

Particle detectors

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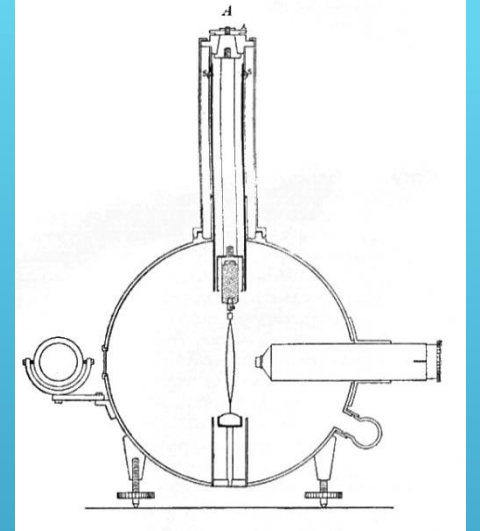
Γενεύη, 20 Απριλίου 2023

Our planet is continuously hit by cosmic rays !

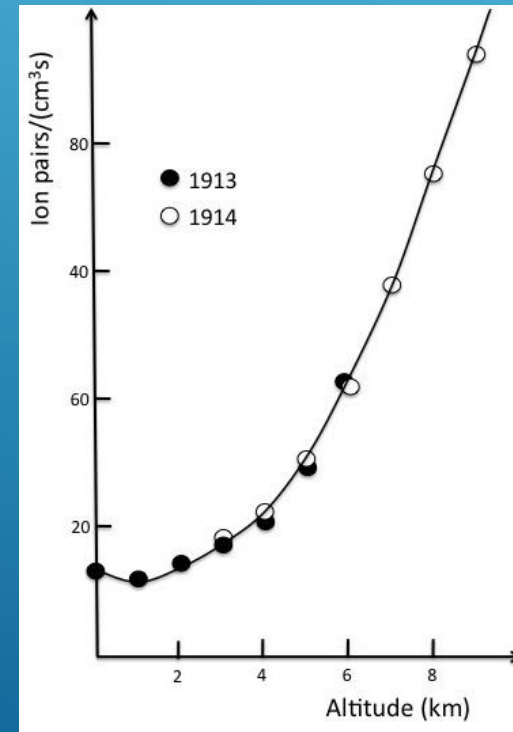


First hints for cosmic rays

- ▶ 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

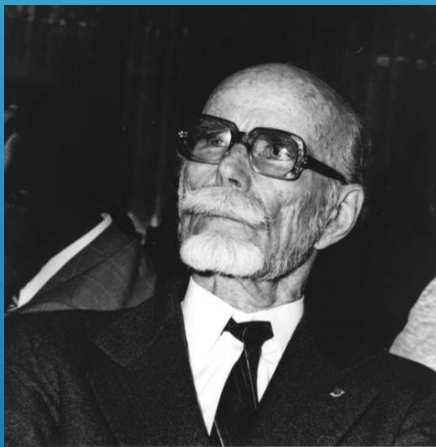


Theodor's Wulf Strahlungsapparat

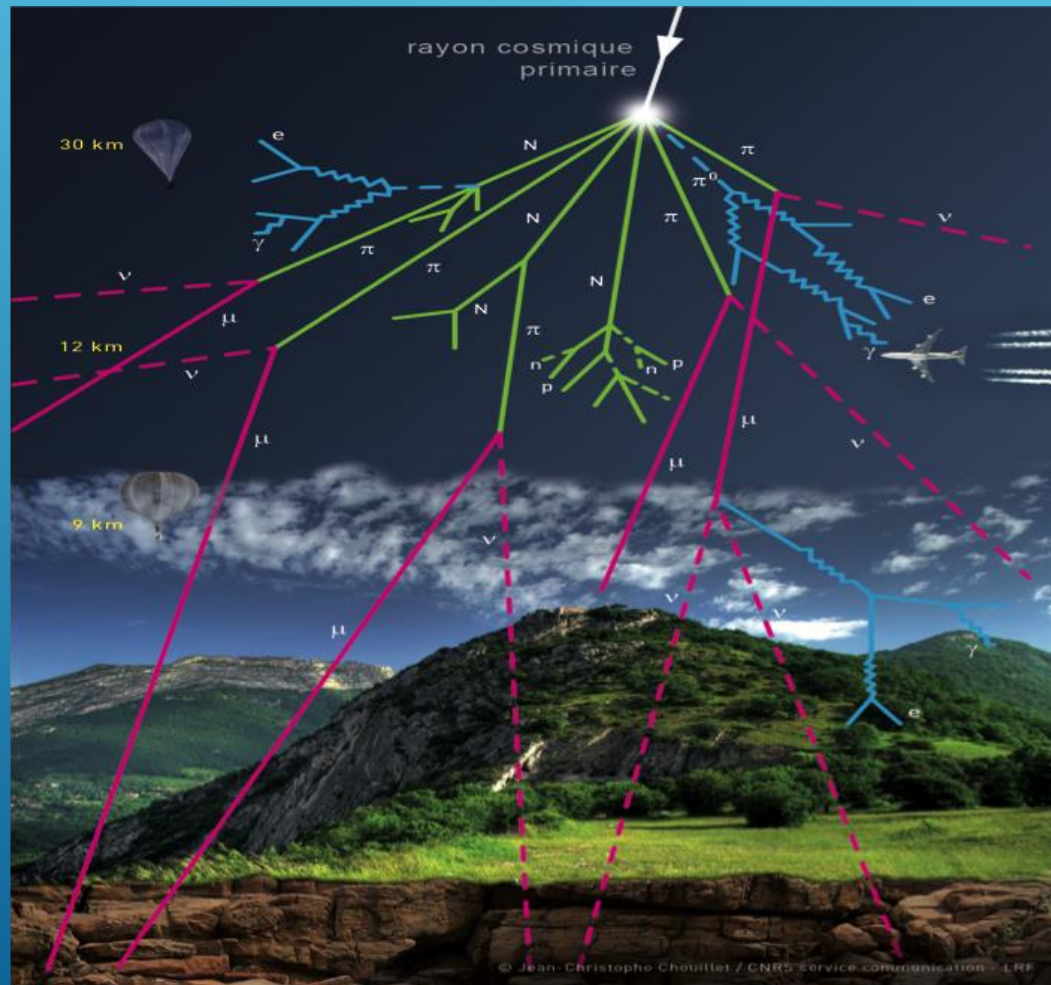


We see showers, particles arrive in group

- ▶ 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: lambda Λ
 - ▶ 1952: xi Ξ
 - ▶ 1953: sigma Σ
- ▶ Birth of a new science: Particle Physics!



Dominiel 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

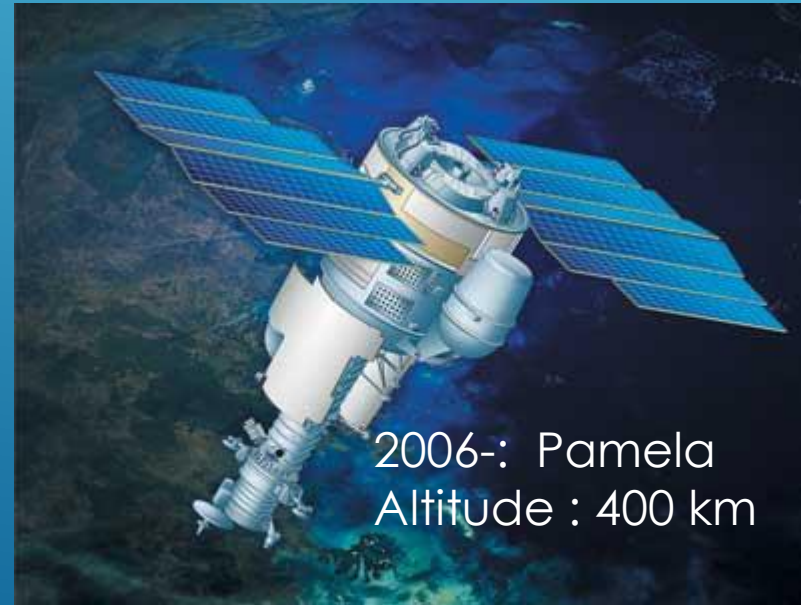
2011-: AMS
Altitude : 400 km



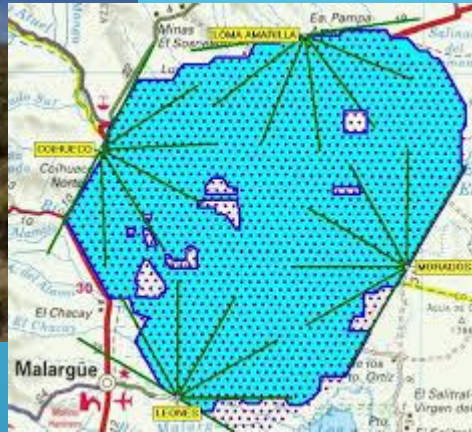
AMS at the international space station looks for anti-matter !



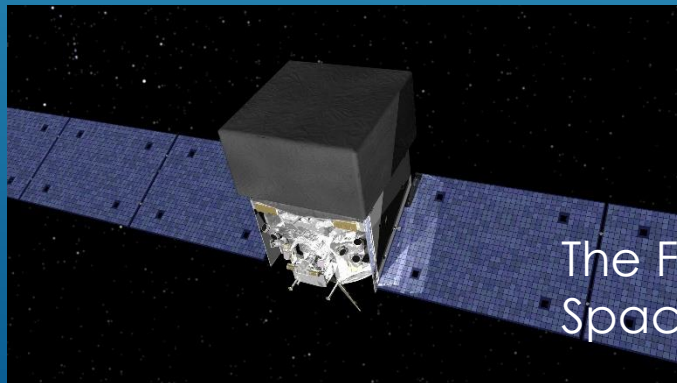
2006-: Pamela
Altitude : 400 km



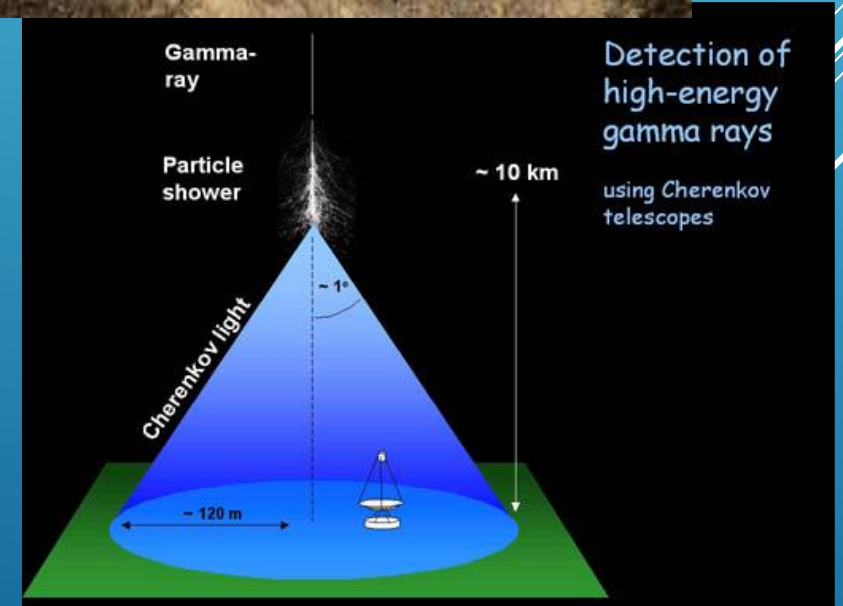
The HESS experiment in Namibia looks for high energy photons



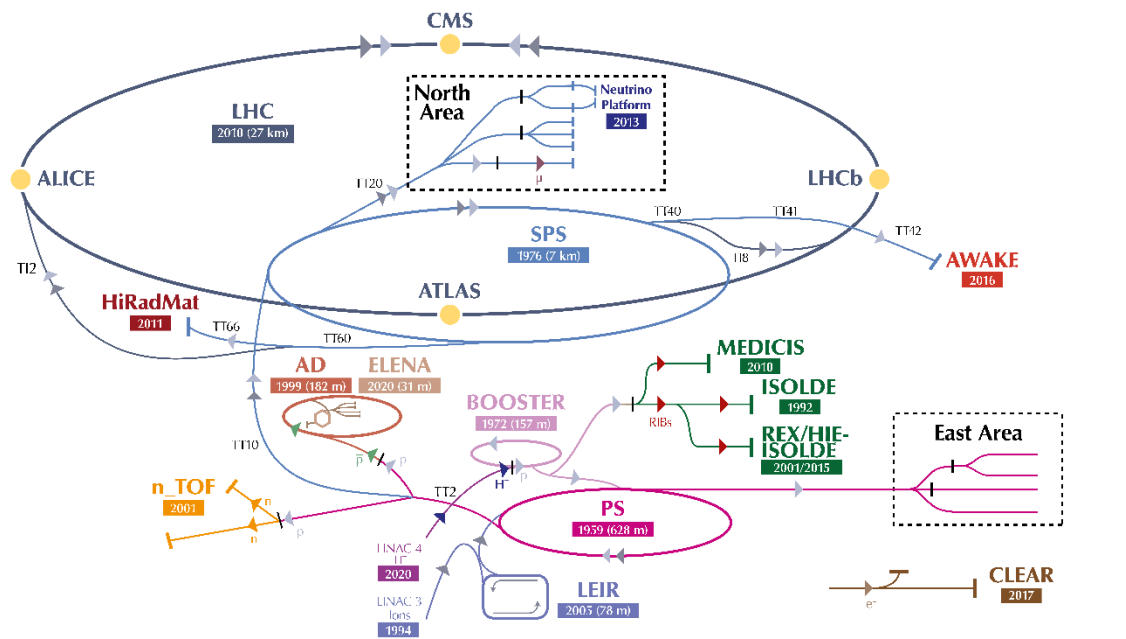
Pierre Auger observatory at Argentina's pampa detects high energy charged particle induced showers using 1600 water tanks of 12K liters separated by 1.5 Km each other. Complemented by fluorescence detectors.



