Particle detectors @ LIP

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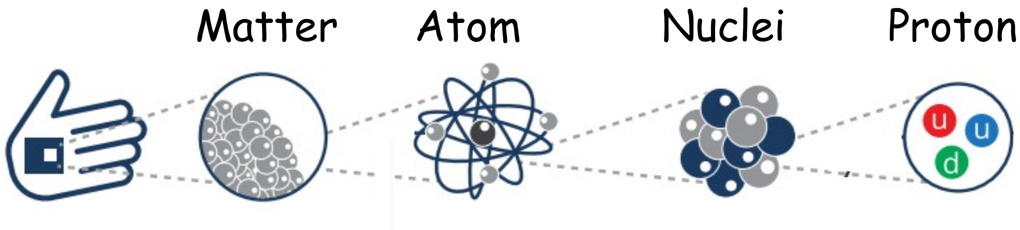
2022 INTERNSHIP PROGRAM

COIMBRA LISBOA MINHO

Outlook

- 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?

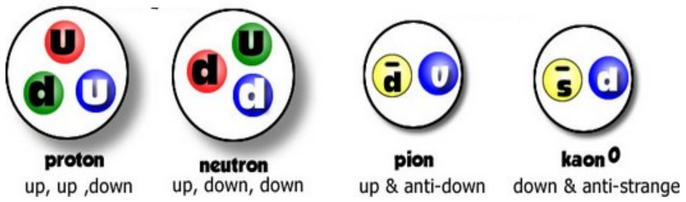


Particles are the fundamental constituents of matter.

	I	II	III	Bosons (Forces)
mass / charge / spin / name	2.4 MeV, ⅔, ½, **u** up	1.27 GeV, ⅔, ½, **c** charm	171.2 GeV, ⅔, ½, **t** top	0, 0, 1, **γ** photon
Quarks	4.8 MeV, -⅓, ½, **d** down	104 MeV, -⅓, ½, **s** strange	4.2 GeV, -⅓, ½, **b** bottom	0, 0, 1, **g** gluon
Leptons	<2.2 eV, 0, ½, ν_e electron neutrino	<0.17 MeV, 0, ½, ν_μ muon neutrino	<15.5 MeV, 0, ½, ν_τ tau neutrino	91.2 GeV, 0, 1, Z^0 weak force
Leptons	0.511 MeV, -1, ½, **e** electron	105.7 MeV, -1, ½, **μ** muon	1.777 GeV, -1, ½, **τ** tau	80.4 GeV, ±1, 1, $W^\pm$ weak force

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

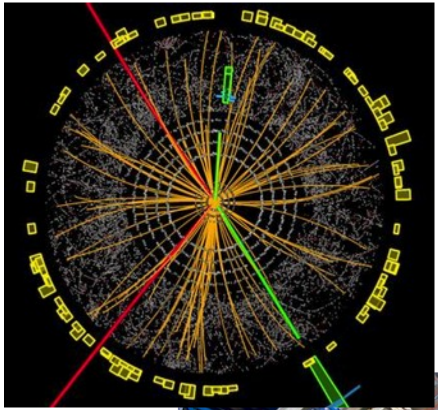
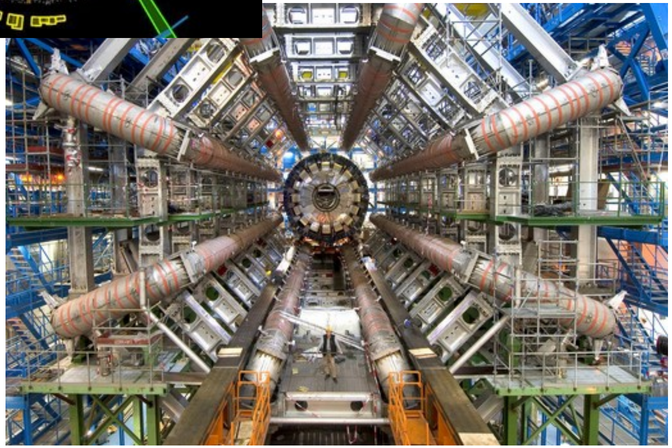


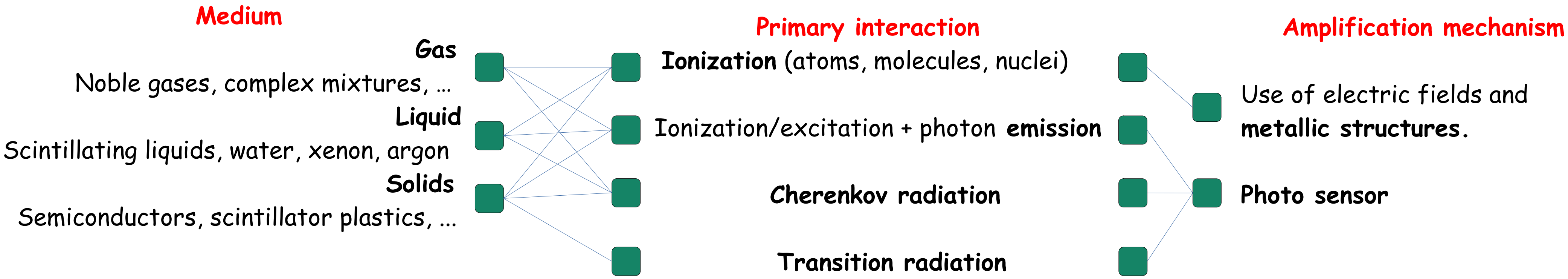
Image of the Higgs Boson

ATLAS measured in 2012 the Higgs boson



ATLAS detector under construction, LHC, CERN.

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.**



Principles of particle detection. Medium.

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 its properties ….. chemical properties, density, photon emission, price, ….

Gases
Noble gases, complex mixtures, ...

Liquids
Scintillating liquids, water, Xenon, Argon,

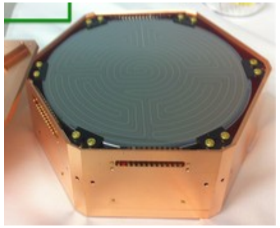

Scintillating liquid

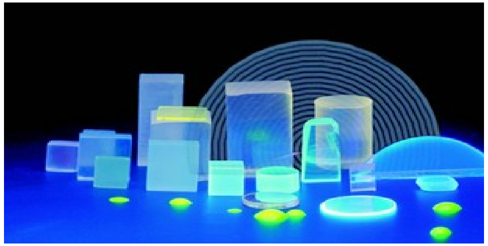

Water tank


Liquid Xenon


Liquid Argon

Solids
Semiconductors, scintillator plastics, ...


Semiconductor detector


Scintillating plastics

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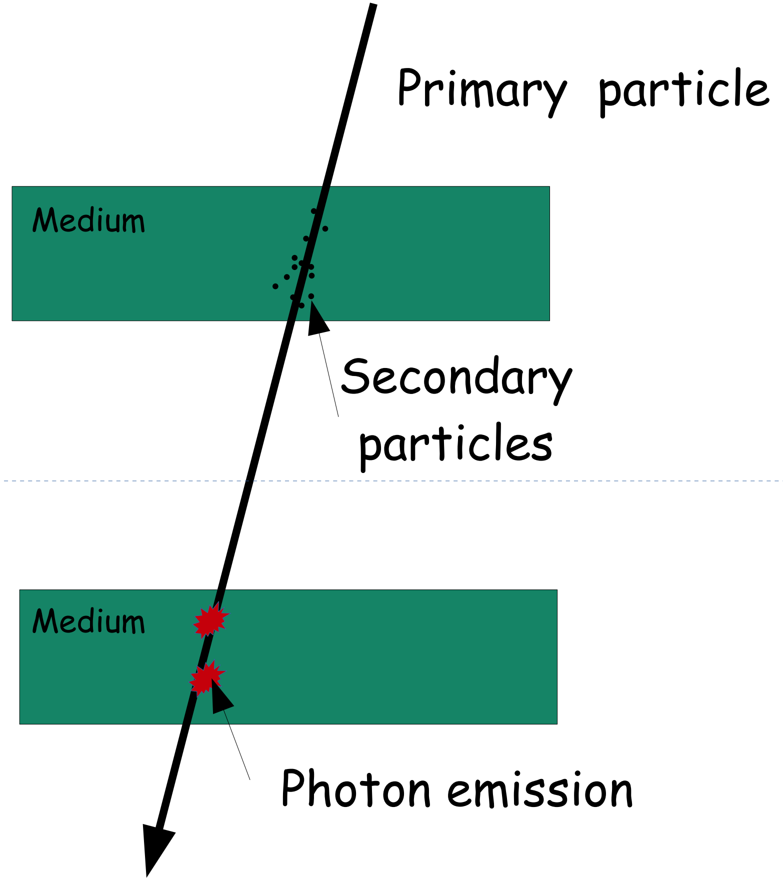
Production of secondary charged particles

Ionization, nuclear reactions, ...

Production of photons

Scintillation, Cherenkov, Transition, ...



Principles of particle detection. Primary interaction. Production of secondary charged particles.

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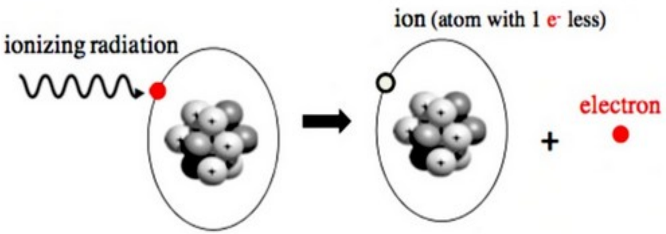
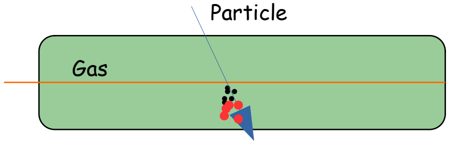
Ionization

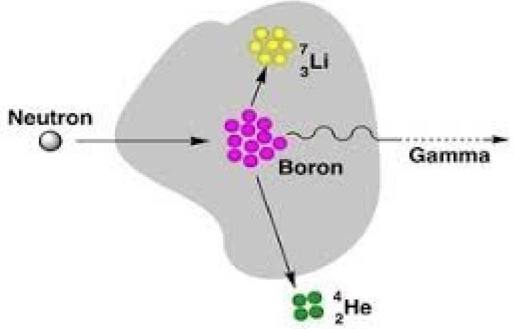


Particle extracts an electron from an atom

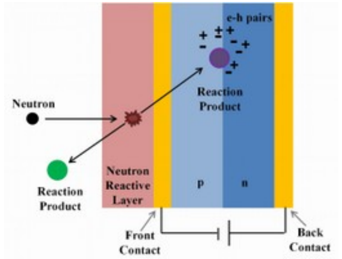


e^{-}/ion pairs creation in a gas filled detector by an incoming particle

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

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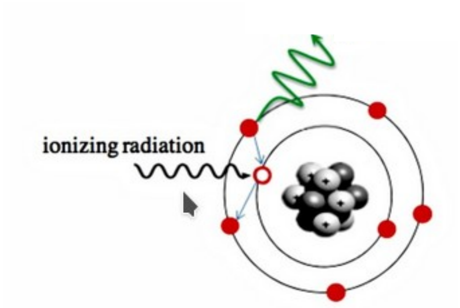
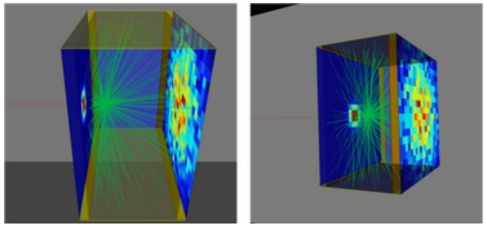
Scintillation

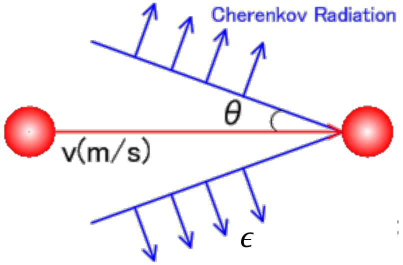


Photon emission from an atom after excitation by an incoming particle



Simulation of photon production in a scintillator

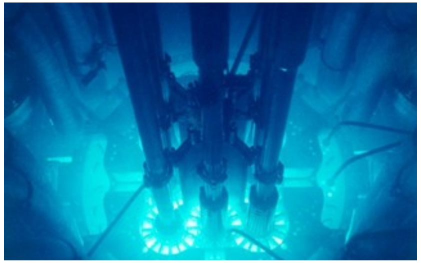
Cherenkov emission



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

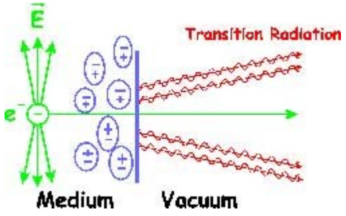
$$\sin(\Theta) = \frac{c}{n_{index} * v_{part}}$$

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



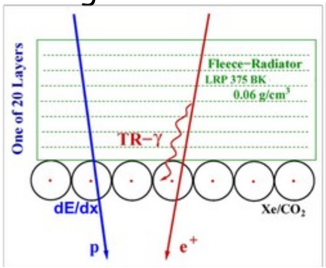
Nuclear reactor emitting Cherenkov light

Transition radiation



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

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



Transition radiation detector schematic

Principles of particle detection. Amplification mechanism.

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

Multiplication of photons using a photo-device.

Electric pulse created by the detector

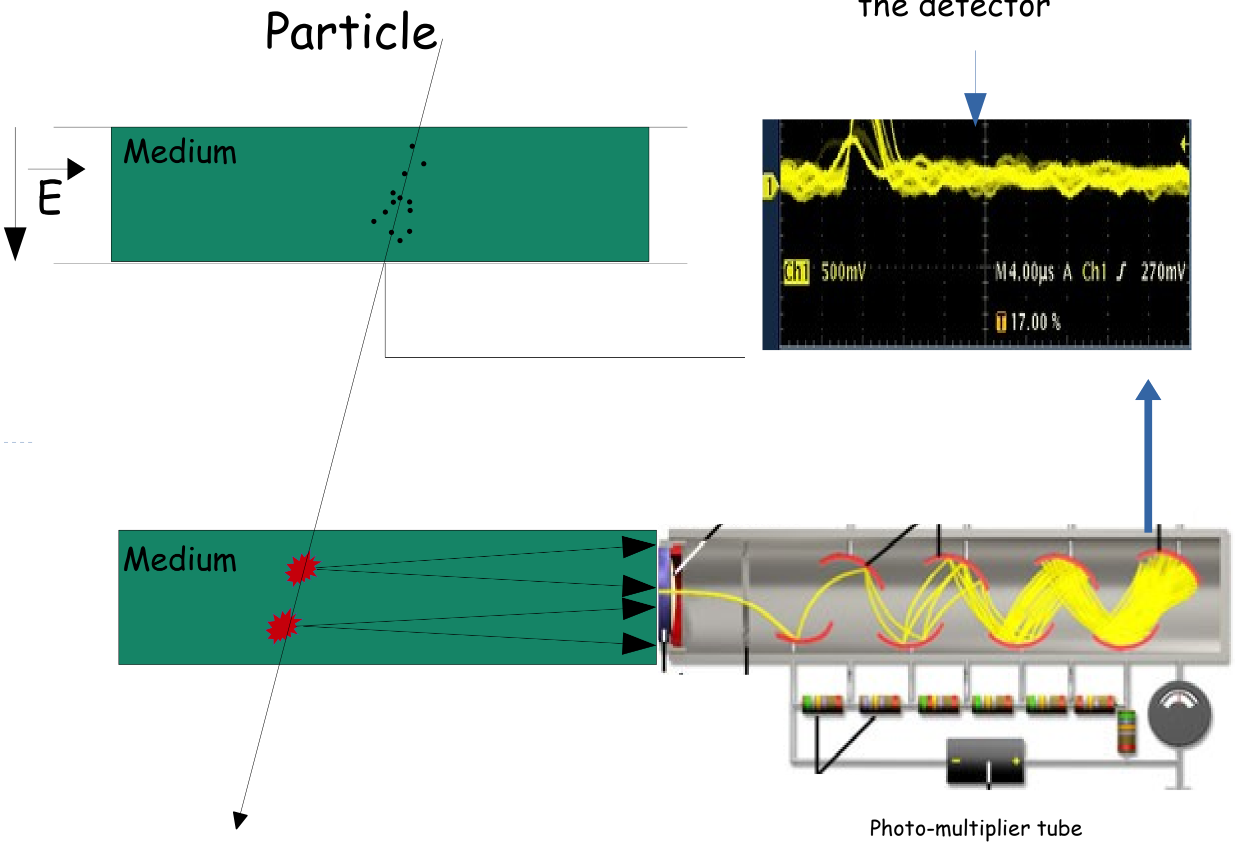


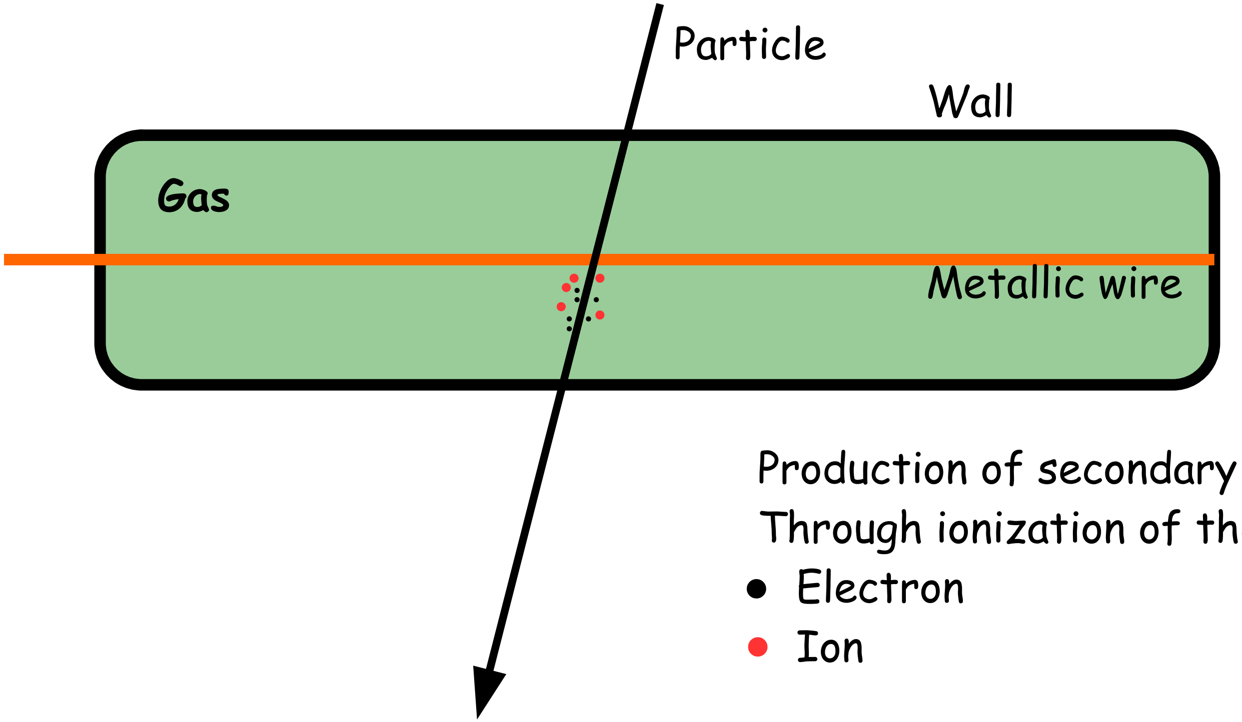
Photo-multiplier tube

Principles of particle detection. Geiger Muller detector

Geiger Muller detector (Cold war version)

