Particle detectors

Γιάννης Καρυωτάκης
Yannis.karyotakis@lapp.in2p3.fr
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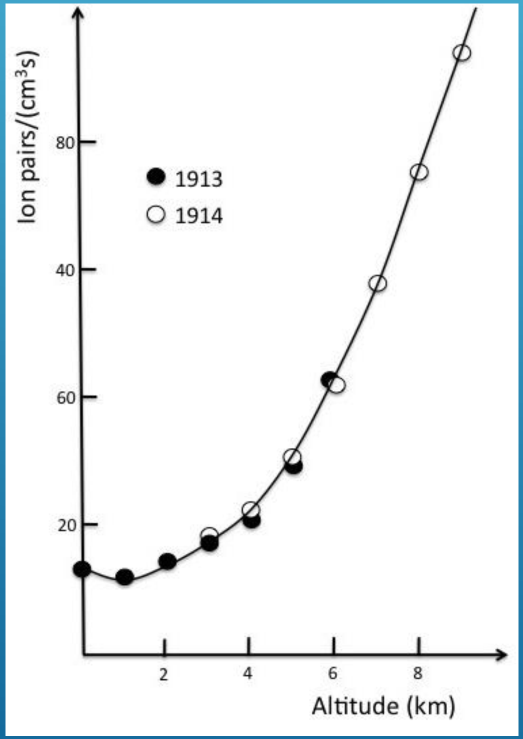
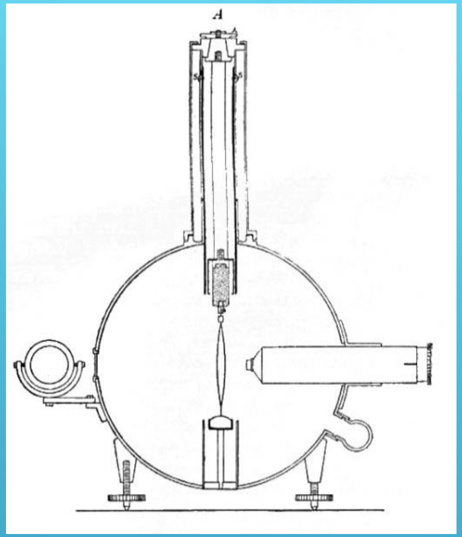
Our planet is continuously hit by cosmic rays !

First hints for cosmic rays

- Electrometers discharge because the air is ionised by radiation (Julius Elster and Hans Geitel 1900)
  - What is the radiation origin ???
    - Radioactive elements on earth's surface ???
    - Viktor Hess : Radiation comes from sky. First balloon experiments. Seven flights.
      - The number of ion pairs increases with altitude
      - Do not come from sun ! Data taking in an solar eclipse



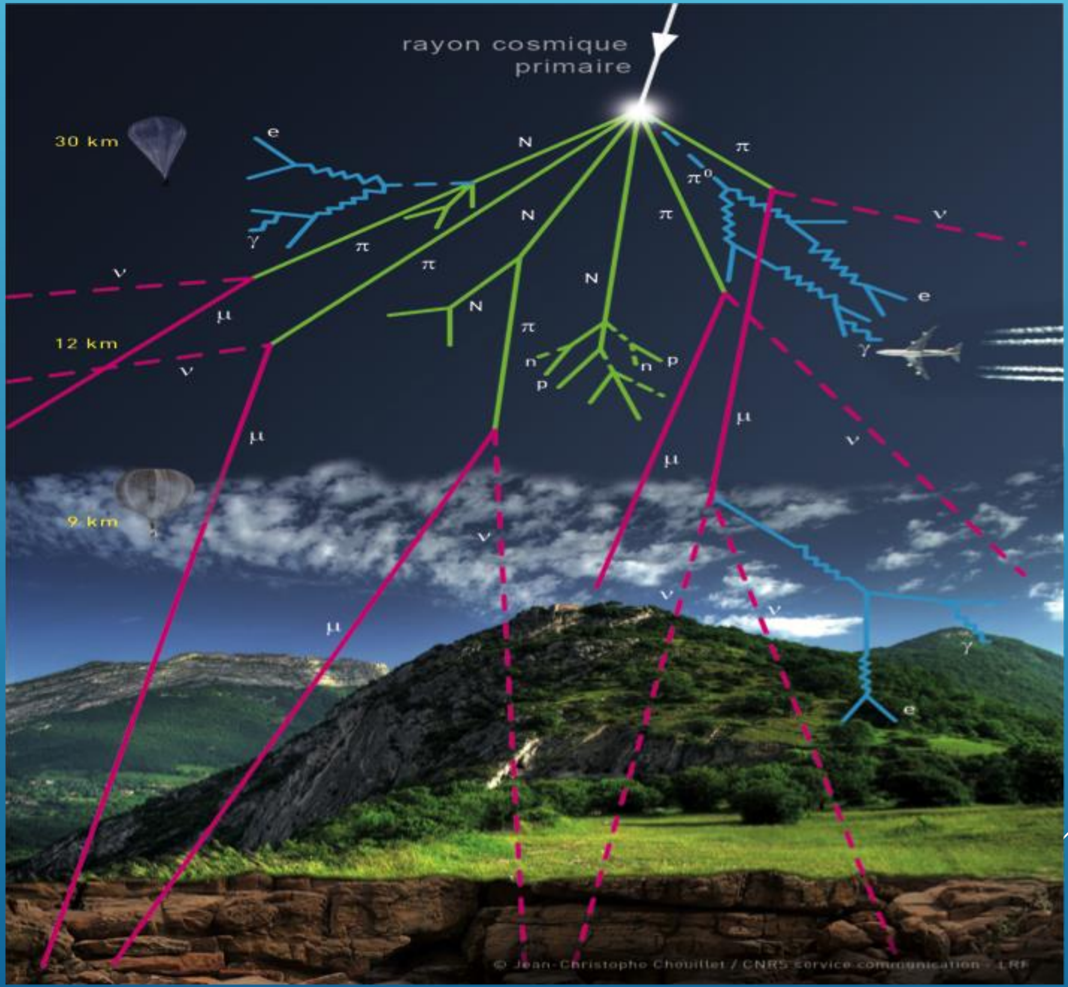


Theodor's Wulf Strahlungsapparat

We see showers, particles arrive in group

- 1937: Pierre Auger positions three Geiger counters separated by 70 m at le Pic du midi
  - Observes coincidences

Pierre Victor Auger
(1899-1993)



Searching for new particles

- Many new particles discovered in the cosmic rays
  - 1932: positron e^+ (first observation of antimatter)
  - 1936: muon μ
  - 1949: pion π
  - 1949: kaon K
  - 1949: lamda Λ
  - 1952: xi Ξ
  - 1953: sigma Σ
- Birth of a new science: Particle Physics!

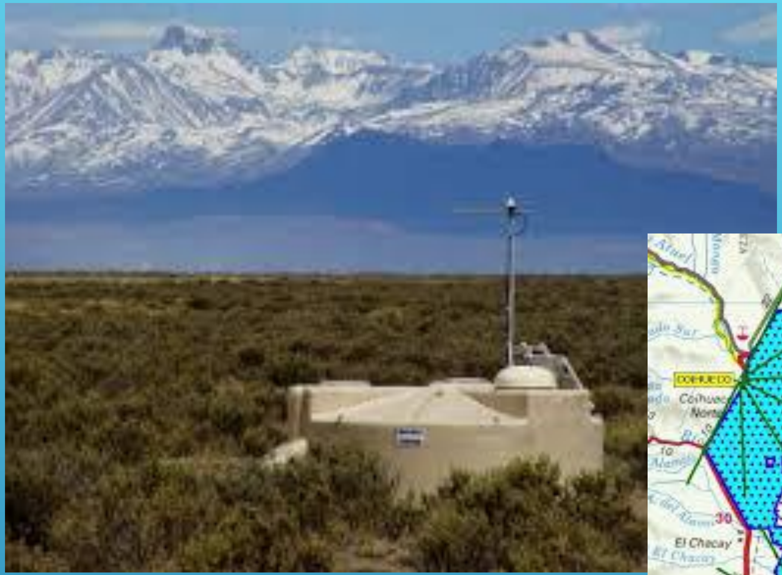
Dominé par le mont Blanc du Tacul, le chalet-laboratoire est situé au début de la vallée Blanche, dans un paysage de neige et de crevasses.

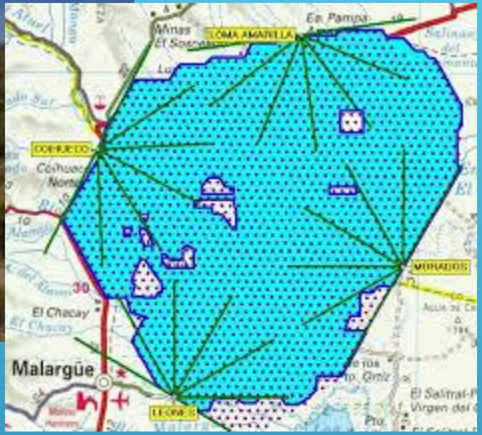
Pioneers at Aiguille du midi close to the Mont Blanc submit. Laboratoire des cosmiques. Louis le Prince-Ringuet

Modern experiments

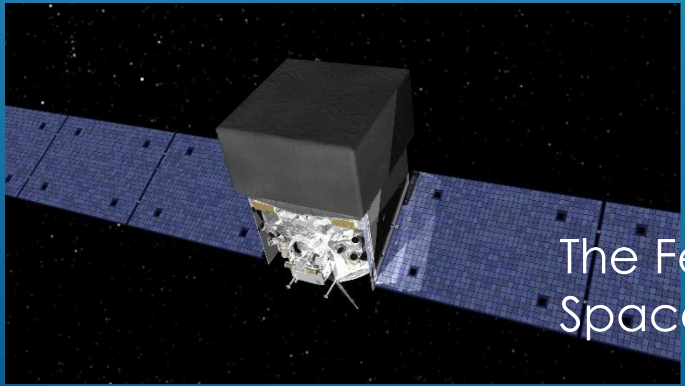
A glimpse to the future

AMS at the international space station looks for anti-matter !



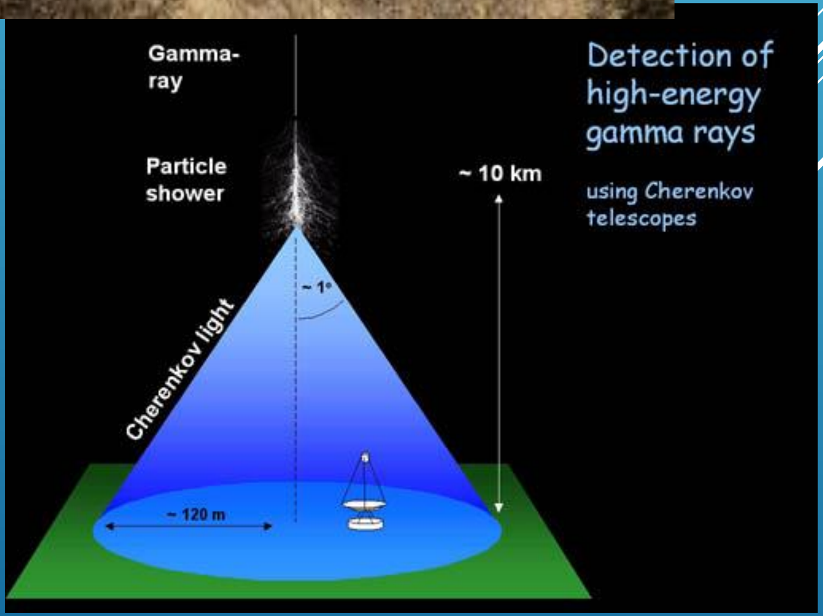


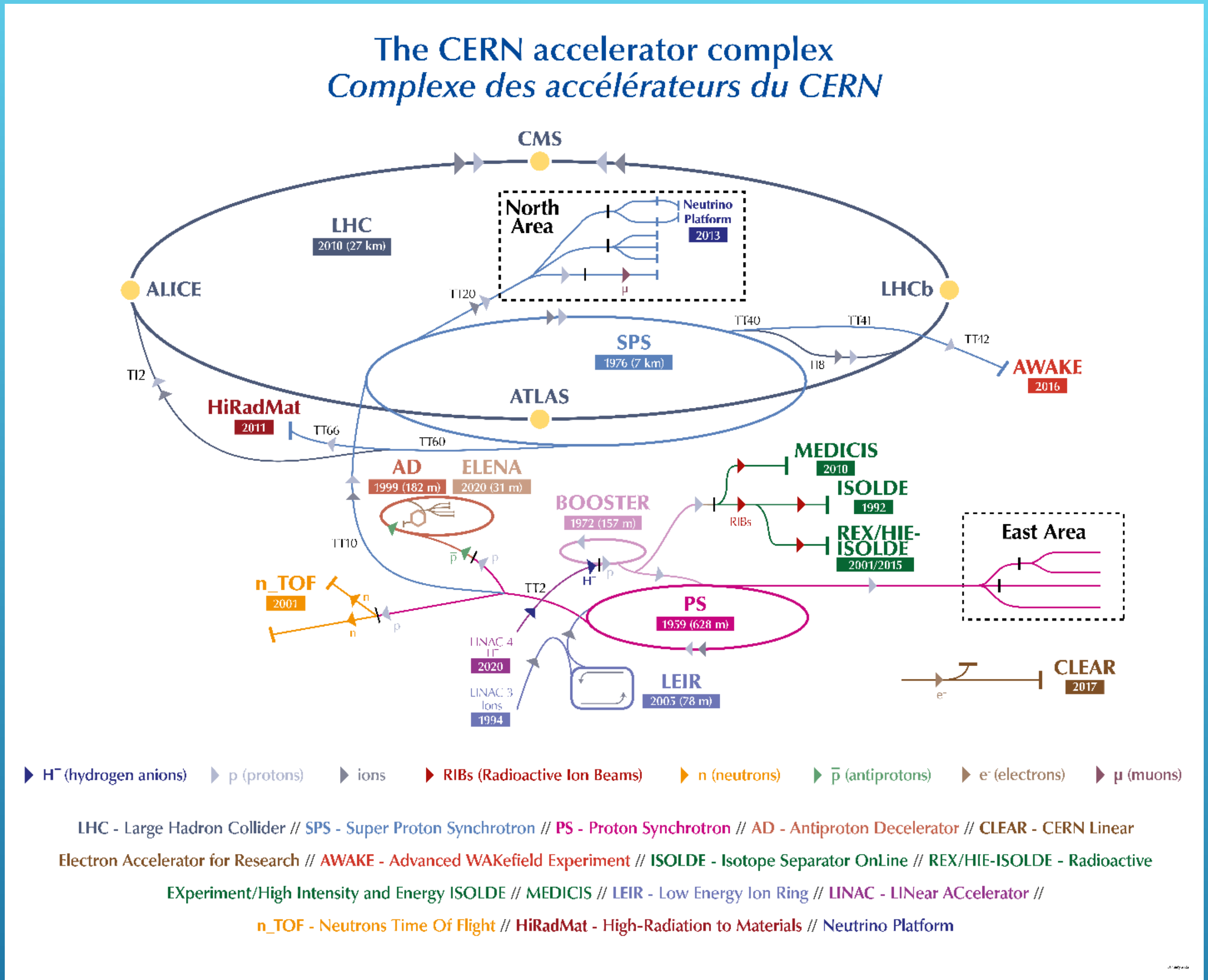
Pierre Auger observatory at Argentina's pampa detects high energy charged particle induced showers using 1600 water tanks of 12K liters separated by 1.5 Km each other. Complemented by fluorescence detectors.



