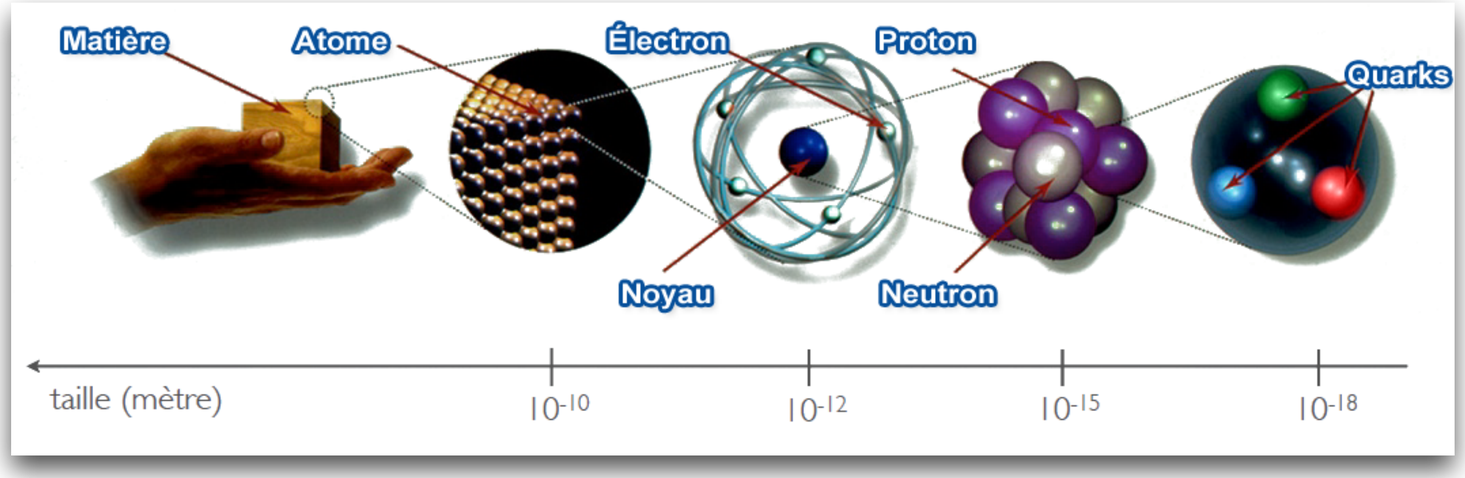
Introduction to detectors

For particle physics and astroparticles

NAREI LORENZO MARTINEZ - LAPP/CNRS - JULY 16TH 2024

What do we want to detect ?



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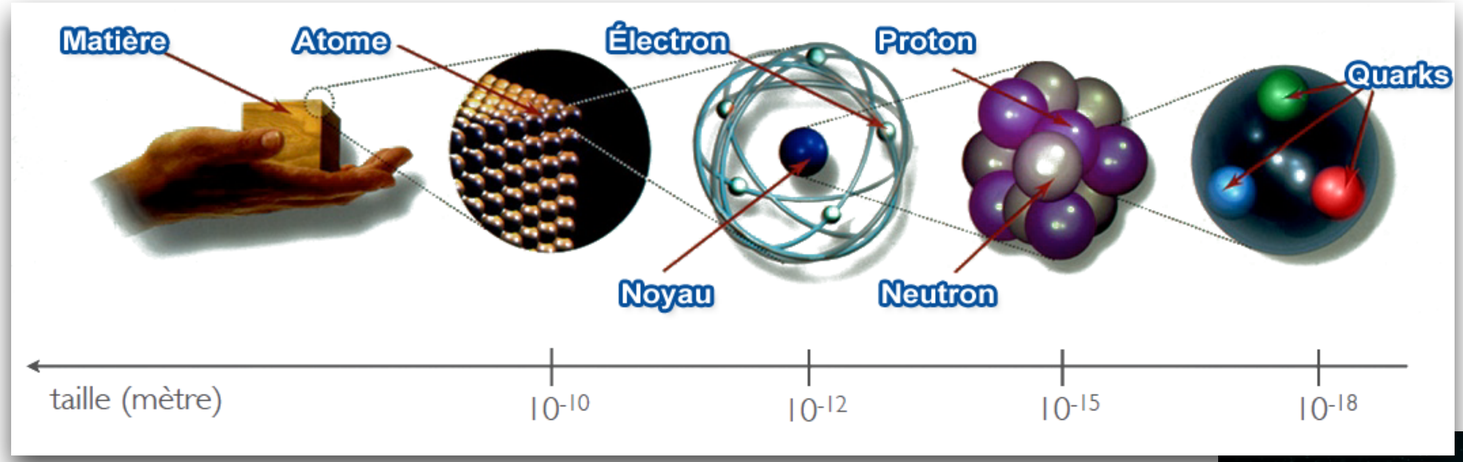
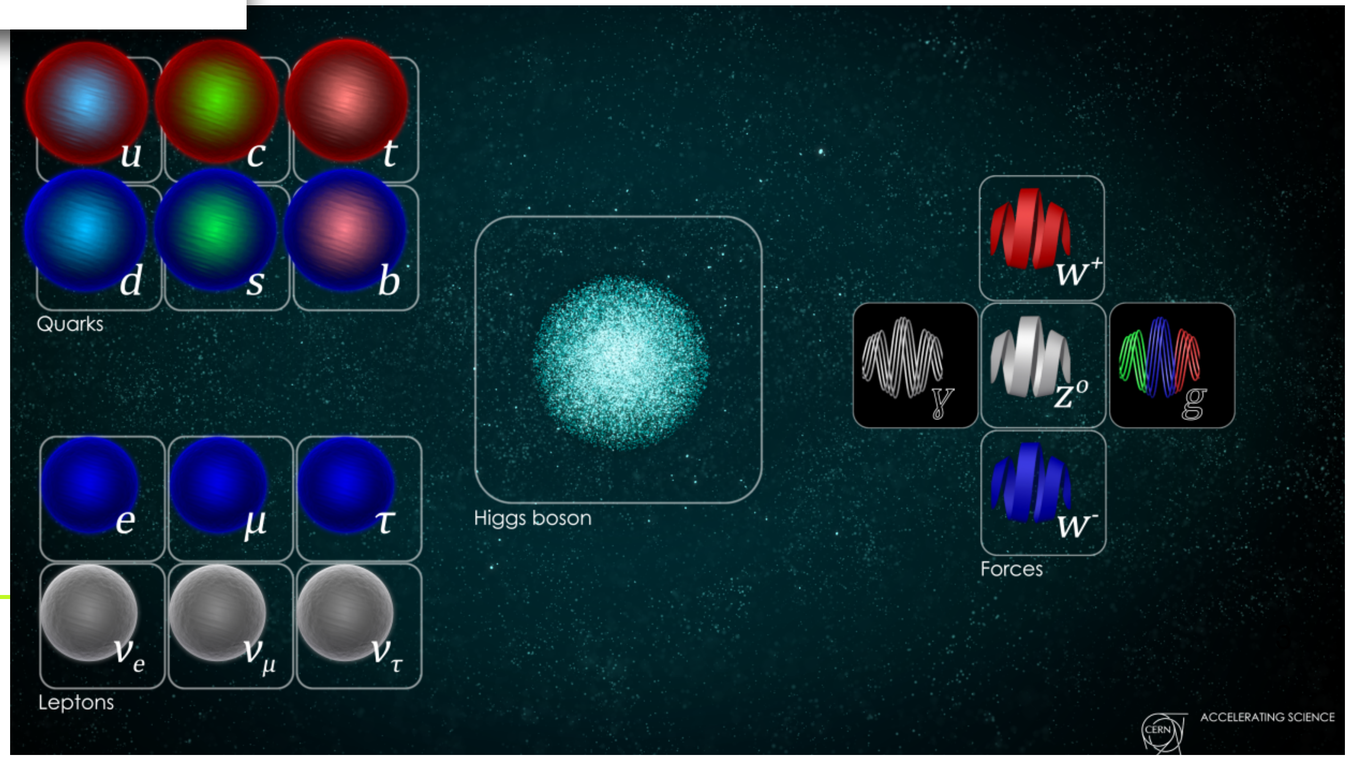


Most of these particules have very low lifetime !

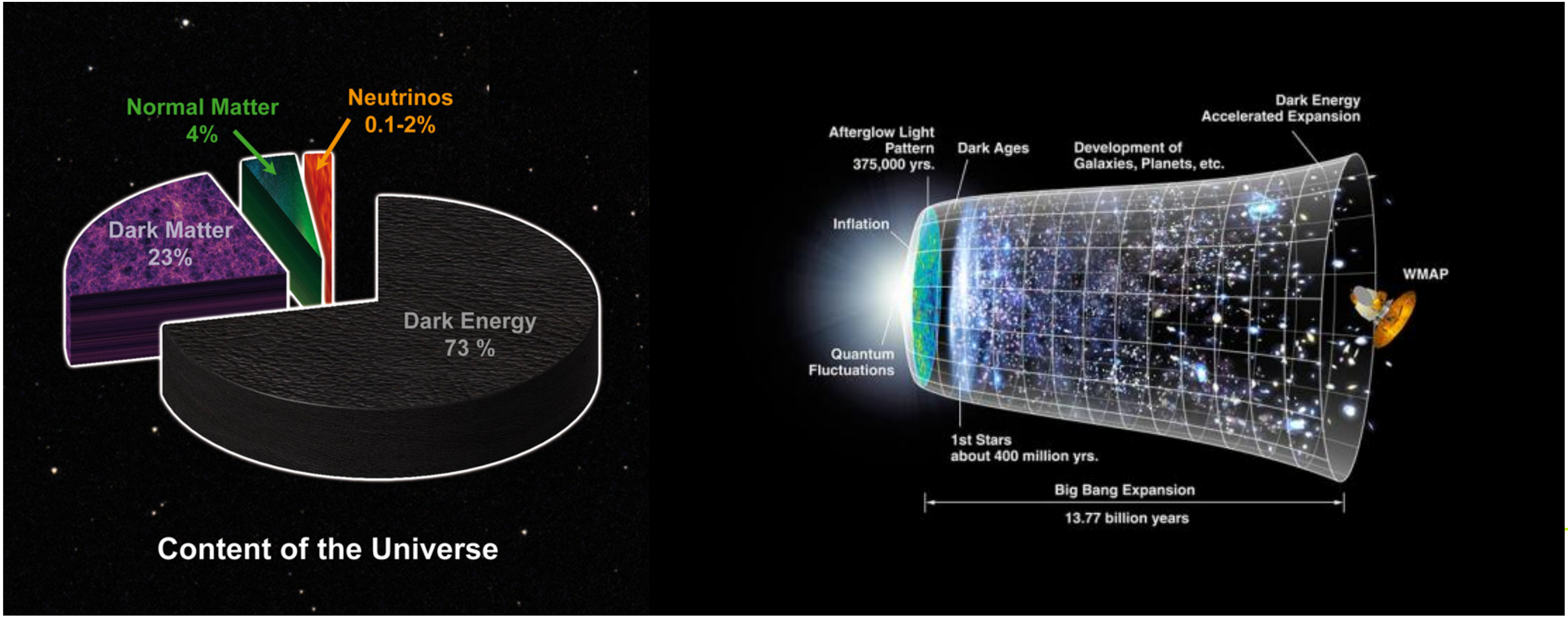
Better understanding of Standard Model

of Particules Physics



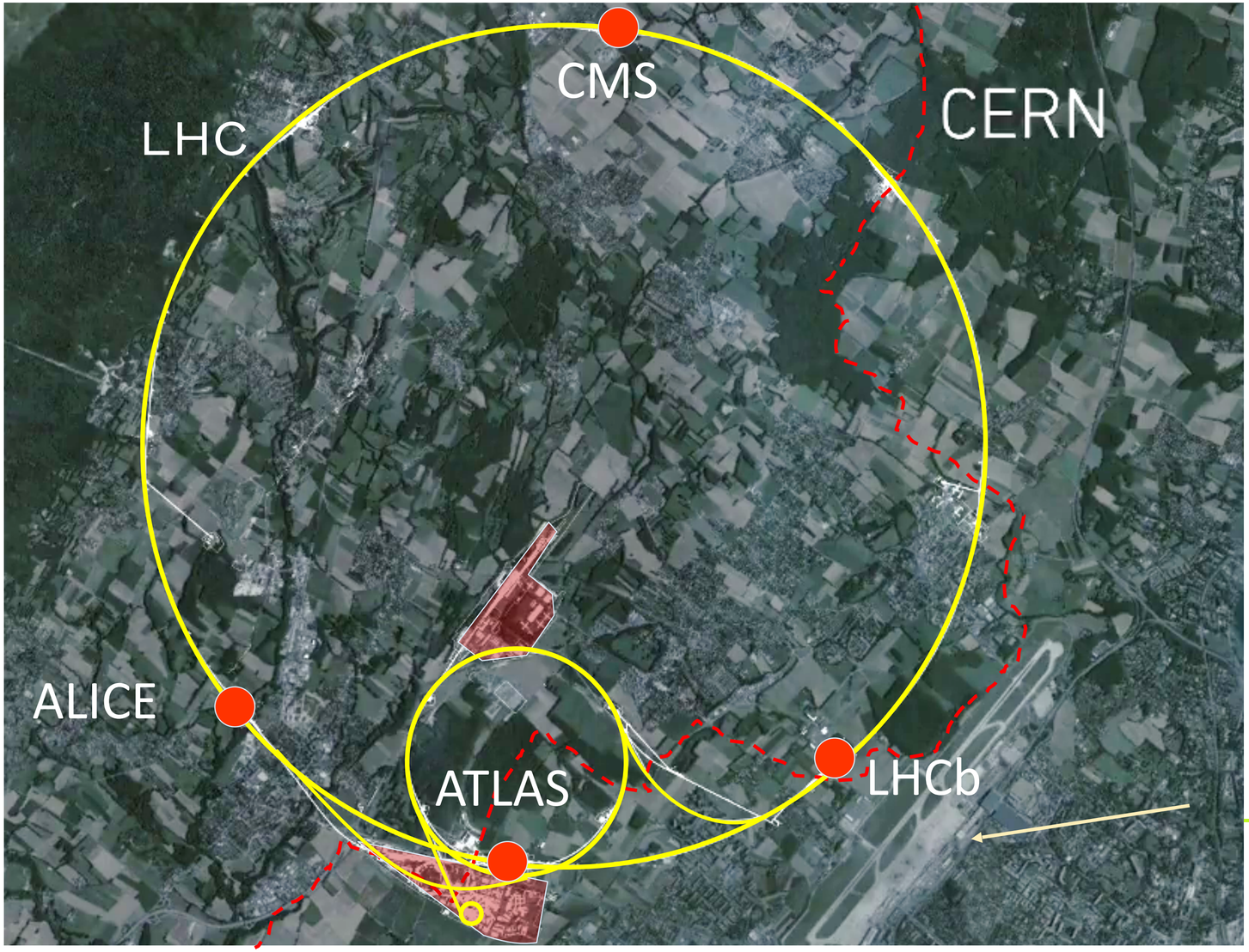
What do we want to detect ?

- **+ unknown particles !**

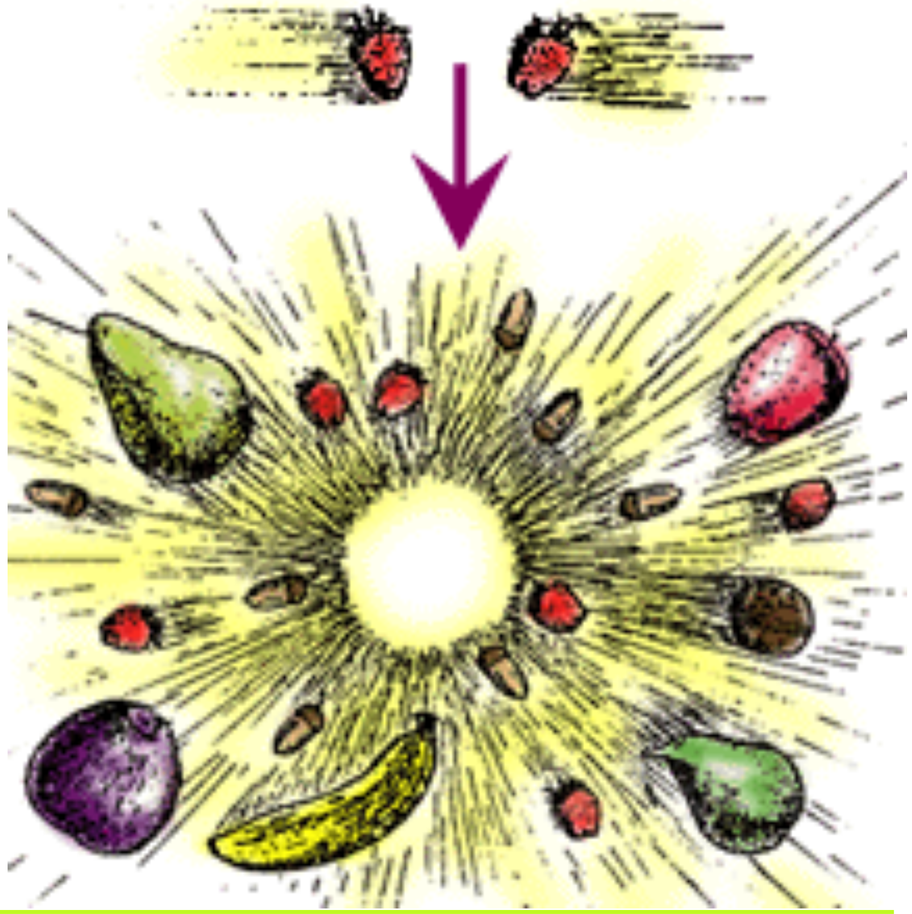


How are high-energy particles produced ?

- **Human accelerators**



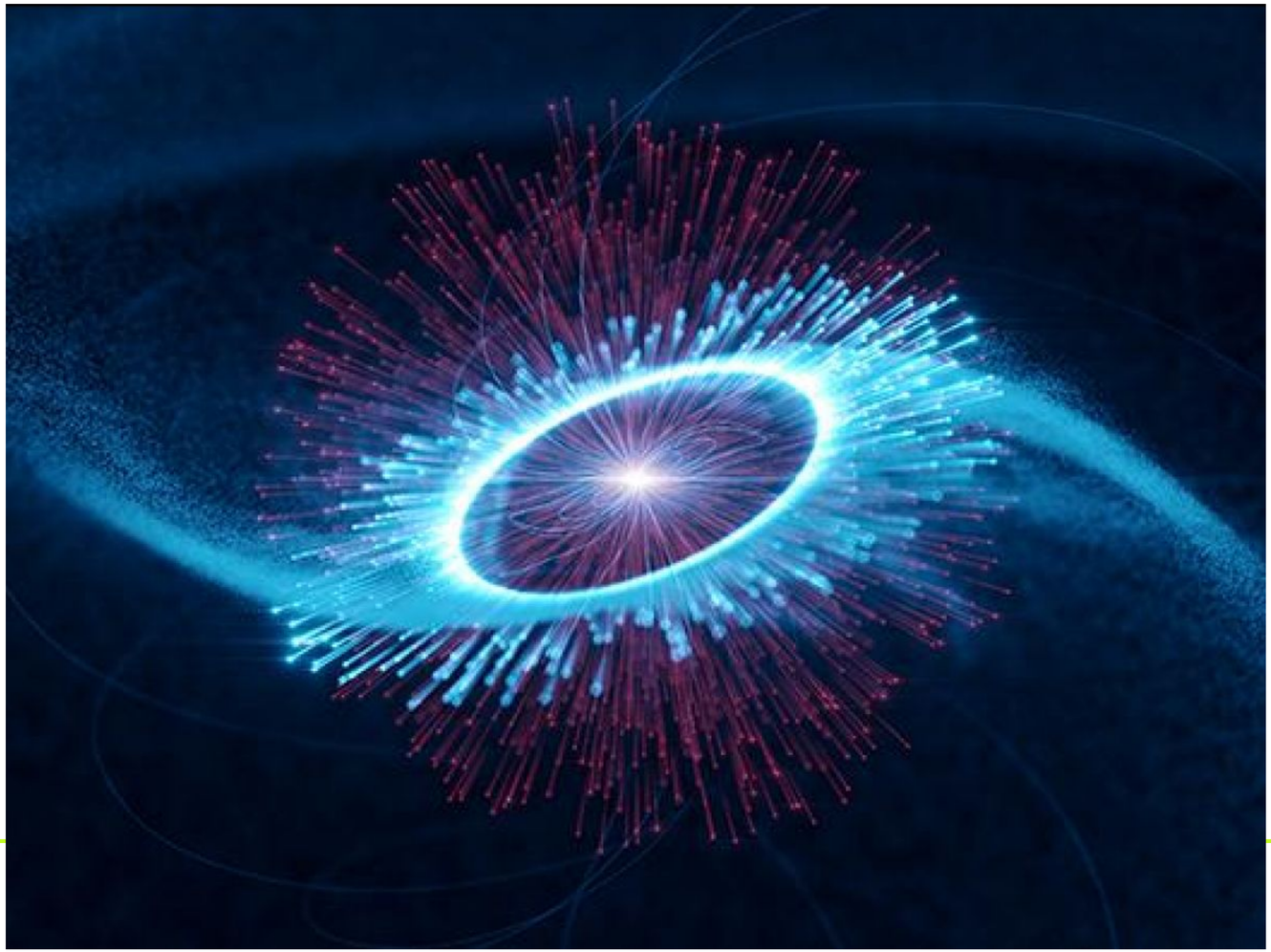
LHC = Large Hadron **Collider**



$E = mc^2$

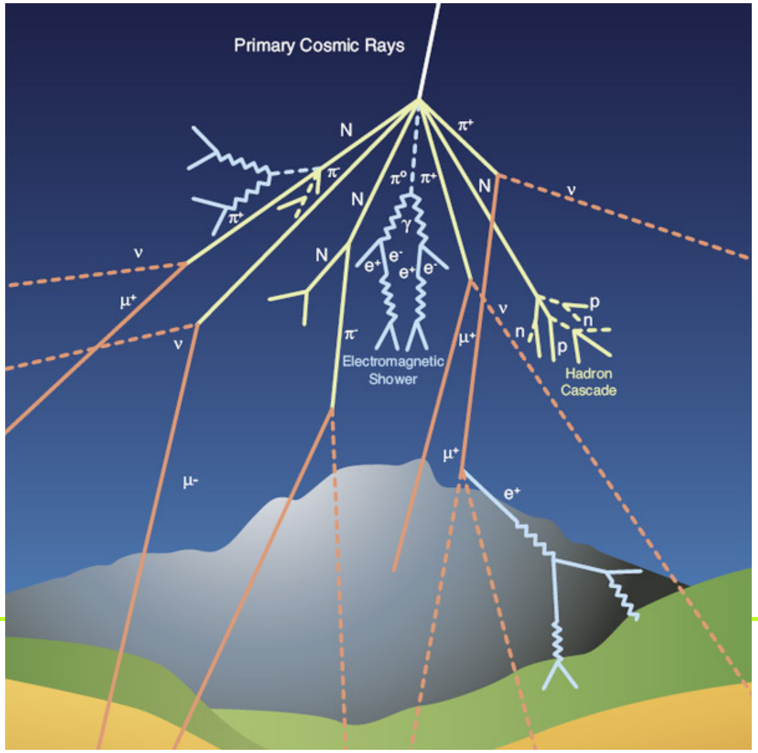
How are high-energy particles produced ?

- **Cosmic accelerators**



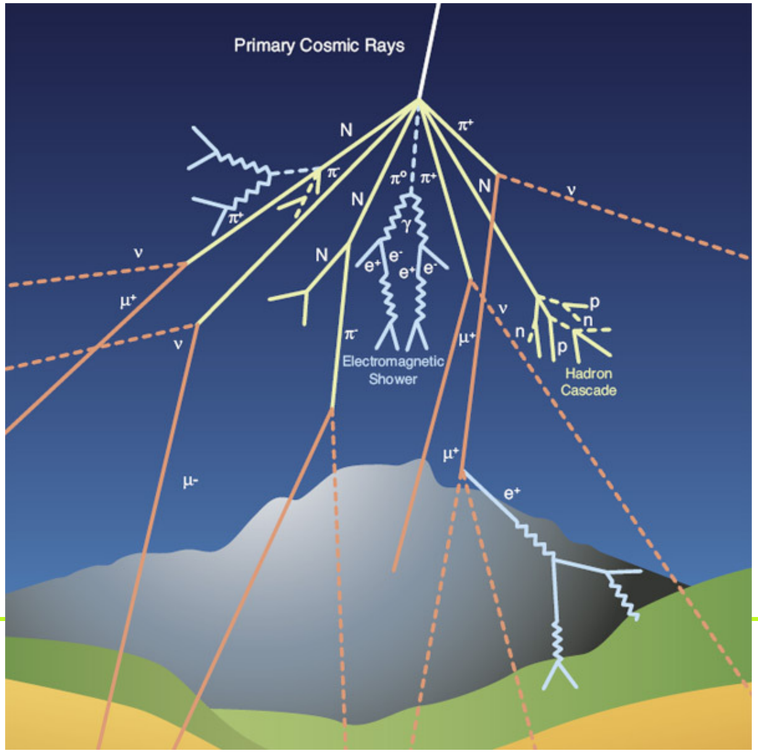
How do we detect particles ?

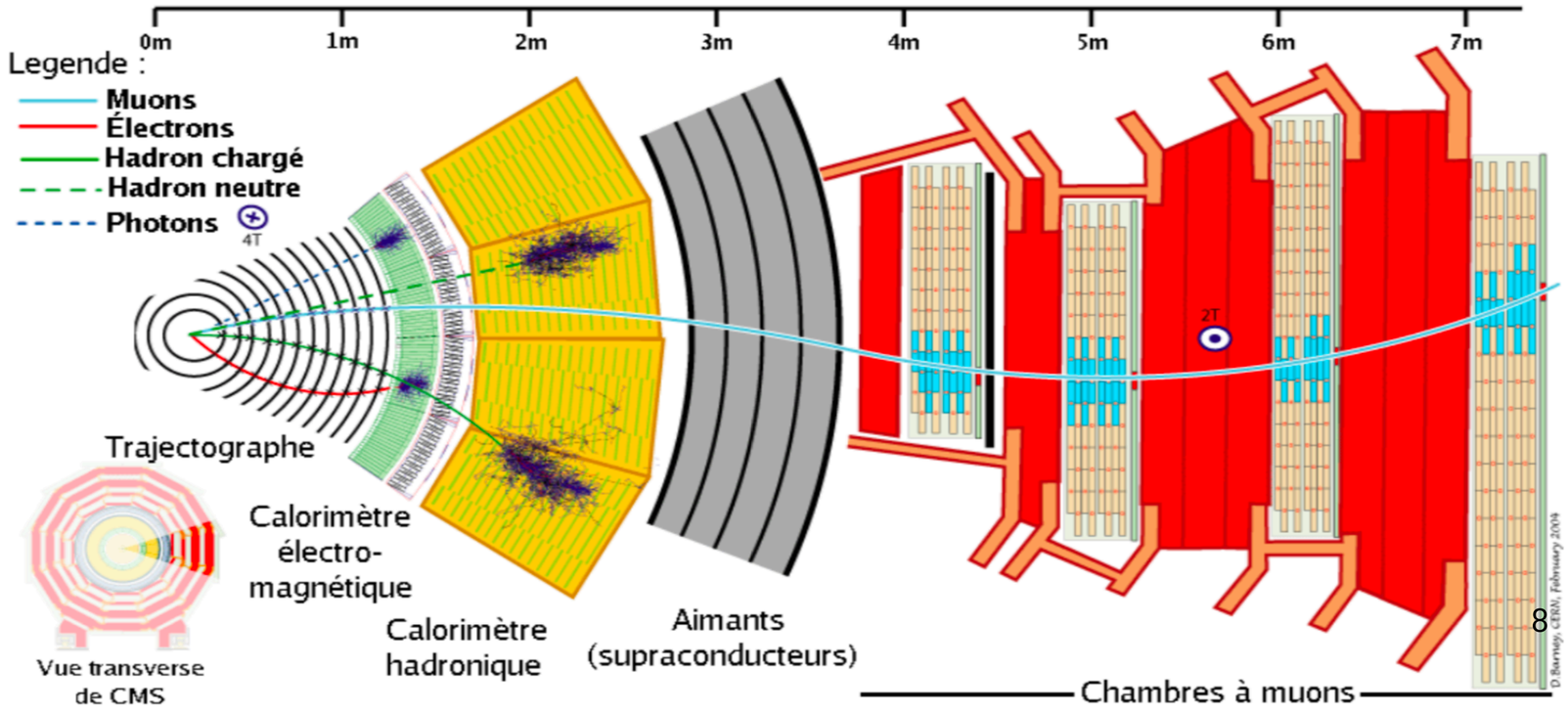
- **Thanks to their INTERACTION with matter ! Examples:**
  - cosmic particles interact with **atmosphere** (hydrogen, oxygen, azote, ….)



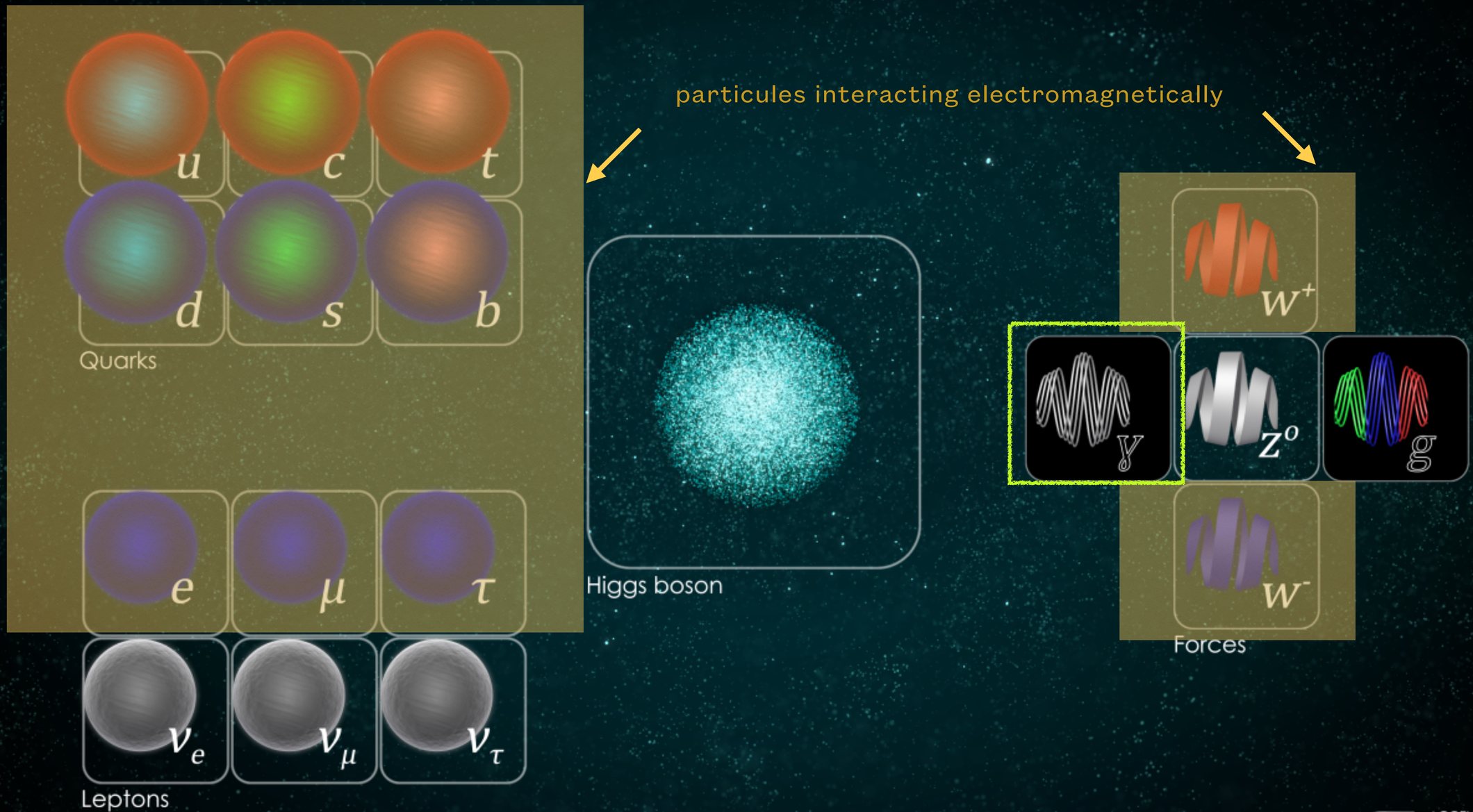
How do we detect particles ?

