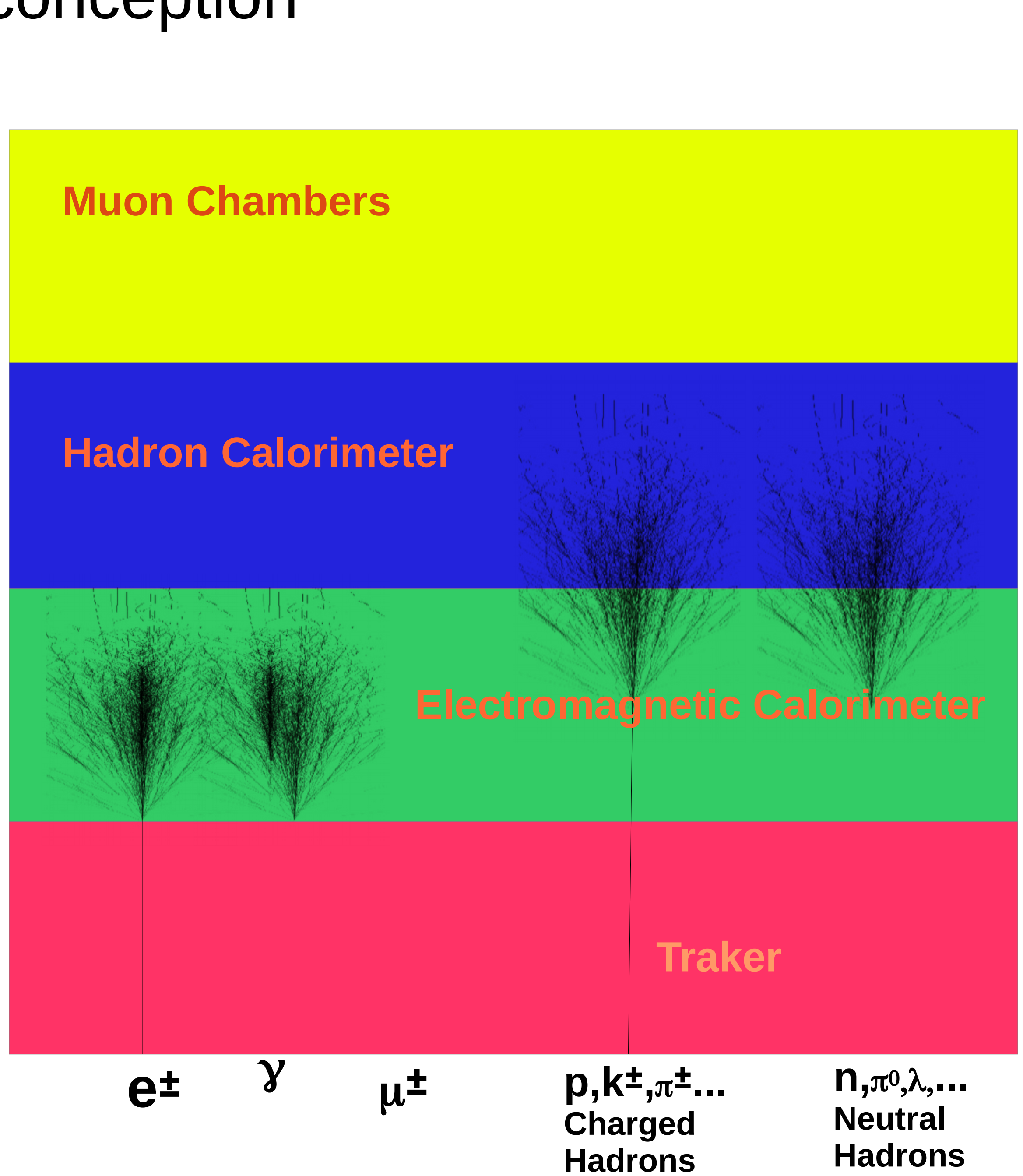


Principle

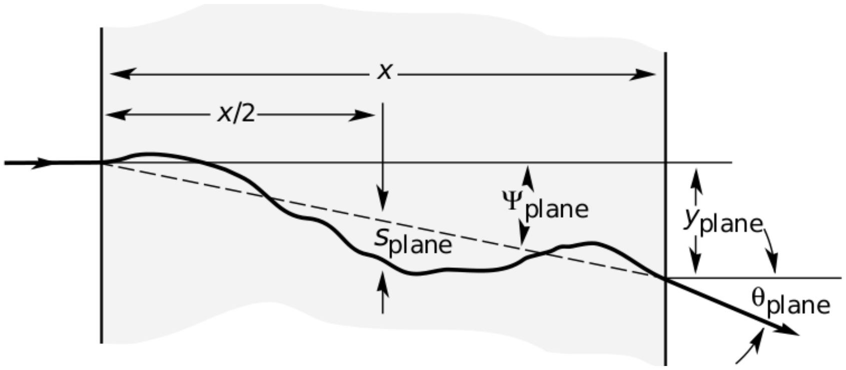
- Muon as Tool
  - Trigger
  - Veto
    - Ice Cube
    - Double Chose
  - Calibration MIP
    - LHC
    - Hess (Telescope)

Interlude: Detectors conception

Coulomb scattering

- Multiple scattering : perturbation (degradation)
  - Deflection
  - => minimize matter ex: Muon spectrometer (ATLAS)

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



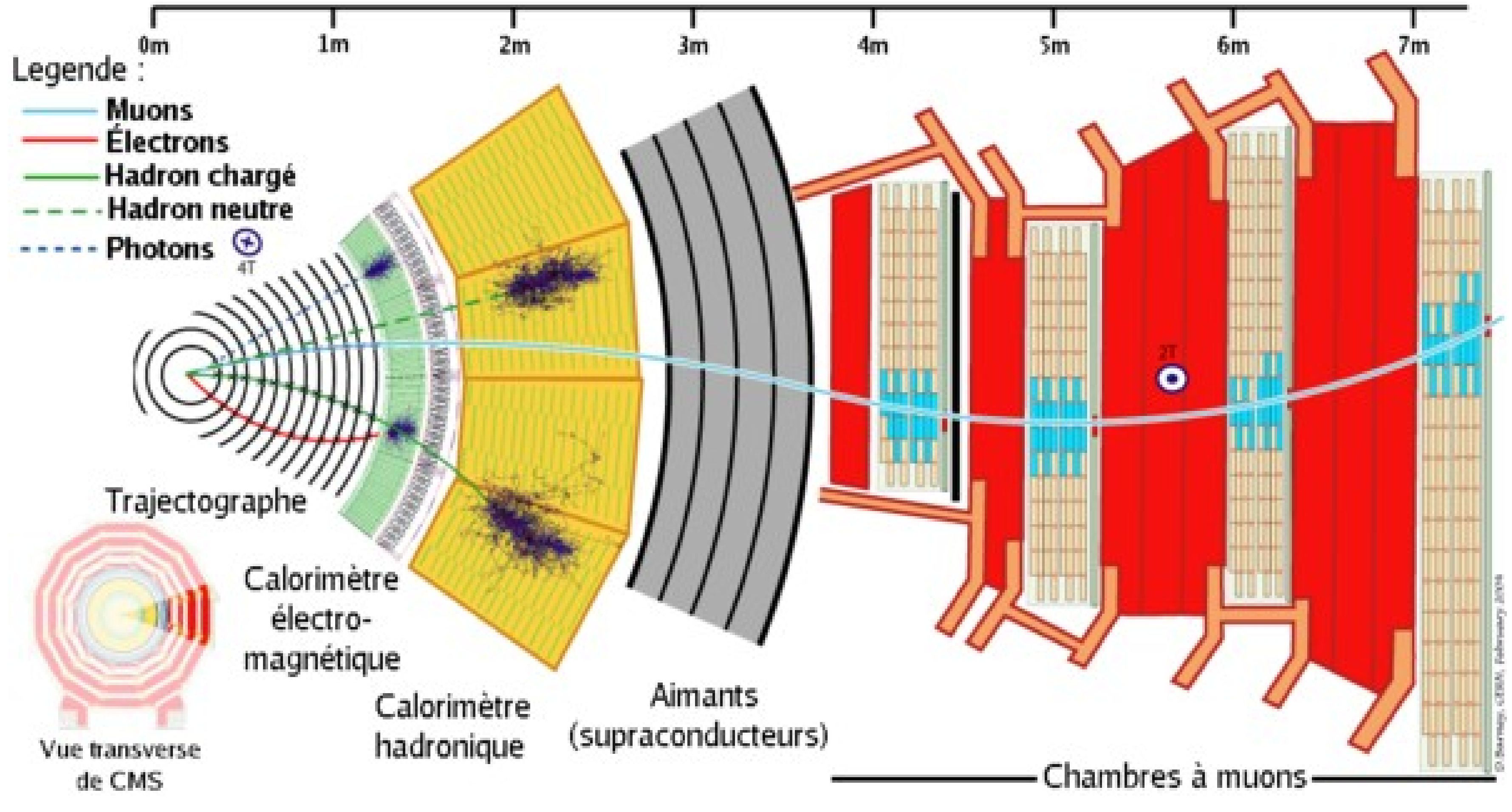
Detectors conception

Principle

Muon detection:

- Tracker (charged particle)
- MIP in calorimeter
- Tracks in Muon chambers

CMS

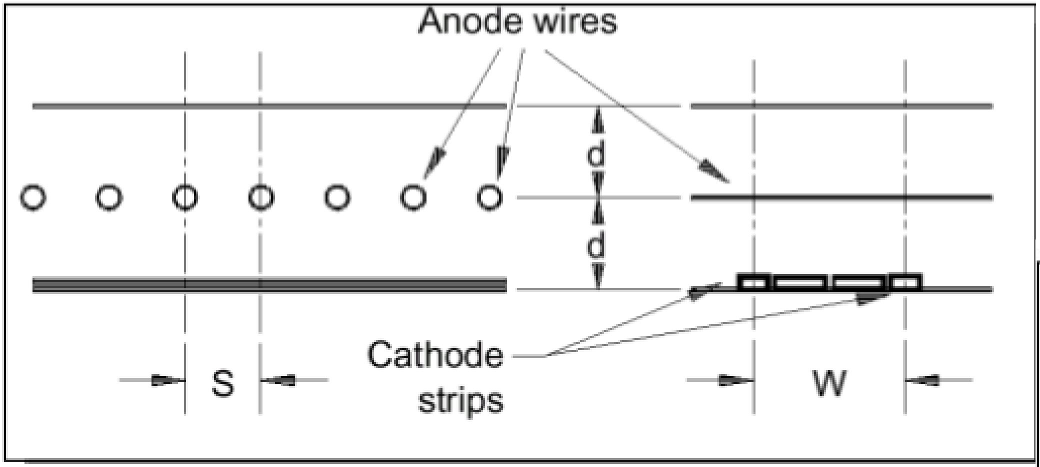


Back to the Detectors

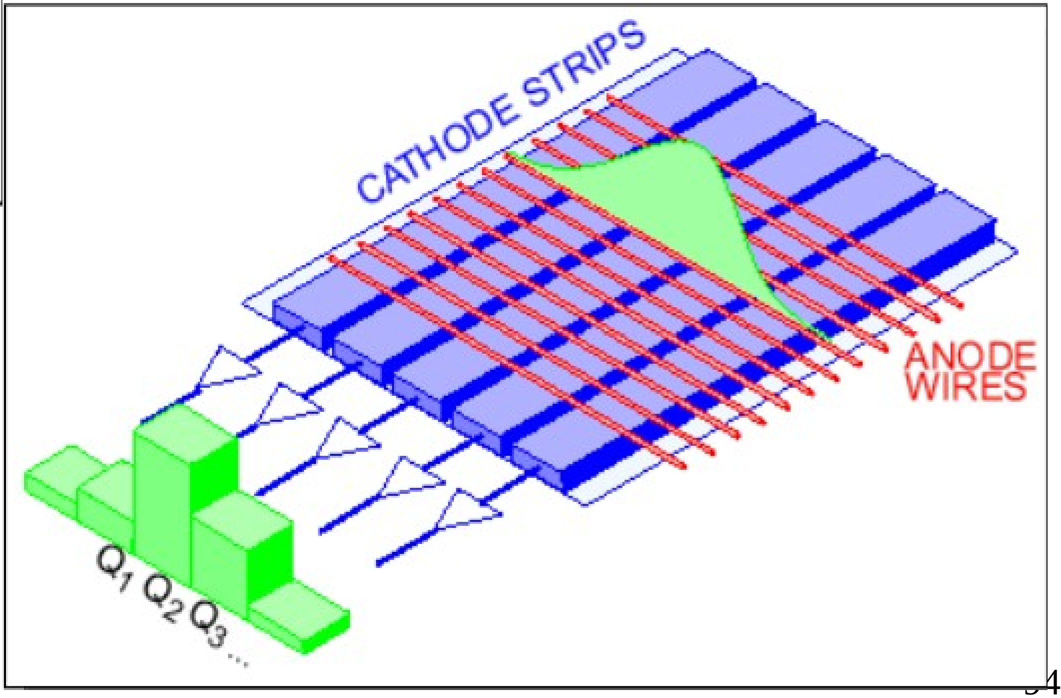
Detectors(Gaseous)

CSC: Cathode Strip Chamber

- Determine muon position by interpolating the charge on 3 to 5 adjacent strips
- Precision (x-) strip pitch ~ 5.6 mm
- Measure Q1, Q2, Q3... with 150:1 SNR to get σx ~ 60 μm.
- Second set of y-strips measure transverse
- coordinate to ~ 1 cm.
- Position accuracy unaffected by gas gain or drift time variations

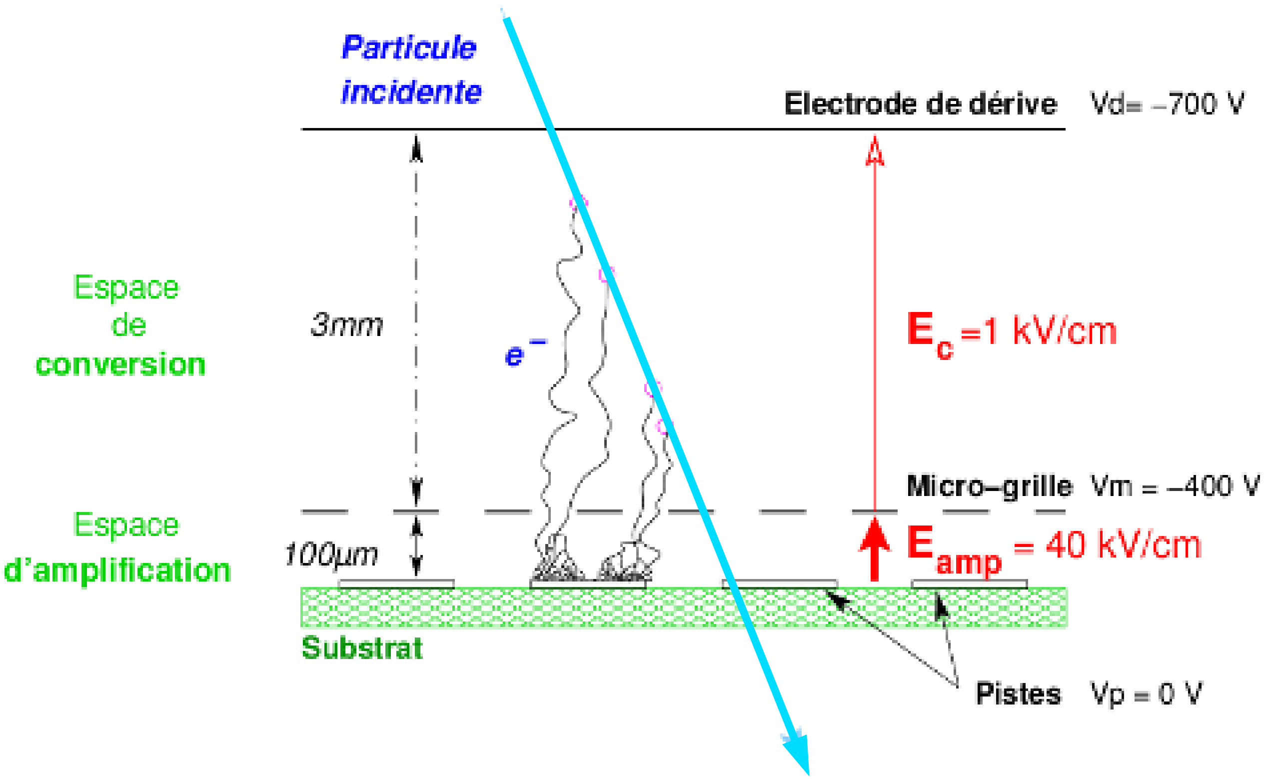


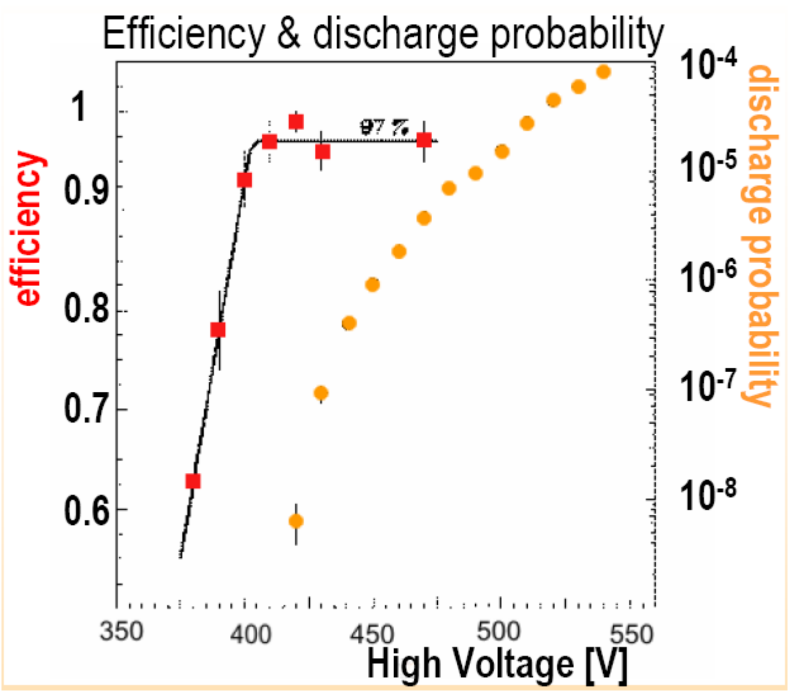
S = 2.54 mm W = 5.60 mm



Micro-Megas

- Giomataris I. et al., NIMA 376 (1996) 29
- Capable of operating at very high rates
- Work in magnetic fields
- Radiation hard and age well.
- Shape and readout segmentation can be adapted to the needs
- Parallel plate structures with straight-forward field shapes.
- Work at very low HV (thin amplification gap)
- Industrially produced





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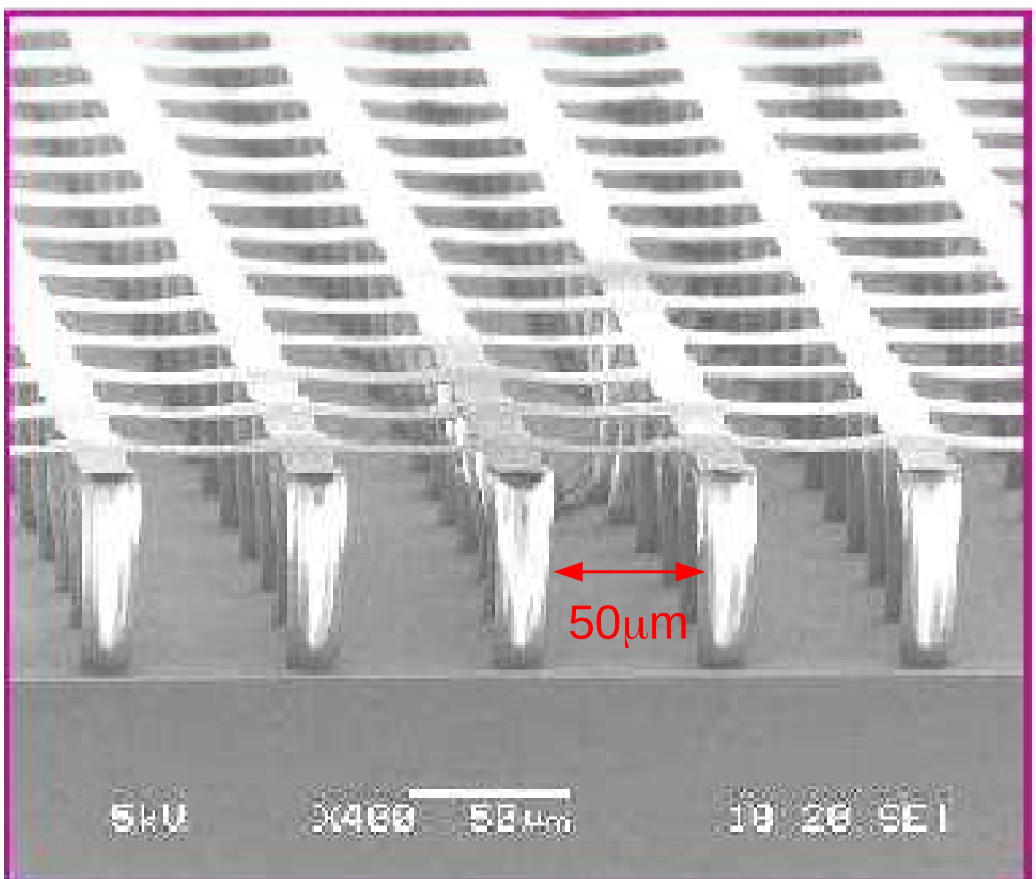
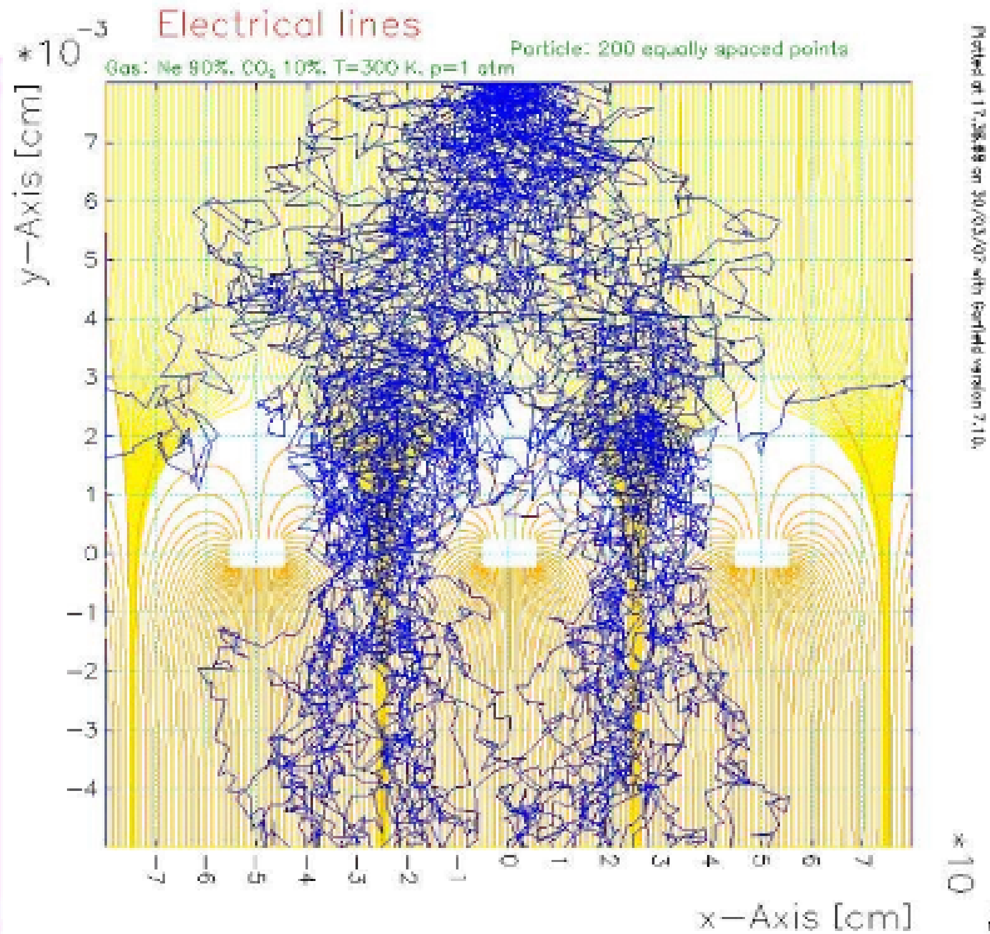


