Detectors

Alberto Blanco
RPC R&D group Leader @ LIP

2026
INTERNSHIP
PROGRAM

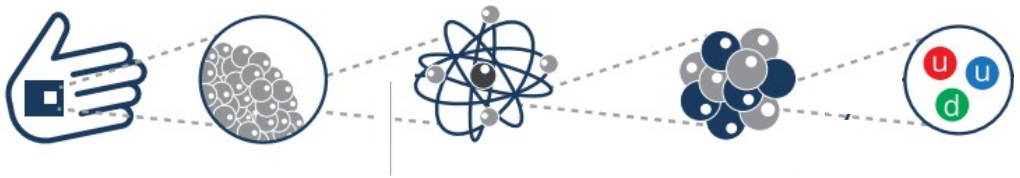
COIMBRA LISBOA MINHO

Outlook

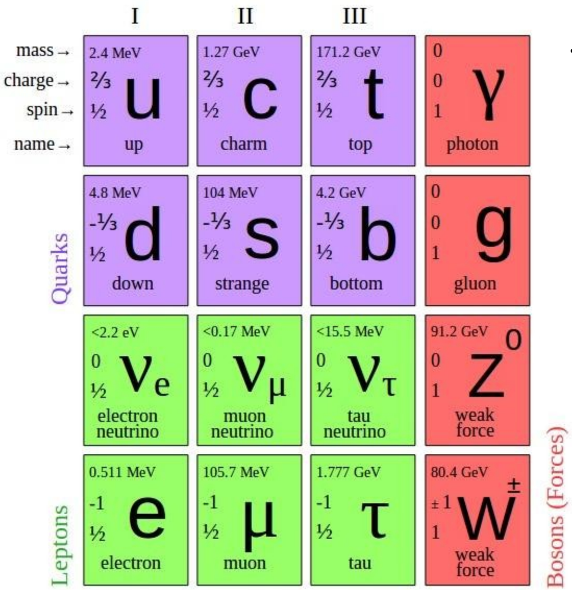
- What is a **particle**? What is a **particle detector**?
- **Principles of particle detection**. Detection medium, primary interaction and amplification mechanics.
- The case of the **Geiger Muller tube, Spark chamber and photo-multiplier tube**.
- **Case examples** @ LIP. HADES, AUGER, LZ, ATLAS and PET.

What is a particle?

Matter Atom Nuclei Proton

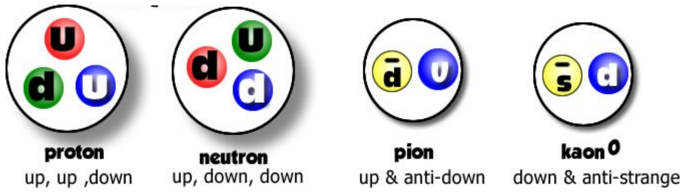


Particles are the fundamental constituents of matter.



Just as the chemical elements are organized in the periodic table, the Standard Model* organizes the **fundamental particles** according to their properties, such as mass or electric charge.

baryons mesons



leptons

* It is the most complete theory developed by particle physicists that explains the basis of (almost) everything that exists in the universe

What does a particle detector do?

A detector is a machine capable of recording particle properties such as: **position, energy, time**, ...
There are numerous types of detectors, using different technologies and measuring different properties of particles.

Image of a tooth

Dental X-ray machine + detector. Measures the quantity and position of X-rays

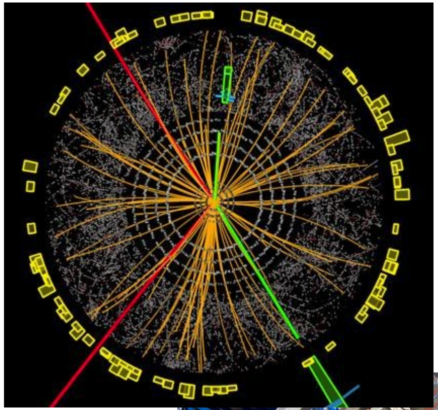
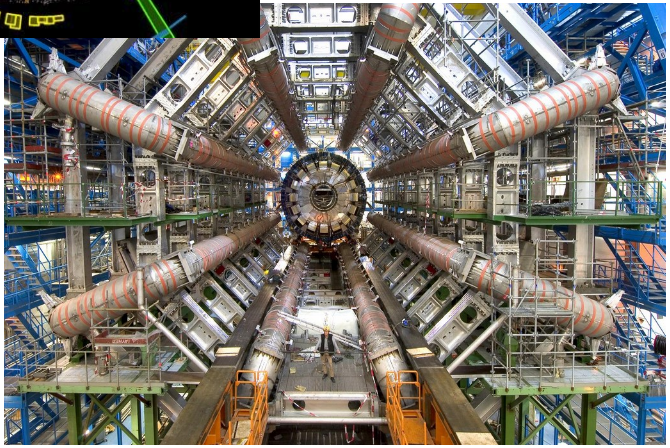


Image of the Higgs Boson

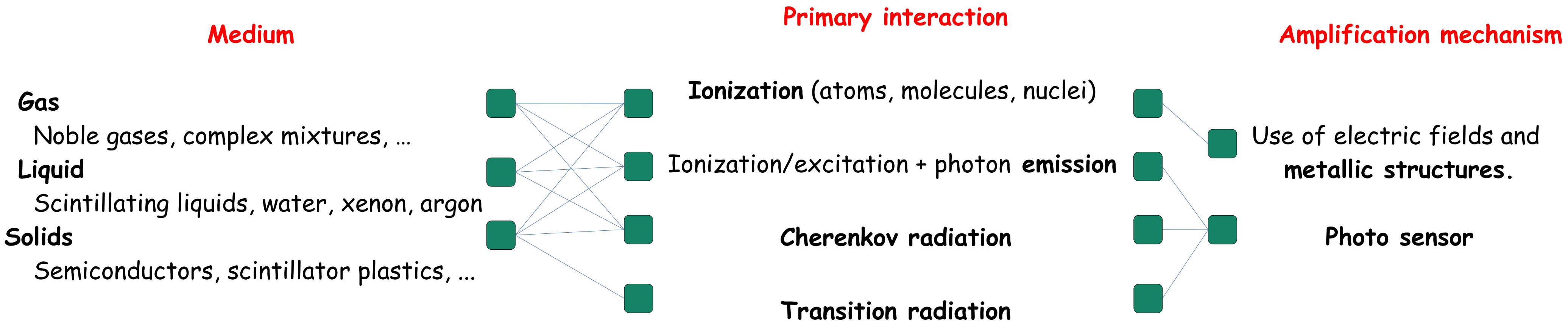
ATLAS measured in 2012 the Higgs boson



ATLAS detector under construction, LHC, CERN.

Principles of particle detection.

The principle is always the same: to detect a particle, it has to interact with the **MEDIUM** it passes through (the detector) leaving part of its energy in it, **PRIMARY INTERACTION**, which is amplified by the detector through some **AMPLIFICATION MECHANISM.**



The principle is always the same: to detect a particle, it has to interact with the **MEDIUM** it passes through (the detector) leaving part of its energy in it, **PRIMARY INTERACTION**, which is amplified by the detector through some **AMPLIFICATION MECHANISM**.

They are selected due their properties ….. chemical properties, density, photon emission, price, ….

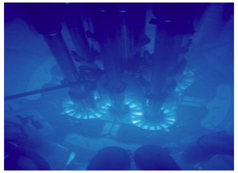
Gases

Noble gases, complex mixtures, ...

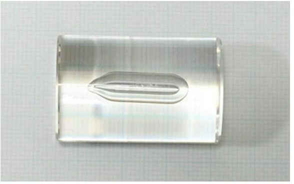
Liquids

Scintillating liquids, water, Xenon, Argon,

Scintillating liquid



Water tank

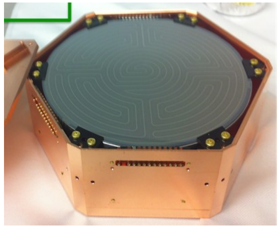


Liquid Xenon

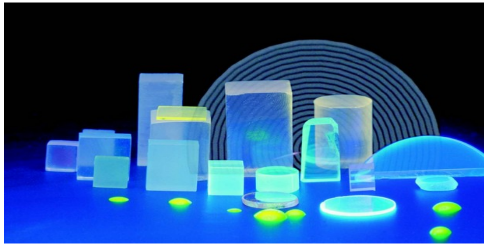
Liquid Argon

Solids

Semiconductors, scintillator plastics, ...

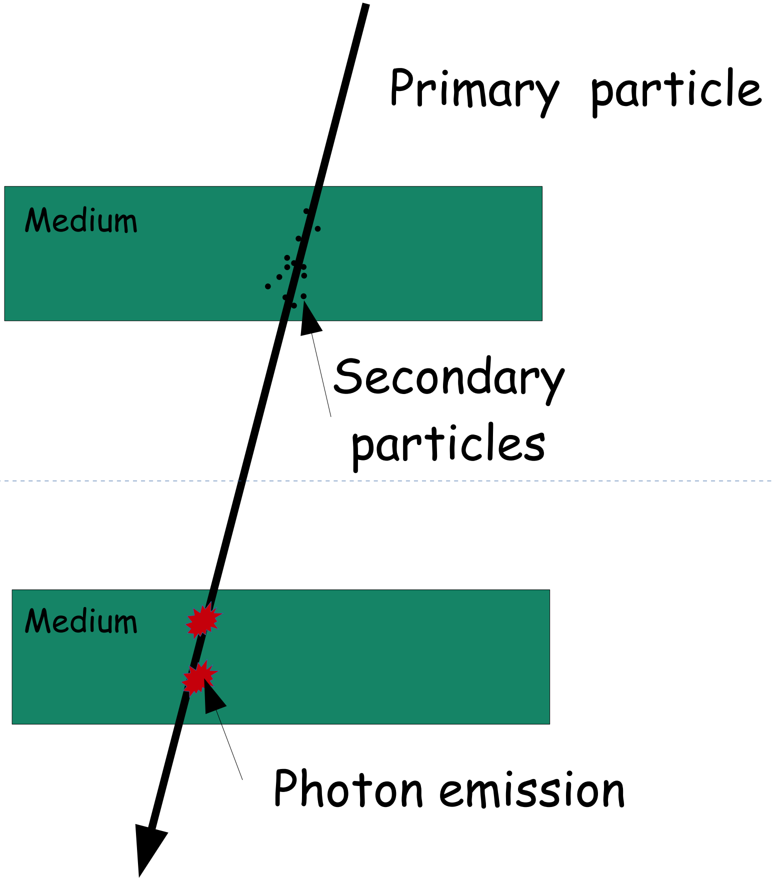


Semiconductor detector



Scintillating plastics

The principle is always the same: to detect a particle, it has to interact with the **MEDIUM** it passes through (the detector) leaving part of its energy in it, **PRIMARY INTERACTION**, which is amplified by the detector through some **AMPLIFICATION MECHANISM**.



Production of secondary charged particles

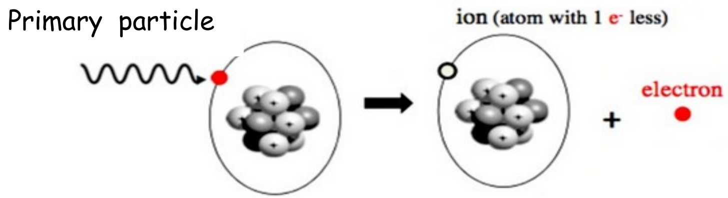
Ionization, nuclear reactions, ...

Production of photons

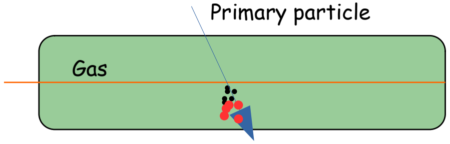
Scintillation, Cherenkov, Transition, ...

The principle is always the same: to detect a particle, it has to interact with the **MEDIUM** it passes through (the detector) leaving part of its energy in it, **PRIMARY INTERACTION**, which is amplified by the detector through some **AMPLIFICATION MECHANISM**.

Ionization

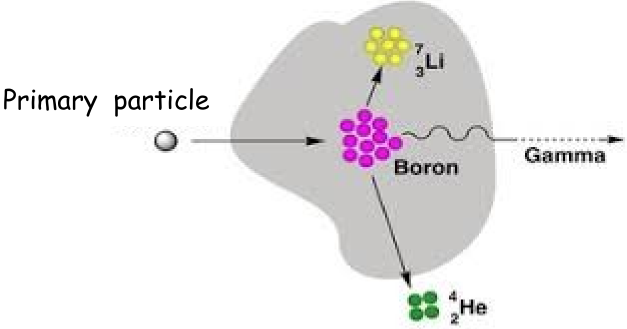


Particle extracts an electron from an atom

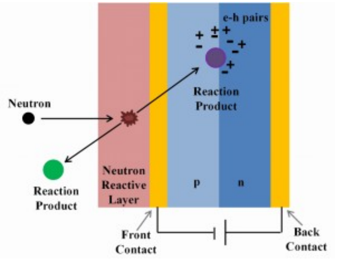


e-/ion pairs creation in a gas filled detector by an incoming particle

Nuclear reaction



Particle extracts two charged fragments + gamma from a nuclear capture

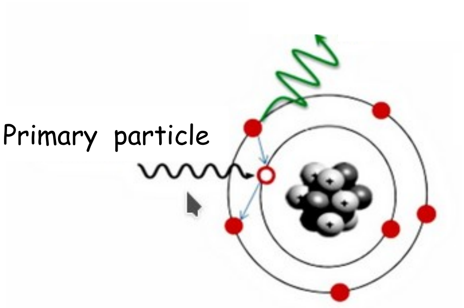


e-/ion pairs creation at a PN junction by the reaction products of a neutron capture in a boron reach layer

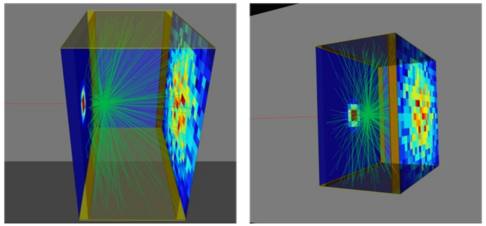
Principles of particle detection. Primary interaction. Photon production.

The principle is always the same: to detect a particle, it has to interact with the **MEDIUM** it passes through (the detector) leaving part of its energy in it, **PRIMARY INTERACTION**, which is amplified by the detector through some **AMPLIFICATION MECHANISM**.

Scintillation



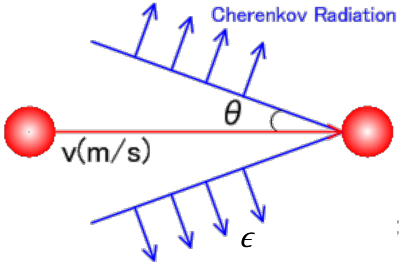
Photon emission from an atom/molecule after excitation by an incoming particle



Simulation of photon production in a scintillator

Cherenkov emission

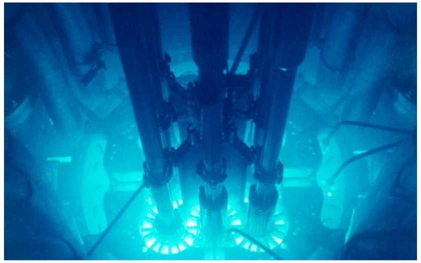
Primary particle



$$v_{part} > \frac{c}{n_{index}}$$

$$\sin(\Theta) = \frac{c}{n_{index} * v_{part}}$$

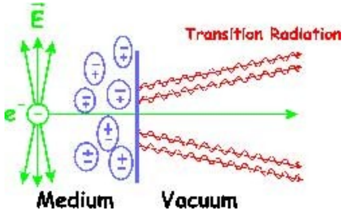
Cherenkov emission from a particle faster than light in a given medium



Nuclear reactor emitting Cherenkov light

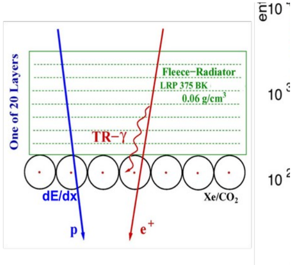
Transition radiation

Primary particle



$$\varepsilon_{r1} \neq \varepsilon_{r2}$$

Transition radiation emission from a particle traveling in an in-homogeneous media



Transition radiation detector schematic

The principle is always the same: to detect a particle, it has to interact with the **MEDIUM** it passes through (the detector) leaving part of its energy in it, **PRIMARY INTERACTION**, which is amplified by the detector through some **AMPLIFICATION MECHANISM**.

Multiplication of secondary particles through the use of **electric fields and metallic structures.**

