Development of the instrumentation and readout schemes of MARTA

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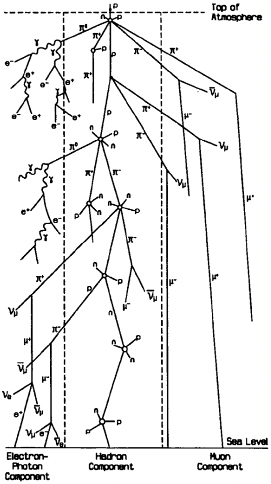
Motivation

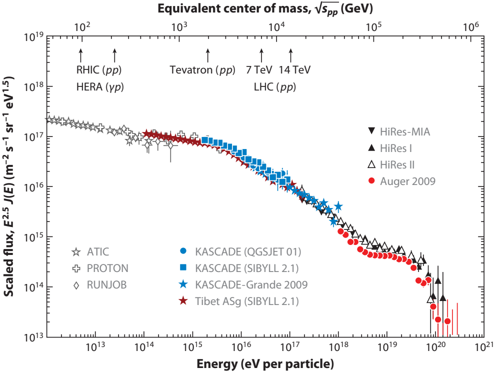
Cosmic rays are extremely energetic particles, created in the most violent events in the universe, that travel the universe.

- They can be either elementary particles or nuclei
- Some of them collide with the earth's atmosphere, after travelling through space for millions of light-years
- The result of such collisions are known as Extensive Air Showers
- After the first interaction, the particles created can be divided into three components: electromagnetic, hadronic and muonic
- **The main questions about cosmic rays are their origins, and how these particles propagate in the universe**
- The focus is mostly on the following three aspects: energy spectrum, primary composition, and arrival direction



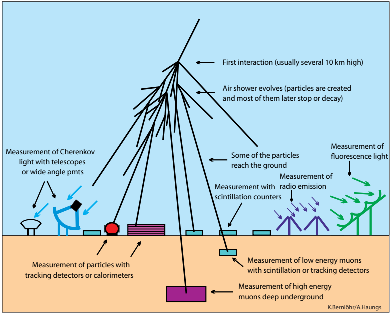
P. K. F. Grieder, Cosmic rays at earth. Bern, Switerland: Elsevier Science, 2001

- Energy spectrum: the flux of particles as a function of their energy
- The variations in slope along the spectrum can be explained by changes in the composition, and even their source (galactic vs extragalatic)
- The end of the spectrum is characterized by a suppression of the flux, best explained by the GZK



R. Engel et al., "Extensive Air Showers and Hadronic Interactions at High Energy," Annual Review of Nuclear and Particle Science, vol. 61, no. 1, p. 467, 2011

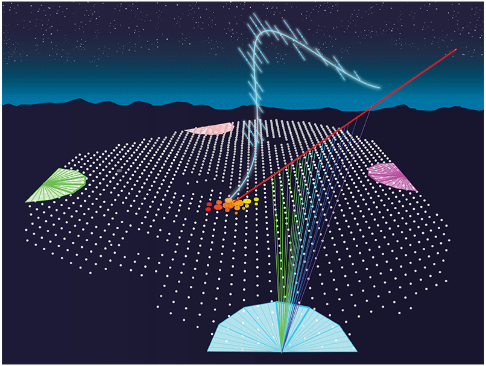
- Cosmic rays can be measured directly, using dectectors installed in satalites, or inderectly by measureing the EAS content at ground level
- Ground detectors can be divided into three types:
    - Particle detectors
    - Light detectors
    - Radio detectors



A. Haungs, "Cosmic rays from the knee to the ankle," Physics Procedia, vol. 61, p. 425, 2015

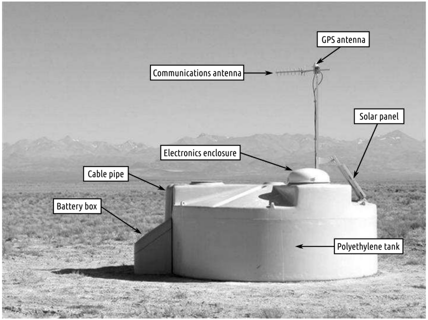
The Pierre Auger Observatory is a hybrid detector that combines multiple detections techniques to measure the extensive air showers.

- Largest cosmic ray observatory in the world, locaded in western Argentina, at 1400 m a.b.s.
- It aims to measure cosmic rays with energies above 10^{17} eV, covering an area of 3000 km^2
- The main detectors of the Observatory are the Surface Detector (SD) and the Fluorescence Detector (FD).

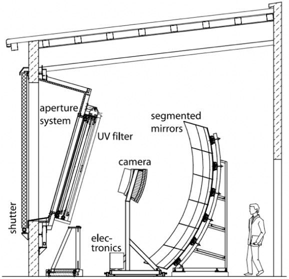


T. Gaisser, "Viewpoint: Cosmic-Ray Showers Reveal Muon Mystery," Physics 9, no. 125, 2016

- The surface detector consists of 1660 water-Cherenkov detector (WCD), 1.5 km apart
- The WCDs are cilinder with a height of 1.2 m filled with 12 tones of ultra pure water
- The SD measures a slice of the EAS at ground level by being responsive to the electromagnetic and muonic components of the shower
- It allows to determine the arrival directions and to estimate the energy of the primary cosmic-ray



- The FD consists of 24 telescopes, in four sites, overlooking the SD array
- The field of view of each telescope is $30^\circ \times 30^\circ$ in azimuth and elevation
- The FD provides information about the shower's development, including the depth of the shower maximum, $X_{\max}$
- The light is emitted isotropically in the ultraviolet part of the spectrum, being mostly produced by the electromagnetic component of the shower
- The energy deposit in the atmosphere by the EAS is proportional to the amount of light emmited, allowing to determine, the primary energy



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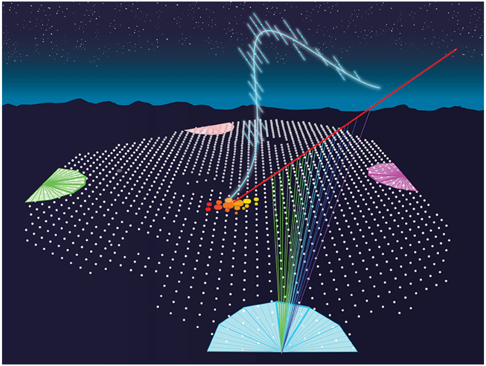
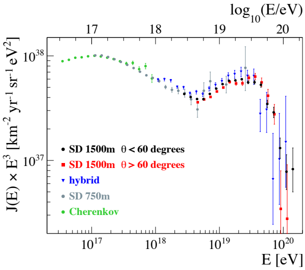
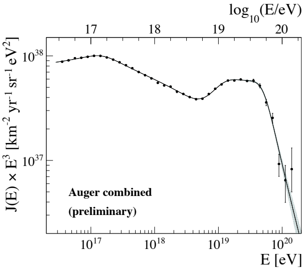
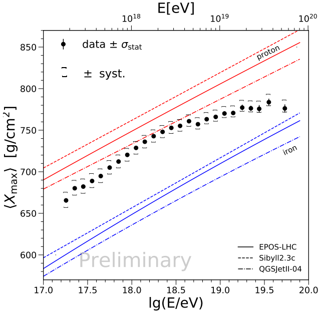


