# Modern Particle Physics Experiments
# **Particle Identification Detectors**


Aleksander Filip Żarnecki

FACULTY OF PHYSICS
UNIVERSITY OF WARSAW


**Lecture 06**

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## Detector concepts

Depending on the particle type and application, particle detectors can be divided into three main classes:

- Tracking detectors
  Measure position/trajectory of charged particles,
  based on energy losses due to ionization or activation of material.
  We try to minimize particle interactions
  $\Rightarrow$ gaseous detectors or thin semiconductor layers
- Calorimeters
  Measure particle energy by absorbing it in the dense medium
  Interactions of high energy incident particle
  $\Rightarrow$ electromagnetic or hadronic cascade
- Particle identification detectors (today)
  Use different processes to improve particle identification capabilities
  Cherenkov detectors, Transition radiation detectors, Time-Of-Flight ...

## References

- Particle Physics Reference Library (vol.2)
  Review of the state of the art in detector physics and related data-taking technology (open access)
- PDG reviews:
  - Passage of particles through matter
  - Particle detectors at accelerators
  - Particle detectors for non-accelerator physics

## Particle Identification Detectors

1. General concept of collider experiments
2. Time-of-Flight measurement
3. Cherenkov detectors
4. Transition radiation
5. Large detector systems

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## General concept - layer structure

Modern universal detectors at particle colliders are build from many different sub-components.

We arrange detectors in such a way as to obtain best measurement for all possible particles, as well as their (at least partial) identification.

$\Rightarrow$ detectors which interact least with produced particles are placed closest to the interaction point   gas detectors, thin silicon sensors

$\Rightarrow$ detectors which absorb particles are placed at largest distances from interaction point   calorimeters, muon detectors

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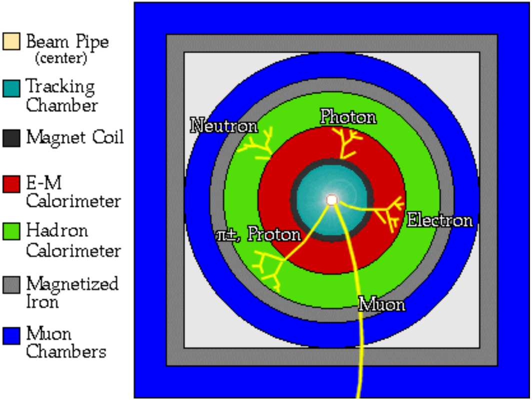

## Universal detector

Layout describing most of recent, present-day and future experiments at colliders (LEP, HERA, Tevatron, LHC, ILC, CLIC, FCCee, FCChh...):

Starting from the center of the detector:

- vertex detector
  as close to the beam line as possible, used to measure the exact position of the interaction point, allows for identification of short-lived particles (secondary vertexes)
  silicon pixel detectors

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Starting from the center of the detector:

- vertex detector
  as close to the beam line as possible, used to measure the exact position of the interaction point, allows for identification of short-lived particles (secondary vertexes)
  silicon pixel detectors
- tracking detectors
  measure tracks of charged particles, allows to determine their momentum from bending in magnetic field
  gas detectors or silicon strip detectors

## Universal detector

- electromagnetic calorimeter
  electron and photon energy measurement
  dense material absorbing EM cascade
  (copper, lead, tungsten)

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  dense material absorbing hadronic cascade (iron, lead, uranium)
  hadronic cascade is many times longer than EM one

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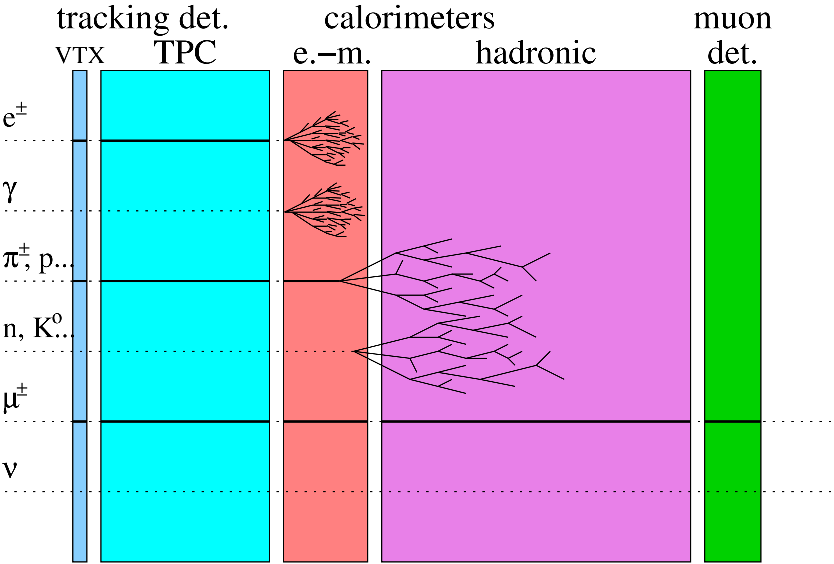
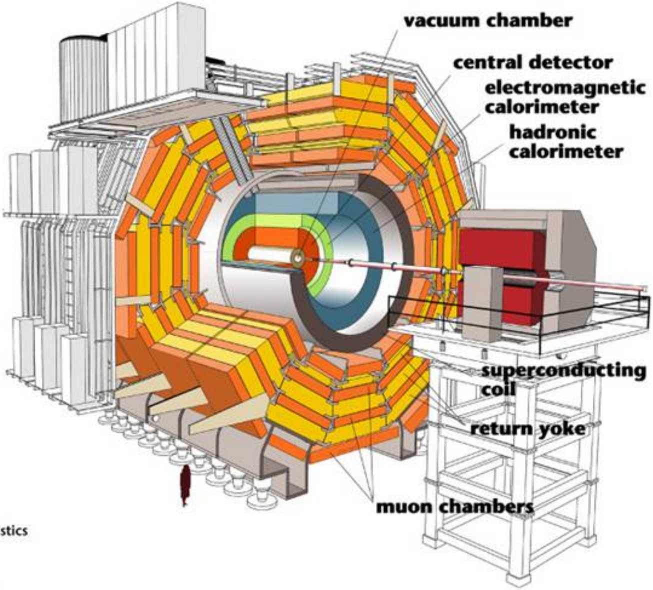
  hadronic cascade is many times longer than EM one

- muon detectors
  identify muons - only charged particles which can pass both calorimeters with small energy losses

