The measurement of cosmic muons with the WILLI-EAS detection system

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Abstract: Air shower simulations with CORSIKA have shown that the muon charge ratio measured in EAS is an observable which can provide information about the primary mass of the cosmic particle producing the EAS and on the hadronic interactions governing the propagation. The EAS detection system is built in IFIN-HH Bucharest, consisting of a mini-array working in coincidence with rotatable WILLI, which measures the muon charge ratio. The detection principle is to measure in coincidence shower parameters with the mini-array and the muon charge ratio with the WILLI detector. The mini-array is formed by 12 detection systems, each consisting of 4 scintillation plates (0.475 × 0.475 m² area), read out by two PMTs. Based on simulations and taking into account the topological environment around WILLI, the optimum configuration of the array has been implemented. From first data, the reconstructed shower cores and incident direction of individual showers have been obtained. New simulations have been performed by adding other 12 stations for the mini-array to increase the sensitive area of shower detection. The quality of the reconstruction of shower parameters will significantly increase and the accessible energy range can be extended to around 10¹⁶ eV, i.e. covering the knee of the cosmic ray spectrum.

Keywords: Methods, instrumentation, muon, charge ratio

1 Introduction

The possibility of measuring the muon charge ratio in Extensive Air Showers was previously investigated in [1,2]. Detailed studies have been done by performing simulations with the CORSIKA code [1,3] for proton and iron nuclei initiated showers with incident energy of 10¹⁵ - 10¹⁶ eV. The simulations and preliminary experimental studies prove that an extension of the array with an extra 12 detection stations will significantly improve the quality of the experiment.

The WILLI calorimeter, installed in IFIN-HH Bucharest, is operated since several years for measuring charge ratio of atmospheric muons at low energies (E < 1 GeV), particularly exploring its directional dependence. Recently it was proposed to combine WILLI detector with a mini-array of 12 scintillators in order to measure muon charge ratio of the muon density of EAS lateral distributions. Such experimental studies could provide detailed information on the shower development under the influence of the geomagnetic field and probably also on hadronic interaction.

2 WILLI-EAS

The WILLI-EAS experiment was developed by building a small EAS-array for the detection of the air showers, operating in connection with the WILLI detector, used for muon charge ratio measurements [3,4]. The WILLI detector, built as a rotatable device embedded in a mechanical frame capable to rotate both in azimuth and zenith [5], is composed of 16 horizontal modules, shielded by 4 modules arranged vertically, used in anti-coincidence for minimizing the background, Fig. 1.

The EAS-array is presently formed of 12 detection stations, each station consisting of 2 independent detectors (Fig. 2), each being composed of 2 scintillator plates (NE114 type) 0.475 × 0.475 m² area and 3 cm in thickness, read by a PMT (EMI 9902 type) through a wave length shifter (NE174 A).

Figure 1: The WILLI detector.

The best configuration of the array, as well as the positioning of the array regarding WILLI detector, are established based on previous simulations [1,2]. Taking into account that the charge ratio effect gets more pronounced with increasing distance away from the shower cores, but the number of showers detected by the array in coincidence with WILLI detector are decreasing with the distance between them, the EAS-array was placed at about 50 m from WILLI. The signals from all 24 PMTs are directed to a front-end & trigger module. The signals from all 24 PMTs are directed to a front-end & trigger through equal cables. The front-end module provides 24 input channels, one for each PMT. Each channel starts with an input preamplifier, the...
Figure 2: The WILLI-EAS detection station.

Table 1: Comparison of array rates and coincidence rates for various data-taking runs.