The Fermi Gamma-ray Space Telescope



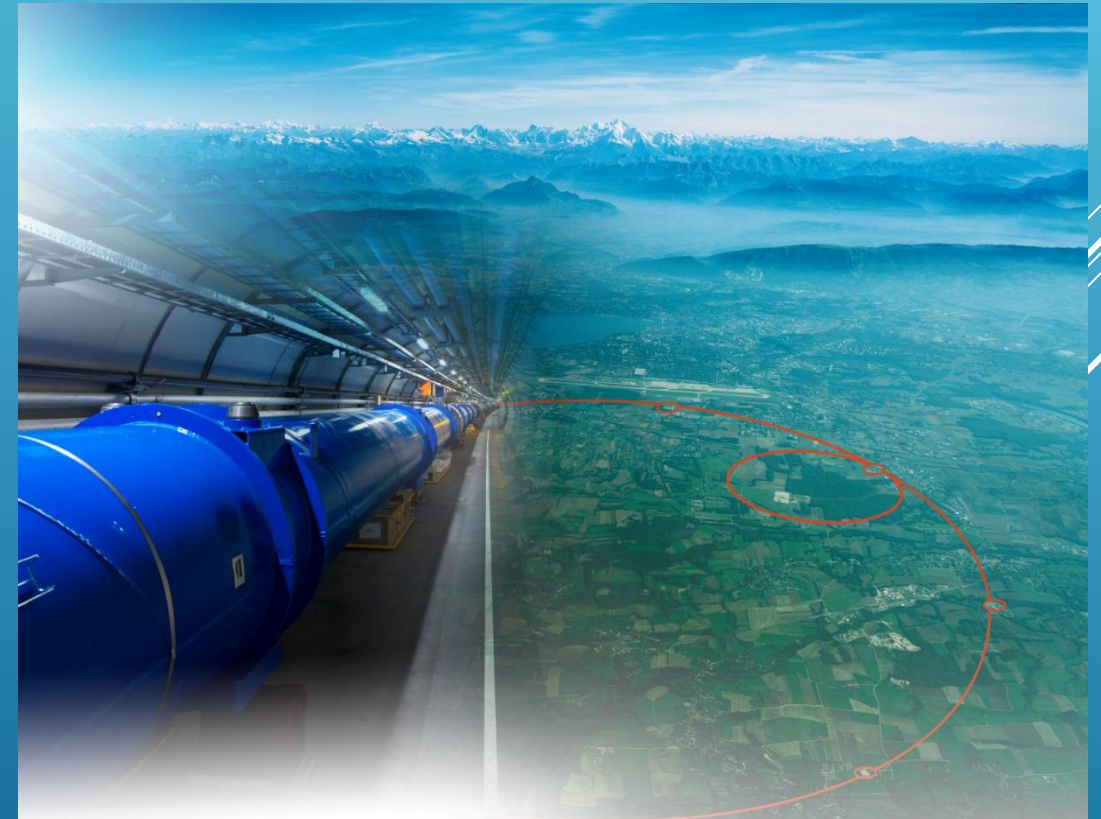
The CERN accelerator complex Complexe des accélérateurs du CERN



▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ \bar{p} (antiprotons) ▶ e^- (electrons) ▶ μ (muons)

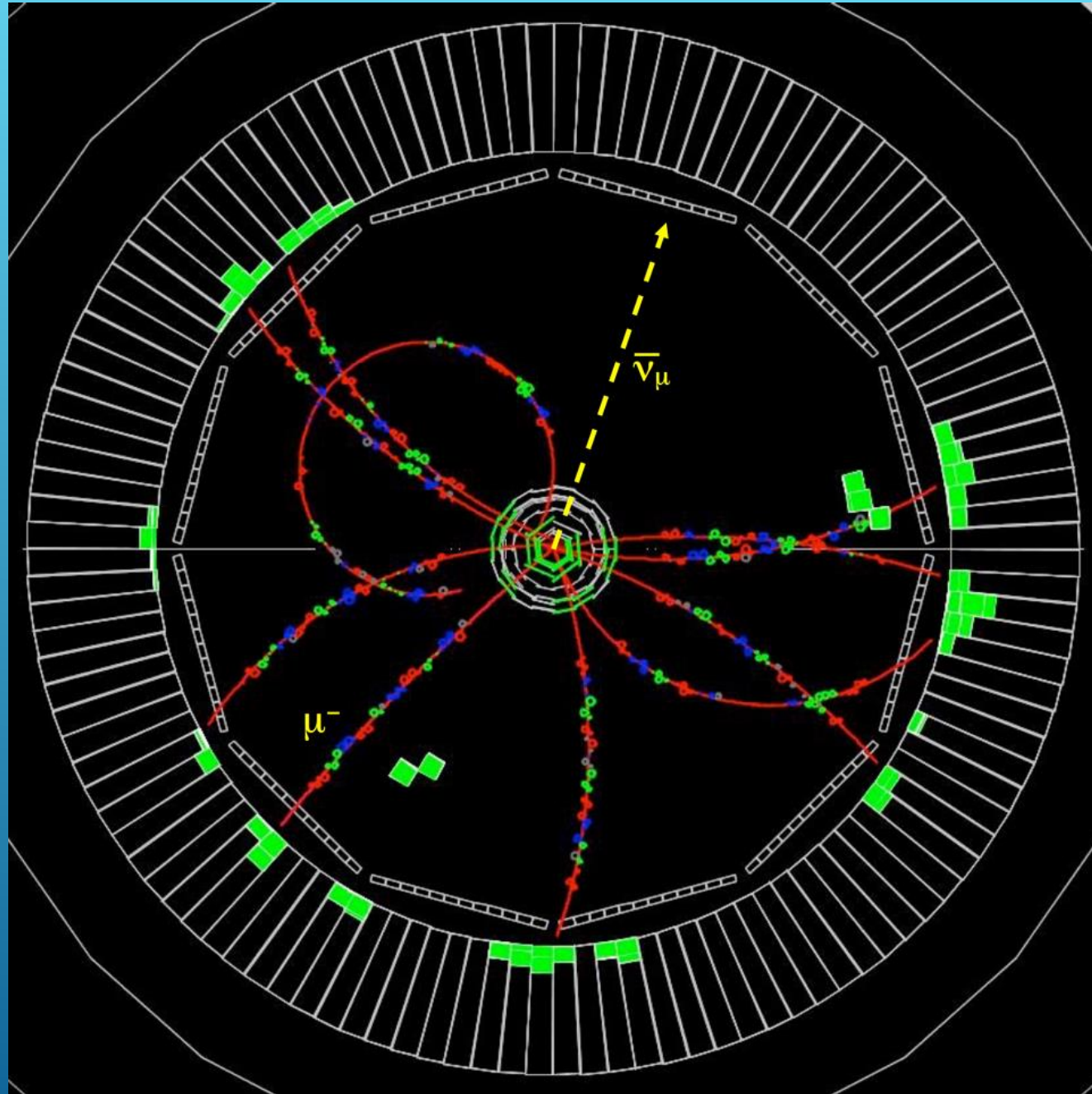
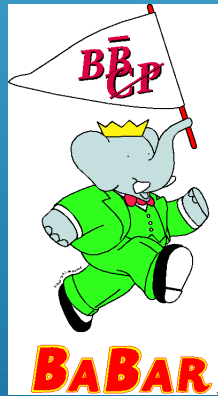
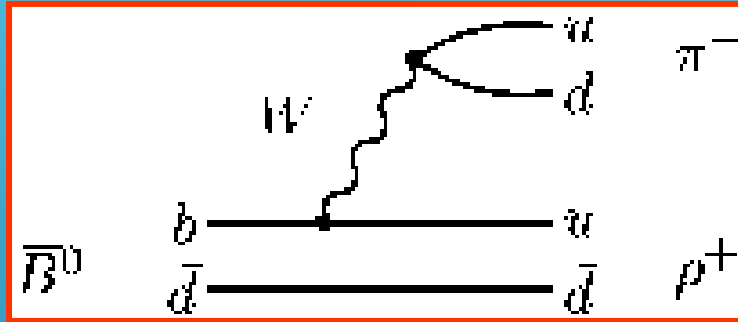
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive Experiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

Emphasis on accelerator physics and detectors



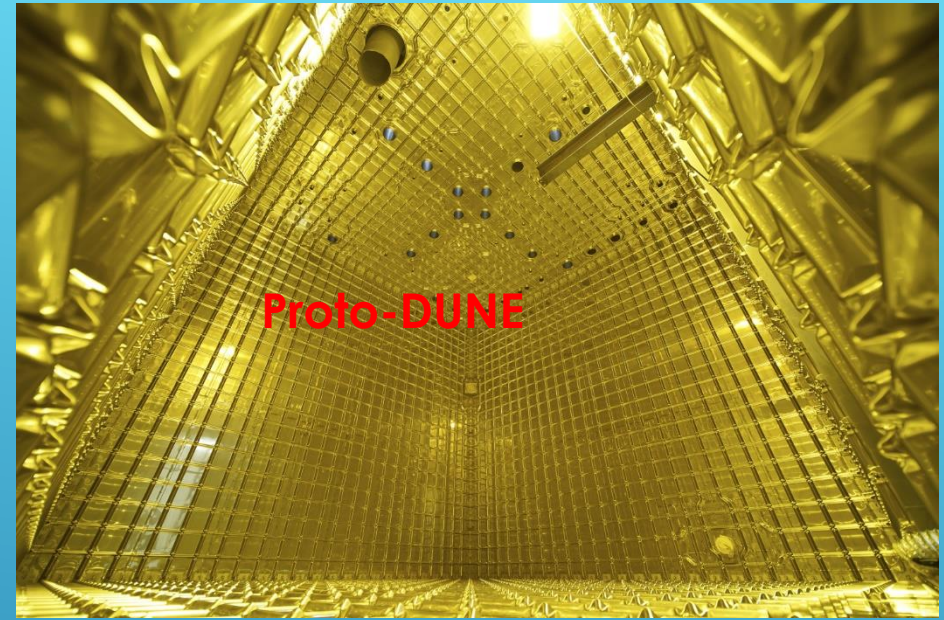
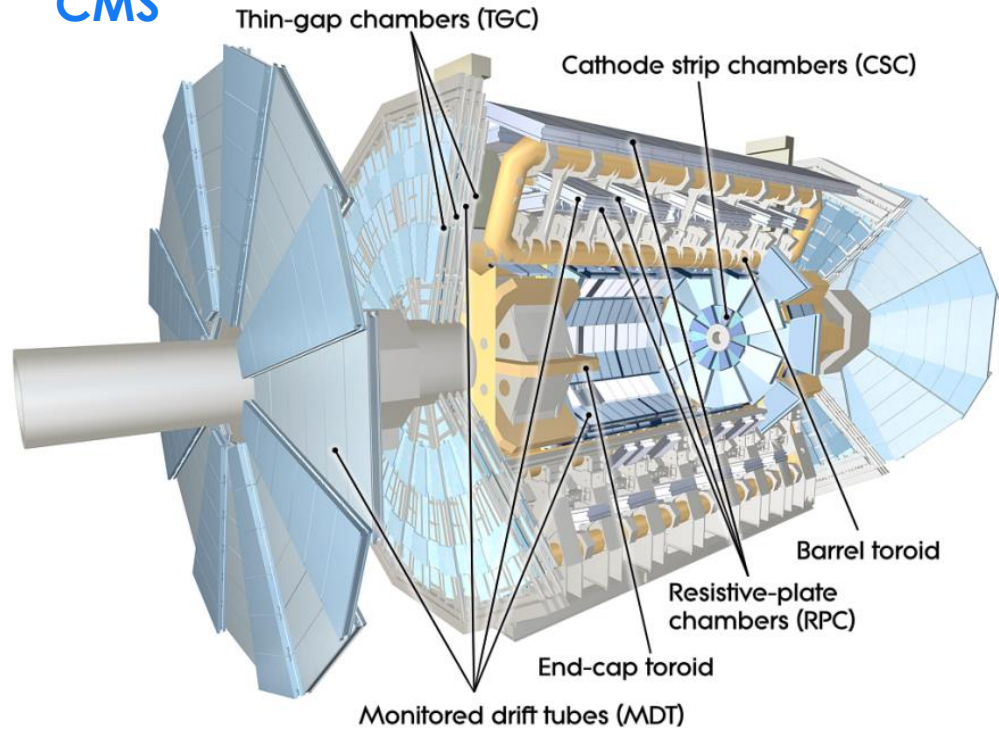
Particle Detectors (1)