# Collider experiments



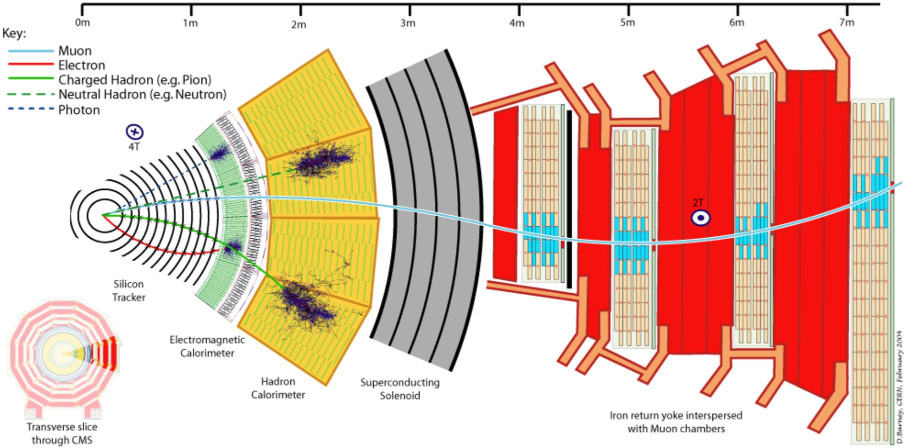
# CMS experiment




Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

## Compact Muon Solenoid - CMS



## Particle Identification

General concept, layout of universal collider experiment allows for partial particle identification. Following particles can be directly identified:

- electrons, positrons and photons
  dense shower in EM calorimeter, with or without matching track
- muons
  charged track + MIP signal in calorimeters + signal in muon detectors
- charged and neutral hadrons
  all other particles (with and without matched track);
  for small fraction of events, more detailed identification is possible based on the decay reconstruction...

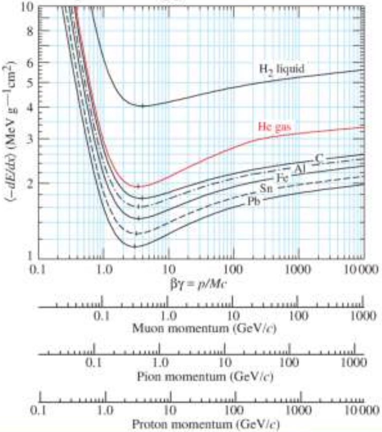
The general problem is that universal detector (tracking+calorimeters) can not differentiate between different hadron types.

**Can we do it with some dedicated instruments?**

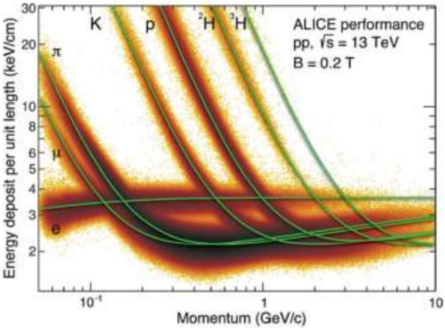
**Ionisation losses** Lecture 4

Universal shape of the dependence for different particles!
Scales with $\beta\gamma = p/M$.

Average energy loss




Ionization losses in ALICE TPC

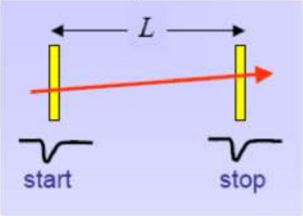



Only partial identification possible...

## Particle Identification Detectors

## Principle of operation

Time of flight measurement can be used to estimate particle mass



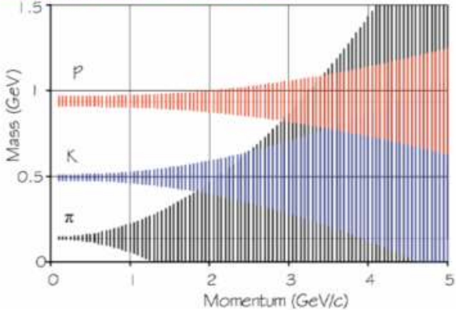

$$p = \beta\gamma m$$

$$l = \beta c t \Rightarrow m^2 = \frac{p^2}{l^2}\left(c^2t^2 - l^2\right)$$

Example:

$l = 12m$, $\sigma_t = 150ps$, $\frac{\sigma_p}{p} = 1\%$

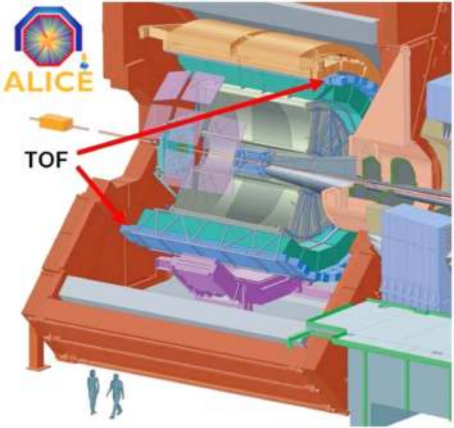
$\pm 1\sigma$ mass uncertainties

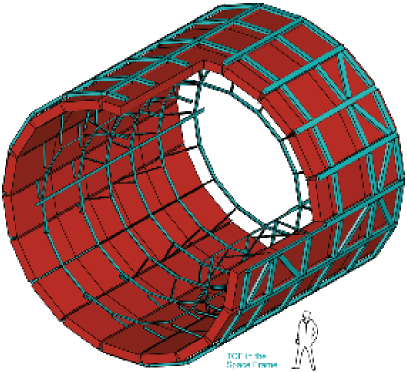



Efficient identification only in low momentum...

## Example: ALICE ToF Detector

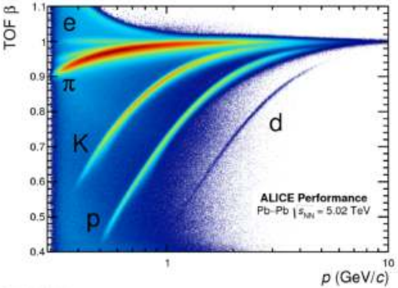
Placed between tracking detector system and calorimeters