- **Thanks to their INTERACTION with matter ! Examples:**
  - cosmic particles interact with **atmosphere** (hydrogen, oxygen, azote, ….)
  - accelerator particles interact with **detectors** (lead, tungsten, copper, silicium, …)



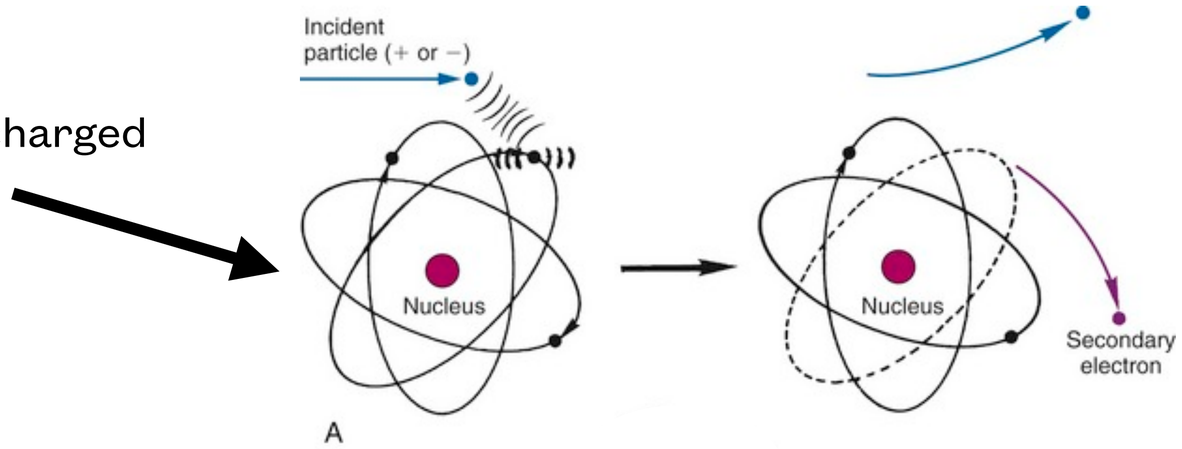


Interaction : Electromagnetic



Interaction of charged particles with matter

- **Ionisation -> primary mechanism of energy loss**
  - remove one or more electrons from an atom near the charged particle's trajectory



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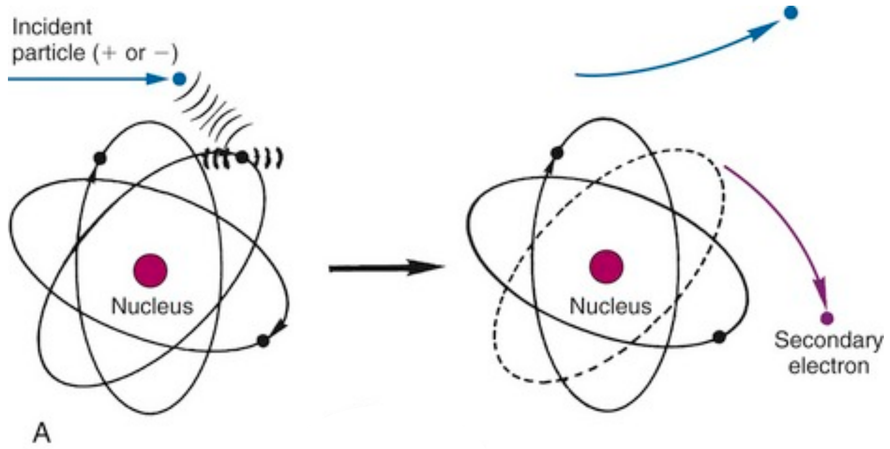
- **Excitation**
  - promote one of atom’s electrons to a higher energy state. Excited atom de-excite and emit low energy ultraviolet photon



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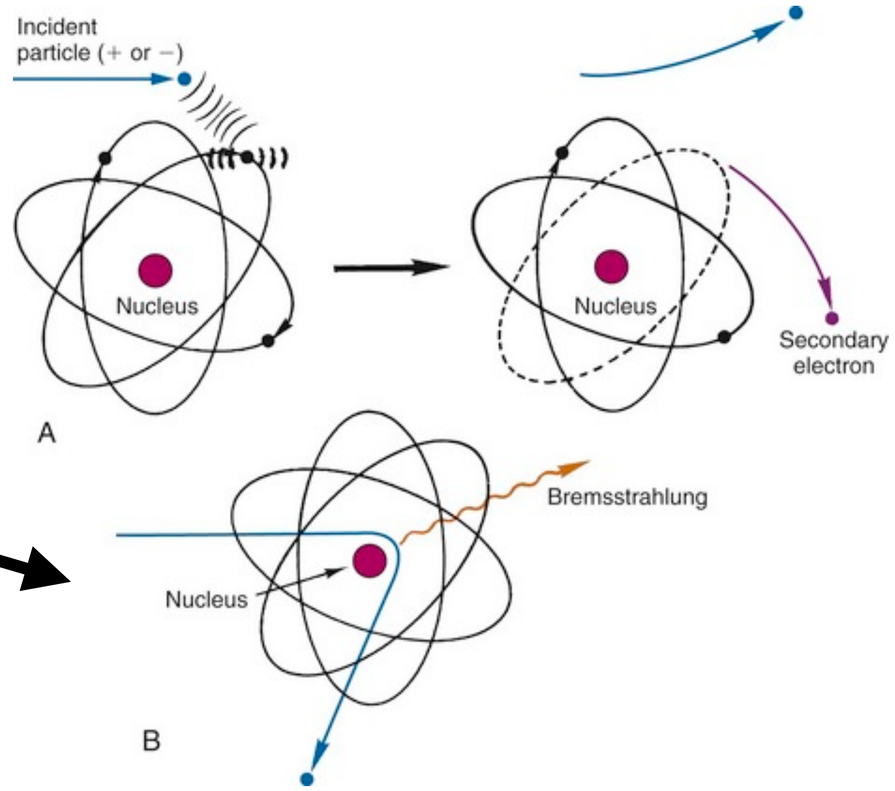
- **Bremstrallung**
  - electromagnetic radiation produced when charged particles are deflected



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- **Bremstrallung**
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- **Cerenkov radiation**
  - blue light emitted by charged particles that travel through a transparent medium (e.g., water) faster than speed of light in that medium. Essentially limited to electrons.

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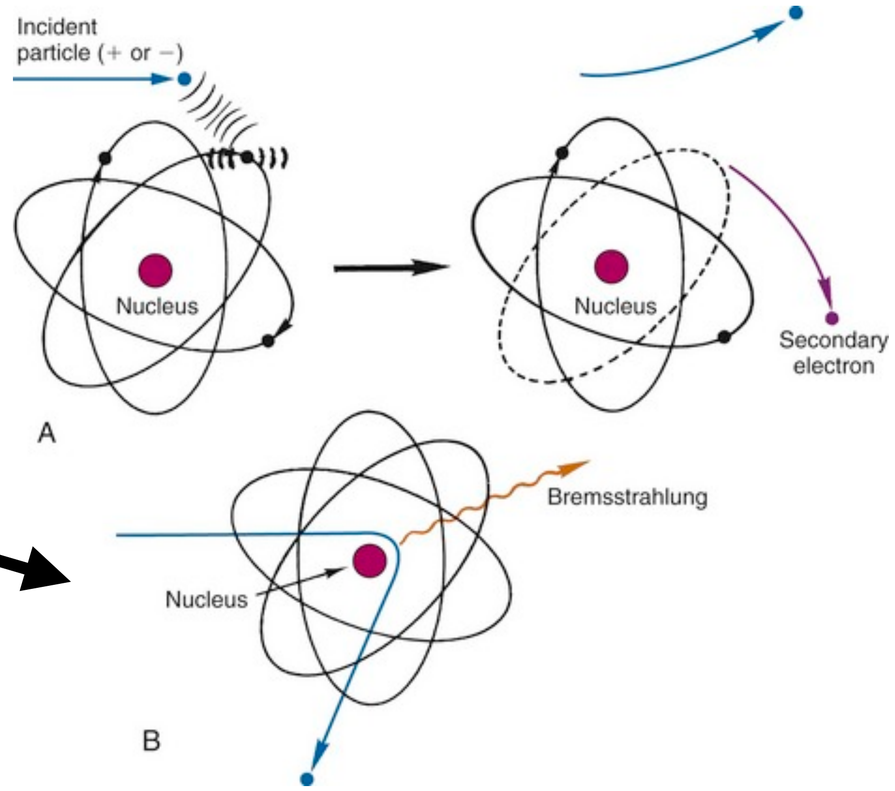
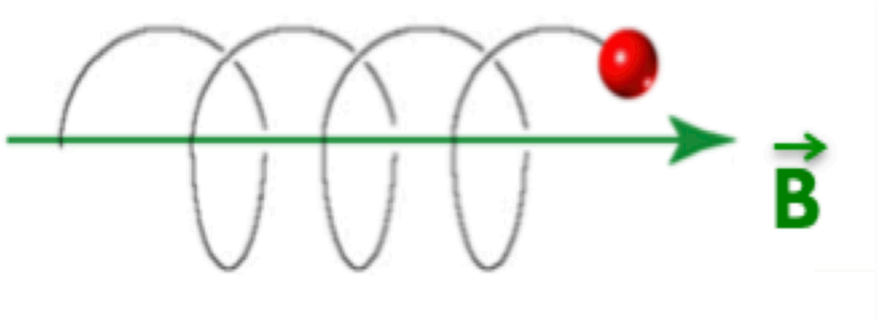


sonic boom of a supersonic aircraft

Charged particle in a magnetic field

- Curvature gives access to mass, charge and momentum of particule



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

$$\mathrm{r} = \frac{\mathrm{mv}}{\mathrm{qB}}$$

radius of curvature

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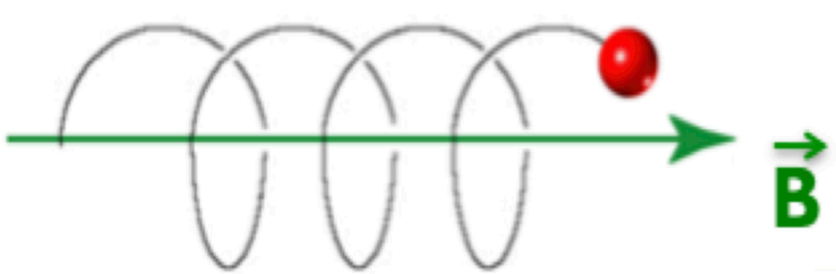

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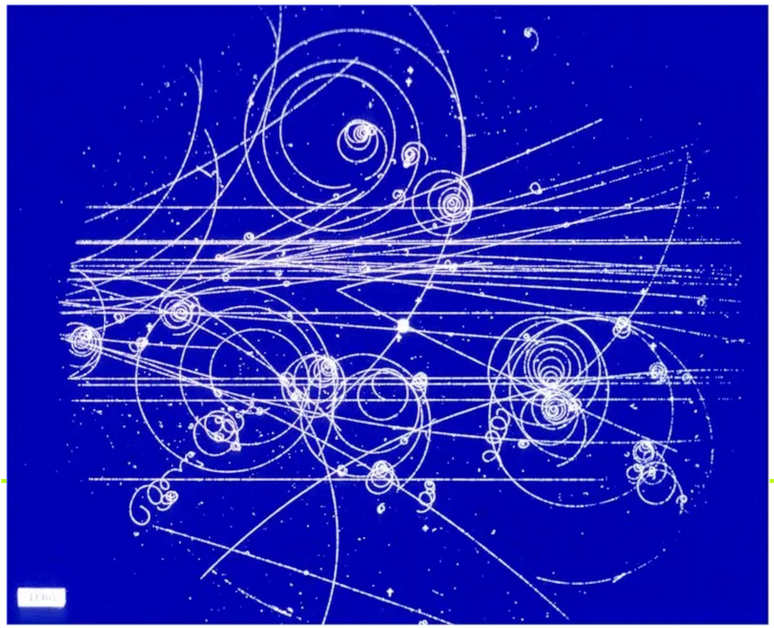
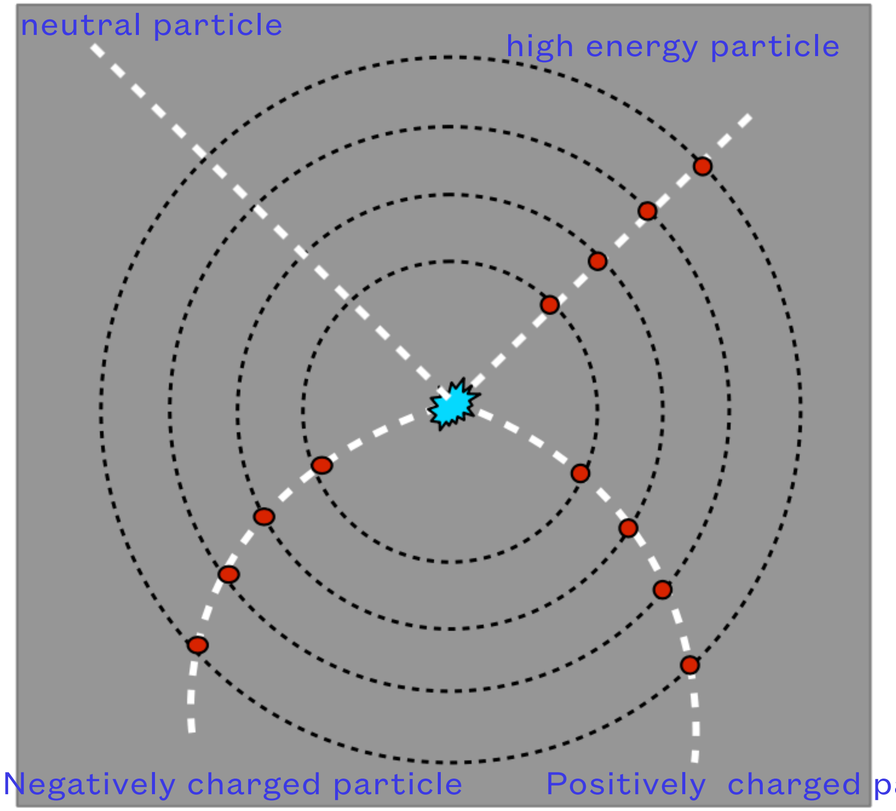


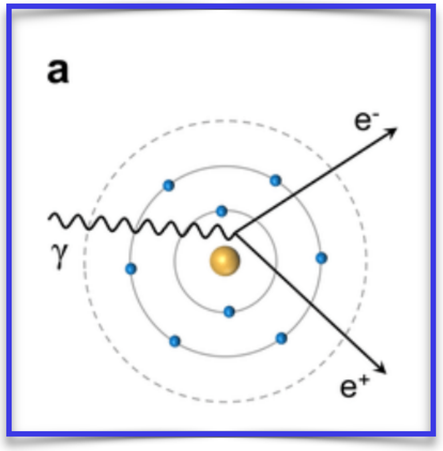
Bubble chamber

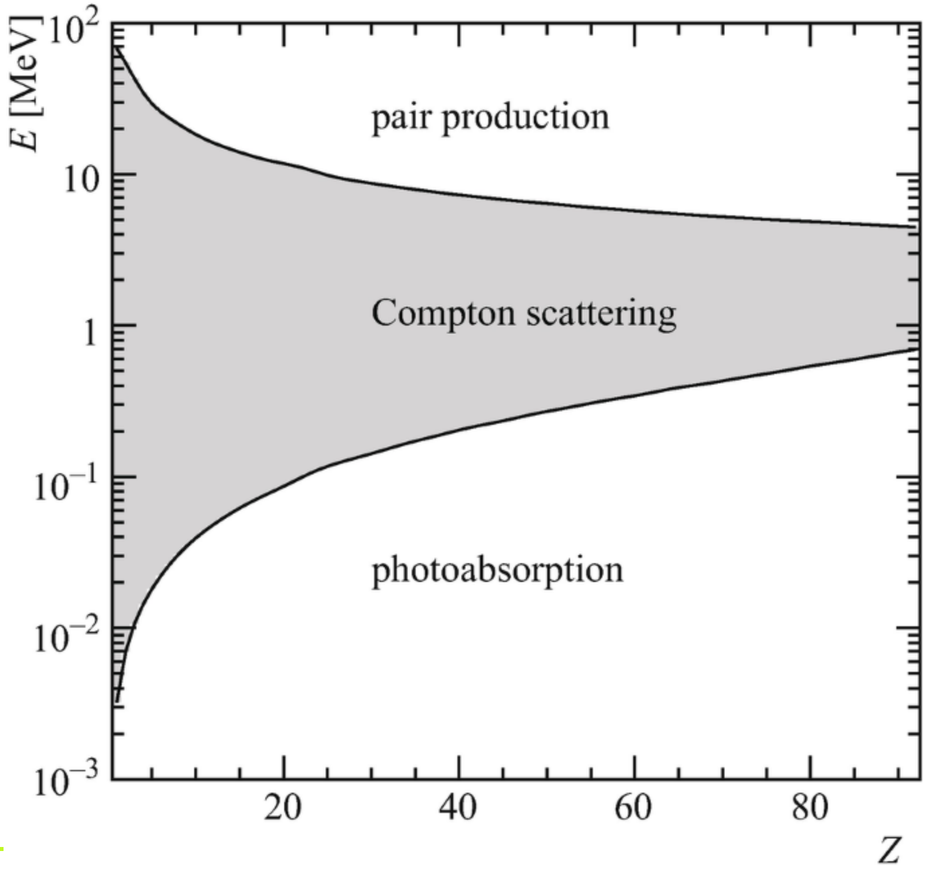


Interaction of photon with matter

- **At high-energy it is essentially pair production**

pair production

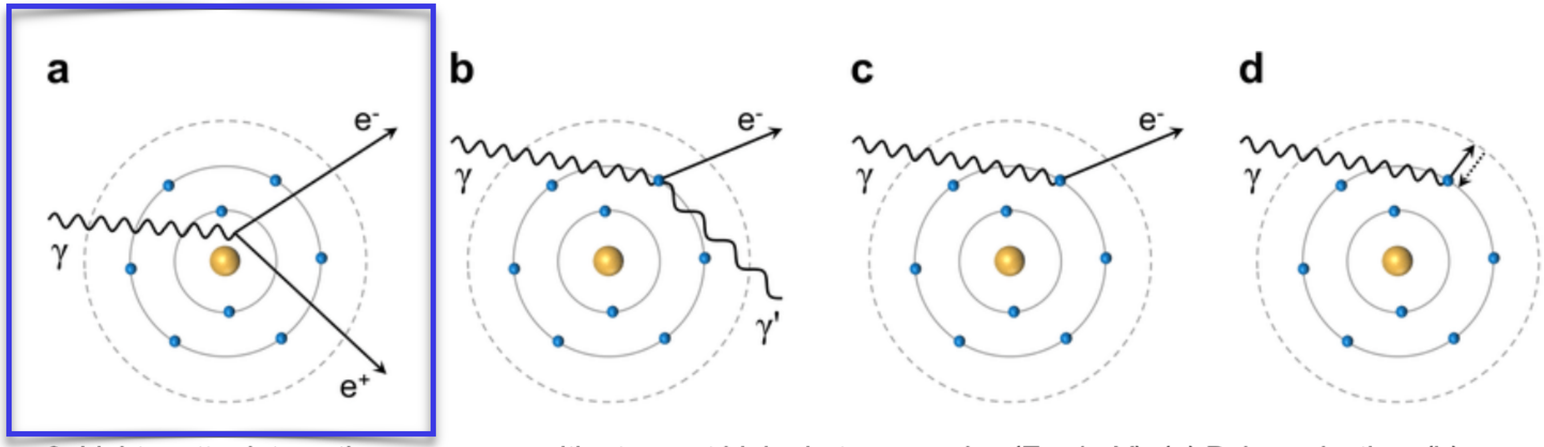




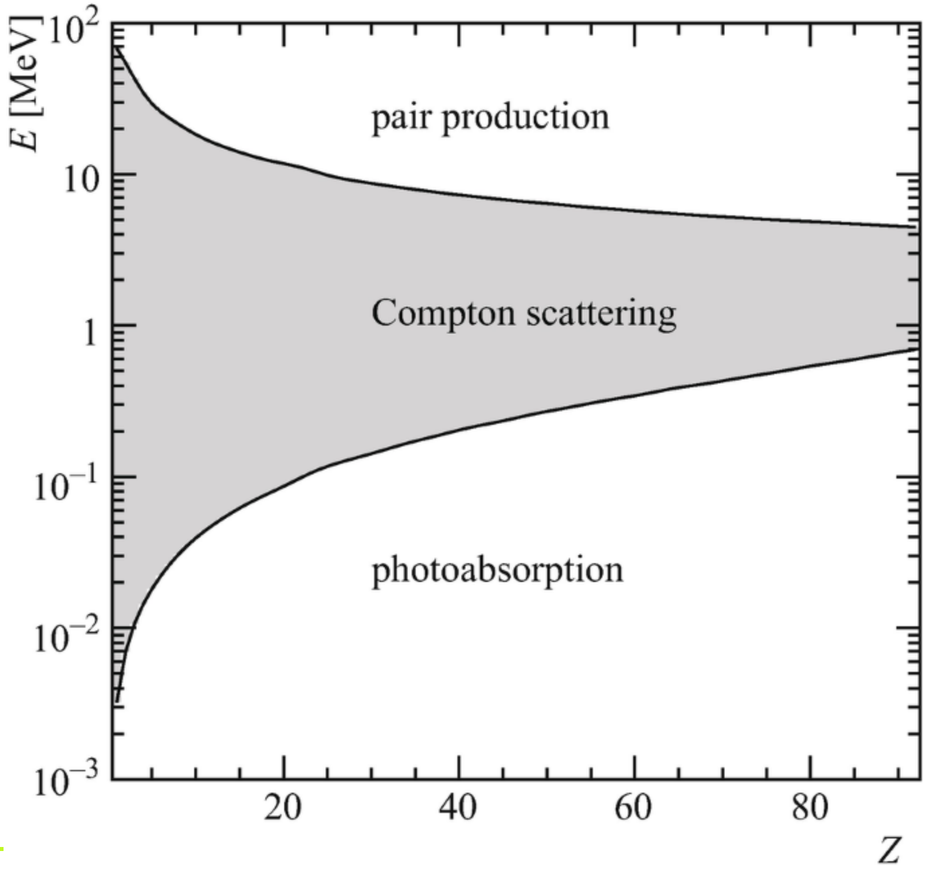
Interaction of photon with matter

- **At high-energy it is essentially pair production**

pair production Compton Scattering Photo-electric Excitation

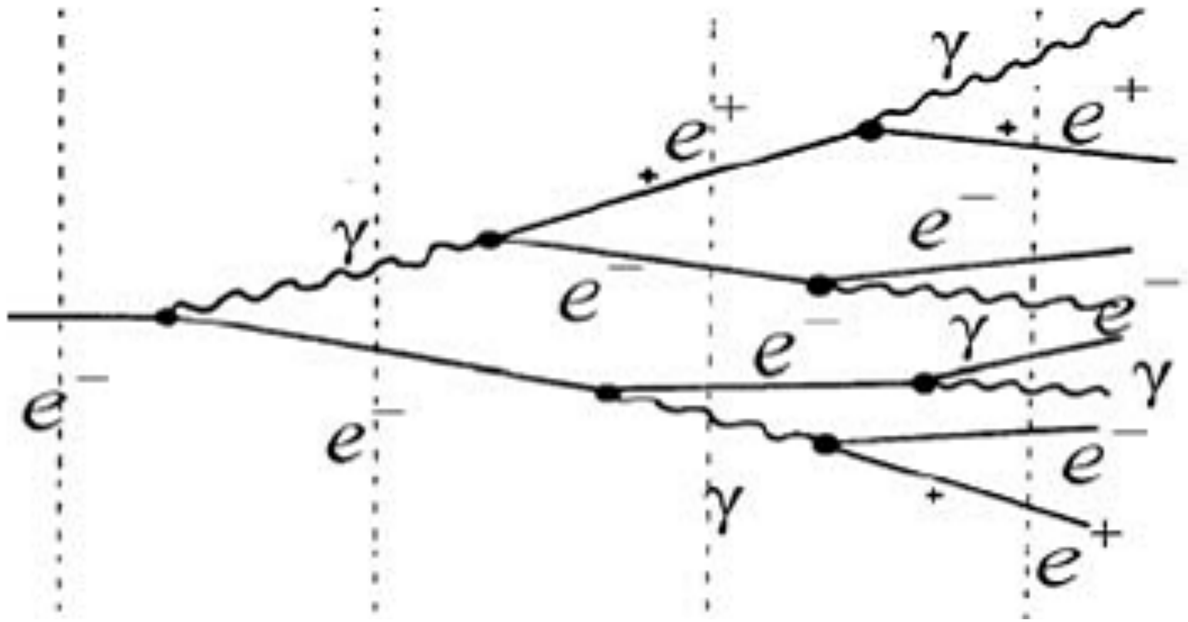


3: Light-matter interaction processes with atoms at high photon energies (E γ 1 eV). (a) Pair production. (b) Compton scattering. (c) Photoelectric effect. (d) Electronic excitation and de-excitation. Yellow spheres: atomic nuclei. Blue spheres: bound electrons.

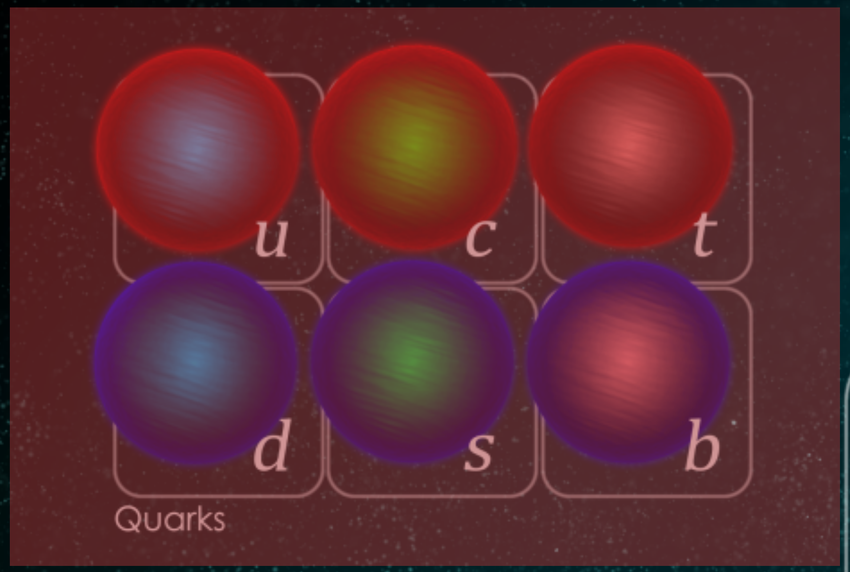


Electromagnetic shower

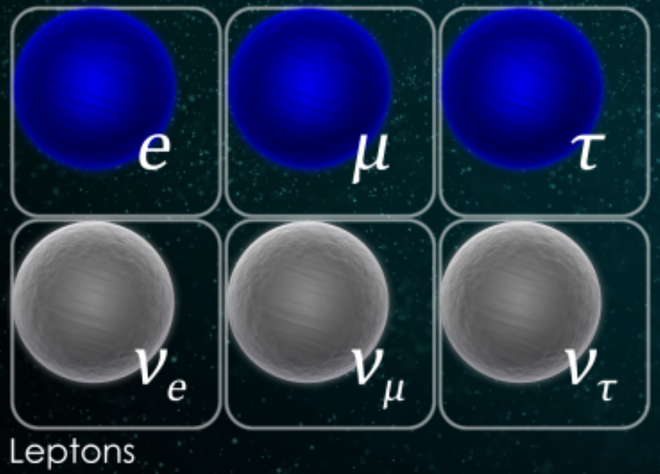
- Bremstrallung + pair production
- Ionisation of medium by electrons play an important role in the detection



Strong interaction



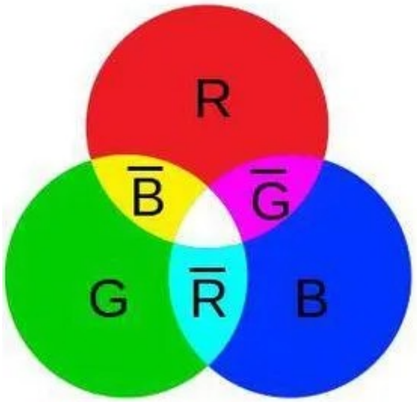
Particules sensitive to strong interaction



Strong force and color charge

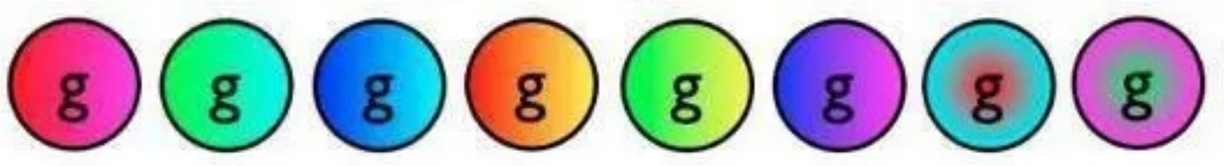
3 colors

3 anti-colors



u u u d d d	c c c s s s	t t t b b b	Quarks
e^- ν_e	μ^- ν_μ	τ^- ν_τ	Leptons
$\bar{u}$ $\bar{u}$ $\bar{u}$ $\bar{d}$ $\bar{d}$ $\bar{d}$	$\bar{c}$ $\bar{c}$ $\bar{c}$ $\bar{s}$ $\bar{s}$ $\bar{s}$	$\bar{t}$ $\bar{t}$ $\bar{t}$ $\bar{b}$ $\bar{b}$ $\bar{b}$	Anti-Quarks
$\bar{e}^+$ $\bar{\nu}_e$	$\bar{\mu}^+$ $\bar{\nu}_\mu$	$\bar{\tau}^+$ $\bar{\nu}_\tau$	Anti-Leptons

