MARTA

Muon Auger RPC for the Tank Array

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Measurements up to 2023 with upgraded detectors!

- Elucidate the origin of the flux suppression and the mass composition at the highest energies
- Sensitivity to 10% proton flux contribution
- Understand hadronic interactions above 60 TeV and constrain new physics phenomena
The importance of determining the muonic shower component

New muonic variables are needed for disentangling mass composition scenarios from hadronic models!
The concept of MARTA

Add a second independent $\mu$ sensitive detector with good space and time resolution

- independent and precise measurements of $N_\mu$ (mean and RMS) and $E$
- Muon Transversal (LDF) and Longitudinal ($X_{\mu_{\text{max}}}$) profiles
- Control of Systematics (cross-calibrations)

RPCs under the tanks
The concept of MARTA

Absorption of the electromagnetic component in the tank, assessing the muonic component by digital counting of hits in the RPCs
Baseline configuration

800 stations covering an area of around 2800 km$^2$:

- 71 stations with 750 m spacing (27 km$^2$)
- 380 stations with 1500 m spacing (750 km$^2$)
- 350 stations with 2600 m spacing (2000 km$^2$)

MARTA in the Auger map

Precast + 4 RPC modules below each tank
Segmentation

256 segments per MARTA station!

Segmentation allows for:

- digital muon counting (with high time resolution)
- definition of fiducial areas (with reduced e.m bkg)
- Definition of control regions (with increased e.m. bkg)
- Powerful methods of calibration and cross-calibration

The amount of material crossed can be accurately computed for each pad and each shower geometry

$\Theta = 40^0$
Expected performance

Mean

\[ E = 10^{19.8} \text{ eV} \quad \Theta = 38^0 \]

For 500m < r < 2000m:
~20% e.m signal (as foreseen)

Station level: digitally counting the number of muons

Resolutions between 10% and 25%
MARTA ultimate saturation: analogic mode for first 100 ns

Saturation with analogic mode for $E = 10^{19.5}$ eV, $\theta = 40^\circ$, $R_{sat} = 100 - 150$ m

- Proton QGSJETII
- $E = 10^{19.5}$ eV
- $\Theta = 40^0$
- Nb particles in the fiducial area

Physics near the Core!
Calibration, cross-calibration and assessing the EAS muon low energy spectrum

Particles per pad per min

It is possible to follow the number of hits in each pad (ε and flux variations) at 1% level every 30 m

Use a MPD like algorithm to reconstruct shower muon trajectories in the tank thanks to a fine segmentation
The MARTA Muon Production Depth (MPD) for determining $X^\mu_{\text{max}}$

Geometrical reconstruction

$$ct_g = \frac{1}{2} \frac{r^2}{z - \Delta}$$

MARTA MPD

$E=10^{19.8}$
$\Theta=38^0$
$r > 700 \text{ m}$
Combined MARTA and Tank Lateral Distribution Functions (LDFs)

Event by event ($\beta$ fixed)

Preliminary resolutions of the order 15% both for $S_{\mu1000}$ and $S_{em1000}$

Tank

All RPC

RPC Fid

$10^{19.8}$ eV

$10^{19}$ eV

$p$/He/N/Fe QGSJet
MARTA LDFs

Mean over 300 events

Mean LDF (ρ and β free!)

Normalization $\rho_{1000}$ and shape $\beta$ parameters of the muon LDFs: additional for assessing the beam composition!
Events taken asking coincidence of scintillators:

- Toy Monte-Carlo
- Data - preliminary

Acquisition with trigger from tank running!
MARTA @ Malargue

Next steps:
• Continue with data taking and analysis
• Install 2 more MARTA stations to measure muon LDFs
• Move to integrated electronics
Thanks for your attention!
Backup slides
Increase the sensitivity to primary photons!

2.2 Physics of air showers and hadronic interactions

Having direct muon information will also greatly enhance our capabilities of studying hadronic interactions. In particular the shower-by-shower correlation of the depth of shower maximum with the number of muons at ground has proven to be a very powerful observable to distinguish different exotic or conventional interaction scenarios. This can be understood by realizing that the depth of shower maximum is mainly determined by the secondary particles of high energy produced in the first few interactions of the cascade. In contrast, muons are produced only if pions decay, which is only the case at low energy. A simulation study for different modifications of hadronic interaction models is shown in Fig. 2.4. Already the comparison of the mean depth of shower maximum with the mean muon number provides strong constraints on the interaction model. The simulations also demonstrate how different scenarios of modified hadronic interactions can be distinguished if the event-by-event correlation of $N_{\mu}$ and $X_{\text{max}}$ can be measured. For details see [57, 95].