$e^+e^- \rightarrow B^0\bar{B}^0 \rightarrow$ decay products

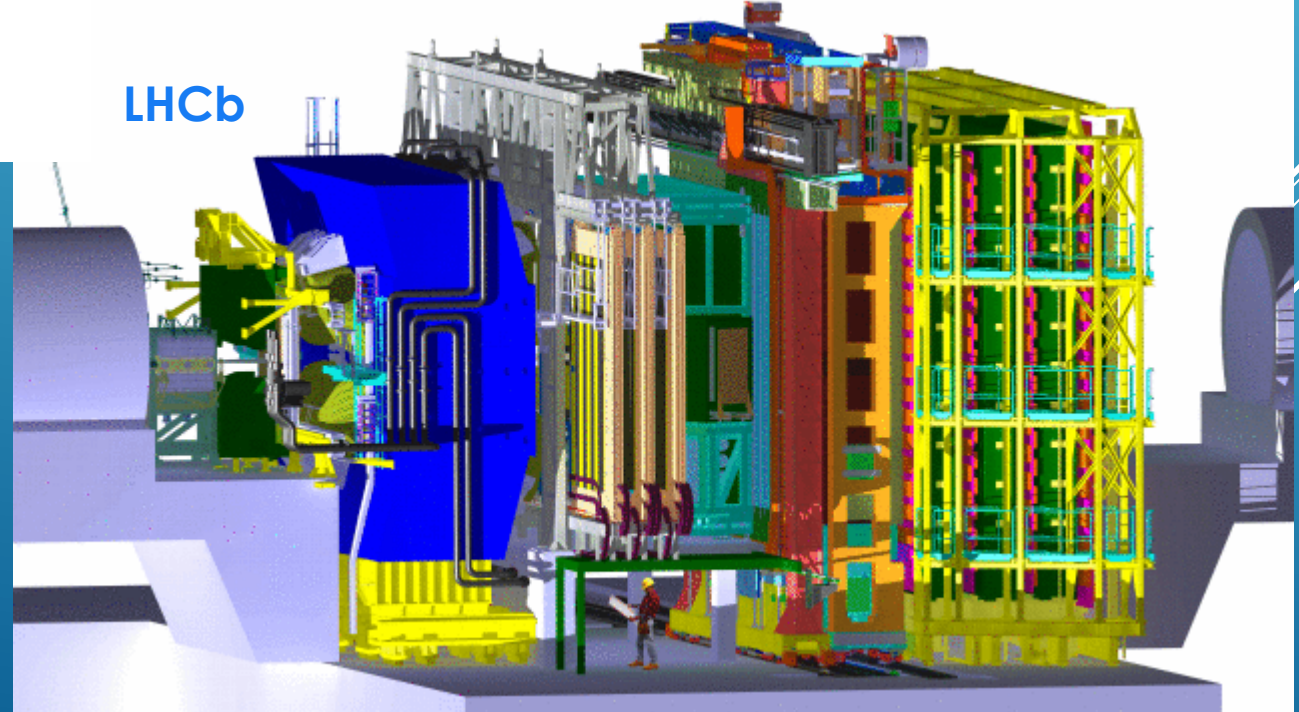


Particle detectors (2)

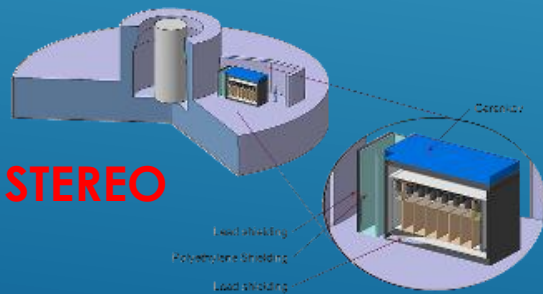
CMS



LHCb



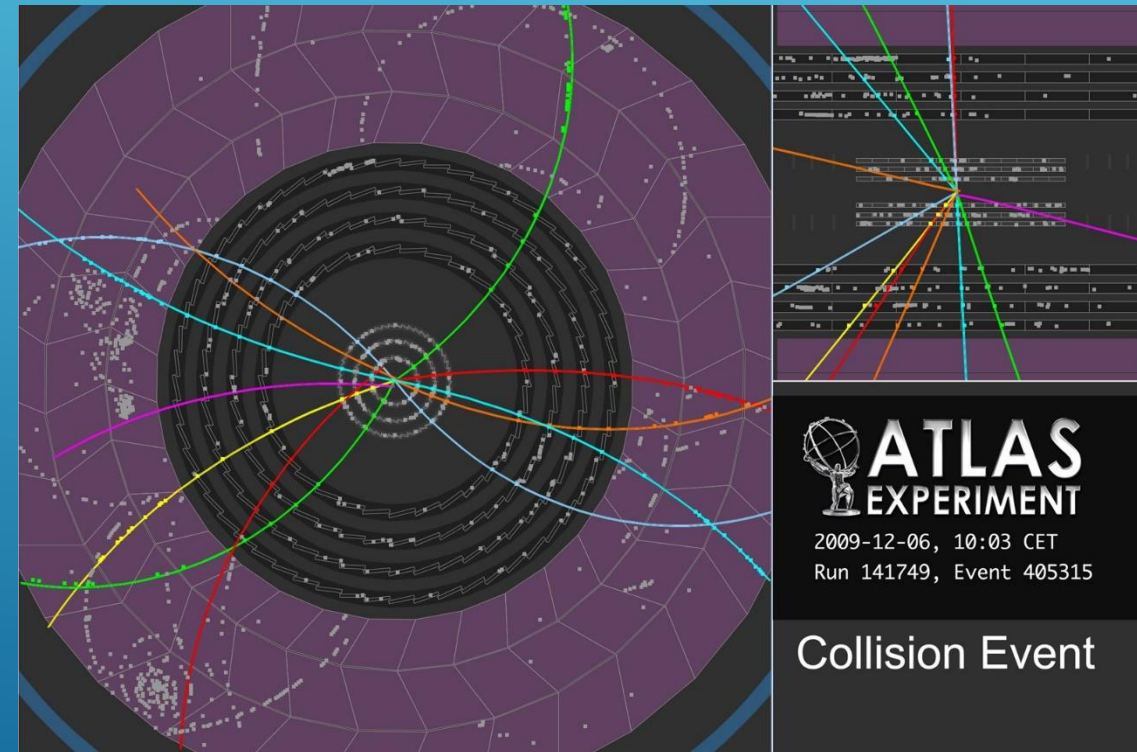
STEREO



PARTICLE DETECTORS

- Particles are detected through their 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.....

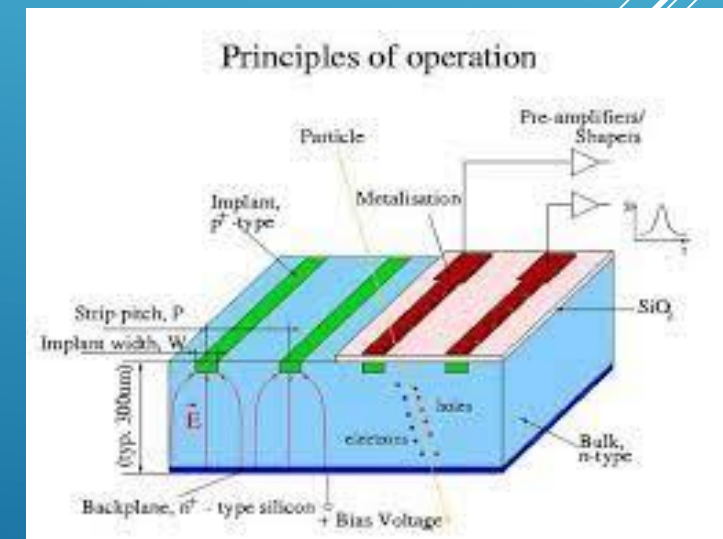
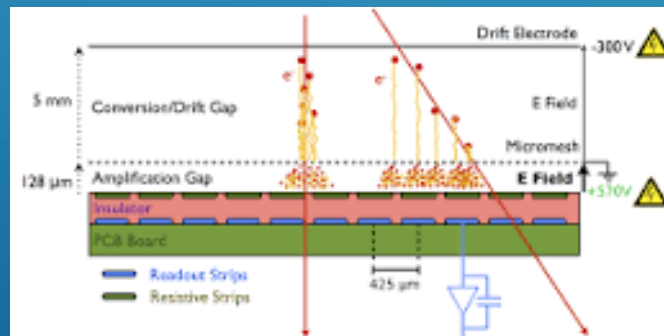
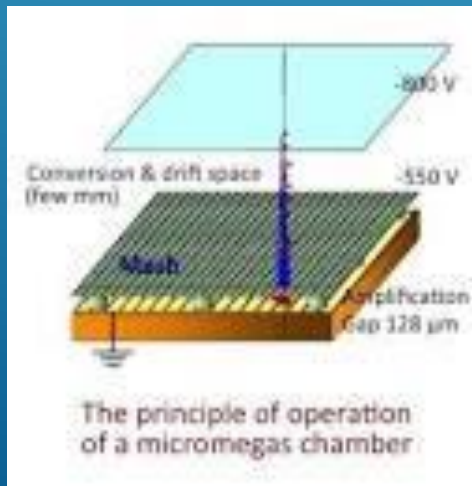
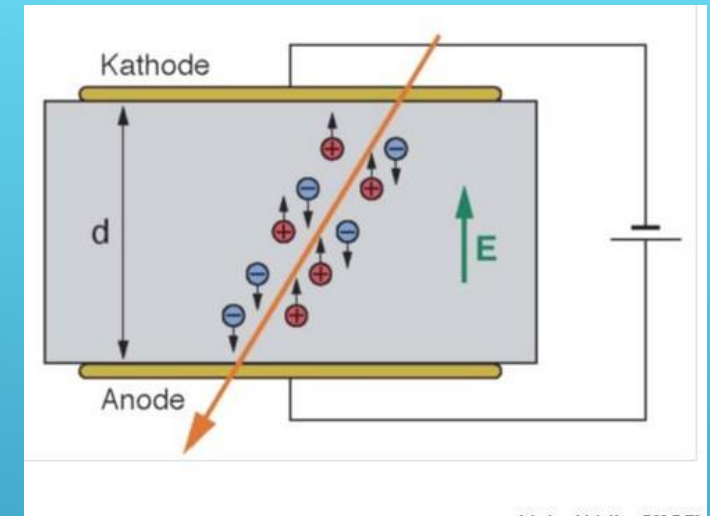
**We know how to measure electrical pulses.
We do not take (almost) photos !!!**

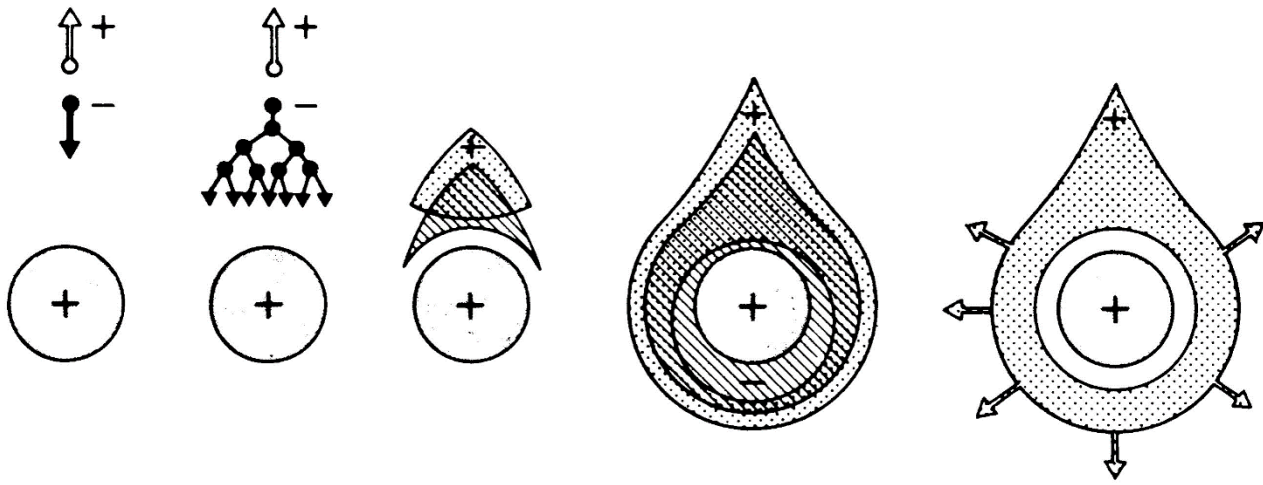


TRACKING DEVICES (CHARGED PARTICLES)

➤ Principle :

