Measurement of azimuthal
dependent cosmic muon flux by
$2\,m \times 2\,m$ RPC stack near Equator at
IICHEP-Madurai

S. Pethuraj$^{a,b}$ V.M. Datar$^b$ G. Majumder$^b$ N.K. Mondal$^c$ K.C.
Ravindran$^b$ B. Satyanarayana$^b$

$^a$Homi Bhabha National Institute,
Mumbai-400094
$^b$Tata Institute of Fundamental Research,
Mumbai-400005
$^c$Saha Institute of Nuclear Physics,
Kolkata-700064
E-mail: s.pethuraj@tifr.res.in, vivek.datar@tifr.res.in, gobinda@tifr.res.in,
nabak.mondal@gmail.com, kcravi@tifr.res.in, bsn@tifr.res.in

Abstract. The proposed 50 kton INO-ICAL experiment is an underground high energy physics experiment planned to be built at Theni, India ($9^\circ 57'N, 77^\circ 16'E$) to study various parameters of neutrino oscillations using atmospheric neutrinos. The Resistive Plate Chamber (RPC) has been chosen as the active detector element for the ICAL detector. An experimental setup consisting of 12 layers of glass RPCs of size $\sim 2\,m \times 2\,m$ has been built at IICHEP, Madurai to study the performance and long-term stability of RPCs produced on a large scale in the Indian industry as well as its readout electronics. In this study, the azimuthal dependence of muon flux at different zenith angles at Madurai ($9^\circ 56'N, 78^\circ 00'E$ and altitude of about 160 m from sea level) are presented along with the comparison of CORSIKA and HONDA predictions.

Keywords: Gaseous detectors, RPC, cosmic rays event generator, muon flux
1 Introduction

The cosmic rays coming from outside of the solar system mainly consists of primary protons and a small fraction of helium and higher atomic number nuclei. The primary cosmic rays interact with the earth’s atmosphere and produce a secondary shower of particles. The study of cosmic rays leads to the understanding of the universe. The primary cosmic rays coming more or less isotropically to the earth are modulated by the earth’s magnetic field which causes asymmetry in intensity of their arrival direction. The primary particles having momentum more than the cut-off rigidity will reach the earth’s atmosphere. The observed asymmetry in the cosmic rays due to the earth’s magnetic field is called “east-west” asymmetry. The secondaries produced in the primary interaction will also follow the asymmetry in the arrival direction. The east-west asymmetry of cosmic ray muons depends on the momentum cutoff, latitude and altitude. Hence this effect in cosmic ray muons has been studied by many experiments in the world[1–4]. The primary interaction will mainly produce pions ($\pi^0$, $\pi^+$ and $\pi^-$). While the neutral pions mostly decay to $\gamma\gamma$, the charge pions $\pi^+$ ($\pi^-$) dominantly decay to $\mu^+$ ($\mu^-$) + $\nu_\mu$ ($\bar{\nu}_\mu$). The muons are the dominant charged particles observed at sea level from the cosmic ray shower. The INO-ICAL will be an underground experiment to study neutrino oscillation parameters [5] to resolve the neutrino mass hierarchy problem. A 12-layer prototype of the INO-ICAL detector was constructed using RPCs of about 2 m × 2 m in dimensions [6] to study the cosmic ray muons. The principal aim of this study is to observe the azimuthal dependency of cosmic ray muons at different zenith angles and to compare the same with the phenomenological models. In this paper, the experimental setup is described in section 2. A preliminary analysis of event data is discussed in section 3. In section 4, the GEANT4 based MC, which is used for detector simulation is described. The estimation of muon flux and its systematic uncertainties due to various parameters are discussed in section 5 and section 6 respectively. Lastly, the observed results are presented along with its comparison with the CORSIKA and HONDA flux models in section 7.
The prototype detector setup

A graphical view of the 12 layer stack of RPCs is shown in figure 1. The size of the RPCs used in the stack are 1.8 m × 1.9 m with an interlayer gap of 17 cm. The Resistive Plate Chamber is a parallel plate chamber, built using two, 3 mm glass plates which are separated by 2 mm gap. The outer sides of the chamber are coated by a thin layer of graphite paint in order to establish the high voltage contact. The RPC detector is operated in the avalanche mode by a continuous flow of gas mixture (C$_2$H$_2$F$_4$ (95.2%), iC$_4$H$_{10}$ (4.5%), SF$_6$ (0.3%)) with a differential bias voltage of ±5 kV. A charged particle passing through the RPC detector ionises the gas mixture, produces an avalanche and induces a fast signal on the external pickup strips. The RPC signals are readout by copper pickup panels, which are orthogonally (X- and Y- plane) placed on both sides of the chamber to record localized coordinates of the particle trajectory. The width of the pick-up strip is 28 mm and the inter-strip gap between strip is 2 mm. The number of strips in X- and Y- plane are 60 and 63 respectively.