Detection medium is a gas

-Medium = gas

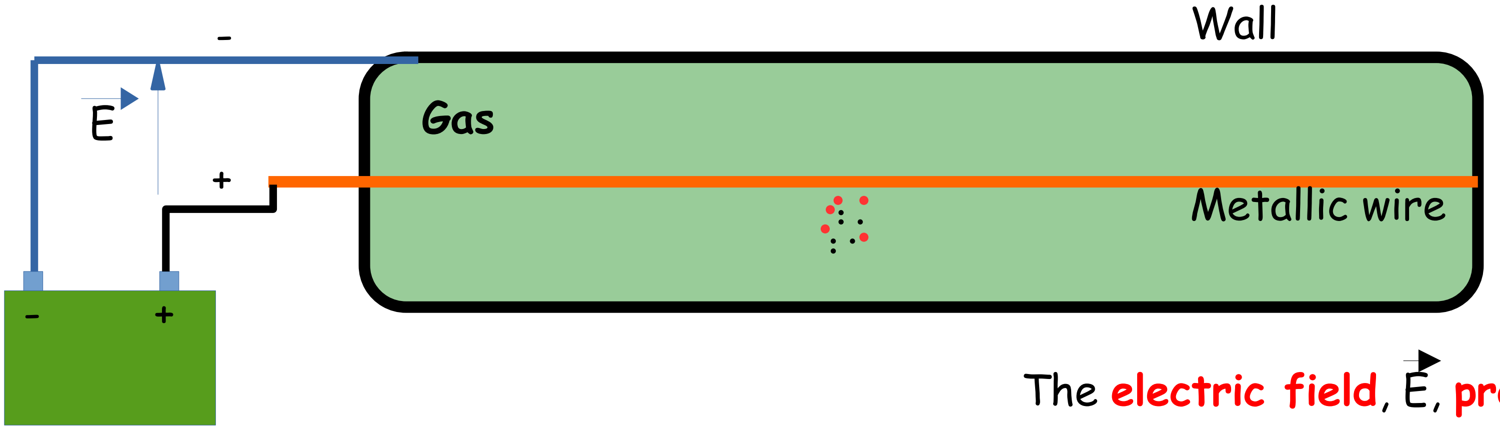


Production of secondary particles
Through ionization of the gas atoms.

- Electron
- Ion

Primary interaction

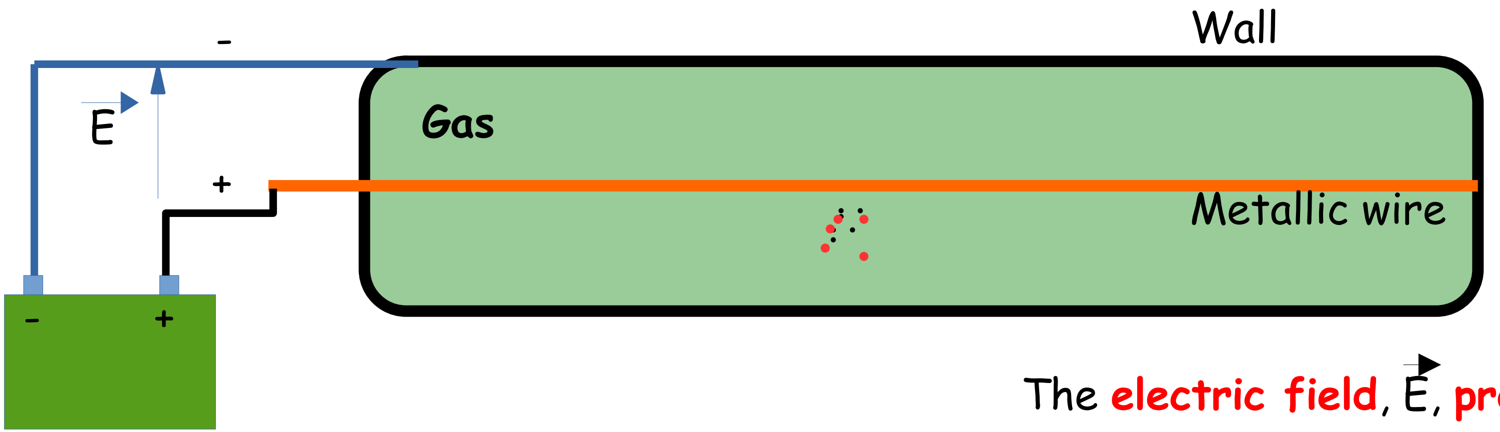
-Medium = gas
-Primary interaction = **production of charged particles**



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
-Primary interaction = **production of charged particles**
-Amplification = use of **electric fields and metallic structures.**



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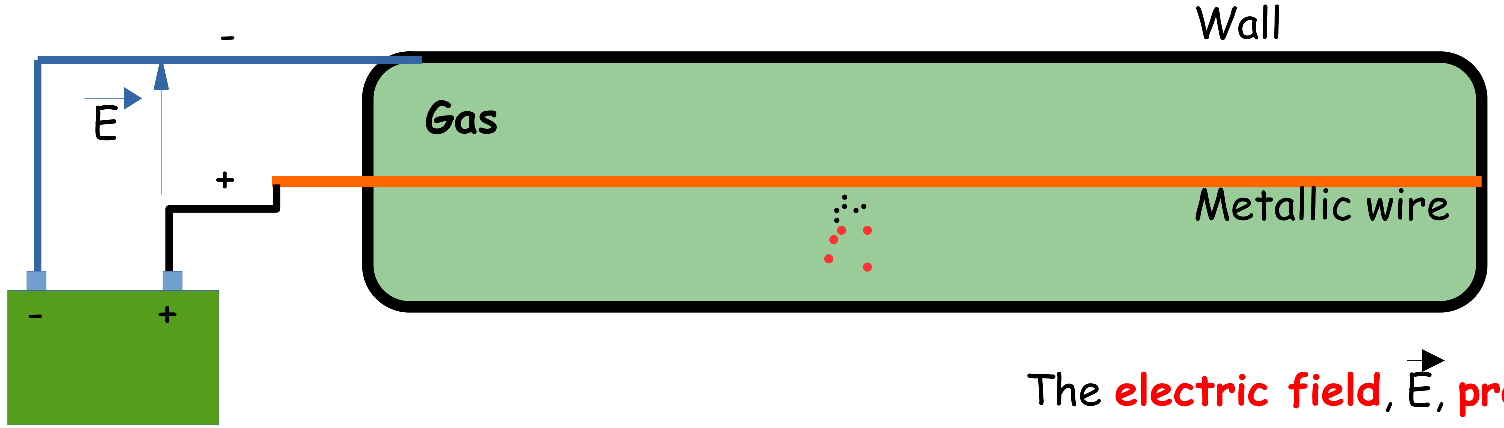

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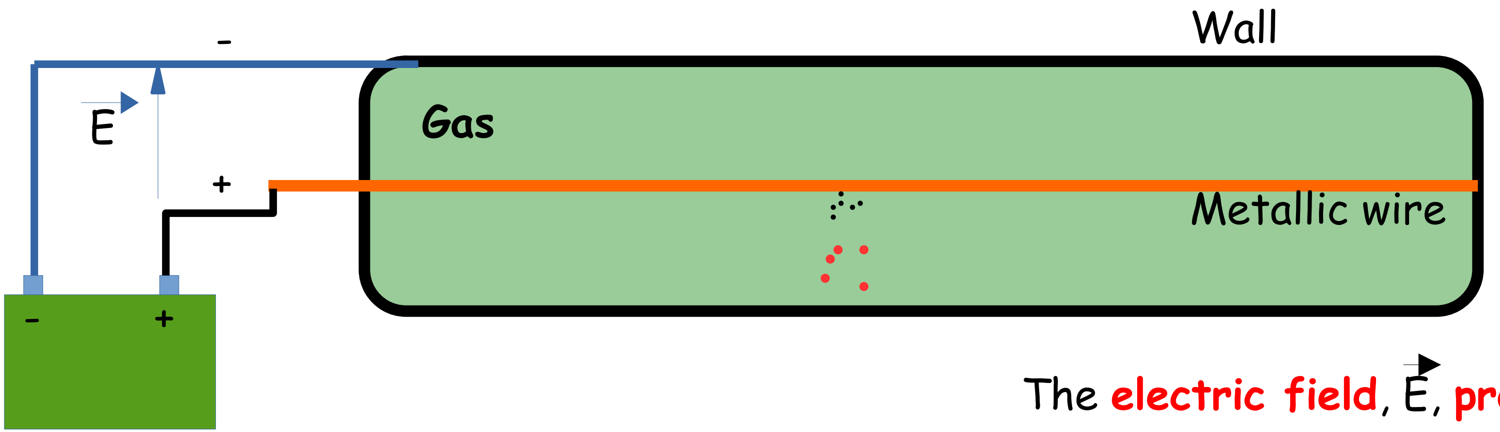

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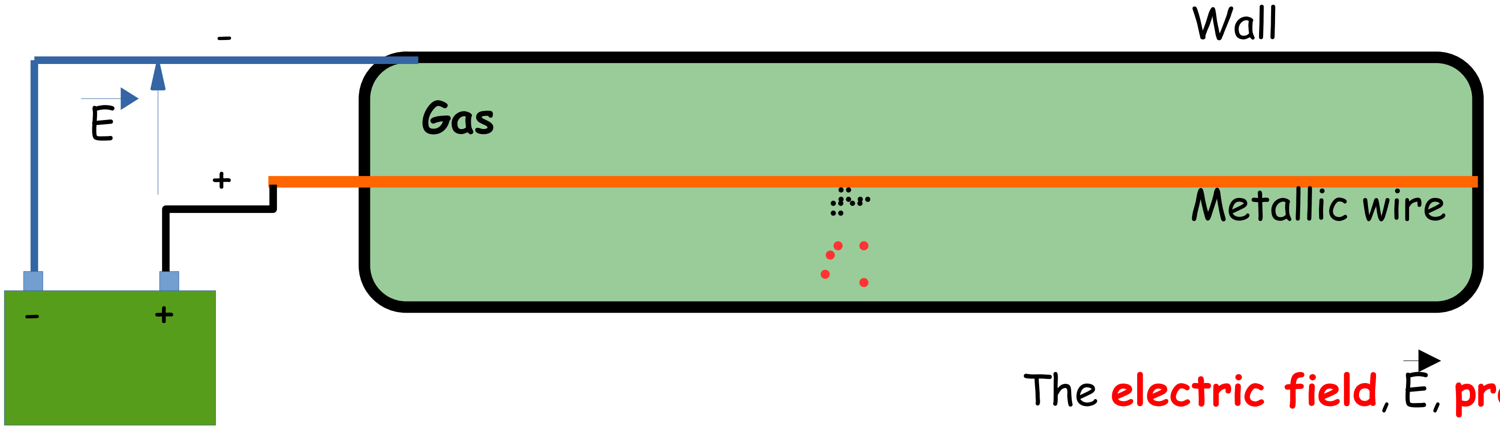

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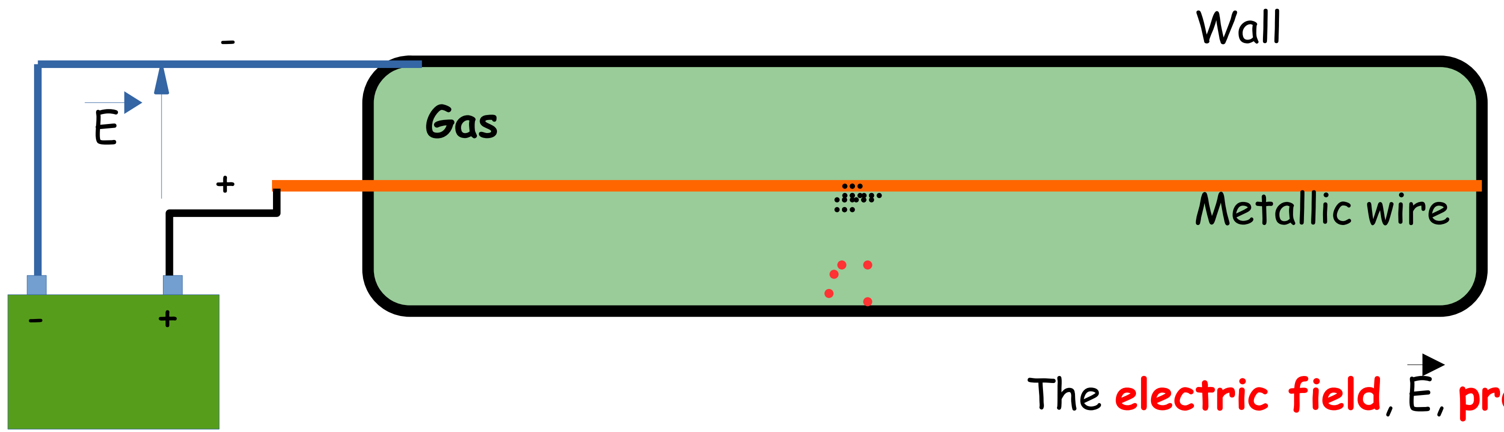

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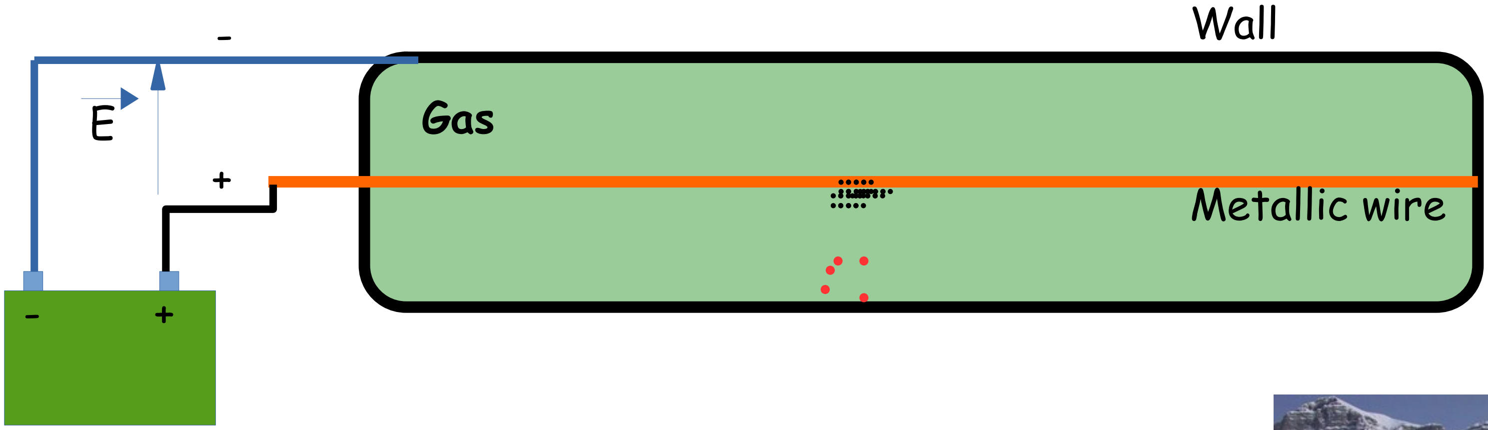
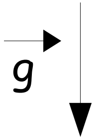
Principles of particle detection. Geiger Muller detector

Avalanche multiplication



Similar phenomenon to snow **avalanches** in the mountains



Snow

Amplification mechanism

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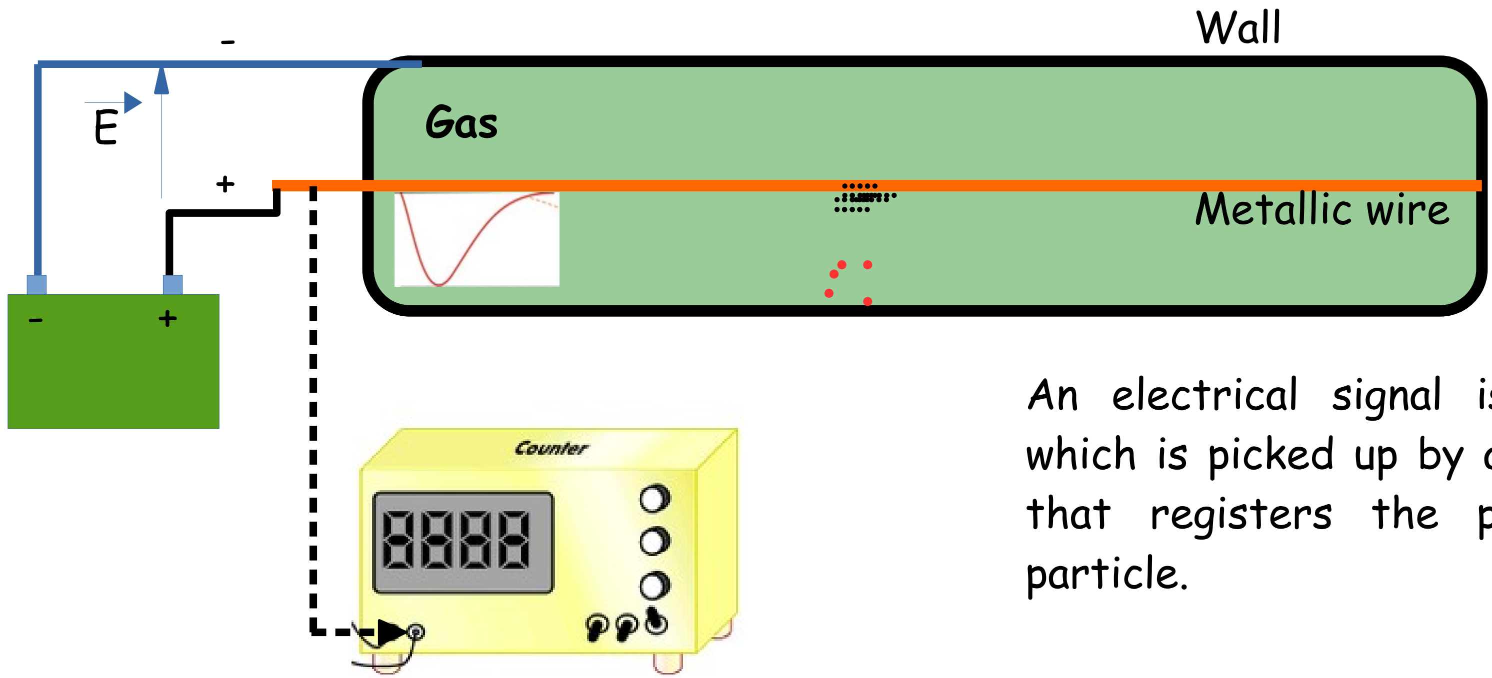

An electrical signal is thus created which is picked up by a electronic unit that registers the passage of the particle.

