SYNOPSIS

1. INTRODUCTION

The elusive neutrino has been among the most exciting particles since its postulation in 1930. The existence of neutrino was postulated by Pauli in a desperate attempt to save the 4-momentum and angular momentum conservations in nuclear $\beta$-decays [1]. After a wait of 26 years, it was detected experimentally in 1956, by Reines and Cowan [2, 3]. From then on, impressive results in the field of neutrino physics have amplified the excitement by many folds. Initially neutrino was assumed to be massless, which went well in accordance with the Standard Model of particle physics. However, the phenomenon of neutrino oscillations [4, 5], i.e., a propagating neutrino changing its flavour, implies that neutrinos are not massless, and thus opens a gateway for the physics beyond the standard model (BSM). The neutrino oscillations are parametrized in terms of a unitary transformation matrix connecting the flavor and mass eigenstates. In the $3$-flavour basis, the elements of this matrix are expressed in terms of three mixing angles $\theta_{12}$, $\theta_{13}$ and $\theta_{23}$, and a CP violating phase $\delta_{cp}$. The amplitude of the neutrino oscillations is determined by these three mixing angles, while the frequency is governed by the mass squared differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$. The magnitude and sign of $\Delta m_{21}^2$ is established from our understanding of solar and reactor neutrino measurements. However in case of $\Delta m_{31}^2$ (or, $\Delta m_{32}^2$) only the magnitude is known, and the unknown sign of $\Delta m_{31}^2$ leads to two possible arrangements of the neutrino mass eigenstates. The normal mass hierarchy (NH) corresponds to

the ordering \( m_1 < m_2 < m_3 \), while the inverted hierarchy (IH) is with the ordering \( m_3 < m_1 < m_2 \). The hierarchy of the neutrino mass eigenstates can be confirmed once the sign of \( \Delta m^2_{31} \) is determined.

Various experiments around the globe are now engrossed in exploring the neutrinos aiming at the determination of the mass hierarchy, the mixing parameters, leptonic CP violation and the absolute neutrino-mass scale. As a part of this effort the India-based Neutrino observatory (INO), a multi-institutional venture, has been initiated in India to build a underground neutrino laboratory \([6]\). The planned magnetized Iron Calorimeter (ICAL) detector at INO would study the oscillations in the atmospheric neutrinos in the GeV range. The ICAL will consist of the Resistive Plate Chamber (RPC) detectors as the active elements \([7]\), interspersed with 5.6 cm thick iron plates. There will be 151 horizontal layers of the iron plates, with 4 cm gaps to place the RPC units. ICAL will be magnetized to about 1.5 Tesla. Three identical modules, of dimensions 16 m \( \times \) 16 m \( \times \) 14.4 m each, will be housed in a cavern with about 1 km of rock coverage, to reduce the cosmic muon background. It would mostly search for \( \nu_\mu \) induced charged current interactions in the iron target.

The ICAL aims at the determination of the neutrino mass hierarchy by exploring the matter effects for \( \nu_\mu \) and \( \bar{\nu}_\mu \) separately, through the charge identification of the muons in the magnetic field. It will also look for precise estimation of the atmospheric mixing parameters (\( \theta_{23} \) and \( |\Delta m^2_{23}| \)). Apart from these, ICAL would also explore the possibility of CPT violation, existence of the sterile neutrinos etc.

### 2. THE HADRON RESOLUTION OF ICAL

This is a GEANT4-based \([8]\) simulation study to quantify the ICAL response to the hadrons, produced in the atmospheric neutrino interactions. The hits in the detector due to the hadrons are the observables in this work.
2.1 NEUTRINO INTERACTIONS IN ICAL

The atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ interact with the iron target through quasi-elastic (QE), resonance scattering (RS) and deep inelastic scattering (DIS) processes. The charged-current (CC) interactions produce muons as well as hadrons. In the sub-GeV range, the QE process dominates, and apart from the recoil nucleons they do not have any other hadrons in the final state. As energy increases, RS and DIS processes start dominating and at a few GeV DIS becomes the most prominent process. Resonance events typically contain a single pion in the final state, though in a small fraction of events there are multiple pions. DIS events produce multiple hadrons. The momentum of the incident neutrino gets distributed among the final state particles i.e., the muon and the hadrons. The muon leaves a long track of hits in the detector with an average strip multiplicity per layer of about 1.4. The muon momentum is reconstructed using a Kalman Filter based algorithm [9]. The hadrons produce a shower, where the hits are confined to a few layers with a much higher strip multiplicity as compared to the muons. The hadron energy [10, 11] and direction [12] can be estimated using the shower hit information.