The induced signals from the pickup strip are amplified and discriminated by a charge sensitive NINO [7] Front-End Board (except layer 11, where Anuspars voltage sensitive Front-End board installed to study the performance of Anuspars chips). The discriminated signals from NINO boards are passed to the FPGA-based Digital Front-End (RPCDAQ-board). The individual signals from
every 8th strips are ORed to get pre-trigger signals (S0 to S7). The 1-fold (S0+S1+...S7), 2-fold (S0.S1+S1.S2+...S6.S7), 3-fold (S0.S1.S2+...S5.S6.S7) and 4-fold (S0.S1.S2.S3+...S4.S5.S6.S7) signals created by RPCDAQ are passed to the Trigger system module via Signal Router Board. The Global Trigger is generated by Global Trigger Logic Board based (GTLB) on X- or Y-plane must have at least one strip hit within 100 ns coincidence window. The coincidence is done for X- and Y-plane independently and the final trigger can be generated by GTLB by OR of Trigger in X- or Y-plane. The event signals in RPCDAQ board stretched to 1 µs to overcome trigger latency from Trigger System to RPCDAQ. Based on the arrival of trigger signals to RPCDAQ, the event signals are latched and sent to the data concentrator and Event Builder via Network Switch. The output of the event builder is stored in a local computer, which is then used for analysis. The flow of signals from the RPCs to the Back-End is shown in figure 2. The different electronics modules are shown in figure 3. The detailed description of signal processing and Data Acquisition system (DAQ) can be found in [8]. The cosmic muons were recorded using the 1-Fold signals from layers 4, 5, 6 and 7 as a trigger. In this study, approximately 92 million events are used with an average trigger rate of 220 Hz. The total data taking period is about ∼5 days. Assuming the energy loss of muons is ∼2 MeVg−1cm2, the minimum momentum cut off in the vertical direction is about 100 MeV.

3 Analysis of Experimental data

The event data consist of two information (i) cosmic ray muon hits1 per layer and (ii) the corresponding time of arrival. The strip hit information is stored as 1 bit per strip. For timing information, the signal from every 8th strips are combined and recorded by TDC. The typical hit patterns observed

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1Hit is the induced strip signal above the set threshold after preamplifier.
Figure 3: (a) NINO Front End board, (b) Anuspars Front End board, (c) RPCDAQ Digital-Front End board, (d) Signal Router Board, (e) Trigger Logic Board (X and Y), (f) Global Trigger Logic Board, (g) Control And Trigger Monitor and Trigger Control And Monitor.

from muon and hadron shower are shown in figure 4. The average strip multiplicity for a signal induced by passage of muon is about 1.3 strip. However, there are a small fraction of events observed with large multiplicities which are mainly due to streamer signals, hadron shower or correlated electronic noise. In figure 5(a) shows a typical strip multiplicity plot. The zero hit in strip multiplicity is due to the inefficiency of the detector. For strip multiplicity of one or two, the observed position resolution is ∼ 7 mm. For strip multiplicity more than 3, the position resolution is of the order of strip unit. The current study uses the information of a layer (X- or Y-plane) only when there is at most three hits in that layer and all hits are in consecutive strips. The selected hit position (arithmetic mean of all position) from all layers are fitted using the straight line in XZ- and YZ-plane using the equation 3.1,

\[ x(y) = \alpha \times z + \beta \]  

(3.1)

where \( x \) or \( y \) is the hit position from the X- or Y-plane respectively for \( Z^{th} \) layer, \( \alpha \) is the slope which is \( \tan \theta \cos \phi \) (\( \tan \theta \sin \phi \)) for XZ (YZ) plane and \( \beta \) is the intercept. Using these four parameters, the exact position of the muon trajectory in all the RPC layers can be computed. Using the muon data, the physical shifts in the detector position in the X- and Y-planes are corrected by an iterative method. In this method, one of the layers is removed in the fitting procedure and the muon trajectory is ex-
Figure 4: (a,b) Typical muon trajectory and (c,d) hadronic shower in RPC stack, (a,c) are XZ views and (b,d) are YZ view.