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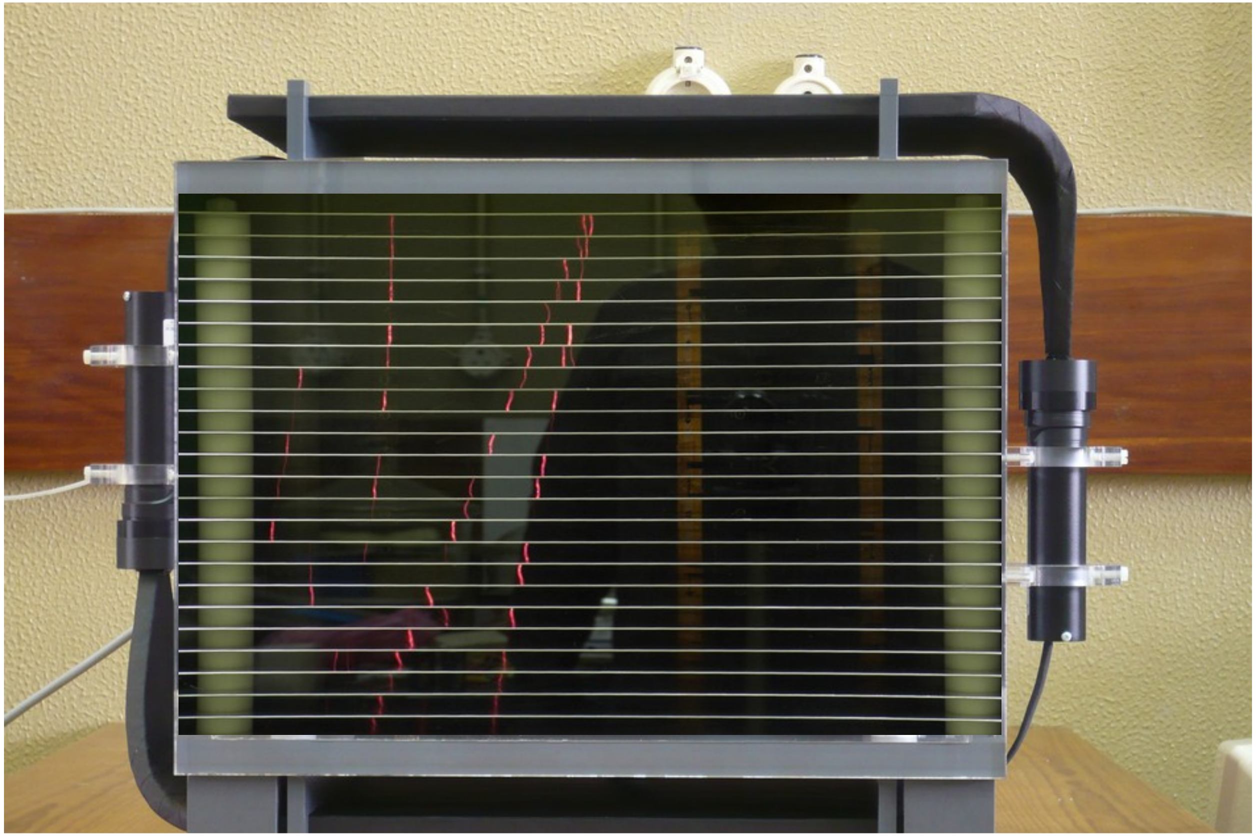
A **spark chamber** is a device that **allows the visualization of the path taken by a particle** (cosmic ray) inside it.



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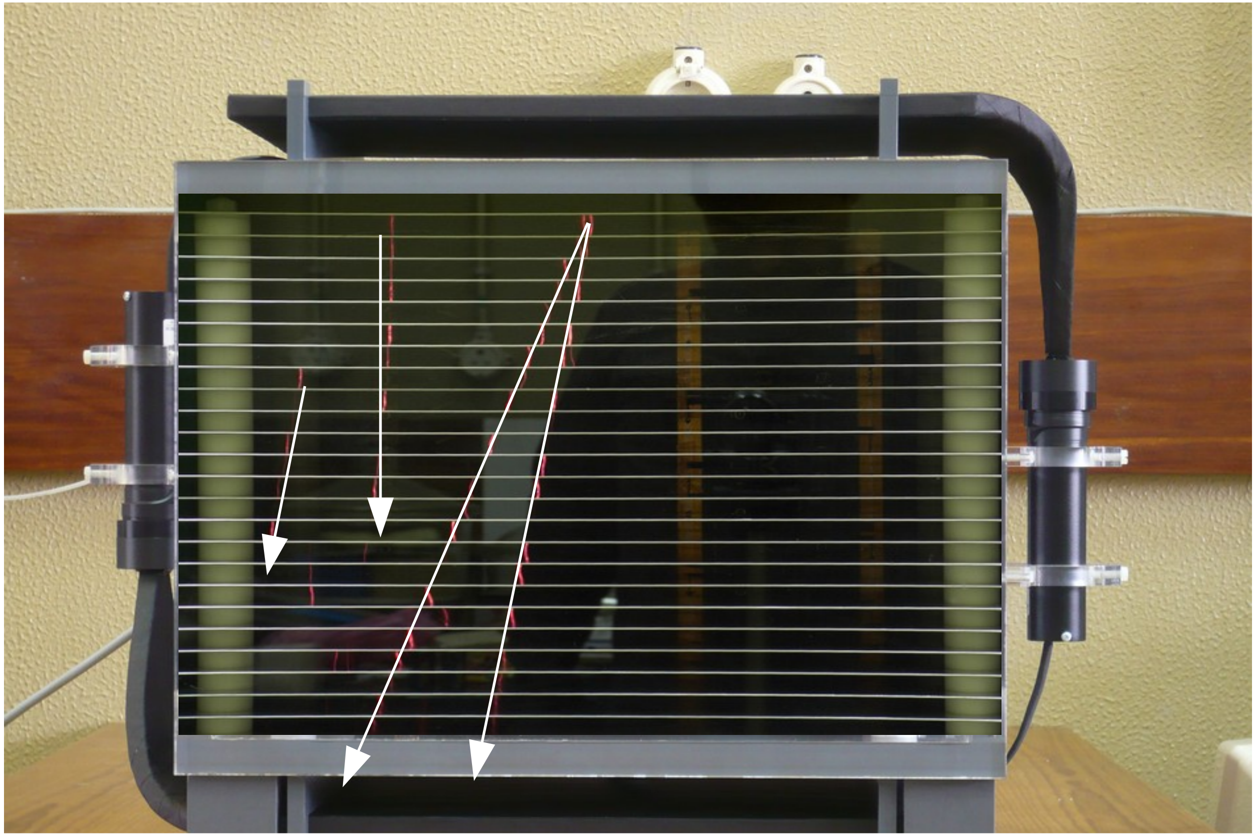

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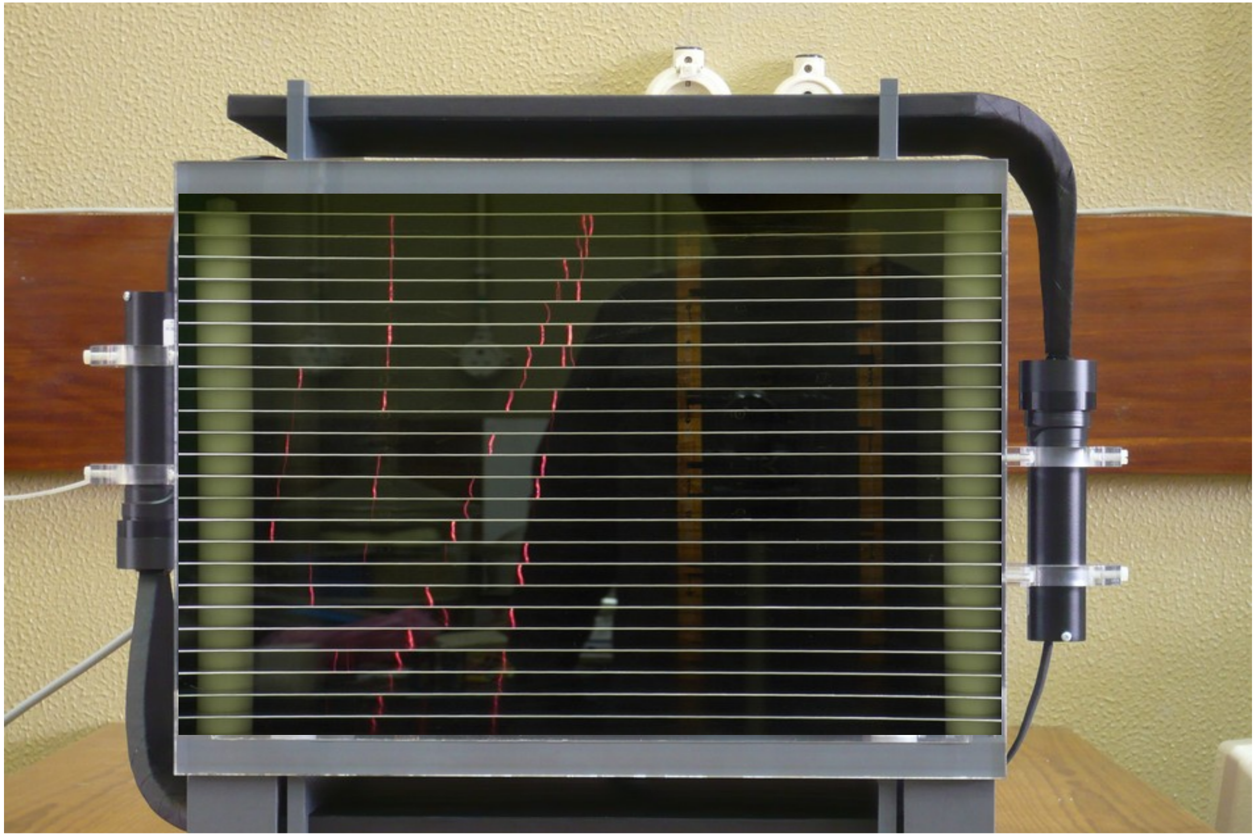

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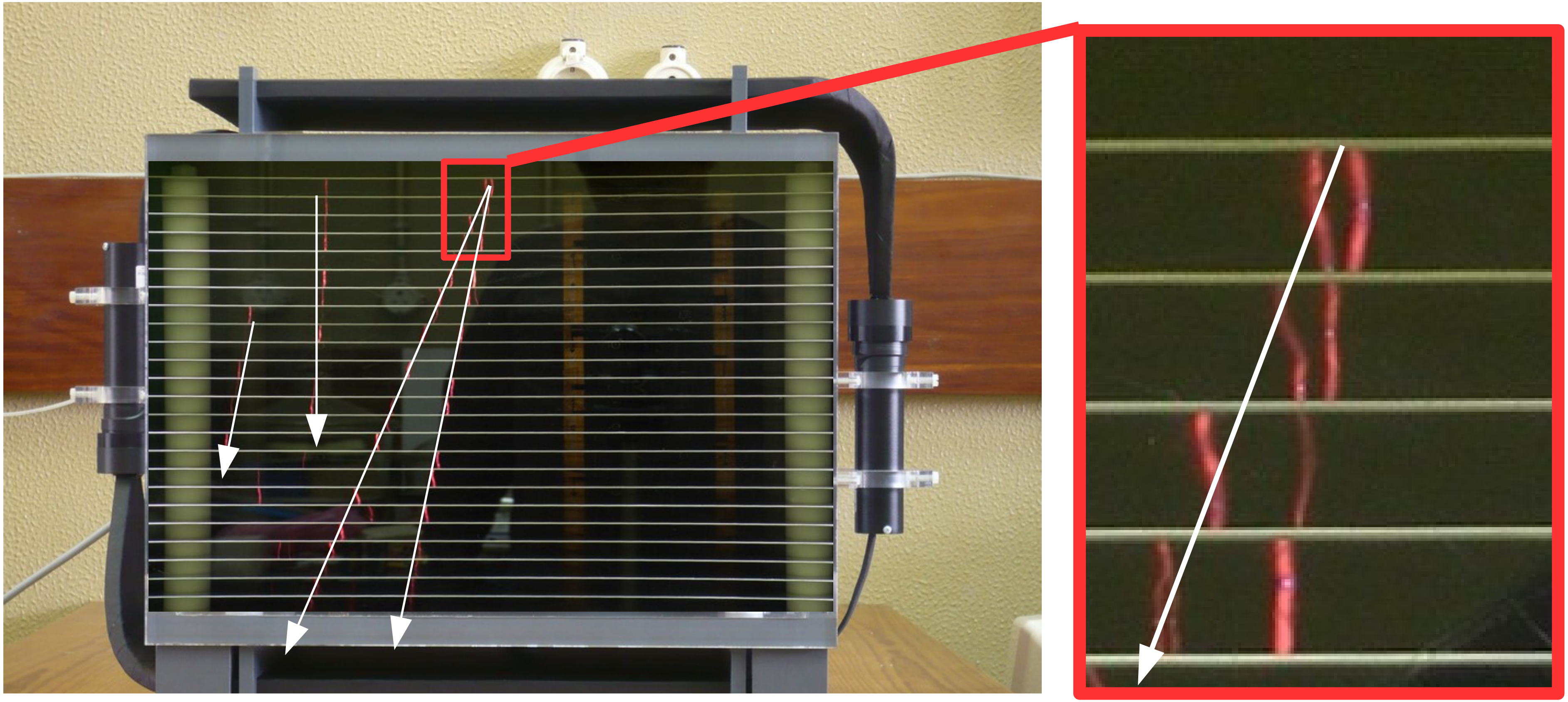

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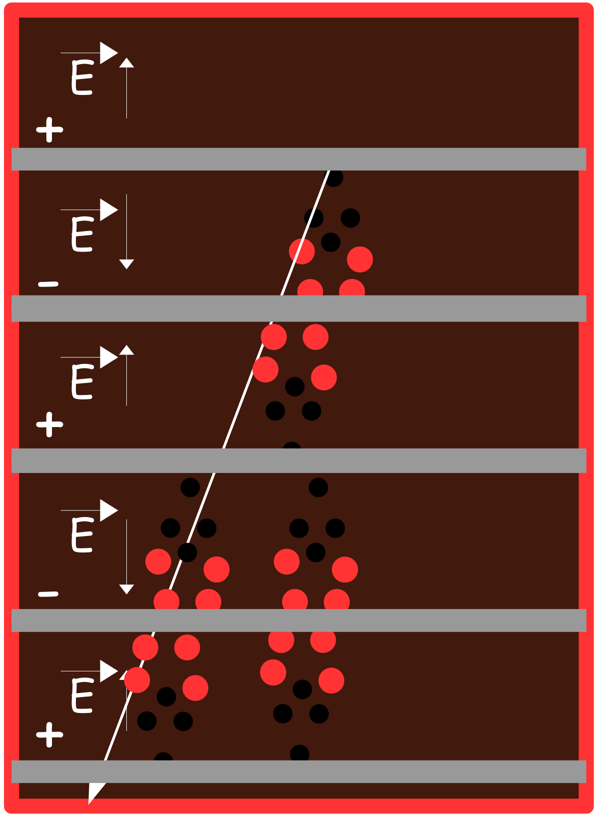
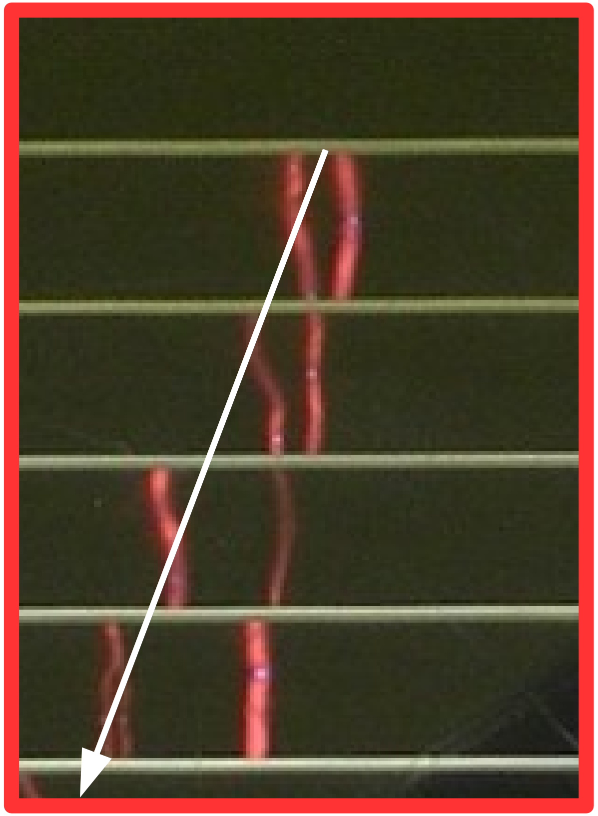