The Fermi Gamma-ray Space Telescope

The HESS experiment in Namibia looks for high energy photons

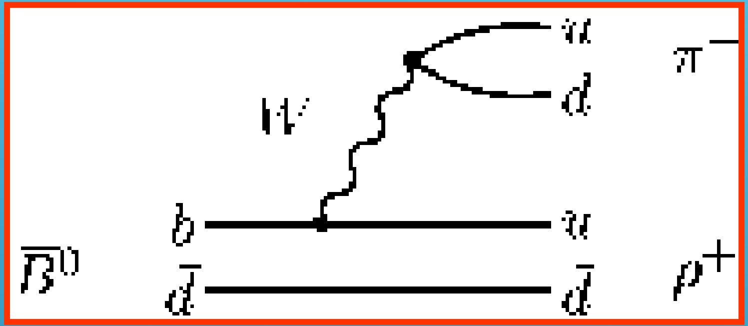


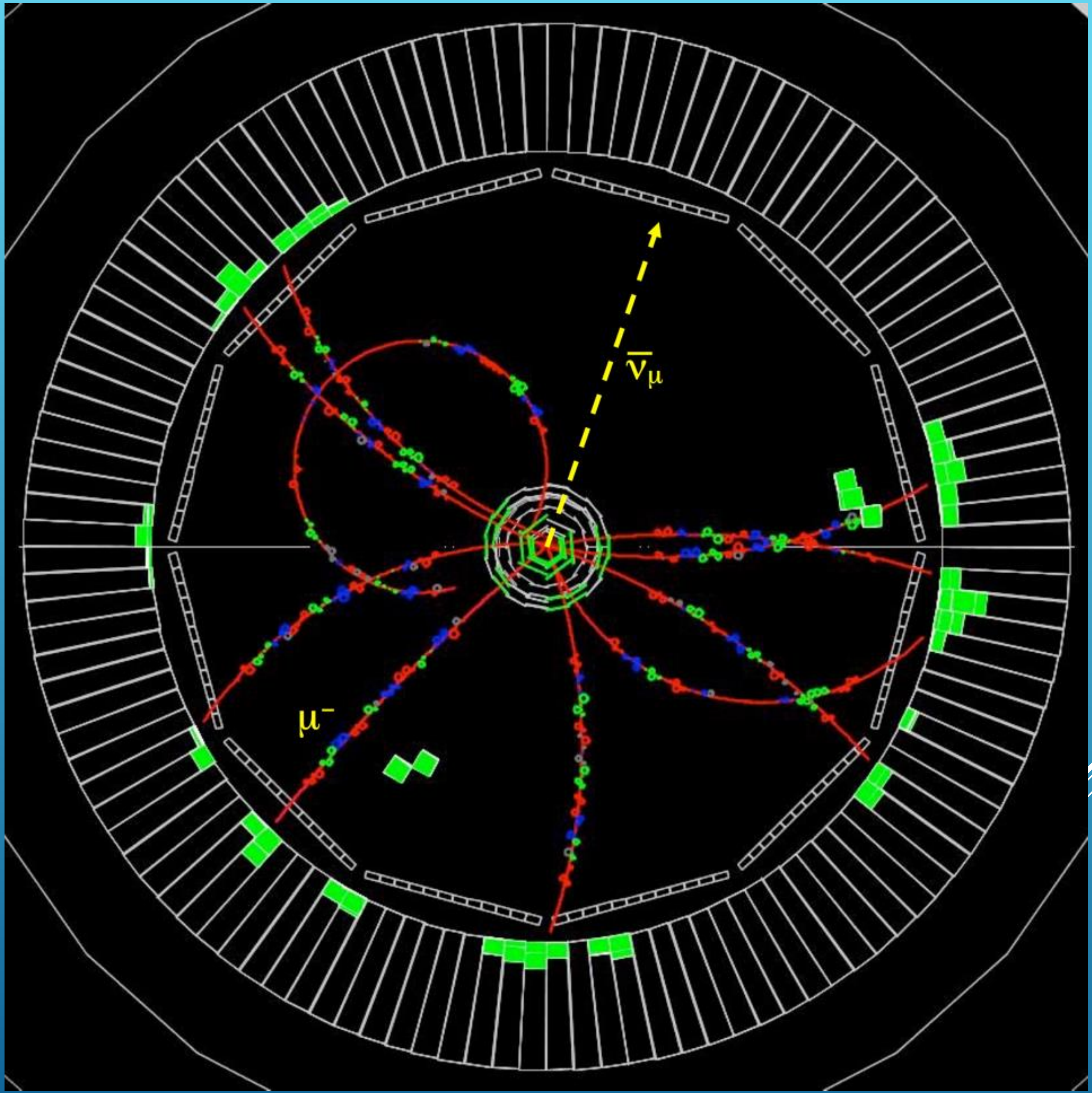


Emphasis on accelerator physics and detectors

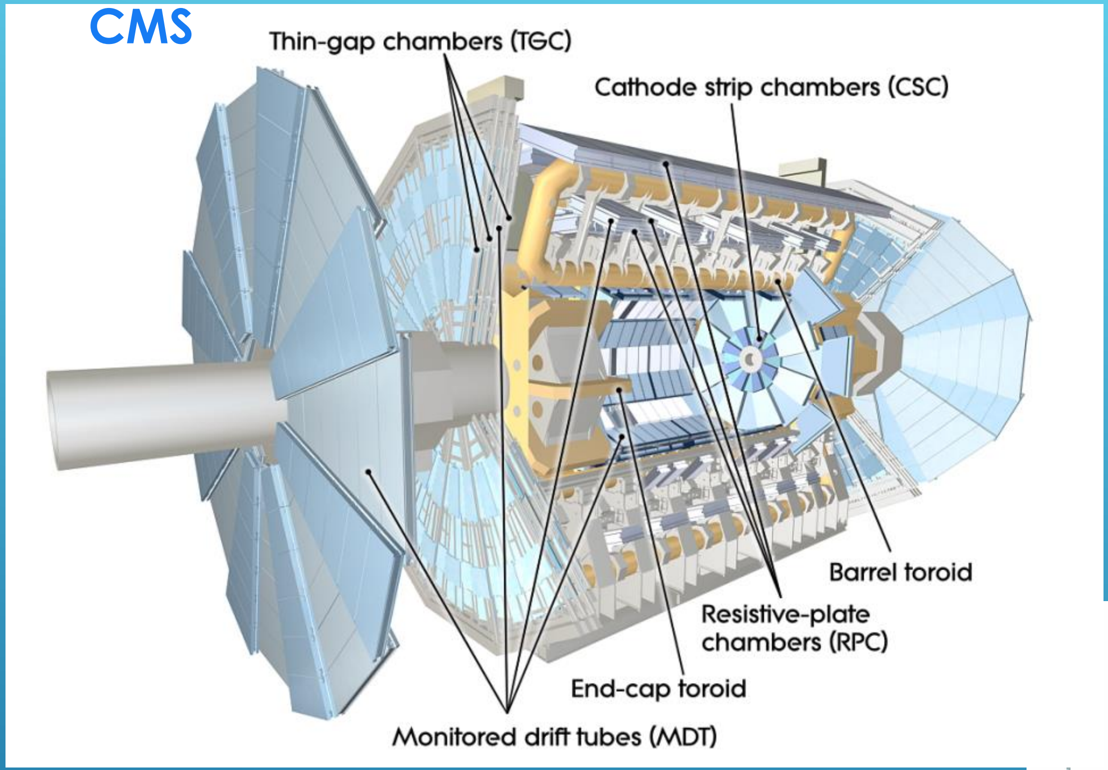
Particle Detectors (1)

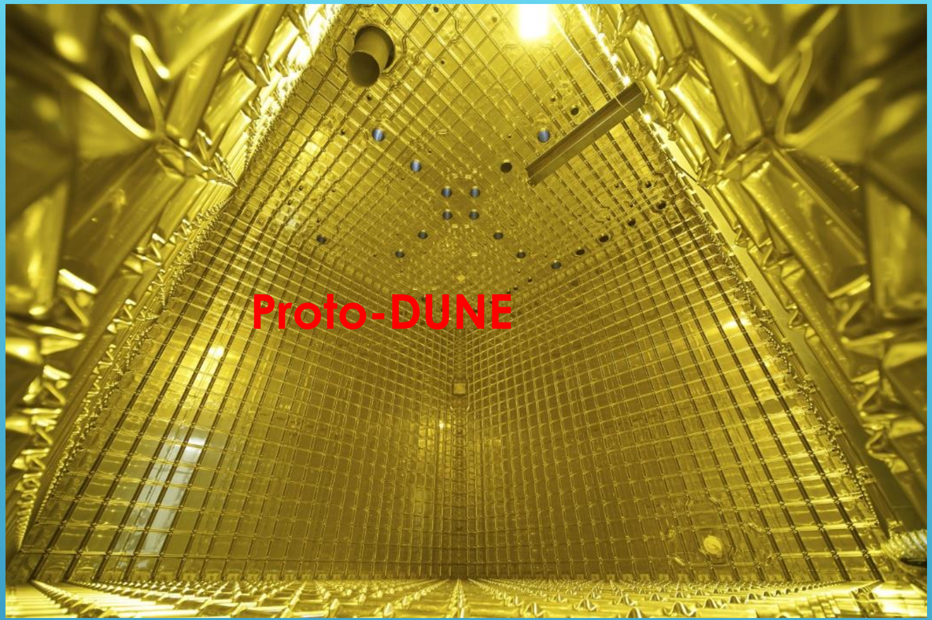
$e^+e^- \rightarrow B^0B^0$ -> decay products

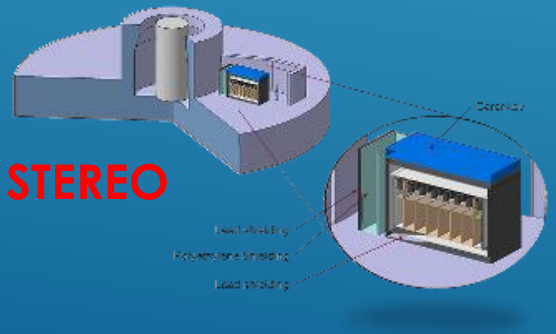


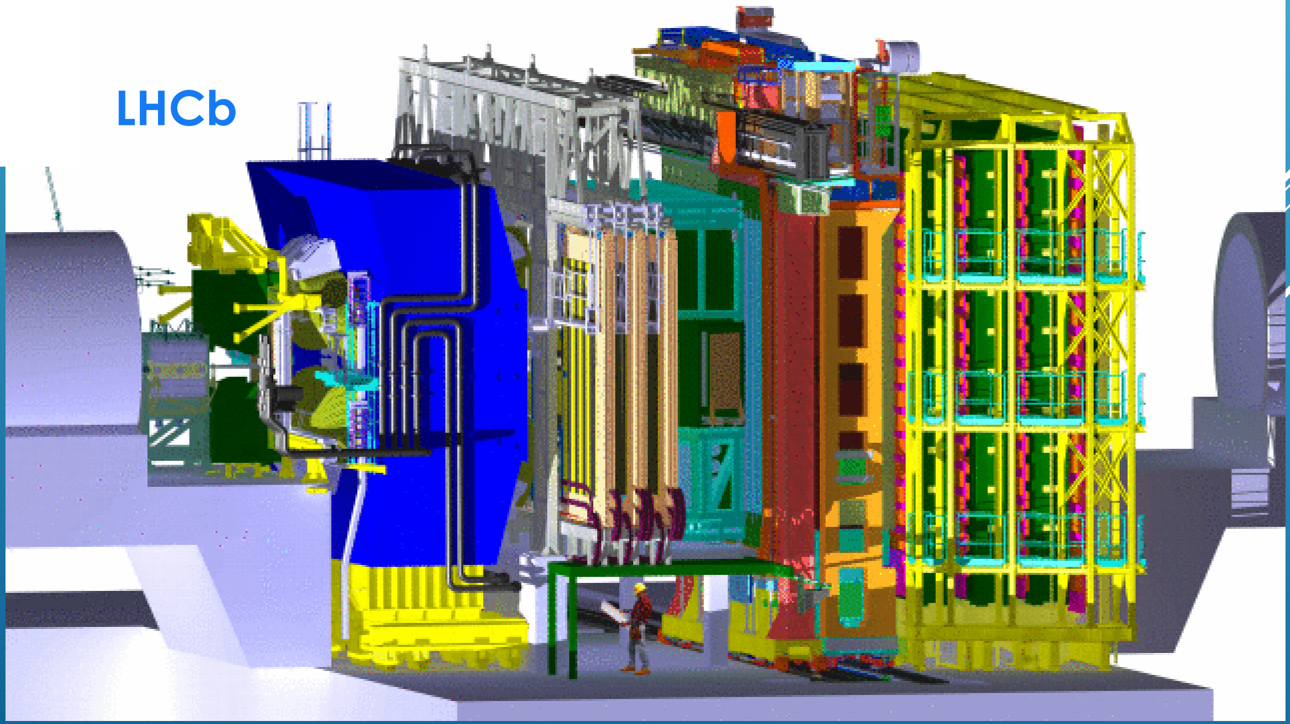


Particle detectors (2)