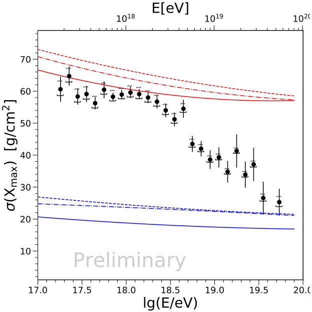
T. Gaisser, "Viewpoint: Cosmic-Ray Showers Reveal Muon Mystery," Physics 9, no. 125, 2016

Results: Energy spectrum and composition





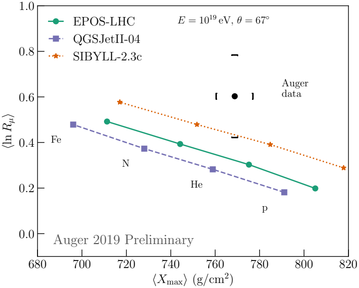




Number of muons

Muons constitute one of the best links to the hadronic interactions in the EAS since these are created in the decay of the shower hadrons

- The WCD measures a combination of the different components of the showers
- The muonic component is determined indirectly, introducing significant uncertainties
- Auger's results show a muon deficit in simulation (or muon excess in data)
- The results call for an independent direct measurement of the muon content

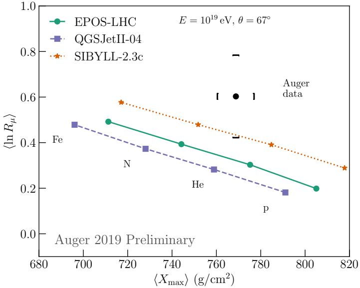


F. Riehn, Measurement of the fluctuations in the number of muons in inclined air showers with the Pierre Auger Observatory, ICRC2019

Number of muons

Muons constitute one of the best links to the hadronic interactions in the EAS since these are created in the decay of the shower hadrons

- A direct, independent and accurate measurement of the muons allows to:
    - Have composition sensitivity on a shower-by-shower basis
    - Study hadronic interactions at the highest energies
    - Improve the sensitivity to photon primaries
    - Better understand and reduce the systematic uncertainties of many different measurements

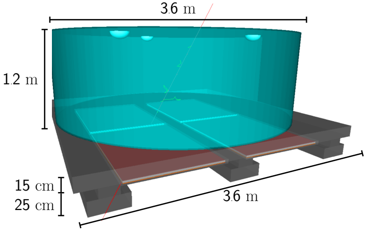


F. Riehn, Measurement of the fluctuations in the number of muons in inclined air showers with the Pierre Auger Observatory, ICRC2019

MARTA

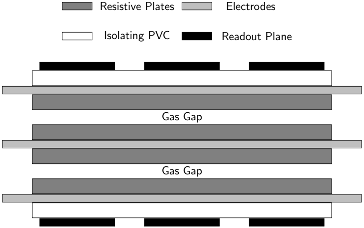
Concept

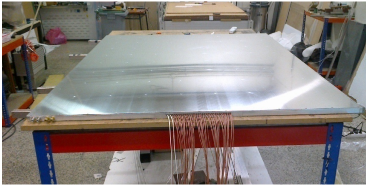
- Four detectors of charged particles are placed inside a concrete structure underneath the WCD
- The mass above will act as shielding for the electromagnetic components
- The two detectors will measure the same particles, and the energies of the muons are mostly the same
- With this setup, the electromagnetic component can be assessed by subtracting the muons measured independently to the total signal given by the WCD
- RPCs were chosen - LIP has experience developing and building this detector



The detector - Resistive Plate Chamber

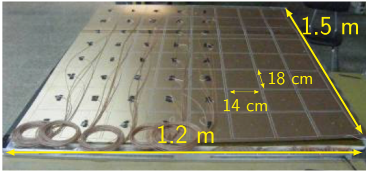
- RPCs are widely used gaseous detectors of charged particles
- Introduced in 1981 as an alternative to spark counters: RPCs are simpler to build, operate and its cost was greatly reduced
- They are known for being robust, low-cost, having high particle detection efficiency, and excellent spatial and time resolutions
- There are a variety of configurations, materials, and gas mixtures being used that allows tuning the RPC to the characteristics of the different applications
- Mostly used in laboratory conditions
- MARTA's configuration: two 1 mm gas gaps, separated by three 2 mm thick glass plates electrodes

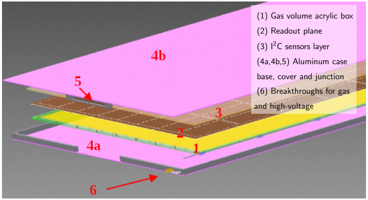




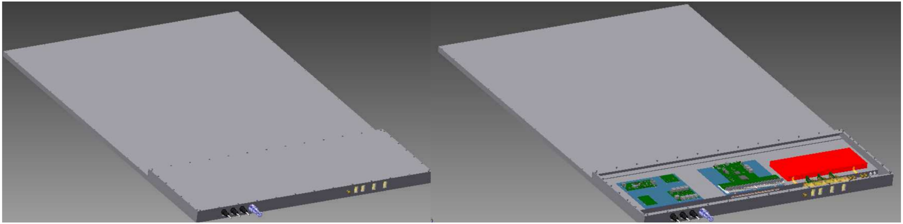
MARTA RPC

- Double gap RPC in avalanche mode with an area of $1.5 \times 1.2\ \mathrm{m}^2$
- High voltage is applied to the outer glasses through a layer of resistive acrylic paint
- The glass stack is enclosed by a gas-tight acrylic box defining the sensitive volume
- It operates with a mono-component gas R-134a, at a flow rate of 4 cc/min
- The readout plane has 64 pickup electrodes distributed in an 8×8 pad grid and is placed on the top of the sensitive volume
- The pads have an area of $14 \times 18\ \mathrm{cm}^2$ and are separated by a 1 cm guard ring making the readout area 90% of the total area



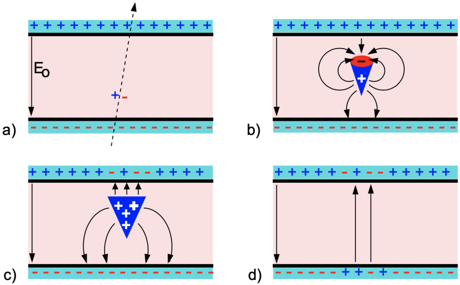


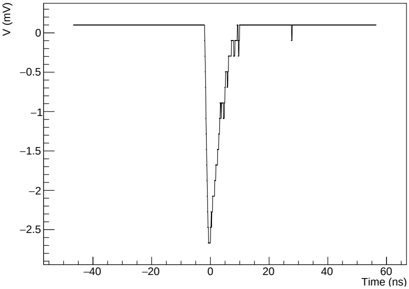
- A MARTA module is a sealed aluminium structure with gas, power, and communication connections
- The sensitive volume is placed inside an aluminium structure that also hosts the electronics
- The electronics box is $0.447 \times 1.285\mathrm{m}^2$, and it contains, the front-end, high voltage and detector monitoring



