The AMIGA enhancement of the Pierre Auger Observatory

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Abstract. AMIGA (Auger Muon and Infill for the Ground Array) is a low energy enhancement for the Pierre Auger Observatory, designed to extend its measurements down to 10^{17} eV to get new insights in the region of the spectrum where the transition between galactic and extragalactic cosmic rays occurs. The current status and preliminary results from AMIGA are presented and discussed in this work.

1. Introduction

While the original proposal for the Pierre Auger Observatory [1] was to study the ultra-high energy cosmic rays from 3×10^{18} eV onwards, AMIGA [2] is an enhancement to detect primary particles above 3×10^{17} eV. It consists of an Infill array of water-Cherenkov detectors, separated by 750 m (the normal spacing for the surface detector is 1500 m) covering an area of 23.5 km^2. Each station is accompanied by a 30 m^2 scintillator counter buried at a depth of 2.3 m to shield from the electromagnetic particles and directly count muons (important information for composition studies). The counter is composed of four independent modules grouped in two with 5 m^2 and two with 10 m^2, as sketched in figure 1. Each module is segmented in 64 plastic scintillator strips (4 cm wide and 1 cm thick to prevent pile-up effects) with optical fibers to collection and transmission of light. The photons are guided to a 64-pixel photomultiplier tube positioned at the center of each module. The scintillators work as counters, i.e., they count signals above a tunable threshold.

2. AMIGA status

The Infill array of water Cherenkov detectors is complete since September 2012, with 61 stations overlooked by three high elevation fluorescence telescopes [3] in the western part of the surface detector (SD) array, shown in the map of figure 2. Data taking started in 2008 and results have already been obtained, like the energy spectrum presented in this work.

A unitary cell (UC) of seven stations with counters forming a hexagon (figure 3) was completed in 2014, but some of the locations still have only one module. The scintillators marked with a yellow circle in the figure are already taking data. Two stations are instrumented with a pair of independent counters called twins (with 30+30 m^2), to allow a direct measurement of the muon counting accuracy. With data from the UC, it will be possible to test the muon

[1] Full author list at http://www.auger.org/archive/authors_2014_10.html

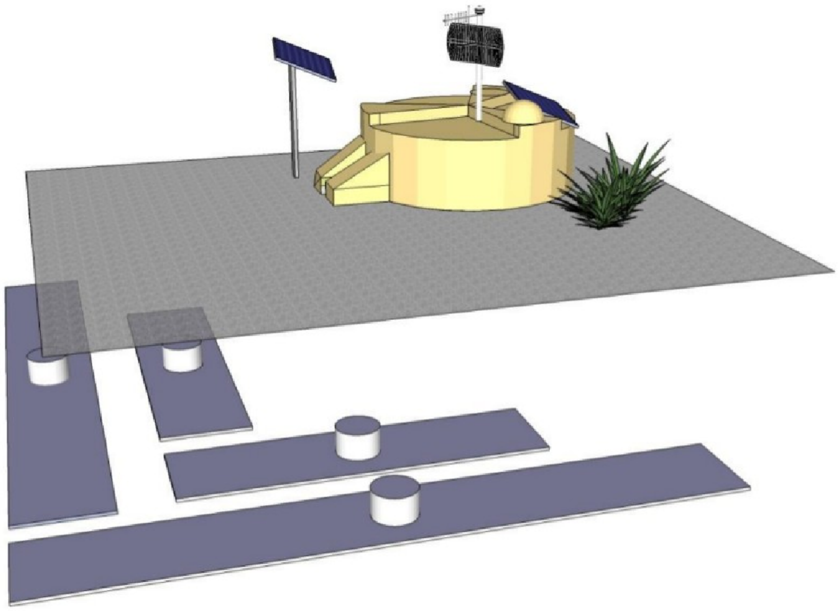

Figure 1. Configuration of the AMIGA stations, with the water Cherenkov detector and buried scintillator modules.