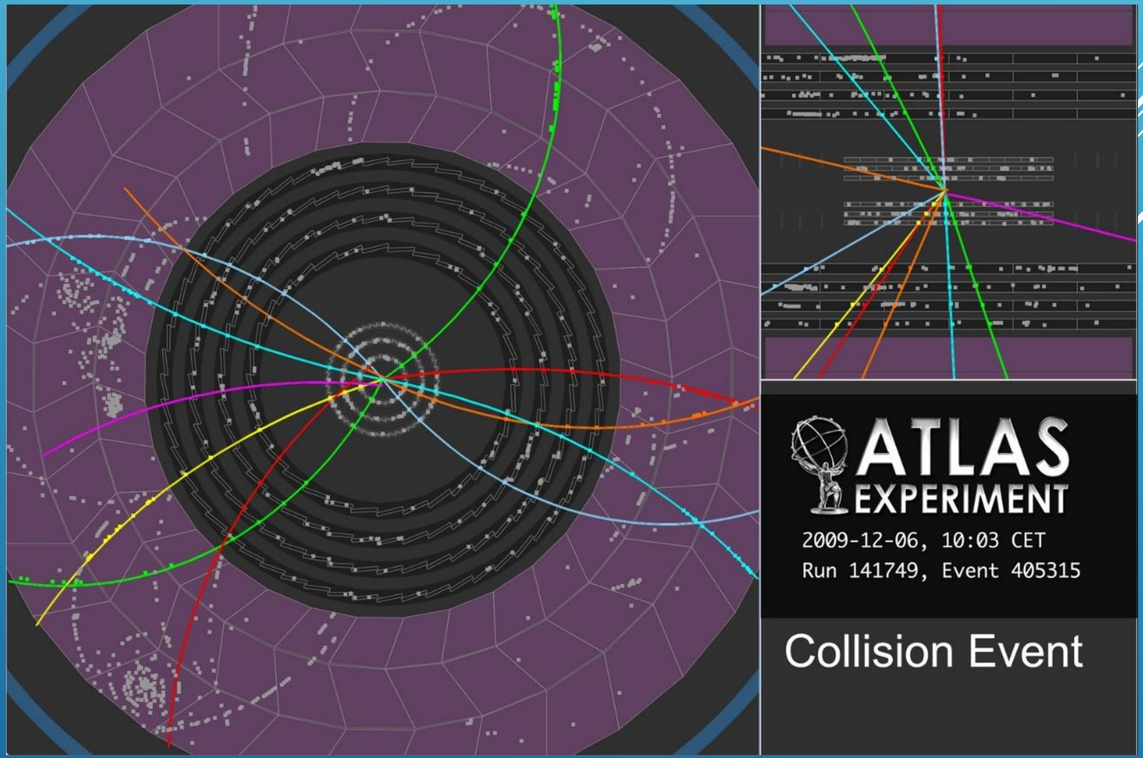




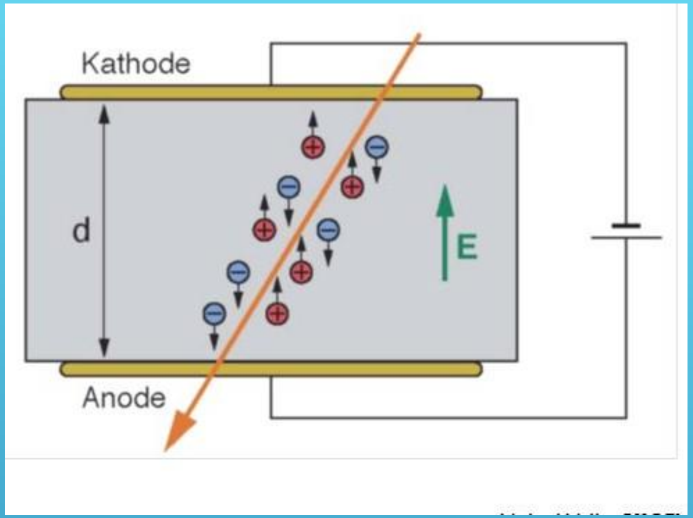
PARTICLE DETECTORS

- Particles are detected through theirs interactions with matter
- What do we need to measure ?
  - Location and then the path or the track
  - Momentum
  - Energy
  - Missing Energy
  - Time
  - Particle's identity, e, μ, π, …..
- For each measurement a dedicated detector
  - Precise position silicon detectors, chambers
  - Magnets
  - Calorimeters
  - Hermetic detectors
  - Cherenkov counters, dE/dx, absorbers…..

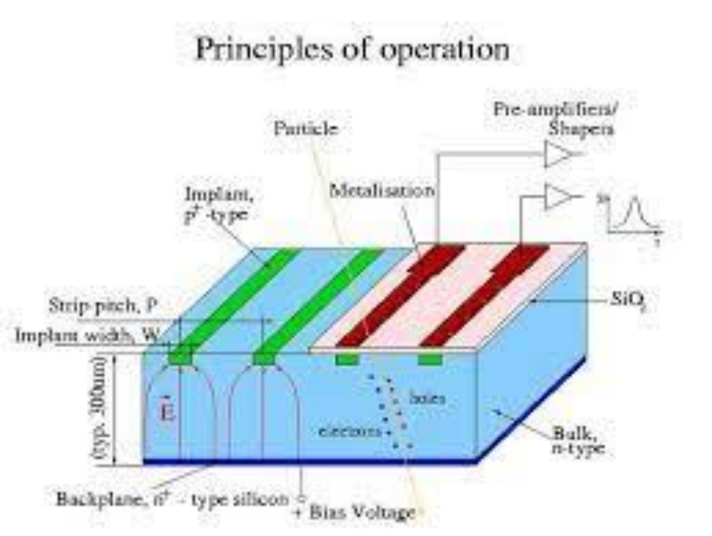
We know how to measure electrical pulses.
We do not take (almost) photos !!!

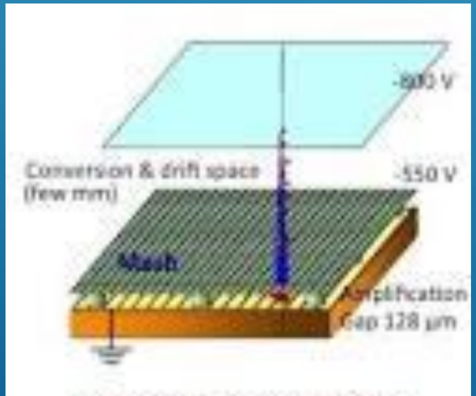


TRACKING DEVICES (CHARGED PARTICLES)

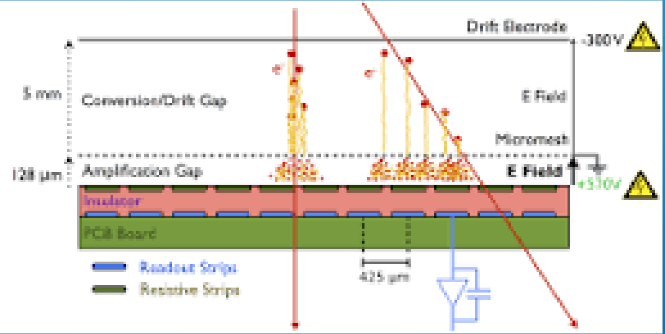


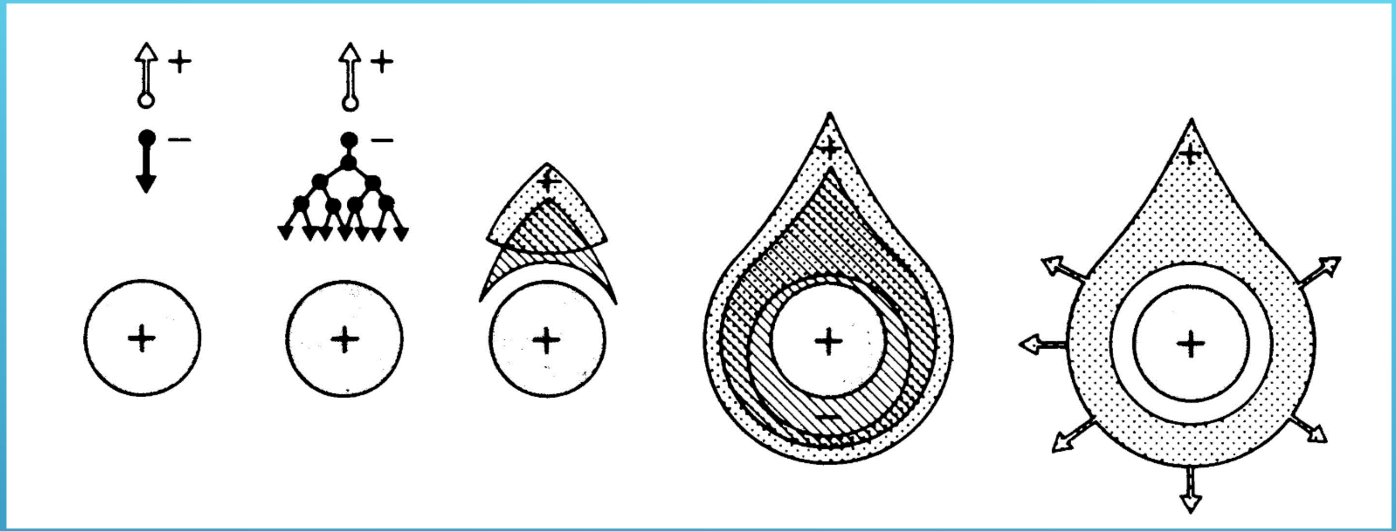
- **Principle :**
  - The incident particle ionizes the detector medium (Si, gas,..) produces e-
  - Detect the electric pulse from e- , may be a challenge
    - Electron multiplication
    - High performance electronics
  - The detector is segmented with sensors of known position in the lab frame. The location precision depends on the sensor's pitch, the electron avalanche size, the sensor's response etc.…



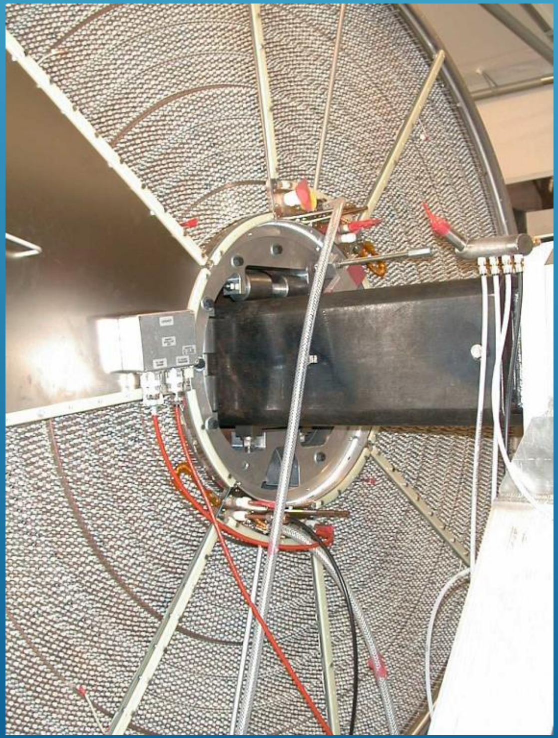


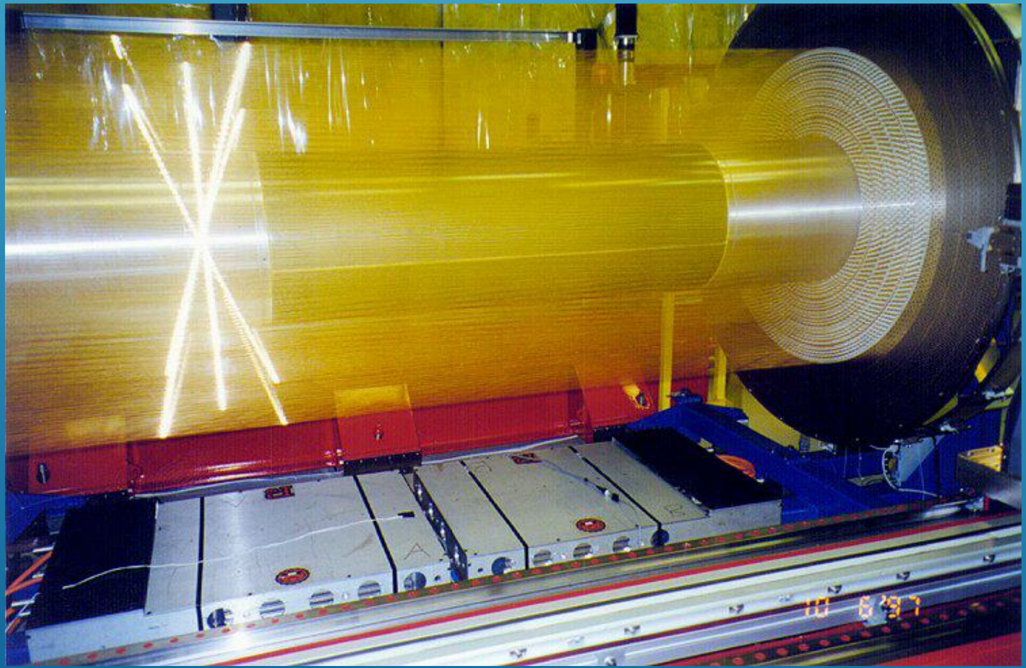
The principle of operation of a micromegas chamber



