Study of Particle Multiplicity of Cosmic Ray Events using 2 m × 2 m Resistive Plate Chamber Stack at IICHEP-Madurai

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Abstract

An experimental setup consisting of 12 layers of glass Resistive Plate Chambers (RPCs) of size 2 m × 2 m has been built at IICHEP-Madurai to study the long term performance and stability of RPCs produced on large scale in Industry. In this study, the data obtained by this setup was analysed to find out the events where more than one trajectories of charged particles are detected within a single trigger window. The results obtained from observation was then compared with different hadronic models of CORSIKA prediction.

Keywords: cosmic ray experiments, cosmic rays detectors, hadronic interaction models

1. Introduction

The 50 kton INO-ICAL\cite{1} is a proposed underground high energy physics experiment at Theni, India (9°57′ N, 77°16′ E) to study the neutrino oscillation parameters using atmospheric neutrinos. It will also determine the sign of the 2-3 mass-squared difference, $\Delta m^2_{23} (= m^2_3 - m^2_2)$ through matter effects, the value of the leptonic CP phase and, last but not the least, the search for any non-standard effect beyond neutrino oscillations. The Resistive Plate Chamber (RPC)\cite{2,3} has been chosen as the active detector element for the ICAL detector. About 28000 glass RPCs of size $\sim 2 \times 2$ m will be used to measure energy and direction of neutrinos. As part of the ICAL R&D programme, a 12 layer stack of 2 m × 2 m Resistive Plate Chambers (RPCs) has been operational at IICHEP, Madurai since last few years to study the cosmic ray muons\cite{4}. The
various detector properties like position and time resolution of RPCs, detector inefficiencies, strip multiplicities, detector noise, etc are studied using this RPC stack to understand the performance and long term stability of the RPCs.

High energetic primary cosmic rays originating in outer space continuously interacts with earth’s atmosphere. These cosmic rays consist of mostly protons with a smaller fraction of higher Z-Nuclei elements. Upon interacting with the earth’s upper atmosphere, they result in showers of secondary particles which are mostly consist of pions ($\pi^{\pm,0}$) and kaons ($K^{\pm}$). The neutral pions mainly decay via electro-magnetic interactions, $\pi^0 \rightarrow \gamma + \gamma$. The charged pions decay to muons and neutrinos via weak-interactions, $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$. The kaons can decay to pions, muons and neutrinos via different decay mode. The resultant muons decay into electrons and neutrinos, $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ and $\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu$. Most of the $\pi$, $K$ decay in flight and do not reach the earth’s surface. The $\gamma, e^\pm$ do not reach the detector directly as they interact with the roof of the laboratory and create electromagnetic showers. The muons are the most abundant charged particle found at sea level from cosmic ray showers. These atmospheric muons are produced at high altitude (average height of 20 km) in the atmosphere and lose almost 2 GeV energy via ionisation loss in the air before reaching the ground. The angular distribution of primary cosmic rays is more or less isotropic. The energy spectrum of the primary cosmic rays follows a power-law, $E^{-\gamma}$. The density of charged particles (mainly muons) per unit surface area at the earth’s surface depends on the composition of primary cosmic ray, power lay parameter ($\gamma$) as well as the model of hadronic interactions at high energy which is not accessible in the laboratory.

The interactions of primary cosmic ray in the air and the resultant air shower has been simulated using the CORSIKA Package[5]. The daughter particles reaching sea level in the air shower simulation in CORSIKA are given as input to the detector simulation. The detector simulation has been performed using GEANT4 toolkit[6]. All the detector parameters obtained from the observed data (e.g. efficiency, noise, strip multiplicity, resolution, etc.) are used in detector simulation to make for a real detector scenario. The principal aim of this work is to observe the charged-particle multiplicity in the atmospheric muon data collected at IICHEP, Madurai and compare it with the air shower
simulation.