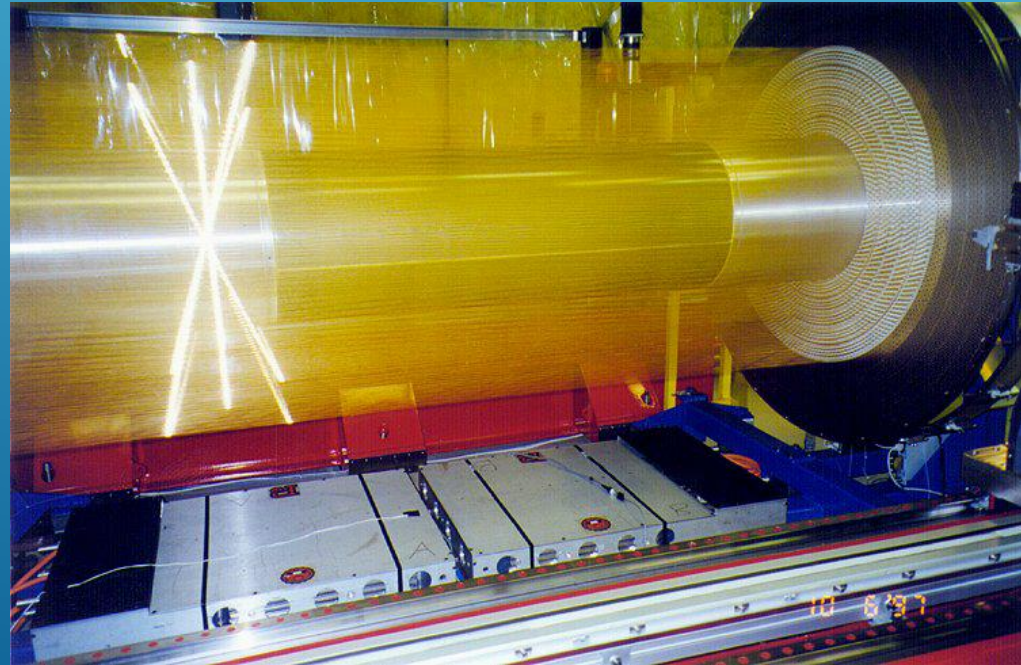
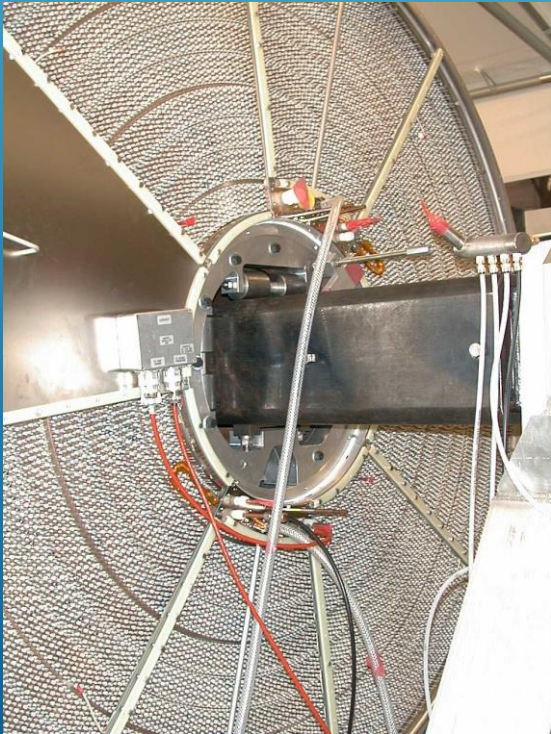
- The incident particle ionizes the detector medium (Si, gas,..) produces e^-
- Detect the electric pulse from e^- , may be a challenge
 - Electron multiplication
 - High performance electronics
- The detector is segmented with sensors of known position in the lab frame. The location precision depends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



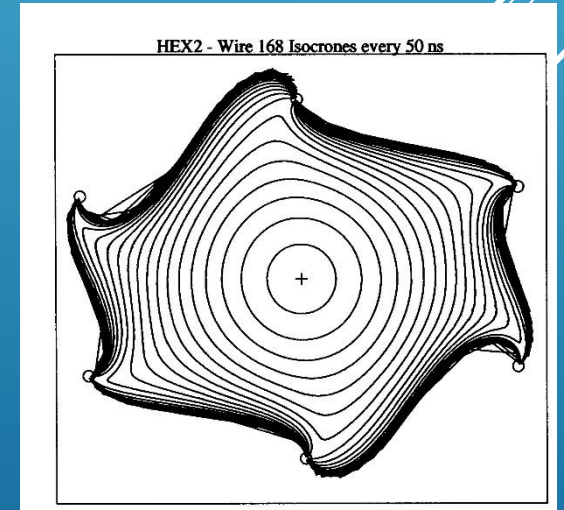


gas	density ρ [g/cm ³]	I_0 [eV]	W [eV]	n_p [cm ⁻¹]	n_T [cm ⁻¹]
H ₂	$8.99 \cdot 10^{-5}$	15.4	37	5.2	9.2
He	$1.78 \cdot 10^{-4}$	24.6	41	5.9	7.8
N ₂	$1.25 \cdot 10^{-3}$	15.5	35	10	56
O ₂	$1.43 \cdot 10^{-3}$	12.2	31	22	73
Ne	$9.00 \cdot 10^{-4}$	21.6	36	12	39
Ar	$1.78 \cdot 10^{-3}$	15.8	26	29	94
Kr	$3.74 \cdot 10^{-3}$	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 ₄ H ₁₀	$2.67 \cdot 10^{-3}$	10.8	23	46	195

given energy loss is much smaller in solid state detectors than in gaseous detectors

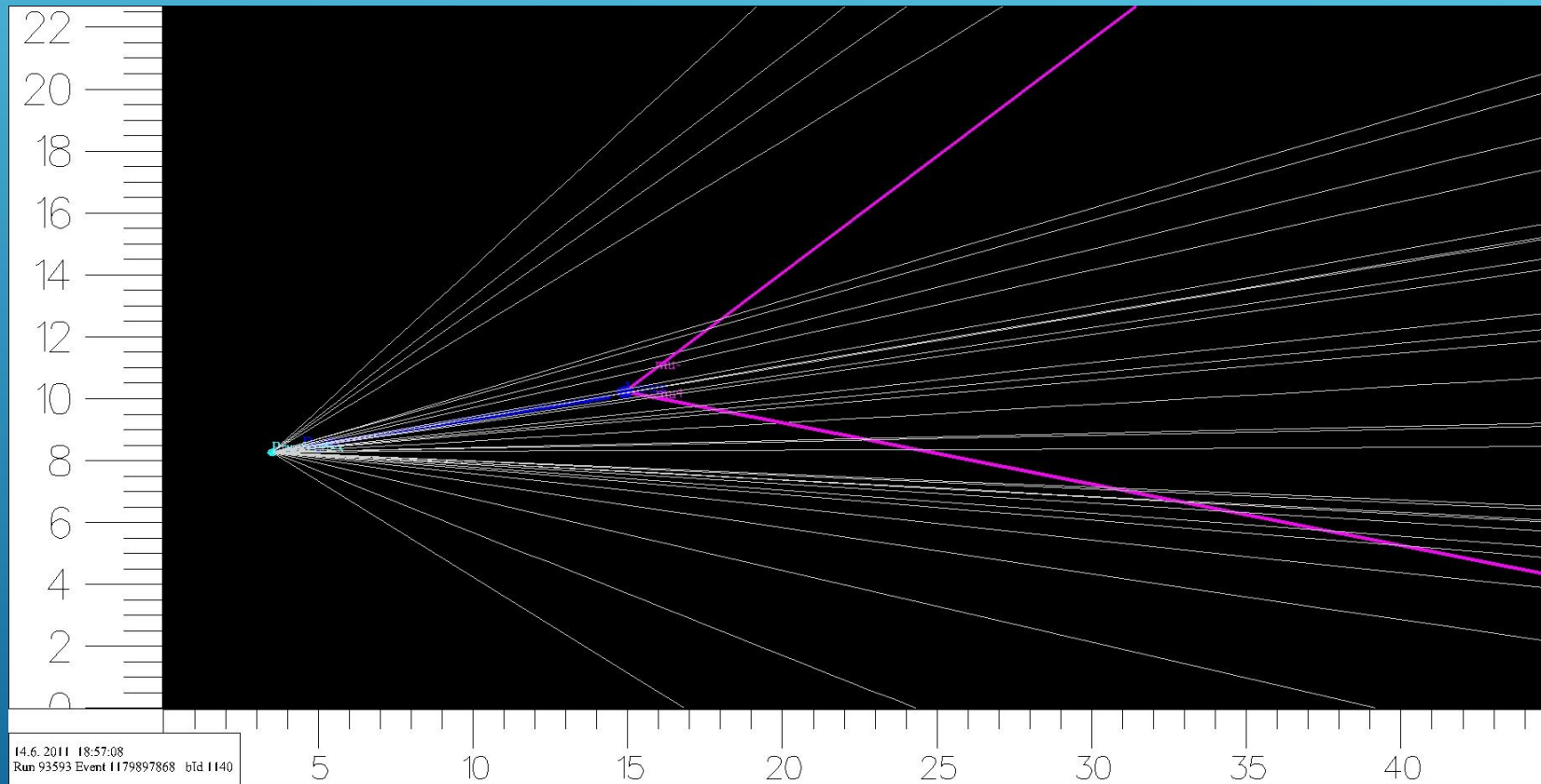


Gas Detectors



LHCb : $B^0 \rightarrow \mu\mu$

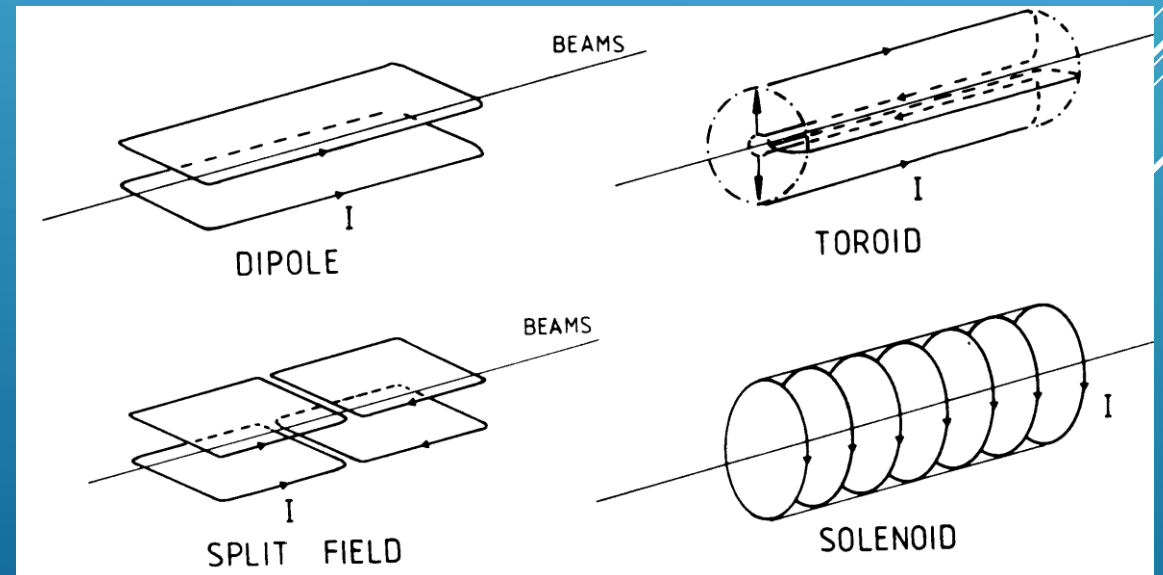
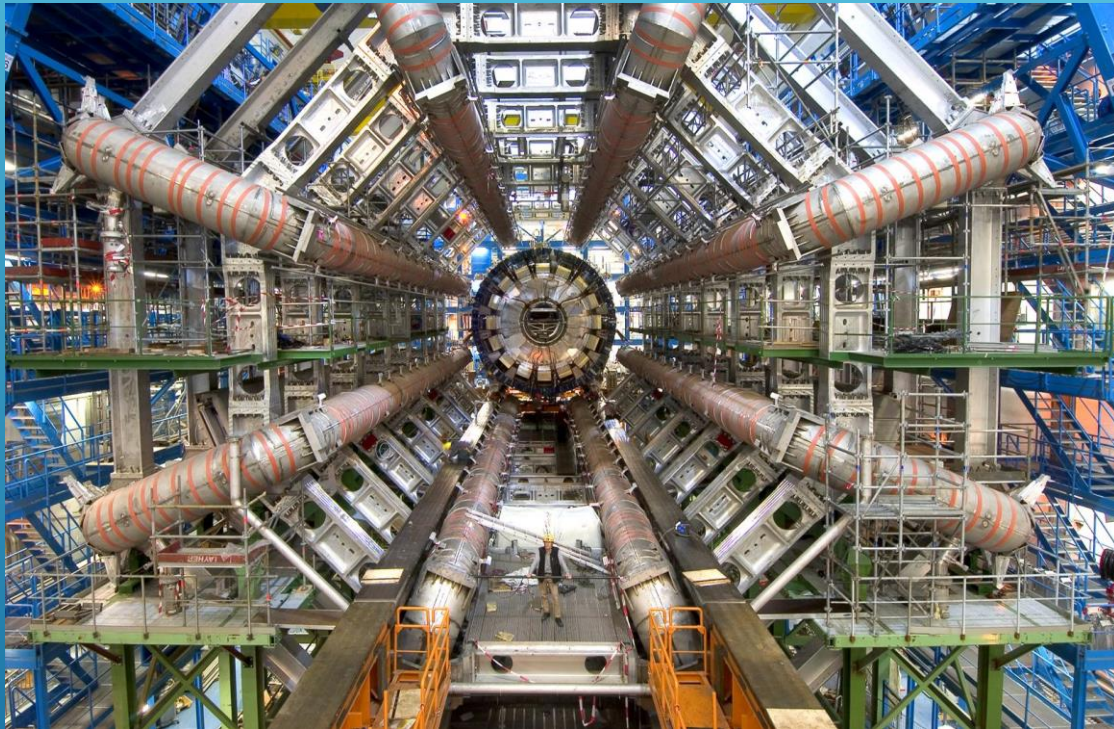
The tracking is able to identify the B meson decaying few mm after it was created by the pp collision