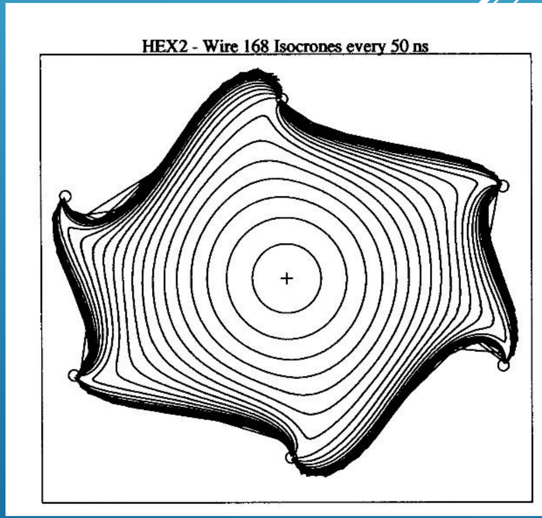


gas	density ϱ[g/cm^3]	I_0[eV]	W[eV]	n_p[cm^{-1}]	n_T[cm^{-1}]
H_2	$8.99 \cdot 10^{-5}$	15.4	37	5.2	9.2
He	$1.78 \cdot 10^{-4}$	24.6	41	5.9	7.8
N_2	$1.25 \cdot 10^{-3}$	15.5	35	10	56
O_2	$1.43 \cdot 10^{-3}$	12.2	31	22	73
Ne	$9.00 \cdot 10^{-4}$	21.6	36	12	39
Ar	$1.78 \cdot 10^{-3}$	15.8	26	29	94
Kr	$3.74 \cdot 10^{-3}$	14.0	24	22	192
Xe	$5.89 \cdot 10^{-3}$	12.1	22	44	307
CO_2	$1.98 \cdot 10^{-3}$	13.7	33	34	91
CH_4	$7.17 \cdot 10^{-4}$	13.1	28	16	53
C_4H_{10}	$2.67 \cdot 10^{-3}$	10.8	23	46	195



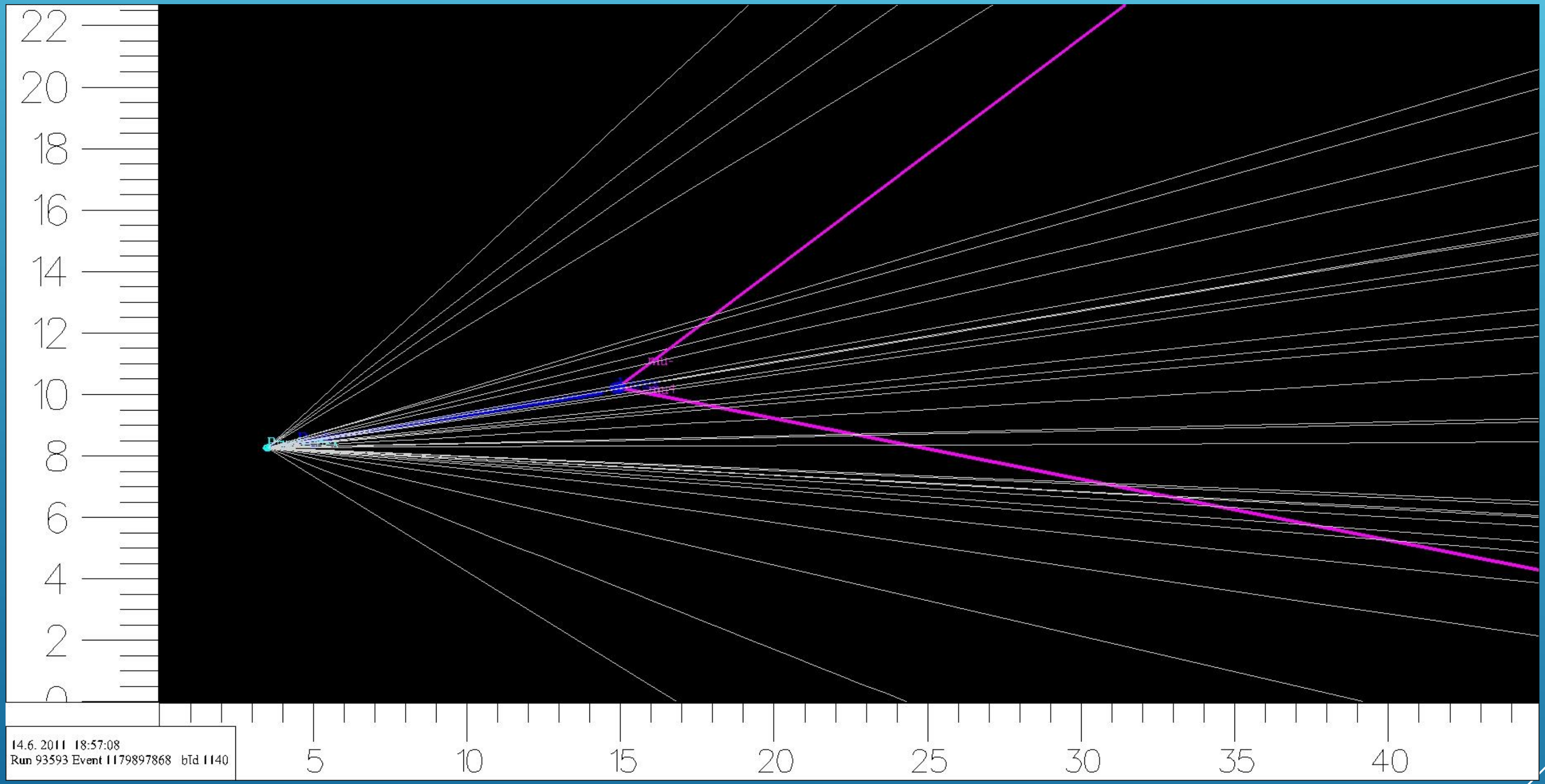


Gas Detectors

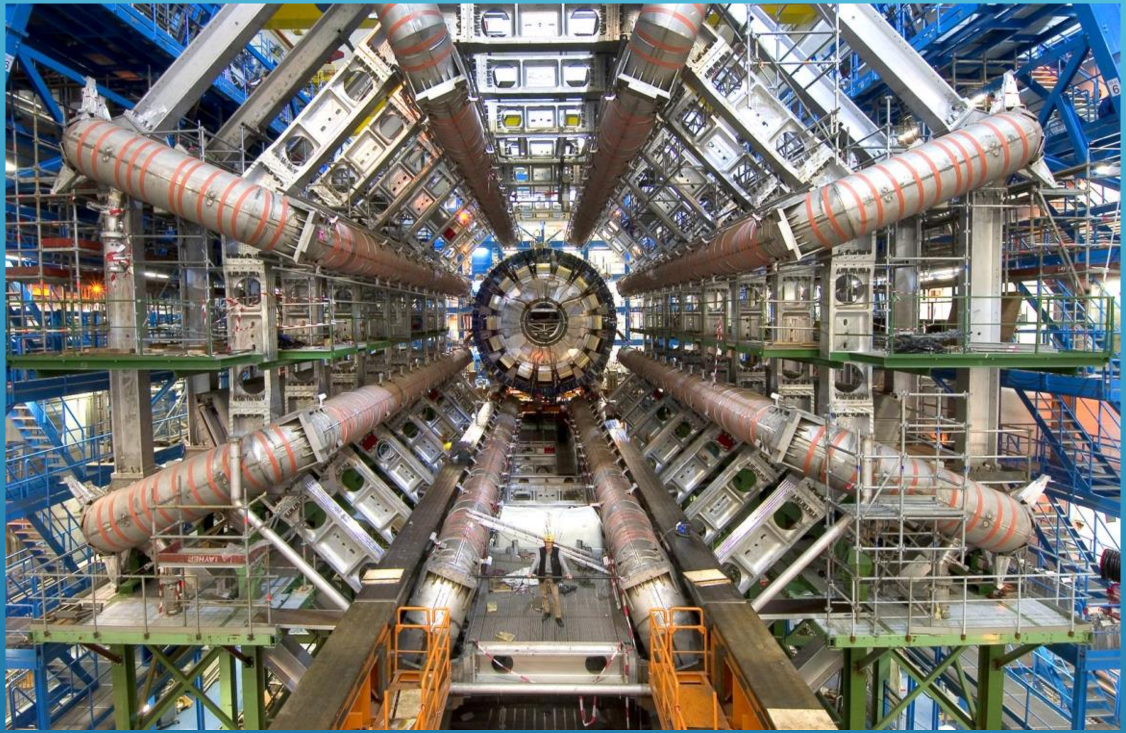


LHCb : B^0->μμ

The tracking is able to identify the B meson decaying few mm after is was created by the pp colision

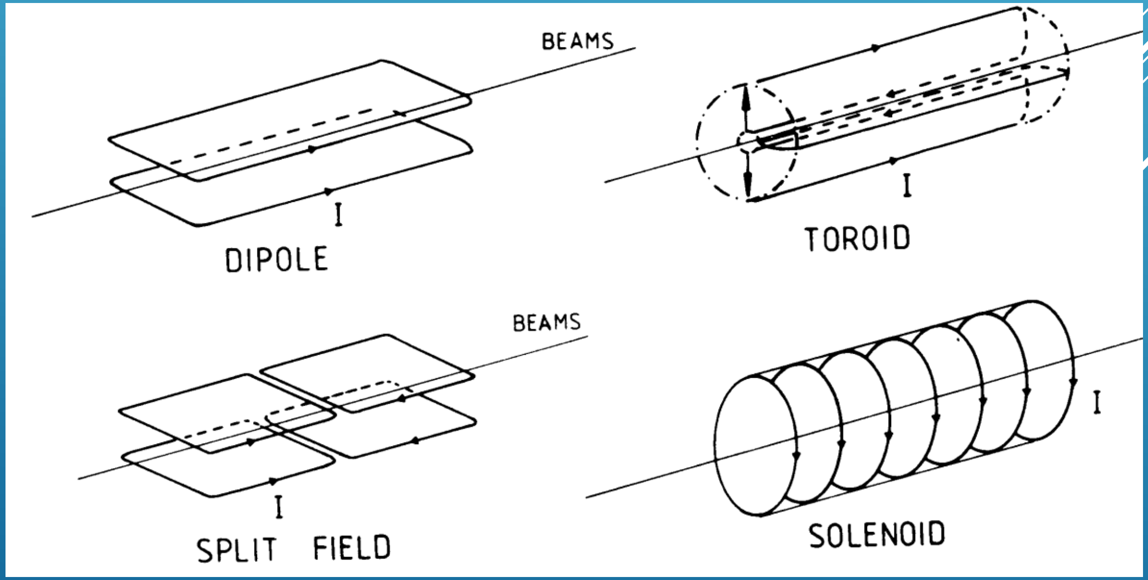


MOMENTUM MEASUREMENT (CHARGED PARTICLES)



We need a magnet

- The particle's trajectory is bent inside the magnet
- We measure the curvature ρ
- $p_t(GeV/c) = 0.3B(Tm)\ \rho$

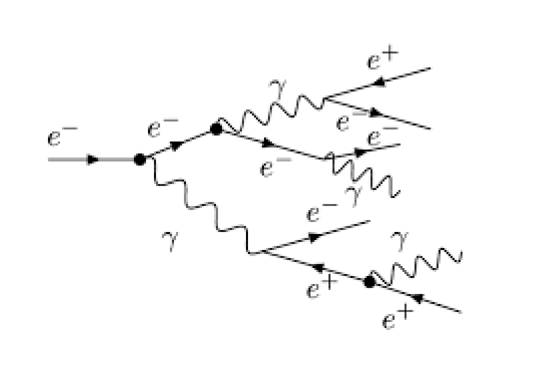


ENERGY AND POSITION MEASUREMENT (NEUTRAL AND CHARGED PARTICLES)

CALORIMETERS

Principle :

- Particles loose their energy in an absorber. We measure that energy
    - If the absorber = detector we measure the total energy
    - If the absorber is inactive we sample the energy losses and compute the energy
    - We detect light produced inside the detection media



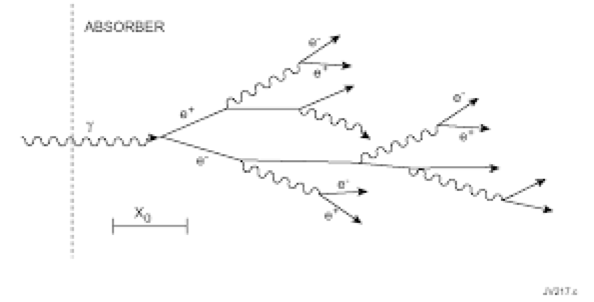
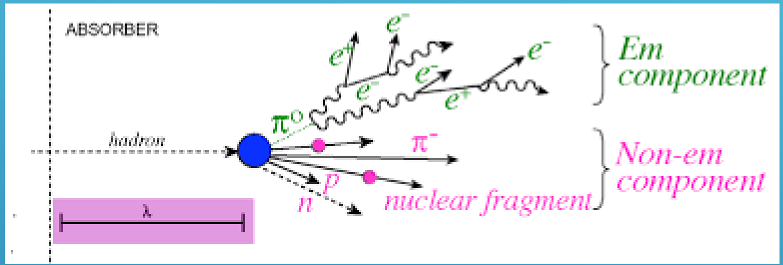
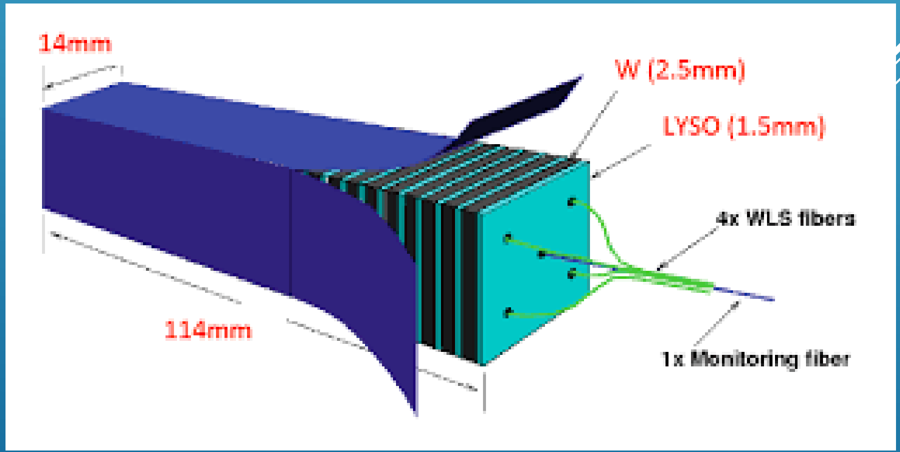


Figure 5: Schematic development of an electromagnetic shower.