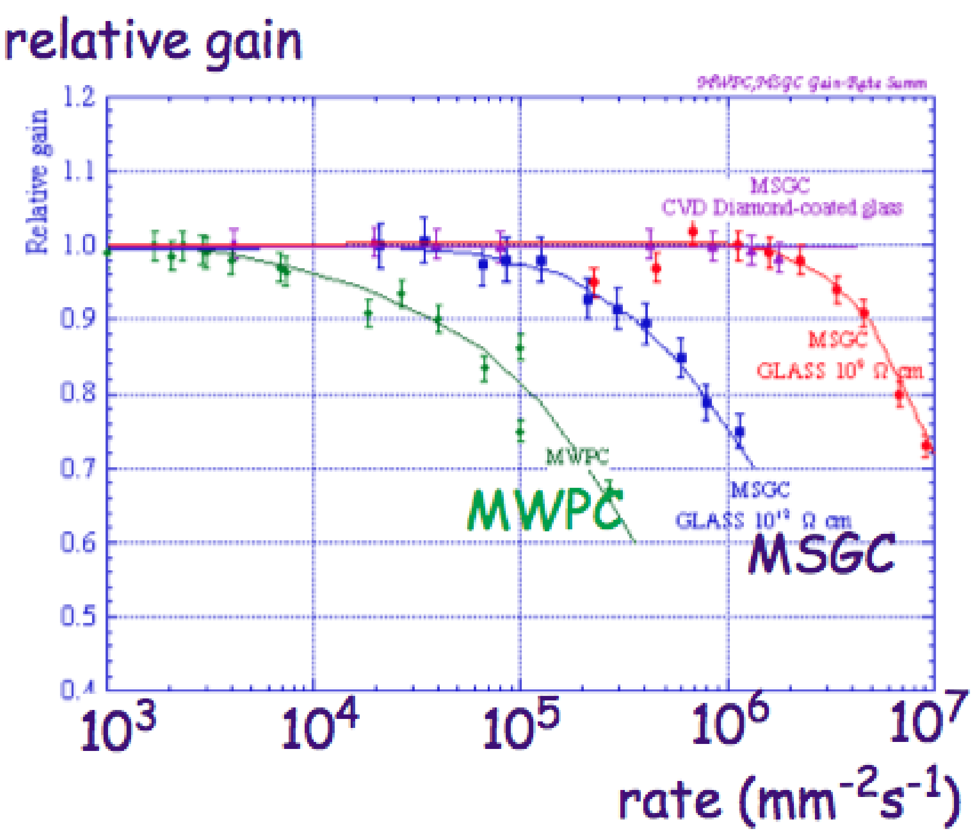


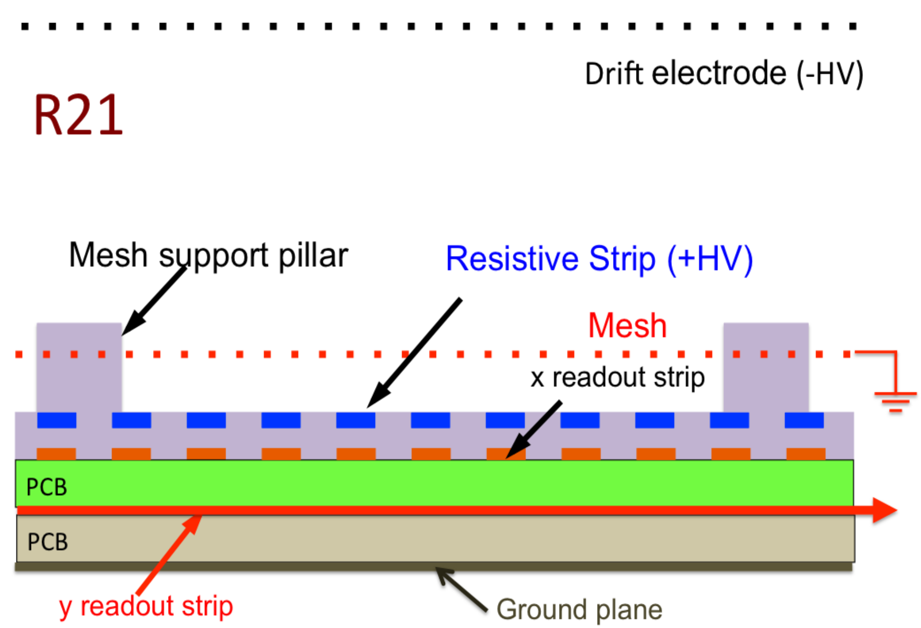
Detectors(Gaseous)

Micro Pattern Gas Detectors

Micro-Megas

- Capable of operating at very high rates
  - Short ion evacuation path => high rate capability
- Very precise readout structures produced using PCB technology (lithography)
- Very good spatial resolution
- Improvement (add of a layer of resistive strips above the readout structure: Spark tolerant without degrading their performance
  T. Alexopoulos et al., NIMA 640 (2011) 110-118





Interlude

Muography

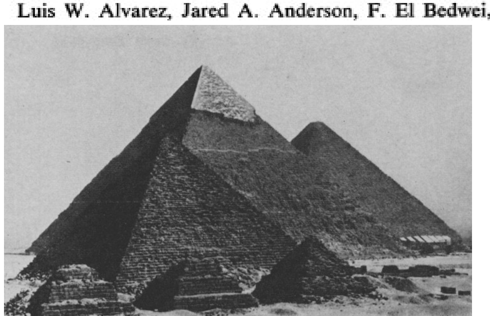
Muography

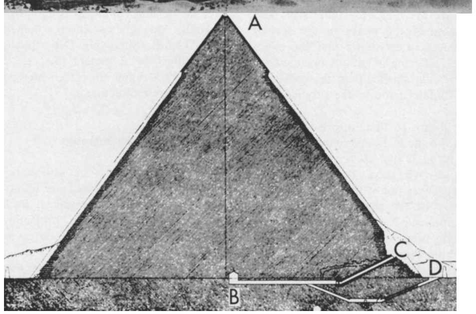
- the probability of muon absorption is proportional to the density
  Muon flux → density map
- Use cosmic muons to analyse Archaeology,Volcanology, buildings structure,...

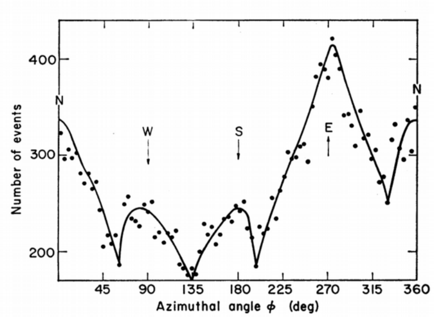
Search for Hidden Chambers in the Pyramids

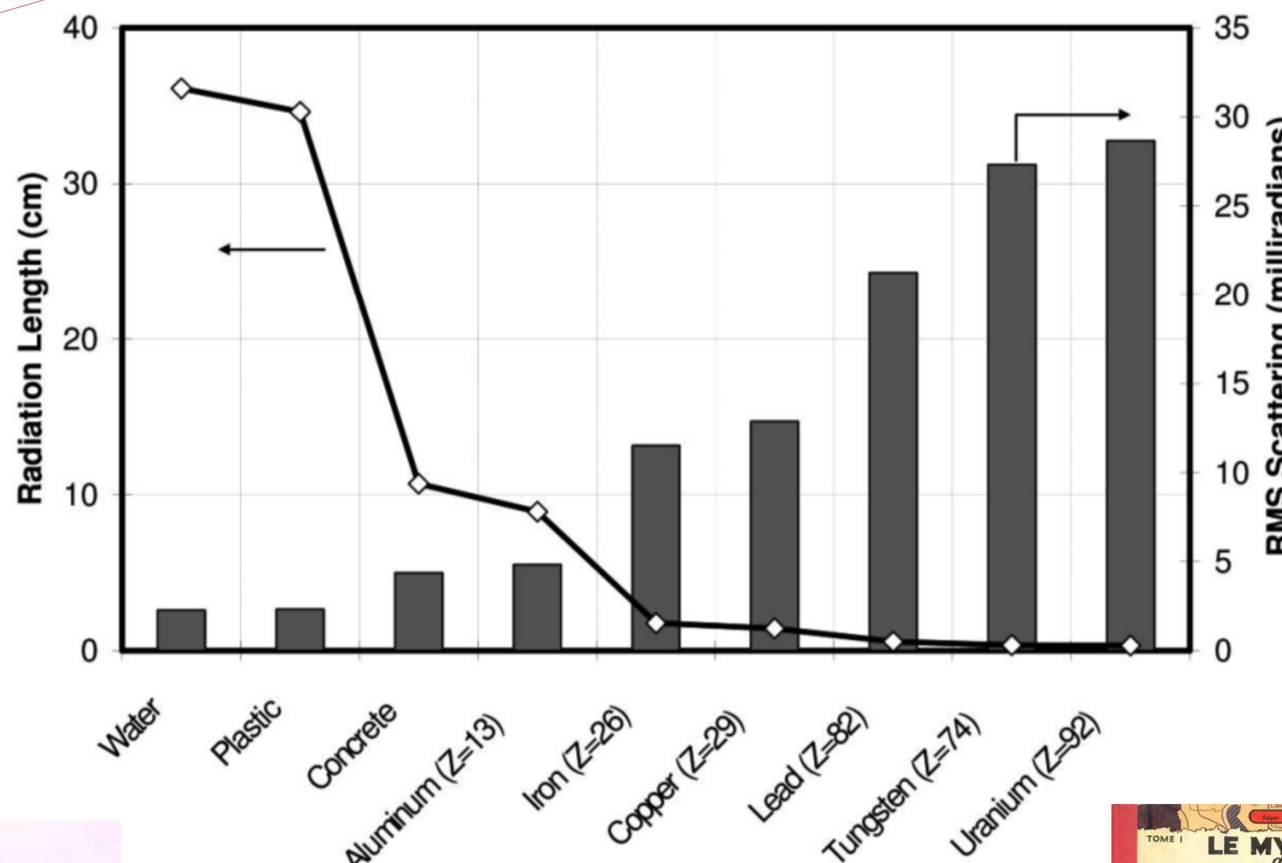
The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

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

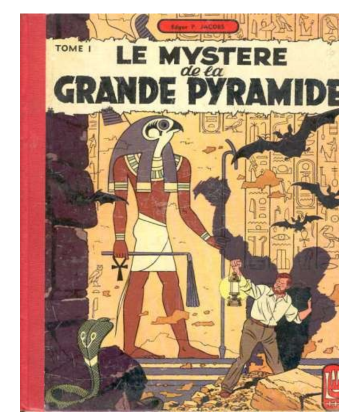








Hidden room in the pyramid? →



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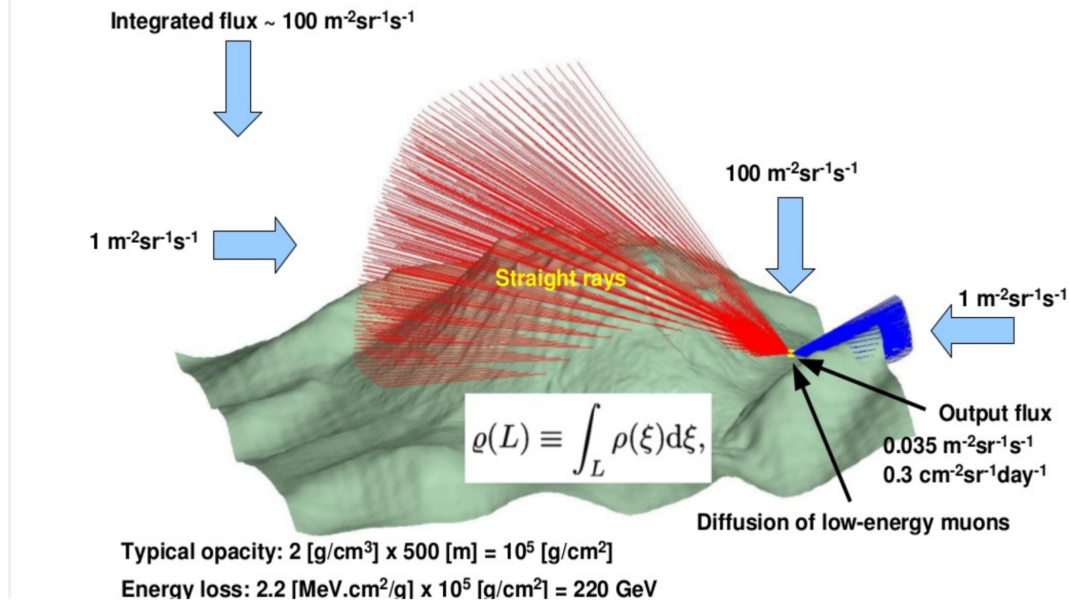
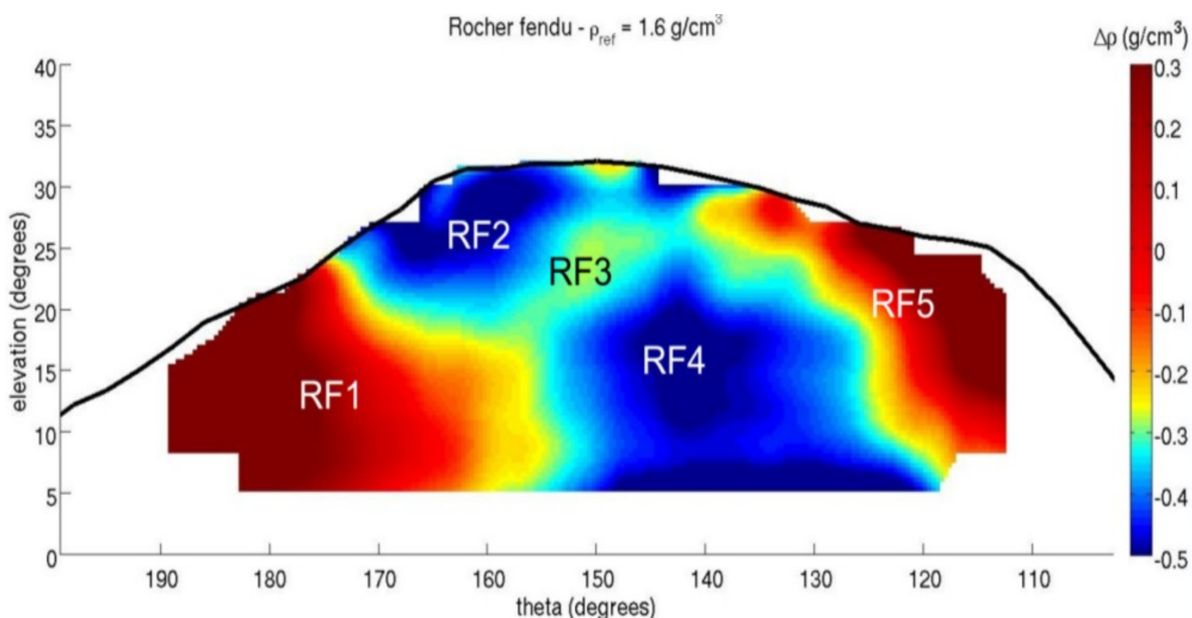
- Use cosmic muons to analyse Archaeology, Volcanology, buildings structure,...





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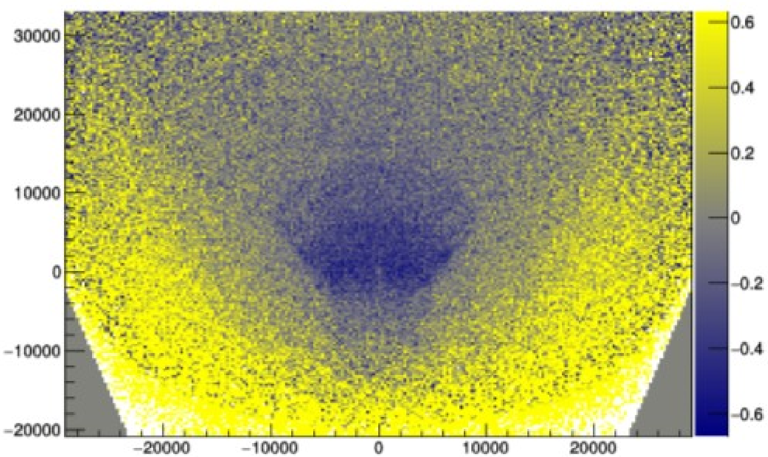


Micro-megas

doi:10.1038/nature24647

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima[1], Mitsuaki Kuno[1], Akira Nishio[1], Nobuko Kitagawa[1], Yuta Manabe[1], Masaki Moto[1], Fumihiko Takasaki[2], Hirofumi Fujii[2], Kotaro Satoh[2], Hideyo Kodama[2], Kohei Hayashi[2], Shigeru Odaka[2], Sébastien Procureur[3], David Attié[3], Simon Bouteille[3], Denis Calvet[3], Christopher Filosa[3], Patrick Magnier[3], Irakli Mandjavidze[3], Marc Riallot[3], Benoit Marini[4], Pierre Gable[5], Yoshikatsu Date[6], Makiko Sugiura[7], Yasser Elshayeb[8], Tamer Elnady[9], Mustapha Ezzy[8], Emmanuel Guerriero[5], Vincent Steiger[4], Nicolas Serikoff[4], Jean-Baptiste Mouret[10,11,12], Bernard Charlès[13], Hany Helal[4,8] & Mehdi Tayoubi[4,13]

The Great Pyramid, or Khufu's Pyramid, was built on the Giza plateau in Egypt during the fourth dynasty by the pharaoh Khufu (Cheops)[1], who reigned from 2509 BC to 2483 BC. Despite being one of the oldest and largest monuments on Earth, there is no consensus about how it was built[2,3]. To understand its internal structure better, we imaged the pyramid using muons, which are by-products of cosmic rays that are only partially absorbed by stone[4–6]. The resulting cosmic-ray muon radiography allows us to visualize the known and any unknown voids in the pyramid in a non-invasive way. Here we report the discovery of a large void (with a cross-section similar to that of the Grand Gallery and a minimum length of 30 metres) situated above the Grand Gallery. This constitutes the first major inner structure found in the Great Pyramid since the nineteenth century[1]. The void, named ScanPyramids' Big Void, was first observed with nuclear emulsion films[7–9] installed in the Queen's chamber, then confirmed with scintillator hodoscopes[10,11] set up in the same chamber and finally re-confirmed with gas detectors[12] outside the pyramid. This large void has therefore been detected with high confidence by three different muon detection technologies and three independent analyses. These results constitute a breakthrough for the understanding of the internal structure of Khufu's Pyramid. Although there is currently no information about the intended purpose of this void, these findings show how modern particle physics can shed new light on the world's archaeological heritage.

The pyramid of Khufu is 139 m high and 230 m wide[1,13]. There are three known chambers (Fig. 1), at different heights of the pyramid, which all lie in the north–south vertical plane[1]: the subterranean chamber, the Queen's chamber, and the King's chamber. These chambers are connected by several corridors, the most notable one being the Grand Gallery (8.6 m high × 46.7 m long × 2.1–1.0 m wide). The Queen's

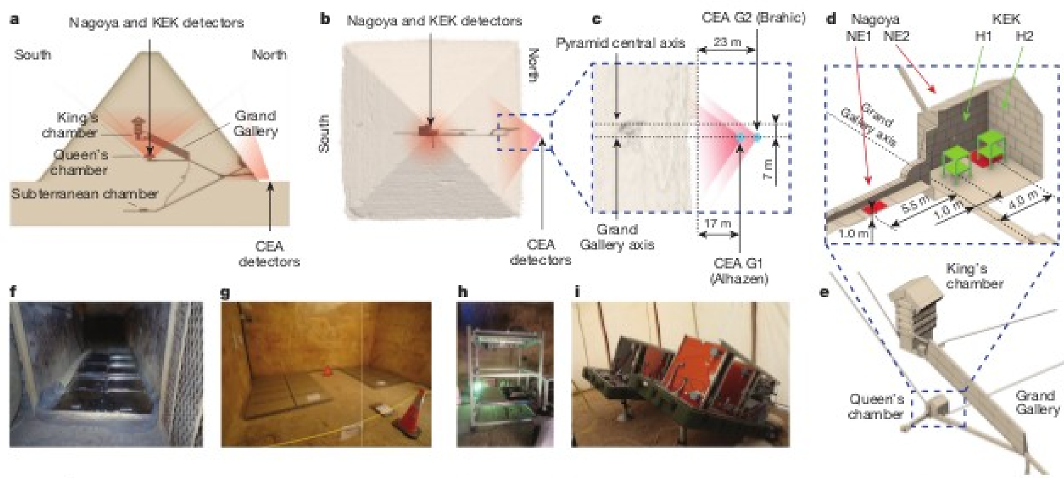
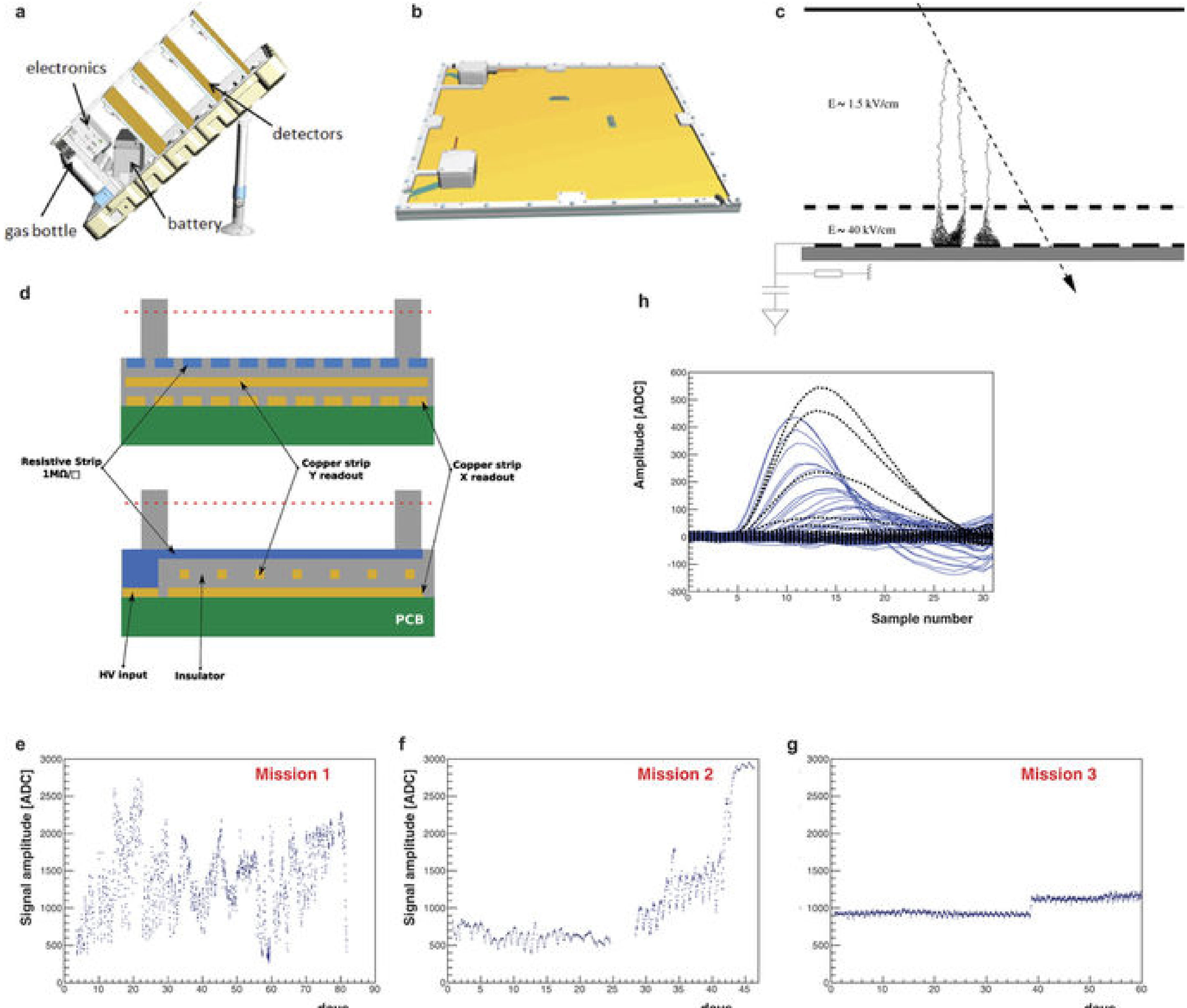


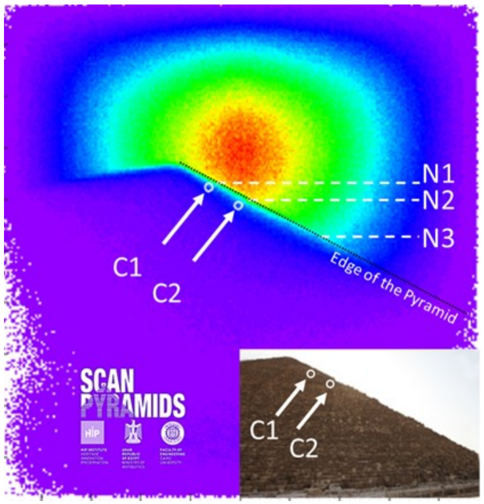
Figure 1 | Muon detectors installed for Khufu's Pyramid. a, Side view of the pyramid, with sensor positions and indicative field of view. **b,** Top view. **c,** Close view of the position of the gas detectors Brahic and Alhazen (CEA). **d,** Orthographic view of Queen's chamber with nuclear emulsion films (Nagoya University, red positions NE1 and NE2) and scintillator hodoscopes (KEK, green positions H1 and H2). **e,** Orthographic view of the main known internal structures. **f,** Nuclear emulsion plates in position NE1 (Nagoya University). **g,** Nuclear emulsion plates in position NE2 (Nagoya University). **h,** Scintillator hodoscope setup for position H1 (KEK). **i,** Gas detectors (muon telescopes, CEA).