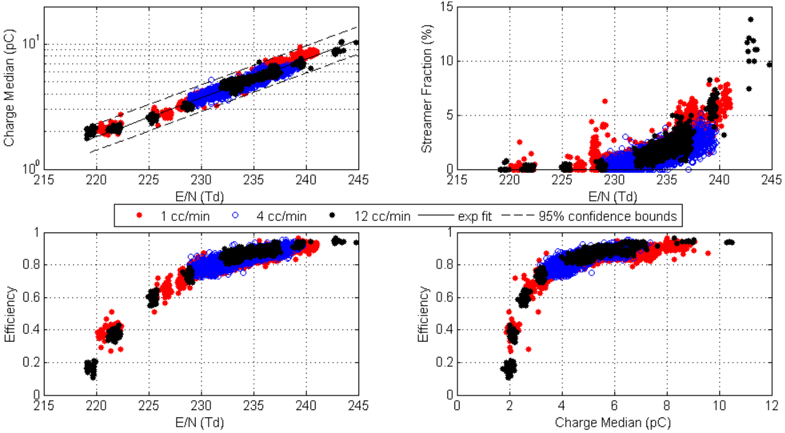
Signal induction

- Whenever a charged particle crosses the detector, it ionizes the gas creating electron-ion pairs
- Due to the strong applied uniform electric field, the free electrons will drift towards the anode while the ions towards the cathode
- During their travel, the electrons will multiply, creating a Townsend avalanche
- The movement of charges inside the gap will induce a current signal in the readout
- The small drift velocities of the ions make the signal induced by them much slower and smaller





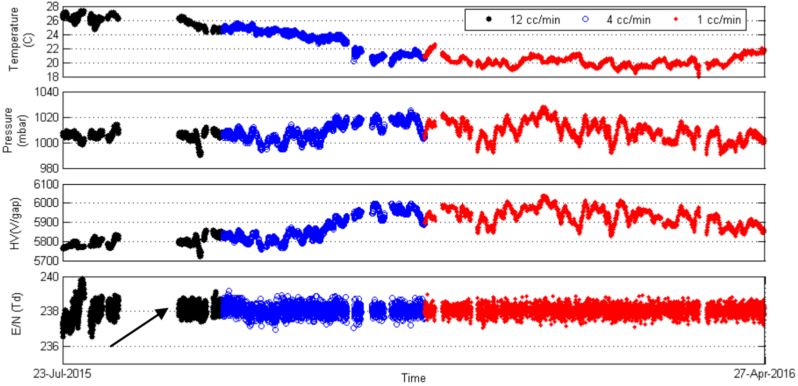
Laboratory tests: Reduced Electric Field, Efficiency, and Charge



L. Lopes, Resistive Plate Chambers for the Pierre Auger array upgrade, JINST 2014

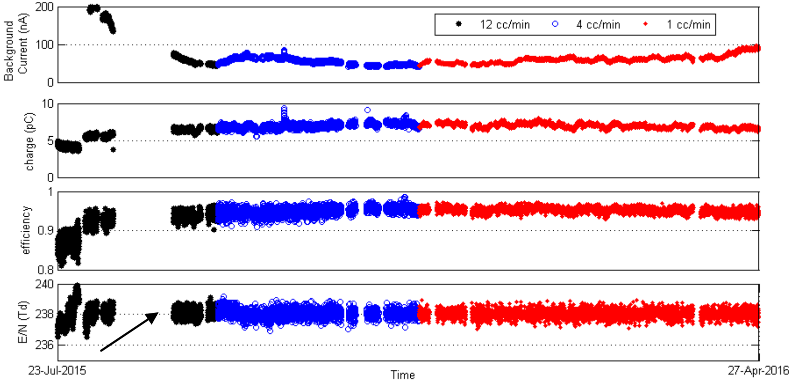
$$\mathrm{E/N} = 0.0138068748 \frac{V_{eff}}{d} \frac{T + 273.15}{P} \; [\mathrm{Td}]$$

Laboratory tests: E/N constant



L. Lopes, Outdoor field experience with autonomous RPC based stations, JINST 2016

Laboratory tests: E/N constant → efficiency stable



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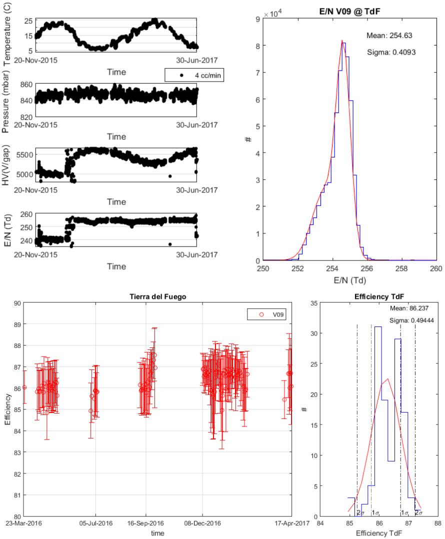
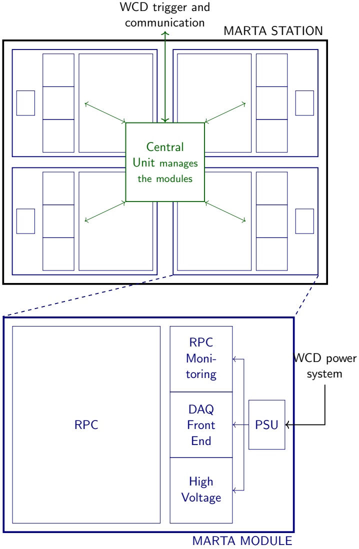
Field tests: Tierra del Fuego setup @ Batata



L. Lopes, Long term experience in autonomous stations and production quality control, JINST 2019

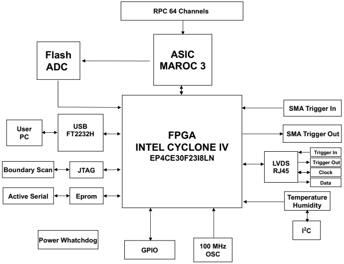
Station

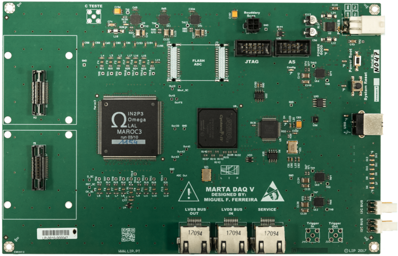
- Each station has four detector modules
- A Central Unit is responsible for the management of the modules and the interface with the WCD
- All the parts of the MARTA station were designed to comply with the strict demands of outdoors operations: limited space, power, minimal maintenance and reliability
- The concrete structure alleviates the significant daily temperature changes
- MARTA takes advantage of the WCD triggers and communications