Avalanche Multiplication



-Medium = gas

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

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

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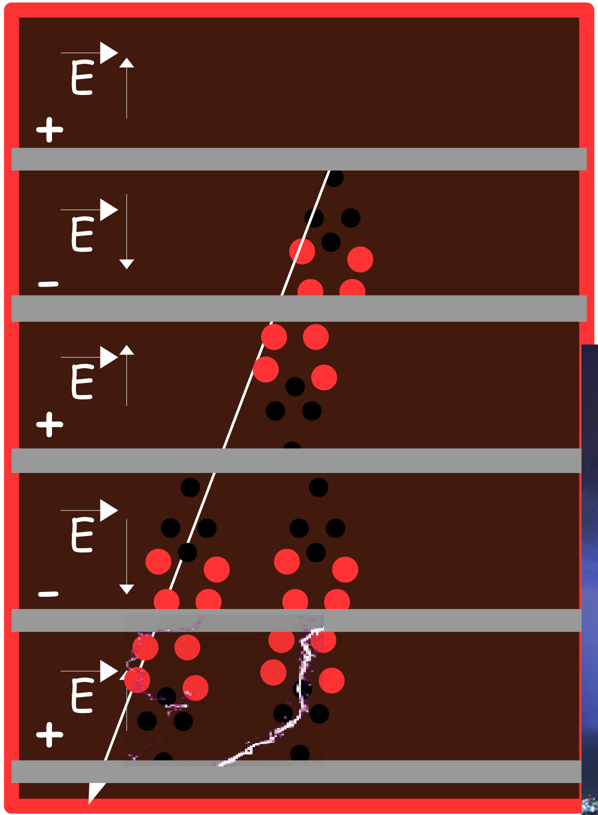

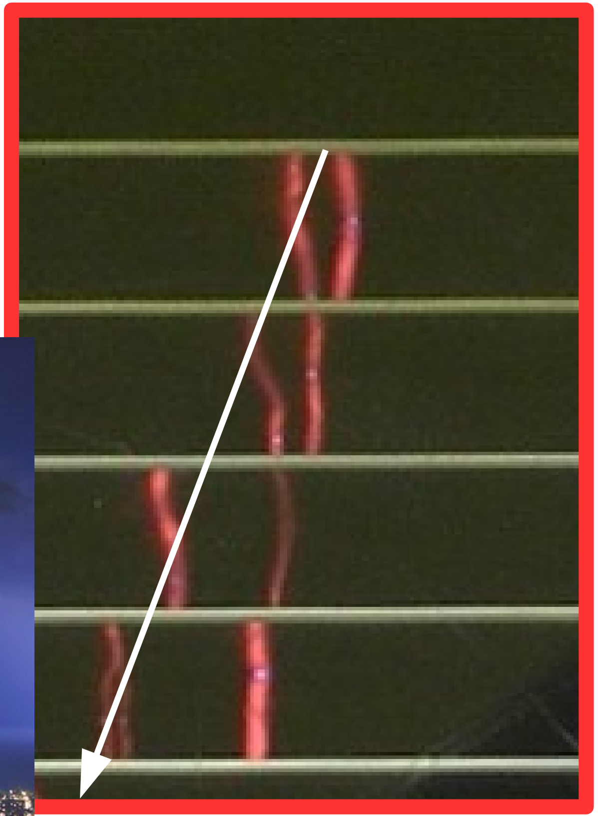

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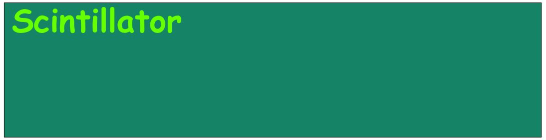
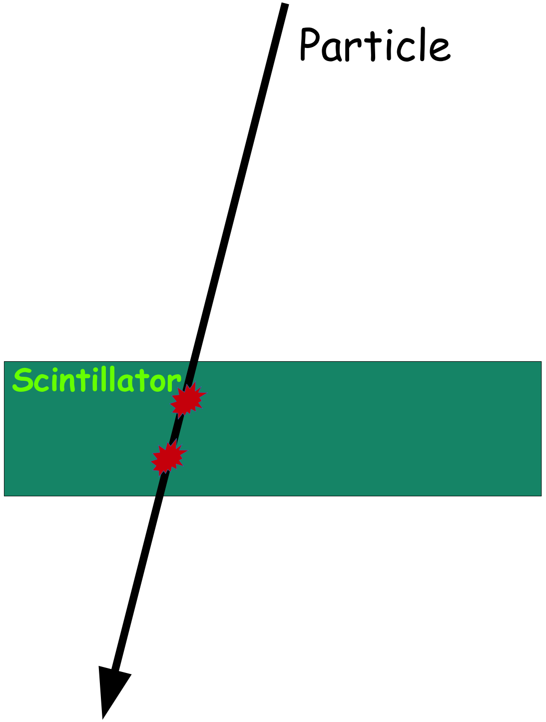
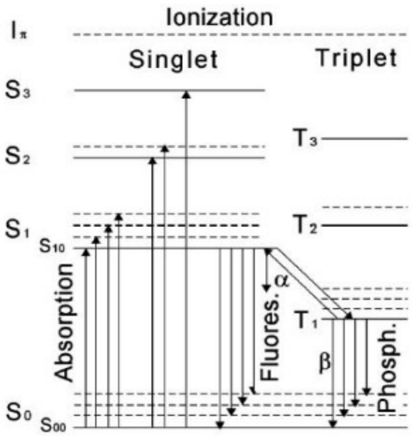
Principles of particle detection. Scintillator + Photo-multiplier



Detection medium is a scintillator

-Medium = scintillator



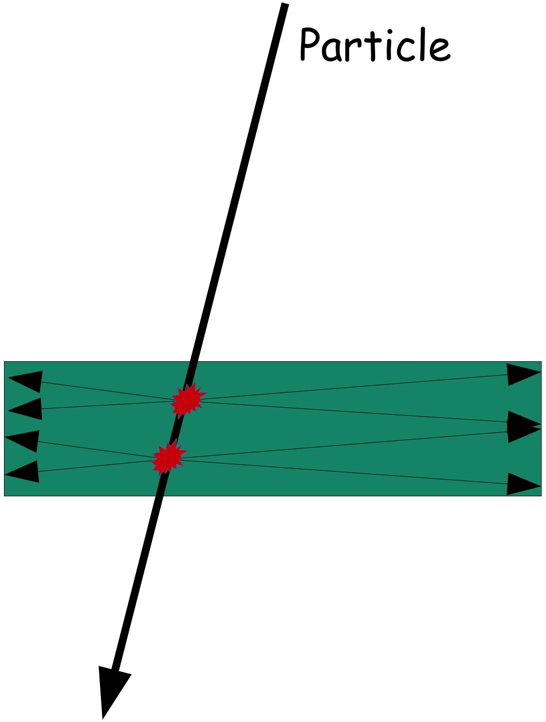


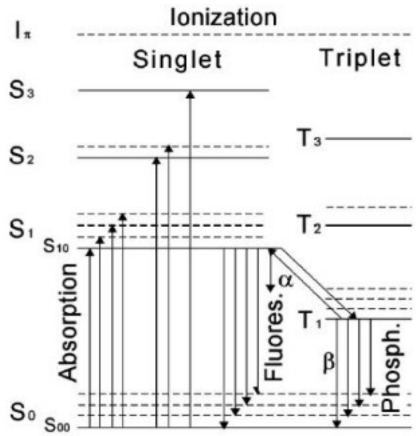
Charged particles deposit energy causing excitation of solvent and dopants molecules. Fast de-excitation by **fluorescense.**

Primary interaction

-Medium = scintillator

- Primary interaction = production of photons





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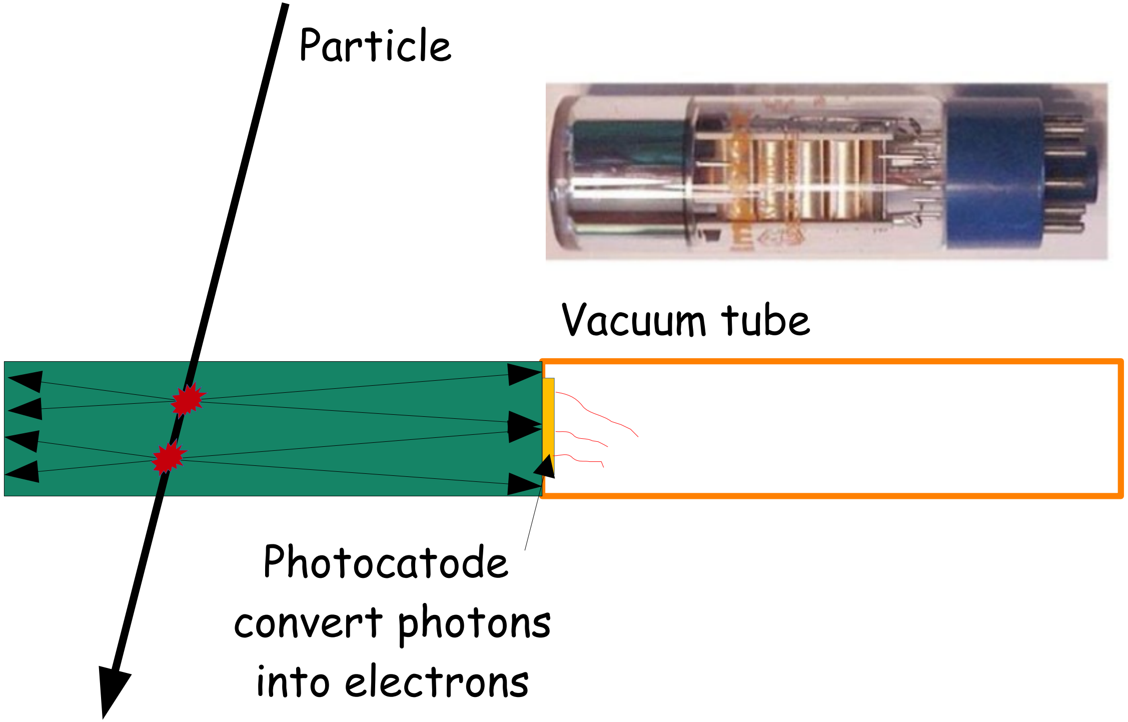
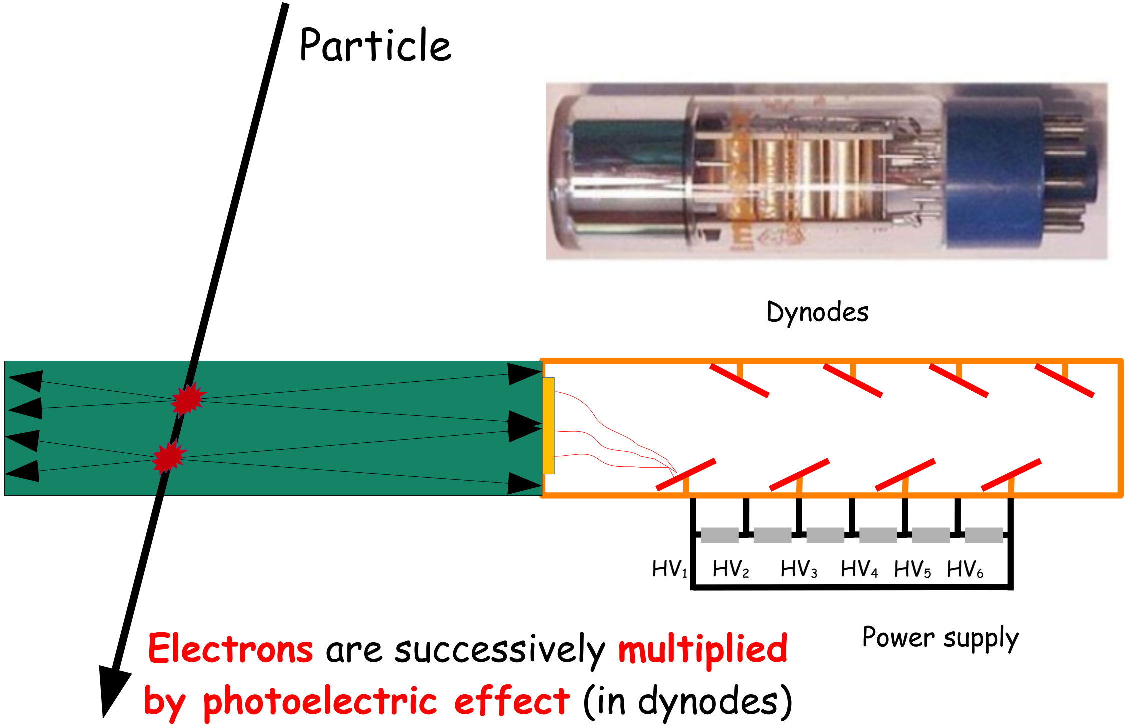


Amplification mechanism

-Medium = 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.

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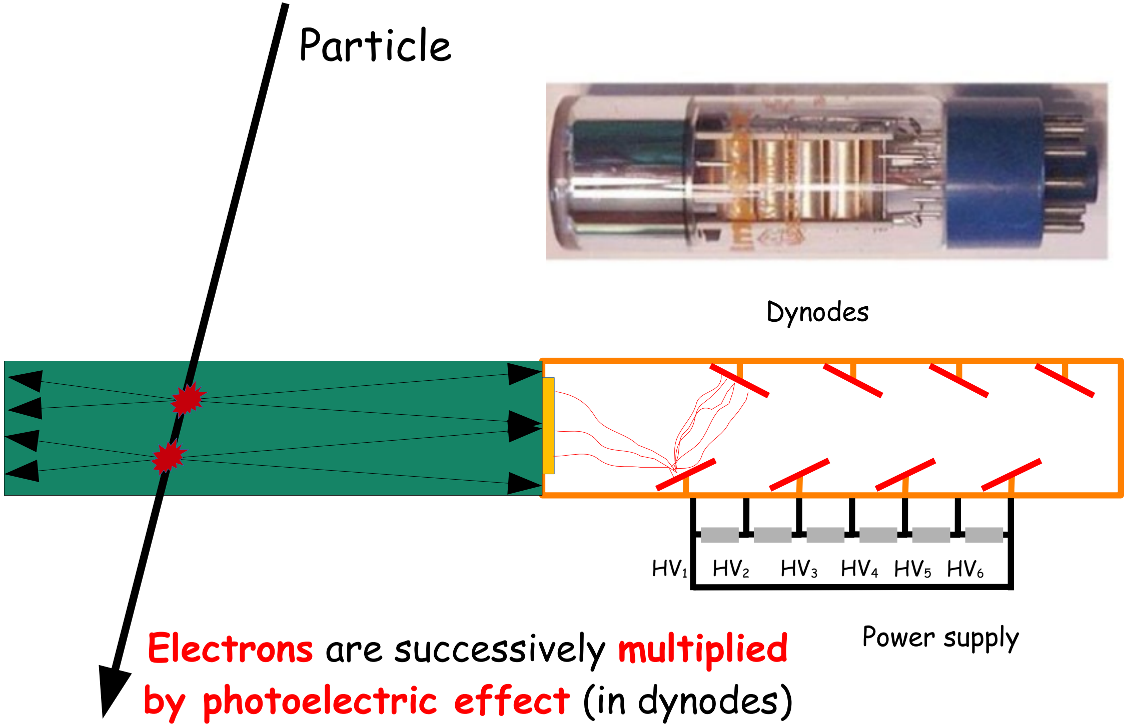

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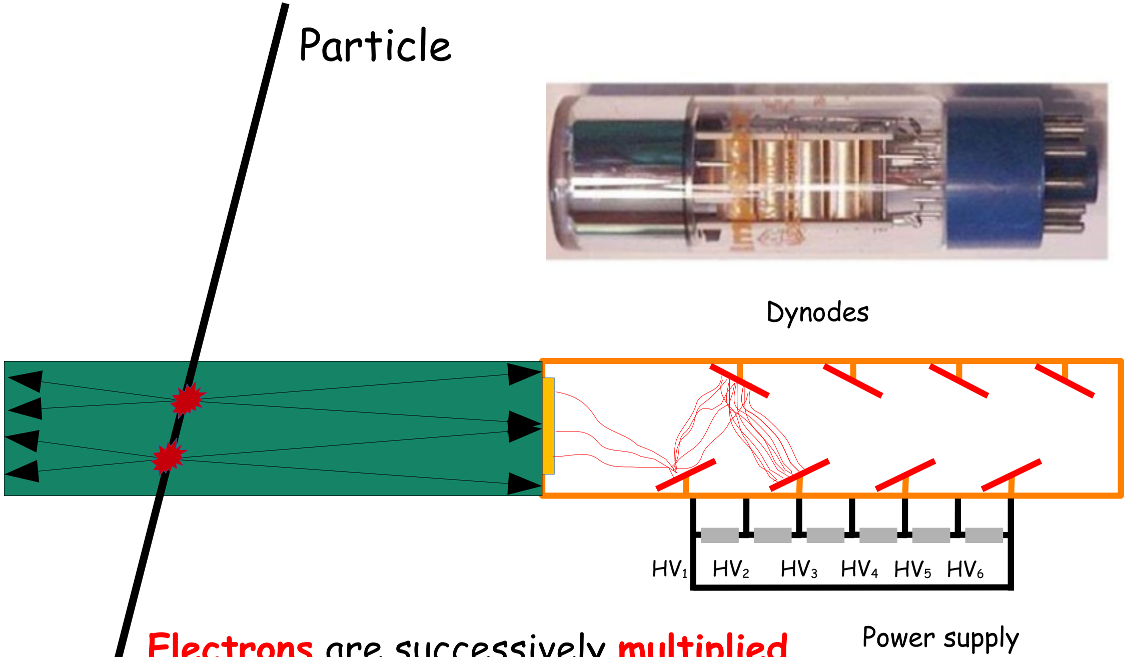