Global chamber alignment was carried out by applying an iterative fit to the hit positions of the RPC strips. The hits were first extrapolated in that layer from the fit using the information of other layers. The offset is estimated by comparing the measured hit position and extrapolated position in that layer. This method is repeated for all the layers. After 4-5 iterations, an overall chamber alignment accuracy of better than 0.2 mm can be achieved. A detailed explanation about the selection criteria as well as the alignment correction procedure can be found in [10].

Multiplicities, X- and Y-residues, uncorrelated and correlated inefficiencies and trigger efficiencies for all the layers are also calculated by extrapolating muon trajectory excluding that layer in fit. The hit inefficiencies and trigger efficiencies are calculated for each 3 cm × 3 cm pixel, in order to match with strip width. The algorithm to calculate the pixel-wise hit inefficiencies and trigger efficiencies is as follows, The extrapolation error \( \epsilon \) on the hit points in a layer is estimated. The deviation \( \delta \) of a fit point from the midpoint of a strip is also calculated. The trajectories, where \( |\delta| + \epsilon \) is within a strip pitch, are only considered for the efficiency measurement. The correlated inefficiencies are estimated using the fraction of events when a fitted muon has passed through a pixel, but there is no hit in that position in both the X- and Y-plane of the detector within 3 cm of the extrapolated point. The pixel-wise correlated inefficiencies of layer-2 are shown in figure 5(b). The uncorrelated inefficiencies on X-plane are calculated when the X-plane does not have any hit, but the Y-plane has a hit. Similarly, the uncorrelated inefficiencies on the Y-plane are also calculated. The uncorrelated inefficiencies for the X- and Y-plane in layer 2 are shown in figure 5(c) and 5(d) respectively. The trigger efficiency is calculated if there is any hit in the layer when a muon has passed through it. A typical trigger efficiency observed in the RPC is shown in figure 5(e). The inefficient spots in every 6 stripes are due to button spacers, which are placed between two glass electrodes to maintain the uniform gap. The trigger efficiencies of the top six layers are estimated using events triggered by the bottom four layers. Similarly, the trigger efficiencies of the bottom six
Figure 5: (a) Strip-hit multiplicity in X-plane and Y-plane in Layer 2, (b) Pixel-wise correlated inefficiencies in Layer 2, (c) Pixel-wise uncorrelated inefficiencies in Layer 2 (X-plane), (d) Pixel-wise uncorrelated inefficiencies in Layer 2 (Y-plane), (e) Pixel-wise trigger efficiencies in Layer 2 (X-plane) and (f) strip multiplicity based on muon hit position in a strip in Layer 2 (Y-plane).

layers are estimated using events triggered by the top four layers.

The similar analysis procedure can be found in [12], which discussed the zenith angular dependence of cosmic ray muon and the vertical flux at the same location using the same experimental setup with different electronics and data acquisition system.