8 gluons



–> THERE ARE THEN 36 QUARKS IN THE THEORY

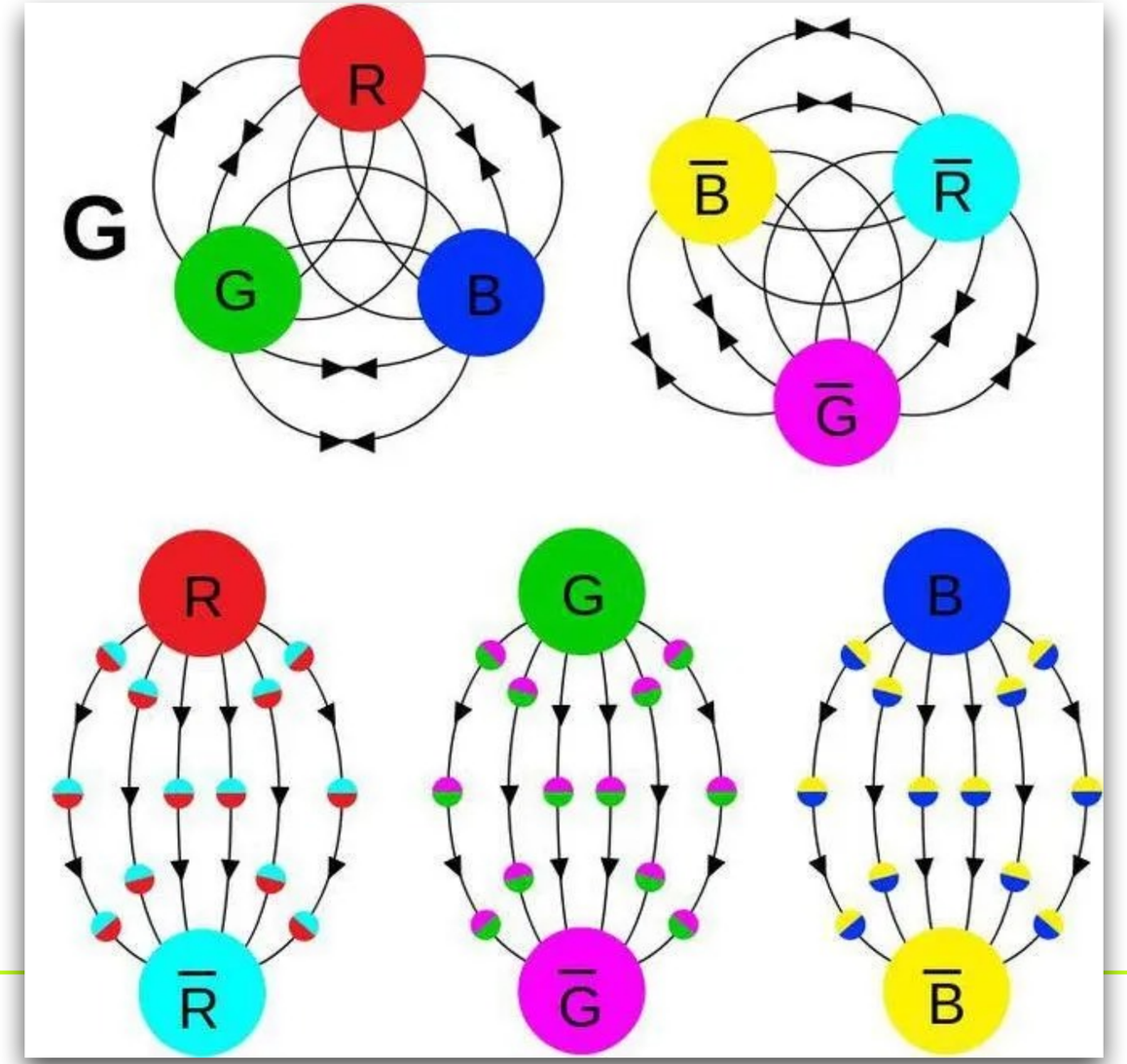
Color confinement

- **Not possible to find a colored particle alone ! Only « white » particles allowed**

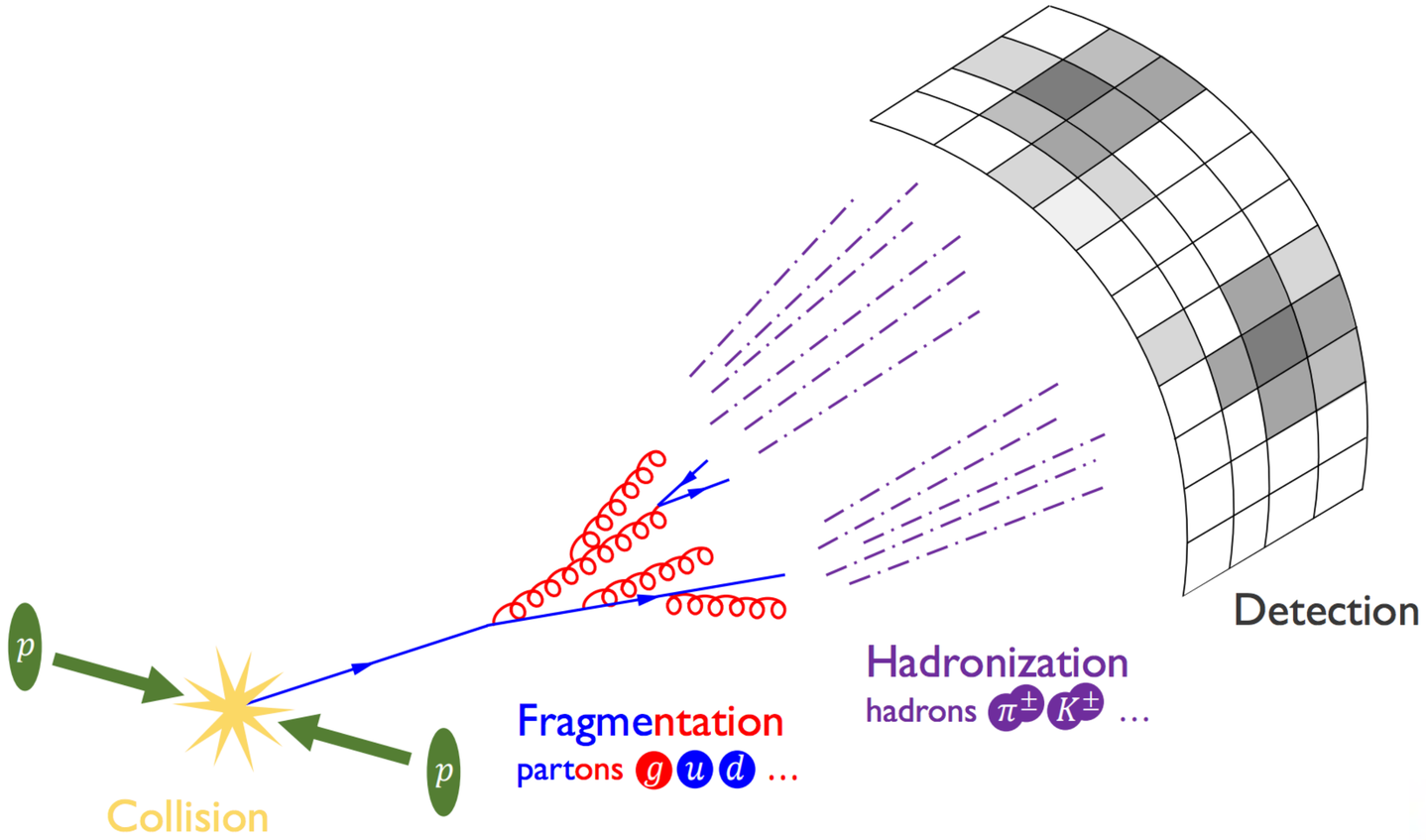
Hadrons

Baryons

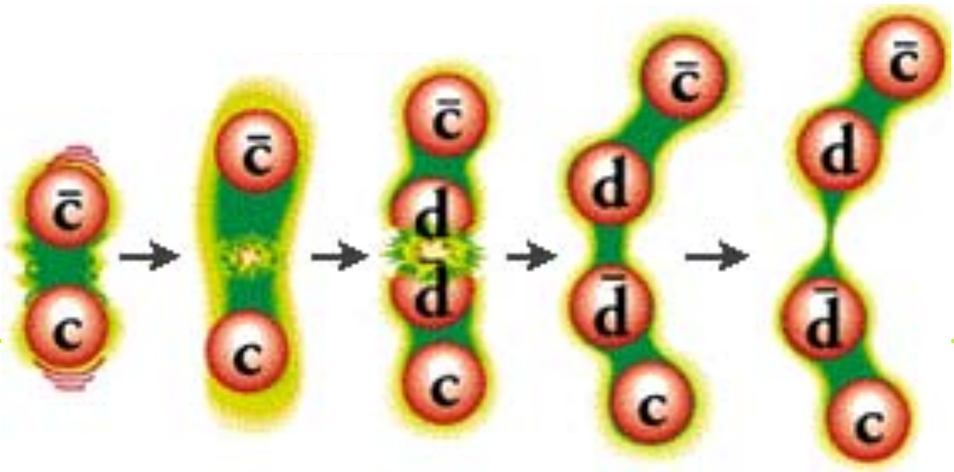
Mésons



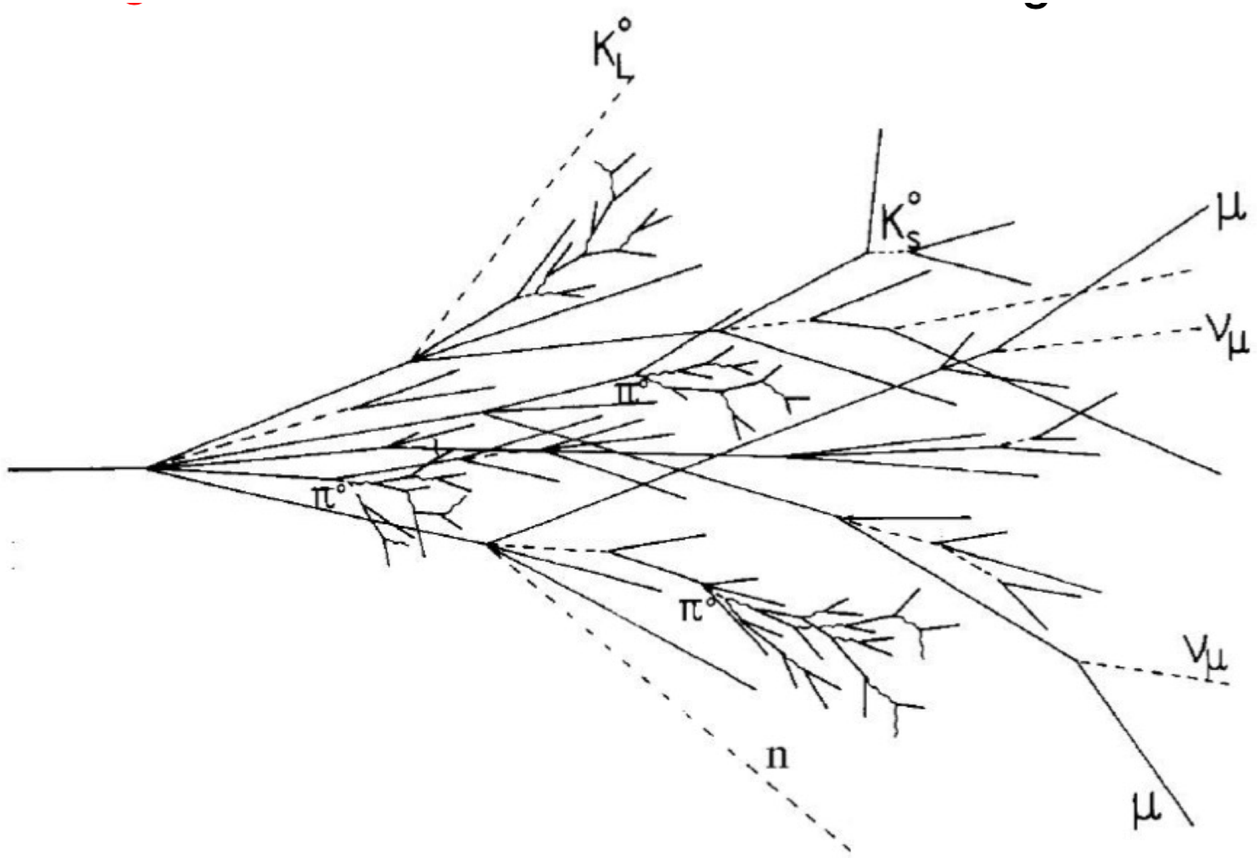
Fragmentation and hadronisation



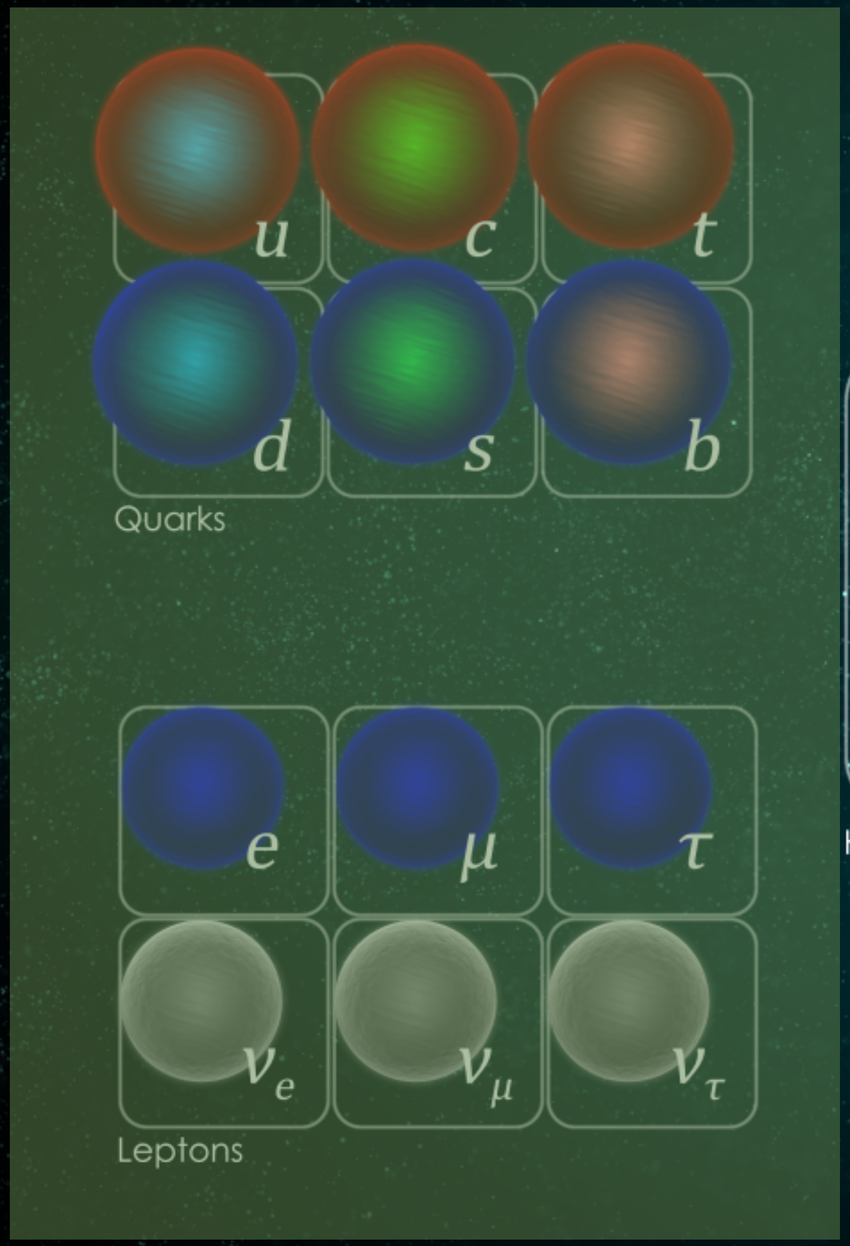
- When a single quark or gluon is emitted, process of fragmentation and hadronisation occurs to « whiten » the particle
- Results in a hadronic shower -> a « jet »



Hadronic shower



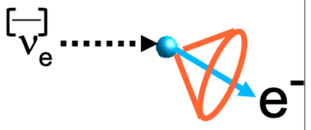
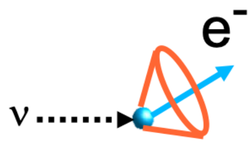
Weak interaction



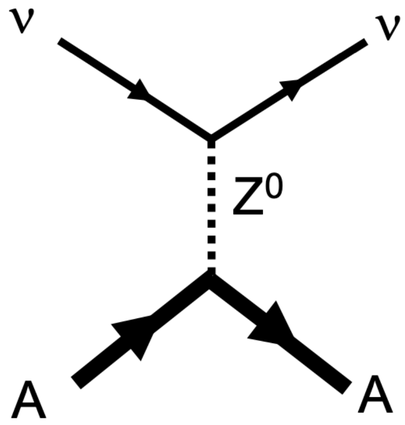
Particules sensitive to weak interaction

Unique force to which neutrinos are sensitive to !

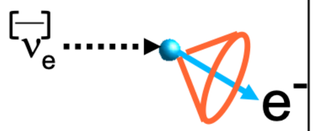
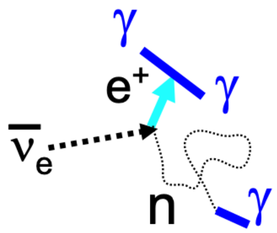
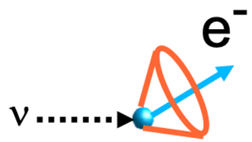
Interaction of neutrinos with matter

	Electrons
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 
Neutral current	 Useful for pointing

- **Very rare interactions and tiny effects**



Interaction of neutrinos with matter

	Electrons	Protons
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 
Neutral current	 Useful for pointing	

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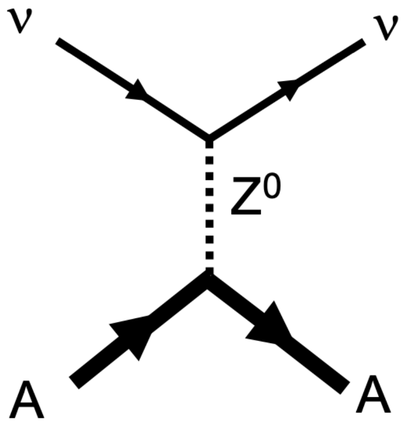

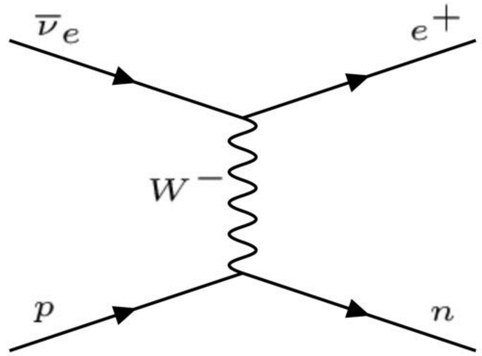

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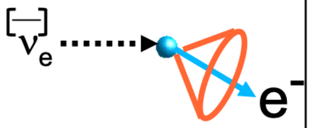
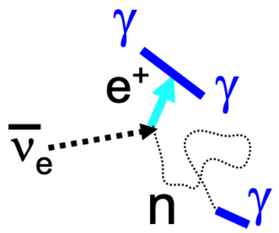
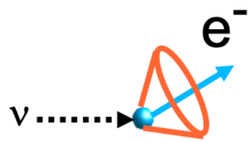
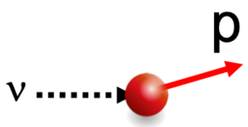
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils

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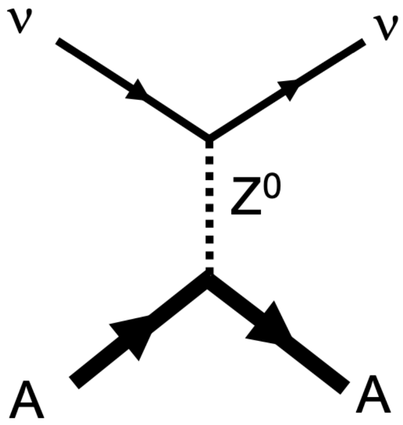
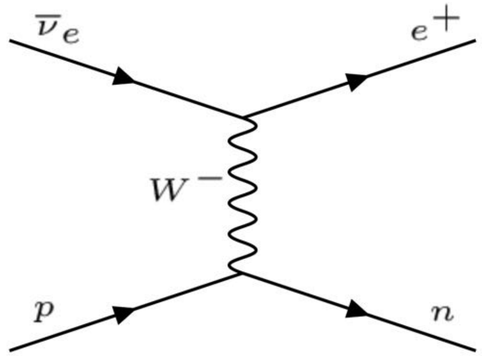
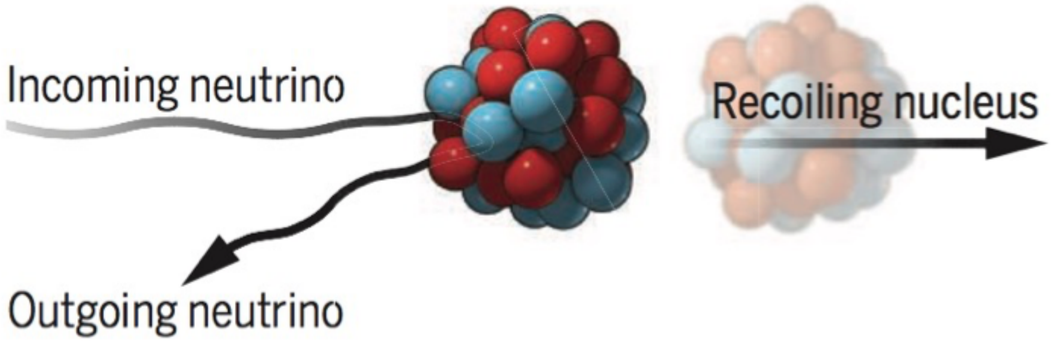






How do we recognize particles ?

- **Thanks to their specific properties !**
- **And the way they interact with matter**

11.02.2030

RÉPUBLIQUE FRANÇAISE

CARTE NATIONALE D'IDENTITÉ / IDENTITY CARD

FR

First name: *W*

Family Name: *Boson*

Birth date : *January 25 1983*

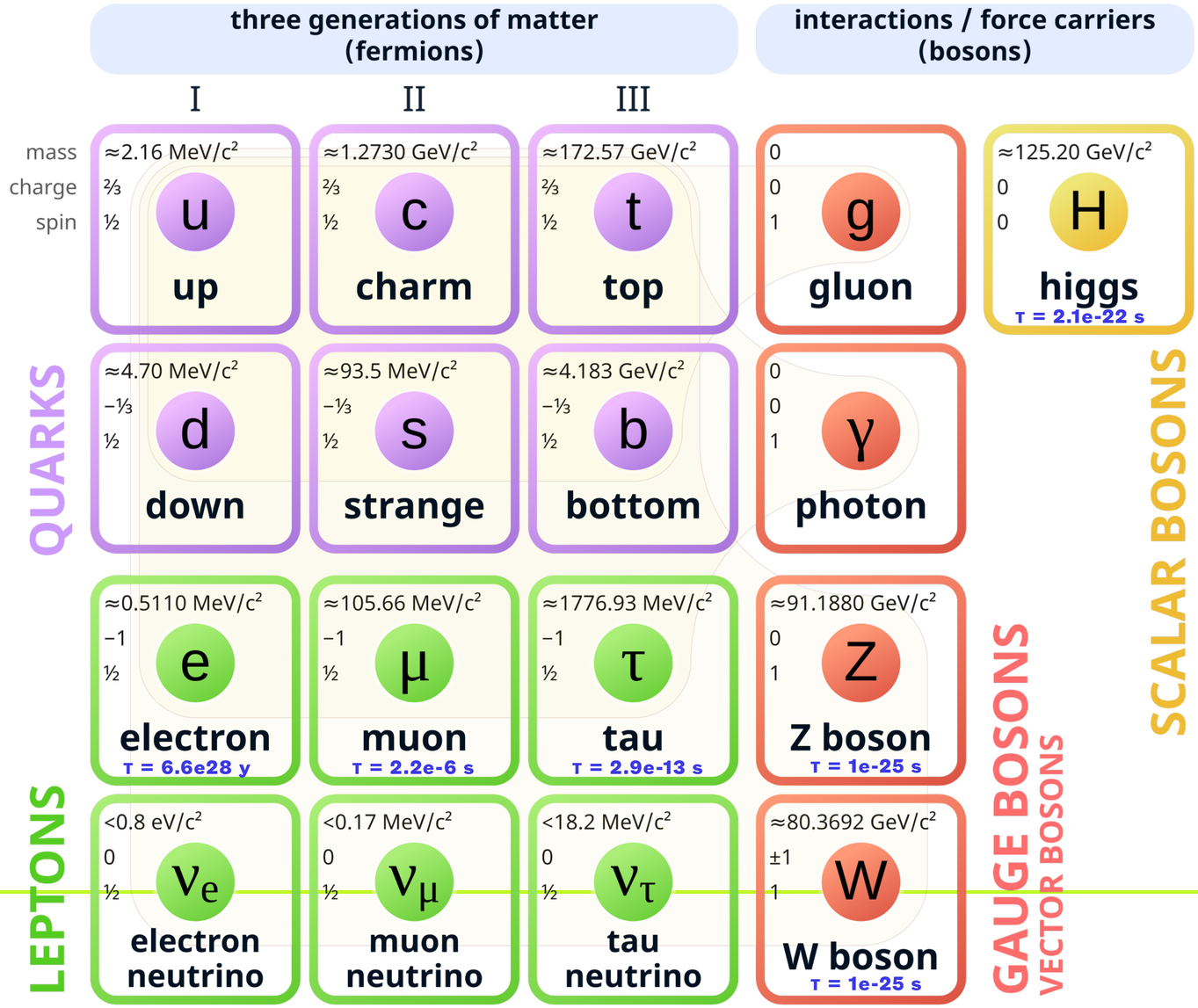
Birth place : *CERN*

Mass : 80.4 GeV / c^2

Charge: *+1 or -1*

Lifetime: *10^{-25} s, decays to quarks or leptons*

Particle mass, charge and lifetime

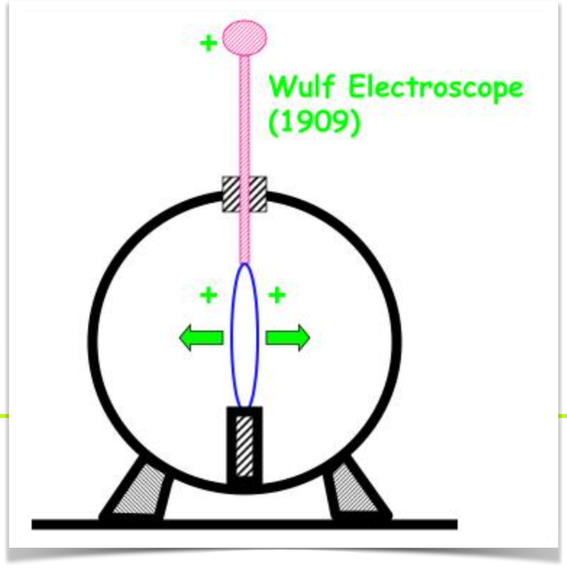


How were particles detected in the past ?

Some examples ....