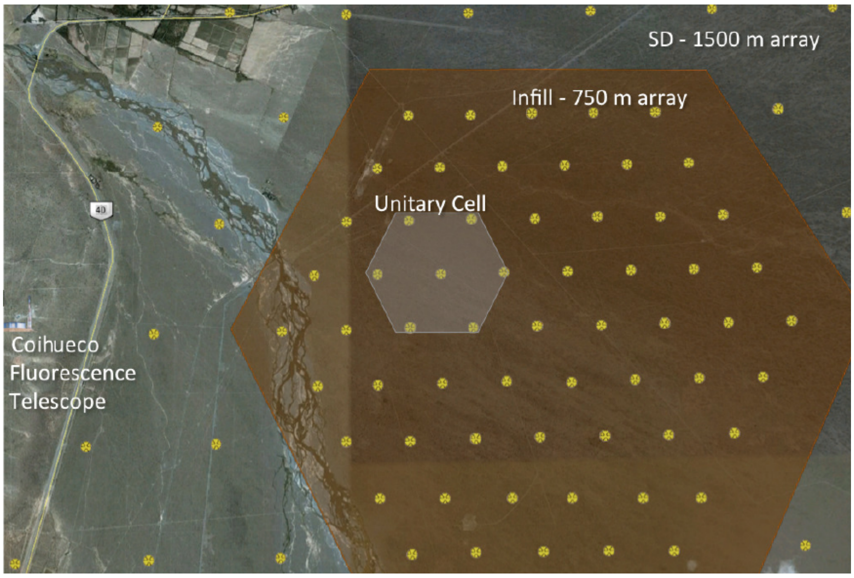

Figure 2. Map of the AMIGA Infill and unitary cell of muon counters.

counting technique, develop the calibration method and validate the detector design, before proceeding to the full deployment.

3. Energy spectrum from the Infill

The energy spectrum from the Infill array [4] was obtained using well reconstructed, high quality events from 08/2008 to 12/2012 (total exposure of (79 ± 4) km^2 sr yr), providing the result from figure 4. The energy is evaluated based on the calibration obtained from a subset of hybrid events (observed both by the Infill stations and the fluorescence telescopes). Up to the energy