2.2 THE HADRON ENERGY CALIBRATION AND RESOLUTION

The propagation of particles in the ICAL detector is simulated using the GEANT4 package, taking into account the realistic input parameters of the RPC detectors and the magnetic field. This simulation provides the location of the passage of the particle in the X and Y strips of the RPC layers. As the hadron shower contains multiple hits per layer, the possibility of false counting (ghost hit) is reduced by using the maximum of X or Y hits for each event. Firstly, $\pi^\pm$, $\pi^0$, $K^\pm$, $K^0$ and protons of certain fixed energies are propagated through ICAL, and it is seen that ICAL cannot distinguish among individual hadrons. Then, the hadrons produced in the atmospheric neutrino interactions, generated using NUANCEv3.5 [13] event generator, are propagated through the detector.
The visible hadron energy depends on various factors such as, the shower energy fluctuation, leakage of energy and invisible energy loss mechanisms. To quantify the ICAL response to hadrons, we use the parameter $E'_{\text{had}}$ as

$$E'_{\text{had}} = E_{\nu} - E_{\mu} \; .$$

Note that, $E'_{\text{had}}$ includes the visible and invisible hadron energies, as well as the energy of the recoil nucleons. All type of hadrons contribute to this energy, however at a few GeV it is dominated by pions.

A typical hadron hit distribution at $E'_{\text{had}} = (3.5 - 3.75)$ GeV for hadrons produced in the neutrino interactions in ICAL is shown in Fig 1a. These distributions are not symmetric and have long tails. After trials of fits with various probability distribution functions (PDF) such as, Gaussian, Landau, Landau convoluted with a Gaussian etc., a good fit is obtained with the Vavilov distribution function [14, 15]. The Vavilov function expresses the energy loss by particles propagating in moderately thick absorbers. The standard Vavilov distribution is described by the two parameters $\kappa$ and $\beta^2$. For $\kappa \leq 0.05$, the Vavilov distribution may be approximated by the Landau distribution, while for $\kappa \geq 10$, it approaches the Gaussian approximation.

The Vavilov PDF is built into the analysis software package ROOT [16], and is modified with extra parameters $P_2$, $P_3$ and $P_4$ to account for x-scaling, the shifting of the peak to a non zero value and normalization, in order to fit the hadron hit distributions. The mean and variance of this modified PDF are

$$\text{Mean}_{\text{Vavilov}} = (\gamma - 1 - \ln \kappa - \beta^2) P_3 + P_2 \; , \quad \sigma^2_{\text{Vavilov}} = \frac{(2 - \beta^2)}{2\kappa} P_3^2 \; .$$

Using these parameters, the hit distributions can be reproduced.
As shown in Fig. 1b, the mean hit ($\bar{n}$) increases with the increase in hadron energy, and saturates at higher energies. It may be approximated by

$$\bar{n}(E'_{\text{had}}) = n_0[1 - \exp(-E'_{\text{had}}/E_0)], \quad (3)$$

where $n_0$ and $E_0$ are constants. The value of $E_0$ is $\sim$ 27 GeV for the $E'_{\text{had}}$ range (0 – 15) GeV. When $E'_{\text{had}} \ll E_0$, the increase in $\bar{n}$ with $E'_{\text{had}}$ is linear. Using linear approximation, the hadron energy resolution can be defined as

$$\sigma/E = \Delta E'_{\text{had}}/E'_{\text{had}} = \Delta n(E'_{\text{had}})/\bar{n}(E'_{\text{had}}). \quad (4)$$

The $\sigma/E$ may be parameterized by

$$\frac{\sigma}{E} = \sqrt{\frac{a^2}{E} + b^2}; \quad (5)$$

where $a$ and $b$ are constants. The hadron energy resolution of ICAL as a function of $E'_{\text{had}}$ is shown in Fig. 2a. The energy resolution ranges from 85% (at 1 GeV) to 36% (at 15 GeV). Similar response have been obtained from the hadrons produced in the neutral current interaction processes. The hadron energy resolution is also studied as a function of the iron plate thickness [11].
The shower hits will be the only observable parameter for the hadrons, when the real ICAL detector starts taking data. Thus a calibration of the hit multiplicity with the $E'_{\text{had}}$ becomes essential to reconstruct the hadron energy. The $E'_{\text{had}}$ distributions for the events binned in hadron hits are fitted with Vavilov distribution function, and the mean and $\sigma$ from this fit are used to produce the calibration as shown in Fig. 2b. This calibration can be used to estimate the $E'_{\text{had}}$. A look up table containing the Vavilov fit parameters is used to include the hadron response in the analysis to determine the physics reach of ICAL.