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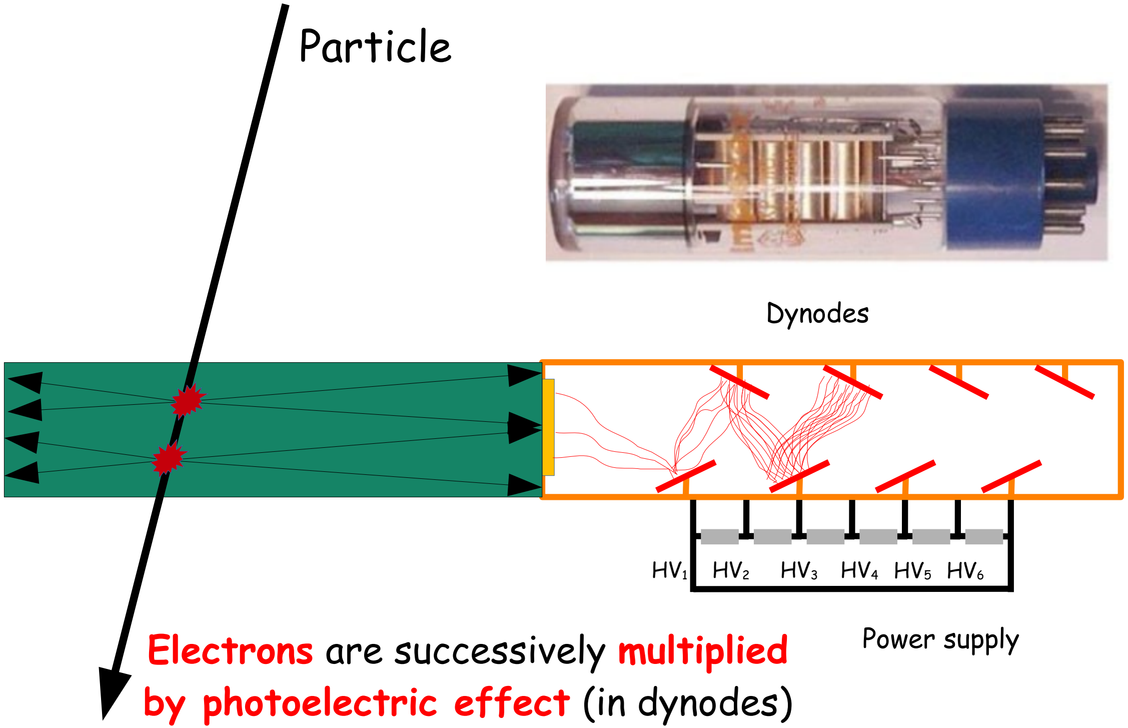

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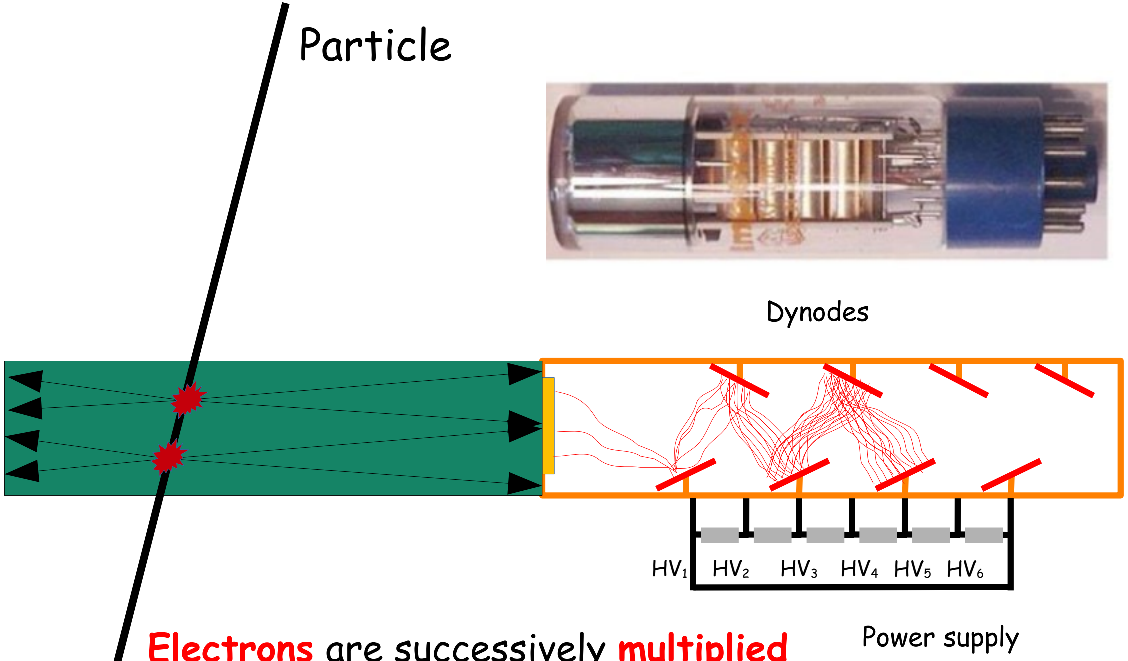

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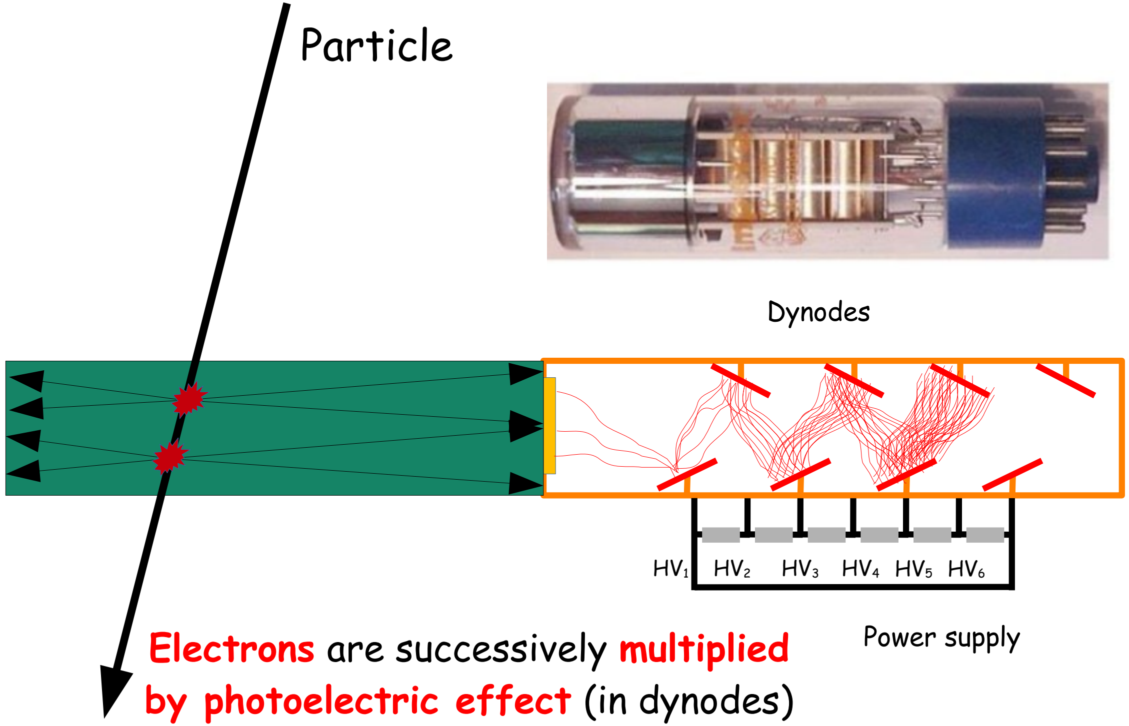

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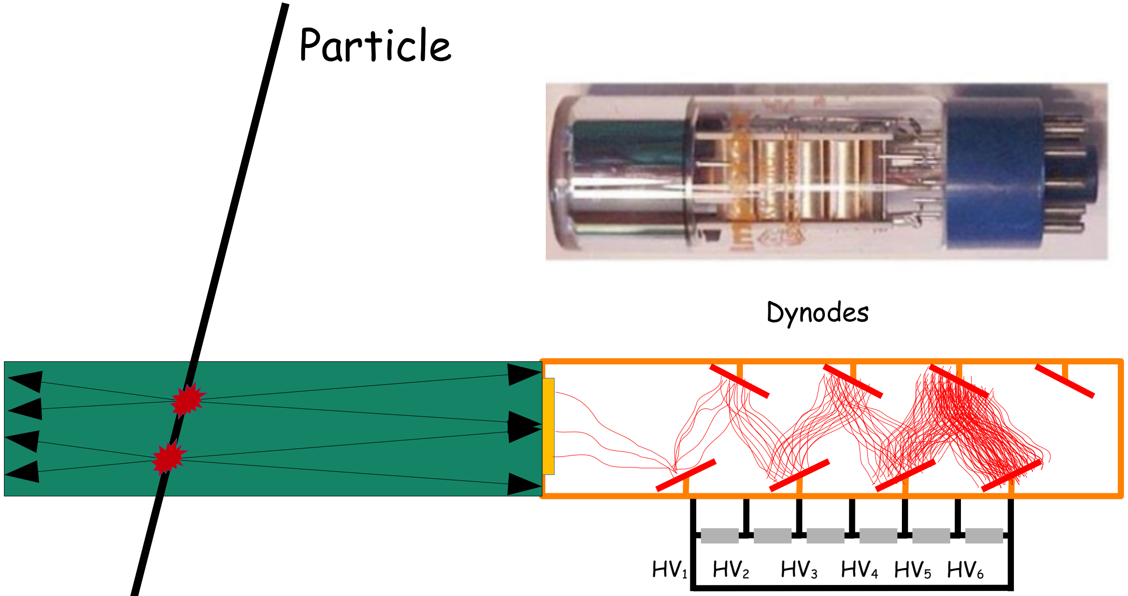
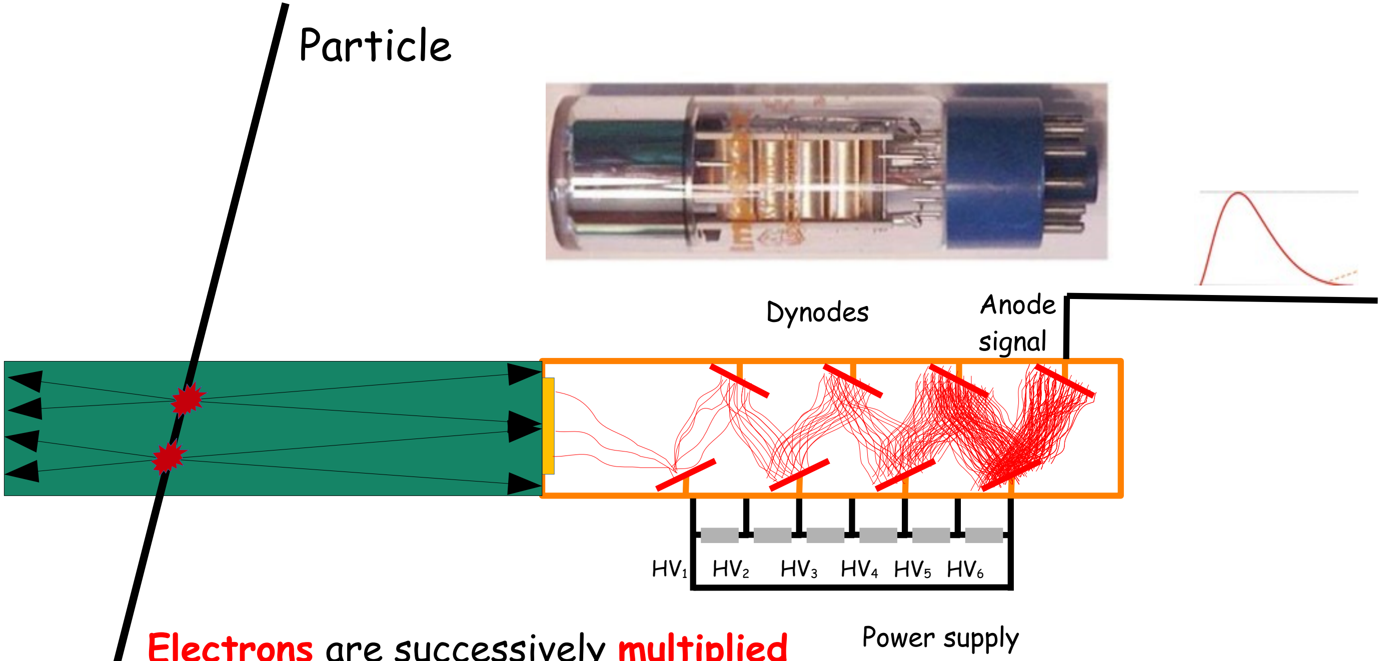


Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

Amplification mechanism

-Medium = scintillator
- Primary interaction = production of photons
-Amplification = use of photo-multiplier

Principles of particle detection. Scintillator + Photo-multiplier

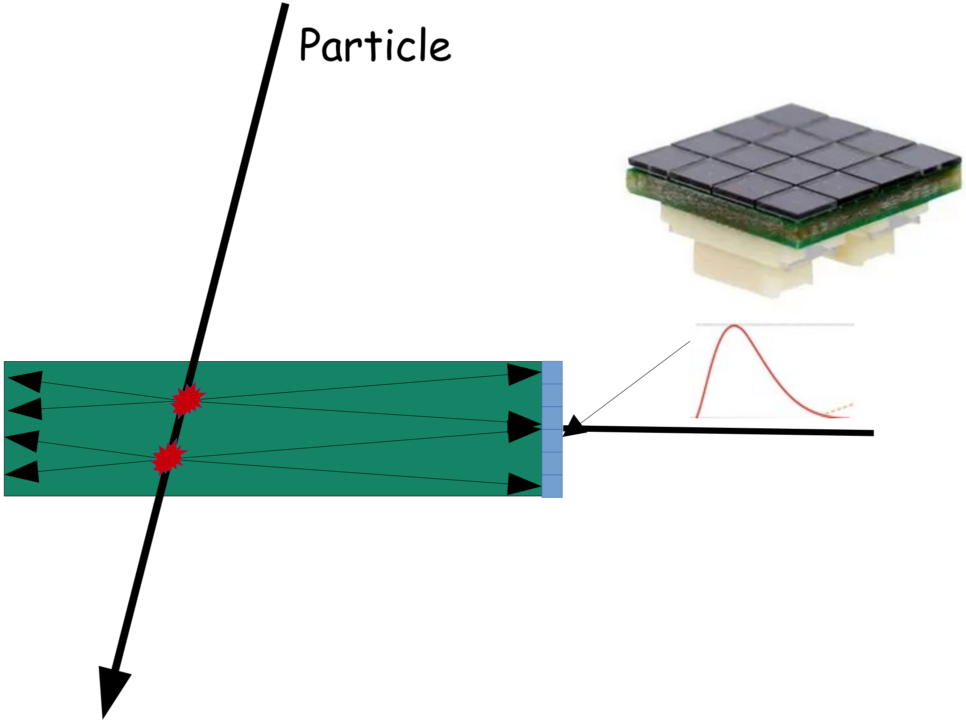


Electrons are successively **multiplied by photoelectric effect** (in dynodes) **and accelerated** by voltage differences.

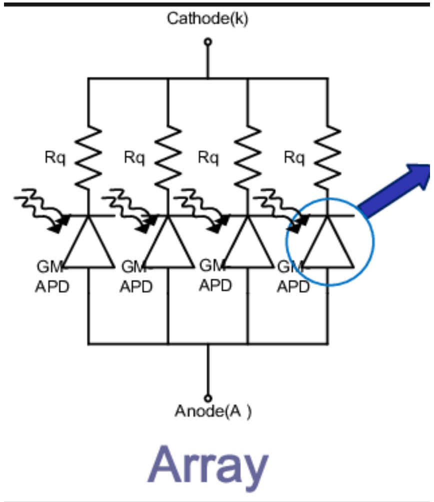
Amplification mechanism

-Medium = scintillator
- Primary interaction = production of photons
-Amplification = use of photo-multiplier

Principles of particle detection. Scintillator + Silicon Photo-multiplier SiPM



Internal structure of a SiPM



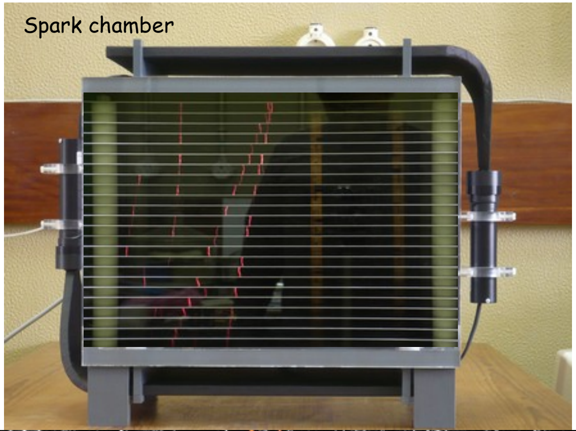
Amplification mechanism

-Medium = scintillator
- Primary interaction = production of photons
-Amplification = use of photo-multiplier

Same performance, cheaper, compact, ...

Particle detector. Readout

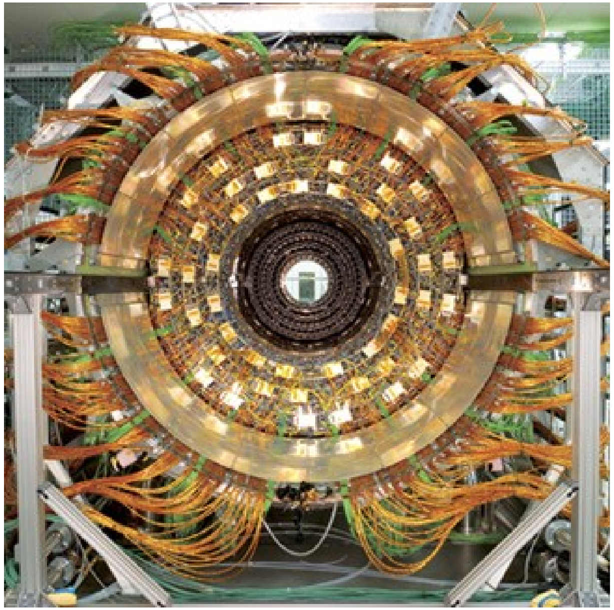
A particle detector also involves, apart from the detector, the **readout electronics and data acquisition (DAQ)** system.