Multiplication of photons using a **photo-device.**

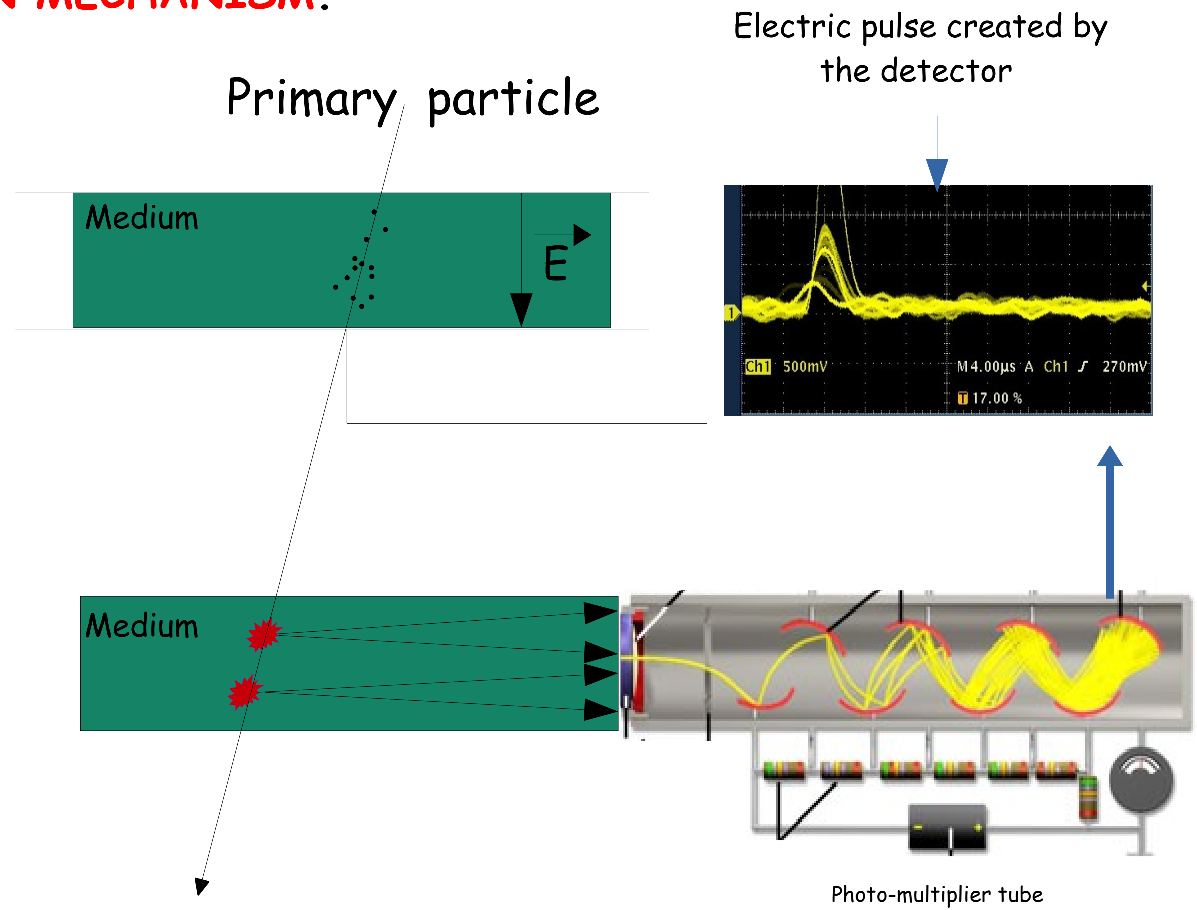


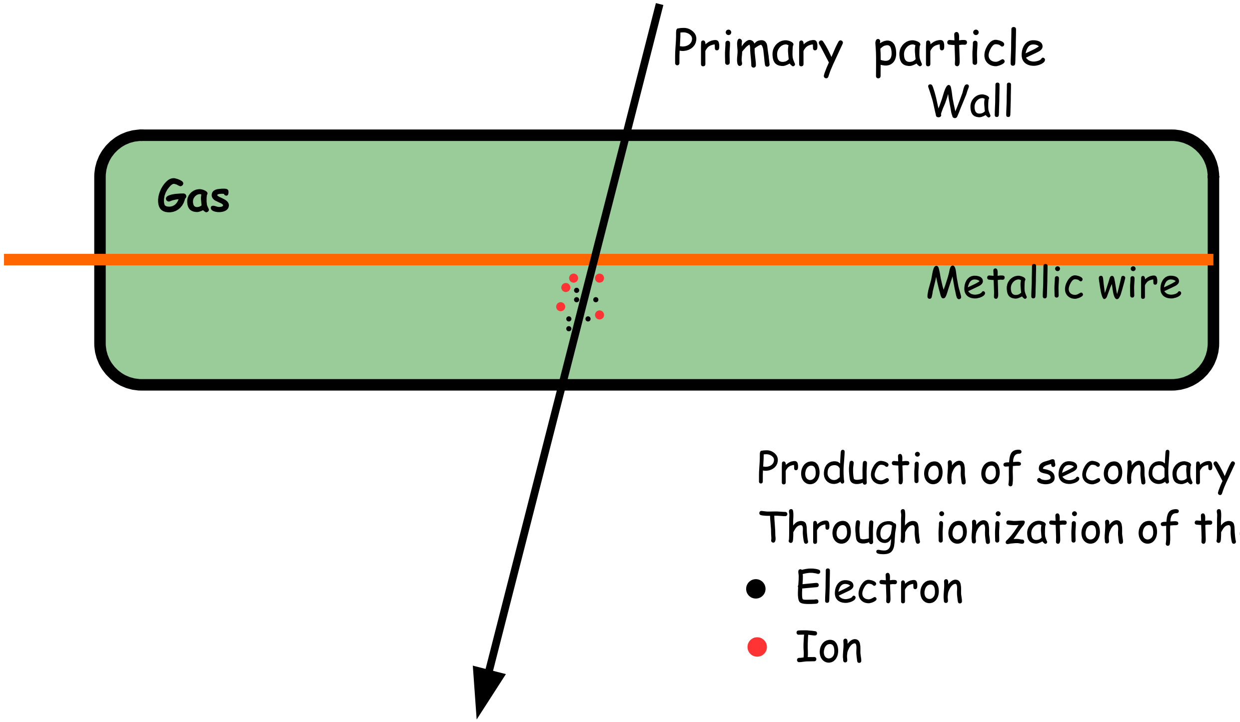
Photo-multiplier tube

Principles of particle detection. Geiger Muller detector.

Geiger Muller detector (Cold war version)

-Medium = gas (nobel gas, He, Ne, Ar)

Detection medium is a gas

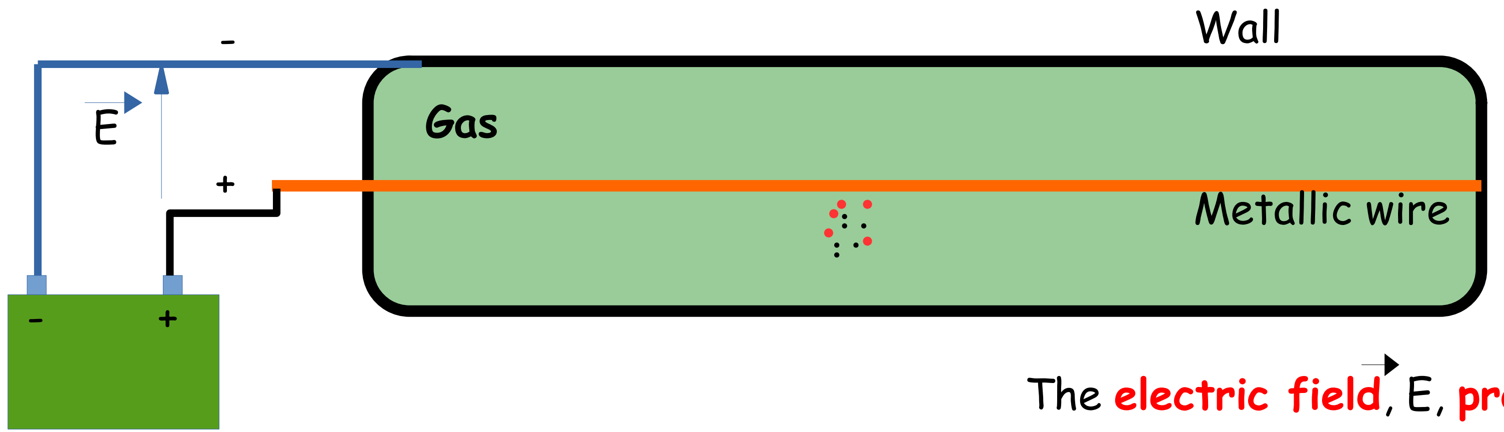


Production of secondary particles
Through ionization of the gas atoms.

- Electron
- Ion

Primary interaction

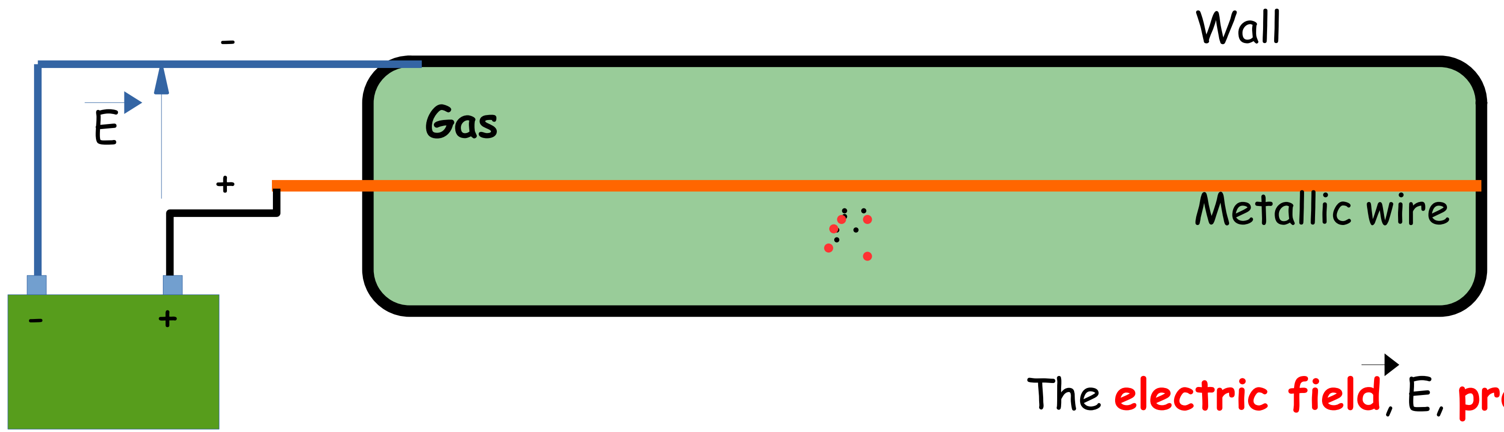
-Medium = gas (nobel gas, He, Ne, Ar)
-Primary interaction = **production of secondary charged particles**



The **electric field**, $\vec{E}$, **provides energy** to the **electrons** and **ions** moving them towards the wire and the wall respectively.

Amplification mechanism

-Medium = **gas (nobel gas, He, Ne, Ar)**
-Primary interaction = **production of secondary charged particles**
-Amplification = use of **electric fields and metallic structures.**

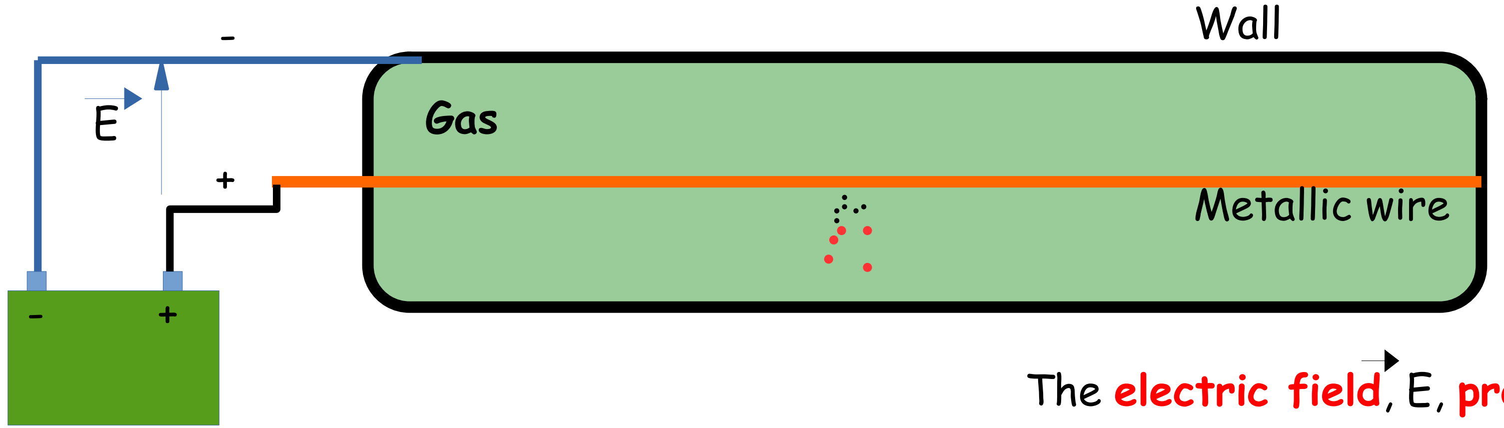


The **electric field**, $\vec{E}$, **provides energy** to the **electrons** and **ions** moving them towards the wire and the wall respectively.

Amplification mechanism

-Medium = **gas (nobel gas, He, Ne, Ar)**
-Primary interaction = **production of secondary charged particles**
-Amplification = use of **electric fields and metallic structures.**

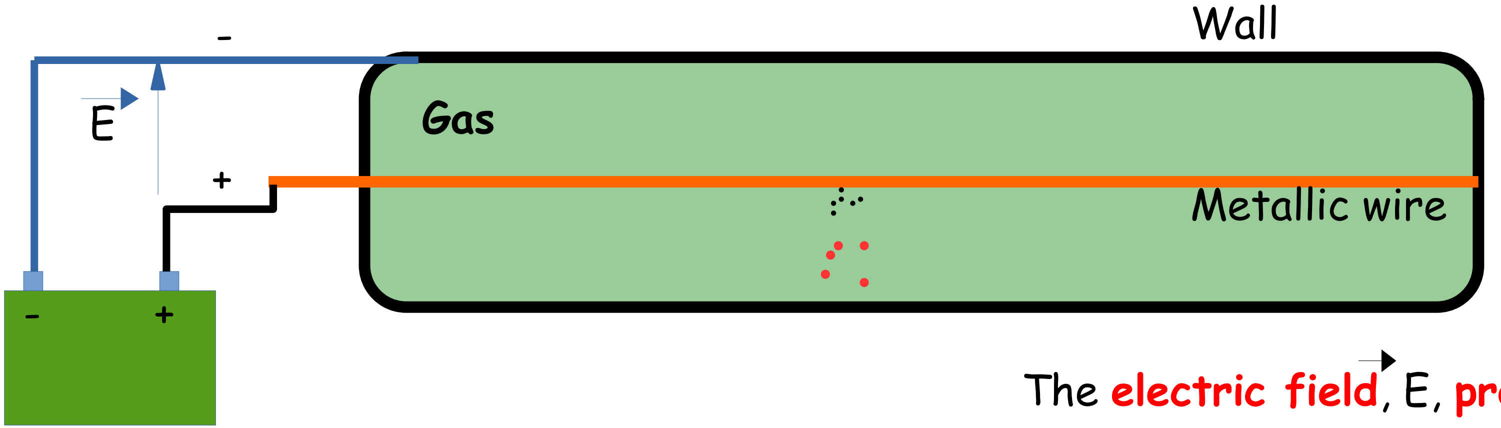
Principles of particle detection. Geiger Muller detector.



The **electric field**, $\vec{E}$, **provides energy** to the **electrons** and **ions** moving them towards the wire and the wall respectively.

Amplification mechanism

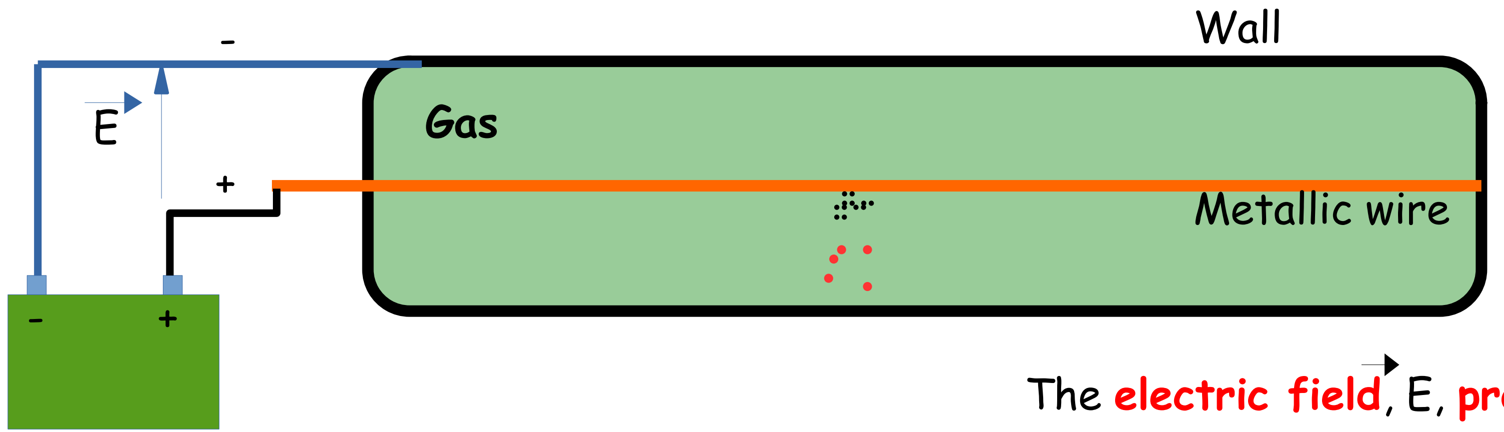
-Medium = **gas (nobel gas, He, Ne, Ar)**
-Primary interaction = **production of secondary charged particles**
-Amplification = use of **electric fields and metallic structures.**



The **electric field**, $\vec{E}$, **provides energy** to the **electrons** and **ions** moving them towards the wire and the wall respectively.

Amplification mechanism

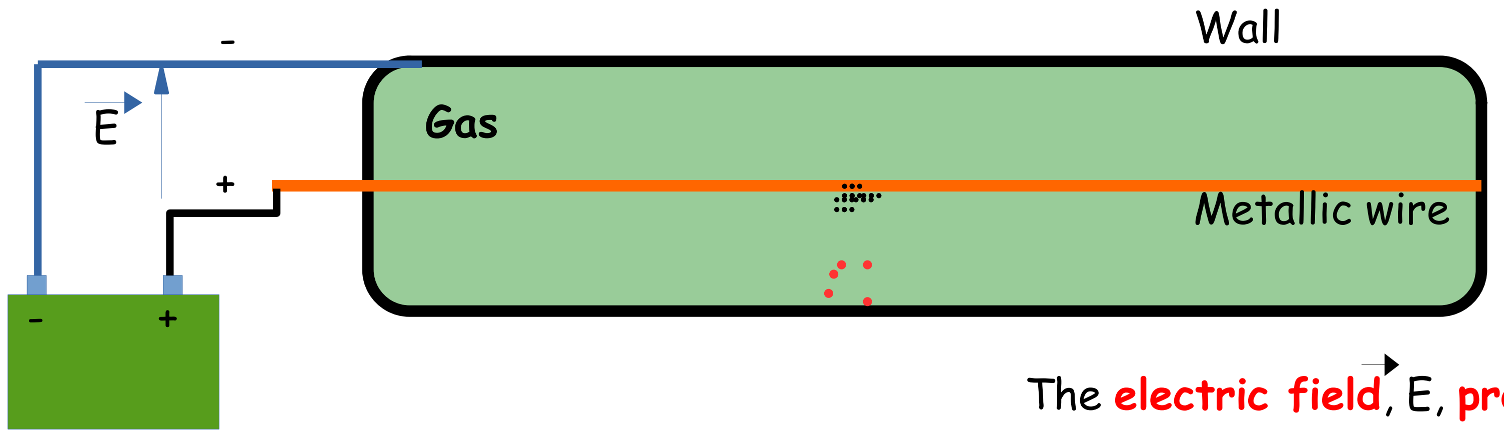
-Medium = **gas (nobel gas, He, Ne, Ar)**
-Primary interaction = **production of secondary charged particles**
-Amplification = use of **electric fields and metallic structures.**



The **electric field**, $\vec{E}$, **provides energy** to the **electrons** and **ions** moving them towards the wire and the wall respectively.

Amplification mechanism

-Medium = **gas (nobel gas, He, Ne, Ar)**
-Primary interaction = **production of secondary charged particles**
-Amplification = use of **electric fields and metallic structures.**

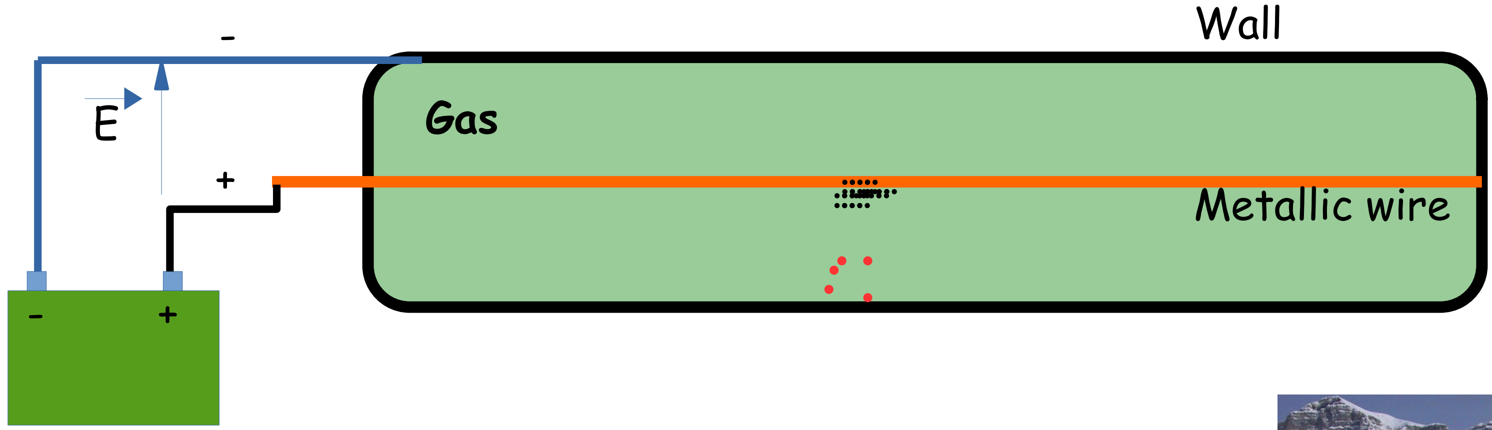


The **electric field**, $\vec{E}$, **provides energy** to the **electrons** and **ions** moving them towards the wire and the wall respectively.