MOMENTUM MEASUREMENT (CHARGED PARTICLES)

We need a magnet

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



ENERGY AND POSITION MEASUREMENT (NEUTRAL AND CHARGED PARTICLES)

CALORIMETERS

Principle :

- Particles lose 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

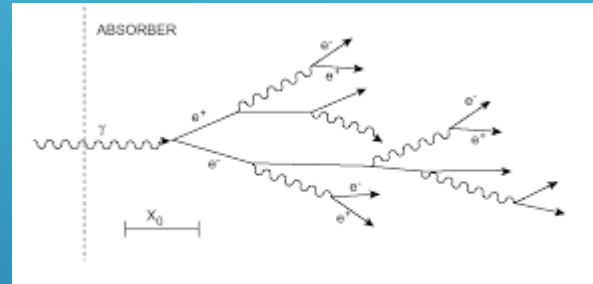
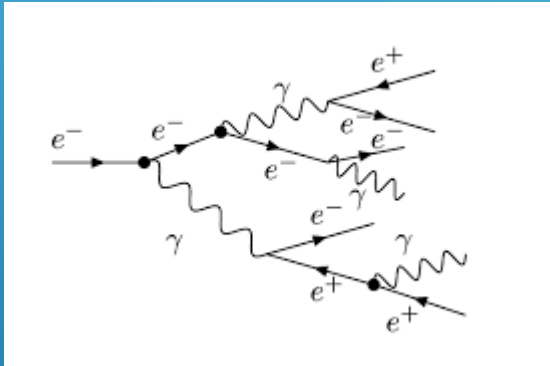
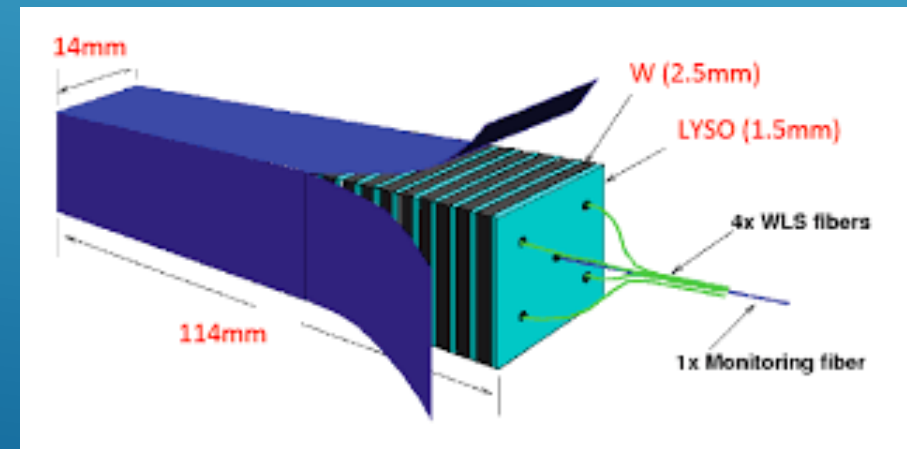
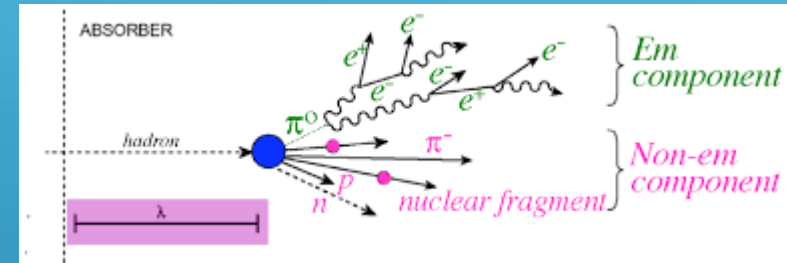


Figure 5: Schematic development of an electromagnetic shower.



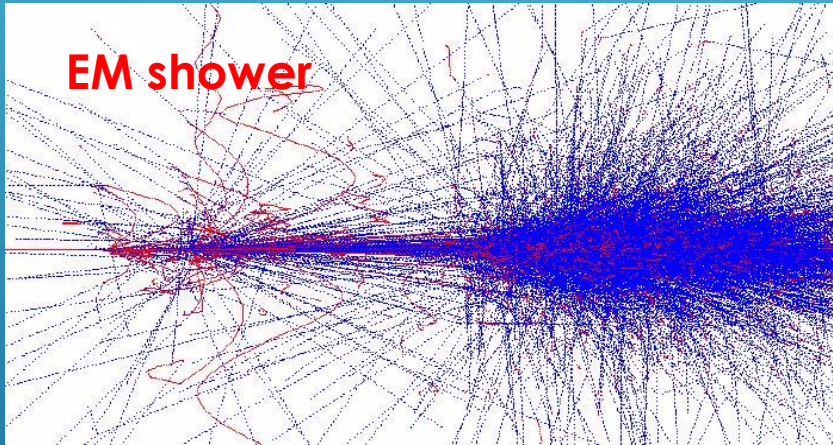
Calorimeters

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



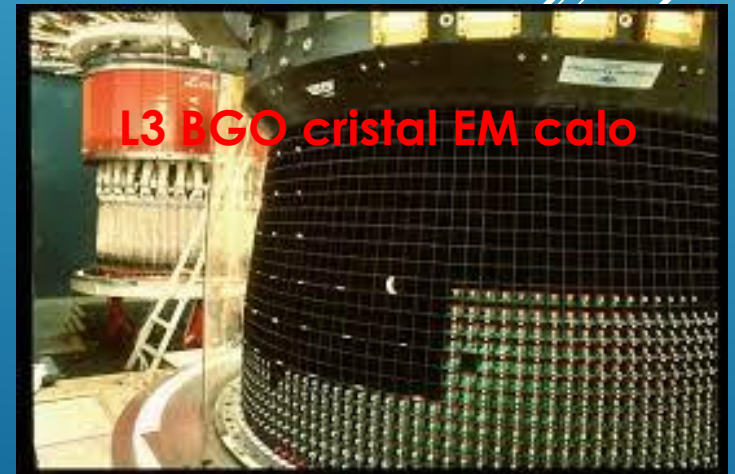
ATLAS LAr EM calo



EM shower



CMS Hadron Calo



L3 BGO cristal EM calo

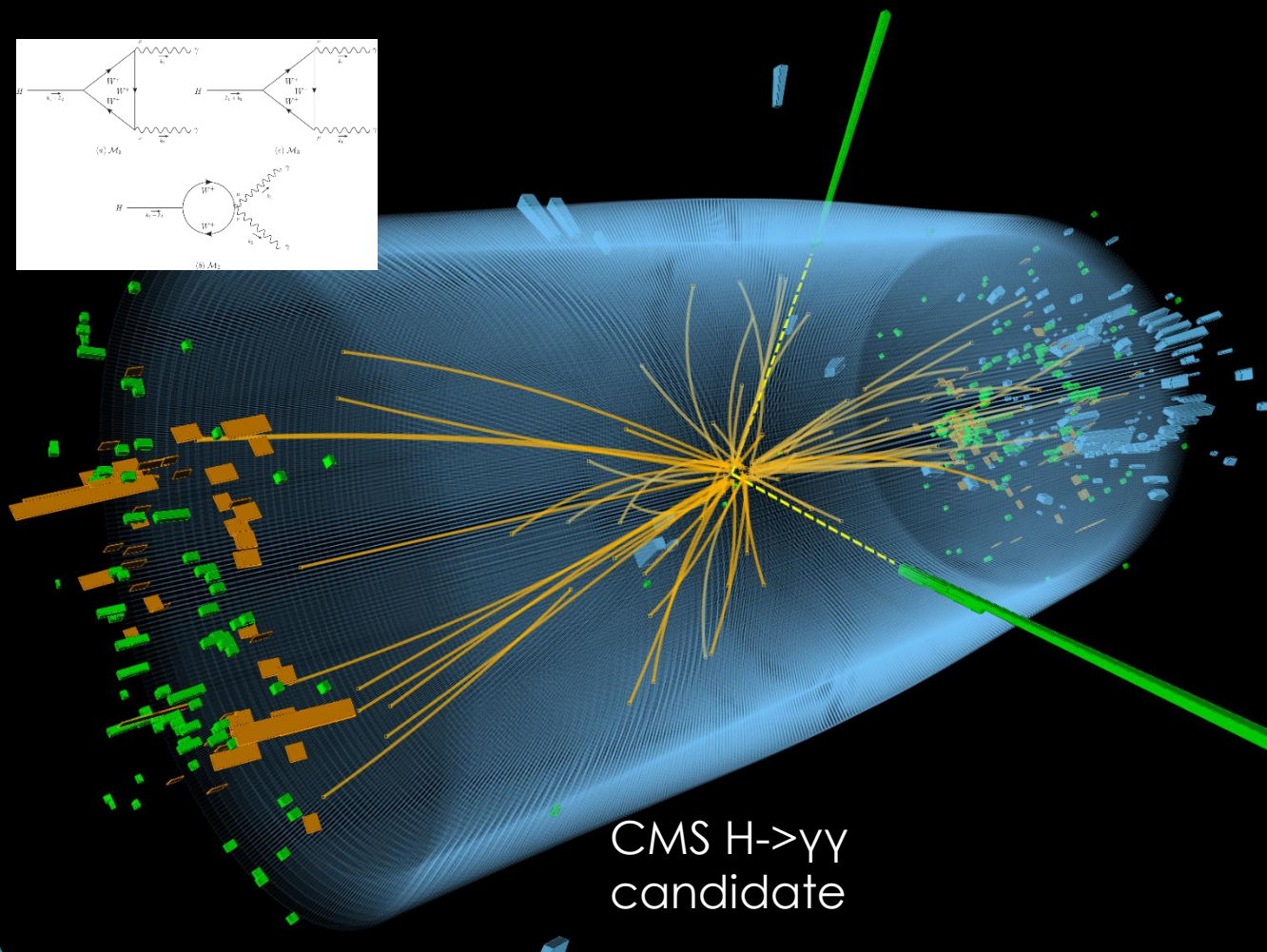
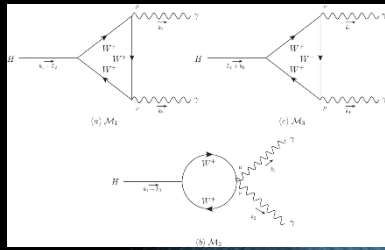
Energy Resolution