Station - Electronics: Front-end

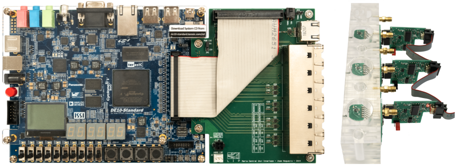
- The 64 RPC channels are read by the MAROC 3 ASIC.
- The RPC signal cables are soldered to a mezzanine board that is connected to the front-end
- An FPGA is responsible for data and measurement management as well as communications via LVDS (low voltage differential signal) with the Central Unit
- DOI: 10.1109/TNS.2018.2879089

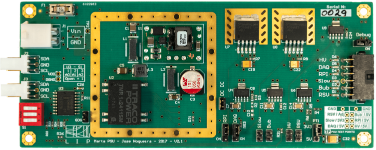


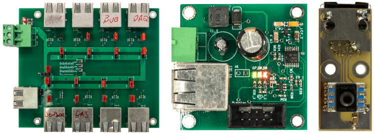


Station - Electronics

- High Voltage: Developed from scratch since no commercially available option would fit. Controlled and monitored via it I^2C, allowing to be dynamically adjusting to keep the reduced electric field constant.
- Power Supply Unit: It gets the 24 V given by the WCD power system and converts it to the required voltages of each component. Also controlled via I^2C.
- Weather monitoring: Composed of a network of temperature, pressure and humidity I^2C sensors placed strategically in the aluminium box

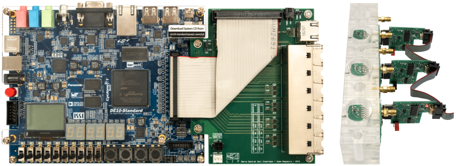
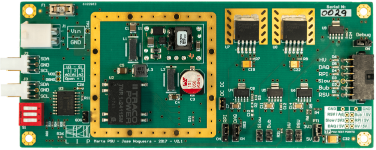
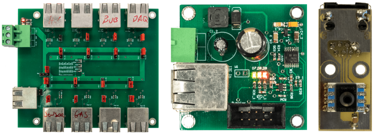






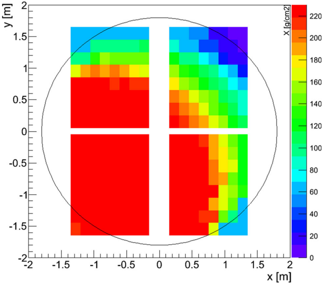
Station - Electronics

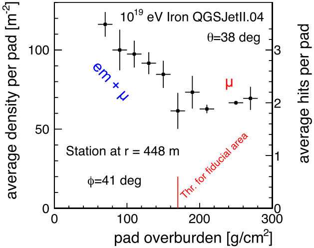
- Gas monitoring: The gas flux is monitored using the bubblers that are installed in the gas input and output. Additionally, a pressure sensor is placed in the gas input
- Central Unit: Controls all the electronics and act as a data concentrator. Based on a development board containing an Intel Cyclone V SoC FPGA with a dual-core ARM hard processor system (HPS). I^{2}C and LVDS buses are available between the Central Unit and each module. It is connected to the network for data transfer with the CDAS

Station expected performance

- The number of muons can be estimated as the number hits in the RPC pads within a fiducial area: pads with a mass overburden greater than $170 \mathrm{g/cm^2}$.
- For a vertical shower that is all pads bellow the WCD
- For an inclined shower with 40° that is 2/3 of the pads
- The muon energy spectrum has its mean energy at about 1 GeV and about 15 % of those are absorbed (energy lower than 340 MeV)

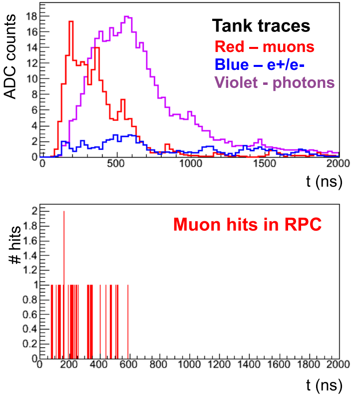




P. Abreu et al., MARTA: a high-energy cosmic-ray detector concept for high-accuracy muon measurement, The European Physical Journal C, 2018

Station expected performance

- The simulated trace of the WCD and RPC signals
- In regions where the density of particles is higher that 35.6 $\mathrm{particles/m^2}$ pile up effects in the pads become relevant
- That is equivalent to the density 500 m from the core of a $10^{19.5}$ eV proton shower with 40°
- The expected rate of atmospheric particles is in the order of 5 - 7 Hz, allowing to reach a statistical precision of 1% every 30 min



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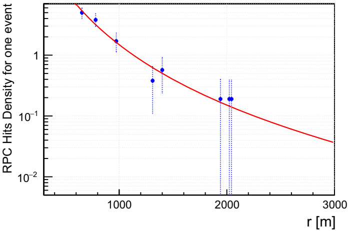
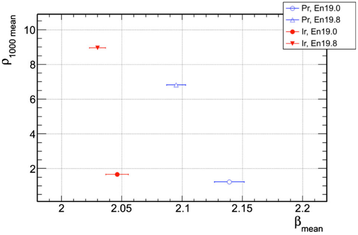
Full array expected performance

- A lateral distribution function (LDF), RPC hits density as a function of the shower core distance, was obtained using simulated results for a $10^{19.8}$ eV proton shower with 38°
- Simulations were performed for different primary and energies
- The mean LDFs for each composition and energy were obtained, and the results for ρ_{1000} and β compared
- The results show a clear separation between proton and iron showers
- In Auger, less then half a year of exposure would be sufficient to reach the statistics used





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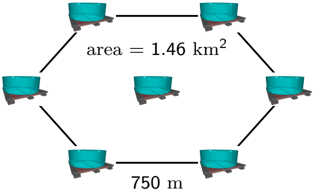
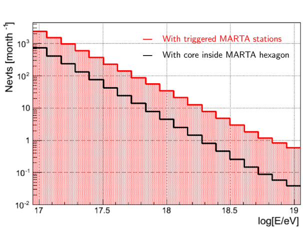
$$\rho_{\mathrm{LDF}}(r,\beta) = \rho_{1000}\left(\frac{r}{1000}\right)^{\beta}\left(\frac{r+700}{1000+700}\right)^{\beta}$$

Engineering Array

- An engineering array of seven MARTA stations is being installed in the Infilled's 750 m array
- Its main goals are to study the MARTA concept, how useful the combined measurement can be, and assess the RPCs performance in the field
- It can also be used to cross-calibrate other detectors in the same region of the array: AMIGA, AERA and the SSD
- The array will not interfere with the normal operation of the standard SD array
- The MARTA EA will measure mostly events in the second knee region of the spectrum, with energies between $10^{16.5}$ eV and $10^{18.5}$ eV