2. Detector Setup

The RPC stack operational at IICHEP, Madurai consisting of 12 RPCs stacked horizontally with an inter-layer gap of 16 cm is shown in Figure 1. An RPC gap is made of two glass electrodes of thickness 3 mm kept at a gap of 2 mm. This gap is maintained using 2 mm thick poly-carbonate buttons. The glass gap is sealed properly to make it gas-tight. A non-flammable mixture of gas is continuously flown inside the glass gaps which serve as the active medium of the detector. In avalanche mode, the mixture of gas consists of R134a (95.2%), iso-C$_4$H$_{10}$ (4.2%) and SF$_6$ (0.3%). Both the outer surfaces of the glass gap are coated with a thin layer of graphite. The RPCs are operated by applying a differential supply of ±5 kV to achieve the desired electric field. The avalanche created by the ionization energy loss of charged particles in the RPCs induces signals in the two orthogonal pickup panels placed on both sides of the glass gaps labeled as X-side and Y-side. The pickup panels are made of parallel copper strips of width 28 mm with 2 mm gap between two consecutive strips. The RPCs used in this detector stack are of the size of 1790 mm × 1890 mm. There are 60 strips on the X side and 63 strips on the Y side for each layer.

Figure 1: The detector stack with 12 layers of RPCs.
The induced signals from the pickup strips are amplified and discriminated by a charge sensitive NINO[7] front end board. In Layer 11 (top most layer), ANUSPAS front end ASIC[8] which is a CMOS, 8-channel, high speed, low power amplifier-discriminator designed for avalanche mode of operation for RPCs is used to study its performance. The discriminated signals from these front end boards are passed to the FPGA-based 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 with 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 the 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 flow of signals from the RPCs to the Back-End is shown in Figure 2. The detailed description of signal processing and the Data Acquisition system (DAQ) can be found in [9]. The 1-Fold signals from layers 4, 5, 6 and 7 are used as trigger to record the cosmic events used in
the present work.

Although the coincidence window is 100 ns, event as well as noise signals in a time window of 800 ns after generation of the trigger also get recorded due to stretching of the event latch. An event typically contains hit (one logic bit per strip indicating the signal in that strip is above or below the threshold value) for each strips and 16 time signal for each layer. One TDC channel records time signal coming from all alternating 8\textsuperscript{th} strips on one side of the layer. In the present work, the cosmic events recorded in the detector for the total observation period of about ∼17 days between August 23, 2017, to September 8, 2017, with a trigger rate of ∼230 Hz are used in the analysis. Assuming the energy loss of muons is ∼2 MeV g\textsuperscript{-1} cm\textsuperscript{2}, the minimum momentum cut off of charged particles in the vertical direction is about 70 MeV, which is mainly due to 15 cm roof of concrete.

3. Monte-Carlo Simulation

The primary cosmic ray shower has been simulated using the CORSIKA(v7.6300) Package. The energy of the primary rays in CORSIKA are generated using the power-law spectrum, $E^{-2.7}$, within the energy range of 10–10\textsuperscript{6} GeV for different primaries (H, He, C, O, Si and Fe). The Gheisha package has been used to model the simulation in low energies whereas QGSJET-II-04 and QGSJET01d packages are used to model in high energy range. The magnetic rigidity cutoff has been implemented according to location of the detector site (9\textdegree56′14.5″ N 78°0′47.9″ E). The minimum energy cutoff for hadrons, muons, electrons and photons at the roof are 50 MeV, 10 MeV, 1 MeV and 1 MeV, respectively in the simulation. To improve the statistics in high energies, a large number of primaries are generated in those ranges. The particles generated by CORSIKA at the observation surface (160 m above mean sea level) are given as input to the detector simulation in GEANT4(v4-10.0.2). The observation plane has been divided into rectangles of the size of the detector’s X–Y cross-section. An event is formed using the information of the particle(s) passing through each of these rectangles. Figure 3 shows CORSIKA generated particle momentum at the observation surface. All the detector parameters (inefficiency, noise, strip multiplicity, resolution, etc) are calculated from the observational data are used in
the digitisation stage of the detector simulation. Figure 4 shows inefficiency, noise and multiplicity profile for one of the RPC in the stack. A detailed study on these parameters can be found in [4]. The observed data and the simulated events are reconstructed using the same algorithm (described in next section).

![Particle momentum at observation level generated by CORSIKA.](image)

Figure 3: Particle momentum at observation level generated by CORSIKA.