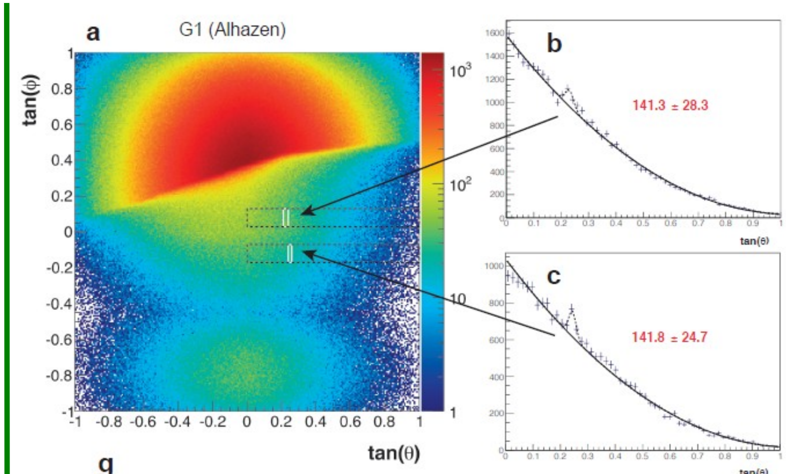
[1]F-lab, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan. [2]High Energy Accelerator Research Organization (KEK), 1-1 oho, Tsukuba, Ibaraki 305-0801, Japan. [3]Institut de Recherche sur les lois Fondamentales de l'Univers (IRFU), Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), Université Paris Saclay, 91191 Gif-sur-Yvette, France. [4]HIP Institute, 50 rue de Rome, 75008 Paris, France. [5]Emissive, 71 rue de Provence, 75009 Paris, France. [6]NHK Enterprises, Inc. (NEP), 4-14 Kamiyama-cho, Shibuya-ku, Tokyo 150-0047, Japan. [7]Suave Images, N-2 Maison de Shino, 3-30-8 Kamineguro, Meguro-Ku, Tokyo 153-0051, Japan. [8]Cairo University, 9 Al Gameya, Oula, Giza Governorate, Egypt. [9]Ain Shams University, Kasr el-Zaafaran, Abbasiya, Cairo, Egypt. [10]Inria, Villers-lès-Nancy F-54600, France. [11]CNRS, Vandœuvre-lès-Nancy F-54500, France. [12]Université de Lorraine, Vandœuvre-lès-Nancy F-54500, France. [13]Dassault Systèmes, 10 Rue Marcel Dassault, 78140 Vélizy-Villacoublay, France.

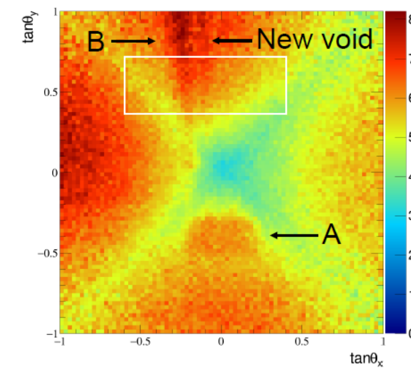

a
electronics
detectors
gas bottle
battery
b
c
E ~ 1.5 kV/cm
E ~ 40 kV/cm
d
Resistive Strip 1MΩ/□
Copper strip Y readout
Copper strip X readout
PCB
HV input
Insulator
h
Amplitude [ADC]
Sample number
e
Mission 1
Signal amplitude [ADC]
days
f
Mission 2
Signal amplitude [ADC]
days
g
Mission 3
days

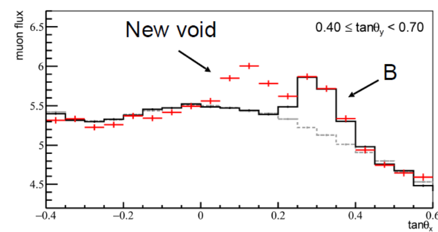
- Discoveries of new cavities large void above the Grand Gallery

2016 CEA 2017

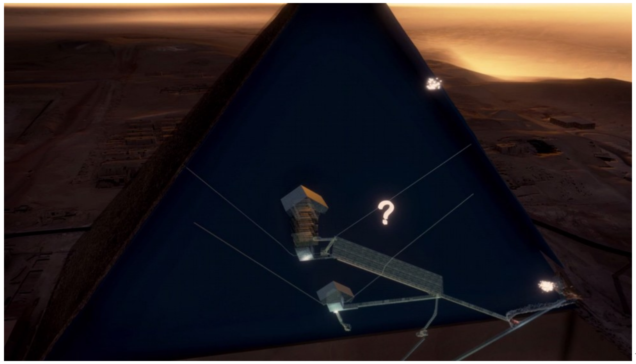


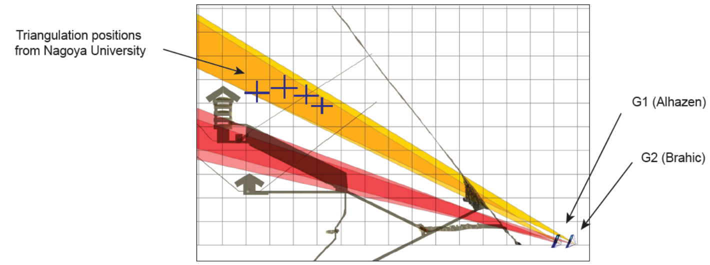






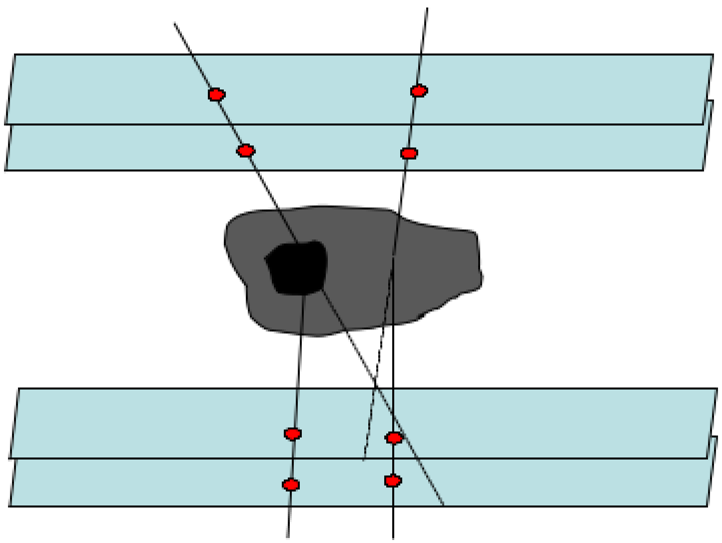
- *Only 2 such voids detected*
- *1st detection ever from outside of a deep structure*

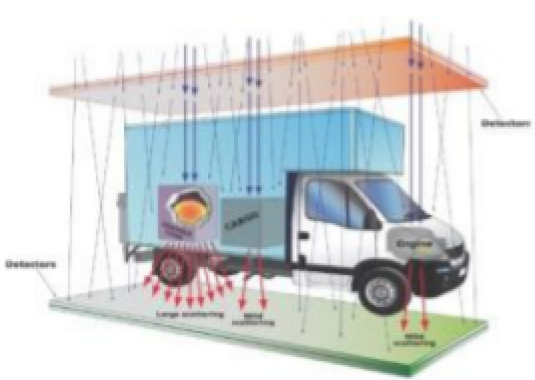


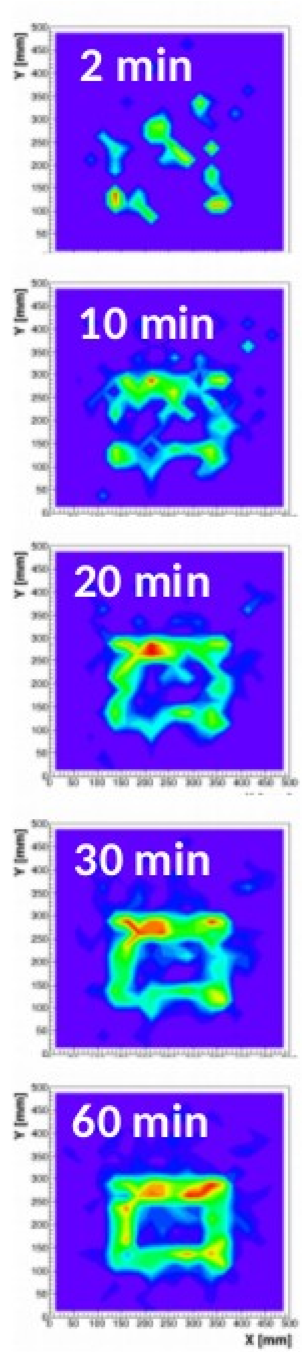


Muography

- Use cosmic muons to analyse truck, container....
- Multiple diffusion:
  - 2 detectors: deviation angle
  - fast (~mn), 3D,

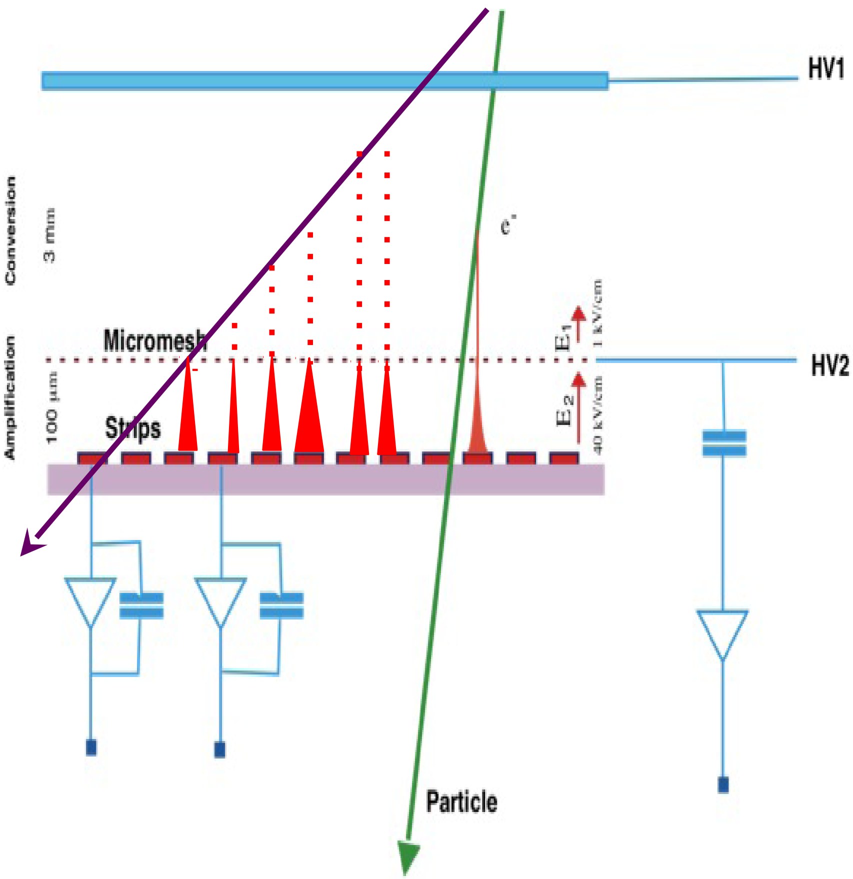


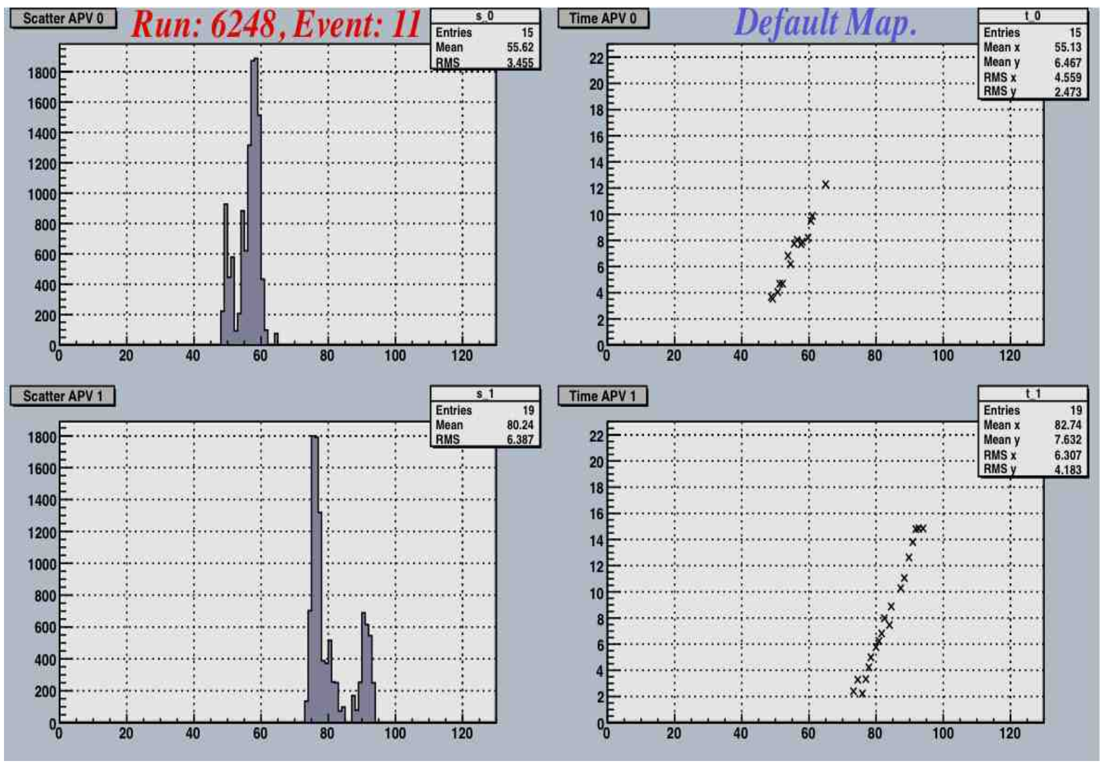




Micro-Megas: μTPC!!!!

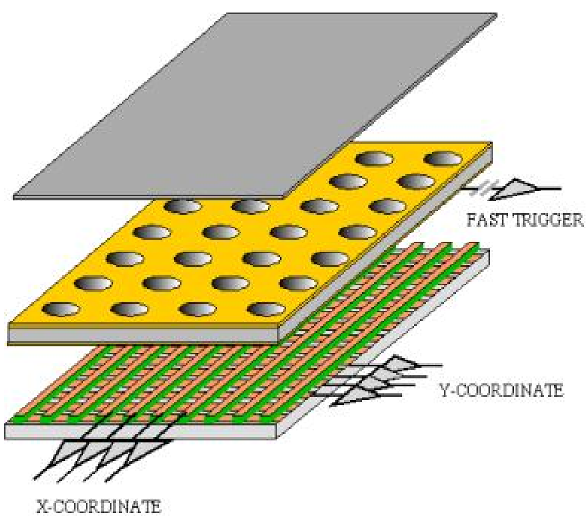
- ”Wide” drift region (typically a few mm)
- Electric field of 100–1000 V/cm
- 100 μm amplification gap with high electrical field (40–50 kV/cm)
    - a factor Em/Ed≈70–100 is required for full mesh transparency for electrons
- Drift velocities of 5 cm/μs (or 20 ns/mm) electrons need 100 ns for a 5 mm gap
- Adding the time arrival of the signals => TPC-like
- Track vectors for inclined tracks

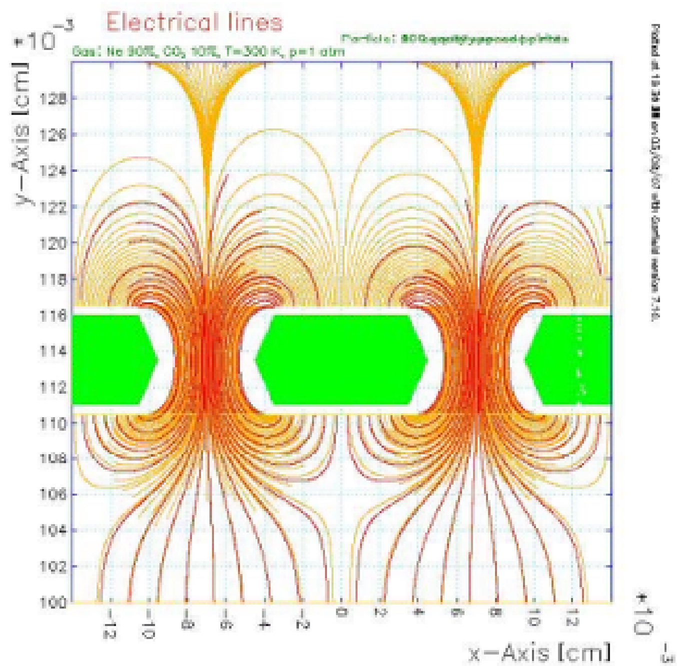


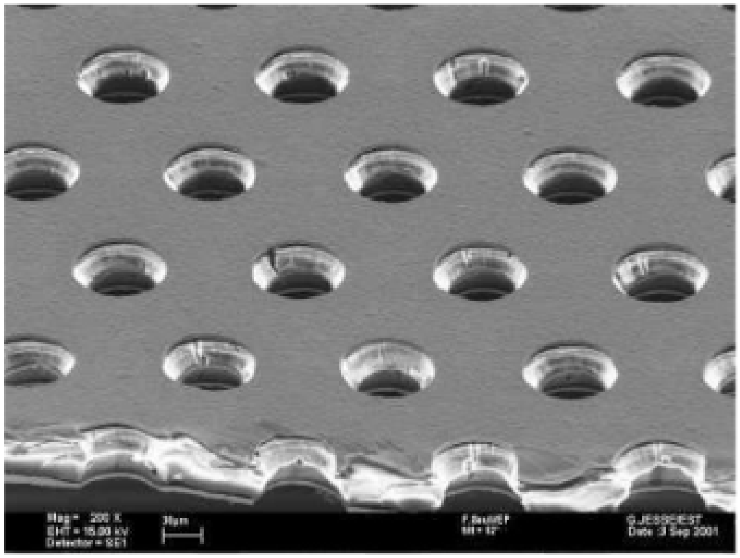


GEM: Gas Electron Multiplier

- F. Sauli at CERN, (R. Bouclier et al., NIM A 396 (1997) 50).
- Parallel plate structure with perforated Cu-clad Kapton foils.
- By applying a potential between conducting foil surfaces a strong electric field develops inside the holes
- Electron multiplication takes place in the field inside the holes
- Hole diameters are 70–120 μm
- Kapton foils are about 50 μm thick



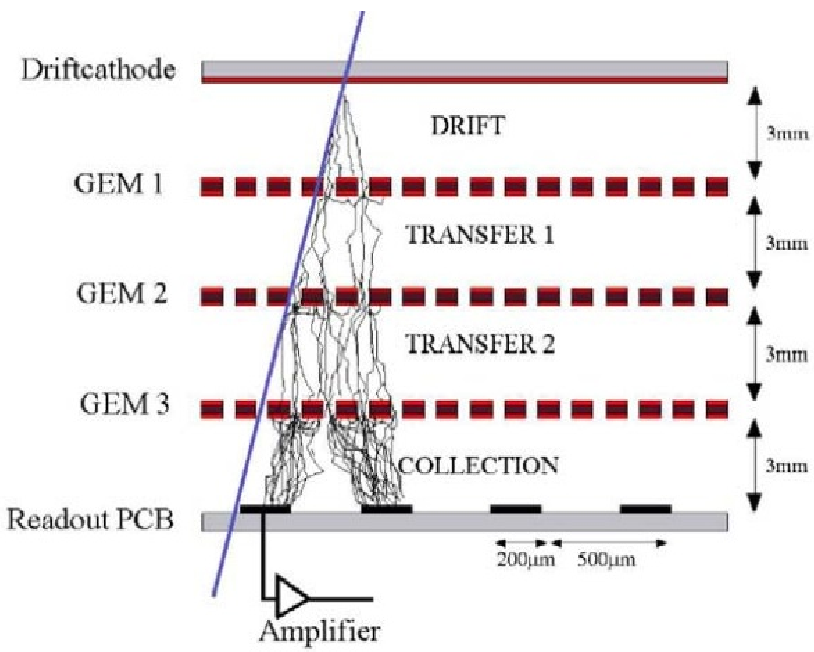




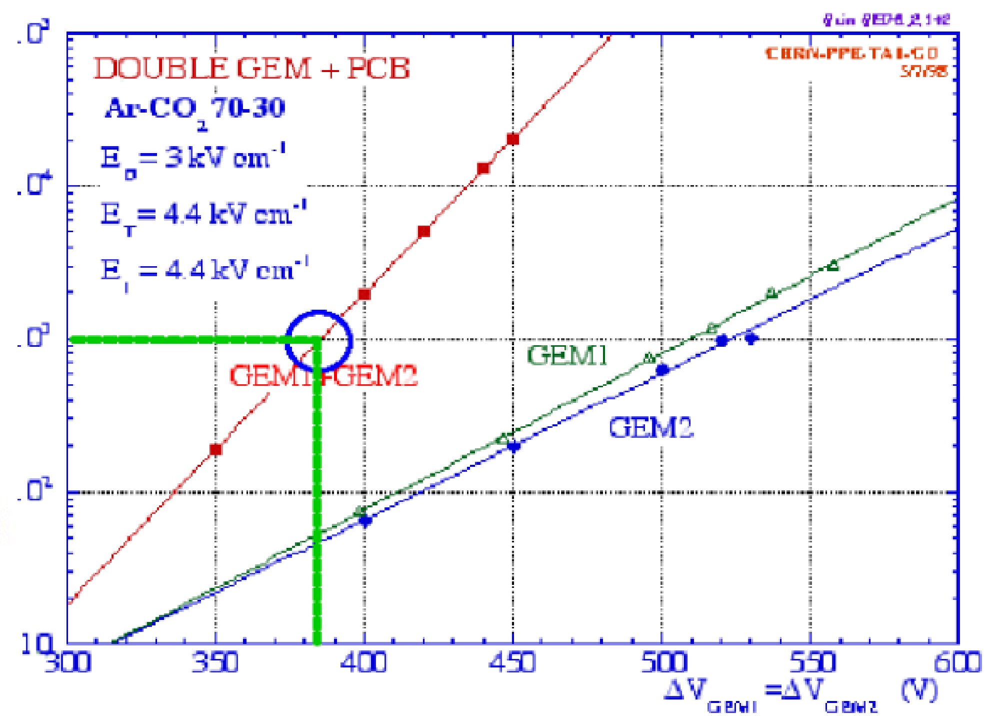
Detectors(Gaseous)