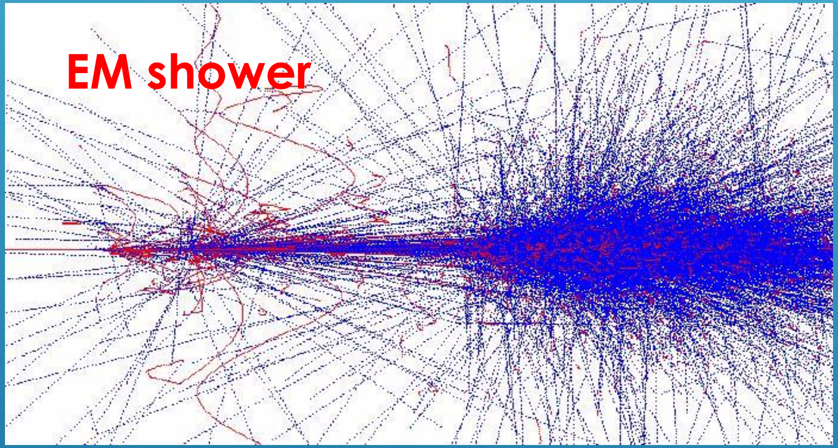


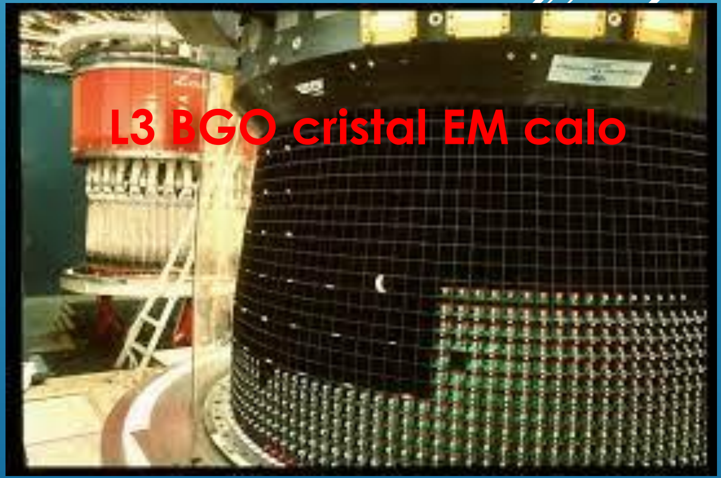


Calorimeters

Heavy, dense detectors, stop almost (but energetic muons) all particles which loose their energy inside

- Electromagnetic for e^{-+} and photons
  - Radiation length X_0, Moliere Radius
- Hadronic for pions, protons
  - Interaction length λ_I, compensation





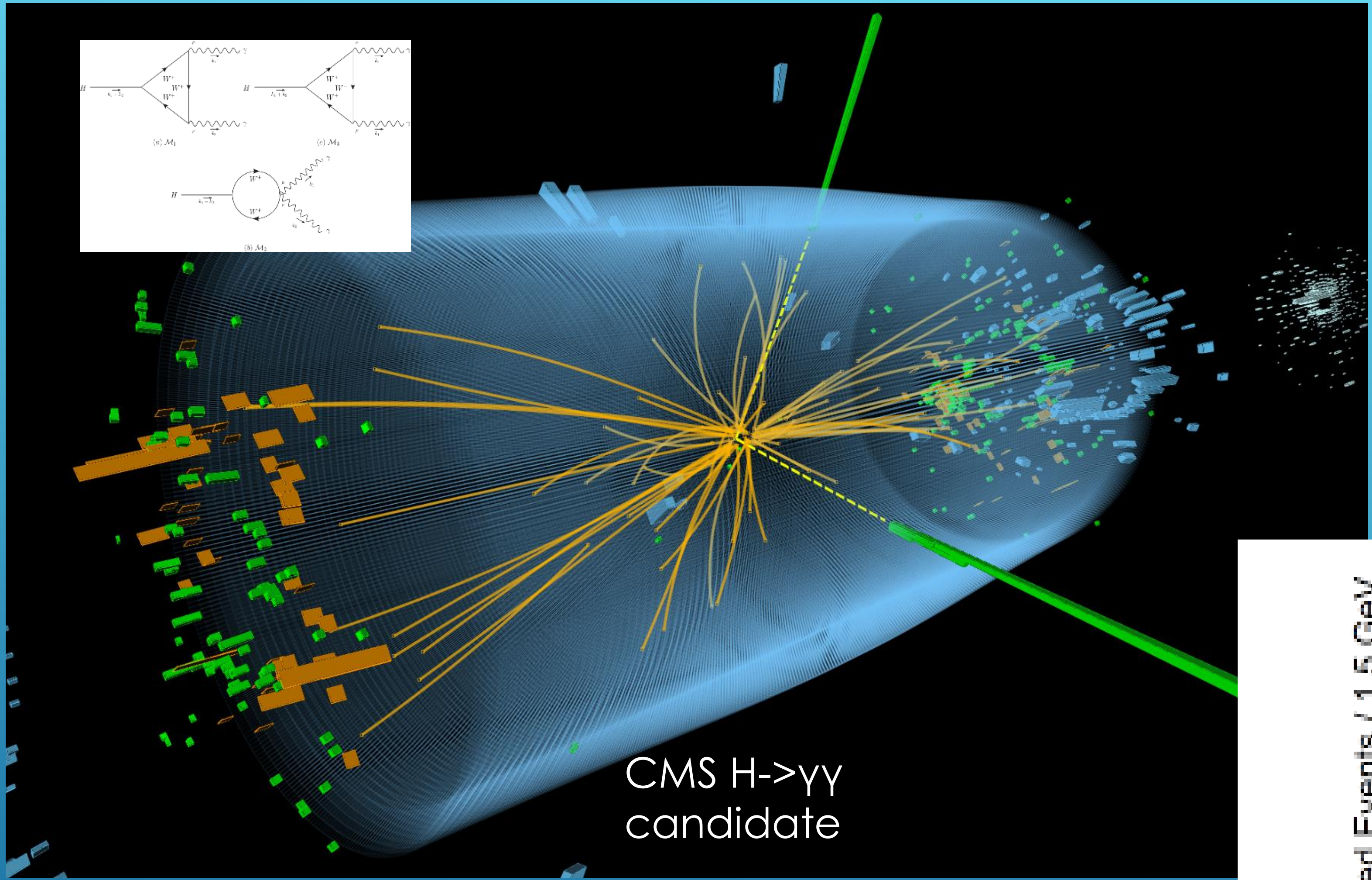
Energy Resolution

a: stochastic term

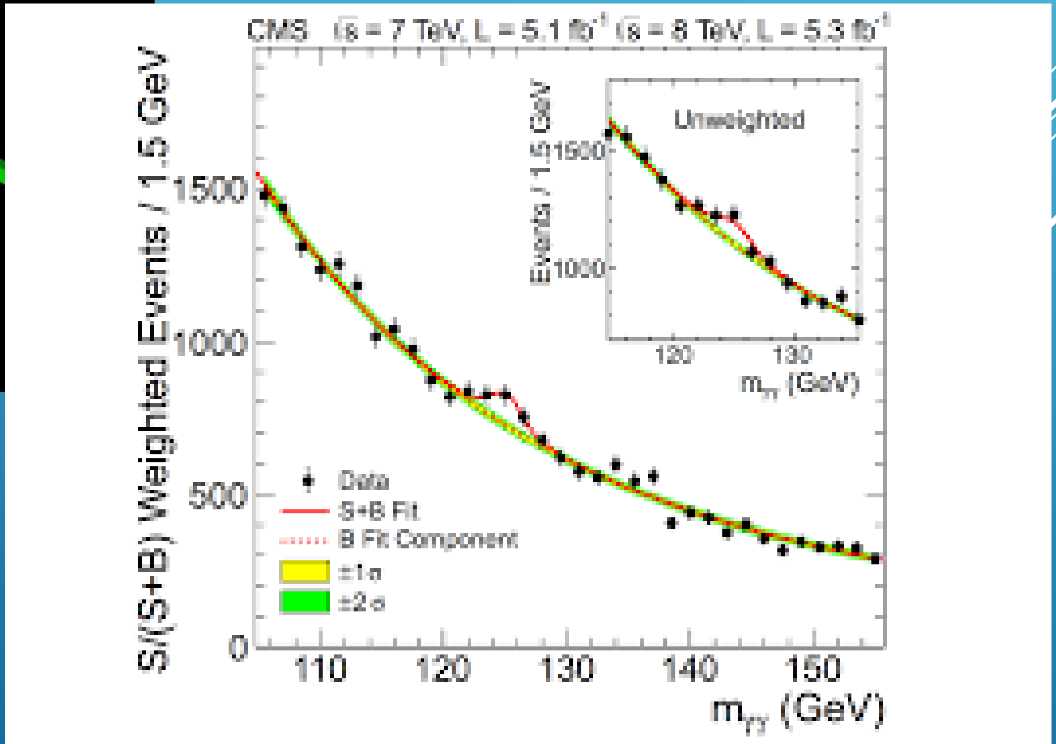
b: Noise

c: constant

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



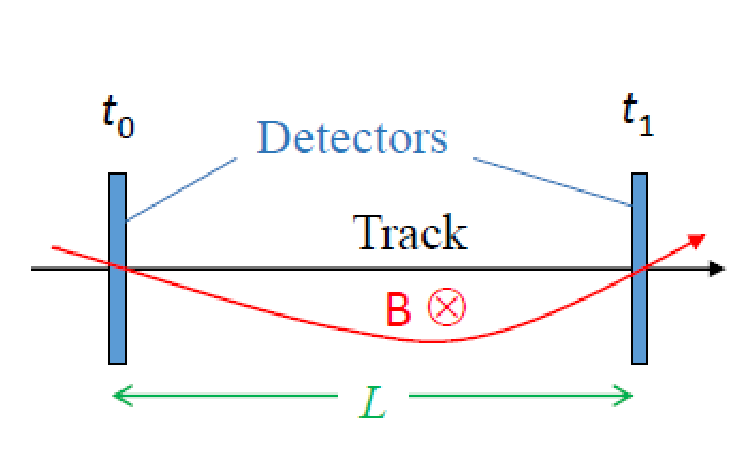
CMS H->γγ
candidate



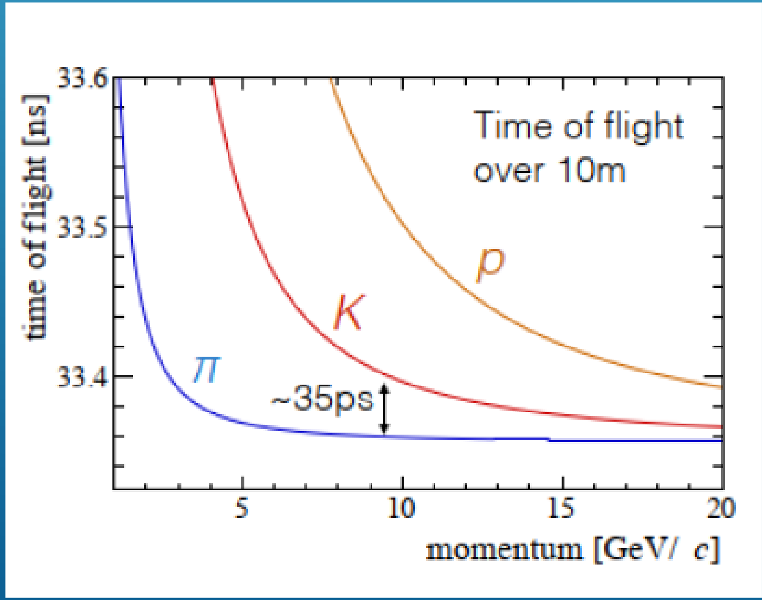
CMS √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 5.3 fb⁻¹
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
m_γγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2σ
m_γγ (GeV)

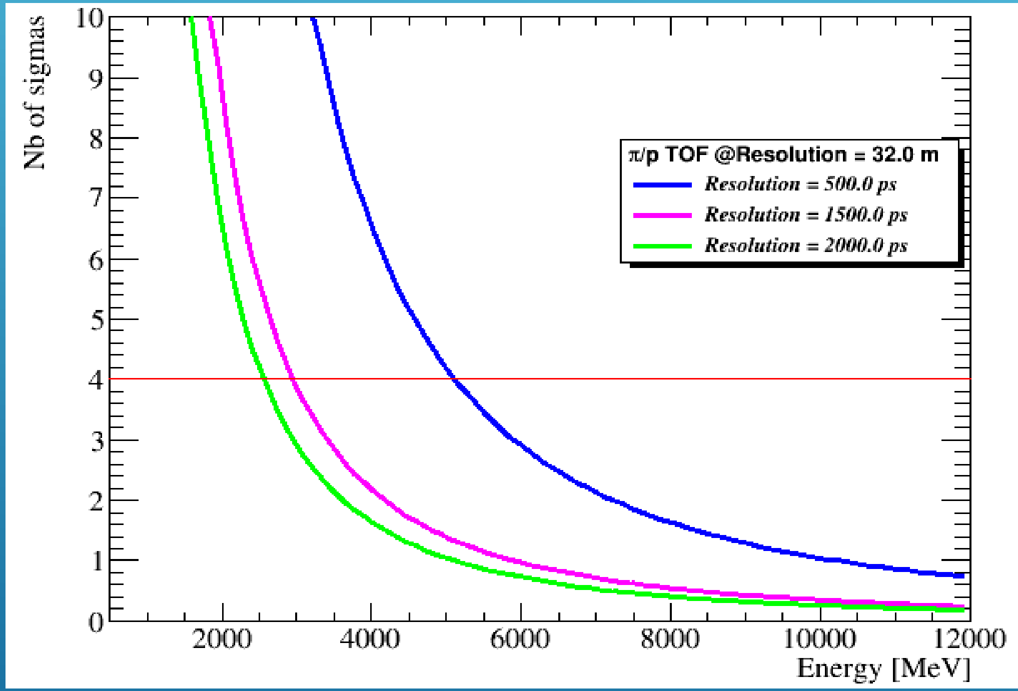
PARTICLE IDENTIFICATION

- TOF heavy particles travel slowly !!! Less than few ns time difference between p and π over 30 m !
- Able today to measure ps !