a : stochastic term

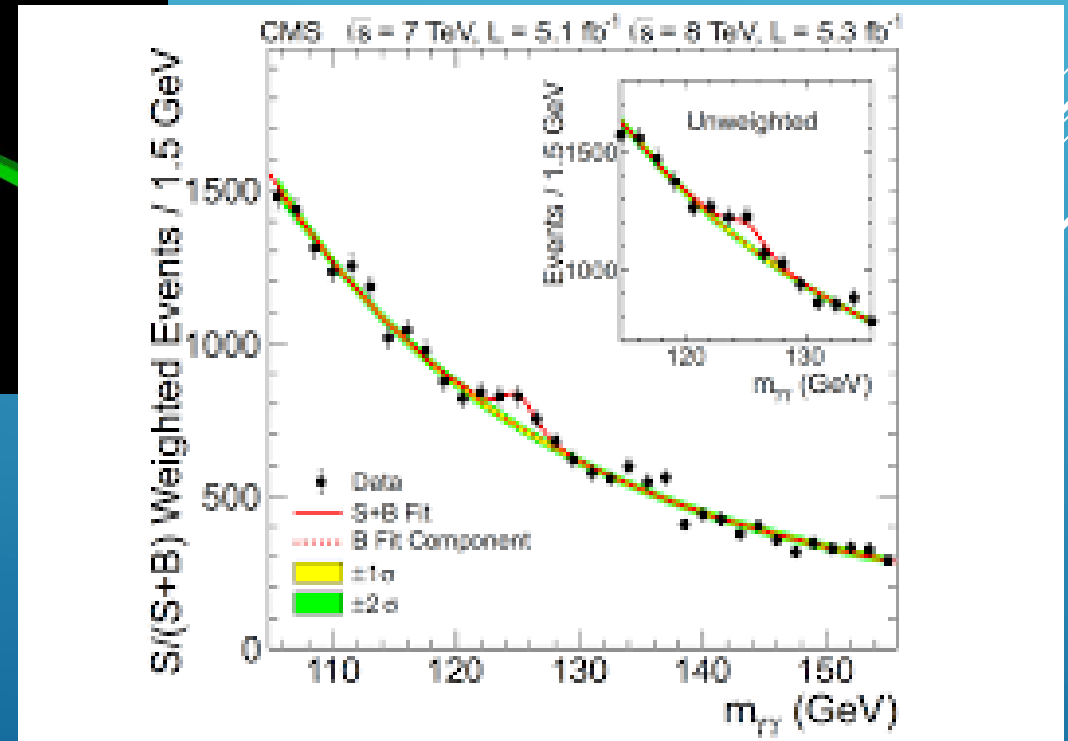
b : Noise

c : constant

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

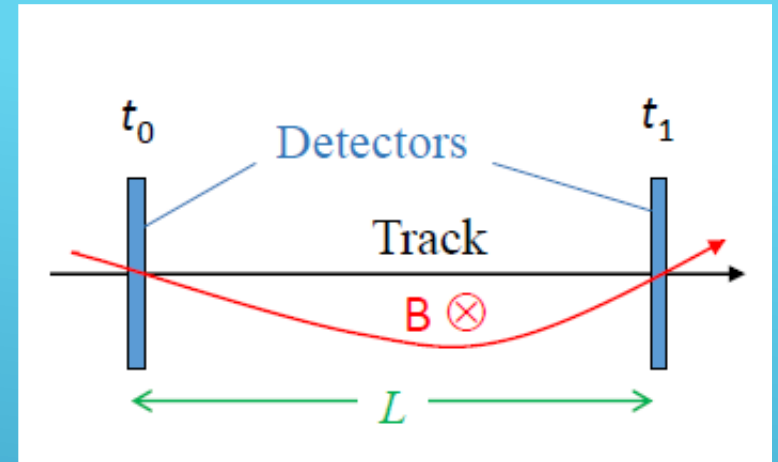


CMS $H \rightarrow \gamma\gamma$
candidate

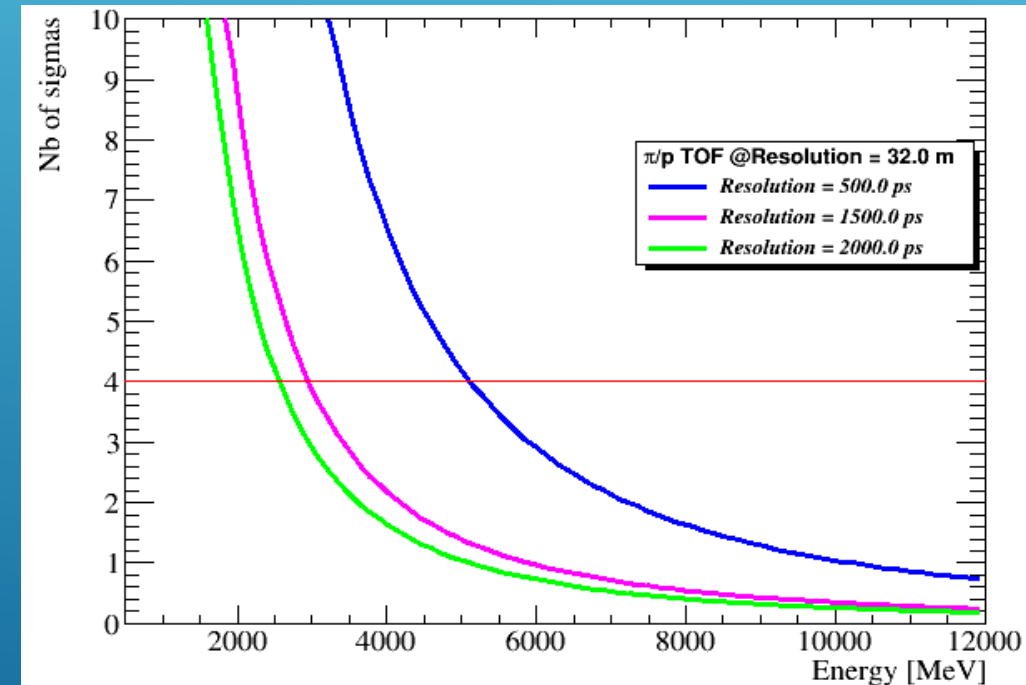
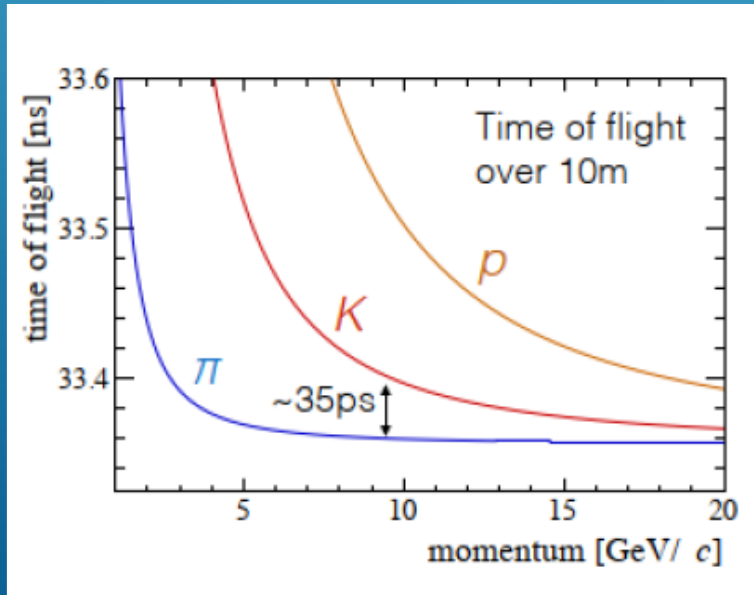


PARTICLE IDENTIFICATION

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



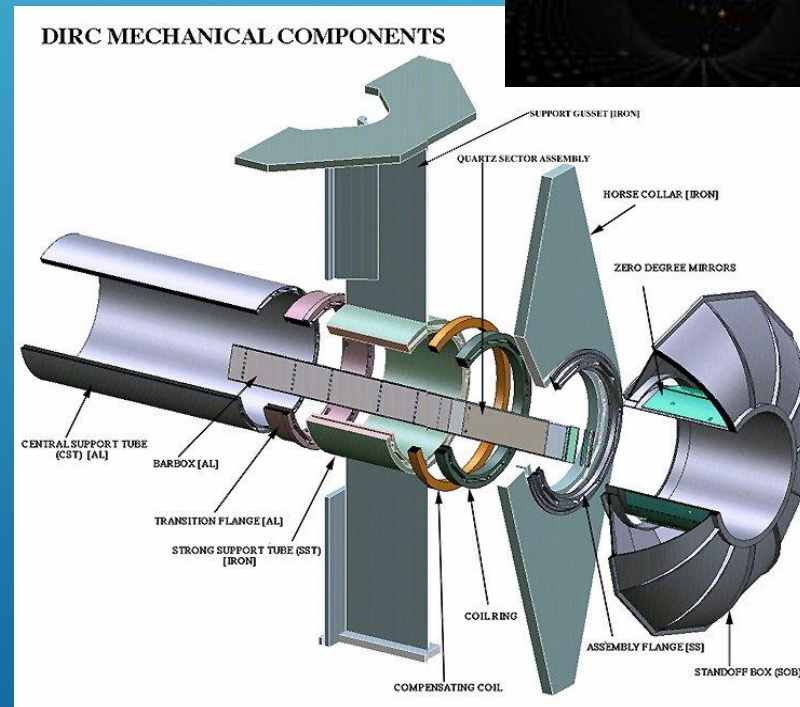
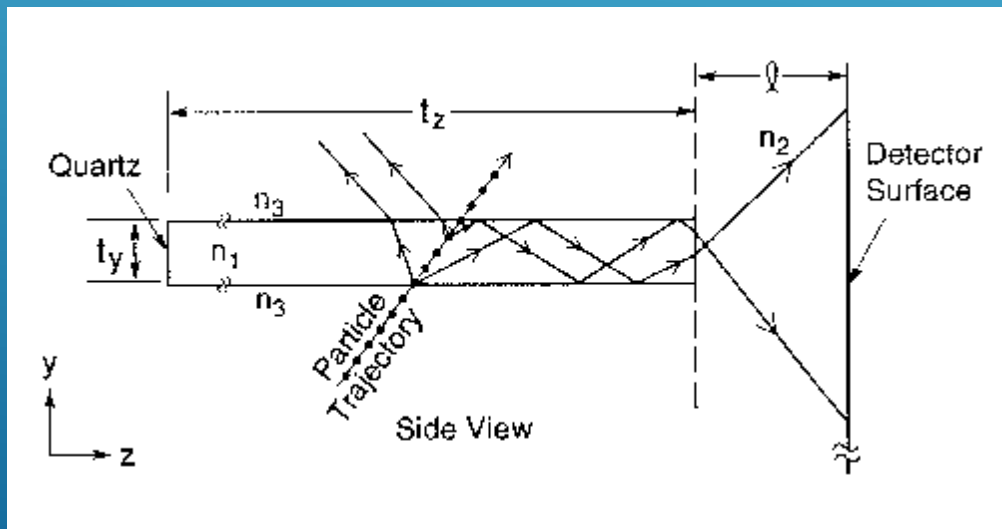
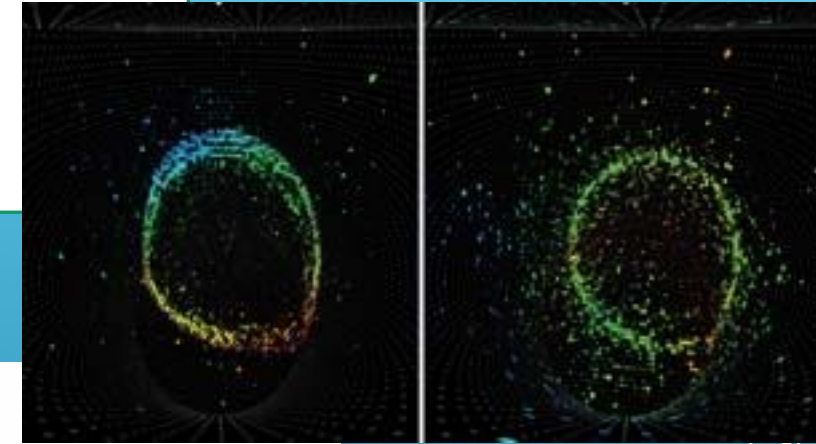
$$\Delta t = \frac{L}{c} \left(\frac{1}{\beta_1} - \frac{1}{\beta_2} \right) = \frac{L}{c} \left\{ \sqrt{1 + \frac{m_1^2 c^2}{p^2}} - \sqrt{1 + \frac{m_2^2 c^2}{p^2}} \right\} \approx \frac{Lc}{2p^2} (m_1^2 - m_2^2)$$



PID CHERENKOV COUNTERS

Particles crossing a medium will emit light at an angle $\cos\theta_c = 1 / (n \beta)$
 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

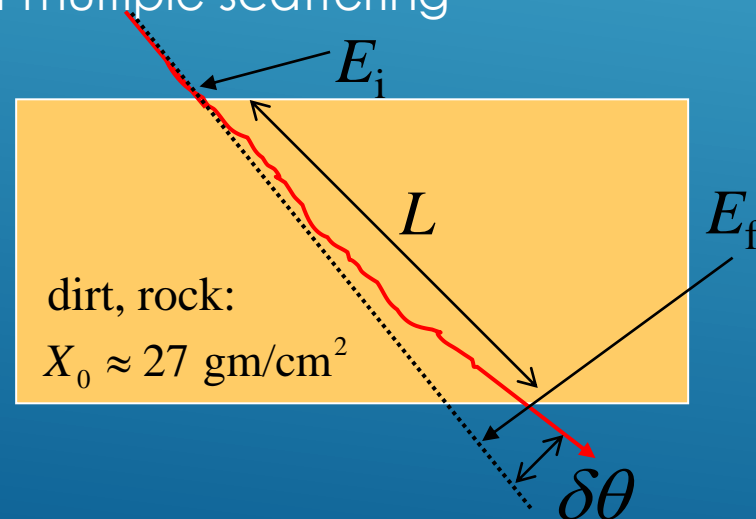
Muons will :

- Interact with matter and will lose their energy by ionization

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

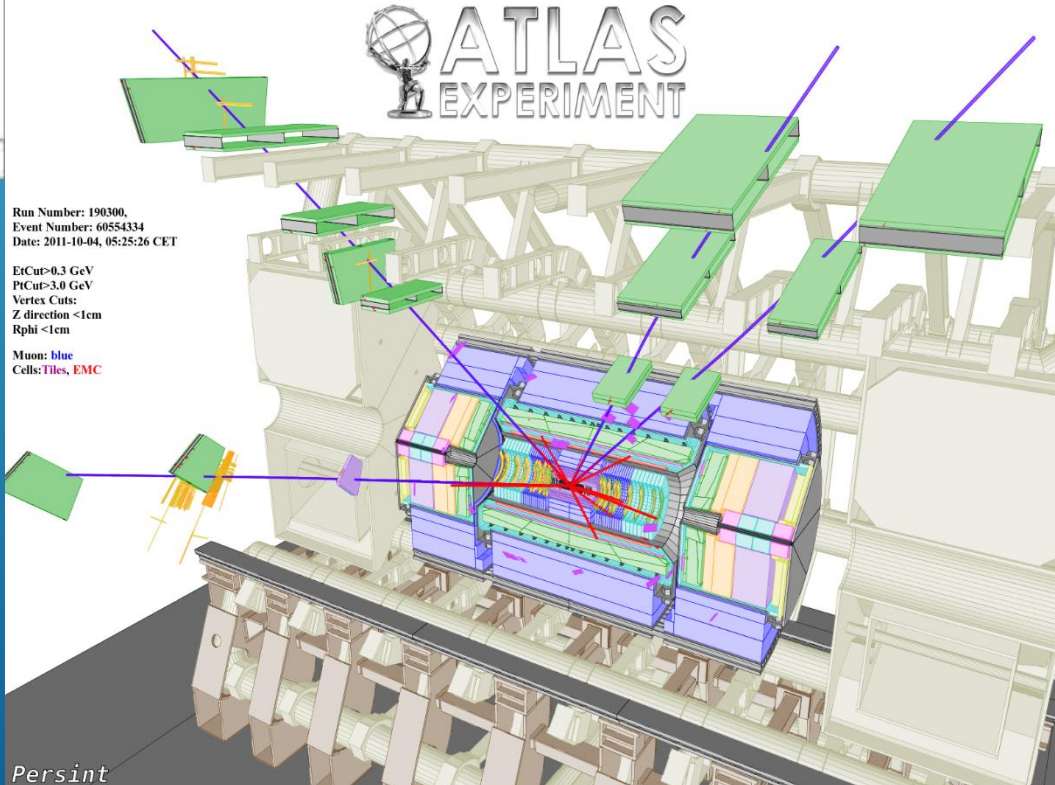
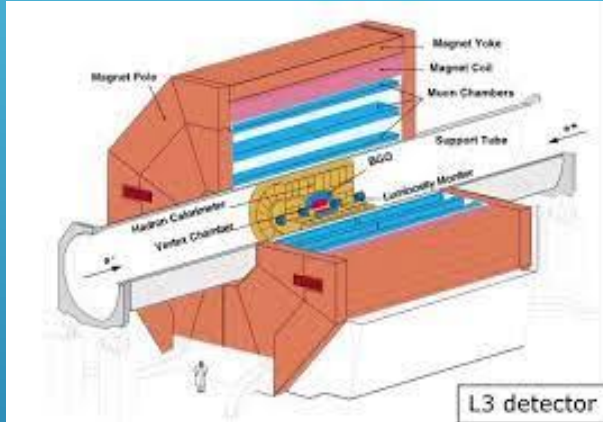
- Change their direction because of multiple scattering