GEM: Gas Electron Multiplier

- Triple GEM
- Lower voltage for the same gain
- Less spark



Gain
~20
~20
~20
~8000

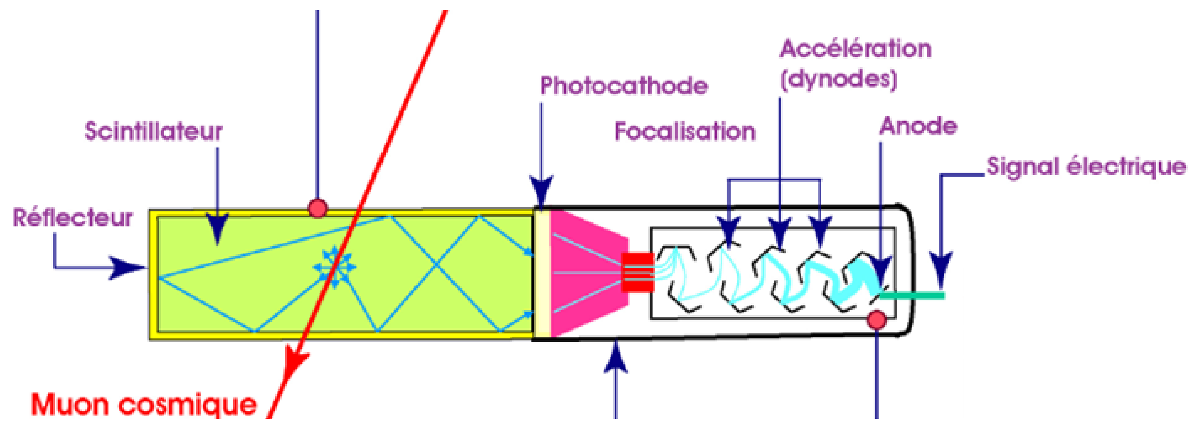


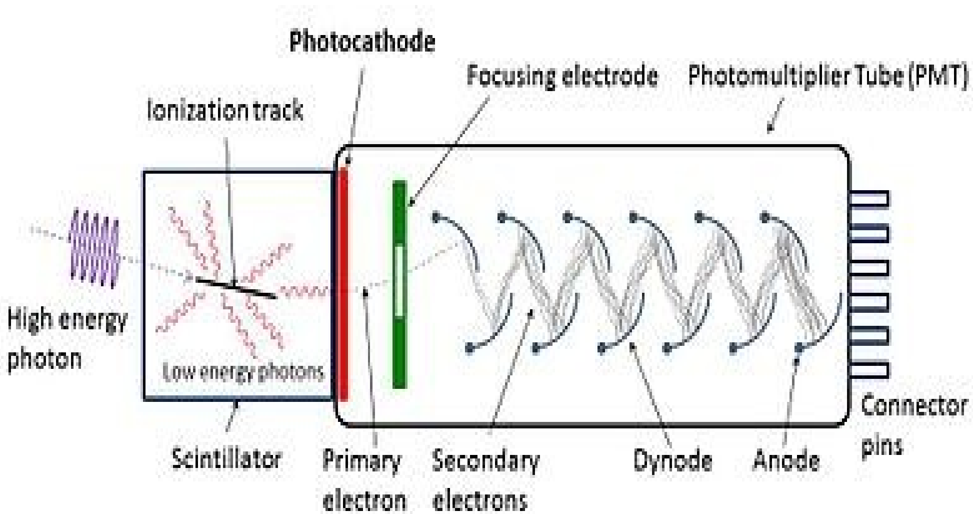
Detectors(Solid)

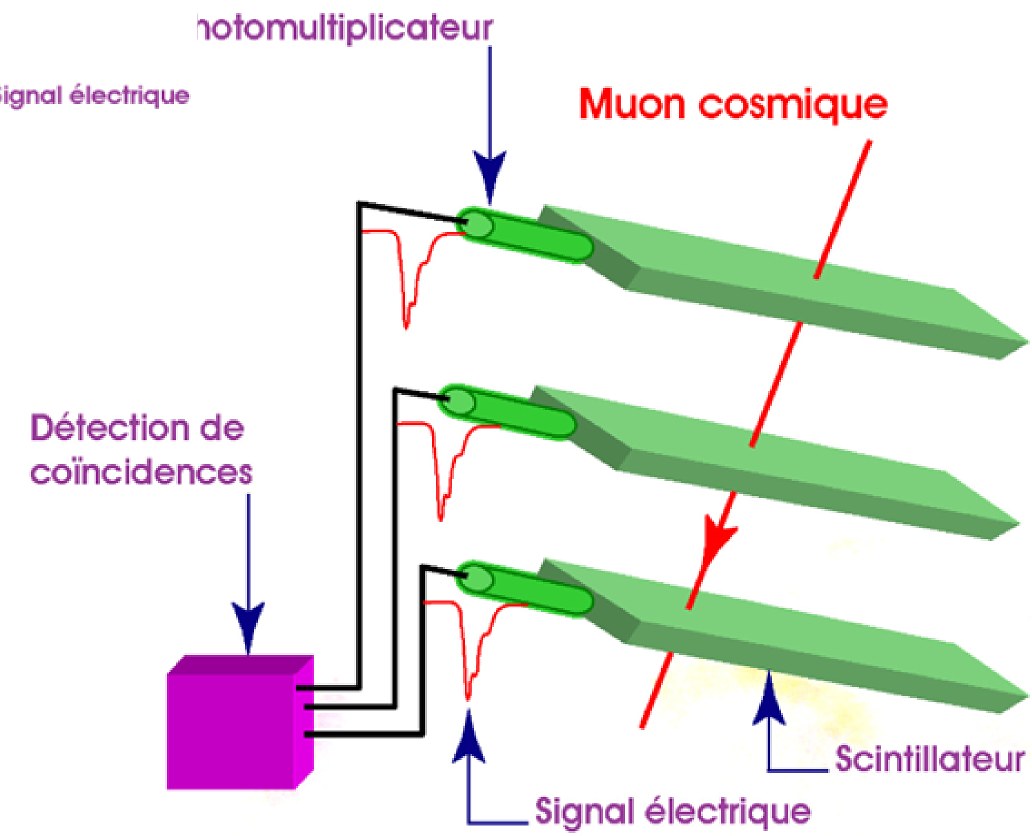
Detectors(Solid)

Scintillator

- Scintillation: atoms are excited by a muon
- Atoms are emitting photons which are detected by the photomultiplier.
- The scintillator is plastic (made from organic matter).



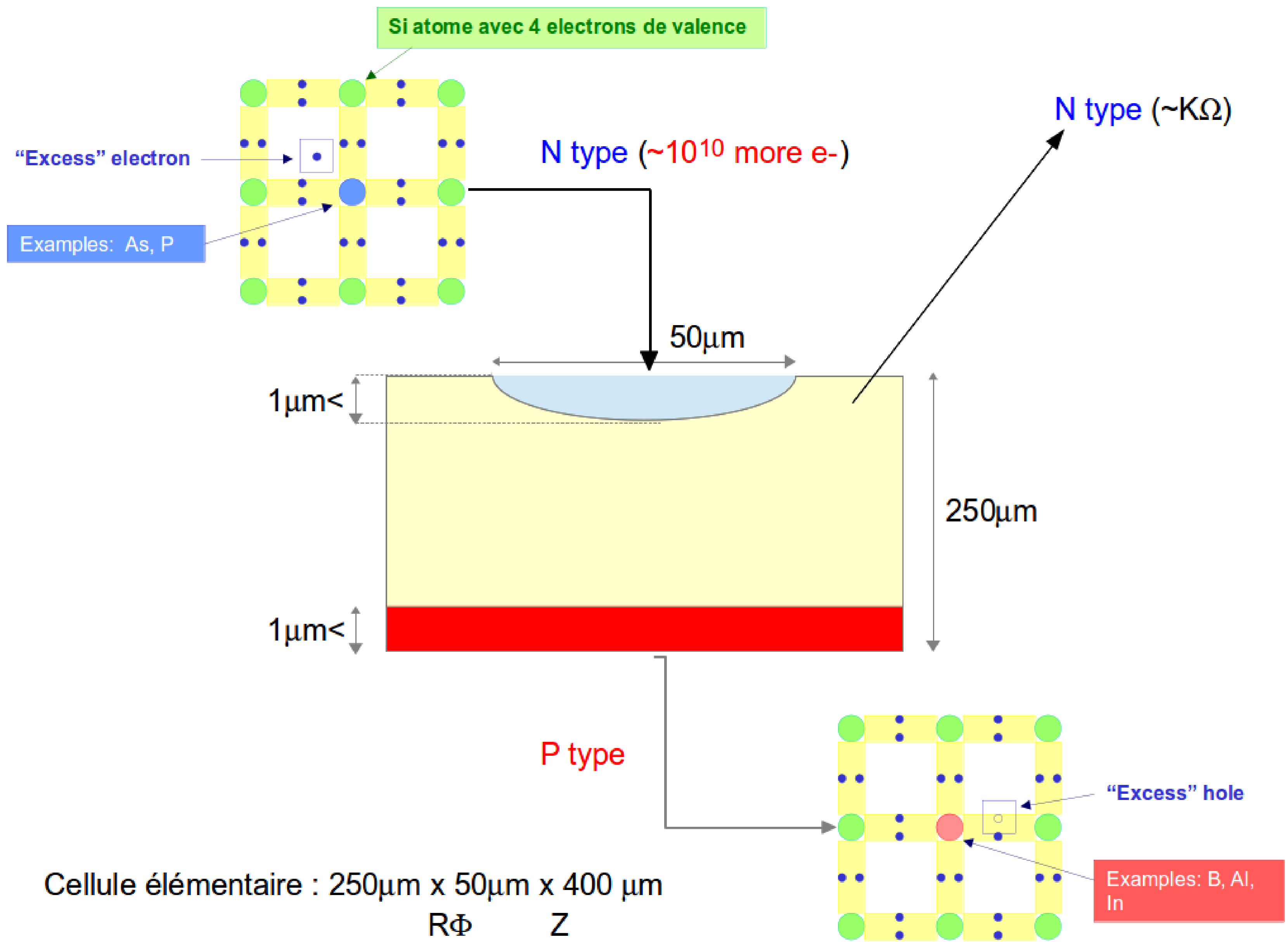




Detectors(Solid)

Silicon: Pixel

- Elementary cell



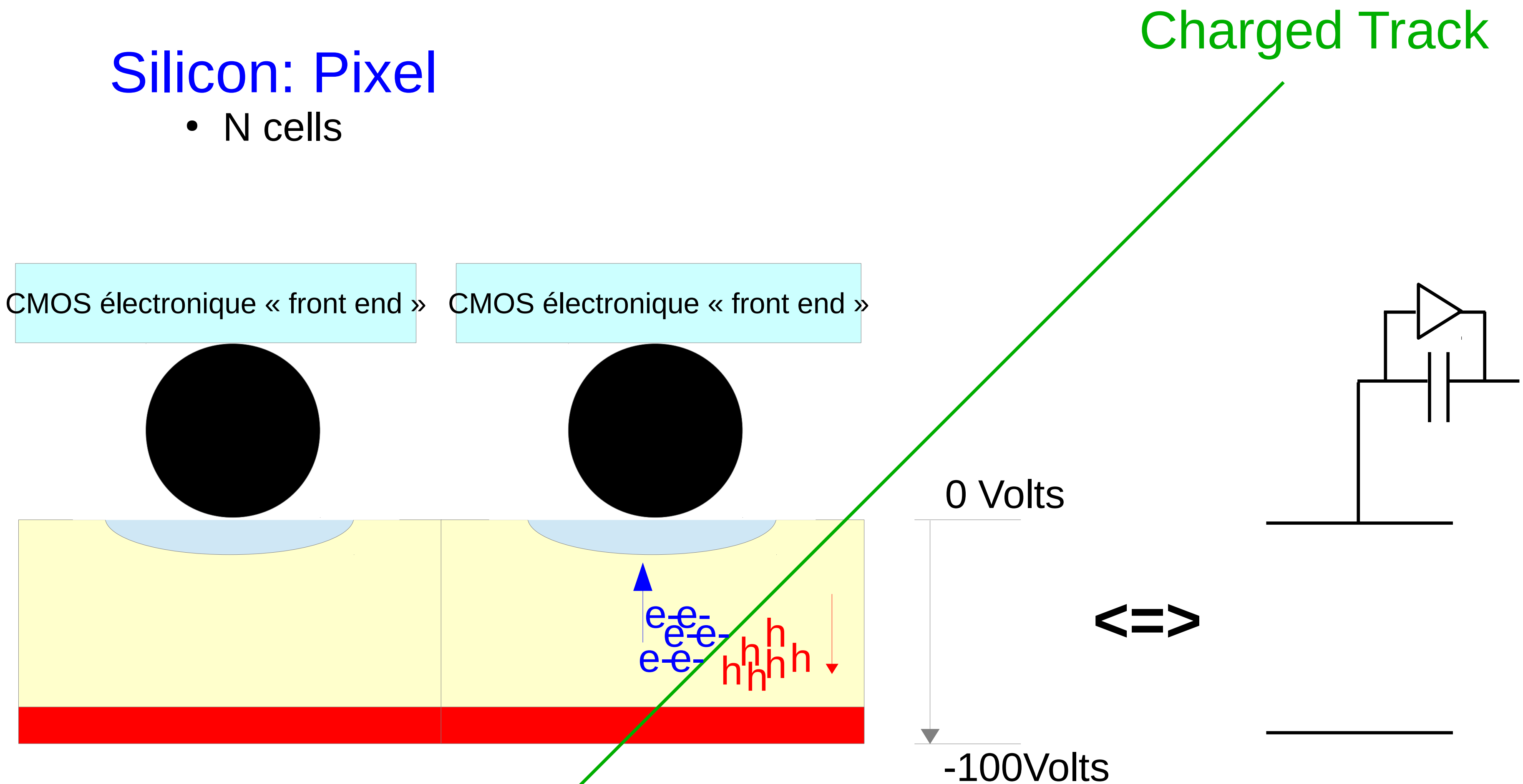
Cellule élémentaire : 250µm x 50µm x 400 µm

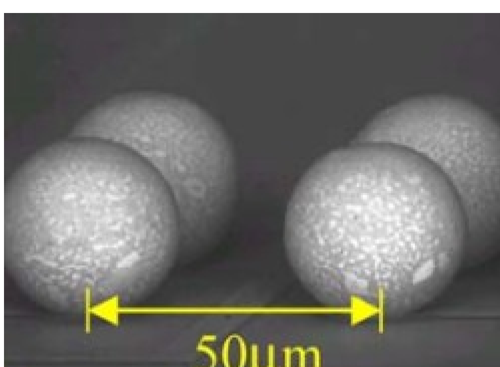
RΦ Z

Detectors(Solid)

Silicon: Pixel

- N cells



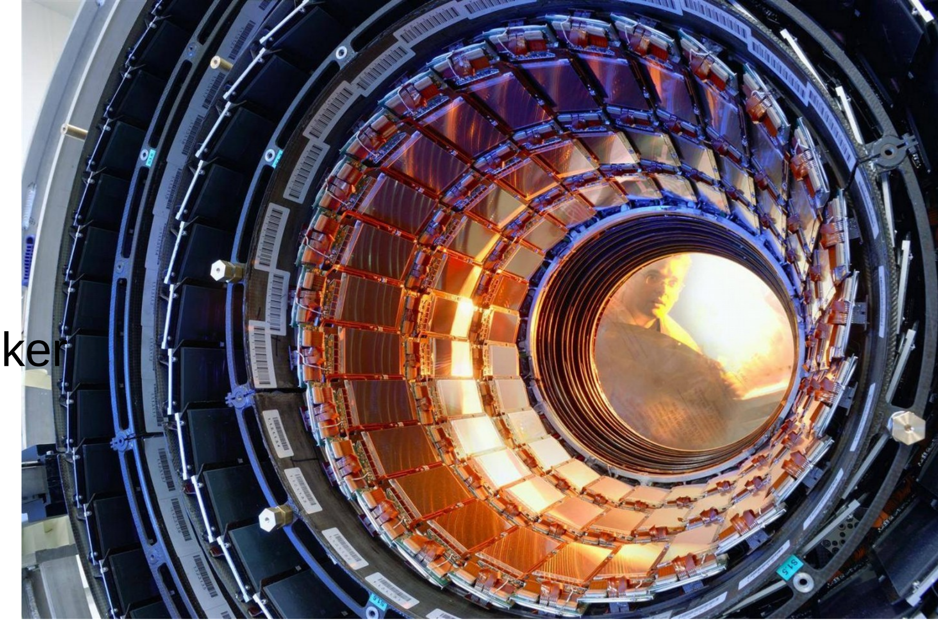


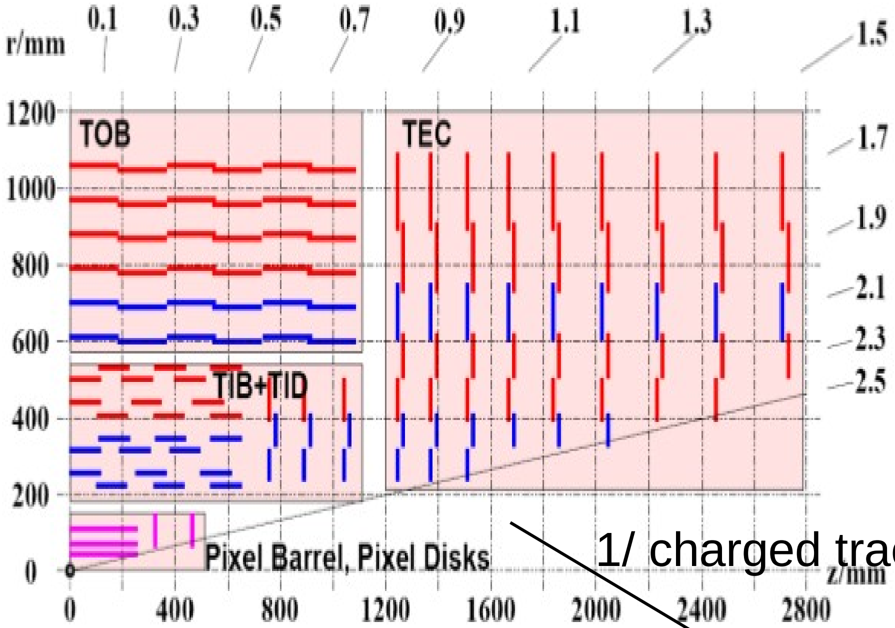
- ~20000 electrons per track
- Times electron collection ~ 5ns

Detectors(Solid)

Silicon Tracker: CMS

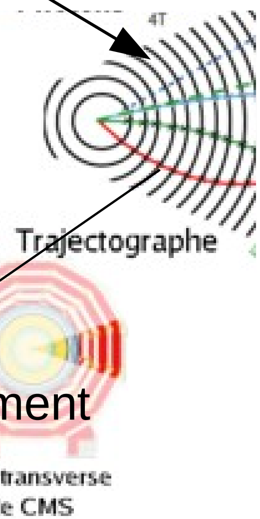
- 11 layers
- 200 m^2 of active silicon for CMS tracker

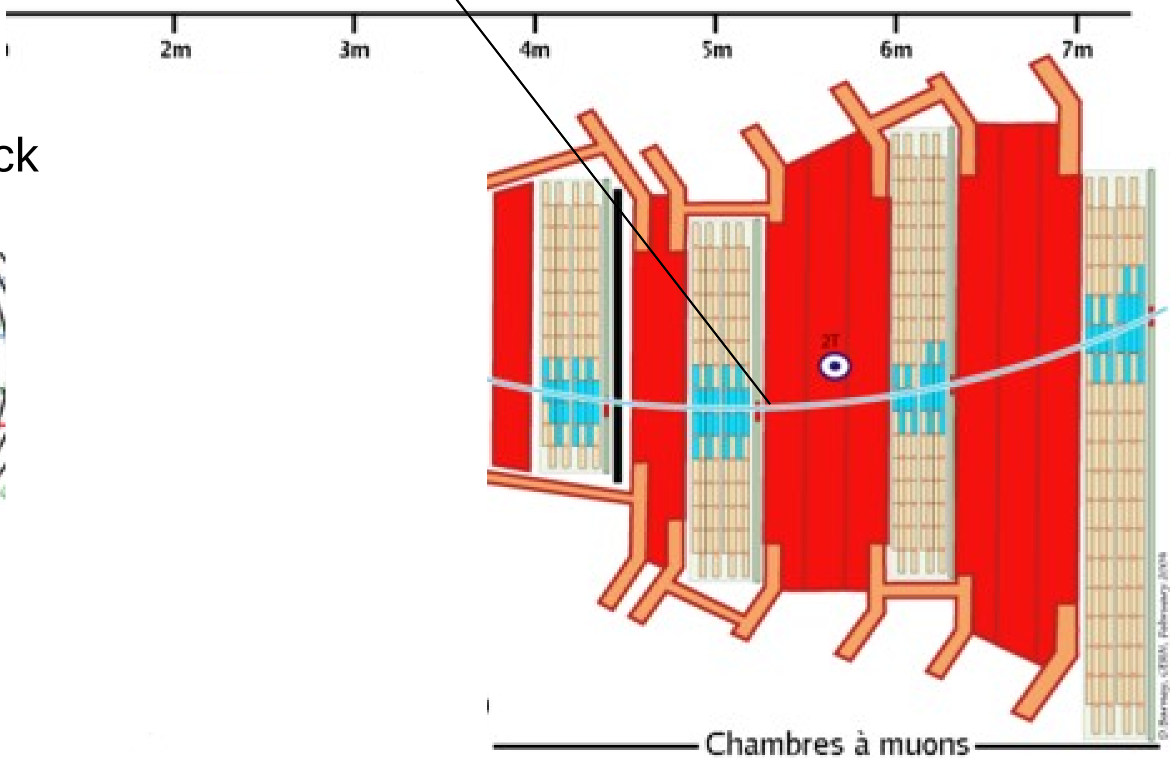




1/ charged track

2/ Muon confirmation





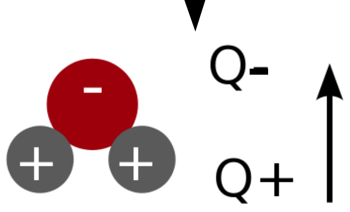
3/ Muon momentum measurement

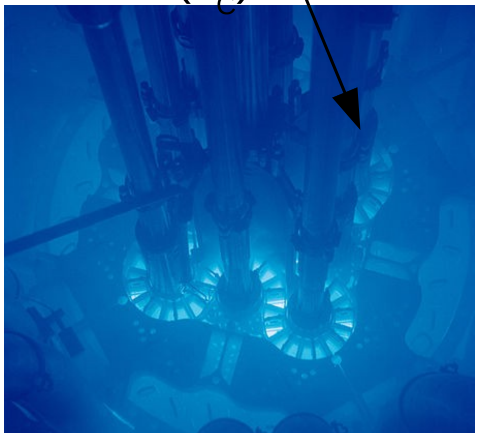
Detectors(Liquid)

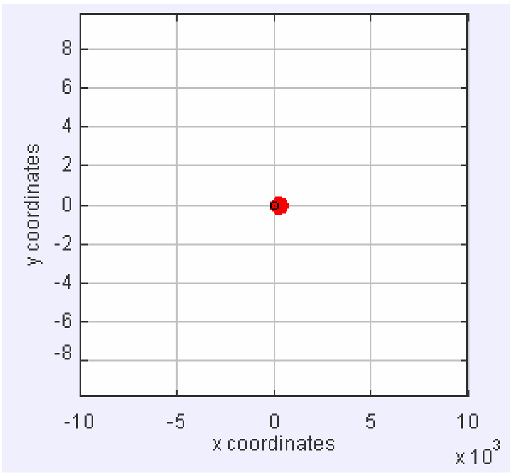
Detectors(Liquid)

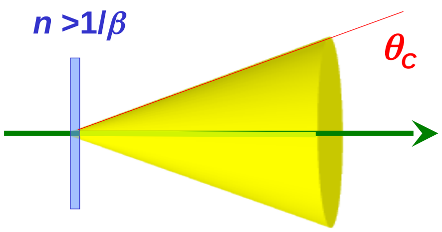
Cherenkov radiation: Photo Multiplier (PM)