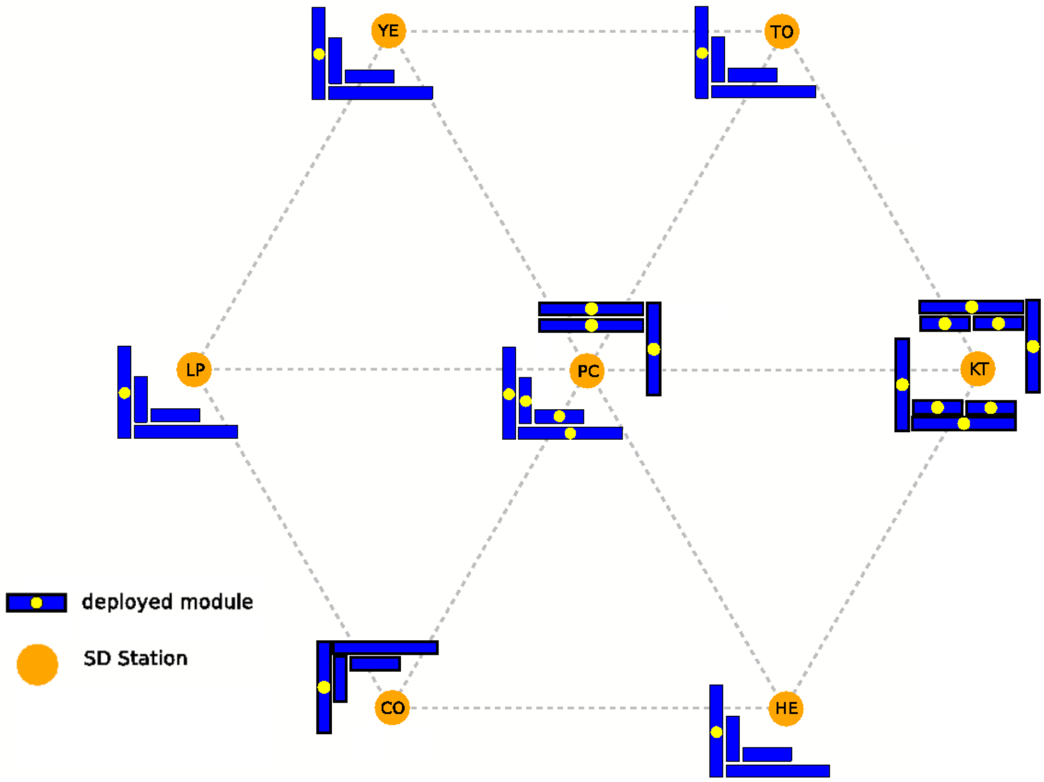

Figure 3. Muon counters of the AMIGA unitary cell. The modules without the yellow dot were not deployed yet.

of the ankle (4×10^{18} eV), a power law fit (red line in the plot) gives a spectral index of ($3.27 \pm 0.02(stat.) \pm 0.07(syst.)$), in agreement with previous results [5]. In figure 5 the spectrum is compared with other results [6] from the surface detector: for the 1500 m array, the inclined events and the hybrid reconstruction. A good agreement is found between them.

4. First results from the buried scintillators

Operation started in March 2013 at the UC. Data from the muon counters are transmitted to the central of acquisition, where they are merged with the surface detector events. The geometry and energy of the shower are taken from the SD, using the usual procedures of reconstruction, and the muon numbers at each station are given by the scintillators. A counting strategy based on laboratory measurements for the duration of the signal of muons from air showers is applied in order to reduce the miscounting due to systematic uncertainties. A pile-up correction is also applied to the total number of muons.

For a given event from the UC, the muonic lateral distribution function (MLDF) is fitted through a KASCADE-Grande like function [7], with particle density given by

$$\rho_\mu(r) = \rho_\mu(450) \left(\frac{r}{r_0}\right)^{-\alpha} \left(1 + \frac{r}{r_0}\right)^{-\beta} \left[1 + (\frac{r}{10r_0})^2\right]^{\gamma},$$

where $\rho_\mu(450)$ and β are the fitting parameters and the others are fixed at $\alpha = 1$, $\gamma = 1.85$ and $r_0 = 150$ m. In figure 6 an example of MLDF is presented, for an event of energy 2.7×10^{18} eV and zenith angle of 39.9°. In this case, all SD stations from the UC were triggered, but some counters are silent (detected less than three muons) or saturated (received more than 21 muons in a time window of 25 ns).