Amplification mechanism

-Medium = **gas (nobel gas, He, Ne, Ar)**
-Primary interaction = **production of secondary charged particles**
-Amplification = use of **electric fields and metallic structures.**

Avalanche multiplication



Similar phenomenon snow **avalanches** in the mountains

$\vec{g}$

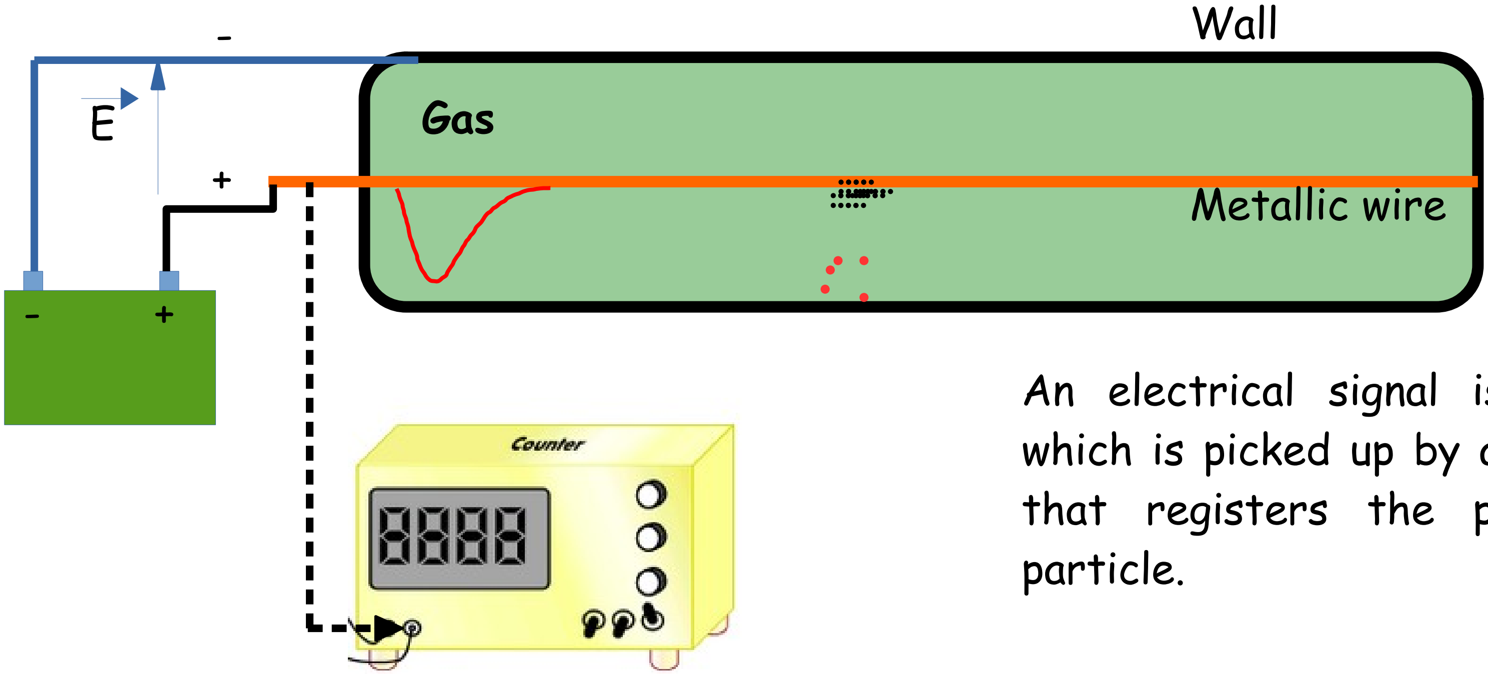
Snow

Amplification mechanism

-Medium = **gas (nobel gas, He, Ne, Ar)**

-Primary interaction = **production of secondary charged particles**

-Amplification = use of **electric fields and metallic structures.**

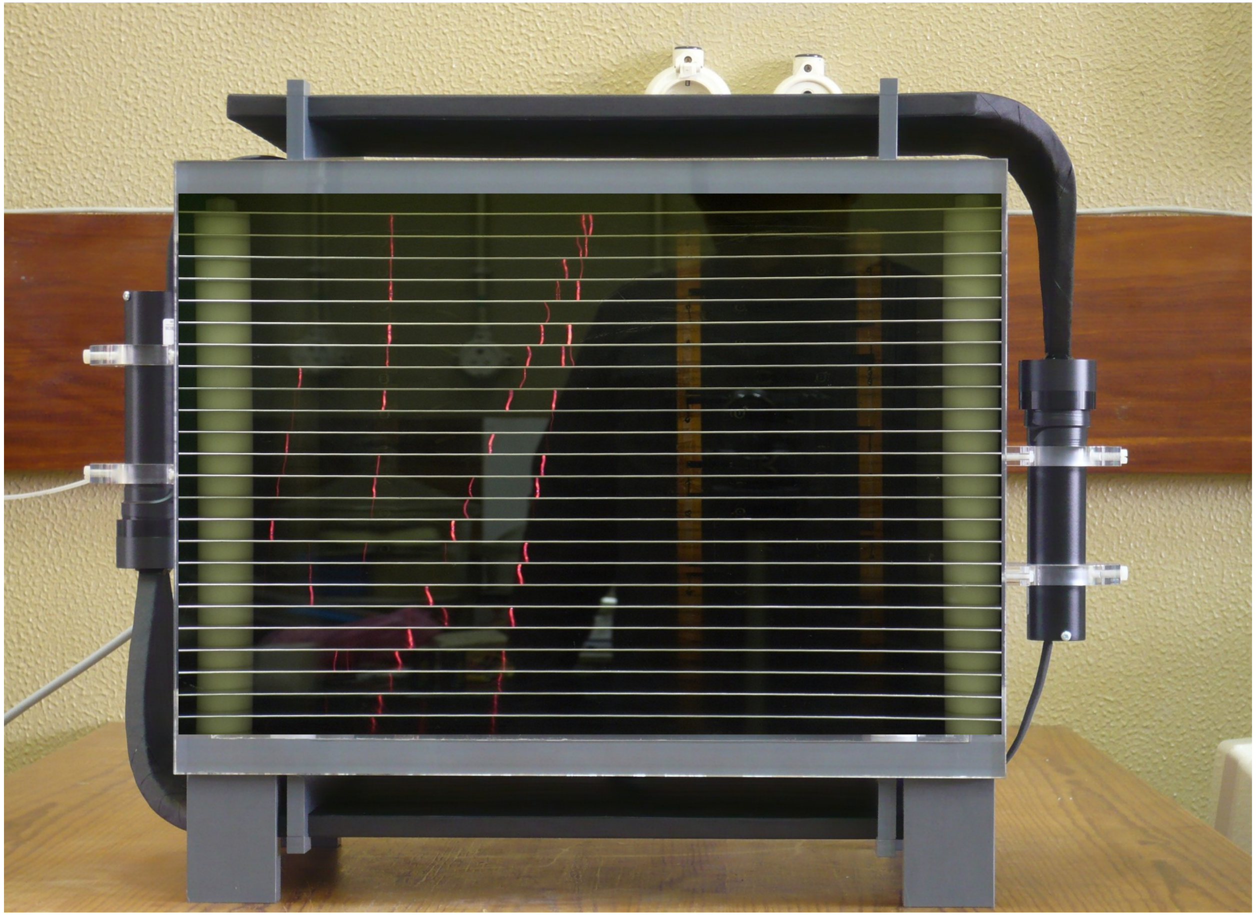


An electrical signal is thus created which is picked up by a electronic unit that registers the passage of the particle.

-Medium = **gas (nobel gas, He, Ne, Ar)**
-Primary interaction = **production of secondary charged particles**
-Amplification = use of **electric fields and metallic structures.**

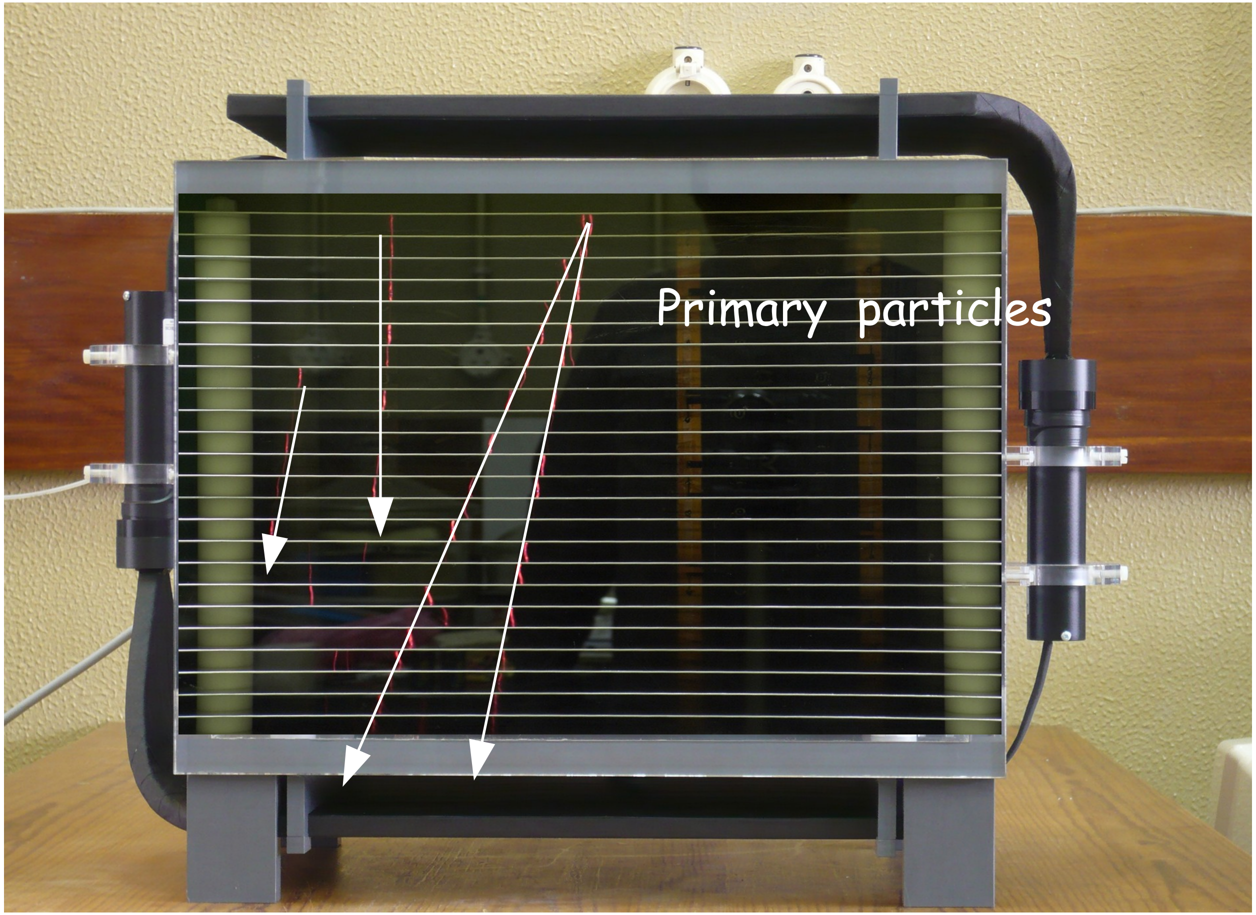
Principles of particle detection. Spark chamber.

A **spark chamber** is a device that **allows the visualization of the path taken by a particle** (cosmic ray) inside it.



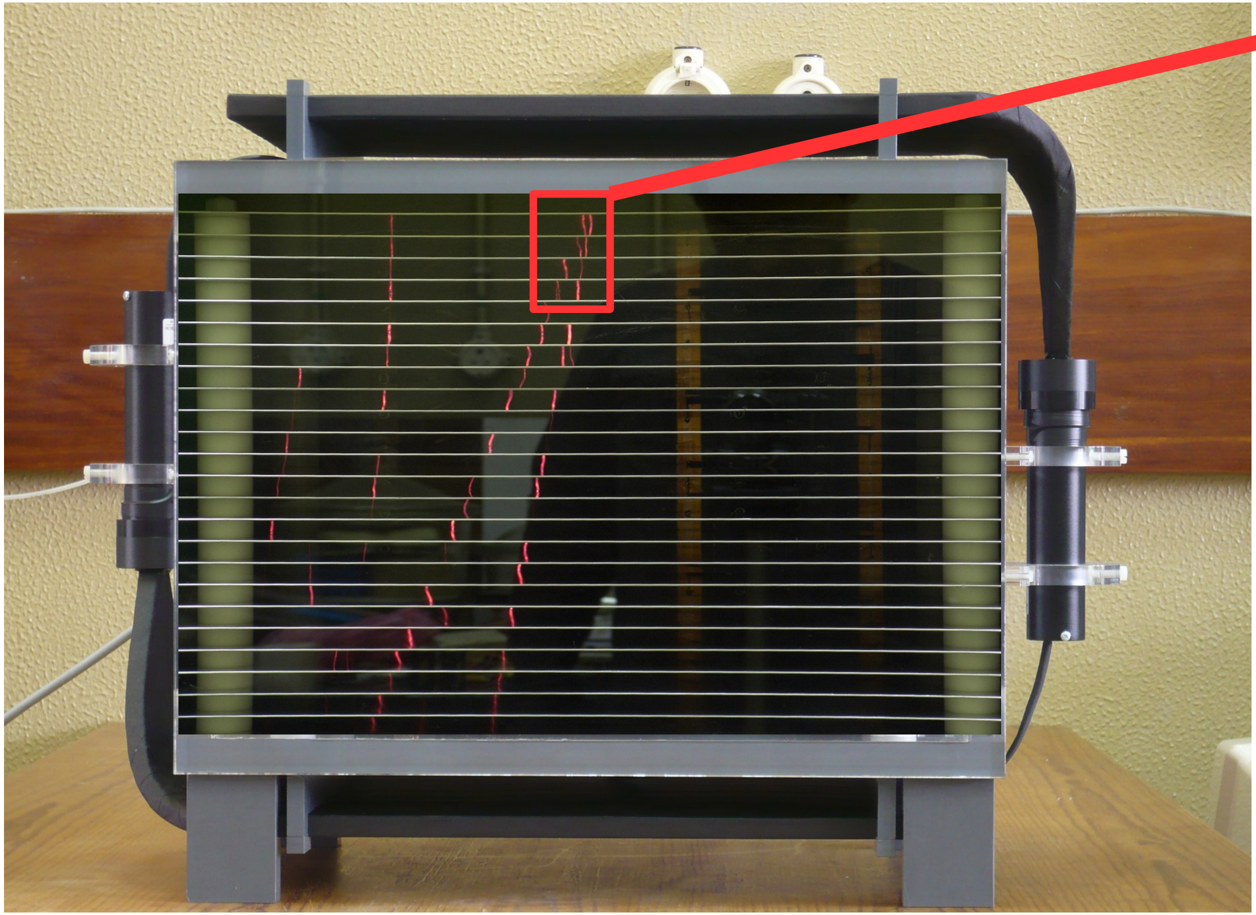
Principles of particle detection. Spark chamber.

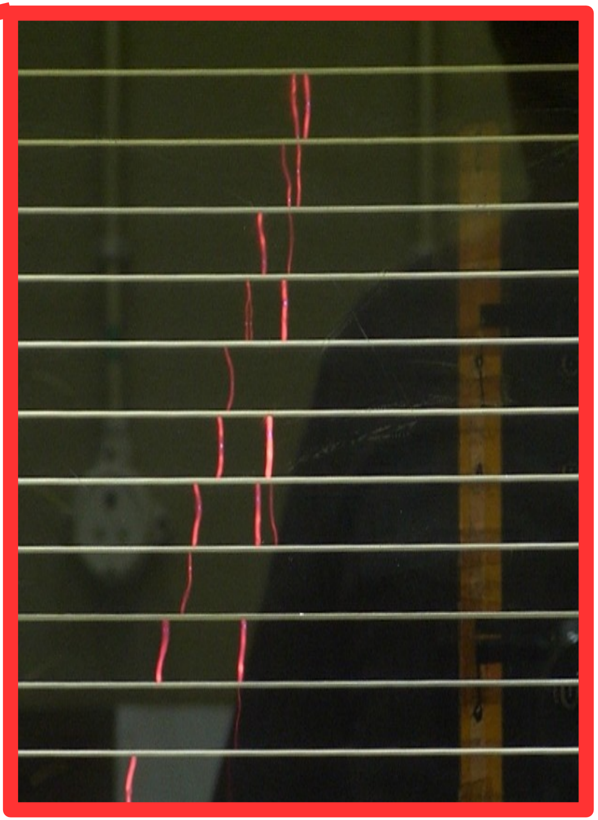
A **spark chamber** is a device that **allows the visualization of the path taken by a particle** (cosmic ray) inside it.



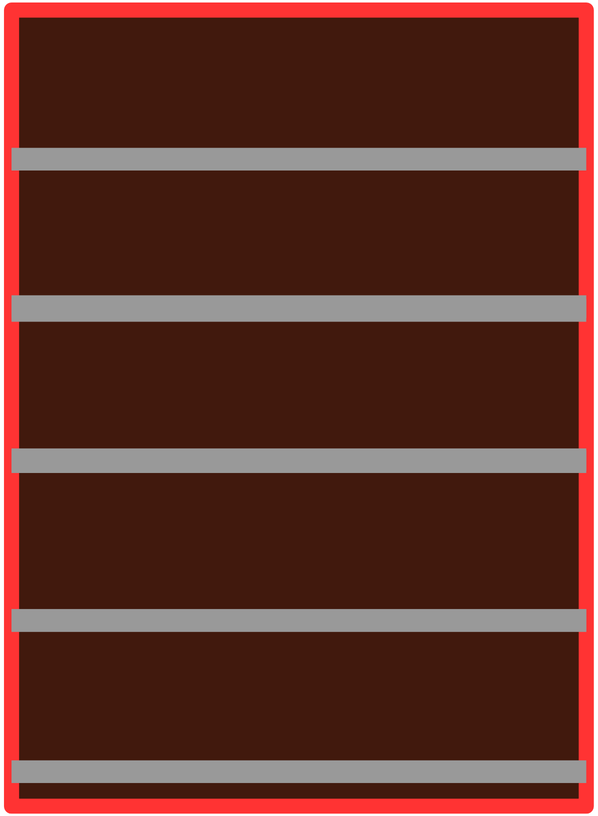
Principles of particle detection. Spark chamber.

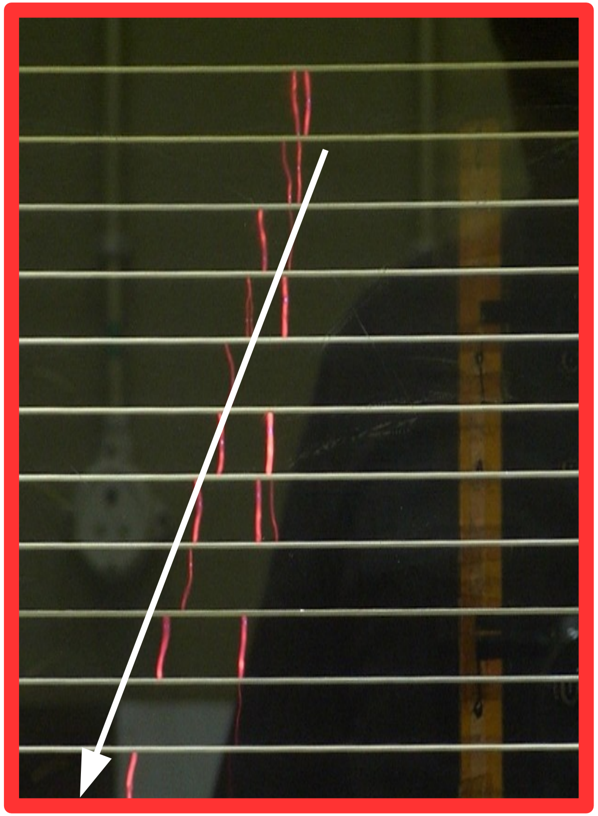
A **spark chamber** is a device that **allows the visualization of the path taken by a particle** (cosmic ray) inside it.