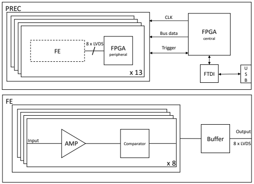


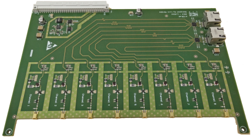


Data acquisition system

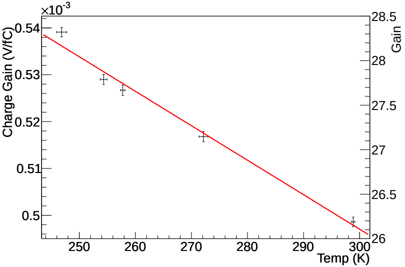
PREC - Prototype Readout Electronics for Counting particles

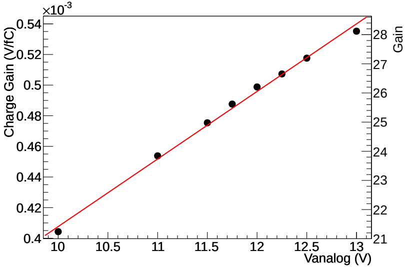
- Built as a proof of concept with discrete electronics
- Low noise, able to discriminate the RPC signals
- Design and characterization published
  doi:10.1088/1748-0221/11/08/T08004
- It has been used in non-MARTA related projects and even with other detectors (silicon PMTs)

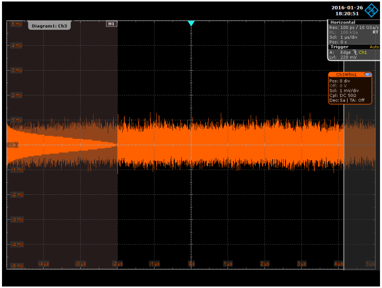


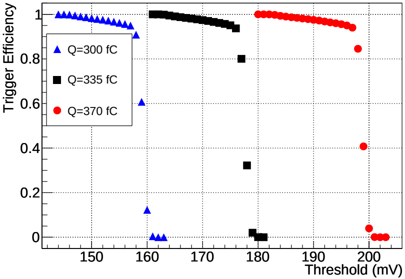


PREC - Characterization



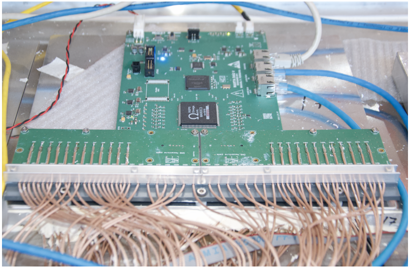






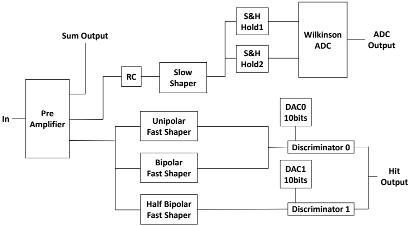
Front-end - Requirements

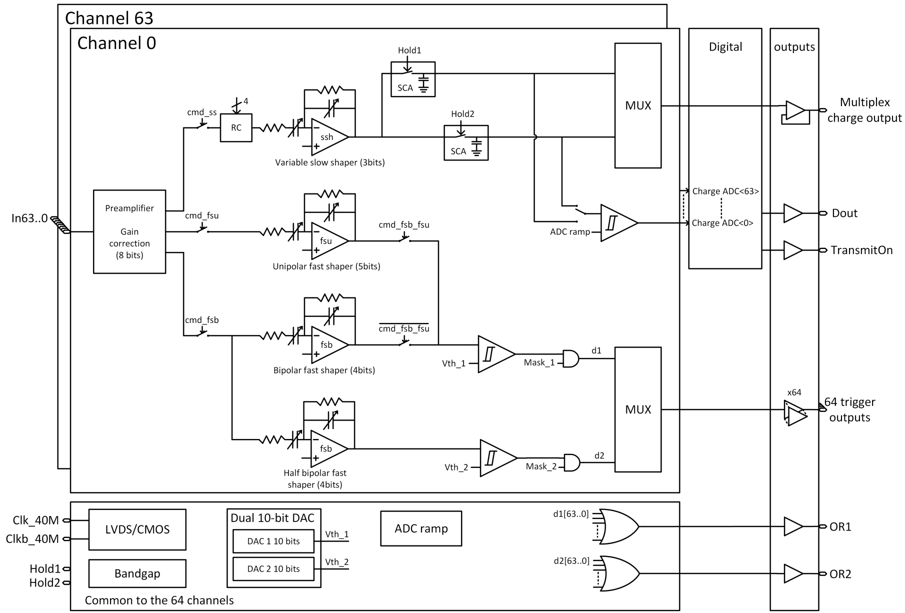
- Fast signal digitization to deal with the fast RPC pulses
- Estimate the number of particles for both the high and low particle density regions of the shower: a complementary charge measurement is necessary
- Low power of a few watts per RPC
- Stable and reliable for low maintenance operation
- Compact design due to space limitation inside the aluminum case
- Trigger inputs and outputs
- Fast lines for communication and data transfer
- Power fail safe mechanism



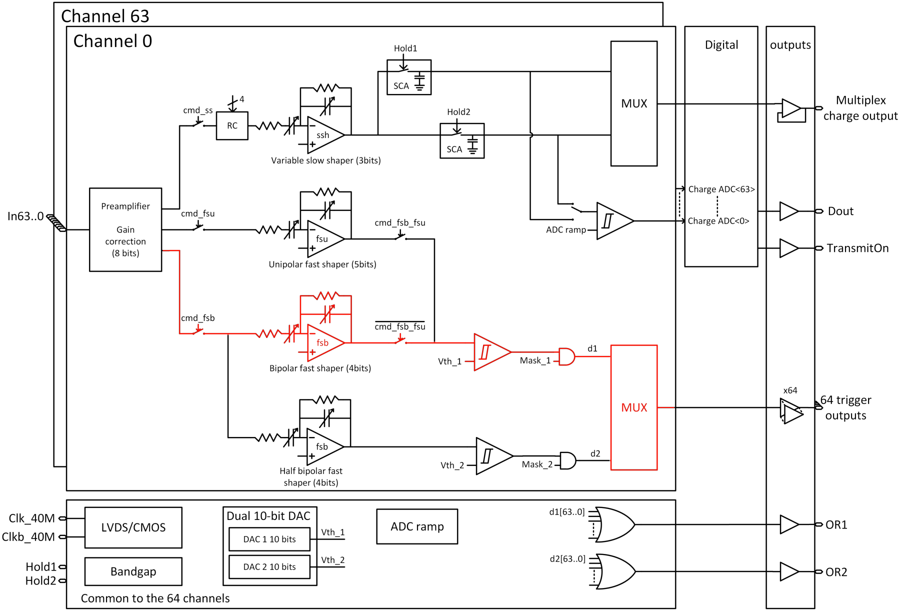
Front-end - ASIC

- Multi Anode Read-Out Chip ASIC, developed by OMEGA
- 64 input channels
- Amplifier with variable gain
- 64 discriminated outputs
- Charge measurements up to ~ 15 pC
- 800+ configurable parameters
- Low power and compact
- Designed and optimized to be used with multi-anode PMTs