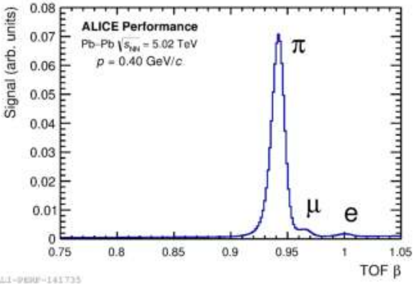



## ALICE ToF: performance arXiv:1809.00574

2D event distribution




Reconstructed $\beta$ for p = 0.4 GeV



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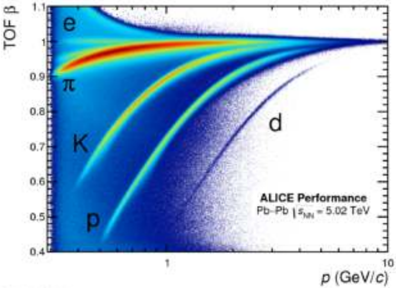
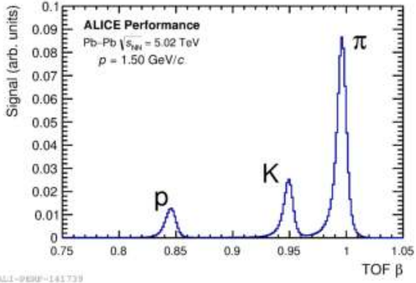
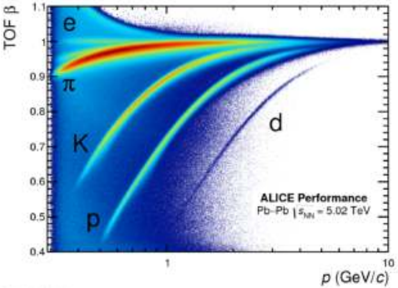



Reconstructed $\beta$ for p = 1.5 GeV

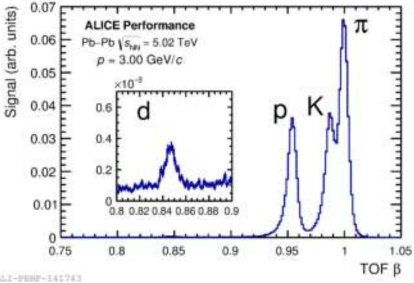


## ALICE ToF: performance arXiv:1809.00574

2D event distribution

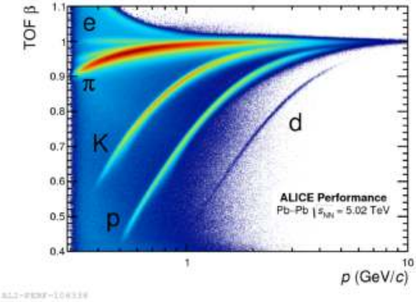



Reconstructed $\beta$ for p = 3 GeV

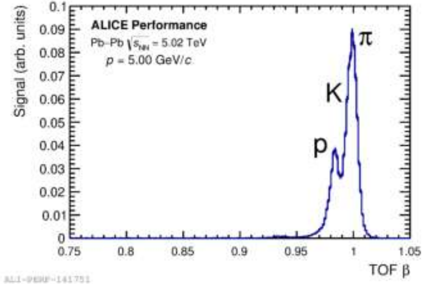


## ALICE ToF: performance arXiv:1809.00574

2D event distribution

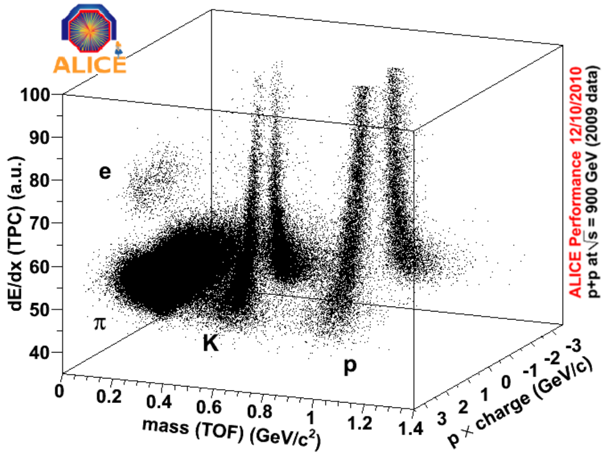



Reconstructed $\beta$ for p = 5 GeV



## ALICE ToF vs dE/dx arXiv:1101.3276

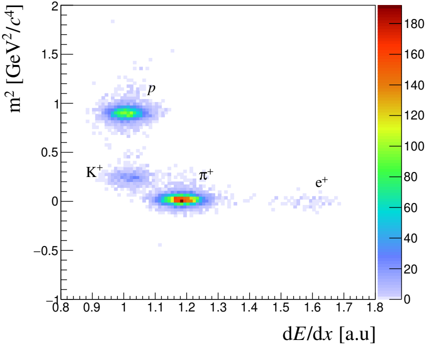
Improved PID capabilities by combining the ionization measurements in the TPC and the mass calculated using the TOF signal



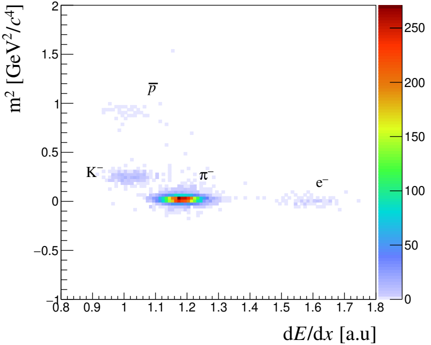
## NA69/SHINE ToF vs dE/dx    P.Podlaski, PhD Thesis

Improved PID capabilities by combining the ionization measurements in the TPC and the mass calculated using the TOF signal

Positive




Negative particles




Example distributions for data bin: 2 GeV/c $< p <$ 3 GeV/c & 0.5 GeV/c $< p_T <$ 0.6 GeV/c

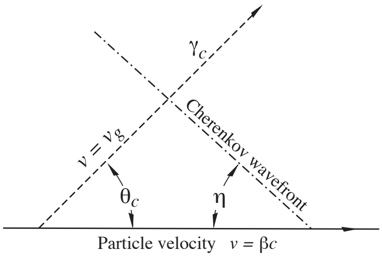
## Particle Identification Detectors

## Cherenkov radiation

When speed of charged particle is greater than the local phase speed of light ($\beta > \frac{1}{n}$), small part of its energy is lost in form of Cherenkov radiation

Angle of radiation:

$$\cos\theta_c = \frac{1}{n\beta}$$




Wide spectra of radiation

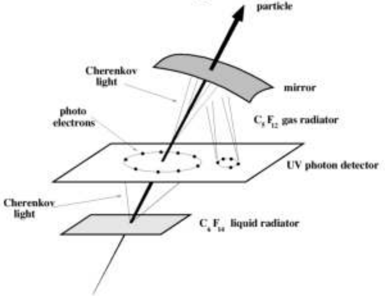
$$\frac{d^2 N_\gamma}{dE_\gamma dx} = \frac{\alpha z^2}{\hbar c} \sin^2\theta_c(E_\gamma) \approx 370 \frac{1}{eV \cdot cm} \cdot \sin^2\theta_c$$