$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left\{\sqrt{1+\frac{m_1^2c^2}{p^2}} - \sqrt{1+\frac{m_2^2c^2}{p^2}}\right\} \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

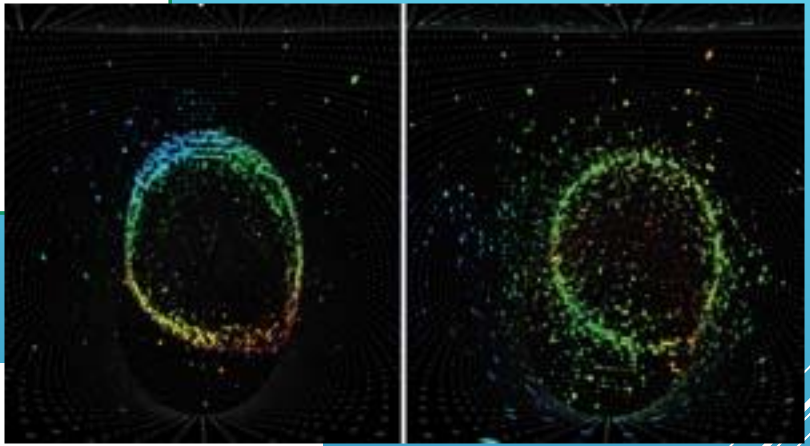


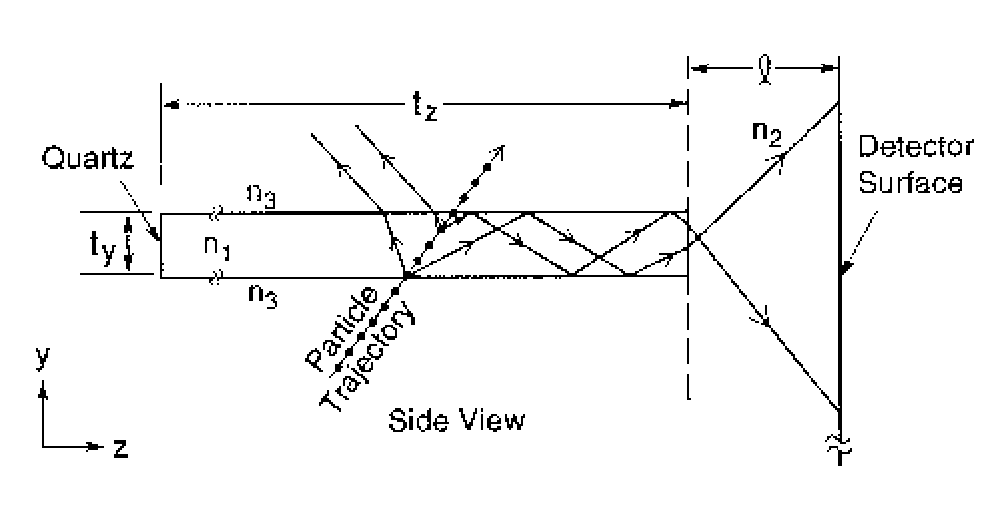


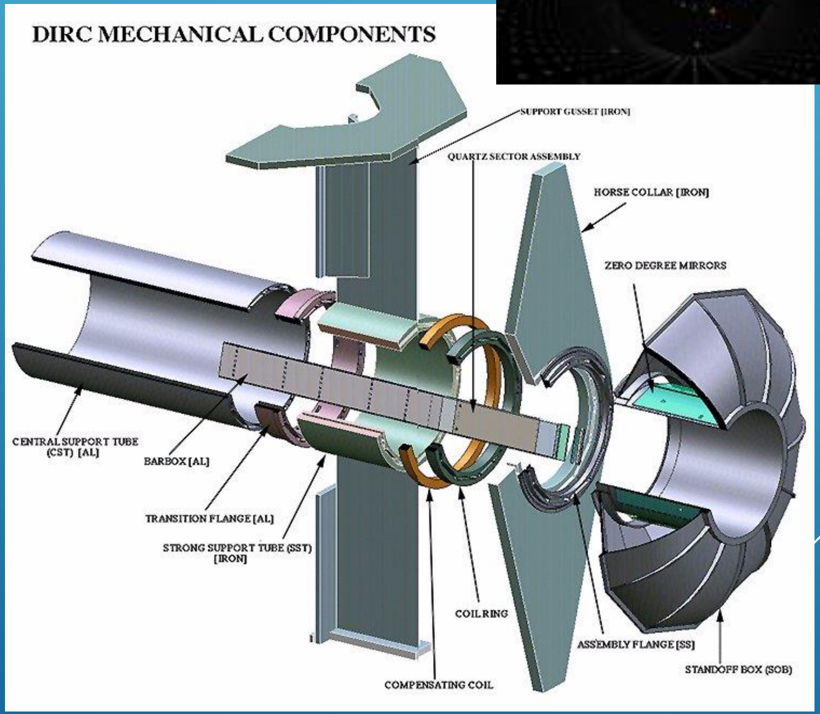
PID CHERENKOV COUNTERS

Particles crossing a medium will emit light at an angle $\cos\theta_c = 1 / (n\ b)$
n = refractive index of the medium

- Measuring θ_c we know the particle
- We need a radiator and a photo detector







Muons and the matter

Muons will :

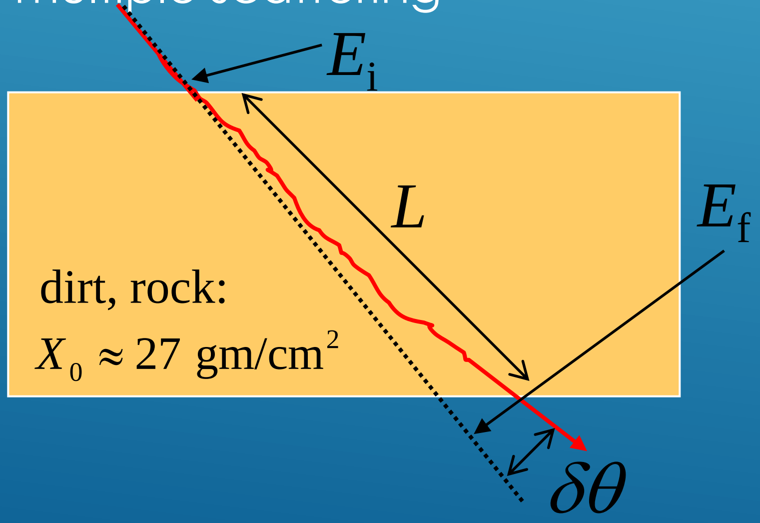
- Interact with matter and will loose their energy by ionization

$$\frac{dE}{dx} \approx 2.3 \text{ MeV/gm/cm}^2 \approx 0.6 \text{ GeV/m} \text{ in rock}$$

- Change their direction because of multiple scattering

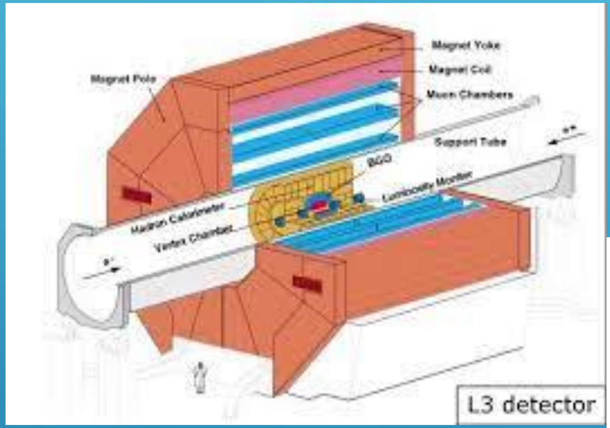
$$\delta\theta = \frac{13.6 \text{ MeV}}{\sqrt{E_i E_f}} \sqrt{\frac{L}{X_0}}$$