2.3 RECONSTRUCTION OF THE HADRON SHOWER DIRECTION

It is difficult to reconstruct the average direction of the hadron showers as accurately as that of muons. Still it is possible to use the position information of the hadron shower hits in the detector and reconstruct the shower direction [12]. When the muon track gets reconstructed in a CC event, the position vectors of the shower hits with respect to the reconstructed interaction vertex can be used. Two methods, namely the centroid method and the orientation matrix method have been used in such cases.
The direction of the centroid of the shower is reconstructed by summing over the position vectors (with respect to the vertex) of each hit in that event. However the accuracy of reconstruction may be slightly increased by taking into account the higher order moments by the use of the orientation matrix technique [17]. In this method, for a collection of unit vectors \((x_i, y_i, z_i), i = 1, ..., n\), the orientation matrix \(T\) is defined as

\[
T = \begin{pmatrix}
\Sigma x_i^2 & \Sigma x_i y_i & \Sigma x_i z_i \\
\Sigma x_i y_i & \Sigma y_i^2 & \Sigma y_i z_i \\
\Sigma x_i z_i & \Sigma y_i z_i & \Sigma z_i^2
\end{pmatrix}
\]  

(6)

The eigenanalysis of this symmetric matrix gives an idea of the shape of the underlying distribution. If we think of a unit mass being placed at each point, then the variation of the moment of inertia of these \(n\) points about any arbitrary axis would provide information about the scatter of the points. The axis about which the moment of inertia is least is defined to be the shower direction. The MIGRAD minimizer algorithm, which is inbuilt in TMinuit class in ROOT has been used for the minimization of the moment.

The hadron shower direction resolution is obtained to be in the range of \((15^\circ - 5^\circ)\). Further, the spread of hits with respect to this direction can also be used to distinguish between the shower due to RS and DIS processes. Since RS events mostly produce a pion, the shower would be confined to a narrower cone compared to the shower produced by multiple hadrons in DIS events.

### 2.4 THE NEUTRINO ENERGY AND DIRECTION RESOLUTIONS

The energy and direction of the incident neutrino have been estimated from the reconstructed momentum of the final state particles through the application of the 4–momentum conservation [12]. The neutrino energy is reconstructed by adding up the reconstructed energies of the muon and the hadrons in each event. For the events fully confined in ICAL, the energy resolution of neutrinos in the ICAL is in
the range $(22 - 26)\%$, whereas for the partially contained events in the detector it is $\sim 30\%$.

The muon and hadron momentum information is used to calculate the $X$, $Y$ and $Z$ projections of the neutrino momenta and eventually the neutrino direction. The resolution of the neutrino zenith angle at the ICAL is in the range $(19^\circ - 7.5^\circ)$. In an alternative approach, the neutrino direction has also been estimated from the average scatter angle between the incident neutrino and the reconstructed final state muon.

3. ENHANCING THE PHYSICS REACH OF ICAL WITH HADRONS

The initial analysis of the physics potential of ICAL was performed using the muon momentum $(E_\mu, \cos \theta_\mu)$ only [18, 19]. The ICAL capability of measuring the hadron energy, though with a relatively poorer resolution, provides additional information on the incident neutrino energy. This information is expected to enhance the ICAL physics reach. The hadron energy can be added to the analysis in multiple ways. First the neutrino momentum $(E_\nu, \cos \theta_\nu)$ was used in place of the muon momentum. However this gives poorer mass hierarchy (MH) sensitivity than the muon-only analysis. The main drawback is that while adding $E_\mu$ and $E'_{\text{had}}$ to calculate $E_\nu$, the advantage of high precision in the $E_\mu$ measurement is partially lost due to the coarser estimation of $E'_{\text{had}}$. Another approach with $(E_\nu, \cos \theta_\mu)$ improves the MH result slightly over the neutrino-only analysis, yet it is not even at par with the result obtained using muon momentum. However, treating $E_\mu$ and $E'_{\text{had}}$ as two separate variables improve the result significantly. In this approach, the correlation between these two quantities in each event is included in the study. The enhancement of the ICAL physics potential with the inclusion of hadron energy has then been obtained using the values $E_\mu, \cos \theta_\mu$ and $E'_{\text{had}}$ from each event as independent variables [20].
The analysis procedure is discussed in the following.