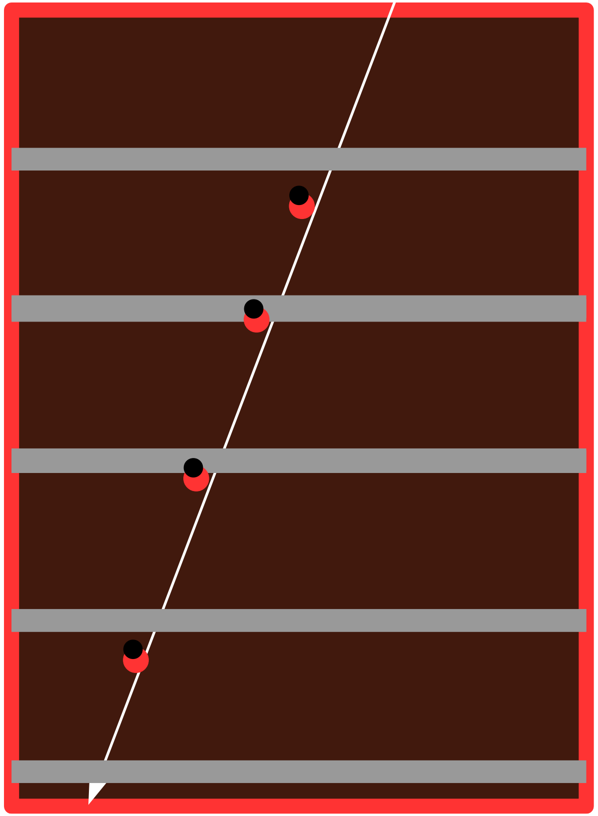
A **spark chamber** is a device that **allows the visualization of the path taken by a particle** (cosmic ray) inside it.

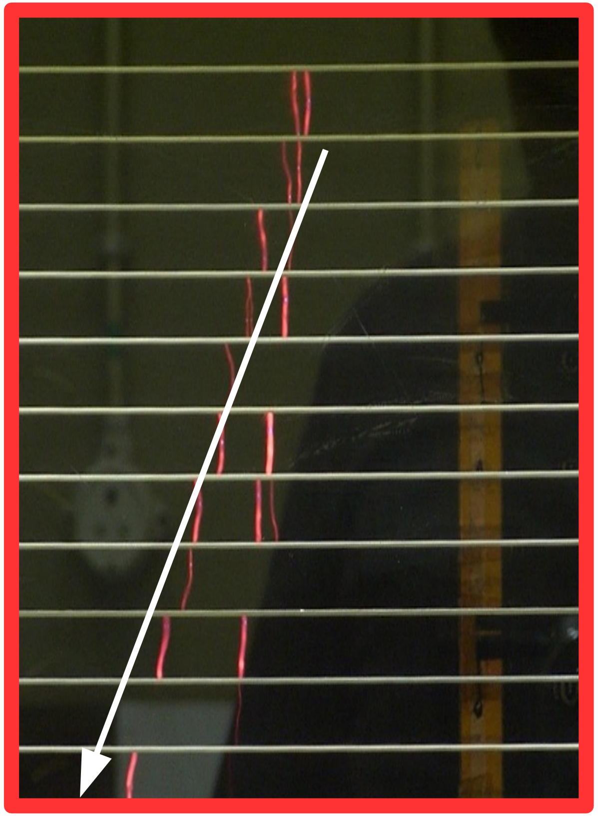




-Medium = **gas (nobel gas, He, Ne, Ar)**

A **spark chamber** is a device that **allows the visualization of the path taken by a particle** (cosmic ray) inside it.

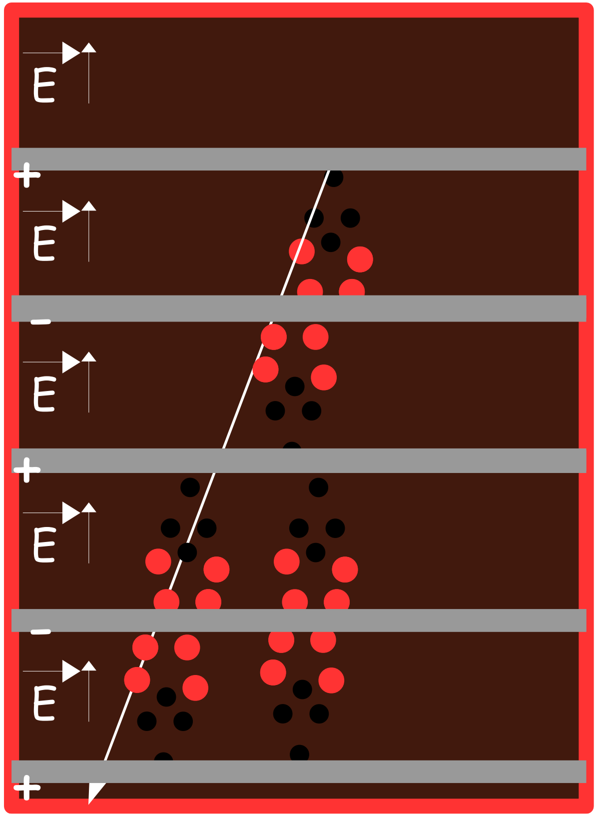




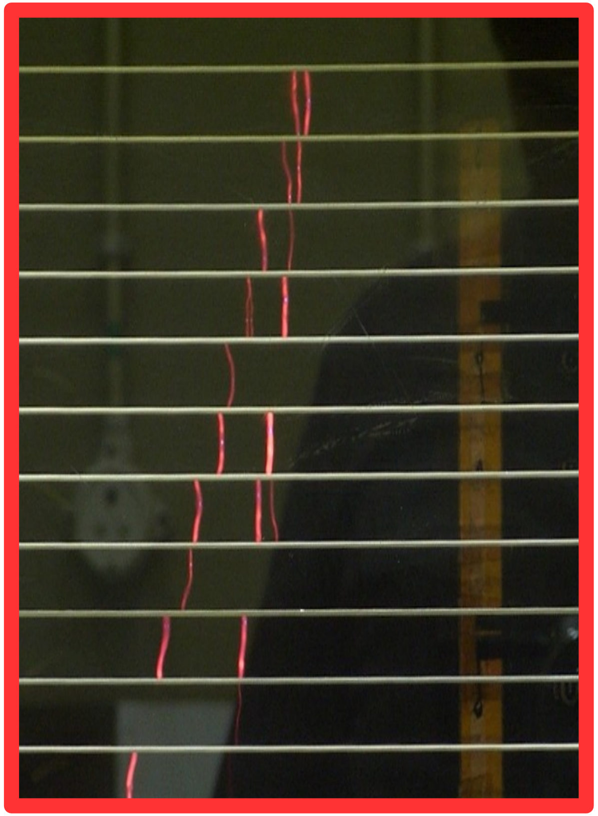
-Medium = **gas (nobel gas, He, Ne, Ar)**

-Primary interaction = **production of secondary charged particles**

A **spark chamber** is a device that **allows the visualization of the path taken by a particle** (cosmic ray) inside it.

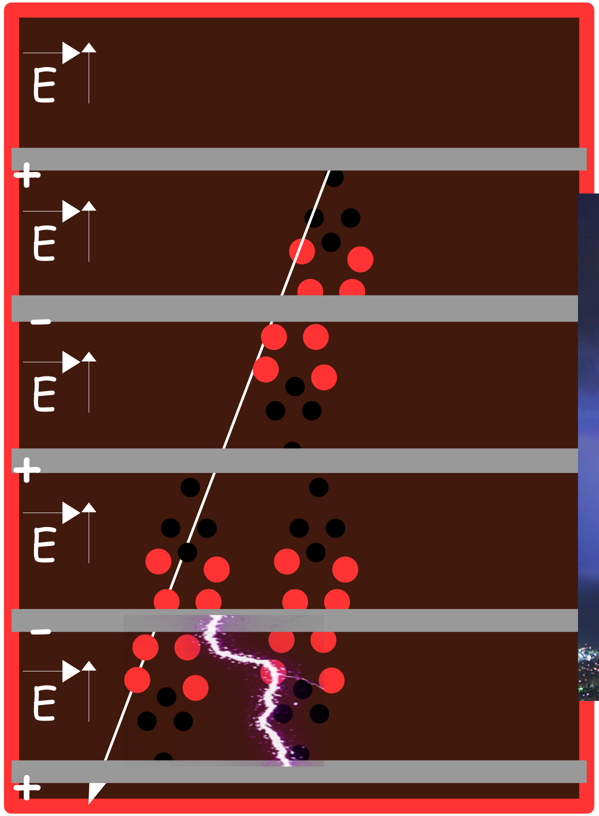


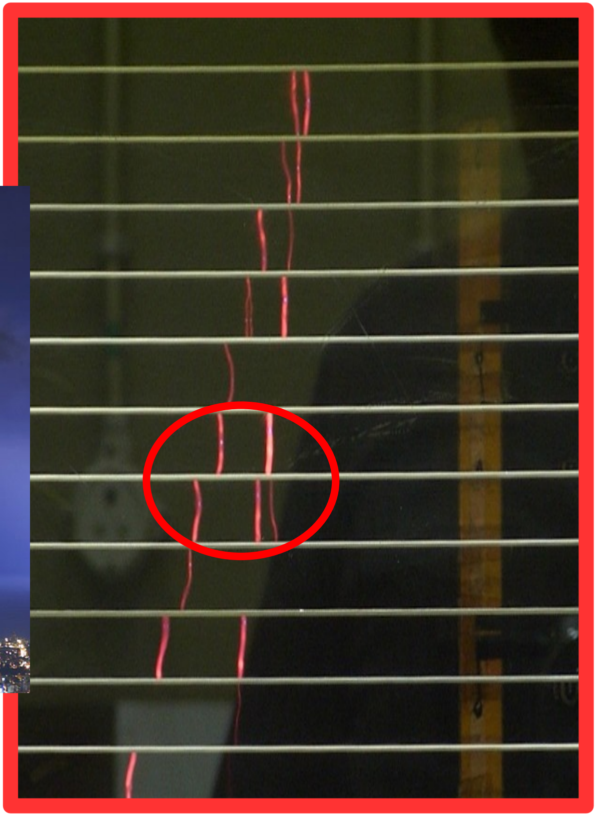
Avalanche multiplication



-Medium = **gas (nobel gas, He, Ne, Ar)**
-Primary interaction = **production of secondary charged particles**
-Amplification = use of **electric fields and metallic structures.**

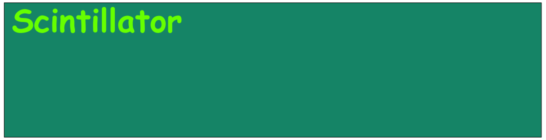
A spark chamber is a device that allows the visualization of the path taken by a particle (cosmic ray) inside it.





-Medium = gas (nobel gas, He, Ne, Ar)
-Primary interaction = production of secondary charged particles
-Amplification = use of electric fields and metallic structures.

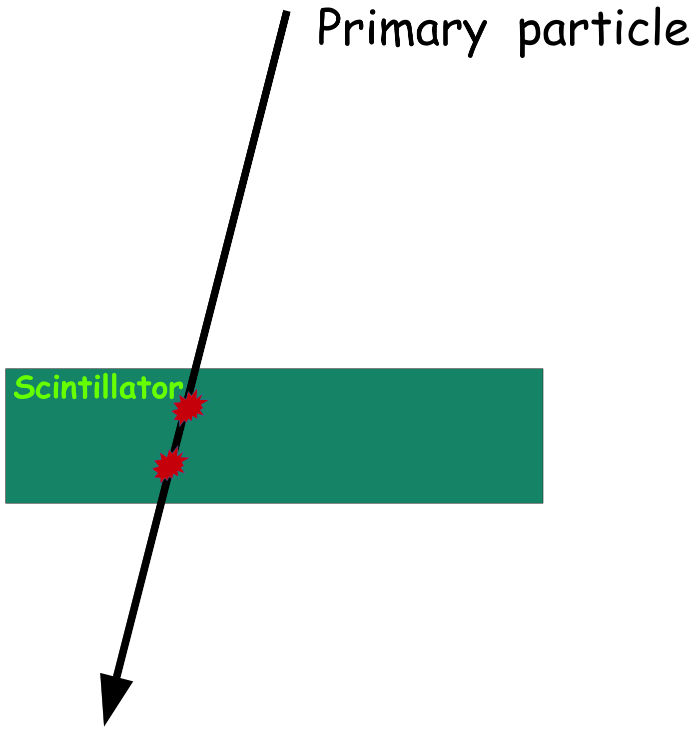
Principles of particle detection. Plastic scintillator + Photo-multiplier.

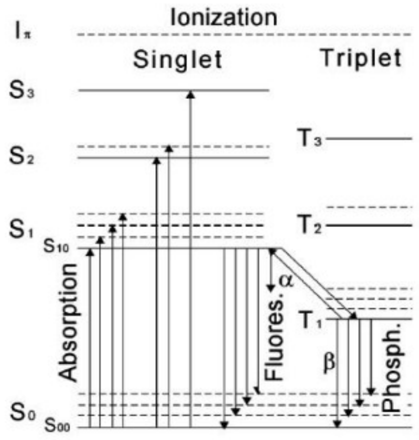


Detection medium is a scintillator

- Medium = Solid. Plastic scintillator

Principles of particle detection. Plastic scintillator + Photo-multiplier.



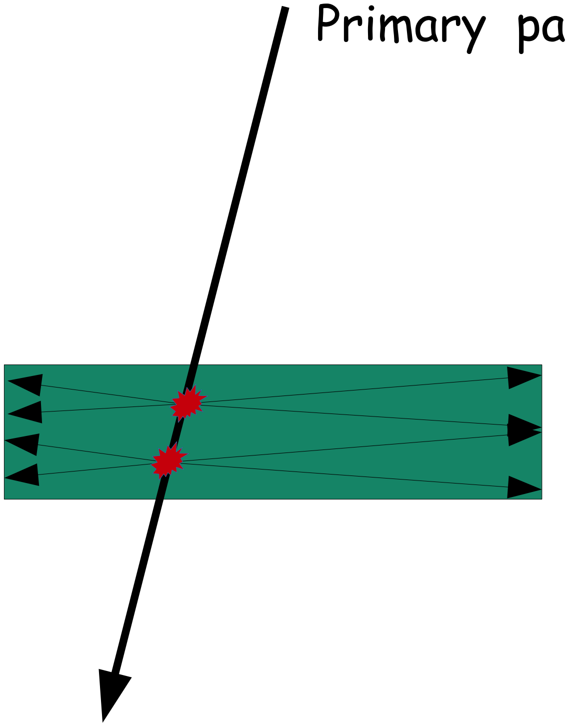


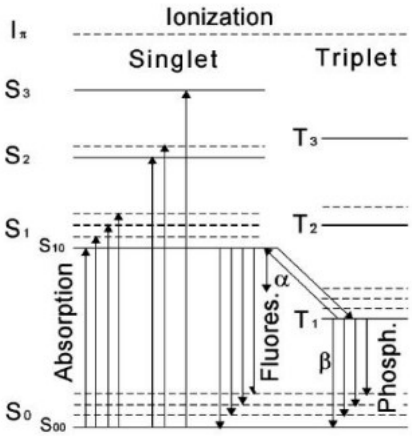
Charged particles deposit energy causing excitation of solvent and dopants molecules. Fast de-excitation by **fluorescense.**

Primary interaction

- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**

Principles of particle detection. Plastic scintillator + Photo-multiplier.



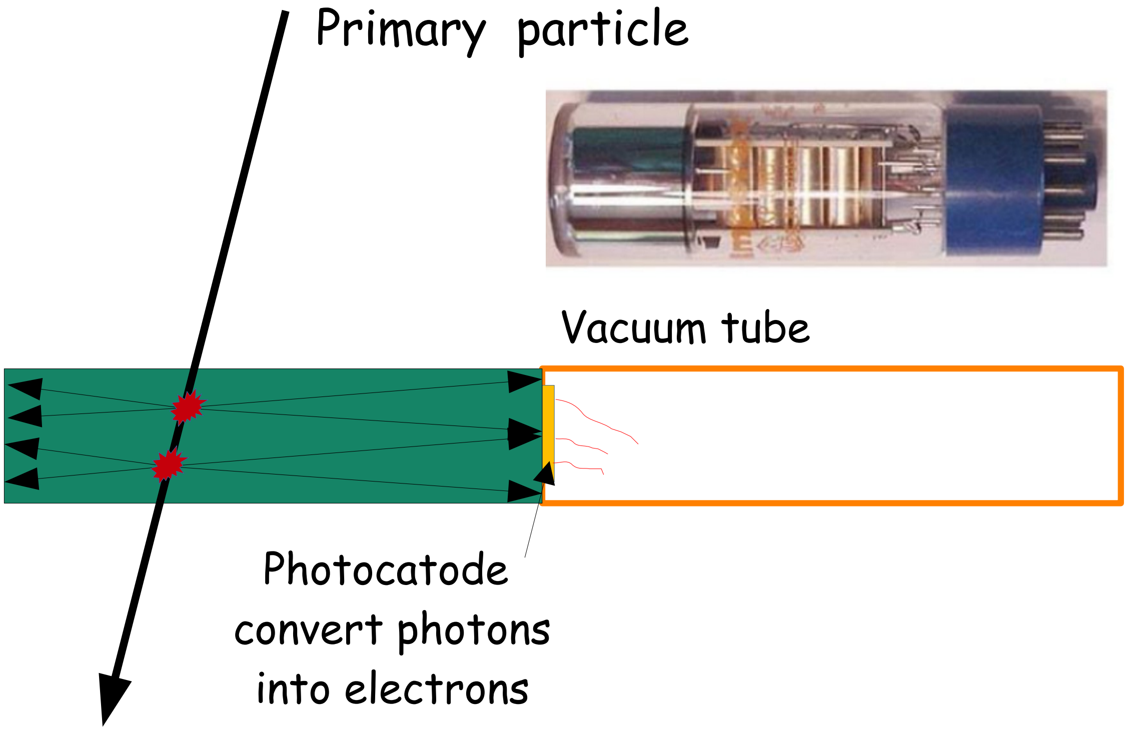


Charged particles deposit energy causing excitation of solvent and dopants molecules. Fast de-excitation by **fluorescense.**

Primary interaction

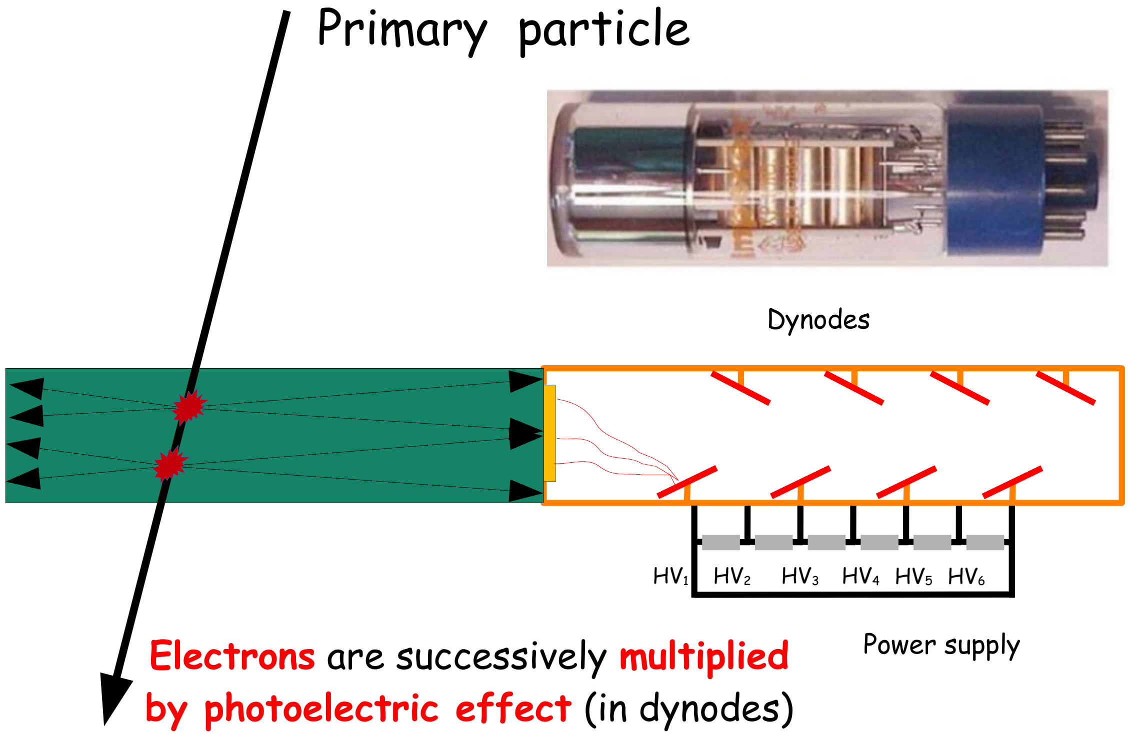
- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**

Principles of particle detection. Plastic scintillator + Photo-multiplier.