Ballons flight and cosmic rays - 1912

- In 1909, Theodor Wulf was looking for origin of ionizing radiation registered on an **electroscope** -> tested on Eiffel tower (300 m) -> no much decrease compared to ground



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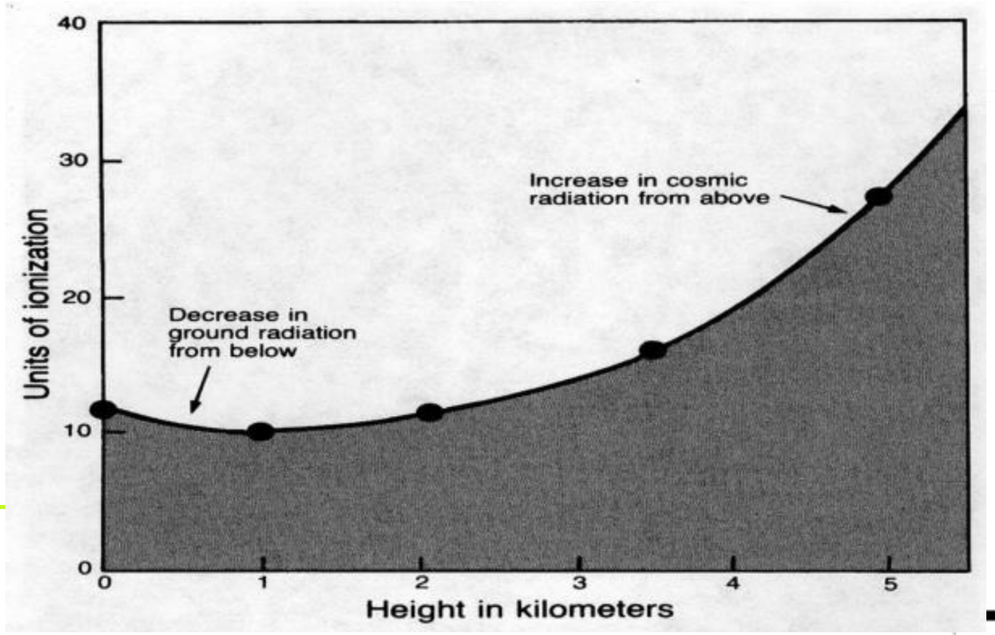
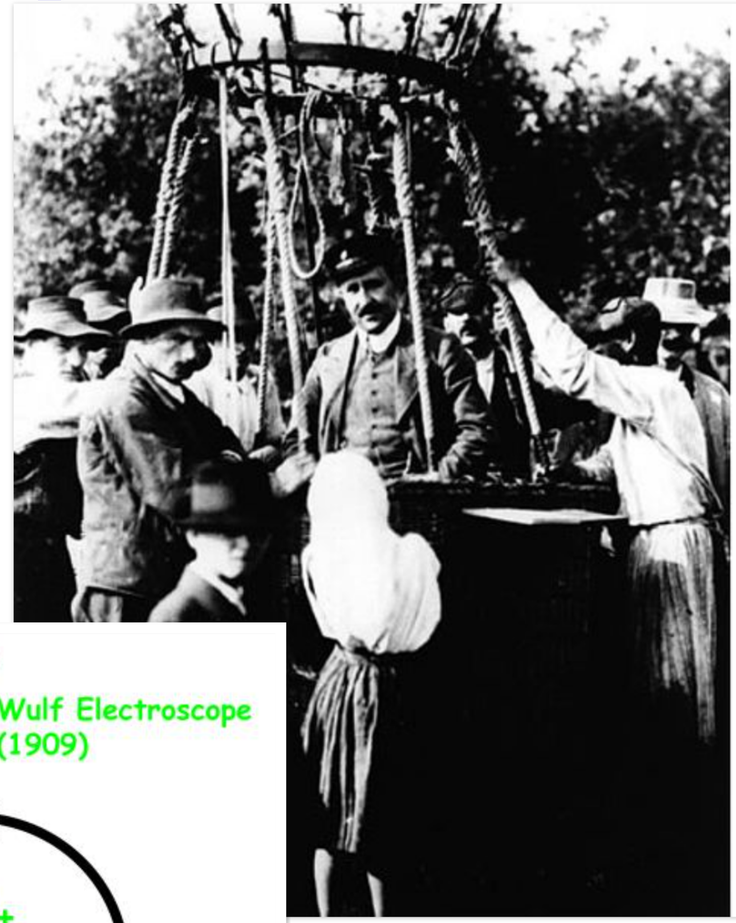
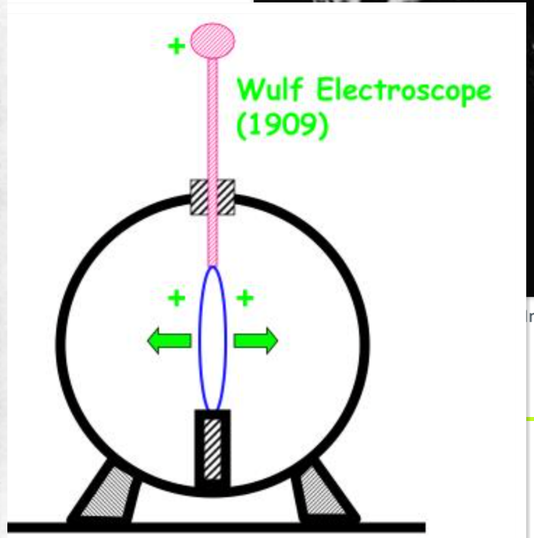
- In 1912, several ascents, one of which at 5300m by Victor Hess -> increase of radiation level ! —> **Discovery of cosmic rays**





(Image:Wikimedia commons)



First neutrino detection and scintillators - 1956

- In 1956, Fred Reines and Clyde Cowan conducted an experiment (project Poltergeist) close to a reactor in USA : two tanks with 200 liters of water with ~40 kg of dissolved cadmium (great absorber of neutrons).
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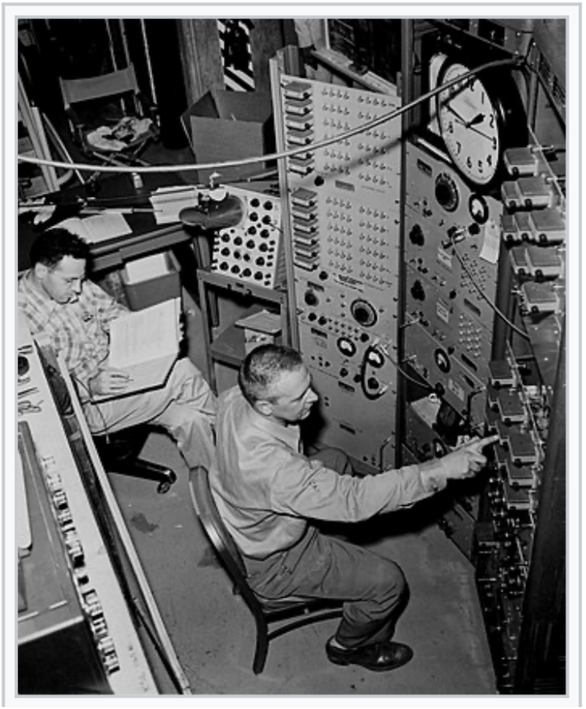

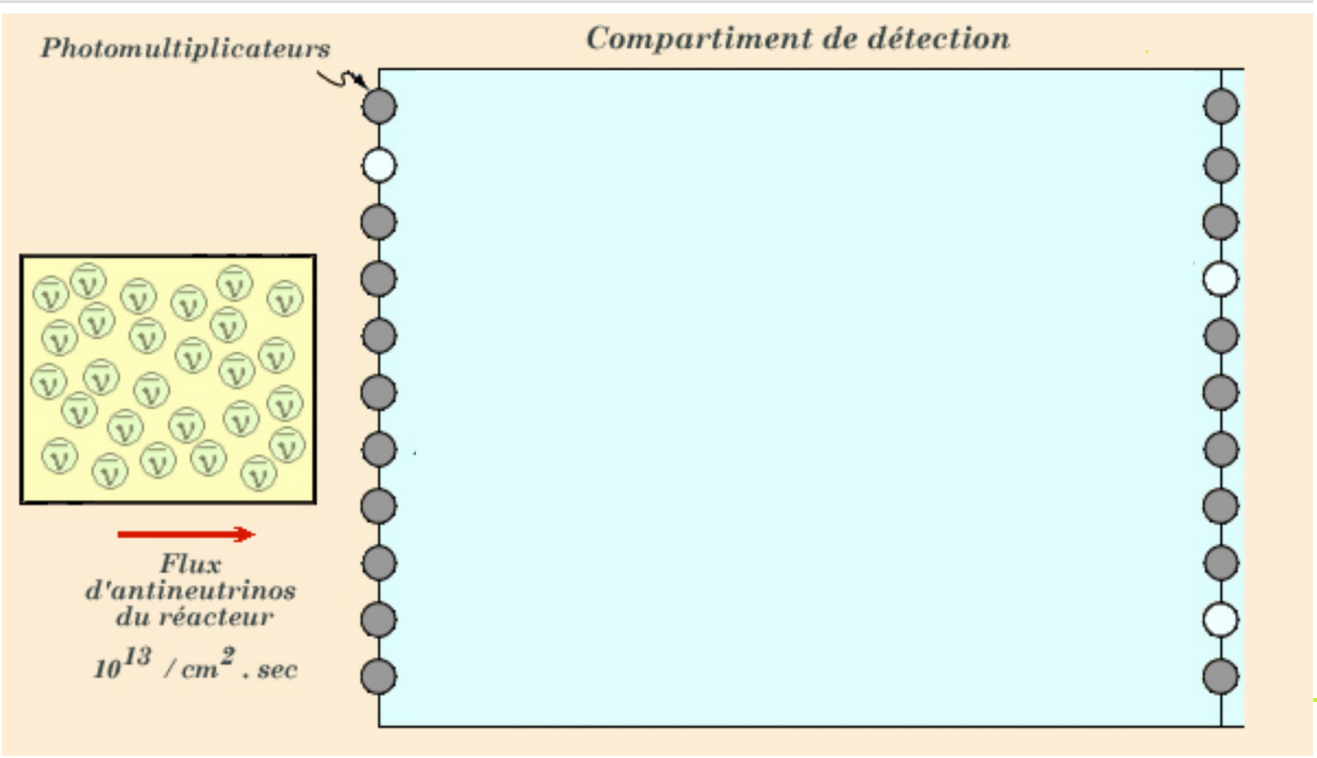

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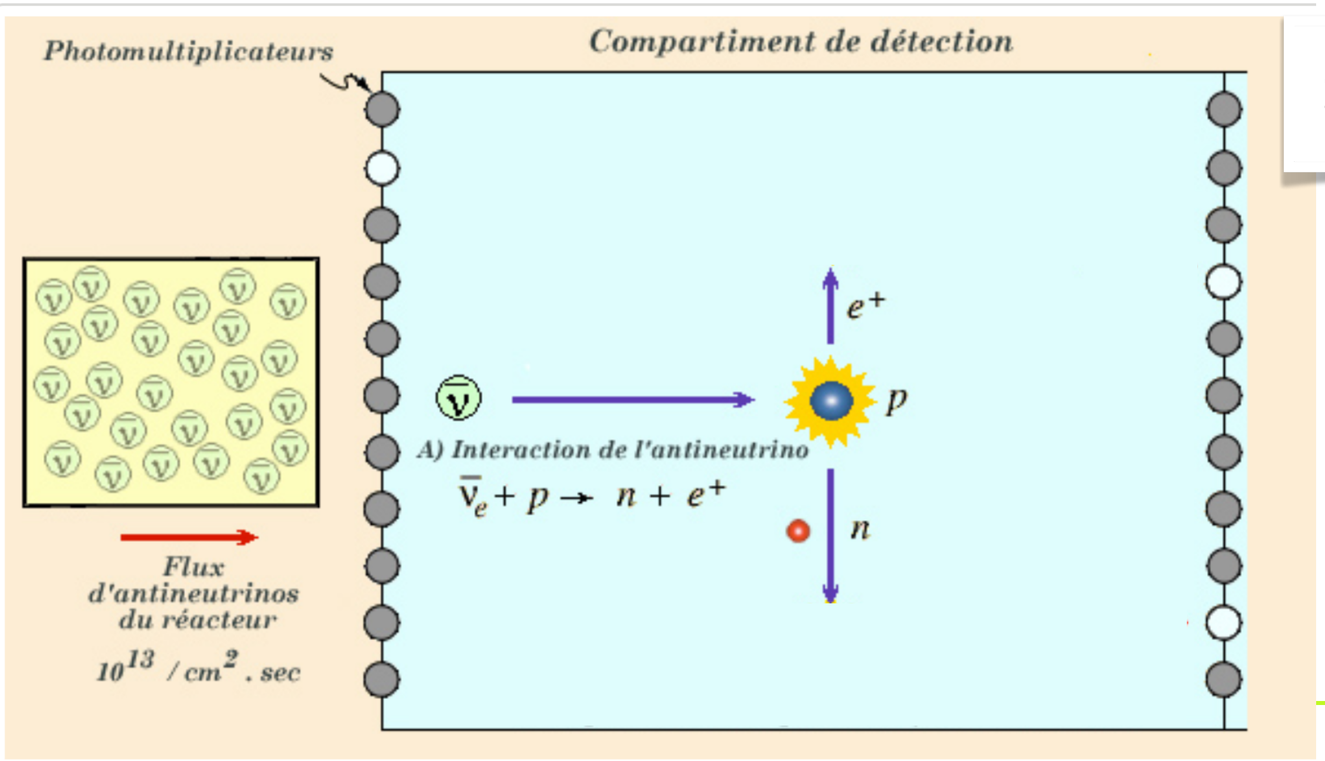

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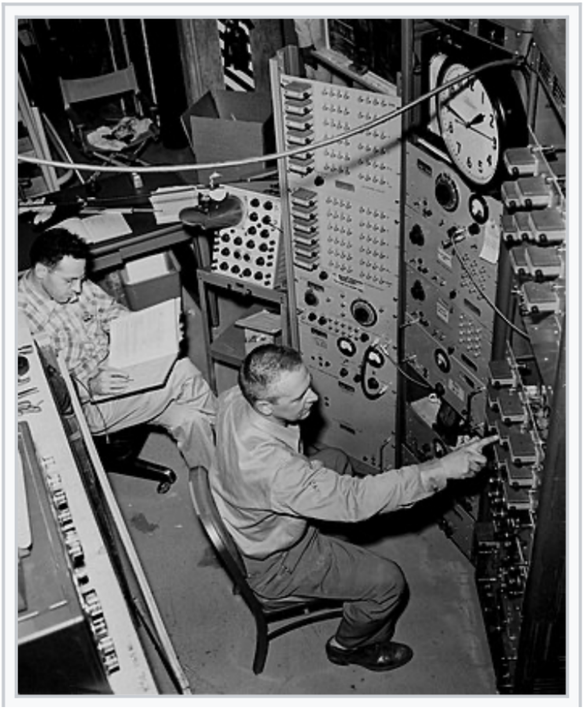

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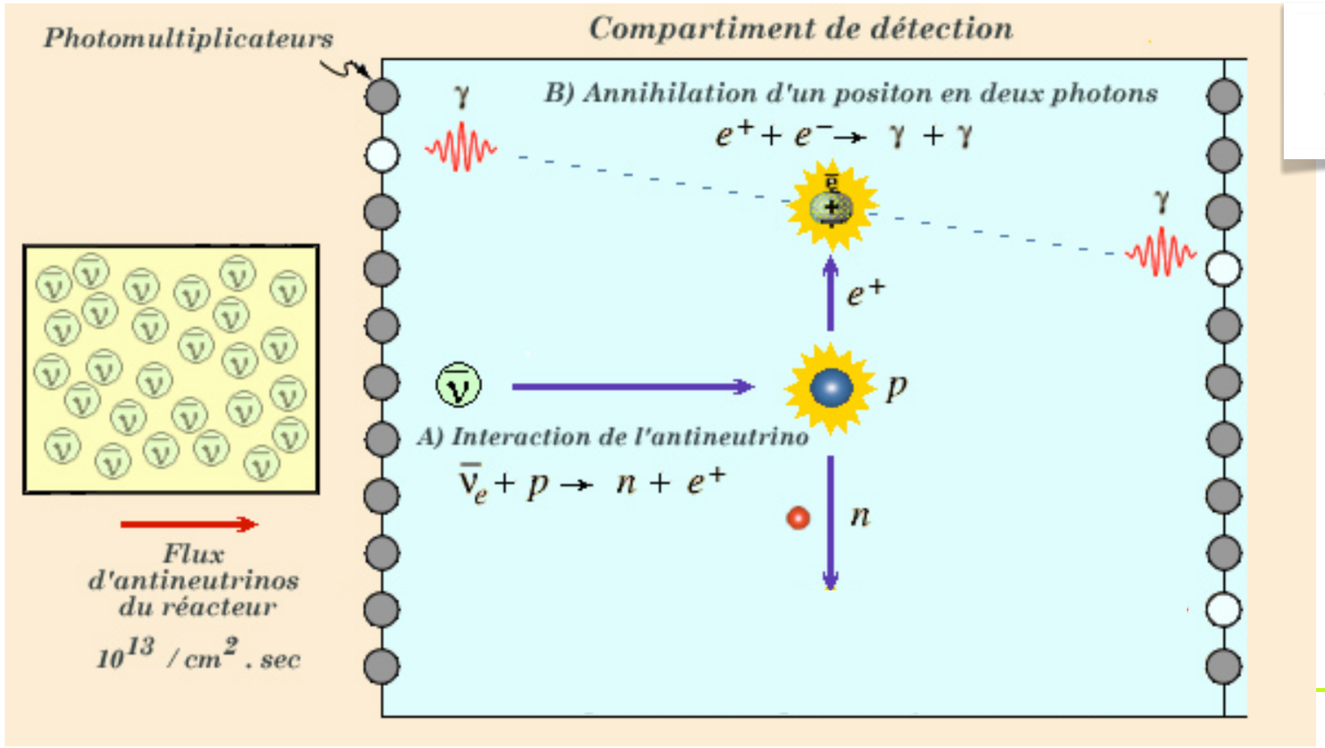

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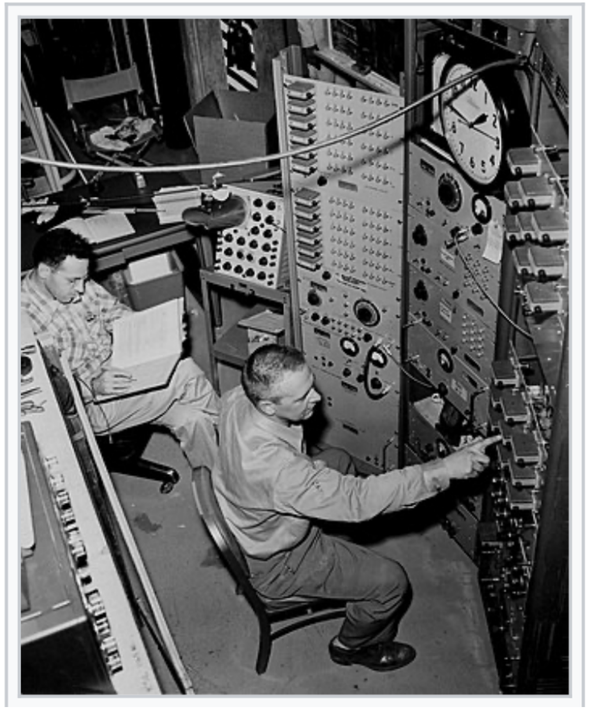

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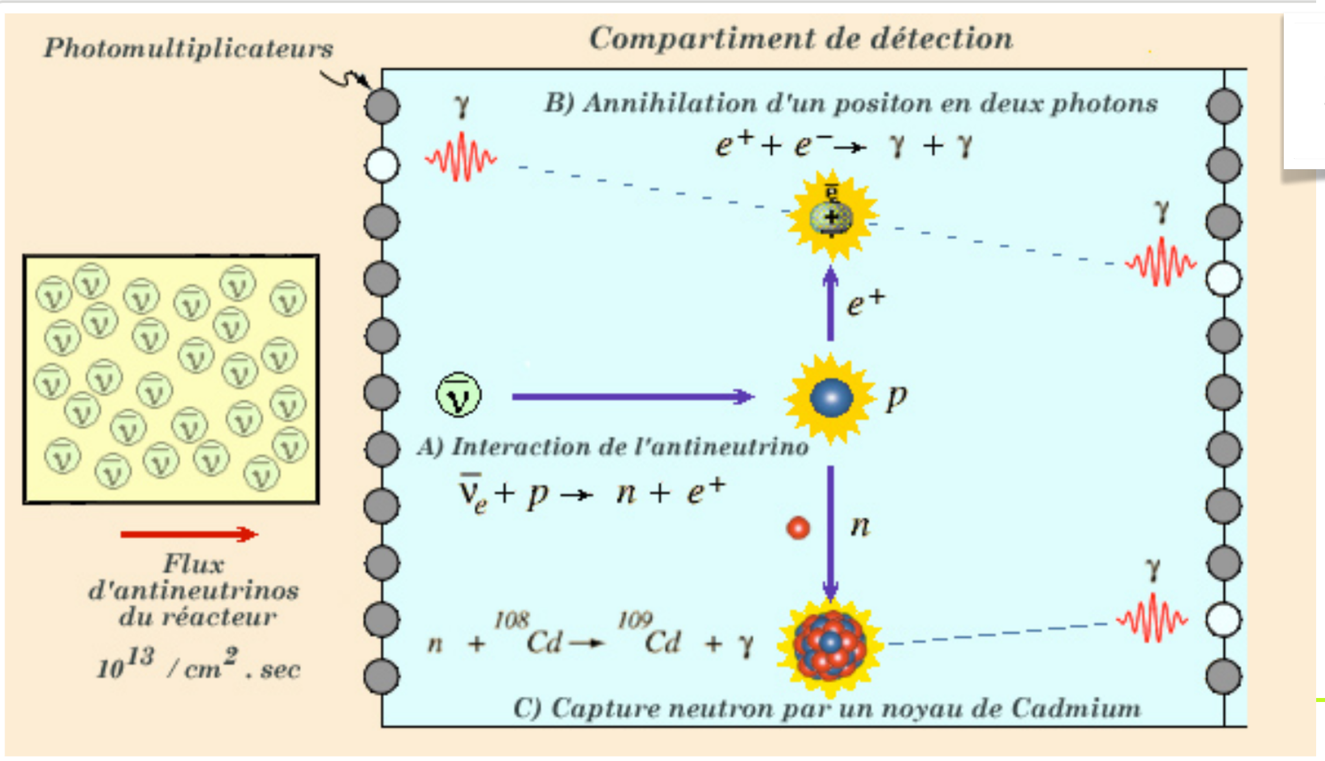

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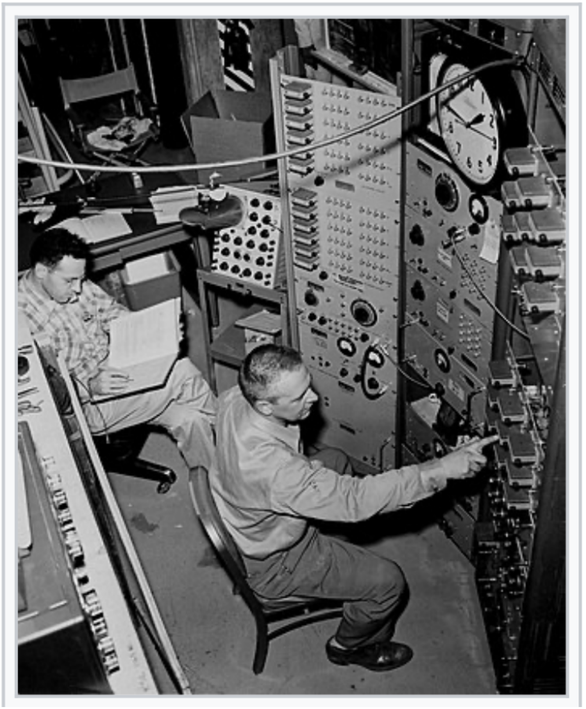

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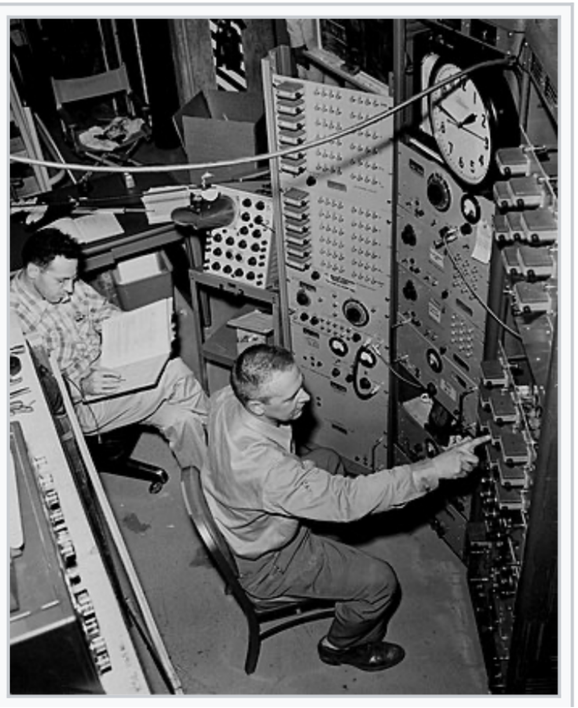
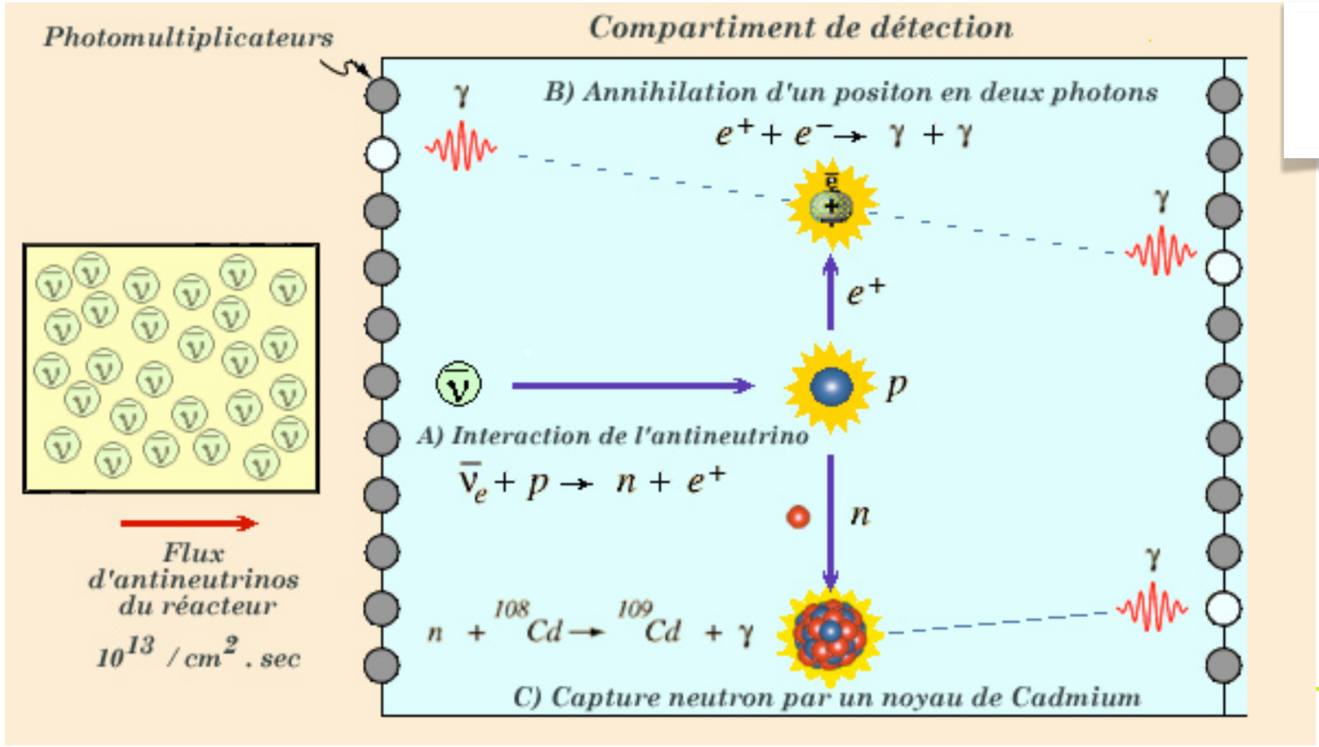
- Water tanks sandwiched between **two layers of organic liquid scintillators** (just invented !) containing 110 photomultiplier tubes —> **observation of neutrino**





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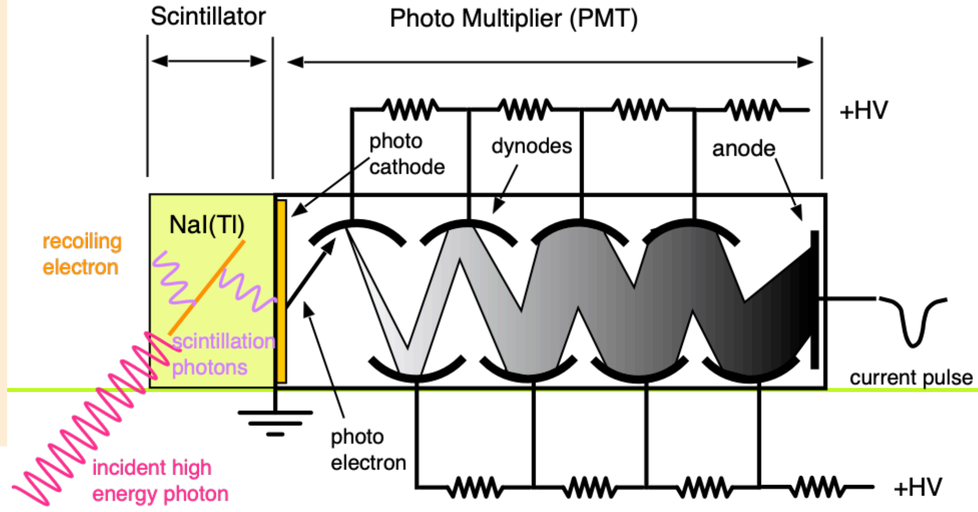

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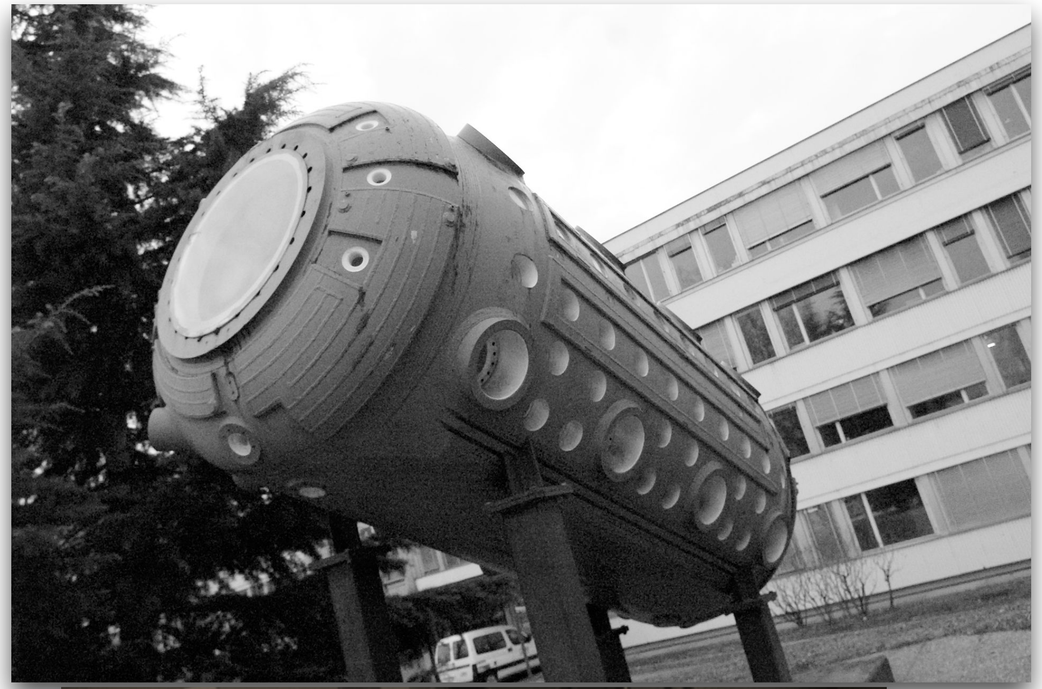
Bubble chamber and neutral current - 1973

- **Bubble chamber (Donald Glaser)**: closed cavity filled with liquid (hydrogen) in metastable state, at precise limit of boiling. When external particle interacts with atoms of the liquid -> small rise in local temperature -> small bubbles form, trajectory curved thanks to magnetic field -> photos
  - **need to examine thousands of photographs !**