![Inefficiency, noise and multiplicity profile of Y side of Layer-2 RPC gap.](image)

Figure 4: (a) inefficiency, (b) noise and (c) multiplicity profile of Y side of Layer-2 RPC gap.

4. Event Reconstruction and Data Selection

The data is initially reconstructed through 2-dimensional projections of the 3-dimensional track(s) on X–Z and Y–Z plane. Figure 5 shows a typical event observed in the stack. The average strip multiplicity observed in these RPCs depends on the gain of the gas gaps. The induced charge sharing between the neighbouring strips is the main cause for this strip multiplicity which is show in Figure 4(c). During the study, the position resolutions for different strip multiplicities of 1, 2, 3 and 4 are observed to be $\sim$6 mm, $\sim$8 mm, $\sim$12 mm and $\sim$22 mm respectively. The position resolution for strip multiplicity more than four is larger than the pitch of the strip (3 cm). Hence, in the present study, the
events with a maximum of four consecutive strip hits are considered for analysis. A straight line fit information of each projection is extracted using the method of Hough Transformation on both X–Z and Y–Z planes. In this case, the equation of straight line in equation 1 is represented as equation 2

\[ x = mz + c \]  
\[ r = z \cos \theta + x \sin \theta \]

where \( m = -\cot \theta \) and \( c = r \cosec \theta \).

There are a lot of advantages to equation 2. The main advantage is that the equation 2 is numerically computable for all possible values of \( m \) and \( c \). Instead of using the usual method, \( r-\theta \) plane is populated using the concept of Cellular Automaton. Figure 6(b) shows a typical \( r-\theta \) plane (called as Hough Space) populated using this method by calculating values of \( r \) and \( \theta \) for each pair of data point shown in Figure 6(a). This method decreases the computation time significantly for the present setup as the complexity of computation is \( N^2 \), \( N \) being the number of layer. Figure 6(a) shows that this method can detect all the tracks avoiding all the noise hits.

Figure 7 shows a shower event which could be due to noise also. The reconstruction inefficiency of the detector stack with time is shown in Figure 8 where efficiency is defined as the ratio of events with at least one reconstructed straight track with the total number of triggered event. It can be observed that the inefficiency of the RPC detectors varies periodically with a daily variation of pressure and temperature. This periodic change in inefficiency does not af-
fect the relative ratio of multiple track events. Approximately 17% of triggered events are rejected based on different selection criteria (i.e. number of layer hits, $\chi^2/\text{ndf}$ cut, passing through full-stack, hadronic showers, etc.). Approximately 6–7% of triggered events are due to noise and hadronic showers. These events are main sources of background to detect pure multiple track events which are $\sim 0.01\%$ of triggered events. Various criteria discussed next are adopted in order to reject these showers as many as possible. Any layer with more than 15 strip hits is tagged as ‘noisy’ and eliminated from track reconstruction. Events with more than 3 ‘noisy’ layers are fully discarded. Layers which are not ‘noisy’ with maximum 10 hit positions (clusters) are only accepted for track reconstruction.

Figure 6: (a) Projection of an event in the detector and (b) populated $r-\theta$ plane using this event.

Figure 7: Example of an extreme shower event.
shows $\chi^2$/ndf of a straight line fit for both data and simulation. The tracks reconstructed with $\chi^2$/ndf less than 10 and more than four-layer hits are used in the analysis. The zenith and azimuth angle distributions are presented in Figure 10(a) and 10(b), respectively. The projections from both X–Z and Y–Z planes are combined to produce final 3-dimensional track(s). The timing information is used to discard any ghost track(s). Figure 11(a) shows the time separation between a pair of track for both simulation and observation. It can be seen that there is a fair amount of events with multiple tracks with a large time gap. Particles originating from different cosmic showers are the sources of these events. The random coincidence of charged particles from different cosmic showers is absent in simulation as only one shower can be simulated at a time in CORSIKA. The skewed angle, minimum skewed distance and its position, between each pair of tracks are calculated. This information helps to determine the origin of the tracks. Figure 12 shows an event where one neutral and two charged particles have originated in the roof. Another similar interaction is shown in Figure 13 where the particles have originated in the detector. In our study, these events have been rejected as these are coming from neutral particles at the surface and/or due to the interaction in the materials of the detector. To calculate the skewed angle resolution for the present setup, the events with multiple particles are simulated in GEANT4. The skewed angle difference between the generated and reconstructed tracks fitted with triple-gaussian function is shown in Figure 14(a). The skewed angle resolution for the detector stack is ($\sigma_0 =$)0.84° if none of the particles are scattered in the medium of the detector or the roof of the building. The skewed angle resolutions is ($\sigma_1 =$)2.1° if one of the particles is scattered and ($\sigma_2 =$)4.5° if both of the particles are scattered. Figure 14(b) shows the skewed angle distribution between tracks originating outside the de-
tector. The long tail part in the case of observed data is contributed by the random coincidences which are absent in simulation.