Amplification mechanism

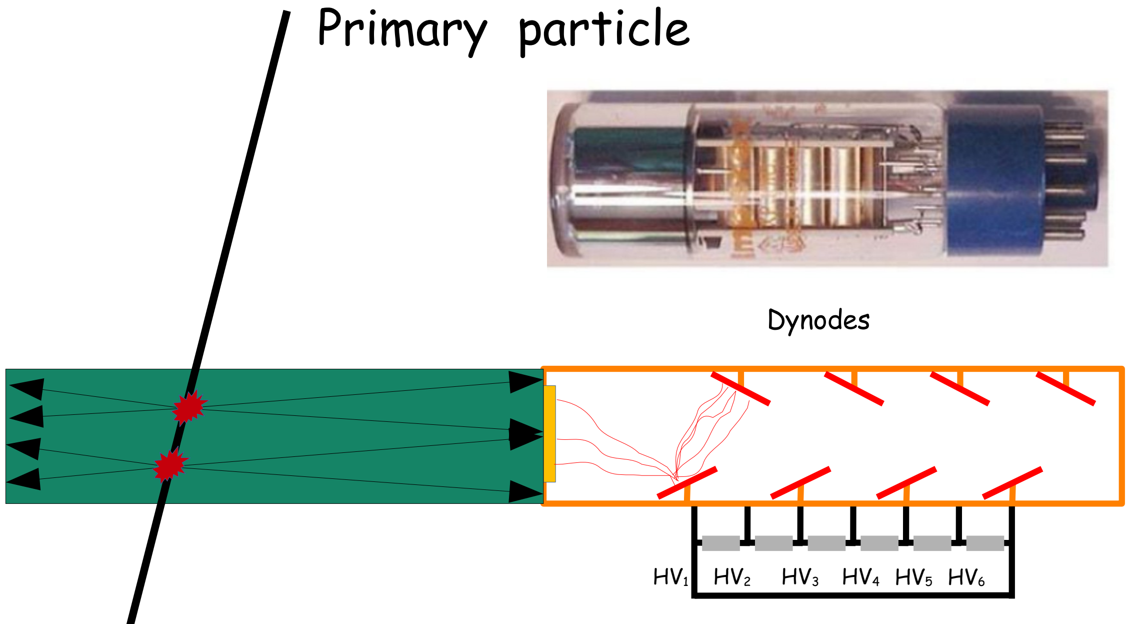
- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**



Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

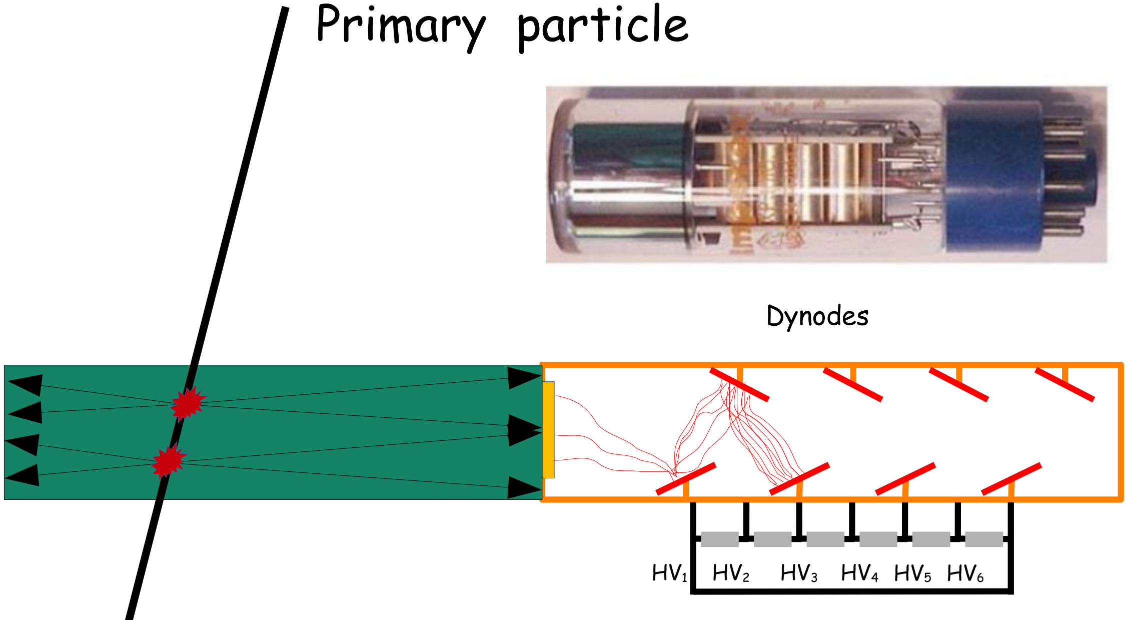
- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**



Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**

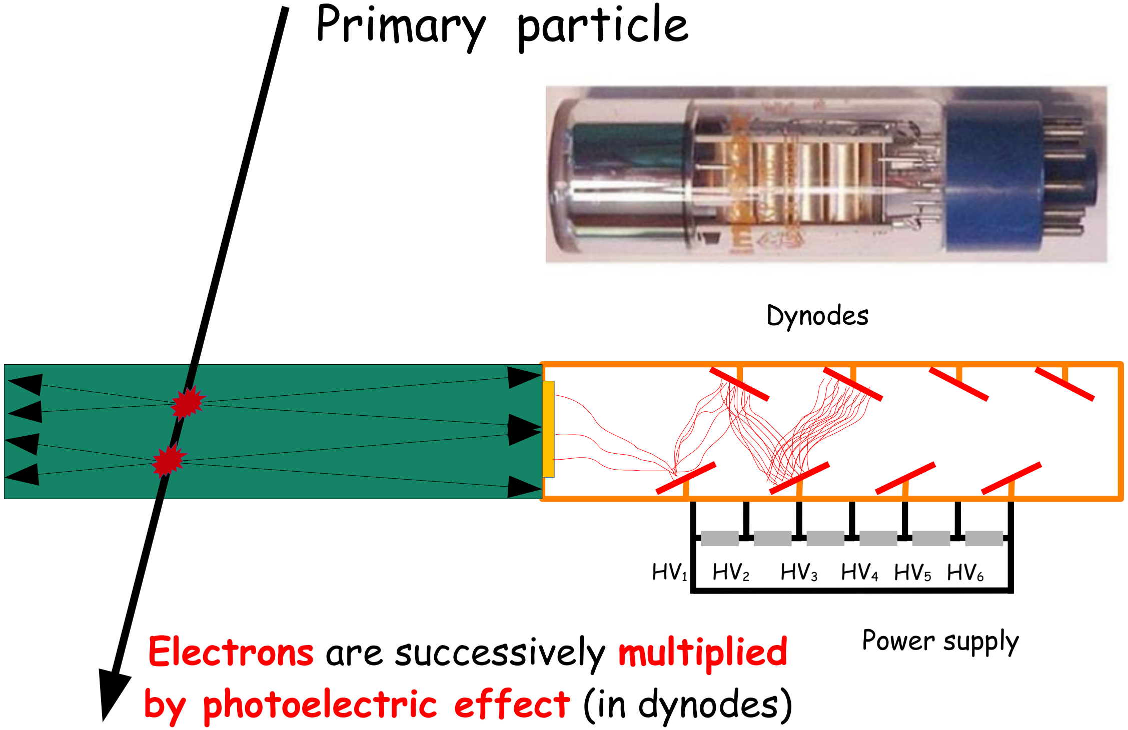


Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**

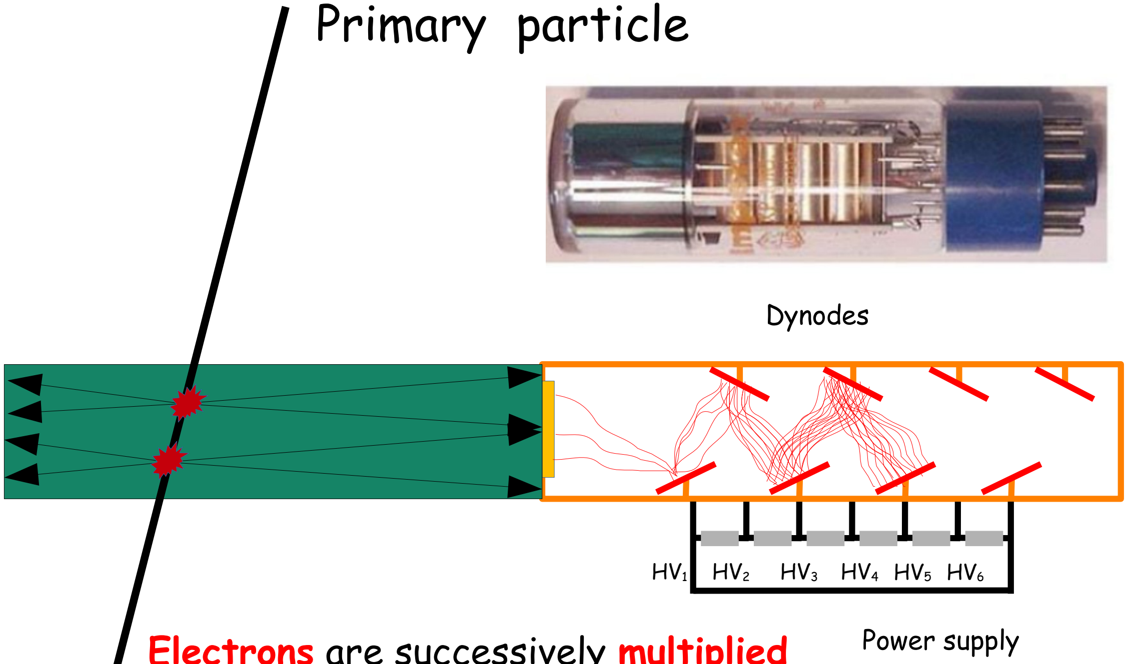
Principles of particle detection. Plastic scintillator + Photo-multiplier.



Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

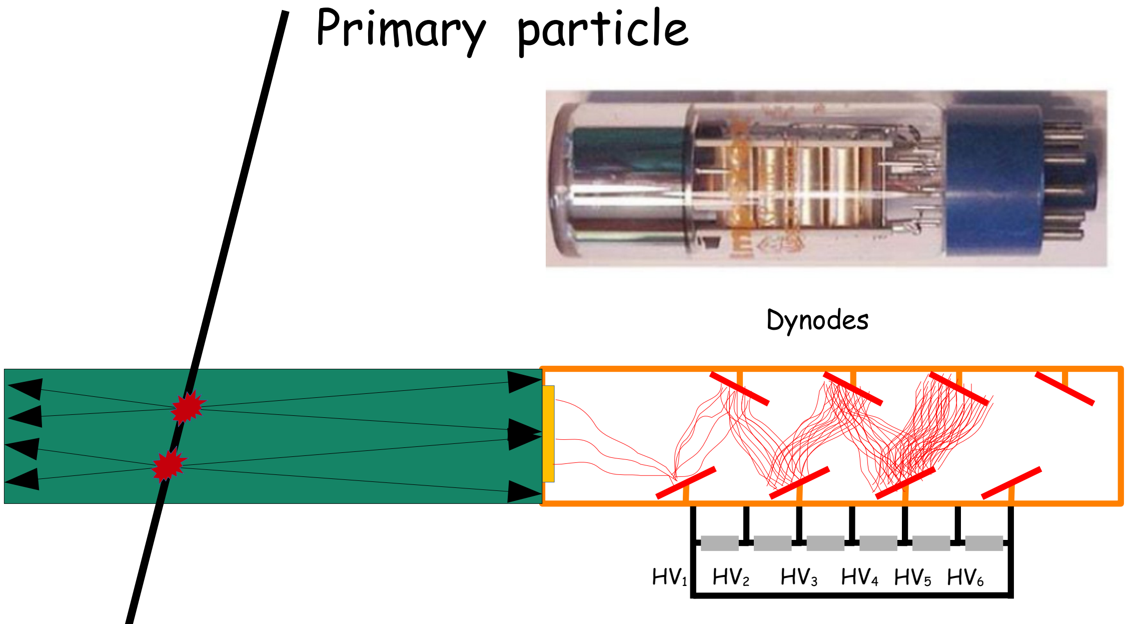
- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**



Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**

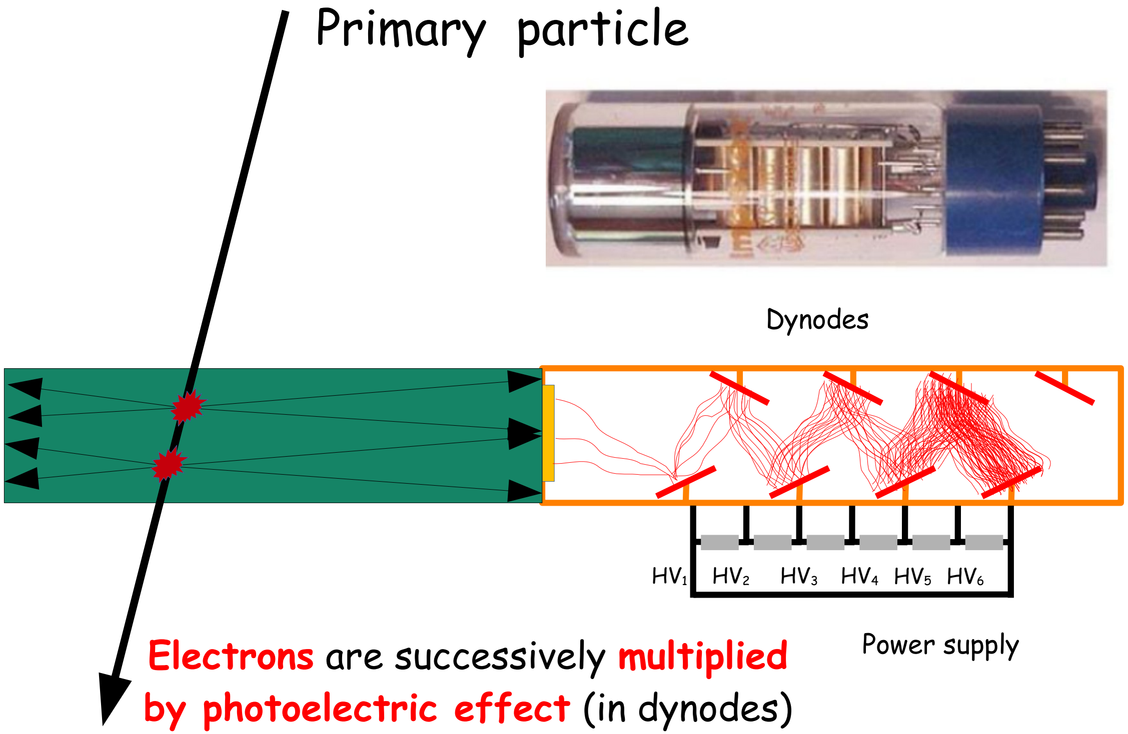


Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**

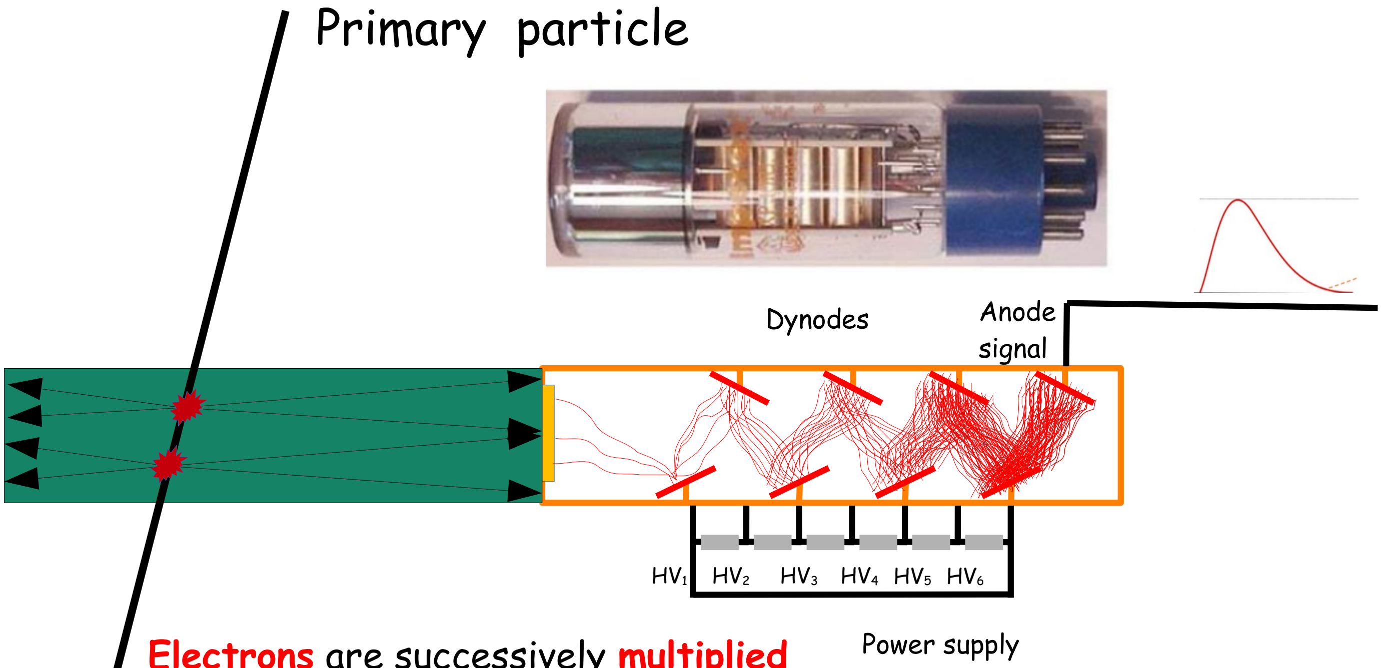
Principles of particle detection. Plastic scintillator + Photo-multiplier.



Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

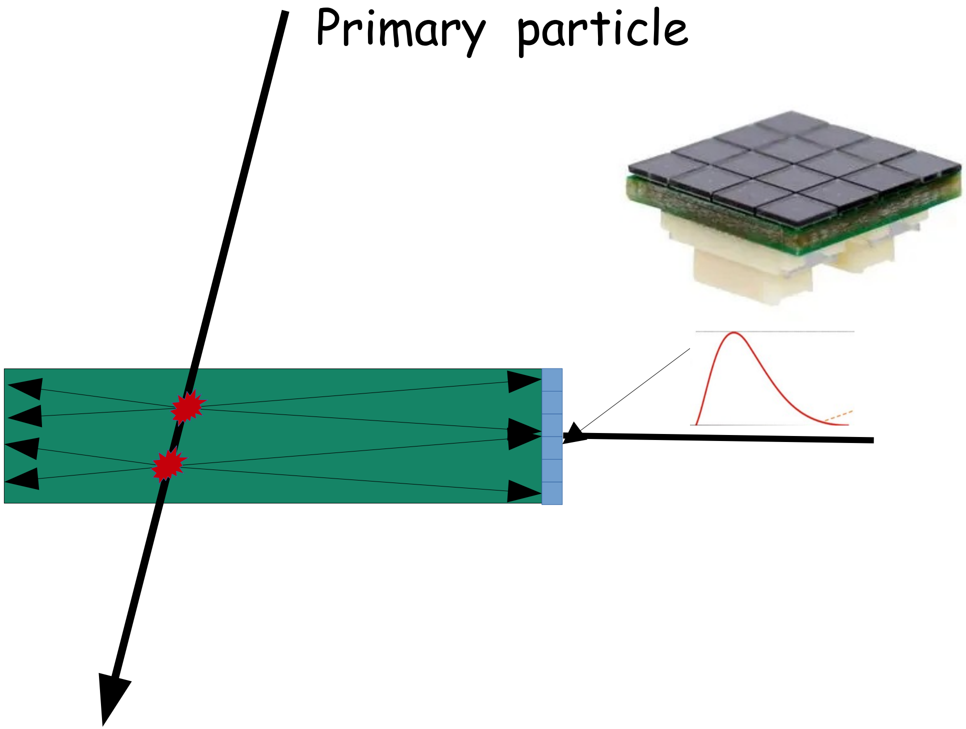
- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**

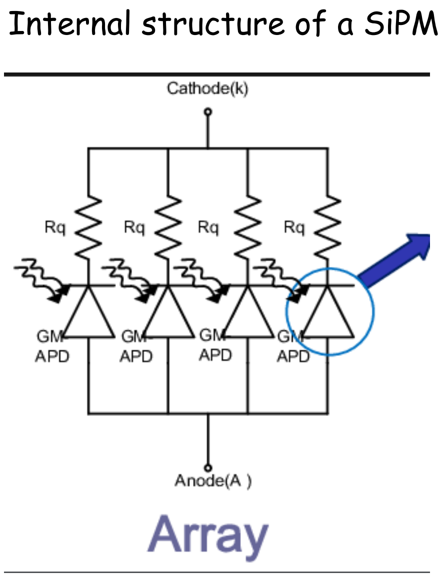


Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**





Amplification mechanism

- Medium = **Solid. Plastic scintillator**
- Primary interaction = **production of photons**
- Amplification = use of **photo-multiplier**

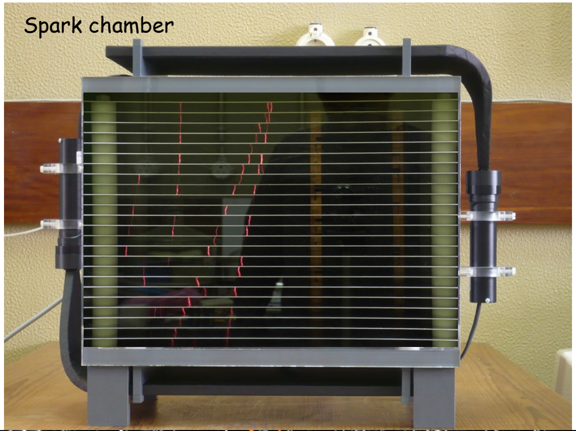
Same performance, cheaper, compact, ….

A particle detector also involves, apart from the detector, the **readout electronics and data acquisition (DAQ)** system.

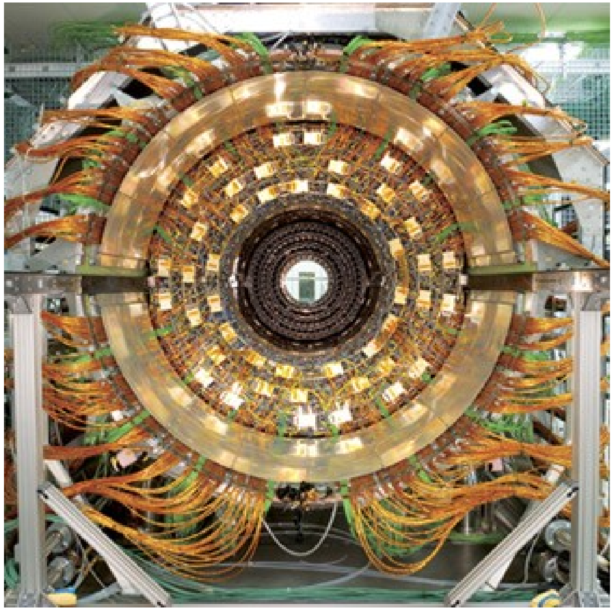
No electronic detector

Electronic detectors

Spark chamber

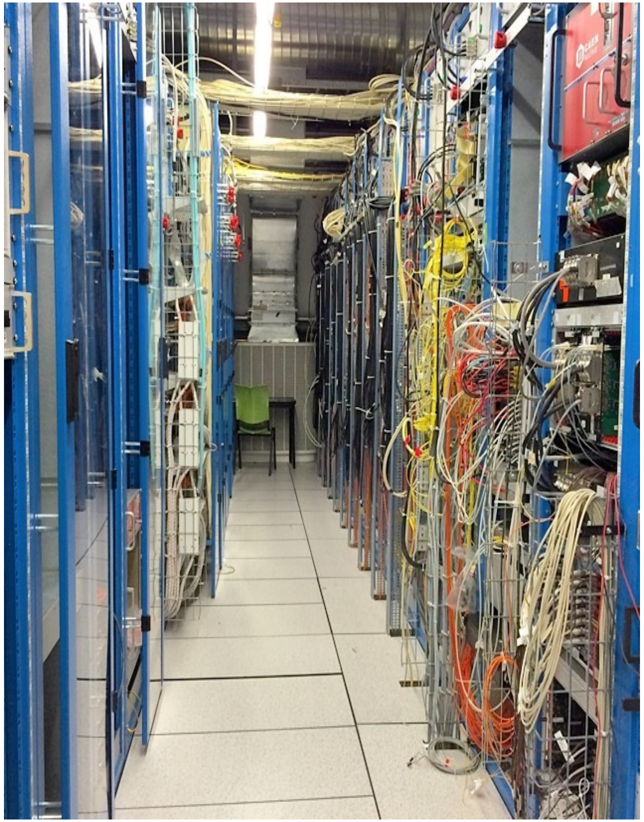


Bubble chamber and blubber chamber photograph



CMS Tracker, CERN

The amount of wiring on the CMS detector at CERN is equivalent to a small village of 10,000 inhabitants

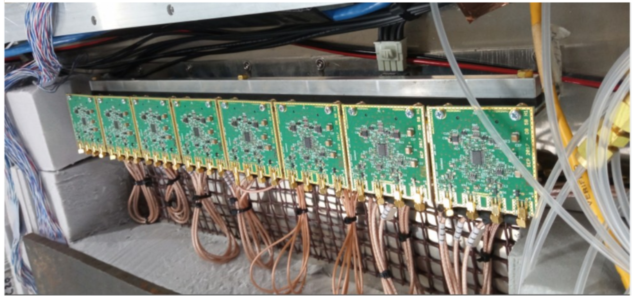


One of the CMS acquisition system room

Front End Electronic (FEE)

In charge to process/manipulate the signals generated by detector.

32 current amplifiers + comparator

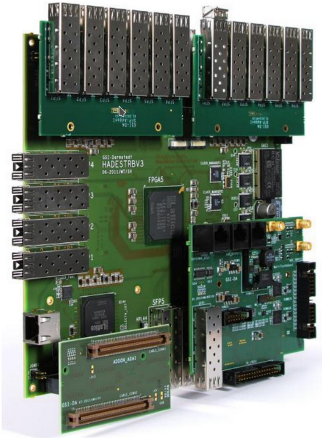


Digitizers

Convert the electric signal into digital words

ADCs, => Analog to Digital Converter

TDCs, => time to Digital Converter



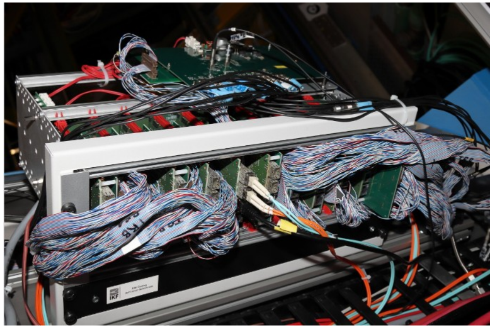
ADC/TDC platform

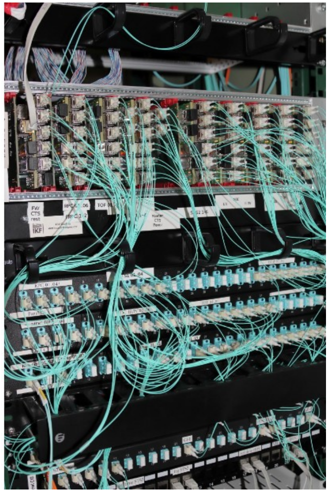
Trigger system

Select interesting particles when it is not possible to measure all of them.

Data Acquisition (DAQ) system

In charge of the government of all components



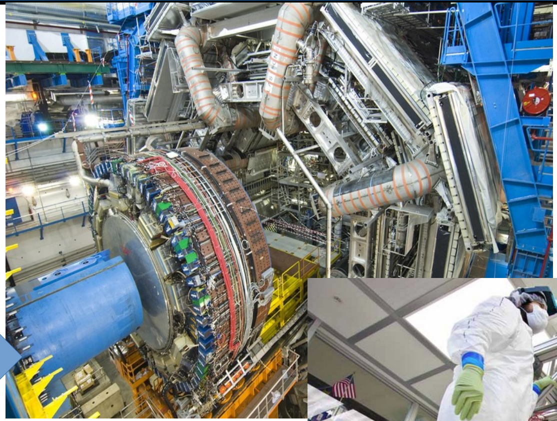


DAQ parts of HADES detector

What are particle detectors used for?

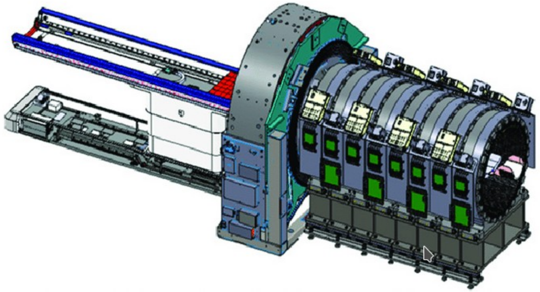
They are fundamentally used in:

- **Nuclear** and **particle physics** and also in **astro-physics** and the **search for dark matter**.
  What are things made of? What goes inside a proton?
  What are neutrinos? What is dark matter?
  How was the universe created?

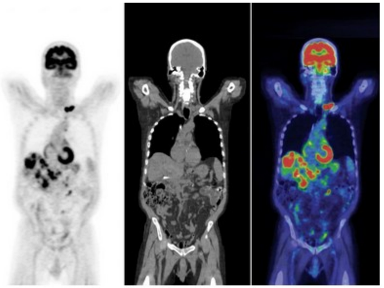


High Energy Particle experiment detector

- **Medical Physics**
  Imaging. X-rays, CT and PET scans.
  Dosimetry (measuring the amount of radiation administered to a patient).

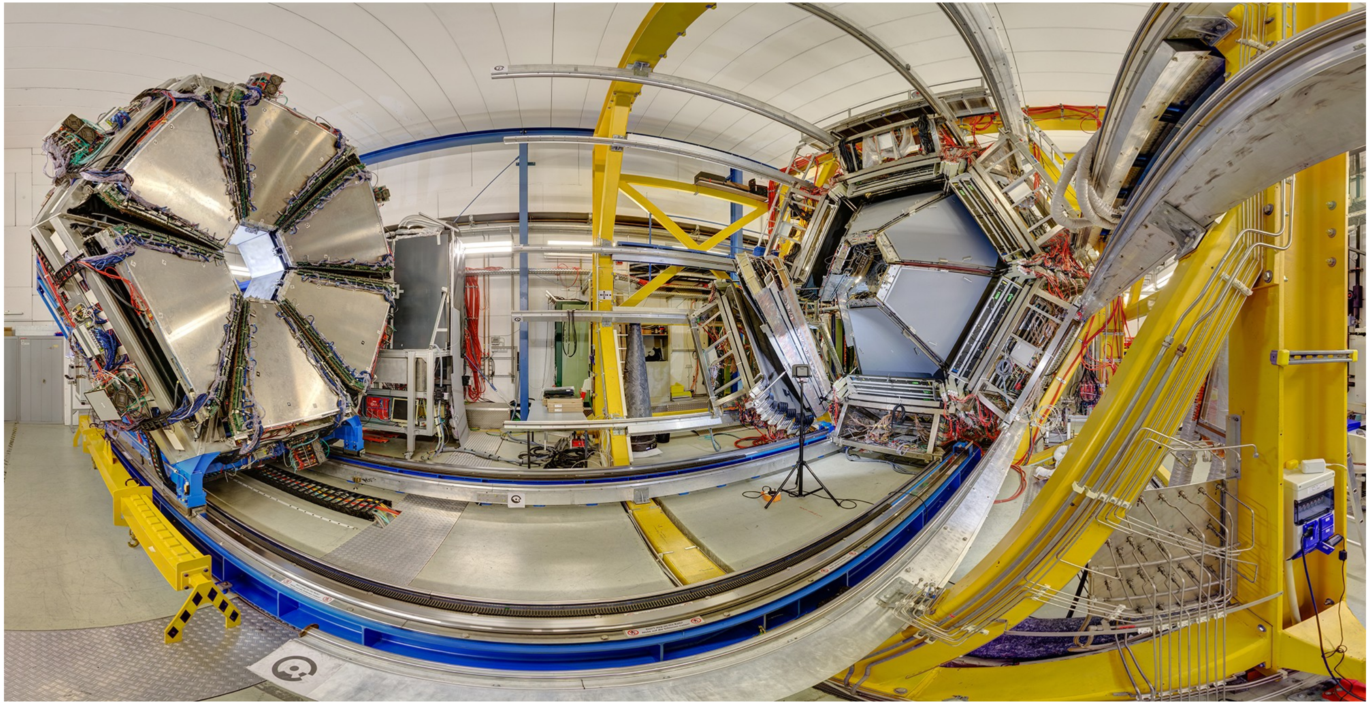


Explorer PET/CT



Study of **"emissivity" and hadron properties in dense and cold nuclear matter**, detected via **e+ e- pairs** (dielectrons) and **strange hadrons**, produced in **proton , pion** and heavy **ion** induced reactions in a **1-3.5 GeV**.

Spectrometer with high invariant mass resolution and high rate capability.
Installed at SIS18, GSI, Darmstadt. http://www-hades.gsi.de/



Project launched in late 1994
6 years R&D and construction

First production run in 2002

International collaboration of 27 institutions from 10 European countries.

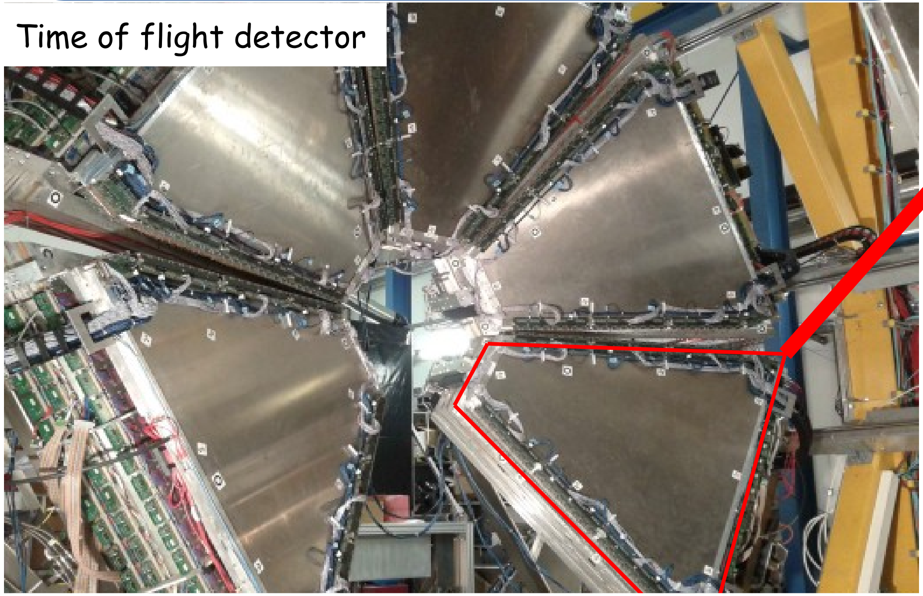
Cyprus, Czech Rep., France, Germany, Italy, Poland, Portugal, Russia, Slovakia, Spain.

Nuclear physics. HADES High Acceptance DiElectron Spectrometer @ GSI, Germany.

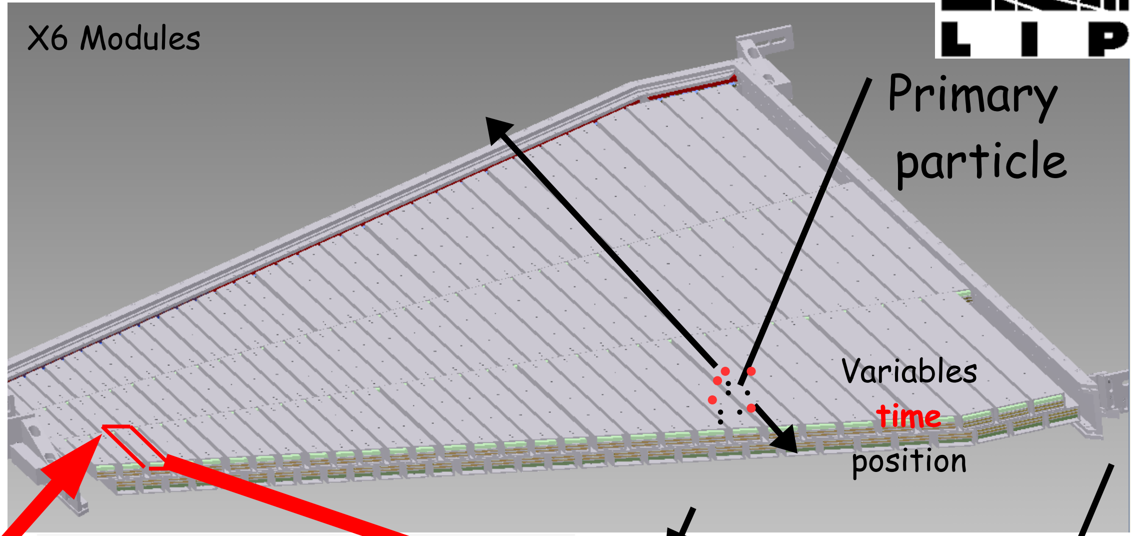
Identification card: HADES RPC-TOF

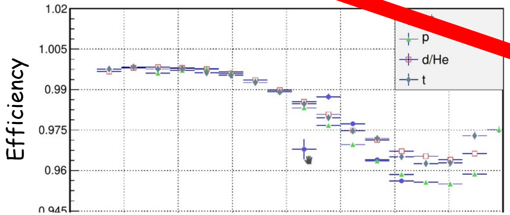
Medium	Gas mixture $C_2H_2F_4 + SF_6$
Primary interaction	Ionization of gas mixture
Amplification	Use of electric fields and strip structures.
Characteristics	**High efficiency > 90 %**, moderate **spatial resolution ~ 1 cm** and extraordinary **timing resolution 60ps**
Readout	x(2400 cells) current amplifiers + discriminator + TDC channels