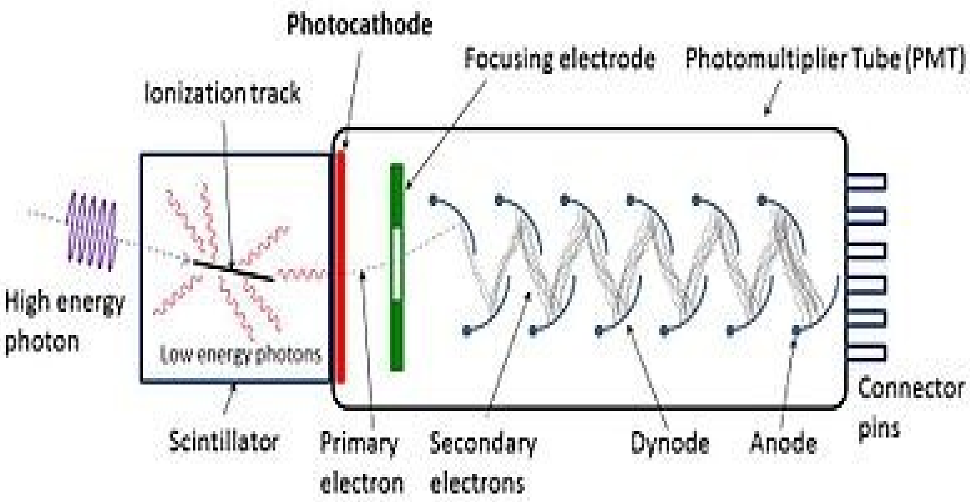
- Relativistic charged particles through a medium of refractive index $n > 1 / \beta$
- Relativistic means that the particle moves faster than the light in the medium
- Cherenkov radiation is tangent to a cone θ_c around the trace: $\cos(\theta_c) = 1 / n\beta$
  - Radiation is due to the polarization of the medium and a dynamic variation of the dipole moment of the molecules of the medium (ie water)
  - Number of photons (Frank-Tamm) is proportional to $Z^2 \sin^2(\theta_c)$







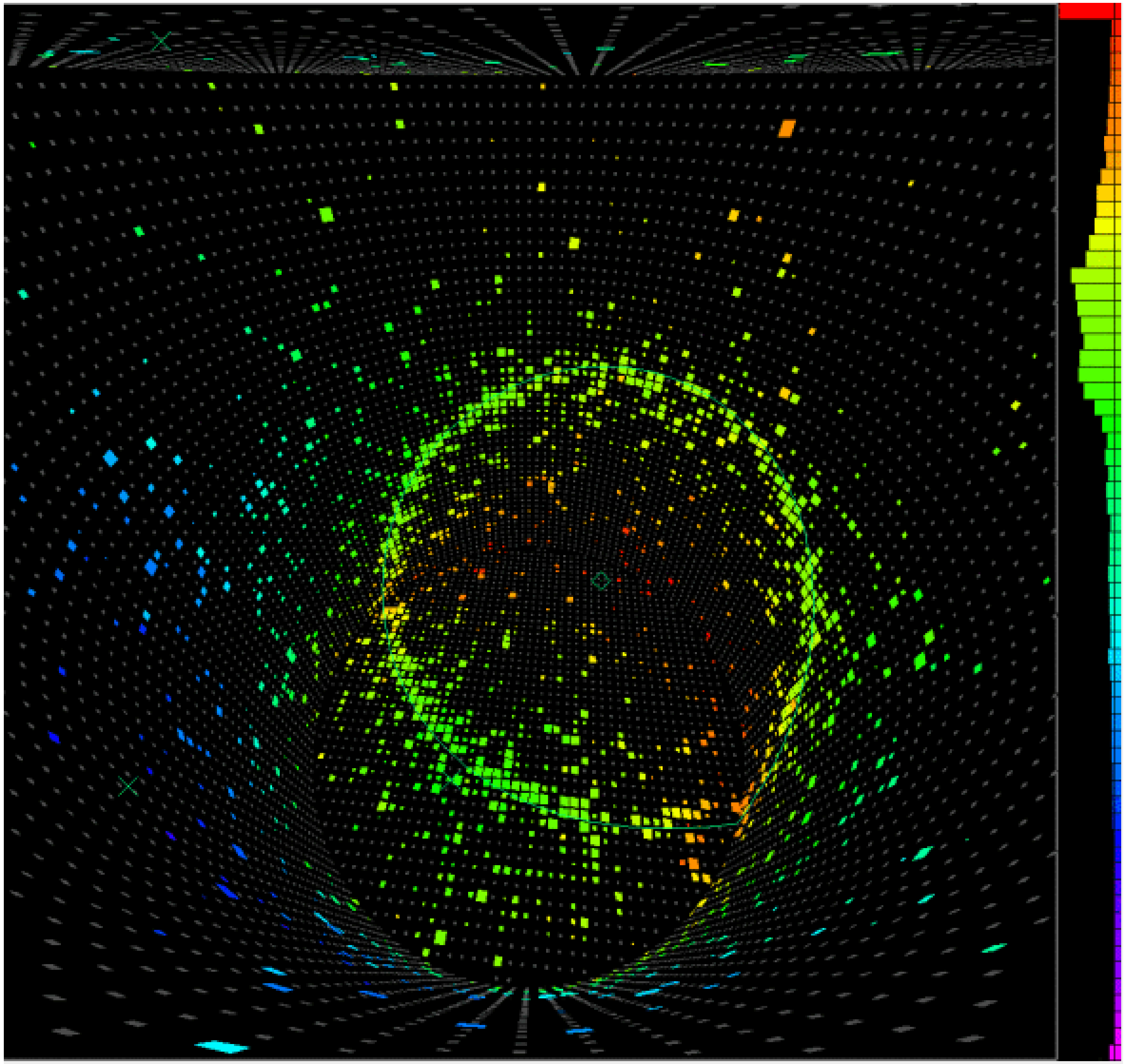




Detectors(Liquid)

Photo Multiplier: Cherenkov radiation

- Mini-Boon

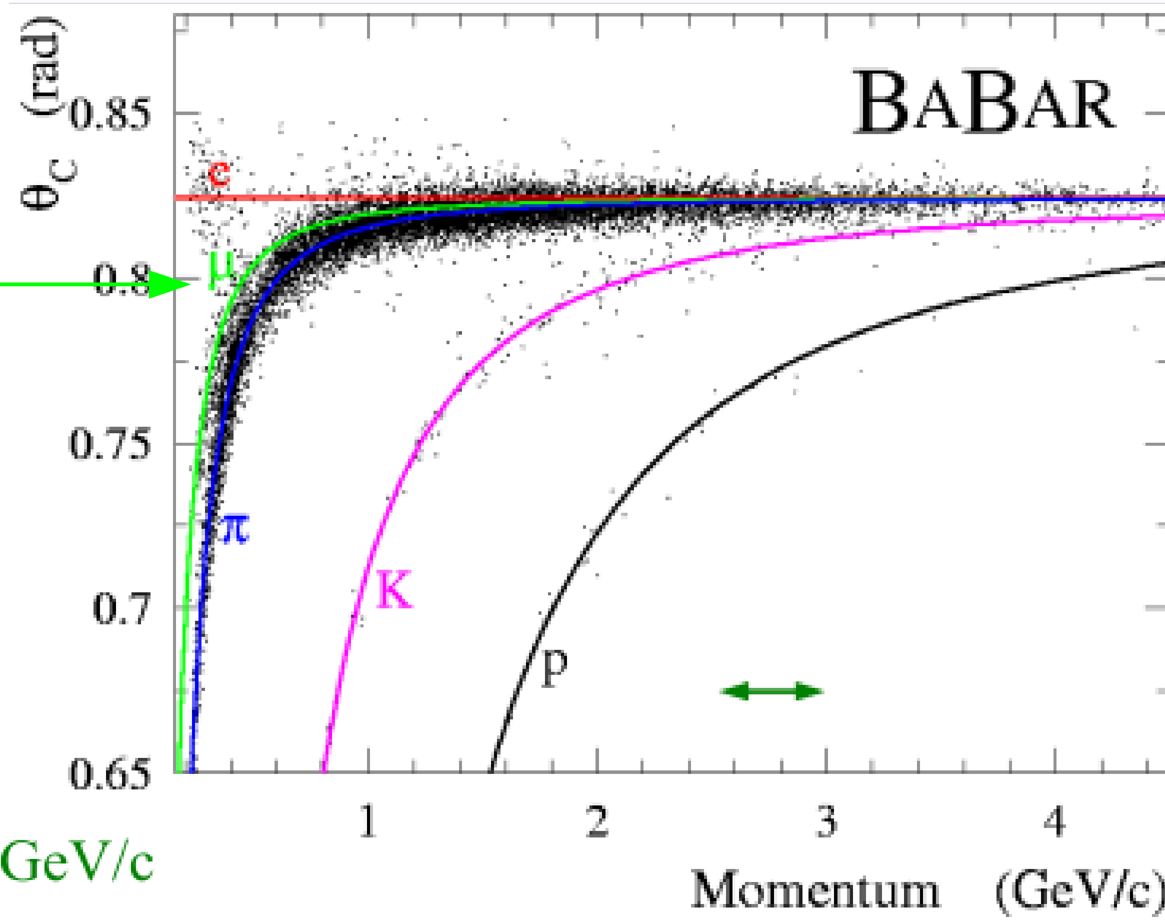


Detectors(Liquid)

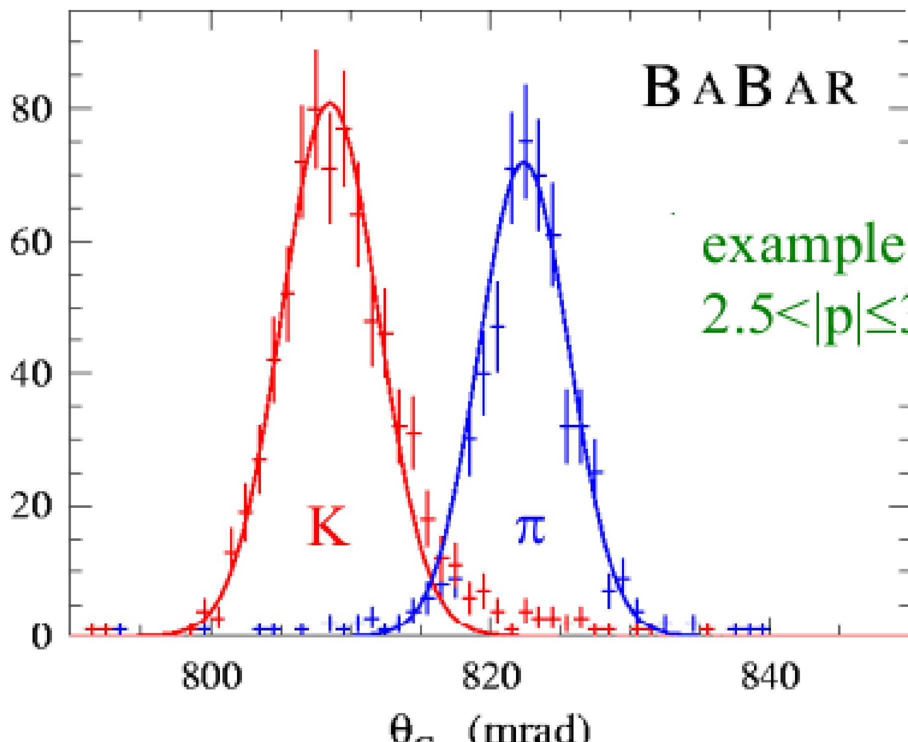
Photo Multiplier: Cherenkov radiation

- Babar identification

Muon



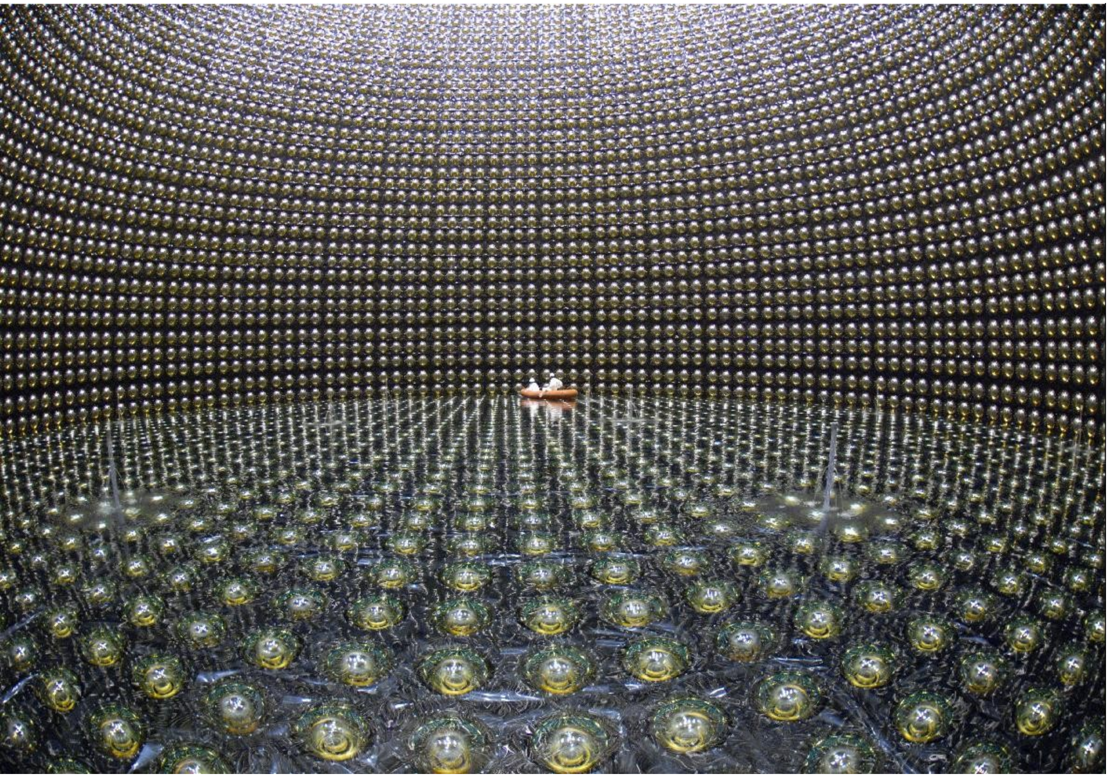
example:
2.5<|p|≤3GeV/c

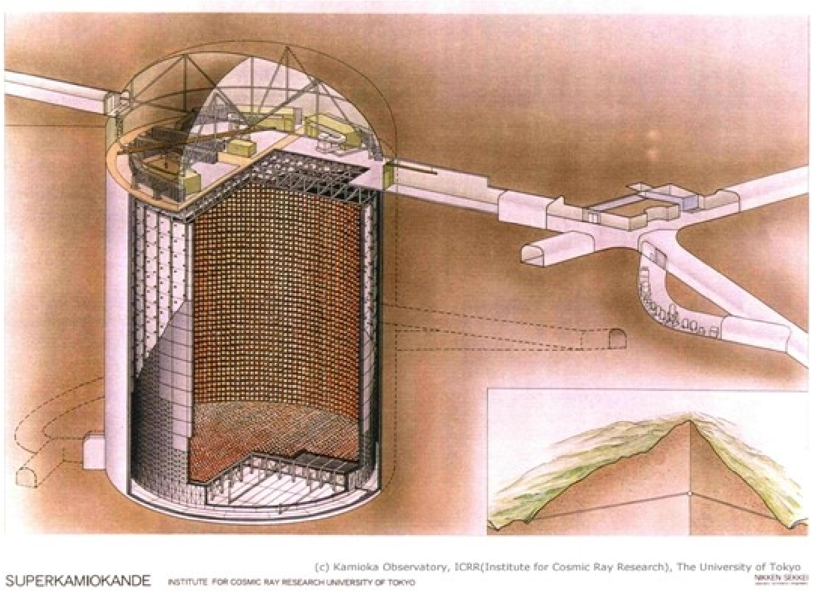


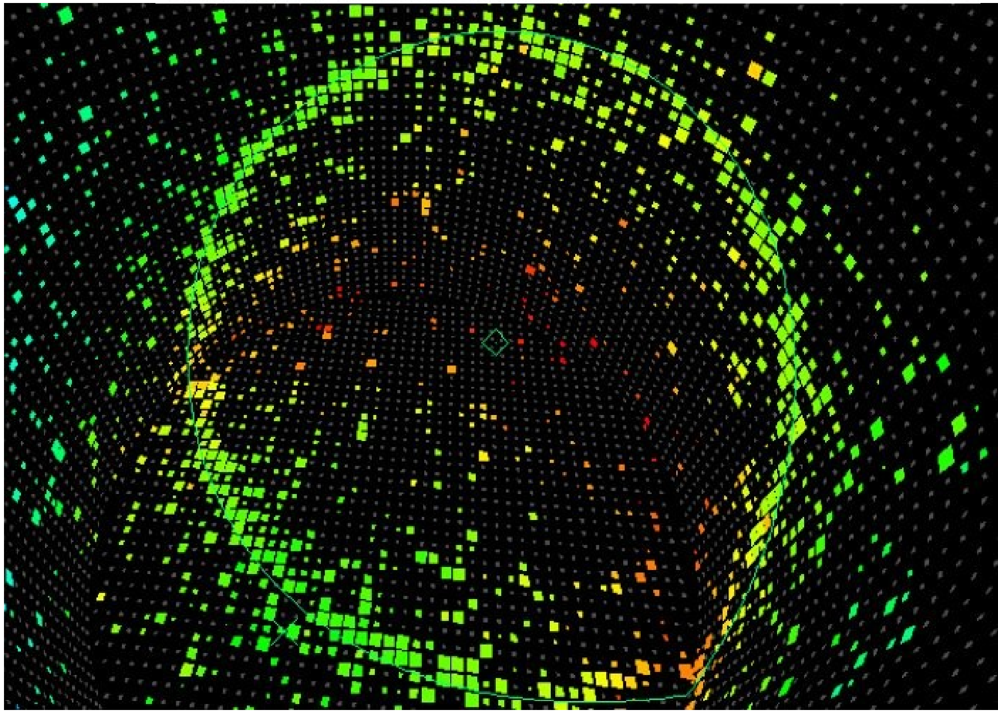
Detectors(Liquid)

Photo Multiplier: Cherenkov radiation

- T2K





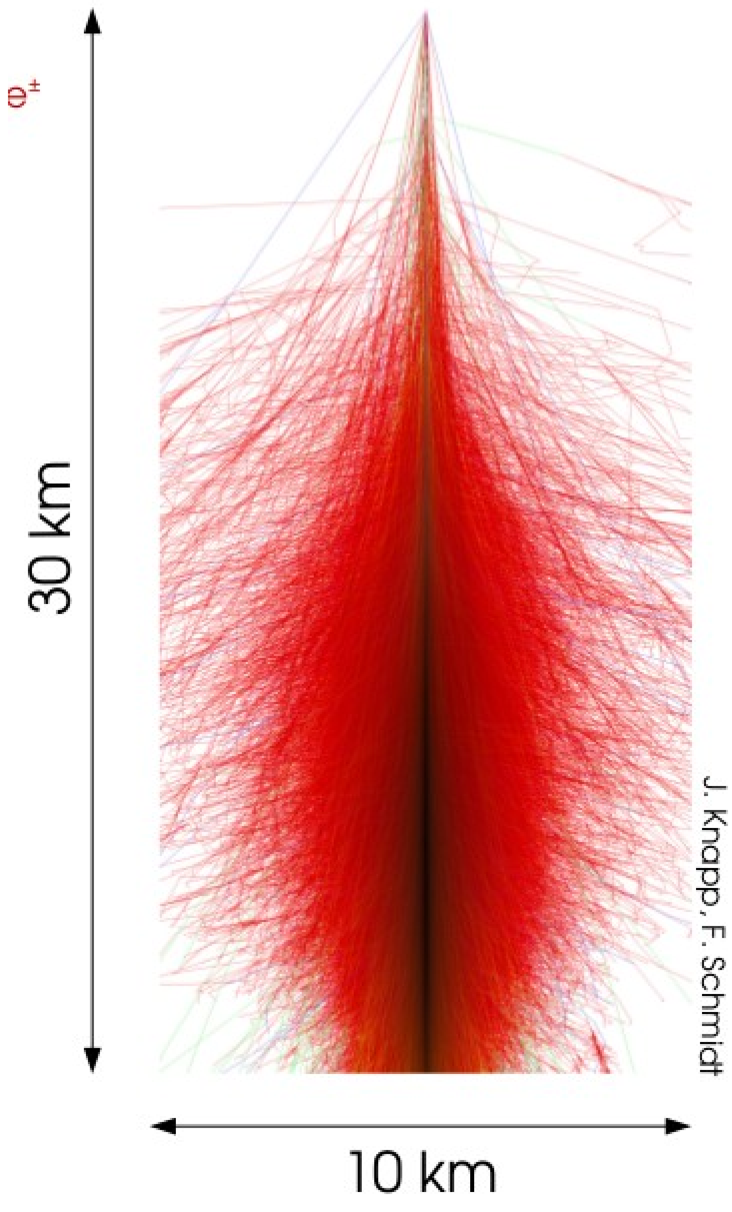


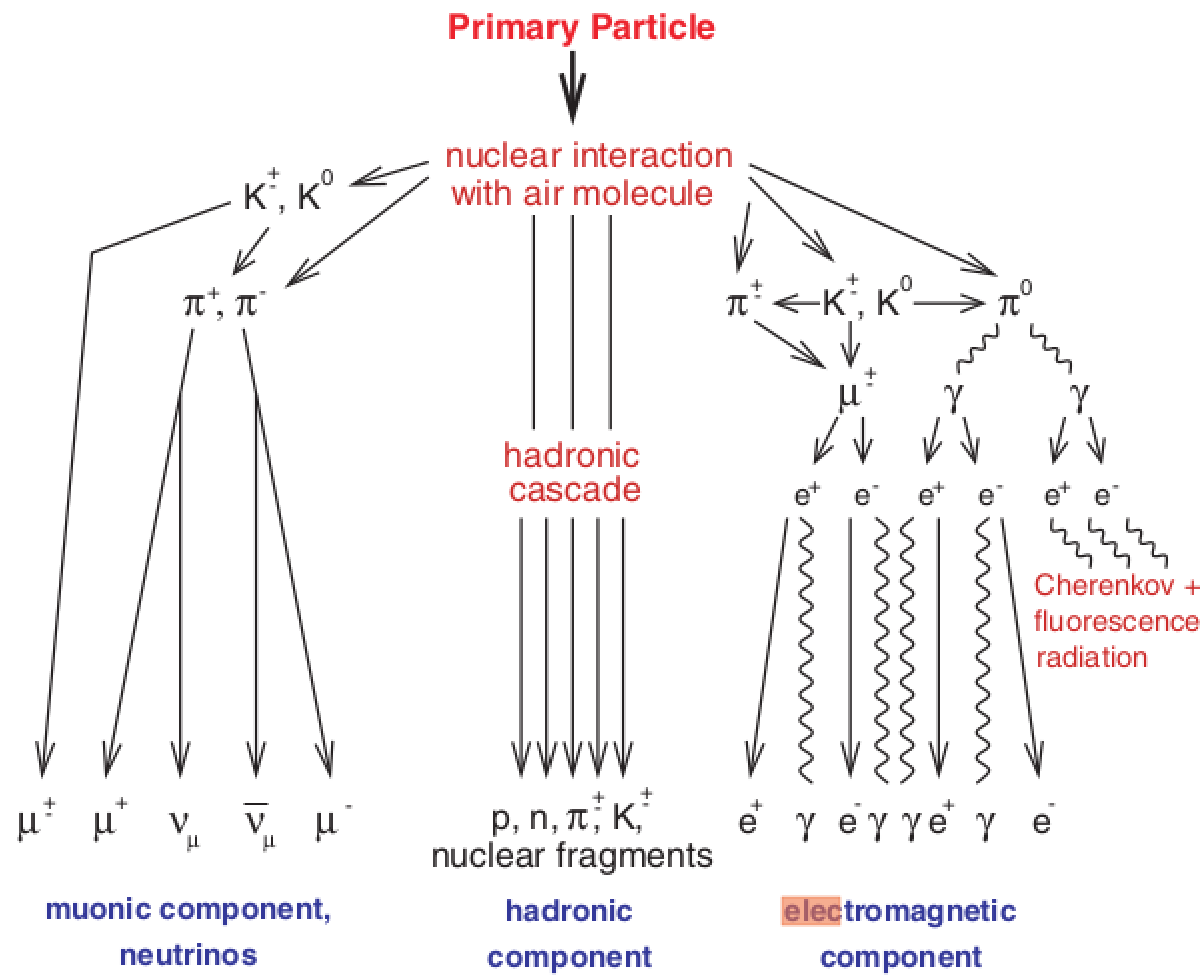
Detectors(Liquid)

