Studies of hadronic interaction models by measuring the flux and the charge ratio of atmospheric muons with the WILLI detector

B.Mitrica*, I.M.Brancus*, A.Saftoiu*, H.Rebel†, O.Sima‡, A.Haungs†, G.Toma*, M.Petcu* and M.Duma*

**Horia Hulubei Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania, P.O.B.MG-6*
†Institut fr Kernphysik, Forschungszentrum Karlsruhe, P.O.B. 3640, Germany
‡Department of Physics, University of Bucharest, P.O.B. MG-11, Romania

***Abstract*. Measurements of the of the low energy (<1 GeV) muon charge ratio and muon flux have been perfomed using WILLI detector. We investigate the azimuthal and the zenithal dependence of the muon flux. The results are compared with complex Monte-Carlo simulation using CORSIKA code taking into account 2 hadronic interaction models (DPMJET and QGSJET2). The results of the energetic, azimuthal and zenithal dependence of the atmospheric muon charge ratio was compared with CORSIKA simulations (DPMJET model). The simulations of the EAS muon charge ratio was performed using CORSIKA code and 2 hadronic interaction models (QGSJET2 and EPOS), in order to to investigate a new experiment WILLI-EAS that will be focused on measurements of the muon charge ratio from individual EAS at primary energy between $10^{14} - 10^{15}$ eV. The results of the simulations shows that the EAS muon charge ratio is influenced by hadronic interaction models.**

***Keywords*: muon, simulation, WILLI**

I. INTRODUCTION

Measurements of the low energy ($<$ 1 GeV) muon flux and muon charge ratio were performed using the WILLI detector [1], [2] which is a compact, modular rotatable system. Each module is formed by a plastic scintillator layer of 3 cm thickness, in 1 cm Al frame box. The detector was used to measure the muon charge ratio and the muon flux, for different azimuthal direction (N,S,E,W) for a mean zenithal angle of $35°$. The results were compared with Monte-Carlo simulations performed with CORSIKA code [3] using 2 hadronic interaction models DPMJET [4] and QGSJET [5]. Beside the studies of the atmospheric muons, we will focuse in the future on the investigation of the charge ratio of the muon density in EAS, so the WILLI detector is extended by a mini array of 12 scintillator plates of $1m^2$. Simulations performed with CORSIKA using 2 hadronic interaction models (QGSJET2[5] and EPOS[6]) shows that EAS muon charge ratio is quite sensitive to the hadronic model.

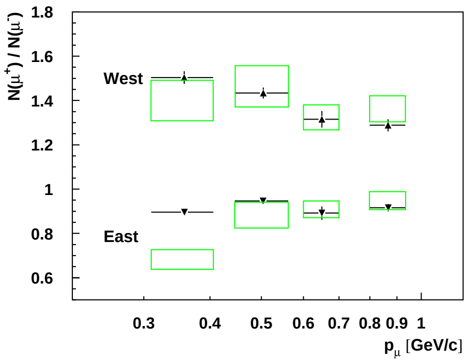

Fig. 1. The energy variation of the muon charge ratio (points) compared with CORSIKA simulations (rectangles)

II. THE MUON CHARGE RATIO

The charge ratio of atmospheric muons has been analysed under various theoretical aspects [7], [8]. The merit of the WILLI detector is that it approaches the very low muon energy range with excellent accuracy. The detector determines the charge ratio of atmospheric muons by measuring the life time of stopped muons in the detector layers: the stopped positive muons decay with a lifetime of 2.2 μs, while negative muons are captured in the atomic orbits, leading to an effectively smaller lifetime depending on the stopping material. The muon charge ratio is determined from the measured decay curve of all muons stopped in the detector, by fitting the measured decay spectrum with the theoretical curve.

For the investigation of the azimuth dependence of the charge ratio of atmospheric muons, a series of measurements [9] has been performed on four azimuth directions of incidence of the atmospheric muons: North, East, South, West, (N, E, S, W) for muons with inclined incidence, mean value at 35^o and mean incident energy 0.5 GeV/c.