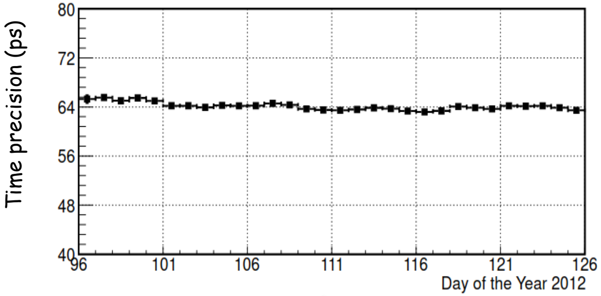
Time of flight detector



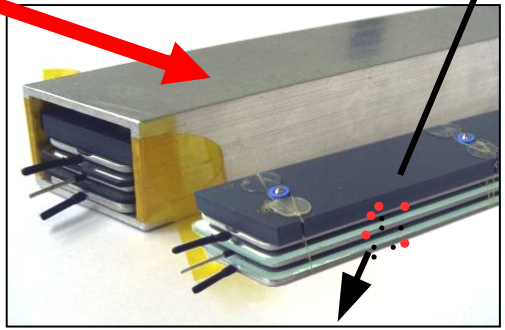
One sector can be visited in Coimbra Detector Laboratory





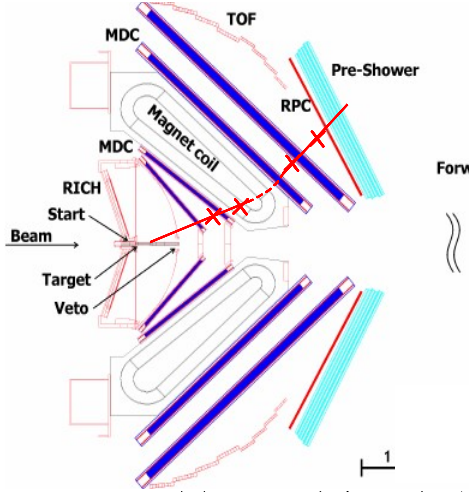


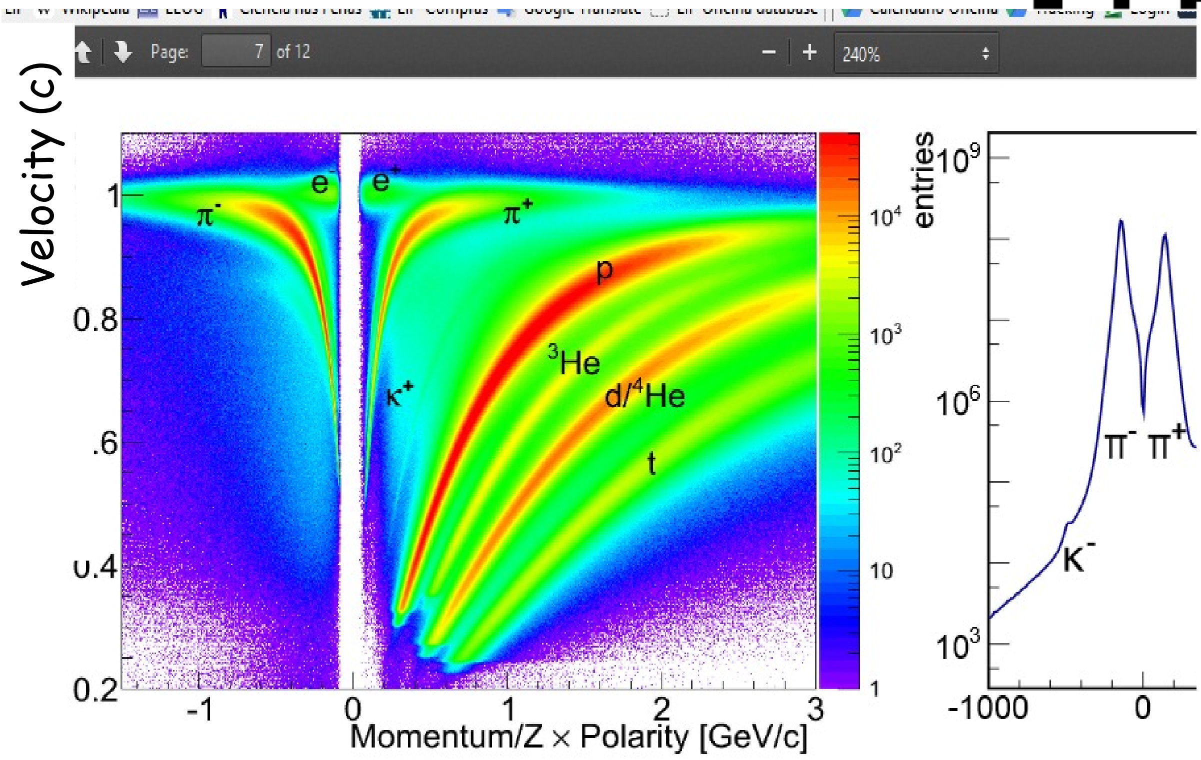
Particle



x1200 Cells

Particle Identification using Time of Flight





Momentum / Z x Polarity (GeV/c)

Tracking: momentum (**p**) & track length determination (**L**)

TOF: time-of-flight **t** measurement

$$t = \frac{L}{v} = \frac{L}{\beta c} = \frac{LE}{pc^2};\; E = \sqrt{p^2c^2 + m^2c^4}$$

$$t = L\frac{\sqrt{p^2c^2 + (m_0c^2)^2}}{pc^2} = \frac{L}{c}\sqrt{1 + \frac{m_0^2c^2}{p^2}}$$

Mass of particle:

$$m_0c^2 = pc\sqrt{\frac{t^2c^2}{L} - 1}$$

=> mass

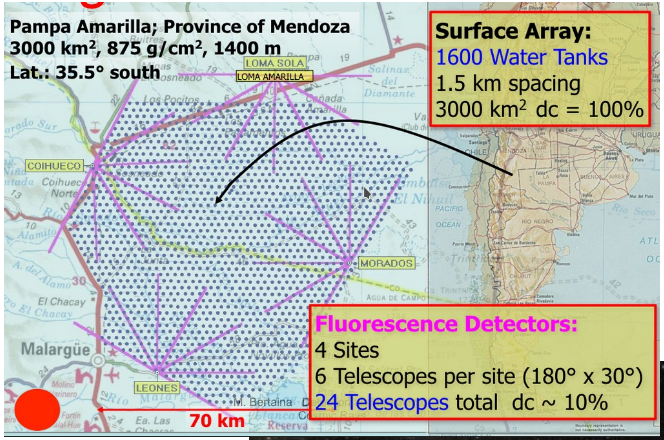
Particles separation power:

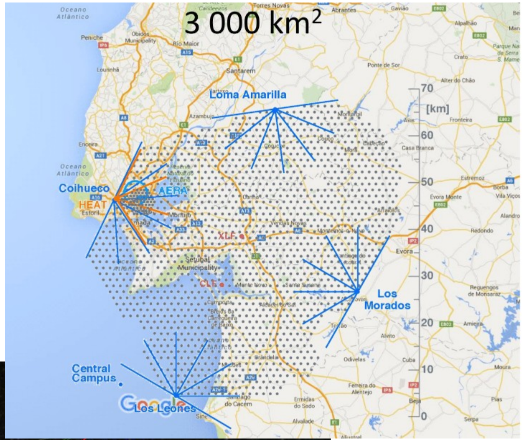
$$N_\sigma = \frac{\Delta t}{\sigma_{TOF}} = \frac{L}{c\sigma_{TOF}}\left(\sqrt{1 + \frac{m_1^2c^2}{p^2}} - \sqrt{1 + \frac{m_2^2c^2}{p^2}}\right)$$

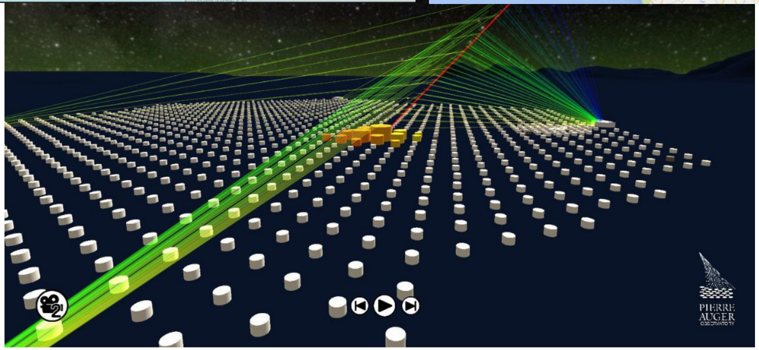
where is σ_{TOF} – time resolution of the TOF system.

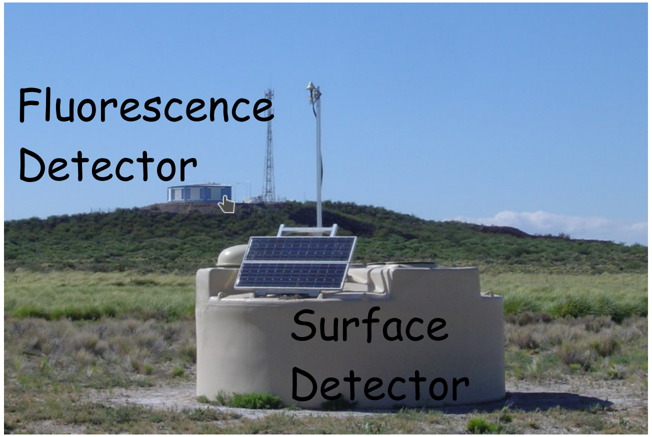
Study and **determine the origin and identity of the high energy cosmic rays**

Hybrid detector composed by a **surface detector** (x1600 units 3000 km², the size of Luxembourg) and x4 **fluorescence detector** installed in Pampa Argentina.









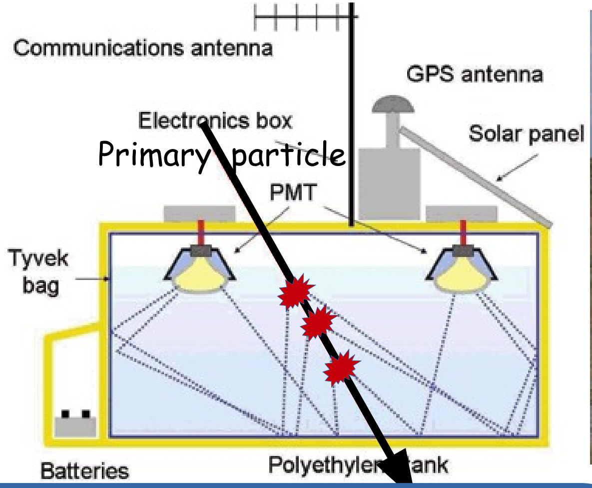
Construction started in 2000, taking data since 2005.

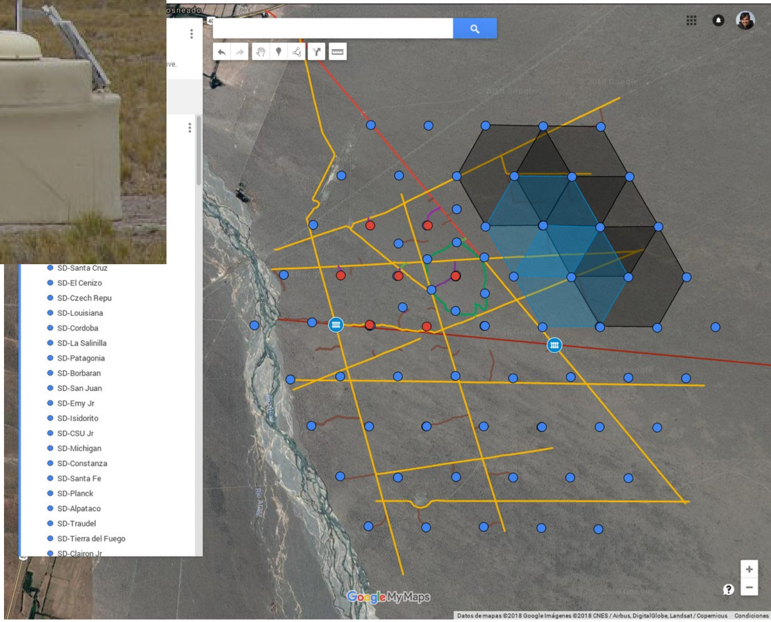
Collaboration of more than 500 physicists and 100 institutions

Study and **determine the origin and identity of the high energy cosmic rays**

Hybrid detector composed by a **surface detector** (x1600 units 3000 km², the size of Luxembourg) and x4 **fluorescence detector** installed in Pampa Argentina.

Variable: **energy** (number of particles)



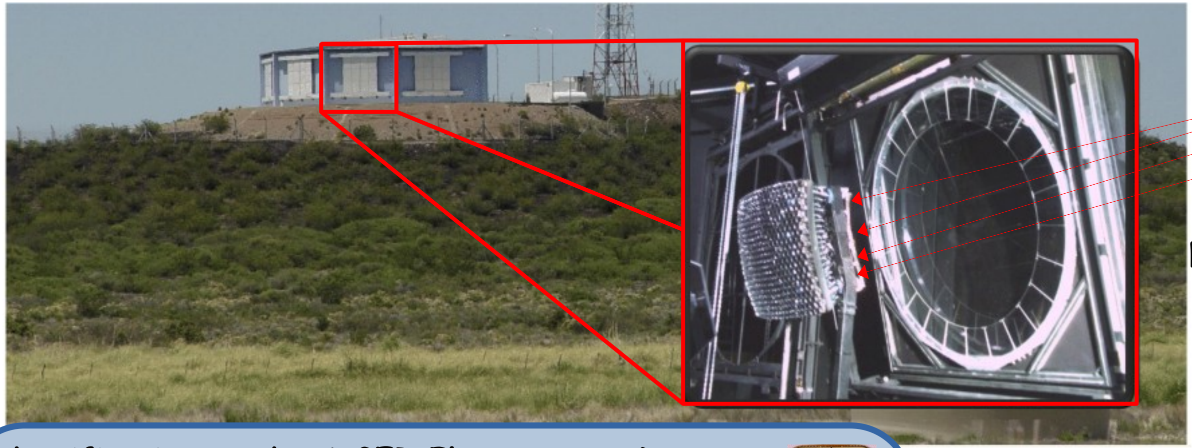


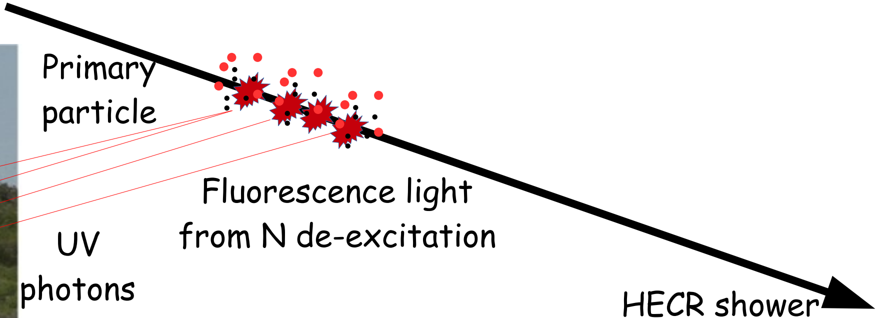
Identification card: AUGER surface detector

Medium	**Liquid. Purified water**
Primary interaction	**Cherenkov light emission**
Amplification	**Photo-multiplier tube (PMT)**
Characteristics	High efficiency, easy, simple to maintain, require little electronics
Readout	x(1600 tanks) x3 channels + digitizer

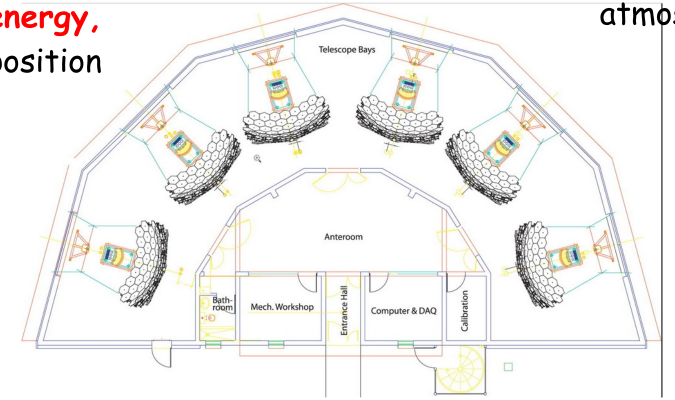
Study and **determine the origin and identity of the high energy cosmic rays**

Hybrid detector composed by a **surface detector** (x1600 units 3000 km², the size of Luxembourg) and x4 **fluorescence detector** installed in Pampa Argentina.





Variables:
energy,
position

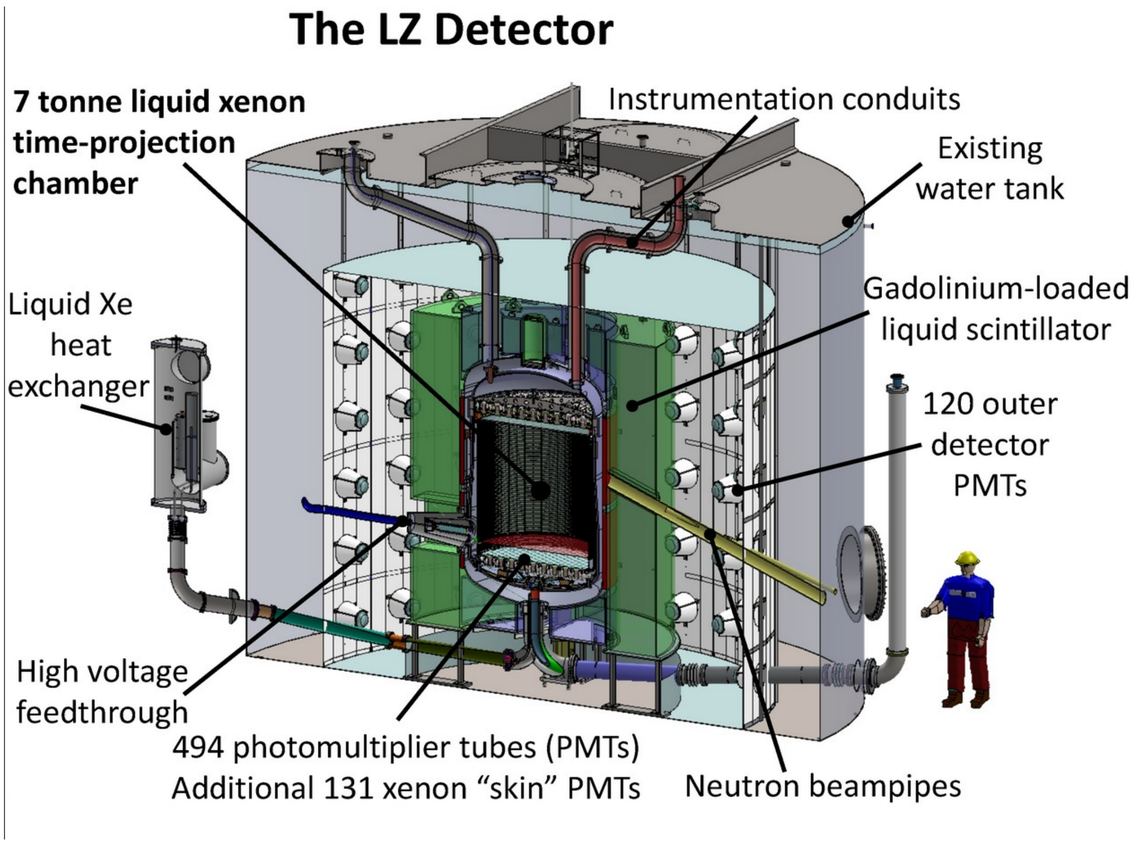


x6 stations in one fluorescence detector

Identification card: AUGER Fluorescence Detector

Medium	**Gas. Atmosphere**
Primary interaction	**Ionization/excitation + photon (UV) emission**
Amplification	**Photo-multiplier tube (PMT)**
Characteristics	Good energy response
Readout	x6 stations x4 detectors x 440 channels + digitizer

Is a **Weakly Interacting Massive Particle** (WIMP) **dark matter** candidate **detector**.