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



MUON IDENTIFICATION

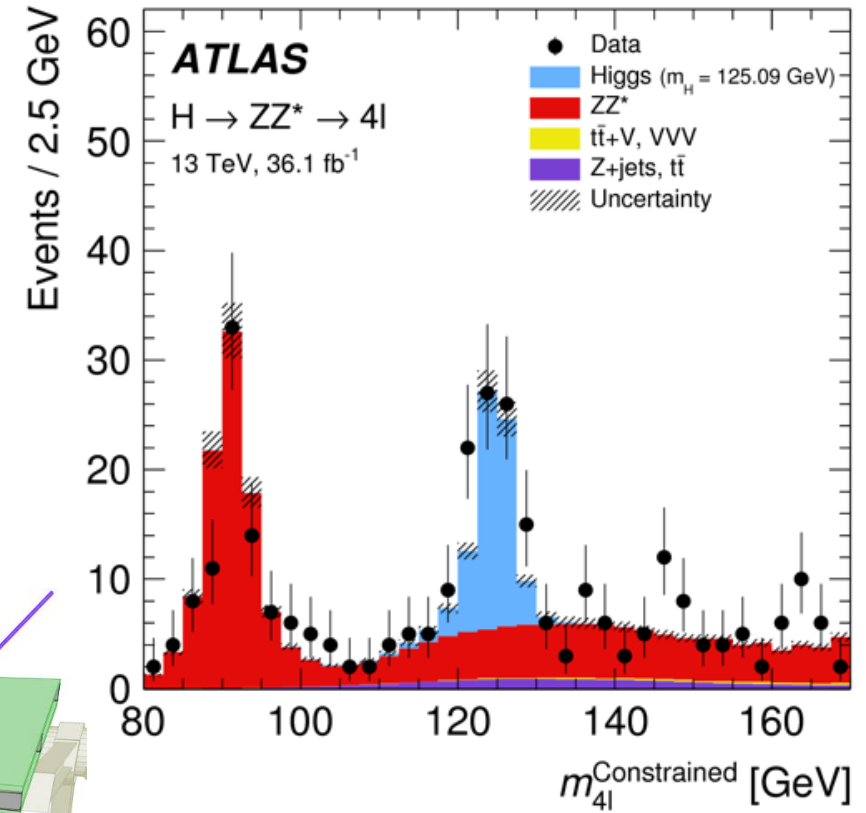
- Tracking Devices behind absorber, usually the calorimeters



Run Number: 190300,
 Event Number: 60554334
 Date: 2011-10-04, 05:25:26 CET

EtCut>0.3 GeV
 PtCut>3.0 GeV
 Vertex Cuts:
 Z direction <1cm
 Rphi <1cm

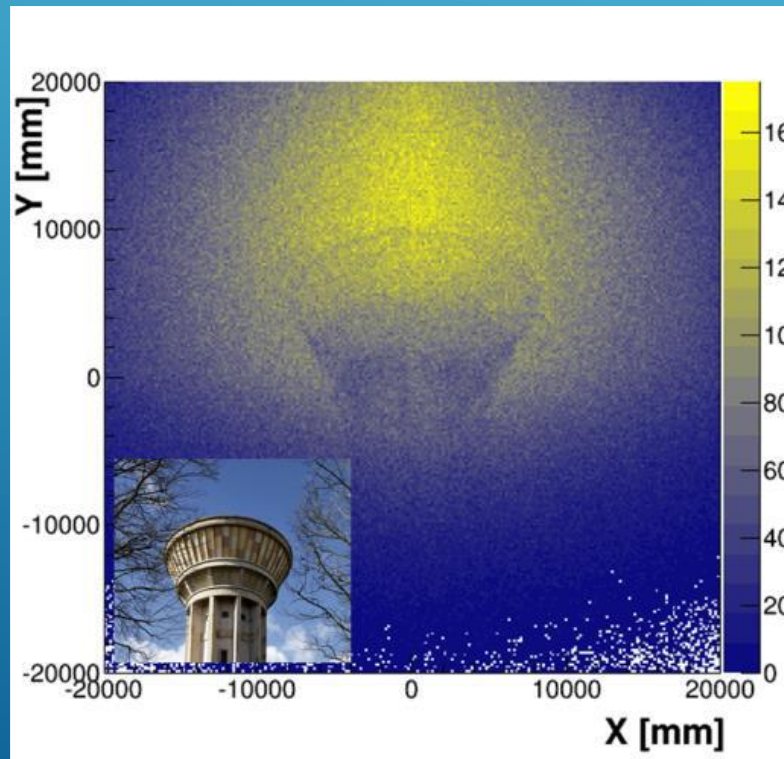
Muon: blue
 Cells: Tiles, EMC



A FUN APPLICATION

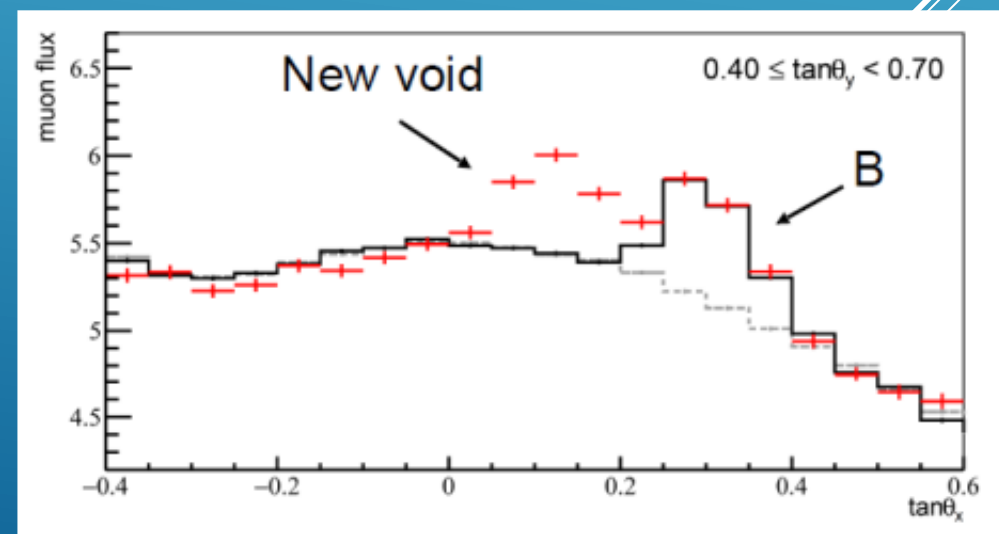
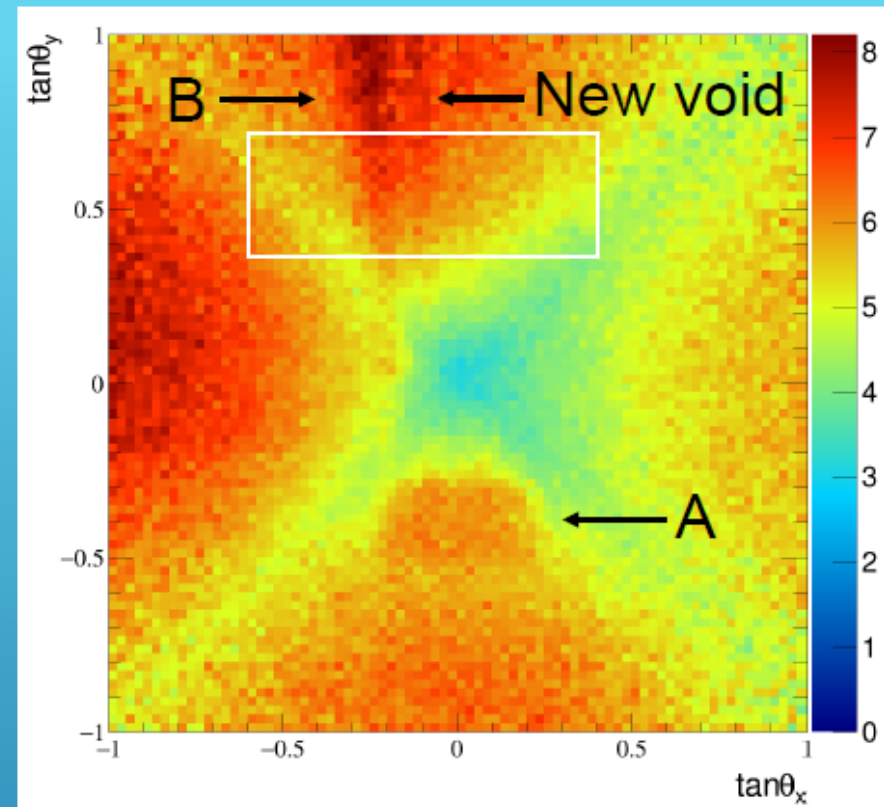
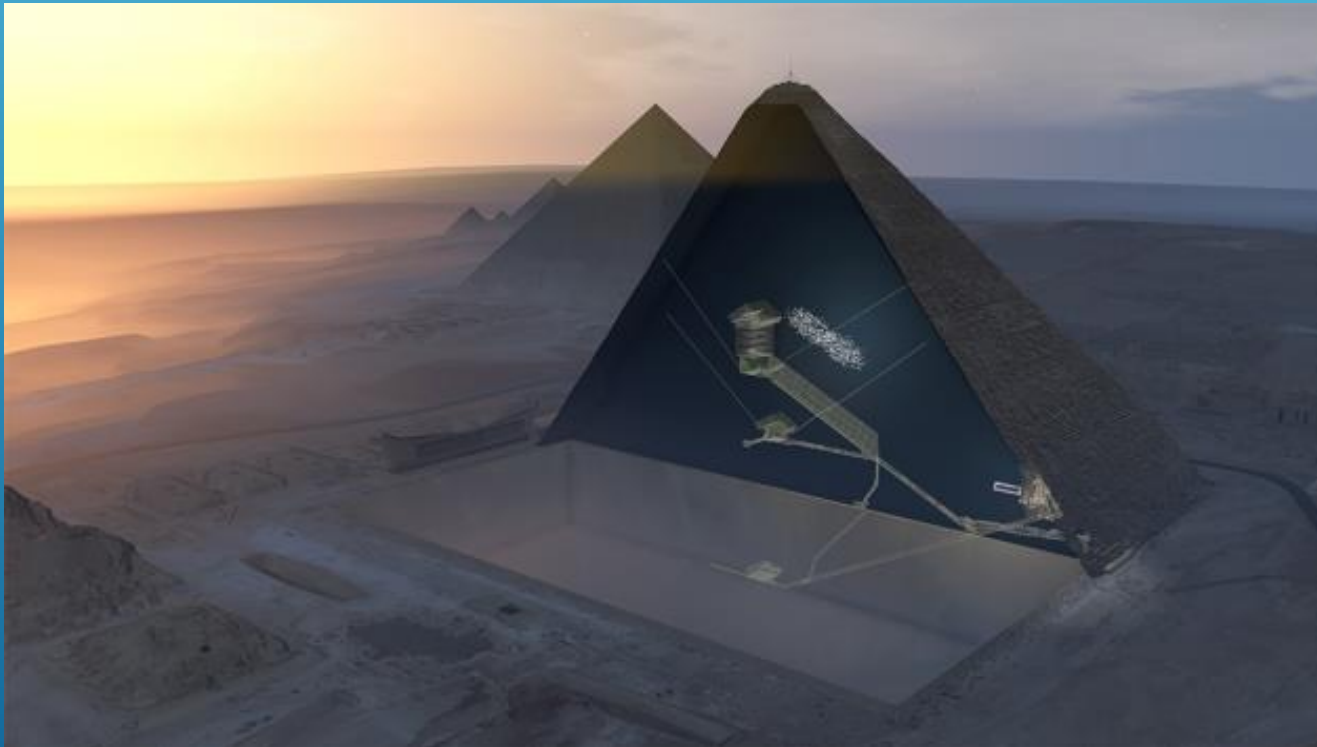
Using muons for scanning !