Bubble chamber and blubber chamber photograph

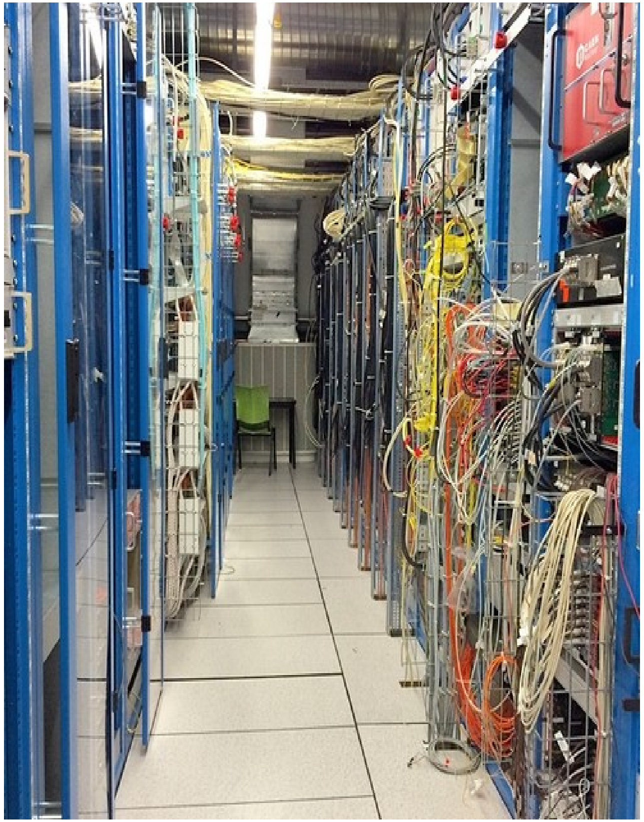
No electronic detector

Electronic detectors



CMS Tracker, CERN

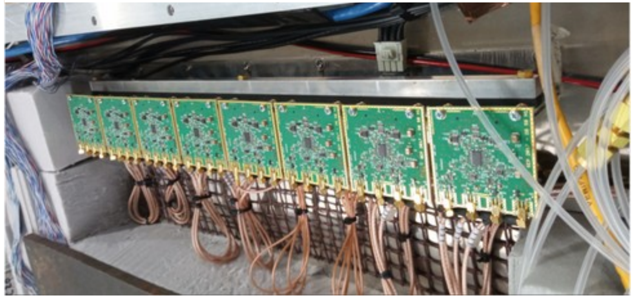
The amount of wiring on the CMS detector at CERN is equivalent to a small village of 10,000 inhabitants



CMS acquisition system room

Particle detector. Main readout elements.

32 current amplifiers + comparator



Front End Electronic (FEE)

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

ADC/TDC platform

Digitizers

Convert the electric signal into digital words

ADCs, => Analog to Digital Converter

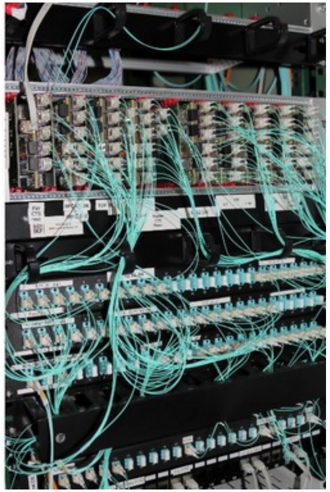
TDCs, => time to Digital Converter

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?

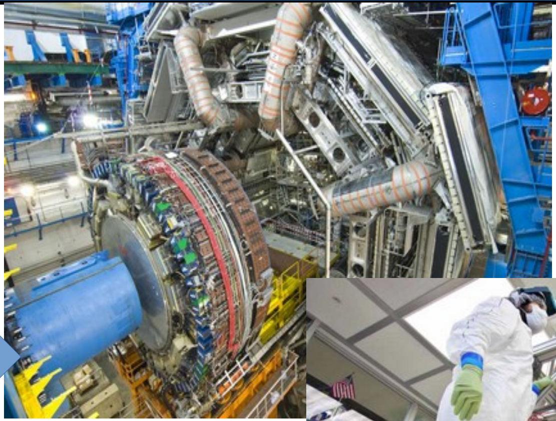
They are fundamentally used in:

- **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?



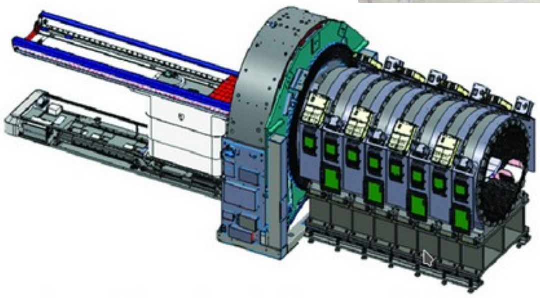
High Energy Particle experiment detector

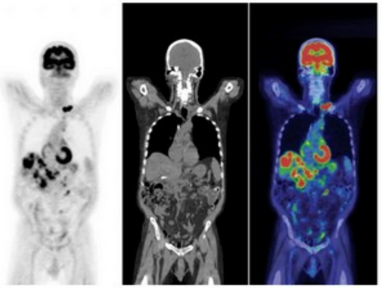
Dark matter detector

- **Medical Physics**

  Imaging. X-rays, CT and PET scans.

  Dosimetry (measuring the amount of radiation administered to a patient).



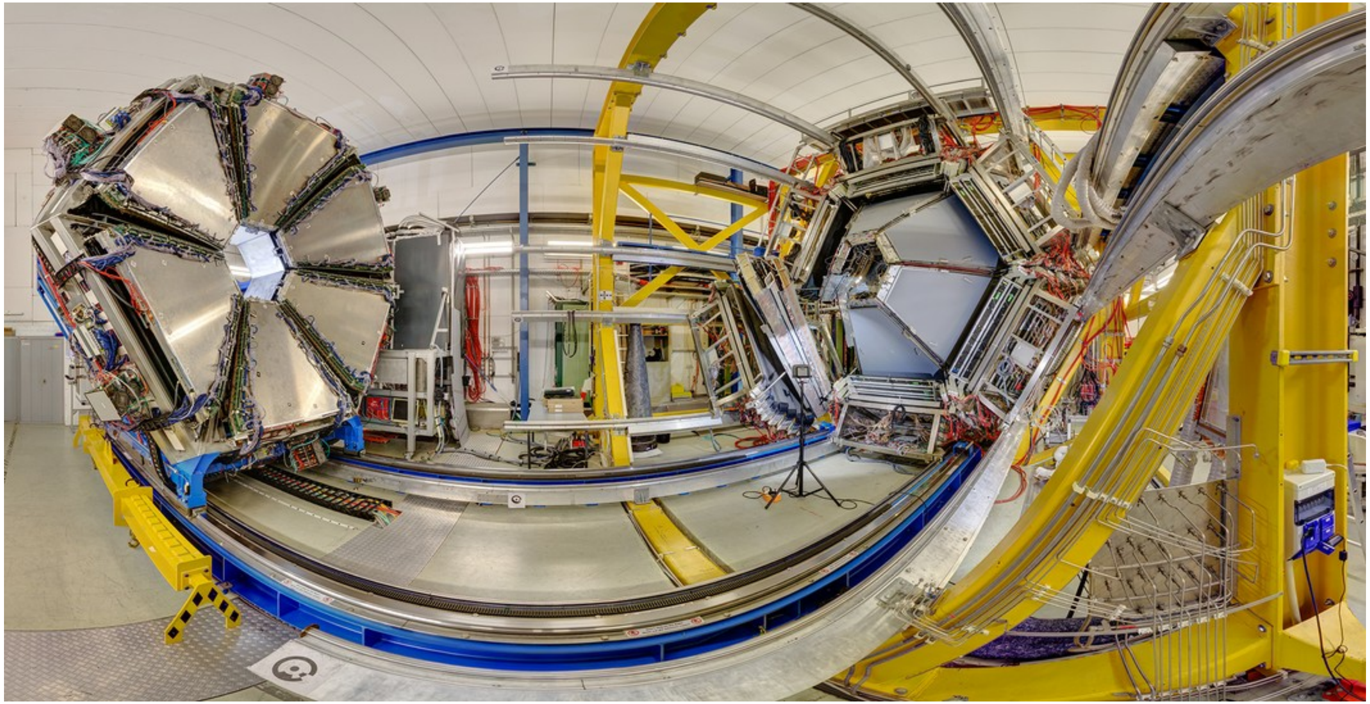


Explorer PET/CT

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

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.

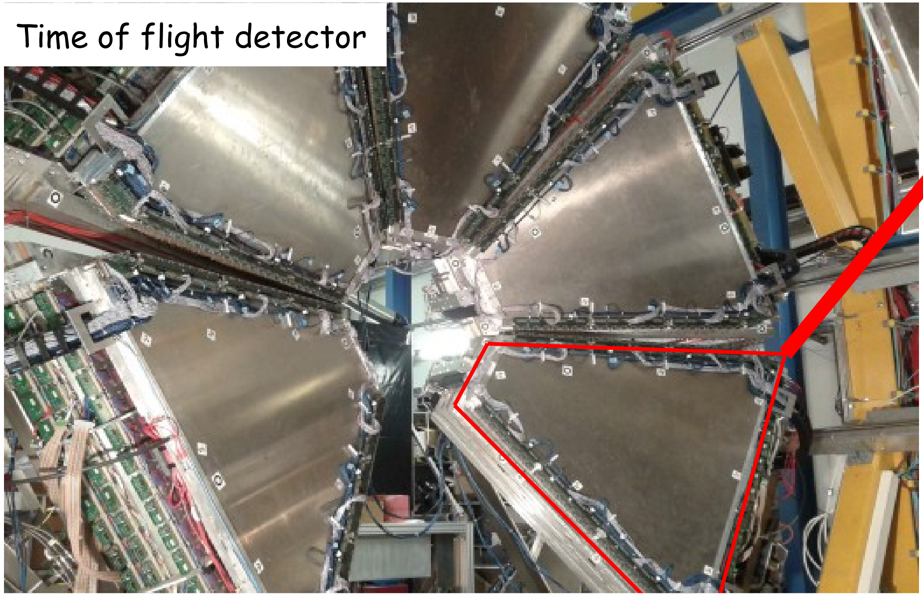
- -Medium = gas mixture $C_2H_2F_4$ + SF_6
- -Primary interaction = ionization of gas mixture
- -Amplification = use of electric fields and strip structures.

Time of Flight detector based on RPCs

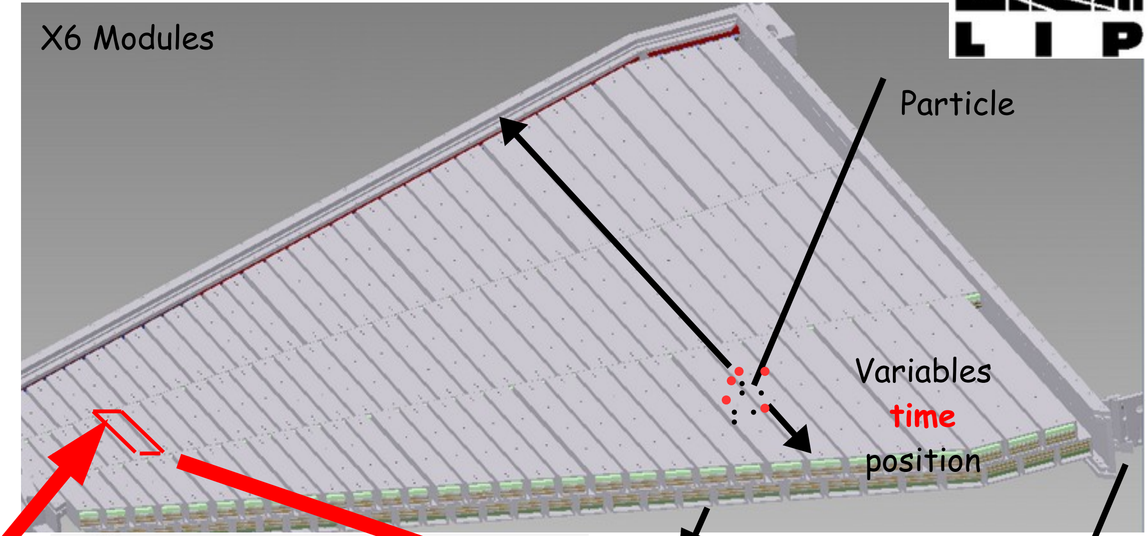
- Characteristics = **high efficiency > 90 %**, moderate **spatial resolution ~ 1 cm** and extraordinary **timing resolution 60ps**

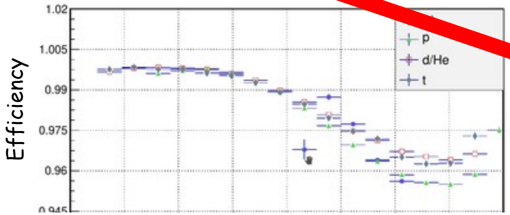
x(2400 cells) current amplifiers + discriminator + TDC channels

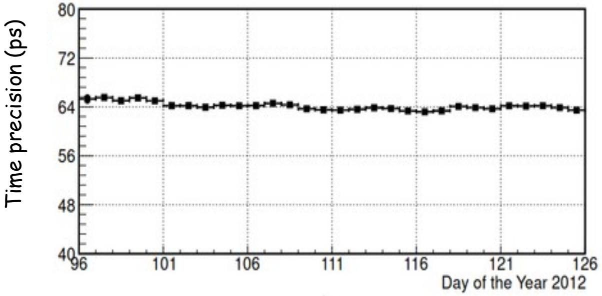
Time of flight detector

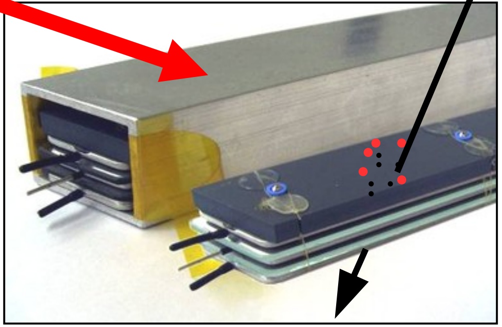


One sector can be visited in Coimbra Detector Laboratory



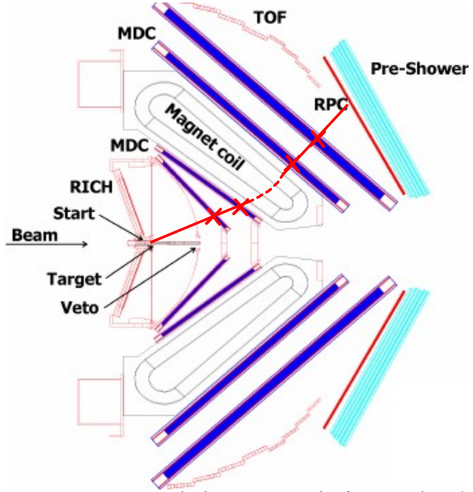


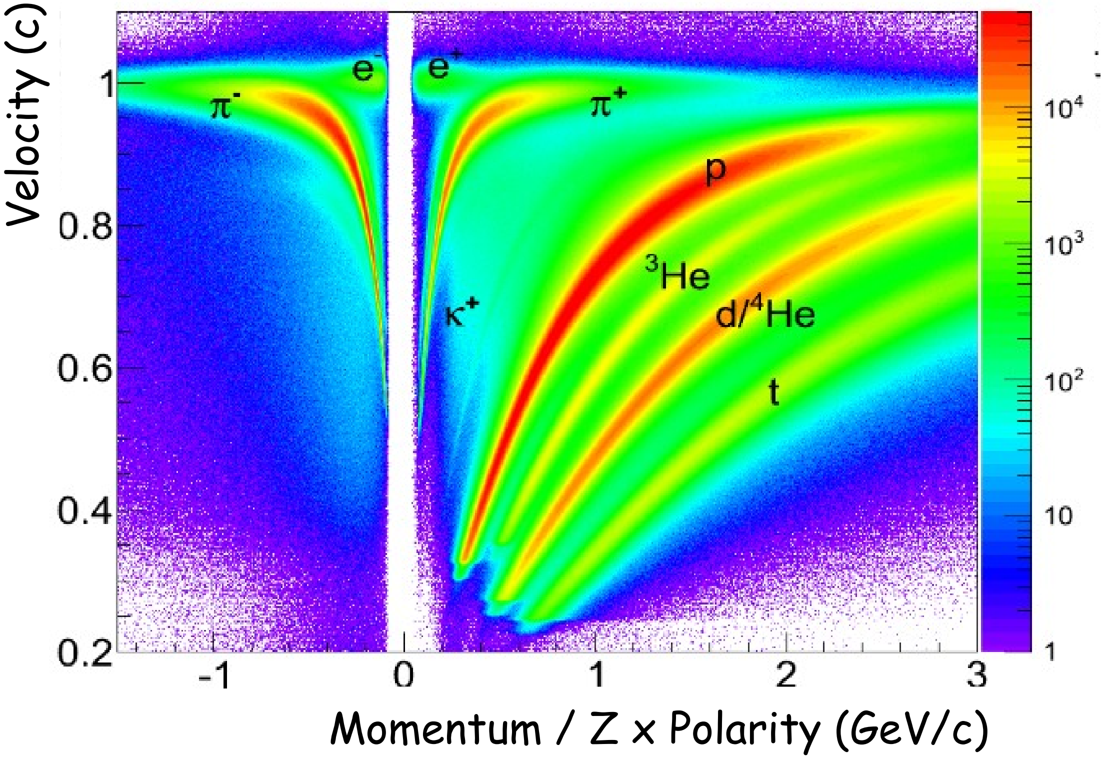




x1200 Cells

Particle Identification using Time of Flight





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

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

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

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

Mass of particle:

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

=> mass

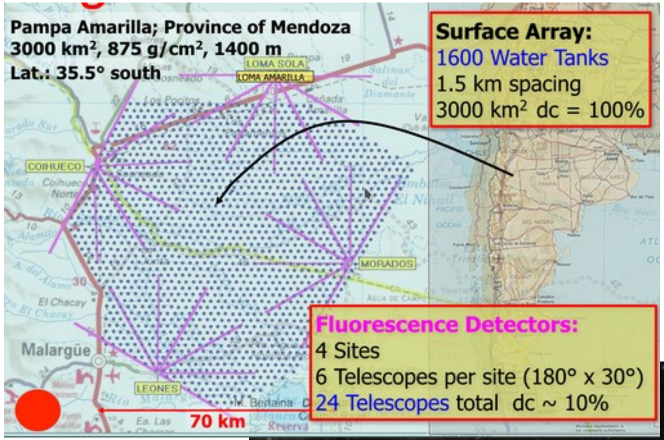
Particles separation power:

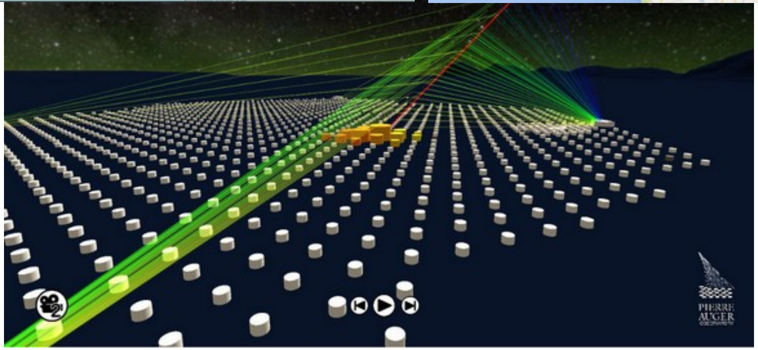
$$N_\sigma = \frac{\Delta t}{\sigma_{TOF}} = \frac{L}{c\sigma_{TOF}}\left(\sqrt{1 + \frac{m_1^2c^2}{p^2}} - \sqrt{1 + \frac{m_2^2c^2}{p^2}}\right)$$

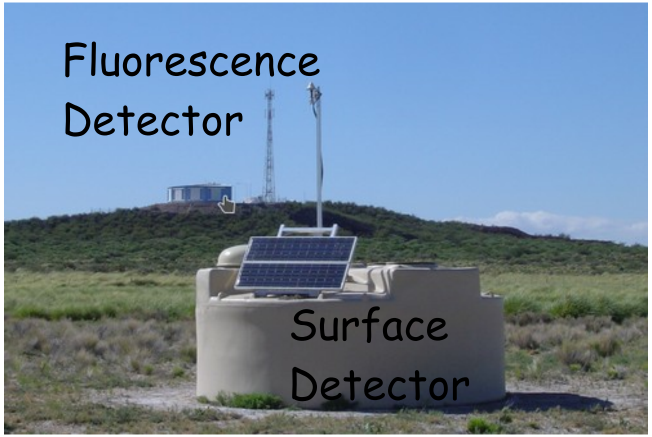
where is σ_{TOF} – time resolution of the TOF system.