4 Monte-Carlo event generation

The GEANT4 toolkit was used to develop Monte Carlo simulation which incorporated the interaction of particles with the detector. The 12 layer RPC stack along with the detector hall was included in the GEANT4 detector geometry to include all the different materials through which a cosmic muon has to traverse. The CORSIKA [11] software is used to generate the secondary particle at an experimental site. In the CORSIKA simulation, 20 million primary protons and 2 million Helium from 10 GeV to 1 PeV with spectral index -2.7 is generated from the top of the atmosphere. The low energy and high energy interaction models used in CORSIKA generation are GEISHA and SIBYLL respectively. The generated primary proton energy is compared to the rigidity cutoff at different \((\theta, \phi)\) bins. The primaries having energy above the rigidity cutoff is allowed to progress, otherwise, a new primary was generated. The secondary particles which are having a vertex of the secondary particles are digitized in the dimension of RPC detector area.
In the GEANT4 simulation, the secondary particles are generated above the ceiling of the building. The various detector parameters like uncorrelated and correlated inefficiencies, trigger efficiencies and strip multiplicity were incorporated during the digitisation process of simulation, which were estimated using the data sample. The steps followed in the MC event generation are, A position and momentum \((x, y, P_x, P_y, P_z)\) of the particle from CORSIKA data is generated on the topmost trigger layer (i.e., layer 7). The generated point is extrapolated to the bottom trigger layer to test the acceptance condition. The event generation vertex on top of the ceiling is calculated for the set of \((x, y, P_x, P_y, P_z)\) and given as input to GEANT4. The simulation of the passage of a particle through the detector geometry is performed by the GEANT4. When the particle, passes through an RPC (sensitive detector volume), the GEANT4 provides the \((x, y, z)\) co-ordinate and the exact timestamp for that point. The coordinates of the hit position are translated into the strip information for the corresponding Z plane. The pixel-wise correlated inefficiency map discussed in the previous section is used to incorporate the correlated inefficiencies in the simulated event. The position (hit position with respect to the strip centre) dependent strip multiplicity, as shown in figure 5(f) is used to implement the multiplicity. The uncorrelated inefficiencies for X and Y strips are incorporated independently based on strip multiplicity using the inefficiency map discuss in the previous section. The trigger efficiencies are incorporated only for the trigger layers (namely layers 4, 5, 6 and 7) in the X- or Y-plane to accept an event. In the experimental data, random noise hits due to electronics and multi-particle shower within the detector volume are also observed. These noise hits are also extracted from data and incorporated during the digitization process. The simulated events are analysed in the same procedure that is used for the experimental data. The comparison of \(\chi^2/\text{ndf}\) and the number of layers hit on both X- and Y- planes are shown in figure 6.

5 Estimation of muon flux at different \((\theta, \phi)\) bins

The number of muons events reconstructed which are having \(\chi^2/\text{ndf}\) less than 8 and more than five layer muon hits used to estimate the intensity of muons at various \((\theta, \phi)\), the equation used to calculate the muon flux at different \((\theta, \phi)\) bins given in equation 5.1,

\[
I_{\theta, \phi} = \frac{I_{\text{data}}}{\epsilon_{\text{trig}} \times \epsilon_{\text{selec}} \times \epsilon_{\text{daq}} \times T_{\text{tot}} \times \omega}
\]

where, \(I_{\text{data}}\) is the number of reconstructed muon at a \((\theta, \phi)\) bin, \(\epsilon_{\text{trig}}\) is the trigger efficiency in that \((\theta, \phi)\) bin, \(\epsilon_{\text{selec}}\) is the event selection efficiency in that \((\theta, \phi)\) bin, \(\epsilon_{\text{daq}}\) is the efficiency due to dead time in the data acquisition system, \(T_{\text{tot}}\) is the total time taken to record the data (in seconds) including DAQ’s dead time (0.5 ms/event) and \(\omega\) is the accepted solid angle times the surface area, which is further defined as,

\[
\omega = \frac{A N}{N'} \int_{\theta_1}^{\theta_2} \sin \theta d\theta \times \int_{\phi_1}^{\phi_2} d\phi
\]

where, \(A\) is the surface area of the RPC in the top triggered layer, \(N\) is the number of events accepted at a \((\theta, \phi)\) bin when the generated position on the top and bottom trigger layer is inside the detector, \(N'\) is the number of events generated on top trigger layer at \((\theta, \phi)\) bin.

6 Systematic studies

The muon flux at different \((\theta, \phi)\) bin can be affected by many systematics related to the uncertainties in the detector parameter and input muon spectrum to the GEANT4 input. To study these variations
many input parameters are changed to propagate the uncertainties of those parameters to flux measurement and the muon flux is estimated. The parameters which are changed in the MC to calculate the flux are, (i) To study the variation of input muon spectrum in the simulation, the default GEANT4 simulation done using the muon spectrum taken from CORSIKA, which has generated using SIBYLL interaction model. The interaction model changed to HDPM interaction model to estimate the muon flux. (ii) To account for the uncertainty in the estimated inefficiency, the binomial error in each 3 cm $\times$ 3 cm pixel is calculated, during the MC generation the inefficiency reduced and increased by 1$\sigma$. (iii) To account for the uncertainty in the estimated trigger efficiency, during the MC generation the trigger efficiency is decreased and increased by 1$\sigma$. (iv) The shower and electronic noise will affect the reconstruction efficiency of the muon. To check the variation of muon flux based on the estimated input noise to MC, the input noise is increased and decreased by 10\% which is approximately the variation of noise during the whole period. (v) The complete geometry of the detector hall along with nearby building around the experimental hall included in the GEANT4 geometry. But there are uncertainties in materials of wall and roof, to account those uncertainties the roof thickness of the building increased by 10\%, which modulates the muon spectrum at low energies. (vi) The low energy muons undergo multiple scattering in the materials in the RPC stack. To take care of that uncertainty, the density of the material inside the detector is changed by 10\%. (vii) The difference in the estimation of reduced-$\chi^2$ distribution in MC sample and data is also considered as a systematics, so the reconstructed muons from the MC is selected with scaled $\chi^2$/ndf. (viii) The muon flux is estimated by the reconstructed muons which are having minimum 5 layer hits, these criteria chosen to compensate large acceptance and larger track length. The flux is estimated for muons which are