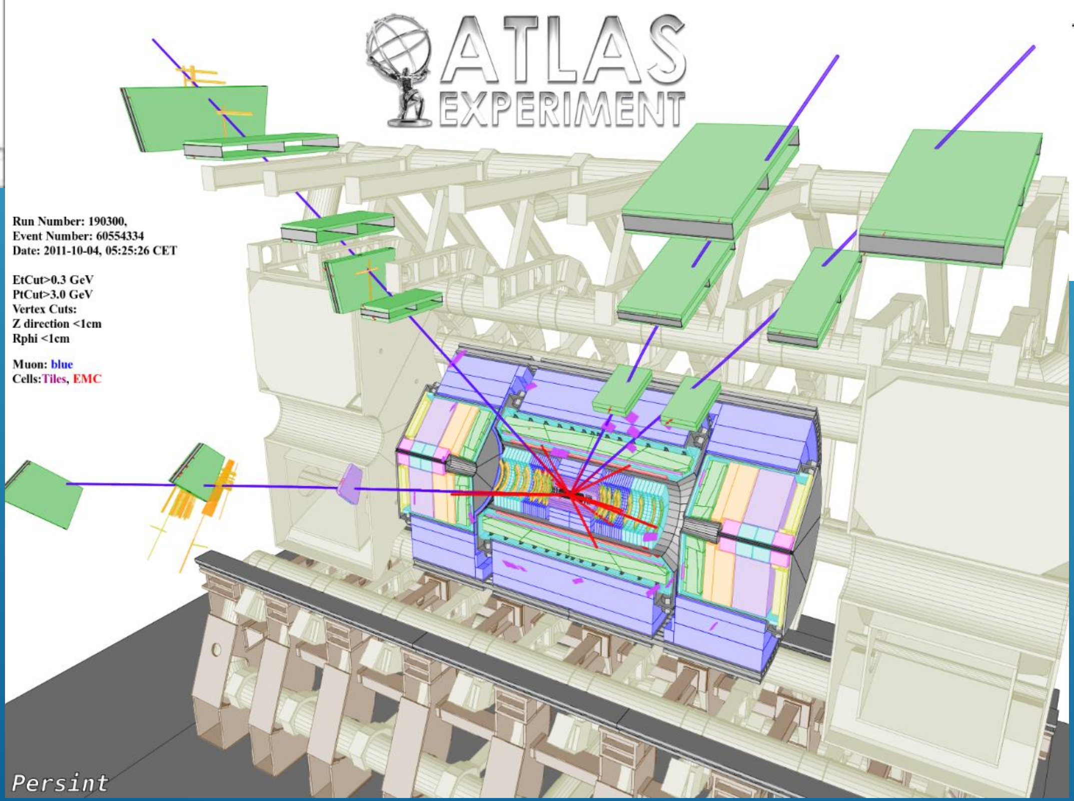
$$E_i - E_f = L \frac{dE}{dx}$$

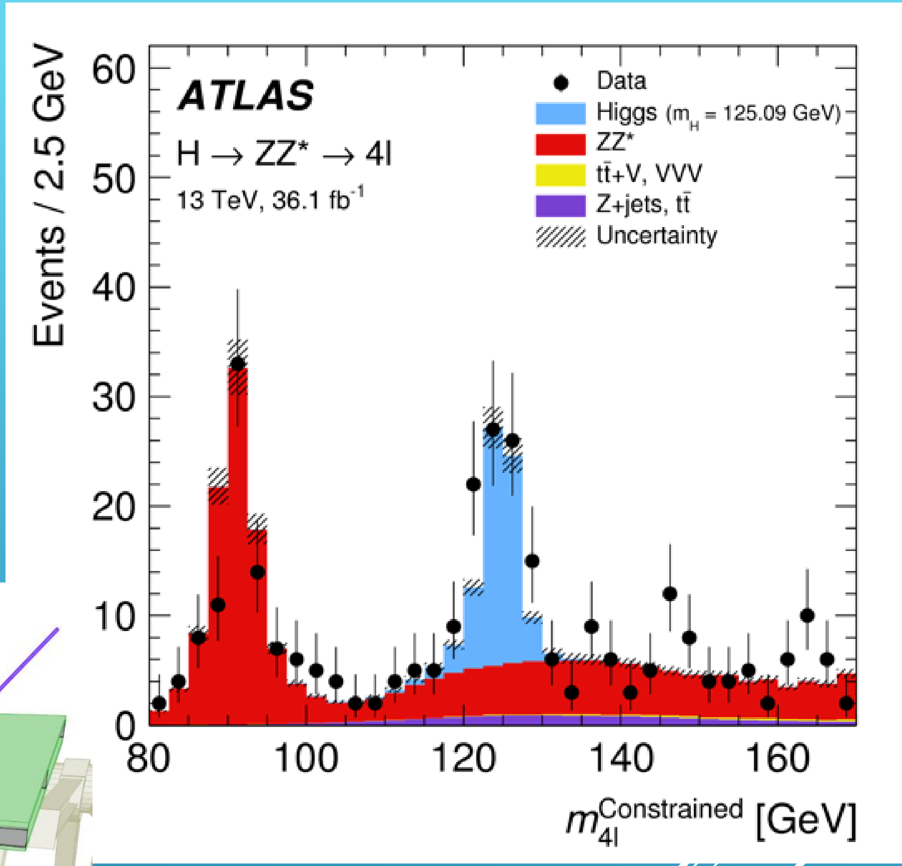


MUON IDENTIFICATION

- Tracking Devices behind absorber, usually the calorimeters







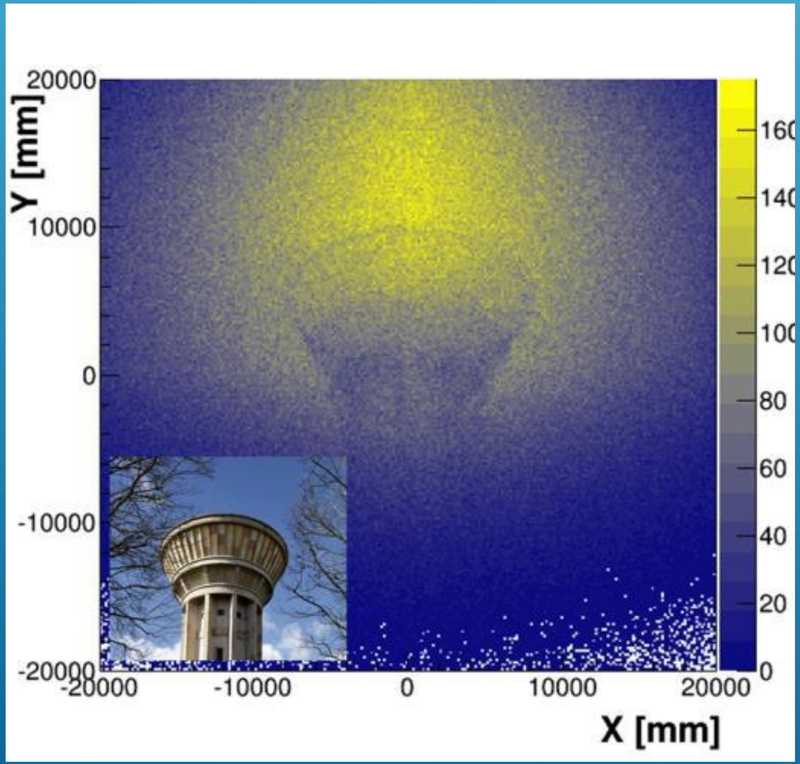
SUMMARY

- Particle detection is based on interactions of incident particles with matter
- We collect charges or light and form an electrical pulse
- Front end electronics + electronics + raw data handling
- Raw data transmission, higher level data samples and decisions
- Data reconstruction, tracks, energies etc, physics objects
- In parallel simulation !

A FUN APPLICATION

Using muons for scanning !

- Muons are very penetrating particles
- Muons will be absorbed by heavy structures or may cross large voids without stopping.
- Muon variation density should image the structures they cross !



The birth of the idea

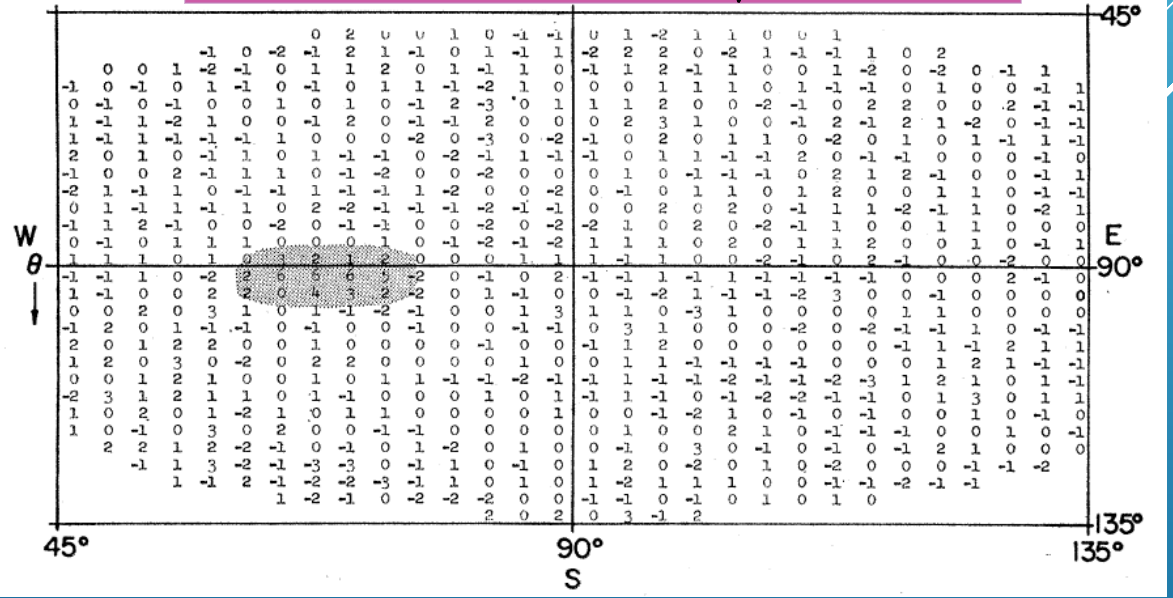
Luis Alvarez* invented muon tomography in 1960's to study the 2nd Pyramid of Chephren

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, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

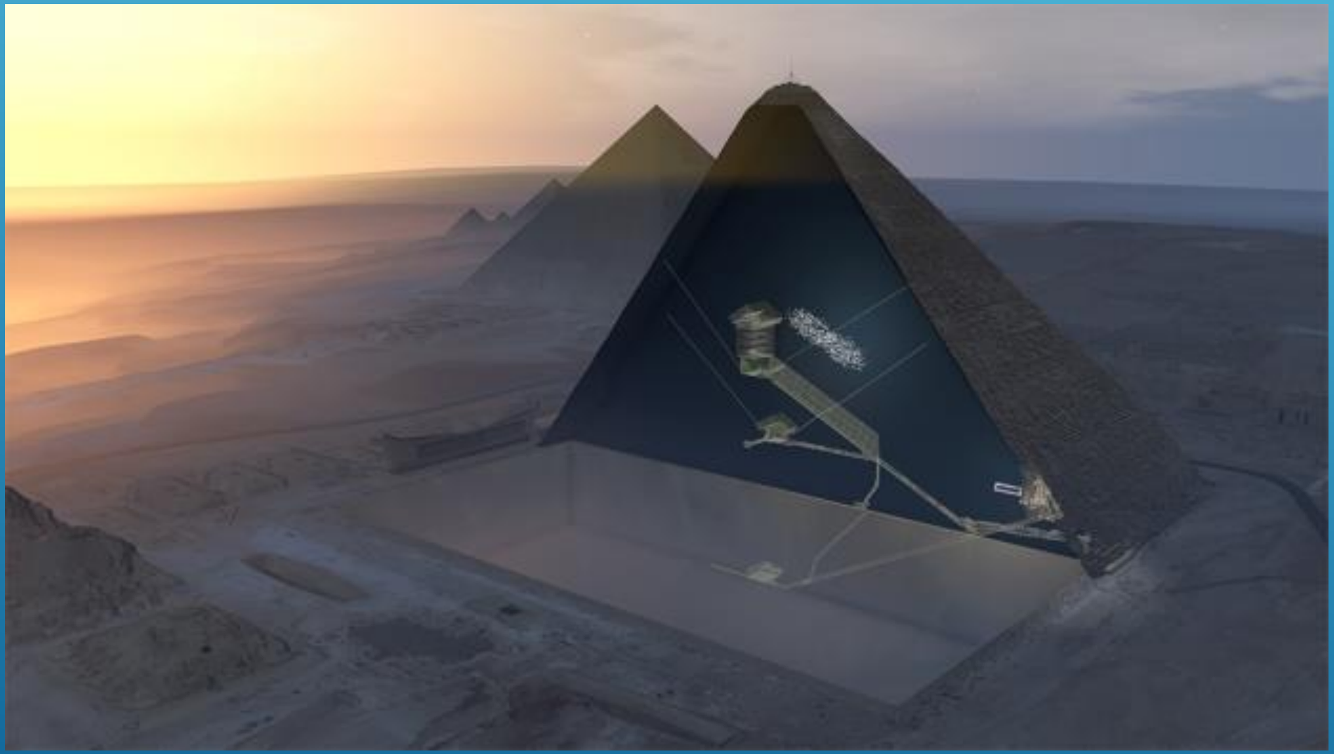
$$(N_{Data} - N_{Pred}) / \sqrt{N_{Data}}$$

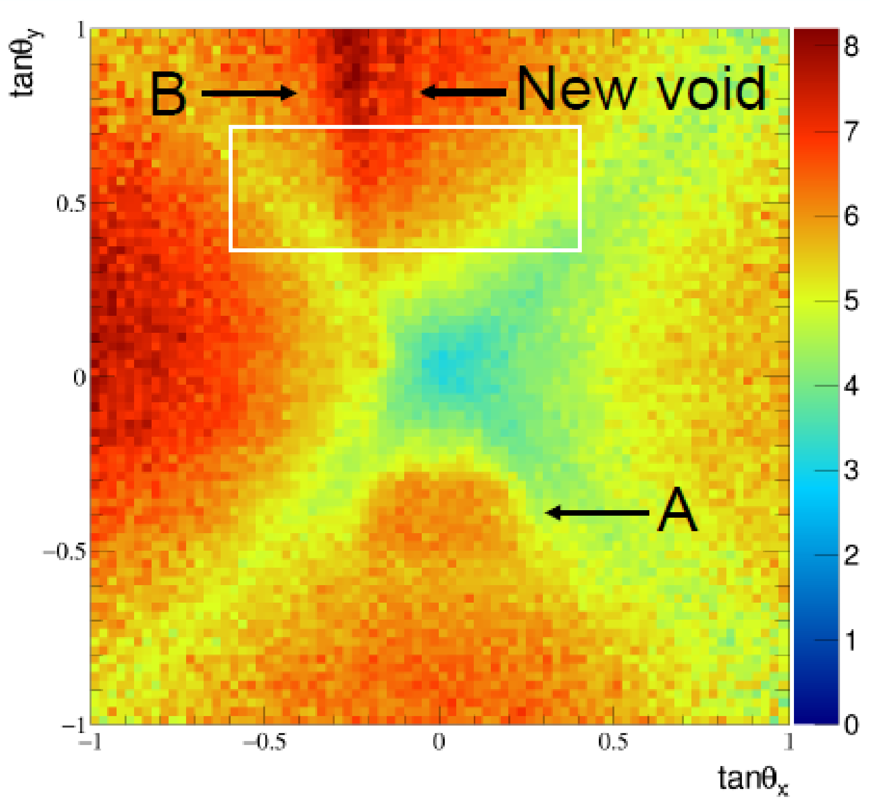


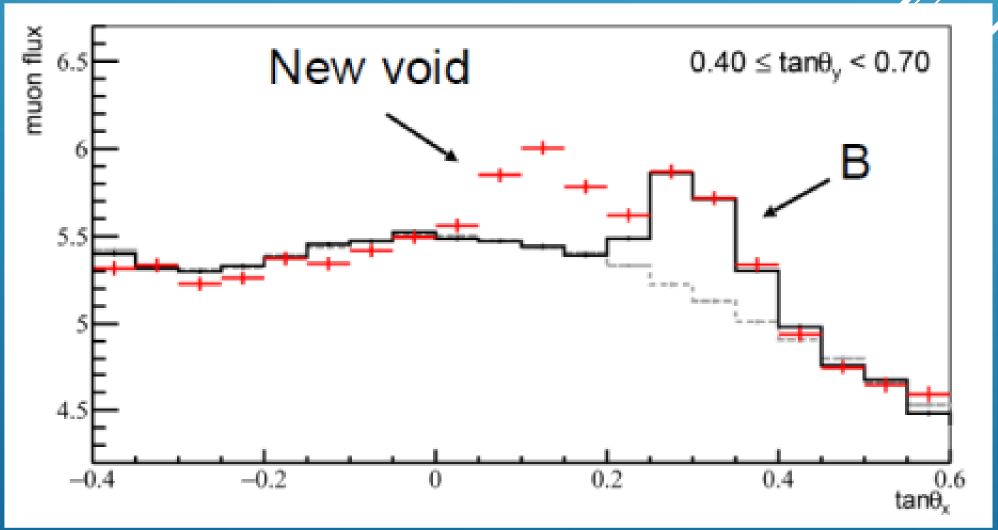
L.W. Alvarez, *et al*, *Search for Hidden Chambers in the Pyramids Using Cosmic Rays*, Science **167**, 832-839, 1970.

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

388 | Nature | VOL 552 | 21/28 DECEMBER 2017







A MORE DIFFICULT CASE : TUMULUS

The Apollonia tumulus as a benchmark for the method

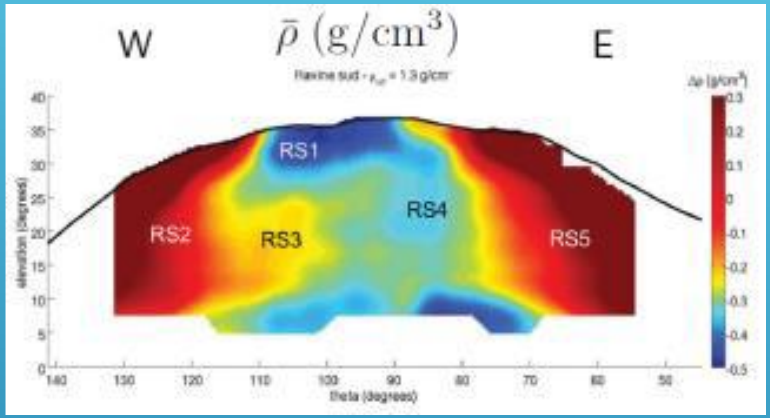
- Existing monument
- Density anomalies detected by other methods

Difficulties :

- Looking for an object with similar density as the surrounding materials ρ~2.3 gr/cm^3 for dirt and 2.5 for marble !
- If any monument, it must be at the horizon level. Very low number of muons, wait a LONG time !
- Muons must cross a lot of dirt. Need high energy muons, their number is even less !