- 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 !



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

388 | Nature | VOL 52 | 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

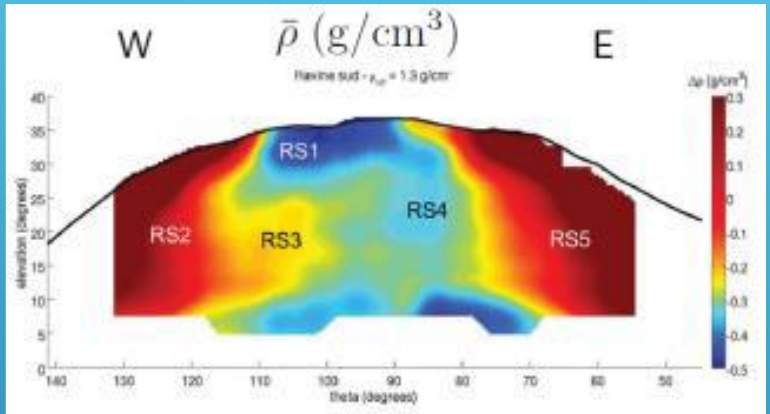
Difficulties :

- Looking for an object with similar density as the surrounding materials $\rho \sim 2.3 \text{ gr/cm}^3$ 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 !





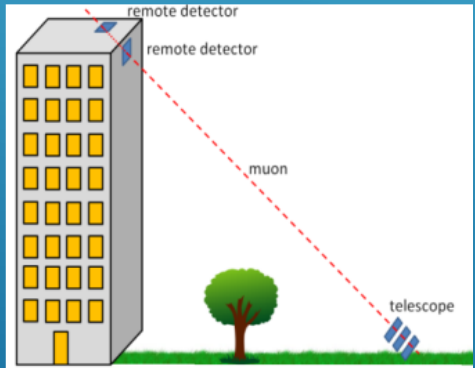
Other applications for muon scanning



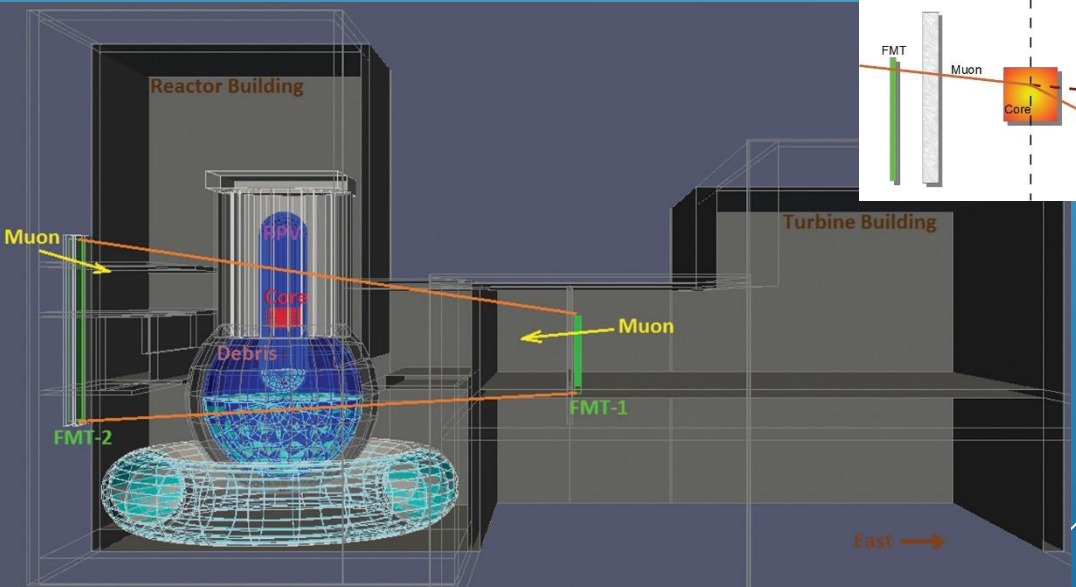
Volcano surveillance, looking to its internal density



Civil engineering



Metrology



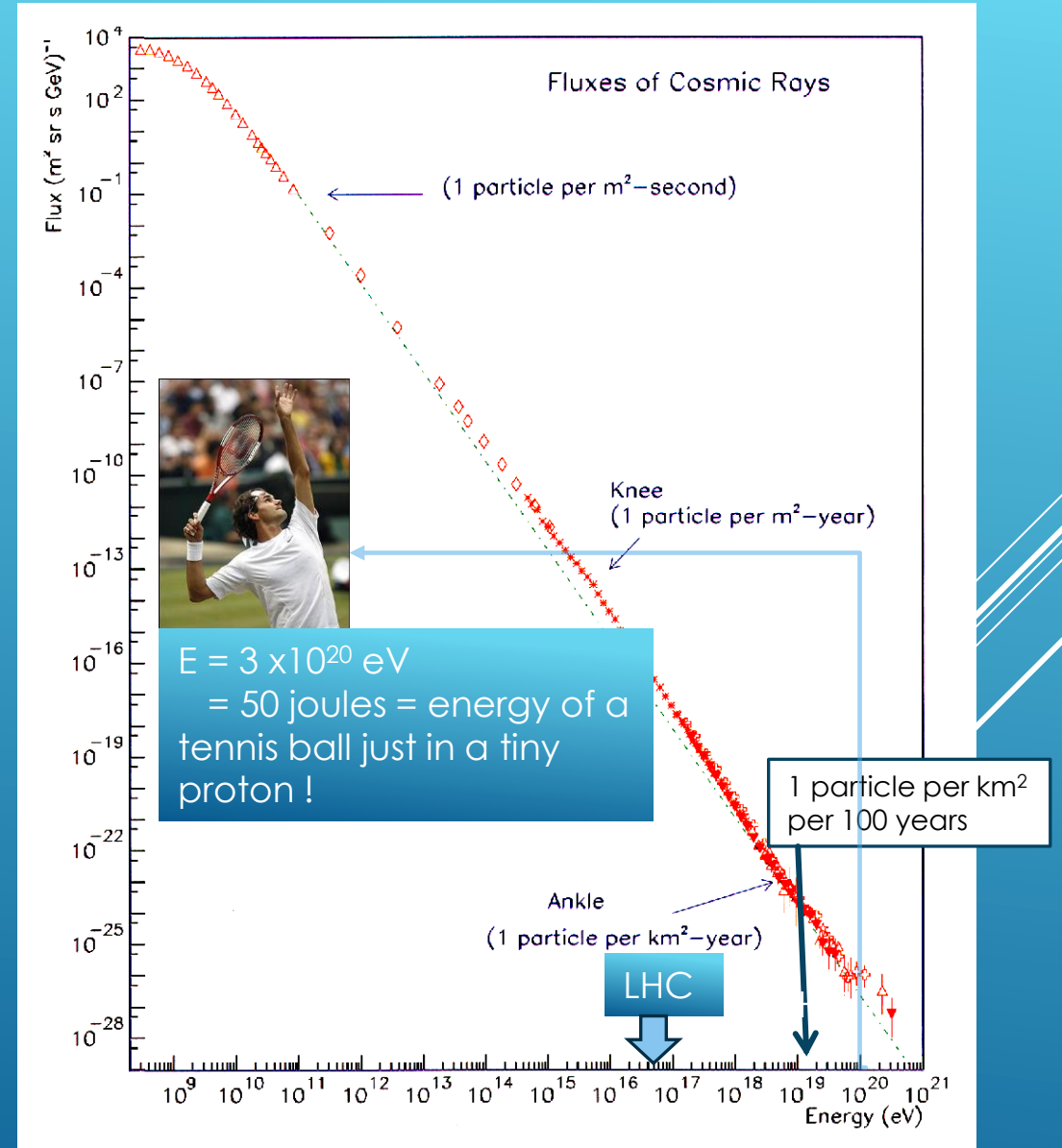
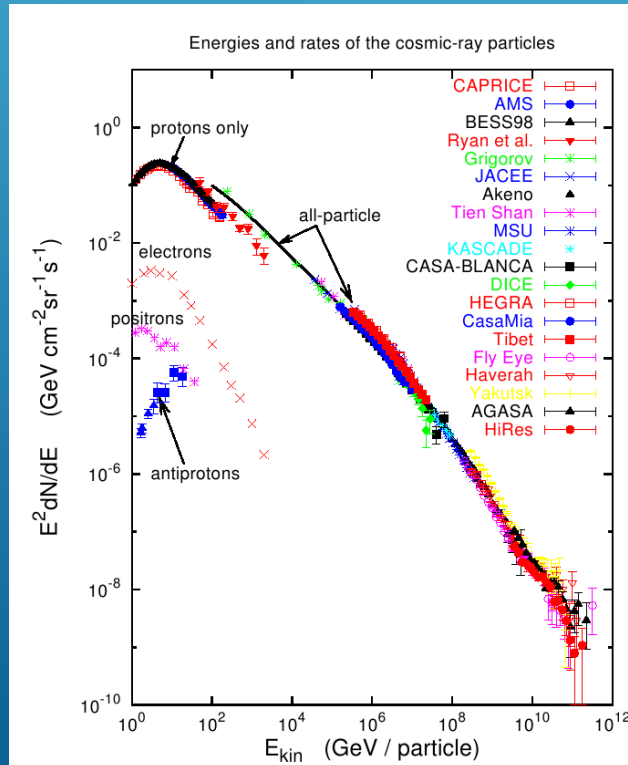
CONCLUSION

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

What we know today !

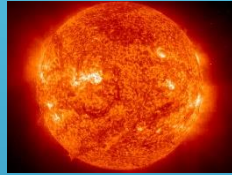
How many particles and what energy ???

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

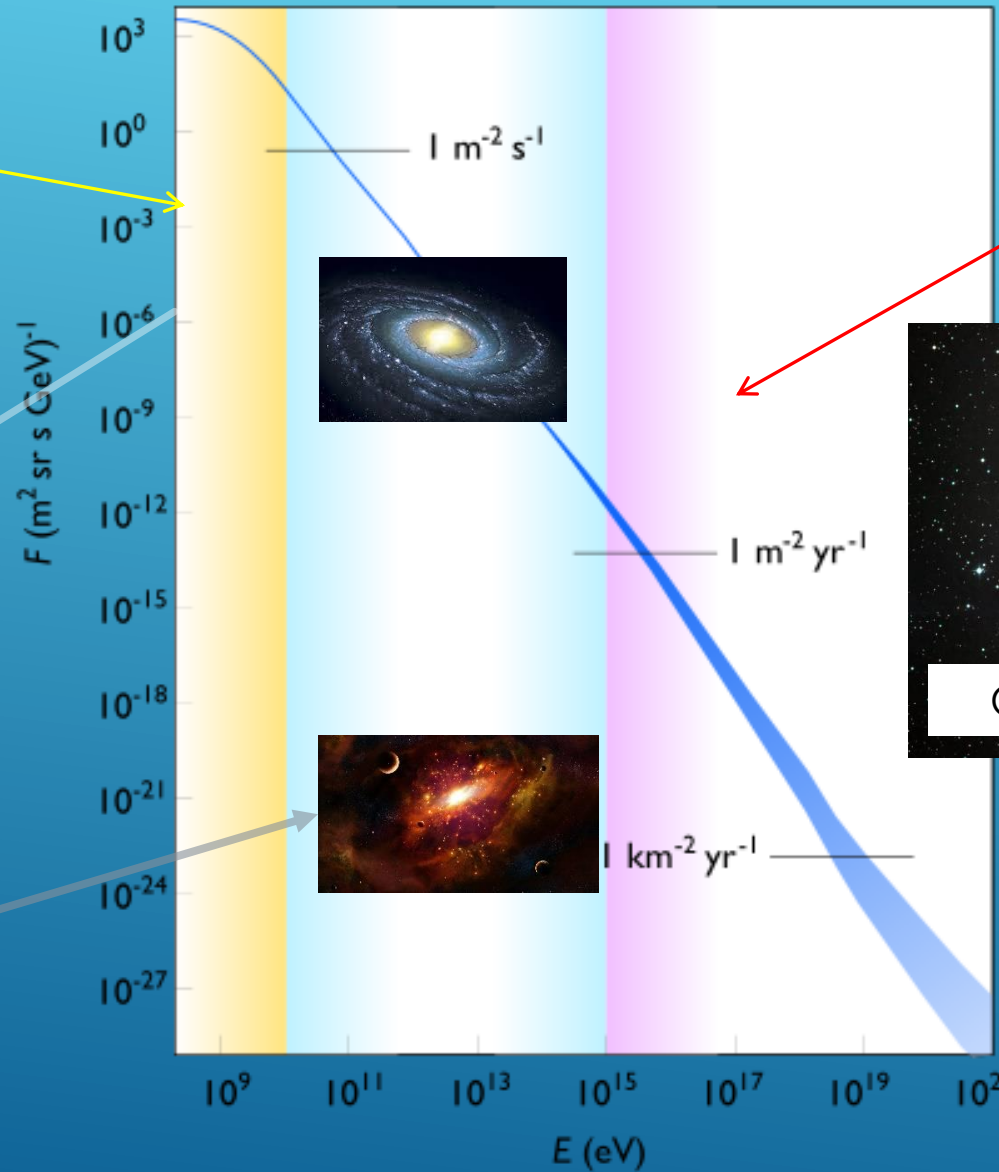


Where do they come from ??

Our sun



Supernova explosion and remnants



Extra galactic