Figure 6: (a,c) $\chi^2$/ndf for Data and MC in X- and Y-plane. (b,d) Number of layers in Data and MC for X- and Y-plane.
having minimum 4 layer hits and the difference is used as a systematic error on the selection criteria. (ix) The data sample is split into two sets as odd numbered and even numbered events, the flux calculated for these two data samples separately.

The relative change in the muon flux for all these systematics are shown in figure 7.

7 Comparison of observed flux with CORSIKA and HONDA prediction

The east-west asymmetry of cosmic ray muons at different places on the earth depends on its geomagnetic latitude and longitude. A comparison of the results in the current study with the CORSIKA prediction for different physics interaction models and HONDA prediction for the INO experimental site. The observed, CORSIKA with different input physics models (namely SIBYLL-GEISHA
Figure 8: Comparison of the azimuthal muon flux with CORSIKA and HONDA predictions.

(SG), VENUS-GEISHA (VG) and HDPM-GEISHA (VG)) and HONDA predictions are shown in the figure 8 along with the following fit function,

\[ f(\phi) = P_0(1 + A \sin(-\phi + \phi_0)), \]

(7.1)

where parameter \( A \) from the fit will give the amplitude of asymmetry of the fit function. The fitted asymmetry parameters, \( A \) and \( \phi_0 \) are shown in figure 9(a) and 9(b) respectively.

Figure 9: (a) Asymmetry parameter for data, CORSIKA and HONDA, (b) \( \phi_0 \) parameter for data, CORSIKA and HONDA.
The comparison of the measured result with the predictions are quantified using equation 7.2,

$$\chi^2 = \sum_\phi \frac{(I^\phi_{data} - I^\phi_{MC})^2}{\sigma^2_{total}},$$

(7.2)

where $I^\phi_{data}$, $I^\phi_{MC}$ and $\sigma^2_{total}$ are the observed muon flux, the MC prediction of flux in various azimuthal bins and total error respectively. The calculated $\chi^2$ from the equation 7.2 is listed in table 1. The $\chi^2$ values for HONDA with data shows better agreement in comparison with CORSIKA and its different models.

| $\cos \theta$ | $\chi^2_{DATA-SG}$ | $\chi^2_{DATA-HG}$ | $\chi^2_{DATA-VG}$ | $\chi^2_{DATA-HONDA}$ |
|---------------|---------------------|---------------------|---------------------|---------------------|
| 1 - 0.95      | 7.48                | 3.58                | 3.50                | 1.29                |
| 0.95 - 0.9    | 4.99                | 9.78                | 4.76                | 4.04                |
| 0.9 - 0.85    | 8.24                | 18.73               | 8.75                | 10.33               |
| 0.85 - 0.8    | 11.59               | 12.23               | 10.26               | 12.33               |
| 0.8 - 0.75    | 24.10               | 34.43               | 37.33               | 11.19               |
| 0.75 - 0.7    | 16.40               | 22.92               | 25.82               | 10.29               |
| 0.7 - 0.65    | 21.16               | 16.10               | 24.95               | 4.48                |
| 0.65 - 0.6    | 25.03               | 25.95               | 28.58               | 8.06                |
| 0.6 - 0.55    | 14.69               | 18.81               | 18.93               | 7.64                |
| 0.55 - 0.5    | 9.11                | 13.43               | 12.19               | 7.11                |

Table 1: The comparison of $\chi^2_{DATA-MC}$ for data with different MC predictions.