Francois Montanet
Experimental astroparticle physics

Photo Multiplier: Cherenkov radiation

- Back to Cosmics



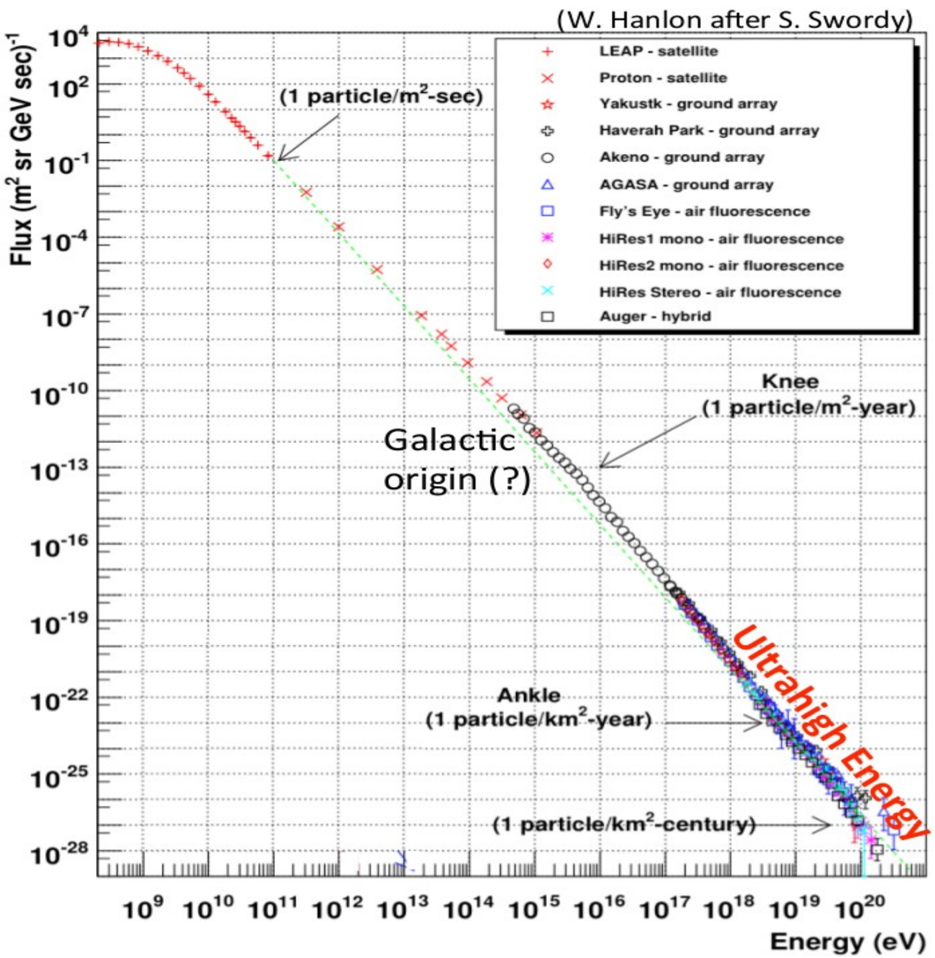


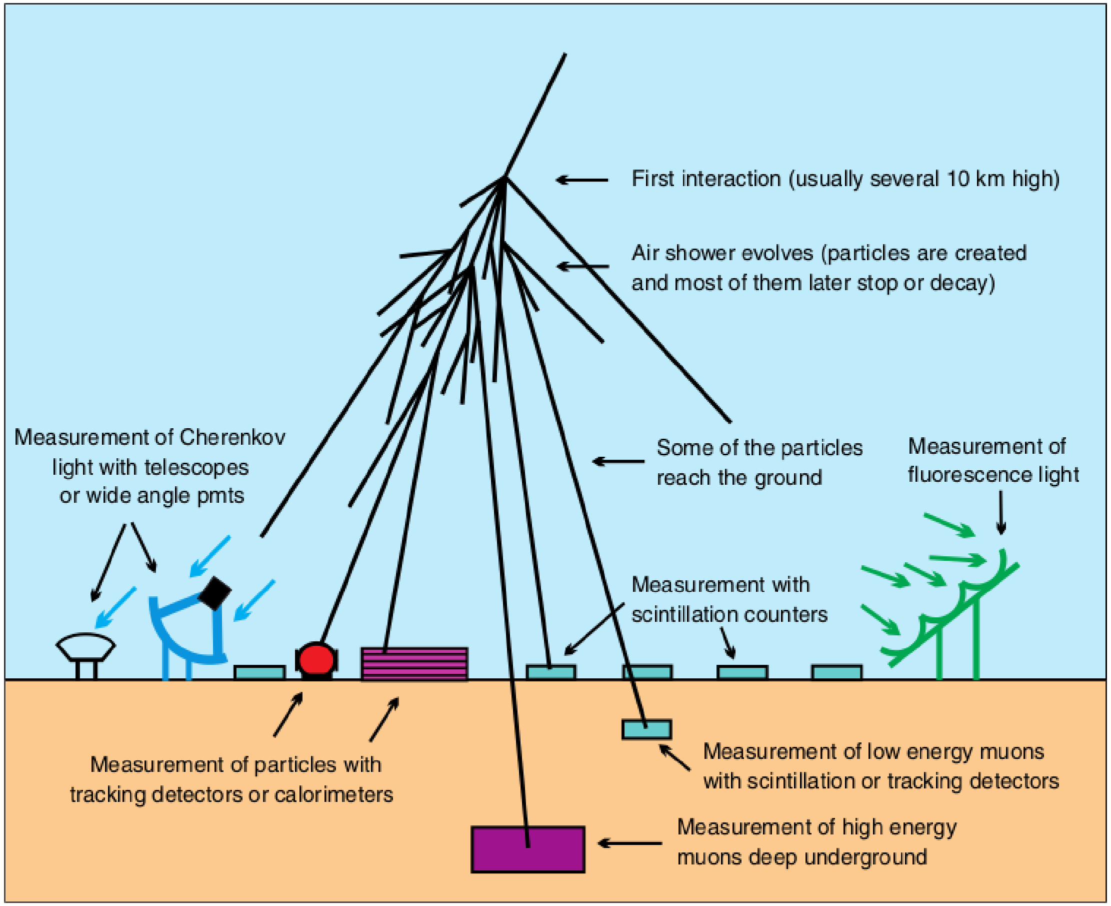
Detectors(Liquid)

Francois Montanet
Experimental Astroparticle Physics

Photo Multiplier: Cherenkov radiation

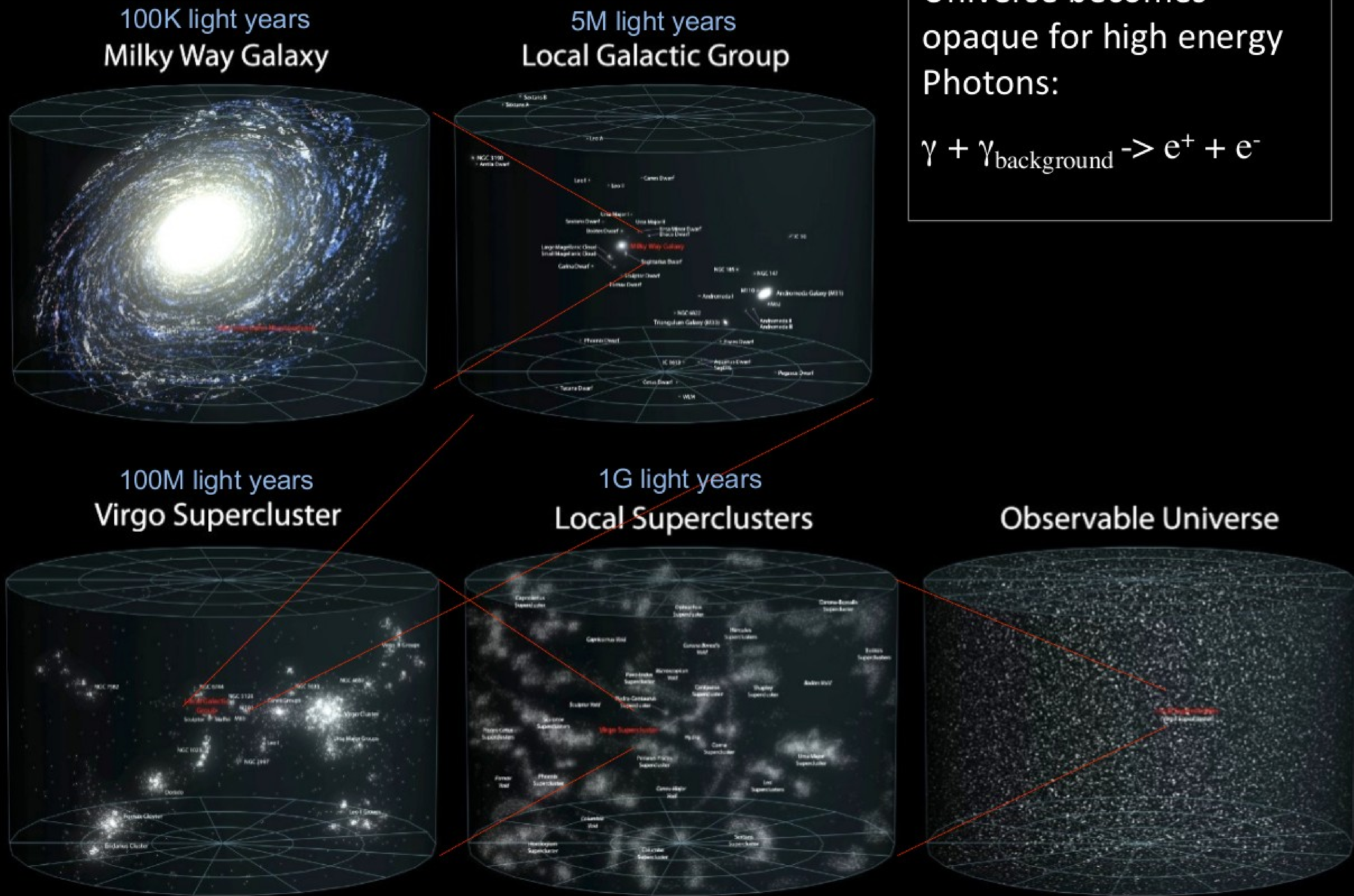
- Back to Cosmics

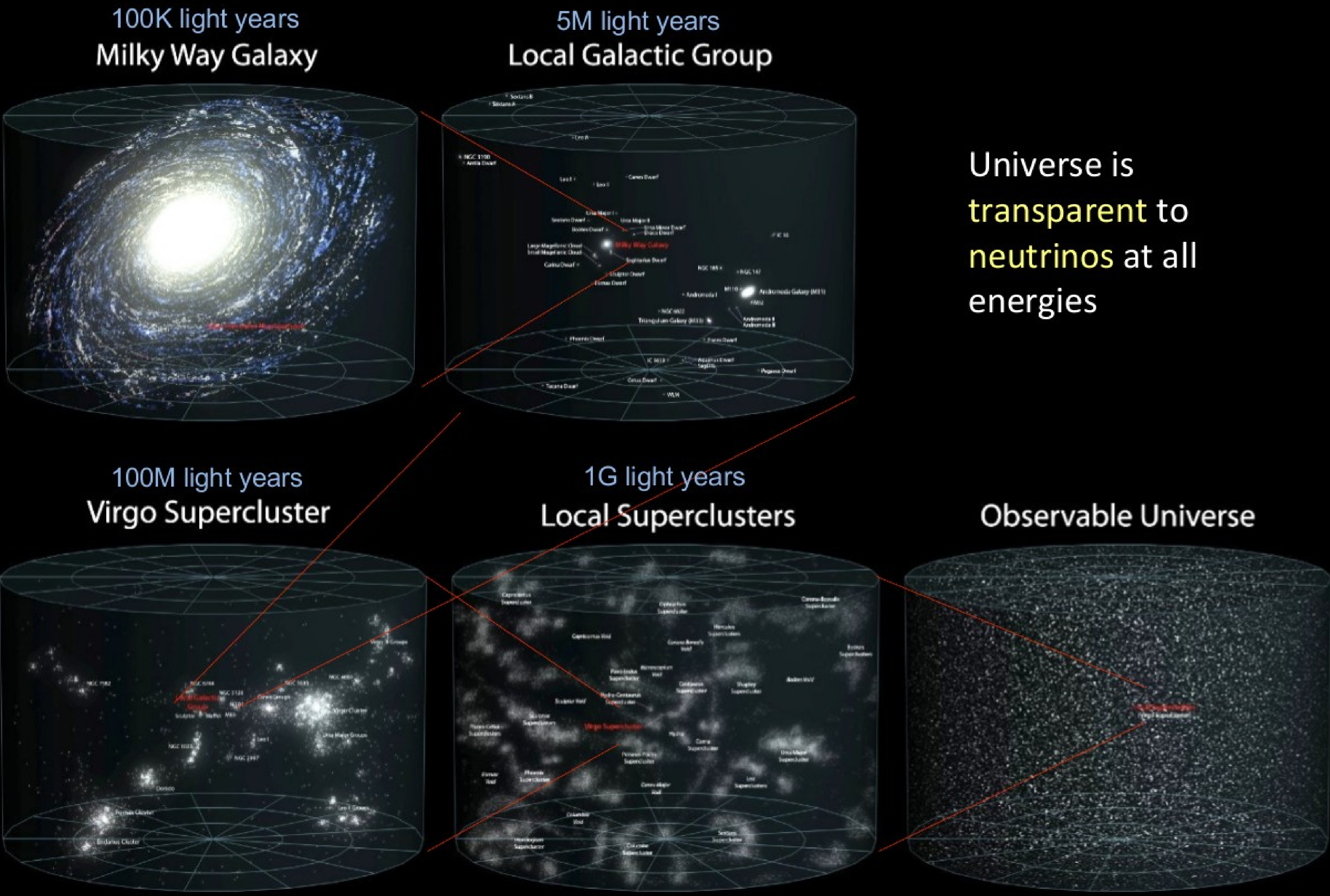




Universe becomes opaque for high energy Photons:

$\gamma + \gamma_{background} \rightarrow e^{+} + e^{-}$



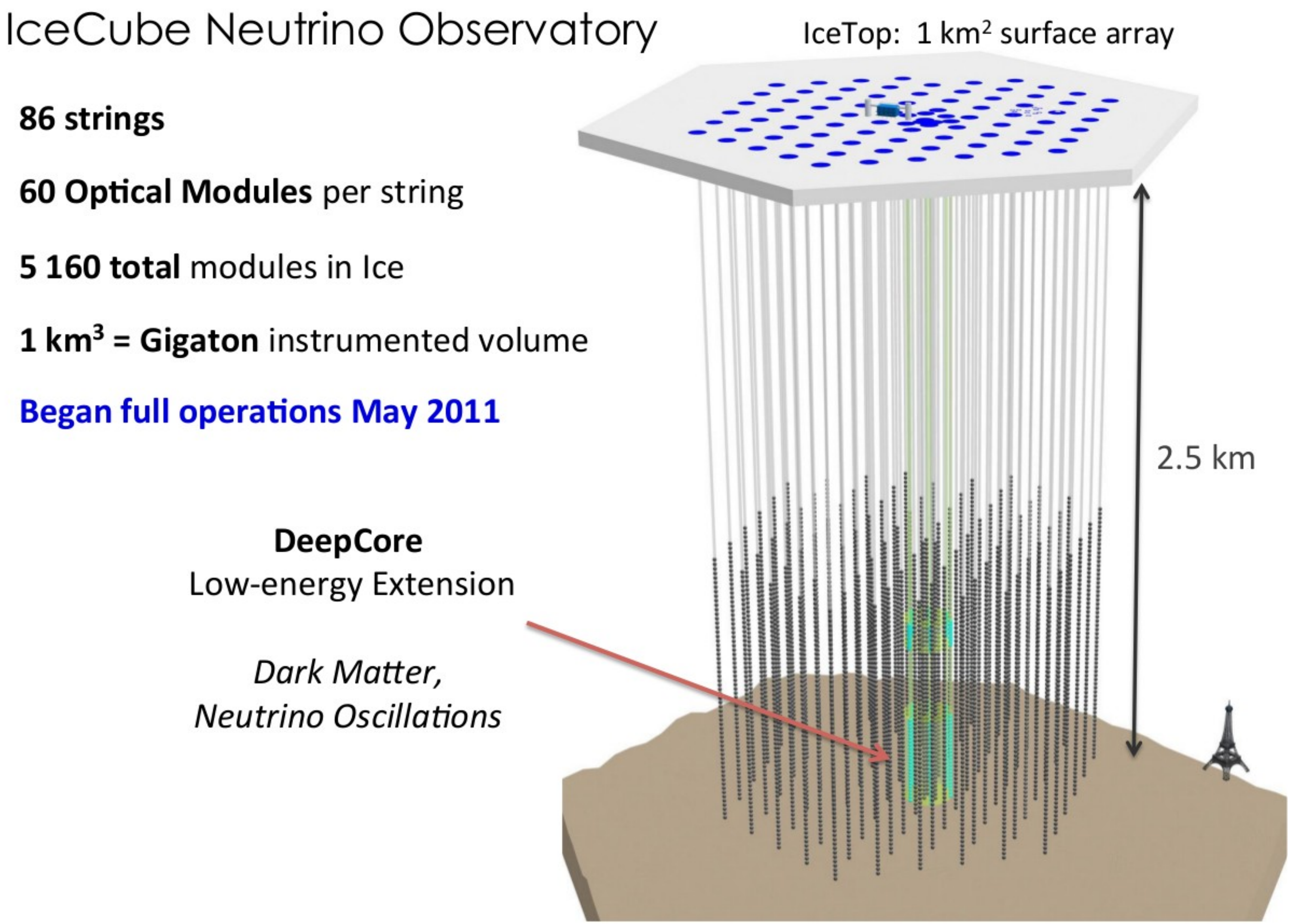


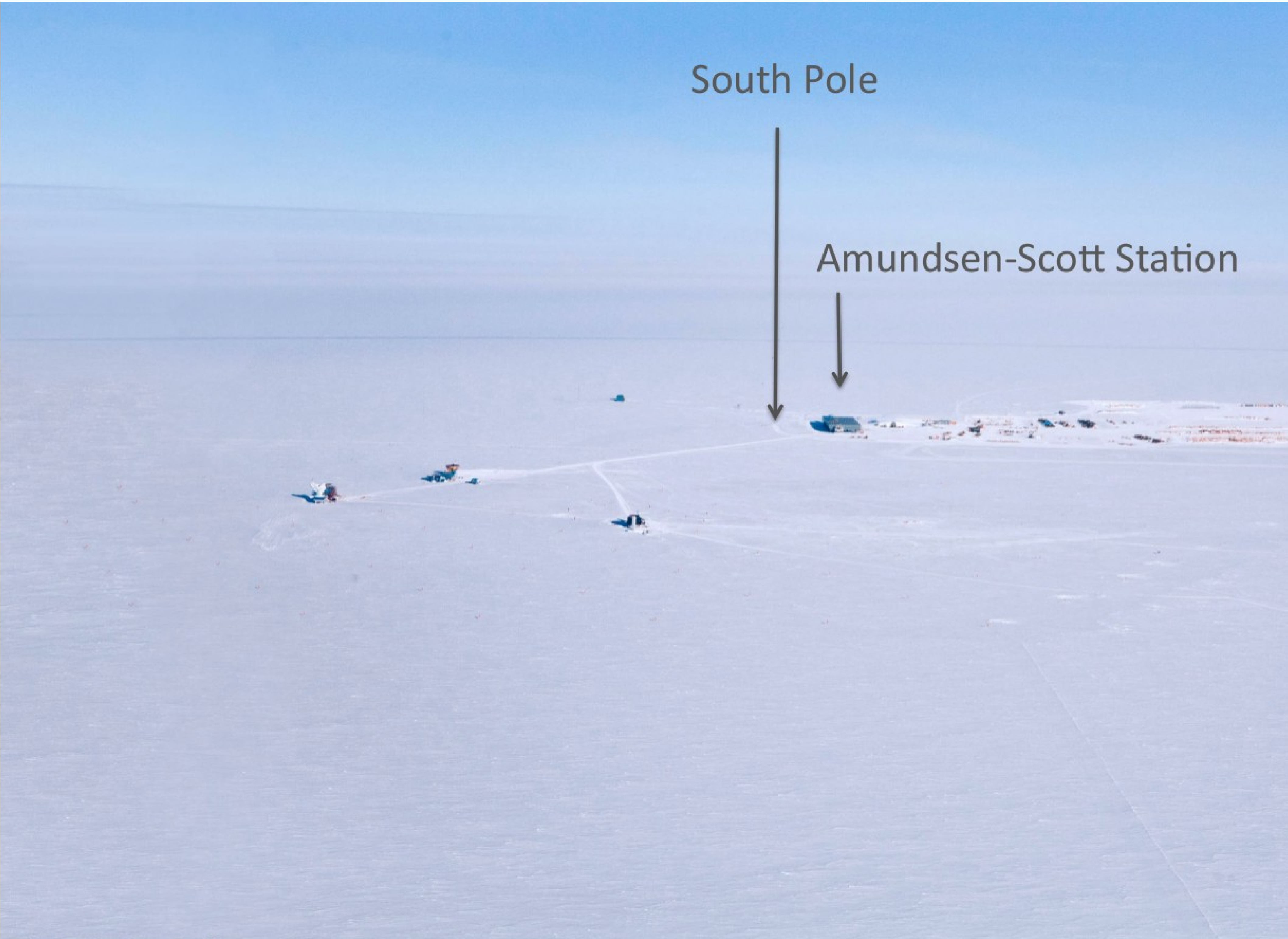
Universe is transparent to neutrinos at all energies

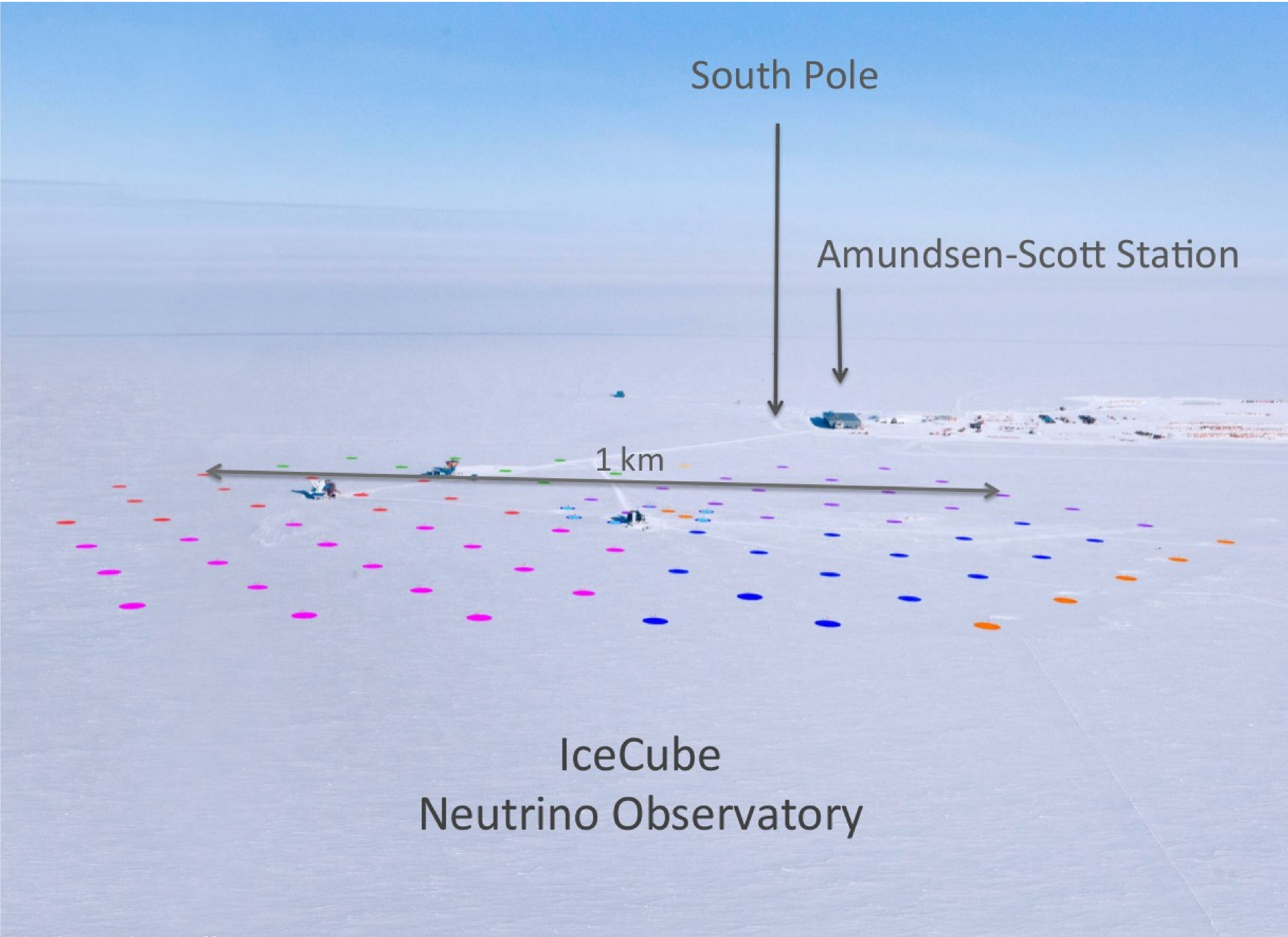
Detectors(Liquid)