Channel 63
Channel 0
In63..0
Preamplifier
Gain correction (8 bits)
cmd_ss
RC
4
ssh
Variable slow shaper (3bits)
Hold1
SCA
Hold2
SCA
MUX
cmd_fsu
fsu
Unipolar fast shaper (5bits)
cmd_fsb_fsu
cmd_fsb
fsb
Bipolar fast shaper (4bits)
cmd_fsb_fsu
fsb
Half bipolar fast shaper (4bits)
ADC ramp
Vth_1
Mask_1
d1
Vth_2
Mask_2
d2
MUX
Digital
Charge ADC<63>
Charge ADC<0>
outputs
Multiplex charge output
Dout
TransmitOn
x64
64 trigger outputs
Clk_40M
Clkb_40M
LVDS/CMOS
Hold1
Hold2
Bandgap
Dual 10-bit DAC
DAC 1 10 bits
DAC 2 10 bits
Vth_1
Vth_2
ADC ramp
d1[63..0]
d2[63..0]
OR1
OR2
Common to the 64 channels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SCA
Hold2
SCA
MUX
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Dout
TransmitOn
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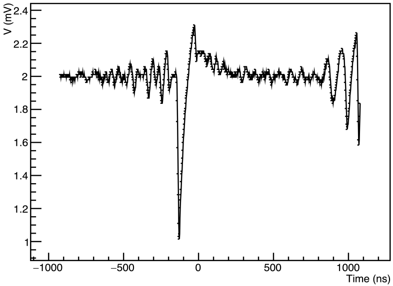
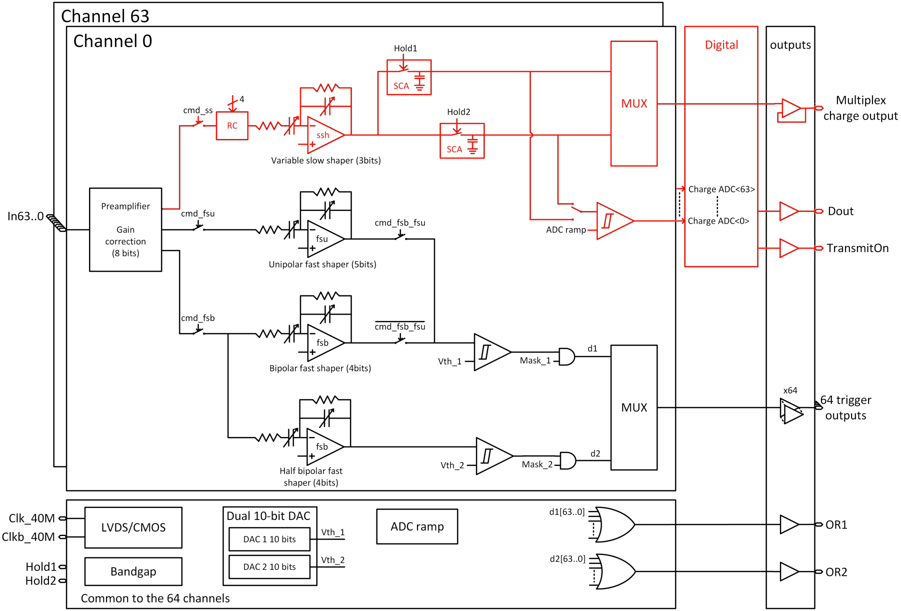
fsb
Bipolar fast shaper (4bits)
cmd_fsb_fsu
Vth_1
Mask_1
d1
MUX
x64
64 trigger
outputs
fsb
Half bipolar fast
shaper (4bits)
Vth_2
Mask_2
d2
Clk_40M
Clkb_40M
LVDS/CMOS
Dual 10-bit DAC
DAC 1 10 bits
DAC 2 10 bits
Vth_1
Vth_2
ADC ramp
d1[63..0]
d2[63..0]
OR1
OR2
Hold1
Hold2
Bandgap
Common to the 64 channels

Fast Shaper branch

- It discriminats the RPC signals → Used to count particle hits
- Three configurable fast shapers can be used
- About 20 ns rising time
- A comparator follows the shaper
- The threshold is set by a 10 bit DAC




Channel 63
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Dual 10-bit DAC
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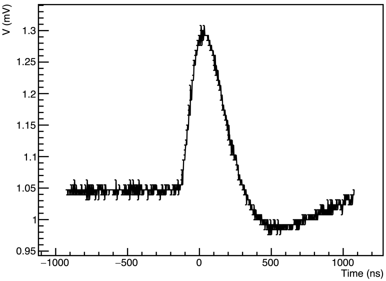
Vth_1
Vth_2
ADC ramp
d1[63..0]
d2[63..0]
OR1
OR2
Hold1
Hold2
Bandgap
Common to the 64 channels

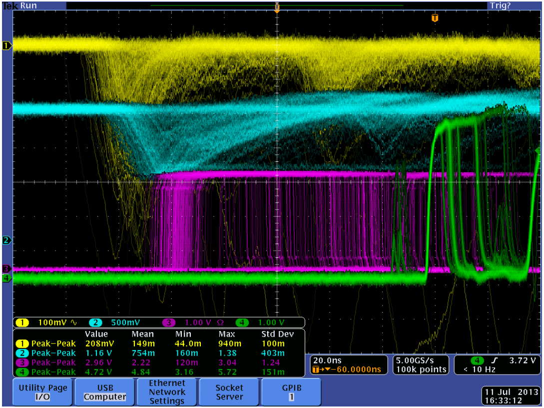
Slow shaper branch

- It will measure the charge induced in the RPC pad
- About 150 ns rising time
- The peak of the slow shaper signal is proportional to the charge
- That value is held by a sample and hold an sent to an ADC
- The 12 bits ramp ADC will convert the peak value to digital



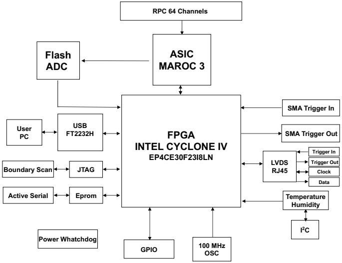
RPC signals - quick measurement

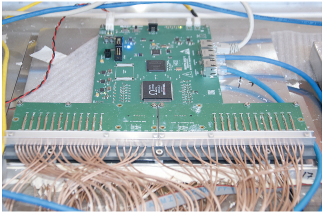
- A quick test was performed using the ASIC's development board
- The RPC signals were measured before and after the fast shaper, and at the discriminator output
- It was shown that the MAROC could be used to acquire the RPC signals