Measurement of the radiation opening angle ⇒ particle velocity

First applications: threshold counters

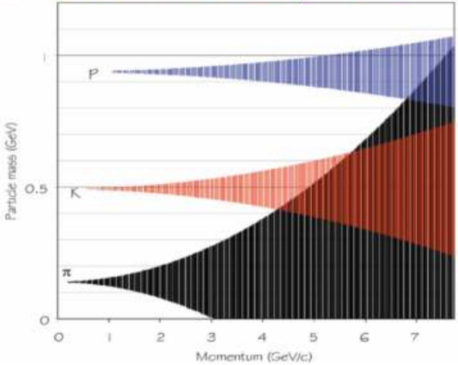
## RHIC Ring Imaging CHerenkov detector

When the light is emitted towards the spherical mirror, it can be focused to form ring images

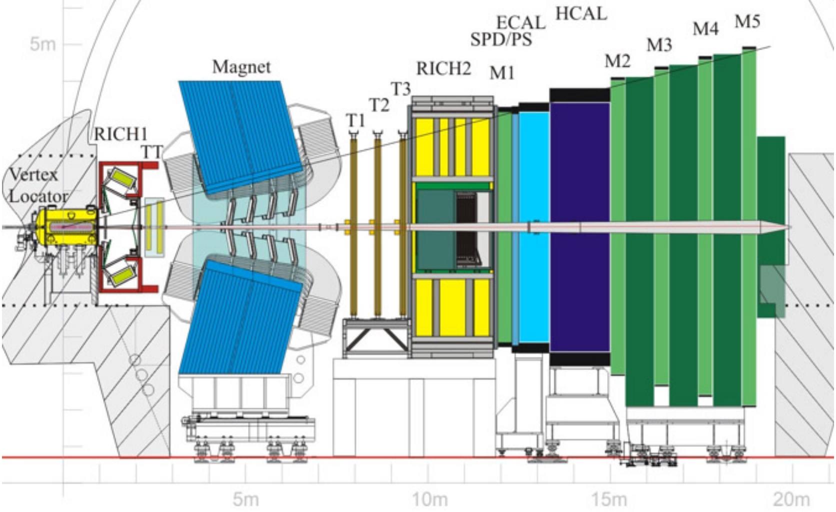



Ring size allows for direct emission angle ⇒ speed determination

Example:
$n = 1.333$, $\sigma_\theta = 15mrad$, $\frac{\sigma_p}{p^2} = 5 \cdot 10^{-5}$

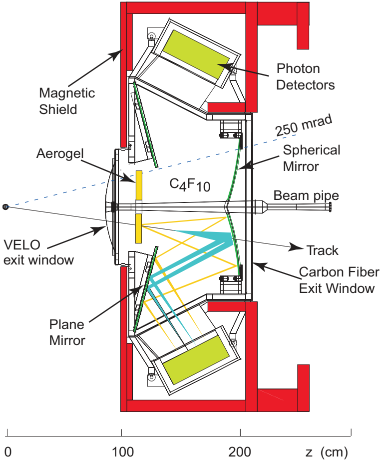


**LHCb detector** The LHCb Collaboration et al 2008 JINST 3 S08005

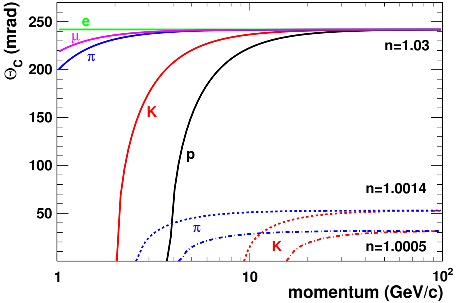


## LHCb RICH arXiv:1101.3276

RICH1




Three radiators to cover large momentum range

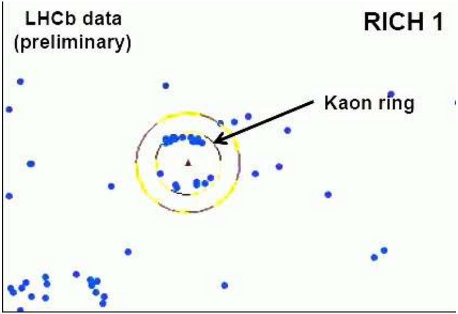


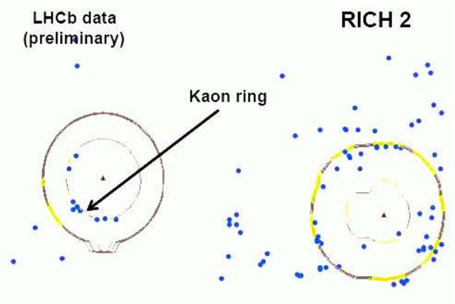

Physics goal:

$K/\pi$ separation up to 100 GeV

## LHCb RICH

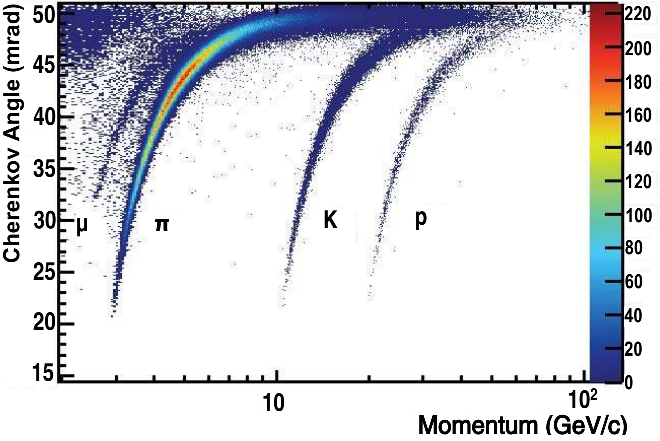
RICH images from first LHCb data



**LHCb RICH** Carla Marin @ ICHEP'2018

Combining light rings and momentum measurements in LHC Run 2:



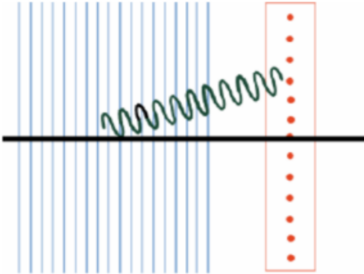
## Particle Identification Detectors

## Transition radiation

Charged particle radiates also when it crosses suddenly from one medium to another with different optical properties