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

Hybrid detector composed by a **surface detector** (x1600 units 3000 km^2, the size of Luxembourg) and x4 **fluorescence detector** installed in Pampa Argentina.







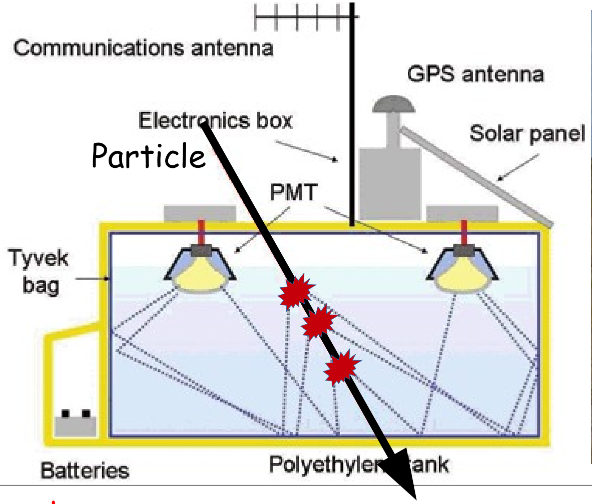
Construction started in 2000, taking data since 2005.

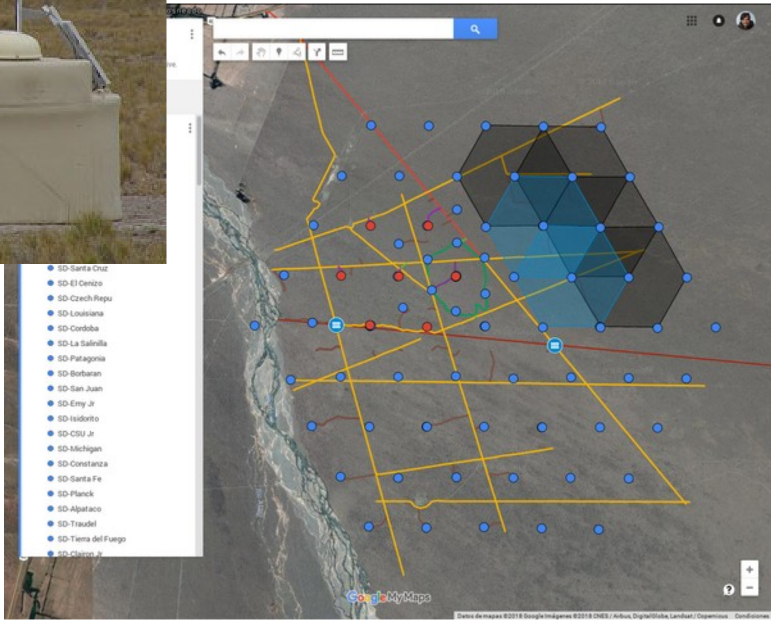
Collaboration of more than 500 physicists and 100 institutions

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

Hybrid detector composed by a **surface detector** (x1600 units 3000 km^2, the size of Luxembourg) and x4 **fluorescence detector** installed in Pampa Argentina.

Variable:
energy (number of particles)





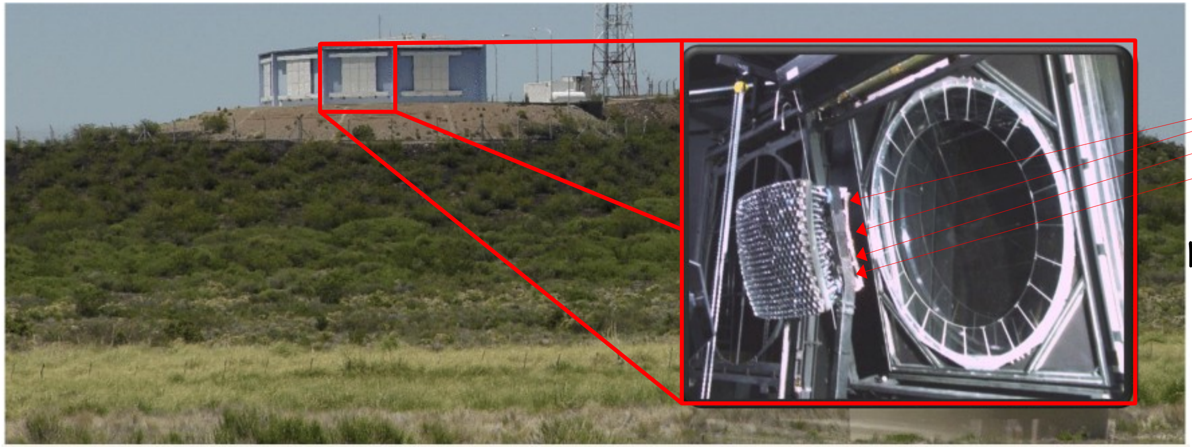
-Medium = purified water
-Primary interaction = Cherenkov light emission
-Amplification = photo-multiplier tube (PMT)

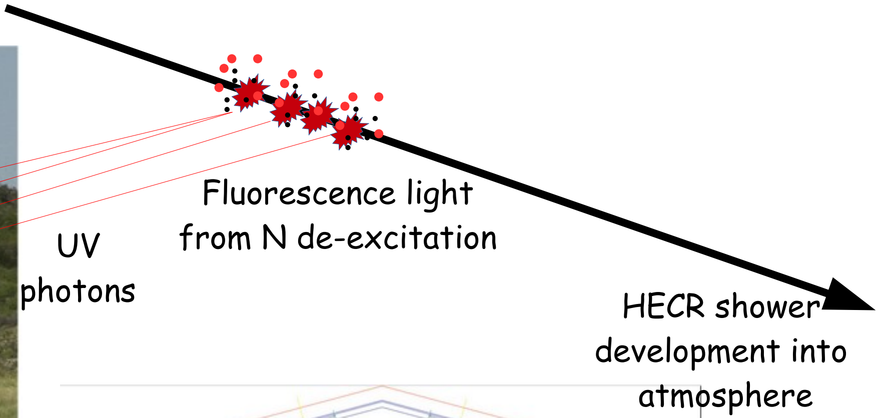
Water Cherenkov tank for particle counting
- Characteristics = **high efficiency, easy, simple to maintain, require little electronics**

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 km^2, the size of Luxembourg) and x4 **fluorescence detector** installed in Pampa Argentina.



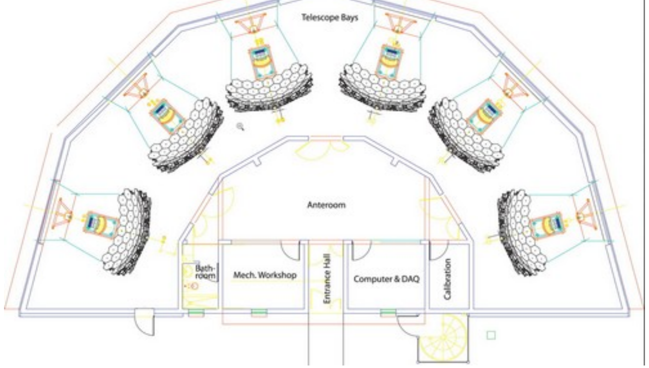


Variables: **energy**, position

-Medium = atmosphere
-Primary interaction = ionization/excitation + photon (UV) emission
-Amplification = photo-multiplier tube (PMT)

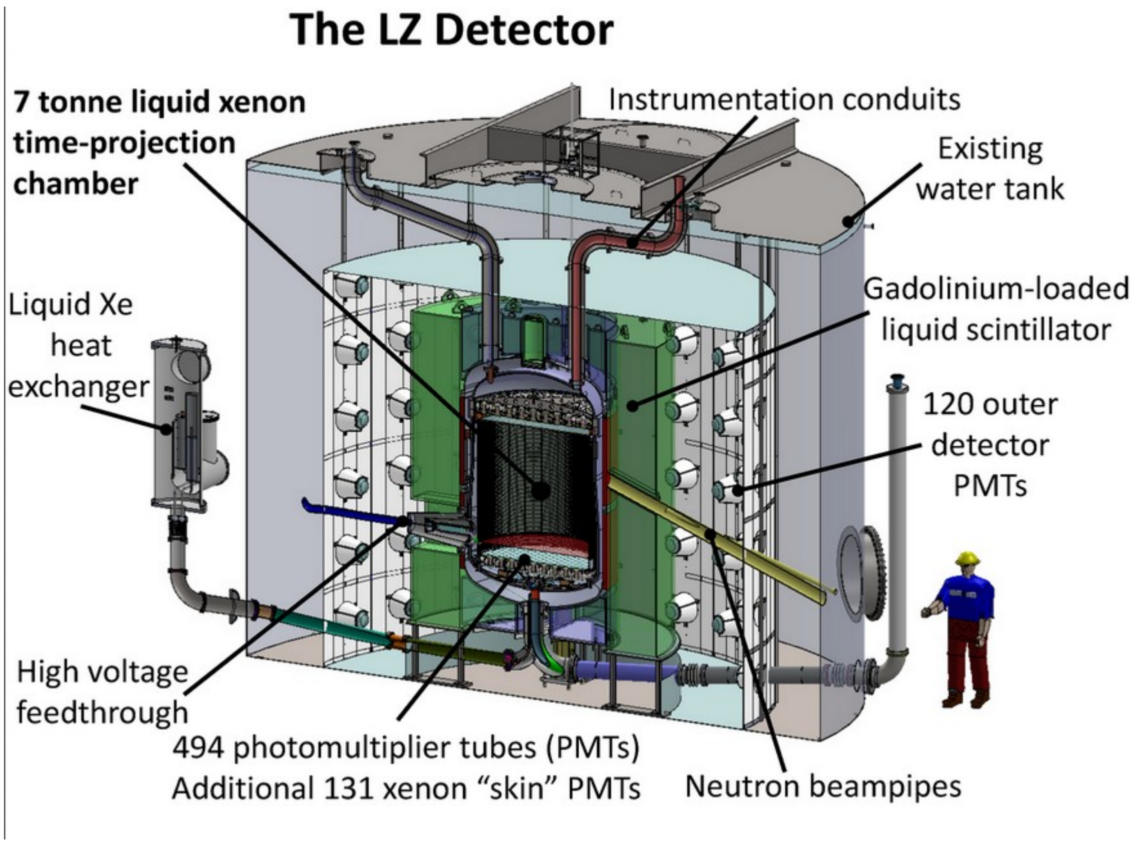
- Characteristics = **good energy response**

x6 stations x4 detectors x 440 channels + digitizer



x6 stations in one fluorescence detector

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

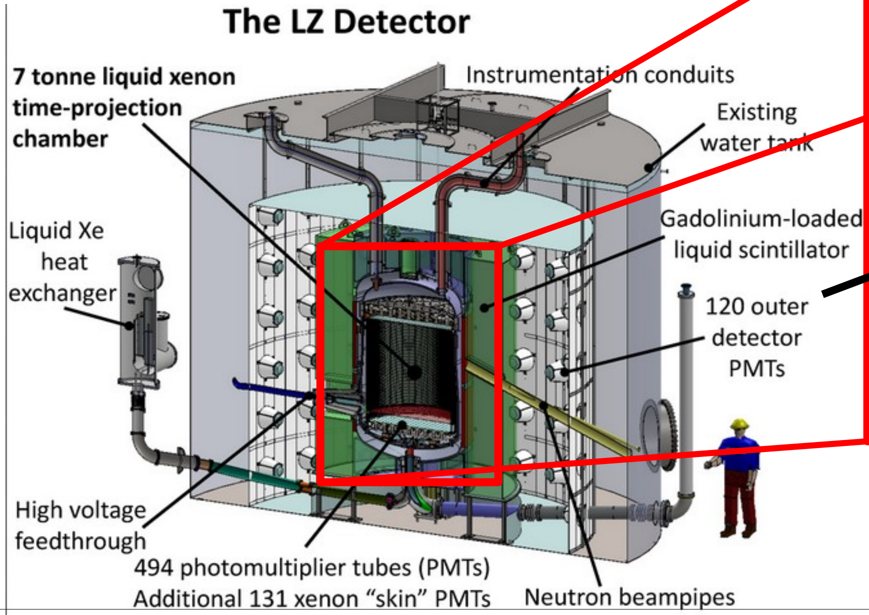


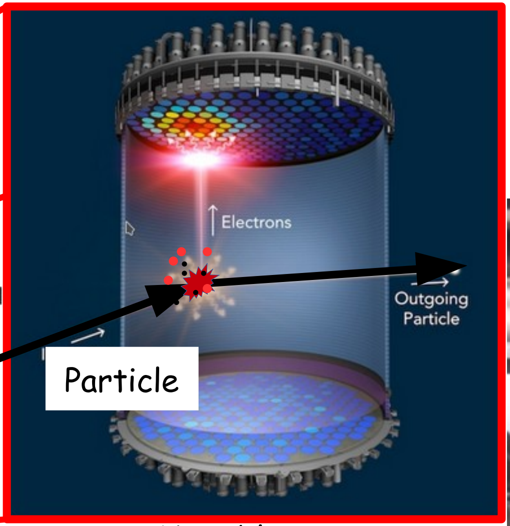
Utilizes 7 tonnes of active **liquid xenon** in a **2-phase (liquid/gas) xenon time projection chamber** (TPC) surrounded by active veto detectors (background minimization).

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

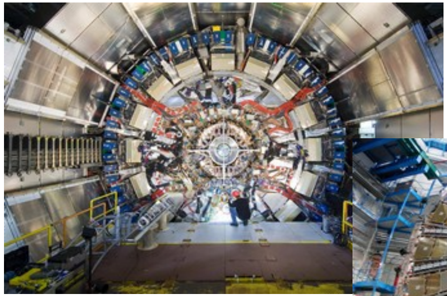
Variables:
position
time
energy

-Medium = liquid xenon
-Primary interaction = nuclear recoil => ionization/excitation + photon emission
-Amplification = photo-multiplier tube (PMT)

494 + 131 + 120 (veto) channels + digitizer

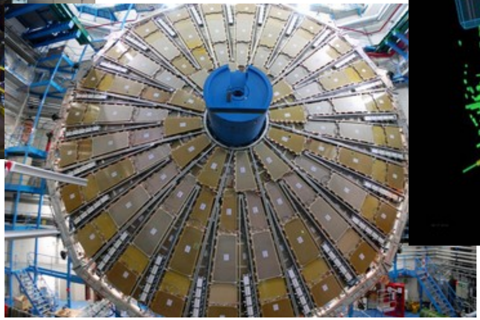
High energy physics. ATLAS A Toroidal LHC Apparatus @ CERN, Switzerland

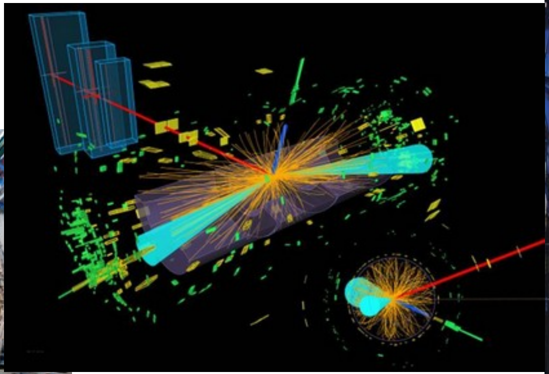
Its purpose is to **detect the Higgs boson and super-symmetric particles (SUSY)** that are predicted by theory but have not yet been detected experimentally and **extensively test the Standard Model.**