The results (see Fig.1,2) show that CORSIKA simulations, based on DPMJET model reproduce relativ well the azimuthal and the variation i.e. the East-West effect as observed by WILLI. The Okayoma Group [10] reported a less pronounced azimuth dependence

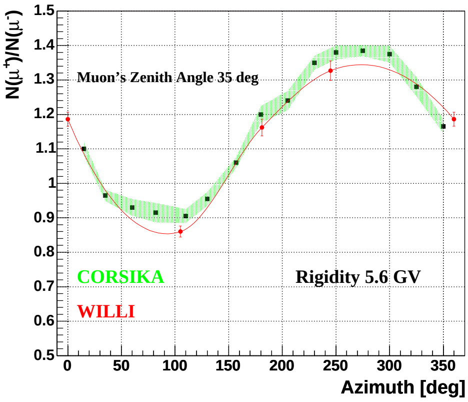

Fig. 2. The azimuthal variation of the muon charge ratio (preliminary)

but considering muons with higher energies (> 1 GeV). The observed asymmetry is attributed to the anisotropy of primary proton flux caused by the geomagnetic cut-off, as well as to the geomagnetic influence on the atmospheric muon propagation.

III. Muon flux measuremnts

Measurements of the flux of low energy muons have been performed by use of the WILLI detector. The results have been compared to Monte Carlo simulations based on DPMJET model and semiempirical approaches of Judge and Nash [11] and of Gaisser [12]. The results agree with the predictions of of the simulations, while the semiemprical formulae have a restricted range of validity (Fig.3). Obviously the approach of Gaisser is only applicable at muon energies above 10 GeV [9].

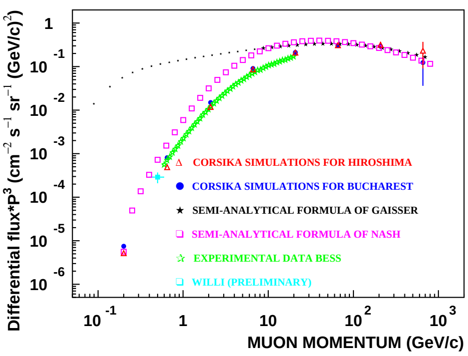

Fig. 3. The muon flux data compared with Monte Carlo simulations and semi-analytical formulae

We have aplied another hadronic interaction model (QGSJET) for simulationg the muon flux in the energy range 0.2 GeV - 1 TeV. Figure 4 shows the muon flux simulated with QGSJET and DPMJET models for a mean zenith angle of 35 ^{o}. Comparing with previously simulation results (DPMJET) we note only very small differences between their predictions.

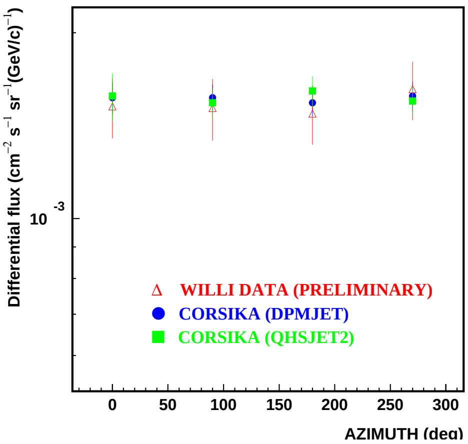

Fig. 4. The azimuthal variation of the muon flux measure by WILLI compared with CORSIKA simulatiuons

IV. WILLI-EAS, a detection system for measuring muon charge ratio in EAS

The difficulty in studying the high cosmic rays is their low intensity, what requires systems of detection covering large surfaces.

KASCADE-Grande [13] is a complex array, area 700 m^2, for investigating the energy spectrum and the mass composition of primary cosmic particle with energies in the knee range, 10^{14} -10^{18} eV. At ISVHECRI 2004 [14] Okayoma group reported results from LAAS experiments for measuring integral cosmic ray spectrum by requiring coincidences at multiple EAS arrays, formed by mini-arrays.