Average radiated energy:

$$W \approx \frac{\alpha}{3}\hbar\omega_p\,\gamma$$



$\omega_p$ - plasma frequency $(\hbar\omega_p \sim 20eV)$

Photon energies: $\hbar\omega \approx \frac{1}{4}\hbar\omega_p\,\gamma$

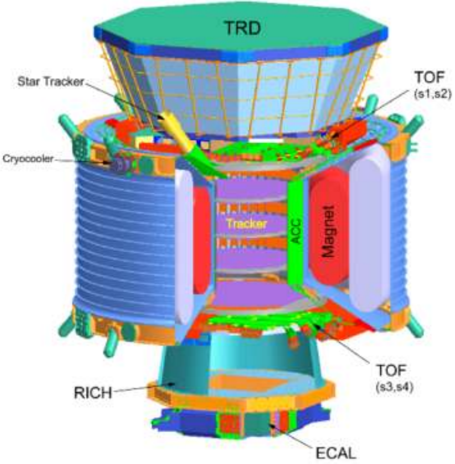
$\Rightarrow$ emission probability $\sim \alpha = \frac{1}{137}$

Signal enhanced by using a stack of N foil radiators

Used mainly for $e^{\pm}$ identification at large energies $(\gamma = E/m)$

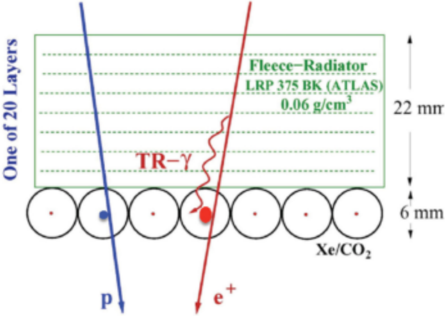
## AMS 02

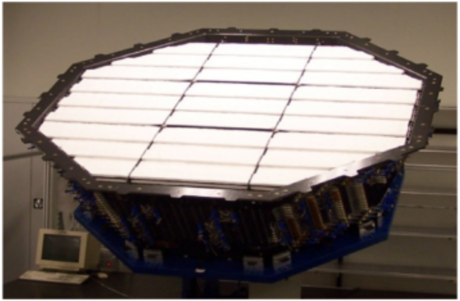
Particle detector at ISS. Multiple particle identification capabilities




## AMS 02 TRD

Detector consists of 20 detection layers (radiator + straw tubes)

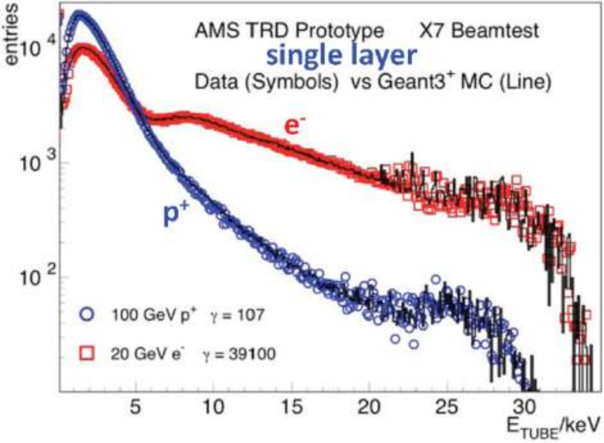


Focus on $e^+/p$ discrimination (radiation $\sim \gamma$)

## AMS 02

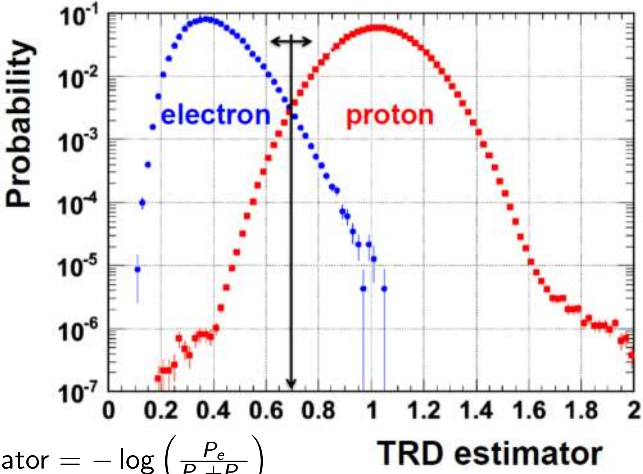
Results of TRD prototype tests at CERN SPS




Electrons radiate much more, but still not enough in single layer...

## AMS 02

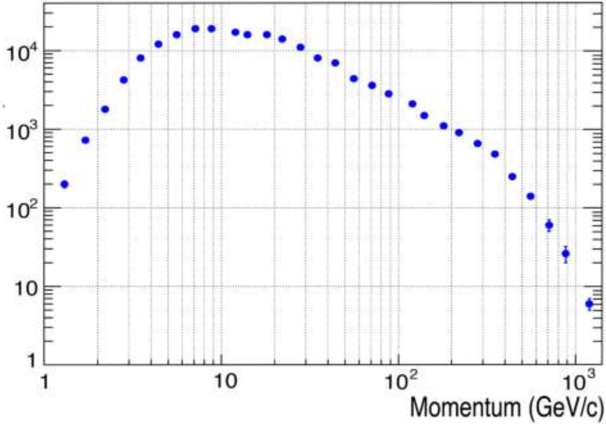
Detector performance (20 layers) as measured at ISS




$$\text{TRD estimator} = -\log\left(\frac{P_e}{P_e+P_p}\right)$$

## AMS 02

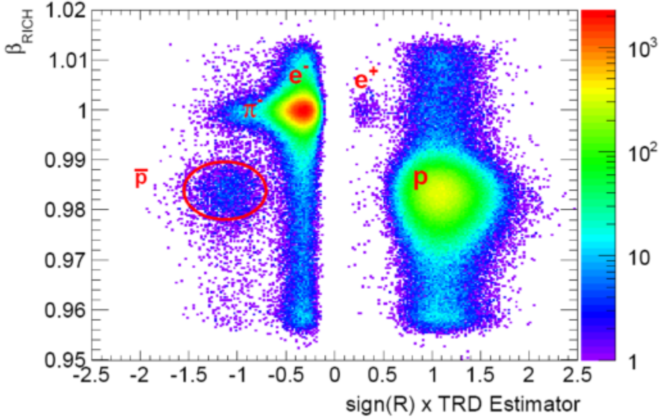
ISS data analysis (20 layers): proton background rejection factor