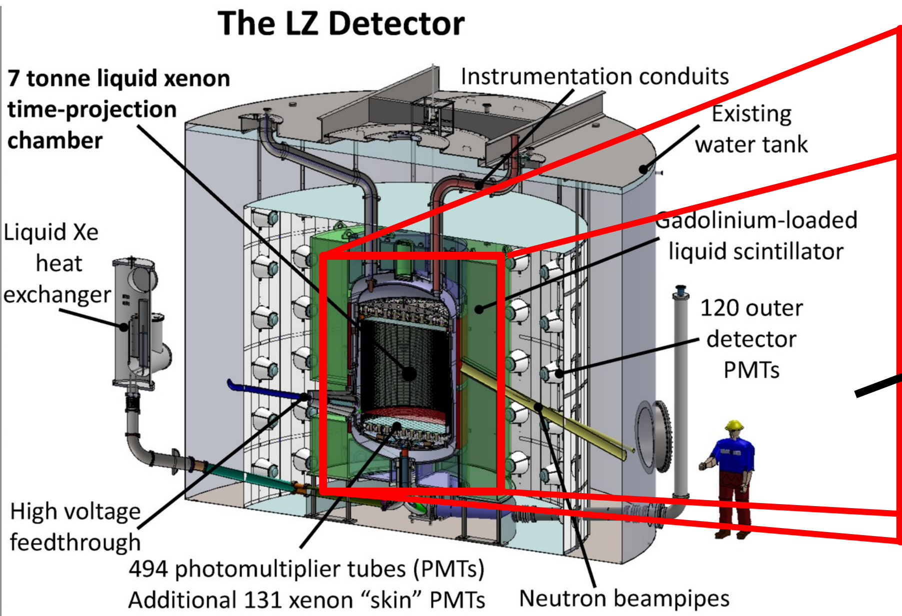


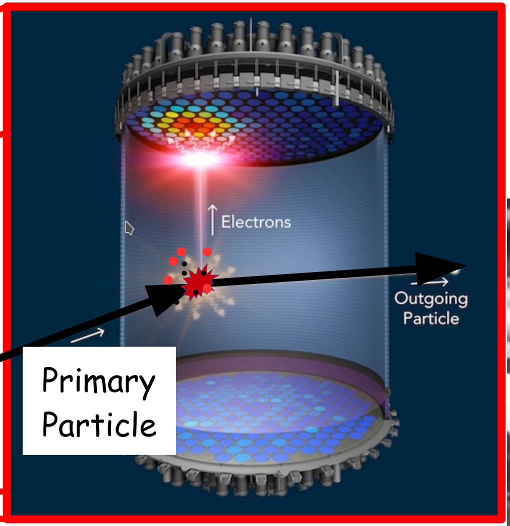
Utilizes 7 tonnes of active **liquid xenon** in a **2-phase (liquid/gas) xenon time projection chamber** (TPC) surrounded by active veto detectors (background minimization).

Construction started in 2020, first results expected in 2022.

Collaboration of more than 250 scientists and 35 institutions in UK, USA, Portugal and Korea.

2-phase (liquid/gas) xenon time projection chamber (TPC)





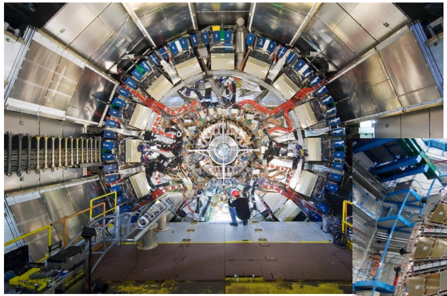
WIMP (dark matter) will create a specific signature in the detector

Variables:
position
time
energy

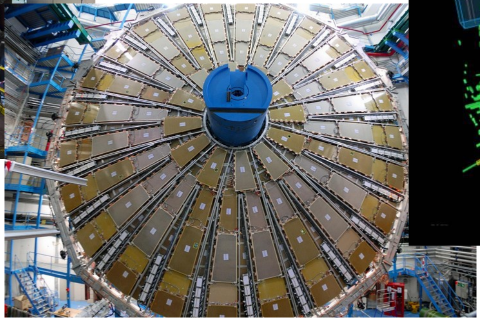
Identification card: LZ

Medium	**Liquid. Xenon.**
Primary interaction	**Nuclear recoil => ionization/excitation + photon emission**
Amplification	**Photo-multipliers tube (PMT)**
Characteristics	Good energy resolution, Robust and low cost.
Readout	**494 + 131 + 120 (veto) channels + digitizer**

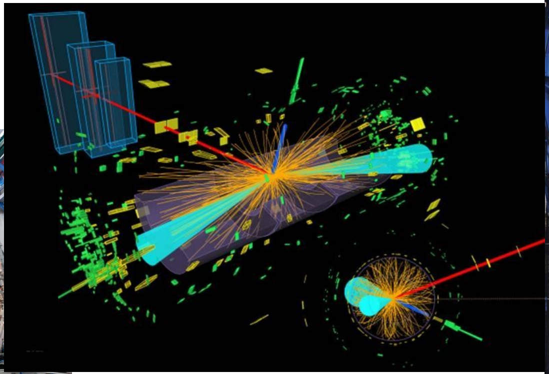
Its purpose is to **detect the Higgs boson and super-symmetric particles (SUSY)** that are predicted by theory but have not yet been detected experimentally and **extensively test the Standard Model.**



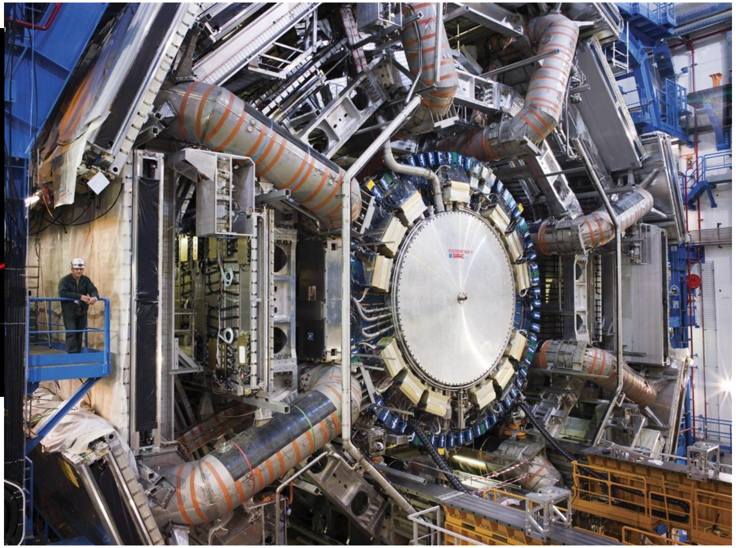
Inner detector



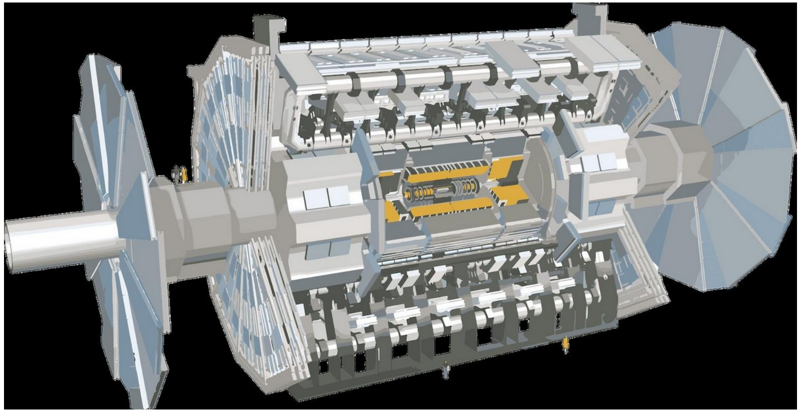
Muon detector



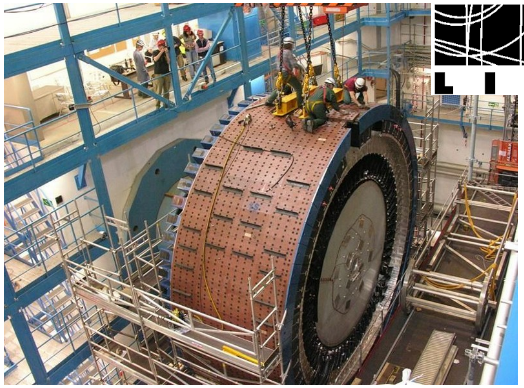
Interaction reconstruction



ATLAS detector open during technical stop



ATLAS technical design



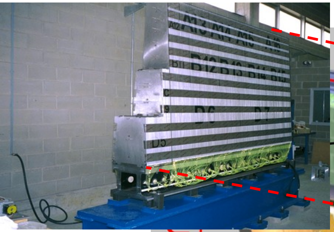
Tile Calorimeter

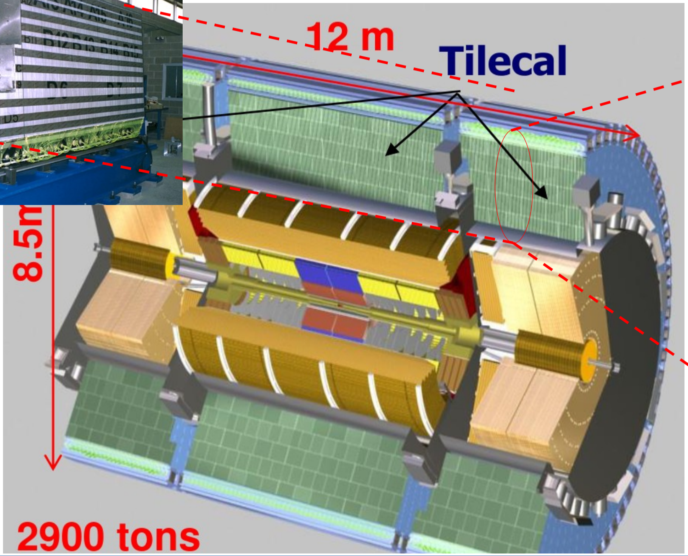
Construction completed in 2008

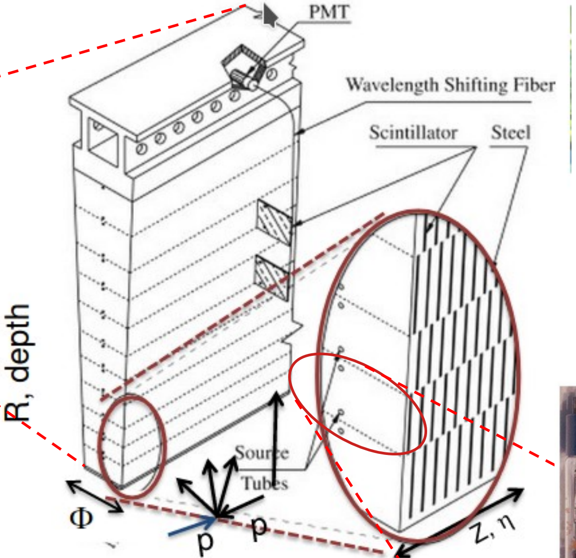
Collaboration of more than 3800 physicists from 257 institutions and 42 countries

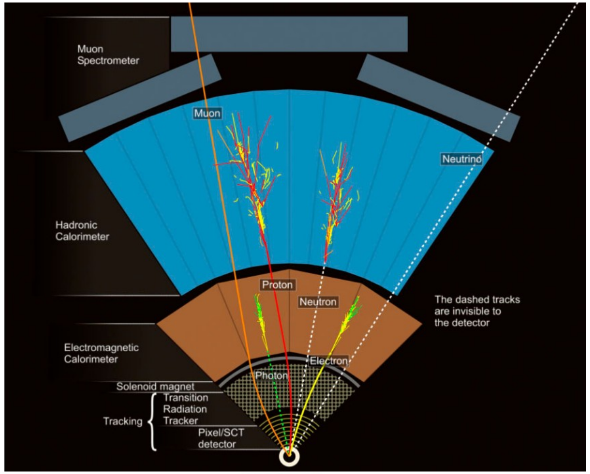
Its purpose is to **detect the Higgs boson and supersymmetric particles (SUSY)** that are predicted by theory but have not yet been detected experimentally and **extensively test the Standard Model**.

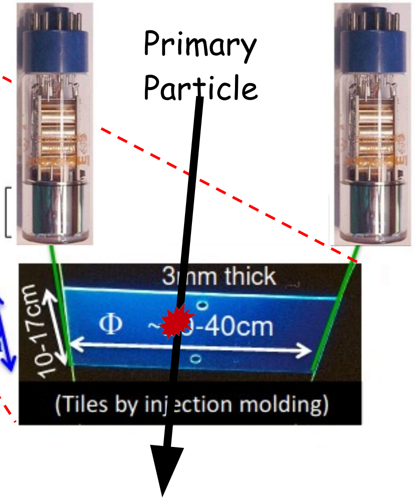
Tile Cal is an hadron calorimeter meant to measure the **energy of hadrons**











Variables:
energy
position
time

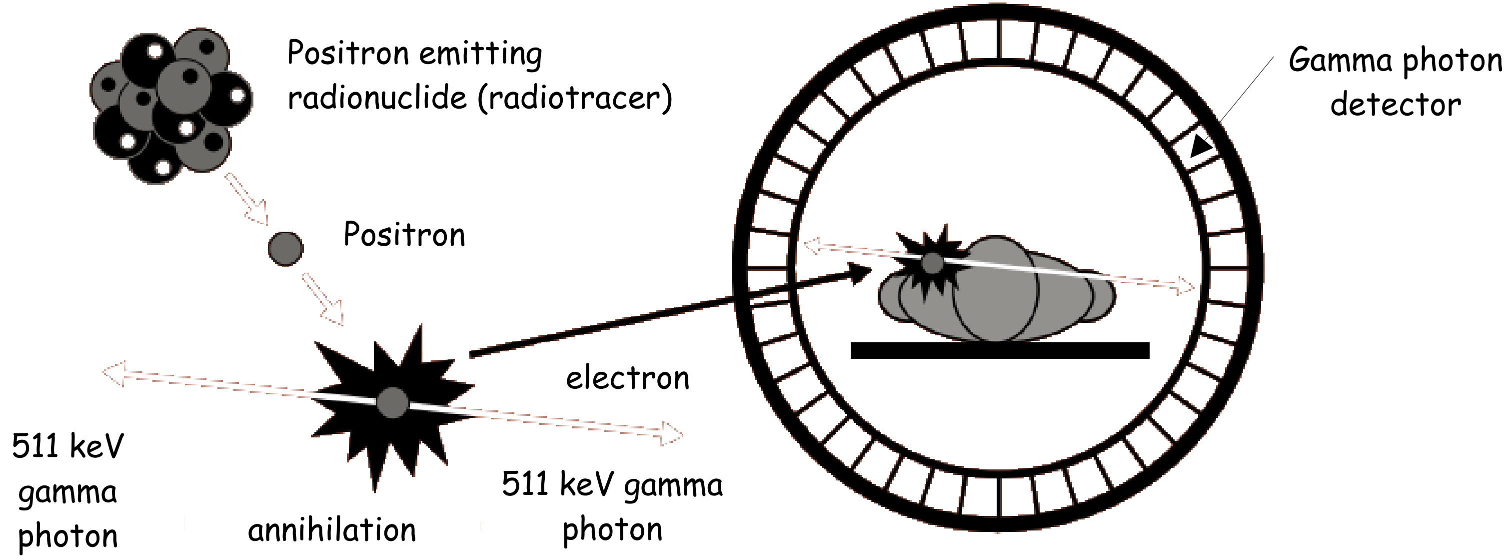
Identification card: ATLAS TileCal

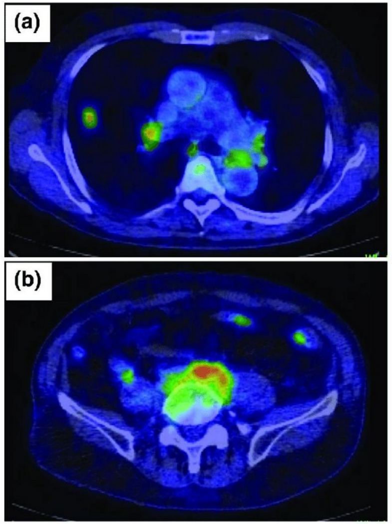
Medium	Solid. Plastic Scintillator
Primary interaction	Ionization/excitation + photo emission
Amplification	Photo-multipliers tube (PMT)
Characteristics	Good energy resolution, Robust and low cost.
Readout	x(10000) channels + digitizer

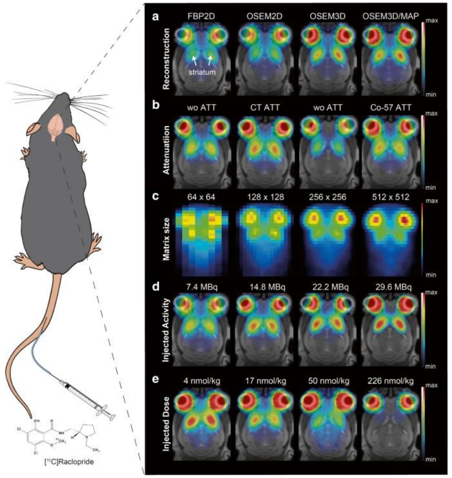
Positron emission tomography (PET) is a **functional imaging technique** that uses radioactive substances known as radiotracers to visualize and measure changes in metabolic processes, and in other physiological activities.

Positron emission
and positron-electron annihilation

PET scanner



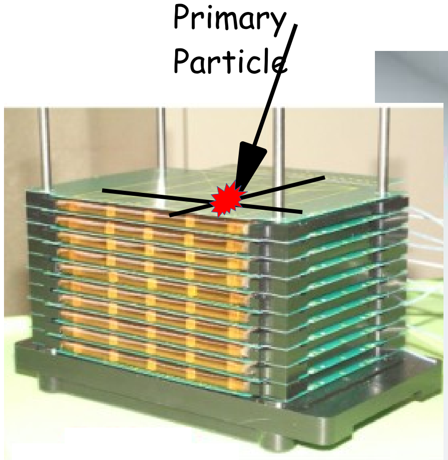




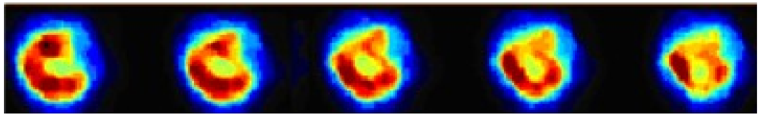
Medical physics. PET with RPC detectors.

Identification card: RPC-PET

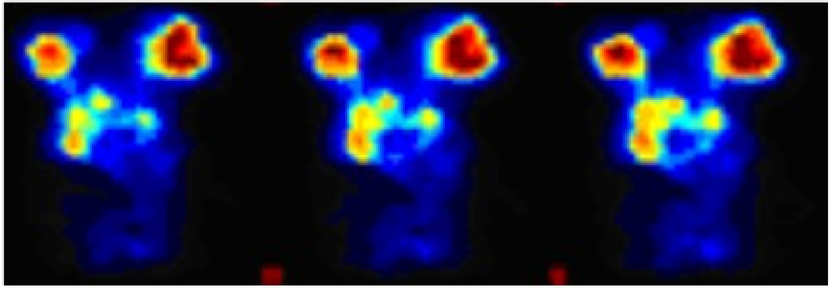
Medium	Gas mixture $C_2H_2F_4$ + SF_6
Primary interaction	Ionization of gas mixture
Amplification	Use of electric fields and strip structures.
Characteristics	Moderate **efficiency,** extraordinary **spatial resolution ~ 0.1 cm** and extraordinary **timing resolution 100ps**
Readout	**x(400) amplifiers + digitizer**



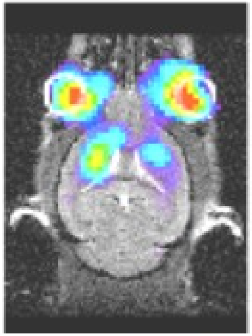
Variables:
position
time



Heart of a mouse. Approximately 10 mm



Head of a mouse



Co-registration with CT

Thank you for your attention !!