Front-end - Design

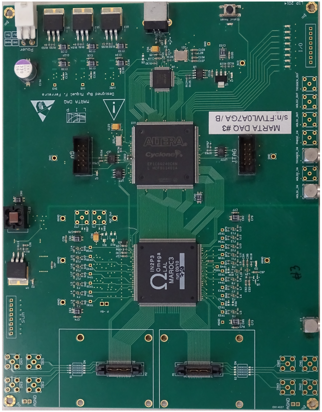
- Input stage
- ASIC digitizes the signals
- FPGA performs all the digital electronics: acquisition management, data storage, and communication
- LVDS and USB to interact with the Central Unit or acquisition PC
- Temperature and humidity monitoring via I^2C
- Power watchdog as a fail-safe
- External and optional flash ADC added to acquire the sum of all RPC channels





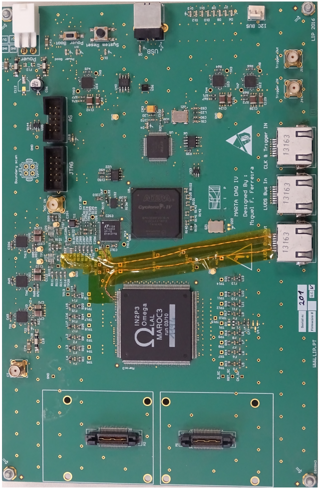
Front-end - First prototype

- Produced in 2014
- Cyclone FPGA
- USB communication
- Connectors routed directly to the FPGA and test points added for debugging
- Most of the firmware and software developments done in this version
- 10 boards assembled



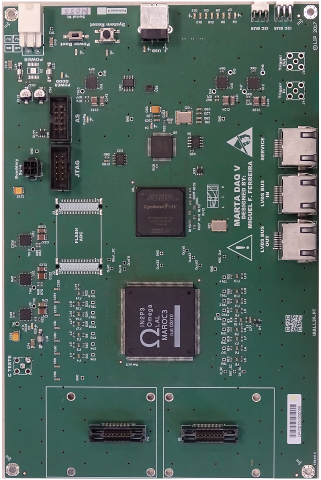
Front-end - Second prototype

- Produced in 2016
- New FPGA: Cyclone IV.
- USB unchanged
- LVDS through RJ45 connectors
- Watchdog
- External flash ADC
- Test points reduced
- 5 boards assembled



Front-end - Production vertion

- Produced in 2017
- Bugs corrected
- External ADC moved to a piggy board
- Final assessments performed with this vertion
- 50+ boards assembled

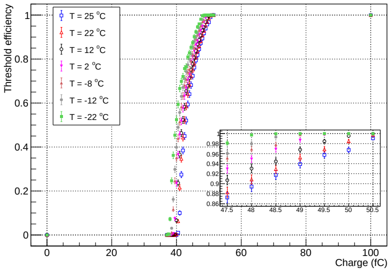


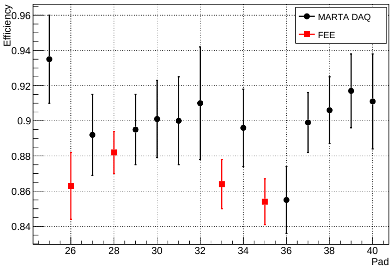
Front-end - Firmware and software

- The FPGA will receive the 64 parallel discriminated outputs and the serial charge output
- The four main modules are:
    - Communication with the Central Unit/acquisition computer
    - Configuration of the ASICs parameters (slow control)
    - Management and storage of the detector hits' measurement
    - Management and storage of the charge measurement
- Acquisition software runs in any computer with Linux and a USB port, including single board computers
- Custom communication protocol designed to communicate with the Central Unit
- Data stored directly in a ROOT tree

Front-end - Performance assessment

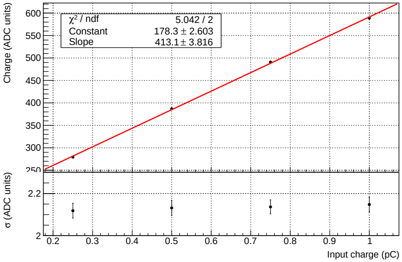
- The threshold s-curve was measured for different temperatures
- The temperature effect is negligible (3 fC)
- The RPC efficiency was measured with this system (12 channels) and an established one (4 channels) at the same time
- Front-end average efficiency 0.895 ± 0.011
- FEE average efficiency 0.866 ± 0.008

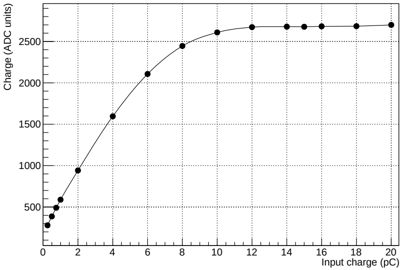




Front-end - Performance assessment

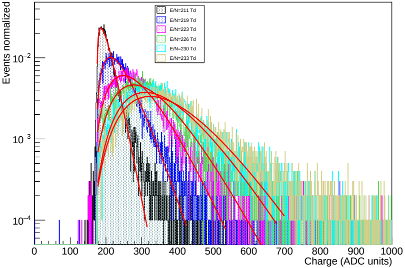
- The charge was measured using a known value (using a capacitor)
- 95% of the events measured in the RPC have less than 1 pC
- These are in the linear section of the calibration

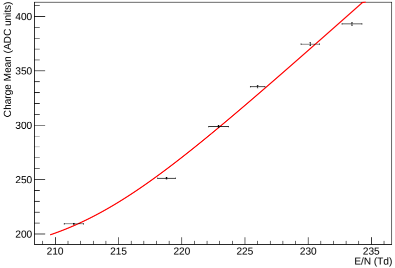




Front-end - Performance assessment

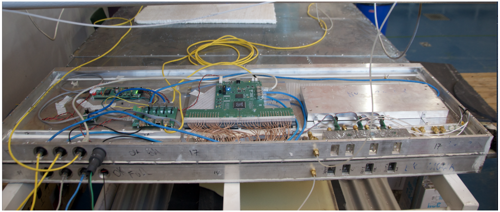
- The RPC charge spectrum varies with the detector's high voltage
- The multiplication of electrons in the gas is a non-trivial problem
- Empirical models have been successfully used to describe data:
  - The spectrum shape is close to a gamma distribution
  - As the high voltage goes up, the shape evolves from a exponential, to a landau, to a gaussian shape
  - High voltage vs mean charge follows the function: $Q(V) = K \ln(1 + e^{a(V - V_0)})$