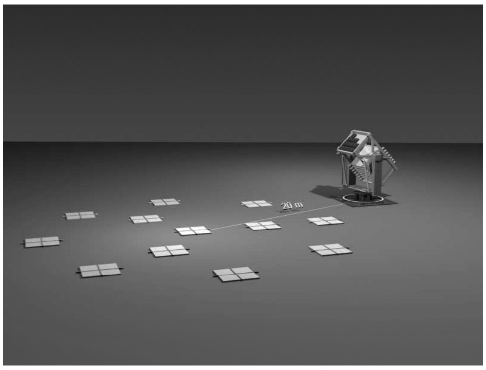

Fig. 5. A possible layout for the mini-array for triggering the WILLI detector.

There are currently some experimental approaches under discussion to measure the charge ratio of the muon density in EAS [15], [16]. Our approach [17] for an appropriate detector installation follows the considerations of [18], which have theoretically (on basis of simulations) revealed very detailed features of the geomagnetic influence on the radial and azimutal variation of muon charge ratio. The forseen installation will link the WILLI device to a nearby located miniarray of detectors for EAS registration which data will help to

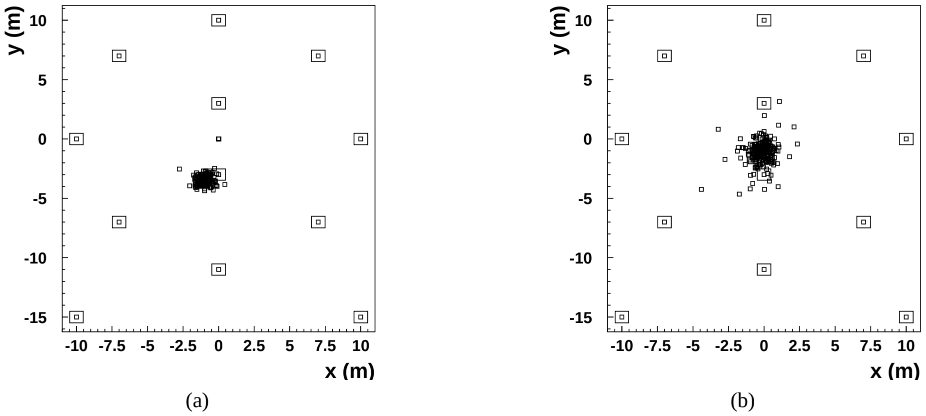

Fig. 6. The reconstructed shower cores for 250 H incident showers placed in the same position for 20^0 (a) and 30^0 (b)

reconstruct the characteristics (core location , direction of incidence etc.).

We have presented [17] the experimental concept for investigating muon charge ratio in EAS by correlating WILLI detector with a mini-array. was develop based on the simulations prediction [18], [19] that shows an integral excess of positive muons in showers, prediction that has been never experimentally tested. The simulations shows that this small effect can slightly vary with the mass of the primary. The mean charge ratio is affected by the geomagnetic field, especially for low energy muons and the simulations show different azimuth variation of the muon densities of opposite charges and an azimuth variation of the muon charge ratio dependent on the direction of EAS incidence and the position of the observer in respect with the Earth's magnetic field.

We have started to scrutinize by simulations the performance of various possible configurations (see Fig.6) and the dependence of the results of acceptance of the WILLI spectrometer [19]. In particular, the layout studies must also include an adequate electronic system for triggering and data acquisition since only one stopped muon per shower can be handled in the present system. We investigate, how the finite angular acceptance of the WILLI spectrometer, positioned at a particular accurately defined distance from the shower core and observing muons from a particular direction will affect the pronounced predicted variation of the charge ratio of the observed muon density.

Using CORSIKA and GEANT codes, simulation studies have been performed for H and Fe generated showers ($10^{14} - 10^{15}$ eV) to study the configuration of EAS array to optimise reconstruction of the shower and the configuration WILLI-EAS for obtaining a significant feature for muon charge ratio in EAS. In order to investigate the best configuration of the array a modified version of SHOWREC[20] program was used. The program perform the reconstruction of the detector response using a parametrisation of the energy deposit in the scintillator plates from the mini-array.