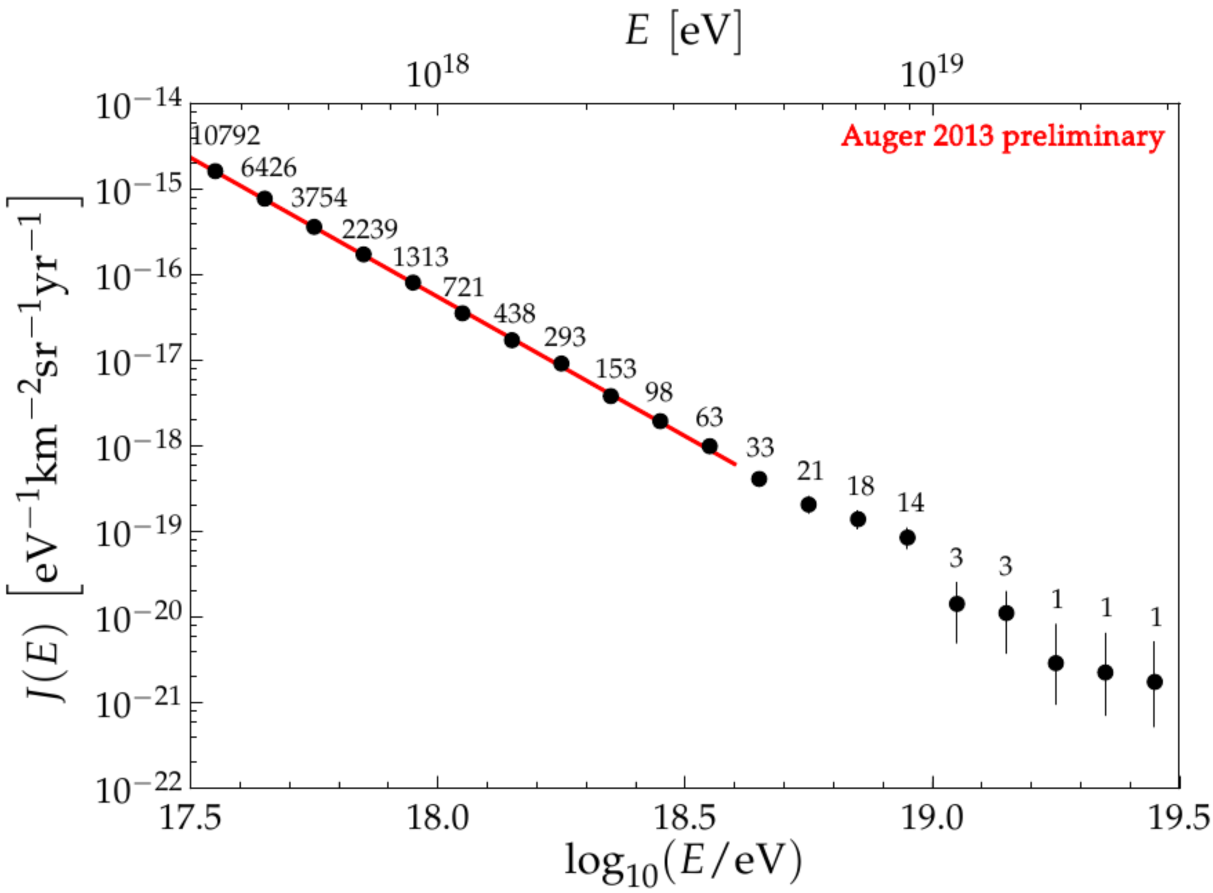

Figure 4. Energy spectrum of events from the 750 m surface detector array.

Despite the still short time of operation, selecting all events with at least two counters, the average measured MLDF (normalized to the fitted muon density at 450 m from the core) was obtained [8] for 230 events with energy above the full efficiency of detection, as shown in figure 7. The points are fitted only in a very limited range of core distance, due to the low number of events. Although preliminary, the radial dependence of the muon densities with the decreasing zenith angle can be seen for the three angular bins evenly separated in $\cos(\theta)\sin(\theta)$.

The accuracy of the muon counters was studied with data from the instrumented twin [9] position. A preliminary comparison of data, with 3000 events above 10^{17} eV, from both counters at the same surface station (with their counts plotted in figure 8) indicates that the detectors are working properly. The red line in the plot represents a perfect behavior, where both detectors count the same number of muons, so the points are expected to be distributed around it. The accuracy seems to increase for higher numbers of muons, as expected, since the poissonian fluctuations decrease.