2.3 Upper limits on photon and neutrino fluxes

The photon and neutrino limits will improve relative to the current ones for several reasons:

- The statistics of the events available for determining the limits will triple relative to the data collected by end of 2012, on which our current limits are based.
- In 2013 two new trigger algorithms (ToTd and MoPS) have been added to the local station software of the SD to lower the trigger threshold. As a result there will be more stations contributing to the typical shower footprint, improving the reconstruction and, for example, photon/hadron separation. New station electronics, as foreseen for the upgrade (see Sec. 3.2), will allow us to improve the triggering algorithms further.
- Already now the photon limits are no longer background free. Improved muon discrimination will help to reduce the background due to hadronic events in our photon candidate sample or to identify photons and neutrinos.
Four RPC engineering prototypes have been produced and tested at LIP Coimbra. Efficiency maps have shown a good uniformity and efficiencies well above 90%. Tests with small scale prototypes point to a flow lower than 1 kg/year of tetrafluorethane, indicating that low gas flow operation is feasible. Efficiency measurements at low gas flux in flux scale prototypes are ongoing in Coimbra and will allow for a more consistent estimate of the gas consumption in large chambers. Measurements show that the background current is very well correlated with temperature, as expected. Preliminary thermal simulations show that daily variations are effectively quenched by the thermal inertia of the system. Remote adjustment of the high voltage should be enough to compensate for seasonal variations of the response due to temperature change, ensuring a high stability of the RPC performance.

The baseline design of MARTA allows the measurement of muons with a position resolution of 15-20 cm (driven by the pad size), a time resolution of 5 ns (driven by the electronics and the GPS) and a very high efficiency. To assess the performance of MARTA, a GEANT4 based simulation of the RPC unit has been developed and included in the Auger Offline software. With the digital read-out only, the number of muons in each station can be directly measured down to about 400 m from the core and pile up corrections allow to recover down to 200 m from the core (for $10^{19.5}$ eV at 40° zenith angle). With the analog read-out (charge integration in about 100 ns for each pad) each station will accurately measure from 1 to at least 10000 muons per detector unit with no saturation. Punch through estimations yield 30% (15%) at 500 m (1200 m) from the core and 40° zenith angle.

Figures B.17 and B.18 summarise some key aspects of the MARTA array performance.

**Figure B.17:**
- (Left) Resolution on the number of muons as a function of the energy for different spacings of the array units.
- (Right) Number of events as a function of the energy - the total expected number of events and the individual contributions from the regions of the array with different spacings are shown.

The resolution on the number of muons $N_{\mu}$ in the shower at ground (integrated from 500 to 2000 m) as a function of the energy is shown (left) for the different spacings of the array units.
2.1. MASS COMPOSITION AND ANISOTROPY

The concept can be extended to hadronic showers as well by introducing one additional parameter, the muon scale $N_{\mu}$, the result is a model that describes showers initiated by protons, nuclei up to iron as well as photon showers using only three parameters: $E$, $X_{\text{max}}$, and $N_{\mu}$. Based on the signal and timing information in individual SD stations we have encouraging results on event-by-event determination of the primary mass exploiting shower universality features to decompose the relative abundances of shower components, e.g. the muon content. Nevertheless, these results are based on Monte Carlo parameterizations only which eventuate in large systematic uncertainties and call for a significant step forward in a direct measurement of individual components of air-shower events.

![Figure 2.2](image)

Figure 2.2: The 1-s contour of the number of muons at maximum of the muon shower development, $\log_{10} N_{\mu_{\text{max}}}$, vs the depth of shower maximum, $X_{\text{max}}$, for fixed energies, $E = 10^{19}$ eV (left) and $E = 5 \times 10^{19}$ eV (right), and fixed zenith angle, $q = 38^\circ$, is shown.

![Figure 2.3](image)

Figure 2.3: Number of muons at maximum of the muon shower development, $\log_{10} N_{\mu_{\text{max}}}$ (left) and depth of shower maximum, $X_{\text{max}}$, for fixed energy, $E = 10^{19}$ eV, and fixed zenith angle $q = 38^\circ$, are shown (EPOS-LHC as generator for hadronic interactions).

Already now one can use universality features of air showers to obtain an efficient parametrization of the electromagnetic shower component. A fit of parametrized shower components to the time traces of the surface detector signals of a high-energy shower yields...