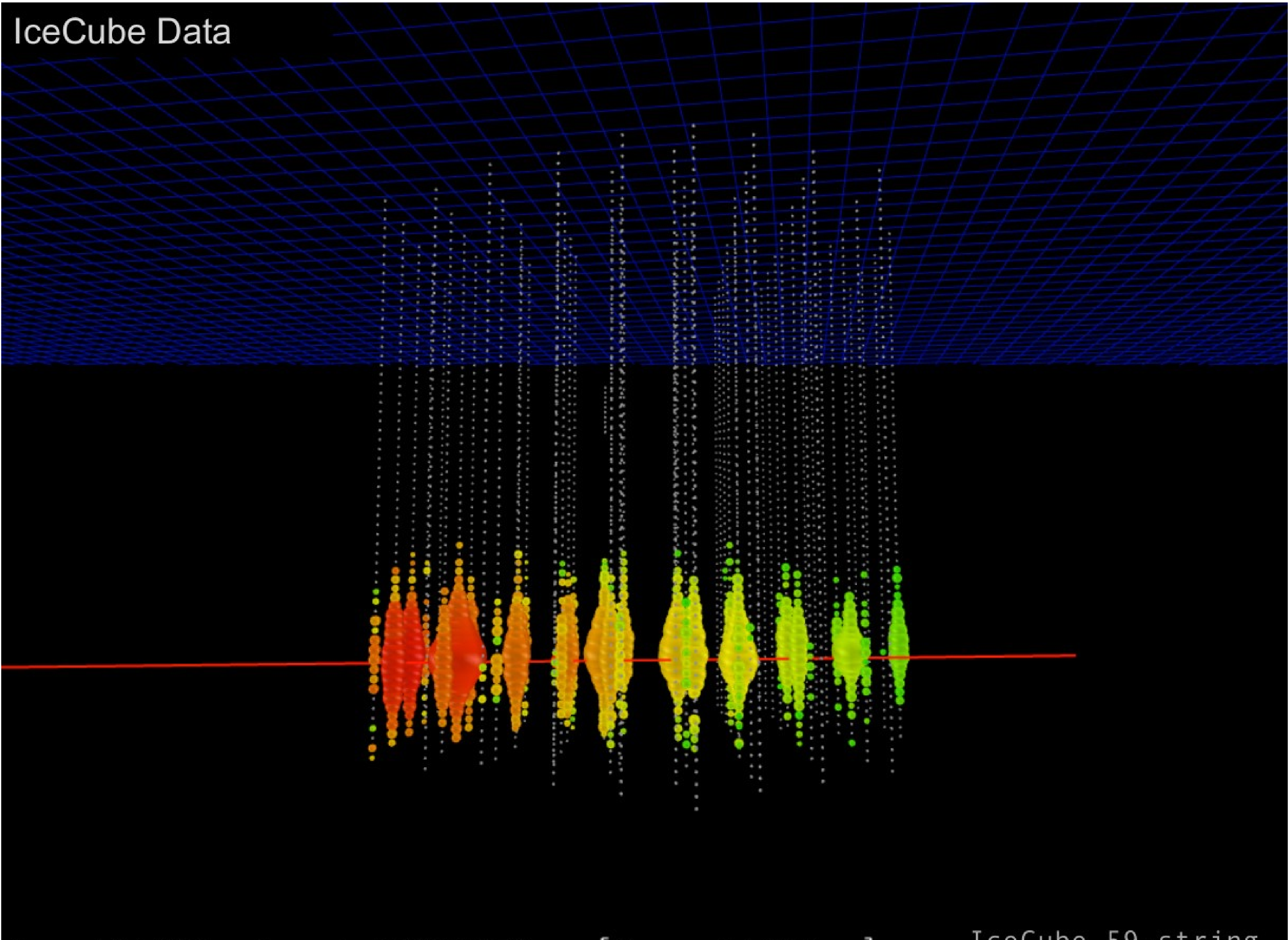
Photo Multiplier: Cherenkov radiation

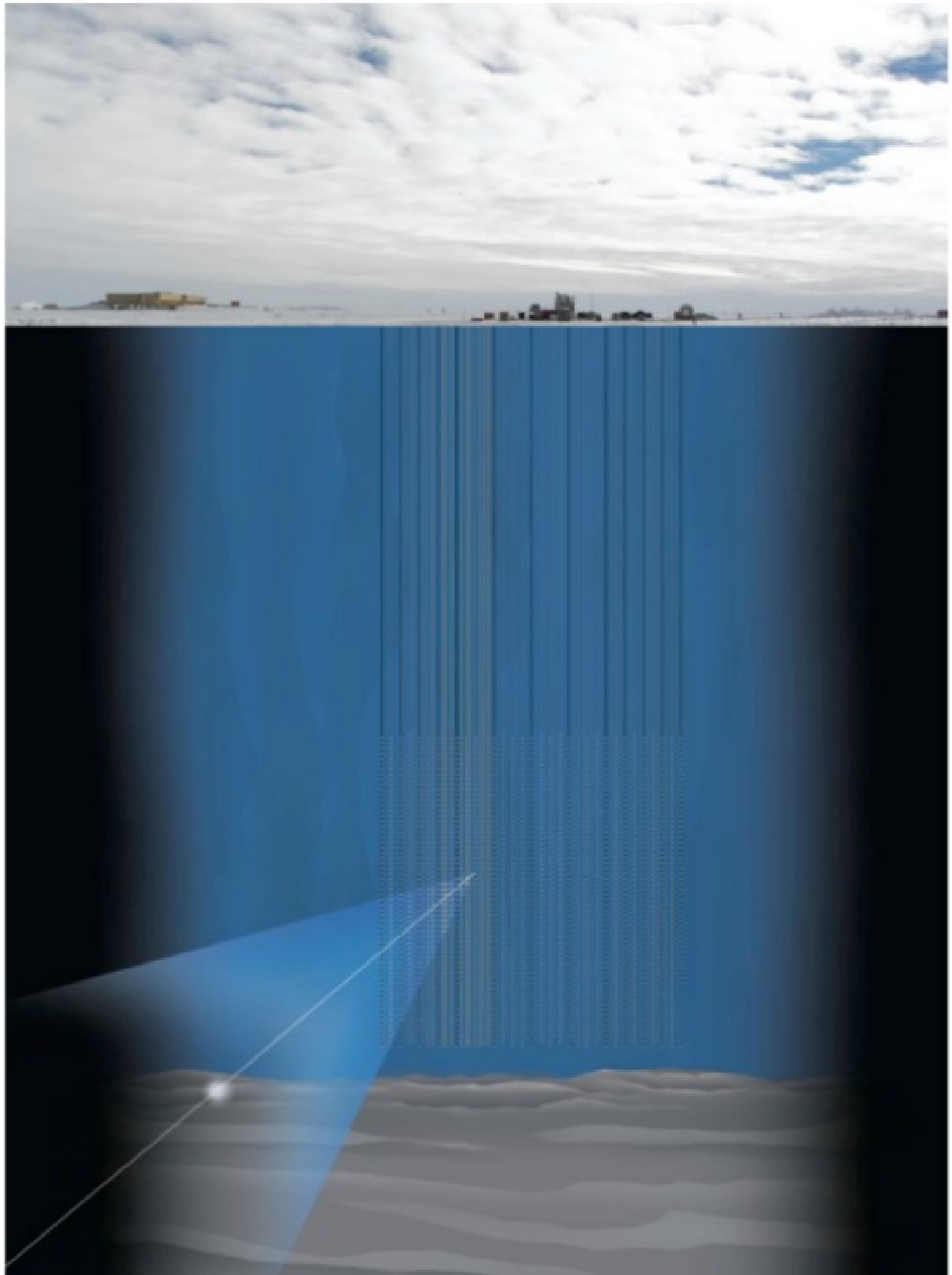
- The muon is detected via Cherenkov radiation in the water or ice