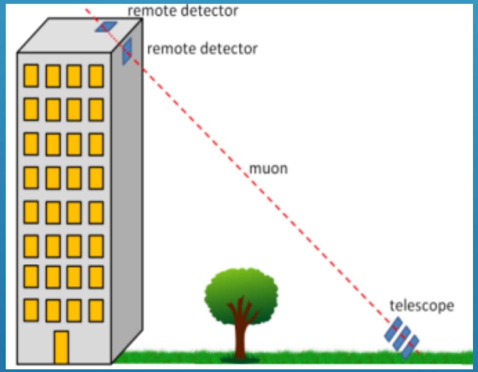

Debon
UnivEarthS
ER-091-XH

Other applications for muon scanning

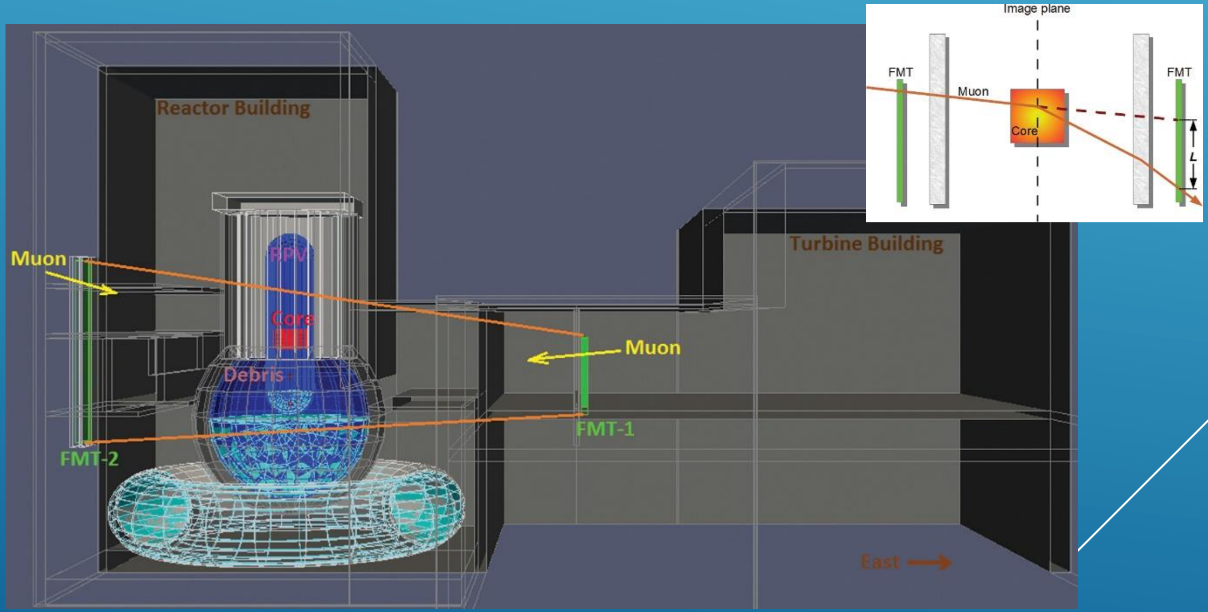


Volcano surveillance, looking to its internal density

Civil engineering



Metrology



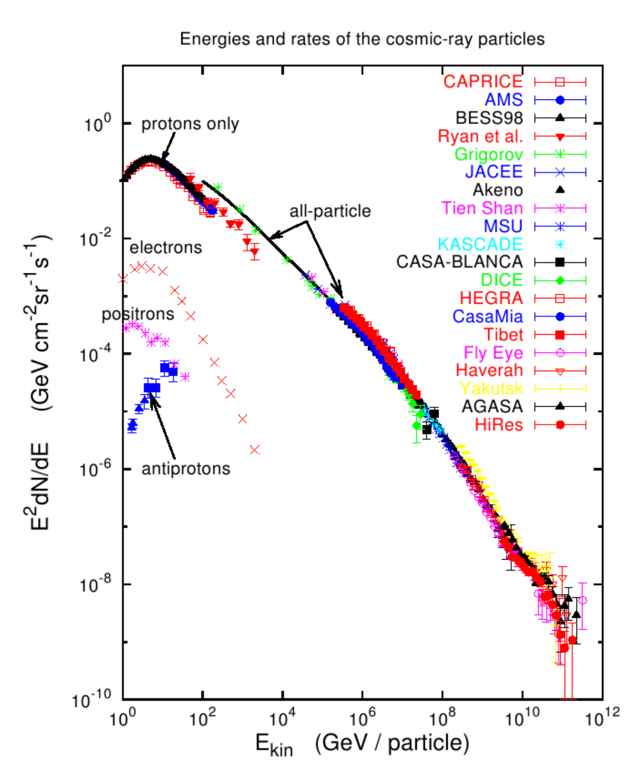
CONCLUSION

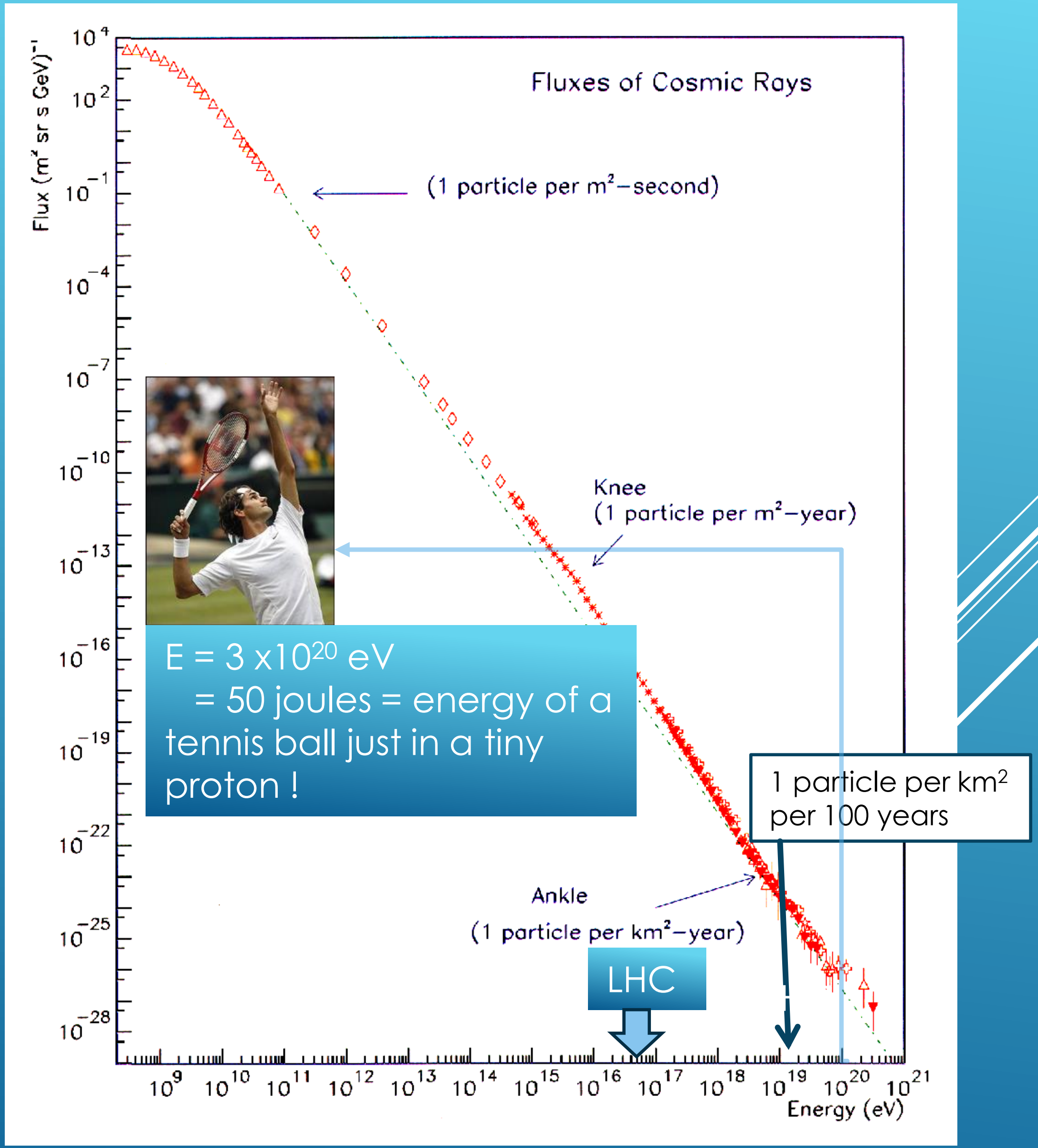
Progress in particle physics, astroparticle and cosmology is closely related with new detectors' developments !

What we know today !

How many particles and what energy ???

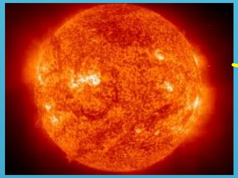
- The energy spans over 12 orders of magnitude
  - Energy spectrum follows $E^{-\gamma}$ where γ = 2.7-3.5
- The flux spans over 32 orders of magnitude !
  - Sea level : 150 particles per m^2 per second

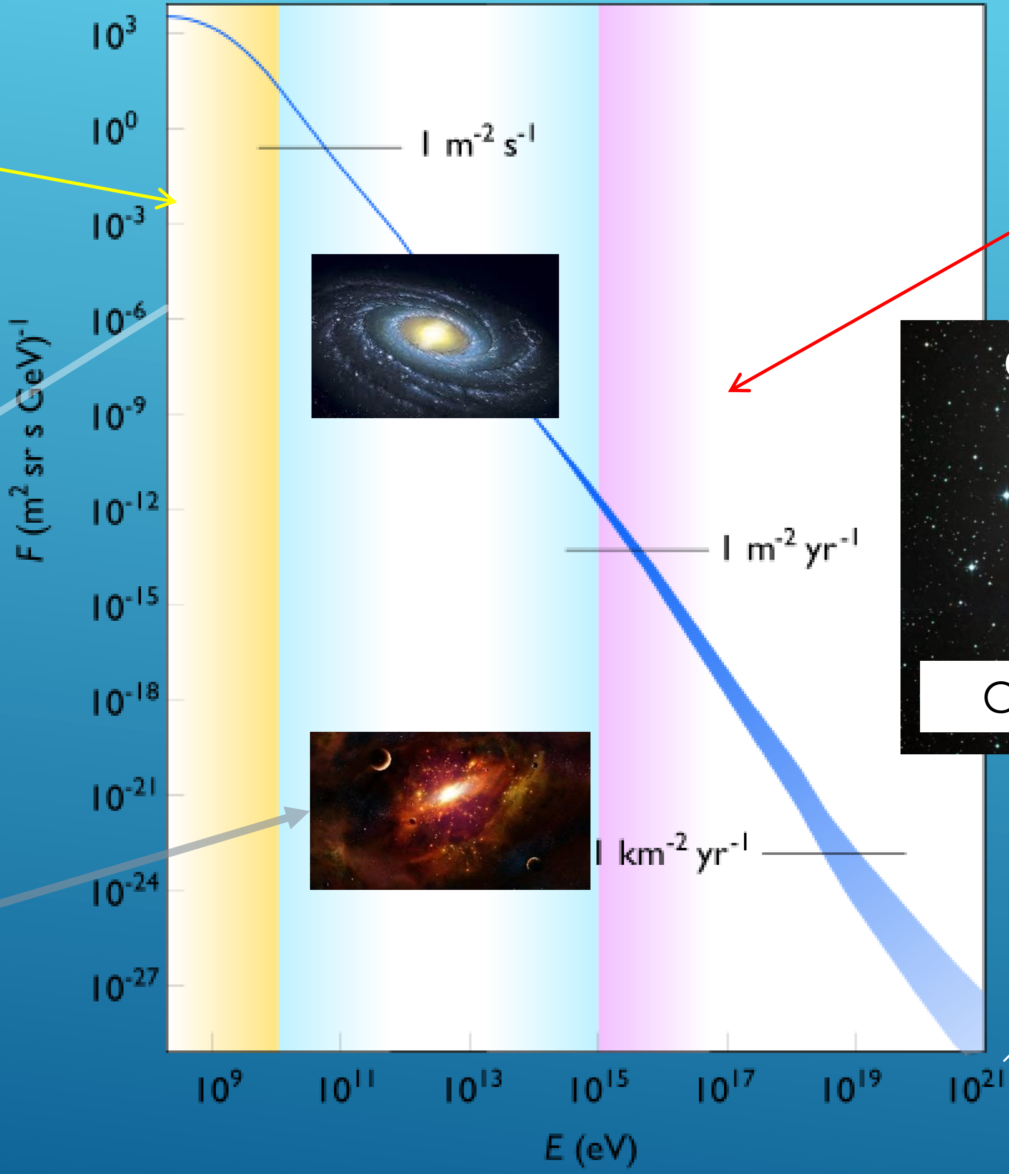




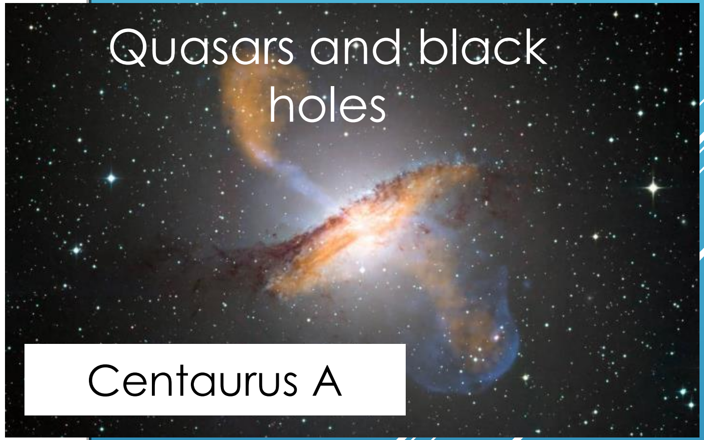
Where do they come from ??

Our sun





Extra galactic



Supernova explosion and remnants