Figure 6 a,b shows the quality of the reconstruction, given by the difference between the reconstructed and the true core position.

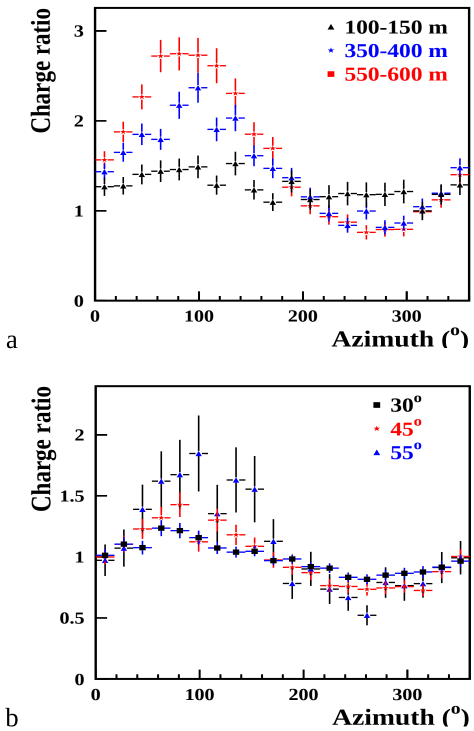

Fig. 7. The dependence of the charge ratio on the azimuth position of WILLI for different positions from the showere core (a) and for different zenith angles (b).

Considering that the H showers are coming from North, angle 45^0, and WILLI is oriented parallel to the shower axis, Fig. 7 a,b shows the dependence of the charge ratio on the azimuth position of WILLI around shower core for various radial ranges and for different zenith angles.

The WILLI-EAS system for measuring muon charge ratio in EAS is under construction, see Fig.5, consisting by a core finder system composed by 12 independent stations, arranged as a mini-array close to WILLI. Each unit is a scintillator plate of 1 m^2, 3 cm thickness, consisting of 4 parts (0.25 x 0.25m^2), measuring the arrival times of the shower front and the energy deposits in the detectors.

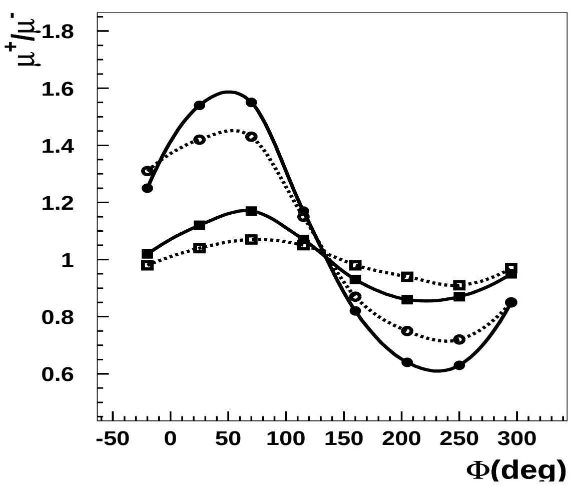

Fig. 8. The dependence of the charge ratio on the azimuth position of WILLI for proton (rectangles) and iron (circles) induced showers using QGSJET (solid line) and EPOS (dotted line) models

Fig. 8 show the dependence of the charge ratio on azimuth position of WILLI around shower core for H and Fe showers using 2 different hadronic interaction models implemented in CORSIKA code QGSJET2 and EPOS. The results of the simulations shows a quite sensitive difference between the two models also for the H an for the Fe showers.

V. Conclusions

The results (charge ratio and flux of atmospheric muons), obtained with the WILLI detector are in good agreement with the predictions of Monte Carlo simulations and a strong difference between the hadronic interaction models was not observe. Simulation studies for the EAS muon charge ratio present a high sensitivity at the hadronic interaction model, and the measurements (we estimate the start of the measurements till the end of 2009), if sufficiently accurate,could be used as a test for different models. The effectcs of the geomagnetic field could be also explore by measuring the EAS muon charge ratio, in order to improve the implementation of the geomagnetic field in simulation codes.

VI. Acknowledgements

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