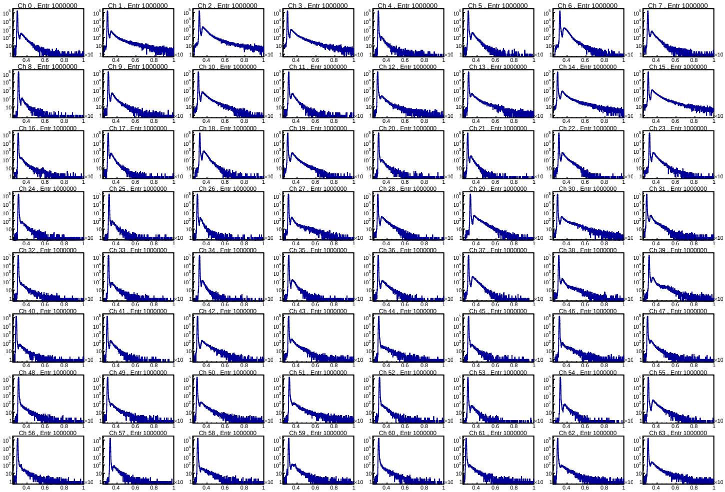


Applications

Engineering array



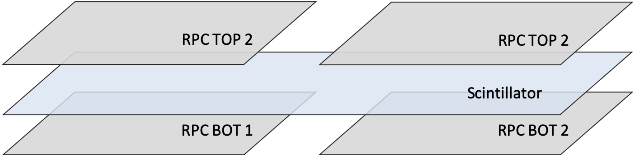
Standalone charge measurement with the front-end



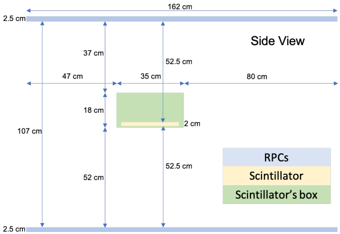
Self-trigger measurement - only an acquisition computer is needed

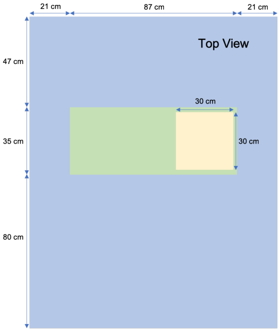
RPC tower setup

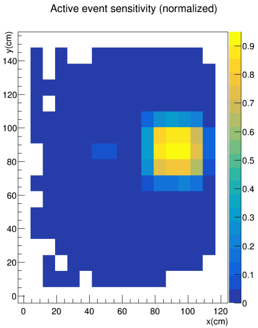
- RPC hodoscope built to test the new Auger's scintillators before deployment
- Installed in the Observatory's assembly building
- Geant4 simulation of the setup prepared



First test successfull with a small scintillator

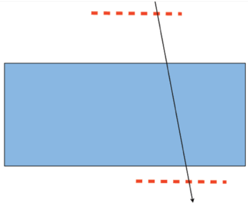






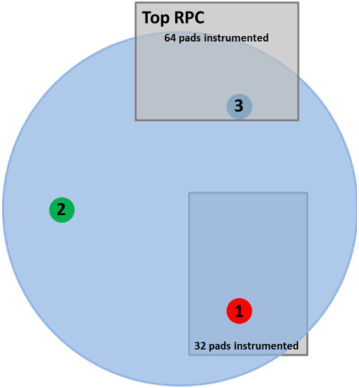
Gianni Navarra tank

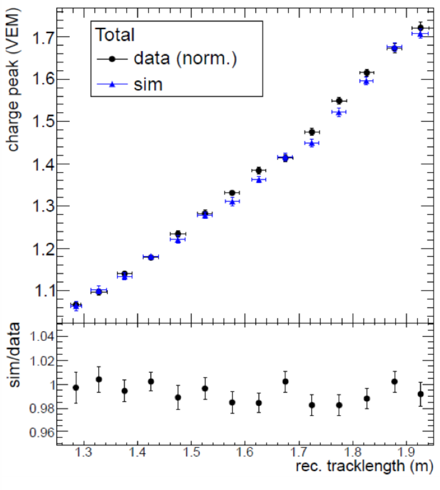
- RPCs used to study the WCD
- Used to select single muons events and to determine their trajectory in the tank
- The signal in the tank is then analysed taking into account the muon trajectory
- Trigger: RPCs coincidence trigger the tank



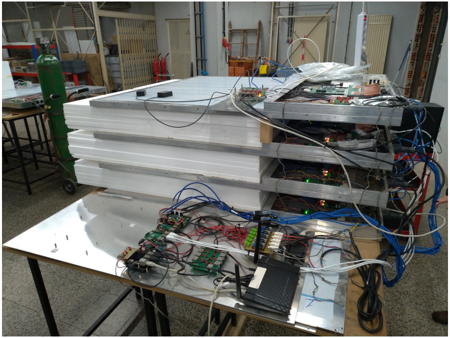
Gianni Navarra tank

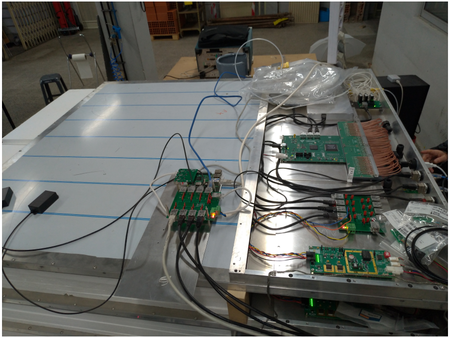
- The results showed no discrepancies between simulation and data were found





Muon tomography





Summary and future

- MARTA was designed to have a direct and independent measurement of the EAS' muons at Auger
- RPCs are placed underneath the water-Cherenkov tank
- A seven stations engineering arrays is being prepared
- The front-end was designed to measure the RPC signals and comply with the strict demands of field operation
- Its main components are the MAROC ASIC that digitizes the signal, and the Cyclone IV FPGA, responsible for measurement and data management, as well as communications
- Two prototypes were produced before the final production version
- The performance of the system was assessed, showing that it works as expected
- Most of the production of the engineering array's parts is done
- First station is close to starting taking data
- Some of the MARTA parts were used in some spin-off measurements:
    - Validation of the scintillators
    - Determination of the muons' trajectory in the tank
    - Muon tomography in the Lousal mine (to be installed)

Thank You

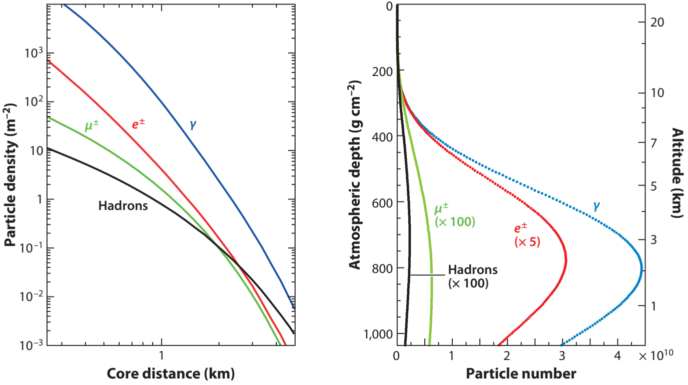


Figura: Average lateral (left) and longitudinal (right) shower profiles for a vertical proton-induced shower of 10^{19} eV. The lateral distribution is calculated using the depth of the Pierre Auger Observatory.