5. Summary

AMIGA is taking data with the full Infill array of surface stations and a Unitary Cell of buried scintillator counters, which are not all complete yet. The reconstruction of first events from this 750 m array allowed the study of the energy spectra above $10^{17.5}$ eV, giving a spectral index of $3.27 \pm 0.02(stat.) \pm 0.07(syst.)$ up to the ankle, compatible with previous results from the surface detector. The first results from the scintillators show that the detectors are working as expected and indicate that the muon counting accuracy can be evaluated when enough data will

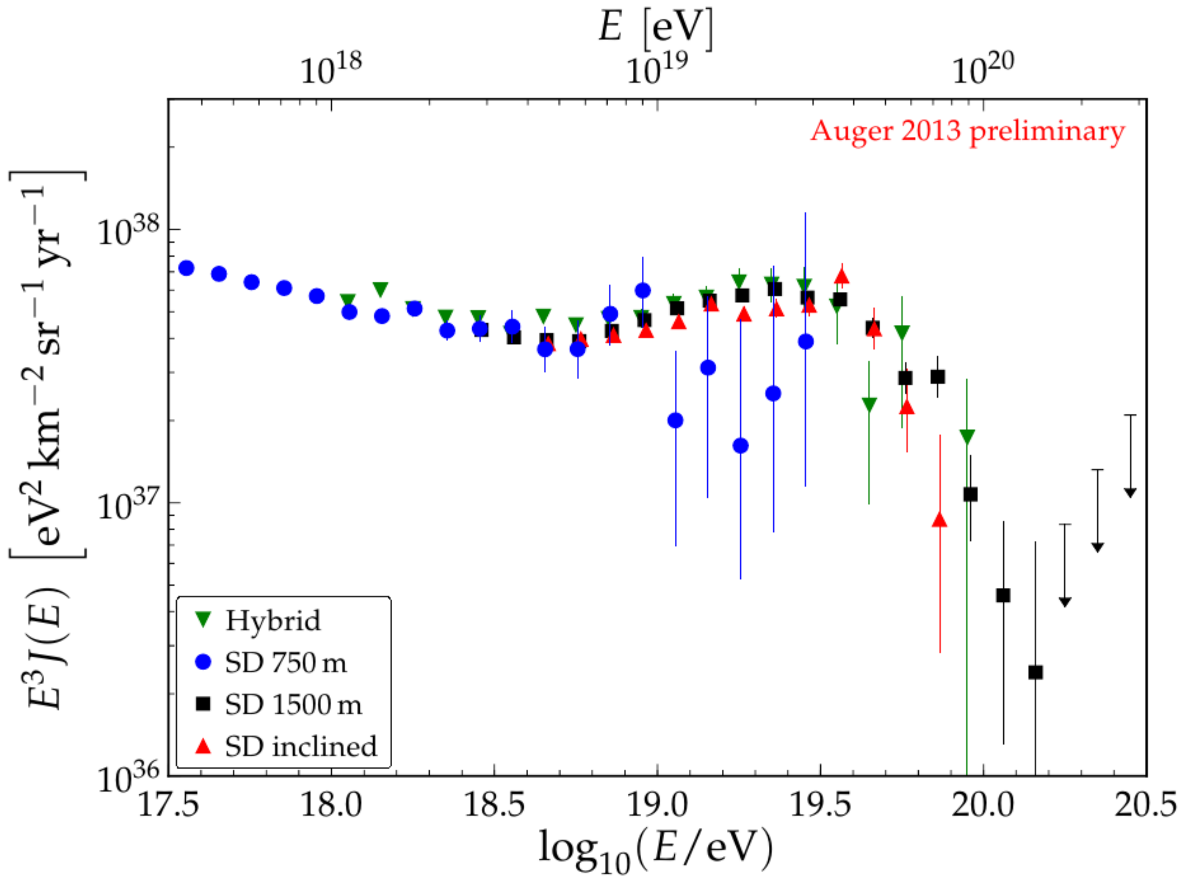

Figure 5. Energy spectra derived from the surface detector and hybrid data.

be collected with the twins.