3.1 THE ANALYSIS PROCEDURE

1. **Event Generation:** NUANCEv3.5, with the ICAL specifications as input, is used as the Monte Carlo event generator to produce atmospheric neutrino interactions. The atmospheric neutrino flux provided by Honda et al. at the Super Kamiokande site is used [21]. In order to minimize the statistical fluctuations, CC $\nu_\mu$ events are produced for a large exposure of 50000 kt – yr and then scaled down to the required exposures. Producing events with such a large exposure at all possible sets of the oscillation parameters is practically impossible, so the event generator is run only once for un-oscillated neutrino flux, and later a re-weighting algorithm is used to incorporate the oscillations.

2. **Inclusion of the oscillations and detector response:** The events are re-weighted using a random selection algorithm. The survival/oscillation probabilities for the certain channel is calculated [22] using the given set of oscillation parameters. The benchmark values of the oscillations parameters are used as in [23, 24, 25]. Then for each event, a uniform random number $R$ between 0 and 1 is generated and compared to the probability to pick/discard that event. The re-weighted events are then binned in the observables $(E_\mu, \cos\theta_\mu, E_{\text{had}}')$ and folded with the ICAL response. The ICAL lookup tables for both muon and hadron response are used. First, the events in each bin were multiplied by the muon reconstruction efficiency and CID efficiency. Then the integrals of the detector response functions of the three observables are evaluated, and using them the measured distribution of the events are obtained.
3. The $\chi^2$ analysis: For the $\chi^2$ analysis the events are re-distributed in wider and non-uniform bins, the bin widths being comparable to the respective resolutions. A scheme of 20 $E_\mu$ bins in the range $1 – 11$ GeV, 21 $\cos \theta_\mu$ bins in the range $[-1, +1]$, and 4 $E_{\text{had}}$ bins in the range $0 – 15$ GeV are used for each polarity of muon.

The Poissonian $\chi^2_{\pm}$ for events with a $\mu^\pm$ is defined as

$$\chi^2_{\pm} = \min_{\xi_l} \sum_{i=1}^{N_{E_{\text{had}}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos \theta_\mu}} \left[ 2(N_{ijk}^{\text{theory}} - N_{ijk}^{\text{data}}) - 2N_{ijk}^{\text{data}} \ln \left( \frac{N_{ijk}^{\text{theory}}}{N_{ijk}^{\text{data}}} \right) \right] + \sum_{l=1}^{5} \xi_l^2.$$  \hspace{1cm} (7)

The following five systematic errors are included in the analysis using the method of pulls [26]: (i) Flux normalization error (20%), (ii) cross-section error (10%), (iii) tilt error (5%), (iv) zenith angle error (5%), and (v) overall systematics (5%). The total $\chi^2$ is obtained by adding the individual contributions from $\mu^-$ and $\mu^+$ events and a 8% prior (at 1σ) on $\sin^2 2\theta_{13}$.

$$\chi^2_{\text{ICAL}} = \chi^2_- + \chi^2_+ + \chi^2_{\text{prior}}.$$  \hspace{1cm} (8)

This $\chi^2_{\text{ICAL}}$ is marginalized over the pull variables $\xi_l$ and over the 3σ allowed range of the relevant oscillation parameters.