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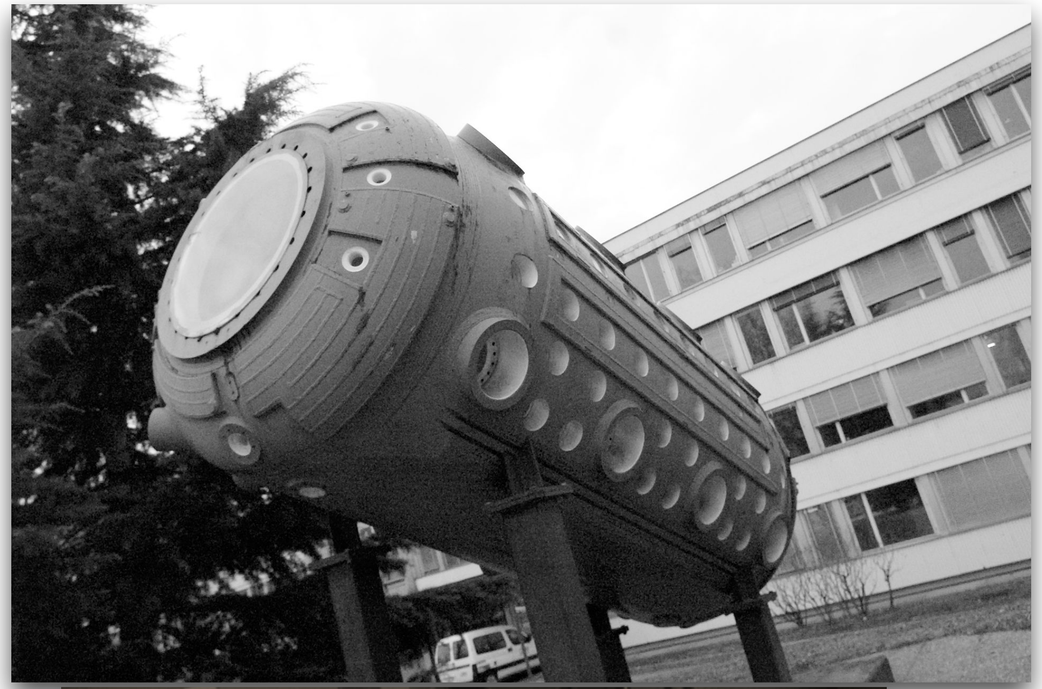
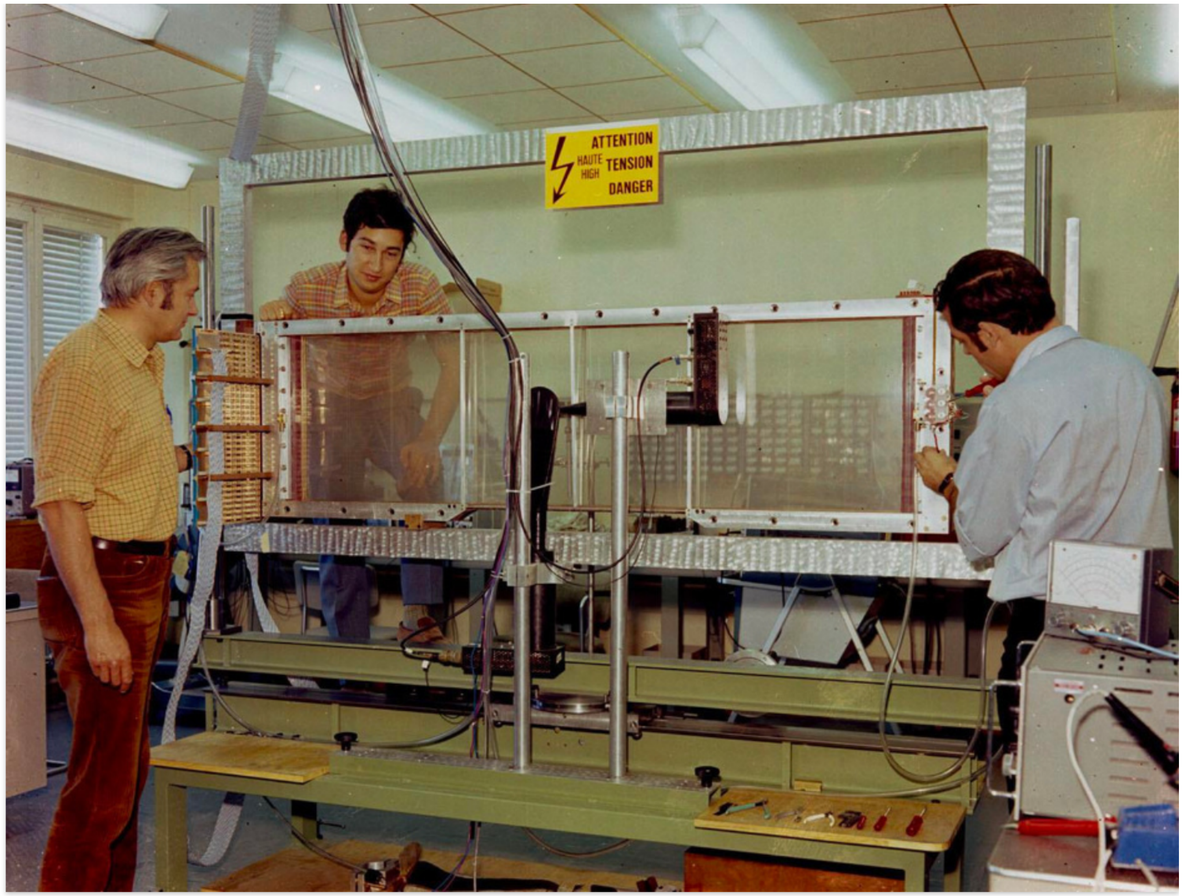
- **Discovery of neutral currents**, Gargamelle (CERN), 1973

Le 19 juillet 1973, le CERN (European Laboratory for Particle Physics) annonçait sa première découverte majeure : les "courants neutres faibles". - 1973-2024 CERN (License: CC-BY-4.0)



Wire chamber - W, Z bosons, gluon - 1968

- 1968: invention by Georges Charpak of **multiwire proportional chamber** -> new detector technique that could record millions of particle tracks each second, instead of examining photograph one by one



Georges Charpak's 'multiwire proportional chamber' particle detector consisted of many parallel wires, each connected to individual amplifiers. Linked to a computer, it could achieve a counting rate a thousand times better than before (Image: CERN)

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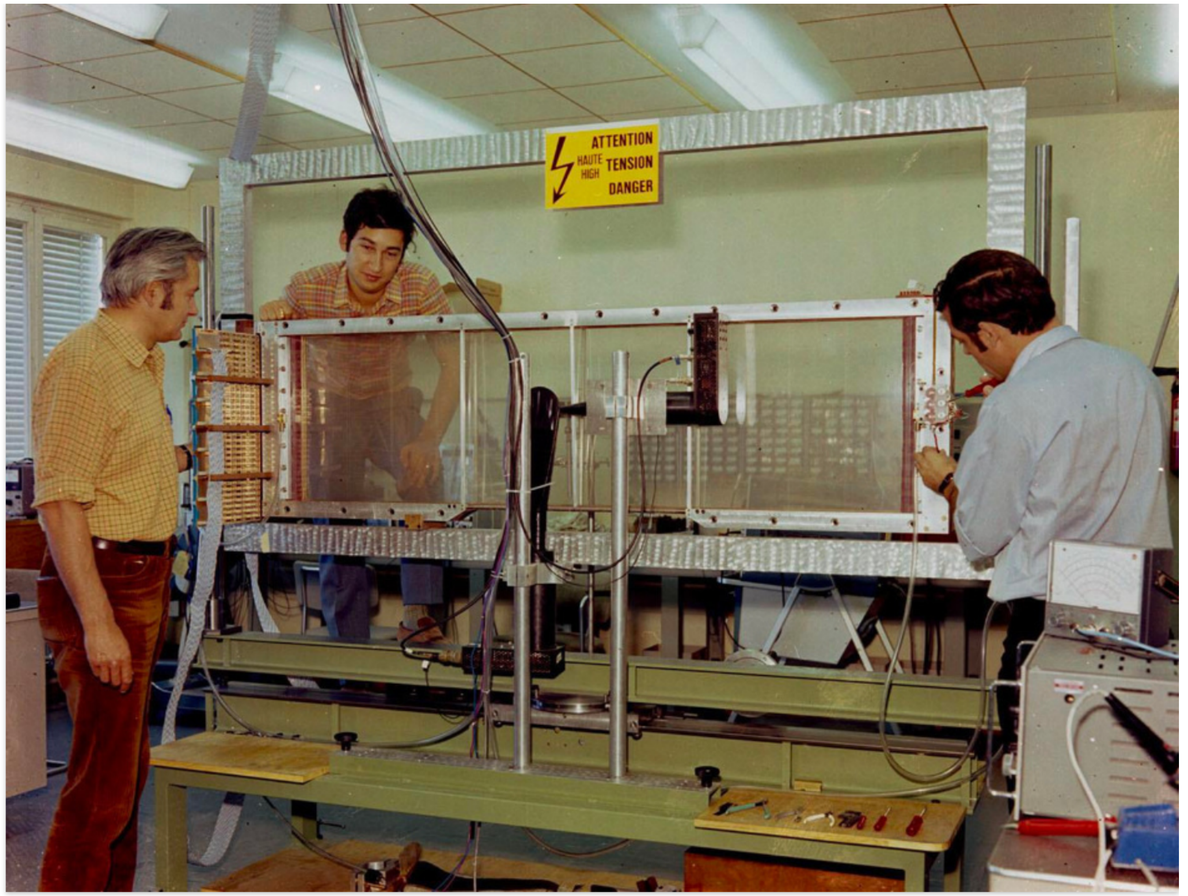

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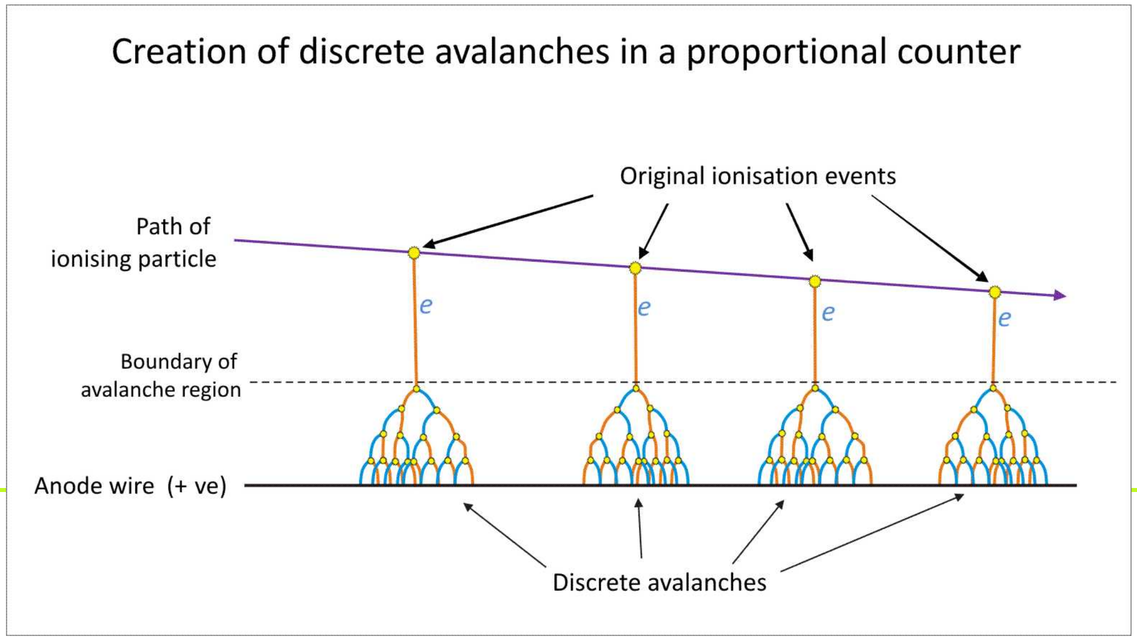

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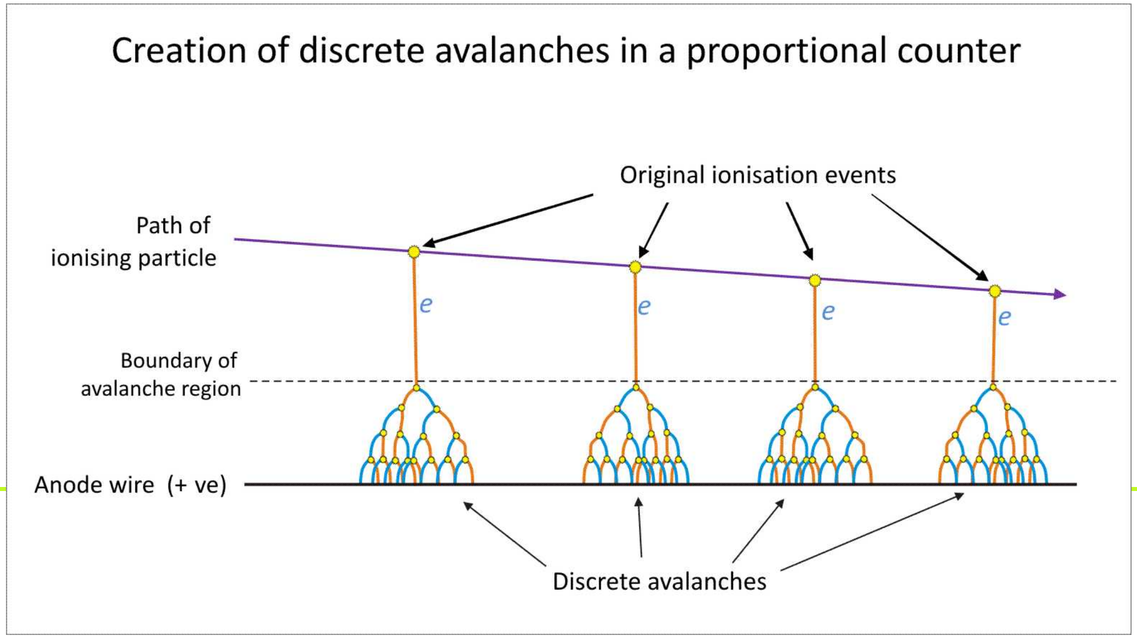
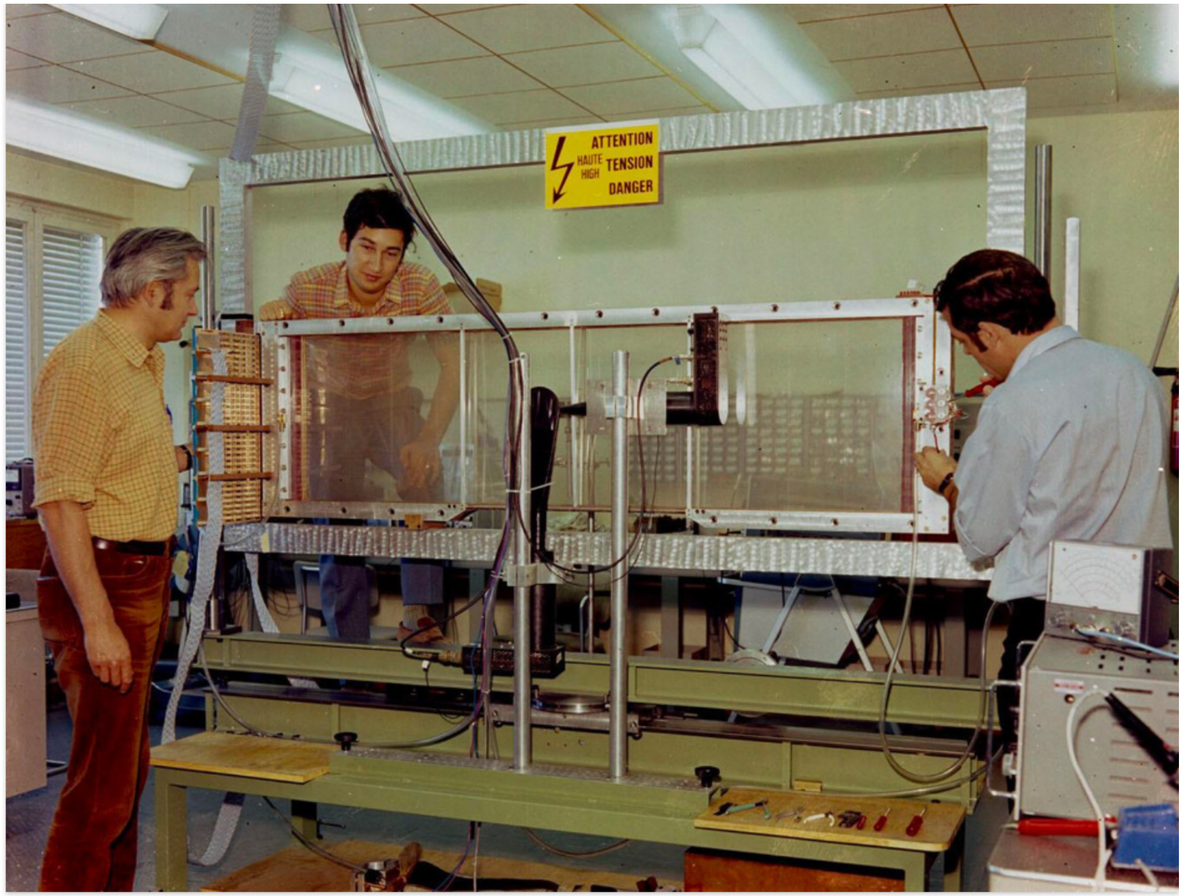
- Thanks to this technique, discovery of **charm quark** (BNL, SLAC - 1975), of **gluon** (TASSO in PETRA- DESY, 1979), and of **W and Z bosons** (UA1/UA2 -CERN, 1983)





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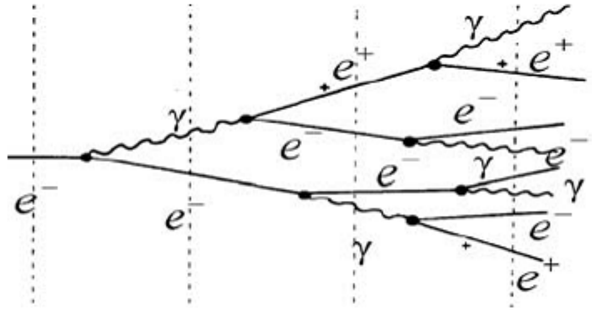
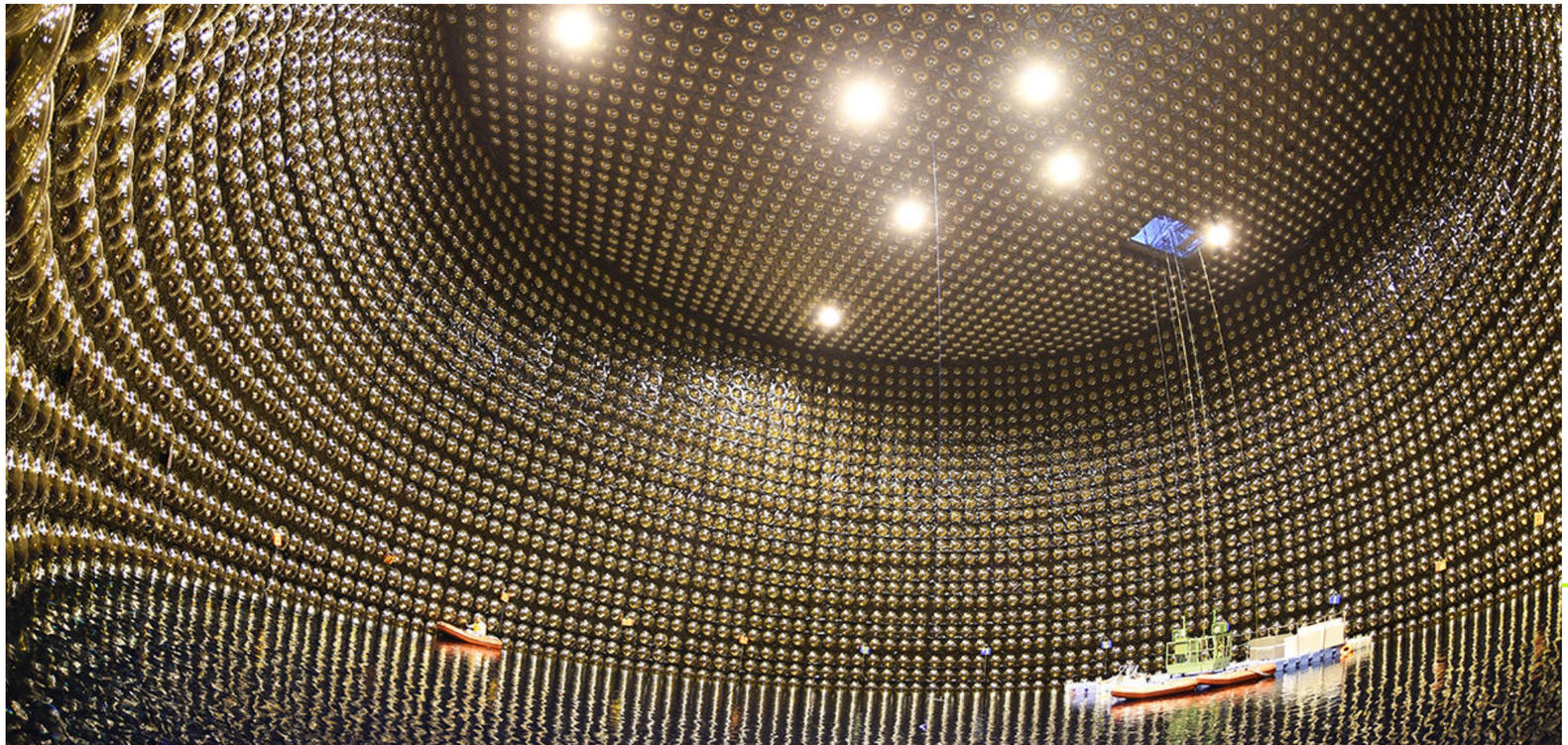
Current detection techniques

Some examples ....

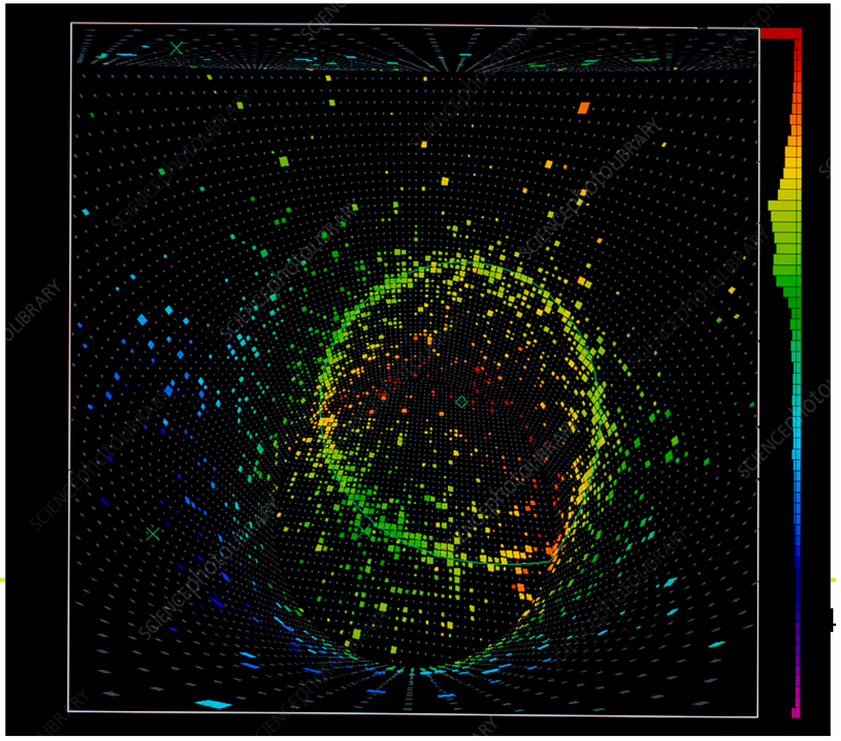
Neutrinos detection

- Very rare interactions -> very large detectors volumes + underground to protect against background
- **Super-Kamiokande (Japan, 1000 m underground)**: 50 000 tons of water with ~10000 PMTs to detect Cerenkov light, 40m x 40 m. Electron-neutrino interacts to create an electron. Electron produces a ‘ring' due to radiation of subsidiary photons that turn into electron-positron pairs -> electromagnetic cascade
  - only 90 candidates in a decade !
- Extension (Hyper-Kamiokande) expected in ~2027 (258 ktons of pure water)



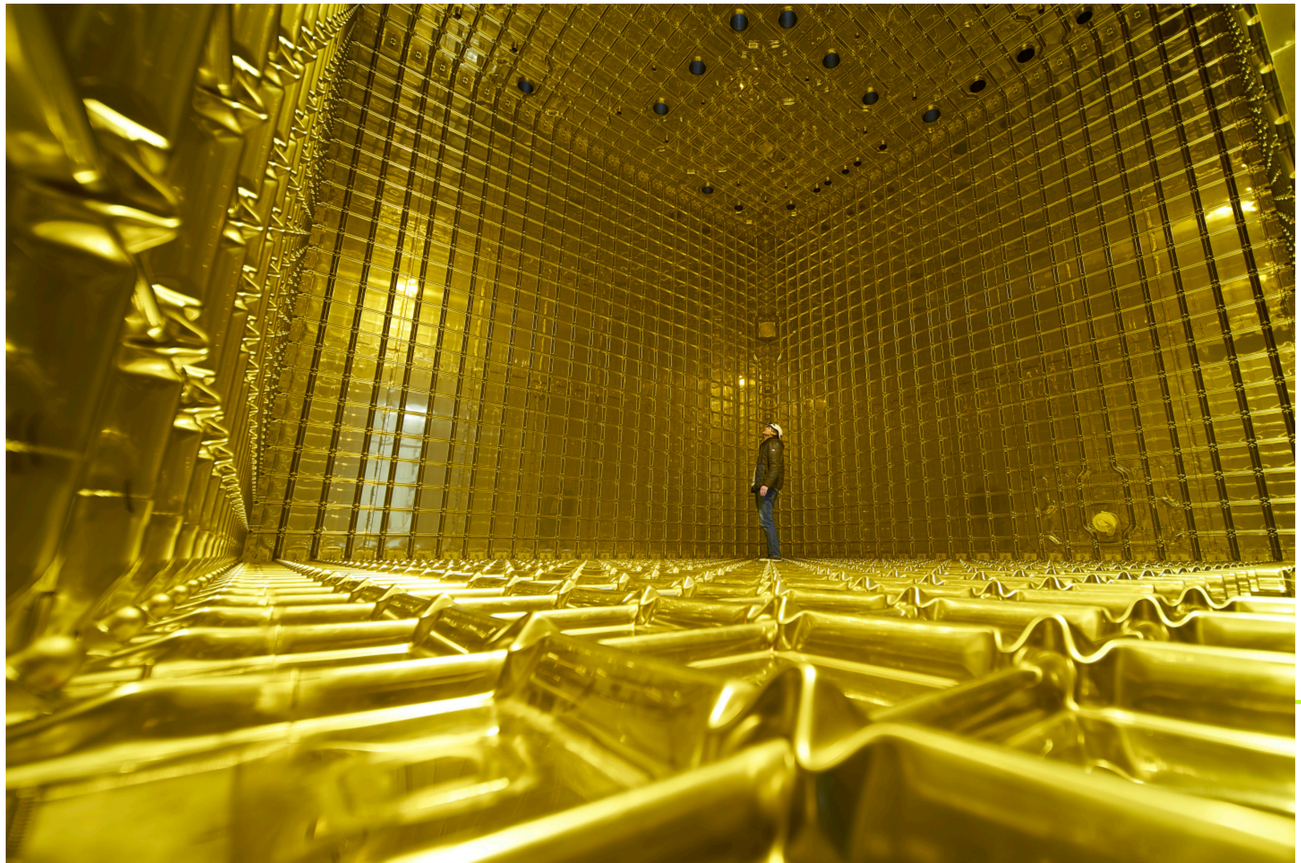


red indicates the earliest light to arrive

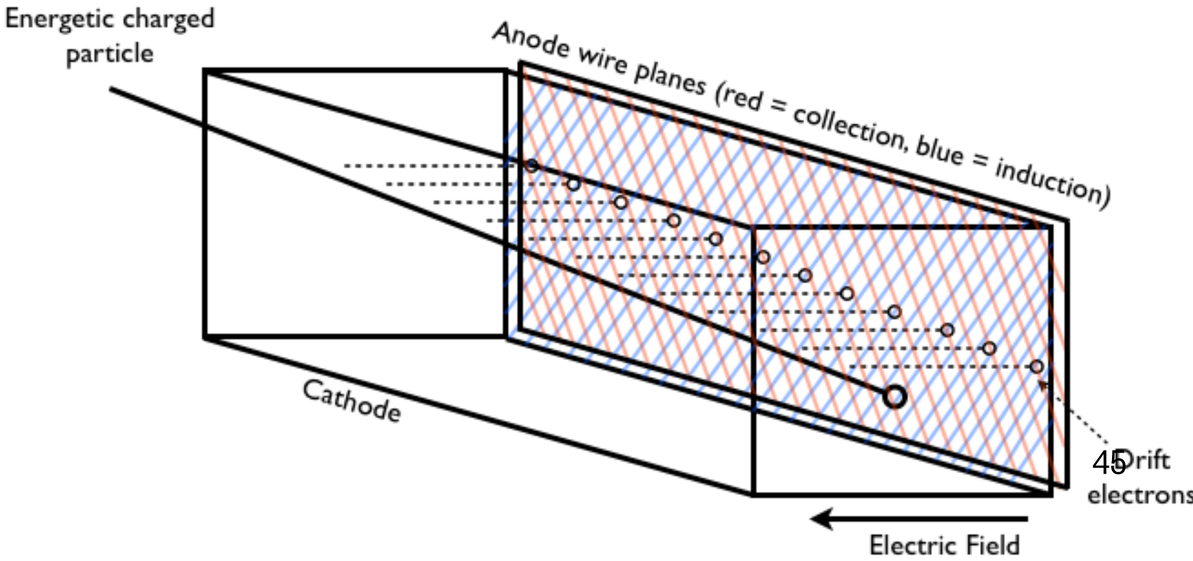


Neutrinos detection

- **Dune (2032)**: 70 ktons of of liquid argon (LAr), 1.5 km underground, when neutrinos enter in detector, they collide with Argon atoms -> charged particules created -> ionisation of the argon detected with time projection chambers (TPC) -> 3D images.
  - argon used because does not reabsorb ionisation electrons (noble element) + scintillations
- ProtoDune currently taking data at CERN, to prove feasibility (20 times smaller than DUNE) -> ***LAPP team !***

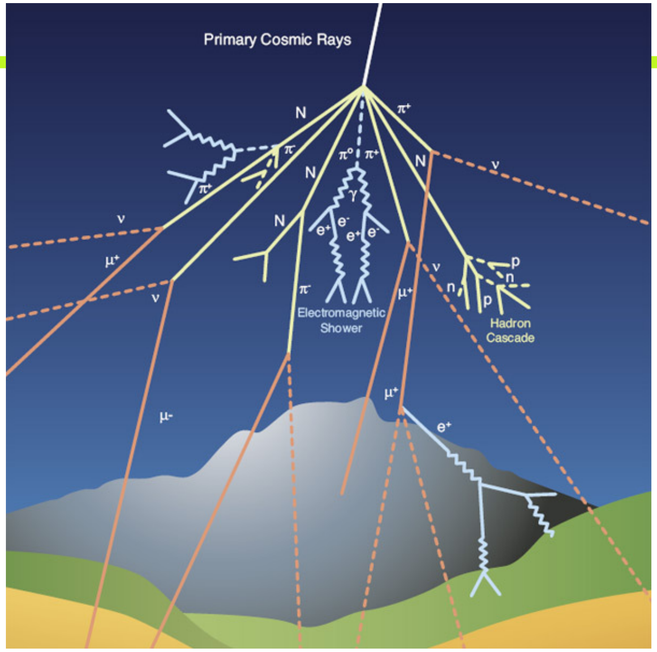


LArTPC



Cosmic rays

- Cosmic particules entering in atmosphere -> cascade -> Cerenkov light cone of ~250 m for a few nanoseconds close to ground



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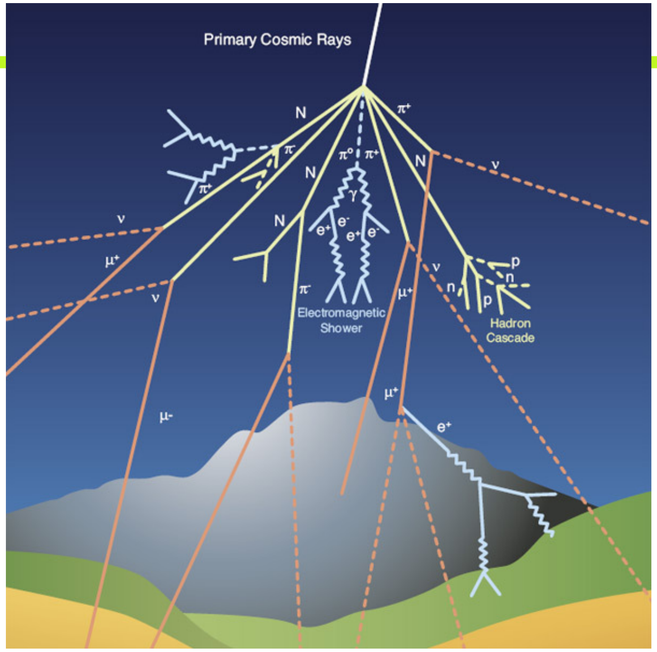