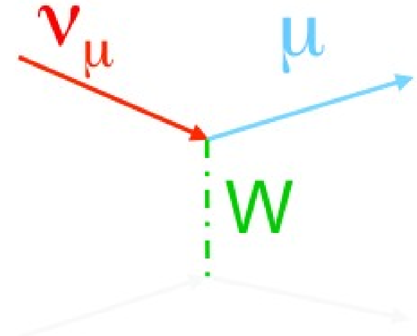



South Pole
Amundsen-Scott Station

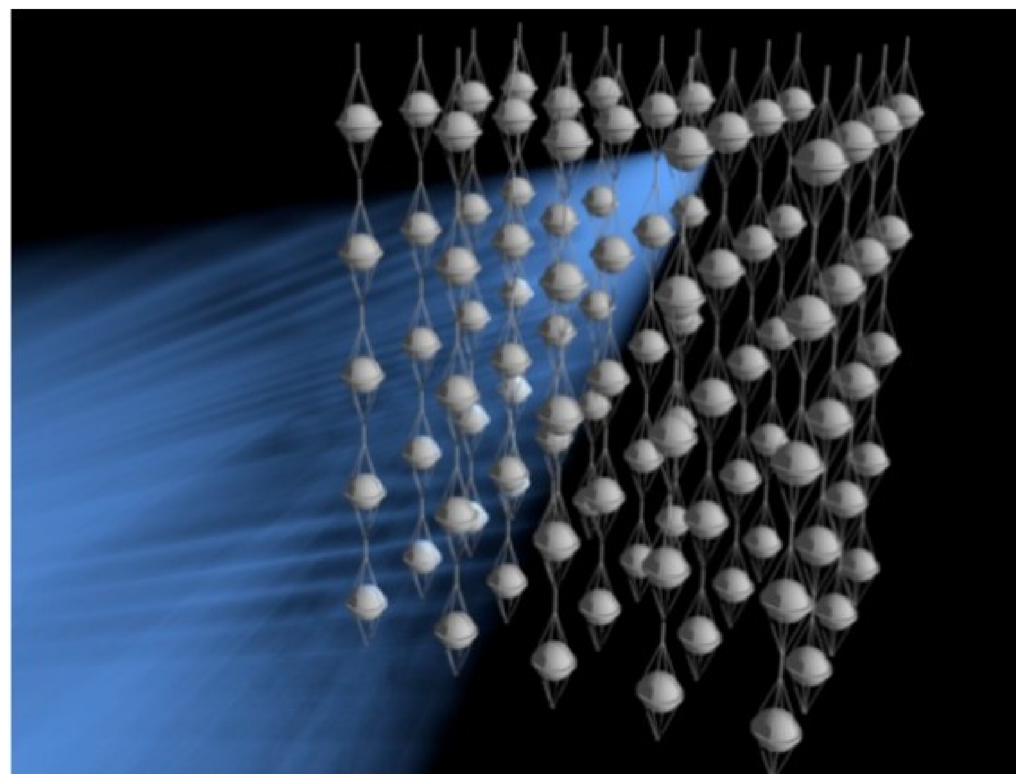

South Pole
Amundsen-Scott Station
1 km
IceCube
Neutrino Observatory

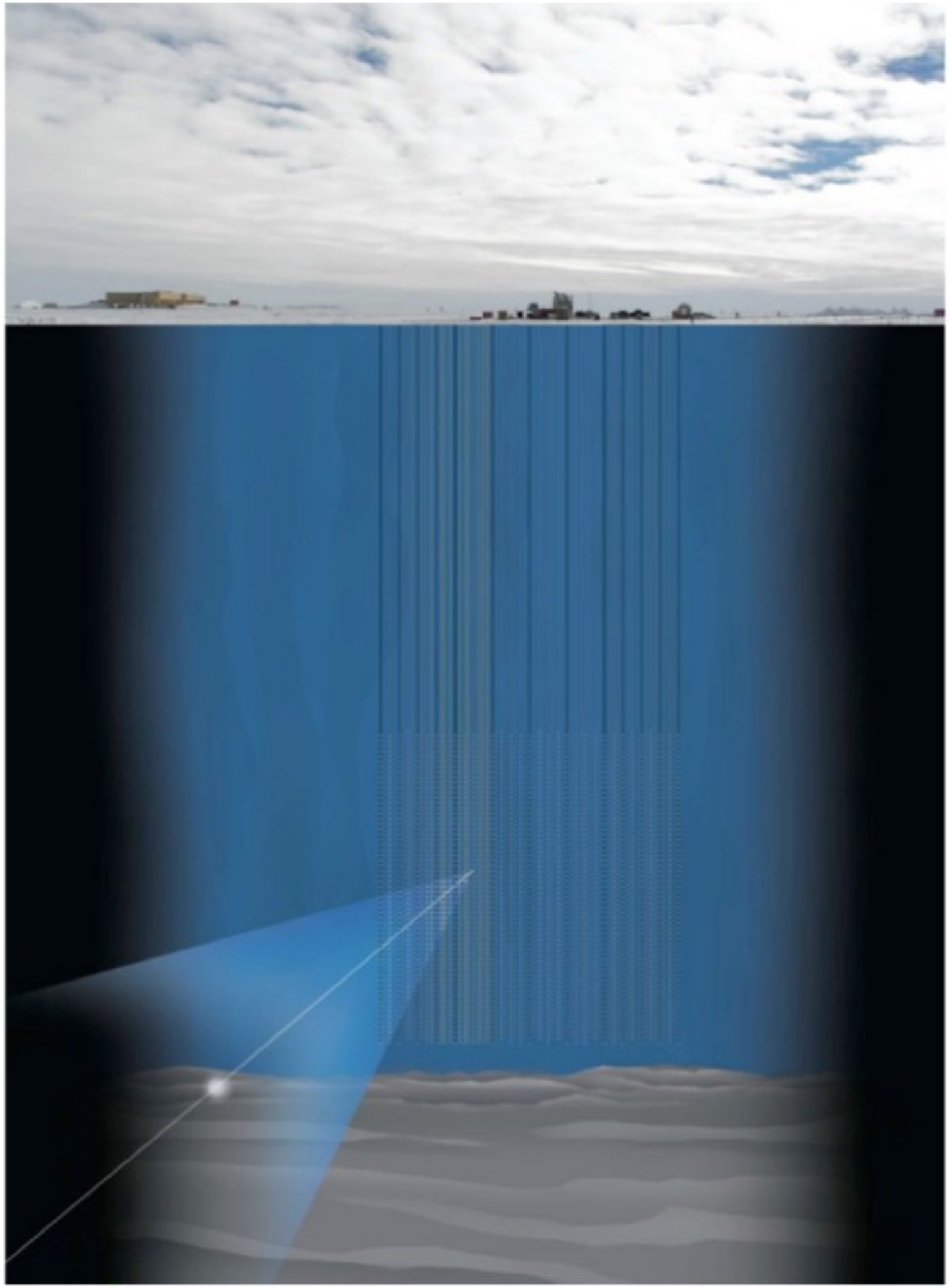

IceCube Data

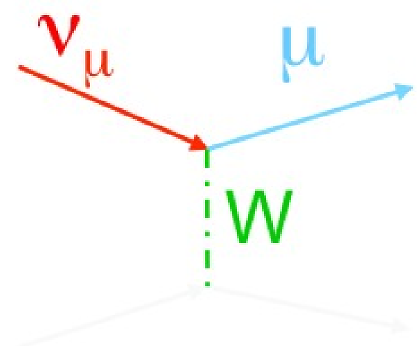




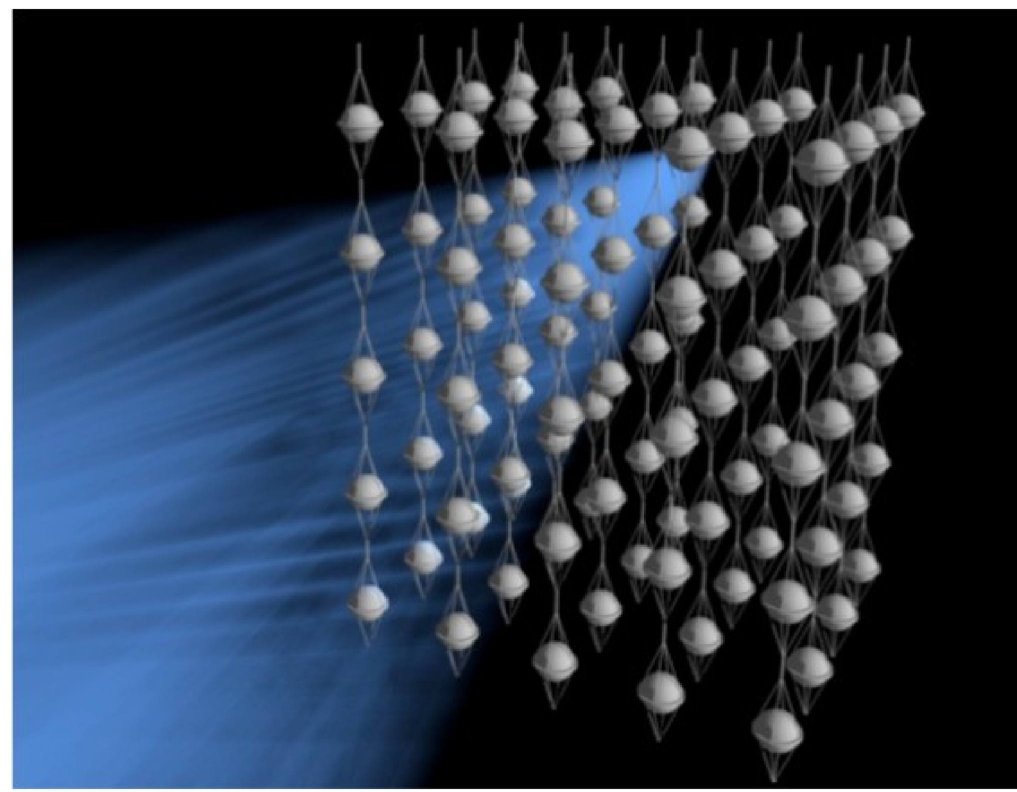
ν μ
μ
W

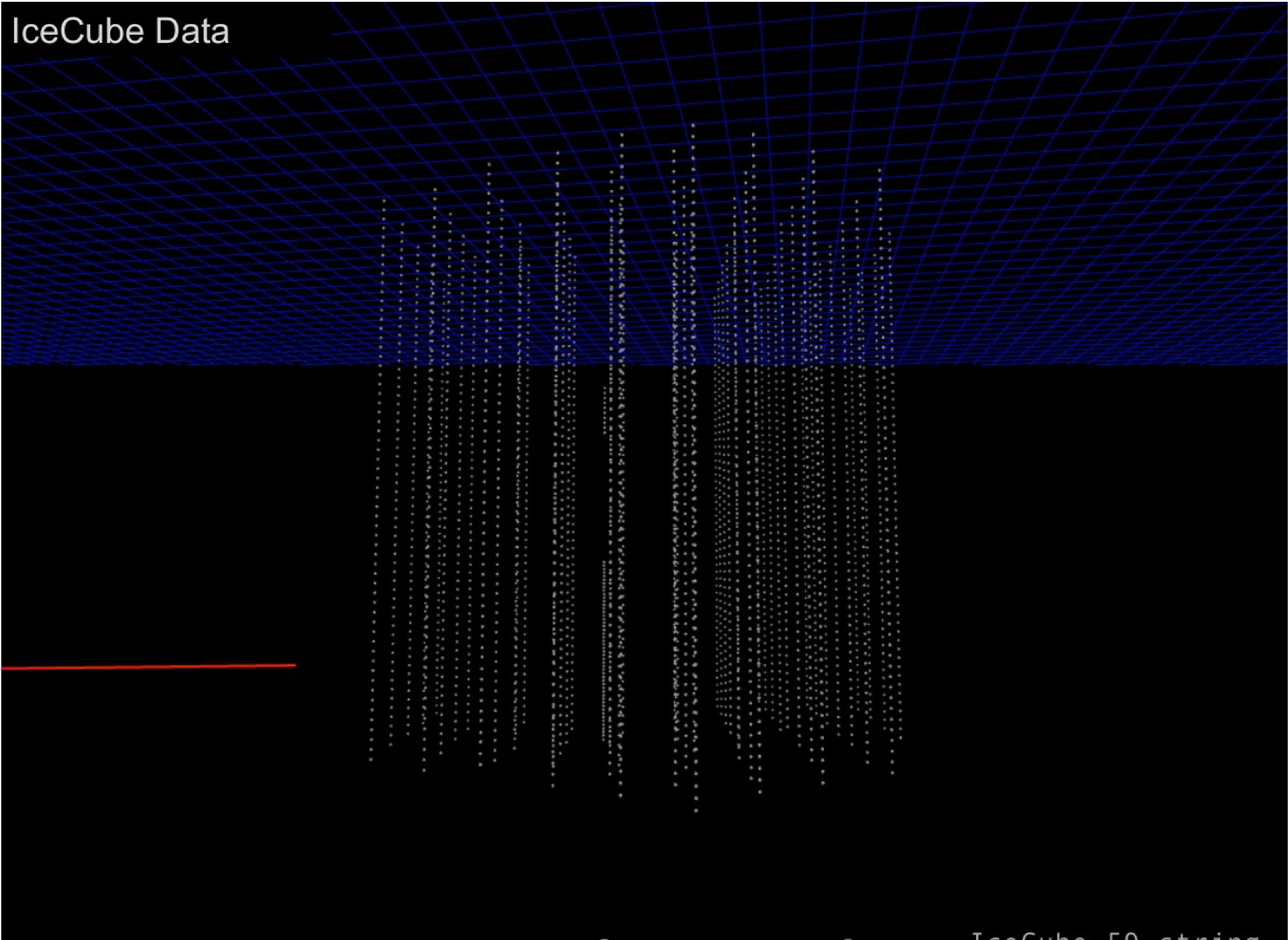


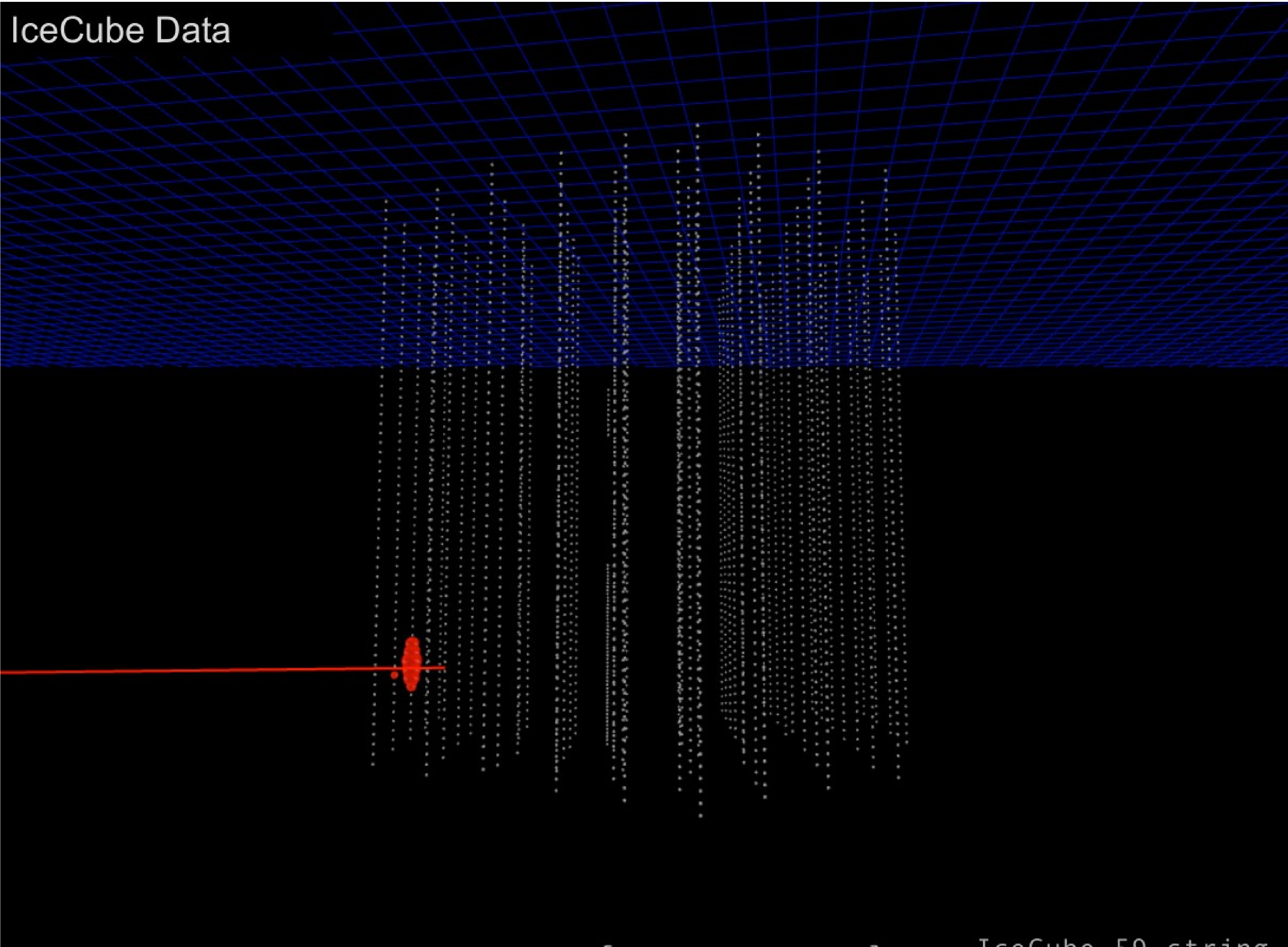




ν_μ
μ
W




IceCube Data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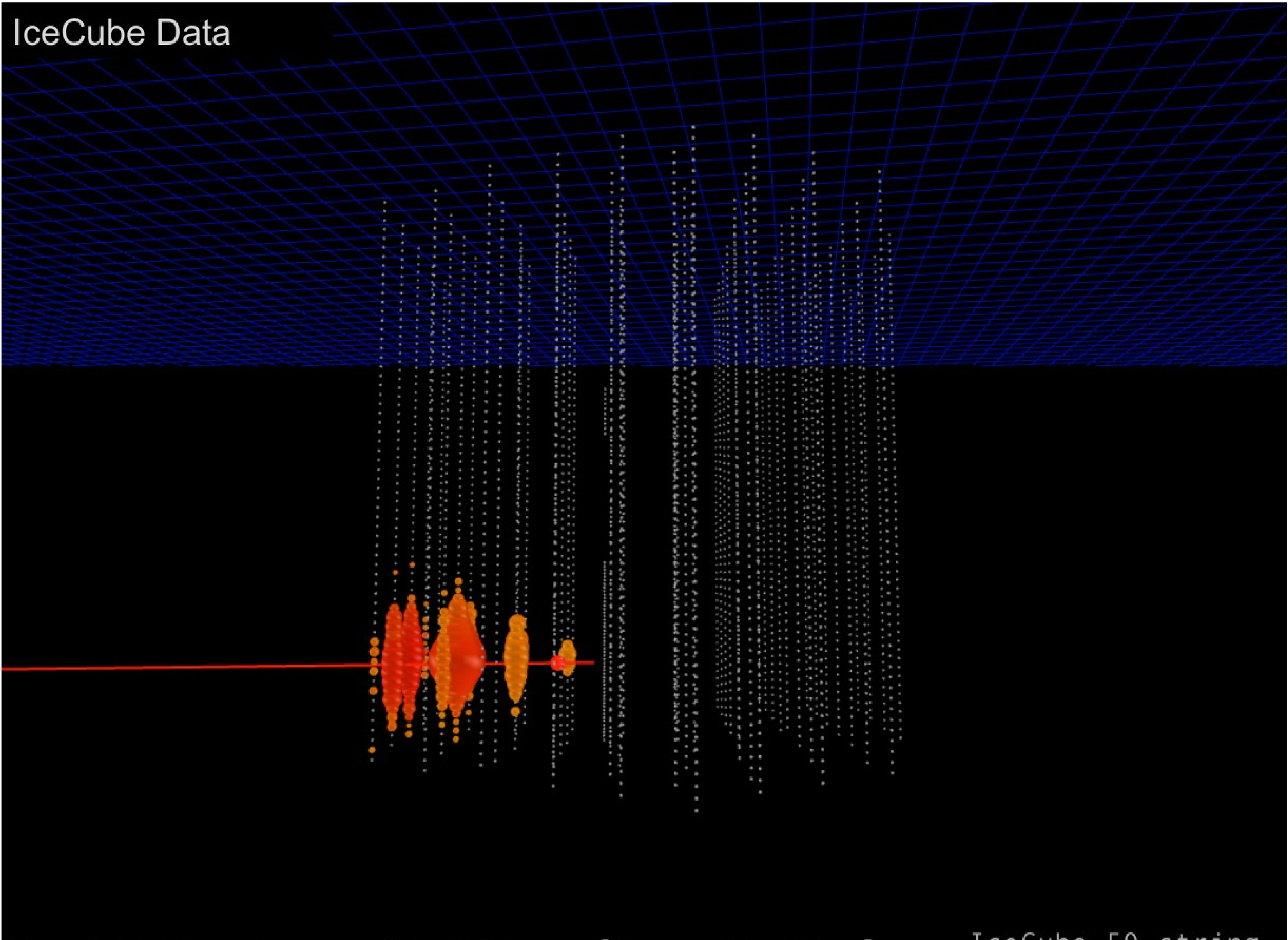
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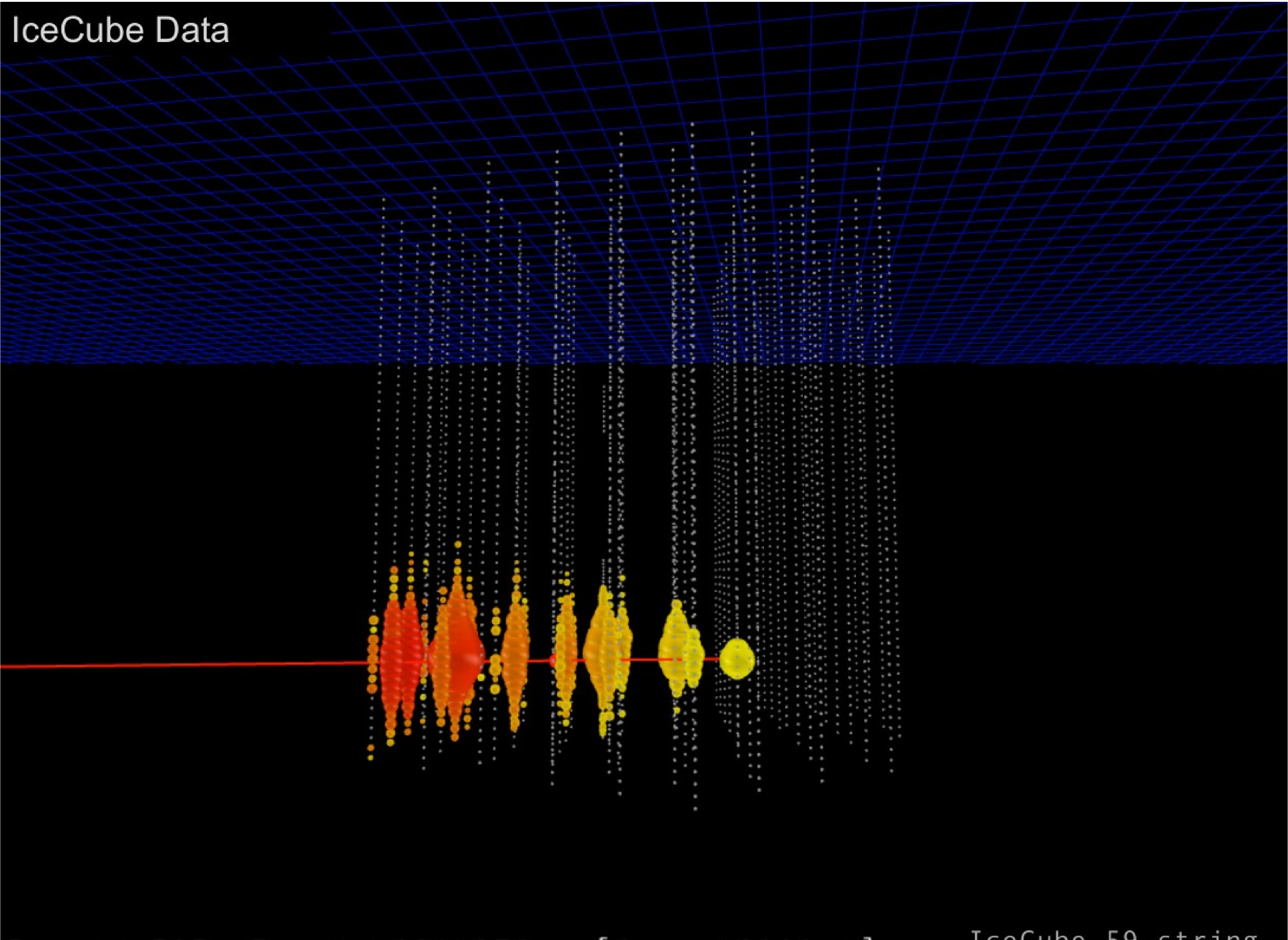
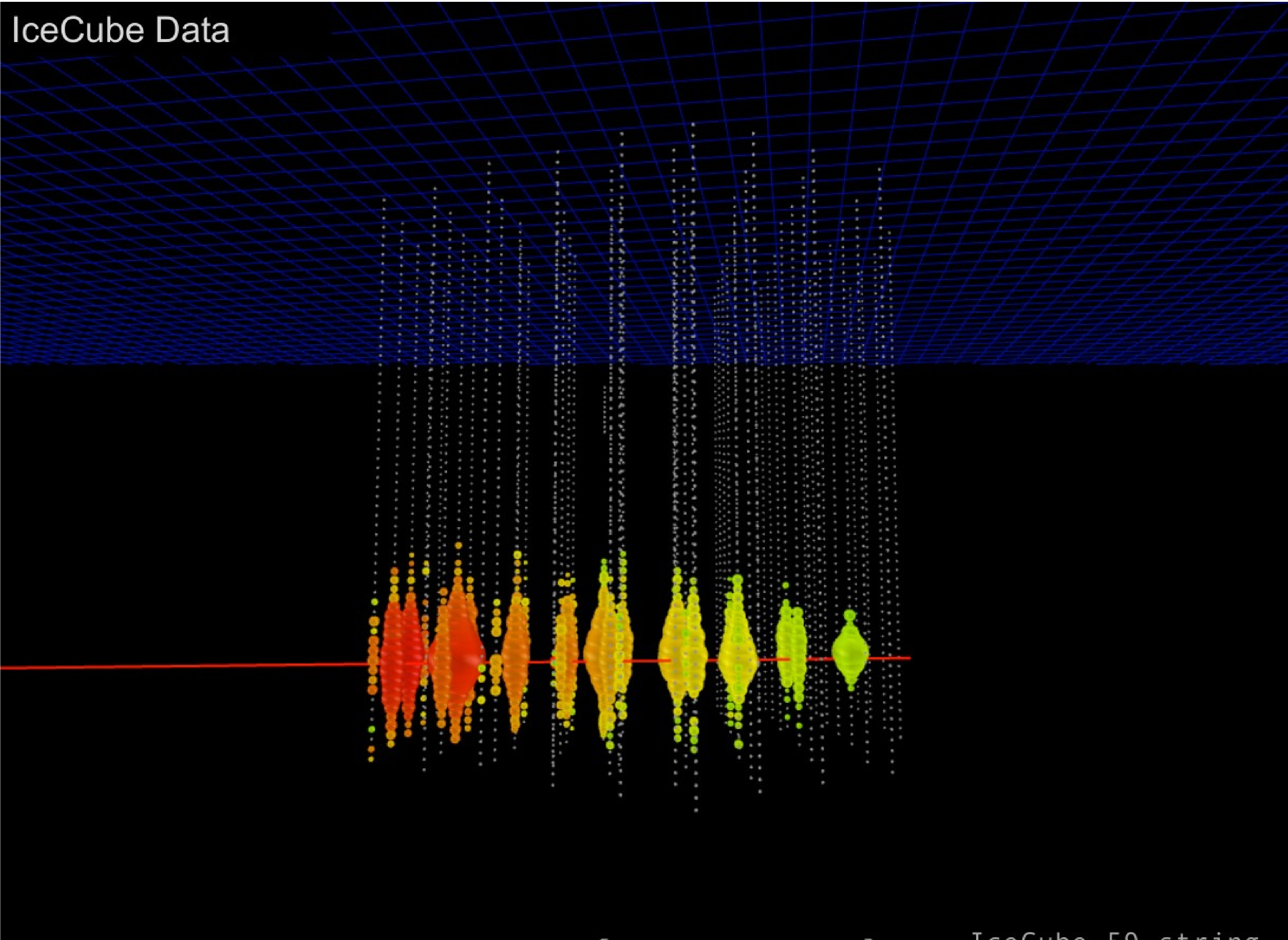
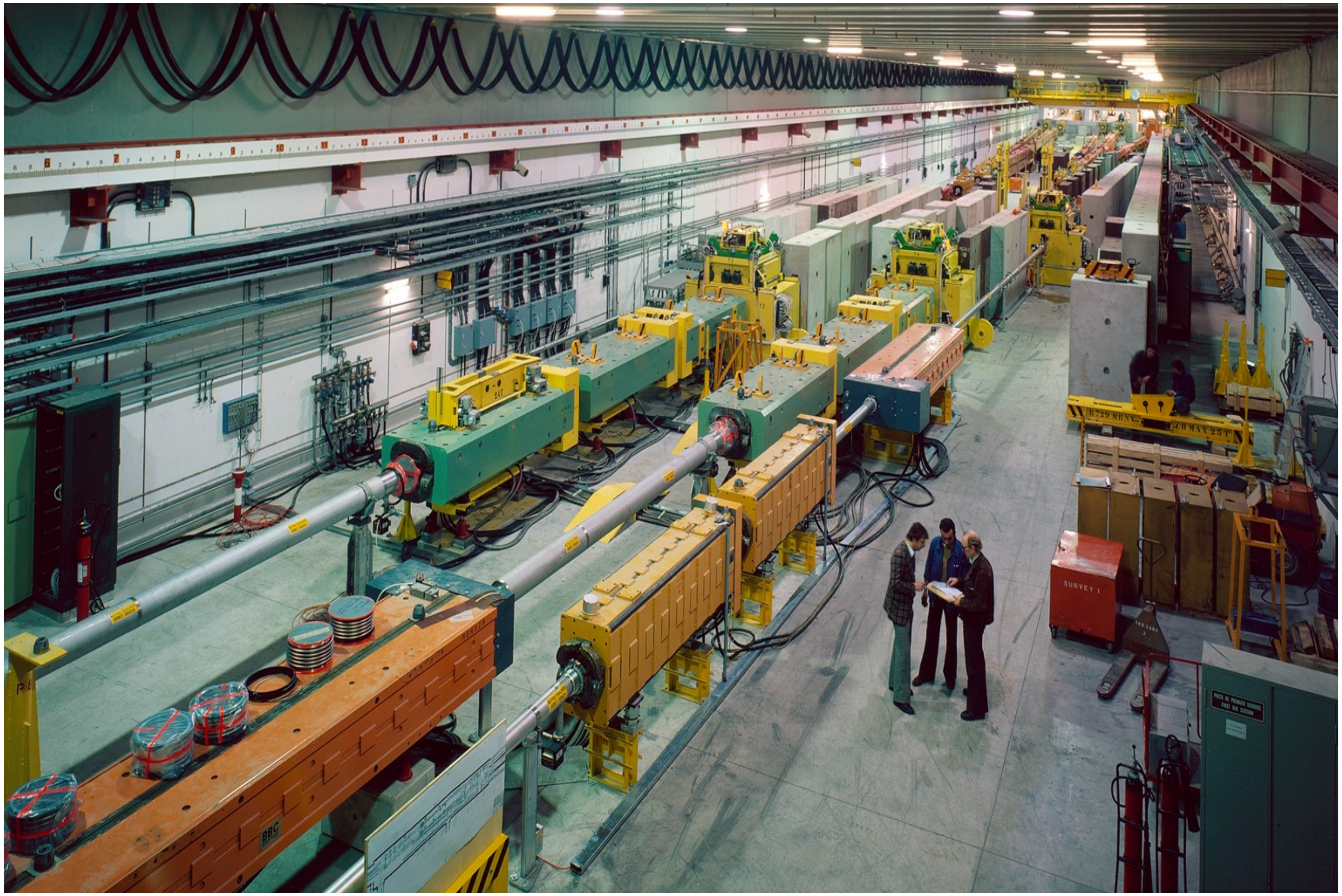

IceCube Data
IceCube 59 string


IceCube Data

Muon

Beam

- In accelerators muons are abundantly produced in hadronic interactions
    - pp -> π + ... and π -> μ $\nu\mu$
- Today muon beams are available at many places in Europe, Asia, and America.
- High energy muon beams, e.g., at CERN SPS, FNAL
- Low/medium energy: PSI, TRIUMF, Los Alamos, BNL, DUBNA, RAL, …



Muon

Muon cooling for a Higgs Factory at CERN ?

New boson sparks call for 'Higgs factory'

physicsworld.com
BEST SPECIALIST SITE FOR JOURNALISM 2011

Jul 5, 2012 15 comments

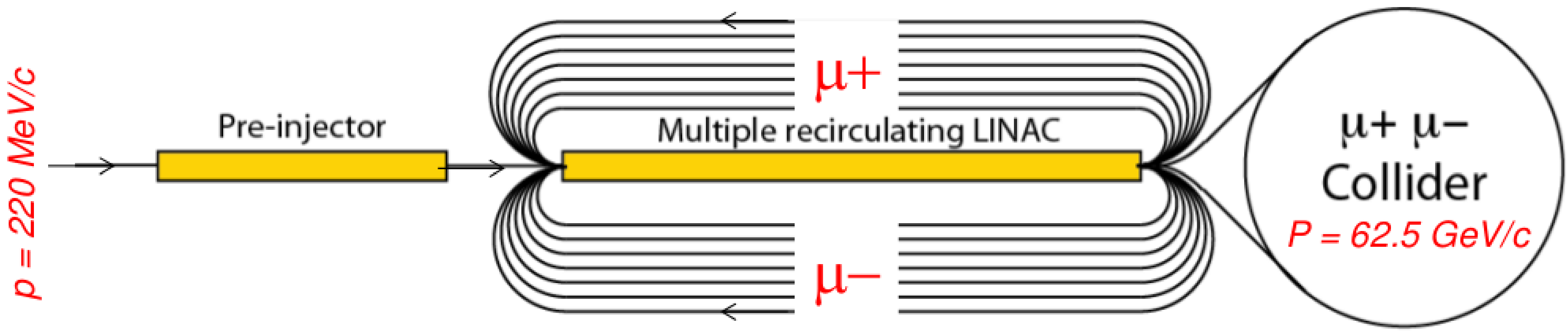
Former CERN boss Carlo Rubbia wants a muon collider

CERN's discovery of a new fundamental particle – most likely a Higgs boson – was barely hours old when physicists speaking at this year's Lindau Nobel Laureate Meeting in Germany argued the case for a new facility to measure its properties in detail. Speaking out in favour of a new machine was former CERN boss Carlo Rubbia, who shared the 1984 Nobel Prize for Physics for the discovery of the W and Z bosons. "The technology is there to construct a Higgs factory," he claimed. "You don't need €10bn; it could be done relatively cheaply."

"With a Higgs of 125 GeV we need only a modest machine, perhaps not a large linear collider." Rubbia points out that muons colliding at a combined energy of roughly 125 GeV would suffice – just over half the energy of LEP and requiring a machine with a much smaller radius.

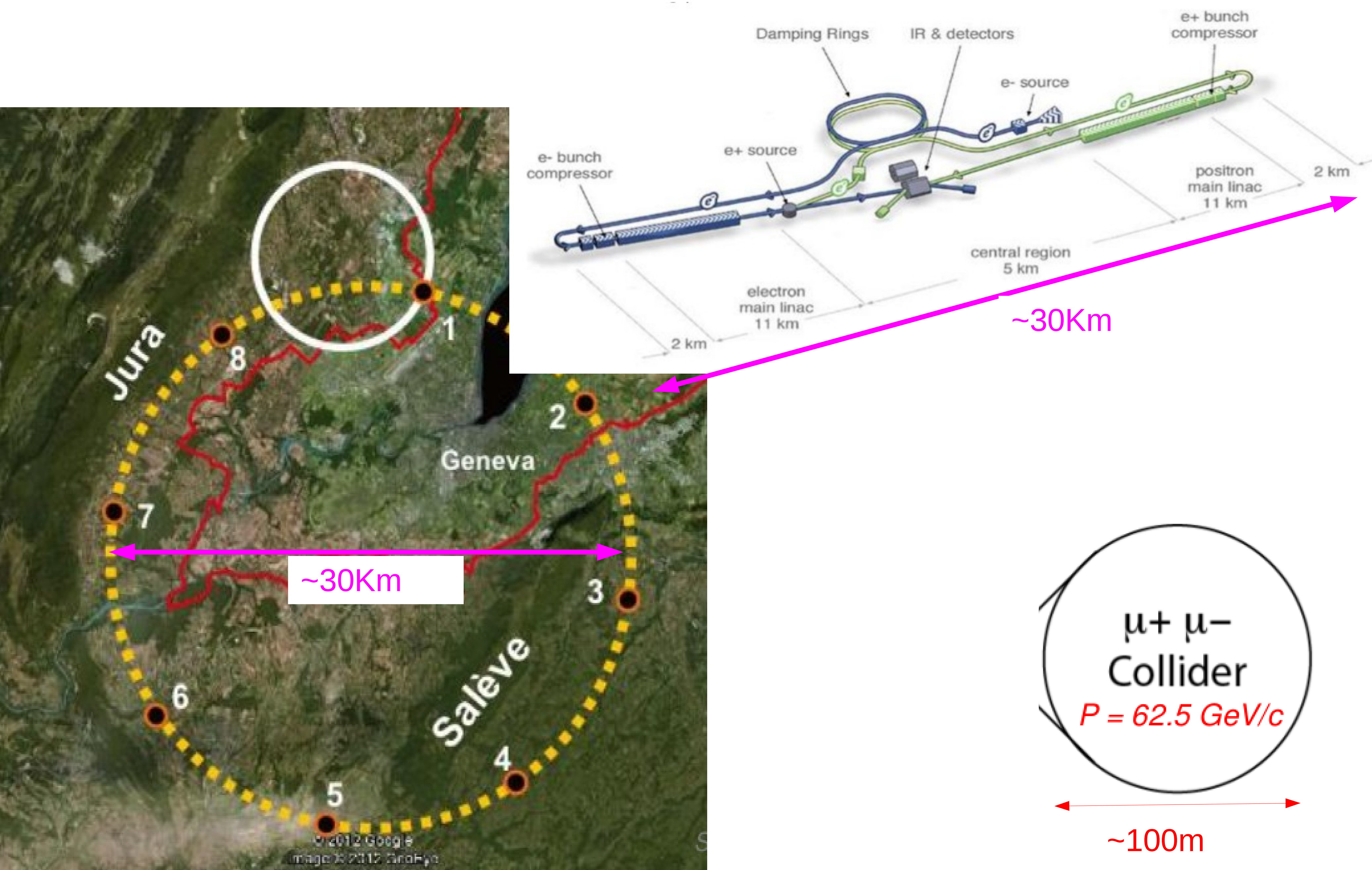
Muon

Muon cooling for a Higgs Factory at CERN ?



Muon

Muon cooling for a Higgs Factory at CERN ?



Summary

- Muon is an elementary particle describe by the SM
  - All its parameters are well known
  - Some tension on g_μ-2 (3.6 sigma)
  - Muons is used in many domain: Astrophysics, particle physics
    - Atmospheric showers, Trigger, Veto,...
- Muon detection
  - started with cloud chambers and Geiger-Müller
  - Detection mechanism always the same: Ionisation
  - The main break-through in tracking detectors: MWPC
  - Spark chambers parallel-plate chambers has lead to RPCs and now MPGDs*
  - MPDGs are probably the new generation of muon detectors being robust
  - GEM, MicroMegas,THGEM...
    - Radiation hard and showing no signs of ageing
    - High rates
    - Excellent spatial resolution
    - Fast (trigger)
- Muo-graphy
- Future: Muon collider?

*Micro Pattern Gas Detectors