3.2 THE MASS HIERARCHY SENSITIVITY OF ICAL

The statistical significance of the analysis to discard the wrong hierarchy is quantified by

$$\Delta \chi^2_{\text{ICAL-MH}} = \chi^2_{\text{ICAL}(\text{false MH})} - \chi^2_{\text{ICAL}(\text{true MH})},$$  \hspace{1cm} (9)

where $\chi^2_{\text{ICAL}}$ (true MH) and $\chi^2_{\text{ICAL}}$ (false MH) are obtained by performing a fit to the observed data assuming true and false mass hierarchy, respectively.
The comparison of the $\Delta \chi^2_{\text{ICAL-MH}}$ obtained in this analysis with that from the muon-only analysis is shown in Fig. 3a, as a function of the ICAL run–time for true NH. After including the $E'_\text{had}$ information, 10 years of running can rule out the wrong hierarchy with $\Delta \chi^2_{\text{ICAL-MH}} \approx 9.5$ (for true NH), and $\Delta \chi^2_{\text{ICAL-MH}} \approx 8.7$ (for true IH), which mark an improvement of about 40% over the muon-only analysis. Fig. 3b shows the range of $\Delta \chi^2_{\text{ICAL-MH}}$ for different true $\sin^2 \theta_{23}$.

Figure 3: (a) $\Delta \chi^2_{\text{ICAL-MH}}$ as a function of the run–time assuming NH as true hierarchy. The red line shows the results with hadron information, while the black dashed line shows the same without including hadron information. (b) The variation of $\Delta \chi^2_{\text{ICAL-MH}}$ for different true values of $\sin^2 \theta_{23}$. The value of $\sin^2 2\theta_{13}$ (true) is taken to be 0.1 and NH is assumed to be the true hierarchy. [20]

3.3 PRECISION ON $\theta_{23}$ and $|\Delta m^2_{32}|$

The precision in the measurements of the parameter $\lambda$ ($\lambda = \sin^2 \theta_{23}$ or $|\Delta m^2_{32}|$), is quantified as

$$\Delta \chi^2_{\text{ICAL-PM}}(\lambda) = \chi^2_{\text{ICAL-PM}}(\lambda) - \chi^2_0,$$

where $\chi^2_0$ is the minimum value of $\chi^2_{\text{ICAL-PM}}$ in the allowed parameter range. It is observed that with the inclusion of $E'_{\text{had}}$ information, 500 kt–yr of ICAL exposure would be able to measure $\sin^2 \theta_{23}$ to a relative 1σ precision of 12% and $|\Delta m^2_{32}|$ to 2.9%. With the muon-only analysis, the same relative precisions would be 13.7% and 5.4%, respectively. The $\sin^2 \theta_{23}$ precision mainly depends on the event statistics, which is not changed by the addition of the $E'_{\text{had}}$ information, thus only a small difference is observed in the two analyses. However, independent measurements of $E'_\mu$ and $E'_{\text{had}}$.
corresponds to a better estimation of $E_\nu$, which appears in the oscillation expression as $\sin^2(\Delta m^2 L/E_\nu)$, thus leading to a significant improvement of the measurement of $\Delta m_{32}^2$. Fig. 4a shows the comparison of $\Delta \chi^2_{\text{ICAL-PM}} (\Delta m_{32}^2)$, with and without hadron energy information. The ICAL 500 kt–yr projected reach has been compared to the current results from other experiments in Fig. 4b.

Figure 4: (a) $\Delta \chi^2_{\text{ICAL-PM}} (\Delta m_{32}^2)$, with and without hadron energy information. The true hierarchy is assumed to be NH. (b) 90% C.L. (2 dof) contours in the $\sin^2 \theta_{23} - |\Delta m_{32}^2|$ plane. The current limits from Super-Kamiokande [27], MINOS [28], and T2K [29] have been shown along with the projected ICAL reach for the exposure of 500 kt-yr, assuming true NH. [20]

3.4 OCTANT OF $\theta_{23}$

In analogy with the MH discovery potential the statistical significance of the analysis to rule out the wrong octant of $\theta_{23}$ is defined as

$$\Delta \chi^2_{\text{ICAL-OS}} = \chi^2_{\text{ICAL}}(\text{false octant}) - \chi^2_{\text{ICAL}}(\text{true octant}).$$

(11)

It is observed that the potential of distinguishing the $\theta_{23}$ octant with the ICAL data alone is rather weak. A 2$\sigma$ identification of the octant is possible with the 500 kt–yr ICAL data alone only when the true hierarchy is NH and the true octant is LO ($\sin^2 \theta_{23}(\text{true}) < 0.395$).
4. DEVELOPMENT OF MULTIGAP RPC DETECTORS