Proton background reduction in $e^+$ flux measurement by factor $\sim 10^4$

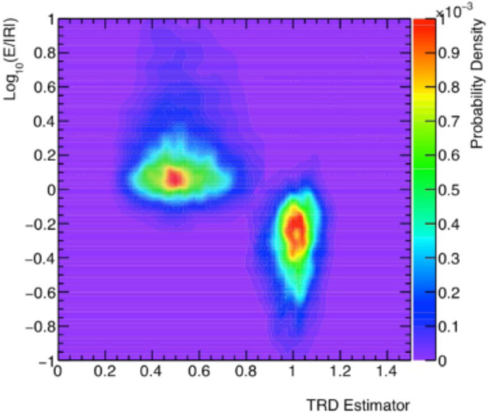
## AMS 02

Correlation of TRD estimator and RICH detector response



## AMS 02

EM calorimeter response (relative to track momentum) vs TRD estimator




For protons, only small fraction of energy is deposited in EM calorimeter

## Particle Identification Detectors

## Primary cosmic rays

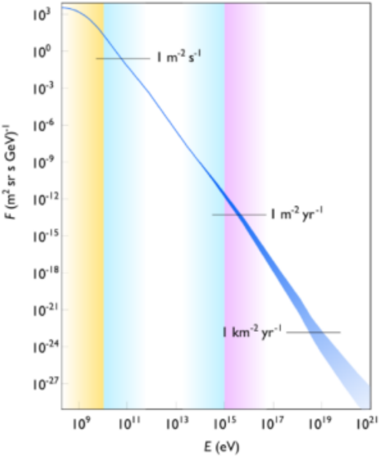
Observed in the cosmic space, outside Earth's atmosphere

Composition:

- protons ($^1H$) $\sim$ 86%
- $\alpha$ particles ($^4He$) $\sim$ 13%
- heavier nuclei $\sim$ 1%
- neutrons, electrons $\ll$ 1%

  (neglecting neutrinos and gammas)

Same as the "composition of the Universe..."

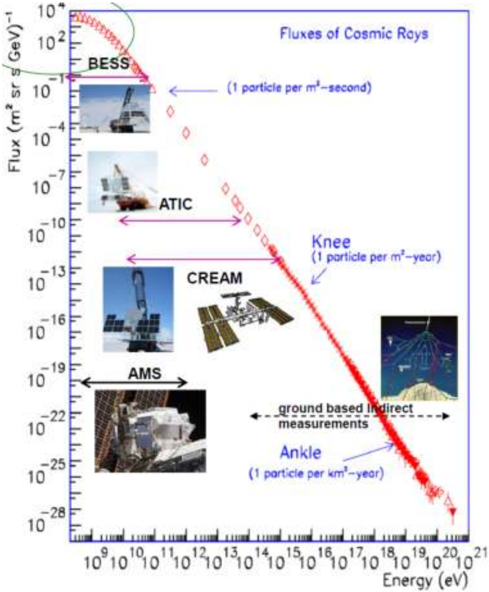


## Primary cosmic rays

Earth's atmosphere shields us from the primary cosmic rays.

They can be measured directly only with stratospheric balloon or satellite experiments

For high energies, we can measure cosmic rays indirectly, by observing development of the Extensive Air Showers (EAS) in the atmosphere or Secondary Cosmic Rays at the surface



## Secondary cosmic rays

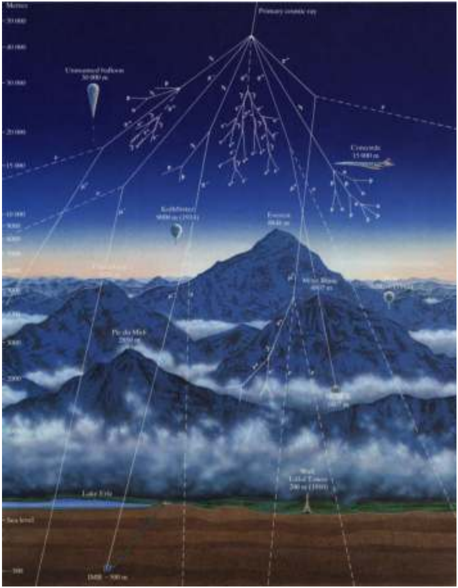
Result of the primary cosmic ray interactions in the Earth's atmosphere. Secondary particles, mainly pions and kaons, are copiously produced in these interactions. Both pions and kaons are unstable, produced in their decay chain are muons and electrons.

At the sea level:

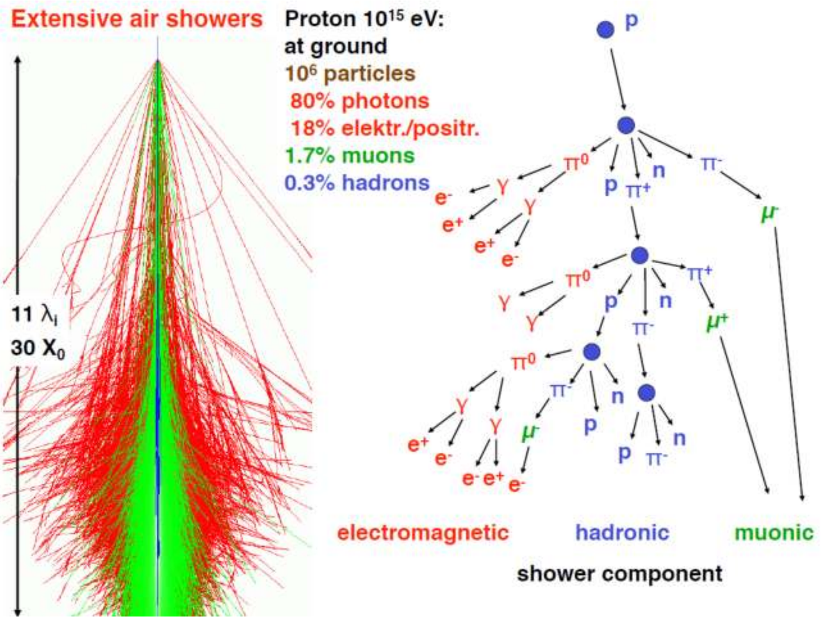
- muons $\mu^{\pm}$ $\sim$70%
- electrons $e^{\pm}$ $\sim$25%
- protons and pions $\pi^{\pm}$ $\sim$3%

Average flux:

180 charged particles per $m^2 \cdot s$



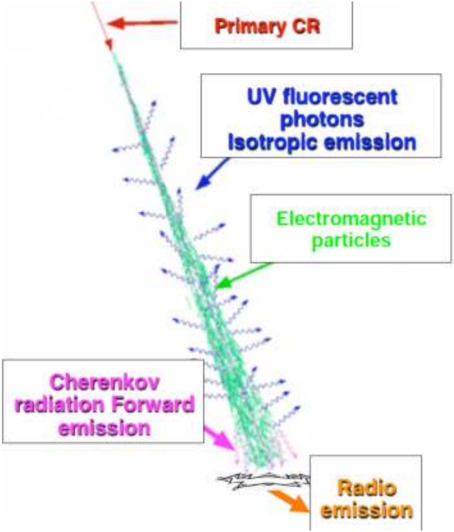
# Large detector systems



## Extensive Air Showers

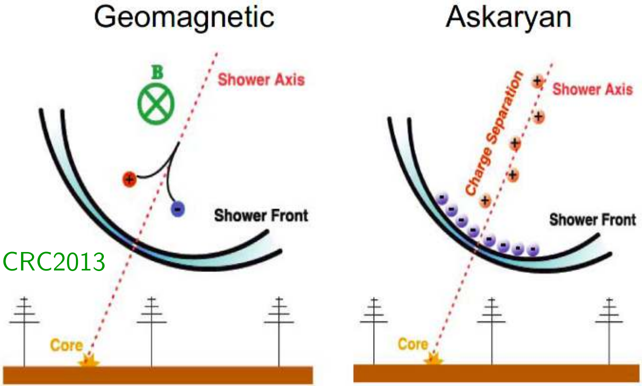
Detection channels:

- charged particles reaching Earth's surface, mainly electrons and muons (secondary cosmic rays)
- Cherenkov radiation from electrons in EM core of the cascade
- fluorescent light from excited nitrogen particles in the atmosphere
- radio emission



## EAS radio emission

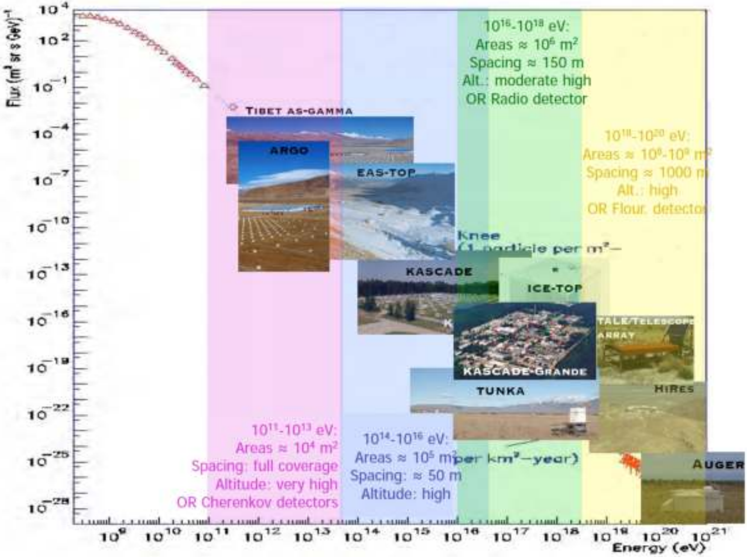
Radio emission is due to the space separation of negative and positive particles in the cascade. Two separation mechanisms:




T. Huege, ICRC2013

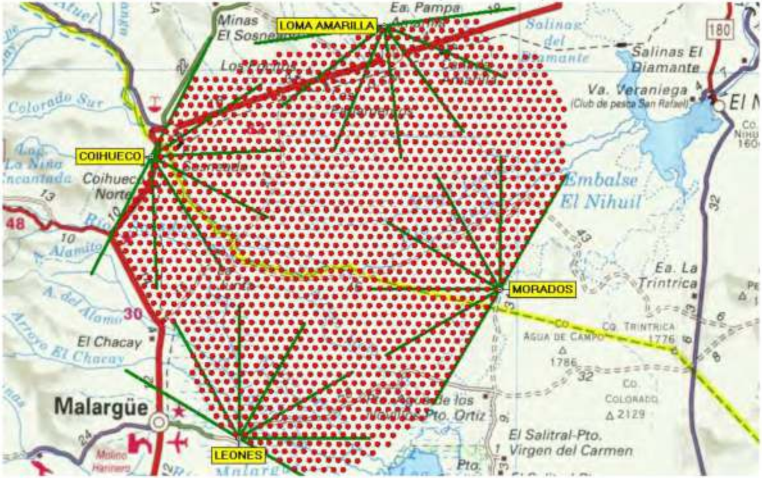
Different polarisation of radio emission for the two components

## Extensive Air Shower experiment



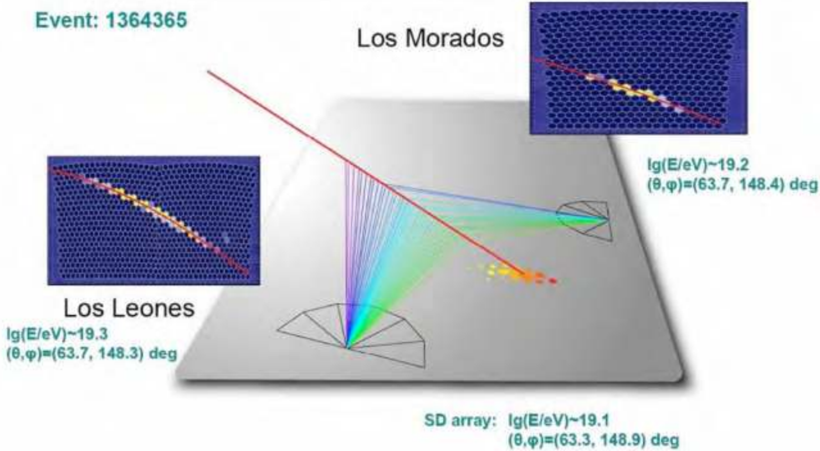
## AUGER

Largest particle physics experiment built so far (3000 km$^2$, 1600 units)
focus on Ultra High Energy Cosmic Rays (UHECR), above $10^{18}$ eV



## AUGER

Hybrid EAS measurement: fluorescent telescopes and surface detectors



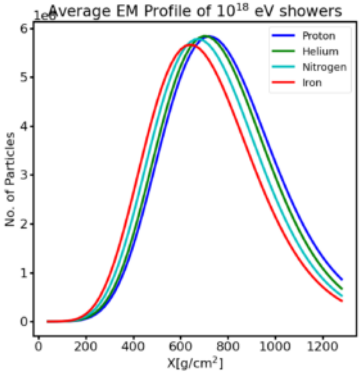

$\Rightarrow$ validation of energy reconstruction and energy calibration

**Primary Cosmic Ray identification** simulations by P.Mitra

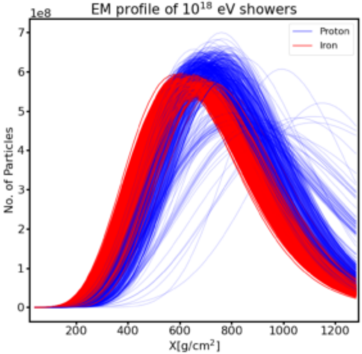
Shower development in the atmosphere depends on the initial particle mass