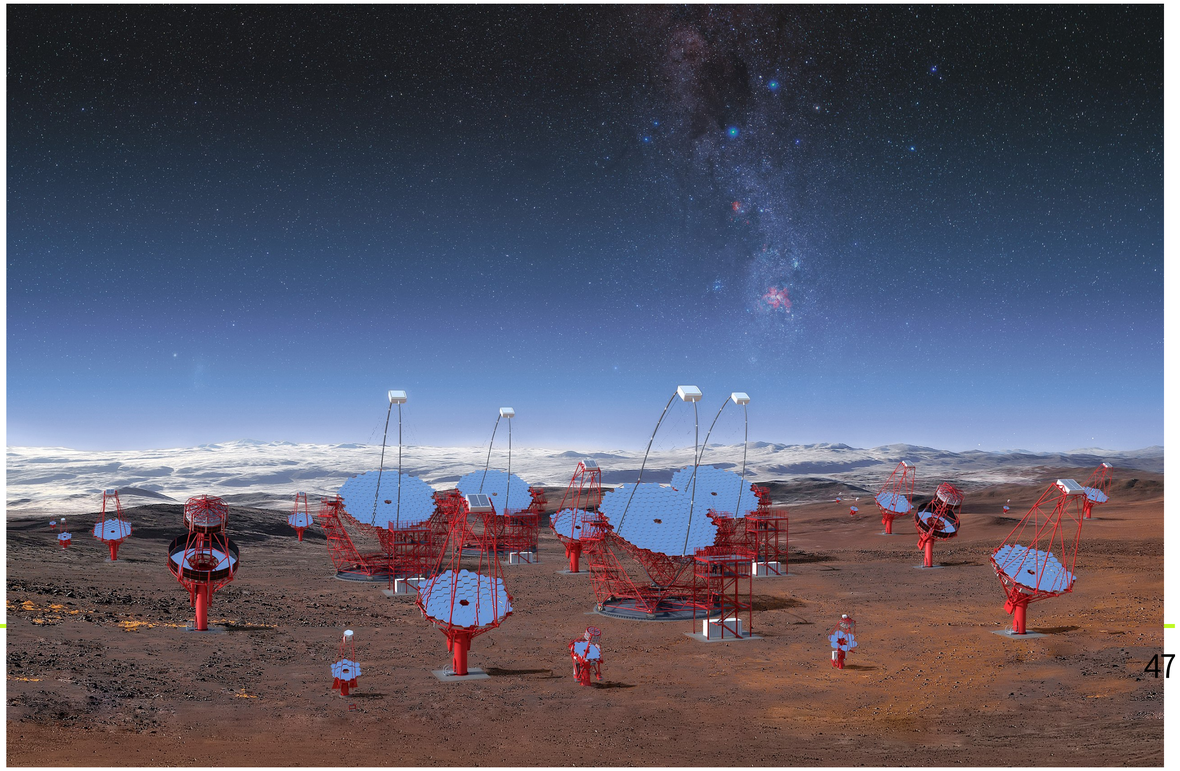

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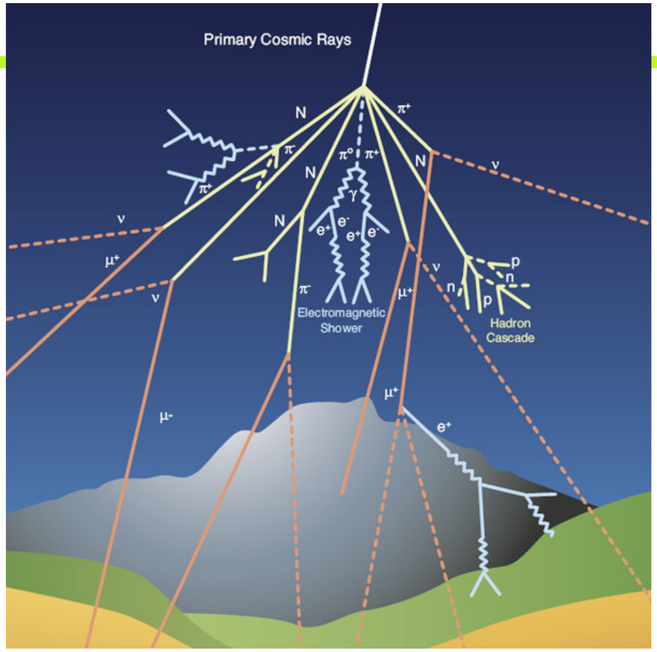
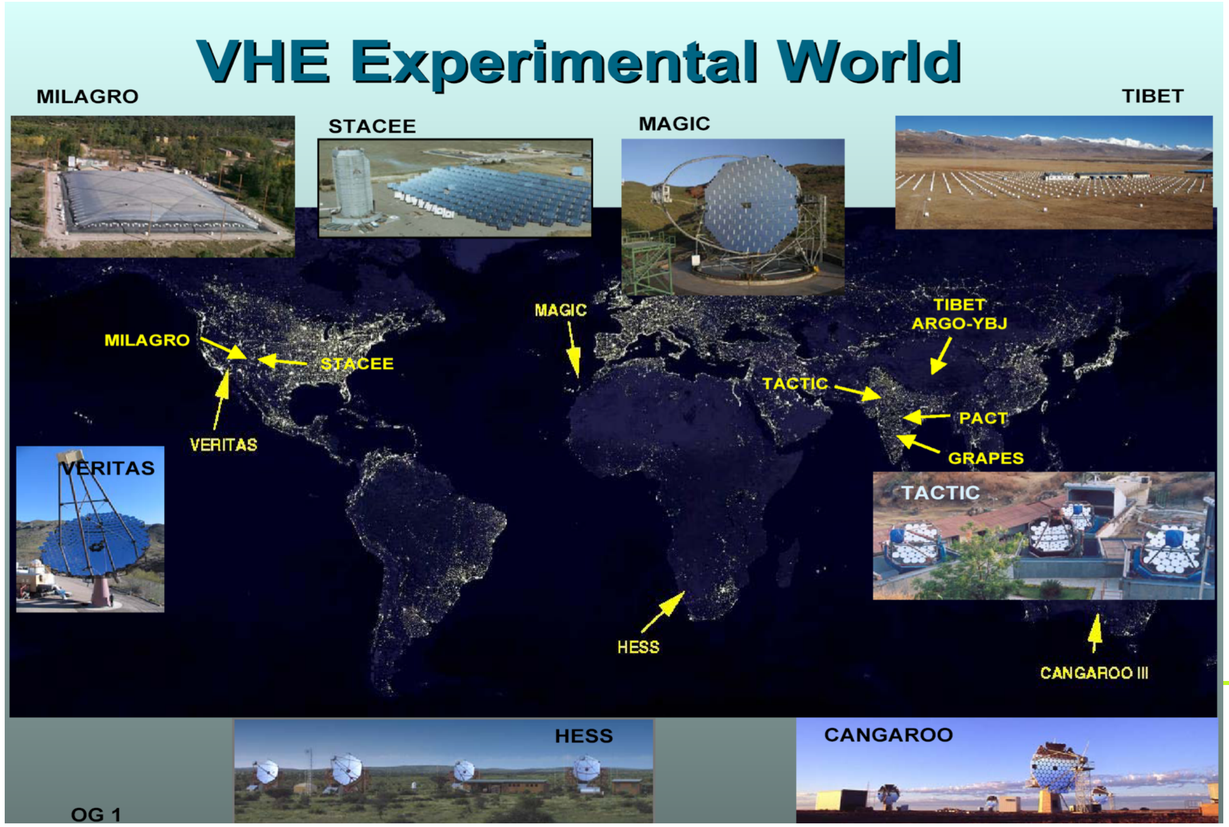
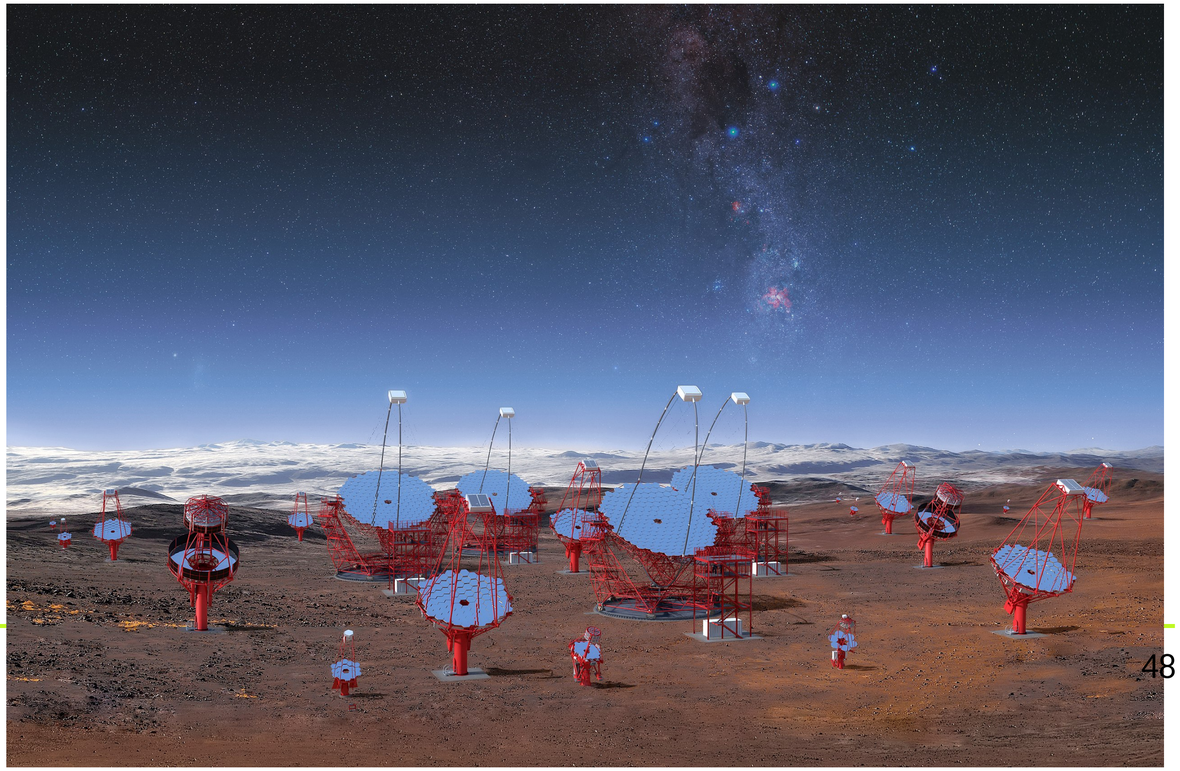
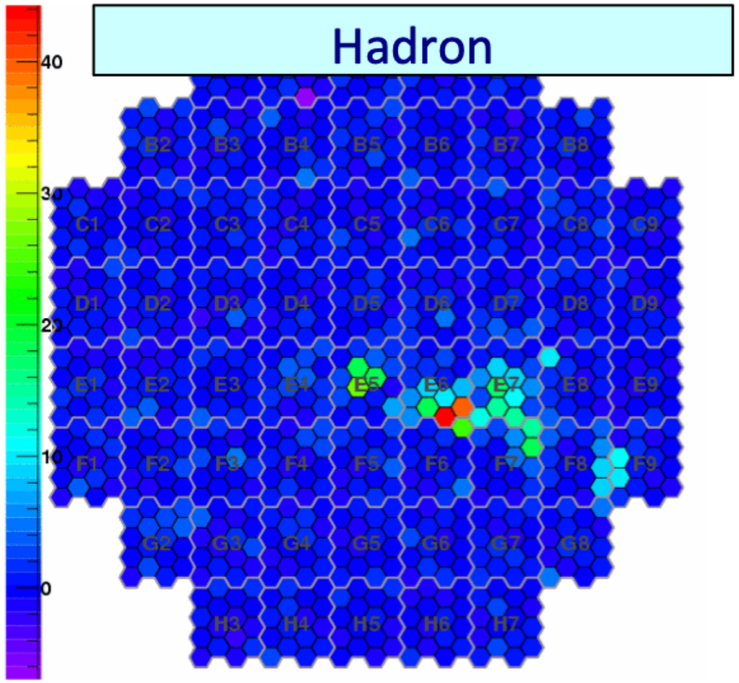
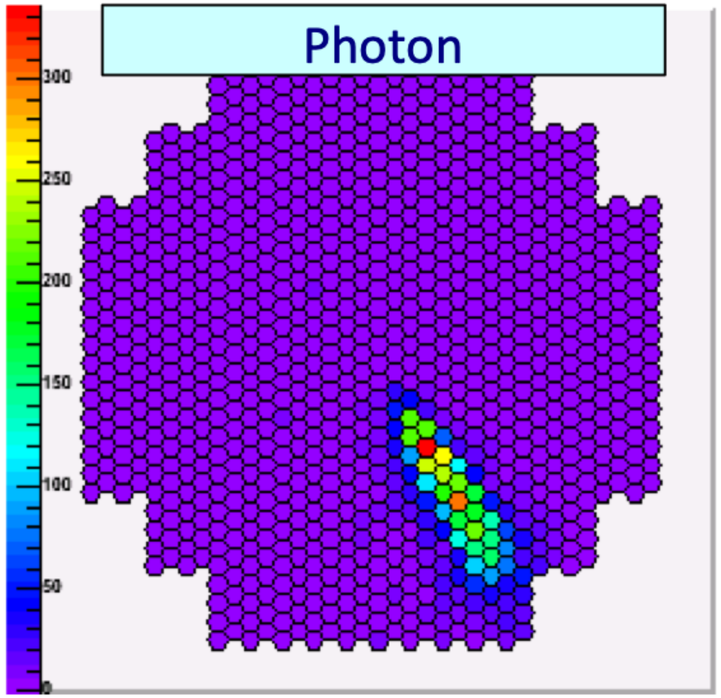






Identifying particule





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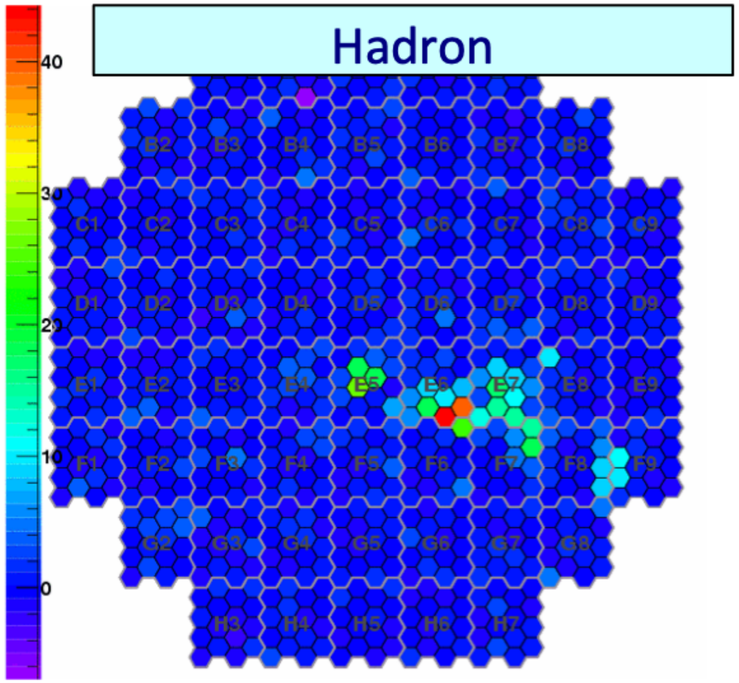
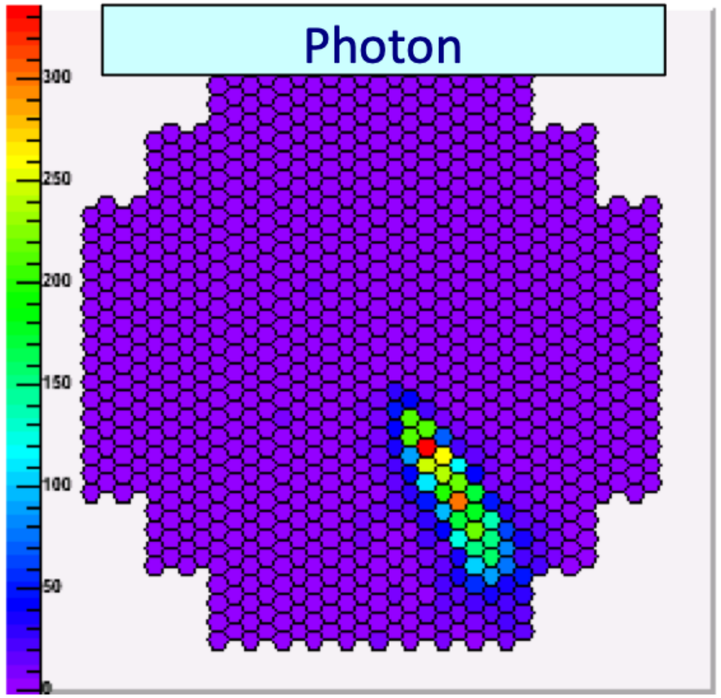
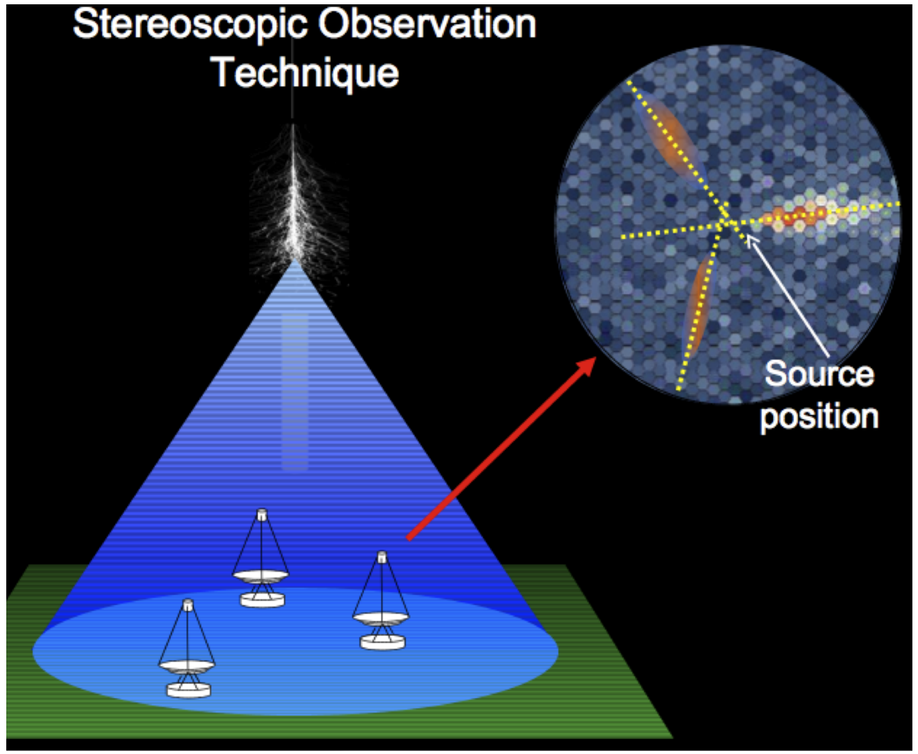
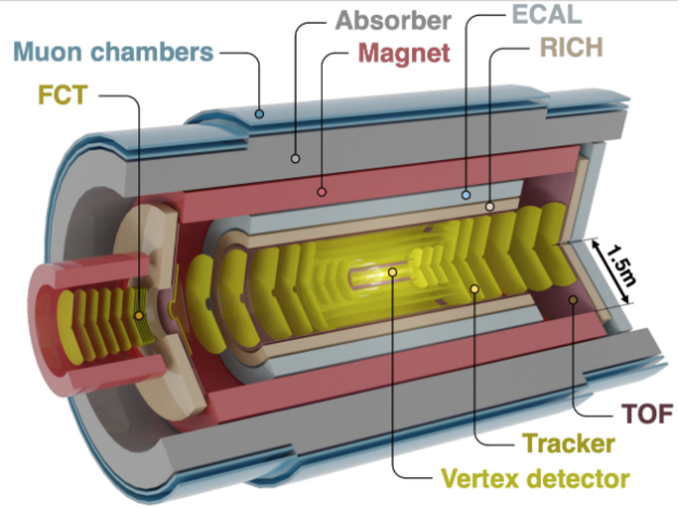






LHC detectors



ALICE

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- Tracker to reconstruct trajectory of produced particles
- Calorimeter to measure the energy
- Muon spectrometer for escaping muons

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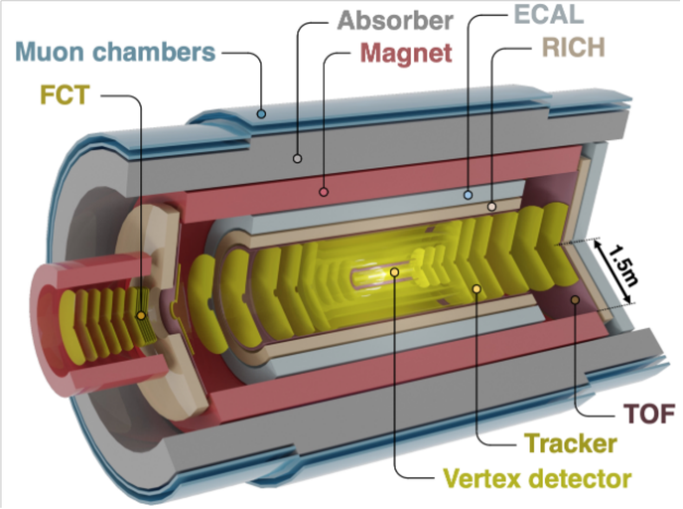
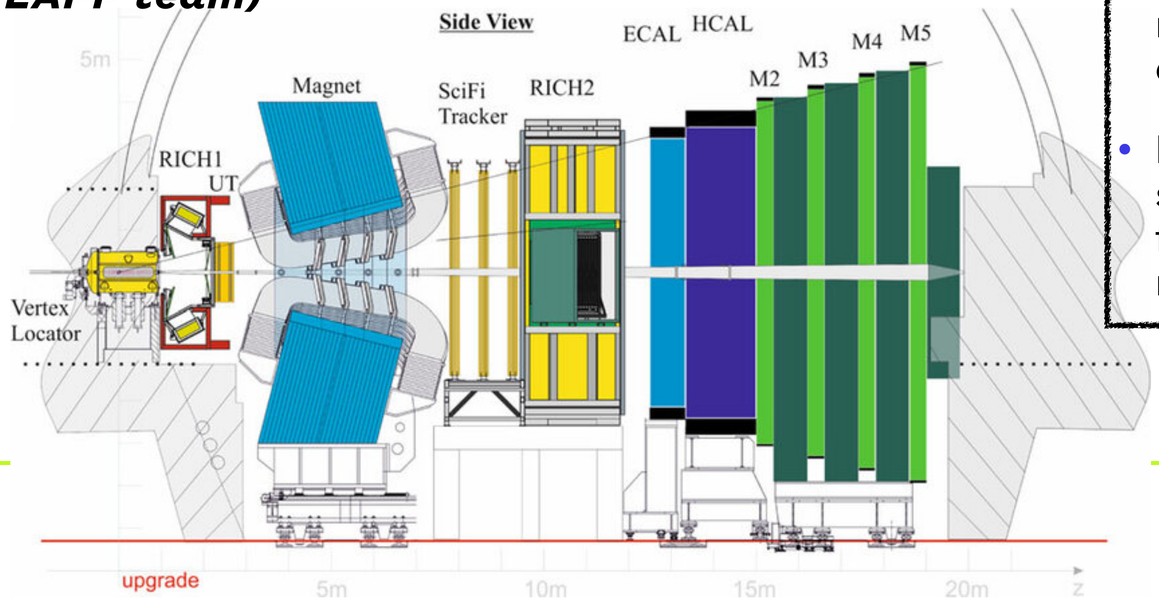


ALICE

LHCb

(LAPP team)



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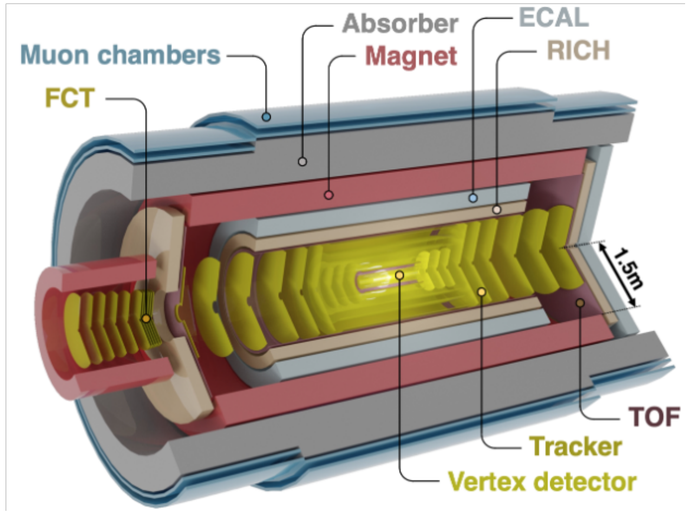
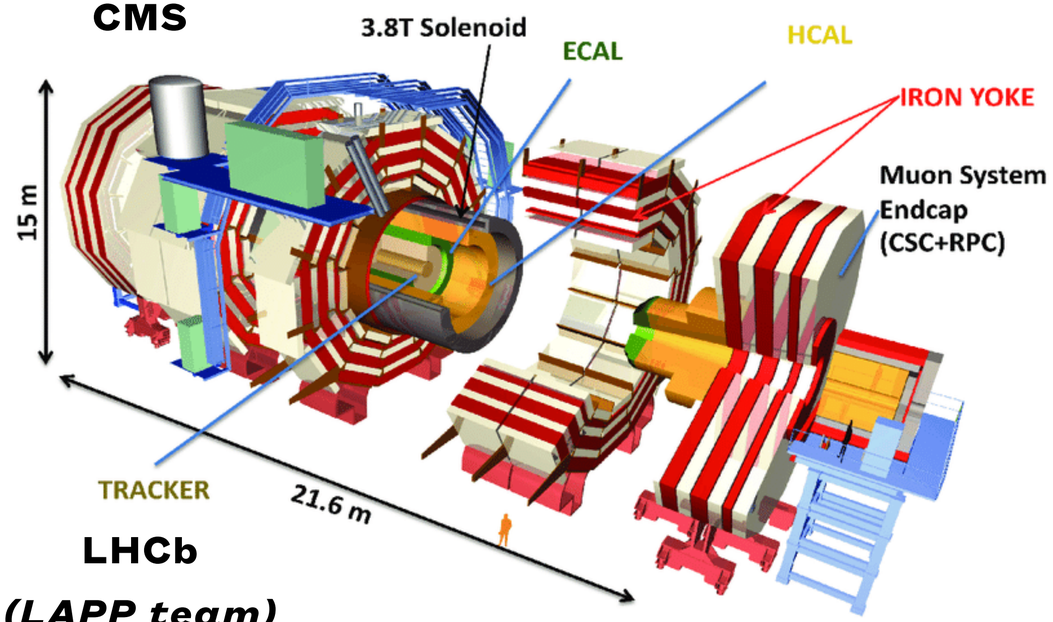


ALICE

CMS



ATLAS

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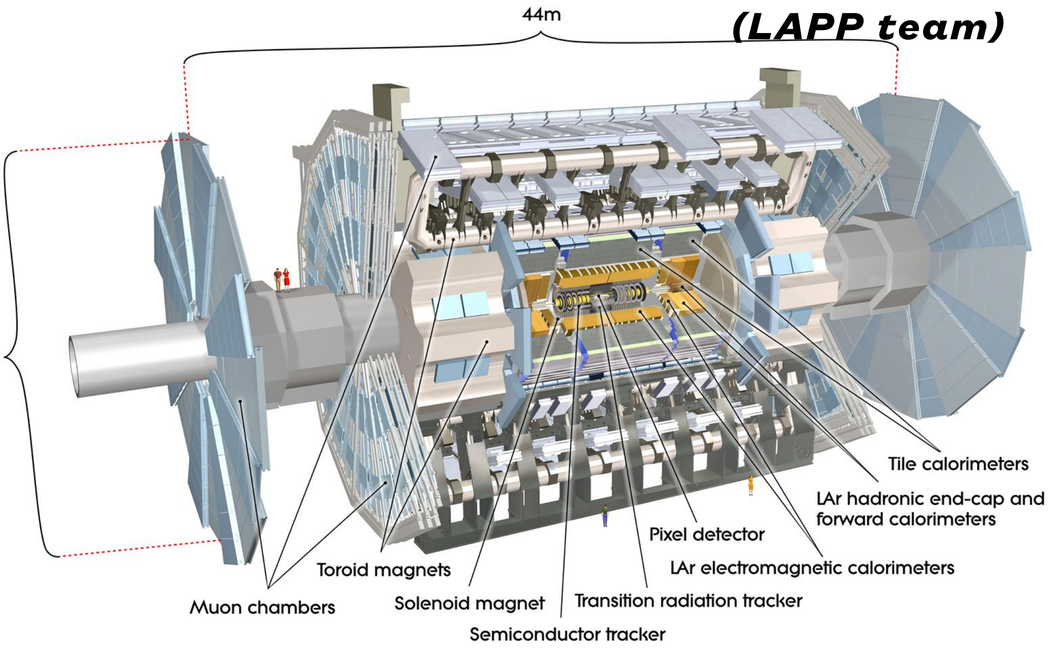

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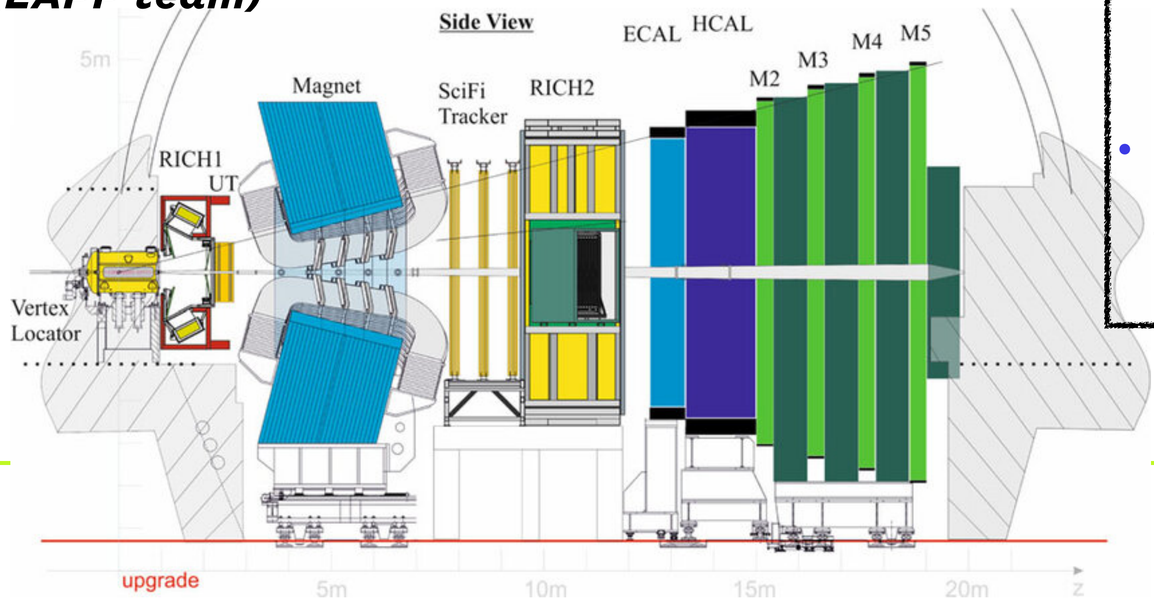