The Multigap Resistive Plate Chambers (MRPCs) [30] are gas ionization detectors with multiple gas sub–gaps made of highly resistive electrodes. The high voltage (HV) is applied at the outer surfaces of the two outermost resistive plates only, while the interior plates are left electrically floating. The presence of multiple gas sub-gaps enables the detector to induce faster signals on the outer electrodes, thus improving the detector’s time resolution. MRPCs have been chosen as optimal elements for many Time–Of–Flight (TOF) detector systems (including ALICE and STAR) due to their excellent time resolution (< 100 ps) and higher efficiency for particle detection [31, 32]. A typical single-gap RPC detector, designed for ICAL, has a time resolution of ~ (1 – 1.5) ns. The use of MRPCs in ICAL would enable us to use the time count of the hits efficiently, and is likely to further improve the direction reconstructions of the muon and the hadron shower. In this work, glass MRPCs with 6 sub-gaps are developed and characterized to probe their potential applications in future ICAL upgrades, as well as in TOF experiments, imaging etc.

4.1 FABRICATION

MRPCs with 6 sub-gaps and of dimensions 305 mm × 305 mm × 7.5 mm are designed and fabricated. Glasses of 2 mm thickness with a conductive coat are used for the outer electrodes. The intermediate glass plates are 400 µm thick.

Small circular spacers of diameter 4 mm, which are made of two sided non conducting adhesive tapes, are used to maintain 250 µm gaps between floating electrodes. The configuration is optimized with sealing the gas gaps by gluing side spacers between the outermost electrodes. To ensure a proper gas flow through the sub–gaps, appropriate blockers are placed. The pickup panel consists of honeycomb panels laminated with copper strips of width 2.8 cm. Figure 5 shows a schematic diagram of the MRPC detector configuration.
4.2 DETECTOR SETUP AND DATA ACQUISITION

The MRPCs are tested and characterized in avalanche mode using a cosmic muon telescope consisting of three scintillator paddles (two on the top of the MRPCs under test and one at the bottom) The coincidence signal from these three paddles are used to trigger the data acquisition system. Signals from the MRPC pickup strips are amplified using NINO ASIC [33] and then taken with the time coincidence of the trigger.

A CAMAC based data acquisition (DAQ) system for the MRPC detector test is set up to record the strip counting rate, strip efficiency and time count. The efficiency is recorded with respect to the trigger through a 2–fold coincidence. The start and stop to the TDC counter are given by the trigger and MRPC signal respectively, and the corresponding time count are recorded.
4.3 CHARACTERIZATION

The MRPCs are operated in avalanche mode using the standard gas mixture of R134a, C$_4$H$_{10}$ and SF$_6$. The MRPC characteristics such as the strip counting rate, chamber current, efficiency and time resolution are studied as a function of the concentration of the gas mixture. Based on this study, the gas mixture is optimized to R134a (91%), C$_4$H$_{10}$ (5%), and SF$_6$ (4%).

![Efficiency and Time Resolution](image)

Figure 6: (a) The efficiency and (b) the time resolution of the MRPC as a function of the applied high voltage.

The efficiency and time resolution of the MRPC with the optimized gas mixture, as a function of the applied high voltage, are shown in Fig. 6. The efficiency increases with the high voltage, and reaches about 95% at 17.9 kV. The time distributions are corrected for the time jitter through an off line calibration of the time count with the charge count of the signal. Note that, for this calibration NINO ASIC is replaced by Anusparsh, which is designed for the ICAL experiment, as the later also provides the analog output required to obtain the charge count. A time resolution of ~ 60 ps is obtained at 17.9 kV. The MRPC is also tested with a Cs-137 source. This reduces the jitter due to the spread in location of the incident particle, and improves the time resolution further by about 10 ps. Thus the introduction of the sub-gaps results in a much improved time resolution over the single-gap configuration which has a typical time resolution in the range of (1 – 1.5) ns.
In addition, MRPCs with their fast timing characteristics, can reduce the jitter in a trigger scheme. This is confirmed by including an MRPC in the trigger set-up of scintillator paddles, to test a single gap RPC. The inclusion of the MRPC reduces the time jitter in the trigger by 50%.