⇒ we can discriminate between single protons and heavier nuclei

Base on average depth of shower maximum for given energy

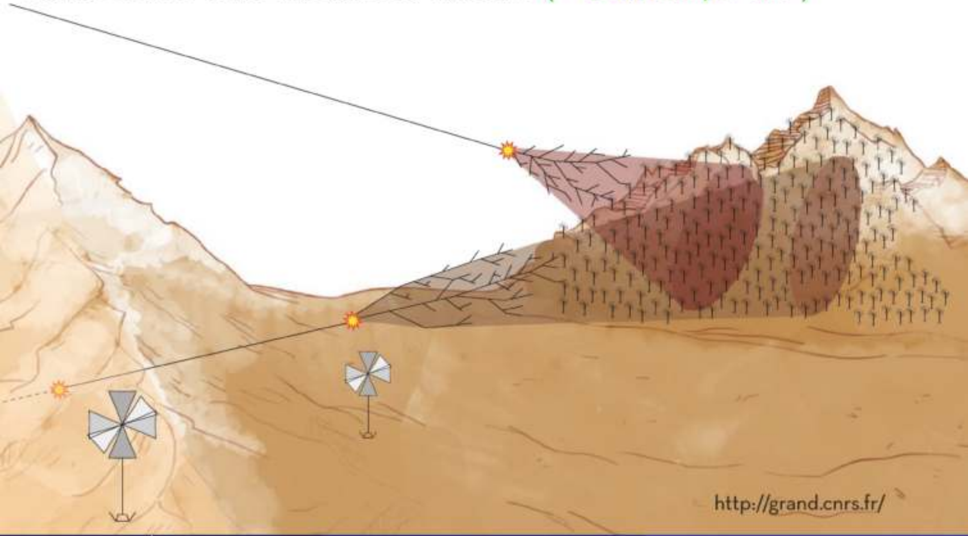



Based on maximum depth variation for given energy



**Giant Radio Array for Neutrino Detection** (GRAND)

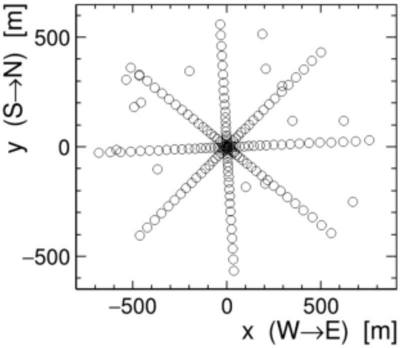
Aim: 200,000 radio antennas on hill sides ($\sim 1$ antena per km$^2$)



**Shower reconstruction** 06_uhcr_detection.ipynb

Principle: shower development is measured on Earth surface with very sparse grid of detectors.

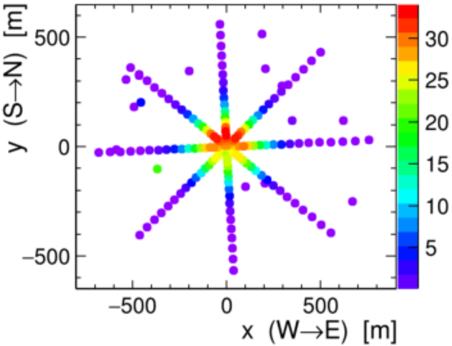
Example configuration used for simulation studies



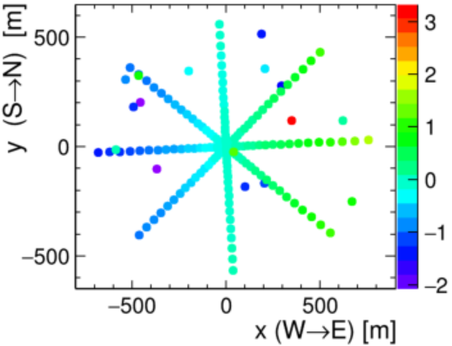
## Shower reconstruction    06_uhcr_detection.ipynb

Principle: shower development is measured on Earth surface with very sparse grid of detectors.

Radio pulse amplitude



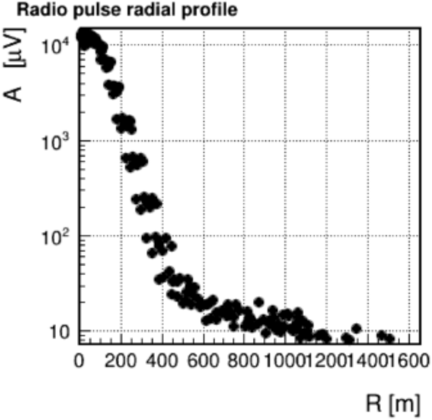

Pulse arrival time



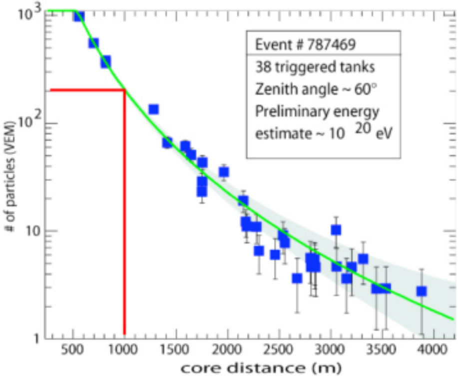
## Shower reconstruction

Reconstructed radial profile can be used to extract shower energy

GRAND simulation



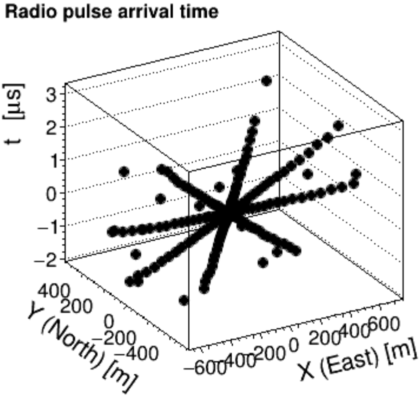

AUGER data




AUGER energy measurement based on S(1000)

## Reconstruction of shower arrival direction

Implement the procedure for fitting the shower arrival direction (zenith and azimuth angles) based on the radio pulse arrival times measured with ground-based antennas.




Reconstruct shower direction for the six example data files available with the lecture notebook.

Try to estimate effective time reconstruction precision