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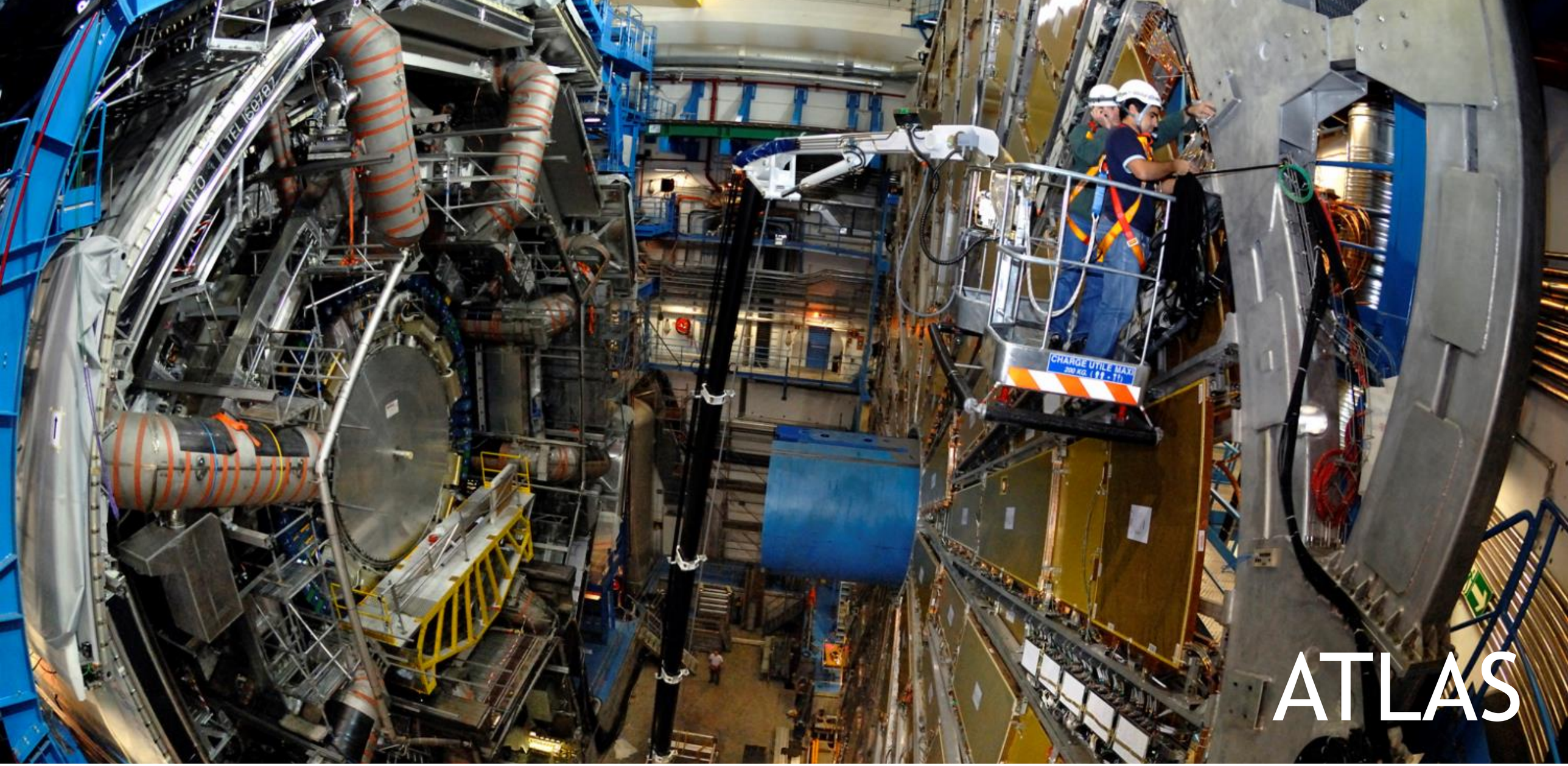
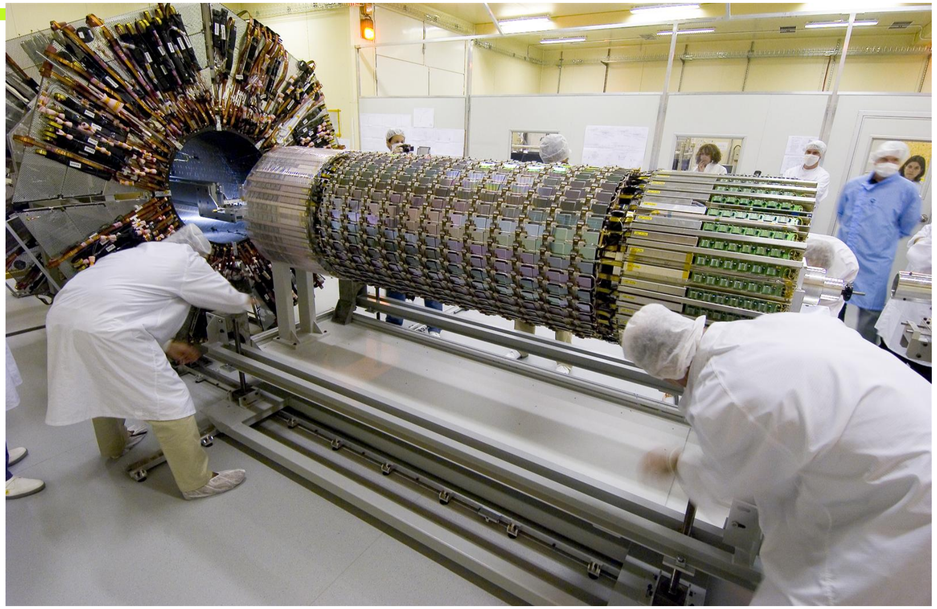


ATLAS

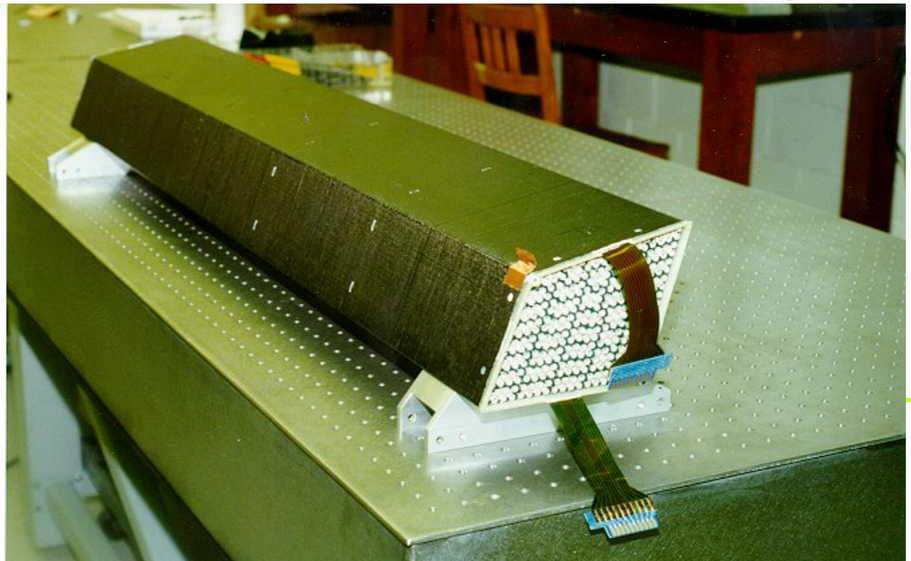
Trackers

- **3 main technologies**
  - **gaseous**: ionization in gaz (electron-ion pair). Amplification needed
  - **silicon** : ionisation in solid material (electron-hole pair). No amplification needed
  - **scintillating fibers** : light detected with photodetectors



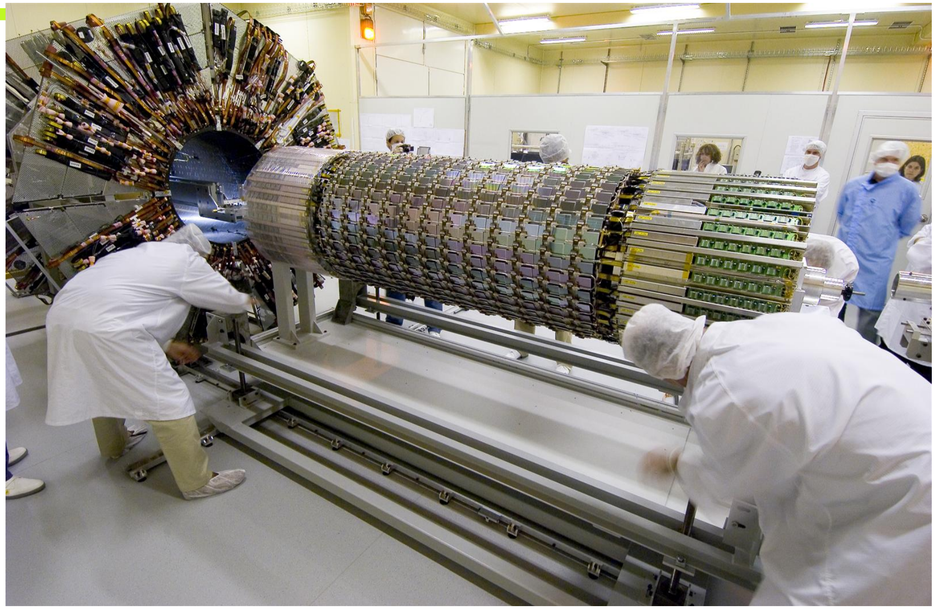
Semiconductor Tracker of ATLAS (silicon)

Transition Radiation Tracker of ATLAS (gas)



Trackers

- **3 main technologies**
  - **gaseous**: ionization in gaz (electron-ion pair). Amplification needed
  - **silicon** : ionisation in solid material (electron-hole pair). No amplification needed
  - **scintillating fibers** : light detected with photodetectors
- Need very low density to avoid shower development
- Measurement of particle momentum and decay vertices



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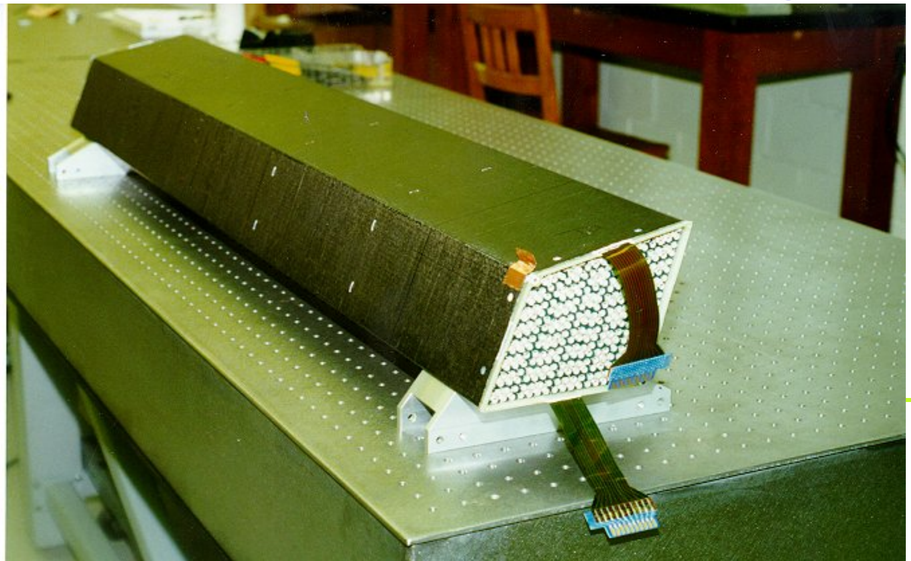
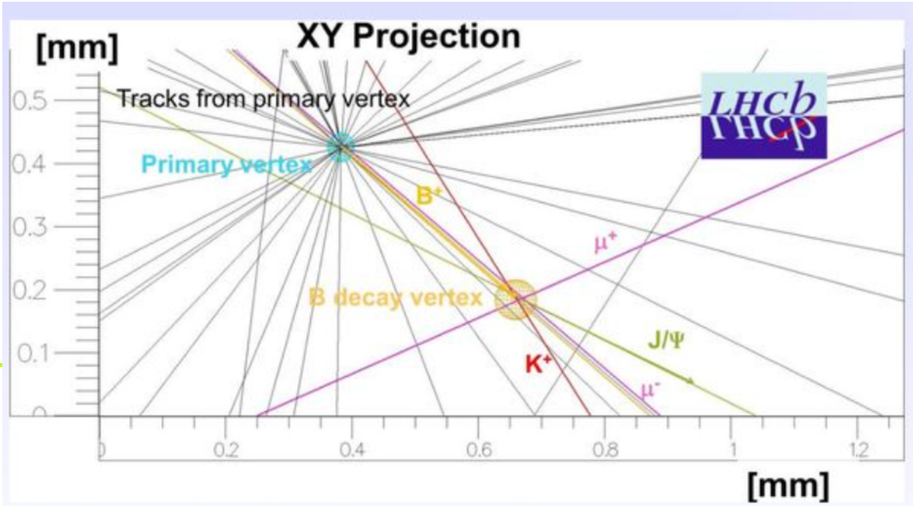
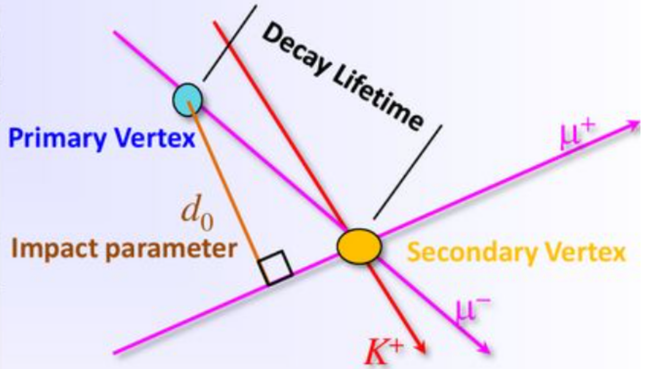


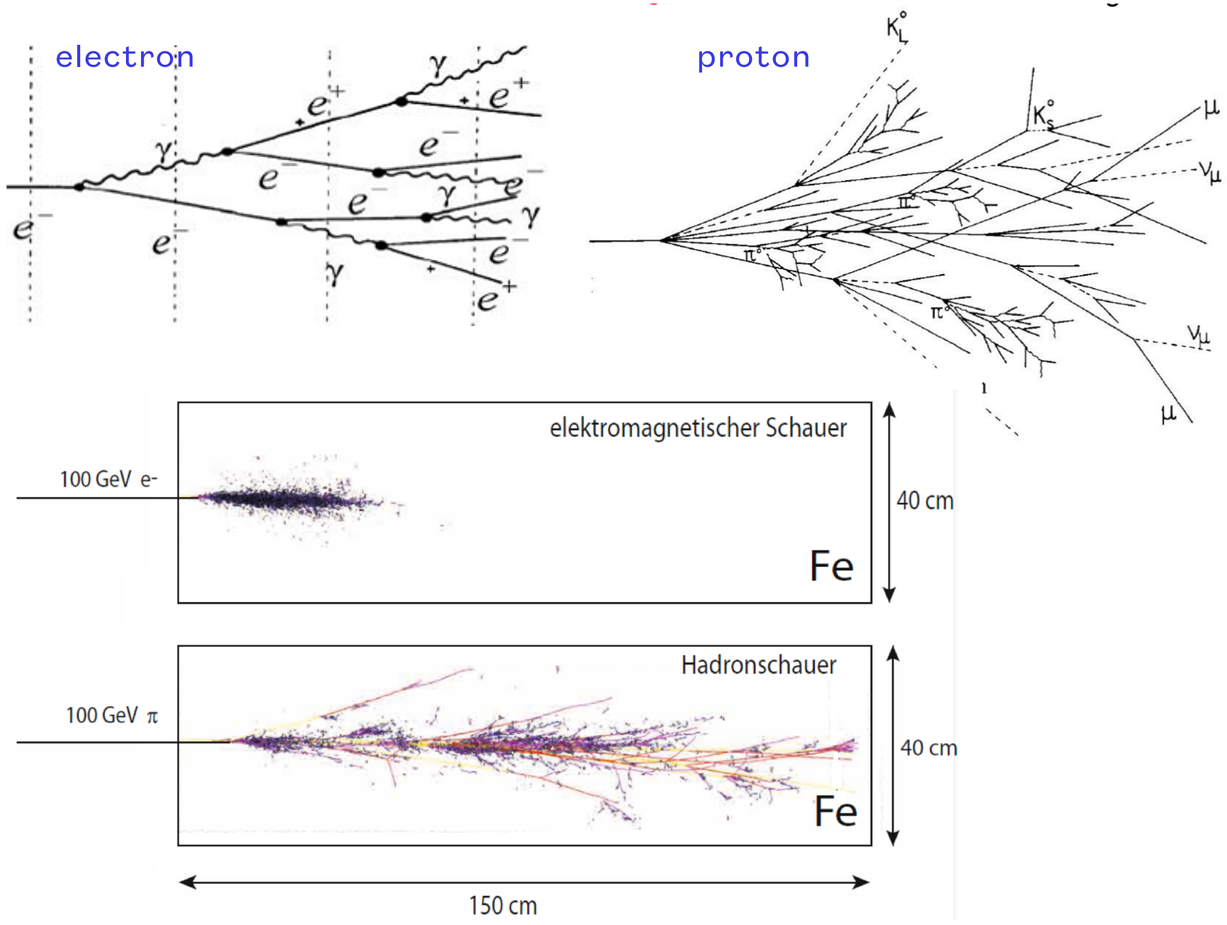
Decay vertices





Calorimeters

- Particules initiates a shower due to dense material (**bremstrallung and pair production**)
  - electromagnetic (electron/photon) or hadronic (particule sensitive to strong force, need denser material to develop completely)



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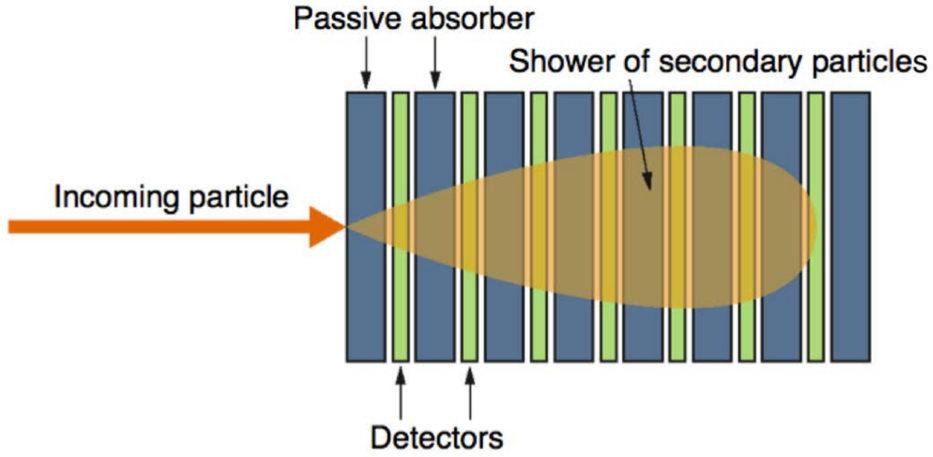
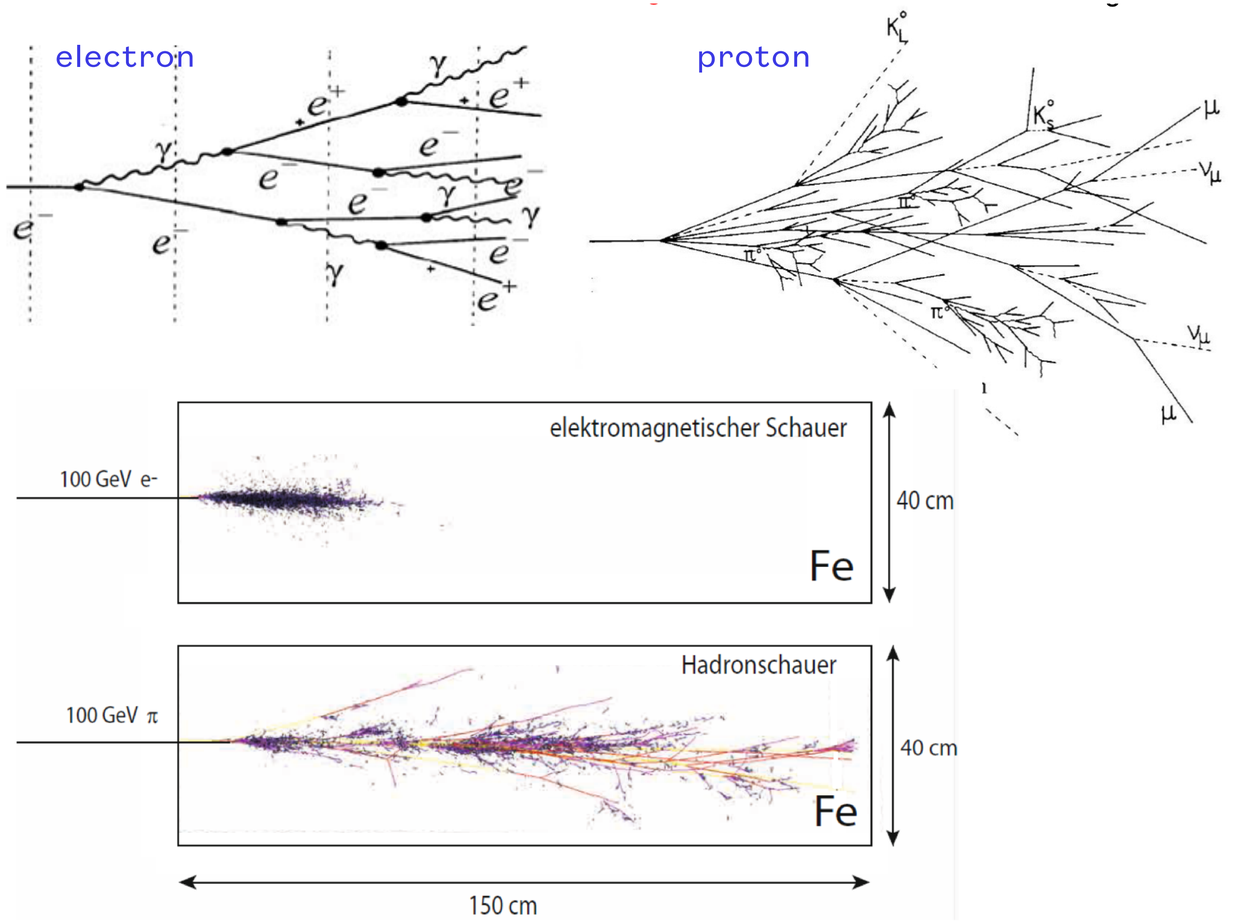
- Shower is either contained **entirely** or **sampled** (dense material and active material)
  - Shape of shower helps to identify the particule





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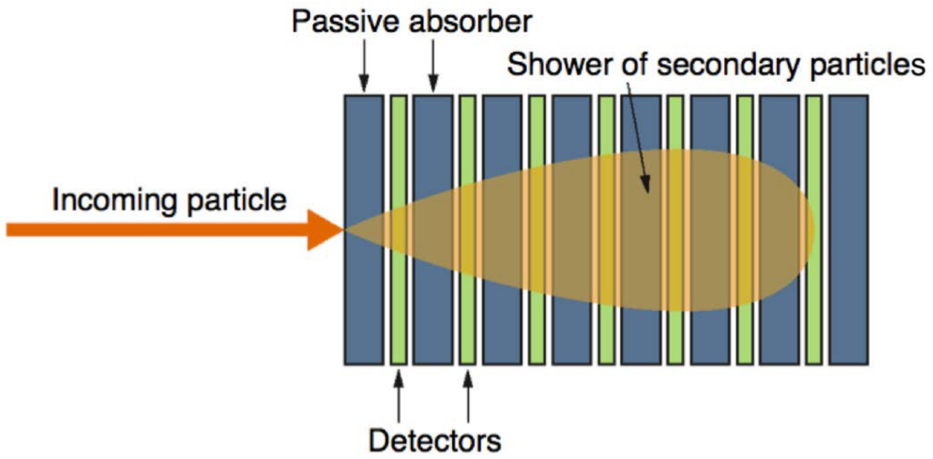
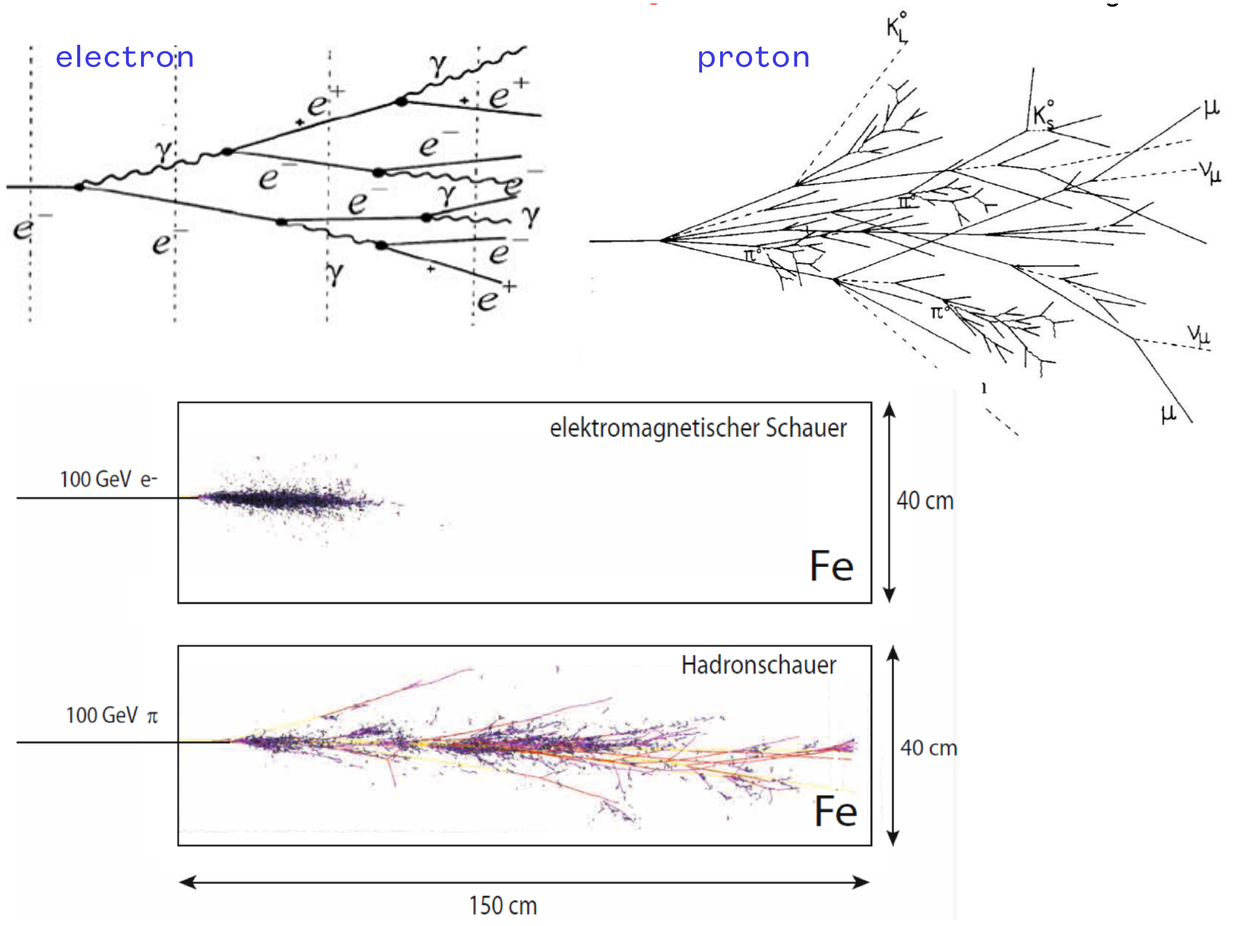
  - Shape of shower helps to identify the particule
- Shower development scales with radiation length
  - distance in which the energy of the particle is reduced by 1/e (≈63.2%) due to bremsstrahlung





	Air	Eau	Al	LAr	Fe	Pb	$PbWO_4$
Z	-	-	13	18	26	82	-
X_0 (cm)	30420	36	8,9	14	1,76	0.56	0.89

Approximation : $X_0 \approx \frac{(716\,\mathrm{g\,cm^{-2}})\,A}{Z(Z+1)\ln(287\sqrt{Z})}$

Calorimeters : energy resolution

- Intrinsic resolution ~1/sqrt(E)
- Electronic noise : 1/E
- Non-uniformities : constant term -> dominant at high energy

$$\frac{\sigma(E)}{E} \approx \sqrt{\left(\frac{c_1}{\sqrt{E}}\right)^2 + \left(\frac{c_2}{E}\right)^2 + c_3{}^2}$$

Homogeneous calorimeters:

Experiment	Material	Energy resolution (E in GeV)
NA48	Liquid Kr	4.8%/√E ⊕ 0.22%
BELLE	CsI(Tl)	0.8%/√E ⊕ 1.3%
CMS	$PbWO_4$	2.7%/√E ⊕ 0.55%*

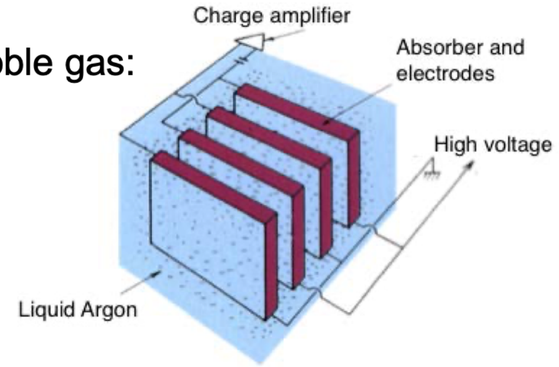
reference

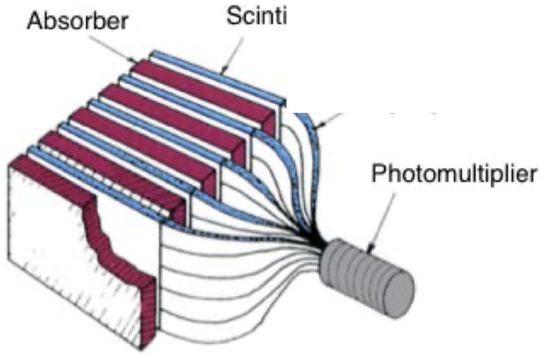
Sampling calorimeters:

Experiment	Detector	Detector thickness [mm]	Absorber material	Absorber thickness [mm]	Energy resolution (E in GeV)
UA1	Scintillator	1.5	Pb	1.2	15%/√E
SLD	liquid Ar	2.75	Pb	2.0	8%/√E
DELPHI	Ar + 20% CH_4	8	Pb	3.2	16%/√E
ALEPH	Si	0.2	W	7.0	25%/√E
ATLAS	liquid Ar		Pb		10%/√E ⊕ 0.7%*
LHCb	Scintillator		Fe		10%/√E ⊕ 1.5%*

* Design values

Liquid noble gas:

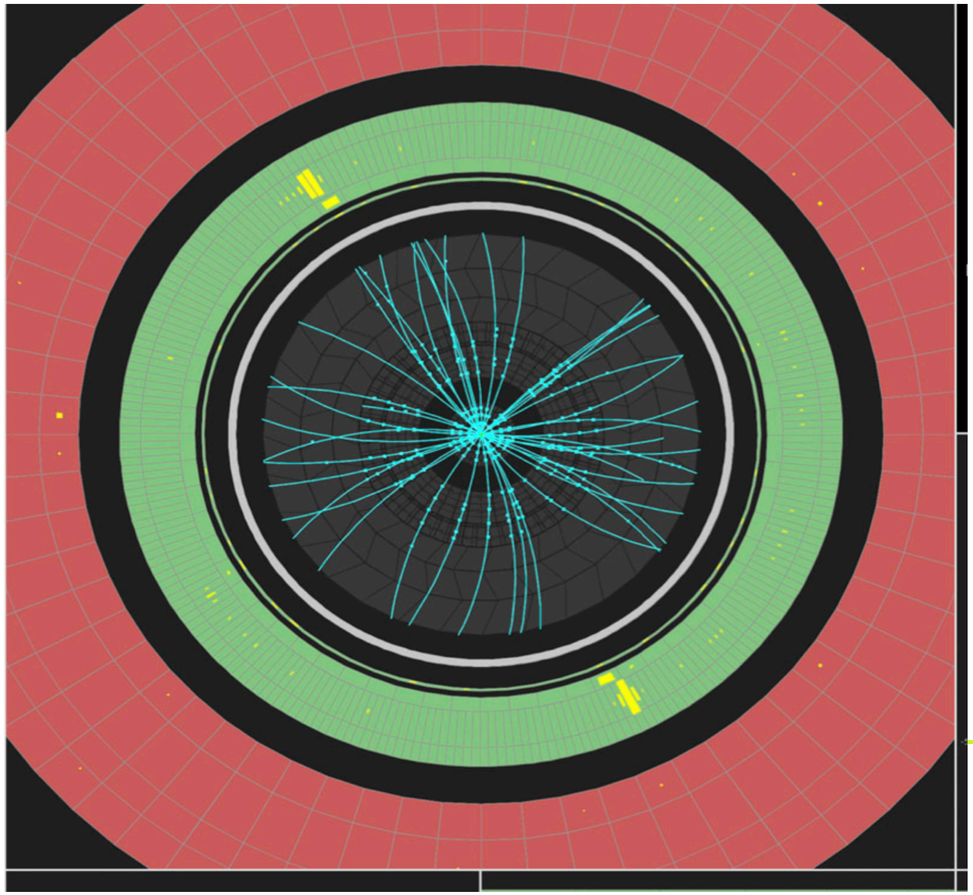


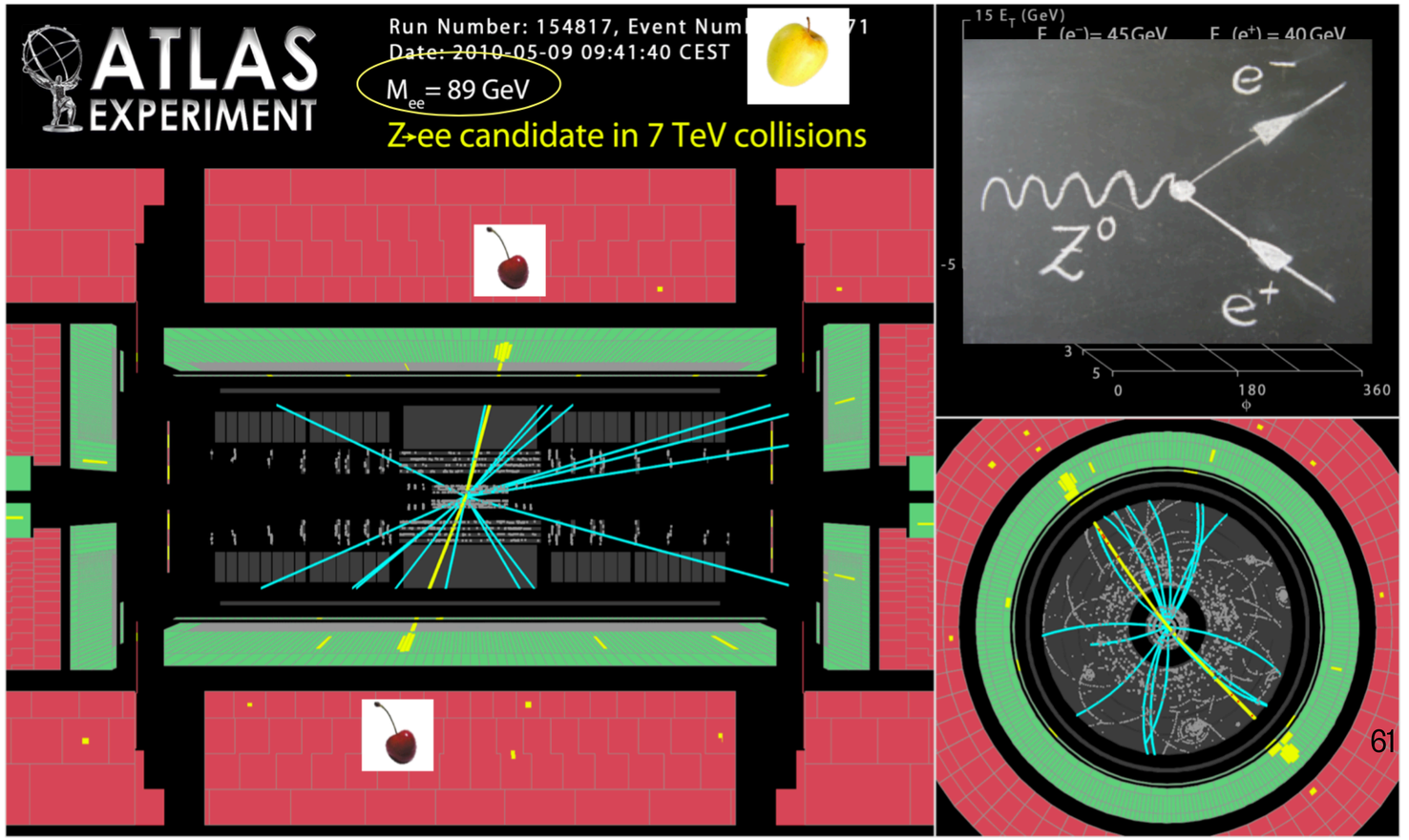


scintillators plates

Photons and electrons in ATLAS

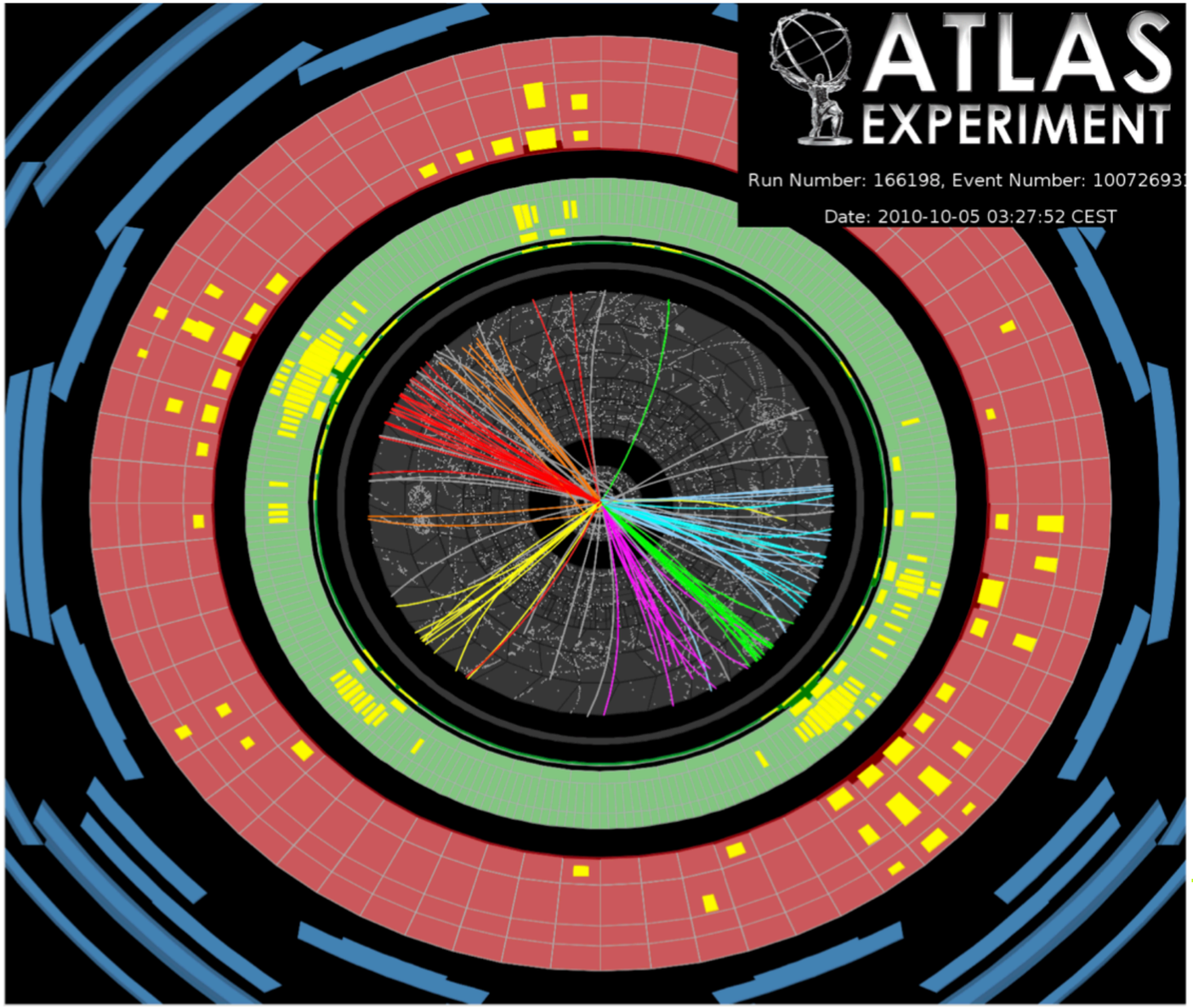
- Reconstructed from **electronic** signals recorded by **readout system**





Jets of hadrons

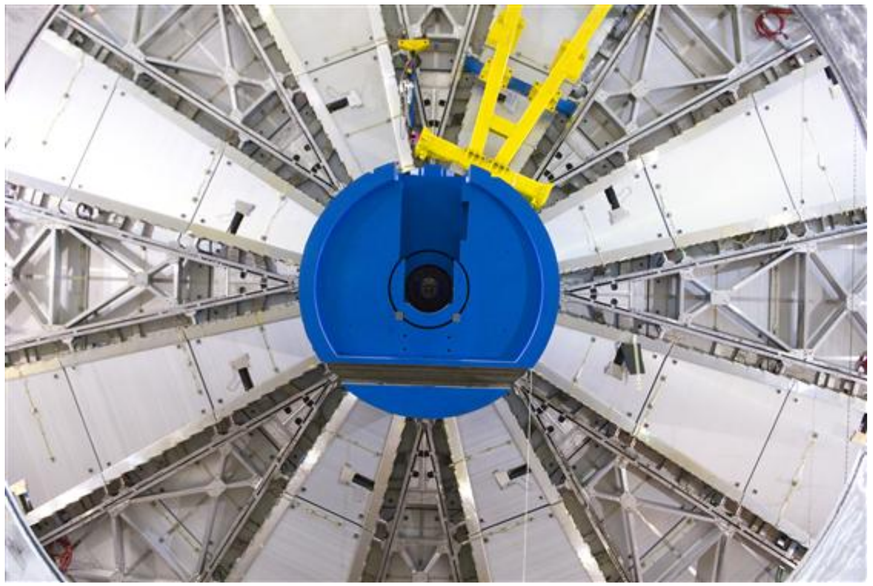
- The hadronisation seen as a « jet » in detector (several hadrons developing hadronic showers at the same time)



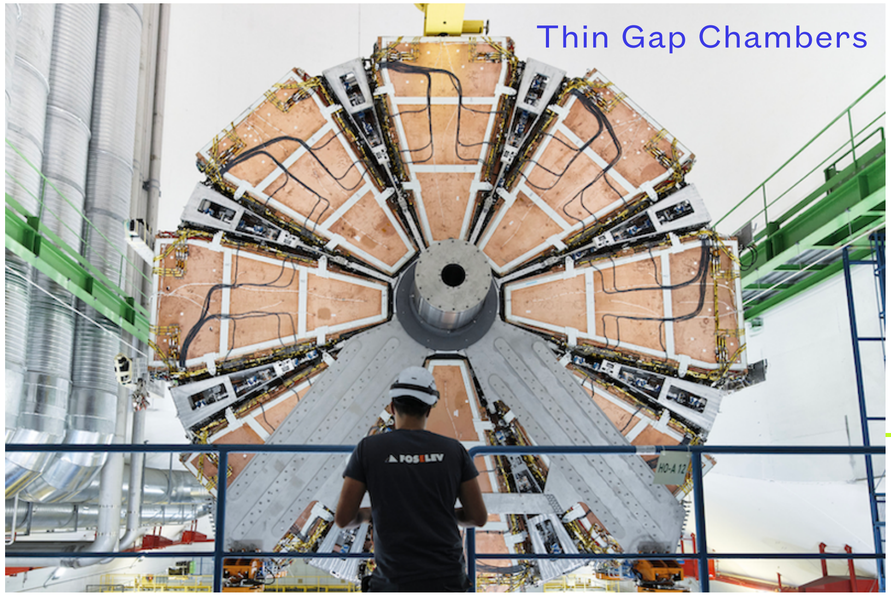
Muon spectrometers

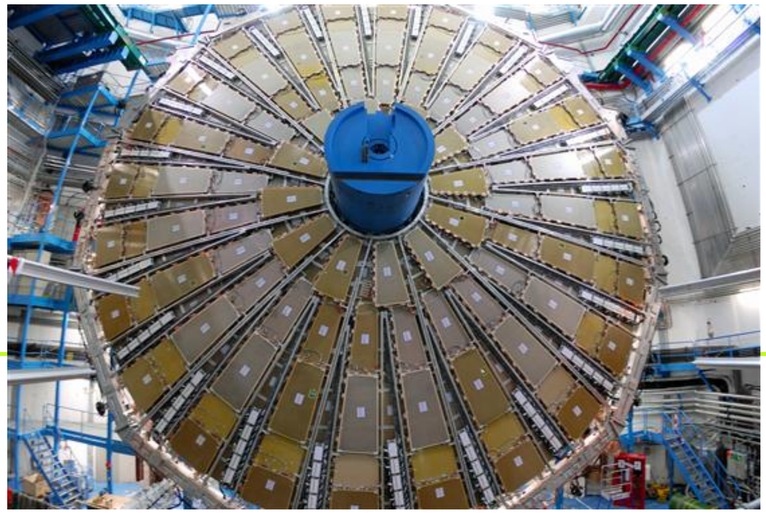
- Identify and measures momentum of muons
- Thousands of chambers, big magnetic field to curve high-energy muons
- Biggest sub-detector
- Main technologies (in ATLAS) : **Monitored Drift Tubes** (0.1 mm precision, aluminium tube filled with gas mixture + wire at the center), **Resistive Plate Chambers** (tracking within 2.5us), **Small-Strip Thin-Gap Chambers** and **Micromegas** (taking in high-intensity collisions

Monitored Drift Tubes

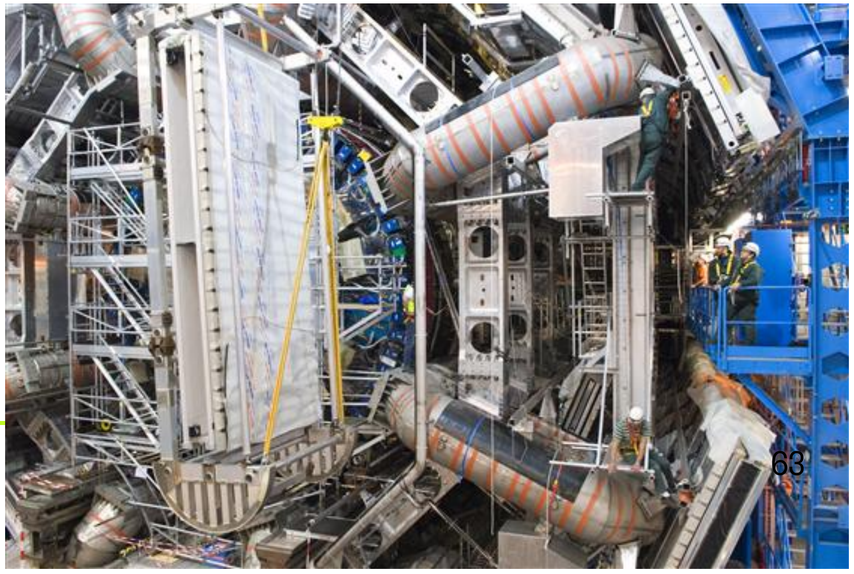


Thin Gap Chambers



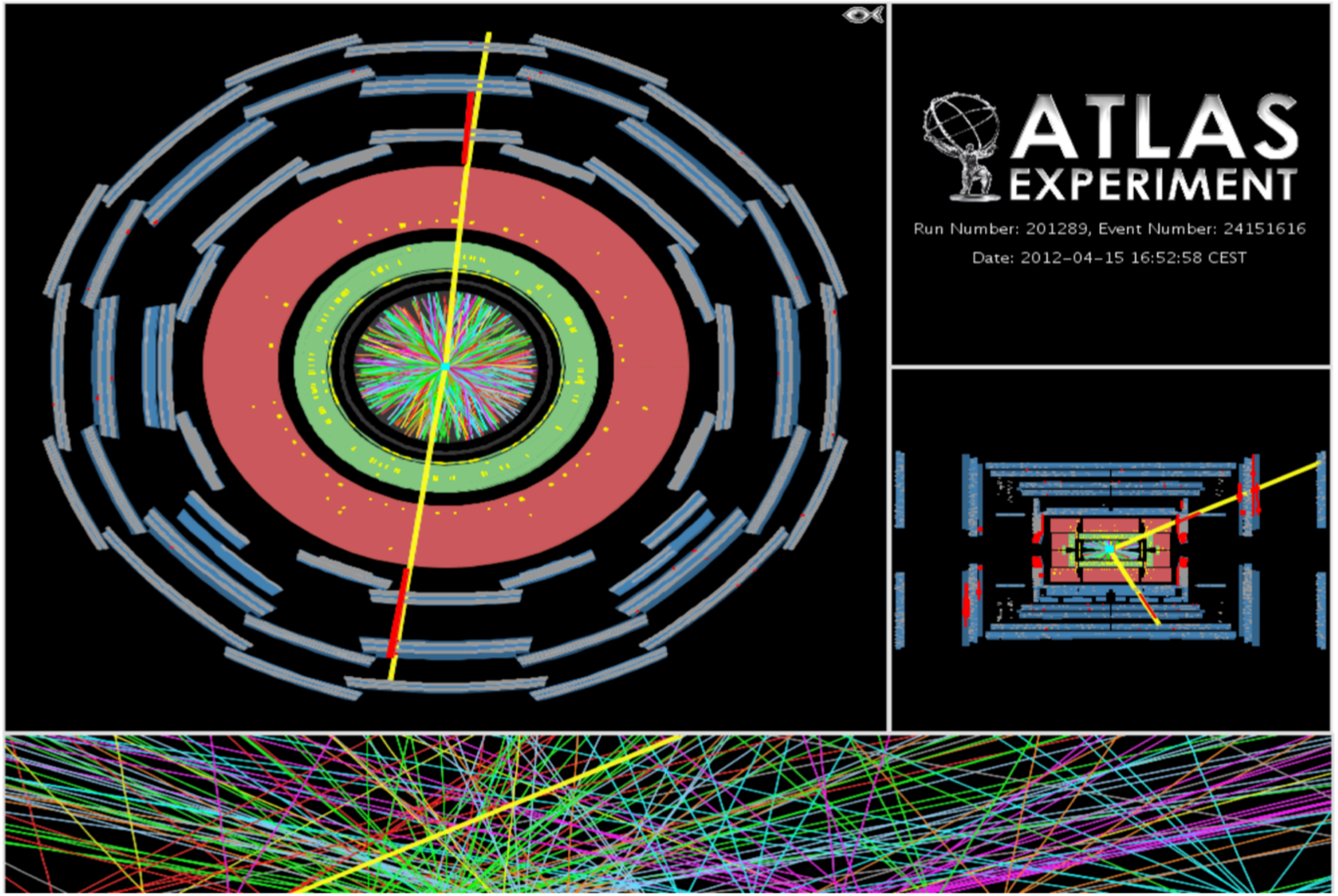


Resistive Plate Chambers

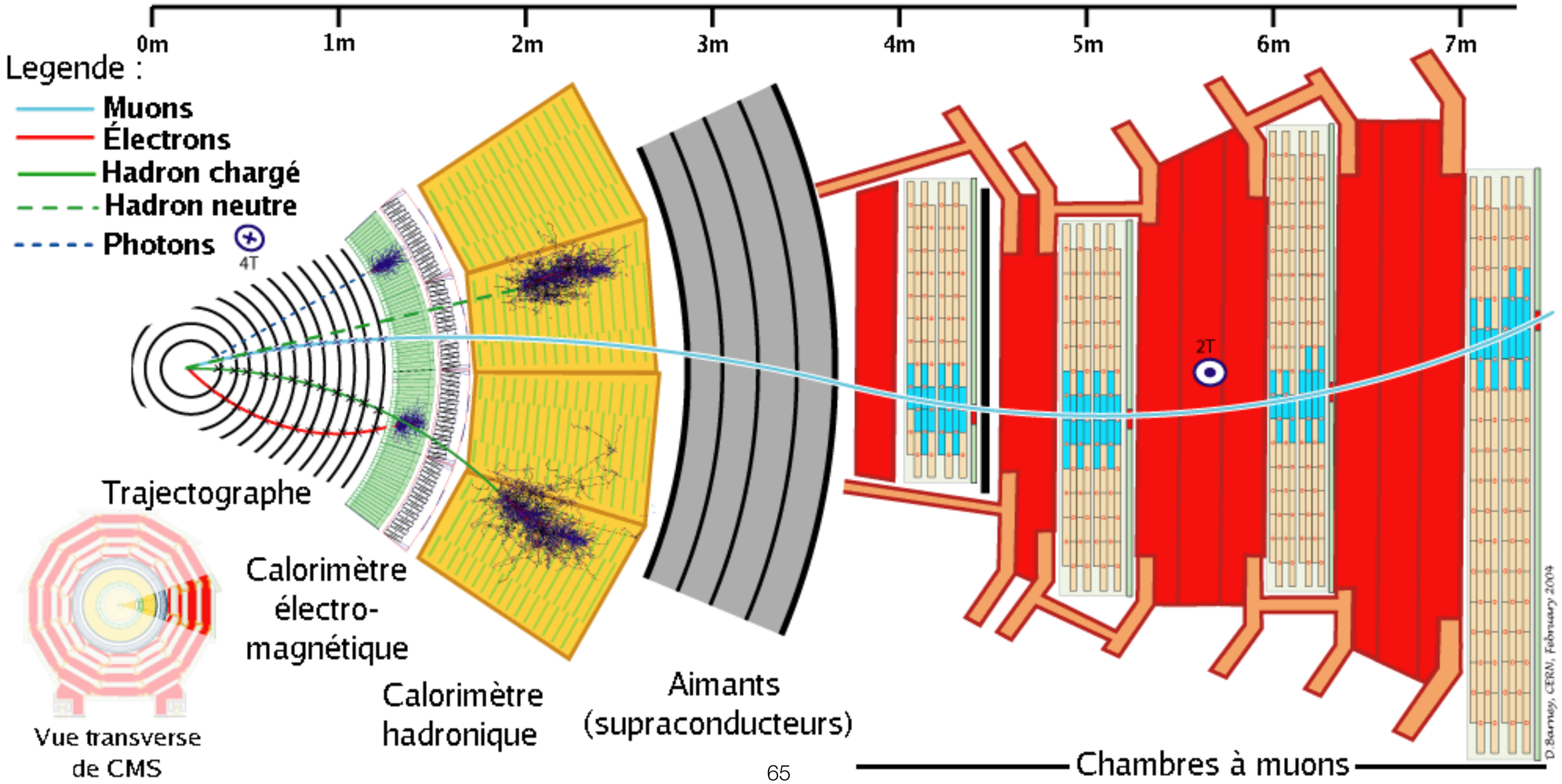


Muons in ATLAS

- Escape calorimeters, track recorded in spectrometer



Particule identification

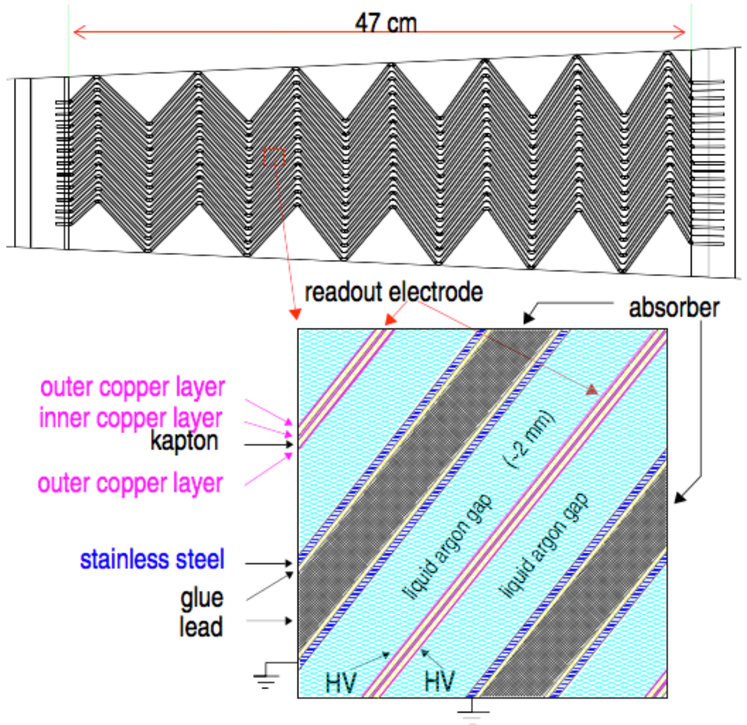


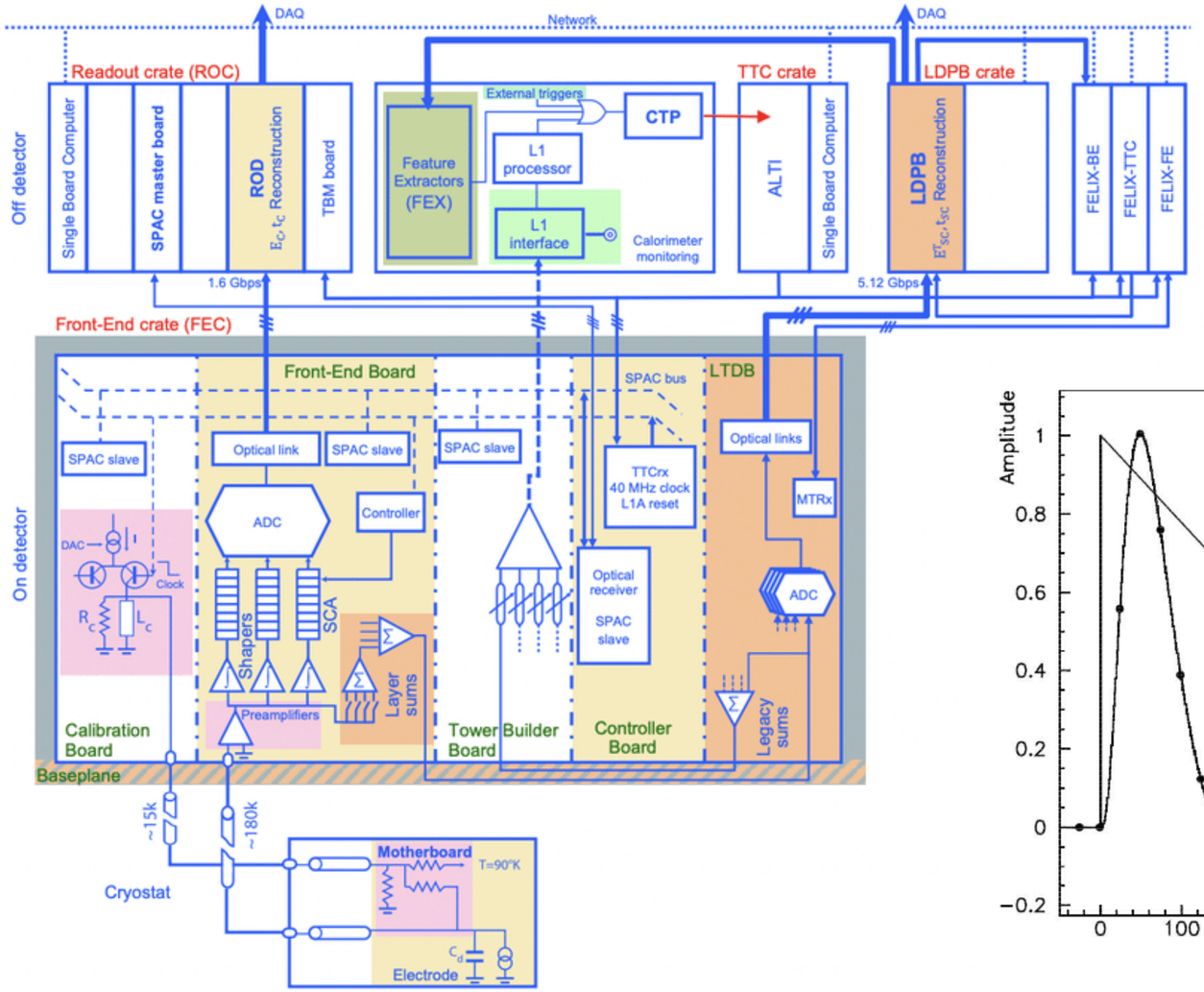
How to read the signal ?

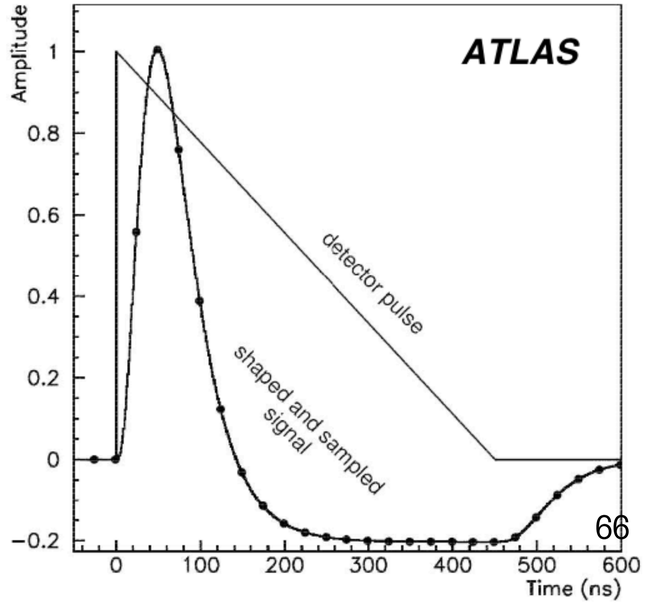
IN DETECTOR :
- AMPLIFICATION AND SHAPING OF SIGNAL
- DIGITIZATION (SAMPLING)
OFF-DETECTOR
- COMPUTATION OF ENERGY, QUALITY, TIMING

–> THOUSANDS OF ELECTRONIC BOARDS !

- Example with ATLAS calorimeter :







Building the future detectors - HL-LHC

Summary

- Detection of particles essentially based on how they interact with matter
- With time, detectors technics have improved : more precision, faster detection, better recording of signals
- Technologies will continue to improve, allowing us to see even deeper in fundamental laws

Thank you !