5. SUMMARY AND FUTURE SCOPE

5.1 SUMMARY

The INO collaboration plans to study the neutrino oscillations in the atmospheric sector, with the 50 kt ICAL detector. Though primarily designed to measure the muon momentum, ICAL is also capable of detecting the hadron shower and measure its momentum. A simulation study is performed to quantify the hadron energy resolution of ICAL using the shower hit information. The hadron energy, parametrized in terms of $E'_{\text{had}} \equiv E_\nu - E_\mu$, is estimated from the hadron hit multiplicity which follows the Vavilov PDF. A calibration of $E'_{\text{had}}$ for the number of hadron hits in an event has been obtained. The hit positions are used to reconstruct the average direction of the hadron shower using orientation matrix technique. The hadron momentum information is further used to obtain the neutrino response of the ICAL.

The reach of ICAL is then studied using the correlated information on the muons and the hadrons. The inclusion of the hadron information improves the ICAL physics potentials by significant amounts. It is found that the ICAL, with 500 kt–yr exposure, would be able to determine the neutrino mass hierarchy with a significance of $\Delta \chi^2_{\text{ICAL-MH}} \sim 9$, which implies about 40% enhancement over the muon-only analysis. The atmospheric neutrino mixing parameters can also be measured more precisely by the inclusion of hadron energy information.
MRPC detectors, with six sub-gaps in each of them, have been developed and characterized in order to probe their potential in the future upgrades of ICAL as well as other applications such as, TOF experiment. The design of the single cell structure has been optimized. These detectors are operated in the avalanche mode with a optimized gas mixture, and their efficiency, time resolution, strip counting rate etc have been studied using a CAMAC based DAQ system. A time resolution of $\sim 60$ ps is obtained at 17.9 kV.

The MRPCs are tested as a part of the external trigger system consisting of scintillators to characterize single gap RPCs, which shows 50% reduction in the time jitter of the trigger. A stack of four MRPCs is now fully operational.

5.2 FUTURE SCOPE

The separation of the muon track and the hadron shower hits would be crucial to use the real data, once ICAL becomes operational. Thus a simulation study to develop an efficient track-shower separation algorithm is important. Also, the neutrino response of the ICAL is coarse, and can be improved by stricter cuts, and with possible improvement in the measurements of the muon momentum and the hadron momentum. The inclusion of the hadron shower direction as the fourth independent variable in the oscillation analysis may be checked for further improvements. A promising work is to modify the oscillation analysis algorithm to study the ICAL potential to detect the sterile neutrinos. The MRPC detectors show good detection efficiency and time resolution, and now they are ready to be tested for possible applications as trigger detector, and in TOF experiments.
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<tr>
<td>AGN</td>
<td>Active Galactic Nuclei</td>
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<tr>
<td>ASIC</td>
<td>Application – Specific Integrated Circuit</td>
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<tr>
<td>CAMAC</td>
<td>Computer Automated Measurement And Control</td>
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<tr>
<td>CC</td>
<td>Charged – Current</td>
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<tr>
<td>CERN</td>
<td>Conseil Europen pour la Recherche Nuclaire, i.e., The European Organization for Nuclear Research</td>
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<tr>
<td>CMB</td>
<td>Cosmic Microwave Background</td>
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<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
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<td>Deep Inelastic Scattering</td>
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<td>ECL</td>
<td>Emitter – Coupled Logic</td>
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<td>FC</td>
<td>Fully – Contained</td>
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<td>FWHM</td>
<td>Full Width at Half Maximum</td>
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<td>GEANT</td>
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<td>GRB</td>
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<td>HWHM</td>
<td>Half Width at Half Maximum</td>
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<td>ICAL</td>
<td>Iron CALorimeter</td>
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<td>IH</td>
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<tr>
<td>INO</td>
<td>India–based Neutrino Observatory</td>
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<td>KamLAND</td>
<td>Kamioka Liquid Scintillator Anti Neutrino Detector</td>
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<td>KS</td>
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<tr>
<td>LVDS</td>
<td>Low – Voltage Differential Signaling</td>
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<td>MH</td>
<td>Mass Hierarchy</td>
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<tr>
<td>MINOS</td>
<td>Main Injector Neutrino Oscillation Search</td>
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<tr>
<td>MRPC</td>
<td>Multigap Resistive Plate Chamber</td>
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<tr>
<td>MSW</td>
<td>Mikheyev – Smirnov – Wolfenstein</td>
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<td>NC</td>
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<td>NH</td>
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<td>RENO</td>
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<td>RS</td>
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<tr>
<td>SCCM</td>
<td>Standard Cubic Centimeter per Minute</td>
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<td>Time – to – Digital Converter</td>
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