6. Acknowledgments

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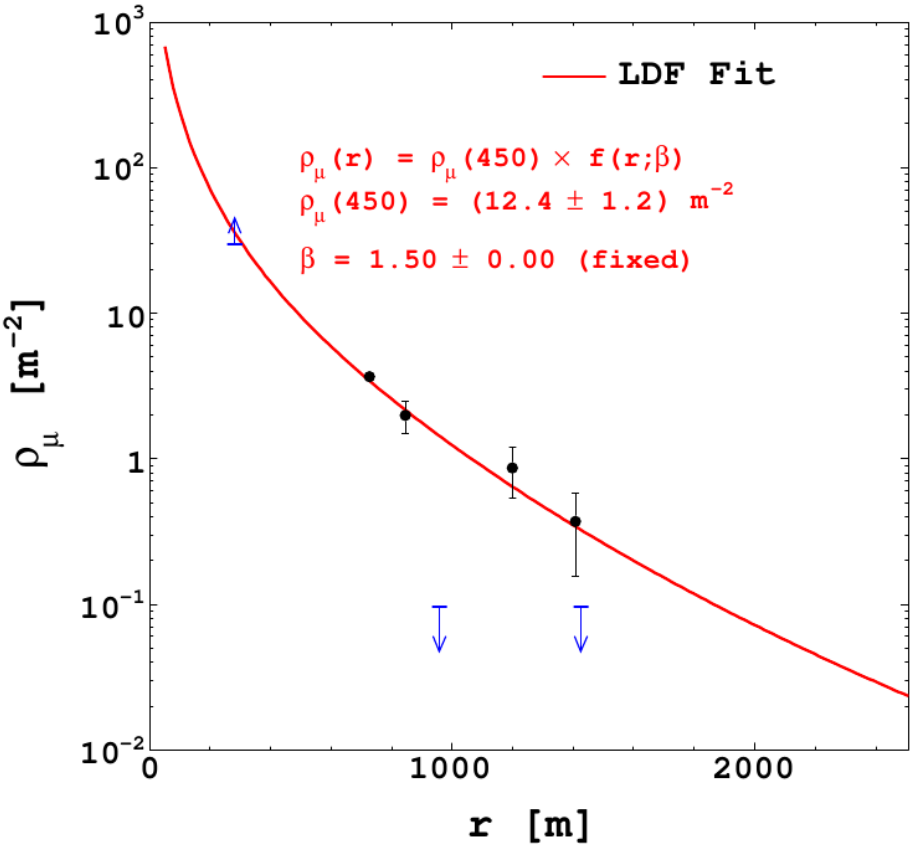

Figure 6. MLDF for an AMIGA event. Blue upward and downward arrows are saturated and silent counters respectively.

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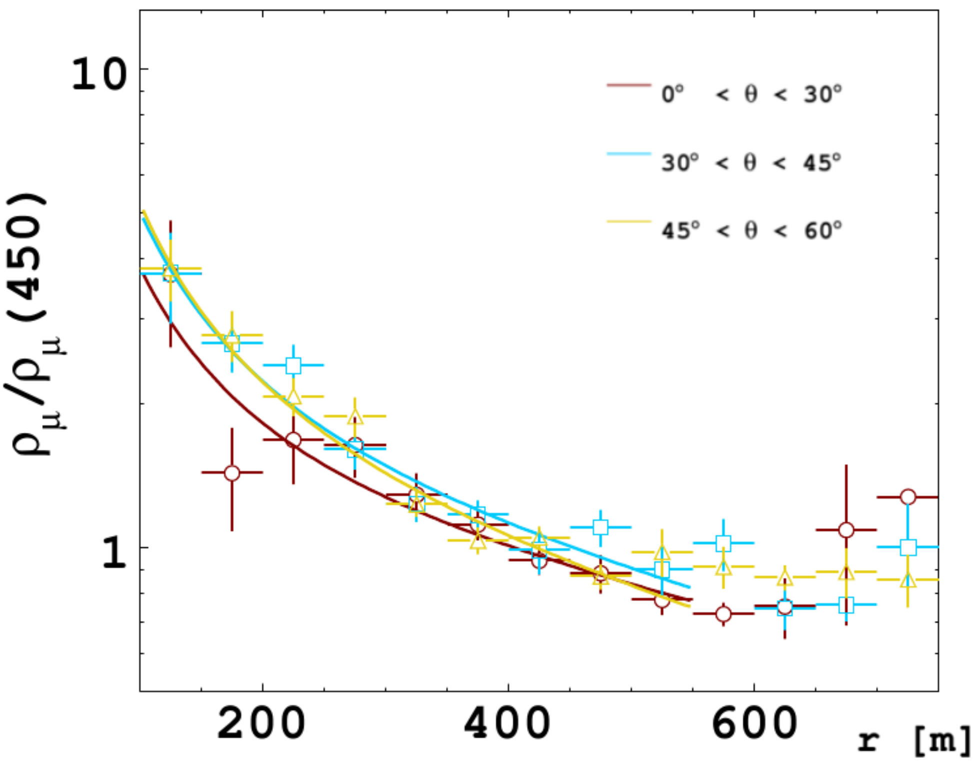