The east-west asymmetry of cosmic muons increases with the zenith angle, $\theta$, as the geomagnetic rigidity for the west direction decreases with the increasing zenith angle while for the east, the rigidity increases. The observed asymmetry in the data and MC predictions are comparable in lower $\cos \theta$ bins, but at higher $\cos \theta$ bins the observed asymmetry in data is higher in comparison with both CORSIKA and HONDA predictions. The amplitude of asymmetry in data is close to the HONDA flux whereas the phase ($\phi_0$) of the asymmetry in data is closer to CORSIKA flux. This result can go as input to the event generator to get a better estimation of neutrino flux at INO-site.

8 Conclusions

The azimuthal dependence of cosmic muon flux at different zenith angles is studied using 2 m × 2 m RPC stack at IICHEP, Madurai, which is close to the geomagnetic equator. The systematic study of the muon flux is estimated by considering the uncertainties in the detector parameters and various physics models. The measurements are compared with CORSIKA generated events with different physics interaction models and HONDA prediction at INO-site. The results at lower $\cos \theta$ bins are comparable to the MC predictions within error. In the higher $\cos \theta$ bins, the asymmetry in data is more as compared to both CORSIKA and HONDA models. This discrepancy will be input to better estimation of neutrino flux at INO-site, Theni. The detector parameters like efficiencies, multiplicity, time and position smearing observed in the data will be input to the INO-ICAL simulation code.

Acknowledgments

We would like to thank Dr.P.K. Mohanty and Mr. Hariharan from GRAPES-3 experiment for providing angle dependent primary cutoff rigidity values for the experimental site. We acknowledge crucial
contributions by A. Bhatt, S.D. Kalmani, S. Mondal, P. Nagaraj, Pathaleswar, K.C. Ravindran, M.N. Saraf, R.R. Shinde, Dipankar Sil, S.S. Upadhya, P. Verma, E. Yuvaraj, S.R. Joshi, Darshana Koli, S. Chavan, N. Sivaramakrishnan, B. Rajeswaran, Rajkumar Bharathi in setting up the detector, electronics and the DAQ systems.

References

[1] Murty, D.S.R. Proc. Indian Acad. Sci. (1953) 37: 317. https://doi.org/10.1007/BF03052714.
[2] Diep, Pham Ngoc et al. Measurement of the east-west asymmetry of the cosmic muon flux in Hanoi - Nucl. Phys. B678 (2004) 3-15.
[3] Thomas H. Johnson et al., The East-West Asymmetry of the Cosmic Radiation in High Latitudes and the Excess of Positive Mesotron, Physical Review, volume 59, January 1, 1941.
[4] Shuhei Tsuji et al., Measurements of muons at sea level, J.Phys.G: Nucl.Part.Phys. 24 (1998) 1805-1822.
[5] ICAL Collaboration, Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO), Pramana J. Phys. (2017)88:79.
[6] R.Santonica, R.Cardarelli, Development of resistive plate counters, Nucl. Instrum. Methods 187 (1981) 377-380. doi:10.1016/0029-554X(81)90363-3.
[7] F. Anghinolfi et al. NINO: an ultra-fast and low-power front-end amplifier/discriminator ASIC designed for the multigap resistive plate chamber, Nucl. Instrum. Methods A 533 (2004) 183-187.
[8] Achrekar S. et al. (2018) Electronics, Trigger and Data Acquisition Systems for the INO ICAL Experiment. In: Liu ZA. (eds) Proceedings of International Conference on Technology and Instrumentation in Particle Physics 2017. TIPP 2017. Springer Proceedings in Physics, vol 212. Springer, Singapore
[9] GEANT4 Collaboration: S Agostinelli et al, GEANT4: A Simulation toolkit, Nucl. Instrum. Methods A506 (2003) 250.
[10] S.Pal, B.Acharya, G.Majumder, N.Mondal, D.Samuel, B.Satyanarayana, Measurement of integrated flux of cosmic ray muons at sea level using the INO-ICAL prototype detector, J. Cosmol. Astropart. Phys. 07 (2012) 033. http://dx.doi.org/10.1088/1475-7516/2012/07/033.
[11] D.Heck, J.Knapp, J.N.Capdevielle, G.Schatz, and T.Thouw, Report FZKA 6019 (1998), Forschungszentrum Karlsruhe; available from https://www.ikp.kit.edu/corsika/70.php
[12] S. Pethuraj et al., Measurement of cosmic muon angular distribution and vertical integrated flux by 2m × 2m RPC stack at IICHEP-Madurai JCAP09(2017)021. https://doi.org/10.1088/1475-7516/2017/09/021.