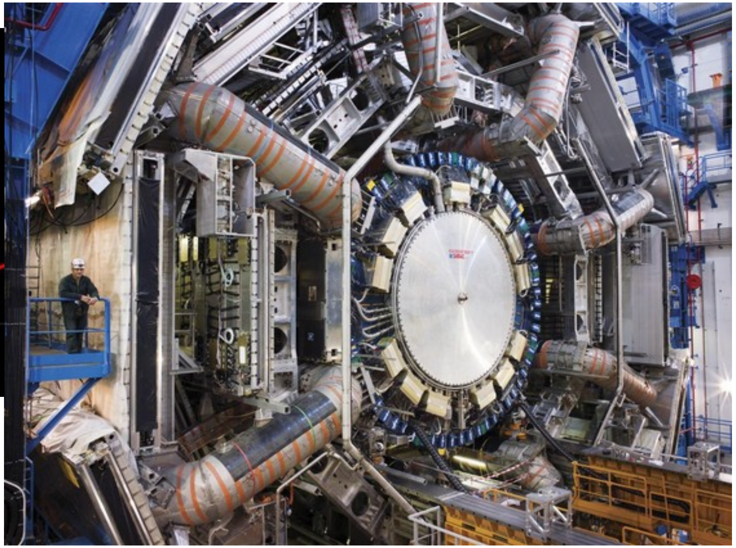
Inner detector

Muon detector

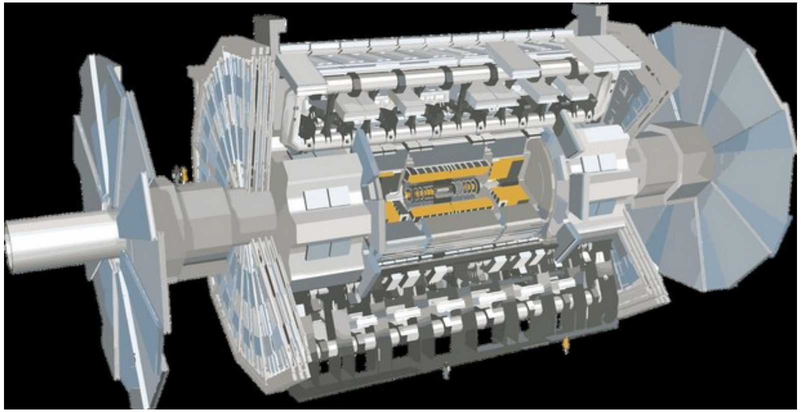




Interaction reconstruction

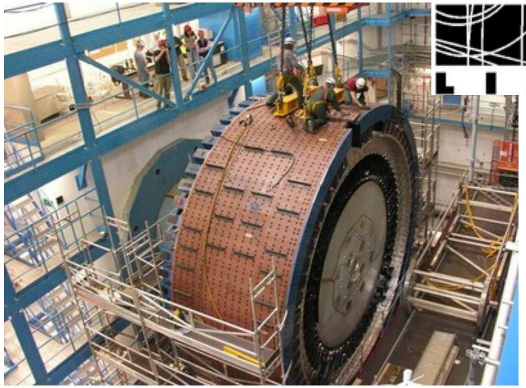


ATLAS detector open during technical stop



ATLAS technical design

Tile Calorimeter



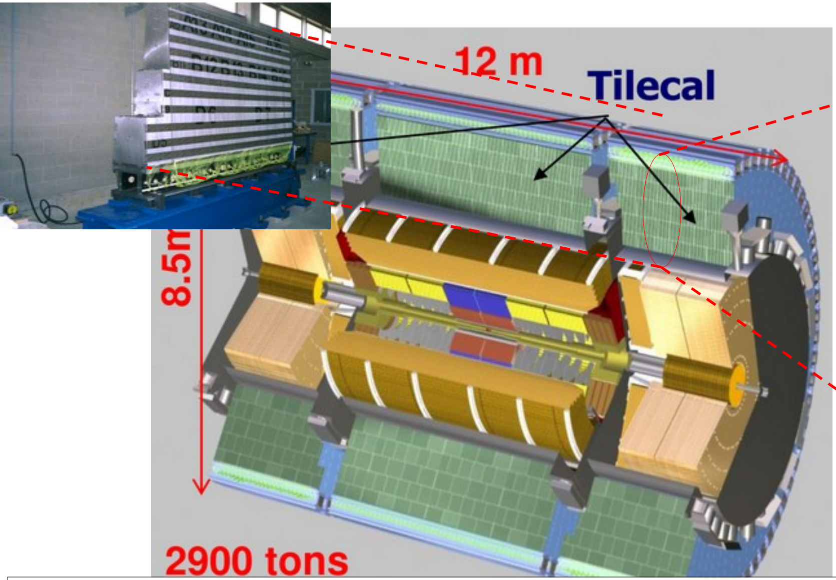
Construction completed in 2008

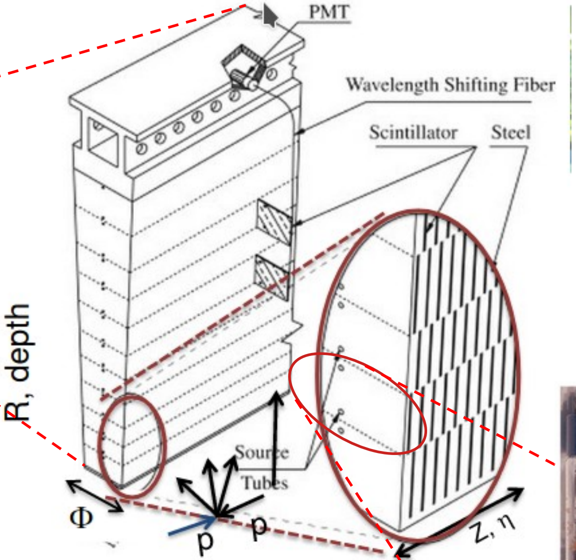
Collaboration of more than 3800 physicists from 257 institutions and 42 countries

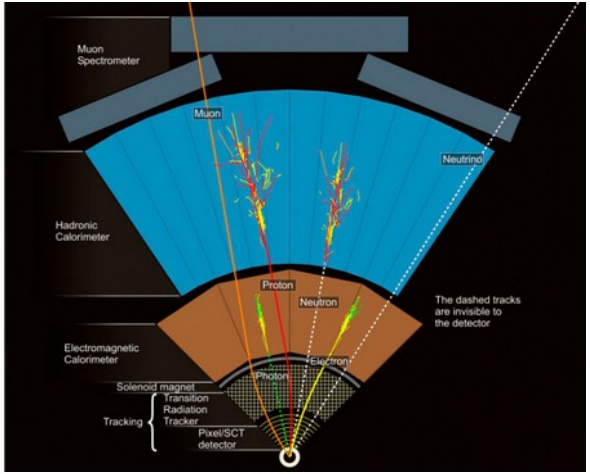
High energy physics. ATLAS A Toroidal LHC Apparatus, Tile Cal @ CERN, Switzerland

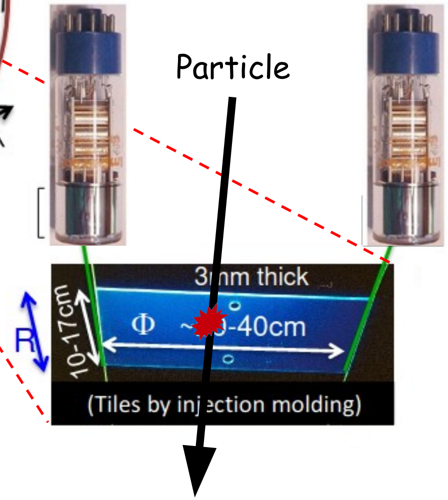
Its purpose is to **detect the Higgs boson and supersymmetric particles (SUSY)** that are predicted by theory but have not yet been detected experimentally and **extensively test the Standard Model**.

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









-Medium = plastic scintillator
-Primary interaction = ionization/excitation + photon emission
-Amplification = photo-multiplier tube (PMT) (after waveLenghtShifter)

Variables:
energy
position
time

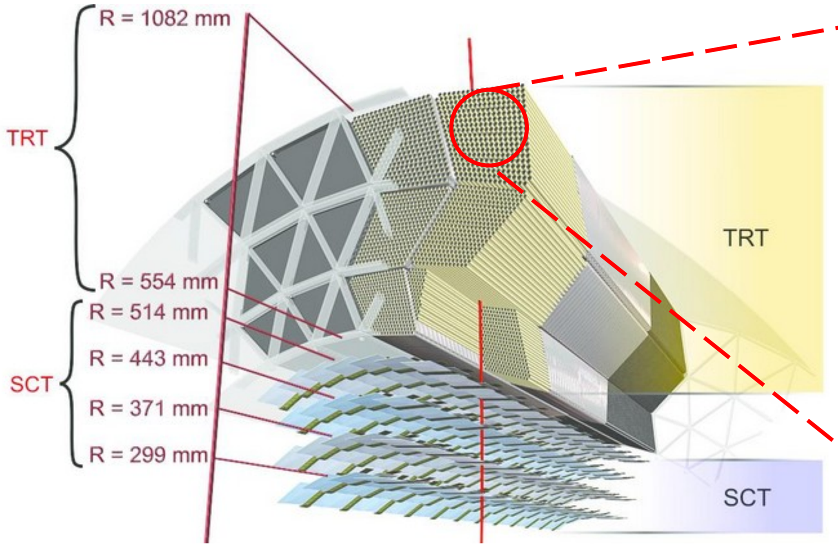
Scintillitor tiles + steel absorber for hadron energy measurement
- Characteristics. **Good energy resolution, Robust and low cost.**

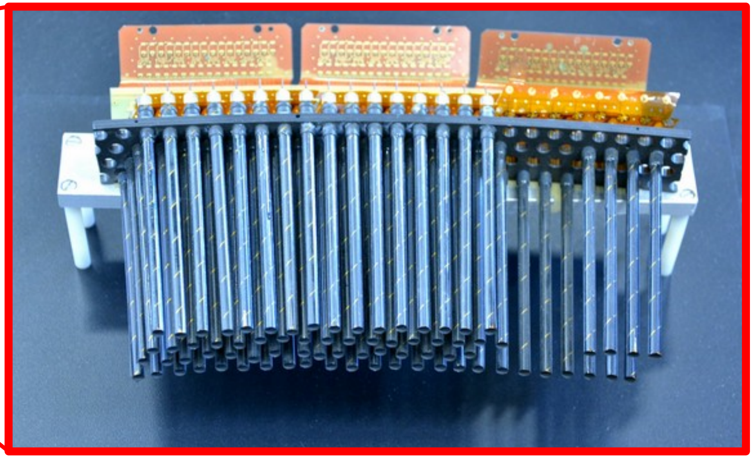
x 10000 channels + digitizer

High energy physics. ATLAS A Toroidal LHC Apparatus, Transition Radiation @ CERN, Switzerland

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.**

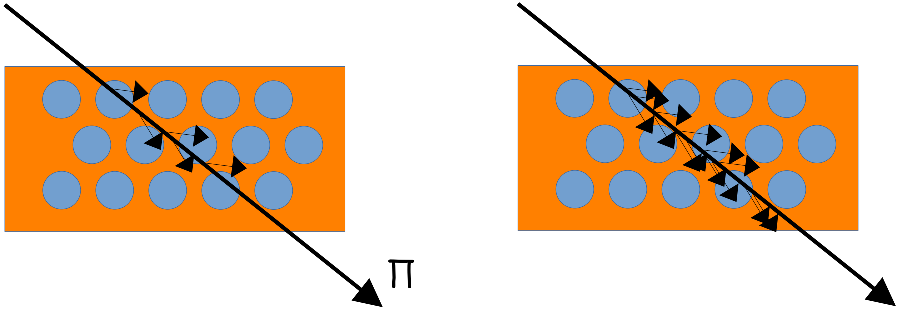
Transition Radiation Tracker => Particle Identification and tracking





Variables:
Discrimination
position
time

Radiator material (polypropylene foils or fibers)
strawTubes



-Medium = polypropylene + gas
-Primary interaction = transition radiation + ionization
-Amplification = use of electric fields

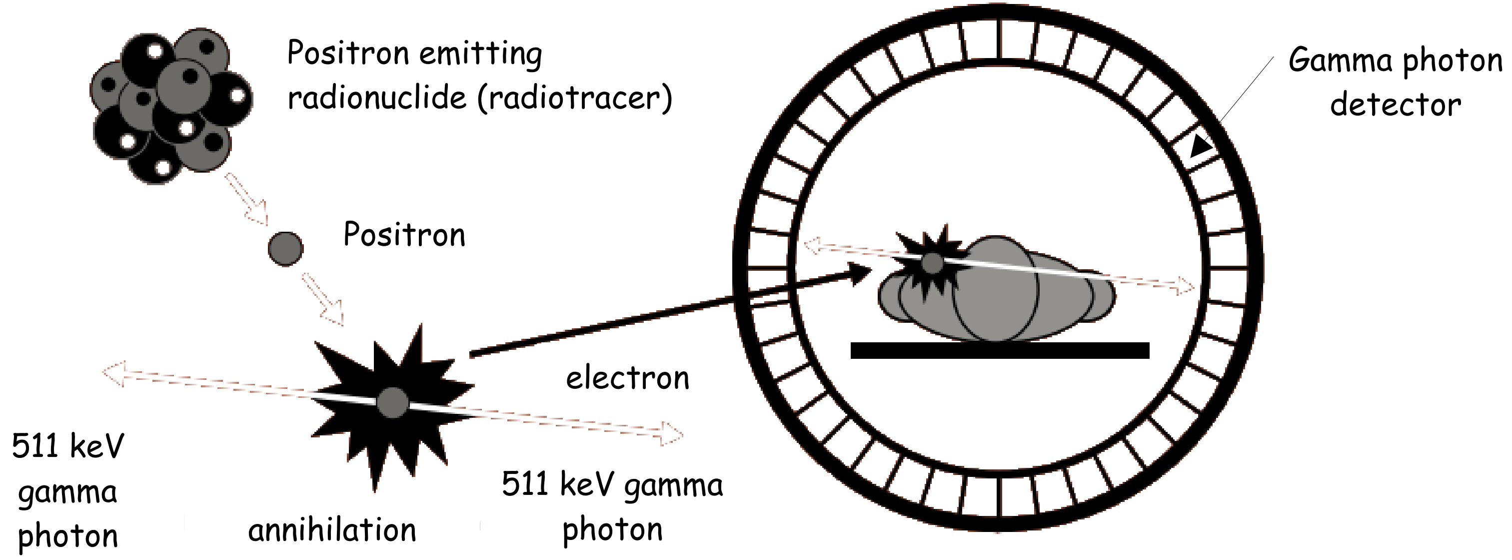
Transition Radiator + Straw tubes

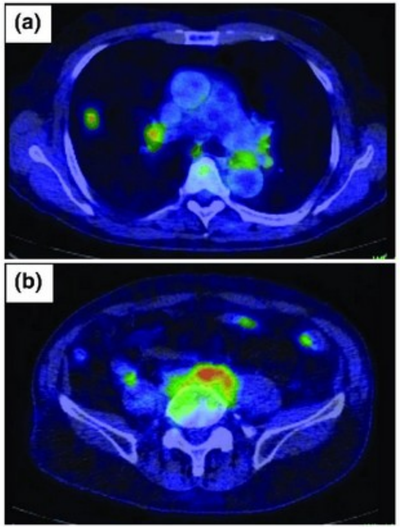
x 370000 channels + digitizer

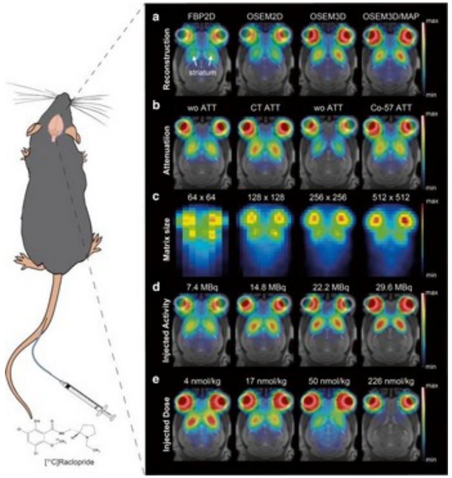
Positron emission tomography (PET) is a **functional imaging technique** that uses radioactive substances known as radiotracers to visualize and measure changes in metabolic processes, and in other physiological activities.

Positron emission
and positron-electron annihilation

PET scanner





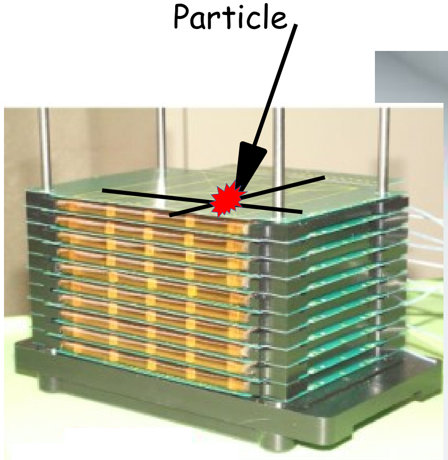


Medical physics. PET with RPC detectors.

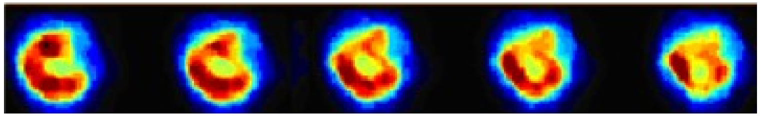
-Medium = gas mixture $C_2H_2F_4$ + SF_6
-Primary interaction = ionization of gas mixture
-Amplification = use of electric fields and strip structures.

PET scanner based on RPCs
- Characteristics = moderate **efficiency**, extraordinary **spatial Resolution ~ 0.1 cm** and extraordinary **timing resolution 100ps**

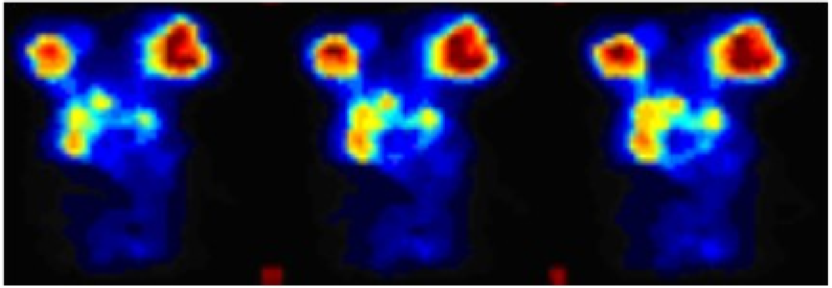
x(400) amplifiers + digitizer



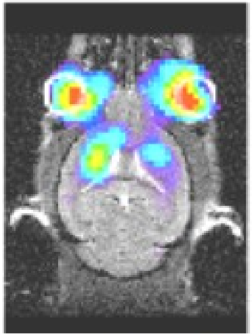
Variables:
position
time



Heart of a mouse. Approximately 10 mm



Head of a mouse



Co-registration with CT

Thank you for your attention !!