Figure 7. Mean muon lateral distribution function obtained with the AMIGA muon counters.

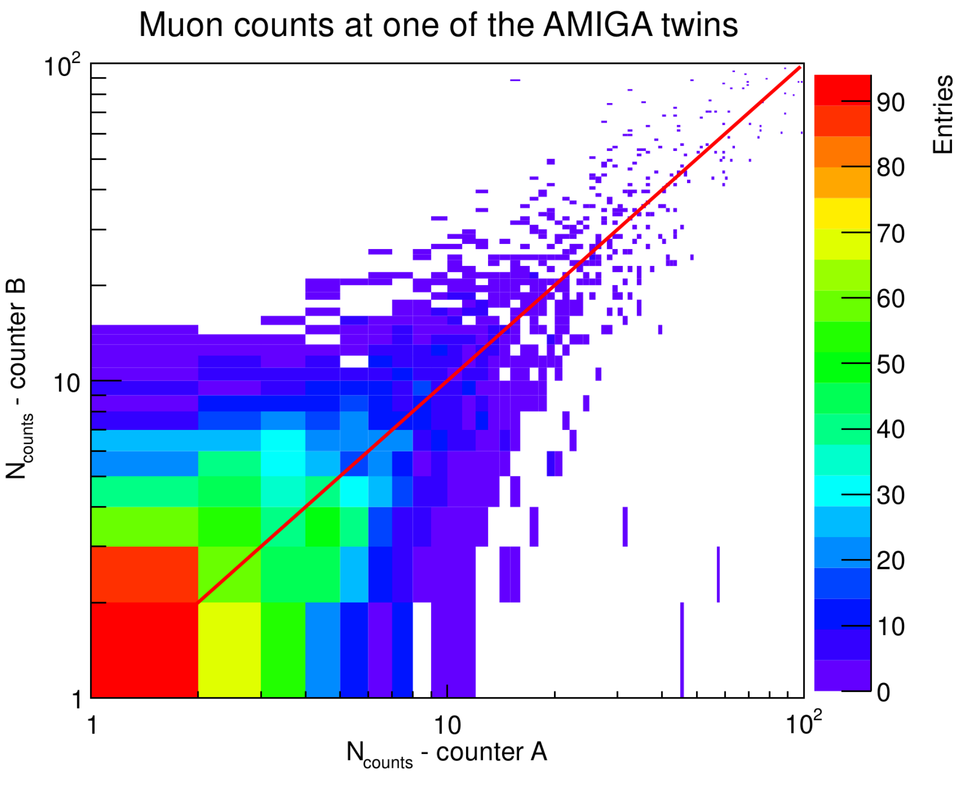

Figure 8. Muon counts in events of a twin muon counter of AMIGA.