<table>
<thead>
<tr>
<th>File name</th>
<th>Rate array [ev/s]</th>
<th>Rate coincidence [evs/s]</th>
<th>Percentage of Array-WILLI coincidences</th>
<th>Percentage of valid events</th>
<th>Trigger condition for the array</th>
<th>WILLI status</th>
</tr>
</thead>
<tbody>
<tr>
<td>run14.dat</td>
<td>0.330</td>
<td>0.051</td>
<td>15.414</td>
<td>0.010</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>run21.dat</td>
<td>0.346</td>
<td>0.0036</td>
<td>1.045</td>
<td>0.256</td>
<td>5</td>
<td>30° charge ratio</td>
</tr>
<tr>
<td>run07.dat</td>
<td>0.302</td>
<td>0.0032</td>
<td>1.048</td>
<td>0.712</td>
<td>5</td>
<td>30° flux</td>
</tr>
<tr>
<td>run10.dat</td>
<td>0.295</td>
<td>0.0027</td>
<td>0.930</td>
<td>41.078</td>
<td>5</td>
<td>30° charge ratio</td>
</tr>
<tr>
<td>run11.dat</td>
<td>0.298</td>
<td>0.0029</td>
<td>0.967</td>
<td>40.235</td>
<td>5</td>
<td>0° charge ratio</td>
</tr>
<tr>
<td>run13.dat</td>
<td>1.153</td>
<td>0.0105</td>
<td>0.912</td>
<td>58.474</td>
<td>3</td>
<td>0° charge ratio</td>
</tr>
<tr>
<td>run15.dat</td>
<td>0.986</td>
<td>0.1163</td>
<td>11.799</td>
<td>56.943</td>
<td>3</td>
<td>0° flux</td>
</tr>
<tr>
<td>run16.dat</td>
<td>0.304</td>
<td>0.0387</td>
<td>12.709</td>
<td>40.578</td>
<td>5</td>
<td>0° flux</td>
</tr>
</tbody>
</table>

signal being then split in two branches.

On the first branch, the signals are passed through a threshold discriminator, set at -50 mV, providing as output a logical signal, that is fed into an FPGA-based trigger logic. This trigger logic first groups each two signals of a station with an OR and then does a multiplicity decision based on the resulting 12 intermediate signals. The signal obtained this way represents the start signal for TDCs and the gate for QDCs acquisition.

In the second branch, the signals are delayed by 130 ns (25 m of cable), then split in two, one for the QDC inputs and the other for TDC stop inputs. Those delay lines are used to wait the TRIGGER signal formation on the first branch.

The information from QDC and TDC is transferred to a PC through a serial connection by a Bridge module. Also the Bridge module verifies the presence of the BUSY flag and registers it, if it is present. The BUSY flag is a signal generated by WILLI detector when an charge ratio event was registered. So, an important condition for an event to be valid is that it must have non zero values for the same channels of TDC and QDC.

3 Preliminary results

In order to set the parameters of the array at their best values, numerous data acquisitions with different configurations for the trigger and WILLI have been performed. The results are presented in Table 1.

In Table 1 are presented some basic results extracted from the data acquisition files taken with the array. The trigger conditions are different from one file to another (minimum 3 or minimum 5 stations must be simultaneously triggered), as well as the WILLI operation mode (charge ratio measurements or flux measurements) and WLLLI direction (vertical or 30° inclined). The duration of runs has been between few hours to 7 days.

Progress is observed in the improvement of the quality of data acquired by the array. The percentage of valid
events (events that have for the same channels non zero values for QDC and TDC) was increased. It can easily be seen looking at the percentage of valid events in Table 1. For measurements with 5 stations for the array trigger, it goes from 0.010% in run14.dat to ≈40% for run10.dat. No important difference is spotted regarding the coincidence array-WILLI rate between data taken with vertical WILLI and data taken with WILLI 30° inclined on the direction of the array. It can be easily observed by comparing the coincidence array-WILLI rate from run10.dat with the rate from run11.dat.

Changing the trigger condition for the array by requiring a coincidence of at least 3 stations instead of 5 stations, the coincidence array-WILLI will increase ≈4 times (as it results from the comparison of run11.dat with run13.dat, Table 1), but the quality of the reconstruction for the showers parameters, like the shower core reconstruction or the azimuthal and zenithal arrival directions of the shower, will be much diminished.

4 Simulation of the new array configuration
An extension of the array with another 12 stations has been proposed (see Fig. 3). Detailed Monte Carlo simulation studies have been performed using CORSIKA code in order to investigate the quality of reconstruction for the new array. The simulation shows a significant improvement of the quality of reconstruction (see Fig. 5). Increasing the number of detection stations will improve the quality of the muon charge ratio results. It is expected that the EAS muon flux will give new information regarding the shower development and hadronic interaction models. It
5 Conclusions
A small EAS-array was built at IFIN-HH, Bucharest and it is now operational. Placed in connection with WILLI detector, it is designed to investigate the muon charge ratio in extended air showers. Technical informations were extracted during preliminary data acquisition in order to improve the properties of the array. The analysis of the muon flux data recorded by WILLI in coincidence with the mini array, should give information about the muon density in extensive air showers.

Simulations were performed with an extended array with additional 12 detection stations. A significantly improvement of the quality of the experiment was obtained. The next step is to reconstruct the shower core and the azimuthal and zenithal arrival directions using valid events from data obtained from the array.

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References

Figure 5: The quality of reconstruction for the new configuration (red line) versus the present one (blue line).