![Graph](image-url)

Figure 9: (a) Number of hit layer and (b) $\chi^2$/ndf of straight line fit.

![Graph](image-url)

Figure 10: (a) Zenith and (b) Azimuth Angle of cosmic rays reaching the detector stack.

In the current study, only the particles generated in the same cosmic ray shower are of interest. All the scattered events and random coincidences need to be rejected. To achieve this, only parallel tracks (skewed angle less than 2.5°) are chosen for comparing simulation and data. Figure 11(b) shows the time difference between a pair of tracks for both simulated and observed data after selecting only parallel tracks. It can be observed that the random coincidences disappear after using only the parallel tracks.

5. Results

The event direction is presumed as a mean direction of individual muons in an event. There is no directional clustering of events. There is also no
Figure 11: Time separation of two tracks for (a) all events and (b) for only parallel tracks.

Figure 12: Particle scattered in the material of roof.

significant modulation of the fraction of multiple tracks during the observation irrespective of periodic changes in trigger rate. The absence of anisotropies in the data justify the assumption of uniform distribution of cosmic ray directions which is used in CORSIKA simulations.

The number of events with one, two, three and four parallel tracks detected in the data are 206003672, 13091, 120 and 4, respectively. The same distribution is found for different cosmic primaries (H, He, C, Si, and Fe) and with different physics packages (QGSJET-II-04 and QGSJET01d). The ratio between normalised multiple track fraction of simulation and observation is presented in table 1.

As per abundances of elements in primary cosmic rays\cite{12,13}, the ratio for 2, 3 and 4 tracks between simulation and data are 0.38, 0.23, and 0.12, respectively if QGSJET01d package is considered. The ratios are clearly showing that there
is a large discrepancy between the observed data and simulation.

A few other experiments (KGF[14], ALICE[15], MACRO[16], DELPHI[17], ALEPH[18], KASCADE-Grande[19], etc.) have also studied the multi-muon tracks in cosmic events. Whereas the present setup is over the ground, except KASCADE-Grande, all other experiments were performed under the ground. The underground experiments have observed events with large multiplicities because of the large size of the detectors and the overburden of rock and soil blocking showers with lower energy. A study based on the aforesaid experiments has also suggested a similar discrepancy between the CORSIKA simulation and observed data. KASCADE-Grande experiment also reported that the attenuation length of muons in the atmosphere from simulation is much smaller than estimation from observed data. Possible source of discrepancies can be improper
Table 1: Ratio of multiple track fractions between simulation and observation for different primaries (H, He, C, O, Si and Fe) and different physics packages (QGSJET-II-04 and QGSJET01d).

function of different species of primary cosmic ray, variation of power law factor, but variation of those parameters within their uncertainty change the result very little. Major discrepancy in the result is due to uncertainty of hadronic interaction models which was not verified in any laboratory experiments at this high energy. Earlier measurements of muon multiplicity along with this result can be used to improve the parameters of hadronic model at high energies (> 300 GeV).

6. Conclusion

In the period between August 23, 2017, to September 8, 2017, approximately 2×10^8 events of cosmic rays were acquired containing at least one reconstructed particle. The comparison of the measured track multiplicity distribution with an equivalent sample of Monte Carlo events reflects that the current physics models of interactions at the earth atmosphere used in this study are unable to reproduce the air showers at the ground.

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